Why Do We Pursue Computational Plasma Physics?

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PHYS:5905 Special Topics in Physics:
Numerical Simulation of Plasmas

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and others . . .

Computational Physics

Computational Physics has become the third pillar of scientific investigation:

Theoretical

Computational

Experimental/Observational

Supercomputers have enabled scientific computation to reach an entirely higher level of sophistication.

For example, achieving efficient petascale computing has become nearly as challenging as the scientific problems that demanded a computational approach.

Computational Plasma Physics

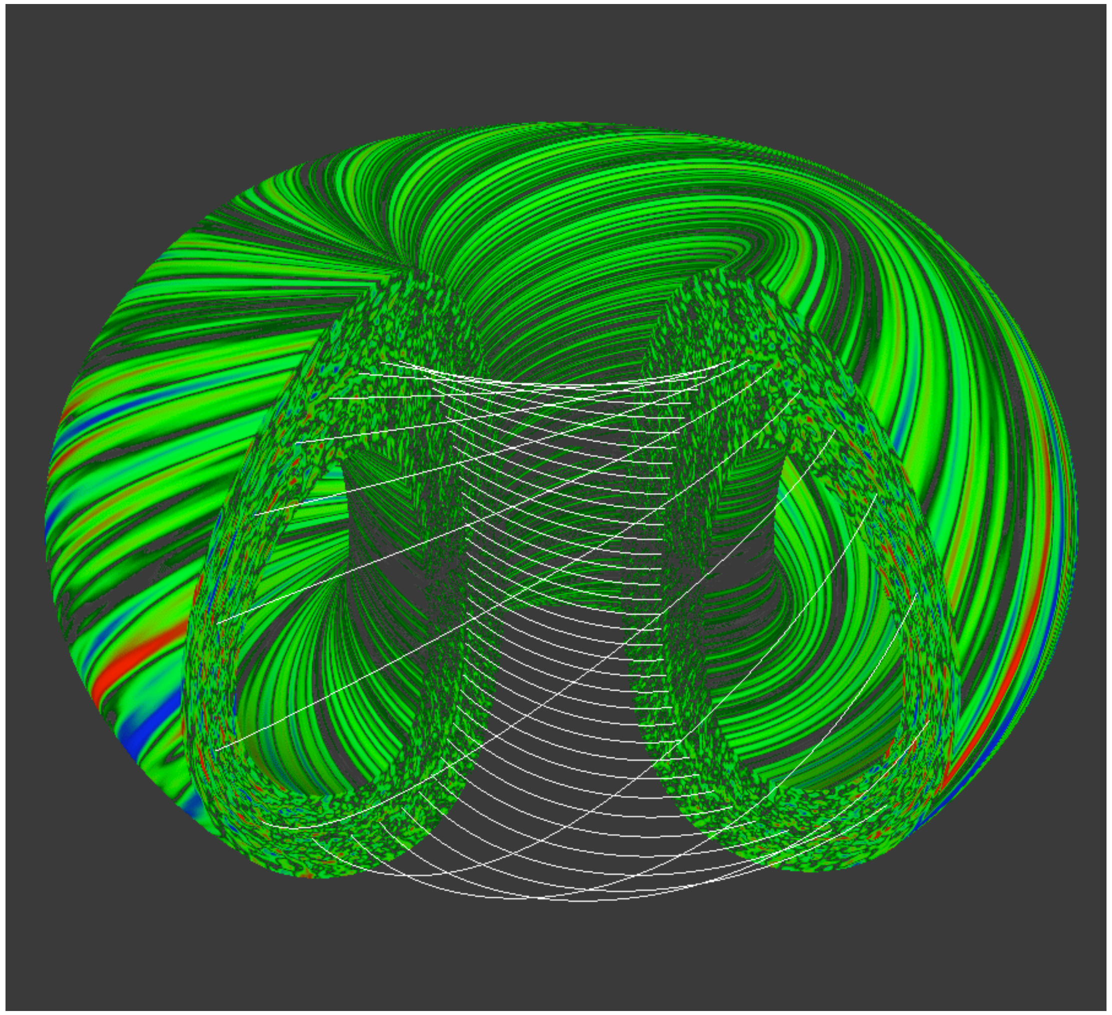
Wide range of problems in Plasma Physics:

Magnetic Confinement Fusion

Plasma from START,
Culham Laboratories, UKAEA

Wide range of algorithms and codes:

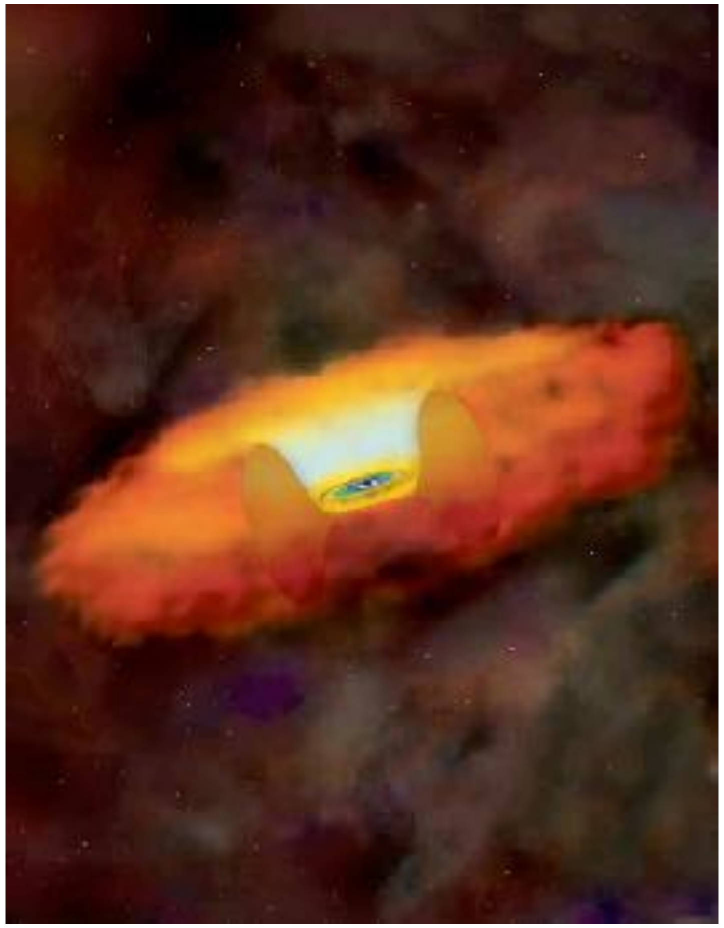
Gyrokinetics



Gyrokinetic Plasma Simulation
(G D Kerbel)

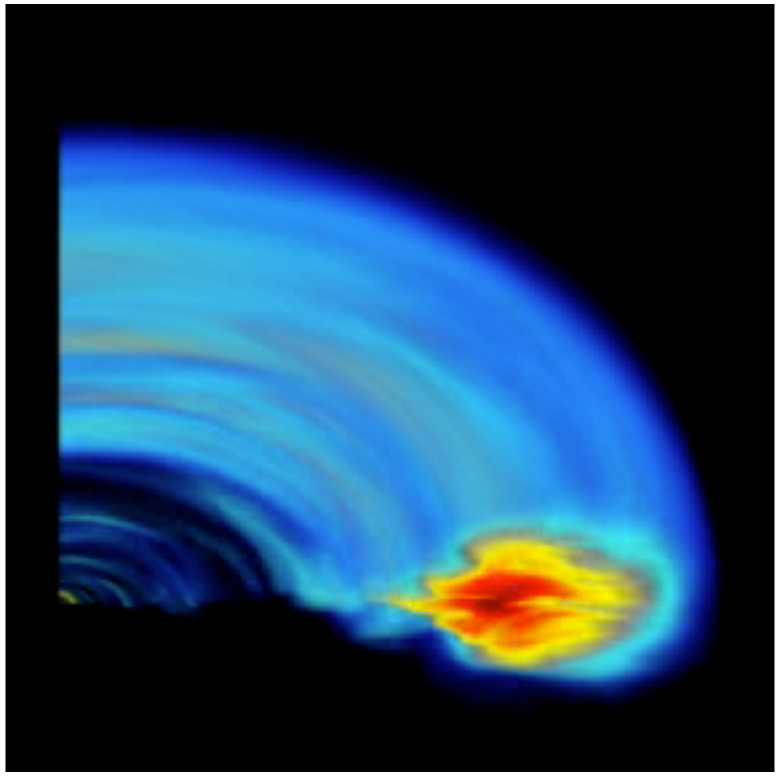
Computational Plasma Physics

Black Hole Accretion Disk



NASA/CXC/SAO
Artist's Conception

Relativistic Magnetohydrodynamics

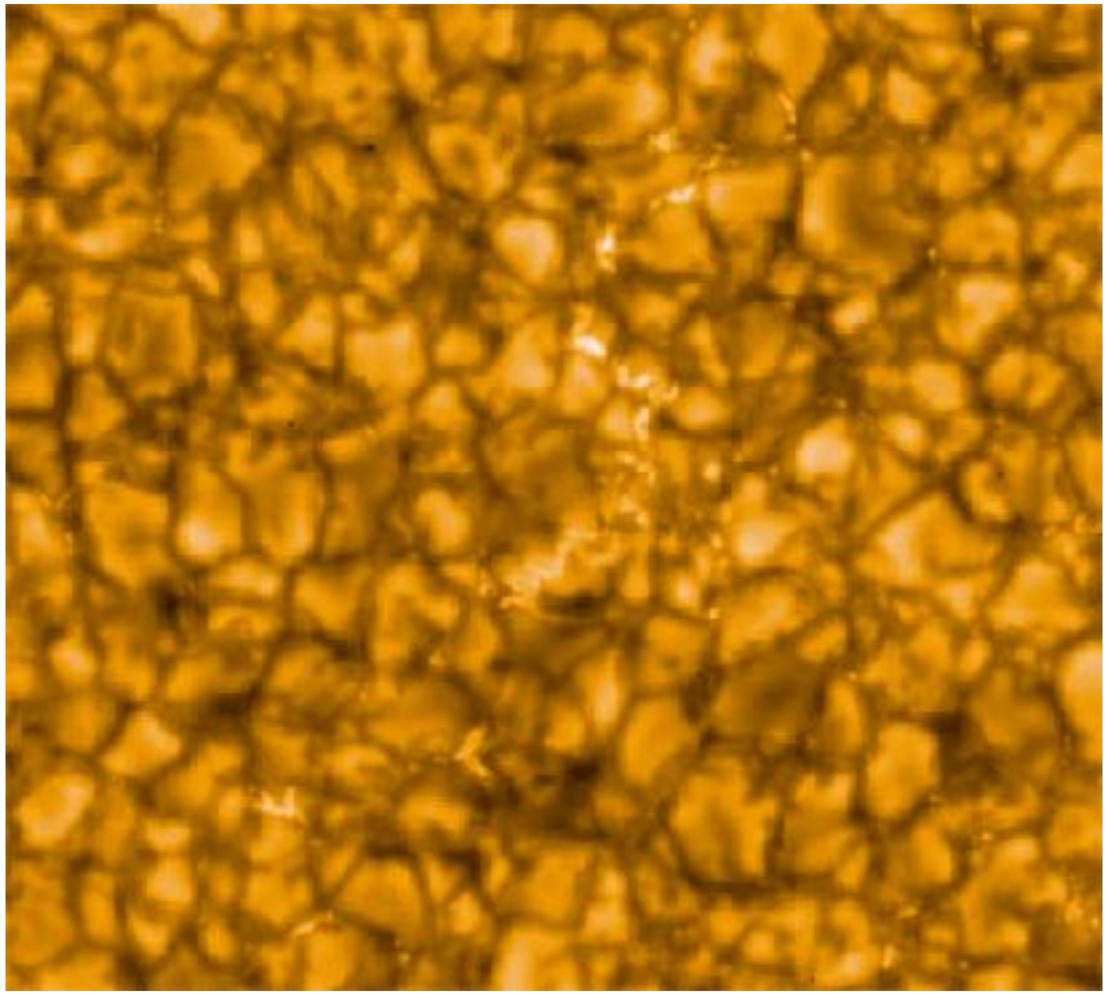


MHD Simulation
(Hawley & Balbus, 2002)

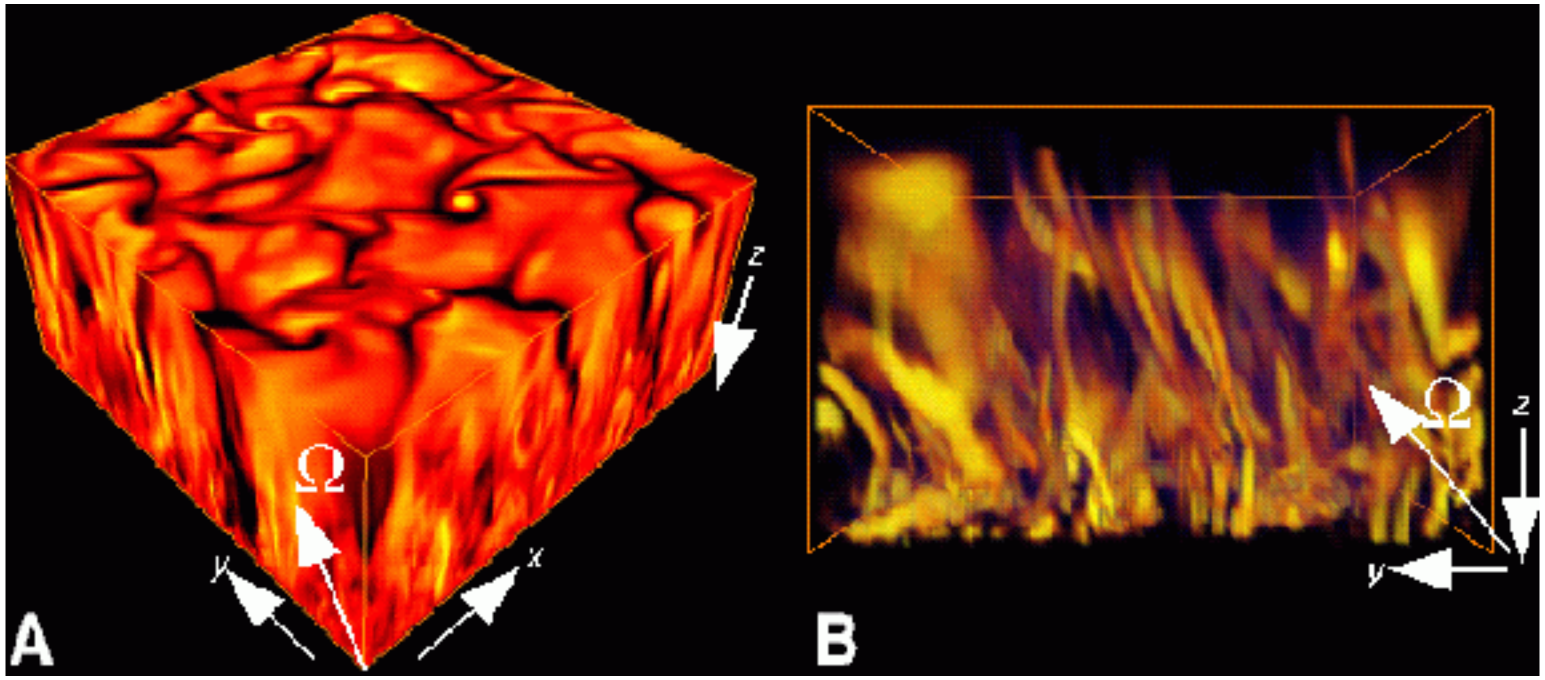
Computational Plasma Physics

Solar Convection

Magnetohydrodynamics



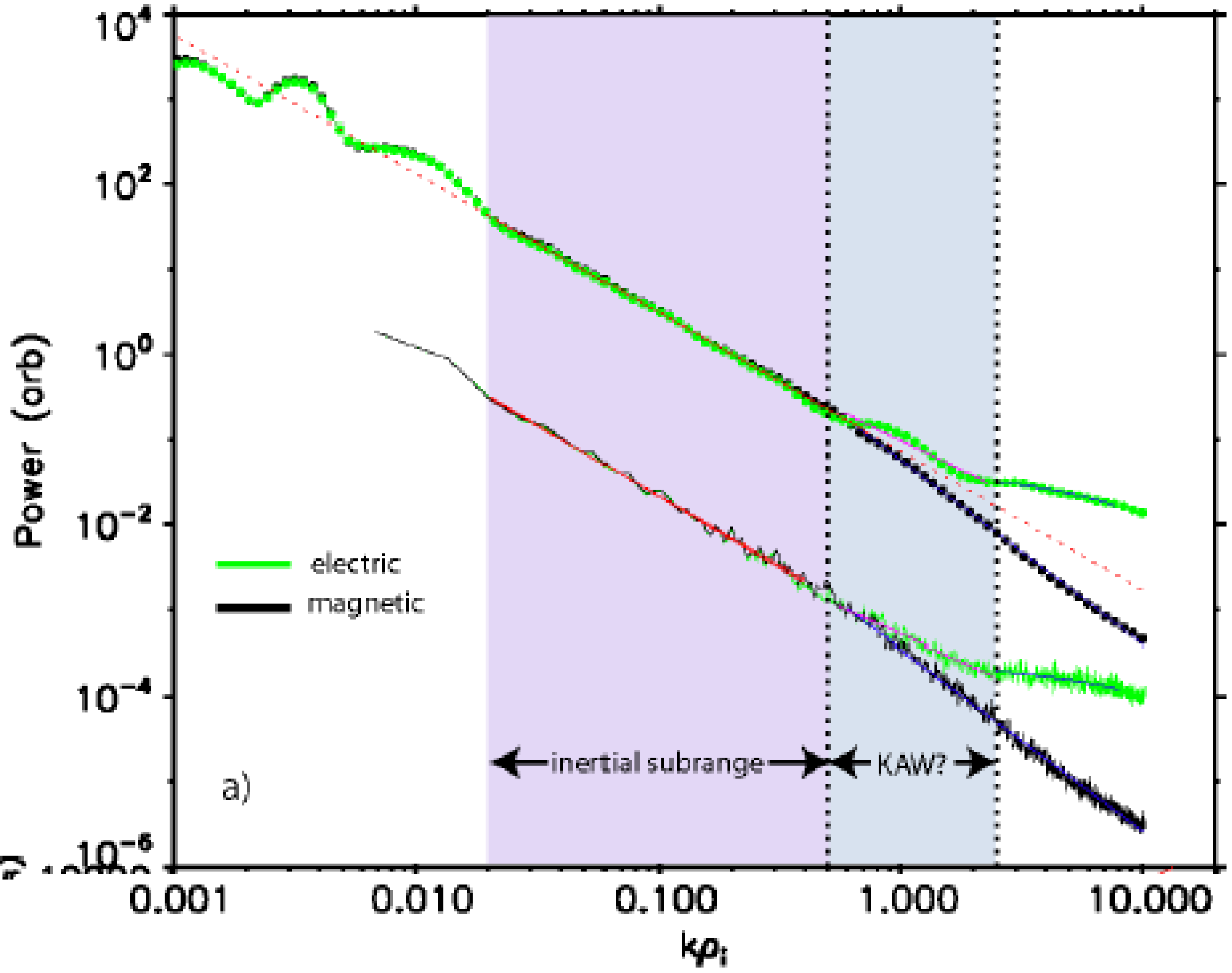
Observations of granulation from Hinode, JAXA



MHD Simulation
(Brummell, Hurlburt, & Toomre 1993)

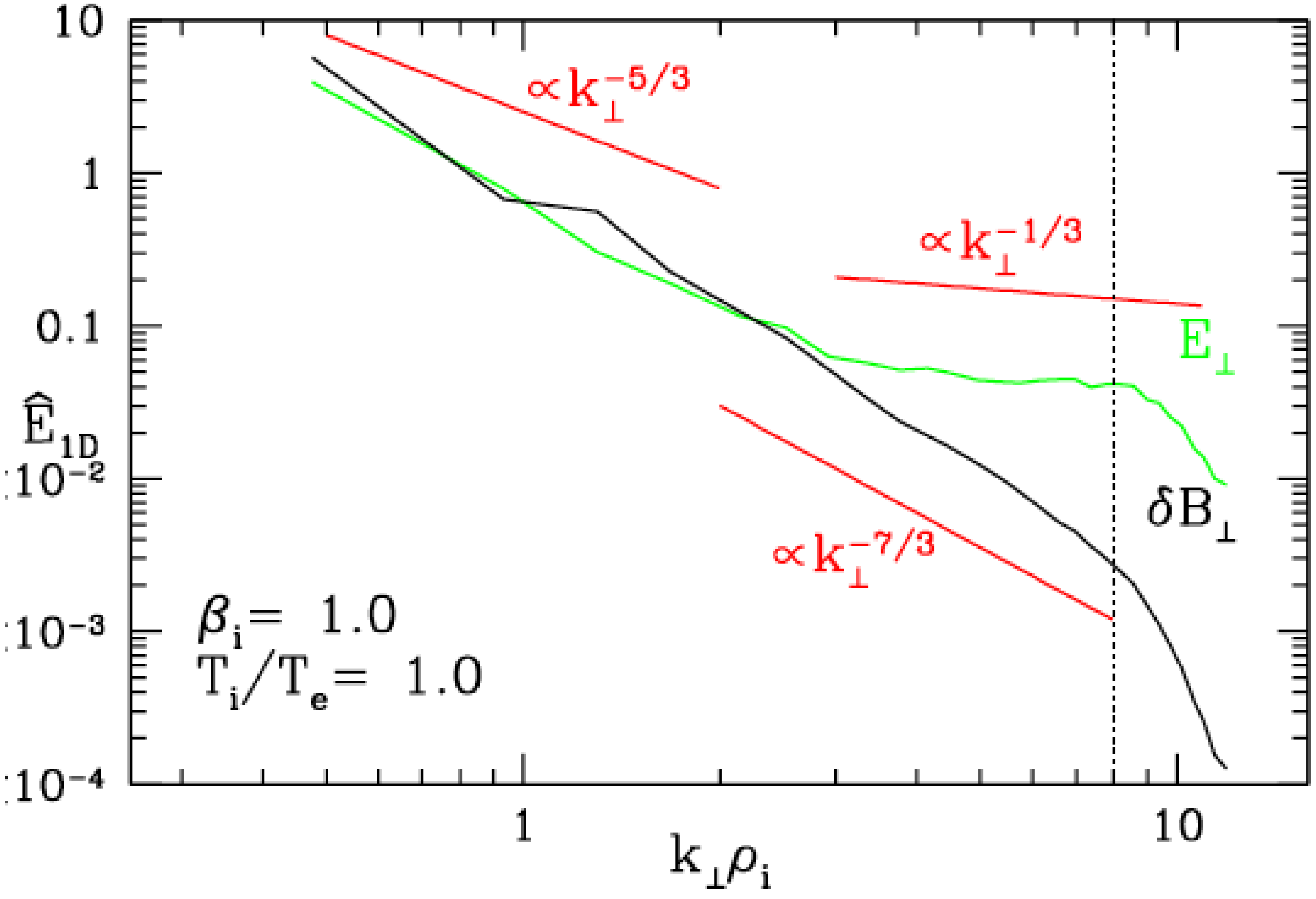
Computational Plasma Physics

Solar Wind Turbulence



Solar Wind Observations, Cluster
(Bale et al., 2005)

Gyrokinetics



Gyrokinetic Turbulence Simualtions
(Howes et al., 2005)

Advancing Science with Simulations

Common Denominator:

How does one use supercomputers to advance science?

I will address this question with examples from fusion research as well as my own research on space and astrophysical plasmas.

Common Question:

What is the most exciting thing one can do with a powerful supercomputer?

Turn it off!

Science is the Goal

What is the goal of high-performance computing?

To run the biggest simulation you can perform on the computer? No!

→ To understand the physics of a complex system.

Sometimes this point is lost in the big business of computing on the world's largest supercomputers.

Specific Scientific Questions

How are simulations used to understand the physics?

Focus on a specific scientific question, or set of questions.

- Simulation results are really just a bunch of numbers

- We generally need to have some idea of what to expect, a theoretical prediction, in order to make sense of the simulation results

- The mere task of formulating a simple question that the simulation can answer often clarifies the scientific issues involved

Examples from Computational Research

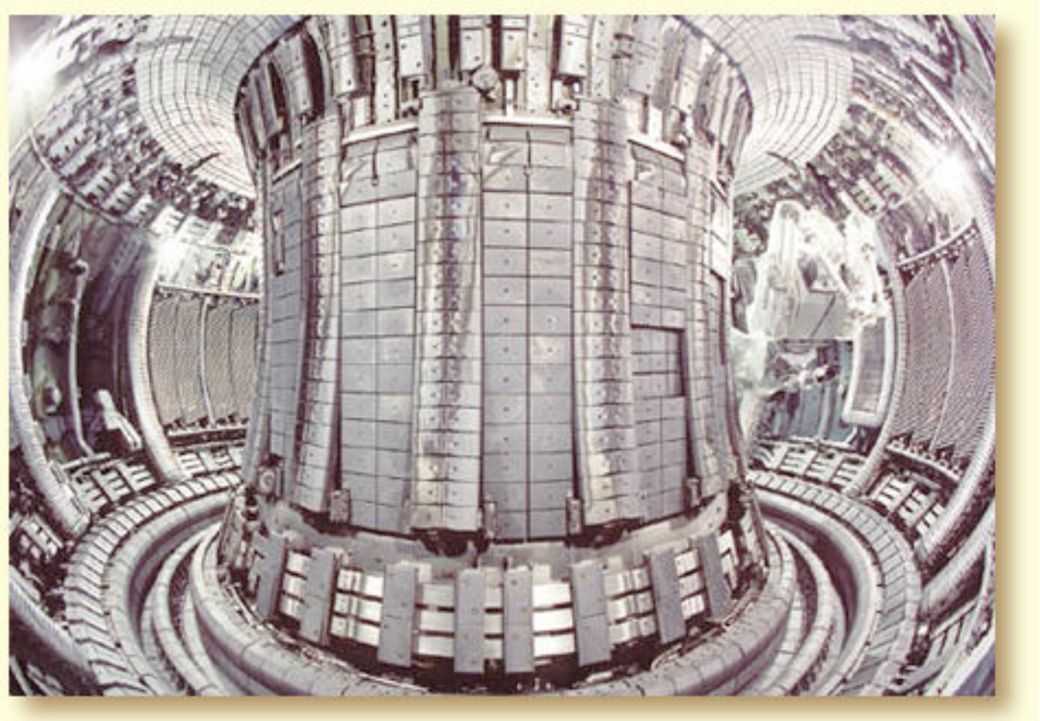
Today I will discuss two detailed examples of successful computational research in plasma physics:

- Magnetic Confinement Fusion:
  Computational science in a mature field
- Kinetic Turbulence in Space and Astrophysical Plasmas:
  Computational science in an emerging field

Magnetic Confinement Fusion

Magnetic Confinement Fusion

A tokamak is a toroidal magnetic chamber to confine plasma



JET tokamak
Culham Laboratories, UKAEA

- Stable plasma equilibria demonstrated for hours on superconducting machines
- Problem is rapid transport of energy, momentum, and particles out of the machine by turbulence

One major goal of fusion:

- To understand and control this turbulence

Understanding comes from studying simulations . . .

Five Steps to Scientific Progress

1. Define the problem in precise mathematical terms

2. Develop multiple,independent algorithms and simulation codes

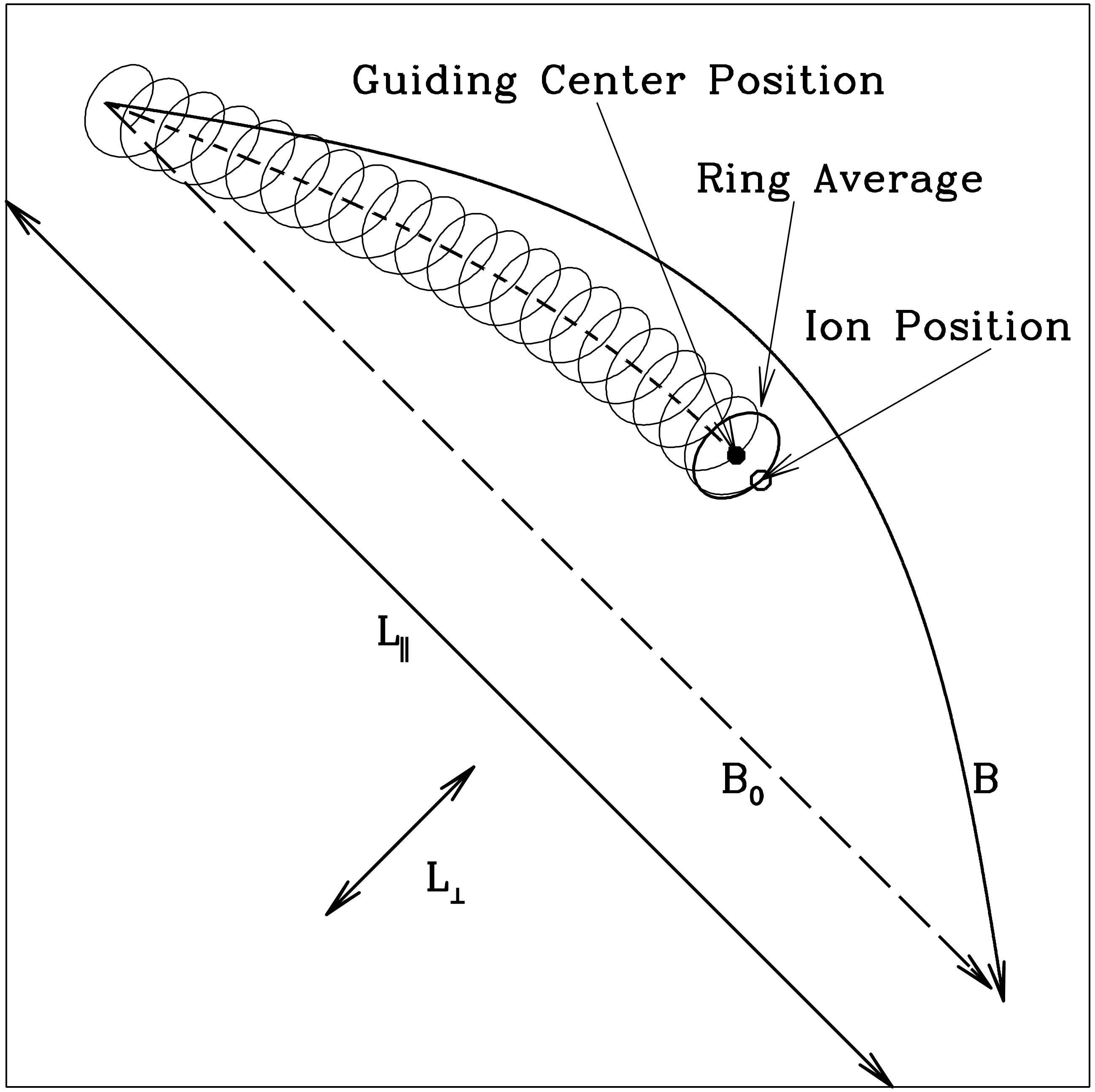
3. Benchmark codes in simple limits and against each other

4. Use simulations to
    a. Study cases of immediate interest
    b. Develop analytical understanding

5. “Turn off” the computer

1. Define the Problem Mathematically

Gyrokinetics is plasma kinetic theory averaged over the Larmor motion. (Rutherford & Frieman 1968; Taylor & Hastie 1968; Frieman & Chen 1982)



- Low-frequency limit eliminates fast cyclotron timescale $\omega \ll \Omega_i$
- Anisotropic $k_\parallel \ll k_\perp$
- Captures: Finite Larmor radius, Landau resonance, and Collisions
- Excludes: Fast wave and cyclotron resonance

These limits of the Gyrokinetic Approximation are well satisfied in fusion plasmas.

The Gyrokinetic-Maxwell Equations

The Gyrokinetic Equation

$$\frac{\partial h_s}{\partial t} + v_\parallel \frac{\partial h_s}{\partial z} = -\frac{q_s F_{0s}}{T_{0s}} \frac{\partial \langle \chi \rangle_{\mathbf{R}_s}}{\partial t} - \frac{c}{B_0} \left\{ \langle \chi \rangle_{\mathbf{R}_s}, h_s \right\} + \left(\frac{\partial h_s}{\partial t} \right)_c$$

Maxwell's Equations

$$\sum_s \frac{q_s^2 n_{0s}}{T_{0s}} \phi = \sum_s q_s \int d^3\mathbf{v} \langle h_s \rangle_{\mathbf{r}}$$

$$-\frac{c}{4\pi} \nabla_\perp^2 (A_\parallel + A_{\parallel a}) = \sum_s q_s \int d^3\mathbf{v}\, v_\parallel \langle h_s \rangle_{\mathbf{r}}$$

$$\frac{c}{4\pi} \nabla_\perp \delta B_\parallel = \sum_s q_s \int d^3\mathbf{v} \langle (\hat{\mathbf{z}} \times \mathbf{v}_\perp) h_s \rangle_{\mathbf{r}}$$

Distribution Function

$$h_s(X, Y, z, v_\parallel, v_\perp, t)$$

Electromagnetic field potentials

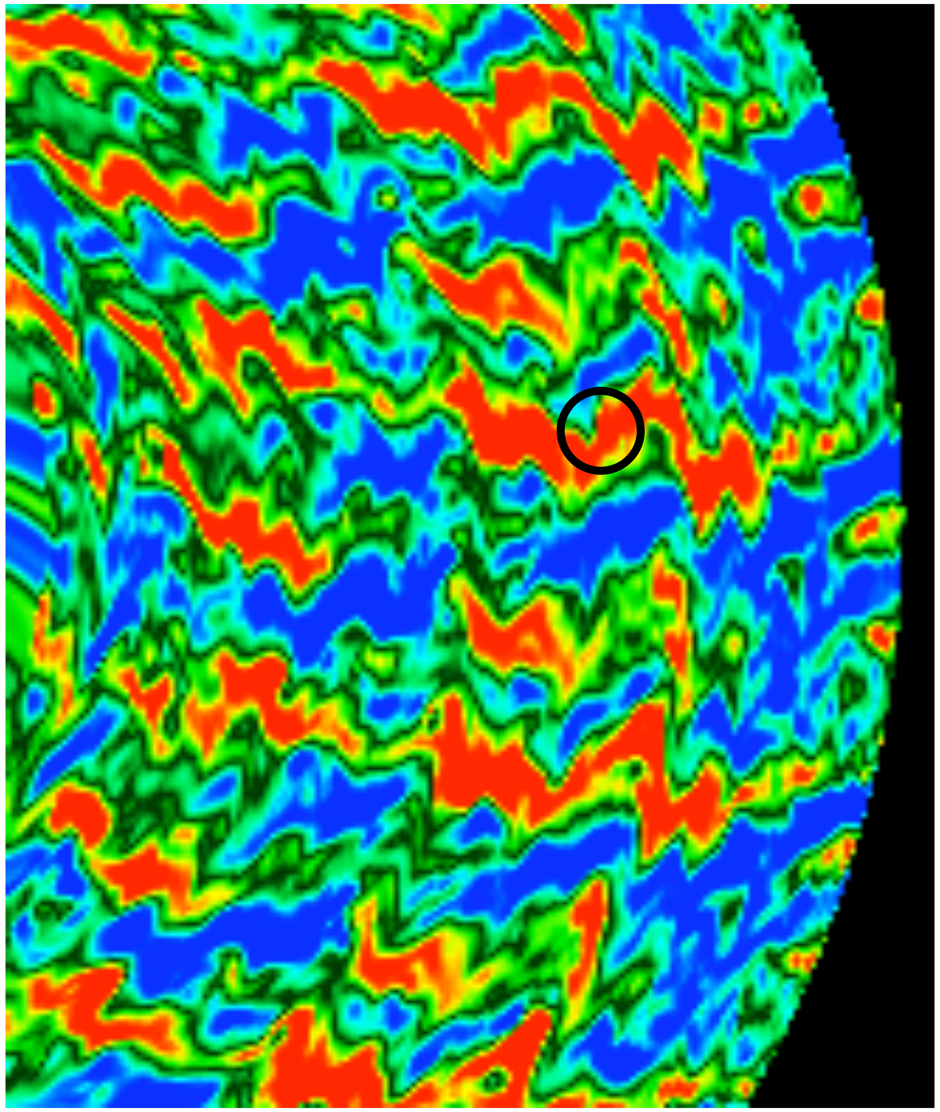
$$\phi(x, y, z, t)$$

$$A_\parallel(x, y, z, t)$$

$$\delta B_\parallel(x, y, z, t)$$

Implementation of Gyrokinetics

Larmor averaging leads to the appearance of Bessel functions in gyrokinetic theory.

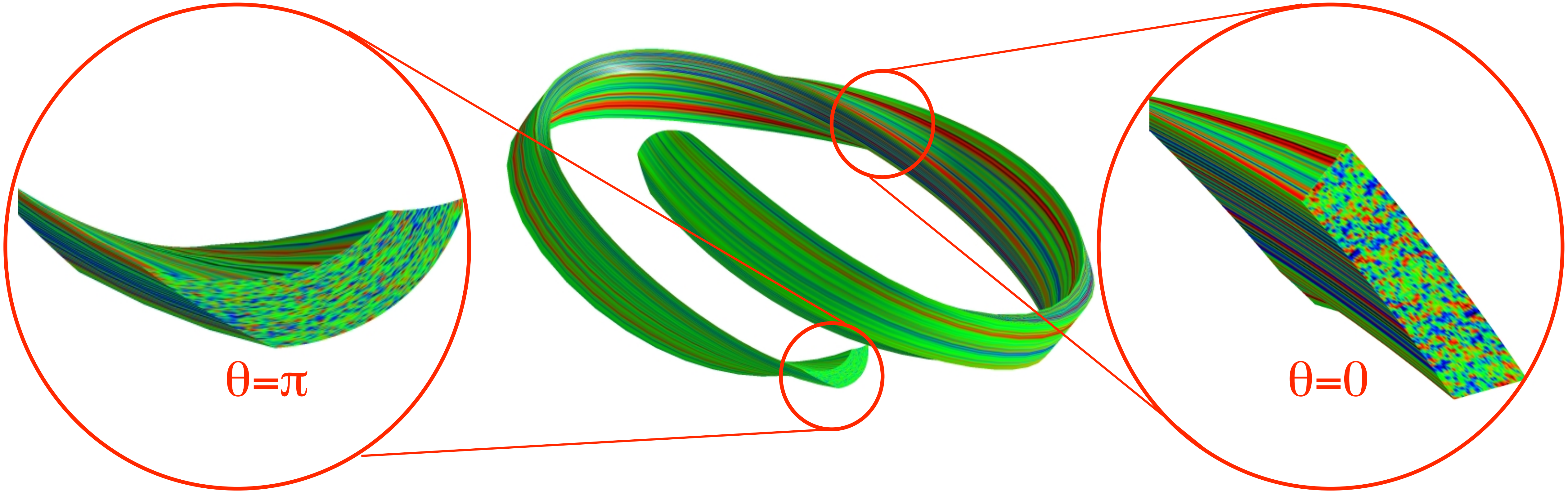


- Average is easy to evaluate in a pseudo-spectral code
- Other codes use fast multi-point Pade approximations

Highly Anisotropic Structures

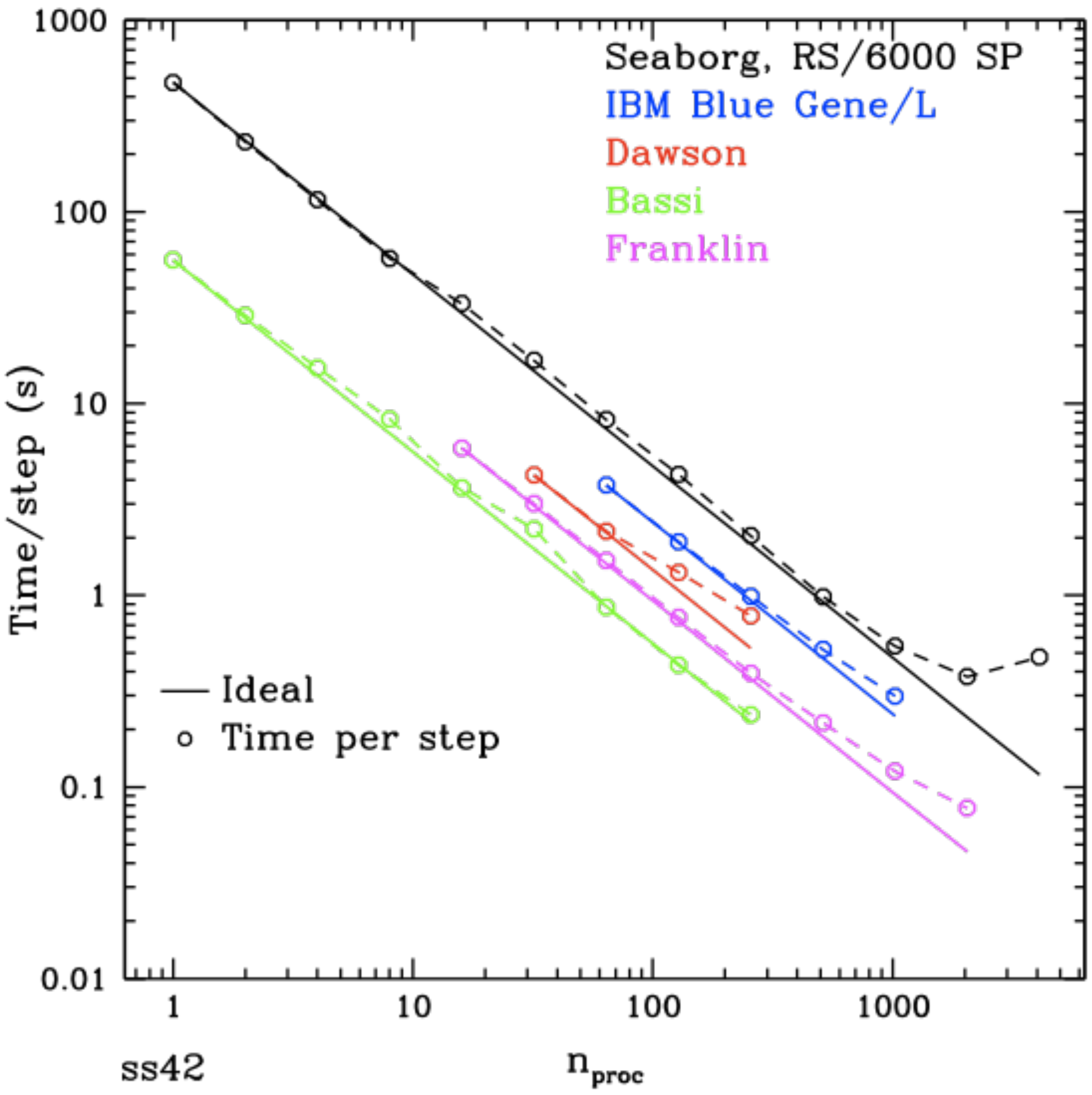
In a fusion plasma, structures are:

- Highly elongated along the magnetic field
- Short correlation lengths perpendicular to field



2. Independently Develop Multiple Codes

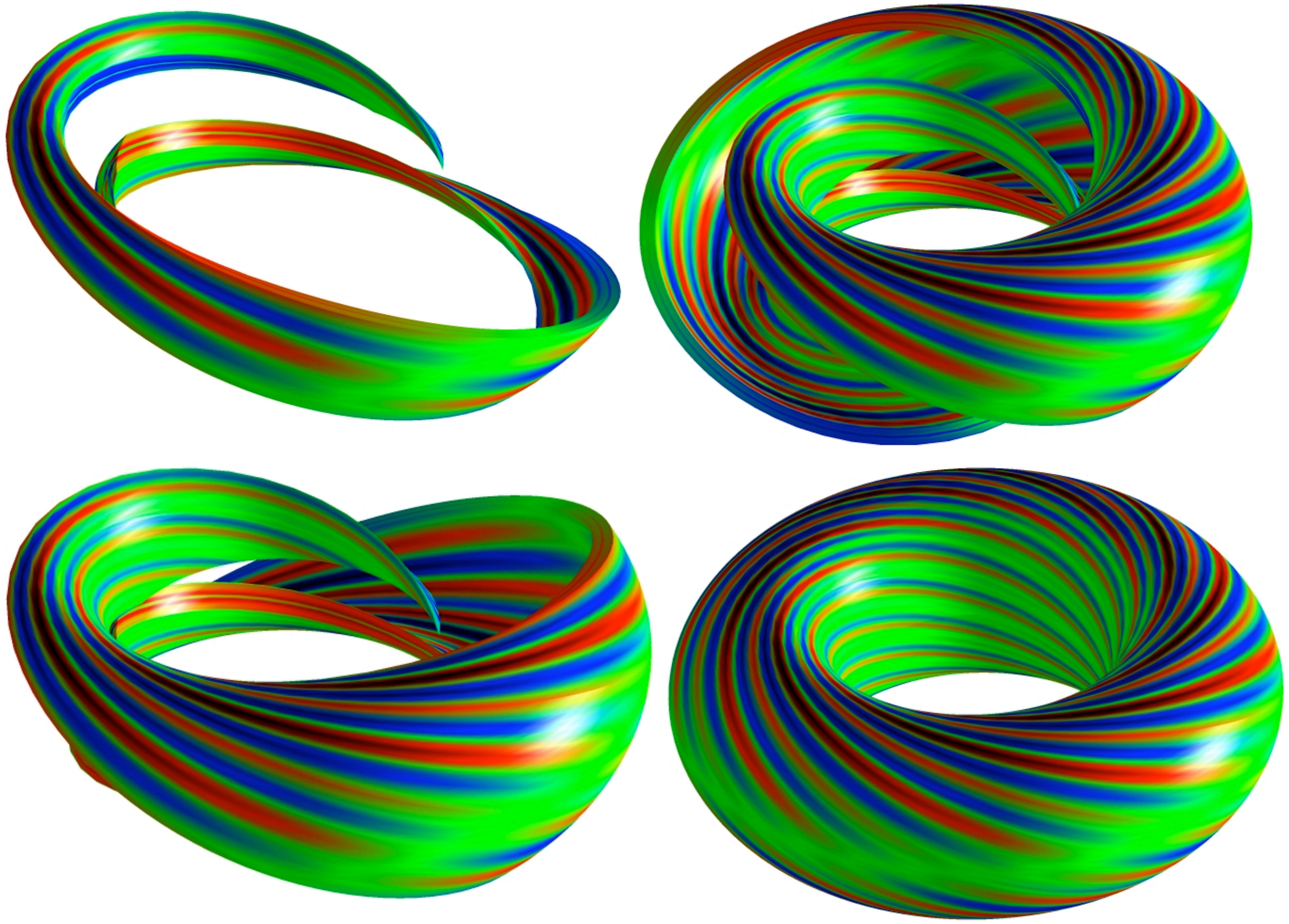
GS2



- Local flux tube code
- Continuum velocity space

2. Independently Develop Multiple Codes

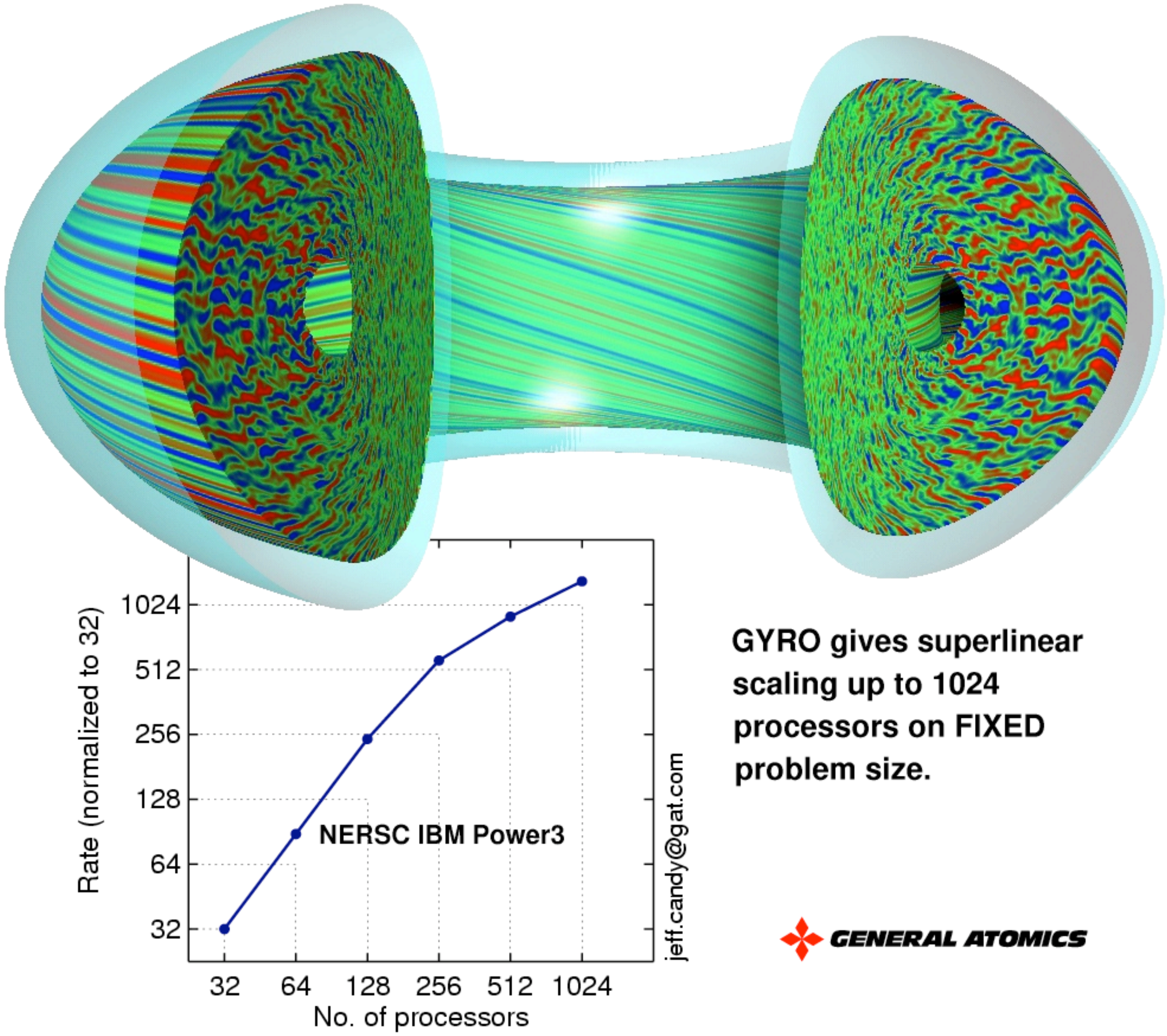
PG3EQ



- Local flux tube code
- Particle-in-Cell (PIC) representation of velocity space

2. Independently Develop Multiple Codes

GYRO

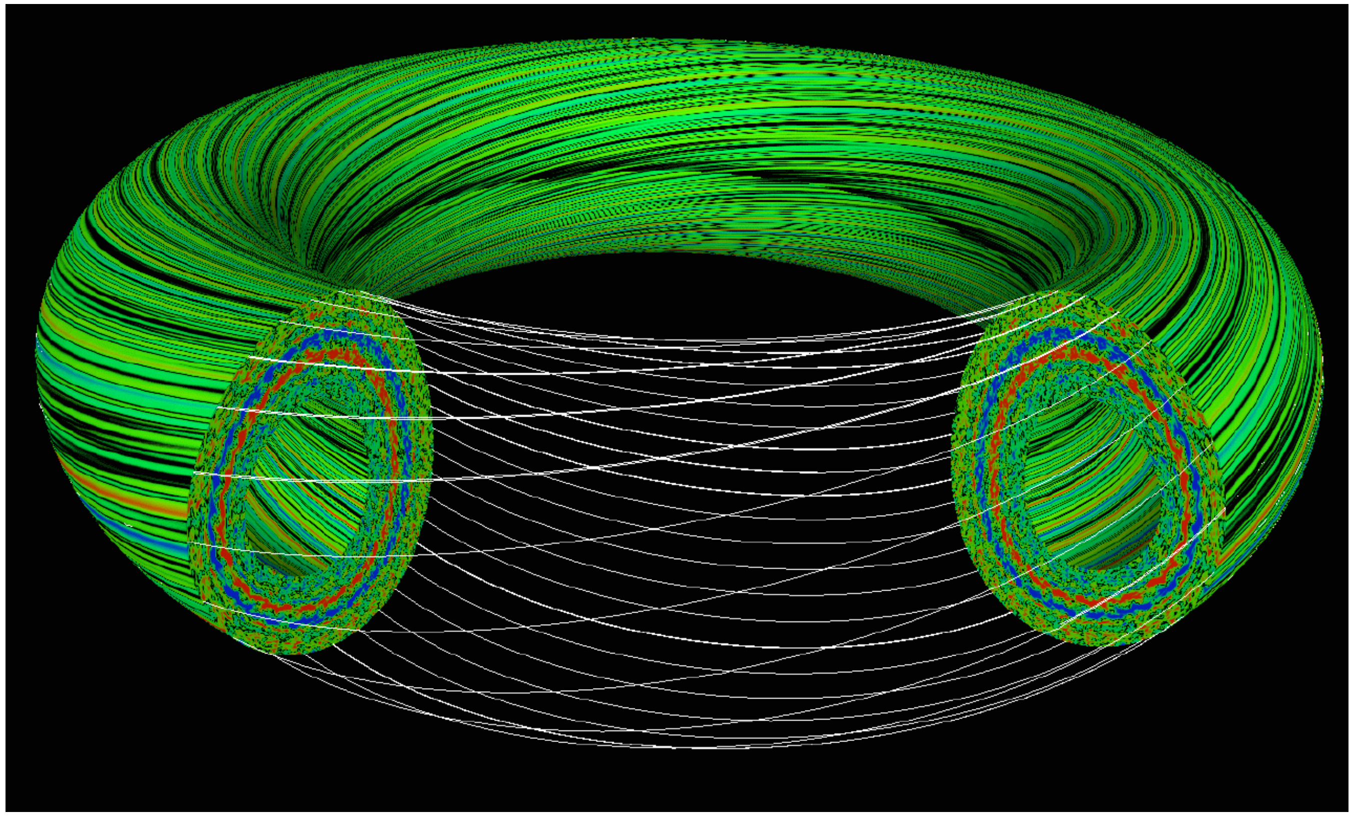


GYRO gives superlinear scaling up to 1024 processors on FIXED problem size.

- Global code
- Continuum velocity space

2. Independently Develop Multiple Codes

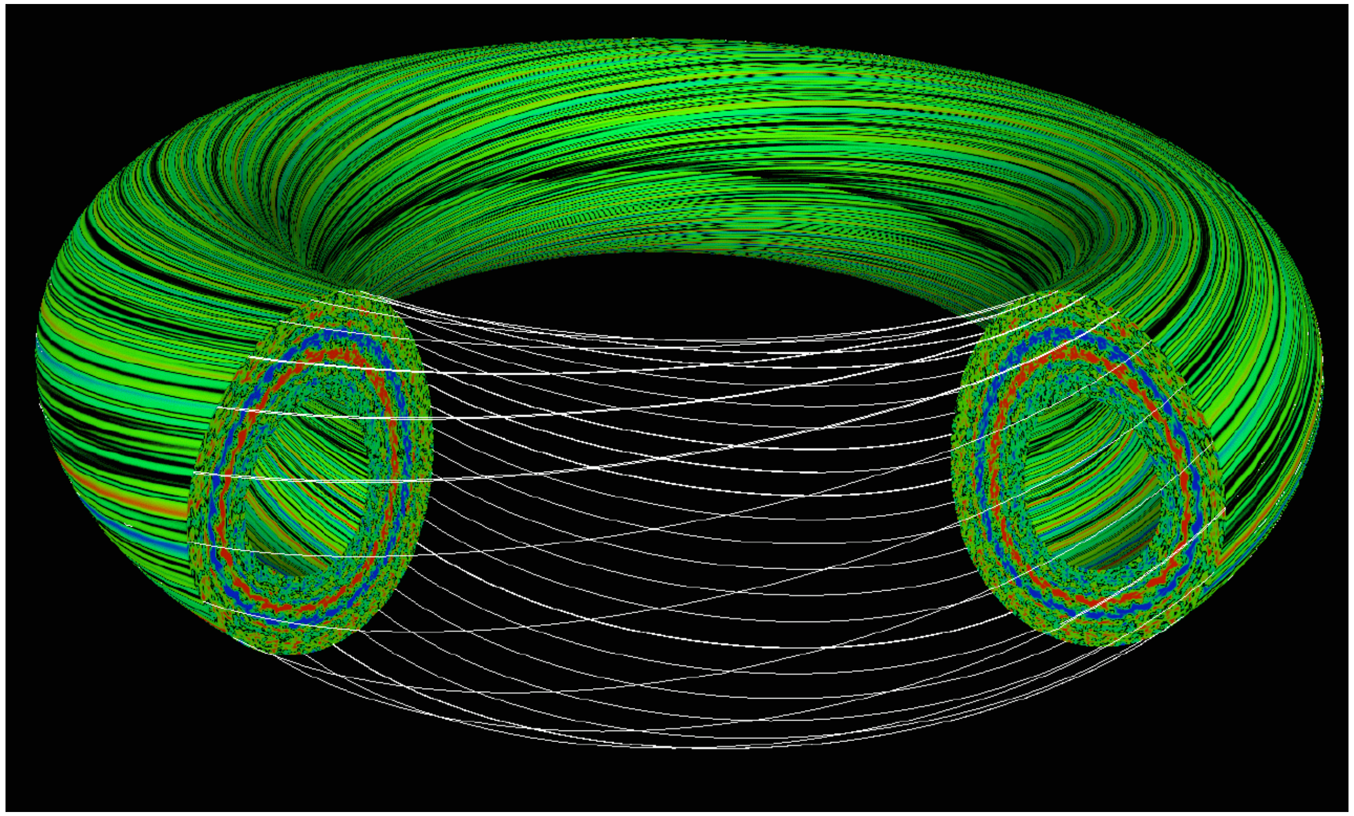
GENE



- Local flux tube and global code
- Continuum velocity space

2. Independently Develop Multiple Codes

FULL

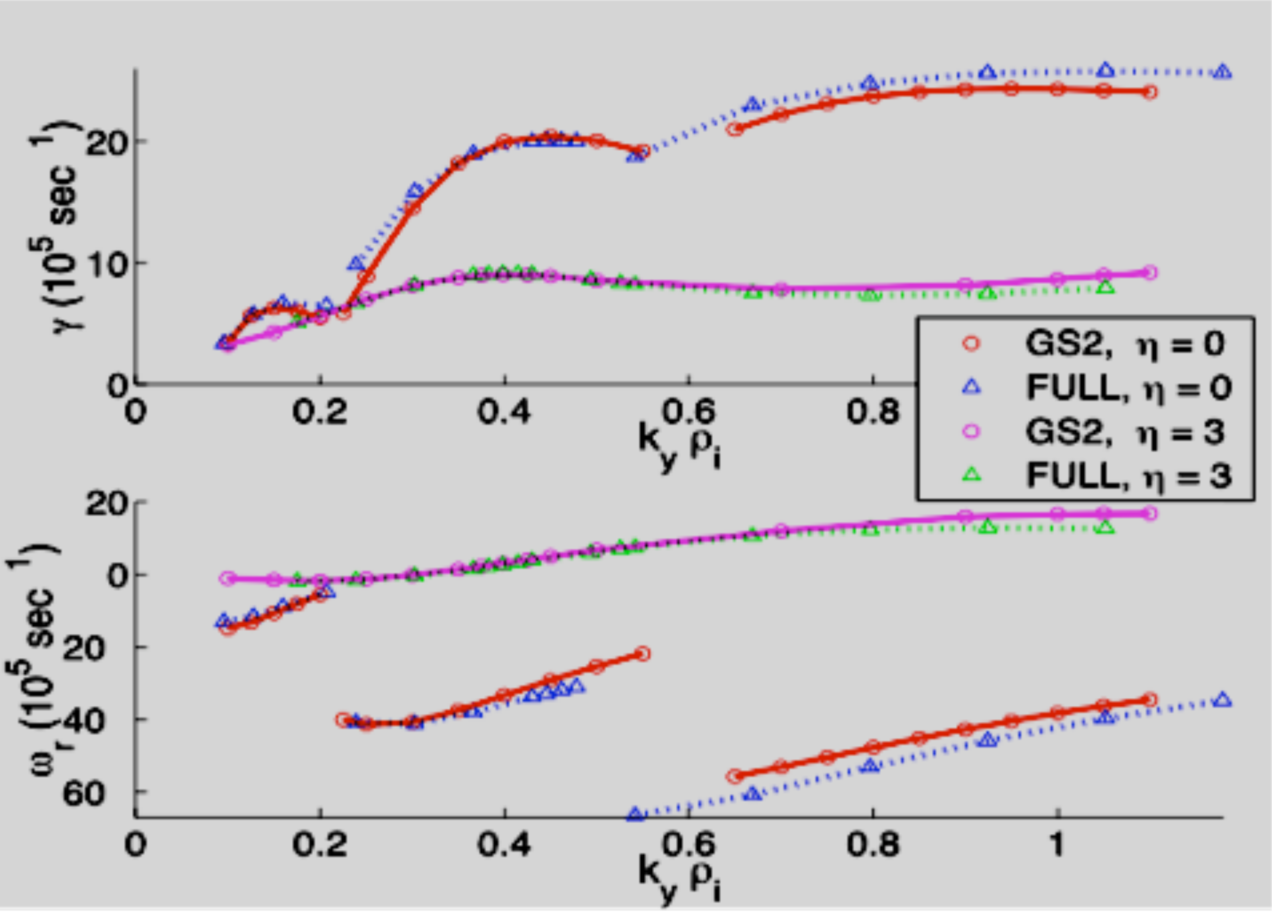


- Linear stability code
- Continuum velocity space

3. Benchmark Codes

Benchmark codes both

- in simple limits
- against each other

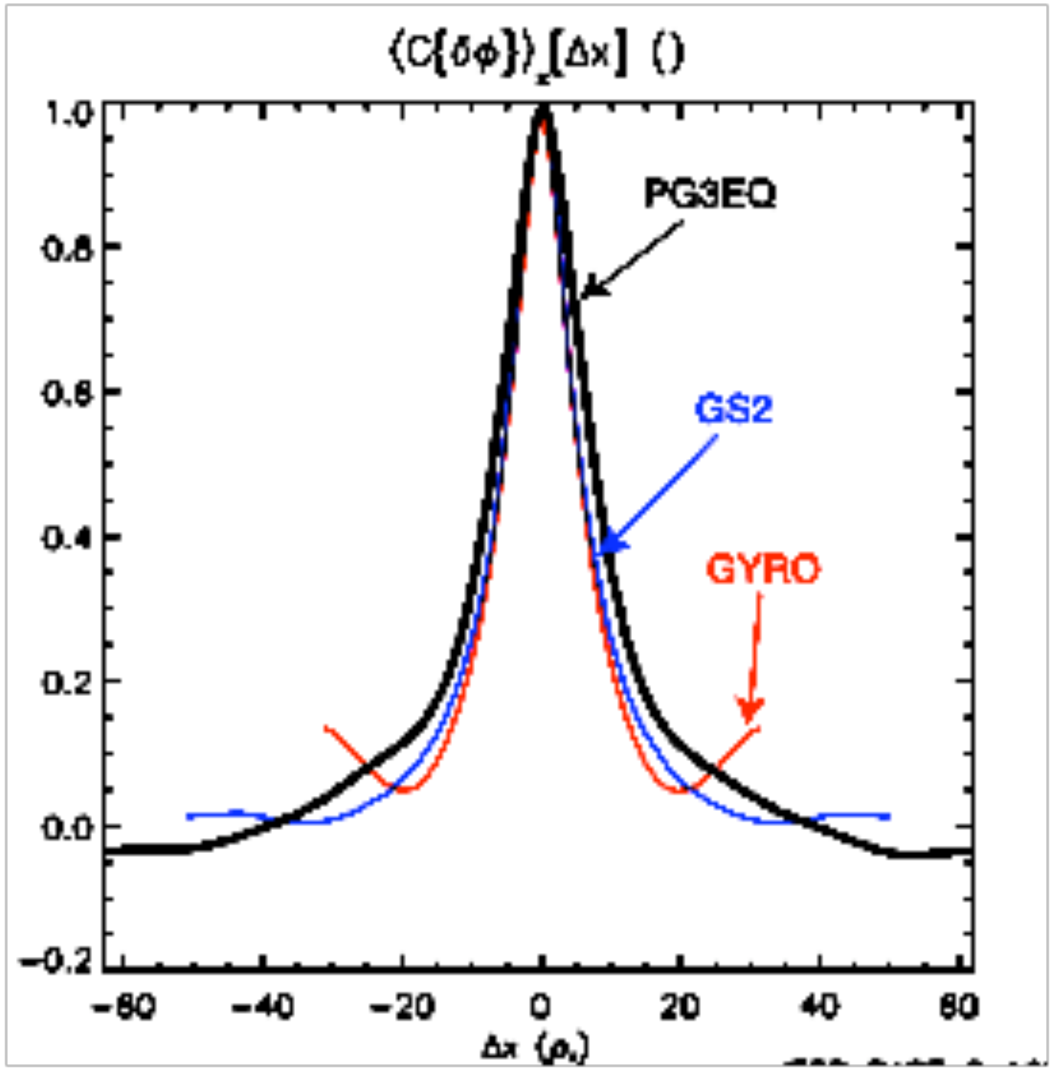


Benchmarks by E Belli, G Rewoldt, G Hammett, and W Dorland

- Linear microstability calculations for NCSX stellarator
- Results from GS2 and FULL agree
- This is a very challenging linear benchmark

3. Benchmark Codes

Benchmark codes against each other



- Radial correlation functions from three independently developed gyrokinetic codes:
    - GS2
    - GYRO
    - PG3EQ

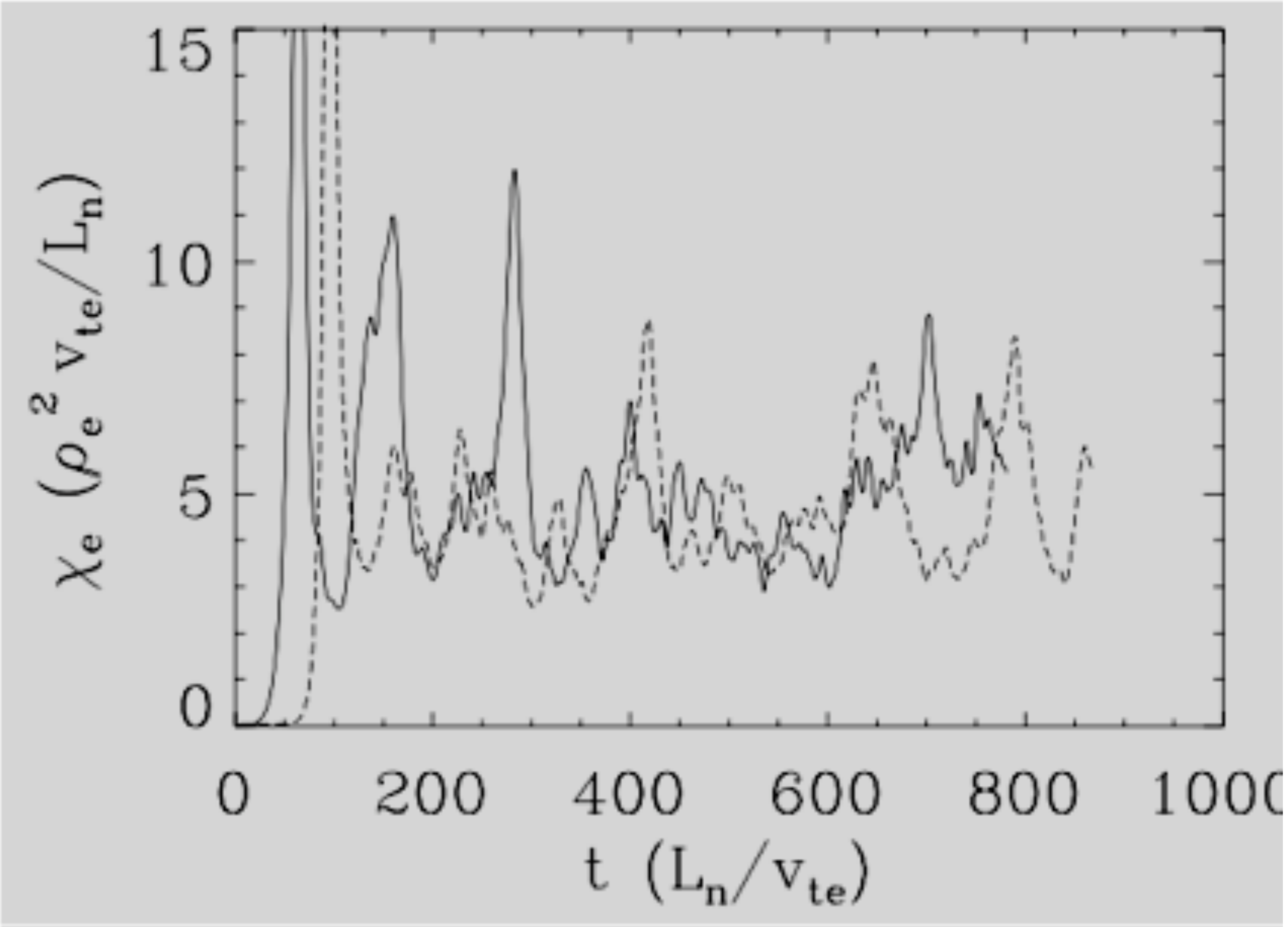
- Identical physical parameters

- This is a very challenging nonlinear benchmark

4a. Study Cases of Immediate Interest

THE UNIVERSITY OF IOWA

Electron Temperature Gradient (ETG) Turbulence

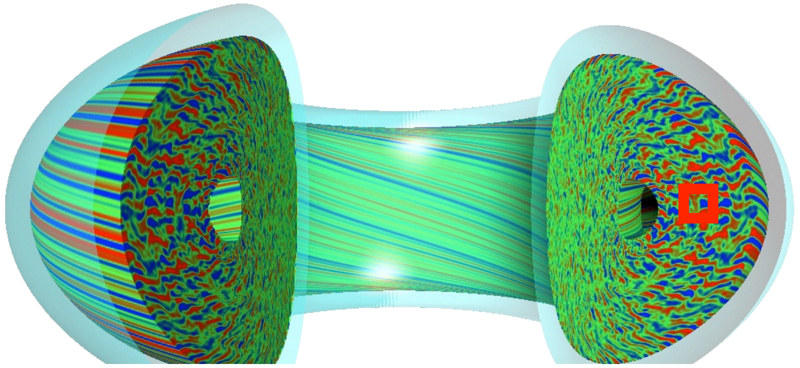


Simulations by W Dorland and F Jenko

- Heat flux for toroidal ETG turbulence
- Average value agrees from two codes
    - GS2
    - GENE
- Demonstrates that ETG turbulence may play a strong role in the loss of heat from fusion plasmas

4a. Study Cases of Immediate Interest

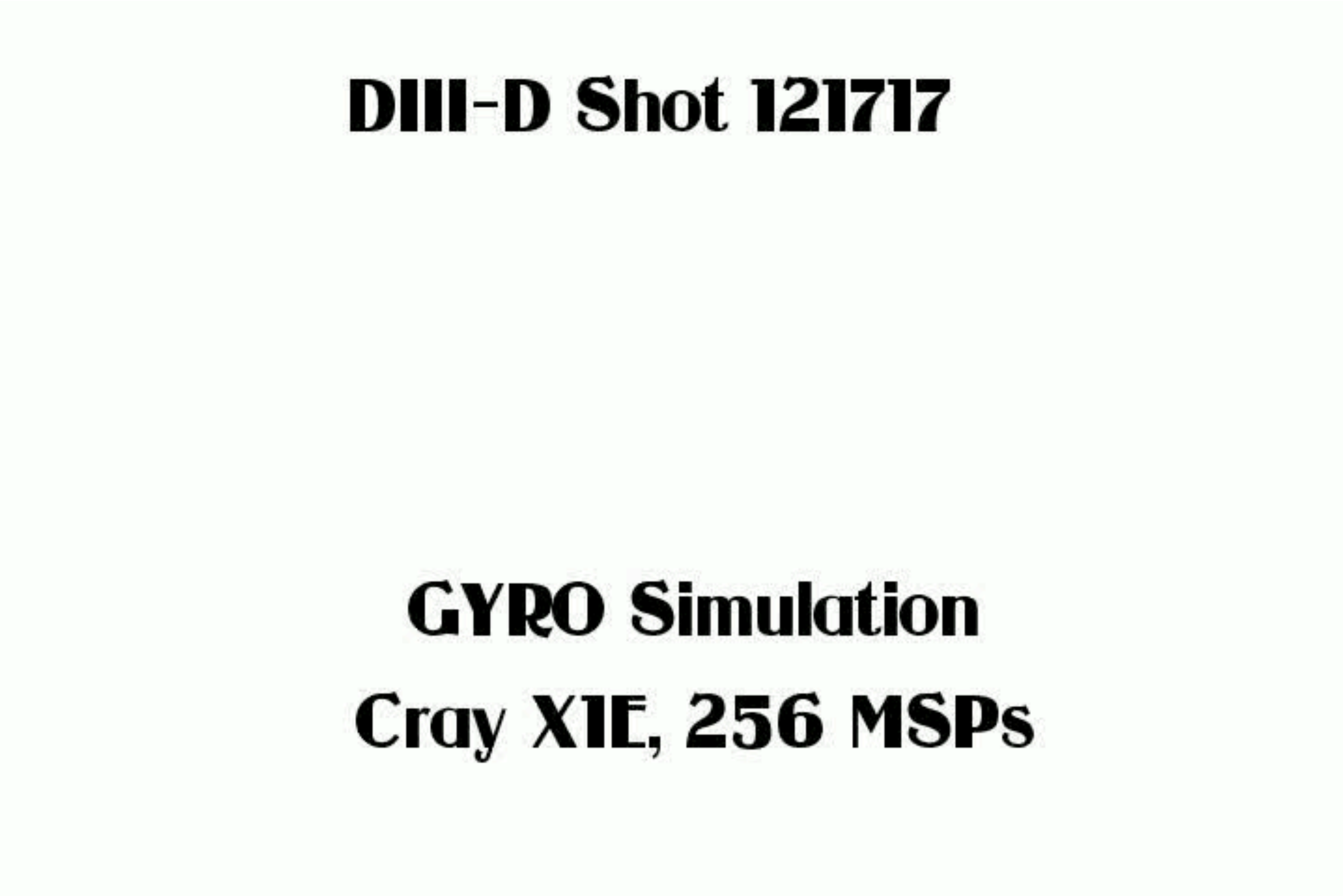
Electron Temperature Gradient (ETG) Turbulence



GYRO ETG-ki Simulation
(c64x64.Bnoi.m20)

4a. Study Cases of Immediate Interest

Ion Temperature Gradient (ITG) Turbulence



DIII-D Shot 121717

GYRO Simulation

Cray X1E, 256 MSPs

4b. Develop an Analytical Understanding

The development of an analytical understanding of turbulent transport in modern fusion experiments is still in progress.

Once we have achieved a sufficient understanding, we can finally reach the final step . . .

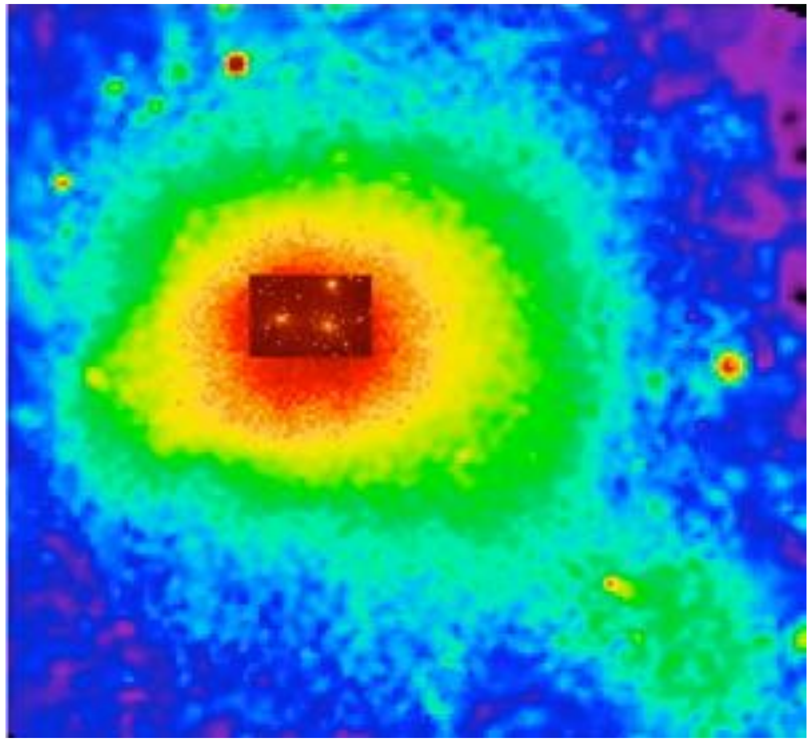
5. "Turn off" the computer!

Kinetic Turbulence in Space and Astrophysical Plasmas

Turbulence in Space and Astrophysics

Turbulence plays an important role in many space and astrophysical environments:

- Galaxy Clusters
- Accretion Disks
- Interstellar Medium
- Star-forming Molecular Clouds
- Convective Stellar Interiors
- Solar Corona and Solar Wind



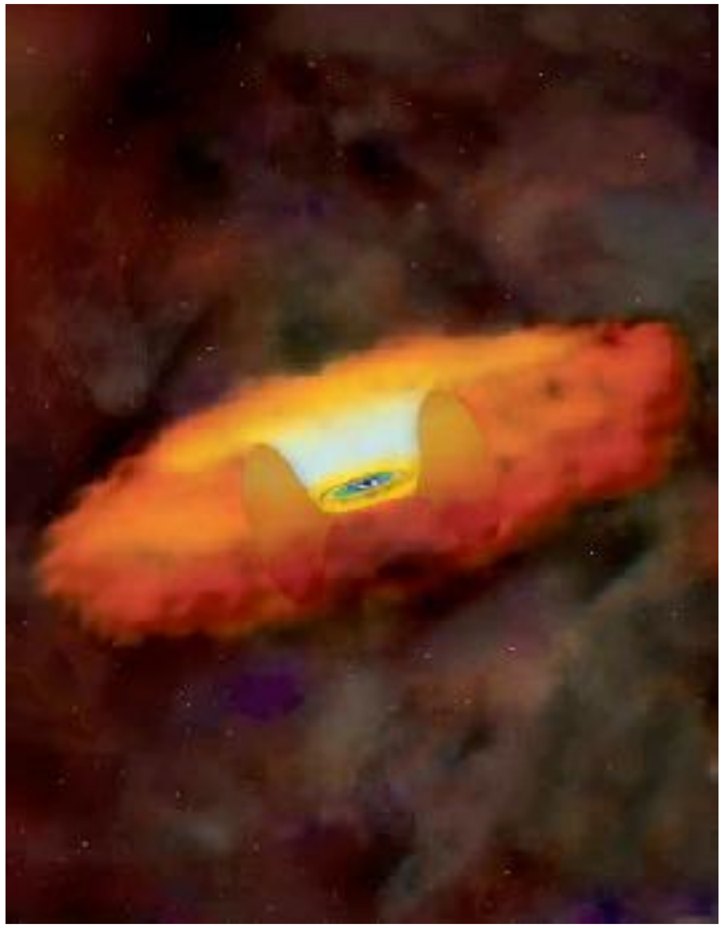
X-ray Image: Coma Cluster (ROSAT)

Why is turbulence important?

Turbulence governs the transport of

- Mass (mixing, accretion)
- Momentum (jet interactions, collisionless shocks)
- Energy (energy flow, heating)

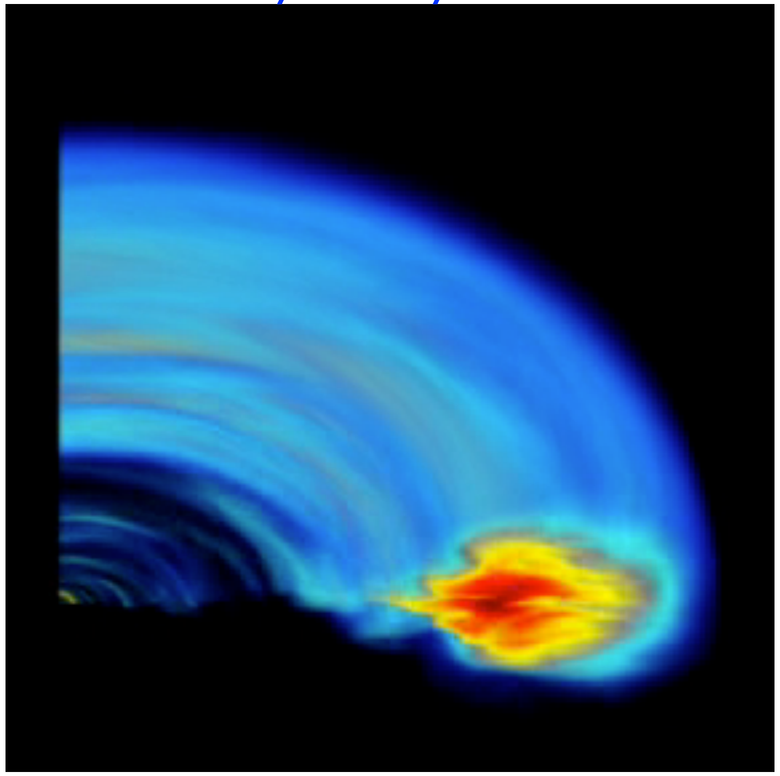
Black Hole Accretion Disks



NASA/CXC/SAO -Artist's Conception

- Matter spirals into the black hole, converting a tremendous amount of gravitational potential energy into heat
- This occurs via several processes:
  - Magnetorotational Instability (MRI) drives turbulence
  - Turbulence cascades nonlinearly to small scales
  - Kinetic mechanisms damp turbulence and lead to plasma heating

Simulation by Hawley & Balbus 2002



- Radiation emitted is function of plasma heating
- Interpretation of X-ray observations requires understanding of kinetic plasma turbulence and resulting plasma heating

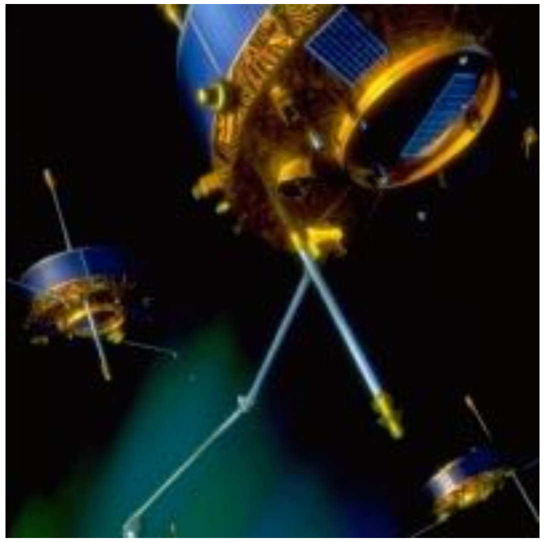
Complementary Approaches

To progress in understanding of turbulence in space and astrophysical plasmas using simulations requires:

Observations

Simulations

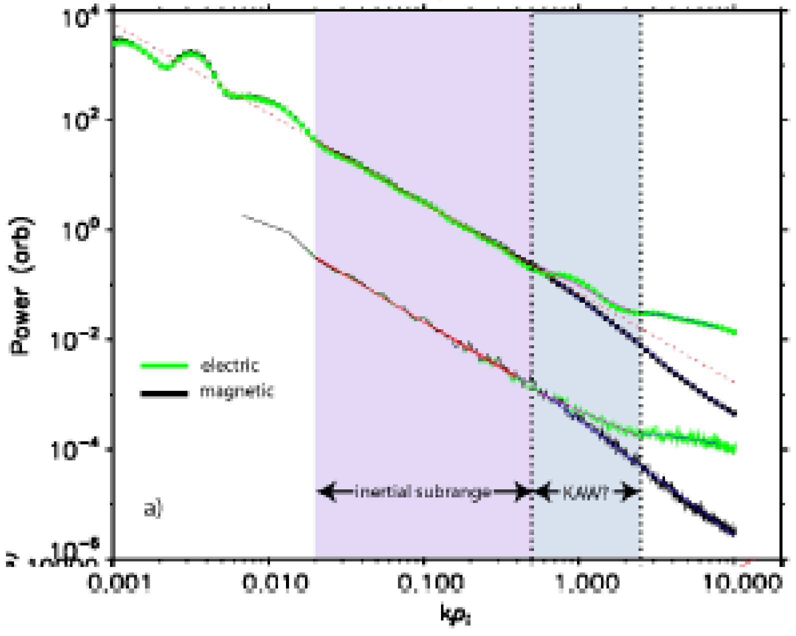
Experiments



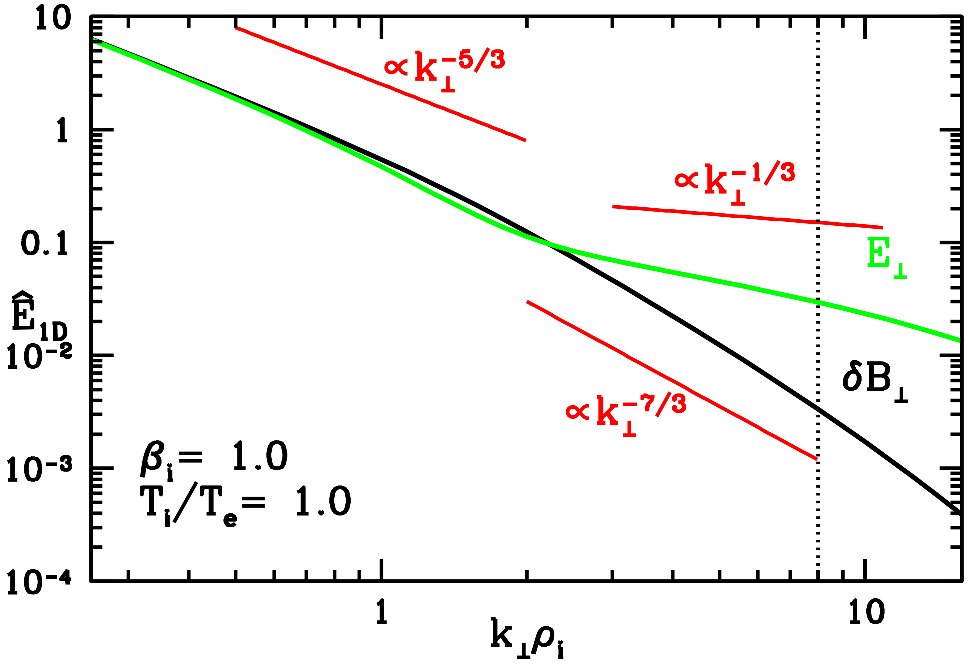
Cluster spacecraft

Theory

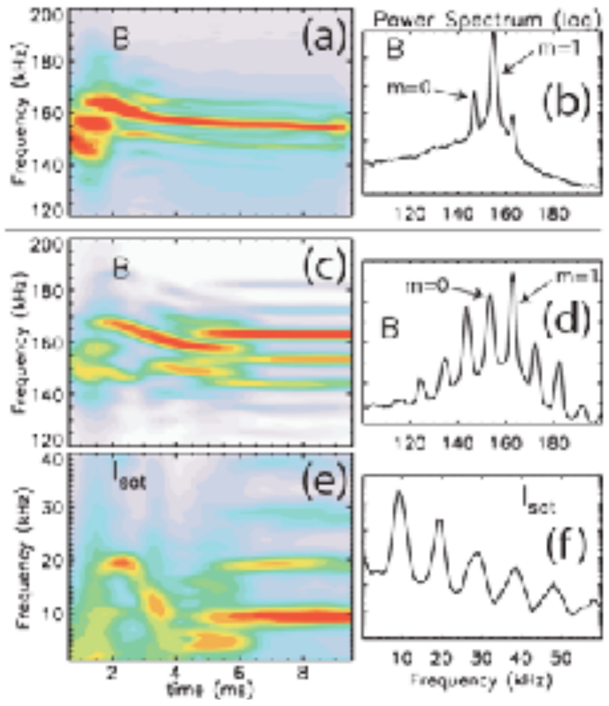
LArge Plasma Device (LAPD), UCLA



Bale et al., 2005



Howes et al., 2008



Carter et al., 2006

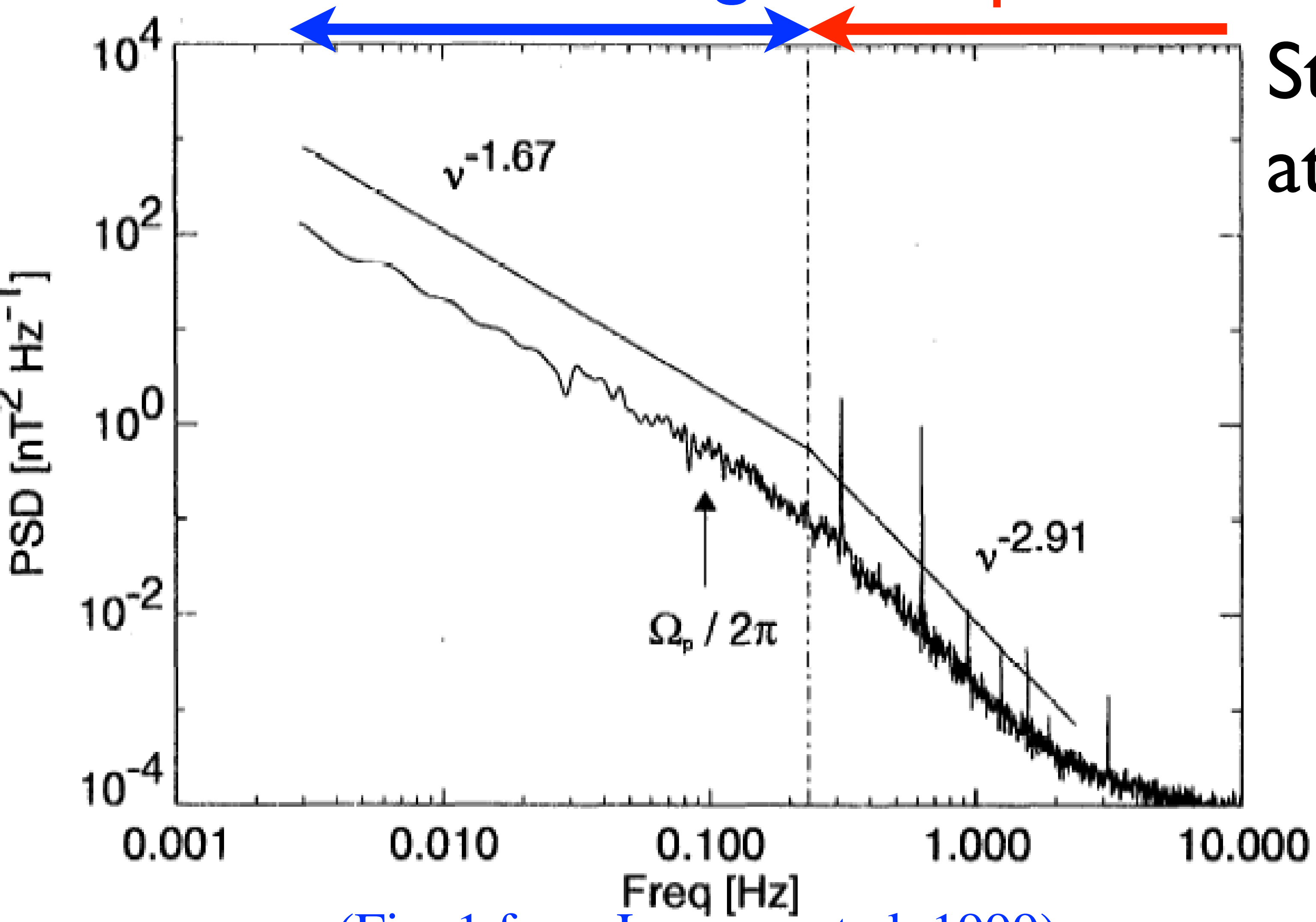
Observation, Theory, and Simulations

1. Identify the scientific question from observations
2. Develop a theoretical model of the behavior
3. Perform numerical simulations to test theory and compare to observations
4. Test theory in regimes beyond observational range, and refine the theory as necessary
5. "Turn off" the computer

1. Identify Scientific Question

Solar Wind Magnetic Energy Spectrum

Inertial Range Dissipation Range



(Fig. 1 from Leamon et al. 1999)

Steeper Dissipation Range attributed to:

- Proton Cyclotron Damping
  (Goldstein, Roberts, & Fitch 1994, Leamon et al. 1998b, Gary 1999)
- Kinetic Alfven Wave Damping
  (Leamon et al. 1998a)
- Whistler Dispersion
  (Stawicki, Gary, & Li 2001)

Physics underlying the dissipation range is not well understood!

What mechanism causes the steeper dissipation range?

2. Develop Theoretical Model

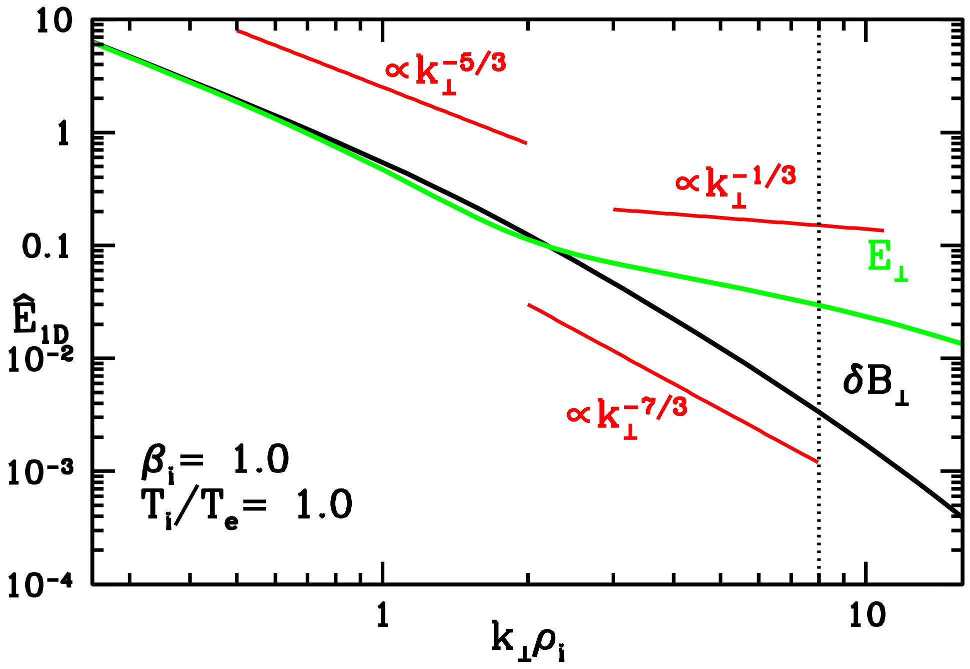
Cascade Model for Kinetic Turbulence

- Cascade Model based on three assumptions: (Howes et al., 2008b)
  1. Kolmogorov Hypothesis: Spectrally local nonlinear transfer
  2. Critical Balance of linear and nonlinear times
  3. Applicability of linear kinetic damping rates

$$\frac{\partial b_k^2}{\partial t} = -\frac{\partial}{\partial \ln k_\perp}\left(\frac{b_k^2 \omega_{nl}(k_\perp)}{C_1 C_2}\right) + \mathcal{S}(k_\perp) - 2\gamma(k_\perp) b_k^2$$

Nonlinear Transfer Source Dissipation

Predicted Magnetic Energy Spectrum

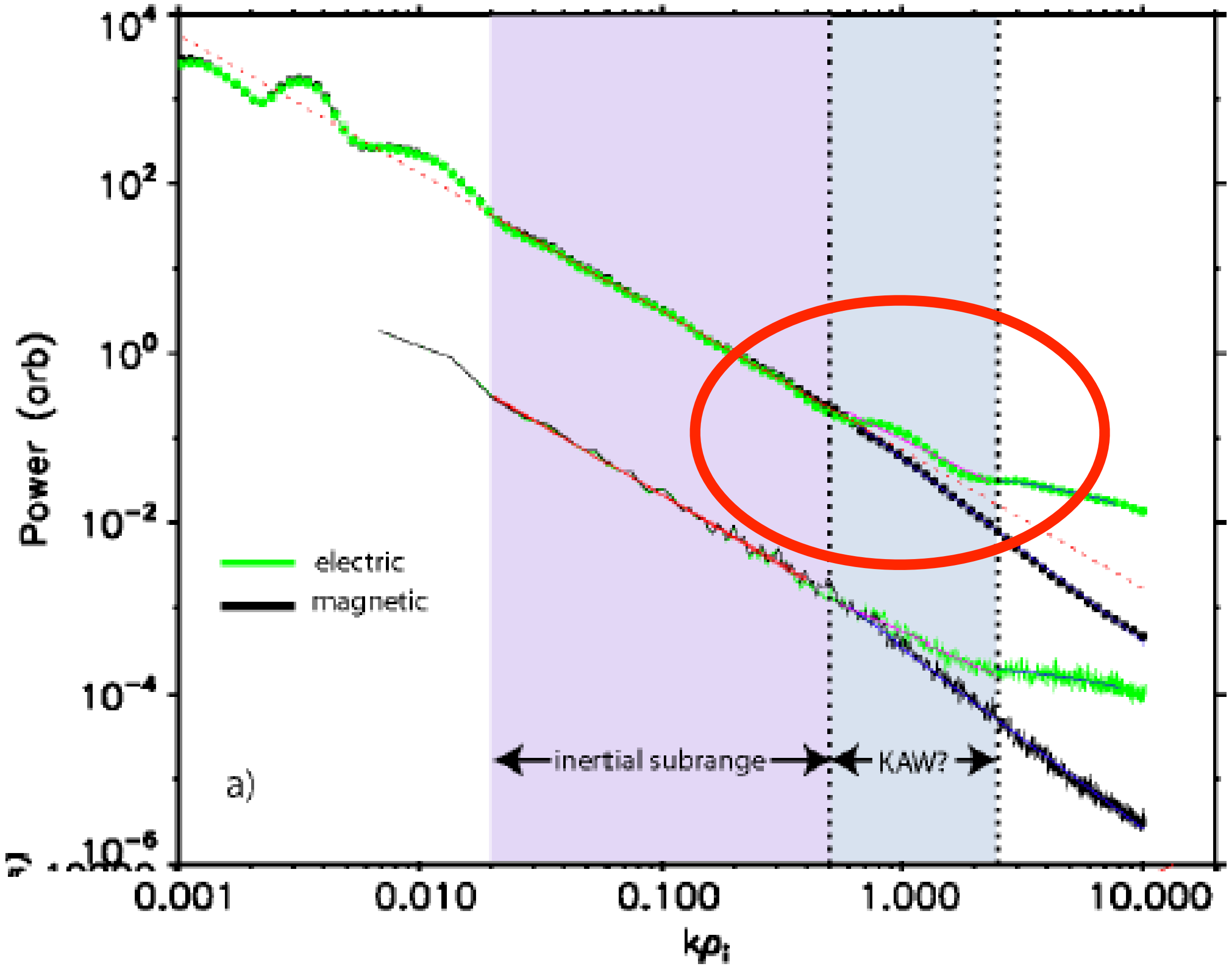


3. Numerical Simulations

Compare Simulations to Observations

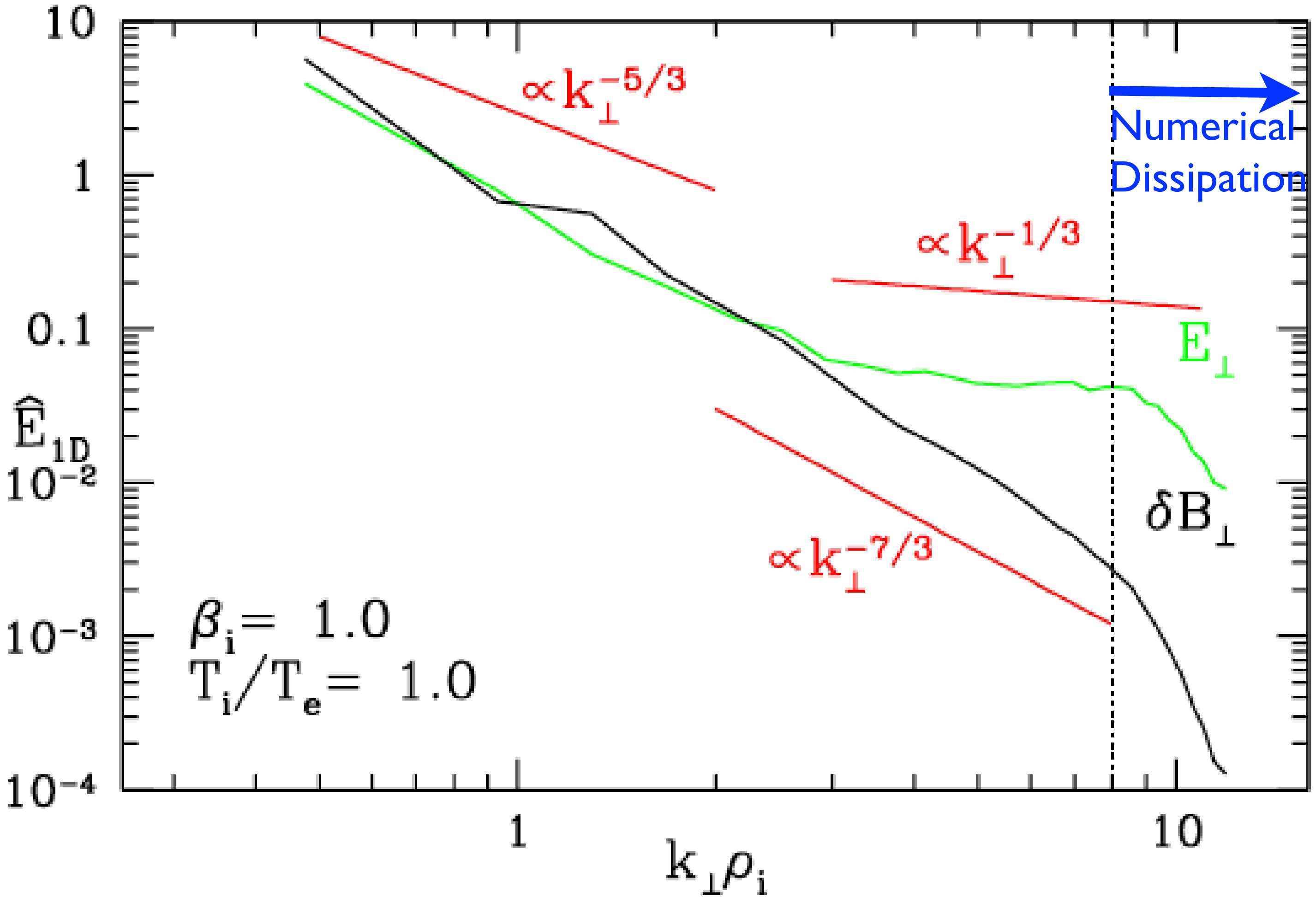
Observations

(Fig. 3 from Bale et al. 2005)



Simulations

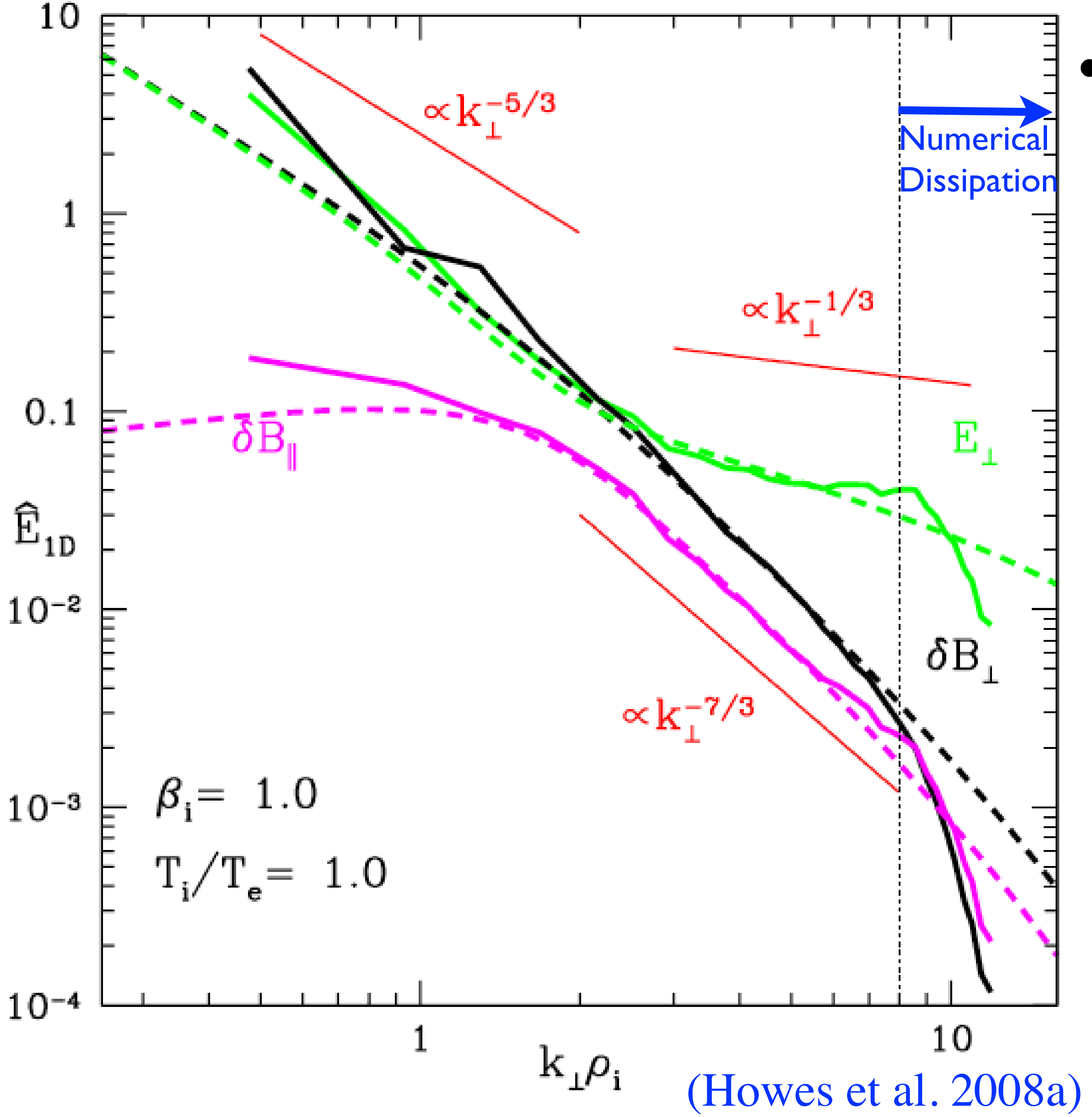
(Howes et al. 2008a)



- Results support the hypothesis that the MHD Alfven Wave Turbulent Cascade transitions to a Kinetic Alfven Wave Cascade

3. Numerical Simulations

Compare Simulations to Theoretical Model



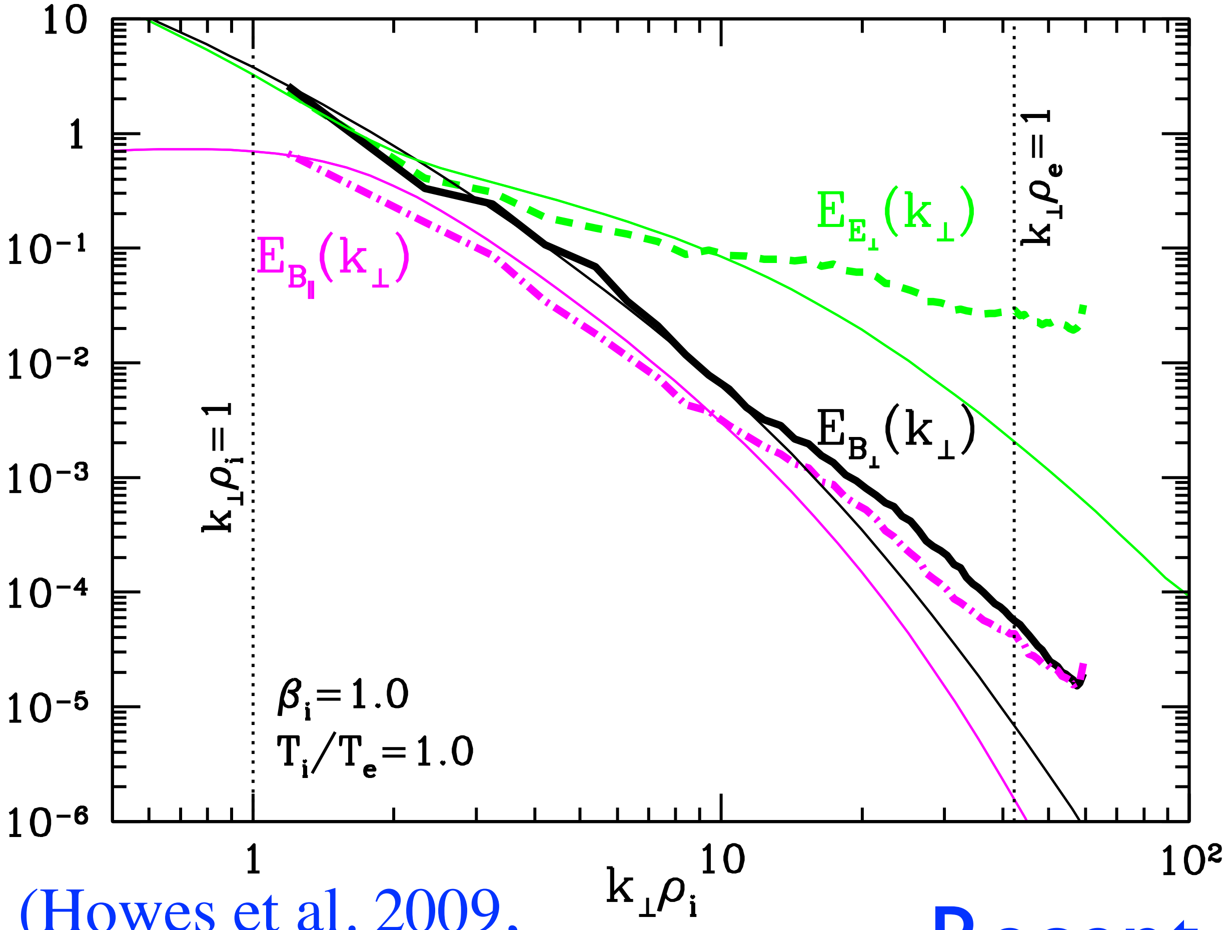
(Howes et al. 2008a)

- Numerical Simulation results (solid) agree well with the Theoretical Prediction (dashed)
- Dynamic range of this simulation is relatively small (factor of 21)

4. Test Theory Beyond Observational Range

Larger scale simulation probes beyond observational range

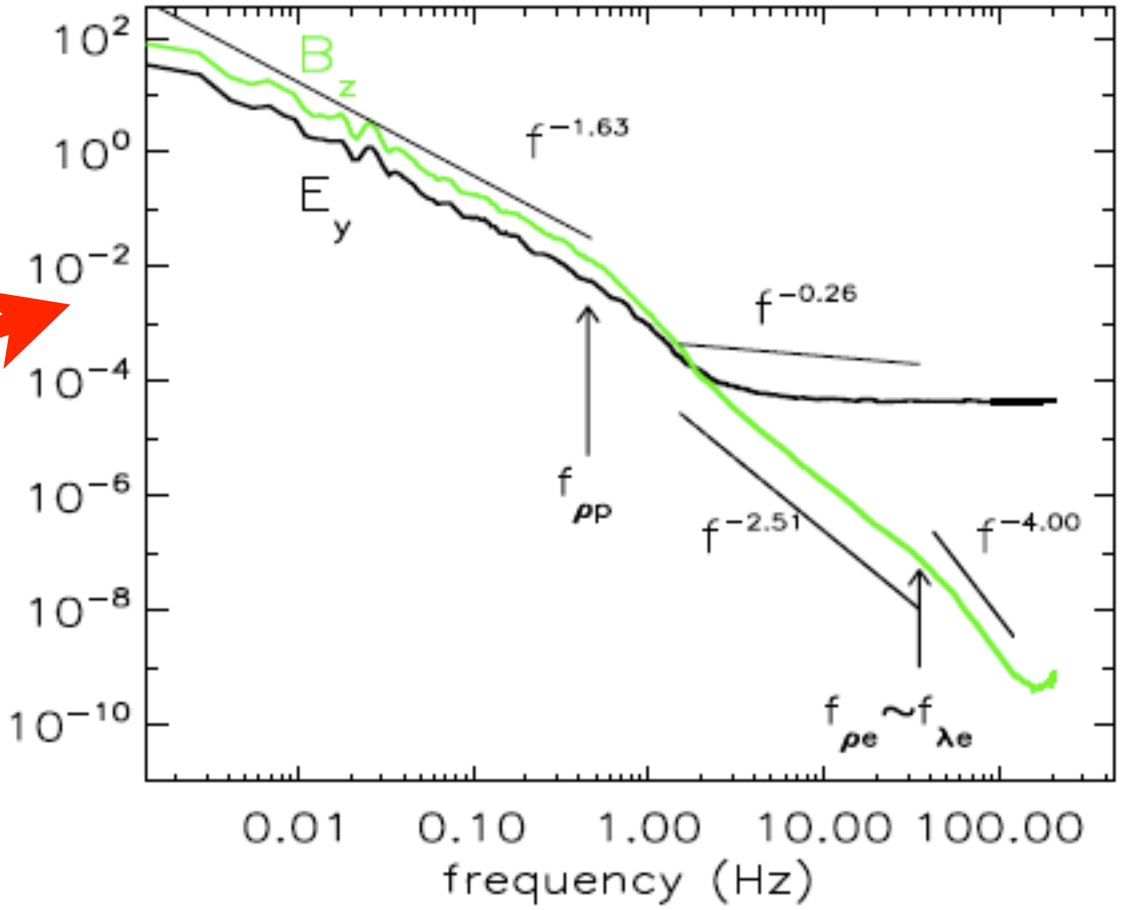
Ion to Electron Scale Simulation



(Howes et al. 2009, in preparation)

- Simulation disagrees with model at high $k_\perp \rho_i$
- Nonlinear simulation results point to necessary refinement of model

Recent Observations



(Sahraoui et al. 2009, in press)

Numerical Simulations can guide theoretical development and lead to a new understanding of the physics!

5. Turn off the Computer

The ultimate goal:

To predict the magnetic energy spectrum in turbulent space and astrophysical systems

without

having to run costly, large-scale simulations

Conclusions

- Numerical simulation is one of the pillars of scientific investigation in plasma physics
- The goal is *not* to run big simulations *but* to understand the physics!
- How do we advance science using computational methods:
  - Focus on a specific scientific question
  - Develop independent algorithms and codes
  - Benchmark the codes
    - Test codes against each other
    - Compare results to theory and to observation/experiment
  - Develop our physical understanding to the point where we do *not* need numerical simulations to predict the behavior

THE END