BNL-64912

Proceedings of RIKEN BNL Research Center Workshop Volume 4

CONF-9709192--Vol.4

NON-EQUILIBRIUM MANY BODY DYNAMICS

September 23-25, 1997

Organizers

Michael Creutz and Miklos Gyulassy

Inauguration Ceremony

September 22, 1997

RIKEN BNL Research Center

Building 510, Brookhaven National Laboratory, Upton, NY 11973, USA

Other RIKEN BNL Research Center Proceedings Volumes:

Volume 1 - Open Standards for Cascade Models for RHIC - BNL-64722
June 23-27, 1997 - Organizer - Miklos Gyulassy

Volume 2 - Perturbative QCD as a Probe of Hadron Structure - BNL-64723
July 14-25, 1997 - Organizers Robert Jaffe and George Sterman

Volume 3 - Hadron Spin-Flip at RHIC Energies - BNL-64724
July 21 - August 22, 1997 - Organizers T.L. Trueman and Elliot Leader

Photographs by Roger Stoutenburgh

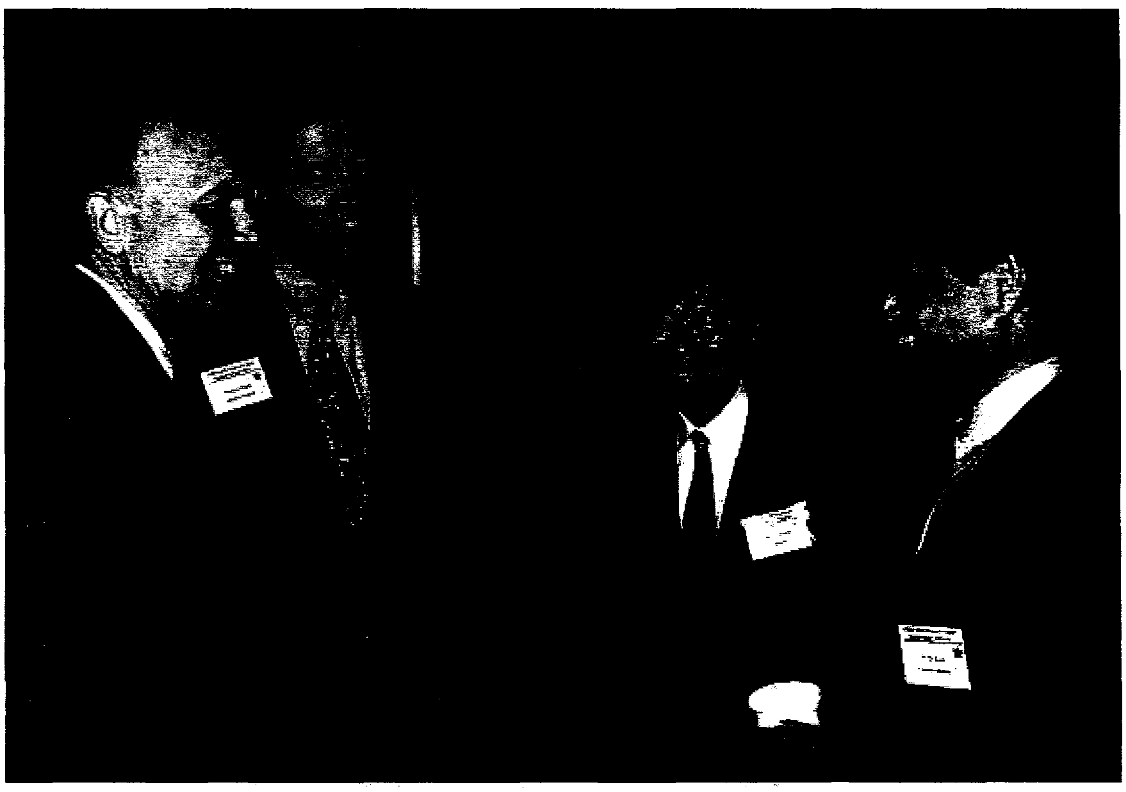
DISCLAIMER

DISCLAIMER

Dr. Akito Arima, President of RIKEN, handing to Professor Lee a plaque with the Japanese characters for "RIKEN BNL Research Center" inscribed in Dr. Arima's calligraphy.

Dr. Arima delivering the first talk at the Inaugural Ceremony.

Mr. Seiji Kojima, Minister, Embassy of Japan.



Dr. Peter Bond, Dr. George Rupp and Professor Lee with Dr. Arima.

Dr. Peter Bond, Interim Director, Brookhaven National Laboratory.

Dr. Peter Rosen, Associate Director for High Energy and Nuclear Physics,
Office of Energy Research, U.S. Department of Energy.

Dr. George Rupp, President, Columbia University.

Dr. David Hendrie, Director, Division of Nuclear Physics, U.S. Department of Energy,
and Dr. Satoshi Ozaki, Head, RHIC Project, Brookhaven National Laboratory.

*Opening Ceremony**

Distinguished guests and colleagues:

Our century has been a period of very rapid progress in science and technology. That progress, to a large extent, depended on the discovery of Quantum Mechanics around 1925. Without Quantum Mechanics, we would not have today's knowledge of atomic physics, molecular structure, nuclear and subnuclear forces, semiconductors, super-conductors, lasers, supercomputers--indeed, a very large part of the twentieth century scientific civilization.

The RIKEN BNL Research Center is for the future. In order to make the Center a success, we have to understand the dynamics of scientific creativity and the best way to nurture it. We may recall the role of the Niels Bohr Institute in the physics of the 1920's. At that time, Bohr had already formulated his old quantization rule and Einstein had completed his Theory of Relativity. A new generation of physicists went through the Niels Bohr Institute, including Heisenberg, Dirac, Fermi, Pauli, Nishina, Rabi and others. While Bohr and Einstein were still active at that time, they did not create Quantum Mechanics. Quantum Mechanics was created by this new group of young physicists, mostly in their twenties.

In the 1930's and 1940's, there were new challenges in nuclear forces and quantum electrodynamics. The heroic generation that invented Quantum Mechanics was still very active. Yet these new problems were solved by Yukawa and Tomonaga at RIKEN, Schwinger, Lamb, Kusch at Columbia, and Feynman, Dyson at Cornell. Again, almost all were in their twenties and thirties.

In the 1950's came the strange particles and their puzzling behavior. Once more, the new physics was made by yet another young generation of physicists: Gell-Mann, Nambu, Yang, myself and others. Then, in the late 1960's and 70's, there remained the tasks of completing the unification of the electromagnetic and the weak

---

*Given by T. D. Lee during the Inauguration Ceremony of the RIKEN BNL Research Center on September 22, 1997.

interactions into a single force--the electroweak force--and the formulating of strong forces in terms of quantum chromodynamics. These tasks were undertaken by still another generation of young physicists, Weinberg, Glashow, Politzer, Wilczek, Gross, 't Hooft and others.

The progress of physics depends on young scientists facing new challenges. To create the new physics, there has to be the right place at the right time for these young scientists. This pattern will not change. The nurturing of new generations of physicists and the writing of new chapters in science are the missions of this Center.

What are the challenges in modern physics? Three of these challenges are listed below:

Challenges in Physics

- Symmetry in theory but violation by experiment.
- Half of the elementary particles are unfree.
- Lack of precision QCD calculations.

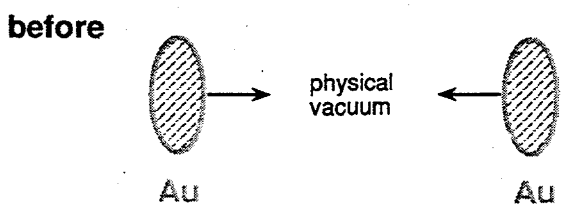
Vacuum state is asymmetrical.
Vacuum is a condensate which confines quarks and gluons.

It was exactly forty years ago that parity nonconservation was discovered. Since then, the basis of our theory has become more and more symmetric. Yet, our experiments have discovered more and more violations. This dichotomy--"symmetry in theory but violation in experiment"-- is one of the puzzles in modern physics.

To appreciate the second challenge, we note that all matter is made of two kinds of elementary particles: Leptons and Quarks. Yet, half of the elementary particles--the Quarks--are un-free. Why?

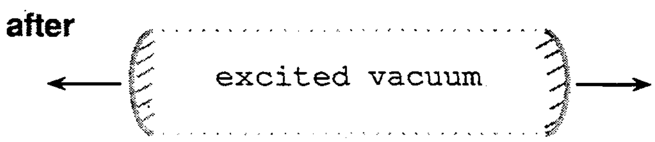
The current theoretical idea is to attribute the solutions of both problems to the structure of the vacuum state. The vacuum state is a state without matter. But it has Lorentz-invariant interactions. Therefore, it is complex, but not an aether. If the vacuum is a medium, violating symmetries and acting like a condensate (similar to the superconductor), then we should be able to change the properties of our vacuum through physical means. This is one of the main purposes of the Relativistic Heavy Ion Collider (RHIC) Project.

RHIC (100 GeV/nucleon)



Is Vacuum a Physical Medium?

T.D.L. and G.C. Wick, Phys.Rev. **D9**, 2291 (1974).



(quark-antiquark gluon plasma)

We now turn to the third challenge in physics: lack of precision QCD calculations. The strong force that binds the nuclei and dictates the motion of the subnuclear particles is described by Quantum Chromodynamics (QCD). At present, we lack precision QCD calculations. Yet, precision is the backbone of physics. To overcome this difficulty, we need *new talents*, *new ideas* and *new powerful supercomputers.*

In the first year of the Center, we have ten new research scientists. Five young ones with two- and five-year appointments, and five senior ones as visiting scientists. These ten will work together, and with BNL and RIKEN scientists.

Research Scientists 1997

Fellows:	D. Kharzeev	(Universität Bielefeld)
	D. Rischke	(Duke University)
Postdocs:	H. Fujii	(Tokyo Metropolitan University)
	M. Wingate	(University of Colorado)
	Y. Yasui	(Kyoto University)
Visiting Professors (full time):		
	R. D. Mawhinney	(on leave from Columbia University)
	S. Ohta	(on leave from KEK)
Visiting Professors:		
	M. Gyulassy	(Columbia University)
	R. Jaffe	(M. I. T.)
	E. Shuryak	(SUNY, Stony Brook)

New talents will generate new ideas. To help these new ideas to fruition, an effective means is to organize workshops.

1997-1998 Workshop Program

Subject	Dates	Organizers
Open Standards for Cascade Models for RHIC	June 23-27	M. Gyulassy
Perturbative QCD as a Probe of Hadron Structure	July 14-25	R. Jaffe G. Sterman
Hadron Helicity Flip at RHIC Energies	Jul. 28-Aug.29	L. Trueman
Non-Equilibrium Many Body Physics	Sept. 23-25	M. Creutz M. Gyulassy
Quarks and Gluons in the Nucleon	Nov. 28-29	K. Yazaki
Use of Teraflop Parallel Processor	End 1997 / Early 1998	R. Mawhinney S. Ohta
RHIC Spin Physics	Spring 1998	G. Bunce M. Tannenbaum
QCD Vacuum and Phase Transitions	1998	E. Shuryak

The first three workshops have already taken place, and the fourth one will start tomorrow. Each workshop addresses a specific physics problem and the participants consist of the Center scientists and other leading experts from all over the world. An important feature for the dissemination of the results of the workshops is to have rapid publication of the proceedings. Here, at the Center, the proceedings are available within two weeks after the workshops. Perhaps this sets a certain kind of world record. Three of the proceedings are in your conference bags.

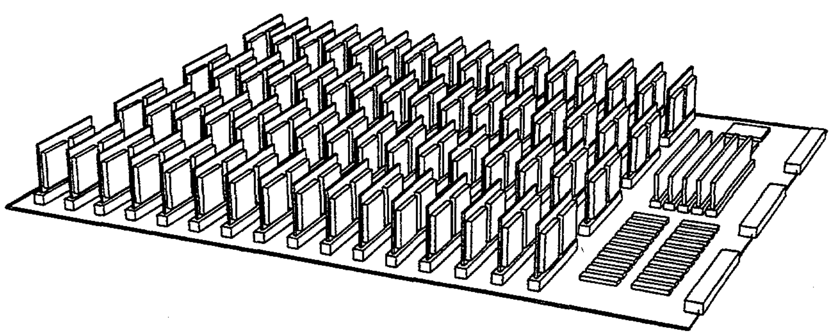
At the Center, there will soon be a powerful parallel processor, with a 0.6 Teraflop computer located at the Center. It will work in tandem with the 0.4 Teraflop at Columbia, giving the full computational ability of 1.0 Teraflop.

Parallel Processor Supercomputer

(N. H. Christ, R. D. Mawhinney and S. Ohta)

RIKEN BNL Research Center	0.6 Teraflop
Columbia Theoretical Physics Group	0.4 Teraflop
	1.0 Teraflop
Number of processors (daughterboards)	20,480
Number of motherboards (each motherboard consists of 64 daughterboards)	320
Completion date	December 1997

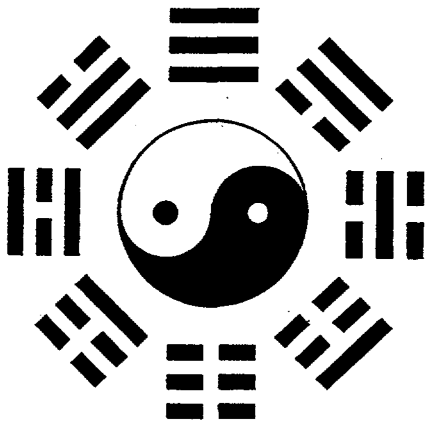
This will be the world's most powerful supercomputer entirely dedicated to the study of quantum chromodynamics. Each daughterboard has the computational power of a workstation, costing less than $100, and there are 64 daughterboards to a motherboard. A module will be on view after the ceremony.



A new center has to be represented by a new symbol. The logo on the cover of this proceedings was designed by me. It is partially based on the ancient Chinese diagrams, *Tai Chi* and *Ba Gua*.

TAI CHI and BA GUA

太極 八卦



Both Tai Chi and Ba Gua are based on duality, the Yin and the Yang, and the long and short. I then incorporated into the logo the idea of Lao Tse.

Lao Tse: Tao Te Ching

(about 550 B.C.)

The Tao generates one, 道生一
One generates two, 一生二
Two generates three, 二生三
Three generates
ten thousand things. 三生萬物

The result is the RIKEN BNL Research Center logo. The red sun is the emblem of Japan, and the colors of the American flag are red, white and blue. The red center in the new design represents unity, the one. The blue and white denote the duality, which is the two. Together, they form the trinity, which is the three. From the three, all else follows. The concept and the aim of the Center are in harmony with Lao Tse's philosophy.

In order to express my feeling for the new physics that will be discovered at RHIC, I wrote the following two lines a few years ago:

核子重如牛

對撞生新態

李政道

Nuclei as heavy as bulls
Through collision
Generate new states of matter.

T. D. Lee

I asked my friend, Li Keran, who was then the President of the Academy of Chinese Painting, to put these words into painting. He produced the remarkable masterpiece that you see on the poster.

This painting is a contrast of statics and dynamics. Li Keran was able to freeze the enormous tension of the bulls into a single instant of time. The very static, yet tense, posture of the bulls forces the viewer to anticipate the violence of the subsequent collision and the change that has to follow. This is very much like what happens in a relativisitc heavy ion collision. The collision time is only about 10^{-22} seconds, that is one-tenth of a billionth of a trillionth of a second. Yet, in that instant, all the 40 TeV energy will be released, and the vacuum will be changed, which will un-confine the quarks and the gluons.

RIKEN BNL RESEARCH CENTER
INAUGURATION CEREMONY

Monday, September 22, 1997
Brookhaven National Laboratory

PROGRAM

10:00 AM Registration Desk Opens
(Physics Department Lounge)

11:00 AM INAUGURATION CEREMONY
(Physics Department Large Seminar Room)

Opening and Welcome
Dr. S. Ozaki, RHIC Project Head

Addresses by
- Prof. Akito Arima, President of RIKEN
- Mr. Seiji Kojima, Minister, Embassy of Japan
- Dr. Peter Rosen, Associate Director for High Energy and Nuclear Physics, Office of Energy Research U.S. Department of Energy
- Dr. George Rupp, President of Columbia University
- Dr. Peter Bond, Interim Director Brookhaven National Laboratory
- Prof. T.D. Lee, Columbia University Director, RIKEN BNL Research Center

12:00 Noon Tour of the RIKEN BNL Research Center Area
(2^{nd} Floor, Physics Center Wing)
Hanging of the Center Name Plate

12:30 PM Luncheon
(Brookhaven Center)

2:00 PM Tour of RHIC Facility
(Collider Center Lobby)
- Tunnel
- STAR Hall
- PHENIX Hall

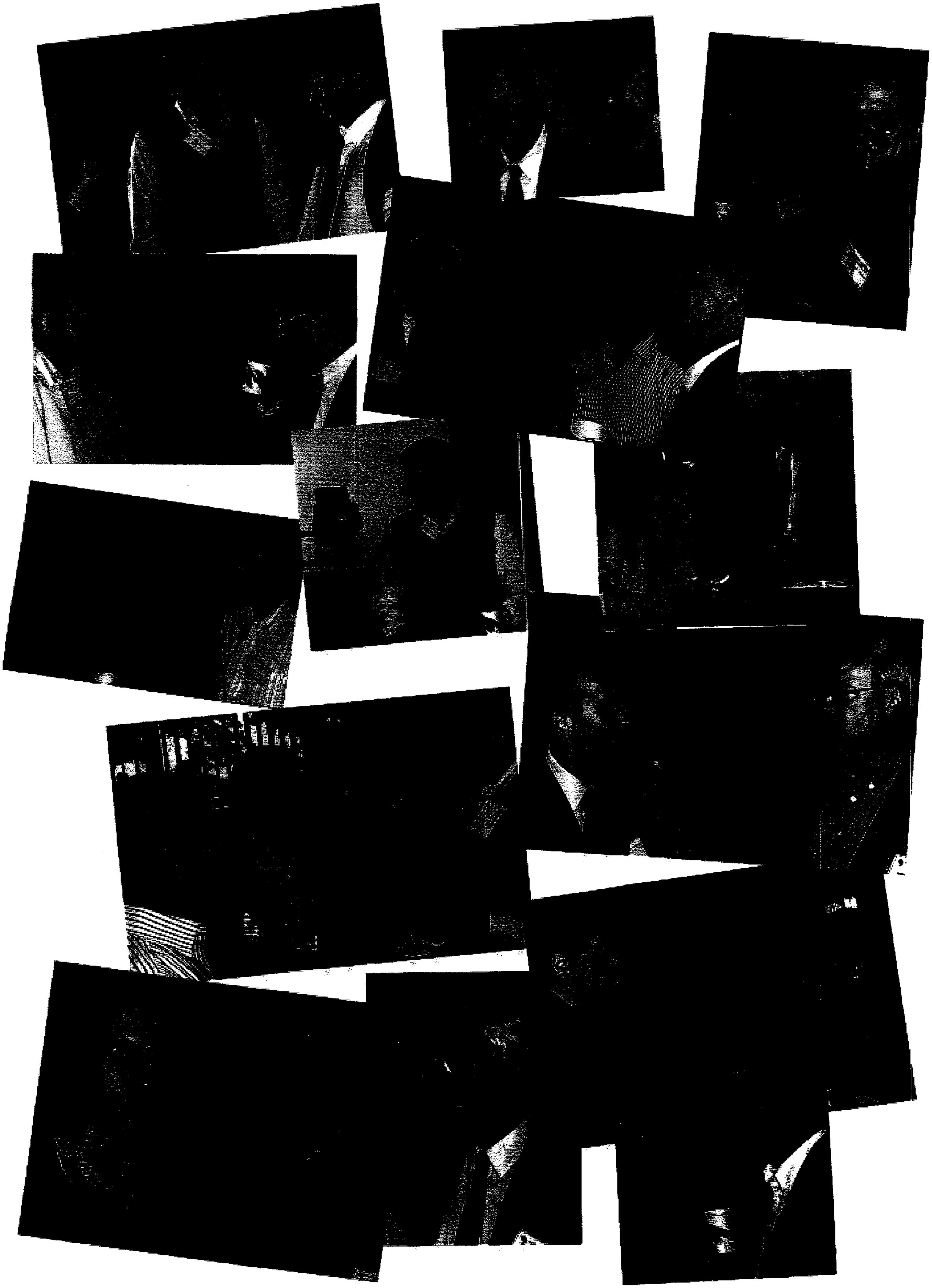
RIKEN BNL Research Center

Bldg. 510, Brookhaven National Laboratory, Upton, NY 11973, USA

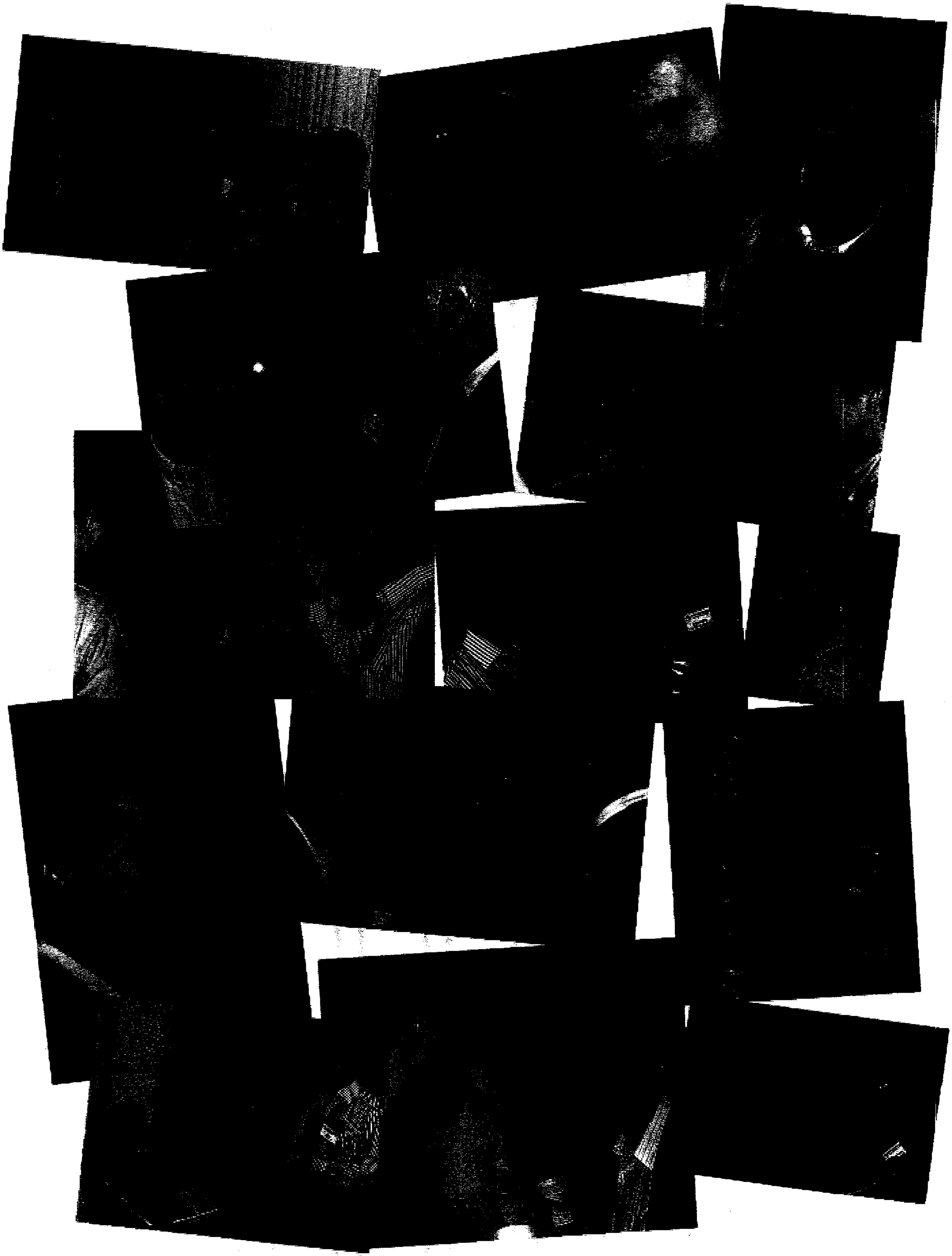
Symposium on

NON-EQUILIBRIUM MANY BODY DYNAMICS

September 23-25, 1997




RIKEN BNL
Center Symposium
Non-Equilibrium
Many
physics



CONTENTS

Preface to the Series

The RIKEN BNL Research Center was established this April at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkysho" (Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including hard QCD/spin physics, lattice QCD and RHIC physics through nurturing of a new generation of young physicists.

For the first year, the Center will have only a Theory Group, with an Experimental Group to be structured later. The Theory Group will consist of about 12-15 Postdocs and Fellows, and plans to have an active Visiting Scientist program. A 0.6 teraflop parallel processor will be completed at the Center by the end of this year. In addition, the Center organizes workshops centered on specific problems in strong interactions.

Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form a proceedings, which can therefore be available within a short time.

T.D. Lee
July 4, 1997

Introduction

This Riken BNL Research Center Symposium on Non-Equilibrium Many Body Physics was held on September 23-25, 1997 as part of the official opening ceremony of the Center at Brookhaven National Lab. A major objective of theoretical work at the center is to elaborate on the full spectrum of strong interaction physics based on QCD, including the physics of confinement and chiral symmetry breaking, the parton structure of hadrons and nuclei, and the phenomenology of ultra-relativistic nuclear collisions related to the upcoming experiments at RHIC. The opportunities and challenges of nuclear and particle physics in this area naturally involve aspects of the many body problem common to many other fields. The aim of this symposium was to find common theoretical threads in the area of non-equilibrium physics and modern transport theories. The program consisted of invited talks on a variety topics from the fields of atomic, condensed matter, plasma, astrophysics, cosmology, and chemistry, in addition to nuclear and particle physics.

Gordon Baym discussed recent developments in Bose-Einstein condensation. Jean-Paul Blaizot discussed the magnetic infrared problems in QED and QCD Plasmas showing the non-exponential decay of quasi-particles in such systems. Fred Cooper discussed a quantum field theory approach to calculating the spectrum of dileptons at RHIC from the nonequilibrium chiral phase transition. Pavel Danielewicz reviewed the techniques of Nonequilibrium Quantum Kinetics. Klaus Kinder-Geiger presented a field theoretic basis for the formulation of parton cascade dynamics. Gabor Kalman gave an overview of the field of Strongly Coupled Coulomb Systems emphasizing the importance of going beyond the RPA approximations including dynamical correlations at strong coupling. Dmitri Kharzeev reviewed the status of the j/psi suppression signature for deconfinement in nuclear collisions. Kazuo Kitahara discussed the Nonequilibrium Thermodynamics of multicomponent hydrodynamic systems. Dimitri Kusnezov discussed a number of Open Questions in Non-Equilibrium Physics. T. D. Lee, the director of the center, discussed his new formulation of non-compact lattice theory to remove artifacts of lattice QCD and provide ultimately a foundation for non-equilibrium quantum dynamics calculations. Larry McLerran discussed the general problem of separating classical field dynamics and parton kinetics in gauge theories. Bernd Müller presented a proposal for such separation and presented numerical results on the problem of color chaos in QCD. Yang Pang discussed the problem of constructing Lorentz covariant transport theories. Rob Pisarski covered the topic of Non-Abelian Debye Screening and the "Tsunami" Problem. Dirk Rischke discussed the Classical Yang-Mills field dynamics in ultra-relativistic nuclear collisions. Ed Shuryak emphasized the role of instanton or tunneling effects in the QCD phase transition and related hadronic observables. Paul Terry discussed current problems in Turbulent (classical E+M) Plasmas. Frank Wilczek presented a novel idea on how instanton effects in QCD could lead to Color Superconductivity at high baryon densities. His speculation that such phenomena may lead to strong parity violation stirred considerable interest and discussion.

The very high quality of the talks by these speakers and the intense discussions during the symposium among the participants served well to launch the theoretical work that will be pursued at the Riken BNL Research Center in the coming years.

Miklos Gyulassy and Michael Creutz are particularly grateful to Yang Pang for extensive help during the organization of this symposium, and none of this would have been possible without the tireless work of symposium secretaries Pam Esposito, Isabel Harrity, and Irene Tramm.

Thanks to Brookhaven National Laboratory and to the U.S. Department of Energy for providing the facilities to hold this symposium.

M. Gyulassy

Co-Organizer

ELIMINATION OF SPURIOUS LATTICE FERMION SOLUTIONS AND NONCOMPACT LATTICE QCD

T. D. Lee

It is well known that the Dirac equation on a discrete hyper-cubic lattice in D dimension has 2^D degenerate solutions. The usual method of removing these spurious solutions encounters difficulties with chiral symmetry when the lattice spacing $\ell \neq 0$, as exemplified by the persistent problem of the pion mass. On the other hand, we recall that in any crystal in nature, all the electrons do move in a lattice and satisfy the Dirac equation; yet there is not a single physical result that has ever been entangled with a spurious fermion solution. Therefore it should not be difficult to eliminate these unphysical elements.

On a discrete lattice, particles hop from point to point, whereas in a real crystal the lattice structure is embedded in a continuum and electrons move continuously from lattice cell to lattice cell. In a discrete system, the lattice functions are defined only on individual points (or links, as in the case of gauge fields). However, in a crystal the electron state vector is represented by the Bloch wave functions which are continuous functions in $\vec{r}$, and herein lies one of the essential differences.

In this new approach we shall keep the lattice spacing ℓ fixed and non-zero. The field operator will be expanded in terms of a suitably chosen complete set of orthonormal Bloch functions

$$\{ f_n(\vec{K} \,|\, \vec{r}) \}$$

where $\vec{K}$ denotes the Bloch wave number restricted to the Brillouin zone, and n labels the different bands. Thus, $e^{-i\vec{K}\cdot\vec{r}} f_n(\vec{K} \,|\, \vec{r})$ has the periodicity of the lattice. The lattice approximation is then derived by either restricting it to only one band (say, $n = 0$), or to a few appropriately defined low-lying bands. Since the inclusion of all bands *is* the original continuum problem, there is a natural connection between the lattice and the continuum in this method. By including the contributions due to more and more bands, one can systematically arrive at the exact continuum solution from the lattice approximation. There is a large degree of freedom in choosing the Bloch functions, as the original continuum theory has no crystal structure. These extra degrees of freedom are analogous to gauge fixing; the final answer to the continuum problem is independent of the particular choice of Bloch functions.

Figure 1. Difference between a discrete lattice and a crystal.

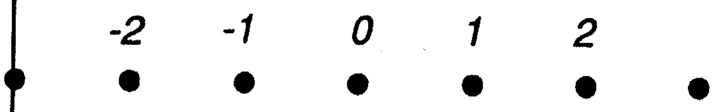
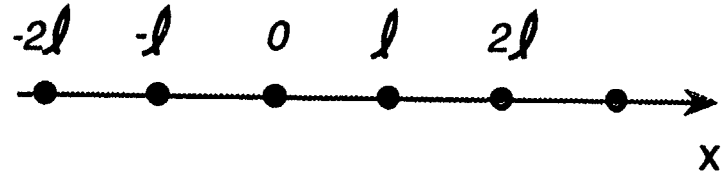
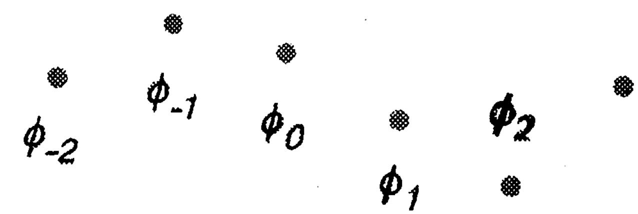
Figure 2. The zeroth-band Bloch function serves as a simple continuum interpolation of discrete values.

Figure 3. Construction of higher-band Bloch functions.

Figure 4. Elimination of spurious lattice fermion solutions (R. Friedberg, T.D. Lee and Y. Pang, J.Math.Phys. **35**, 5600 (1994)).

Figure 5. Noncompact lattice QCD in the Coulomb Gauge (R. Friedberg, T.D. Lee, Y. Pang and H.C. Ren, Phys.Rev. D**52**, 4058 (1995)).

Fig. 1

	discrete lattice	*crystal*
Configuration	only lattice sites, no inside 	lattice sites embedded within a continuum 
Field	$\phi_j =$ 	$\phi(x) = \sum_n \sum_K q_n(K)\, f_n(K \mid x)$ n = different band
Wave number	$-\pi \leq K\ell = \theta \leq \pi$ $\longleftrightarrow$	same K = *Bloch wave no.*
	$q(K) = \sum_j e^{iKx_j}\, \phi_j$	$f_n(K \mid x+\ell) = e^{iK\ell} f_n(K \mid x)$

Strategy

1. 0th band: simple continuum interpolations of discrete values (lattice approximation)

2. $n \neq 0$ bands: close to Fourier series (radiative corrections)

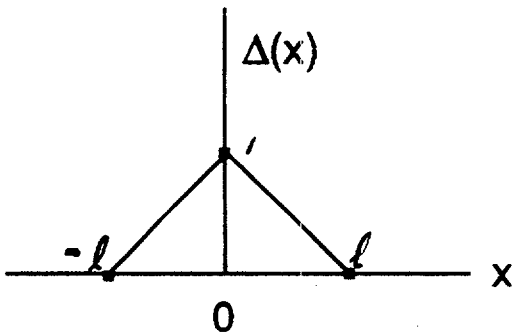
$\therefore$ lattice $\rightarrow$ continuum, without $\ell \rightarrow 0$.

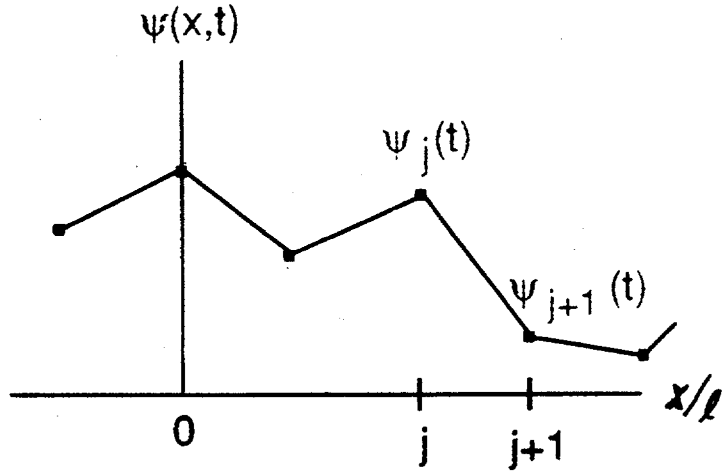
Fig. 2

Example: Spin 1/2 field ψ in 1+1 dimension

$$\psi(x, t) = \sum_n \sum_K q_j^n(t)\, f_n(K \mid x)$$

<u>0th band (n = 0) Bloch function $f_0(K \mid x)$</u>





$$\Delta(x) = \begin{cases} 1 - \dfrac{|x|}{\ell}, & |x| < \ell \\ 0, & |x| > \ell \end{cases} \quad ; \quad \psi(x,t) = \sum_j \psi_j(t)\ \Delta(x - j\ell)$$

Write $\quad \psi(x,t) = \sum_K q_j^0(t)\ f_0(K \mid x)$

$$f_0(K \mid x) = \sqrt{\frac{3}{L(2 + \cos K\ell)}}\ \sum_j e^{ijK\ell}\ \Delta(x - j\ell)$$

$|K\ell| < \pi \qquad$ Brillouin zone

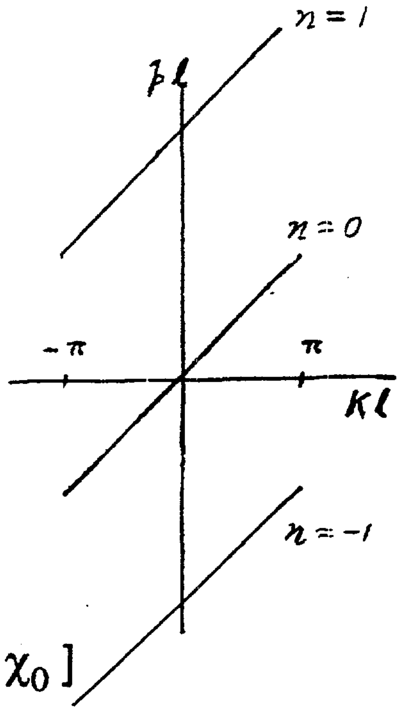
Lattice locality:

$$\sum_j e^{-iKx_j} f_0(K \mid x) \propto \Delta(x - x_j) = 0 \quad \text{if } |x - x_j| > \ell$$

Figure 3

Example: Spin 1/2 field ψ in 1+1 dimension (cont.)

$$\psi(x, t) = \sum_n \sum_K q_j^{\,n}(t)\, f_n(K \mid x)$$



0th band (n = 0) Bloch function $f_0(K \mid x)$

Construction of a complete set of orthonormal Bloch functions $\{ f_n(K \mid x) \}$

Let $\quad \chi_p(x) = \dfrac{e^{ipx}}{\sqrt{L}} \quad , \qquad p = K + \dfrac{2\pi n}{\ell}$

Write $\quad \chi_p(x) = \chi_n(x) = \dfrac{e^{iKx}}{\sqrt{L}} \cdot e^{i2\pi n x/\ell}$

$n \neq 0 \quad f_n(K \mid x) = \chi_n - \dfrac{a_n}{1+a_0}\,[\, f_0(K \mid x) + \chi_0 \,]$

$$a_n = \int_0^L f_0(K \mid x)^* \, \chi_n(x)\, dx \,, \qquad \text{for } \underline{\text{all}}\ n$$

1. $f_n(K \mid x + \ell) = e^{iK\ell} f_n(K \mid x) \,, \qquad |K\ell| < \pi$

2. $\displaystyle\int_0^L f_n(K \mid x)^* \, f_m(K' \mid x)\, dx = \delta_{nm}\, \delta_{KK'}$

---

for $\quad f_0(K \mid x) = \sqrt{\dfrac{3}{L(2+\cos K\ell)}} \displaystyle\sum_j e^{ijK\ell}\, \Delta(x - j\ell)$

$$\longrightarrow \quad a_n = \sqrt{\frac{3}{2+\cos K\ell}} \left[\frac{2(1-\cos K\ell)}{(2\pi n + K\ell)^2} \right]$$

In D-dim $\qquad a_{\vec{n}} = \displaystyle\prod_{\mu=1}^{D} a_{n_\mu}$

Fig. 4

$\frac{1}{i}\frac{\partial}{\partial x}$ in terms of band functions $\{f_n(K\,|\,x)\}$

$$f_0(K\,|\,x) = \sqrt{\frac{3}{2+\cos\theta}}\ \sum_j e^{ij\theta}\,\Delta(x - j\ell)$$

$\theta = K\ell\ ,\qquad |\theta| < \pi\qquad$ Brillouin zone

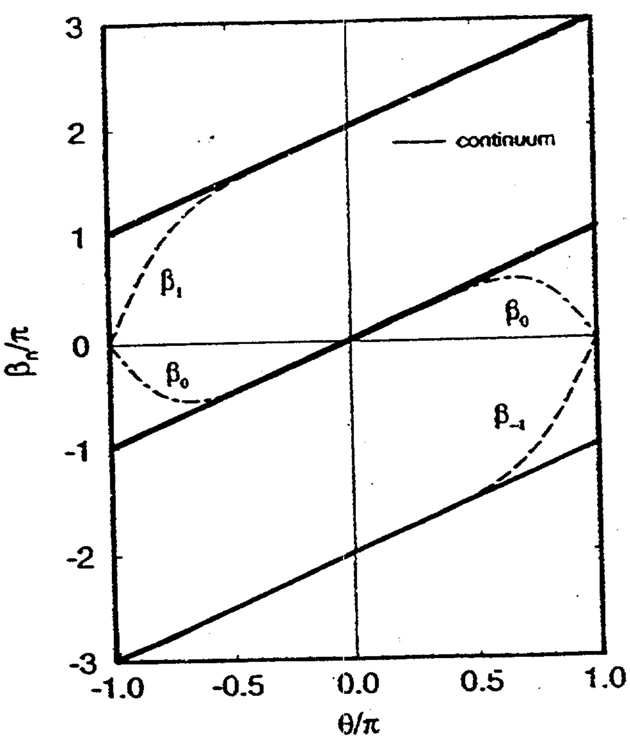
$$\beta_0 \equiv \ell \int f_0^*(K\,|\,x)\ \frac{1}{i}\ \frac{\partial}{\partial x}\ f_0(K\,|\,x)\,dx$$

$$= \frac{3\sin\theta}{2+\cos\theta}$$

n^{th} band

$$\beta_n \equiv \ell \int f_n^*(K\,|\,x)\ \frac{1}{i}\ \frac{\partial}{\partial x}\ f_n(K\,|\,x)\,dx$$

— exact continuum eigenvalue $p\ell = \theta + 2\pi n$



$|n| > 1$, $\beta_n \cong$ continuum result within $< 1\%$

$n = 0$ and -1 together remove the spurious degeneracy at $\theta = \pi$ to $\pm\sqrt{10} = \pm 1.006\,\pi$!

Fig. 5

Noncompact Lattice QCD

0th band $\qquad A_\mu^m(\vec{r}, t) = \sum_K q^m(\vec{K}, t)\, F_\mu(\vec{K} \,|\, \vec{r})$

superscript $\qquad m = 1, 2, \cdots, n^2 - 1$ *color index*

1. Bloch wave function $\qquad F_\mu(\vec{K} \,|\, \vec{r} + \vec{\ell}) = e^{i\vec{K}\cdot\vec{\ell}}\, F_\mu(\vec{K} \,|\, \vec{r})$

   $\vec{K}$ within the Brillouin zone

2. lattice locality $\qquad \sum_{\vec{K}} e^{-i\vec{K}\cdot\vec{r}_j}\, F_\mu(\vec{K} \,|\, \vec{r}) = 0$

   if $|\vec{r} - \vec{r}_j| > \nu\ell, \qquad \nu = O(1)$

3. continuum gauge condition

   Coulomb gauge $\qquad \vec{\nabla}\cdot\vec{A}^m(\vec{r}, t) = 0$

should hold at all continuum $\vec{r}, t$
within each band (0 th, or any other band)

$$f(K/x) \propto \sum_{n=1}^{N} e^{iKn\ell}\, \Delta(x - n\ell), \qquad g(K/x) \propto \sum_{n=1}^{N} e^{iKn\ell}\, Q(x - n\ell)$$

$$\frac{dQ}{dx} = \Delta(x) - \Delta(x - \ell)$$

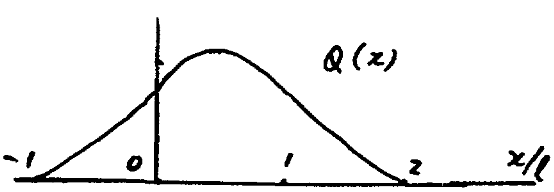
$$\frac{dg}{dx} \propto f$$

$$\partial F_x/\partial x \propto \partial F_y/\partial y \propto \partial F_z/\partial z$$

$$F_x(\vec{K}/\vec{r}) = g(K_x/x)\, f(K_y/y)\, f(K_z/z)$$

$$F_y(\,''\,) = f(\,''\,)\, g(\,''\,)\, f(\,''\,)$$

$$F_z(\,''\,) = f(\,''\,)\, f(\,''\,)\, g(\,''\,)$$



ON THE NONEQUILIBRIUM THERMODYNAMICS

Kazuo KITAHARA
Tokyo Institute of Technology
In collaboration with
Dr. Kunimasa MIYAZAKI National Institute of Matereals Engineering
Prof. Dick BEDEAUX Leiden University

Physica A 230 (1996) 600 - 630

What is Thermodynamics?

Thermodynamics is the discipline of phenomenology.

The description of nature on the macroscopic level.

The bases of thermodynamics:

- **Conservation Law**
  Energy Conservation (The First Law)
  Momentum Conservation, Mass Conservation
- **Irreversibility**
  The entorpy production(The Second Law)
- **Extensivity**
  Entropy is proportional to the size of the system.
  Gibbs-Duhem Relation

Independent of microscopic details.

Importance of General Framework of Thermodynamics

Thermodynamics gives guiding principles for microscopic formulations of non-equilibrium statistical mechanics.

Levels of Description of Macroscopic Systems:

- **Hydrodynamical Level**

  Themodynamics, Hydrodymanics, Diffusion Equation, Chemical Kinetics

  Description of macroscopic variables;

  Irreversibility is postulated.

- **Kinetic Level**

  Boltzmann equation, Master equation, Vlasov equation

  Fluctuations are described in terms of probability distributions.

  Irreversibility is postulated.

- **Microscopic Level**

  Liouville equation.

  Equivalent to mechanics of the total systems.

  Irreversibility is not postulated, but results from the equation.

Thus it is important to formulate all hydrodynamic equations in terms of "entropy". Then we can discuss fluctuations.

The hydrodynamics involves flow of matters. Therefore, we have to include flow variables in "entropy". However, in traditional thermodynamics, "entropy" is a function of *internal energy*, *volume* and *mass*, but not of **flow variables**.

The aims of this report are:

1. To show how to include flow variables of multi-component fluids in entropy
   We examine the concept of internal energy and show that total energy rather than internal energy is more appropriate as independent variable.

2. To derive hydrodynamics for each component of mixture
   Navier-stokes equation for one-component fluid is well established but that for multi-component fluid is not well established. We use the Ansatz of "symplectic" structure in the reversible part of hydrodynamics to derive the "Navier-Stokes equation" for mixture.

3. To show the modification of Onsager reciprocity relation in the presence of mass flow

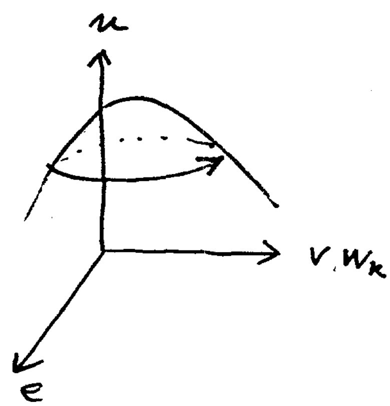
4. Rederivation of Fluctuation-Dissipation theorem for mixture.

5. (If time allows)
   Mori formalism vs. Green-Kubo formula

New Gibbs Relation using Gibbs Duhem relation

We combine the total energy expression

$$e = u + \frac{|\mathbf{v}|^2}{2} + \sum_{k=1}^{n} c_k \frac{|\mathbf{w}_k|^2}{2}$$



and Gibbs-Duhem relation

$$u = e - \frac{v^2}{2} - \sum c_k \frac{w_k^2}{2} \Rightarrow \begin{cases} Ts = u + Pv - \sum_{k=1}^{n} \mu_k c_k \\ \\ sdT = vdP - \sum_{k=1}^{n} c_k d\mu_k \end{cases}$$

extend $u \to (e, \vec{v}, \vec{w}_k$

Then, we arrive automatically at the new Gibbs relation

$$\begin{aligned} d(\rho s) &= \frac{1}{T} d(\rho e) && \text{total energy density} \\ &- \frac{\mathbf{v}}{T} \cdot d(\rho \mathbf{v}) && \text{momentum density} \\ &- \sum_{k=1}^{n-1} \frac{\mathbf{w}_k - \mathbf{w}_n}{T} \cdot d\mathbf{J}_k = -\sum_{k=1}^{n} \frac{\vec{w}_k \cdot d\vec{J}_k}{T} && \text{diffusion flow density} \\ &- \sum_{k=1}^{n} \frac{1}{T} \left(\mu_k - \frac{|\mathbf{v}|^2}{2} - \frac{|\mathbf{w}_k|^2}{2} \right) d\rho_k && \text{mass density} \end{aligned}$$

Note $\mathbf{J}_k = \rho_k \mathbf{w}_k$ (Diffusion mass flow). $\sum_{k=1}^{n} \mathbf{J}_k = 0$ by definition.

Without matter flow,

$$d(\rho s) = \frac{1}{T} d(\rho u) - \sum_k \frac{\mu_k}{T} d\rho_k$$

(Gibbs relation)

Extensive Variables, Intensive Parameters, Thermodynamic Forces

$$d(\rho s) = \sum_j F_j da_j$$

a_j density of an extensive variable

F_j intensive parameter

extensive variables	density variables	intensive parameters	thermodynamic forces
energy	ρe	$\frac{1}{T}$	$\nabla\left(\frac{1}{T}\right)$
momentum of barycentric flow	$\rho \mathbf{v}$	$-\frac{\mathbf{v}}{T}$	$-\nabla\left(\frac{\mathbf{v}}{T}\right)$
momentum of diffusional flow $k=1,\cdots n-1$	$\mathbf{J}_k = \rho_k \mathbf{v}_k$	$-\frac{\mathbf{w}_k - \mathbf{w}_n}{T}$	$-\frac{\mathbf{w}_k - \mathbf{w}_n}{T}$
mass $k=1,\cdots n$	ρ_k	$-\frac{1}{T}\left(\mu_k - \frac{\lvert\mathbf{v}\rvert^2}{2} - \frac{\lvert\mathbf{w}_k\rvert^2}{2}\right)$	

Entropy Production

Ansatz

$$d(\rho s) = \sum_j F_j da_j$$

The hydrodynamic equations for the density variables should be written as

$$\frac{\partial a_i}{\partial t} = \sum_j M_{ij} F_j + \sum_j L_{ij} F_j$$

where M_{ij} is antisymmetric and L_{ij} is a positive definite matrix.

Then we have

$$\frac{\partial(\rho s)}{\partial t} = \sum_{ij} L_{ij} F_i F_j \geq 0$$

The Onsager's coefficients L_{ij} correspond to irreversible processes. M_{ij} describe reversible porcesses and may be nonlinear functions of a_i. The antisymmetricity gives the clue to derive the unknown hydrodynamic equations for the multi-component fluids.

Continuum System

Since we deal with field variables, the hydrodynamic equation is integro-differential equation.

$$\frac{\partial a_i(\mathbf{r})}{\partial t} = \int d^3\mathbf{r}' \sum_j \{a_i(\mathbf{r}), a_j(\mathbf{r}')\} F_j(\mathbf{r}') + \int d^3\mathbf{r}' \sum_j L_{ij}(\mathbf{r}, \mathbf{r}') F_j(\mathbf{r}')$$

where we introduced the notation

$$M_{ij} \rightarrow \{a_i(\mathbf{r}), a_j(\mathbf{r}')\}$$

Then we have

$$\frac{dS}{dt} = \int d^3\mathbf{r} \frac{\partial(\rho s)}{\partial t} = \int d^3\mathbf{r} \sum_{ij} L_{ij} F_i F_j \geq 0$$

Recent Devlopments in Bose-Einstein Condensation

Gabor KALMAN

Boston College

STRONGLY COUPLED COULOMB SYSTEMS

OCP
- Ion traps (3D)
- Electrons on the surface of liquid He (2D)
- Storage rings (1D)

One single charge component in an inert neutralizing background

Electron Gas
- Metals (3D)
- Semiconductor quantum wells (2D)
- Quantum wires (1D)
- Quantum dots (0D)

Dense electron-ion plasma
- Inertial fusion
- Gas discharges
- Exploding wires

Heavy particles in a polarizable background

Liquid Metals

Meso-scopic plasmas
- Dusty plasmas
- Charged colloids

Binary mixtures	Planetary interiors White dwarfs	*2 different ions in a neutralizing back-ground*
Electron-hole plasmas	Semiconductors	
Positive and negative ions with repulsive core	Electrolytes Molten salts	*Strongly correlated positive and negative charges*
Logarithmic plasmas	Vortices Computer	*Solution of the 2D Poisson equation*

STANDARD RESPONSE FUNCTIONS (OF THE "FIRST KIND"):

linear response function

$$\langle \rho \rangle^{(1)} \sim \chi_1 \hat{\rho}$$

perturbation

$$\langle \rho \rangle^{(2)} \sim \chi_2 \hat{\rho} \hat{\rho}$$

quadratic response function

Standard FDT (linear):

$$\chi_1 \sim \langle \rho(1) \rho(2) \rangle^{(0)} \Rightarrow \quad S(\underline{k}\ \omega)$$

Quadratic FDT:

$$\chi_2 \sim \langle \rho(1) \rho(2)\ \rho(3) \rangle^{(0)} \Rightarrow \quad S(\underline{k}_1\ \omega_1, \underline{k}_2\ \omega_2)$$

three point dynamical structure factor

(G. Kalman and X.Y. Gu, 1987., K.S. Golden, G. Kalman and M. Silevitch, 1972)

RESPONSE FUNCTIONS OF THE "SECOND KIND":

linear response function

$$\langle \rho(1)\rho(2)\rangle^{(1)} \sim \Xi_1 \hat{\rho}$$

perturbation

$$\langle \rho(1)\rho(2)\rangle^{(2)} \sim \Xi_2 \hat{\rho}\hat{\rho}$$

quadratic response function

FDT of the "second kind": (X.Y. Gu, G. Kalman, Z.C. Tao, 1992):

$$\Xi_1 \sim \langle \rho(1)\rho(2)\rho(3)\rangle^{(0)}$$

$$\Xi_2 \sim \langle \rho(1)\rho(2)\rho(3)\rho(4)\rangle^{(0)}$$

N.B.:

$$\begin{tikzcd}
\chi_1 & \chi_2 \arrow[dl, leftrightarrow] & \chi_3 \arrow[dl, leftrightarrow] \\
\Xi_1 & \Xi_2 &
\end{tikzcd}$$

(G. Kalman and X.Y. Gu, 1987., K.S. Golden, G. Kalman and M. Silevitch, 1972)

DYNAMICAL MEAN FIELD THEORY

A DMFT can be based on the quadratic response and the quadratic Fluctuation Dissipation Theorem. Again, a self-consistent non-perturbative Mean Field Theory is obtained for $\varepsilon(k\omega)$.

$$\varepsilon = 1 - \varphi\chi_1\{F(12)\}$$

$$\Downarrow$$

$$F(12) = \text{Velocity averaged } \langle F(12) \rangle$$

$$= \langle \rho(1)\rho(2) \rangle^{(1)}$$

Approximation of F(12)

$$\Rightarrow \Xi$$

$$\Xi \Rightarrow \chi_2 \Rightarrow \chi_1 {}^* \chi_1$$

Quadratic Fluctuation Theorem

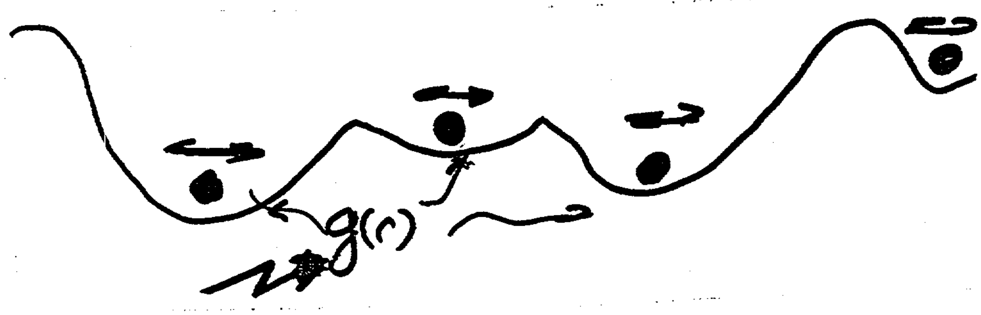
Approximation of χ_2

(K.S. Golden and G. Kalman, 1989)

The DMFT provides a dynamical $\varepsilon(k\omega)$, satisfies the High Frequency Sum Rules and gives a much better description of collective modes.

Quasi Localized Charge Approximation

For strong coupling the particles are localized on a "short" time scale in local potential fluctuations.



Correlations determine the average position of the particles. Their motion can be described in terms of the almost canonical collective cooridinates

$\xi^{A}_{K,\alpha}$ and $\pi^{A}_{K,\alpha}$

A:species index

$$\xi^{A}_{i,\alpha} = \frac{1}{(N_A m_A)^{1/2}} \sum_{\mathbf{k}} \xi^{A}_{\mathbf{k},\alpha} e^{i\mathbf{k}\cdot\mathbf{x}_i^A},$$

$$\pi^{A}_{i,\alpha} = \left[\frac{m_A}{N_A}\right]^{1/2} \sum_{\mathbf{k}} \pi^{A}_{\mathbf{k},\alpha} e^{i\mathbf{k}\cdot\mathbf{x}_i^A}.$$

$\xi^{A}_{i,\alpha}$ is the displacement and $\pi^{A}_{i,\alpha}$ is the associated momentum.

Main Equations:

Equation of Motion for the collective coordinate $\xi_{k,l}$

$$\{\omega^2 - C_{ij}(k)\}\xi_{k,i} = 0,$$

where $C_{ij}(k)$ is the dynamical matrix in layer-space:

$$C_{ij}(k) = {}^{n}\!/_{m}\,\varphi_{ij}(k)\,k^2 + D_{ij}(kq)\,.$$

The correlational effects are represented through the D-functions:

$$D_{ij}^{\mu\nu}(k) = \frac{n}{mA}\sum_{k'} k'^{\mu} k^{\nu} \varphi_{ij}(k')\, g_{ij}(|k-k'|) - \delta_{ij}\varphi_{il}(k)\, g_{ij}(k')$$

where $\varphi_{ij}(k)$ and $g_{ij}(k)$ are the Fourier transforms of the interaction potential and the pair correlation function respectively. The latter are supplied by HNC.

The dispersion relations reads

$$\varepsilon_{L,T} = 1 - \omega_{2D}^2(k)\{\omega^2 I - D_{L,T}(k)\}^{-1},$$

where $\varepsilon_L = 0 \leftrightarrow$ L modes and $\varepsilon_T = \infty \leftrightarrow$ T modes

Recent Devlopments in Bose-Einstein Condensation

Gordon BAYM

University of Illinois/Urbana-Champaign

BOSE-EINSTEIN CONDENSATION
THEN AND NOW

1924 – S.N. Bose : light quanta as particles
- new statistics

1924 – A. Einstein : extension to monatomic gases

1925 – A. Einstein : condensation $N = N_0 + \sum_{p \neq 0} n_p$

1932 – J. McLennen et al : discovery of He II

1938 – J. Allen + A. Misener ; P. Kapitza :
superfluidity of He II

1938 – F. London : He II is Bose Condensed!!

1947 – N. Bogoliubov : theory of weakly interacting Bose gas

1949 – L. Onsager : quantization of vorticity in He II

1951 – O. Penrose : long range order in single particle correlation function $\langle \psi^\dagger(r) \psi(r') \rangle$

1957 – Lee, Huang + Yang : theory of Bose gases

1958 – S. Beliaev : full quantum field theory description of interacting Bose liqs.

1987–93 J. Wolfe, A. Mysyrowicz, D. Snoke, J.-L. Lin, ... : BEC of paraexcitons in Cu_2O

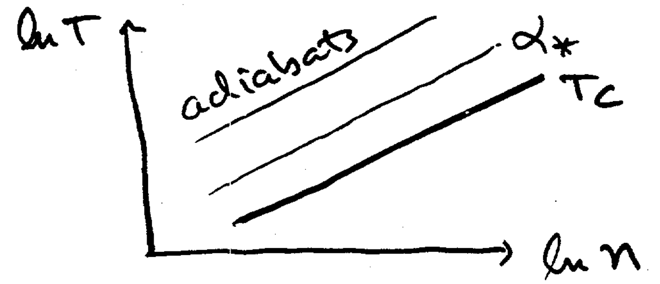
1995 : BEC in trapped atomic systems
^{87}Rb, ^{7}Li, ^{23}Na

EXCITON ENTROPY

(G. Kavoulakis, G.B. & J. Wolfe PRB 53 (1996) 7227)

On adiabat = constant entropy / particle = S :

$$T \sim n^{2/3}, \quad \alpha = -\mu/T \text{ fixed}$$



$$T \frac{dS_{ortho}}{dt} \simeq \text{Auger heating} - \text{phonon cooling}$$

$$\simeq \underbrace{b\, n_{ortho}}_{\frac{1}{n_0}\left(\frac{n_0}{n_{ortho}}\right) n_0 (n_{ortho})} - a T^{3/2}$$

: vanishes on adiabat α_0

$n_0 \sim 0.05\, T_K^{3/2} \times 10^{18}/cm^3$

RAPID APPROACH TO FIXED POINT

$$\frac{d\alpha}{dt} \simeq -\frac{\alpha - \alpha_*}{\tau_*}$$

$$\tau_* = -\frac{T}{b} \frac{\partial S_{ortho}}{\partial n_{ortho}}\Big)_T \simeq \frac{5}{2} \frac{\zeta(5/2)}{\zeta(3/2)} \frac{k_B}{a T^{1/2}}$$

~ 25 psec at $T = 60$ K

BOSE CONDENSATION OF MAGNETICALLY TRAPPED ATOMS

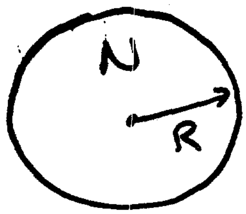
Laser cool to $\lesssim$ mK

Evaporatively cool to T_c and below $\Rightarrow dN/dt < 0$

ATOM	GROUP	TRAP	N	T_c (nK)	N_{cond}	EXPTS
^{87}Rb	JILA		2×10^4	100	900	TOF
$a \approx 60Å$	95	TOP				Oscillatory modes
	97	"Baseball"	7×10^6	670	2×10^6	2 overlapping cond.
	UTexas 5/97			30	2×10^4	TOF
	Stanford 6/97		1×10^4	300		
^{23}Na	MIT					
$a \approx 30Å$	95	Optical plug	2×10^6	2000	5×10^5	TOF
	96-97	Ioffe	15×10^6	1500	5×10^6	Direct imaging Osc. modes Cond. interference Sound
	Rowland 6/97	Ioffe			10^6	Laser TOF
^7Li	Rice	Permanent	10^5	100		
$a \approx -15Å$	95-97	magnet			500-800	

SIZE OF CLOUD $(T \to 0)$

$$E_{oscillator} \approx E_{interaction} \gg E_{kinetic}$$



PER PARTICLE

$$E_{osc} \sim m\omega_\perp^2 R^2/2$$

$$E_{int} \sim \frac{4\pi\hbar^2 a}{m} \underbrace{\frac{N}{R^3}}_{\rho}$$

$$E_{osc} \sim E_{int} \Rightarrow \quad R^5 \sim 8\pi a_\perp^4 a N \qquad \left(a_\perp^2 = \frac{\hbar}{m\omega_\perp}\right)$$

$$\boxed{\left(R/a_\perp\right) \sim \left(\frac{8\pi a N}{a_\perp}\right)^{1/5} \equiv \zeta}$$

$$\zeta = 4.2 \left(\frac{a}{100 a_0} \; \frac{N}{10^4} \; \frac{10^4 \text{Å}}{a_\perp}\right)^{1/5} \gg 1$$

$$E_{ke} \sim \frac{\hbar^2}{2mR^2} \sim \frac{1}{\zeta^4} E_{osc} \ll E_{osc}$$

G.B. & C.J. PETHICK, PRL v.76 JAN 1, 1996, p6

Nonabelian Debye screening and the "tsunami" problem

Robert D. PISARSKI

Department of Physics
Brookhaven National Laboratory
Upton, NY 11973

The phenomenon of Debye screening is familiar from electrolytes and many other systems. Recently, it has been recognized that in nonabelian gauge theories at high temperature, even perturbatively Debye screening is much more complicated than in nonrelativistic systems. This was originally derived as "hard thermal loops".

Hard thermal loops have been derived perturbatively, by a semiclassical truncation of the Schwinger-Dyson equations, and by classical kinetic theory. In this talk I give a pedagogical derivation, following that of Kelly, Liu, Lucchesi, and Manuel.

The derivation is valid not just for a thermal distribution, but (modulo certain obvious restrictions) for an arbitrary initial distribution of particles. Consider, for example, the "tsunami" problem: suppose that one starts, at time $t = 0$, with a spatially homogenous, infinite wall of particles, all moving with the same velocity at the speed of light.

At short times, a perturbative analysis can be used. A scalar tsunami exhibits screening; that is, the high density of particles acts to restore the symmetry. A gluon tsunami is shown to screen transverse modes, but no collective mode; that is, there is no tsunami plasmon.

The behavior of the evoluation of a gluonic tsunami at long times cannot be studied perturbatively because the energy density is proportional to the inverse of the coupling. This can be studied in an $O(N)$ theory in the limit as $N \to \infty$. The initial distribution was a smeared, spherically symmetric tsunami, with momenta peaked about a nonzero value. If the theory is originally in a spontaneously broken phase, and the tsunami density is so high that the symmetry is restored, then initially there is spinoidal instability, as in a DCC. In momentum space, the tsunami shell quickly collapses to one peaked about zero momentum; at infinite time all particles pile up at zero momentum.

This talk is based on unpublished work with D. Boyanovsky, H. J. de Vega, R. Holman, S. P. Kumar to appear soon.

RDP: Assume initial distribution of particles = tsunami wave @ $t=0$

tsunami wave: <u>all</u> particles move $\bar{c}$ <u>same</u> momentum p_0, $p_0^2 = 0$

= high density ($\Rightarrow$ bosons)

= spatially homogeneous

$t=0$: $\begin{matrix} \rightarrow & \rightarrow & \rightarrow \\ \rightarrow & \rightarrow & \rightarrow \\ \rightarrow & \rightarrow & \rightarrow \end{matrix}$ = finite energy & momentum density

Q: If one starts $\bar{c}$ a tsunami wave @ $t=0$, what happens as $t \to \infty$?

Perhaps - ? - as $t \to \infty$, tsunami wave evolves into boosted $\underbrace{\text{thermal}}_{}$ distribution

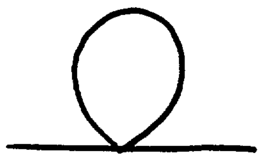
has $\neq 0$ energy & momentum density

But exactly how does a tsunami wave thermalize?

Tsunami wave @ short times

Initially, one should be able to use perturbation theory

Scalar tsunami wave:

$\Delta m^2 \sim$  $\sim +\lambda \int d^4p \; f_0(p)$

$$f_0^{\text{tsunami}} \sim \rho_0 \, \delta(p^2) \, \delta^3(\vec{p} - \vec{p}_0)$$

$$\Rightarrow \Delta m^2 \sim + \frac{\lambda \rho_0}{|p_0|}$$

$\Rightarrow$ tsunami wave screens;

high density in wave acts to restore the symmetry

in a scalar theory

Gluon tsunami wave @ short times

Let p_0 = preferred vector, $p_0^2 = 0$:

Gluon self energy has 4 fnc's:

$$\Pi^{\alpha\beta}(k) = \Pi_t\,\delta^{\alpha\beta} + \Pi_\ell\,k^\alpha k^\beta + \Pi_c\,(k^\alpha p_0^\beta + p_0^\alpha k^\beta) + \Pi_d\,p_0^\alpha p_0^\beta$$

Ward id. $k^\alpha \Pi^{\alpha\beta} = 0 \Rightarrow$ 3 ind. fnc.'s. Taking

$$f_0^{\text{tsunami}} \sim \rho_0\,\delta(p^2)\,\delta^3(\vec{p} - \vec{p}_0)$$

find

$$\Pi_t \sim + \frac{g^2 N}{|p_0|}\rho_0\,,\quad \Pi_\ell = 0\,,\quad \Pi_c, \Pi_d = \text{infrared singular}$$

Taking $p_0 \cdot A = 0$ gauge, effective prop.

$$\Delta^*_{\alpha\beta} = \underbrace{\frac{1}{k^2 + \Pi_t}}_{\text{std. transverse mode}} \left(\delta^{\alpha\beta} - \frac{p_0^\alpha k^\beta + k^\alpha p_0^\beta}{p_0 \cdot k} - \underbrace{\frac{k^2}{k^2 - \Pi_\ell}(\Pi_t + \Pi_\ell)}_{\text{collective mode}} \frac{p_0^\alpha p_0^\beta}{(p_0 \cdot k)^2} \right)$$

For (simplest) gluon tsunami, <u>only</u> screening of transverse mode, <u>no</u> coll. mode

$\Rightarrow$ no tsunami "plasmon" - ?

Scalar tsunami wave @ large N

Boyanovsky, de Vega, Holman, Kumar & RDP:

Take $\vec{\Phi} \in O(N)$ symmetry:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \vec{\Phi})^2 + \frac{1}{2} m^2 \vec{\Phi}^2 + \frac{1}{8}\frac{\lambda}{N}(\vec{\Phi}^2)^2$$

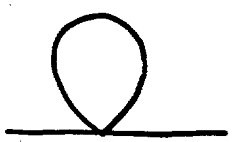
Solve exactly as $N \to \infty$, keeping $\lambda \sim O(1)$ fixed.

At $N = \infty$, can not thermalize:

$$\tau^{-1}_{\text{thermal}} \sim \int |\times|^2 \sim \left(\frac{\lambda}{N}\right)^2 \cdot N$$

$$\Rightarrow \tau_{th} \sim N$$

However, can study screening:

$\Delta m^2 \sim$  $\sim \left(\frac{\lambda}{N}\right) \cdot N \sim \lambda$

ind. of $N \to \infty$

$N = \infty$

Decompose

$$\vec{\Phi}(\vec{x},t) = \left(\sqrt{N}\,\phi(t) + \chi(\vec{x},t),\ \vec{\pi}(\vec{x},t)\right)$$

$\phi(t)$: spatially constant, zero momentum mode.

χ : ignore as $N \to \infty$

$\vec{\pi}(\vec{x},t)$: $N-1 \Rightarrow$ keep

At $N=\infty$, can solve for $\phi(t)$:

$$\left(\frac{d^2}{dt^2} + m^2_{bare} + \frac{\lambda}{2}\left(\phi^2(t) + \langle\pi^2\rangle(t)\right)\right)\phi = 0$$

where

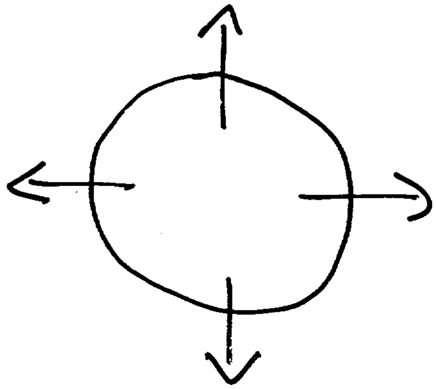
$$\langle\pi^2\rangle = \int \frac{d^3k}{(2\pi)^3} \langle a_k\, a_{-k}\rangle$$

$= \int$ mode sum in wave functional

$N=\infty \sim$ Hartree approximation including constraint on $\langle\pi^2\rangle$

Spherical tsunami wave

For technical reasons, easiest to impose spherical symmetry:



particles @ $t=0$

$$\sim \rho_c \exp\left(-\frac{(k-k_0)^2}{\xi^2}\right)$$

Choose initial conditions so that c/o tsunami, $\exists$ spon. sym. breaking:

$$m^2 < 0, \ \rho_0 = 0 \ , \quad m^2 > 0, \ \rho_0 \neq 0$$

$\lambda = 10^{-3}$, but $\rho_0 = 4 \cdot 10^4$.

Find spinodal instability at small times:

modes @ $k \sim k_0$ collapse to $k \sim 0$ very quickly

$t \to \infty$: modes pile up about $k=0$

Heavy Quarks and Nuclei,

or

The Charm & Beauty of Nuclear Physics

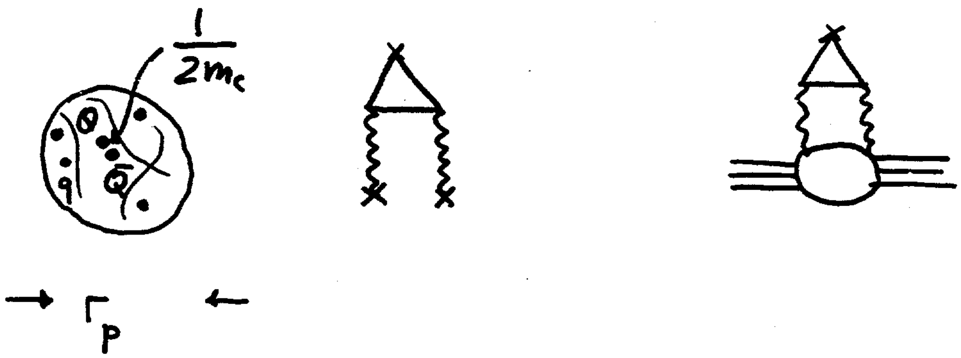
D. Kharzeev

RIKEN-BNL Research Center

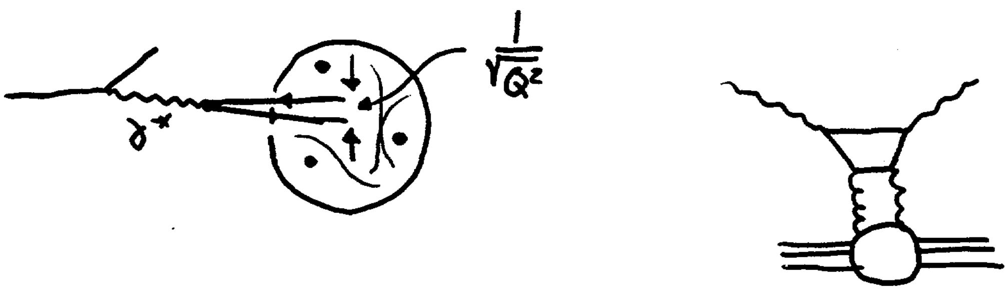
1. *Why heavy quarks?*
2. *Heavy quarkonium in QCD vacuum and in matter*
3. *Phenomenology of quarkonium production*
4. *Induced decay of QCD vacuum in heavy ion collisions? Implications for quarkonium production*
5. *Outlook*

Why heavy quarks are interesting?

Because they probe the structure of the vacuum and nuclear matter at short distances $\sim \frac{1}{2m_c}$

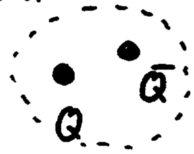


Similar to Deep Inelastic Scattering, which probes the nucleons and nuclei at distances $\sim \frac{1}{\sqrt{Q^2}}$.



When heavy quarks are brought on mass shell, they can form bound states – quarkonia.

Heavy quarkonia are "naturally" (as opposed to $q\bar{q}$ in DIS) SMALL:

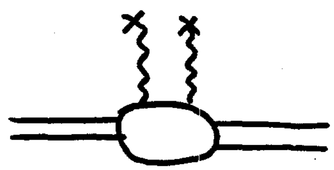


$$r \sim \frac{1}{m_Q \alpha_s(r^{-1})}$$

Because of the asymptotic freedom, their couplings to external fields can be systematically analyzed (OPE / perturbation theory).

<u>Example 1</u> : quarkonium and condensates

$(\bar{Q}Q)$ in external fields :



OPE <=> multipole expansion

the leading term – quadratic Stark effect in external (chromo)electric field:

$$E_{int} = -\frac{1}{2}\alpha_E \langle \vec{E}^{a\,2} \rangle$$

← external field

↑ electric polarizability

In QED, $\langle \vec{E}^2 \rangle > 0$ – negative shift of the level

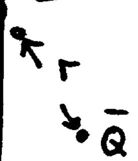
• In QCD, $\langle \vec{E}^{a\,2} \rangle < 0$ => <u>positive</u> shift of the level

$$\langle \vec{E}^{a\,2} \rangle = -\frac{1}{4}\underbrace{\langle G^a_{\mu\nu} G^a_{\mu\nu} \rangle}_{>0} < 0$$

– imaginary chromo-electric field

What does this imply ?

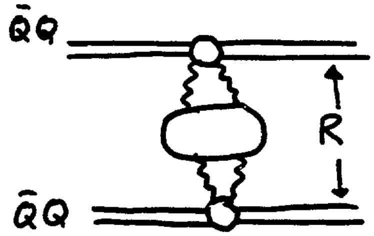
$\boxed{\alpha_E \sim r^3}$ => The interaction energy grows when the radius of the system increases; confinement ??



<u>Condensates may be responsible for confinement</u>

WHAT IF THE CONDENSATES MELT ?

Example 2: quarkonium – quarkonium interaction at low energy



$= \mathcal{M}(q)$

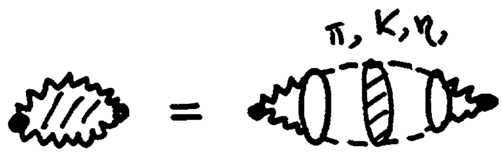
$$\mathcal{M}(q) = \int d^4x\, e^{iqx} \langle \phi | \left(i \sum_m \alpha_m O_m(0) \right) \left(i \sum_k \alpha_k O_k(x) \right) | \phi \rangle$$

$$\longrightarrow \sim \int d^4x\, e^{iqx} \alpha_E^2 \langle G^2(0), G^2(x) \rangle$$

At short distance R, perturbative evaluation is appropriate, $\langle G^2(0), G^2(x) \rangle =$ 

- At large distances $R \gg r_{Q\bar{Q}}$, the interaction becomes non-perturbative (even though $r_{Q\bar{Q}} \ll \Lambda_{QCD}^{-1}$!):

$$\Pi(q^2) = i \int d^4x\, e^{iqx} \langle 0 | T\{G^2(0), G^2(x)\} | 0 \rangle = \int ds\, \frac{\rho(s)}{q^2 - s}$$



← dispersion representation; $\rho(s) \sim |F(s)|^2$

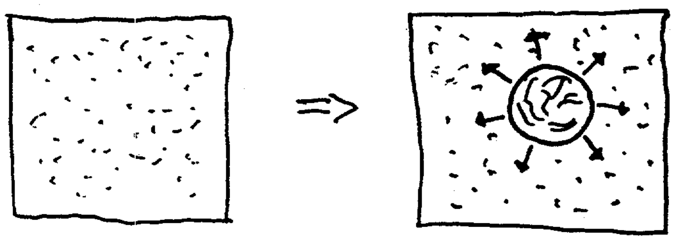
scalar formfactor inferred from hadron spectroscopy

$$\langle 0 | G^2 | \pi\pi \rangle = q^2 + O(m_\pi^2)$$

- Light quarks are very important for the dynamics of quarkonia $\Longrightarrow$ unquench lattice QCD!

Example: (Landau & Lifshitz, v. 5)

- Decay of metastable state by bubble formation



the free energy needed to produce a bubble

surface area

$$F = -V\delta P + A\sigma$$

← surface tension

volume

the pressure difference

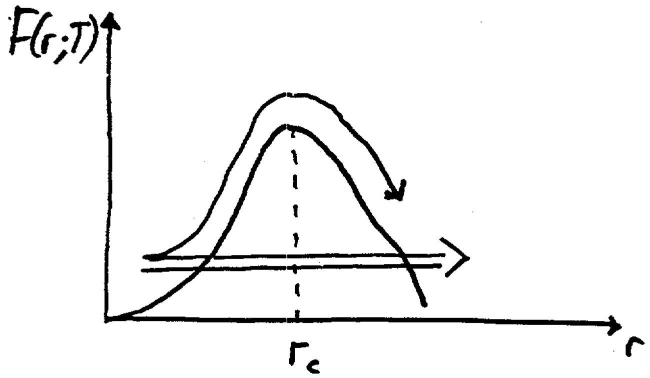
$$\delta P \simeq L \cdot \tau \quad \leftarrow \quad \tau \equiv \frac{T - T_c}{T_c}$$

↑

latent heat

for spherical bubbles,

$$F(r;T) = -\frac{4\pi r^3}{3} L\tau + 4\pi r^2 \sigma$$



$$\left.\frac{\partial F}{\partial r}\right|_{r=r_c} = 0 \quad \Longrightarrow \quad r_c(T) = \frac{2\sigma}{L\tau}$$

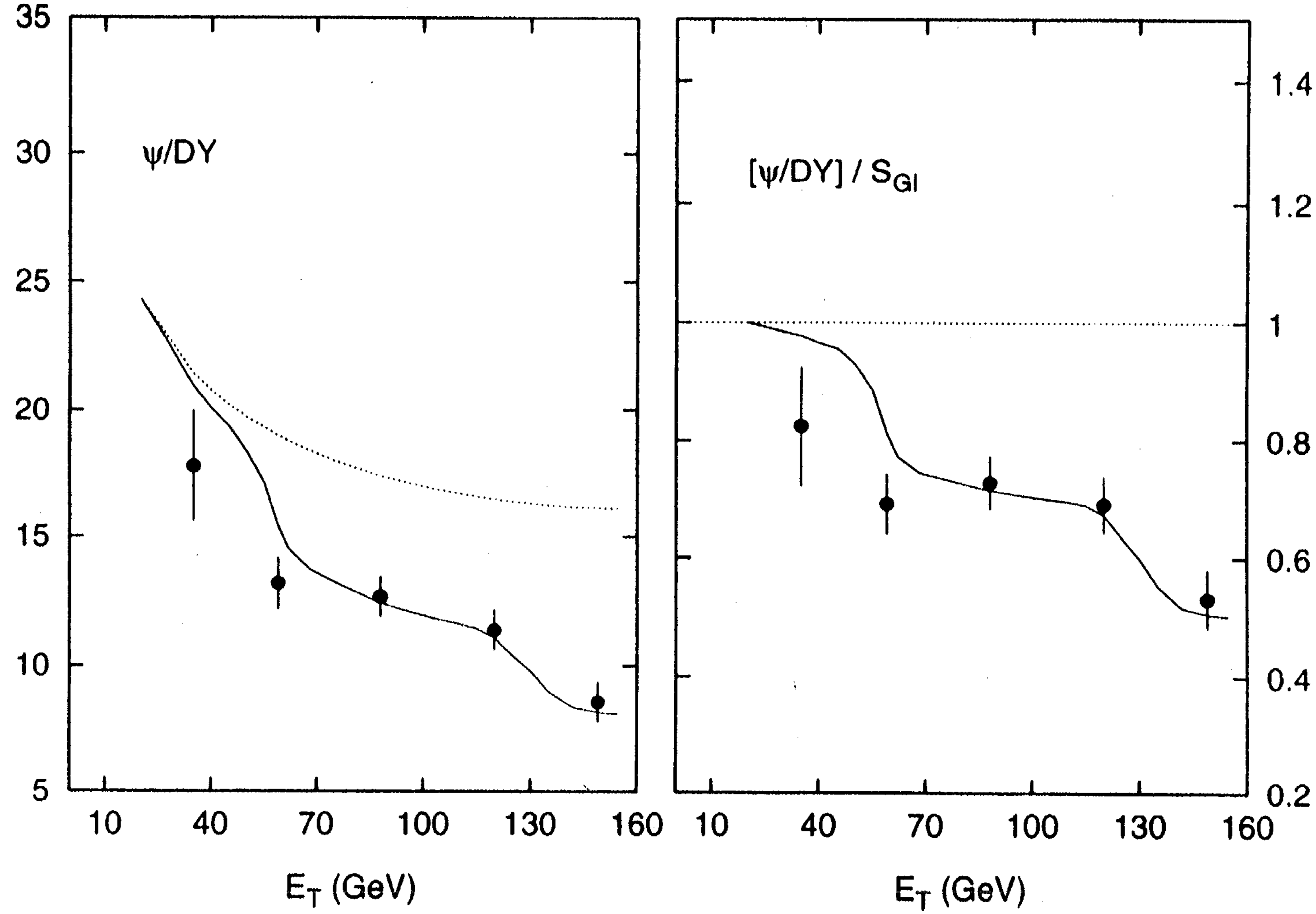
the rate of bubble formation

$$R \sim \exp\left(-\frac{F(r,T)}{T}\right) \simeq \exp\left(-\frac{16\pi\sigma^3}{3TL^2\tau^2}\right)$$

↑

non-analytical behavior

D. K., M. Nardi, H. Satz
hep-ph/9707308 10 Jul 1997



D.K., M. Nardi; H. Satz
hep-ph/9702273
PLB '97

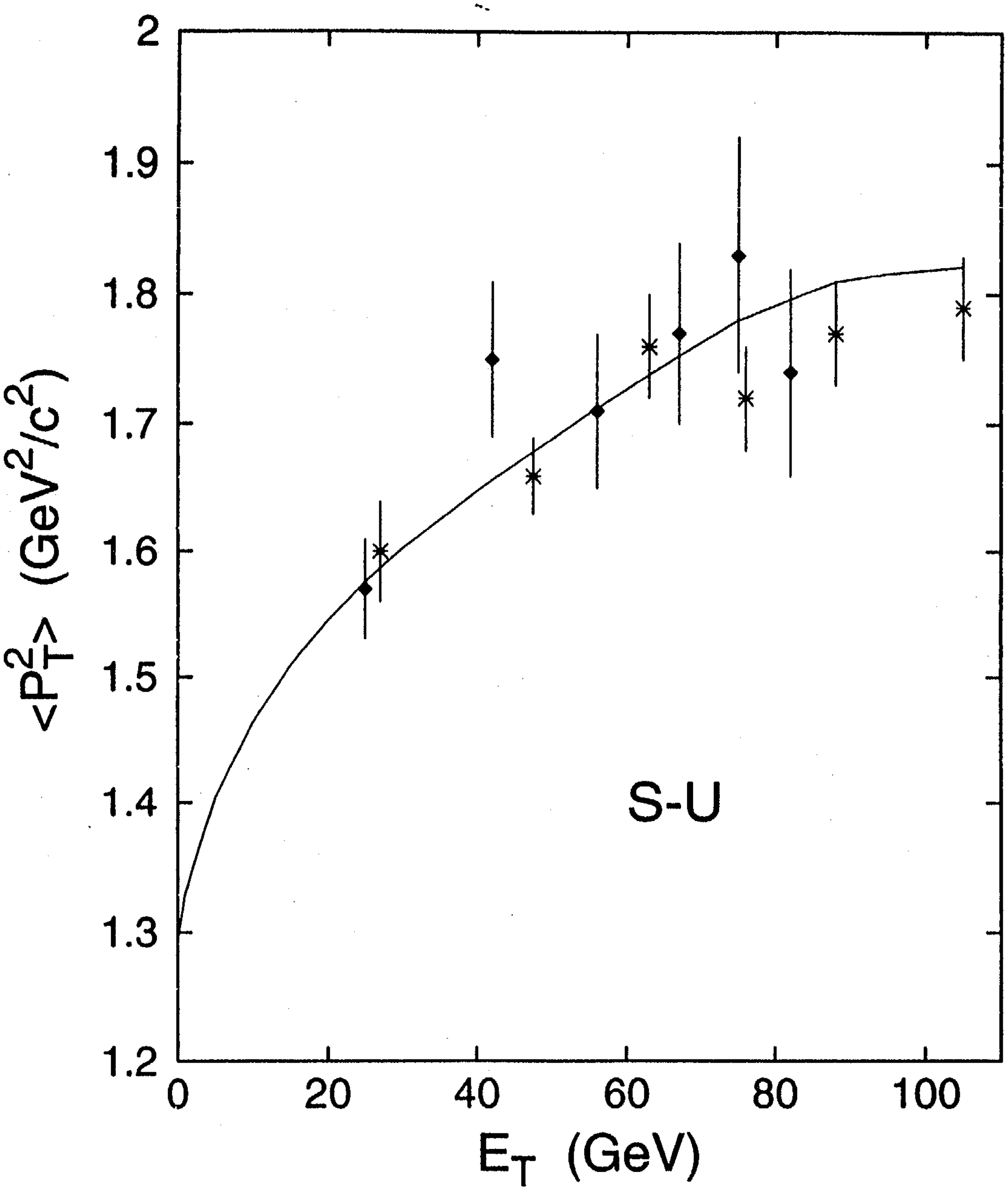


Fig. 1.

D.K., M. Nardi, M. Satz
hep-ph/9702273
PLB '97

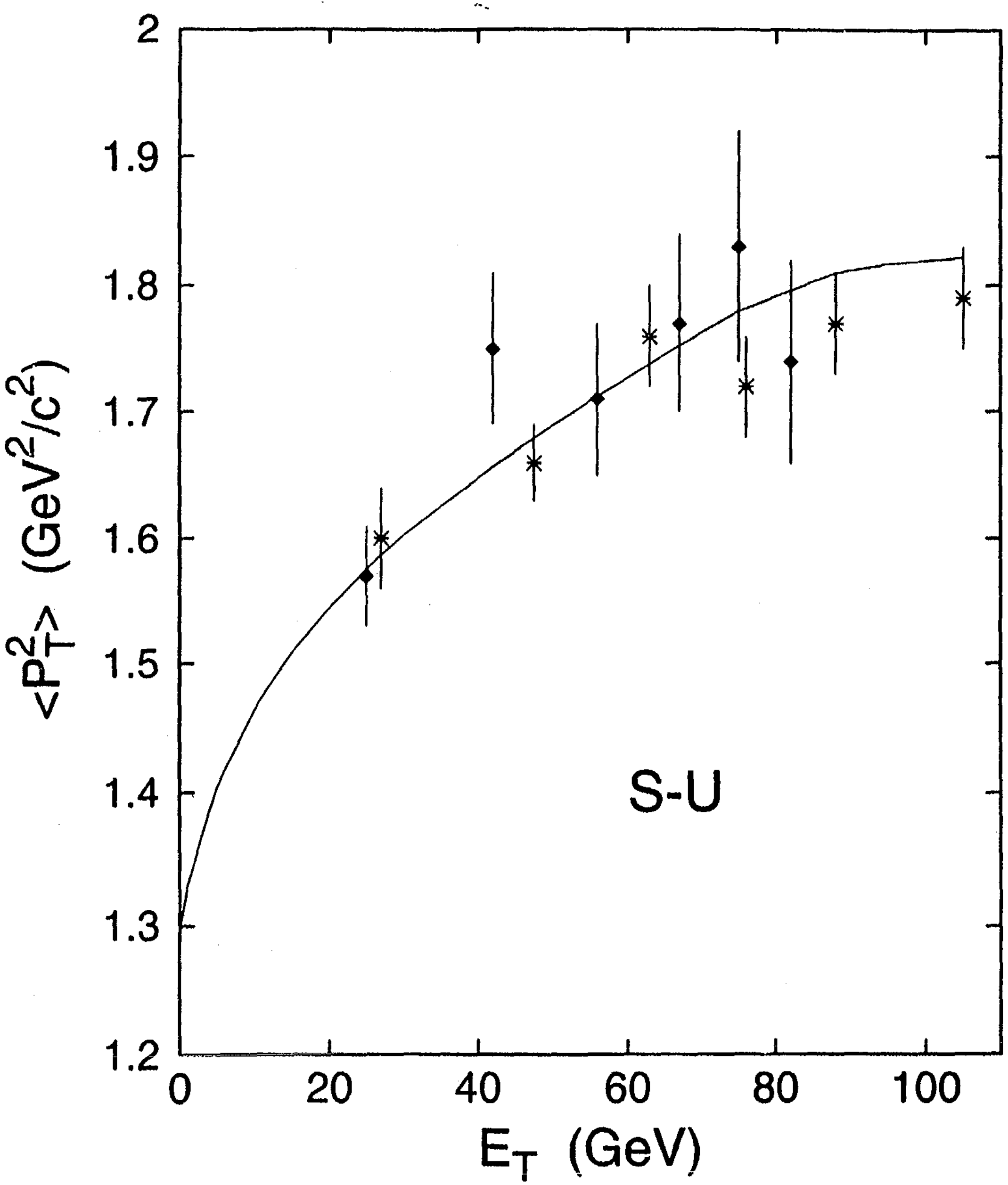


Fig. 1.

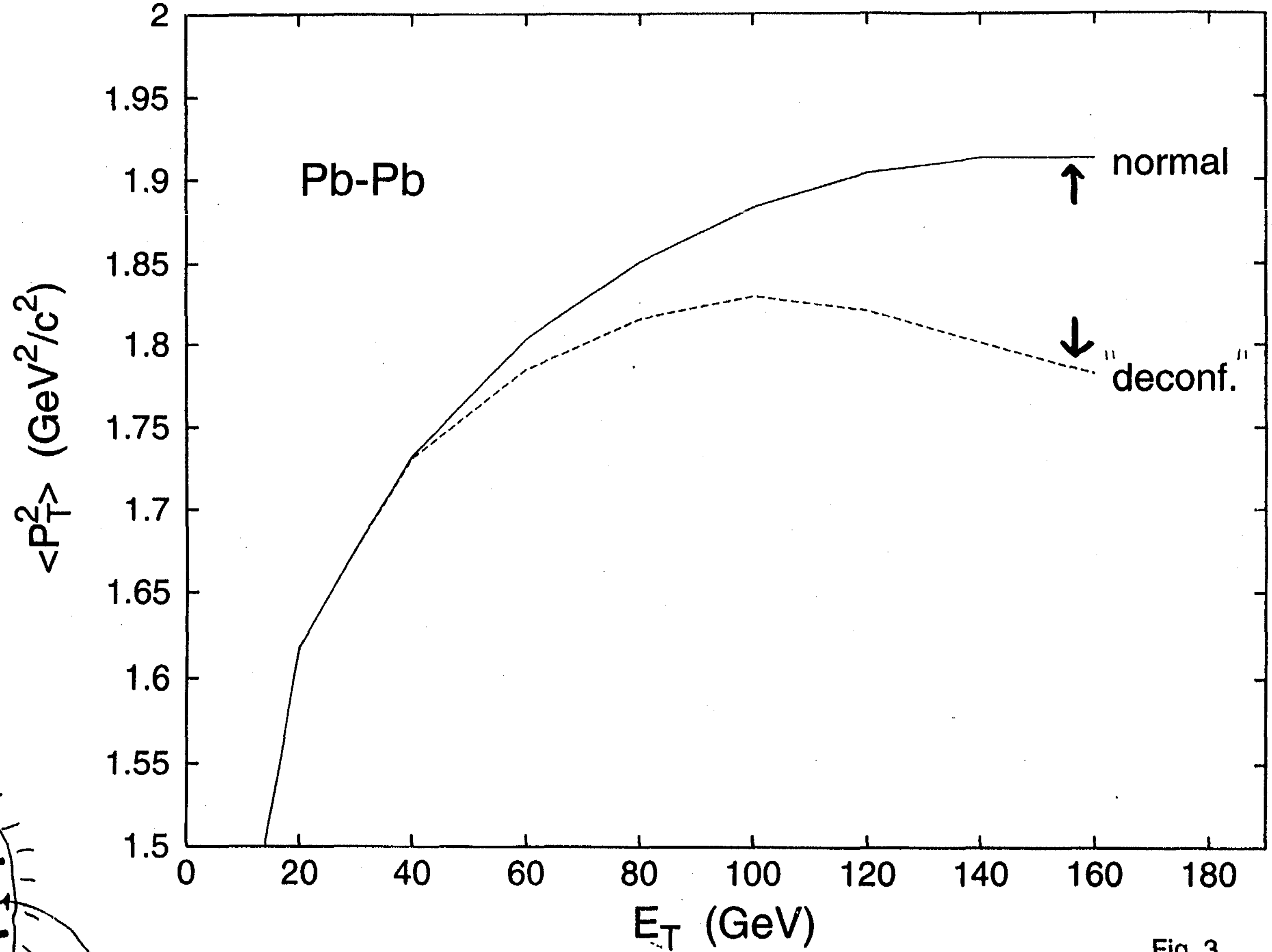
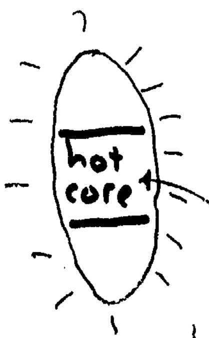


Fig. 3



J/Ψ's from the "hot core", having the largest p_T, are dissociated!

D. K., M. Nardi, H. Satz
hep-ph/9702273, Phys. Lett. B, 97

NON-ABELIAN FIELD DYNAMICS IN THE EARLY STAGE OF ULTRARELATIVISTIC NUCLEAR COLLISIONS

DIRK H. RISCHKE
RIKEN-BNL Research Center, Physics Dept., Brookhaven National Laboratory
Upton, NY 11973, U.S.A.
E-mail: drischke@nt1.phys.columbia.edu

In [1] it was argued that the gluon field of a large, ultrarelativistic nucleus can be considered as a classical field for small values of the longitudinal momentum fraction x and on transverse momentum scales $\Lambda_{\rm QCD}^2 \ll k_\perp^2 \ll \mu^2$, where μ^2 is the transverse area density of color charges. The authors of [2] estimated $\mu \simeq 0.4$ GeV for collisions of Au–nuclei at RHIC energies. Based on this argument, the gluon field produced in a collision of two ultrarelativistic nuclei is computed perturbatively by solving the classical Yang–Mills equations order by order in the strong coupling constant g [3]. It is shown that to first order in g, the spectrum of produced gluons is identical to that obtained in a perturbative quantum calculation of gluon Bremsstrahlung [4]. It is also identical with that of a coherent quantum state generated by independent collisions between the (classical) color charges in the two nuclei [5]. The perturbative solution is unstable under perturbations [6]. The instabilities arise from the non-Abelian terms in the equations of motion for the gluon field [7], which enter only at higher order in the perturbative solution scheme [3]. The decay rate of the perturbative solution is shown to be of order μ. Since the non-Abelian terms describe the self-interaction of the produced gluon field, and since such interactions lead to thermalization, the decay rate provides an estimate for the thermalization time scale of classical color fields in ultrarelativistic nuclear collisions. For Au–nuclei, this time scale is therefore of order 0.5 fm/c, in agreement with results for the kinetic thermalization time scale [8].

[1] L. McLerran and R. Venugopalan, Phys. Rev. D49 (1994) 2233, 3352, D50 (1994) 2225.
[2] M. Gyulassy and L. McLerran, nucl–th/9704034.
[3] A. Kovner, L. McLerran, and H. Weigert, Phys. Rev. D 52 (1995) 3809, 6231; Yu.V. Kovchegov and D.H. Rischke, hep–ph/9704201, Phys. Rev. C (in press).
[4] J.F. Gunion and G. Bertsch, Phys. Rev. D 25 (1982) 746.
[5] S.G. Matinyan, B. Müller, and D.H. Rischke, nucl–th/9705024, Phys. Rev. C (in press).
[6] S.G. Matinyan, B. Müller, and D.H. Rischke, preprint no. DU–TH–150, submitted to Phys. Rev. C.
[7] C. Gong, S.G. Matinyan, B. Müller, and A. Trayanov, Phys. Rev. D 49 (1994) R607; C.R. Hu, S.G. Matinyan, B. Müller, and D. Sweet, Phys. Rev. D 53 (1996) 3823.
[8] E.V. Shuryak, Phys. Rev. Lett. 68 (1992) 3270.

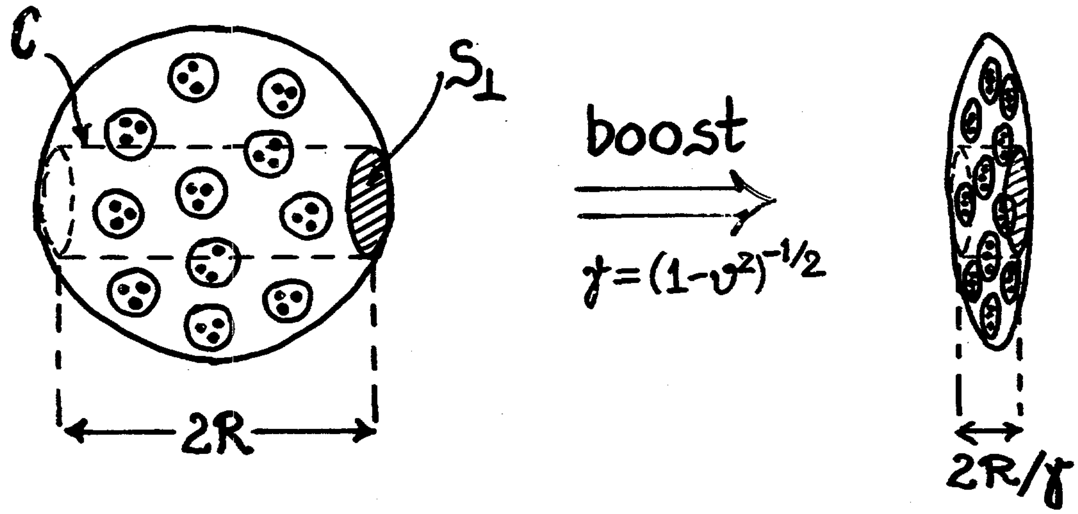
Non-Abelian field dynamics in the early stage of ultrarelativistic nuclear collisions

Miklos Gyulassy, Yuri V. Kovchegov Columbia Univ.

Sergei G. Matinyan, Berndt Müller Duke University

Dirk H. Rischke RIKEN-BNL Research Center

Motivation:



# of valence color charges in cylinder C:

$$N = 3\, n_0\, 2R\, S_\perp$$
$$= 6\, n_0\, r_0 A^{1/3} S_\perp$$
$$\simeq 6 \cdot 0.17 \cdot 1.12\; A^{1/3} \frac{S_\perp}{fm^2}$$
$$\boxed{N \simeq 1.14\, A^{1/3} \frac{S_\perp}{fm^2}}$$
$$\simeq 6.68 \frac{S_\perp}{fm^2}$$

$A \simeq 200$

Transverse area density of valence color charges:

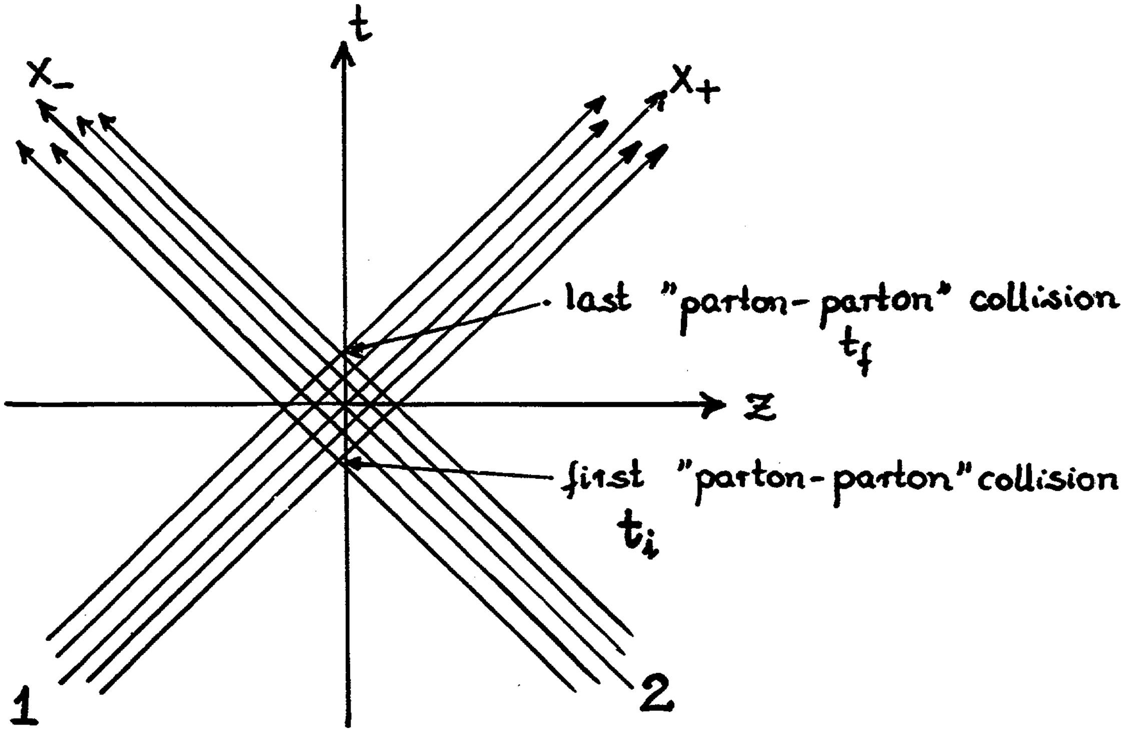
$$\mu^2 = \frac{N}{S_\perp}$$
$$\simeq 1.14\, A^{1/3}\, fm^{-2}$$
$$\boxed{\mu^2 \simeq \left[210\, A^{1/6}\, \mathrm{MeV}\right]^2}$$
$$\simeq [0.5\ \mathrm{GeV}]^2$$

$A \simeq 200$

M. Gyulassy, L. McLerran, nucl-th/9704034

Classical gluon radiation in ultrarelativistic AA-collisions:

Yu. V. Kovchegov, D.H.R., hep-ph/9704201, PRC 56 (97) 1084



Prior to t_i: charges don't "talk" to each other

⇒ Solution is Abelian, as for single nuclei.

Collisions ($t_i \le t \le t_f$) lead to corrections.

⇒ Corrections can be computed perturbatively!

$$\underset{}{A^\mu} = \underset{O(g)}{A^{(1)\mu}} + \underset{O(g^3)}{A^{(3)\mu}} + \dots \quad , \quad J^\mu = \underset{O(g)}{J^{(1)\mu}} + \underset{O(g^3)}{J^{(3)\mu}} + \dots$$

Equations of motion in Lorentz gauge:

$$\Box A^{\mu} = \mathcal{J}^{\mu} + ig\,[A_{\nu}, \partial^{\nu} A^{\mu} + F^{\nu\mu}]$$

$$\Rightarrow \quad \Box A^{(1)\mu} = \mathcal{J}^{(1)\mu}$$

$$\Box A^{(3)\mu} = \mathcal{J}^{(3)\mu} + ig\,[A^{(1)}_{\nu}, \partial^{\nu} A^{(1)\mu} + F^{(1)\nu\mu}] \equiv \tilde{\mathcal{J}}^{(3)\mu}$$

$$\vdots$$

$\mathcal{J}^{(1)}$ is the initial color charge current,

$A^{(1)}$ is the Abelian solution.

(I.e., nothing happens, nuclei pass through each other without noticing ...)

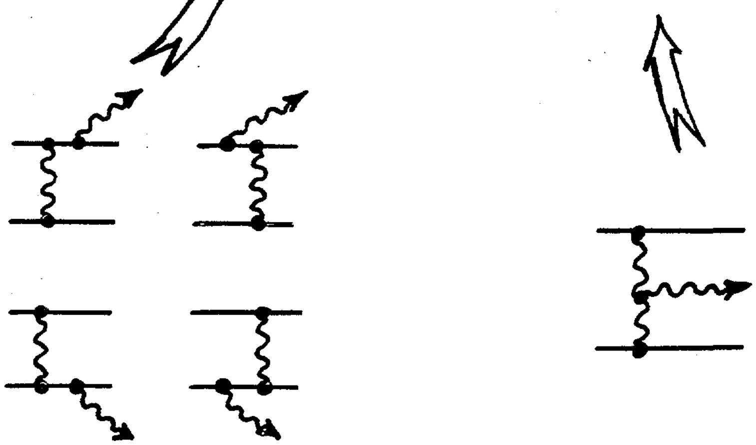
$\mathcal{J}^{(3)}$ can be determined from covariant current conservation, $\mathcal{D}_{\mu} \mathcal{J}^{\mu} = 0$.

Equation for $A^{(3)}$ is linear differential equation

$$\Rightarrow \; A^{(3)\mu}(x) = \int d^4x'\, G_r(x-x') \Big(\mathcal{J}^{(3)\mu}(x') + ig\,[A^{(1)}_{\nu}(x'), \partial^{\nu} A^{(1)\mu}(x') + F^{(1)\nu\mu}(x')] \Big)$$

Diagrammatic correspondence:

$\mathcal{J}^{(3)} \sim [A^{(1)}, \mathcal{J}^{(1)}]$



Gluon bremsstrahlung!

Thermalization of classical color fields:

S.G. Matinyan, B. Müller, D.H.R.,
nucl-th/9708053

Perturbative solution $A^{(3)}$ is not a true, self-consistent solution of the YM equations.

Non-linear terms ($\hat{=}$ self-interaction of produced gluons) will lead to decay of $A^{(3)}$, and - eventually - to thermalization of the classical color fields.

Estimate thermalization time scale via linear stability analysis:

$$A^{\mu}(x) = A^{(3)\mu}(x) + \alpha^{\mu}(x)$$

$$\alpha^{\mu}(x) = \alpha^{\mu}_{a} T^{a} e^{ik\cdot x}$$

$$\Rightarrow M^{\mu\nu}_{ab}(k, A^{(3)})\, \alpha^{b}_{\nu} = \ldots \quad \text{(inhomogeneous terms)}$$

Modes of propagation for perturbation α^{μ} are given by

$$\det M(k, A^{(3)}) = 0$$

$$\Rightarrow 8(N_c^2-1) \text{ roots (modes) } \omega_i(k, A^{(3)})$$

Decay rate of $A^{(3)}$:

$$\boxed{\Gamma \equiv |\Im m\, \omega_1| \simeq b^{-1} \simeq \mu}$$

$\Rightarrow$ Time scale for thermalization of classical color fields:

$$\boxed{\tau_{th} \simeq \Gamma^{-1} \simeq \mu^{-1} \simeq 0.5\,fm}$$

agrees with estimates for time scale of kinetic equilibration ("hot-glue" scenario,
E. Shuryak, PRL 68 (92) 3270)

COLOR SUPERCONDUCTIVITY

Frank WILCZEK

Institute for Advanced Study
School of Natural Sciences
Princeton, NJ 08540

The asymptotic freedom of QCD suggests that at high density — where one forms a Fermi surface at very high momenta — weak coupling methods apply. These methods suggest that chiral symmetry is restored and that an instability toward color triplet condensation (color superconductivity) sets in. Here I attempt, using variational methods, to estimate these effects more precisely. Highlights include demonstration of a negative pressure in the uniform density chiral broken phase for any non-zero condensation, which we take as evidence for the philosophy of the MIT bag model; and demonstration that the color gap is substantial — several tens of MeV — even at modest densities. Since the superconductivity is in a pesudoscalar channel, parity is spontaneously broken.

This talk is based on unpublished work with M. Alford and K. Rajagopal, to appear soon.

QCD at Finite Density

Methods

× lattice — non-positive measure

× SUSY — statistics crucial

? $N \gg 1$ — seems that $N=3$ matters (also: even-odd)

perturbative — limited to asymptotics

variational — not systematic — but this is what I'll use!

Phenomena

chiral symmetry restoration

color superconductivity

This talk:

The Model

Chiral Symmetry Alone

Color Superconductivity Alone

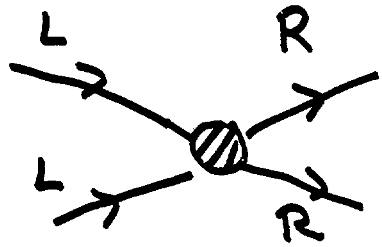
Both Together

What was Left Out

Conclusions

work with: M. Alford
K. Rajagopal

I. The Model



$+ \text{ h.c.}$

$$\mathcal{H} = K \left(u^{*\dot{a}}_{R\alpha}\, u^{b\beta}_{L}\, d^{*\dot{c}}_{R\gamma}\, d^{d\delta}_{L} - u^{*a}_{R\alpha}\, d^{b\beta}_{L}\, d^{*c}_{R\gamma}\, u^{d\delta}_{L} \right)$$

$$\epsilon_{ac}\,\epsilon_{bd} \left(3\,\delta^{\alpha}_{\beta}\,\delta^{\gamma}_{\delta} - \delta^{\alpha}_{\delta}\,\delta^{\gamma}_{\beta} \right) + \text{h.c.}$$

$$K = c\, F(p_1^2)\, F(p_2^2)\, F(p_3^2)\, F(p_4^2)$$

$$F(p) = \left(\frac{\Lambda^2}{\Lambda^2 + p^2} \right)^{\frac{1}{2} \text{ or } 1}$$

- index structure from QCD

  instanton

- momentum structure to implement

  physics of asymptotic freedom

  (not a formal cutoff)

  (factorized form for later

  convenience)

- very important feature: $U_A(1)$

  broken

- comment on history: $\overset{\text{BCS}}{\overset{\downarrow}{\text{N J-L}}}$

  relationship of

  the two

II Purely Chiral

ground state

trial wave function

$$|\Psi(\theta_k)\rangle = \prod_p \left(\cos\theta_L(p) + e^{i\phi_L(p)} \sin\theta_L\, a_L^\dagger(p)\, b_R^\dagger(-p)\right)$$
$$\prod_p \left(\cdots_R \cdots\right) \qquad |0\rangle$$

gap equation

$$1 = 8\pi g^2 \int_0^\infty dp \; \frac{p^2 F(p)^4}{\sqrt{p^2 + \Delta^2 F(p)^4}}$$

fixing 1 parameter:

require $\Delta = 300$ MeV.

calculation also 'fixes' sign of $\mathcal{H}$

peculiarities of $n_B \neq 0$

'natural' trial wave function

who mixes?

$\Rightarrow$ fill up to μ, then use previous form

interpretation of μ: Fermi momentum, or $\sim n^{1/3}$ (not chemical potential)

modified gap equation: just change lower limit to μ!

energy expression

$$\frac{6}{\pi^2} \int_{\mu}^{\infty} dp \quad p^3 \left[\frac{F(p)^4 \, \Delta(\mu)^2}{p^2 + F^4\Delta^2 + p\sqrt{p^2 + F^4\Delta^2}} \right]$$

$$- \frac{3\,\Delta(\mu)^2}{8\pi^3 g^2} + \frac{3\mu^4}{2\pi^2} \leftarrow$$! surprising form

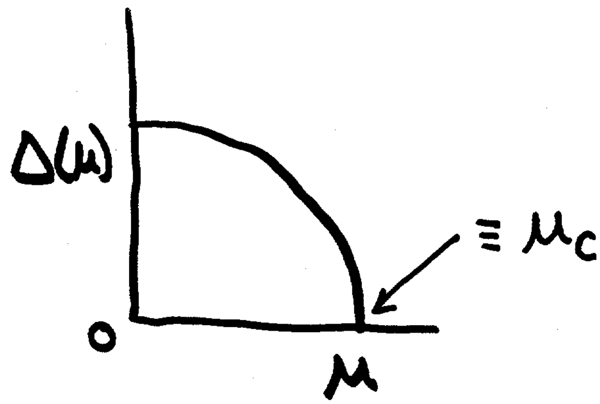
density expression

$$\frac{2\mu^3}{\pi^2}$$

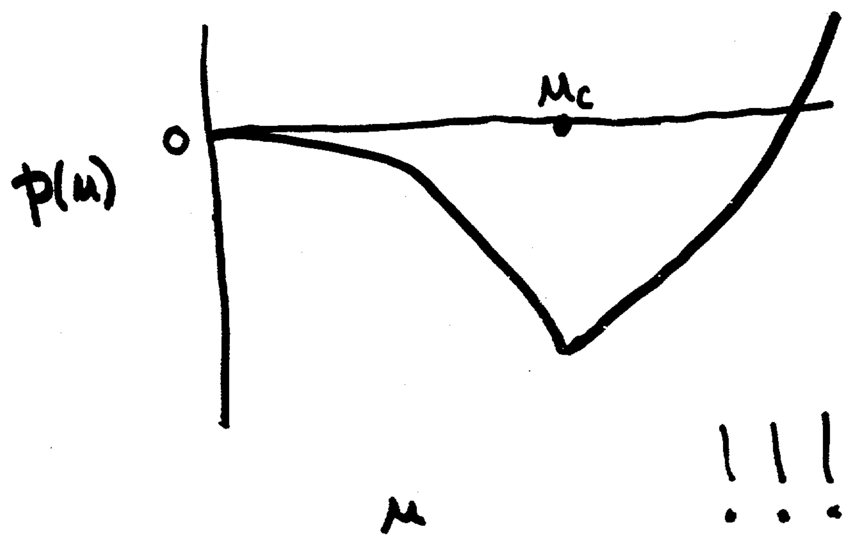
Nevertheless, $\mu_E = \Delta$ at $\mu = 0$.

Results

gap



pressure $= n\dfrac{\varepsilon'}{n'} - \varepsilon$



!!!

implications of $p<0$

mechanical instability of
uniform χSB phase

droplet formation - presumably, to
nucleons

nucleons are droplets
of chirally symmetric phas
(MIT bag)

$p=0$ point?
past $\Delta=0$
bag constant from $\mathcal{E}(\mu=0)$

~~nature of~~

nature of phase transition

percolation

modest densities (n_{proton}, $\approx 2.5\ n_{nuclear}$?)

very different from

finite T, $\mu = 0$

(note $T_c \ll m_N$)

spray paint vs.

pontillism

numerical values (GeV units)

	"cutoff"	μ_c	$\mu(p=0)$	ε
Steep	.3	.101	.170	4.24×10^{-5}
	.5	.135	.209	9.66×10^{-5}
	.7	.162	.235	1.55×10^{-4}
shallow				
	.3	.130	.201	8.41×10^{-5}
	.5	.167	.241	1.70×10^{-4}
	.7	.229	.266	2.54×10^{-4}

$\underbrace{<}_{\text{small}}$ $\qquad$ not silly

III Purely Superconducting

trial wave function

$$\prod_p \left(\cos\theta_p + e^{i\phi} \sin\theta_p \, a^{+\,\text{red}}_{u_L}(p) \, a^{+\,\text{white}}_{d_L}(-p) \right)$$

$$\text{"} \qquad\qquad c^+ \quad c^+$$

$$\text{"} \qquad\qquad b^+ \quad b^+$$

$$\times \prod_p \; (L \to R) \qquad\qquad |0\rangle$$

- everybody pairs, both above + below FS
- blue quarks passive (or χ_{blue} SB !)
- now μ is the chemical potential

- form of condensate suggested by 'crossed' channel. $I=0$, $J=0$.
- phase of LL vs. RR condensate meaningful ($U_A(1)$ breaking!). sign fixed by χSB (or directly from QCD).

$P = -$ favored !!

|| Parity is spontaneously broken by QCD at high density ($T=0$).

gap equation

$$1 = 2\pi g^2 \left[\int_0^\mu dp\, p^2 \frac{F(p)^4 \Delta(\mu)^2}{\sqrt{(\mu - p)^2 + F(p)^4 \Delta(\mu)^2}} \right.$$

$$+ \int_\mu^\infty dp\, p^2 \frac{F(p)^4 \Delta(\mu)^2}{\sqrt{(p-\mu)^2 + F(p)^4 \Delta(\mu)^2}}$$

$$\left. + \int_0^\infty dp\, p^2 \frac{F(p)^4 \Delta(\mu)^2}{\sqrt{(p+\mu)^2 + F(p)^4 \Delta(\mu)^2}} \right]$$

energy expression

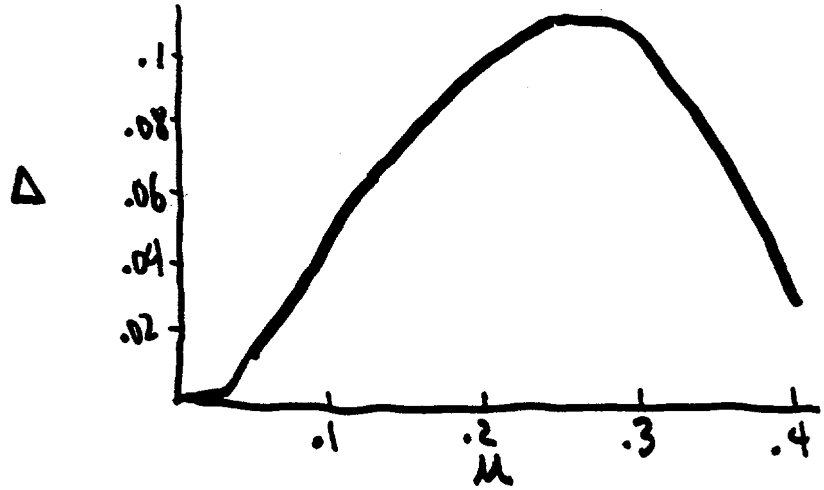
$$\frac{2}{\pi^2} \left[\int_\mu^\infty dp\, p^3 \frac{F^4 \Delta^2}{(p-\mu)^2 + F^4\Delta^2 + (p-\mu)\sqrt{(p-\mu)^2 + F^4 \Delta^2}} \right.$$

$$- \int_0^\mu$$

$$\left. + \int_0^\infty \right]$$

$$+ 3\mu^4/2\pi^2 - \Delta^2/2g^2\pi^3$$

sample result for gap



steep, .3

- Shape easy to understand qualitatively (density of states vs. cutoff)
- Already substantial at $\mu(p=0)$

- Effect on eqn. of state (i.e. pressure) very small.

IV Both Together (technique)

The tractable generalization of BCS:

$$|\Phi\rangle = S|0\rangle$$

$$S = \exp\left(\sum c_{ij}\, a_i^\dagger a_j^\dagger\right)$$

N.B.: not unitary

Then ~~with~~ defining

$$\rho_{\ell m} \equiv \langle\Phi|\, a_\ell a_m \,|\Phi\rangle / \langle\Phi|\Phi\rangle$$

$$\tilde{c}_{ij} = c_{ij} - c_{ji} = C$$

using

$$a_m|\Phi\rangle = \tilde{c}_{mi}\, a_i^\dagger |\Phi\rangle$$

we get

$$\rho = -(1 - CC^*)^{-1} C$$

From this, with

$$A_{\ell m} \equiv \frac{\langle \Phi | a^\dagger_\ell a_m | \Phi \rangle}{\langle \Phi | \Phi \rangle},$$

$$A = -C^*(1 - CC^*)^{-1} C$$

main effect: "competition" for ~~the~~ quarks

With a bit more juggling, ~~defining~~

$$\sigma_{q\ell m p} \equiv \langle \Phi | a_q a_\ell a_m a_p | \Phi \rangle / \langle \Phi | \Phi \rangle$$

$$= -\rho_{qp}\rho_{\ell m} + \rho_{qm}\rho_{\ell p} - \rho_{q\ell}\rho_{mp}$$

$$B_{q\ell m p} \equiv \langle \Phi | a^\dagger_q a^\dagger_\ell a_m a_p | \Phi \rangle / \langle \Phi | \Phi \rangle$$

$$= -\tilde{C}^*_{qi}\,\tilde{C}_{\ell j}\,\sigma_{jimp} + \underbrace{\tilde{C}^*_{q\ell}\,\rho_{mp}}_{\text{usual term!}}$$

etc.

V. What Was Left Out

gluons

s quarks

electrostatics

T

dynamics

other interaction possibilities

other ordering possibilities

VI Conclusions

- Uniform baryon number in the chirally broken phase is mechanically unstable ($p<0$). Strongly suggests droplet (= nucleon) formation.
- At the $p=0$ point, the condensate is long gone, $\xrightarrow{\sim}$ MIT bag
- Suggests the phase transition is by percolation. Precise characterization by π propagation.
- Significant color superconductivity immediately upon percolation.

- P is then (very likely) spontaneously broken.
- Magnitude of gap typically several 10s $\approx$ 100 MeV.; sensitive to density, details of interaction.
- Many identifiable possibilities for further work.

Colored Chaos

Berndt MÜLLER

- *Introduction*
  - *Ergodicity and Chaos*
- *Classical Yang-Mills Theory*
  - *Hamiltonian Dynamics*
  - *Metric Properties*
  - *Lyapunov Exponents*
  - *KS Entropy*
- *Hard Thermal Loops*
  - *Dynamical Realization*
  - *Lattice Formulation*
  - *Numerical Results*

A. Trayanov , C. Gong , S. G. Matinyan

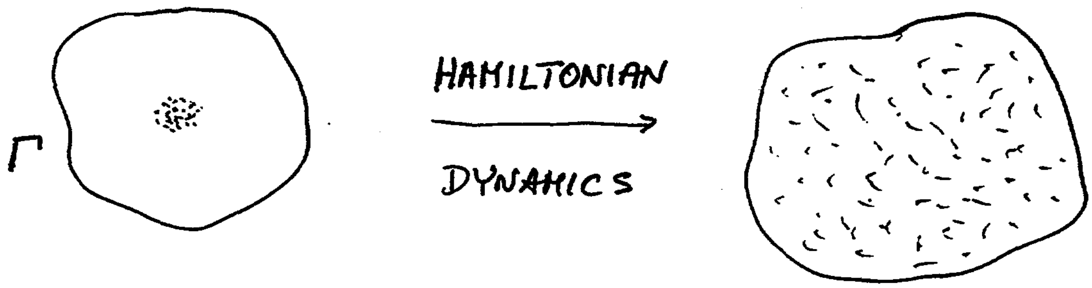
C. R. Hu , G. Moore

ERGODICITY & CHAOS

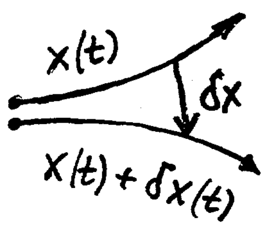
CONDITION WHETHER A CLASSICAL DYNAMICAL SYSTEM "THERMALIZES"?

INTIMATELY CONNECTED WITH PROBLEM OF ERGODICITY:

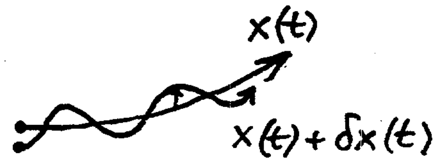
$$\langle X \rangle_t = \lim_{t\to\infty} \frac{1}{t}\int_0^t X(t')\,dt' \overset{?}{=} \langle X \rangle_{PS} = \int d\mu(q,p)\, X(q,p)$$



REQUIRES THAT NEARBY TRAJECTORIES DIVERGE:



AS OPPOSED TO



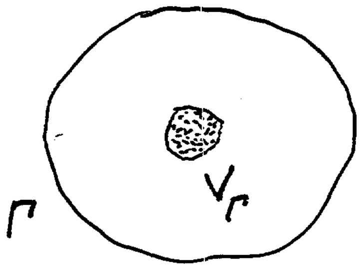
$$\| \delta x(t) \| \approx e^{\lambda t} \qquad\qquad \| \delta x(t) \| \sim e^{\pm i\omega t}$$

$$\lambda \equiv \lim_{\substack{t\to\infty \\ \delta x(0)\to 0}} \frac{1}{t} \ln \frac{\| \delta x(t) \|}{\| \delta x(0) \|} \qquad \text{LYAPUNOV EXPONENT}$$

$\lambda > 0$: UNSTABLE TRAJECTORY

λ imaginary : STABLE TRAJECTORY

KOLMOGOROV – SINAI ENTROPY



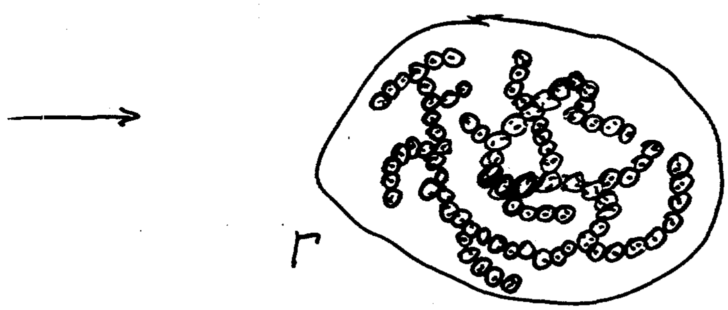
LIOUVILLE'S THEOREM:

$$\frac{d}{dt} V_\Gamma(t) = 0 \quad \text{FOR HAMILTONIAN SYSTEMS.}$$

ENTROPY: $S = k_B \ln V_\Gamma + \text{const.}$

COARSE-GRAINED ENTROPY:

e.g. ASSOCIATE A SMALL SPHERE OF RADIUS r_0 WITH EACH POINT IN Γ THAT IS OCCUPIED.



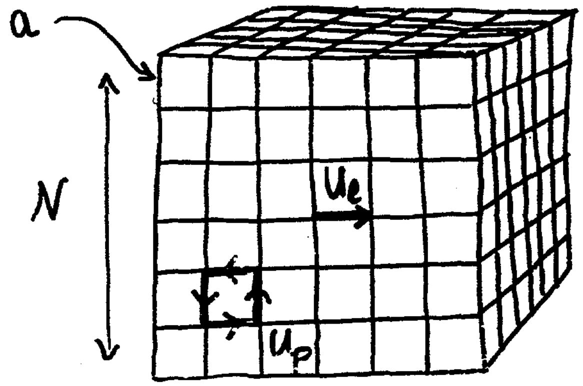
$$\overline{V}_\Gamma > V_\Gamma$$

$$\frac{d}{dt}\overline{S} = \frac{d}{dt} k_B \ln \overline{V}_\Gamma = k_B \sum_{\lambda_i > 0} \lambda_i^{(+)} \quad \text{KS – Entropy}$$

= Rate of entropy growth

$$\tau_S = \frac{\overline{S}_{eq}}{\frac{d}{dt}\overline{S}} = \begin{cases} \text{characteristic time of} \\ \text{approach to equilibrium} \end{cases}$$

CHAOS IN LATTICE GAUGE THEORY



$$U_\ell = e^{-i\int_\ell \vec{A}^a \tau^a d\vec{x}} \quad \text{Link}$$

$$U_p = U_4^\dagger U_3^\dagger U_2 U_1$$

elementary plaquette

$$H = \frac{g^2}{a}\sum_\ell \frac{1}{2} E_\ell^2 + \frac{4}{g^2 a}\sum_p \left[1 - \frac{1}{2}\mathrm{tr}\, U_p\right] \qquad \text{for } SU(2)$$

classical limit : $\quad E_\ell^a \to -\frac{ia}{g^2}\mathrm{tr}\left(\tau^a \dot{U}_\ell U_\ell^\dagger\right)$

$$H = \frac{a}{g^2}\sum_\ell \mathrm{tr}\left(\dot{U}_\ell \dot{U}_\ell^\dagger\right) + \frac{4}{g^2 a}\sum_p \left(1 - \frac{1}{2}\mathrm{tr}\, U_p\right)$$

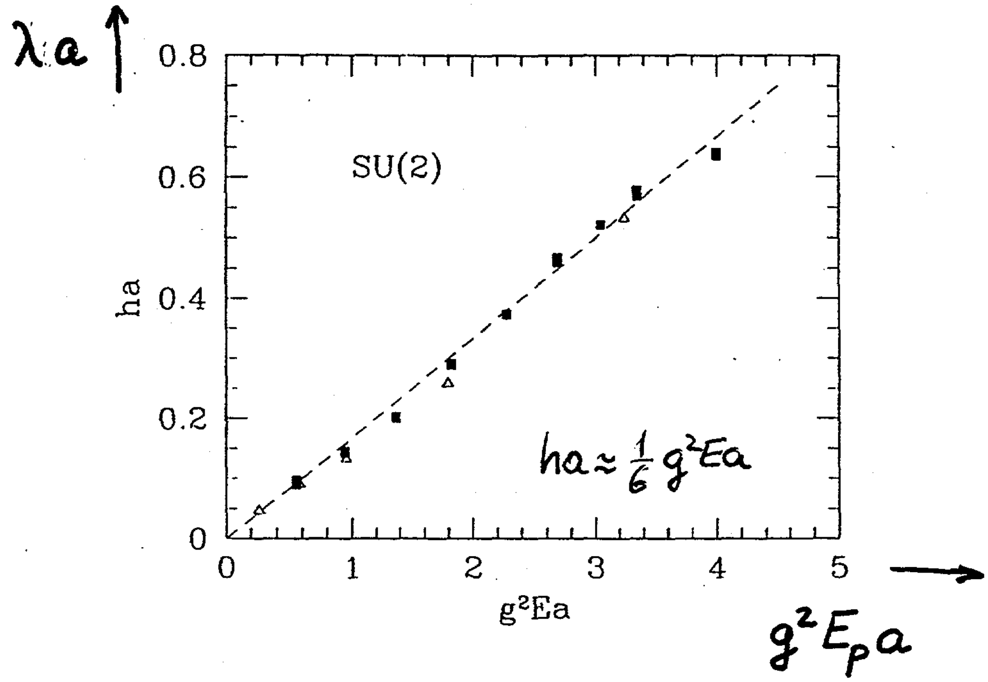
Distance measure:

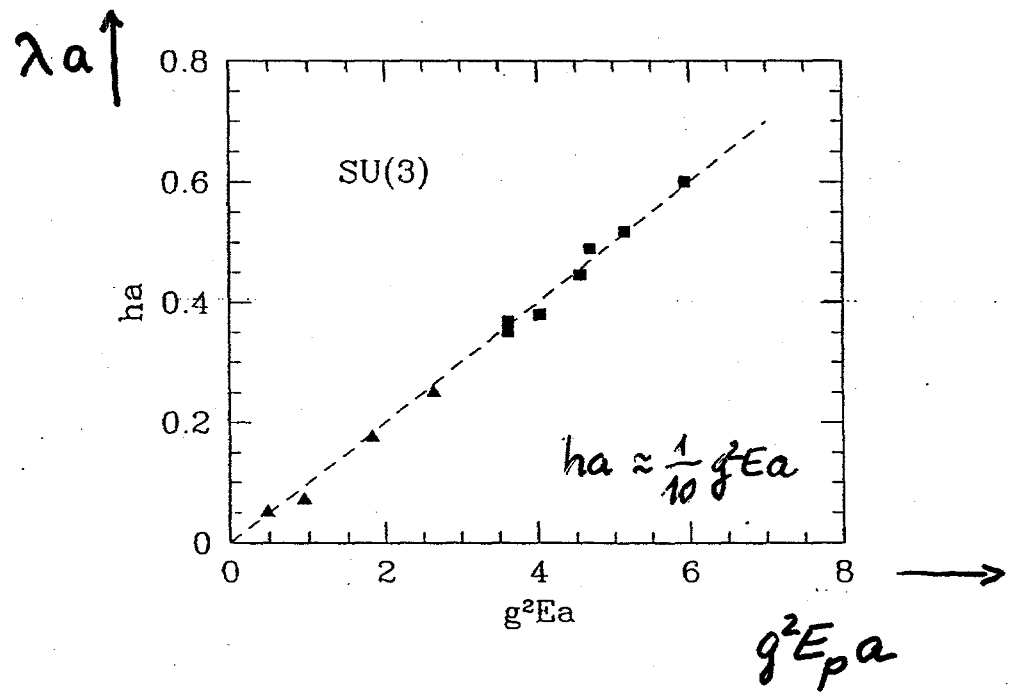
$$D[U_\ell, U_\ell'] = \frac{1}{2N_p}\sum_p \left|\mathrm{tr}\, U_p - \mathrm{tr}\, U_p'\right|$$

$$\xrightarrow{a\to 0} \frac{1}{2V}\int d^3x \left|B(x)^2 - B'(x)^2\right|$$

Begin with $U_\ell(0)$, $U_\ell'(0)$; integrate EOM and follow evolution of $D(t)$.

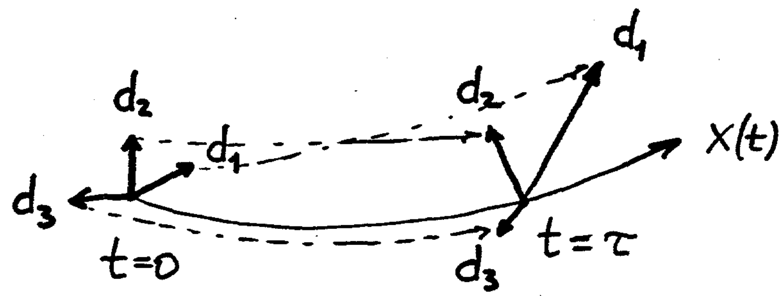
Maximal Lyapunov exponent





Scaling: $\lambda a = f(g^2 E_p a)$

COMPLETE LYAPUNOV SPECTRUM



SET UP n NEIGHBORING TRAJECTORIES

$$X(t) + d_i(t) \qquad i = 1, \dots, n$$

WITH $\quad \| d_i(0) \| = D_0 \quad$ AND $\quad \vec{d}_i(0) \cdot \vec{d}_k(0) = \delta_{ik}$

RE-ORTHONORMALIZE AT t :

RESCALING FACTORS : $\quad s_i^{(k)}, \ i = 1, \dots, n$

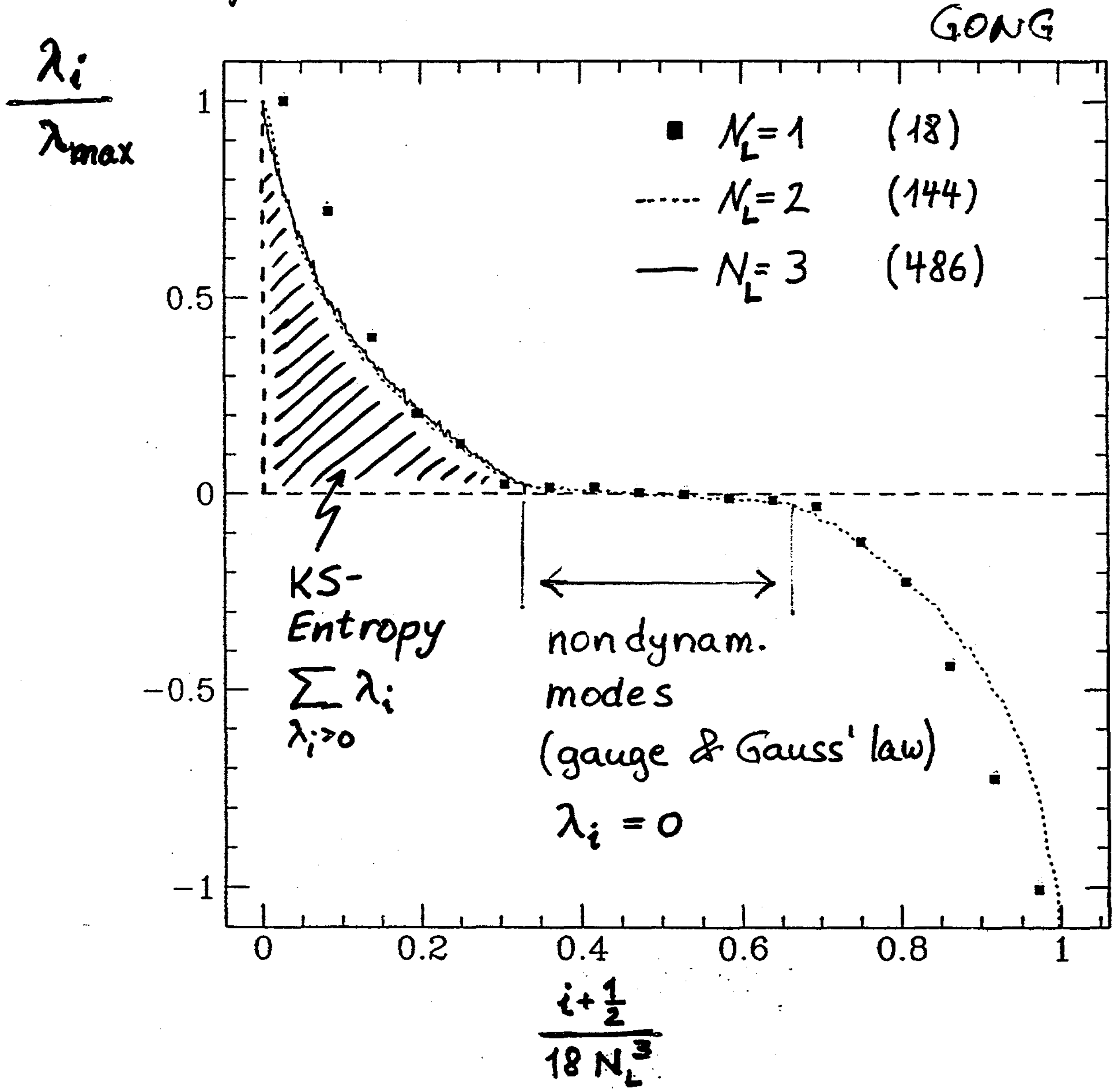
$$\lambda_i = \lim \frac{1}{\nu} \sum_{k=1}^{\nu} \frac{\ln s_i^{(k)}}{\tau}$$

$d_i(t)$ must be integrated in tangent space $T_{X(t)}$.

For SU(2) choose $\mathcal{U}_\ell = (u_0, \vec{u})_\ell$ and imbed

$$T_{X(t)} \subset \mathbb{R}^3 \times \mathbb{R}^4 \quad .$$

Complete Lyapunov spectrum for SU(2)



$\sum_{\lambda_i>0} \lambda_i \sim N_L^3 \sim$ Lattice volume :

KS entropy is an extensive quantity.

COMPLETE KS-ENTROPY [FOR SU(2)]

$$\dot{S}_{KS} \equiv \sum_{\lambda>0} \lambda_i \approx c\,\lambda_0\, N_L^3 \qquad c_2 \approx 2.0$$

$$\lambda_0 a = b\, g^2 \frac{E}{3N_L^3}\, a \qquad b_2 \approx \frac{1}{6}$$

Eliminate λ_0, divide by volume:

$$\dot{\sigma}_{KS} = \frac{1}{V} \sum_{>0} \lambda_i \to \frac{bc}{3} g^2 \varepsilon \quad , \text{ where } \varepsilon = \frac{E}{V}$$

Thermodynamics for scale invariant system:

$$\varepsilon = -P + \sigma T \quad \text{and} \quad P = \frac{1}{3}\varepsilon \leadsto \varepsilon = \frac{3}{4}\sigma T$$

Yields:

$$\dot{\sigma}_{KS} = \frac{bc}{4} g^2 \sigma T \qquad (N \to \infty)$$

$$\boxed{\tau_S^{-1} = \frac{\dot{\sigma}_{KS}}{\sigma} = \frac{bc}{4} g^2 T}$$

Probably also true for SU(3):

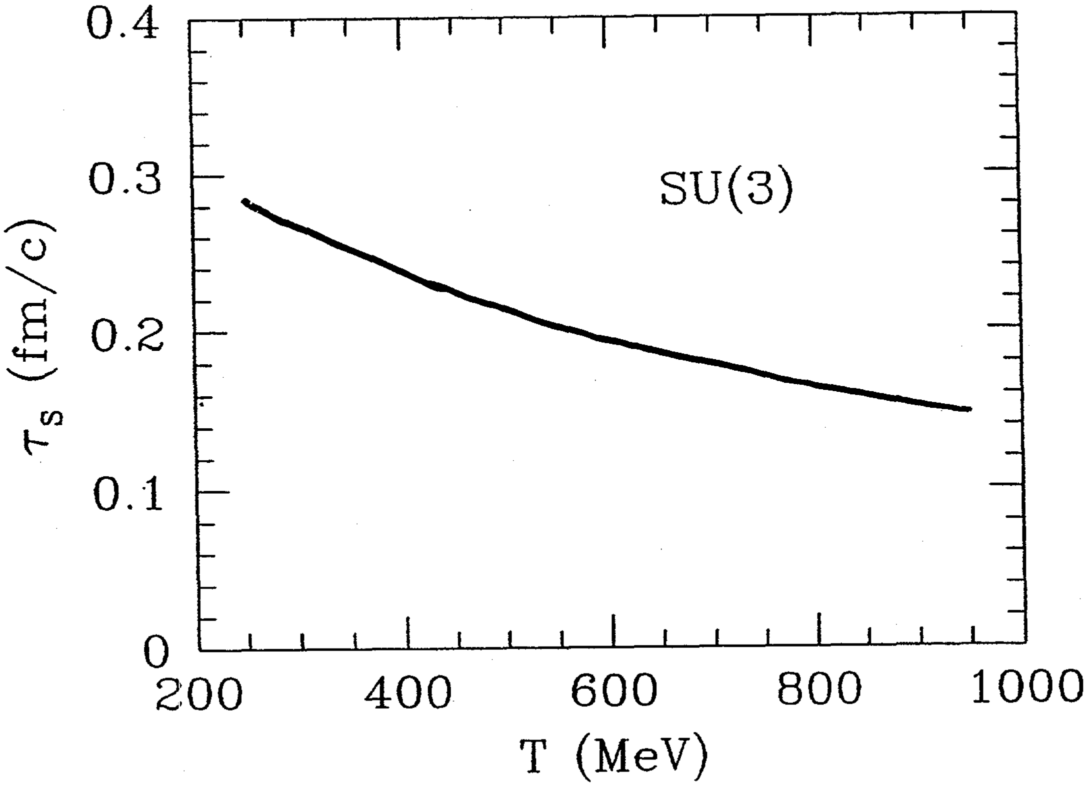
We know that $b_3 \approx \frac{1}{10}$, but not c_3.

C. GONG

Coupling constant from thermal gauge theory

$$g(T)^2 = \frac{(4\pi)^2}{11 \ln (\pi T/\Lambda)^2}$$

$$\tau_s^{-1} \equiv \lambda = 0.53 g^2 T$$



BEYOND THE CLASSICAL LIMIT

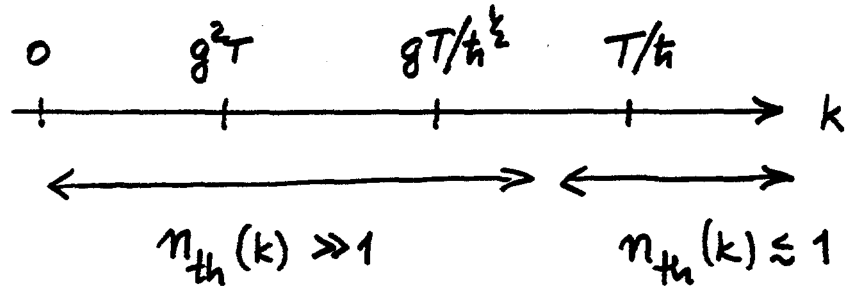
with
Chaoran Hu
Guy Moore

PROBLEMS WITH CLASSICAL LIMIT:

∴ UV CATASTROPHE (RAYLEIGH - JEANS)

∴ ABSENCE OF SCALE FIXING g

WEAK COUPLING



CLASSICAL LIMIT: $n_{th}(k) = \dfrac{1}{e^{\hbar\omega/T} - 1} \longrightarrow \dfrac{T/\hbar}{\omega}$

MAYBE APPLIED TO <u>EFFECTIVE</u> LONG-DISTANCE THEORY AFTER INTEGRATING OUT "HARD THERMAL" MODES ($k \gtrsim T/\hbar$).

$\longrightarrow$ • SCALE FOR $g \longmapsto g(T)$

• DYNAMICAL LENGTH SCALE ω_p^{-1}

(PLASMA FREQUENCY $\omega_p^2 = \frac{N_c}{9} g^2 T^2$)

EFFECTIVE LONG-DISTANCE ACTION

(Taylor, Wong, Braaten, Pisarski, ...)

$$\Gamma = \Gamma_0 + \Gamma_{HTL} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} - \frac{3}{2}\omega_p^2 \int \frac{d\hat{v}}{4\pi} F^a_{\mu\lambda} v^\lambda (v\cdot D)^{-2} v_\nu F^{a\nu\mu}$$

GENERATES EFFECTIVE INTERACTIONS

... "HARD THERMAL LOOPS"

PROBLEMS WITH Γ_{HTL}:

∴ HIGHLY NONLOCAL IN SPACE + TIME

∴ $\mathrm{Im}\,\Gamma_{HTL} \neq 0$ IN MINKOWSKI SPACE

∴ HTL'S INCLUDE SOFT MODES; HOW TO CUT BETWEEN HARD AND SOFT MODES IN A GAUGE INVARIANT WAY?

POSSIBLE SOLUTION:

REPRESENT HARD THERMAL MODES BY CLASSICAL PARTICLES. (EIKONAL LIMIT)

WONG'S EQUATIONS

$$m\dot{x}^\mu = p^\mu \qquad m\dot{p}^\mu = g\,Q^a F^{a\mu\nu} p_\nu$$

$$m\dot{Q}^a = -g f^{abc} p^\mu A^b_\mu Q^c$$

(NO SPIN COUPLING TO YM FIELD)

TRANSPORT EQ'S FOR PARTICLE DISTRIBUTION

$$f(x^\mu, p^\nu, Q^a) \qquad \text{(HEINZ)}$$

SATISFY NON-ABELIAN VLASOV EQUATION

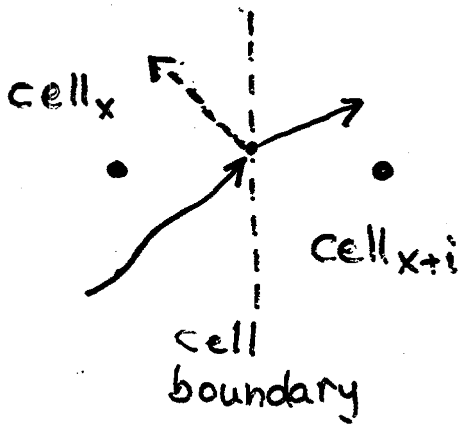
$$0 = p^\mu \left[\frac{\partial}{\partial x^\mu} - g\,Q^a F^a_{\mu\nu} \frac{\partial}{\partial p_\nu} - g f^{abc} A^b_\mu Q^c \frac{\partial}{\partial Q^a} \right] f(x,p,Q)$$

WITH YM EQUATIONS

$$D_\mu F^{\mu\nu} = g \int dp\, dQ\; p^\nu f(x,p,Q) \equiv j^\nu(x)$$

Technical aspects:

- Magnetic field acts on particles at each time step.
- Electric field only acts when particle enters (leaves) a cell.
- Particle is reflected, if kinetic energy is insufficient: electric boundary force



- Ordering of updates to ensure P and T conservation
- "Leapfrog" updates to ensure symplectic particle dynamics

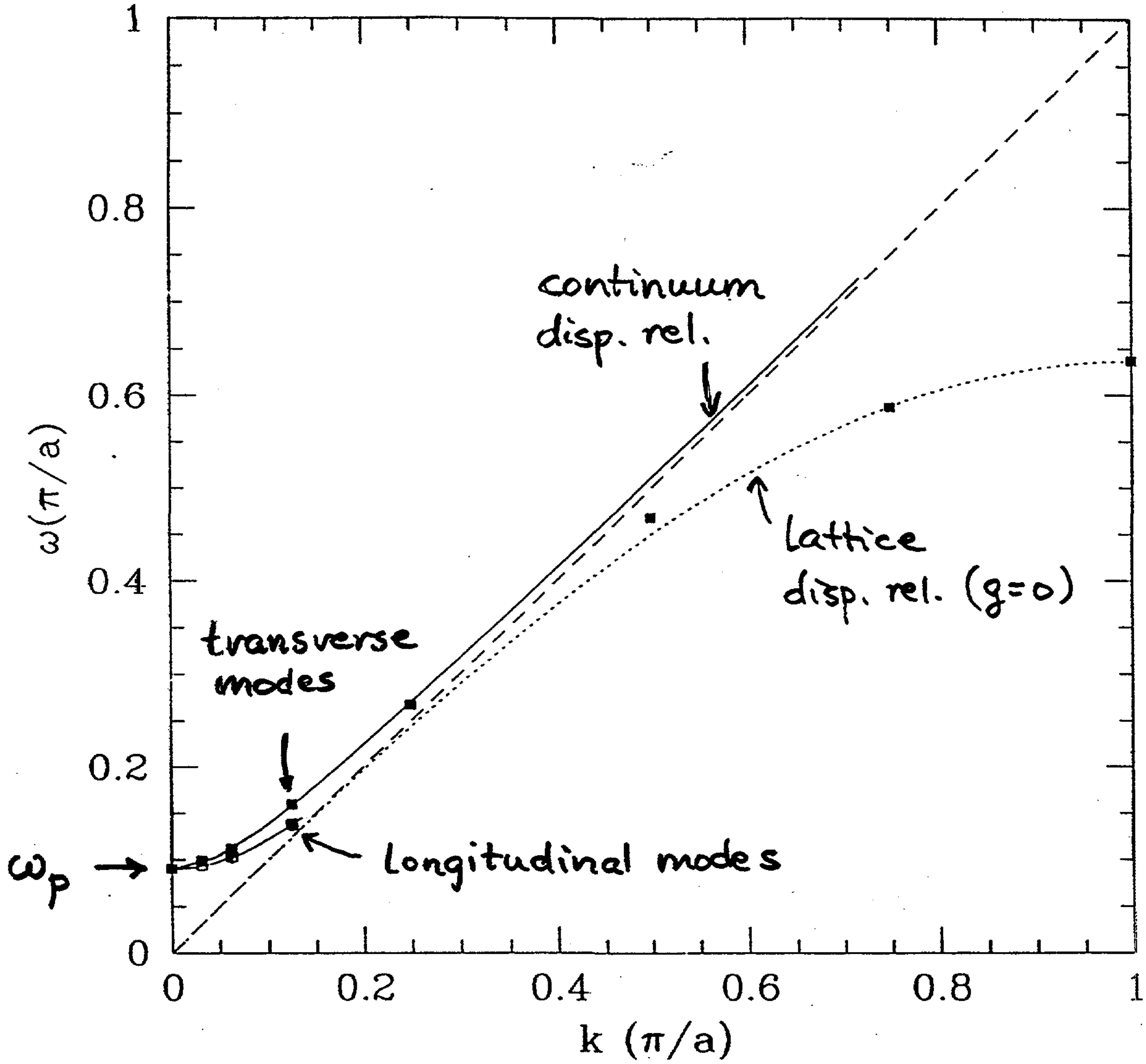
Present calculations $\rightarrow$ 32^3 lattices.

Energy conservation $\sim 10^{-5}$, Gauss' law $\sim 10^{-10}$.

Parameters: $a = 1$, $\Delta t = 0.1$, $na^3 \gtrsim 100$.

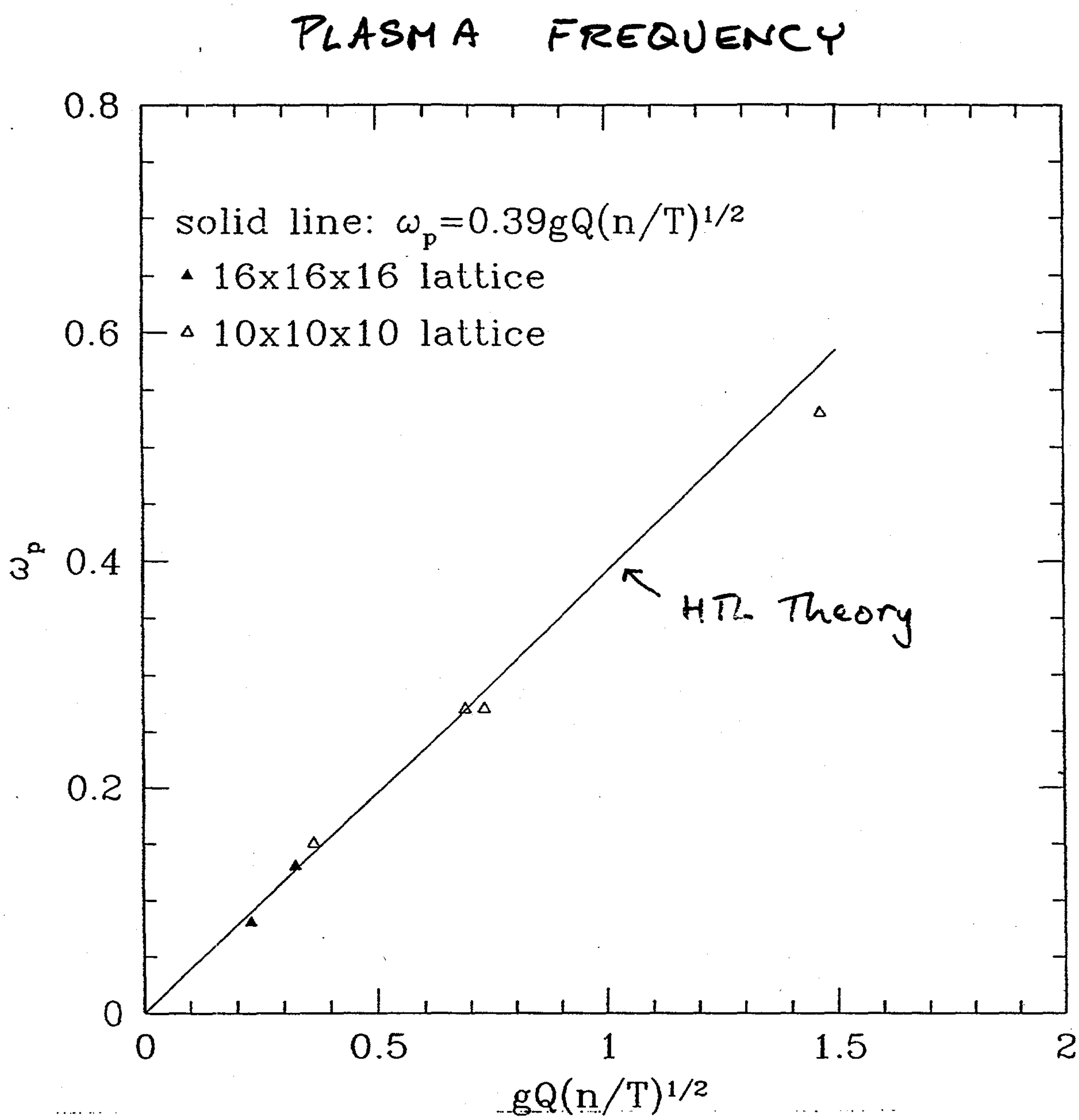
$\sum_i^{cell} Q_i^a = 0$ initially for all cells.

Vary: g, Q, T, (na^3). $\quad Q = \sqrt{2}$ for $SU(2)$ gauge particles

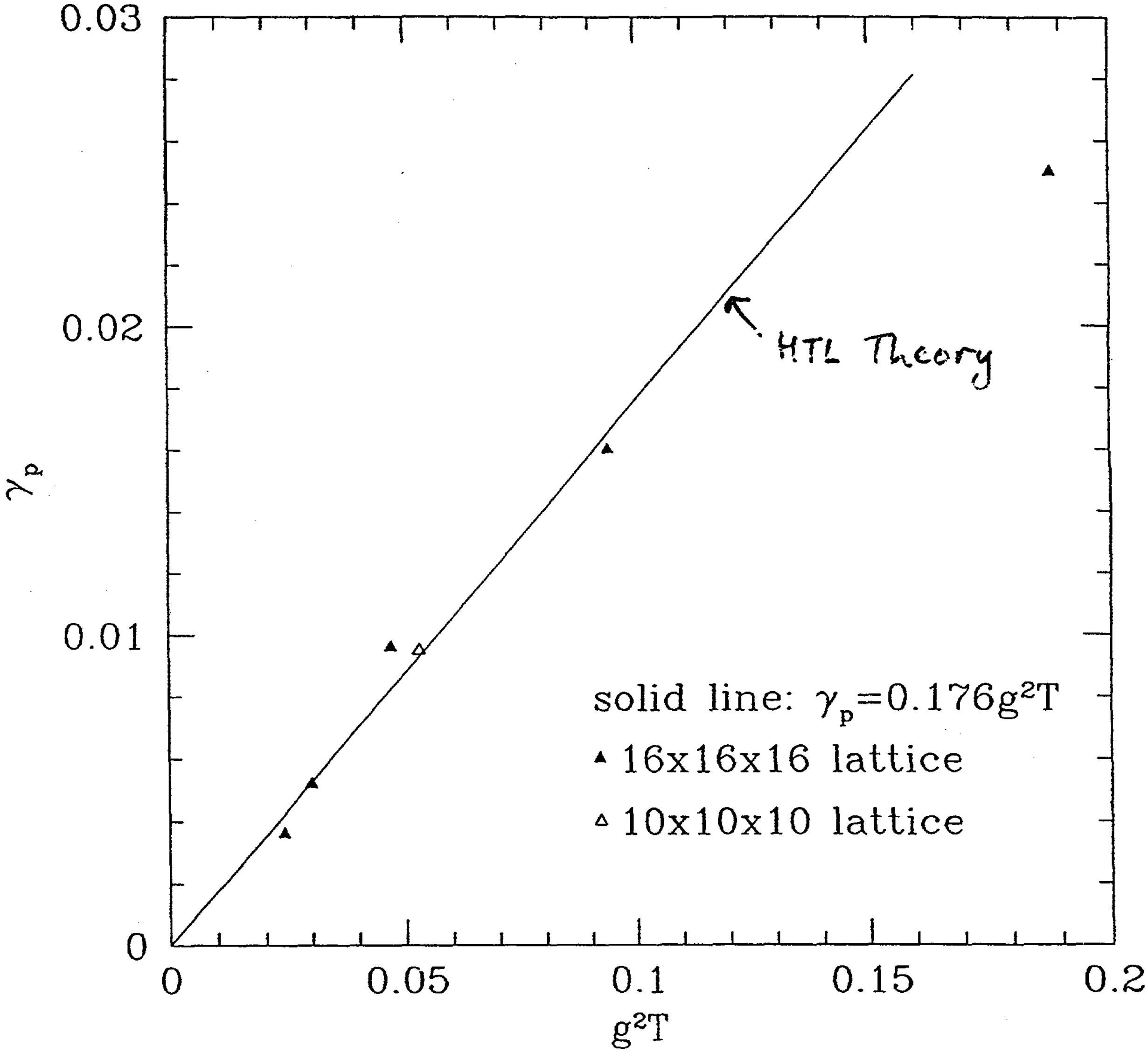


Lattice dispersion relation $\omega(k)$

Free field: $\omega(k) = \frac{2}{a} \sin \frac{ka}{2}$


PLASMA FREQUENCY
0.8
0.6
0.4
0.2
0
ω_p
solid line: ω_p=0.39gQ(n/T)$^{1/2}$
▲ 16x16x16 lattice
△ 10x10x10 lattice
HTL Theory
0
0.5
1
1.5
2
gQ(n/T)$^{1/2}$

"PLASMON" DAMPING



Linear Response Analysis:

Drive (abelian) system with current

$$\mathbf{j}(x,t) = \hat{j}\, j_0 \sin(\omega t) \sin(kx)$$

<u>Transverse</u> perturbation $(\hat{j} \perp \hat{x})$: $\quad \Pi = \Pi_r + i\Pi_i$

$$\langle \mathbf{j}(x,t) \cdot E(x,t) \rangle = \frac{j_0^2}{4} \frac{\omega \Pi_i(\omega,k)}{(\omega^2 - k^2 - \Pi_r)^2 + \Pi_i^2} \longrightarrow \Pi_i$$

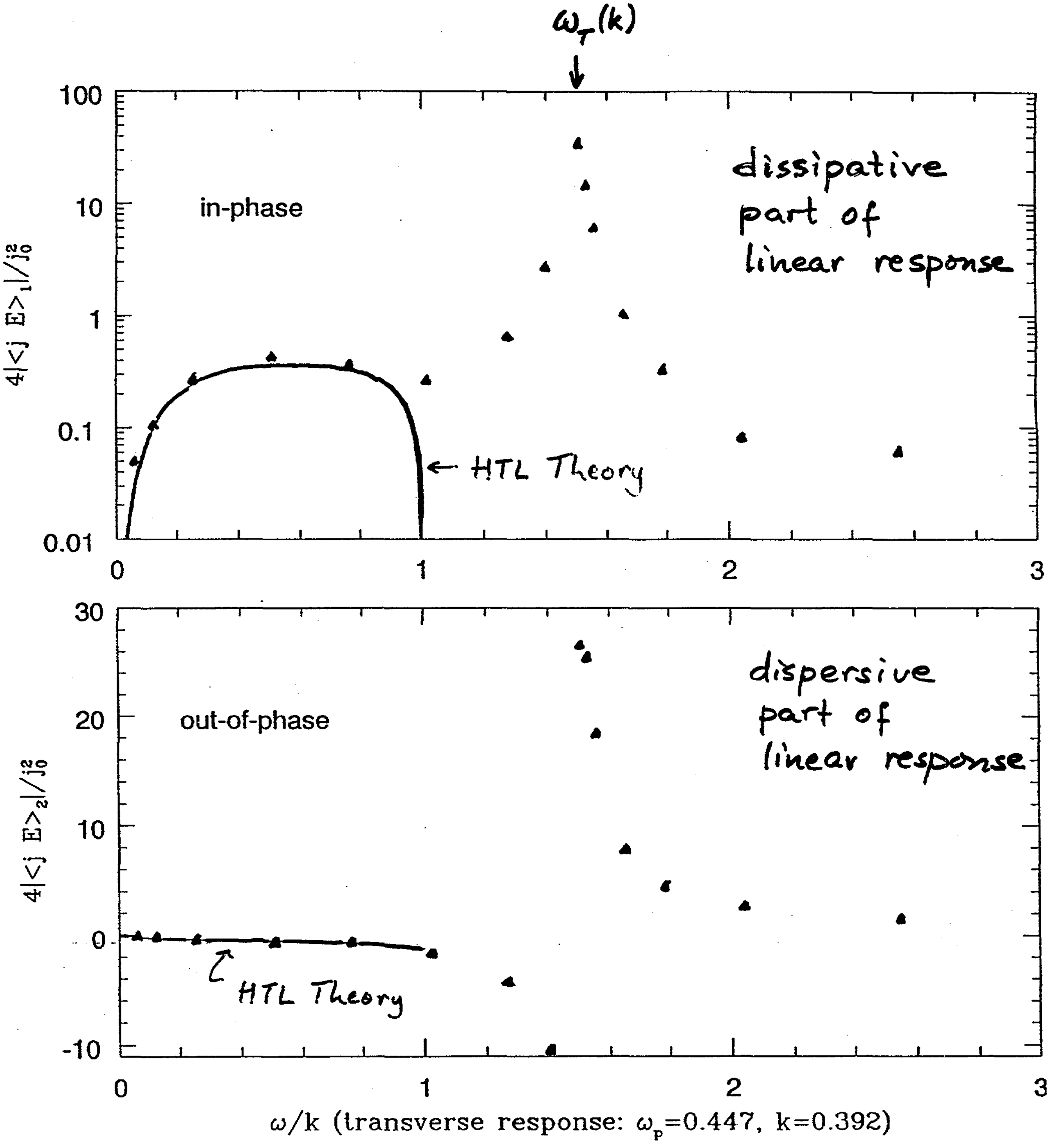
$$\langle \mathbf{j}(x,t) \cdot E(x,t-\tfrac{T}{4}) \rangle = \frac{j_0^2}{4} \frac{\omega(\omega^2 - k^2 - \Pi_r)}{(\omega^2 - k^2 - \Pi_r)^2 + \Pi_i^2} \longrightarrow \Pi_r$$

HTL theory predicts:

$$\Pi_r(k,\omega) = \frac{3}{2}\omega_p^2 \frac{\omega^2}{k^2}\left[1 + \frac{1}{2}\left(\frac{k}{\omega} - \frac{\omega}{k}\right) \ln\left|\frac{\omega+k}{\omega-k}\right|\right]$$

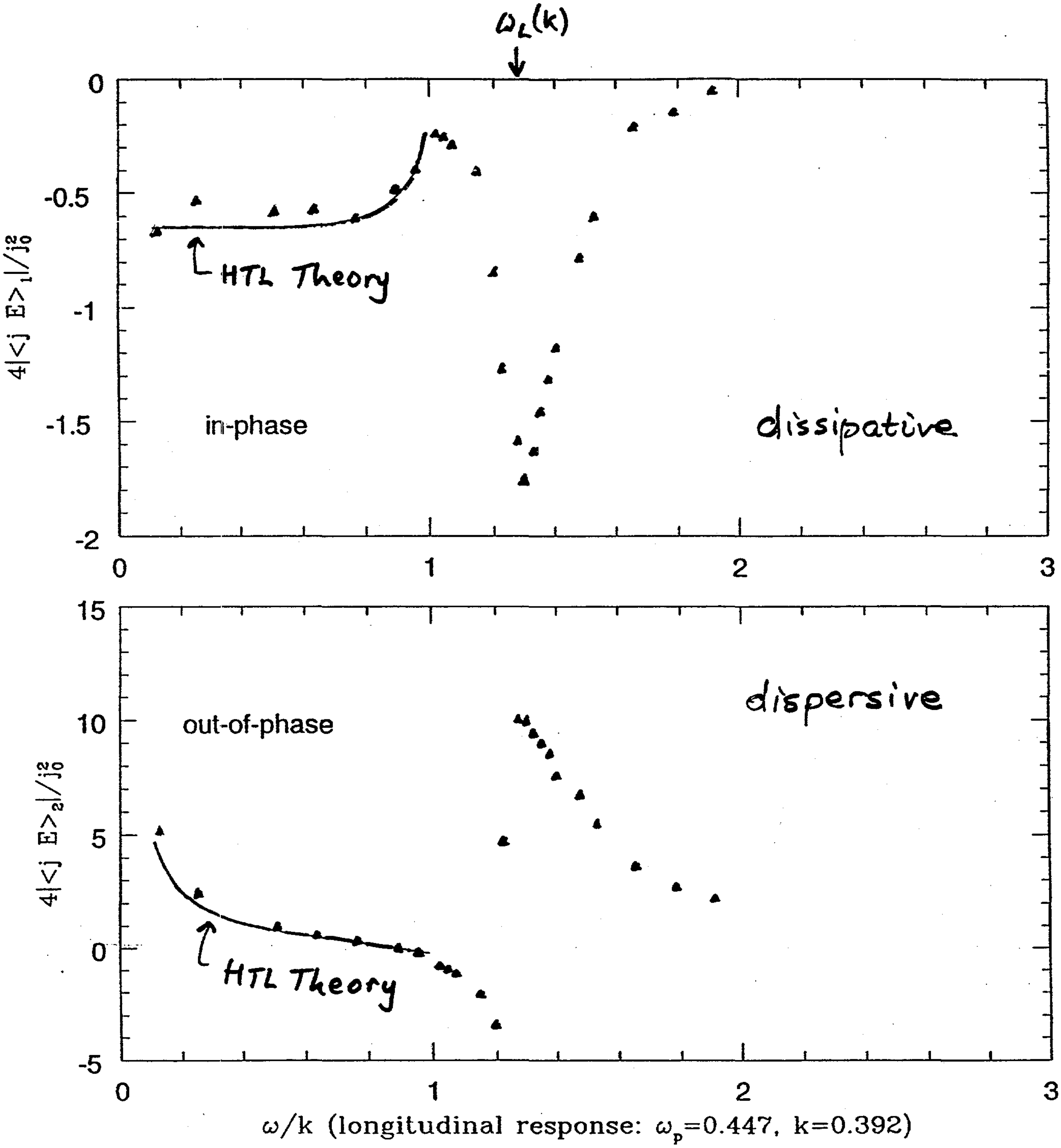
$$\Pi_i(k,\omega) = -\frac{3\pi}{4}\omega_p^2 \frac{\omega^2}{k^2}\left(\frac{k}{\omega} - \frac{\omega}{k}\right)\theta(k^2 - \omega^2)$$

Similar expressions hold for <u>longitudinal</u> perturbation $(\hat{j} = \hat{x})$.



Transverse response

(abelian theory)



Longitudinal response

(abelian theory)

CONCLUSIONS + OUTLOOK

- classical YM theory is chaotic
  KS entropy (growth rate) $\sim g^2 T \times V$
  indicates $\tau_{therm} \lesssim 0.5$ fm/c

- Local lattice formulation of real-time YM theory with HTL
  numerical implementation works:
  $\omega_p(k)$, γ_p, linear response

- Calculations in progress:
  - Chern-Simons number diffusion in SU(2)
  - Color conductivity

- Possible generalizations:
  - collisions among particles
  - initial states far off equilibrium

Classical Yang Mills Dynamics

Larry McLERRAN

University of Minnesota

Problems with Monte-Carlo Simulation of Real Time Processes

I Description + Motivation for Real Time Monte Carlo

II Origin of Ultra-violet Catastrophe (Rayleigh-Jeans revisited.)

III Solution of problem in $\lambda\phi^4$

IV Why solution won't work in Gauge Theory

V Why the problem is important for Electroweak B+L Violation

Real Time Monte Carlo: The Method

at a Grigoriev + Rubakov + refs. there

Bosonic theory with small mass

$T/M_{eff} >> 1$

Consider processes at small k (large λ)

$T/k >> 1$

Would like to compute a field-field correlation function:

$$\langle \phi(t,k)\, \phi(0,k') \rangle$$

$$t \sim \frac{1}{\omega} \quad , \quad T/\omega >> 1$$

For bosons

$$n(E) \sim \frac{1}{e^{\beta E}-1} \sim \frac{T}{E} >> 1$$

All low k states are multiply occupied => Dynamics is classical!

Classical calculation of
$\langle \phi(t,x)\,\phi(0,x')\rangle$

At $t=0$, distribution of

$$\Pi = \dot\phi(0,\vec{x}), \quad \phi(0,\vec{x})$$

determined by

$$e^{-\beta H_{cl}}$$

$$H_{cl} = \int d^3\vec{x}\; \frac{1}{2}\Pi^2(0,\vec{x}) + \frac{1}{2}(\nabla\phi(0,\vec{x}))^2 + V(\phi(0,\vec{x}))$$

Given one value of $\phi^1(0,\vec{x})$, $\Pi^1(0,\vec{x})$,
$\phi^1(t,\vec{x})$, $\Pi^1(t,\vec{x})$ determined by solving classical equations:

$$\langle \phi(t,\vec{x})\,\phi(0,\vec{x}')\rangle = \frac{\sum_i \phi^i(t,\vec{x})\,\phi^i(0,\vec{x})\,e^{-\beta H_i}}{\sum_i e^{-\beta H_i}}$$

$\therefore$ Determine initial condition by Monte-Carlo, average over different conditions

What's wrong with real time Monte-Carlo?

Rayleigh - Jeans Divergence:

Consider energy density of ideal gas:

$$\mathcal{E} = \int^{\Lambda} d^3p \; E \; n(E)$$

$$= \int^{\Lambda} d^3p \; E \; \frac{T}{E} \sim T\Lambda^3$$

Energy density dominated by U.V. because phase space huge.

Classical equations: with enough time, phase space will be saturated $\Rightarrow$ will flow to UV

or

for initial conditions, expect sensitivity to highest allowed frequency Λ. Take $\Lambda \to \infty$, expect dependance

Classical Real Time Monte-Carlo

... U V Cut

UNUSUAL DILEPTONS AT RHIC A FIELD THEORETIC APPROACH BASED ON A NON-EQUILIBRIUM CHIRAL PHASE TRANSITION

FRED COOPER

LOS ALAMOS NATIONAL LABS

Talk at RIKEN-BNL Workshop

Collaborators

Dileptons - Yuval Kluger V. Koch

Field theory

Emil Mottola, J. P. Paz, S. Habib, Y. Kluger

TDHF - S. Y. Pi

DCC's

+ J. Dawson et al ! M. Lampert

RHIC - GREAT CHALLENGE TO FIELD THEORIST

T D LEE

(1) Consistent formulation of Quantum time evolution problems LANL

(2) Initial Conditions ??

McClerran, .. Klaus Geiger - Mueller
Parton Event Generator?
classical?

PRODUCTION OF PLASMA

a) Perturbative - Partons

b) Non Perturbative flux tube
Vacuum sparking - Schwinger

(4) HADRONIZATION ???

(5) THERMALIZATION ? .. 1/N ?
Computer power?

(6) Effects of Phase Transitions
Nonequilibrium

(7) Inhomogeneous evolutions -
computer power ??

(8) CONFINEMENT - REALTIME

Bibliography

F Cooper + S. Y. Pi — 1985 Phys Rev D

mil ttola

F. Cooper and E. Mo, *Phys. Rev. D* **36**, 3114 (1987); *Phys. Rev. D* **40**, 456 (1989).

Y. Kluger, J. M. Eisenberg, B. Svetitsky, F. Cooper, and E. M., *Phys. Rev. Lett.* **67** 2427 (1991); *Phys. Rev.* **D45** (1992) 4659; *Phys. Rev.* **D48** (1993) 190.

F. Cooper, S. Habib, Y. Kluger, E. M., J. P. Paz, and, P. R. Anderson, *Phys. Rev.* **D50** (1994) 2848.

S. Habib, Y. Kluger, E. M., and J. P. Paz, *Phys. Rev. Lett.* **76**, 4660 (1996).

F. Cooper, S. Habib, Y. Kluger, and E. M., hep-ph/9610345, *Phys. Rev.* **D** (1997) ~~(in press)~~. 55, 6471

F. Cooper, Y Kluger, U. Koch

in preparation

Cooper Kluger Mottola Paz

Phys Rev D 51, 2377 (1995)

Kluger, Koch, Randrup, X N Wang (1997)
LBNL-40175

OUTLINE:

(0) REVIEW TWO PICTURES FOR DISCUSSING NON-EQUILIBRIUM PROCESSES: (A) SCHRODINGER PICTURE–TIME DEPENDENT VARIATIONAL APPROACH

(B) HEISENBERG PICTURE- CLOSED TIME PATH PATH INTEGRAL+LARGE N

(1) DISCUSS MODEL OF THE NON-EQUILIBRIUM CHIRAL PHASE TRANSITION- O(4) LINEAR SIGMA MODEL IN A MEAN FIELD (LARGE N) APPROXIMATION

(2) NATURAL QUENCHING (COOLING) DUE TO THE EXPANSION OF THE LORENTZ CONTRACTED ENERGY DENSITY INTO THE VACUUM- (BOOST INVARIANT KINEMATICS)

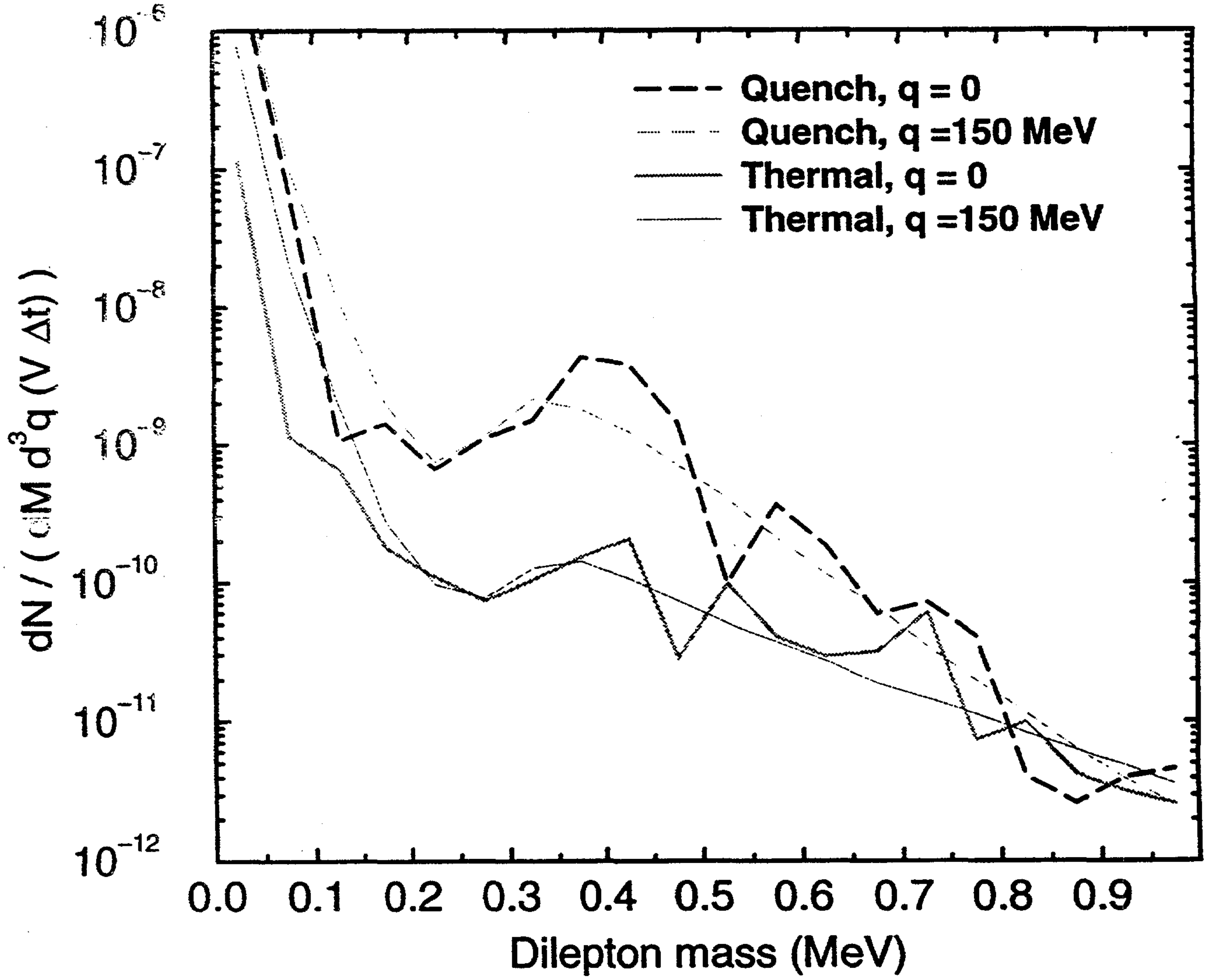
(3) THIS COOLING ALLOWS ONE TO START IN THE CHIRALLY SYMMETRIC PHASE AND END IN THE CHIRAL SYMMETRY BROKEN PHASE

(4) WE SEE THE GROWTH OF UNSTABLE MODES WHEN THE ORDER PARAMETER (EFFECTIVE MASS) GOES NEGATIVE DURING THE EVOLUTION

(5) WE SEE A LOW MOMENTUM DISTORTION IN THE SINGLE PARTICLE DISTRIBUTION OF SECONDARIES

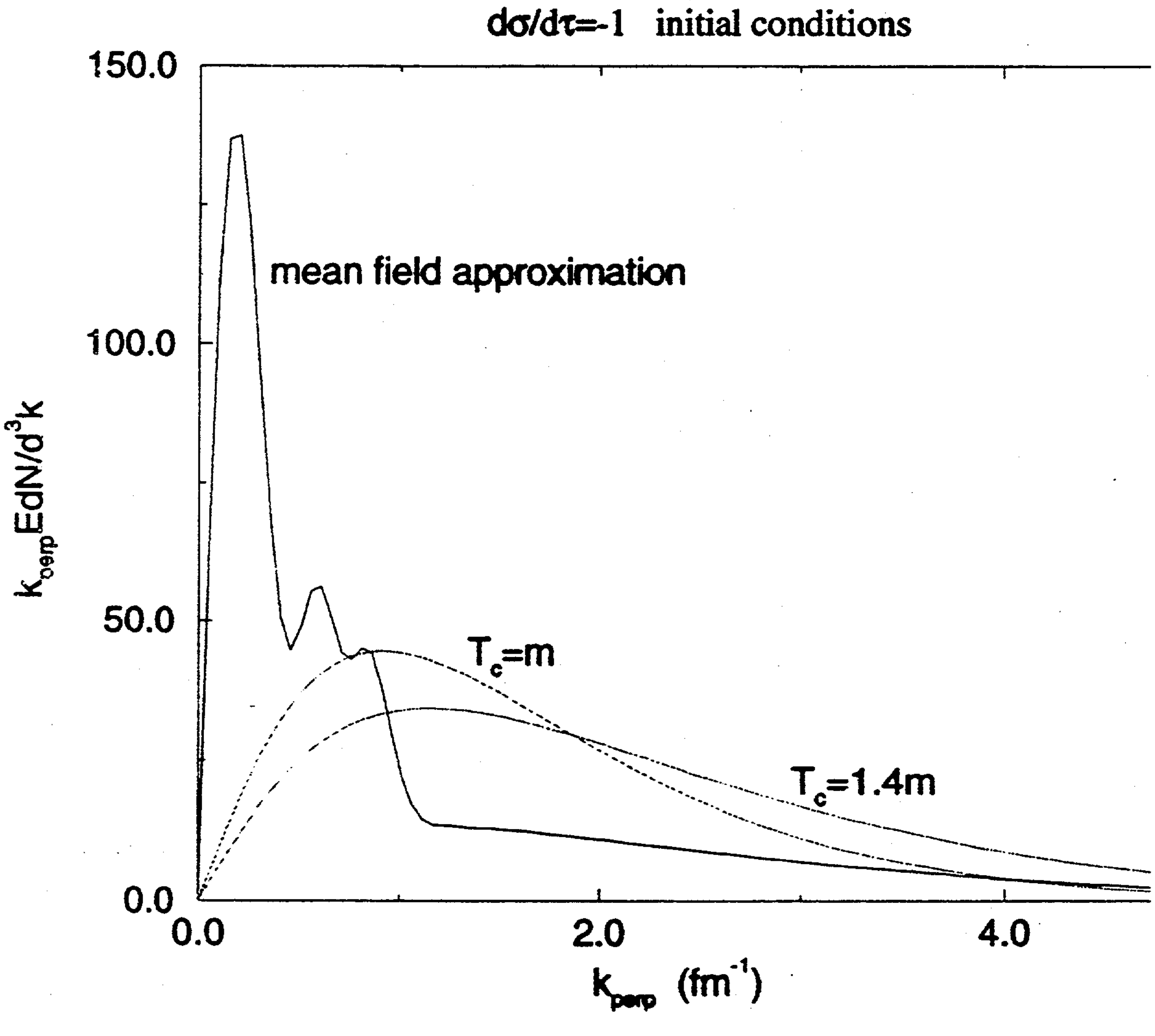
(6) WE RECONSTRUCT TYPICAL CLASSICAL CONFIGURATIONS BY SAMPLING THE QUANTUM DENSITY MATRIX AND SEE DOMAINS

(7) WE SHOW HOW TO CALCULATE THE DILEPTONS SPECTRUM FROM THIS TIME EVOLVING PLASMA USING SCHWINGER'S CLOSED TIME PATH FORMALISM AND LSZ REDUCTION METHODS



Quench, q = 0
Quench, q =150 MeV
Thermal, q = 0
Thermal, q =150 MeV
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
dN / (dM d^{3}q (V Δt))
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
Dilepton mass (MeV)

Enhancement
of low momentum pions



Covariant Transport Theory

Yang Pang

Department of Physics, Columbia University, New York, NY 10027

and

Department of Physics, Brookhaven National Laboratory, Upton, NY 11973

pang@rhic.phys.columbia.edu

Many phenomenological models for relativistic heavy ion collisions share a common framework - the relativistic Boltzmann equations (Figure 1). Within this framework, a nucleus-nucleus collision is described by the evolution of phase-space distributions of several species of particles. The equations can be effectively solved with the cascade algorithm (Figure 2) by sampling each phase-space distribution with points, i.e. δ-functions, and by treating the interaction terms as collisions of these points. In between collisions, each point travels on a straight line trajectory.

In most implementations of the cascade algorithm, each physical particle, e.g. a hadron or a quark, is often represented by one point. Thus, the cross-section for a collision of two points is just the cross-section of the physical particles, which can be quite large compared to the local density of the system. For an ultra-relativistic nucleus-nucleus collision, this could lead to a large violation of the Lorentz invariance (Figure 3). By using the invariance property of the Boltzmann equation under a scale transformation (Figure 4), a Lorentz invariant cascade algorithm can be obtained.

The General Cascade Program – GCP – is a tool for solving the relativistic Boltzmann equation with any number of particle species and very general interactions with the cascade algorithm (Figure 5).

Anonymous FTP server for GCP: `rhic.phys.columbia.edu`

Web server for GCP: `http://rhic.phys.columbia.edu/gcp`.

References:

[1] Yang Pang, *High Baryon Density from Relativistic Heavy Ion Collisions*, in *Proceedings of CCAST Symposium/Workshop on Particle Physics at Fermi Scale*, Beijing, May 1993, Edited by Y. Pang, J. Qiu, and Z. Qiu, (Gordon Breach, New York, 1993), p451.

[2] Yang Pang, *General Cascade Program*, in Proceedings of RHIC'96, CU-TP-815 (1997).

[3] Miklos Gyulassy, *Open Standard for Cascade Models for RHIC*, Proceedings of RIKEN BNL Research Center Workshop, Volume 1.

Relativistic Boltzmann Equation

$$p^\mu \partial_\mu \mathcal{W}_a(\vec{x},t,\vec{p}) = \sum_n \sum_{b_1,b_2,\cdots,b_n} \int \prod_{i=1}^{n} \frac{d^3\vec{p}_{b_i}}{(2\pi)^3 2E_{b_i}} \mathcal{W}_{b_i}(\vec{x},t,\vec{p}_{b_i})$$
$$\sum_m \sum_{c_1,c_2,\cdots,c_m} \int \prod_{j=1}^{m} \frac{d^3\vec{p}_{c_j}}{(2\pi)^3 2E_{c_j}} \mid A_{n\to m} \mid^2$$
$$(2\pi)^4 \delta^4(\sum_{i=1}^{n} p_{b_i} - \sum_{j=1}^{m} p_{c_j})$$
$$[-\sum_{i=1}^{n} \delta_{ab_i} \delta^3(\vec{p} - \vec{p}_{b_i}) + \sum_{j=1}^{m} \delta_{ac_j} \delta^3(\vec{p} - \vec{p_{c_j}})]$$

Probability Distribution: $\mathcal{W}_a(\vec{x},t,\vec{p})$

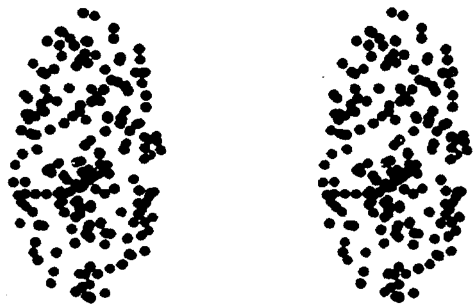
S-Matrix:

$$< c_1, c_2, \cdots, c_m \mid S \mid b_1, b_2, \cdots, b_n >$$
$$= A_{n\to m}(2\pi)^4 \delta^4(\sum_{i=1}^{n} p_{b_i} - \sum_{j=1}^{m} p_{c_j})$$

Cascade

1. Initial condition

$$\mathcal{W}_a(\vec{x},t,\vec{p}) = \sum_i \delta^3(\vec{x}-\vec{x}_i(t))\,\delta^3(\vec{p}-\vec{p}_i)$$



2. Straight line trajectories

$$\vec{v}_i = \frac{\vec{p}_i}{E_i}$$

$$\vec{x}_i(t) = \vec{x}_i(0) + \vec{v}_i\, t$$

3. Collision at closest approach

$$d \le \sqrt{\frac{\sigma_{total}}{\pi}}$$

4. Outgoing channel selection

partial cross-sections:

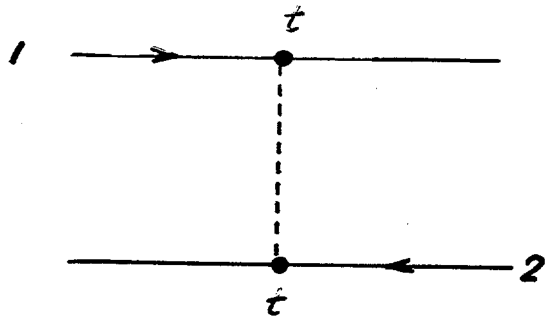
elastic, inelastic (productions of pion, strange, ...)

5. Momentum distribution

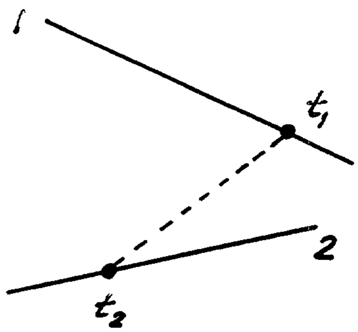
$$\int d\,(\mathrm{phase-space})\,|A|^2$$

Repeat steps 2-5

Violation of Lorentz Invariance in Cascade Algorithm



c.m. frame



global frame

Collision performed in local frame
Time ordering done in global frame

Simultaneity in c.m.	$\neq$	Simultaneity in global frame

$\rightarrow$ Violation of causality

Lorentz Invariance

Boltzmann probability function

$$\mathcal{W}(\vec{x},\vec{p},t) = \sum_{i}^{N} \delta^3(\vec{x} - \vec{x}_i(t))\delta^3(\vec{p} - \vec{p}_i)$$

Decompose each particle into a large number λ of partons

$$N \to \lambda N \qquad \mathcal{W} \to \lambda \mathcal{W} \qquad \text{with} \qquad \lambda \to \infty$$

cross-section $\sigma \to \sigma/\lambda$, so that

mean free path $\ell \sim (\mathcal{W}\sigma)^{-1}$ fixed

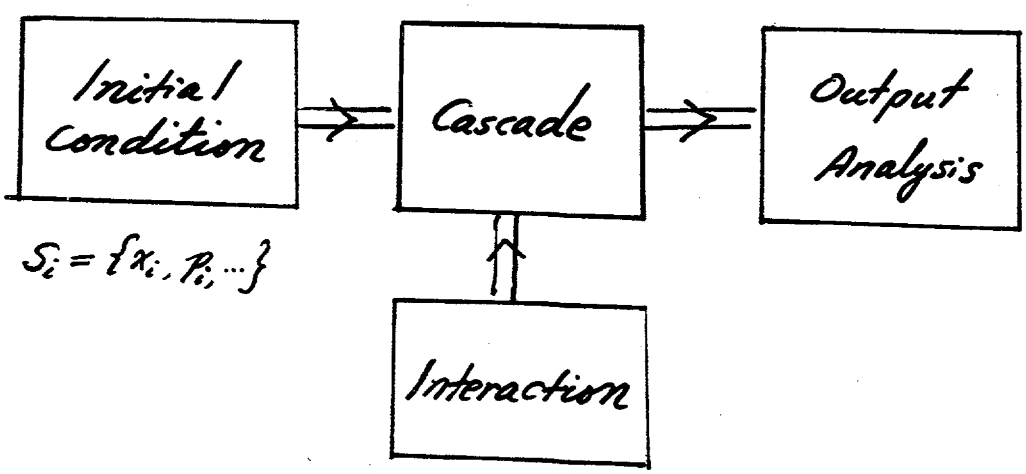
collision distance $d = \sqrt{\sigma/\pi} \to 1/\sqrt{\lambda} \to 0$

Cascade Model $\to$ Relativistic Boltzmann Equation

General Cascade Program (GCP)

- Code $\neq$ Model

- One universal code for many different cascade models



$S_1 + S_2 \rightarrow S_1' + S_2' + \dots$

σ_{total}

$S_i' = \{x_i', p_i', \dots\}$

QCD Space-time description of high-density particle matter in high-energy collisions

... from clean e^+e^- to dirty nuclei ....

Klaus Kinder-Geiger

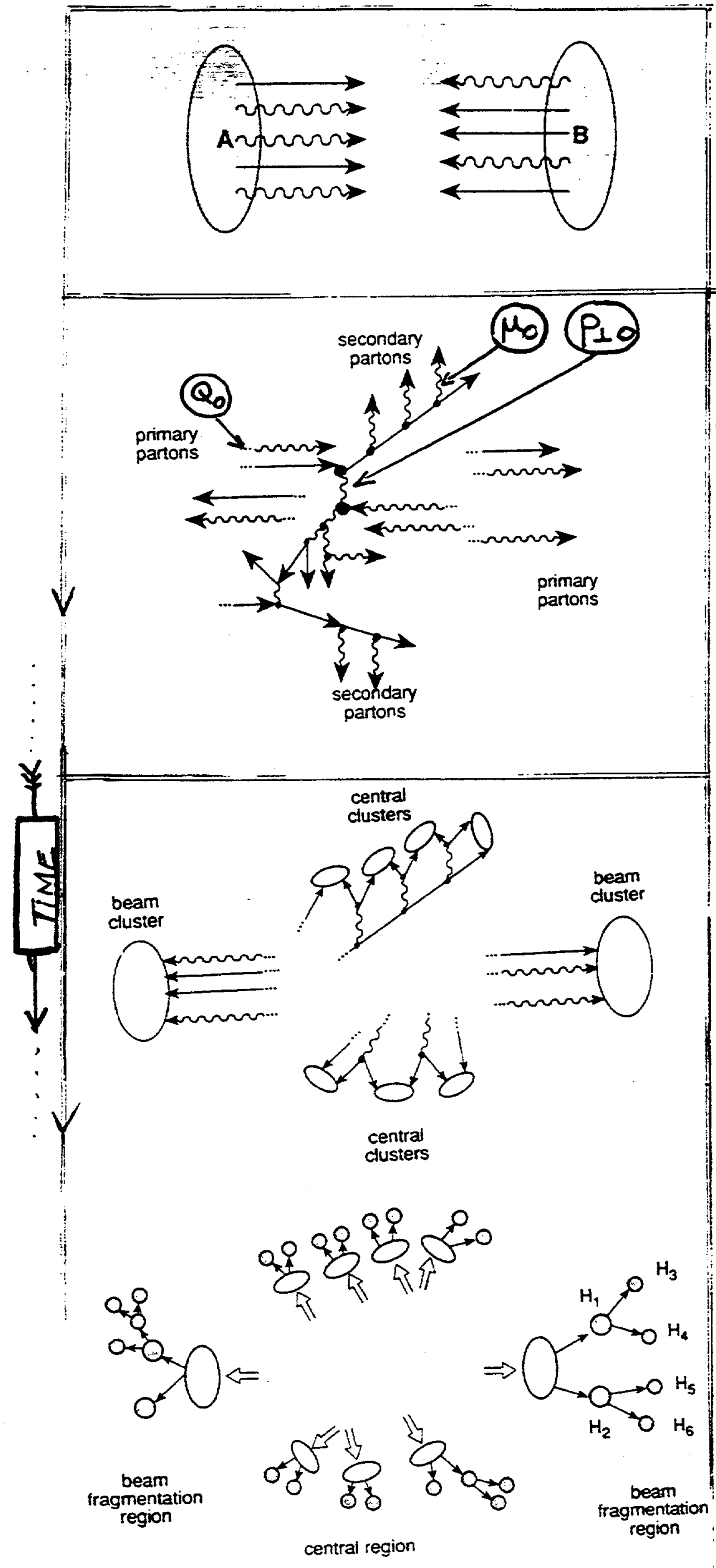
Kay Kay Gee

BNL

- Why at all ?
- How to ?
- Does it make sense ?
- What then ?

4/3

THE PARTON CASCADE MODEL



- INITIAL STATE

SCALE: Q_0^2

- PARTON CASCADE DEVELOPMENT

SCALE: $[Q_0^2, \mu_0^2]$

- PARTON RECOMBINATION (preconfinement)

SCALE: $[\mu_0^2, \Lambda^2]$

- CLUSTER FRAGMENTATION (confinement)

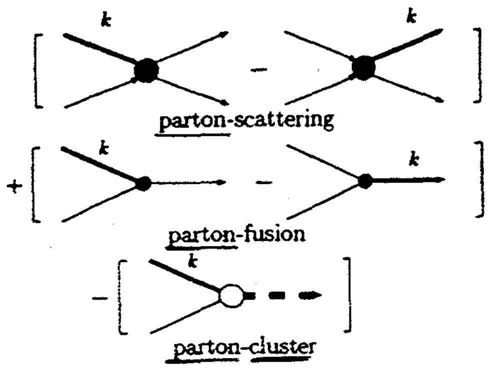
SCALE: Λ^2

4/6

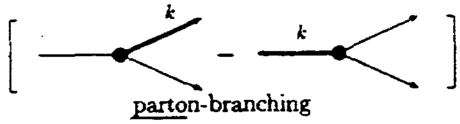
Closed set of "balance" equations

- **partons:**

$$k \cdot \frac{\partial}{\partial r} F_p =$$

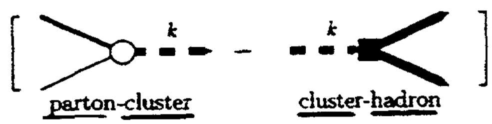


$$k^2 \frac{\partial}{\partial k^2} F_p =$$



- **pre-hadronic clusters**

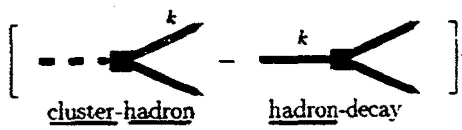
$$k \cdot \frac{\partial}{\partial r} F_c =$$



$$k^2 \frac{\partial}{\partial k^2} F_c \approx 0$$

- **hadrons**

$$k \cdot \frac{\partial}{\partial r} F_h =$$



$$k^2 \frac{\partial}{\partial k^2} F_h \approx 0$$

Microscopic dynamics $\longrightarrow$ macroscopic observables

Lorentz-invariant 1-particle distribution ("Wigner function"):

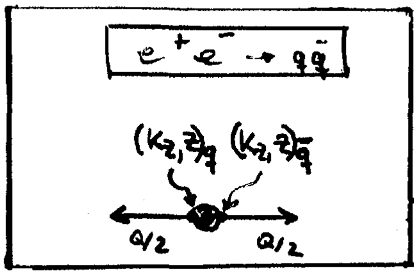
$$F_a(r,k)\, d^4r\, d^4k \;=\; \begin{cases} \#\text{ of particles } a = g, q, \text{cluster}, \pi, K, p \ldots \\ \text{at time } t \text{ within } dt\text{, position in } d\vec{r} \text{ around } \vec{r}, \\ \text{energy (momentum) in } dE\,(d\vec{k}) \text{ around } E\ (\vec{k}). \end{cases}$$

$$r^\mu = (t,\vec{r})\;;\quad k^\mu = (E,\vec{k})\;;\quad k^2 \begin{cases} = m^2 & \text{on shell} \\ < m^2 & \text{space-like} \\ > m^2 & \text{time-like} \end{cases}$$

Initial value problem: specify initial state at time $t = t_0 \equiv 0$:

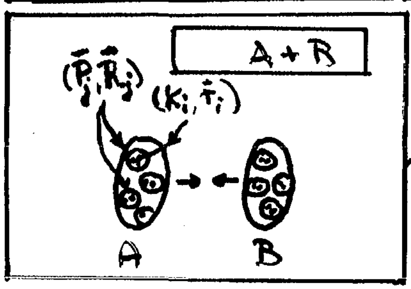
$$F_a^{(0)}(r,k) \equiv F_a(t=0,\vec{r}\,|\,E,\vec{k}) = \frac{dN_a(t=0)}{d^3r\, d^3k\, dE}$$

$$= \mathcal{P}_a(E,\vec{k}) \otimes \mathcal{R}_a(\vec{r})$$



e.g.

$$\sum_{i=q,\bar{q}} \left[\delta(E_i - \tfrac{Q}{2})\,\delta(k_{z_i} \pm \tfrac{Q}{2})\,\delta^2(\vec{k}_\perp)\right]\left[e^{-z_i^2 Q^2}\,\delta^2(\vec{r}_\perp)\right]$$



e.g.

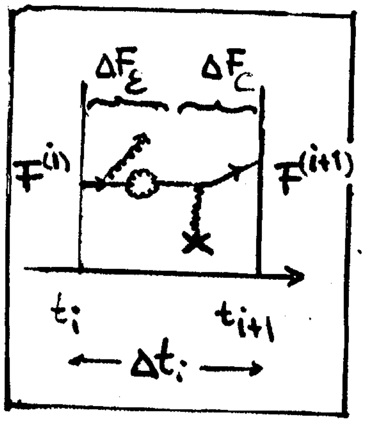
$$\sum_{j=1}^{A+B}\sum_{i=1}^{n(j)} \left[f_a^j\!\left(\frac{k_{zi}}{P_j}, Q_0^2\right) g(\vec{k}_{\perp i})\right]\left[e^{-\nu^2(\vec{r}_i-\vec{R}_j)^2}\, h^{A(B)}(\vec{R}_j,\vec{r}_j)\right]$$

For $t > t_0 = 0$, solve coupled evolutional & collisional cascade in small timesteps :

$$\frac{\partial}{\partial \ln k^2} F_a(r,k) = \mathcal{E}_a(F) \otimes F_a$$

$$k \cdot \frac{\partial}{\partial r} F_a(r,k) = C_a(F) \otimes F_a$$

Iterative 2-step procedure : trace particle history $t_i = t_{i-1} + \Delta t_i$ from t_0 with $F_a^{(0)}(t_0)$:



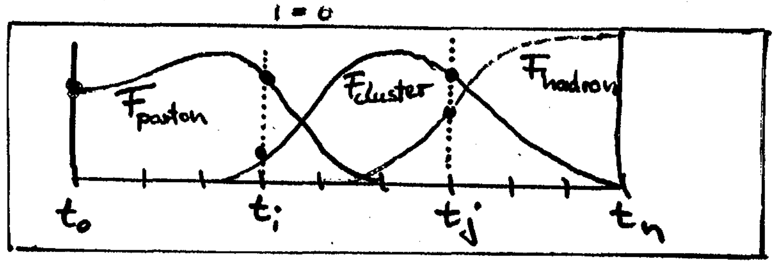
$$F^{(i+1)} = F^{(i)} + \Delta F_{\mathcal{E}}^{(i)} + \Delta F_C^{(i)}$$

$$\Delta F_{\mathcal{E}}^{(i)} = \Delta \ln k^2 \, \mathcal{E}(F^{(i)}) \otimes F^{(i)} \cdot \Theta(\Delta t_i - \Delta \ln k^2)$$

$$\Delta F_C^{(i)} = \frac{\Delta t}{E} \, C(F^{(i)}) \otimes F^{(i)} \cdot \Theta(\Delta t_i - \Delta |\vec{r}|)$$

At any finite $t = t_n > t_0$ microscopic particle history is contained in

$$F_a(t, \vec{r} | E, \vec{k}) = \sum_{i=0}^{n} F_a^{(i)}(t_i, r | E, \vec{k})$$



$\boxed{\text{From statistical physics: extract from } F \text{ macroscopic, spacetime-dep. quantities:}}$

particle current: $$n_a^\mu(t,\vec r) = d_a \int \frac{d^4k}{(2\pi)^4}\, k^\mu\, F_a(t,\vec r\,|\,E,\vec k)$$

energy mom. tensor: $$T_a^{\mu\nu}(t,\vec r) = d_a \int \frac{d^4k}{(2\pi)^4}\, k^\mu k^\nu\, F_a(t,\vec r\,|\,E,\vec k)$$

entropy current: $$S_a^\mu(t,\vec r) = d_a \int \frac{d^4k}{(2\pi)^4}\, k^\mu \left\{ F_a \ln(F_a) - \theta_a (1+\theta_a F_a) \ln(1+\theta_a F_a) \right\}$$

$\boxed{\text{Define 'local flow velocity}}$

$$u^\mu(t,\vec r) = \frac{n^\mu}{\sqrt{n_\nu\, n^\nu}}$$

$\boxed{\text{Get Lorentz-invariant, scalar density profiles}}$

number density: $$\rho_a(t,\vec r) = n_{\mu_a} n_a^\mu \quad \rightsquigarrow \quad \frac{dN}{d^2k_\perp}$$

energy density: $$\mathcal{E}_a(t,\vec r) = -\tfrac{1}{3} T_a^{\mu\nu}\left(g_{\mu\nu} - u_{\mu_a} u_{\nu_a}\right) \quad \rightsquigarrow \quad \frac{dE_\perp}{dy}$$

pressure: $$P_a(t,\vec r) = T_a^{\mu\nu}\, u_{\mu_a} u_{\nu_a}$$

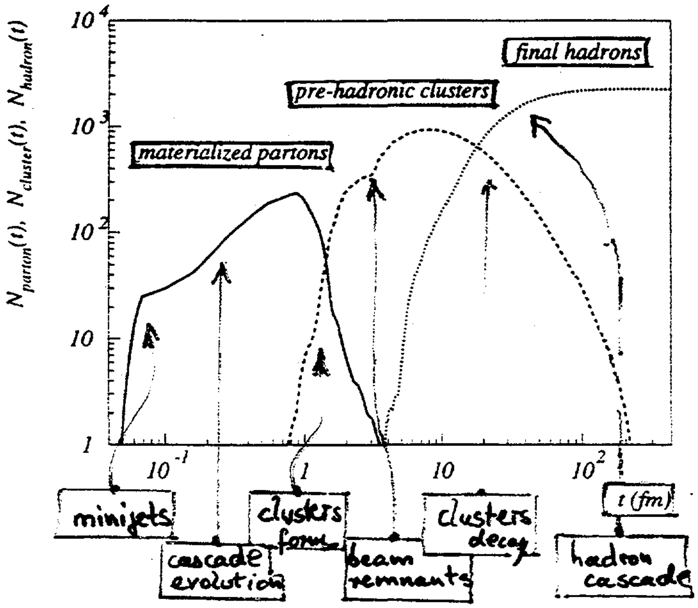
$$\rightsquigarrow \quad \frac{d\langle k_\perp\rangle}{dz}$$

entropy density: $$S_a(t,\vec r) = S_a^\mu\, u_{\mu a}$$

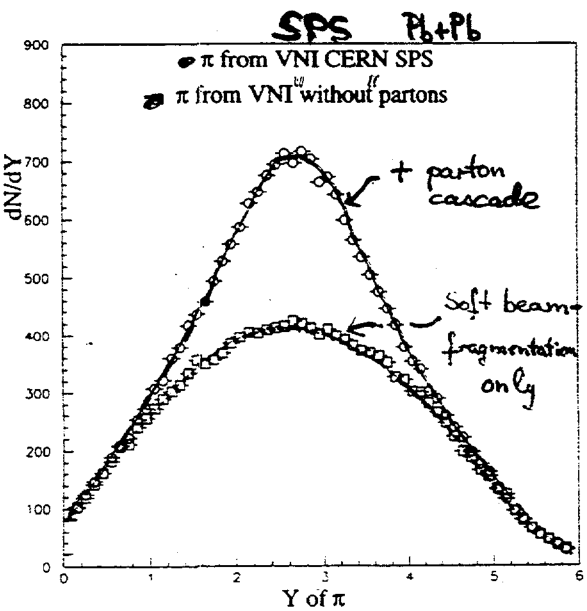
eff. temperature: $$T_a(t,\vec r) = \frac{\mathcal{E}_a + P_a}{S_a} \quad \rightsquigarrow \quad \frac{dT}{d^2r_\perp}$$

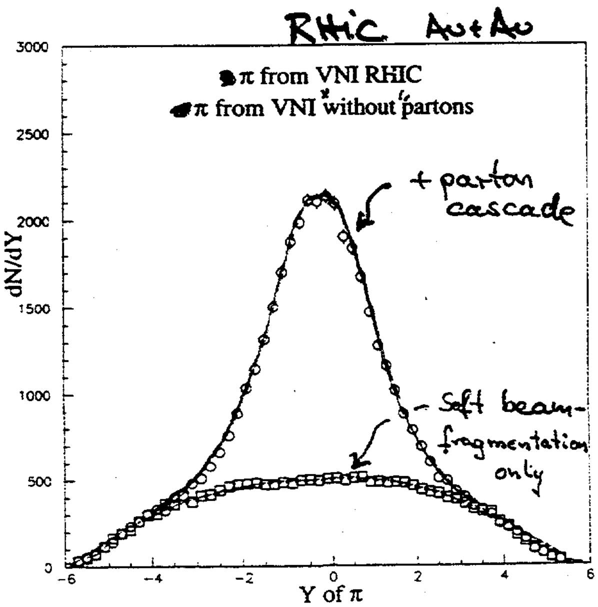
Longacre & KKG 97

Timevolution of Pb+Pb @ CERN SPS



"Partonic contribution" in final hadron yield

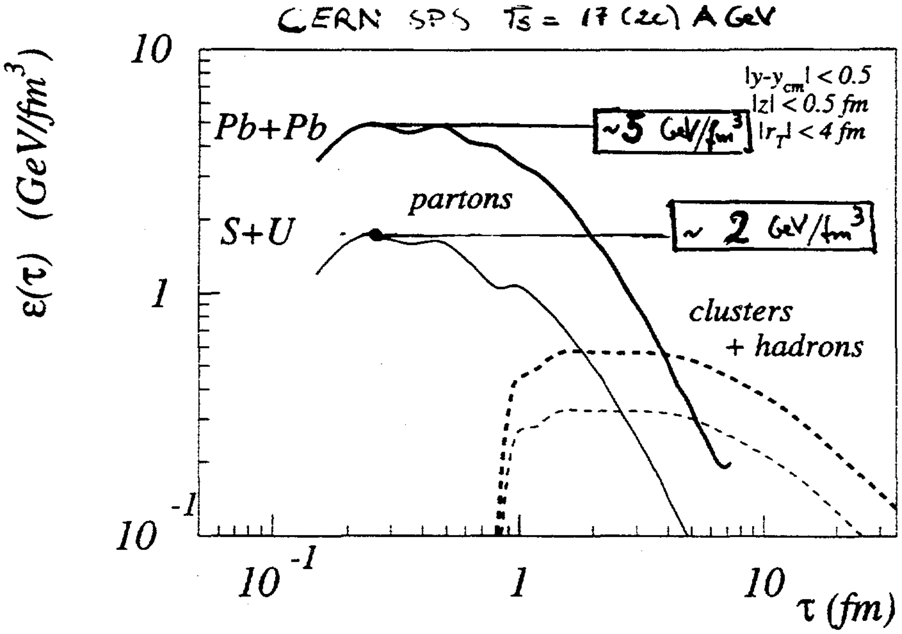




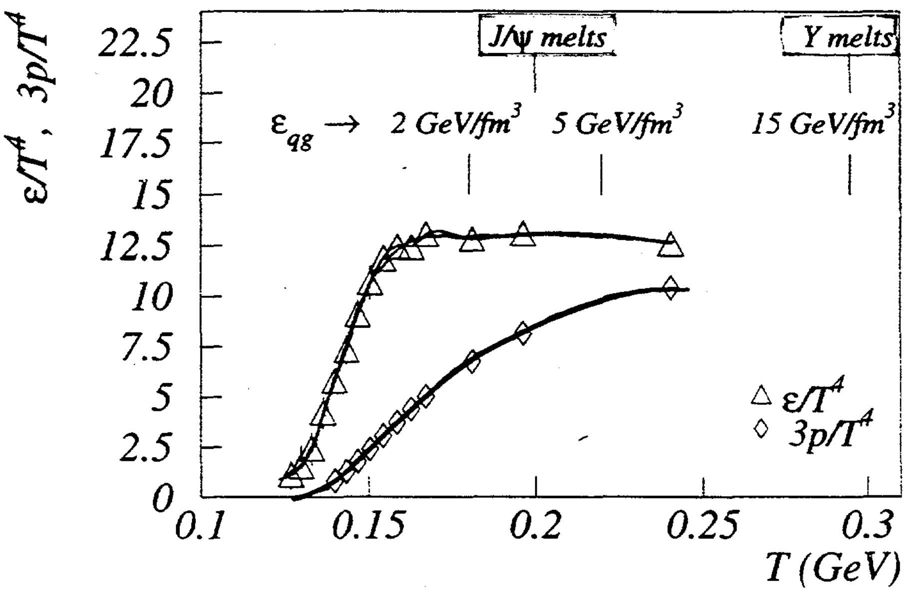
7/5

Energy density: Parton Cascade vs. Lattice QCD

B. Mueller & KKG '97



VNi-3.2
KKG, 97

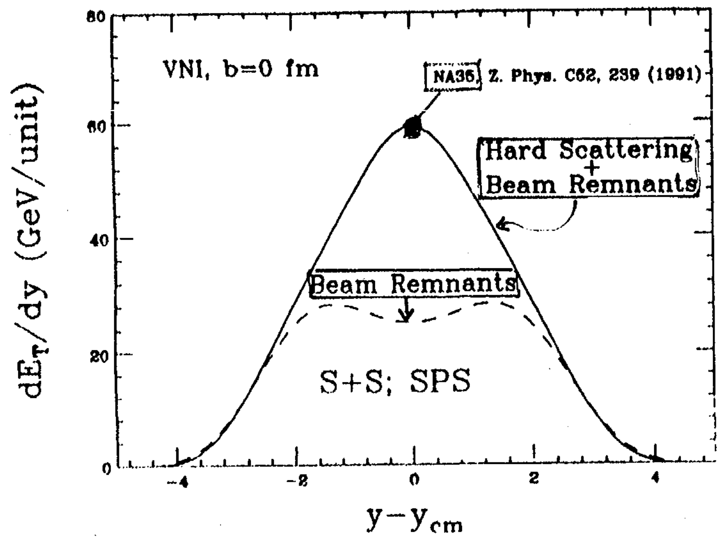


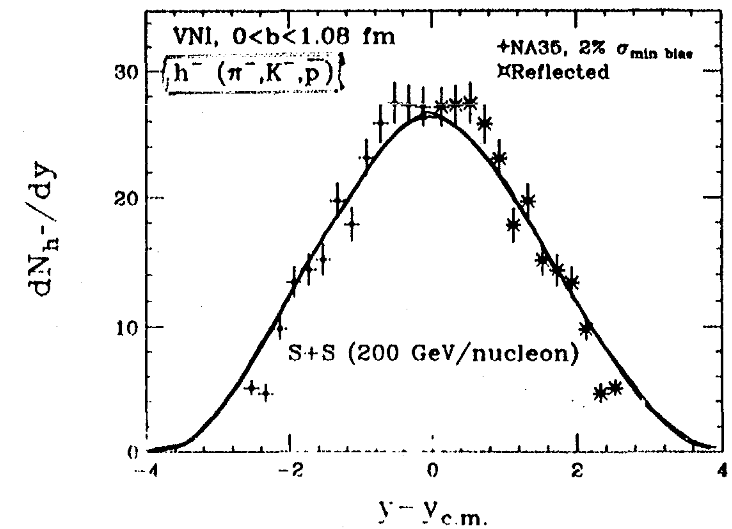
Karsch & Satz '96

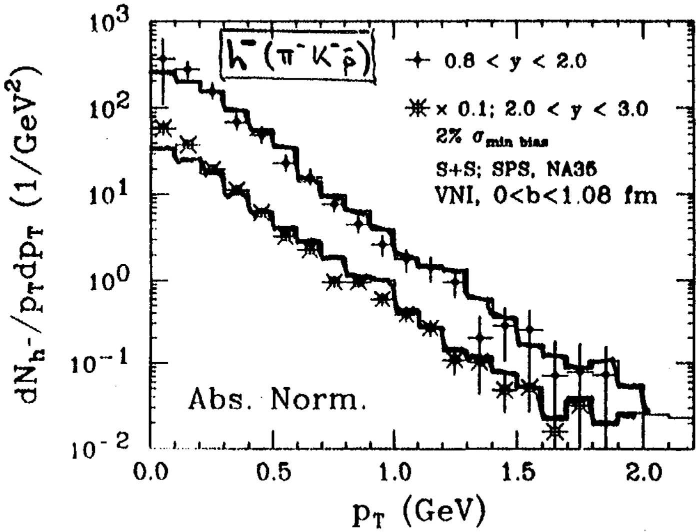
MILC Coll.,
Blum et al. '96

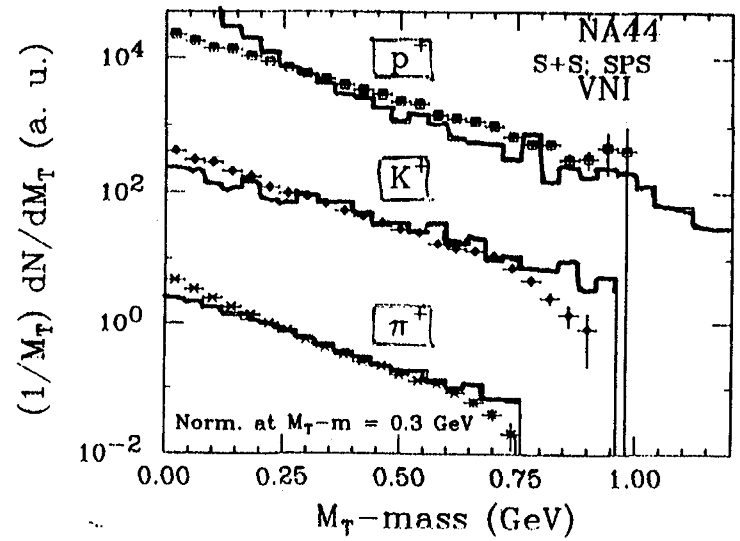
CERN SPS S+S @ 200 A GeV

Srivastava & KKG 97





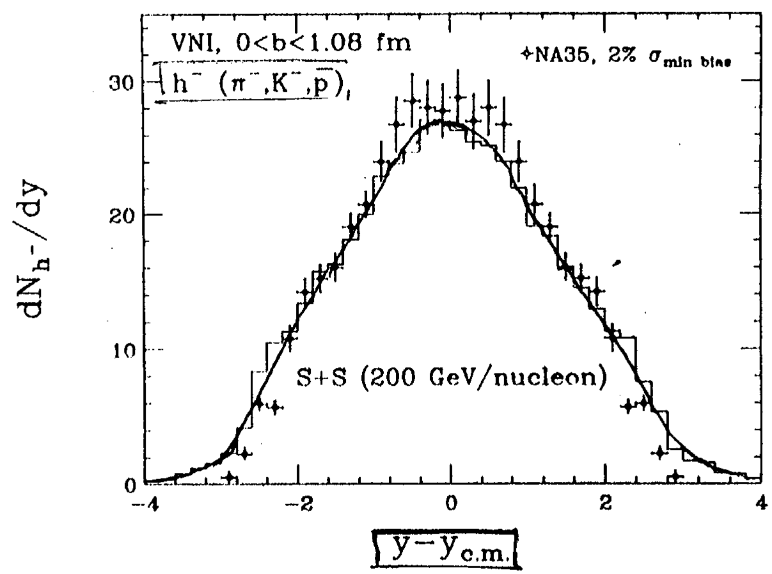


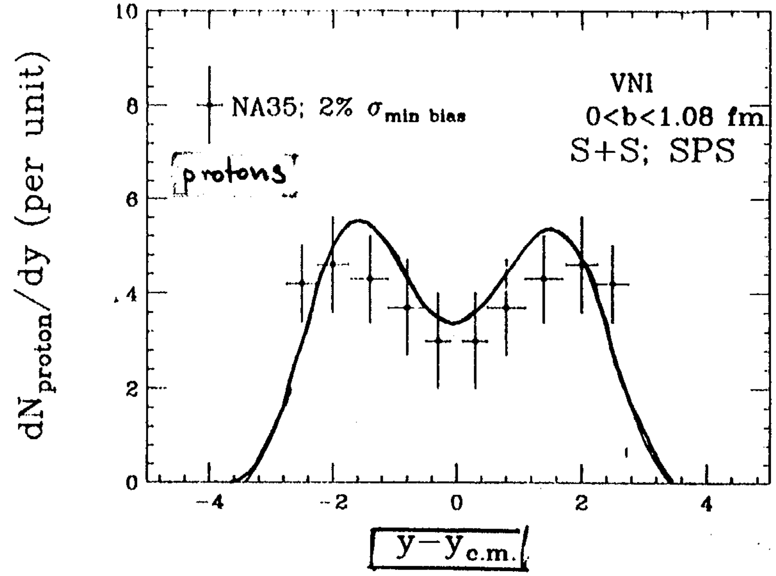


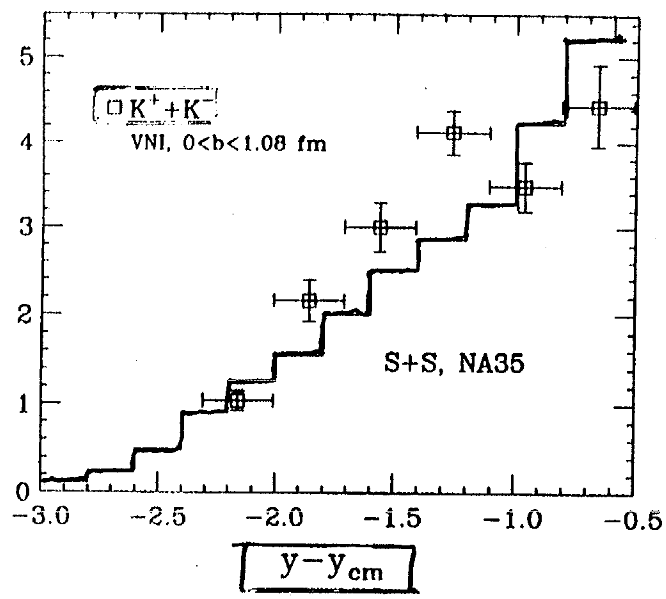
7/3

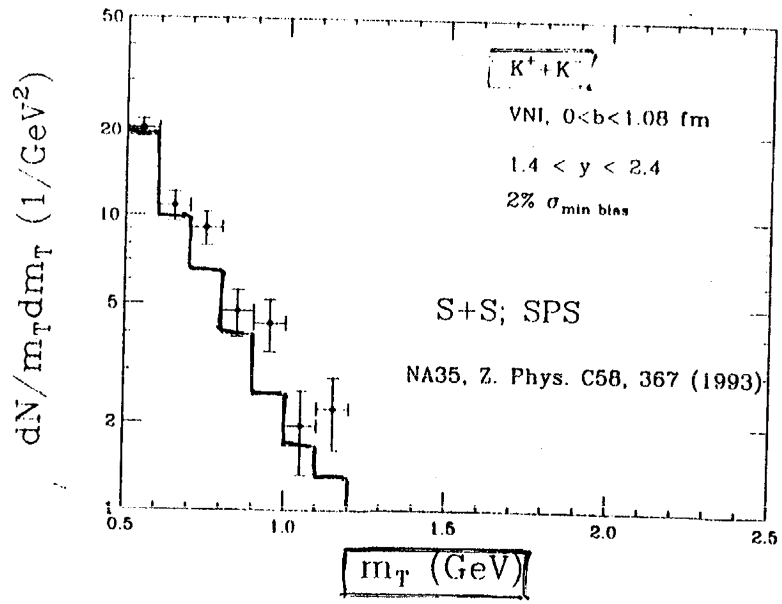
CERN SPS S+S @ 200 AGeV

Srivastava '97
& KKG





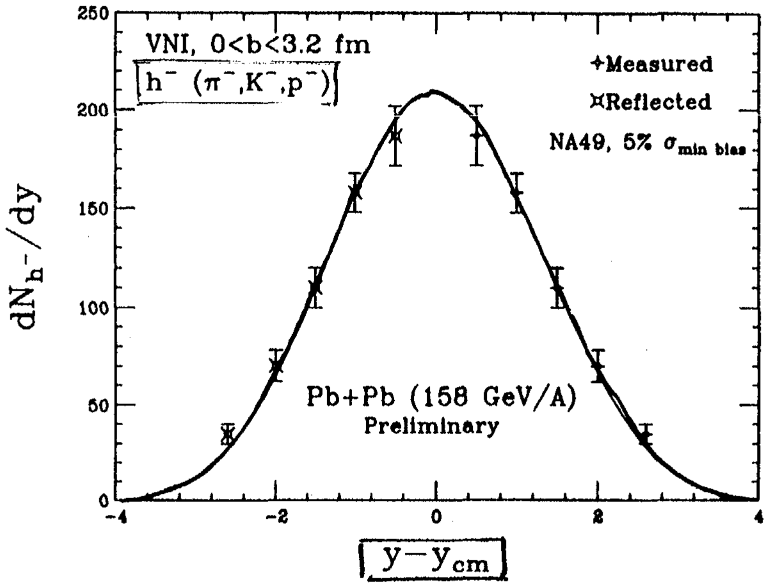


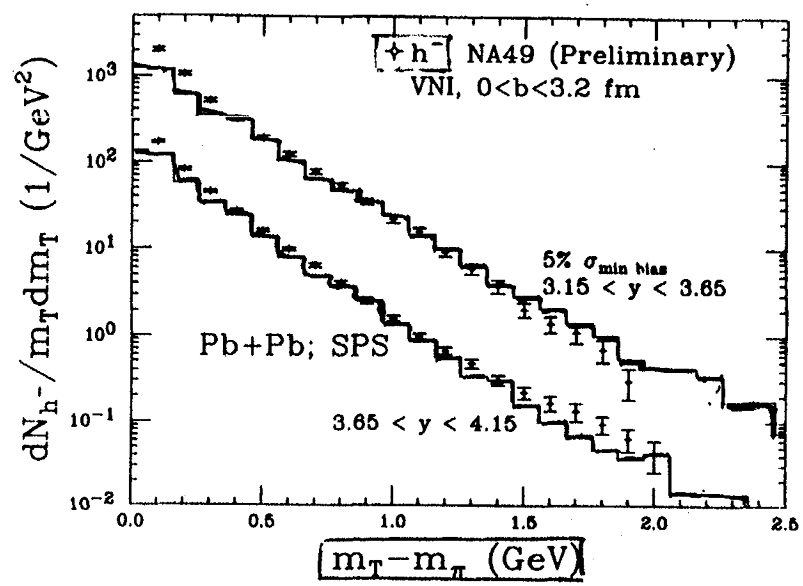


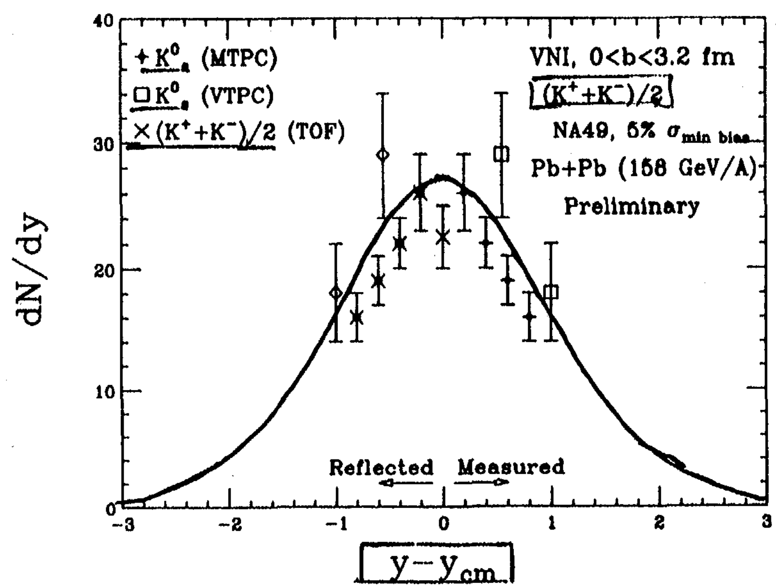
1/4

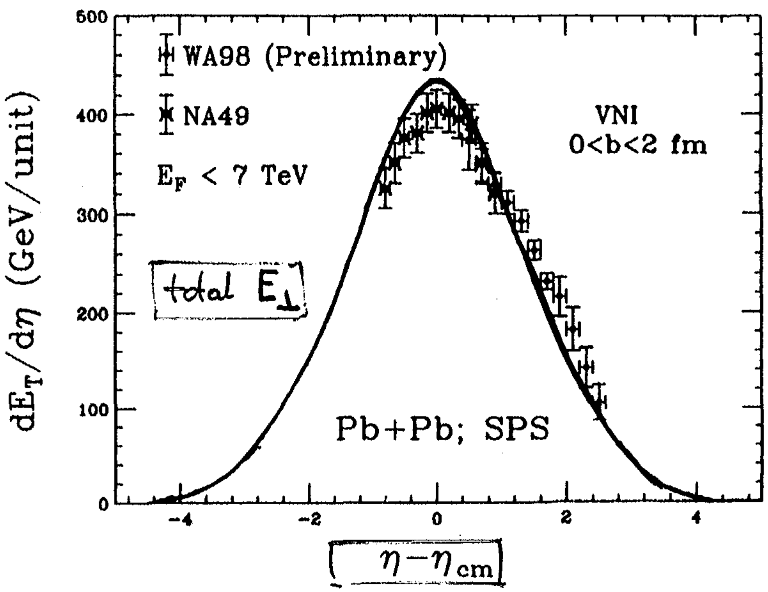
CERN SPS Pb+Pb @ 158 A GeV

Srivastava & KKG '97

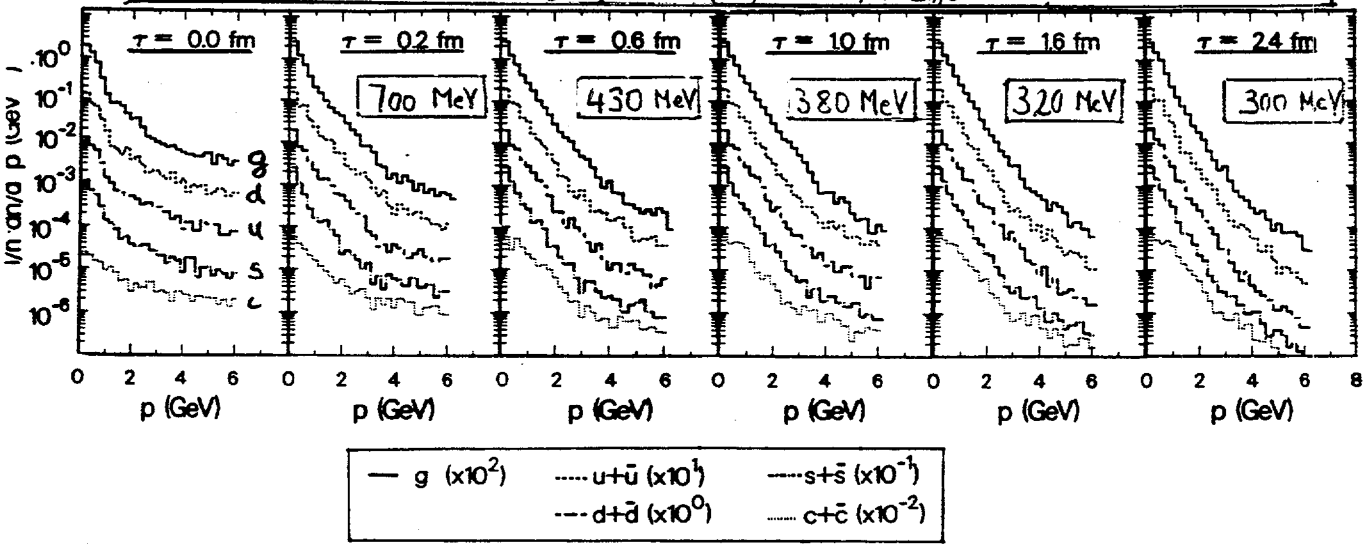




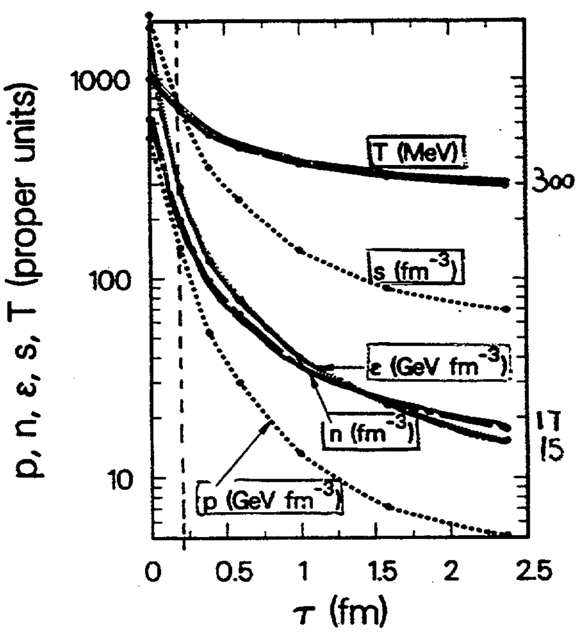


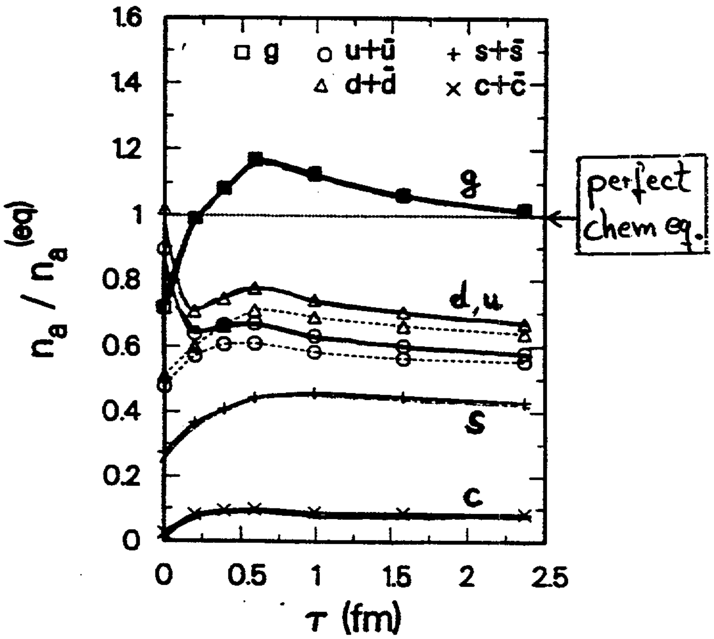


Momentum distributions $\quad \frac{1}{\bar{n}_a}\frac{d\bar{n}_a}{d^3p}(\tau) = \frac{1}{(2\pi)^3}\frac{1}{\pi R^2 \Delta\eta}\int_{-\Delta\eta/2}^{\Delta\eta/2} d\eta \int_0^R d^2 r_\perp \, \underline{F_a}(\tau,\eta,r_\perp;y,m_\perp)$



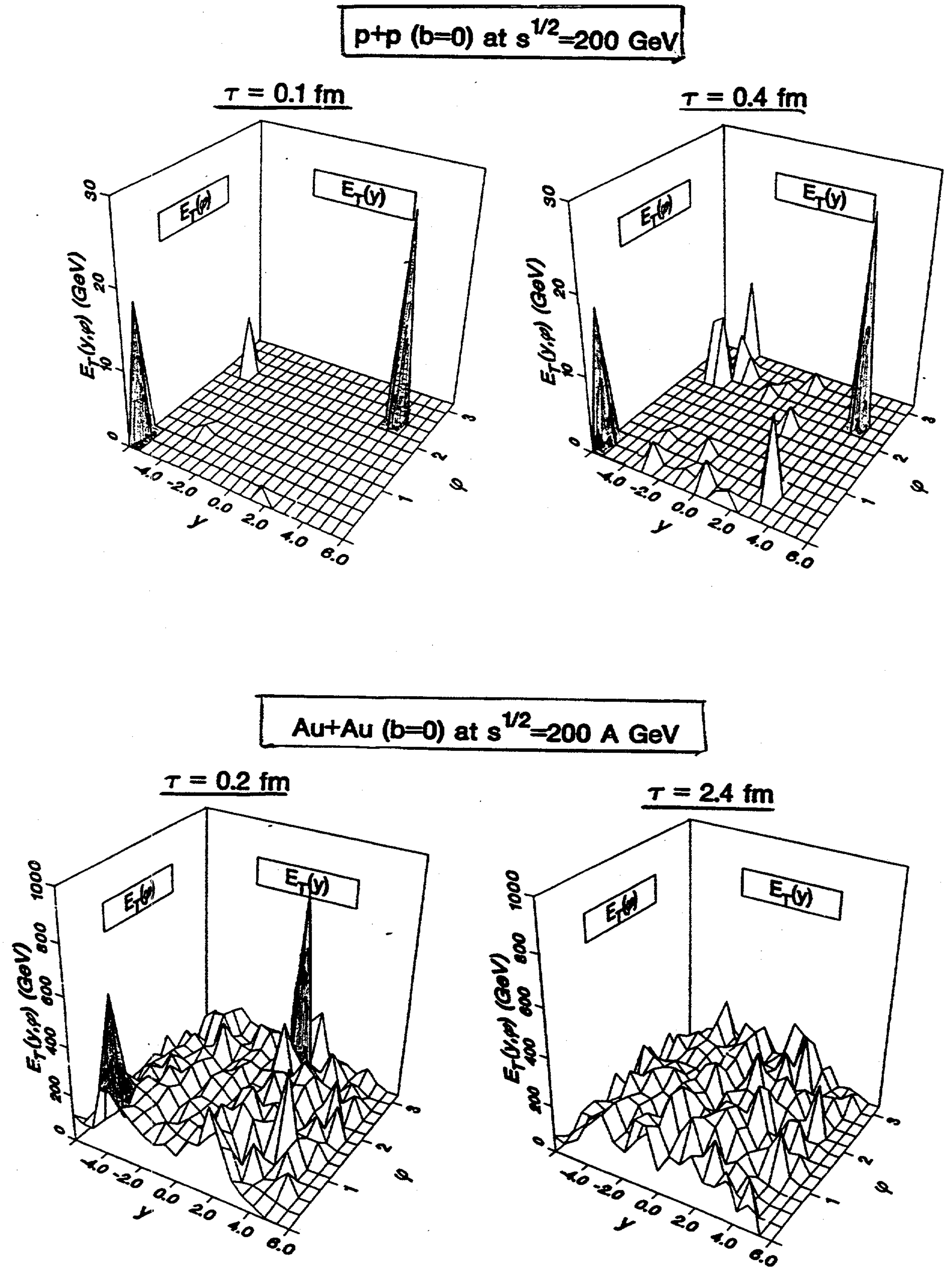
Central Au+Au at $s^{1/2} = 200$ A GeV





CENTRAL REGION:

$-1 \leq \eta \leq 1 \qquad 0 \leq r_\perp \leq 5\,\text{fm}$



"JET QUENCHING" (Wang; Gyulassy)

9/10

Project Perspectives for AB collisions

hard probes:

- heavy $Q\bar{Q}$ production / evolution / quarkonium formation
  framework: KKG'97

- jet propagation / energy loss / $p_\perp$ - broadening
  framework: Baier et al. 96, Huang + Wang '96

thermodynamics:

- Space-time profiles of ε, p, entropy, regions of local thermo (chemical equilibrium)
  framework: KKG '93

event-by-event physics

- identification of "anomalous" events, large multiplicity, distinct momentum spectra, A-dep. & impact parameter.
  framework: Odyniec et al.

Space-time structure from novel HBT approach:

- "freeze-out" radii & time, size & life-time of deconfined parton matter, correlations!
  framework: Heinz et al. '96

Recent Developments in Plasma Turbulence and Turbulent Transport

P.W. Terry[1]

Department of Physics
University of Wisconsin-Madison
Madison, WI

Localized nonlinear structures occur under a variety of circumstances in turbulent, magnetically confined plasmas, arising in both kinetic and fluid descriptions, i.e., in either wave-particle or three-wave coupling interactions. These structures are non wavelike. They cannot be incorporated in the collective wave response, but interact with collective modes through their shielding by the plasma dielectric. These structures are predicted to modify turbulence-driven transport in a way that is consistent with, or in some cases are confirmed by recent experimental observations. In kinetic theory, non wavelike structures are localized perturbations of phase space density. There are two types of structures. Holes are self-trapped, while clumps have a self-potential that is too weak to resist deformation and mixing by ambient potential fluctuations. Clumps remain correlated in turbulence if their spatial extent is smaller than the correlation length of the scattering fields. In magnetic turbulence, clumps travel along stochastic magnetic fields, shielded by the plasma dielectric. A drag on the clump macro-particle is exerted by the shielding, inducing emission into the collective response. The emission in turn damps back on the particle distribution via Landau damping. The exchange of energy between clumps and particles, as mediated by the collective mode, imposes constraints on transport. For a turbulent spectrum whose mean wavenumber along the equilibrium magnetic field is nonzero, the electron thermal flux is proportional to the ion thermal velocity. Conventional predictions (which account only for collective modes) are larger by the square root of the ion to electron mass ratio. Recent measurements are consistent with the smaller flux. In fluid plasmas, localized coherent structures can occur as intense vortices. These structures resist mixing because the strongly sheared flow in their periphery enhances the decorrelation of the ambient eddies that accomplish mixing. There is a threshold in vortex amplitude for the enhanced decorrelation that is exceeded when the straining rate of eddies due to the vortex shear is greater than the straining rate due to turbulent interactions. It is also possible to produce flow shear in plasmas as part of a phase transitions to new dynamic equilibria with different balances between mean forces in the turbulent plasma. In regions of flow shear, fluctuations and transport are observed to be reduced6 in accordance with theory. The creation and manipulation of flow shear induced transport barriers has led to plasma discharges in which fluxes have been reduced to the levels of collisional transport.

[1]E-MAIL: pwterry@facstaff.wisc.edu

Recent Developments in Plasma Turbulence and Turbulent Transport

P. W. Terry
University of Wisconsin - Madison

Examine:

Strongly correlated nonlinear structures in turbulent plasmas, effect on turb. transport

- Theory and expt.
- Phase space structures (Granularity)
  (wave-particle)
- Flow shear
  (3-wave)

Strongly Coherent Structures in turbulent plasmas reduce transport

1. Granular phase space structures

• Holes — particles trapped by $\left\{ \begin{array}{l} \text{self potential} \\ + \\ \text{neutralizing} \\ \text{dielectric} \end{array} \right.$

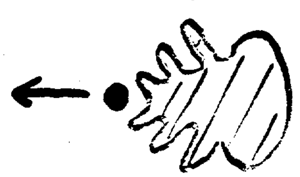
Deep holes resist "tidal deformation" by ambient turbulence $\Rightarrow$ coherent structure

• Clumps — Self-trapping weak $\rightarrow$ tidal deformation
$\Rightarrow$ clumps mixed by turbulence

- smaller structures mixed more slowly
- Driven by free energy in gradients

Both holes, clumps distinct from collective modes

- Nonlinear
- Move ballistically (macro particle)
- Experience drag from shielding dielectric
- Emit radiation (collective mode)



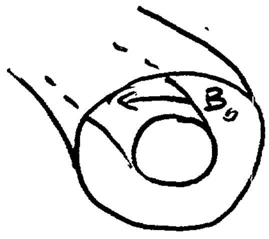
- Transport reduced

2. Localized structures also occur in fluid plasma turbulence

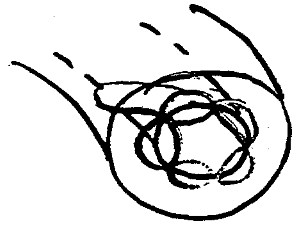
- Stable flow shear suppresses turbulence, turbulent transport
- Theory: suppression if shear strain rate $\gg$ turbulent strain rate
- Intense vortices have strong shear in periphery
  $\Rightarrow$ Resist mixing of vorticity by ambient eddies
  $\rightarrow$ coherent structure (analogous to hole)
  (weak vortex gets mixed - analogous to clump)
- Flow shear is also generated in phase transitions of plasma equilibrium
  (dynamic "equilibrium" under balance of heat source and turbulent heat flux)
  - produces dramatic reduction of transport
  - Responsible for enhanced confinement modes in fusion plasmas
    (transport reduced to collisional levels)

Plasmas loose heat from particle motion along turbulent magnetic fields

- Collective instabilities perturb B_0 $\Rightarrow$ Islands

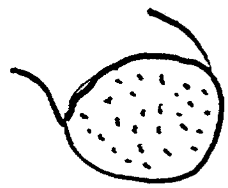


No perturbation



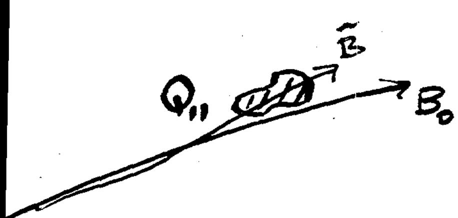
$m = 5$ island perturbation

- Islands on neighboring surfaces (torii) overlap when $\tilde{B}$ large enough $\Rightarrow$ stochasticity
  - Field lines wander egodically in volume



No flux surfaces in volume

- Radial heat flux : correlation of field aligned flux, radial magnetic field component



$$Q_r = \langle Q_{\parallel} \tilde{B}_r \rangle$$

(heat flux)

$$Q_{\parallel} = \int v_{\parallel} \tfrac{1}{2} m v^2 \tilde{f}(x,v,t)\, d^3v$$

Perturbed (nonlinear) particle distribution (Vlasov equation)

$\tilde{B}_r$: Ampere's law with $\tilde{J}$ from perturbed distributions

Conventional calculation of Q disagrees with experiment

- Conventional calculation
  - Solve for $\tilde{f}$ from Vlasov equation (drift kinetic eq.)
  - Treat $\tilde{f}$ as response to field (a la Pisarski)
  - propagtor : wave particle resonance broadened by nonlinear scattering

  $\Rightarrow \quad Q_e = V_e D_m \leftarrow$ magnetic diffusivity

- Measurement $Q_e \sim V_i D_m$

- Unconventional calculation (Terry, et al., P.P. '96)
  - part of $\tilde{f}$ not response to field $\Rightarrow$ can't be included in dielectric
  - New part of $\tilde{f}$: Ballistic macroparticle (shielded by dielectric)
    - Arises from turbulent scattering
    - Neighboring particles scatter apart slowly $\Rightarrow$ remain correlated, propagate as macroparticle
    - Drag shielding cloud - emit (cerenkov)
    - Emission constrains transport $Q_e \sim V_i D_m$

Theory of ambipolar constraint in heat transport

Consider self-consistent interaction of collective response (in $\tilde{Q}_{\|e}$, $\tilde{B}_r$) and
ballistic (non-collective) particle motion

1) Self-consistency $\Rightarrow$ momentum, energy conservation in wave particle interaction

Electron following $\tilde{B}$ must exchange energy, momentum with field

2) Clumps: electrons move along B in bunches

• Neighboring particles follow nearly aligned fields $\Rightarrow$ track each other

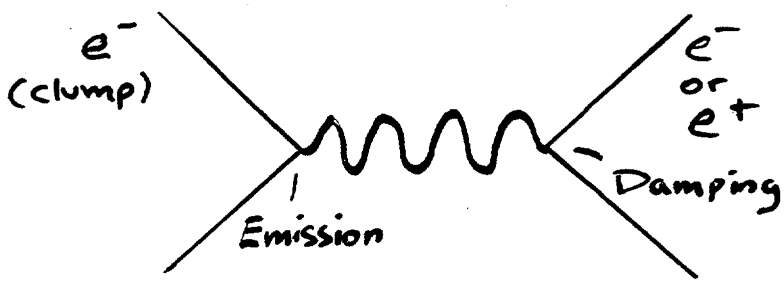
$\Rightarrow$ particles within $\perp$ correlation length move as macroparticle : Nonlinear evolution of $\langle f(x_1,v_1,t)f(x_2,v_2,t)\rangle$

• Moving macroparticle shielded by plasma dielectric

• Macroparticle emits into collective mode

Transport is generated by *turbulent* particle-<u>particle collisions</u>

Two step process: Clumps emit into waves, waves damp on particle distribution (irreversibility)



Clumps: Emission vertex resonant
(ballistic motion $\Rightarrow \omega = k_{\|} v_{\|}$)

Collisionless plasma: damping vertex resonant
($\omega = k_{\|} v_{\|}$)

$\Rightarrow$ Particle-wave-particle scattering is elastic
Behaves as a classical particle-particle collision

e–e :
- no convective loss (like-particles)
- contributes only if $\nabla T \neq 0$

e–i :
- unlike particles $\Rightarrow$ transport occurs
- naturally appears in electon transport theory

Heat flux has non-ambipolar and ambipolar <u>constrained components</u>

$$Q_e = \Big\{ \underbrace{-v_e D^{(e\text{-}e)}_{\nabla T} \frac{1}{L_{T_i}}}_{\text{non-ambipolar constrained}} - \underbrace{v_i \Big[D^{(e\text{-}i)}_{\nabla n} \frac{1}{L_{n_i}} + D^{(e\text{-}i)}_{\nabla T} \frac{1}{L_{T_i}} \Big] \Big\} nT}_{\text{ambipolar constrained}}$$

$$D^{(e\text{-}e)}_{\nabla T} = \sum_{k,\omega} D_k \frac{u^2}{v_e^2} \exp(-u^2/v_e^2)$$

($u = \omega/k_{||}$ = phase velocity along B_o)

$$D^{(e\text{-}i)}_{\nabla n} = \sum_{k,\omega} 2D_k \frac{u^2}{v_i^2} \frac{\tilde{v}^2}{v_e^2} \Big[1 + \frac{\omega}{\omega_*} \Big] \exp(-u^2/v_i^2)$$

$$D^{(e\text{-}i)}_{\nabla T} = \sum_{k,\omega} 2D_k \frac{u^2}{v_i^2} \frac{\tilde{v}^2}{v_e^2} \Big[\frac{u^2}{v_i^2} - \frac{1}{2} \Big] \exp(-u^2/v_i^2)$$

where $D_k = \dfrac{b_k^2}{B_o^2} \dfrac{1}{2\pi^{1/2}|k_{||}|}$

and $u = \omega/k_{||} << v_e, v_i$ is assumed

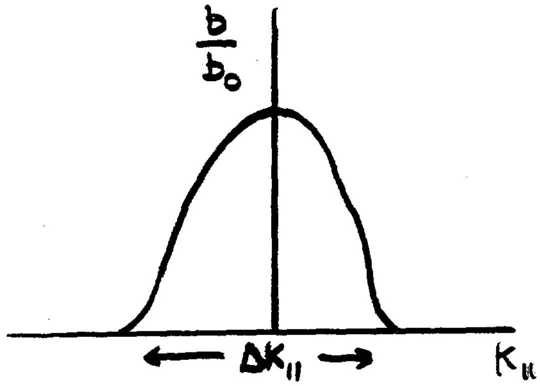
$D^{(e\text{-}e)}_{\nabla T}$ – Electron conductive loss

$D^{(e\text{-}i)}_{\nabla T, \nabla n}$ – Ion conductive, convective losses

Spectrum sum over b_k^2 determines whether <u>electron or ion terms dominate</u>

1) If b_k^2 has very large wavelength along B_o

$(B_o \cdot k = 0)$



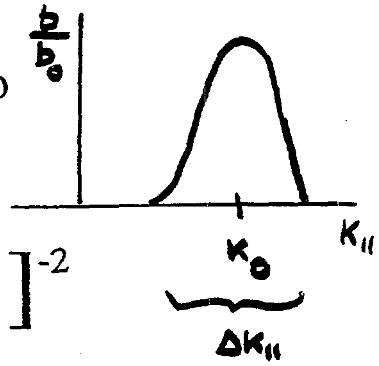
$$\sum_{k_\parallel} D_k \frac{u^2}{v_j^2} \exp(-u^2/v_j^2) \;\rightarrow\; D_k\Big|_{k_\parallel = \Delta k_\parallel}$$

$$\Rightarrow \quad v_e D^{(e\text{-}e)} >> v_i D^{(e\text{-}i)}$$

$\Rightarrow$ No ambipolar constraint on heat transport

2) If b_k^2 has small wavelength along B_o

$(B_o \cdot k = 0)$



$$\sum_{k_\parallel} D_k \frac{u^2}{v_j^2} \exp(-u^2/v_j^2) \;\rightarrow\; D_k\Big|_{k=k_o} \frac{u^2}{v_j^2} \left[1 - \frac{\Delta k_\parallel^2}{4k_o^2}\right]^{-2}$$

$$\Rightarrow \quad v_e D^{(e\text{-}e)} \approx \frac{u^2}{v_e} \quad << \quad v_i D^{(e\text{-}i)} \approx \frac{u^2}{v_i}$$

$\Rightarrow$ Transport is manifestly ambipolar constrained

$$Q \approx v_i D$$

MST edge: Distant modes govern transport

- Cross power spectrum:
  $Q_e \neq 0$ for $\upsilon < 20$ KHz

- υ vs. $n \Rightarrow$
  $\upsilon < 20$ KHz for $m = 1$, $n = 5\text{-}8$
  Rational surface deep in core, $k_{\|}$ large

- $k_{\|} \approx 0$ modes in edge
  $\upsilon \approx 100$ KHz
  $m=1$, $n = 50\text{-}80$ $\Rightarrow$ negligible contribution
  $(\tilde{b}^2/B_o^2 \approx k^{-5/2})$ to transport

Theory yields $Q_e \approx v_i D^{(e-i)}$

- $\omega \rightarrow$ rotation $\Rightarrow u \lesssim v_i$
- $D_{\nabla n} >> D_{\nabla T}$

$\boxed{Q_e \approx v_i D_{RR} L_n^{-1} nT}$

- Convective
- Ambipolar constrained

Consistent with experiment

Conclusions

- MST – Magnetic fluctuation induced heat flux in edge is convective and ambipolar constrained ($\nabla T \neq 0$)

- Clumps of parallel streaming electrons

  Consequence of nonlinear scattering

  Ambipolar constraints introduced through shielding by ions and electrons

  $Q_e \approx v_i D_{RR}$ Dominant modes remotely situated

  $Q_i \approx v_e D_{RR}$ Dominant modes locally resonant

- Qualitative agreement of theory with experiment

  Flux magnitude – quantitative
  (core vs. edge)
  Scalings – future study

Structures in systems with 3-wave coupling

Ex: n.l. evolution of vorticity : Navier-stokes
Driftwaves

- Flow shear in intense vortex suppresses mixing by ambient turbulence
- Equilibrium flow shear also suppresses turbulence, transport
  - Routinely used in fusion to create transport barriers

Coherent Structures in decaying 2D N.S. turb.

- Simulations : localized vortices emerge from random background

- Background turbulence decays, structures don't
  - $\Rightarrow$ structure lifetime $\gg$ structure turnover time
  - eddy lifetime $\approx$ eddy turnover time

- Structures : core vorticity $\gg$ mean sq. shear stress

  periphery mean sq. shear stress $\gg$ vorticity

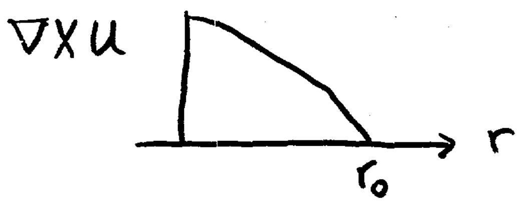
$$C_G \lesseqgtr 0 \quad \begin{matrix} \text{core} \\ \text{periphery} \end{matrix}$$

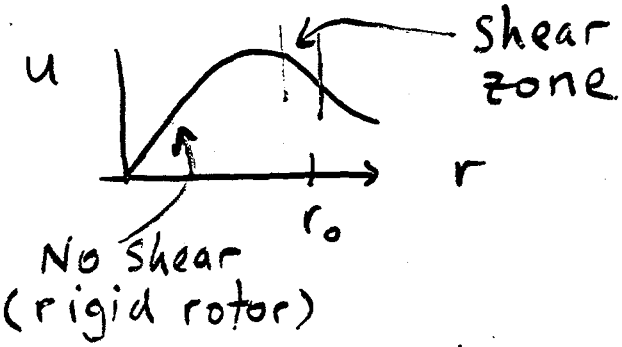
Gaussian Curvature

- What enables structures to escape being mixed by ambient turbulence?

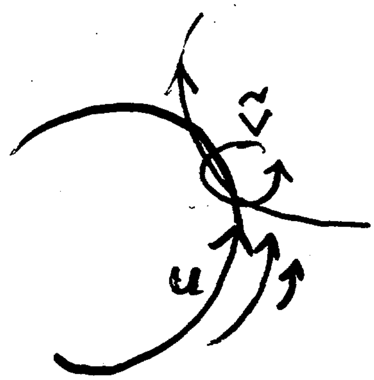
Shear flow in vortex edge suppresses mixing by ambient turbulence

Localized vorticity $\Rightarrow$ large shear in edge





Vorticity evolution for turbulence in shear zone:



$$\frac{\partial}{\partial t}\nabla\times\tilde{v} + \underbrace{r\frac{d}{dr}\left(\frac{u}{r}\right)}_{\tau_s^{-1}}\frac{\partial}{\partial\theta}\nabla\times\tilde{v} + \underbrace{\tilde{v}\cdot\nabla}_{\tau_T^{-1}}(\nabla\times\tilde{v}) = S$$

Theory: In turbulence, strong (stable) shear hastens decorrelation of eddies

(Biglari, Diamond, Terry, Phys. Fluids B, 1990)

Consider advection of quantity χ in sheared flow:

$$\frac{\partial}{\partial t}\chi + V_E(r)\cdot\nabla\chi + (\underset{\sim}{V}\cdot\nabla)\chi = S$$

Two rates govern dynamics

1) Shear decorrelation rate

$$\tau_s^{-1} = \left[V_E(r+\Delta) - V_E(r)\right]\lambda^{-1} \simeq \Delta\frac{dV_E}{dr}\lambda^{-1}$$

differential advection across Δ

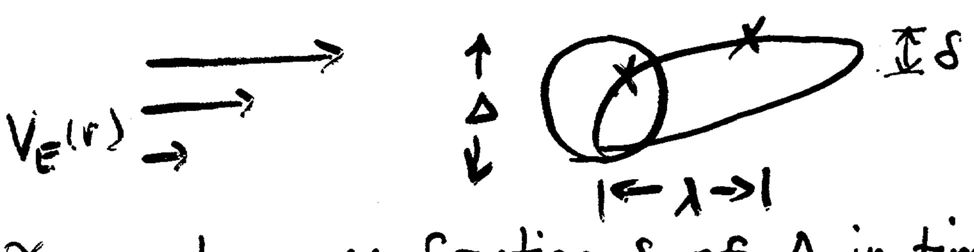
flow-wise correlation length

2) Turbulent strain rate (eddy turnover rate)

$$\tau_t^{-1} = V\cdot\nabla \rightarrow \frac{V}{\Delta}$$

(same parameterization for RDT)

If $\tau_s^{-1} > \tau_T^{-1}$, spanwise correlation ($\Delta$) shrinks



χ parcel moves fraction δ of Δ in time it covers λ

Balance of shear and turbulent strain rates determines extent of spanwise scale contraction

- Rapid transit over correlation length $\lambda \Rightarrow$ spanwise step over correlation time reduced

$$\delta \frac{dV_E}{dr} \lambda^{-1} = \frac{V}{\delta}$$

$$\Rightarrow \delta = \left(\frac{V\lambda}{dV_E/dr} \right)^{1/2}$$

$\Rightarrow$ spanwise scale shrinks as dV_E/dr increases

- correlation time decreases because $\delta < \Delta$

$$\frac{1}{\tau} \approx \frac{V}{\delta} = \left(\frac{dV_E/dr \cdot V}{\lambda} \right)^{1/2}$$

$$\Rightarrow \tau \propto (dV_E/dr)^{-1/2}$$

- Fluctuations decrease because δ decreases (for constant S)

$$S \approx \frac{V}{\delta} \chi \Rightarrow \chi \propto \left(dV_E/dr \right)^{-1/2}$$

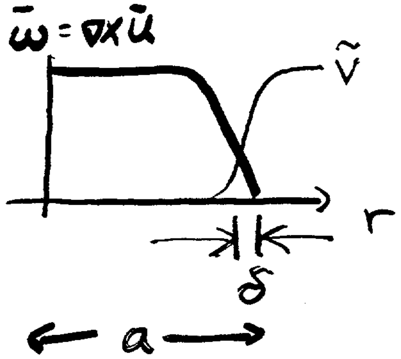
(Basic arguments apply to vorticity, flow, scalars)

Asymptotic boundary layer analysis: Intense vortices have edge shear barrier to mixing (of their vorticity) by ambient turbulence (Terry, et al., Phys. Fluids A, 1992)

- Consider PDF for vortex amplitudes at scale k^{-1}

$\rightarrow$ larger amplitudes (for fixed k)
$\Rightarrow$ larger shear $\Rightarrow$ distortion, suppression of ambient turbulence

- Condition $\tau_s^{-1} > \tau_T^{-1}$ gives critical vortex amplitude for suppression
- For $\tau_s^{-1} > \tau_T^{-1}$ ($\omega_k > \omega_{k\,crit}$) turbulence mixing into vortex from surrounding turbulence confined to layer:



δ : From asymptotic B.L. analysis of EDQNM closure eqs.

$$\delta = \left[\frac{\tilde{v} \lambda}{r \frac{d}{dr}\left(\frac{\bar{u}}{r}\right)} \right]^{1/2}$$

Agrees with dimensional analysis result

- Vortex lifetime estimated from mix-in time of edge layer:

$$\tau_{vor} > \left(\frac{a}{\delta}\right)^{3/2} \tau_* \gg \tau_T$$

Steady Sheared E×B flow induces transport barriers in turbulent plasmas

- Spontaneously generated barriers (H-mode, VH mode, NCS·ERS mode)
  - Threshold exceeded for external power
  - plasma begins spin-up
  - gradients increase in T, n in regions of dv_E/dr
  - Fluctuations drop in regions of dv_E/dr
  - process as bifurcation of equilibrium
  - Suppression occurs in shear decorrelation rate > turbulent decorrelation rate
- Externally driven barriers (biased probe, current inj., RF wave inj, magnetic breaking)
  - correlation length (in r) decreases in region of $\frac{dv_E}{dr}$
  - correlation time decreases
  - turbulent fluxes decrease
- modeling and theory
  - simple theory yields semiquantitative agreement with experiment
  - extensive modeling shows dv_E/dr has dramatic effect on predicted diffusivities

Conclusions

- Plasma turbulence is efficient transport mechanism
  (Electron heat loss $10^3 \times$ collisional rate)
- Coherent structures formed by nonlinearities affect transport

  1) Phase space granularity

     - momentum, energy constraints slow electron heat loss rate by $v_i/v_e \sim \sqrt{m_e/m_i}$
     - Involves emission into collective response by nonlinear macroparticle

  2) Shear flow (3-wave coupling $\leftrightarrow$ self advection)

     - Shear in edge of intense vortex - shears apart ambient turbulent eddies - resists mixing
     - Shear flow produced in fusion plasmas
       Transport reduced to collisionless levels
       $\Rightarrow$ turbulence free operation
     - Mechanism occurs in plasmas, neutral fluid wall flow, ocean and atmospheric flows

Quasiparticle Lifetimes and Infrared Physics in QED and QCD Plasmas

Jean-Paul BLAIZOT[1]

Service de Physique Théorique
CEA–Saclay
91191 Gif-sur-Yvette Cedex
France

The perturbative calculation of the lifetime of fermion excitations in a QED plasma at high temperature is plagued with infrared divergences which are not eliminated by the screening corrections. The physical processes responsible for these divergences are the collisions involving the exchange of longwavelength, quasistatic, magnetic photons, which are not screened by plasma effects. The leading divergences can be resummed in a non-perturbative treatement based on a generalization of the Bloch-Nordsieck model at finite temperature. The resulting expression of the fermion propagator is free of infrared problems, and exhibits a *non-exponential* damping at large times: $S_R(t) \sim \exp\{-\alpha T\, t\, \ln \omega_p t\}$, where $\omega_p = eT/3$ is the plasma frequency and $\alpha = e^2/4\pi$.

[1]E-MAIL: blaizot@spht.saclay.cea.fr

Quasiparticles and Infrared Physics in QED and QCD plasmas

What can we learn (about properties of the quark-gluon plasma) from weak coupling calculations?

- $g\left(\frac{T}{\Lambda}\right) \ll 1$ when $T \ggg \Lambda$
- I.R. difficulties in high orders of perturbative expansion
- Still, the structure emerging from weak coupling calculations seems to be robust (after appropriate <u>resummations</u>)
- precise statements can be made...

This talk: <u>Lifetime</u> of <u>quasiparticle</u> (and collective) <u>excitations</u> in QED.

<u>Refs</u>: J-P. B and Edmond IANCU

PRL <u>76</u> (1996) 3080
PRD <u>55</u> (1997) 973
hep-ph/9706397 to appear in PRD

Hierarchy of scales

T "hard" particles

$$p \sim T \qquad \lambda_{Th} \sim \frac{1}{p} \sim \frac{1}{T}$$

$$n \sim T^3 \qquad r_0 \sim \frac{1}{T} \sim \lambda_{Th}$$

gT "Soft" collective excitations

$$\lambda_D^{-2} \sim \frac{n g^2}{T} \sim g^2 T^2$$

Screening length $\rightarrow \lambda_D \sim \frac{1}{gT} \gg \lambda_{Th} \sim r_0$

Regime of small coupling and many particles
Long wavelength modes are "classical"

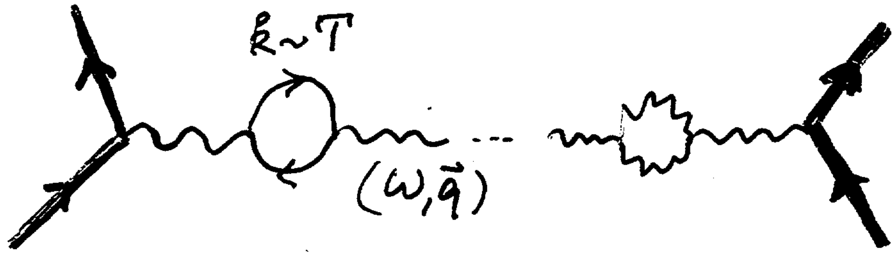
$g^2 T$ "magnetic scale"

- difficulties with pert. th. in high orders (I.R. divergences)
- "no" magnetic screening (QED)
  QCD magnetic mass?
- genuine non perturbative physics
  3d effective theory
- I.R. pbs in damping rates, corrections to Debye mass, lifetime of quasiparticles

$$\gamma \sim g^2 T \ln\left(\frac{gT}{\mu}\right)$$

SCREENING AND LANDAU DAMPING

- Medium modifies propagation of exchanged particles



(in Cb gauge) $$D_{00}(\omega, \vec{q}) = \frac{-1}{\vec{q}^{\,2} + \Pi_e(\omega, \vec{q})}$$ (longitudinal electric)

$$D_{ij}(\omega, \vec{q}) = (\delta_{ij} - \hat{q}_i \hat{q}_j) \frac{-1}{\omega^2 - \vec{q}^{\,2} + \Pi_t(\omega, \vec{q})}$$ (transverse magnetic)

- Screening of static electric fields

$$\Pi_e(\omega = 0, \vec{q}) \xrightarrow[q \to 0]{} m_D^2$$

$$V(r) \sim \frac{e^{-m_D r}}{r}$$

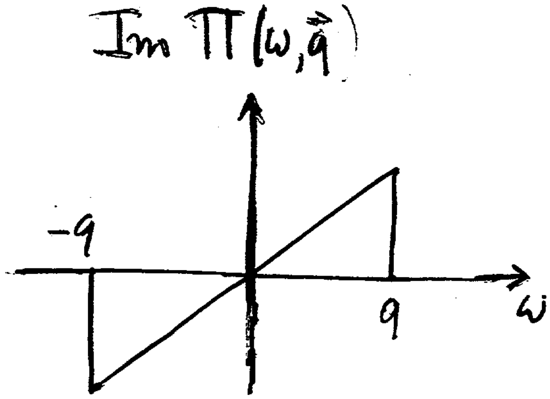
- No screening of static magnetic fields (QED)

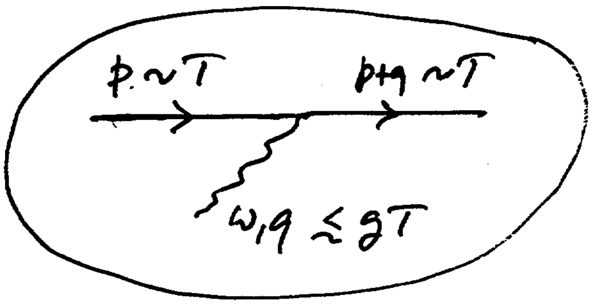
$$\Pi_t(\omega = 0, \vec{q}) = 0$$

but time dept magnetic fields are screened

$$\Pi_t(\omega \ll q) \simeq i \frac{\omega}{q} m_D^2$$

Im $\Pi(\omega, \vec{q})$ is dominated by phase space for "Landau damping" processes





$$\mathrm{Im}\, \Pi(\omega, q) \propto \int d^3p \;\; \delta(\omega - (\varepsilon_{p+q} - \varepsilon_p)) \;\; \times$$
$$\times \left[n_p (1 - n_{p+q}) - n_{p+q} (1 - n_p) \right]$$

$$\varepsilon_{p+q} - \varepsilon_p \simeq \vec{q} \cdot \vec{v}_p = q \cos\theta \quad \left(\text{L.D.} \quad \frac{\omega}{q} = v\cos\theta \right)$$

$$n_p (1 \pm n_{p+q}) - n_{p+q} (1 \pm n_p) = n_p - n_{p+q} \simeq -\vec{q} \cdot \vec{v}_p \, \frac{dn}{d\varepsilon_p}$$

$$\mathrm{Im}\, \Pi(\omega, \vec{q}) \propto \; - \frac{\omega}{q} \;\; \theta(q - |\omega|) \; \underbrace{\int dp \;\, p^2 \frac{dn}{d\varepsilon_p}}_{\propto \, - m_D^2}$$

Quasiparticles and Collective modes

Quasiparticles

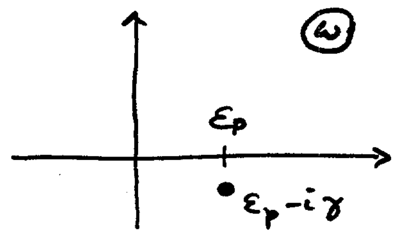
$$\langle a_p(t)\, a_p^{+}(0)\rangle \sim e^{-i\varepsilon_p t}\; e^{-\gamma t}$$

quasiparticle energy

$1/\gamma \equiv$ lifetime of q.p. excit.

pole of (retarded) propagator at

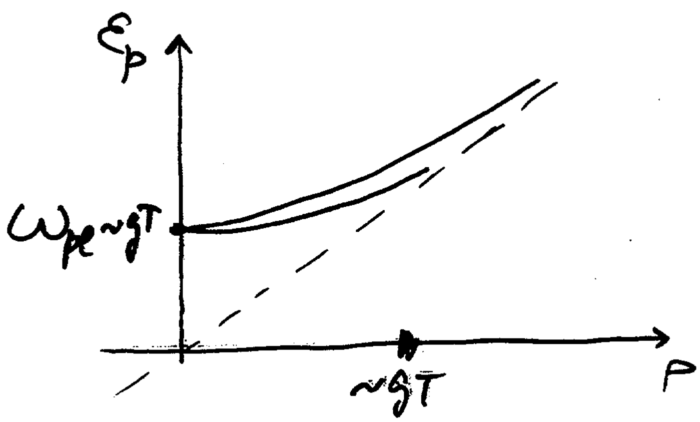
$$\omega = \varepsilon_p - i\gamma$$



Quasiparticles are well defined excitations if $\gamma \ll \varepsilon_p$

In hot gauge theories $\varepsilon_p \sim T$ $\gamma \sim g^2 T$

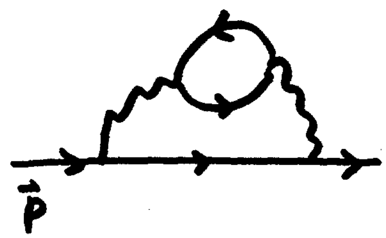
Collective excitations

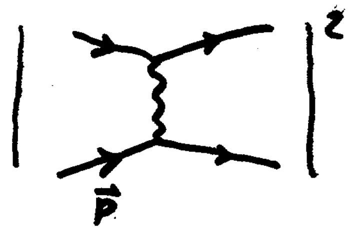


LOWEST ORDER CALCULATION

<u>Physics</u>: collisions of the added particle with the plasma constituents

<u>Calculation</u>

$\Sigma \sim$ 

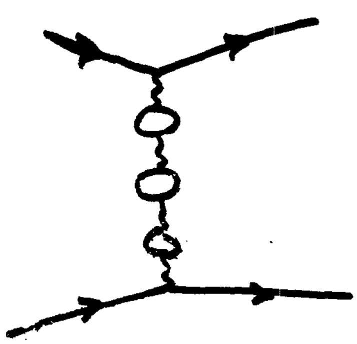
$\mathrm{Im}\,\Sigma \sim$ 

$$\gamma \sim n \; \sigma$$

$$n \to T^3 \qquad \sigma \to \int dq^2 \frac{d\sigma}{dq^2} \qquad \frac{d\sigma}{dq^2} \sim \frac{g^4}{q^4}$$

$$\gamma \sim g^4 T^3 \int dq^2 \frac{1}{q^4}$$

Screening corrections



$$\frac{1}{q^2} \to \frac{1}{q^2 + m_D^2} \qquad m_D \sim gT$$

$$\gamma \sim g^4 T^3 \int \frac{dq^2}{(q^2+m_D^2)^2} \sim \frac{g^4 T^3}{m_D^2} \sim g^2 T$$

<u>But</u> no screening for static magnetic interactions!

ROLE OF "STATIC PHOTONS"

TRANSVERSE CONTRIBUTION TO γ

$$\gamma \sim g^4 T^3 \int^{\omega_p} dq \int_{-q}^{q} dq_0 \, \frac{1}{q^4 + \left(c\,\omega_p^2 \frac{q_0}{q}\right)^2}$$

DOMINANT CONTRIBUTION CONCENTRATED AT SMALL q_0. IN FACT

$$\frac{1}{q^4 + \left(c\,\omega_p^2 \frac{q_0}{q}\right)^2} \underset{q \to 0}{\sim} \frac{\delta(q_0)}{\omega_p^2\, q}$$

THEN

$$\gamma \sim g^2 T \int^{\omega_p} \frac{dq}{q}$$

FREQUENCY DEPENDENCE OF $\Pi(\omega, \vec{q})$ PROVIDES SOME SCREENING BUT NOT ENOUGH.

Damping of excitations in cold/dense plasma

$$(T=0 \,,\ \mu \gg m)$$

(B. Vanderheyden and J-Y. Ollitrault)

② longitudinal mode

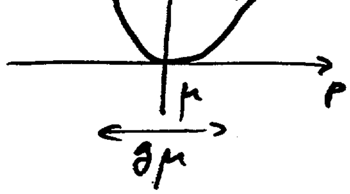
$$\gamma \sim g^4 \underset{\underset{\mu^2 (g\mu)}{\uparrow}}{n} \int \frac{dq^2}{(q^2+m_D^2)^2} \qquad m_D \sim g\mu$$

$$\gamma \sim g^3 \mu \qquad\qquad (\text{comp. to } g^2 T)$$

close to Fermi surface (Pauli pciple)

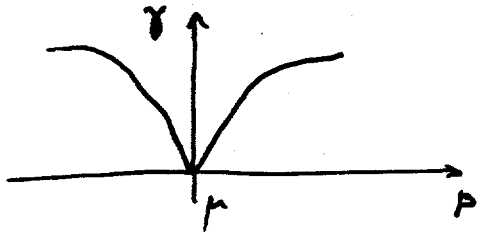
$$\gamma \sim g(p-\mu)^2$$

(F.L. theory)

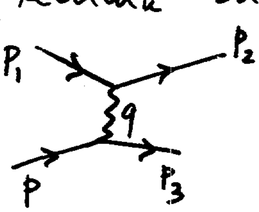


③ transverse modes

$$\gamma \sim g^2 |p-\mu|$$



④ Remark on phase space factors



$$n_1(1-n_2)(1-n_3) + (1-n_1)n_2 n_3 = (n_1-n_2)\big(1+N(q_0)-n_3\big)$$

$$q_0 = \varepsilon_1 - \varepsilon_2$$

$$\approx -q_0 \frac{dn}{dp_1} N(q_0) \simeq -T\frac{dn}{dp_1} \qquad T\neq 0 \quad \mu = 0$$

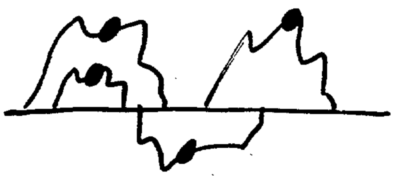
or

$$\approx -\frac{dn}{dp_1} q_0 (1-n_3) \qquad T=0 \quad \mu\neq 0$$

Infrared divergences in all orders

$$\gamma \sim g^2 T \ln\left(\frac{gT}{\mu_{IR}}\right)$$

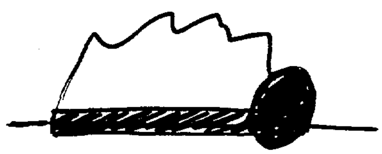
IR cut-off



$$\gamma \sim g^2 T \left(\frac{g^2 T}{\mu}\right)^{\ell}$$

NB. I.R. cut-off not enough
... and there is no magnetic mass in QED.

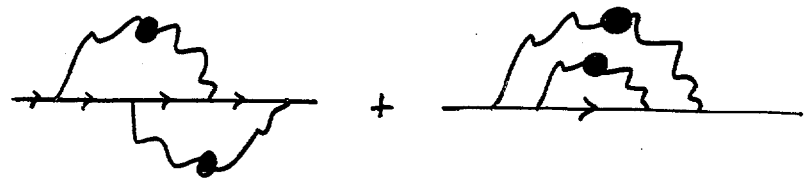
Need to resum all diagrams of the quenched approximation (i.e. all fermion loops ignored, except for the hard thermal loop):



This can be done (in the appropriate kinematical domain)

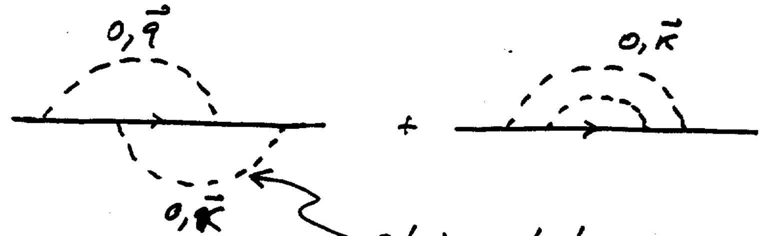
Two loop correction

$$\Sigma^{(2)} = \sum_{q_0, k_0}$$



$\xrightarrow{\omega = p}$

dominant mass shell singularity



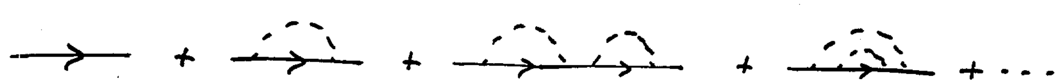
static photon propagator

$$\frac{1}{\vec{q}^{\,2}}$$

No HTL corrections any more!

In order to resum all the most divergent diagrams, it is best to work in time representation ($1/t \sim$ I.R. cut-off)

$S =$



Functional integral for S

$$S(x,y) = \int \mathcal{D}\vec{A}(x)\; G(x,y|A)\; e^{-\frac{1}{2}(A\, D_0^{-1} A)}$$

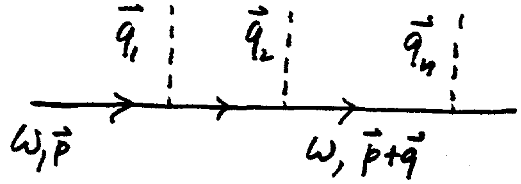
with

$$i\gamma^\mu(\partial_\mu + ig A_\mu)\, G(x,y|A) = \delta(x-y)$$

$$(A\, D_0^{-1} A) = \frac{1}{T} \int d^3x\, d^3y\; A_i(\vec{x})\, D_{0\,ij}^{-1}(\vec{x}-\vec{y})\, A_j(\vec{y})$$

Bloch – Nordsieck approximation

Approximate expression for $G(x,y|A)$



$\omega \sim p$
$p \gg q_i$

$$S_0(\omega, \vec{p}+\vec{q}) = \frac{\omega\gamma^0 - (\vec{p}+\vec{q})\cdot\vec{\gamma}}{\omega^2 - (\vec{p}+\vec{q})^2} \simeq \frac{1}{\omega - \vec{v}\cdot(\vec{p}+\vec{q})} \cdot \underbrace{\frac{\gamma_0 - \vec{v}\cdot\vec{\gamma}}{2}}_{\Lambda_+(\vec{p})}$$

$$\left(\vec{v} = \frac{\vec{p}}{\varepsilon_p} = \hat{p} \right)$$

$$\mathrm{Tr}\{\Lambda_+ \gamma^i \Lambda_+ \gamma^j \ldots\} = v^i v^j$$

Simplified Feynman rules

$$S_0 \longrightarrow G_0(\omega, \vec{p}+\vec{q}) = \frac{1}{\omega - \vec{v}\cdot(\vec{p}+\vec{q})}$$

$$\gamma^i \longrightarrow v^i$$

The equation for $G(x,y|A)$ becomes

$$i v^\mu (\partial_\mu + ig A_\mu) G(x,y|A) = \delta(x-y)$$

It can be solved exactly

Solving the BN equation

$$\begin{cases} i\, v\cdot\left(\partial_x + igA(x)\right) G_R(x,y|A) = \delta^{(4)}(x-y) \\ G_R(x,y|A) = 0 \qquad \text{if} \quad x_0 < y_0 \end{cases}$$

i) $A = 0$

$$G_R(x-y) = i\,\theta(x_0-y_0)\,\delta^{(3)}\left(\vec{x}-\vec{y}-\vec{v}(x_0-y_0)\right)$$

ii) $A \neq 0$

$$G_R(x-y) = i\,\theta(x_0-y_0)\,\delta^{(3)}\left(\vec{x}-\vec{y}-\vec{v}(x_0-y_0)\right) U(x,y|A)$$

$$U(\vec{x}, \vec{x}-\vec{v}t|\vec{A}) = \exp\left\{ig\int_0^t ds\ \vec{v}\cdot\vec{A}(\vec{x}-\vec{v}s)\right\}$$

The fermion propagator

$$S_R(x,y) = \int \mathcal{D}\vec{A}\ \ G_R(x,y|A)\,\exp\left(-\tfrac{1}{2}(A\,D_0^{-1}A)\right)$$

$$S_R(t,\vec{p}) = i\,\theta(t)\,e^{-ipt}\ \Delta(t)$$

$$\Delta(t) \equiv \int \mathcal{D}\vec{A}\ \ U(\vec{x},\vec{x}-\vec{v}t|\vec{A})\,\exp\left(-\tfrac{1}{2}(A\,D_0^{-1}A)\right)$$

The function $\Delta(t)$

$$\Delta(t) = \exp\left\{ -g^2 T \int^{\omega_p} d^3q \;\; \tilde{D}(q) \;\; \frac{1-\cos(t\,\vec{v}\cdot\vec{q})}{(\vec{v}\cdot\vec{q})^2} \right\}$$

$$\tilde{D}(q) \equiv v^i D^0_{ij} v^j = \frac{1}{\vec{q}^{\,2}} \quad (\text{in F. gauge})$$

Recovering the one-loop result

$$\frac{1-\cos(t\,\vec{v}\cdot\vec{q})}{(\vec{v}\cdot\vec{q})^2} \underset{t\to\infty}{\sim} \pi t\, \delta(\vec{v}\cdot\vec{q})$$

$$\Delta(t) \sim e^{-\gamma t} \qquad \gamma \propto g^2 T \int^{\omega_p} \frac{dq}{q}$$

But integral over q is I.R. finite

$$\Delta(t) \simeq \exp\left\{ -\frac{g^2 T}{4\pi} t \left[\ln(\omega_p t) + \underset{\text{undetermined at this stage}}{C} \right] \right\}$$

Extensions

- include contributions of non vanishing Matsubara frequencies $\to$ fixes C
- QCD

MAIN RESULT

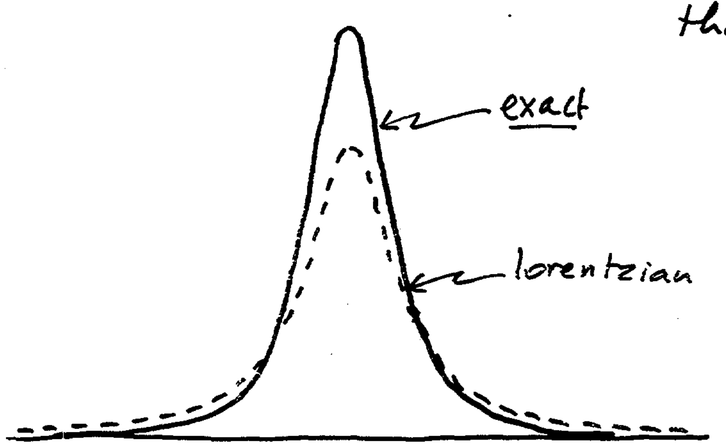
$$\left| S_R(t \gg 1/\omega_p) \right| \propto \exp\left\{ -\alpha T t \left(\ln(\omega_p t) + 0.12652\ldots + O(g) \right) \right\}$$

Retarded prop for a massless fermion with m^t. $p \sim T$

$\alpha = \dfrac{g^2}{4\pi}$

Remarks

- quasiparticle exists and spectral density not too different from that given by P.T. with an I.R. cut-off



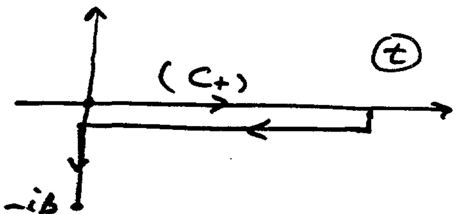
- damping is not exponential (no "Fermi Golden Rule")
- Fourier transform of $S_R(t)$ has no singularity
- Analogous result found for propagation of light in random media with noise correl. fct. $\sim 1/r$.

Including non-vanishing Matsubara frequencies

A similar structure is obtained

$$S_R(t,\vec{p}) = i\,\theta(t)\, e^{-it\,\vec{v}\cdot\vec{p}}\,\Delta(t)$$

$$\Delta(t) = \exp\left\{-\frac{i}{2}\int_{C_+} d^4x\, d^4y\; j^\mu(x)\, D_{\mu\nu}(x-y)\, j^\nu(y)\right\}$$



to be compared with

$$\Delta(t) = \exp\left\{\frac{T}{2}\int d^3\vec{x}\, d^3\vec{y}\; j^\mu(\vec{x})\, D_{\mu\nu}(\vec{x}-\vec{y})\, j^\nu(\vec{y})\right)$$

Result

$$\Delta(t) \underset{t > 1/\omega_p}{\simeq} \exp\left\{-\alpha T t\left[\ln(\omega_p t) + 0.12652 + O(g)\right]\right\}$$

independent of gauge fixing

NB. In gauges with unphysical degrees of freedom, an I.R. cut-off needs to be introduced in gauge sector to remove spurious contributions

QCD

Similar analysis.

$$\left\{\begin{array}{l} S(x-y) = \int \mathcal{D}A \; G(x,y|A)\, \exp\left(-\frac{1}{4T}\int d^3x \; F^a_{ij} F^a_{ij}\right) \\ i\, v\cdot D_x \; G(x,y|A) = \delta^{(4)}(x-y) \end{array}\right.$$

Result analogous to QED

$$S_R(t,\vec{p}) = i\,\theta(t)\, e^{-it\vec{v}\cdot\vec{p}}\, \Delta(t)$$

$$\Delta(t) = \int \mathcal{D}A \;\; \mathrm{Tr}\, U(\vec{x},\vec{x}-\vec{v}t)\, \exp\Big(-\frac{1}{2T}\int d^3x \underbrace{B^2}_{\text{chromo-mag. field}}\Big)$$

$$U(\vec{x},\vec{x}-\vec{v}t) = \mathcal{P}\exp\left\{ig\int_0^t ds \;\; \vec{v}\cdot\vec{A}(\vec{x}-\vec{v}(t-s))\right\}$$

The functional integral (Euclidean) could be done on a lattice with lattice spacing $a \sim 1/gT$

<u>NB</u>. Magnetic mass may be irrelevant. Damping occurs for times t:

$$1/\omega_p \ll t \ll 1/g^2 T$$

Open Problems in Non-Equilibrium Physics

Dimitri KUSNEZOV

Yale University

Open Problems in Non-Equilibrium Physics

The current understanding of non-equilibrium physics is largely limited to expansions around equilibrium. From the statistical mechanics point of view we would like to know how to approach general non-equilibrium physics.

For instance, we can ask the following:

- ❐ **What can we say about dynamical systems when we are far from equilibrium?**
- ❐ **Can we define a non-equilibrium ensemble and use that to compute properties of the system?**
- ❐ **What role does the chaotic nature of the dynamics play a role in transport?**

Outline:

I. **Approaches to Non-Equilibrium Statistical Mechanics;**

II. **Classical and Quantum Processes in Chaotic Environments;**

III. **Classical Fields in Non-Equilibrium Situations: Real time dynamics at finite temperature;**

IV. **Phase Transitions in Non-Equilibrium conditions;**

V. **Conclusions**

Non-Equilibrium distributions

Is there a measure for non-equilibrium systems?

- **We consider a dynamical evolution:** (S_t, A, μ)
  Birkhoff proved ('30s) the closest thing to what Boltzmann wanted:

$$\int F(x) d\mu = \int \overline{F(x)} d\mu$$

- **More recently we have the *SRB theorem* (Sinai-Ruelle-Bowen) which tells us that for certain types of dynamical evolution, we can relate time averages to a measure:**

$$\lim_{t \to \infty} \frac{1}{t} \int dt' g(S_t \dot{x}) = \int g \, d\mu / \int d\mu$$

μ is called the *SRB measure*.

This measure does not have to be the canonical measure when you are in 'equilibrium', and it is difficult to compute even in simple systems.

We now find that the measures that are determined in the NESS are *fractal* . and of measure zero in the full dynamical space.

Real time quantum dynamics with temperature: *(DK, Bulgac, DoDang...)*

It is possible to develop a real time, finite temperature theory using chaos.

Start with a Hamiltonian and identify the few important degrees of freedom. If the remaining terms are chaotic, then the interactions can be described by a suitably designed random matrix theory. The influence functional can be analytically computed.

We can be prove that:

☆ **Quantum `chaotic' interactions lead to true thermodynamic behavior in only a singular limit;**

☆ **The examination of the second cumulant alone is not sufficient to conclude that the dynamics is thermal;**

☆ **A real time density matrix can evolve to a stationary state described by non-thermal distributions.**

III. Fields Theory in Non-Equilibrium Environments

There are many approaches that one can take to developing a finite temperature formalism:

- **Influence functionals - integrate out hard modes** ***(Son [gauge theory], Muller, Greiner [ϕ^4],...)***
- **Thermo-field dynamics** ***(Umezawa,...);*** **Local equilibrium** ***(Zubarev...);***
- **Fokker-Planck equations** ***(Gyulassy,...)***

⋮

And so forth. The main distinction is how the thermal fluctuations are introduced. However these are not well suited for general situations, such as temperature or pressure gradients which are large.

It is worth examining what might happen to a field theory when it is strongly out of equilibrium.

IV. Non-Equilibrium Phase Transitions

Using such techniques, we are exploring what happens to phase boundaries in the NESS.

For example, by placing a phase transition in thermal boundary conditions, we can explore the steady states phase boundary determined by the local temperature T(x).

It is simple to extend the formalism to *SU(N)* to treat gauge theories *(DK '93)*.

One can add dynamic cooling, such as the simulation of thermal expansion:

$$T_{hot}(t) = T_{hot,0}/(t + t_0)$$

One can then ask how the hot regions cool and what happens to the phase boundaries. Do pockets develop, or is it rapid evaporation?

V. Conclusions

The only thing we really know about transport is the weak field limit. For general features of non-equilibrium problems, we are guided by simple models and simulations. From these we find:

Phase space distributions can become fractal;

There can be large departures from Green-Kubo predictions;

Non-equilibrium steady states have many unusual properties which do not arise as simple extensions of equilibrium ideas; an entirely new approach seems needed;

We have applied these ideas to classical and quantum systems - but now we need to extend these to field theory.

In the non-equilibrium steady state, it seems that entropy is not defined, even in the weak field limit. Its value diverges. Is there a consistent definition we can use here?

Does any of this survive in the continuum limit?

Nonequilibrium Quantum Kinetics

P. Danielewicz

MSU-NSCL

$\longrightarrow$ Nuclear Reactions at Intermediate and High Energies

Introduction

Many degrees of freedom in high-energy reactions, with the multitude of stages, generally force one to use a limited description for the reactions, primarily relying on the single-particle quantities in the time representation.

Staple of intermediate-energy heavy-ion reaction-simulations: the Boltzmann equation (BE); currently extended to the simulations of high-energy reactions, particularly their late stages.

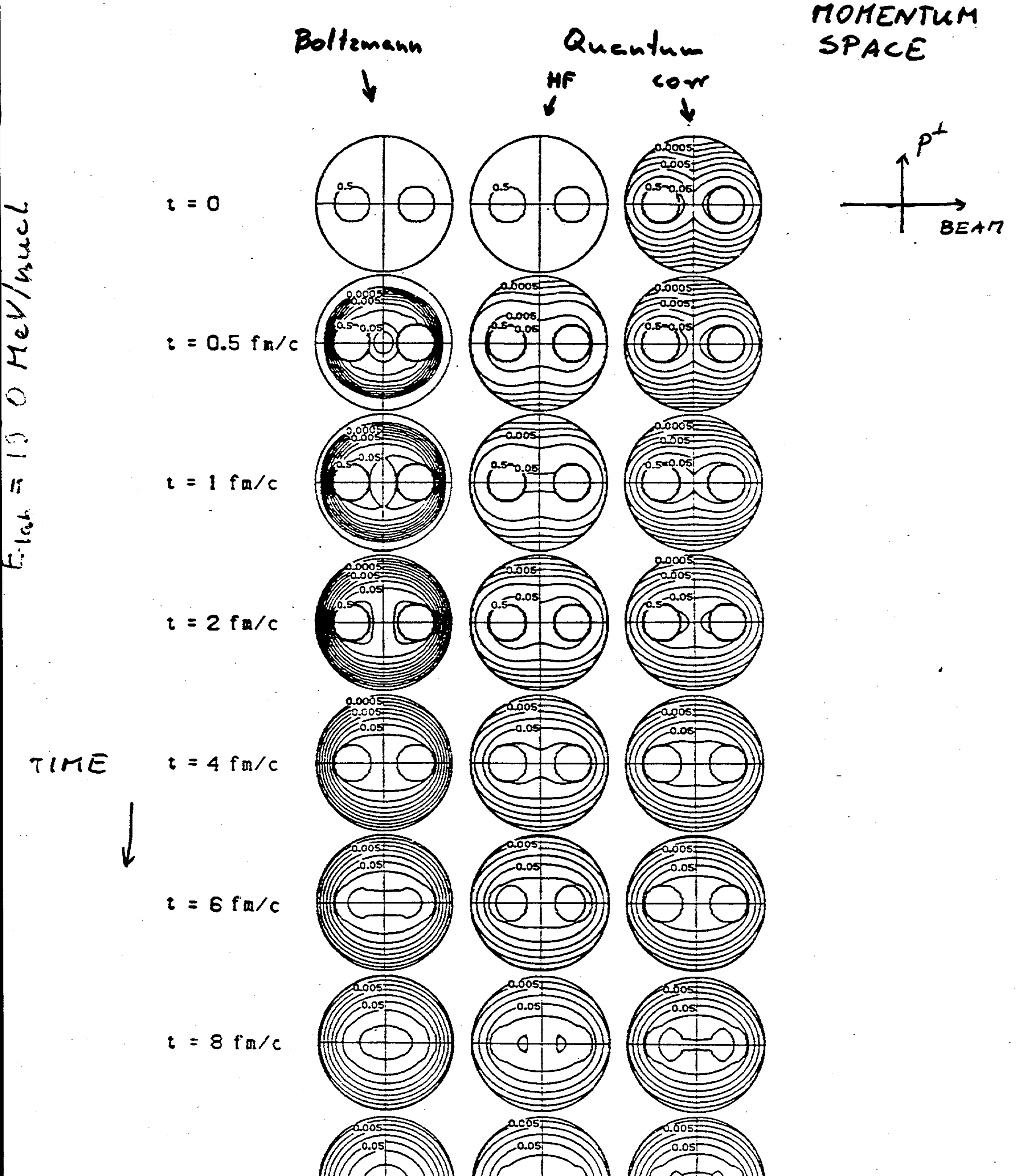
Phenomenological BE utilizes phase-space distribution f, mean-fields, collision rates modified by statistics.

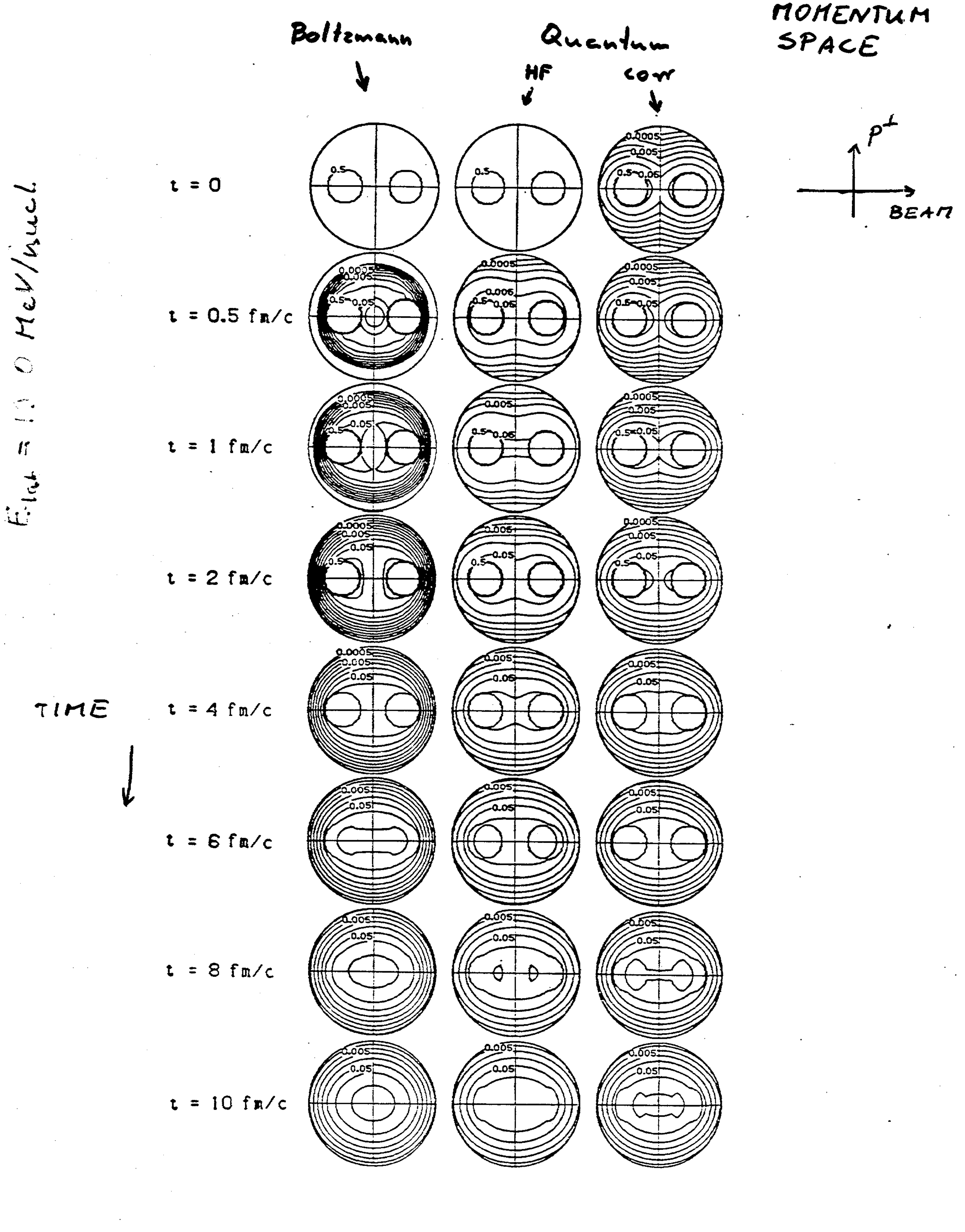
No mean-field and statistics $\longrightarrow$ cascade

Concerns about validity ...

Real-time theory: evolution of physical quantities in a quantum many-body system.

Complex even at a 1-ptcle level.


MOMENTUM SPACE
Boltzmann
Quantum
HF
corr
BEAM
t = 0
t = 0.5 fm/c
t = 1 fm/c
t = 2 fm/c
t = 4 fm/c
t = 6 fm/c
t = 8 fm/c
t = 10 fm/c
TIME



Boltzmann
Quantum
HF
corr
MOMENTUM SPACE
$p^{\perp}$
BEAM
t = 0
t = 0.5 fm/c
t = 1 fm/c
t = 2 fm/c
t = 4 fm/c
t = 6 fm/c
t = 8 fm/c
t = 10 fm/c
TIME
0.5
0.05
0.005
0.0005

Processes with 3 quasiparticles:

$$\mathcal{K}^{<}(\mathbf{p}) = \sum_{N=n,p} \int d\mathbf{p}_N \, d\mathbf{p}_p \, d\mathbf{p}_n \, d\mathbf{p}'_N \, \overline{|\mathcal{M}^{npN\to Nd}|^2}$$
$$\times \delta(\mathbf{p} + \mathbf{p}_N - \mathbf{p}_p - \mathbf{p}_n - \mathbf{p}'_N)$$
$$\times \delta(\epsilon_d + \epsilon_N - \epsilon_p - \epsilon_n - \epsilon'_N) \, f_p \, f_n \, f'_N \, (1 - f_N)$$

TIME REVERSAL

$$\overline{|\mathcal{M}^{npN\to Nd}|^2} = \overline{|\mathcal{M}^{Nd\to npN}|^2}$$

PRODUCTION BREAKUP

and

$$d\sigma^{Nd\to npN} \propto \overline{|\mathcal{M}^{Nd\to npN}|^2}$$

Data for deuteron breakup may be used to describe production!

$A = 3$ cluster production ...

PHASE–SPACE RETARDED PROPAGATOR

ANALYTIC

$$G^{+}(\Delta x, q) = \frac{1}{\pi}\,\theta(\Delta x_0)\,\theta(\Delta x^2)\,\frac{\sin\left(2\sqrt{(\Delta x\cdot q)^2 - \Delta x^2 q^2}\right)}{\sqrt{(\Delta x\cdot q)^2 - \Delta x^2 q^2}}$$

propagates through displacement Δx with momentum q

- $\theta(\Delta x_0) \Rightarrow$ causality
- $\theta(\Delta x^2) \Rightarrow$ in light–cone
- $\sin(\ldots)/(\ldots) \Rightarrow$ damped oscillation
- if particle on–shell, favors classical trajectory

$$q_0^2(\Delta x_L - \Delta x_0)^2 \lesssim 1$$

- if off–shell, favors classical trajectory w/ off–shell velocity

$$q_0^2(\Delta x_L - \frac{q_L}{q_0}\Delta x_0)^2 + q^2(\Delta\vec{x}_T)^2 \lesssim 1$$

CONCLUSIONS

- 1-ptcle quantum nonequilibrium well understood at a qualitative level
- physical quantities in terms of retarded amplitudes: clear interpretation, explicit causality, venu for phenomenology
- only few nontrival nonequilibrium quantal calculations actually carried out up to now
- limitations of semiclassical kinetic theory exhibited
- in many practical applications the semiclassical theory compares well with data
- possible evidence for memory effects in reactions below 200 MeV/nucleon
- extensions of the semiclassical theory: backward scattering, composite particle production
- extreme high-energy: relativity + QM; Feynman diagrams in phase space

RIKEN/BNL workshop
Sept. 97

The QCD Phase Transitions: from mechanism to observables

E.V. Shuryak, Stony Brook/MIT

theory

- **Finite T transition: the $\bar{I}I$ molecules**
- **Finite μ (density) transition: diquarks (Cooper pairs, $\bar{I}I\bar{I}I$... polymers**

exp.

- **The "softest point" of EOS as a source of discontinuous behaviour as a function of collision energy/centrality**
- **Flow and EOS**
- **Summary**

Two bottom-lines: 1.Chiral symmetry is restored when instantons re-group from the random to clustered liquid
2.Lattice-type EOS with strong first order transition is compatible with the AGS/SPS flow data (and lead to long-lived state in between).

$\boxed{\text{QCD with } N_c = 2}$

$\boxed{N_c = 2} \xleftarrow{?} \boxed{N_c = 3 \text{ real world}} \xrightarrow{???} \boxed{N_c \to \infty}$

- **The exact opposite to the large N_c limit:** in the following respects:

- **Baryons are not much heavier than mesons, but are degenerate with them due to Pauli-Gursey symmetry (PGSY)**

- **Unlike SUSY different number of baryons and mesons**

- **In particular, the lowest baryons (or diquark) should be bound as strongly as the lowest meson, the massless pions.** (if $m_q \to 0$)

- **The general pattern of symmetry breaking is $SU(2N_f) \to Sp(2N_f)$ (Peskin) and the number of Goldstone modes is (Smilga-Verbaarschot)**

$$N_{goldstones} = 2N_f^2 - N_f - 1$$

Let us mention two cases specifically. For $N_f = 1$ there is *no* goldstones*. For the most interesting case $\boxed{N_f = 2}$ the coset (ratio) of full group over remaining one is

$$K = SU(4)/Sp(4) = SO(6)/SO(5) = S^5 \qquad (1)$$

which means the 5-dim sphere with 5 massless modes: three of those are pions, plus scalar diquark S and its anti-particle $\bar{S}$!

- **Rotations on the 5-dim sphere along Goldstone directions cost no energy, and by doing so in the direction of the scalar diquark one naturally obtains states with the diquark density from zero to n_0. What is very important, the scalar diquark acquire the role of former sigma meson, and therefore it becomes massive.**

*Recall that due to U(1) anomaly, even the corresponding meson, *eta'*, is massive. The diquark similar to what we need cannot even exist due to Pauli principle.

Diquarks in the real world

$N_c = 3$

(*) $\boxed{m_{scalar} \simeq 500\text{ MeV}}$

deeply Bound

$\boxed{m_{vector} \gtrsim 700\text{ MeV}}$ $\boxed{\simeq 2m_{const}}$

Instanton model

E.S. Schäfer, Verbaarschot 95

$\Rightarrow$ $\boxed{m_\Delta - m_N \simeq 400\text{ MeV}}$
$\boxed{m_{\Sigma_c} - m_{\Lambda_c} \simeq 200\text{ MeV}}$

(*) Particle data:

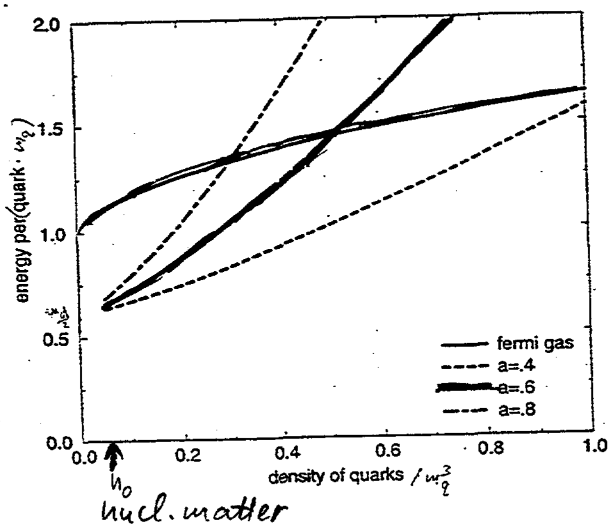
$m_{\Sigma_c} - m_{\Lambda_c} \simeq 170\text{ MeV}$

$m_\Delta - m_N \simeq 300\text{ MeV}$

(*) Compare quark Fermi gas to interacting Bose gas (condenced!)

— $a = 0.6/m_q \simeq 0.3\text{ fm}$ scattering length

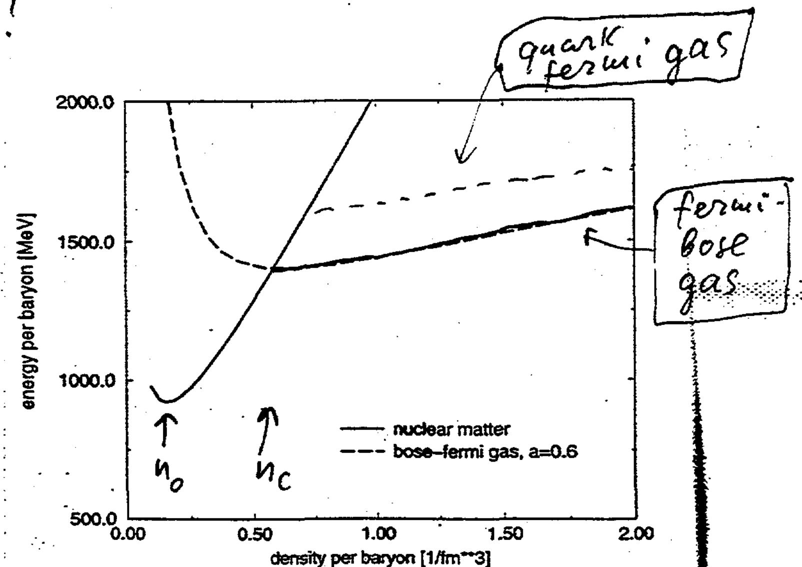
Large gain for $n_q \lesssim 10 n_0$!



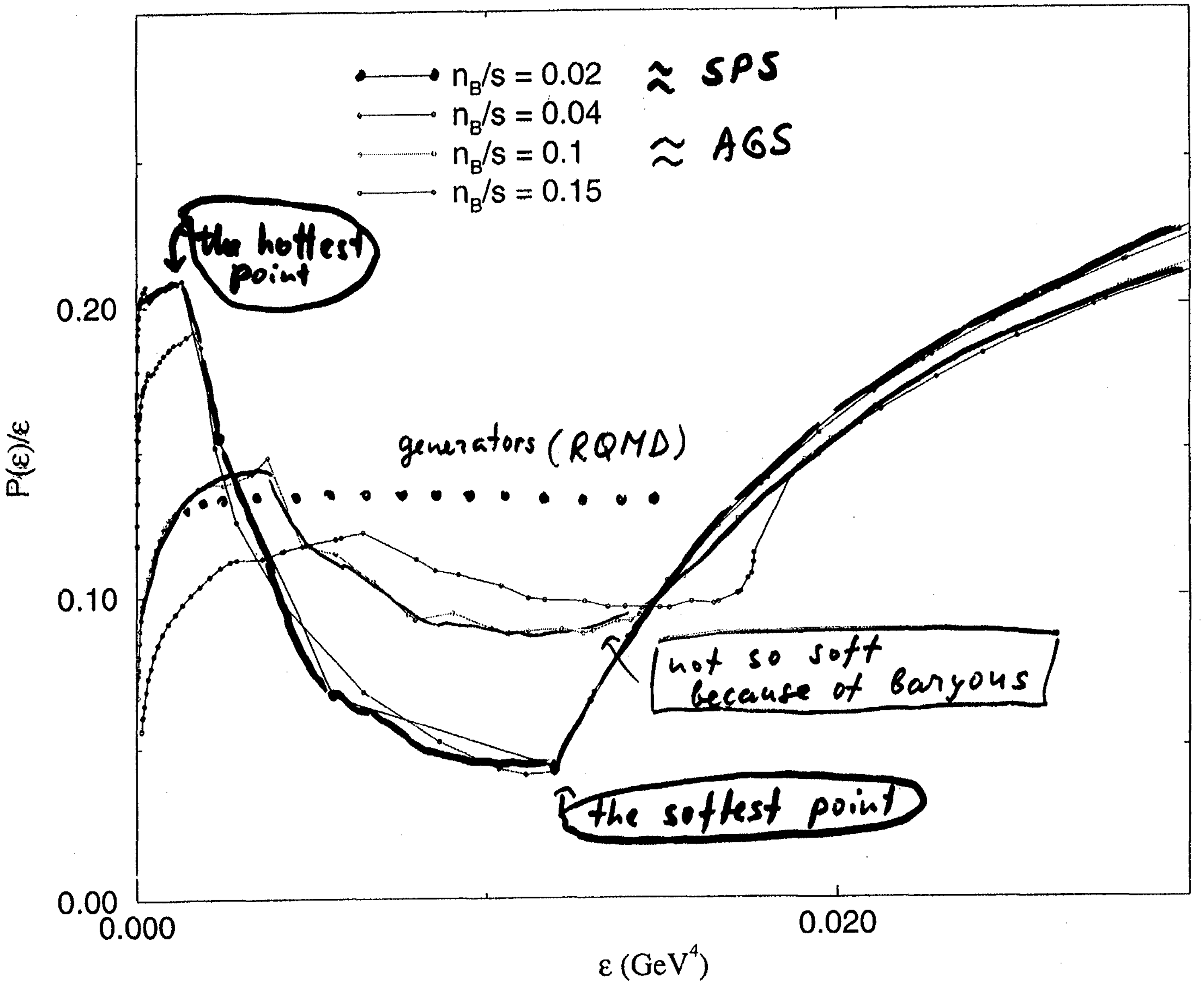
(*) Semi-realistic calculation

(Added Bag term, for "deconfinement" fitted to $T_c = 160\text{ MeV}$)

Gain in energy/baryon by about 400 MeV!



P/ε calculated on the proper path

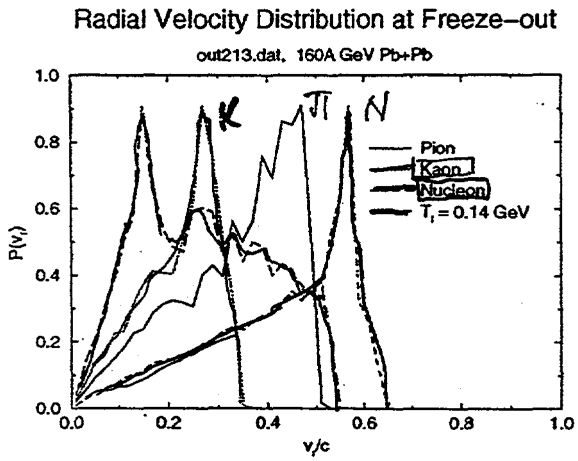


$n_B \neq 0$ does matter!

1) N has very large $\sigma_{\pi N}$ due to Δ

2) $\frac{\pi}{N} \sim 6$, so the nucleon freezeout is very late

$\Rightarrow$ extra push



← traditional isotherm

FIG. 21. Transverse velocity distribution over the various freeze-out surfaces for $\boxed{\text{160A GeV}}$ Pb+Pb collision

At AGS

$\pi/N \sim 1$

and they freeze-out together

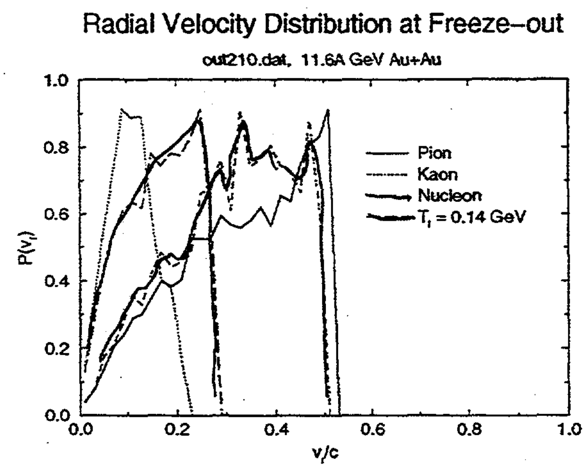
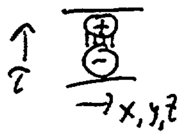
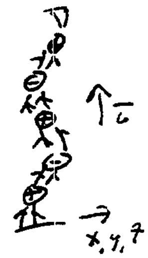


FIG. 22. Transverse velocity distribution over the various freeze-out surfaces for $\boxed{\text{11.6A GeV}}$ Au+Au collision

- Chiral symmetry is restored when instantons re-group from the random to clustered liquid. In all cases clusters are localized in space and de-localized in Euclidean time



- At finite T the transition happens when the "Matsubara box" is of the size of the $\bar{I}I$ molecule



- At high density there appear "polymers", representing diquarks (or Cooper pairs). Analogy to $N_c = 2$ QCD may be instructive: light scalar diquark may Bose-condense rather early. Superconductivity at large density is inevitable.

- Lattice-type EOS with strong first order transition has the "softest point" at which p/ϵ is very small. That leads to long-lived fireball at particular collision energy/impact parameter

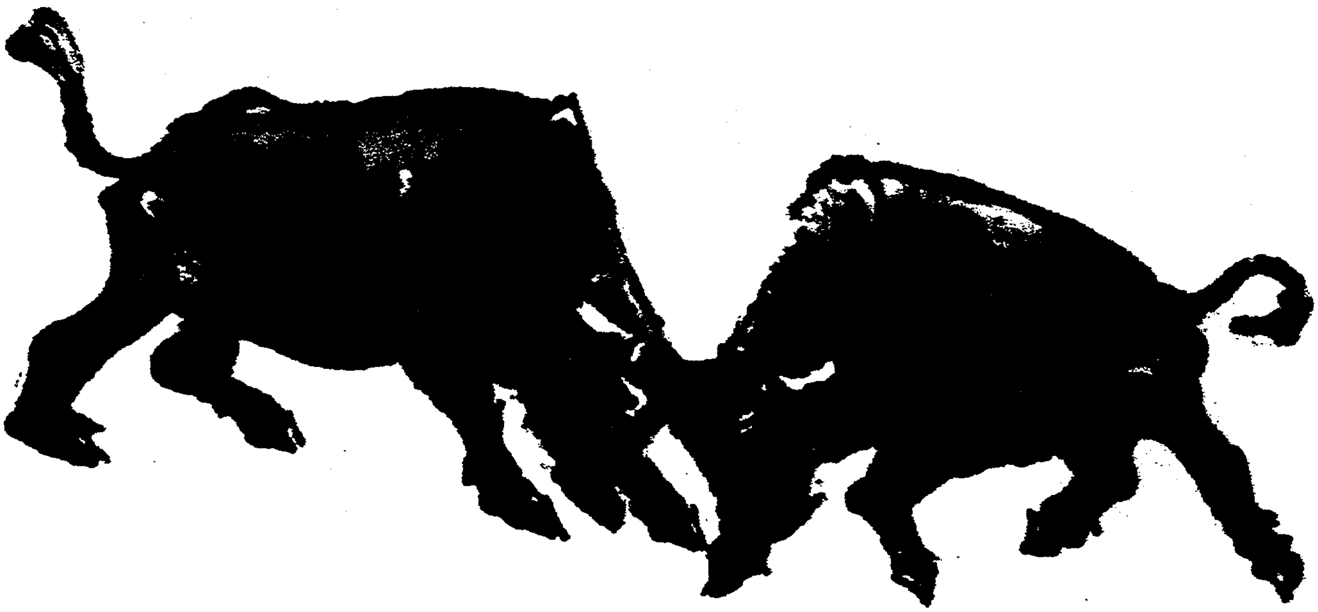
- The observed discontinuous behavior of J/ψ suppression roughly corresponds to the softest point.

- Lattice-type EOS with strong first order transition is compatible with the AGS/SPS radial flow data, provided correct freeze-out condition is imposed

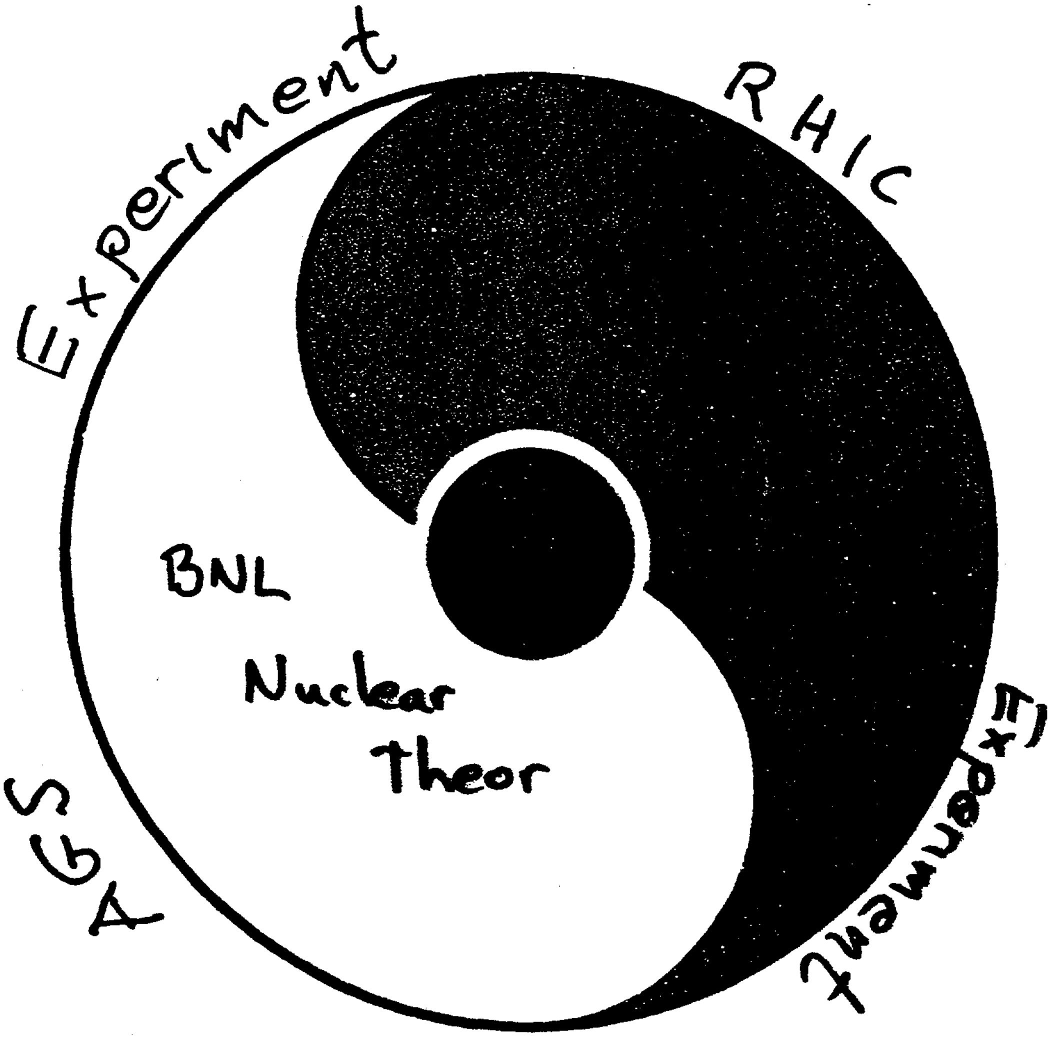
Riken BNL Research Center

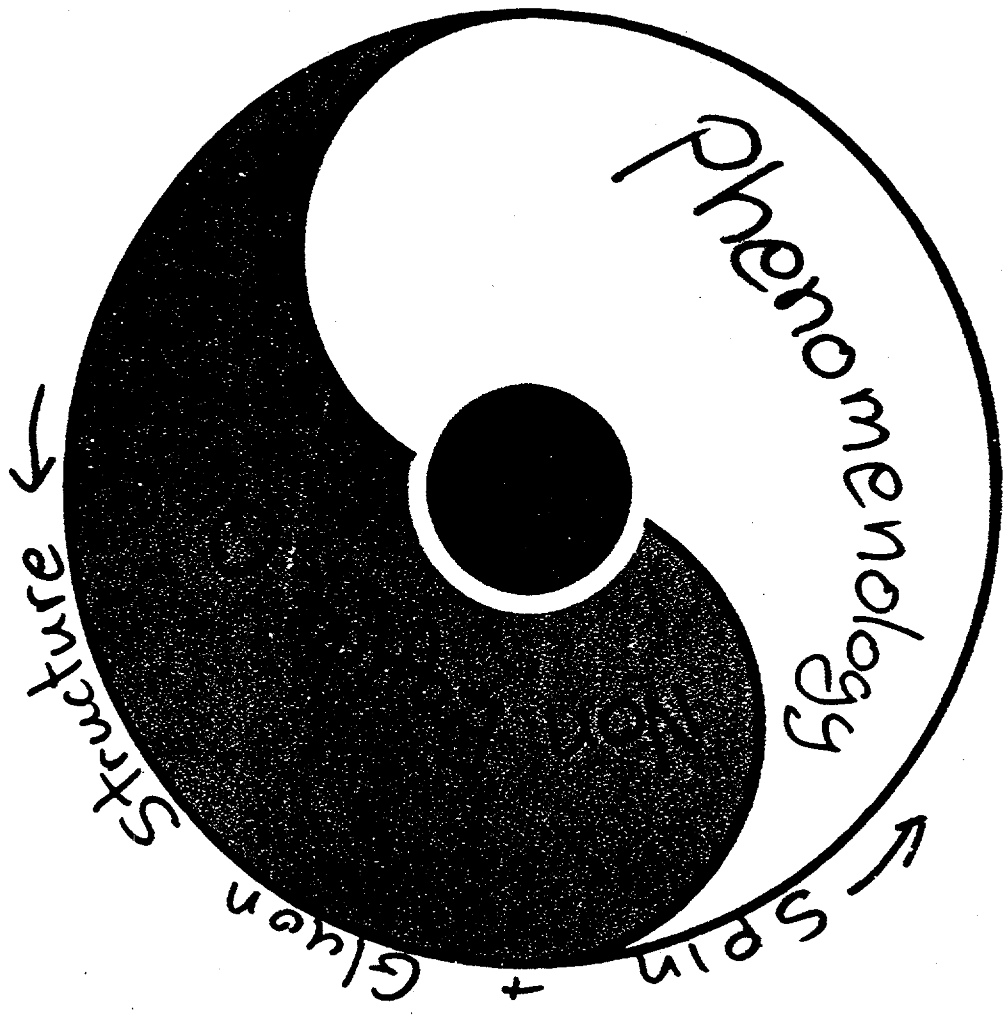
Symposium Goals:

Promote intense theoretical debate on frontier problems



M. Gyulassy
9/25/97


Experiment
RHIC
BNL
Nuclear
Theor
AGS
Experiment


Phenomenology
Spin + Gluon Structure

Equilibrium Many Body Physics

Lattice Driving force behind RHIC physics

$T_c \sim 150\,\mathrm{MeV}$, $\Delta T_c \sim 20\,\mathrm{MeV}$

But
1) $m_\pi/m_\rho \approx 0.5$ $m_N/m_\rho \approx 1.4$ still off
2) no $T < T_c$ hadronic phase
3) no $\mu_B \neq 0$ method

Symposium Highlights

1) RBRC Teraflop Project to address 1 + 2
2) T.D. Lee Noncompact Lattice
   - remove lattice artifacts
   - fill space between lattice points with physics!
3) R. Pisarski, J. P. Blaizot
   pQCD Resummation techniques
   quasiparticles + screening
4) F. Wilczek, E. Shuryak
   Effective Lagrangians, Variational metho

$\hookrightarrow$ finite μ_B problem

($\rho_B \sim 3\rho_0$ at RHIC)

T D Lee et al.

Fig. 5

Noncompact Lattice QCD

0^{th} band $\qquad A^{m}_{\mu}(\vec{r}, t) = \sum_{K} q^{m}(\vec{K}, t)\, F_{\mu}(\vec{K} \,|\, \vec{r})$

superscript $\qquad m = 1, 2, \cdots, n^2 - 1$ color index

1. Bloch wave function $\qquad F_{\mu}(\vec{K} \,|\, \vec{r} + \vec{\ell}) = e^{i\vec{K}\cdot\vec{\ell}}\, F_{\mu}(\vec{K} \,|\, \vec{r})$

   $\vec{K}$ within the Brillouin zone

2. lattice locality $\qquad \sum_{\vec{K}} e^{-i\vec{K}\cdot\vec{r}_j}\, F_{\mu}(\vec{K} \,|\, \vec{r}) = 0$

   if $|\vec{r} - \vec{r}_j| > \nu\ell$, $\qquad \nu = O(1)$

3. continuum gauge condition

   Coulomb gauge $\qquad \vec{\nabla}\cdot \vec{A}^{m}(\vec{r}, t) = 0$

should hold at <u>all</u> continuum $\vec{r}, t$
within <u>each</u> band $\quad$ (0^{th}, or any other band)

$$f(K|x) \propto \sum_{n=1}^{N} e^{iKn\ell}\, \Delta(x - n\ell), \qquad g(K|x) \propto \sum_{n=1}^{N} e^{iKn\ell}\, Q(x - n\ell)$$

$$\frac{dQ}{dx} = \Delta(x) - \Delta(x - \ell)$$

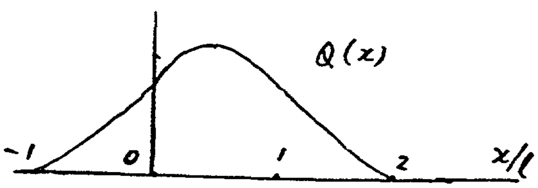
$$\frac{dg}{dx} \propto f$$

$$\partial F_x/\partial x \propto \partial F_y/\partial y \propto \partial F_z/\partial z$$

$$F_x(\vec{K}|\vec{r}) = g(K_x|x)\, f(K_y|y)\, f(K_z|z)$$

$$F_y(\,\text{"}\,) = f(\,\text{"}\,)\, g(\,\text{"}\,)\, f(\,\text{"}\,)$$

$$F_z(\,\text{"}\,) = f(\,\text{"}\,)\, f(\,\text{"}\,)\, g(\,\text{"}\,)$$



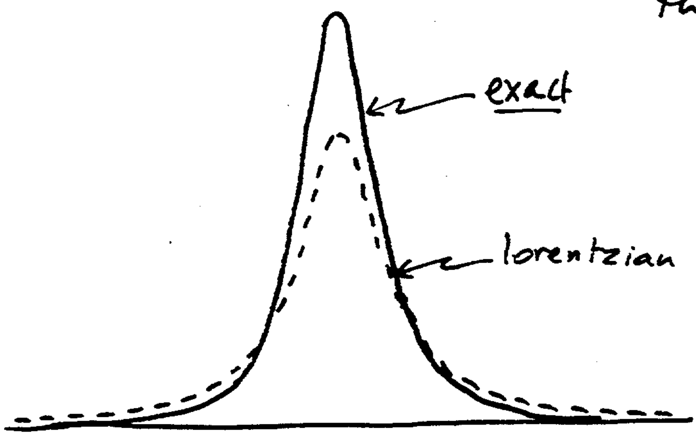
MAIN RESULT

$$\left| S_R(t \gg 1/\omega_p) \right| \propto \exp\Big\{ -\underbrace{\alpha}_{\frac{g^2}{4\pi}} T\, t \Big(\ln(\omega_p t) + 0.12652\ldots + O(g) \Big) \Big\}$$

Retarded prop for a massless fermion with mt. p ~ T

Remarks

- quasiparticle exists and spectral density not too different from that given by P.T. with an I.R. cut-off



- damping is not exponential (no "Fermi Golden Rule")

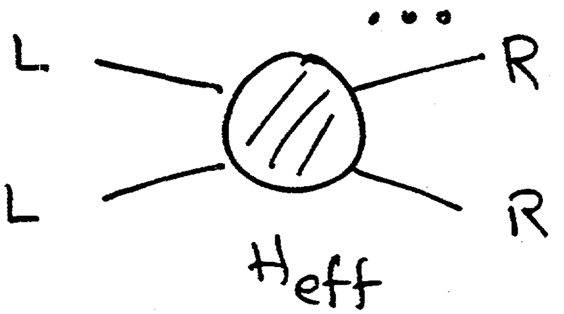
- Fourier transform of $S_R(t)$ has no singularity

- Analogous result found for propagation of light in random media with noise correl. fct. ~ $1/r$.

Wilczek, Rajagopal, Alford

Color Superconductor

$$|\Psi\rangle = \prod \left(\cos\theta_p + e^{i\phi_p} \sin\theta_p \, a^{\dagger\,\text{Red}}_{u_L}(p) \, a^{\dagger\,\text{Green}}_{d_L}(-p) \right) |0\rangle$$



$+ \underbrace{\delta H}_{\text{How big?}}$

Passive blue quarks?

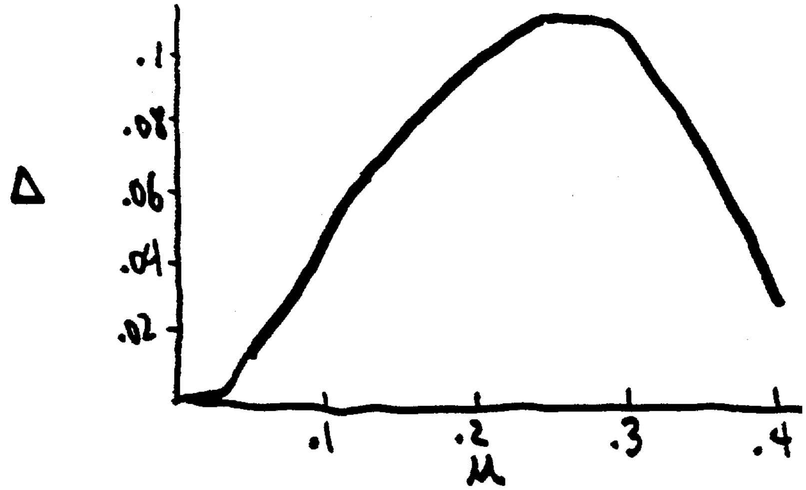
LL vs RR condensate

Predicts Parity violation by QCD near $\mu \sim 200-500\,\text{MeV}$!

* Yes, No experiment!

Λ polarization?

sample result for gap



steep, .3

- Shape easy to understand qualitatively (density of states vs. cutoff)
- Already substantial at $\mu(p=0)$

- Effect on eqn. of state (i.e. pressure) very small.

Non-Equilibrum Many Body Physics

Lessons from "real" systems

G. Baym - Bose condensates excitons, atom

G Kalman - Strongly Coupled Coulomb System

Beyond RPA - role of correlations

K. Kitahara - Binary mixtures

non-conserved transport

$$\frac{\partial J_i}{\partial t} = - \xi \left(\vec{v}_i - \langle \vec{v} \rangle \right)$$

friction

↳ AGS, SPS flow π K p

D. Kusnenov: Non-equilib stat mech

P. Terry: Turbulent Plasmas

non-linear clumps + holes

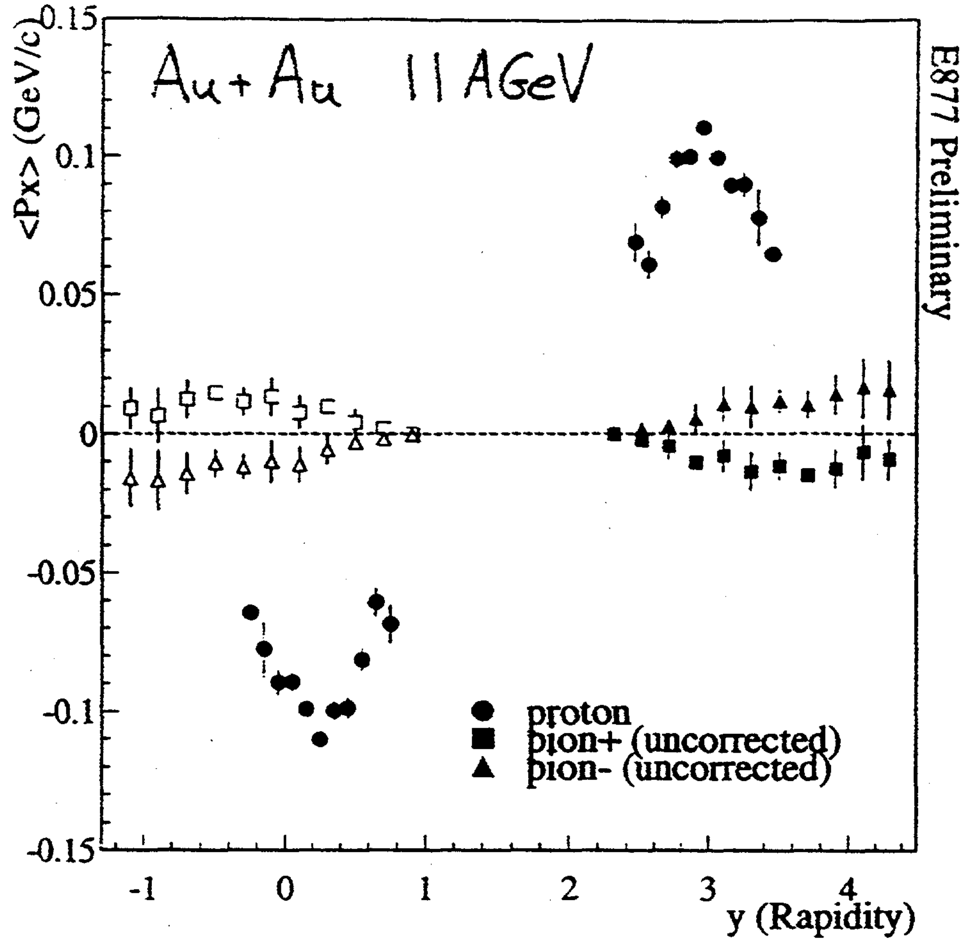
wave-particle 3 wave

↳ classical Yang Mills like

< p_x > vs. Rapidity

E877 Stachel, Braun-Munzinger et al

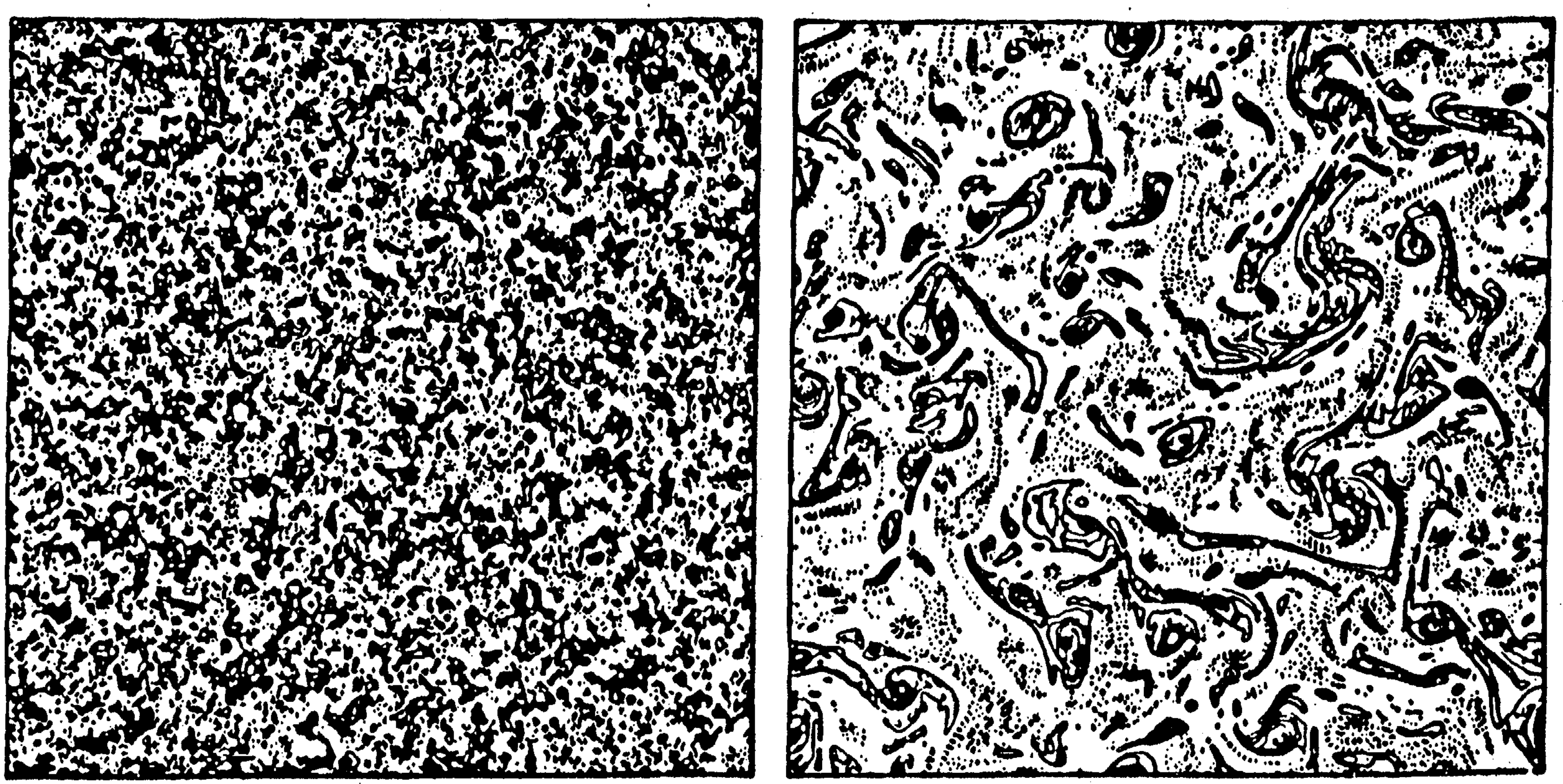
Proton and Pion Flow at top 10% centrality



- Nucleons carry the flow.
- Charged pions show opposite flow behavior (Coulomb?).
- Flow peaks at $< p_x >$=100-120 MeV/c just below beam rapidity.

(From Mcwilliams '84)

(a) $t = 0$ (b) $t = 2.5$



Constant q contours - Early time

Non-Equilibrium QCD:

K. Geiger – Off shell Parton Cascade

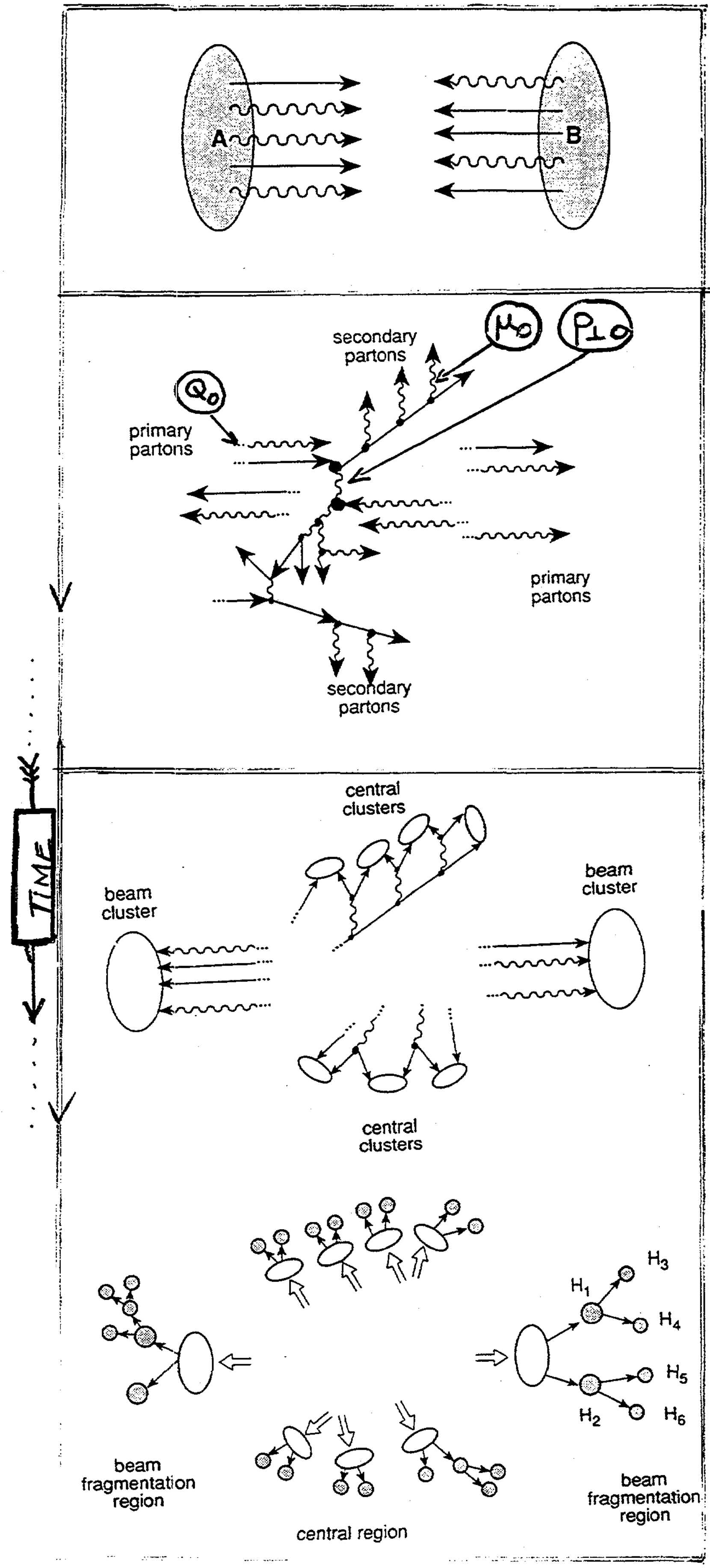
Y. Pang – General Cascade Program

D. Rischke – Classical Yang Mills
(in perturbation)
future numerics
problem RJ instab

B. Muller –
L. McLerran
Hybrid YM + parton gas
CYM $k < 1/a$
partons $k > 1/a$
(see T.D. Lee on correct path)

F. Cooper –
P. Danielewicz
Real time Keldish
↳ Quantum transport

4/3



- INITIAL STATE

$\boxed{\text{SCALE: } Q_0^2}$

- PARTON CASCADE DEVELOPMENT

$\boxed{\text{SCALE: } [Q_0^2, \mu_0^2]}$

- PARTON RECOMBINATION (preconfinement)

$\boxed{\text{SCALE: } [\mu_0^2, \Lambda^2]}$

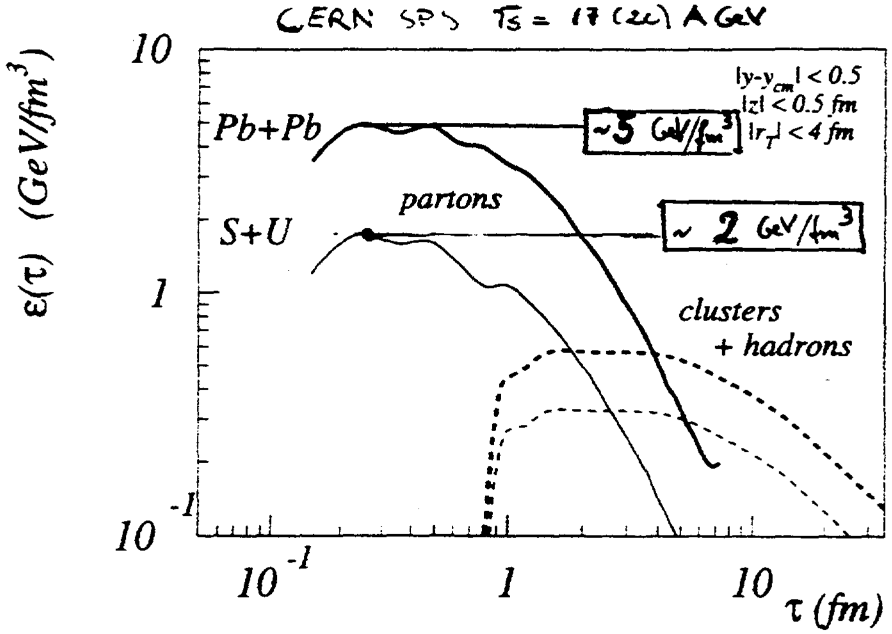
- CLUSTER FRAGMENTATION (confinement)

$\boxed{\text{SCALE: } \Lambda^2}$

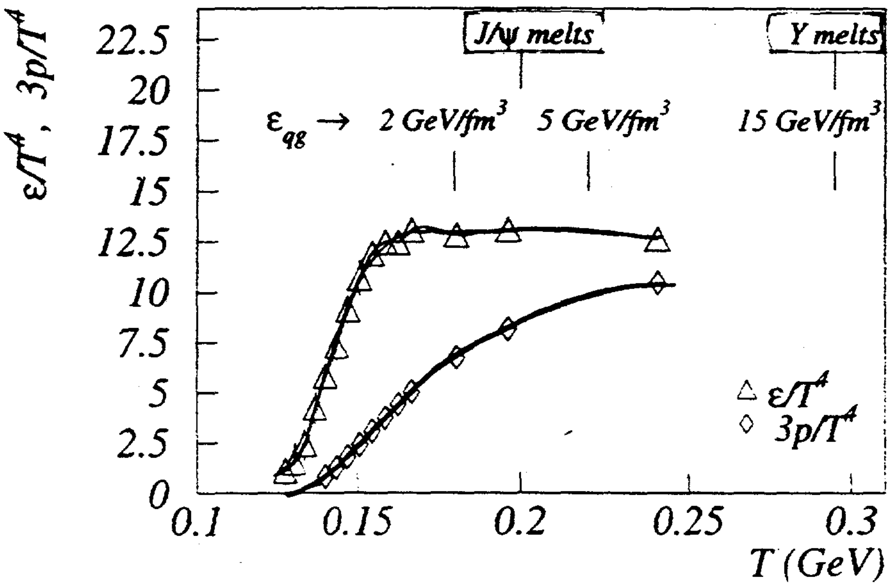
1/5

Energy density: Parton Cascade vs. Lattice QCD

B. Mueller & KKG '97



VNi-3.2 KKG, 97



Karsch & Satz '96

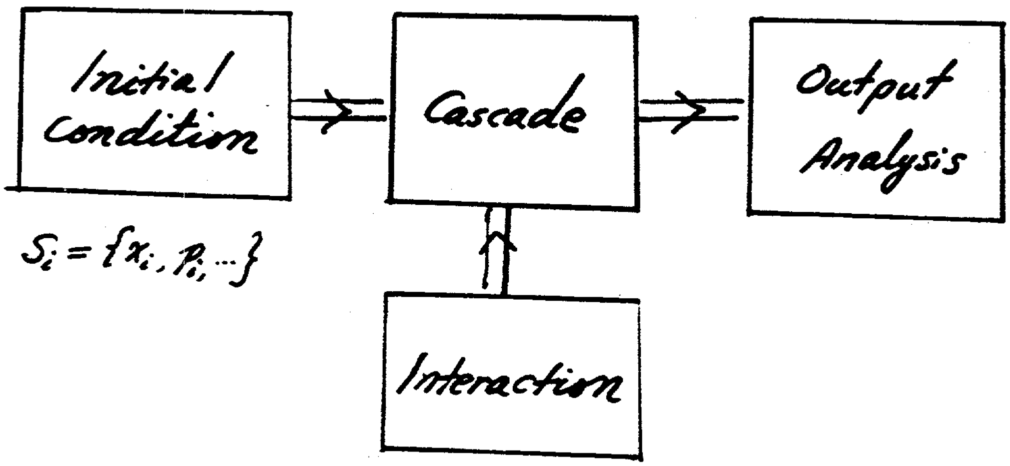
MILC Coll., Blum et al. '96

Y. Pang

General Cascade Program (GCP)

- Code $\neq$ Model

- One universal code for many different cascade models



$S_i = \{x_i, p_i, \ldots\}$

$S_1 + S_2 \longrightarrow S_1' + S_2' + \ldots$

σ_{total}

$S_i' = \{x_i', p_i', \ldots\}$

RIKEN BNL Research Center workshop on Open Standard for Cascade Models for RHIC

(organized by M. Gyulassy)

led by Yang Pang

- One serious problem facing almost all cascade models

Code = Model

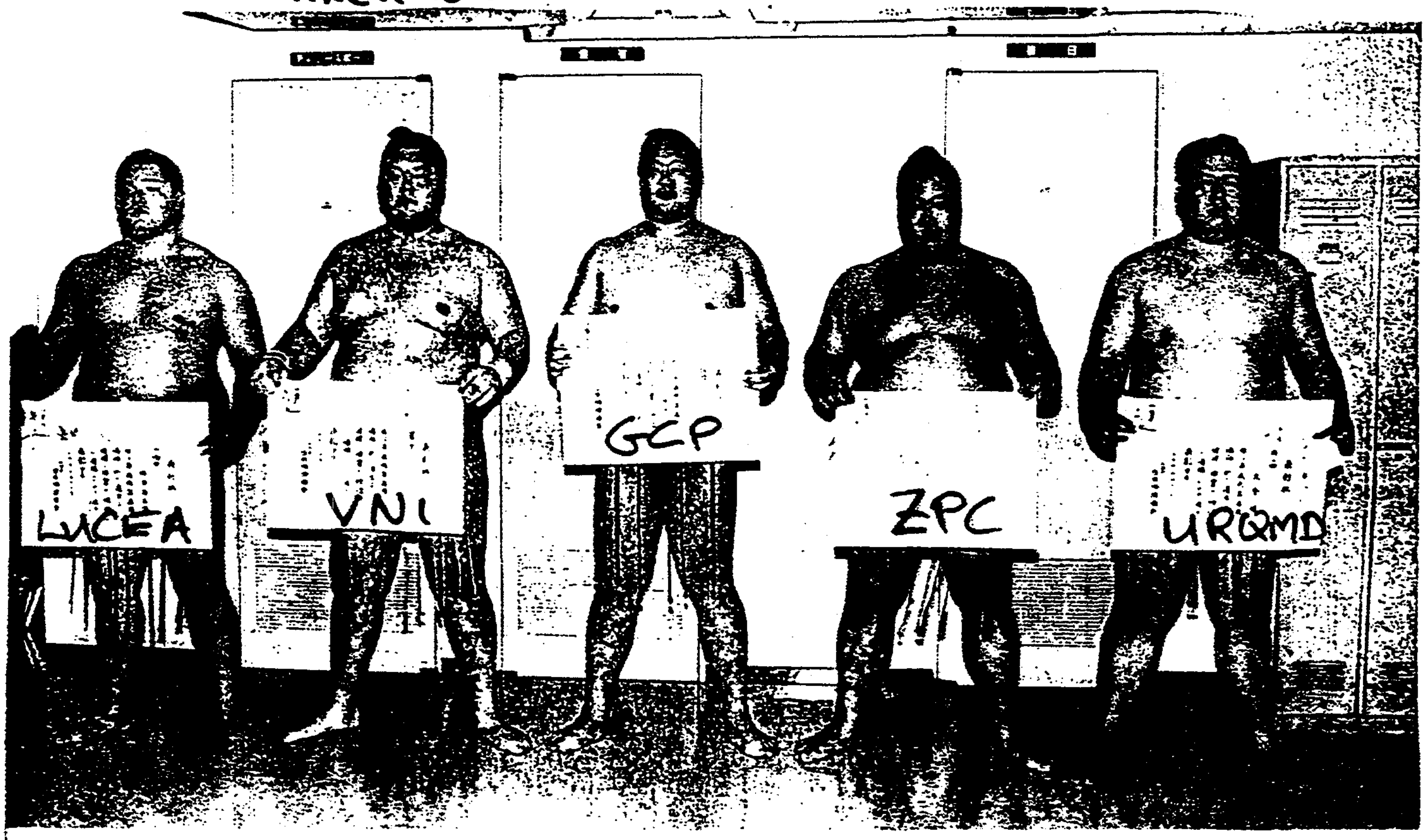
- It is necessary to establish certain standards on the accessibility of the source code and documentations, the ability to perform standardized tests, and a system of version control.

- The Open Standard Codes and Routines (OSCAR) has been established to address the problem.

http://rhic.phys.columbia.edu/rhic/
http://rhic.phys.columbia.edu/oscar/

Current Contenders for OSCAR award

Riken BNL Research Center



左から
十両・時津海「新十両で優勝なんて、全然、思わなかった。諫早農高、東農大（相撲部）時代も含めて初優勝です。やることなすことうまくいった。いろいろな攻め方が結果的にみんなよかった。できすぎであとが怖い。賞金の使い道？　とりあえず好きなカルビと冷メンをいっぱい食べます（笑い）」
幕下・闘牙（千葉県市川市出身、高砂部屋。S49年7月4日生まれ、本名・玉城順。H3年初場所初土俵。189センチ、161キロ、得意は突き、押し）
三段目・耀面竜（岐阜県養老郡出身、高砂部屋。S44年9月29日生まれ、本名・日比政樹。S60年春場所初土俵。191センチ、140キロ、得意は突き、押し、右四つ、寄り）
序二段・福の隆（東京都福生市出身、二子山部屋。S47年7月2日生まれ、本名・井上高雄。S63年春場所初土俵。181センチ、154キロ、得意は左四つ、寄り、上手投げ）
序ノ口・大金（山梨県中巨摩郡出身、阿武松部屋。S49年9月2日生まれ、本名・大金優。H9年春場所初土俵。183センチ、145キロ、得意は突き、押し）

Future OSCAR awards

stay tuned . . .

喜びの三賞受賞者と十両以下各段優勝者 56

左から敢闘賞・土佐ノ海、殊勲賞・玉春日、敢闘賞・栃東、技能賞・小城錦

Equations of motion in Lorentz gauge:

$$\Box A^\mu = \mathcal{J}^\mu + ig\,[A_\nu, \partial^\nu A^\mu + F^{\nu\mu}]$$

$$\Rightarrow \quad \Box A^{(1)\mu} = \mathcal{J}^{(1)\mu}$$

$$\Box A^{(3)\mu} = \mathcal{J}^{(3)\mu} + ig\,[A_\nu^{(1)}, \partial^\nu A^{(1)\mu} + F^{(1)\nu\mu}] \equiv \tilde{\mathcal{J}}^{(3)\mu}$$

$$\vdots$$

$\mathcal{J}^{(1)}$ is the initial color charge current,

$A^{(1)}$ is the Abelian solution.

(I.e., nothing happens, nuclei pass through each other without noticing ...)

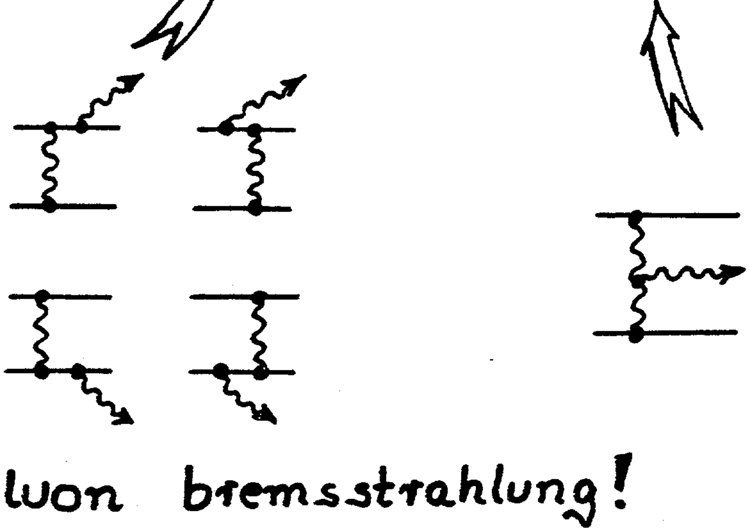
$\mathcal{J}^{(3)}$ can be determined from covariant current conservation, $\mathcal{D}_\mu \mathcal{J}^\mu = 0$.

Equation for $A^{(3)}$ is linear differential equation

$$\Rightarrow A^{(3)\mu}(x) = \int d^4x'\, G_r(x-x') \left(\mathcal{J}^{(3)\mu}(x') + ig\,[A_\nu^{(1)}(x'), \partial^\nu A^{(1)\mu}(x') + F^{(1)\nu\mu}(x')] \right)$$

Diagrammatic correspondence:

$\mathcal{J}^{(3)} \sim [A^{(1)}, \mathcal{J}^{(1)}]$



Gluon bremsstrahlung!

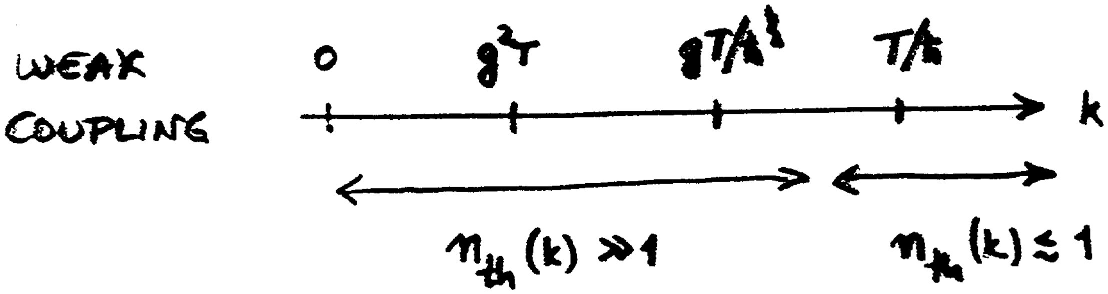
BEYOND THE CLASSICAL LIMIT

with
Chaoran Hu
Guy Moore

PROBLEMS WITH CLASSICAL LIMIT:

∴ UV CATASTROPHE (RAYLEIGH - JEANS)

∴ ABSENCE OF SCALE FIXING g



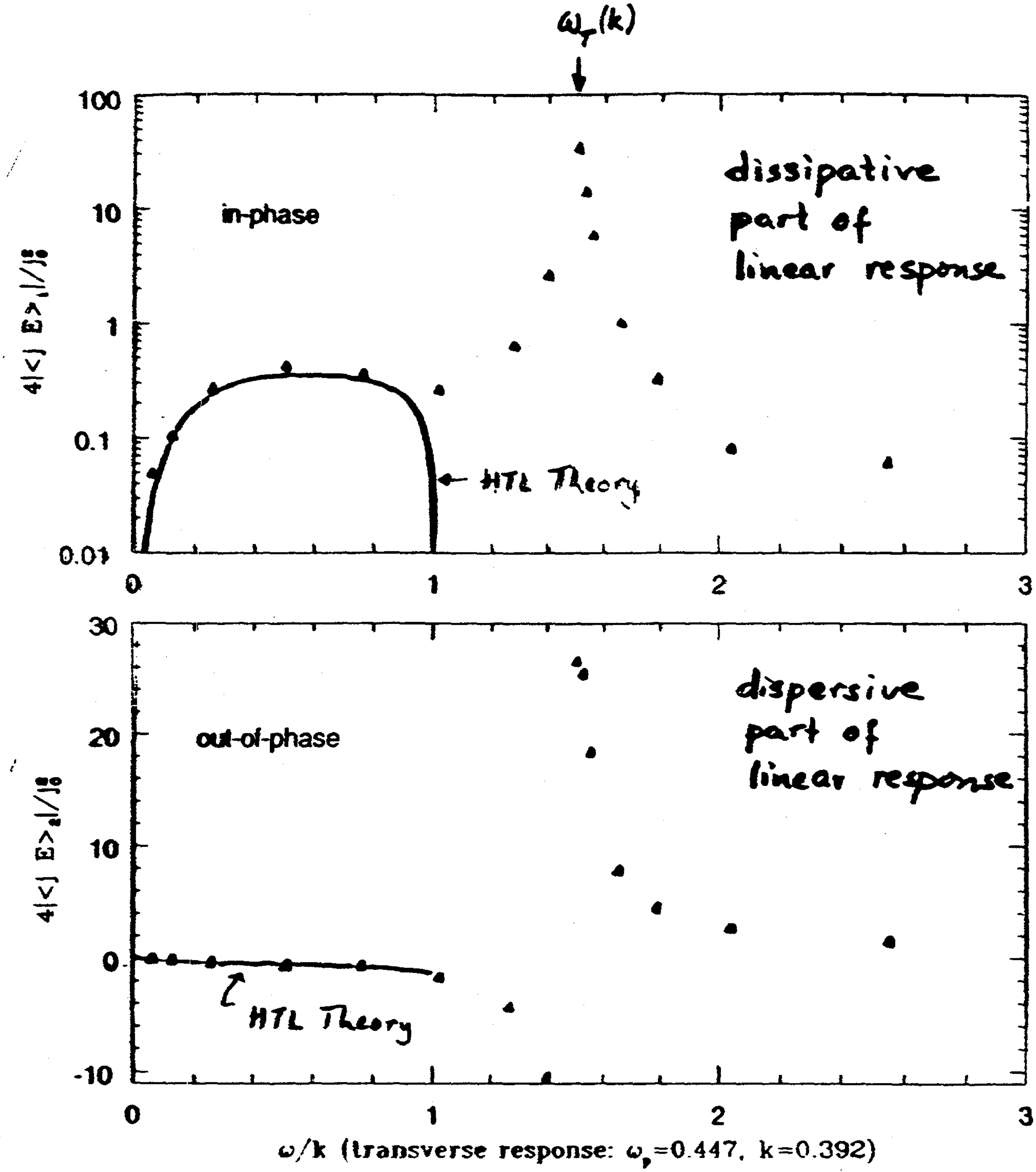
CLASSICAL LIMIT: $n_{th}(k) = \frac{1}{e^{\hbar\omega/T}-1} \longrightarrow \frac{T/\hbar}{\omega}$

MAYBE APPLIED TO EFFECTIVE LONG-DISTANCE THEORY AFTER INTEGRATING OUT "HARD THERMAL" MODES ($k \gtrsim T/\hbar$).

→ • SCALE FOR $g \longmapsto g(T)$

• DYNAMICAL LENGTH SCALE ω_p^{-1}

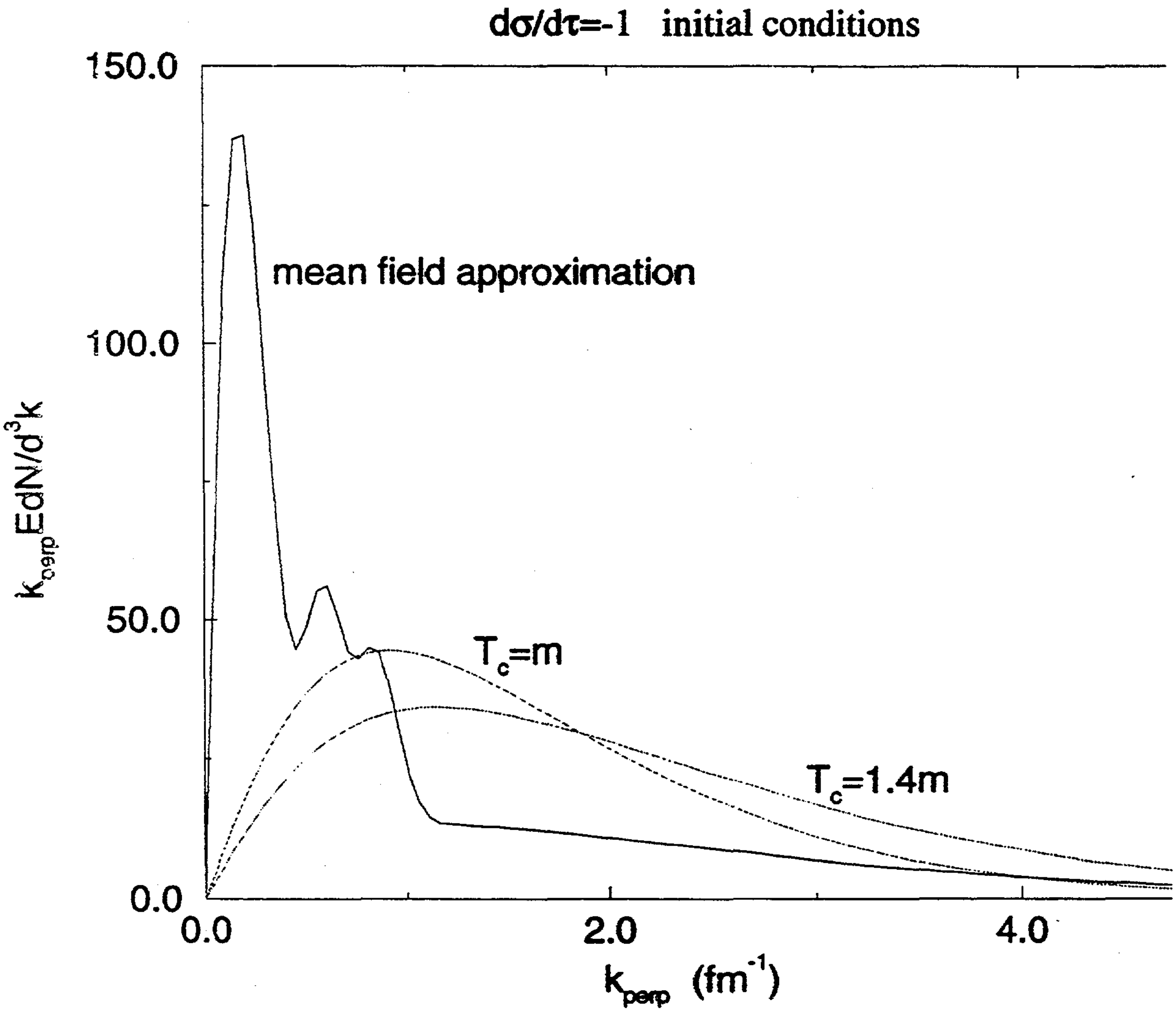
(PLASMA FREQUENCY $\omega_p^2 = \frac{N_c}{9} g^2 T^2$)



Transverse response

(abelian theory)

Enhancement
of low momentum pions



Importance of close ties of Center to experiment

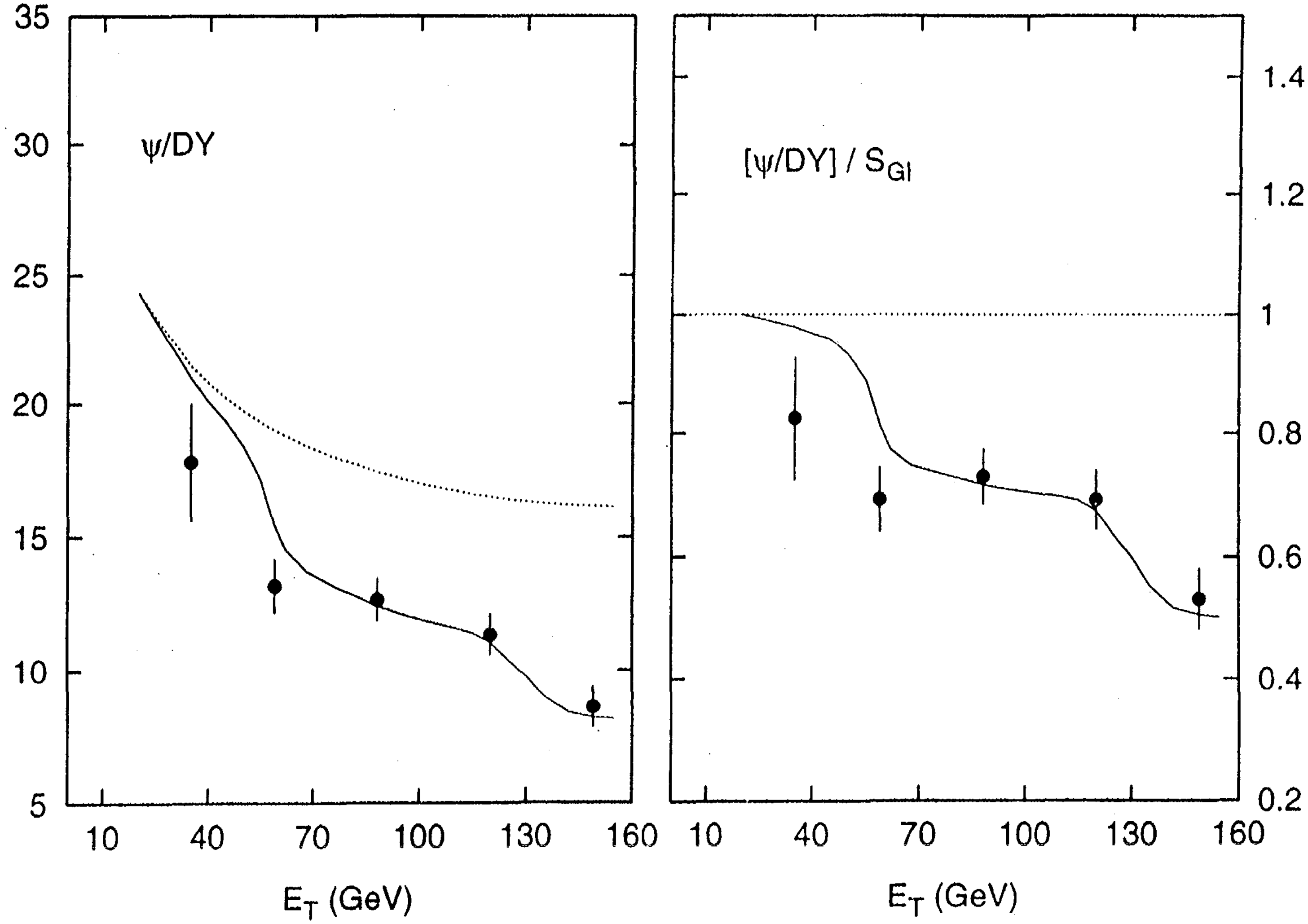
Complexity of non-equilib many body phenomena

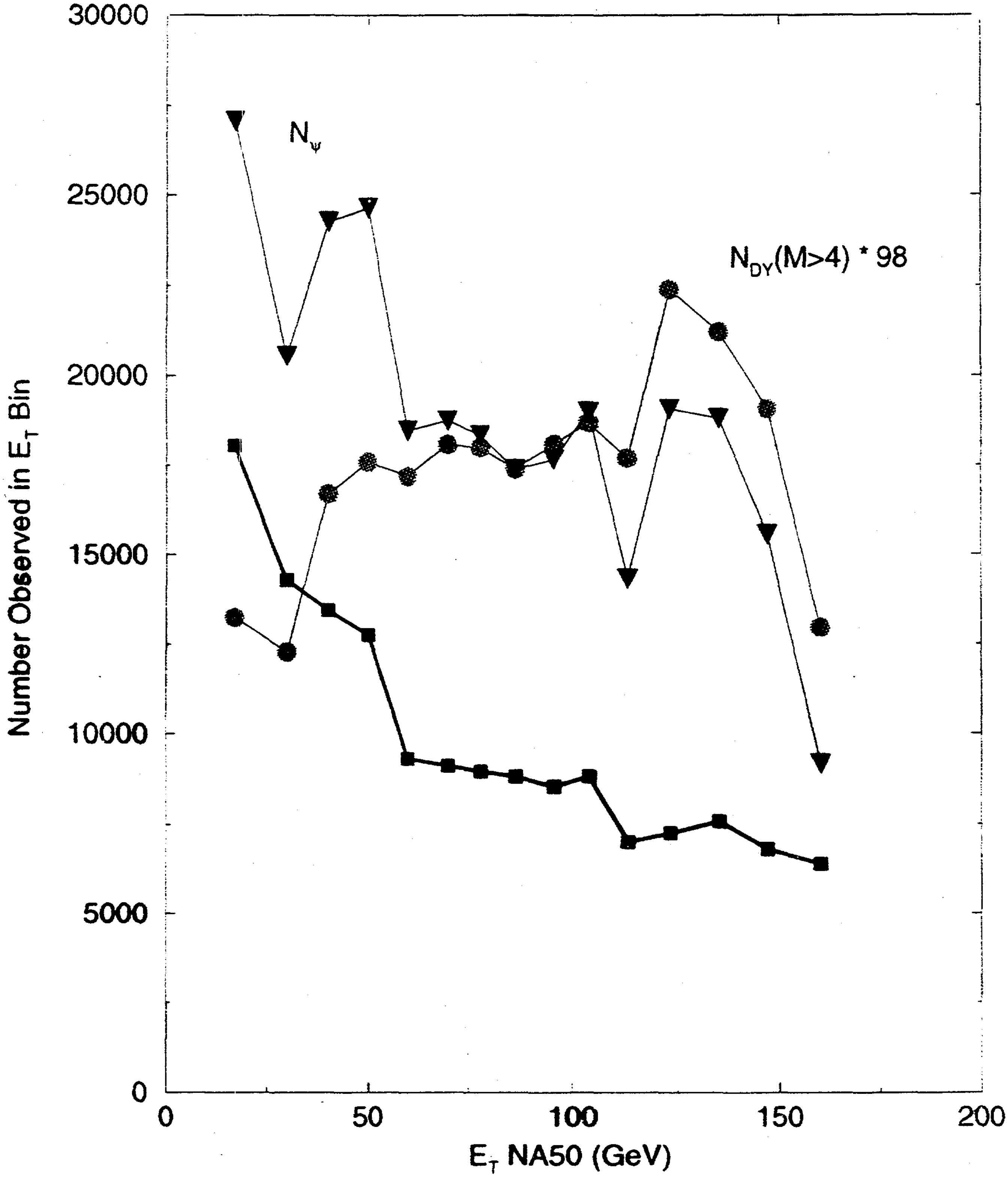
Theory $\Longleftrightarrow$ Experiment
$g=1$

D. Kharzeev

J/ψ suppression

D. K., M. Nardi, H. Satz
hep-ph/9707308   10 Jul 1997




30000
25000
20000
15000
10000
5000
0
Number Observed in E_T Bin
N_ψ
$N_{DY}(M>4)$ * 98
0
50
100
150
200
E_T NA50 (GeV)

Thanks to:

Mike Creutz and Yang Pang
coorganizers

Pam Esposito
Isabel Harrity
Irene Tramm

Heroic Stars who made it possible

The speakers and participants for helping launch RBRC in style

Good luck: TD + Young Crew!

RIKEN BNL RESEARCH CENTER

SYMPOSIUM ON NON-EQUILIBRIUM MANY BODY PHYSICS
SEPTEMBER 23 - 25, 1997

PHYSICS DEPARTMENT - LARGE SEMINAR ROOM

AGENDA

Tuesday Morning, September 23

[Chair - Robert Jaffe]

09:00 -- 09:55 T.D. Lee (Columbia University/RIKEN BNL Research Center)

Opening Remarks and Non-Compact Lattice

10:30 -- 11:25 Kazuo Kitahara (Tokyo Institute of Technology)

Non-Equilibrium Thermodynamics

11:30 -- 12:25 Gabor J. Kalman (Boston College)

Strongly Coupled Coulomb Systems

Tuesday Afternoon, September 23

[Chair - Tetsuo Matsui]

01:30 -- 02:25 Gordon A. Baym (University of Illinois/Urbana-Campaign)

Recent Developments in Bose-Einstein Condensation

02:30 -- 0 3:25 Rob Pisarski (Brookhaven National Laboratory)

Non-Abelian Debye Screening and the "Tsunami Wave" Problem

[Chair - John Harris]

04:00 -- 04:55 Dmitri Kharzeev (RIKEN BNL Research Center)

The Charm of Nuclear Physics

05:00 -- 05:55 Dirk Rischke (RIKEN BNL Research Center)

Instabilities and Inhomogeneities in the Early Stage of Ultrarelativistic Heavy-ion Collisions

RIKEN BNL RESEARCH CENTER

SYMPOSIUM ON NON-EQUILIBRIUM MANY BODY PHYSICS

SEPTEMBER 23 - 25, 1997

PHYSICS DEPARTMENT - LARGE SEMINAR ROOM

AGENDA, CONTINUED

Wednesday Morning, September 24

[Chair - Michael Creutz]

09:00 -- 09:55 **Frank Wilczek** (Institute for Advanced Study/Princeton University)

Color Superconductivity

10:30 -- 11:25 **Berndt Müller** (Duke University)

Color Chaos

Wednesday Afternoon, September 24

[Chair - Bill Zajc]

01:45 -- 02:40 **Larry D. McLerran** (University of Minnesota)

Classical Yang Mills Dynamics

02:45 -- 03:40 **Fred Cooper** (Los Alamos National Laboratory)

Dileptons at RHIC from the Non-Equilibrium Chiral Phase Transition: A Quantum Field Theory Approach

[Chair - Anthony Baltz]

04:00 -- 04:55 **Yang Pang** (Columbia University/Brookhaven National Laboratory)

Covariant Transport Theories

05:00 - 05:55 **Klaus Kinder-Geiger** (Brookhaven National Laboratory)

QCD Parton Cascade Dynamics at RHIC

RIKEN BNL RESEARCH CENTER

SYMPOSIUM ON NON-EQUILIBRIUM MANY BODY PHYSICS
SEPTEMBER 23 - 25, 1997

PHYSICS DEPARTMENT - LARGE SEMINAR ROOM

AGENDA, CONTINUED

Thursday Morning, September 25

[Chair - Miklos Gyulassy]

09:00 -- 09:55 Paul W. Terry (University of Wisconsin)

Turbulent Plasmas

10:30 - 11:25 Jean-Paul Blaizot (CEA Saclay)

Quasiparticles and Infrared Physics in QED and QCD Plasmas

Thursday Afternoon, September 25

[Chair - Gerry Brown]

01:30 - 02:25 Dimitri Kusnezov (Yale University)

Open Questions in Non-Equilibrium Physics

02:30 -- 03:25 Pawel D. Danielewicz (Michigan State University)

Non-Equilibrium Quantum Kinetics

03:30 - 04:25 Edward Shuryak (SUNY/Stony Brook)

The QCD Phase Transitions: from Mechanism to Observables

04:30 - 05:00 Closing Remarks - Miklos Gyulassy

Participant List
Symposium on Non-equilibrium Many Body Physics
September 23-25, 1997

Brent H. Allen
Smith Laboratory
The Ohio State University
174 W 18th Street
Columbus, OH 43210

Anthony J. Baltz
Physics Department
Brookhaven National Laboratory
Upton, NY 11973-5000

Gordon A. Baym
Loomis Laboratory of Physics
University of Illinois
1110 W. Green St
Urbana, IL 61801

Paolo Bedaque
INT
University of Washington
Seattle, WA 989195

Jean-Paul Blaizot
Service de Physique Théorique
CEN-Saclay
91191 Gif-sur-Yvette, France

Gerald E. Brown
SUNY/Stony Brook
Stony Brook, NY 11794

Norman Christ
Department of Physics
Columbia University
New York, NY 10027

Fred Cooper
Los Alamos National Laboratory
Theoretical Division/T-8
P O BOX 1663, Mls B285
Los Alamos, NM 87545

Hank Crawford
LBL 50–245
1 Cyclotron Road
Berkeley, CA 94820

Michael Creutz *(ORG)*
Physics Department
Brookhaven National Laboratory
Upton, NY 11973-5000

Tamas Csörgö
MTA KFKI RMKI
P O BOX 49
H-1525 Budapest 114
Hungary

Pawel D. Danielewicz
Nat. Superconducting Cyclotron I
Michigan State University
East Lansing MI 48824

Peter Filip
Institute of Physics
Slovak Academy of Sciences
Dubravska cesta 9
Bratislava SK 842 28
Slovak Republic

Hirotsugu Fujii
RIKEN BNL Research Center
Bldg. 510
Upton, NY 11973-5000

Moshe Gai
Department of Physics, U46
University of Connecticut
2152 Hillside Road
Storrs, CT 06260-3046

Charles Gale
Physics Department
McGill University
3600 University Street
Montreal, QC
Canada H3A-2T8

Stefan Gieseke
Inst. für Theor. Phys.
Universität Bremen
Kufsteiner Str
28359 Bremen, Germany

Maurice Goldhaber
Physics Department
Brookhaven National Laboratory
Upton, NY 11973

Xiaofeng Guo
Department of Physics
Columbia University
538 W 120th Street
New York, NY 10027

Miklos Gyulassy *(ORG)*
Department of Physics- MS 5202
Columbia University
550 W 120th St.
New York, NY 10027

Timothy Hallman
Physics Department
Brookhaven National Laboratory
Upton, NY 11973-5000

John Harris
Physics Department, WNSL-West 311
Yale University
272 Whitney Avenue
New Haven, CT 06250

Barbara Jacak
Dept of Physics & Astronomy
SUNY/Stony Brook
Stony Brook, NY 11794

Bob Jaffe
Department of Physics
MIT
Cambridge, MA 02139
and RIKEN BNL Research Center

Stephen Johnson
Dept of Physics & Astronomy
SUNY/Stony Brook
Stony Brook, NY 11794

Gabor J. Kalman
Department of Physics
Boston College
Chestnut Hill MA 02167

Dmitri Kharzeev
RIKEN BNL Research Center
Building 510
Upton, NY 11973-5000

Venkatesh V. Kidambi
Department of Physics
Northeastern University
Boston, MA 02115

Klaus Kinder-Geiger
Department of Physics
Brookhaven National Laboratory
Upton, NY 11973-5000

Kazuo Kitahara
Department of Applied Physics
Tokyo Institute of Technology
Ookayama 2-12-1, Meguro-ku
Tokyo 152, Japan

Yuval Kluger
T8 B285, Theor. Div.
Los Alamos National Laboratory
Los Alamos, NM 87545

Gerd J. Kunde
Yale University
272 Whitney Ave.
New Haven, CT 06520

Dimitri Kusnezov
Center for Theoretical Physics
Sloane Physics Laboratory
217 Prospect St.
Yale University
New Haven, CT 06520-8120

Jean-Francois Lagae
HEP Division
Argonne National Lab.
9700 S. Cass Avenue
Argonne, IL 60439

Chang-Hwan Lee
Department of Physics
SUNY/SB
Stony Brook, NY 11794

Kimyeong Lee
Department of Physics- MS 5210
Columbia University
New York, NY 10027

T.D. Lee
Physics Department
Columbia University
New York, NY 10027
and RIKEN BNL Research Center

Guogiang Li
Department of Physics
SUNY/SB
Stony Brook, NY 11794

Hui Li
Department of Physics
Yale University
New Haven, CT 06520

Gunnar Martens
Inst. für Theor. Phys.
Universität Bremen
Kufsteiner Str.
28359 Bremen, Germany

Tetsuo Matsui
Yukawa Inst. for Theor. Phys.
Kyoto University
Kitashirakawa Oiwake-cho
Sakyo-ku
Kyoto 606, Japan

Joe McGrory
Division of Nuclear Physics, ER-2
Office of High Energy & Nuclear P
Department of Energy
19901 Germantown Rd.
Germantown, MD 202874-1290

Larry McLerran
Tate Laboratory of Physics
University of Minnesota
116 Church St SE
Minneapolis MN 55455

Denes Molnar
Department of Physics
Columbia University
New York, NY 10027

Berndt Müller
Department of Physics
Duke University
PO Box 90305
Durham NC 27708-0305

James L. Nagle
Nevis Laboratories
P O BOX 137
Irvington, NY 10533

Kristi Pance
Department of Physics
Dana Research Center
Northeastern University
Boston, MA 02115

Yang Pang
Department of Physics, Box 16
Columbia University
New York, NY 10027
and Brookhaven National Lab.

Rob Pisarski
Physics Department
Brookhaven National Laboratory
Upton, NY 11973-5000

Madappa Prakash
Department of Physics
SUNY/SB
Stony Brook, NY 11794

Krishna Rajagopal
Department of Physics
MIT 6-308A
Cambridge, MA 02139

Ralf Rapp
Department of Physics
SUNY/SB
Stony Brook, NY 11794

Dirk H. Rischke
RIKEN BNL Research Center
Building 510
Upton, NY 11793-5000

N.P. Samios
Physics Department
Brookhaven National Laboratory
Upton, NY 11973-5000

Jack Sandweiss
Physics Department
Yale University
P O BOX 208121
New Haven, CT 06520-8121

Bernd Schlei
Los Alamos National Laboratory
Theoretical Div. DDT-DO
P O BOX 1663, MIs B283
Los Alamos, NM 87545

Edward Shuryak
Department of Physics
SUNY-Stony Brook
Stony Brook NY 11794-3800

Heinz Sorge
Physics Department
SUNY/Stony Brook
Stony Brook, NY 11794

Michael J.Tannenbaum
Physics Department
Brookhaven National Laboratory
Upton, NY 11973-5000

Derek Teany
Department of Physics
SUNY/SB
Stony Brook, NY 11794

Paul Willis Terry
Department of Physics
University of Wisconsin
1150 University Ave
Madison WI 53706

Thomas A. Trainor
Nuclear Physics Lab.
University of Washington
Seattle, Wa 98195

Larry Trueman
Physics Department
Brookhaven National Laboratory
Upton, NY 11973-5000

Michel Tytgat
Physics Department
Brookhaven National Laboratory
Upton, NY 11973-5000

Stephen E. Vance
Department of Physics
Columbia University
538 W 120th St.
New York, NY 10027

Benoit Vanderheyden
Loomis Lab. of Physics
University of Illinois
1110 West Gren
Urbana, IL 61801

Momchil Velkovsky
Department of Physics
Brookhaven National Laboratory
Upton, NY 11973

Urs Achim Wiedemann
University of Regensburg
Univeritaetsstr. 31
D-93040 Regensburg
Germany

Frank Wilczek
Institute for Advanced Study
Olden Lane
Princeton NJ 08540

Matt Wingate
RIKEN BNL Research Center
Building 510
Upton, NY 11973-5000

Xihong Yang
Nevis Laboratories
P O BOX 137
Irvington, NY 10533

W.A. Zajc
Columbia University
Nevis Labs
P O BOX 137
Irvington, NY 10533

Bin Zhang
Department of Physics
Mail Code 9334
Columbia University
New York, NY 10027

RIKEN BNL Center Symposium/Workshops

Title:	**Color Superconductivity, Instantons, and Parity (Non?)Conservation at High Baryon Density**
Organizer:	Miklos Gyulassy
Date:	11 November 1997

Title:	**Physics with Parallel Processors**
Organizers:	TBD
Dates:	January, 1998 (tentative)

For information please contact:

Ms. Pamela Esposito
RIKEN BNL Research Center
Building 510A, Brookhaven National Laboratory
Upton, NY 11973, USA
Phone: (516)344-3097 Fax: (516)344-4067
E-Mail: rikenbnl@bnl.gov
Homepage: http://penguin.phy.bnl.gov/www/riken.html

RIKEN BNL RESEARCH CENTER

INAUGURATION CEREMONY

SEPTEMBER 22, 1997

Li Keran

NON-EQUILIBRIUM MANY BODY DYNAMICS WORKSHOP

SEPTEMBER 23-25, 1997

Speakers:

G. Baym
J. P. Blaizot
F. Cooper
P. Danielewicz
K. Kinder-Geiger
D. Kharzeev
K. Kitahara
D. Kusnezov
T. D. Lee
L. McLerran
B. Müller
Y. Pang
R. Pisarski
D. Rischke
E. Shuryak
P. W. Terry
F. Wilczek

Organizers: M. Creutz
M. Gyulassy