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ATHENA IN THE BEGINNING

Numerics, Principles, Science & Lessons Learned

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Athena++ Meeting

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IN THE BEGINNING…

- In early 2002 I applied for a post-doc position with Jim…
- We spoke on the phone and he described his vision:
- Develop an advanced, high-order Godunov MHD code
- Give it a cool name like Athena, the goddess of wisdom, as a successor to Zeus
- And then… give it away to the astrophysics community.

- Lucky for me, Jim offered me the job!
- This project was exactly what I wanted to solve, so I jumped in with both feet.
- May 2002, we bought a house and moved to Bowie Maryland
- There I met Takayoshi Sano, Neal Turner, Eve Ostriker, Peter Teuben

- A few months later, Jim accepted a position at Univ. of Cambridge and moved his family to England…

ATHENA / CAMBRIDGE RELEASE 1.0

- In Nov. 2002, Peter Teuben and I visited Jim in Cambridge
- We worked long hours, completely restructured the code, and set the path forward
- The goals were simplicity and minimalism, how many buttons do you need on a remote?

- Peter wrote the first version of par.{c,h} loosely based on Fortran Namelists and XML
  <block>
  parameter = value # comment

- We came up with the concept of "Outputs", output blocks and expressions
- Peter wrote the first version of output.{c,h}
- He even implemented run-time compilation of expressions and shared object loading!

- We explored a variety of Constrained Transport methods, but none were really successful

CONSTRAINED TRANSPORT

- Why is $\nabla \cdot B = 0$ so critically important and what “metric” for $\nabla \cdot B$ is important?
- Godunov, Finite Volume, Discontinuous Galerkin methods are based on the integral form of the conservation laws.

$$\partial_t Q + \nabla \cdot \mathbf{F} = 0$$

- Consider simulating a uniform plasma with a dipole magnetic field (excluding the dipole)
- The flux divergence in the conservation law for the momentum and energy equations

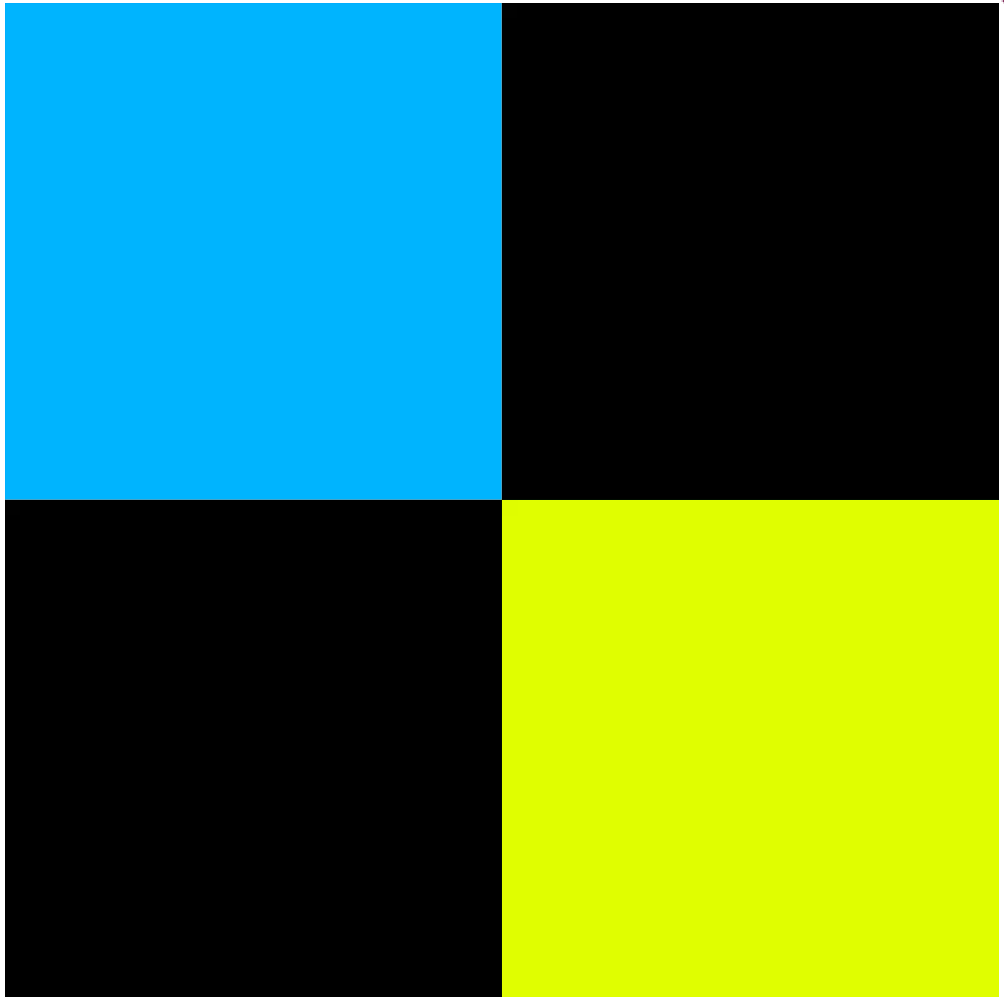
$$\partial_t \rho \mathbf{v} = \mathbf{B}(\nabla \cdot \mathbf{B})$$

$$\partial_t E = (\mathbf{B} \cdot \mathbf{v})(\nabla \cdot \mathbf{B})$$

- It’s the zone face normal component of the B-field in the fluxes that matters.
- Toth (JCP, 2000) showed that $\nabla \cdot B$ errors in the 8-wave scheme can introduce errors in satisfying the Rankine—Hugoniot relations.

MULTIDIMENSIONAL RIEMANN PROBLEMS

- Lax & Liu (SIAM JSC 1998) study **19** genuinely different 2-dim. Riemann problems for a polytropic gas.
- Each quadrant is separated by a single elementary wave (shock, rarefaction, slip)
- The hydrodynamic complexity is significant!
- Given that HD has 3 waves and MHD 7, the potential complexity for MHD is impractical as a building block.
- One option was to use a 2-dim. HLLE Riemann solver following B. Wendroff (CM&A v38, p. 175, 1999)
- We Need a "Model"



Mass Density

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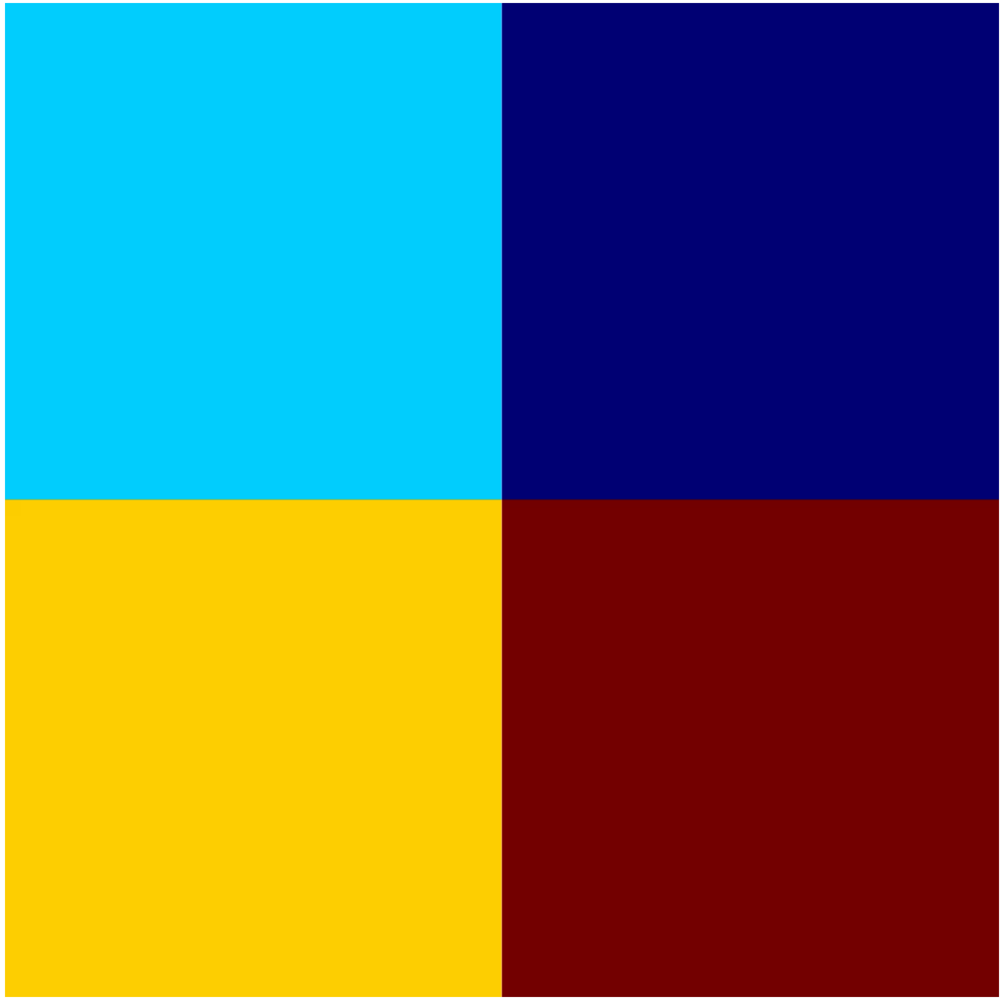


Mass Species (Color)

CALCULATING A CT ELECTRIC FIELD

- Unfortunately, the history from the original Athena repo. was lost.
- I have a separate git repository with this commit message
- Date: Wed Dec 3 19:47:07 2003 +0000

  I added a function named integrate_emf_corner() which implements the
  no-dissipation method for constructing an emf at grid cell corners.
- (2005) JCP (received May 2004) Jim and I published a 2D MHD method using CT and CTU.

- The idea was to find a “model” consistent with 1D planar symmetry and dissipation
- If $\partial_y = 0$, average Riemann E_z in y-direction
- If $\partial_x = 0$, average Riemann E_z in x-direction
- Otherwise up-wind, average, …, we explored a couple of possibilities.

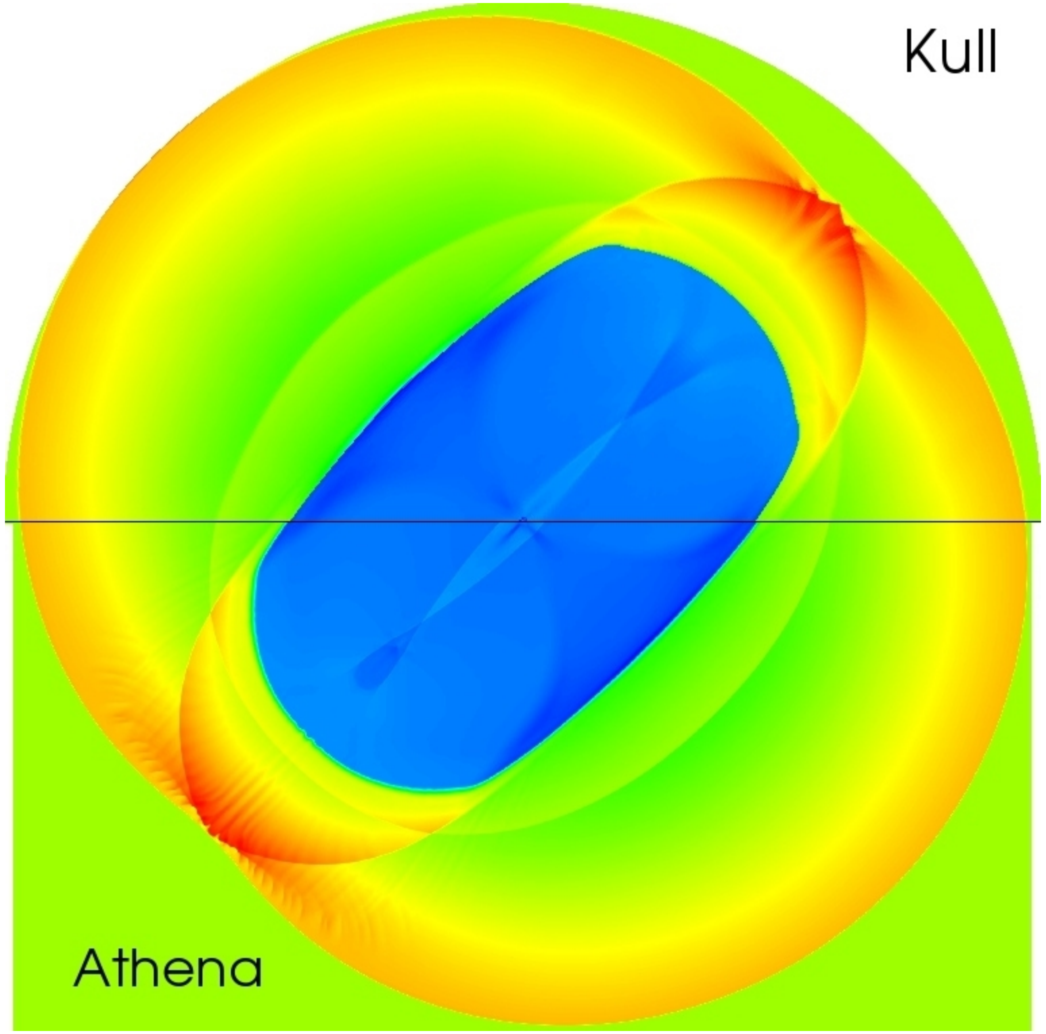
- (2004) Londrillo & Del Zanna published similar CT methods

VERIFICATION TESTING

- In the JCP (2005) Jim and I presented results from a lot of tests

  1. B-field Loop advection
  2. Circularly polarized Alfven waves
  3. Rotated MHD Shock Tube evolution
  4. Linear Wave convergence
  5. Perturbed current sheet evolution
  6. MHD Blast wave problem

- The density perturbations at the “shock front” in the MHD Blast problem always seemed funny.
- It’s a slow-mode shock corrugation instability
- “The Corrugation Instability in Slow Magnetosonic Shock Waves” J. M. Stone & M. Edelman, ApJ (1995)



LOW-β MHD EQUILIBRIA – SOLVING THE GRAD-SHAFRANOV EQ.

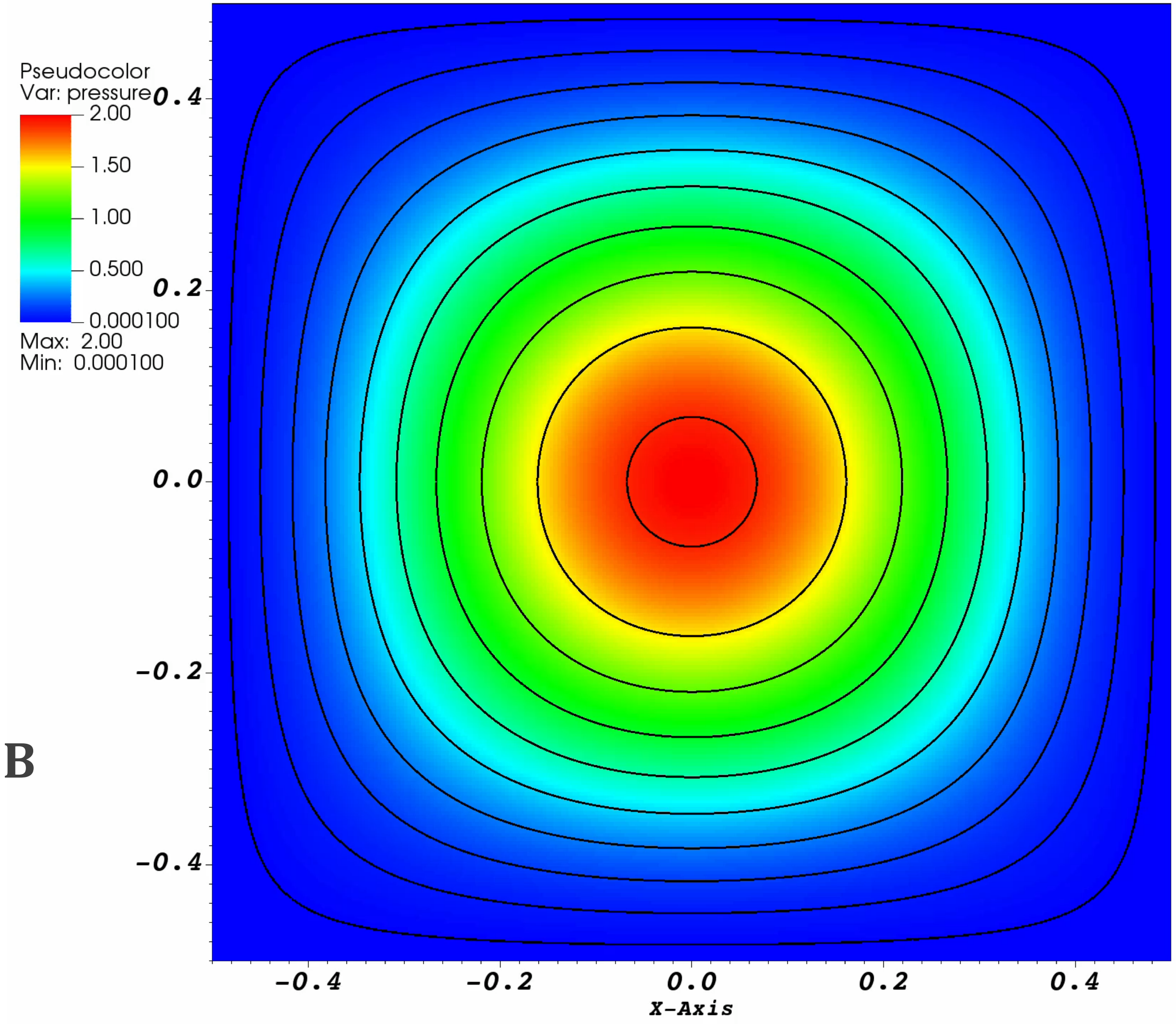
- The Grad-Shafranov equation describes 2D MHD equilibria via

$$\nabla^2\psi = -\mu\left(\frac{dP}{d\psi}\right)$$

$$P(\psi) = P_0 + (2 - P_0)\left(\frac{\psi}{\psi_{max}}\right)^2$$

$$\mathbf{B} = \nabla\psi \times \hat{\mathbf{k}}$$

- $P_0 = 10^{-4}$ & $1.8\text{x}10^{-4} \leq \boldsymbol{\beta} \leq 2.7\text{x}10^{4}$
- Using “periodic” BCs. with antisymmetric $\mathbf{B}$
- Test the equilibrium under advection. Does it maintain the equilibrium?



WRAPPING UP THE NUMERICS

- In May 2006, I moved from Princeton to Albuquerque

- 2008 JCP (Received Sept. 2006) presented the 3D CTU + CT MHD method
- 2008, ApJS “Athena: a new code for astrophysical MHD”
- 2009, New Astronomy “A simple unsplit Godunov method for multidimensional MHD”
- 2010, ApJS “Implementation of the Shearing Box Approximation in ATHENA”

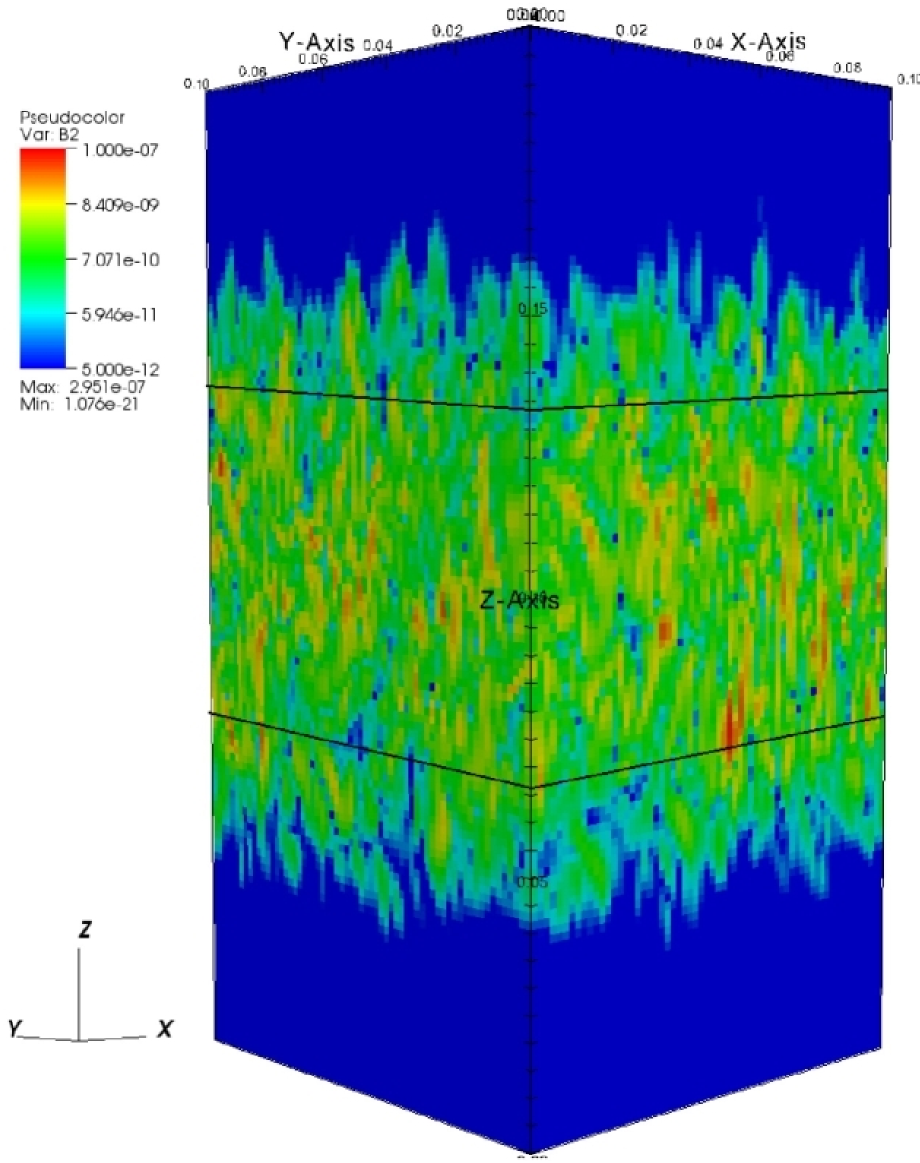
- One important aspect of all of Jim’s papers on numerics is that he includes the details.
- The papers include step-by-step instructions - there’s no “special sauce” omitted.

- All the while, science was getting done in parallel.

MAGNETOTHERMAL INSTABILITY

- Nonlinear Evolution of the Magnetothermal Instability in Two Dimensions
  Ian J. Parrish & James M. Stone, ApJ (2005)
- Saturation of the Magnetothermal Instability in Three Dimensions
  Ian J. Parrish & James M. Stone, ApJ (2007)

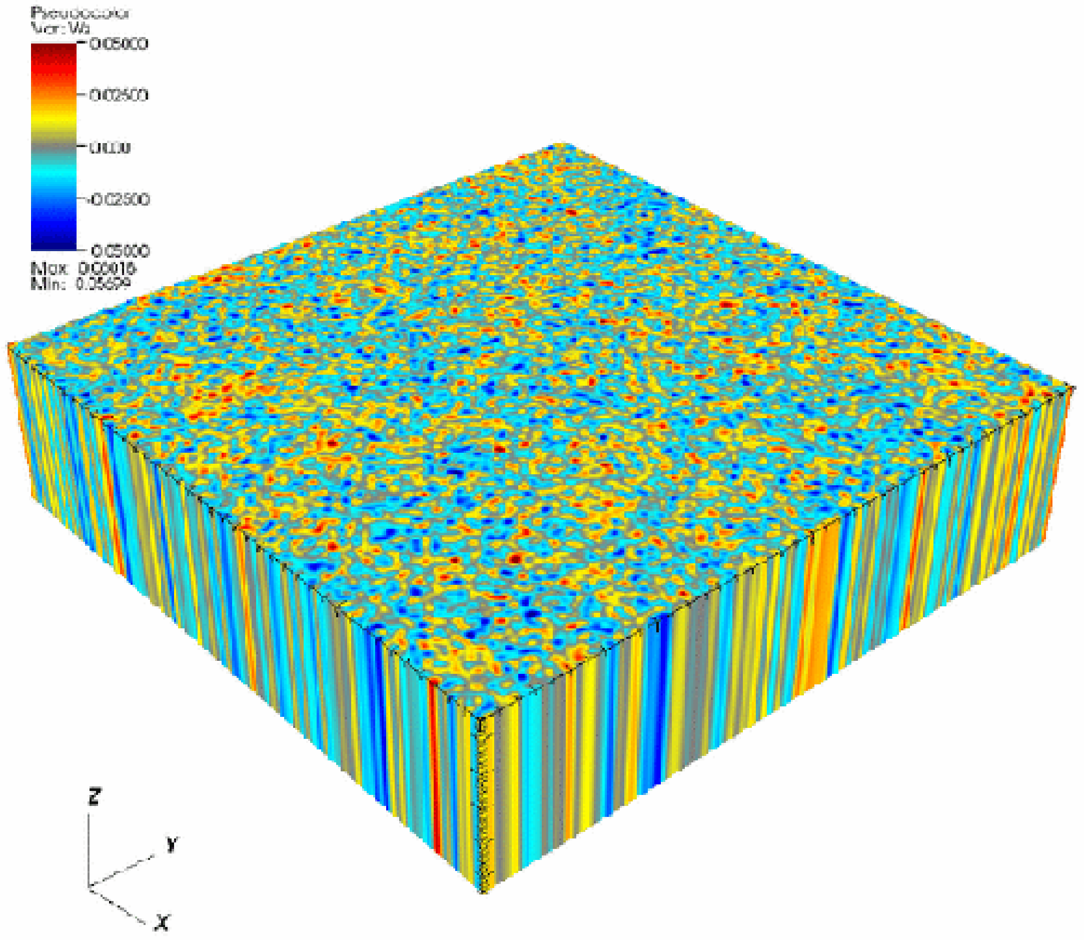
- Anisotropic thermal transport alters the stability condition from depending on the entropy gradient to one of temperature gradient



3D HYDRODYNAMIC VORTICES IN DISKS

- Three-dimensional Compressible Hydrodynamic Simulations of Vortices in Disks Yue Shen, James M. Stone, and T. A. Gardiner, ApJ (2006)

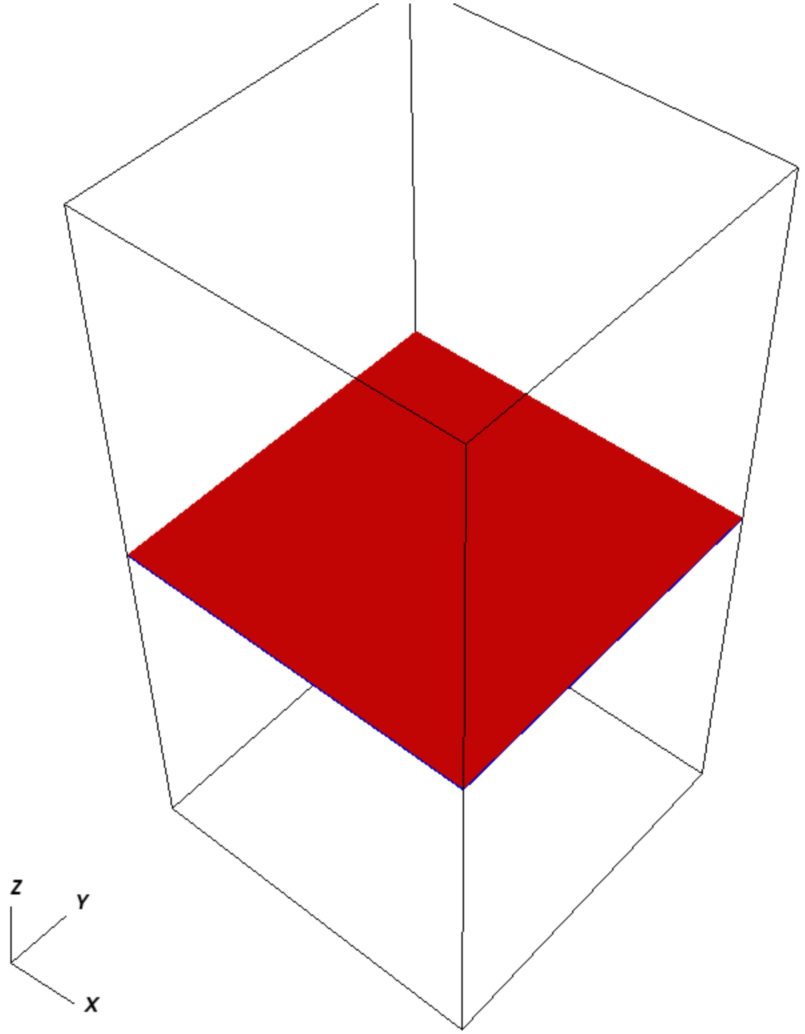
- Linear amplitude, leading waves were proposed as a possible route to nonlinear hydrodynamic turbulence.
- Instead, they were observed to be KH unstable
- In 3D, vortices are unstable to bending modes
- Only wide (length/width < 1) vortices survive



MAGNETIZED RAYLEIGH TAYLOR INSTABILITY

- The Magnetic Rayleigh-Taylor Instability in Three Dimensions
  James M. Stone and Thomas Gardiner, ApJ (2007)
- Nonlinear Evolution of the Magnetohydrodynamic Rayleigh-Taylor Instability
  James M. Stone & Thomas Gardiner, PoF (2007)

- Wave modes parallel to B are stabilized below a critical wavelength.
- Mixing is reduced monotonically with increasing B-field strength.



IN SUMMARY…

- The original intent in developing Athena was to give it away to the astro. community.
- Friends & colleagues benefit from a tool on which to build their work.
- Students see the nuts and bolts of how to write a simulation code.
- Detractors use it as ammunition to criticize your work.
- For open science, this is the way…

- The continued evolution in the physics treated by Athena and the growth of the community is inspiring and I continue to be proud of my early contributions – Thank You.

- Thank you Peter – your contributions continue to stand the test of time.

- Thank you Jim for hiring me as a post-doc and giving me the opportunity, challenge & support.