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Title: Institutional Computing: Final Report Quantum Effects on Cosmology: Probing Physics Beyond the Standard Model with Big Bang Nucleosynthesis

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Institutional Computing: Final Report

Quantum Effects on Cosmology: Probing Physics Beyond the Standard Model with Big Bang Nucleosynthesis

Scientific and Programmatic Impact

The current one-year project allocation (`w17_burst`) supports the continuation of research performed in the two-year Institutional Computing allocation (`w14_bigbangnucleosynthesis`). The project has supported development and production runs resulting in several publications[1, 2, 3, 4] in peer-review journals and talks. Most significantly, we have recently achieved a significant improvement in code performance. This improvement was essential to the prospect of making further progress on this heretofore unsolved multiphysics problem that lies at the intersection of nuclear and particle theory and the kinetic theory of energy transport in a system with internal (quantum) degrees of freedom.

The scientific impact of the project spans three areas of our ongoing, LDRD-ER supported work on the physics neutrinos and nuclei in the early universe: *i*) neutrino energy and flavor transport in the early universe in a complete *quantum kinetic* treatment; *ii*) testing the assumptions of homogeneity and isotropy in the presence of neutrino flavor oscillation physics in the early universe and other astrophysical environments; and *iii*) considering the extension of the existing codes to inhomogeneous, anistropic environments, such as supernovae.

The project exploits the advent of new precision astronomical and cosmological observations with the recently commenced construction of the new class of 30-meter telescopes (the *Thirty Meter Telescope*, the *Giant Magellan Telescope* and the *European Extremely Large Telescope*) to use primordial or Big Bang nucleosynthesis (BBN) to constrain the microphysics of the standard models of particle and nuclear physics. (Please see the previous report for a more detailed description of the overview, motivation and approach to constructing a large-scale simulation code for the project.) These objectives are challenging to achieve and our collaboration is the first to attempt it. We've made significant progress on the development of a code that numerically solves the full neutrino quantum kinetic equations in the early universe under the influence of (general relativistic) gravity and a full coupling of the these to the other cosmic constituents (photons, electrons, positrons, and light nuclei) assumed to be in equilibrium.

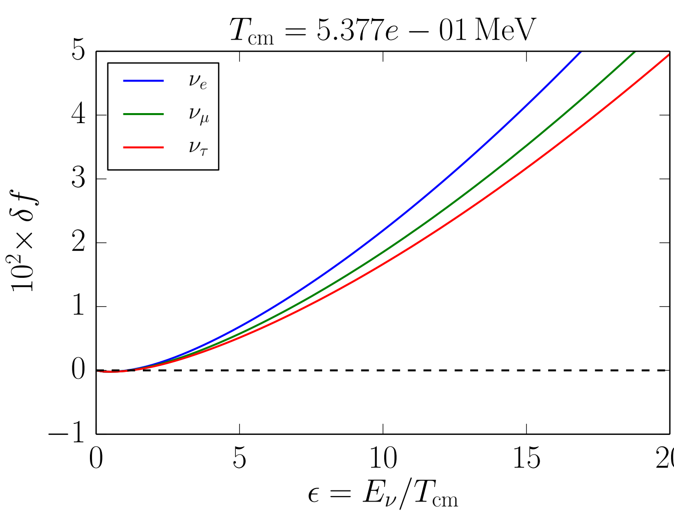

Figure 1: Deviation of the diagonal elements of the neutrino flavor density matrix from thermal computed with the newly developed method of the momentum-dependent corotating frame solution of the quantum kinetic equations.

The main line of our recent effort has been the generalization of the semi-classical (partially quantum field theoretic) Boltzmann description of the neutrino momentum distributions, which solve a non-linear integro-partial differential dynamical equation of the schematic form

$$\Big[\partial_t - pH[f;t]\partial_p\Big] f_i(p,t) = \mathscr{C}_i[f,\overline{f}], \tag{1}$$

where $f_i(p,t)$ is the momentum and time-dependent neutrino distribution function (a similar equation holds for anti-neutrinos, $\overline{f}_j$), $H[f;t]$, the Hubble expansion rate of the universe, is a *functional*, which is an integral over all momenta p of the neutrino distribution function $f(p,t)$, and $\mathscr{C}_i$ is a functional describing the collisions of the neutrinos with other neutrinos, anti-neutrinos and the remaining cosmic constituents; t is the universal, comoving time and i is a vector index in flavor space denoting the neutrino flavor. This equation, solved for the first time in a self-consistent manner in the previous code version of BURST was reported in the previous project report. The new code version of BURST is a significantly generalized code required to solve the quantum kinetic equation for the neutrino flavor density matrix ρ, which physics was neglected in the previous code version. Schematically, the neutrino quantum kinetic equation is written as

$$\Big[\partial_t - pH[\rho;t]\partial_p\Big]\rho(p,t) - i\left[\Big(H_V + H_{\nu\nu} + H_{\mathrm{matter}}\Big), \rho(p,t)\right] = \mathscr{C}[\rho,\overline{\rho}]. \tag{2}$$

Incorporation of the neutrino flavor dynamics requires the generalization from the flavor-vector f_i to the 3×3 flavor matrix ρ and the addition of the related commutator term (the second term on the left-hand side of Eq.(2)) for the flavor dynamics. This term introduces several new complications from that of Eq.(1) including a new ultra-high frequency time-scale due to the so-called vacuum neutrino flavor oscillation term H_V and an additional non-linearity in the 'coherent' neutrino self-interaction $H_{\nu\nu}$.

Our code development efforts have been focused in two main areas: improving the performance of numerical methods that are used both in the previous BURST (semi-classical) code version and the current (quantum kinetic) version; and in proposing and developing (by the PI, Paris) and implementing (by the postdoctoral fellow, Grohs) a new method to eliminate the ultra-high frequency oscillations introduced by the the vacuum oscillation term $H_{\nu\nu}$ in Eq.(2). Here, we introduced the time- and momentum-dependent unitary transformation

$$\tilde{\rho}(p,t) = e^{-itH_V(p,t)}\rho(p,t)e^{+itH_V(p,t)}, \tag{3}$$

to the co-rotating neutrino vacuum flavor basis. Care must be executed in the evaluation of the other terms in this basis and we have solved this simpler but also complex issue, as well. Our efforts have resulted in a performance improvement two, separate, multiplicative factors: numerical methods optimization has resulted in a speed-up of a factor of 30 of the previous code version; the co-rotating frame approach, without which progress would have essentially ceased, results in a speed-up factor of 10^4 over the direct approach of Runge-Kutta(4/5) Cash-Karp semi-implicit numerical integration without the elimination the vacuum oscillation term. Results of this work, which permit the current moves toward production runs of the full quantum-kinetic, early universe code BURST, are shown in Fig.1. The seminal (and still preliminary) result, previously not observed in the work of our group or, to our knowledge, any of the 10 or so groups working internationally on this problem, is the distinct nature of the three curves in the figure; previous works, which do not employ self-consistent approaches that we here use, "established" the flavor equilibration at comparable time, which in this figure is few 10's of seconds after the Big Bang. Our result disagrees with this "well known" assumption since Fig.1 shows three distinct curves (as opposed to the previous results which have two or more curves overlapping and indistinguishable).

Publication List

[1] Vincenzo Cirigliano, Mark W. Paris, and Shashank Shalgar. Effect of collisions on neutrino flavor inhomogeneity in a dense neutrino gas. *Physics Letters B*, 774:258 – 267, 2017.

[2] Shashank Shalgar. Multi-angle calculation of the matter-neutrino resonance near an accretion disk. *Journal of Cosmology and Astroparticle Physics*, 2018(02):010, 2018.

[3] E. Grohs, George M. Fuller, C. T. Kishimoto, and Mark W. Paris. Lepton asymmetry, neutrino spectral distortions, and big bang nucleosynthesis. *Phys. Rev.*, D95(6):063503, 2017.

[4] E. Grohs and George M. Fuller. Insights into neutrino decoupling gleaned from considerations of the role of electron mass. *Nuclear Physics B*, 923:222 – 244, 2017.

Selected Talks & Conference Organization

L. Johns (UC San Diego LANL-affiliated graduate student)

- *Neutrino oscillations with a cosmic lepton asymmetry*
  Invited talk at QuEPCO 2017 (Quantum Effects on Precision Cosmological Observations) in Santa Fe, NM, August 2017.

- *Geometric phases in collective neutrino oscillations*
  Invited talk at QuEPCO 2017 in Santa Fe, NM, August 2017.

- *The cosmic lepton asymmetry and neutrino flavor transformation*
  Poster presented at the Gordon Research Conference (GRC) at Hong Kong University of Science and Technology, June 2017. Outstanding Poster award.

- *The cosmic lepton asymmetry and neutrino flavor transformation*
  Talk at the Gordon Research Seminar (GRS) at Hong Kong University of Science and Technology, June 2017.

E. Grohs (LANL Theoretical Division, Group T-2, National Science Foundation N3AS Postdoctoral Fellow)

- *Big Bang Nucleosynthesis in High Precision Neutrino Cosmology*
  Ohio State CCAPP Seminar, 20 Jan 2017
  Dame Astrophysics Seminar, 31 Jan 2017
  University of Kentucky Seminar, 16 Feb 2017
  Theory Seminar Michigan State University, 21 Feb 2017
  University of Minnesota Nuclear Seminar, 10 Mar 2017
  Conference East Lansing, MI, 29 Jun 2017

- *The BURST Code*
  QuEPCO Workshop Santa Fe, NM, 23 Aug 2017

- *Neutrino Energy Transport and Quantum Kinetics*
  Canadian Institute for Theoretical Astrophysics, Toronto, ON, 07 Sep 2017

- *Neutrino Quantum Kinetics and the Early Universe, NPAC Forum Seminar*
  University of Wisconsin, 12 Oct 2017

- *Neutrino Quantum Kinetics and the Early Universe*
  T2 Nuclear Seminar, LANL, 28 Nov 2017
- *Coupled Primordial Nucleosynthesis and Neutrino Flavor/Decoupling*
  Physics Implications for CMB S4, N3AS Annual Meeting San Diego, CA, 11 Jan 2018

S. Shalgar (LANL Theoretical Division, Group T-2, Postdoctoral Researcher)

- NUPAC seminar at University of New Mexico, March 7, 2017
  Title: Effect of collisions on collective neutrino oscillations
- Talk given at quantumdc meeting in Los Alamos National Laboratory, October 13, 2017
  Title: Neutrino flavor oscillations in astrophysics and cosmology
- Talk given at the quantumdc meeting in University of California, San Diego, January 10, 2018
  Title: The Halo problem
- Talk given at the N3AS collboration meeting in University of California, San Diego, 12th January, 2018
  Title: Disturbing Neutrino Flavor Field Spatial Instability in the Early Universe and Supernovae

G. Fuller (UC San Diego Professor, Director CASS)

- Organizer: Quantum Effects on Precision Cosmological Observations
  Santa Fe, NM, August 2017
  `http://cnls.lanl.gov/QuEPCO`

V. Cirigliano (Lab scientist, T-2 LANL)

- Organizer: Quantum Effects on Precision Cosmological Observations
  Santa Fe, NM, August 2017

M. Paris (Lab scientist, T-2 LANL)

- Organizer: Quantum Effects on Precision Cosmological Observations
  Santa Fe, NM, August 2017

Media

Numerical simulations shed new light on early universe
Science on the Hill, Santa Fe New Mexican
`http://bit.ly/2Ga3Ujf`

Financial Impact

The past year has seen an expansion in funding support from various sources enabled largely by the HPC-IC allocation for FY17. Paris is PI on a recently awarded LDRD-ER (20170430ER: *Quantum Effects on Cosmological Observables: Probing Physics Beyond the Standard Model*) and support from the LANL Center for Space and Earth Sciences Student Fellowship program ($60k/year for three years, a form of LDRD support). My UCSD student collaborator, L. Johns, won a DOE Office of Science Graduate Student award (with Paris as the LANL PI) to support his work on the implementation of quantum kinetic effects into the existing BURST code. Current National Science Foundation funding for the PI's (Paris) primary collaborator at UC-San Diego (G. Fuller) is being leveraged for travel and conference support purposes to further work related to that reported here. Additional funds of $20k were awarded to host the QuEPCO 2017 conference (mentioned above) from CNLS LDRD, and DOE Office of Science-Nuclear Physics.