GYRO on the Cray X1E: High Performance on a 5D Code with Extreme Bandwidth Requirements

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GA: R. Waltz, C. Estrada-Mila, J. Kinsey
ORNL: M. Fahey, P. Worley

GENERAL ATOMICS

GYRO on the Cray X1E: An Technical Overview

Our chief weapon is surprise ... surprise and fear ... fear and surprise ...

Our two weapons are fear and surprise ... and ruthless efficiency ...

Our three weapons are fear, surprise, and ruthless efficiency ...

and an almost fanatical devotion to the Pope ...

Our four ... no ...

Amongst our weapons....

Amongst our weaponry ... are such elements as fear, surprise ...

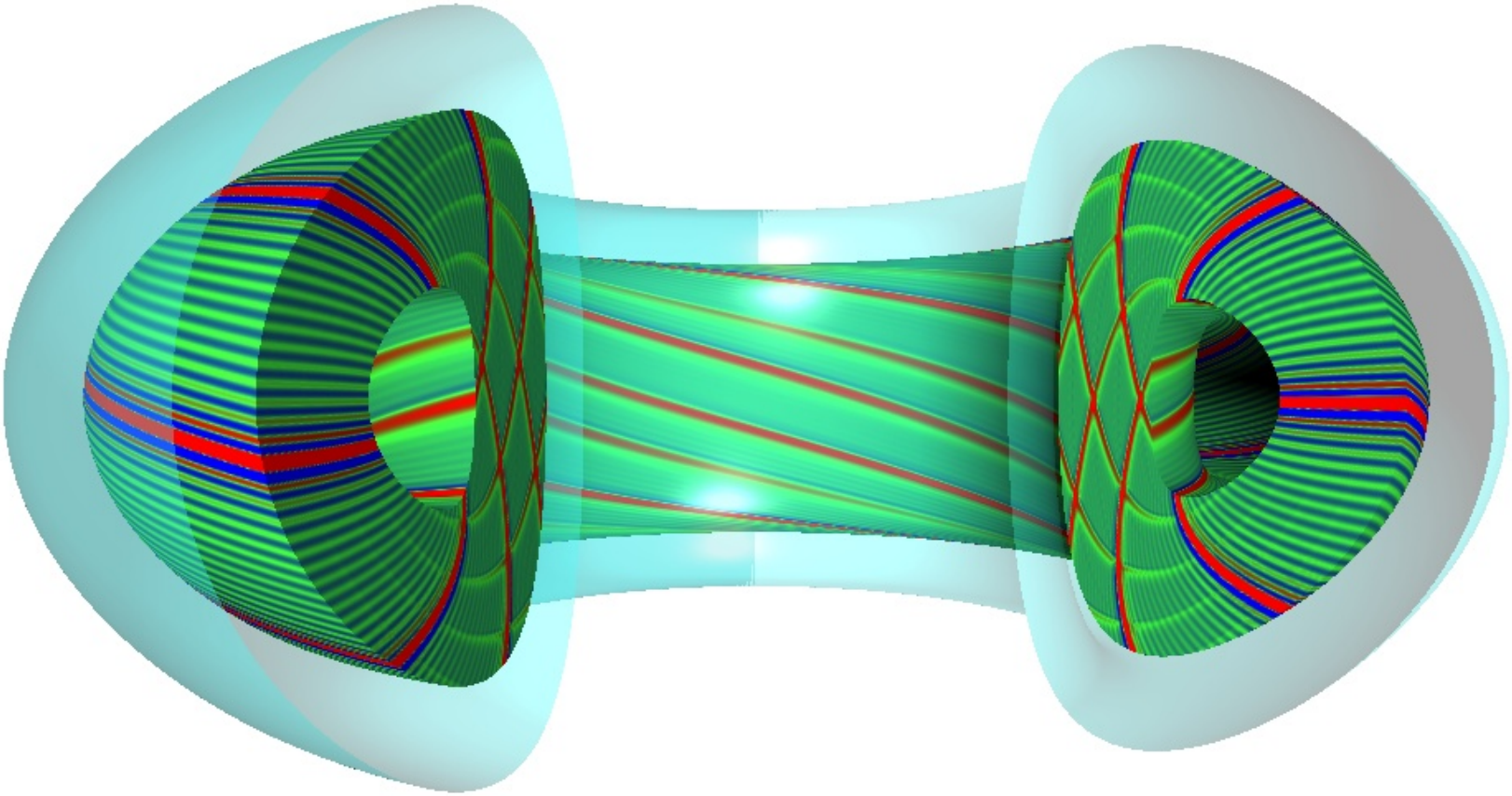
GYRO on the Cray X1E: An Technical Overview

- **GYRO**
  - computes **turbulent flux** of particles and energy in a tokamak
  - solves the **gyrokinetic equations**
  - uses a 5-D **Eulerian** grid
  - was developed at **General Atomics**, starting in late 1999.
  - is the **most comprehensive** code of its kind

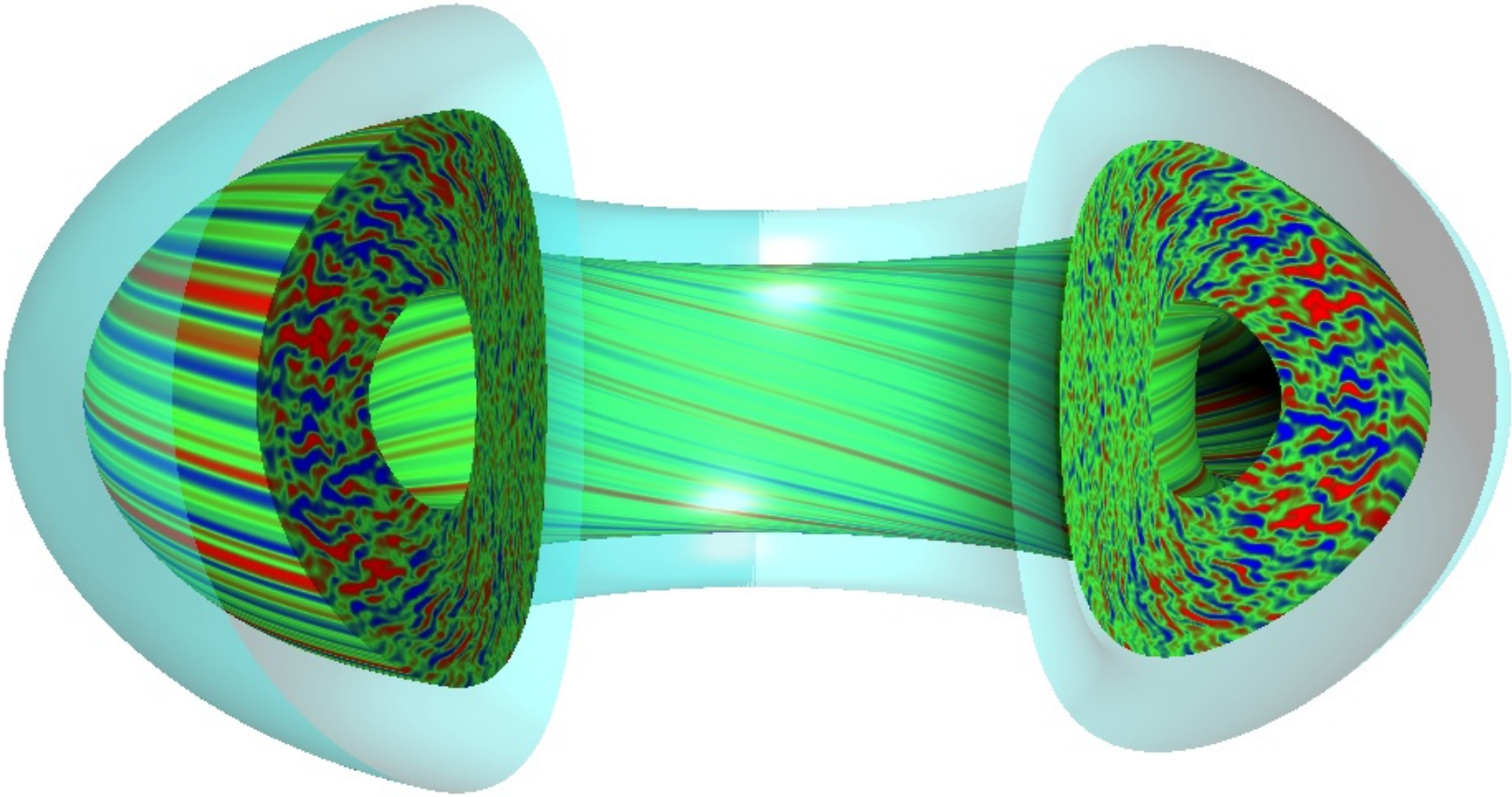
GYRO on the Cray X1E: An Technical Overview

- Port to the ORNL Cray X1 done by **Mark Fahey** in 2003
  - with modest effort, the code **vectorized well**
- Exhaustive performance tests published by Worley, Fahey and others.
  - GYRO loop structure and memory access patterns are conducive to good performance
  - high X1E communication bandwidth on the allows excellent GYRO **scalability**

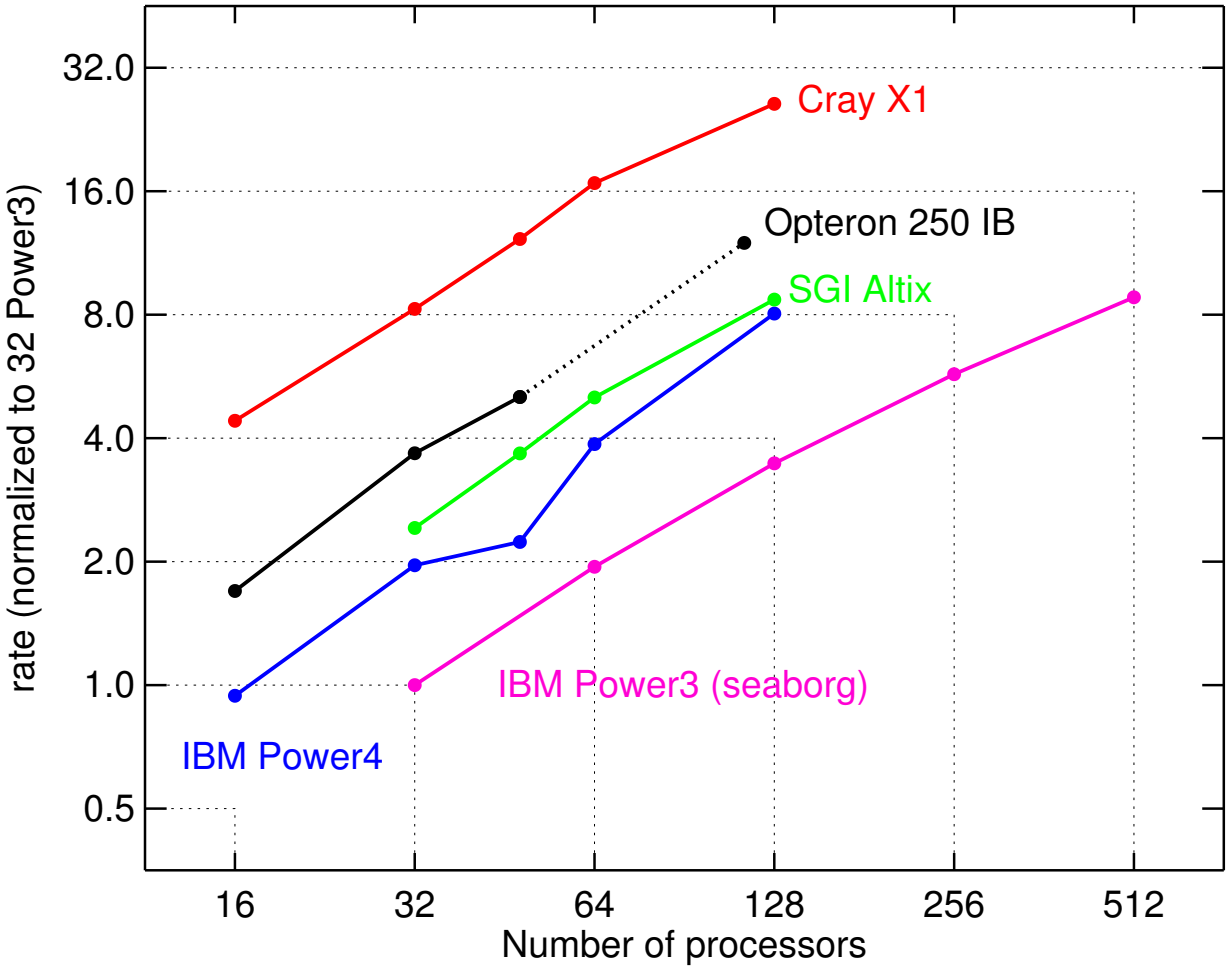
GYRO Overview: A 5D Eulerian Turbulence Code



GYRO Overview: A 5D Eulerian Turbulence Code



Very Good Performance on the Original X1
Some Data Courtesy of Mark Fahey (ORNL)



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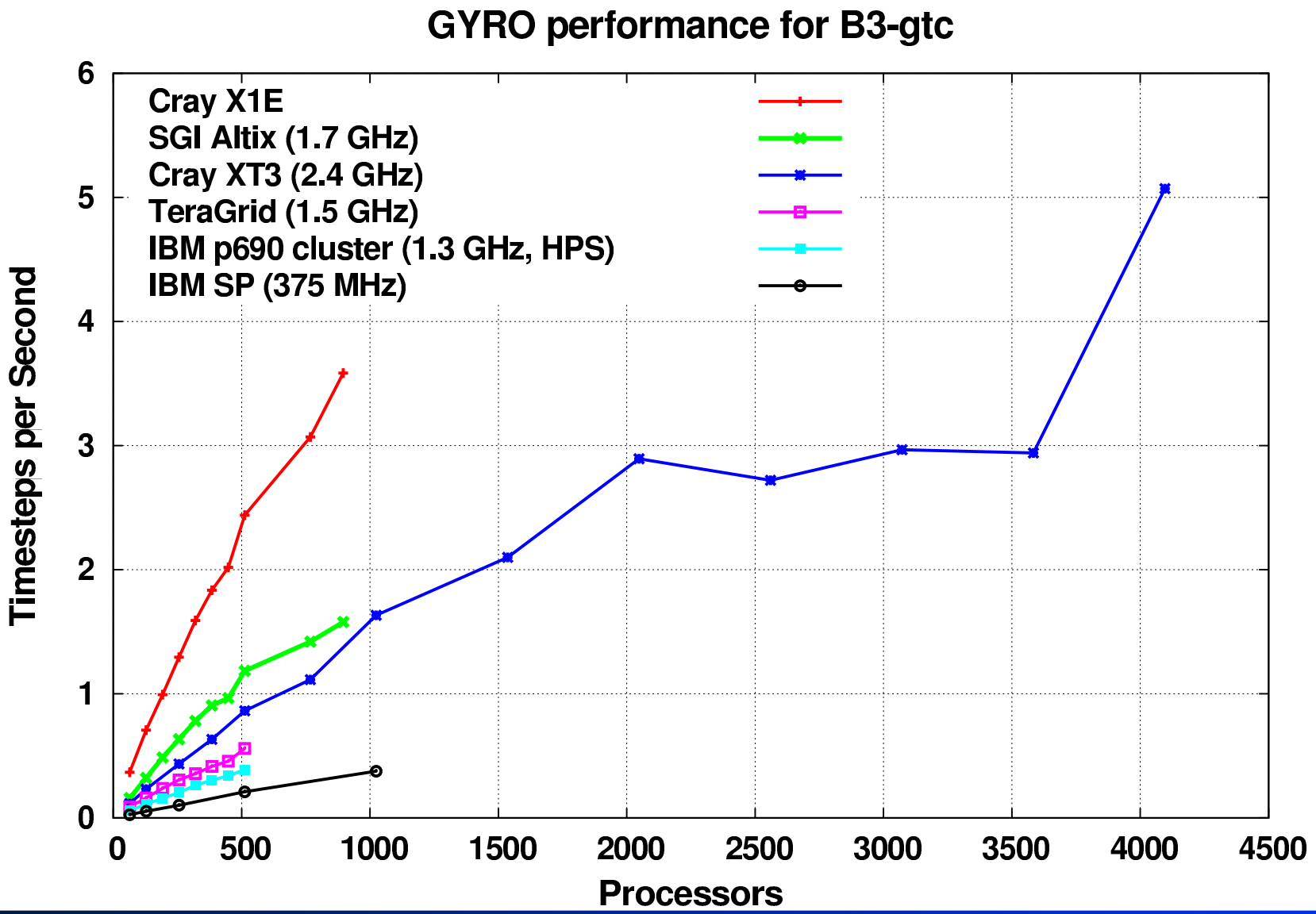
Very Good (non-FFT) Performance on the X1E
Results Courtesy of Pat Worley (ORNL)



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Symbolic Distribution Scheme: Each box is a processor

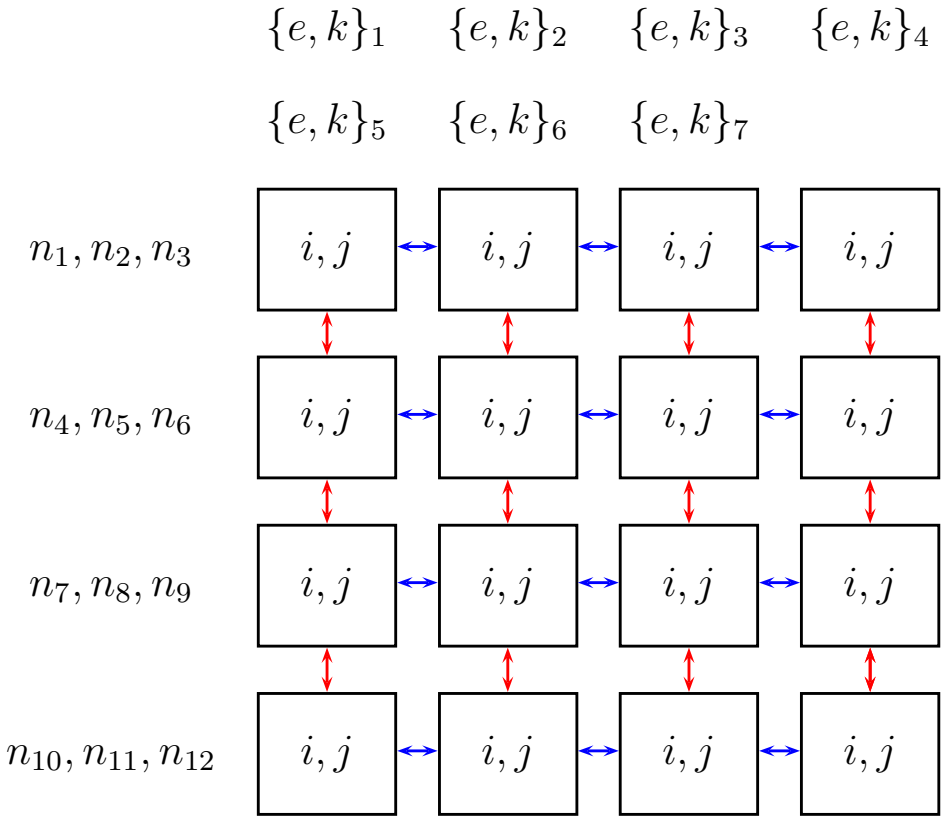
$f([n], \{e, k\}, i, j)$

$n \doteq$ (spectral) binormal direction

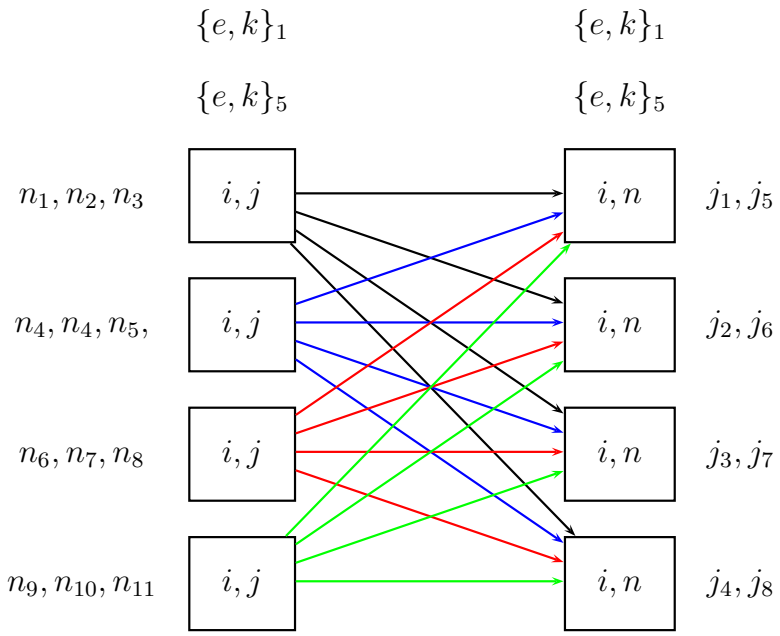
$i \doteq$ radial direction

$j \doteq$ parallel direction

$\{e, k\} \doteq$ 2D velocity space

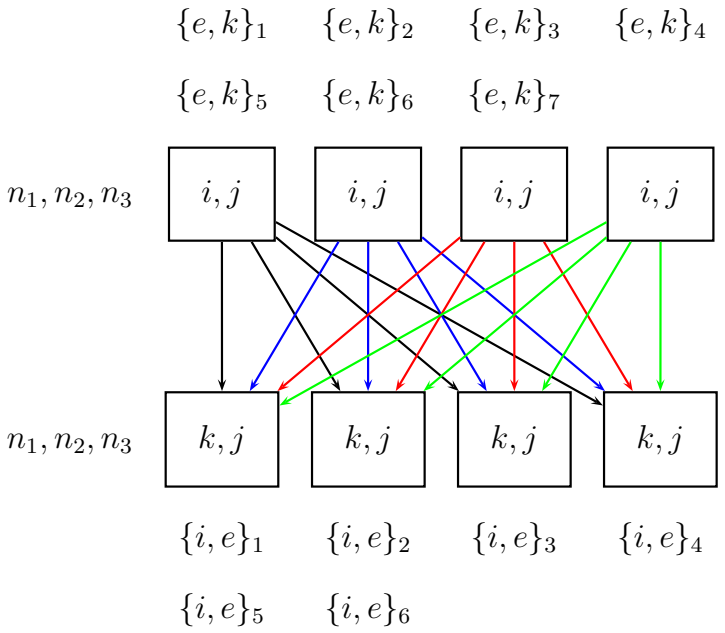


All-to-All Communication only on Subgroups



$$f([n],\{e,k\},i,j)$$

$$\rightarrow f([j],\{e,k\},i,n)$$



$$f([n],\{e,k\},i,j)$$

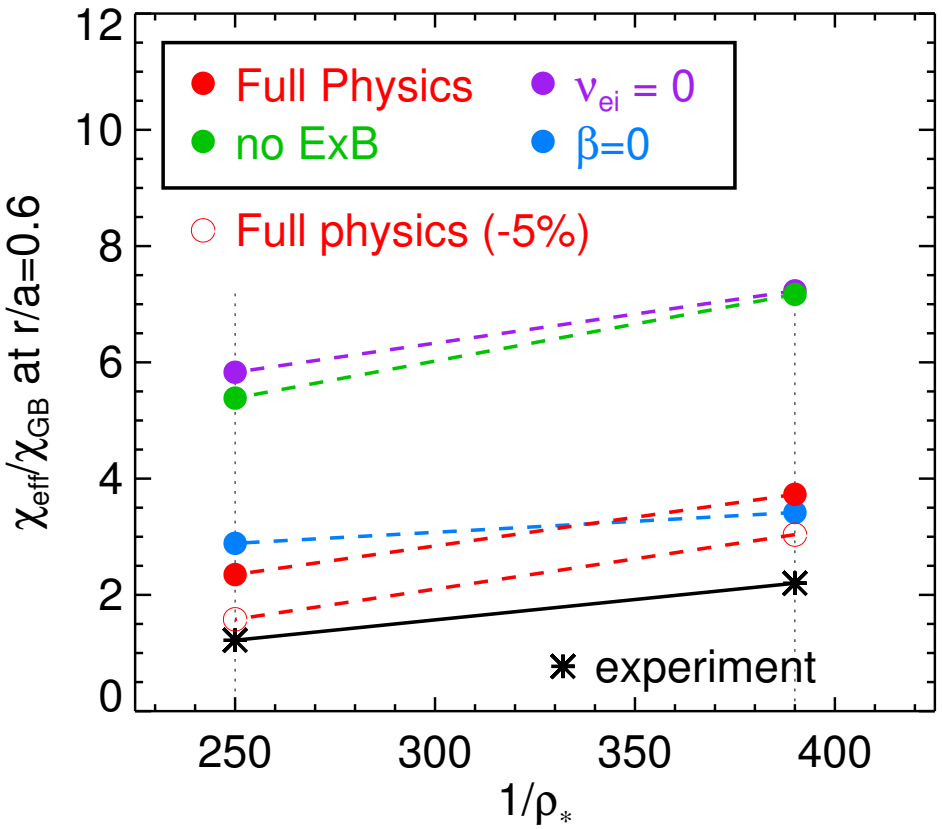
$$\rightarrow f([n],\{i,e\},k,j)$$

Matching Experimental Power Flows in DIII-D L-mode Plasmas

Phys. Rev. Lett **11** (2003) 045001.

Simulations can match between-shot transport scaling, and can match power flows within a factor of two.

Most realistic gyrokinetic simulations ever published.

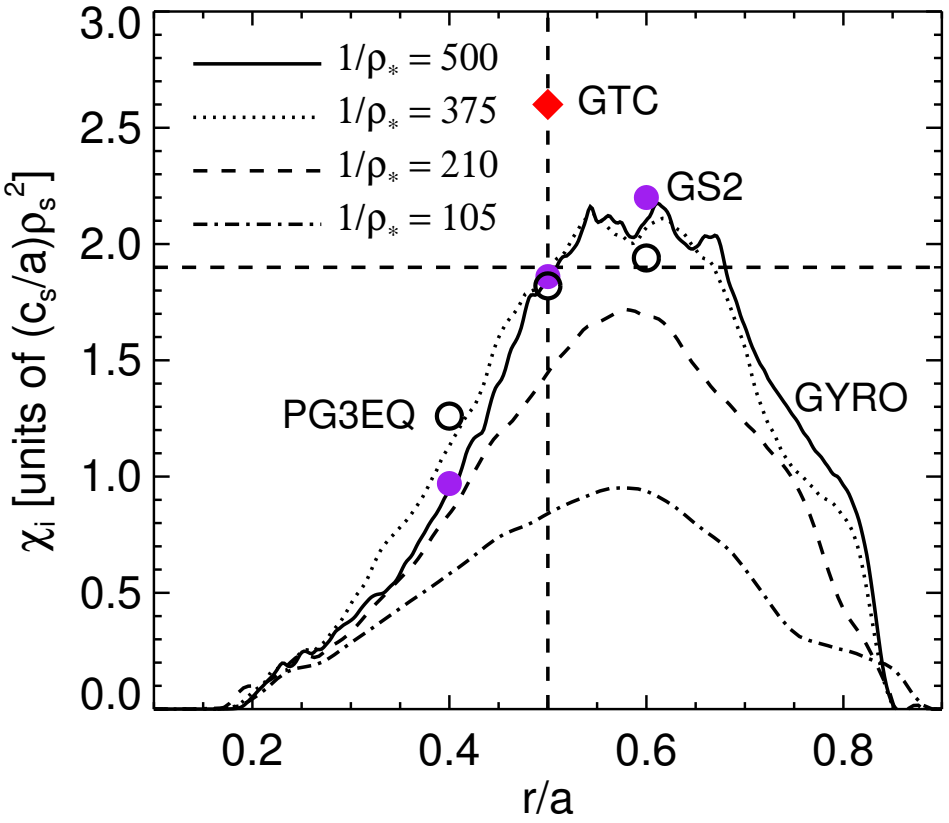


The Local Limit of Global Simulations

Phys. Plasmas **11** (2004) L25.

Local simulations are the rigorous limit of global simulations as the gyroradius to system size decreases.

The largest case is Worley's B3-GTC benchmark case.

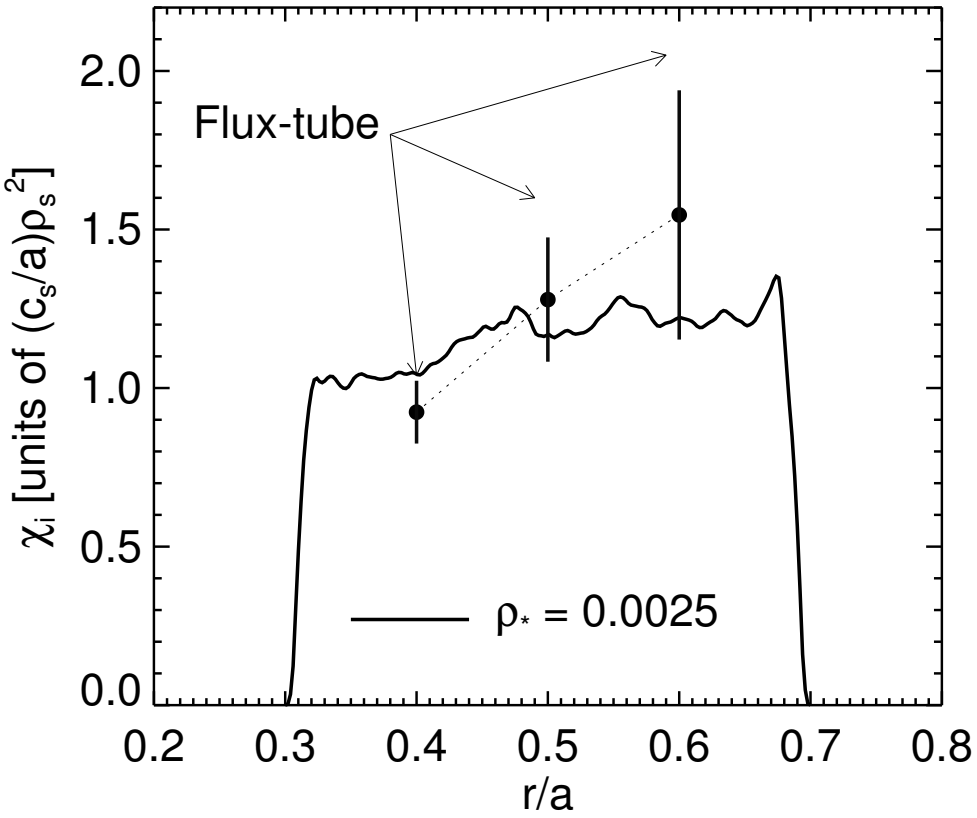


Transport in the Vicinity of a Minimum-q Surface

Phys. Plasmas **11** (2004) 1879.

Transport is smooth across a minimum-q surface. Local and global results give consistent picture.

Done exclusively on the X1.

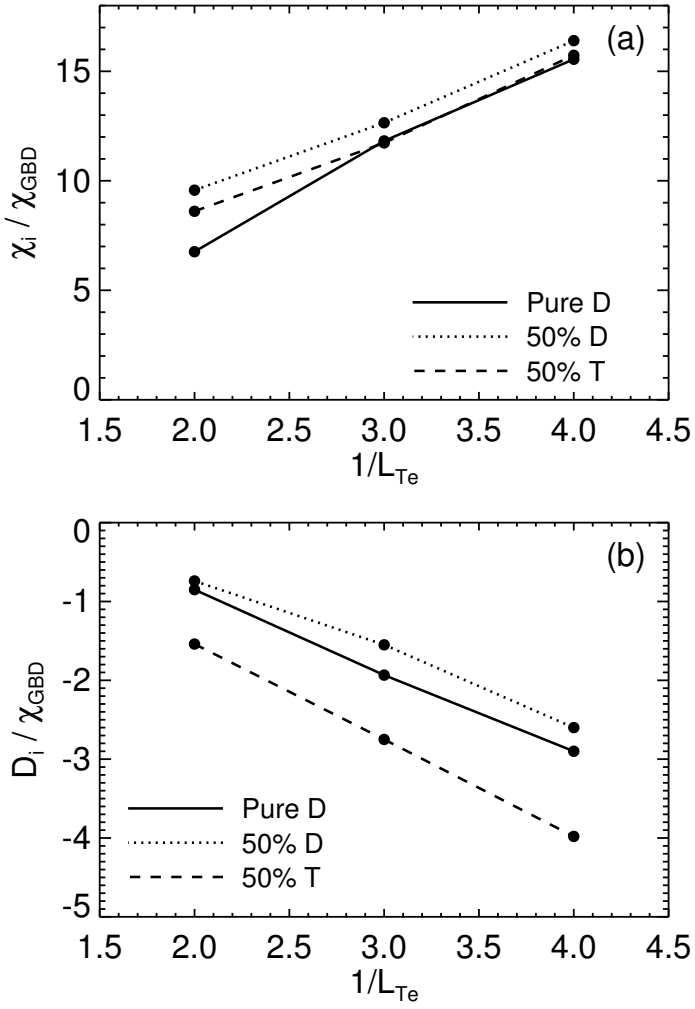


Particle Transport in Reactors: Helium Pinch and Deuterum-Tritium flow Separation

Phys. Plasmas **12** (2005) 022305.

Discovered particle flow separation effect in D-T (reactor) plasmas. Tritium (T) is better confined than Deuterium (D). Developed analytic theory via FLR symmetry breaking.

First systematic gyrokinetic study of impurity transport.

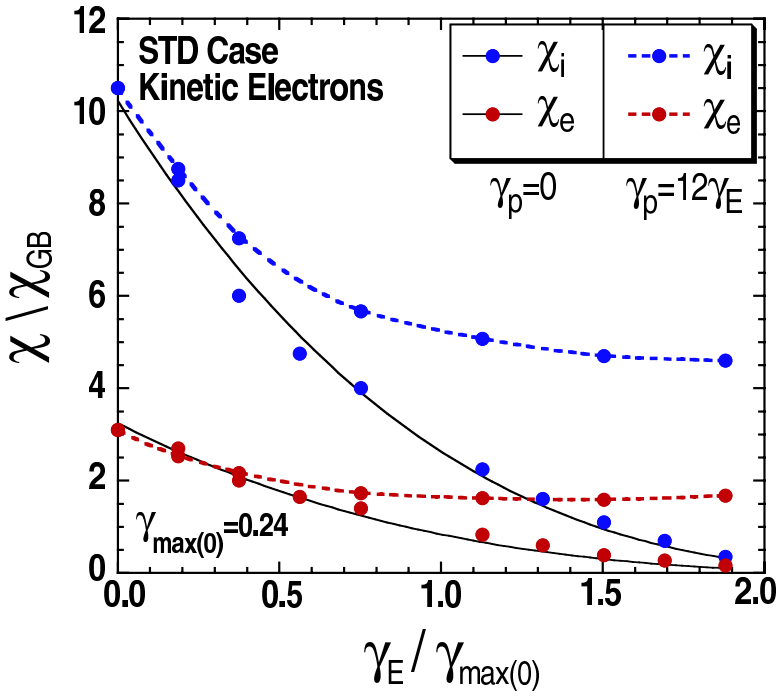


ExB Shear Stabilization of Turbulence

Phys. Plasmas **12** (2005) 062302.

In the DIII-D tokamak, equilibrium sheared $\mathbf{E} \times \mathbf{B}$ rotation is a powerful stabilizing mechanism.

First and only systematic gyrokinetic study of $\mathbf{E} \times \mathbf{B}$ shear stabilization with kinetic electrons.

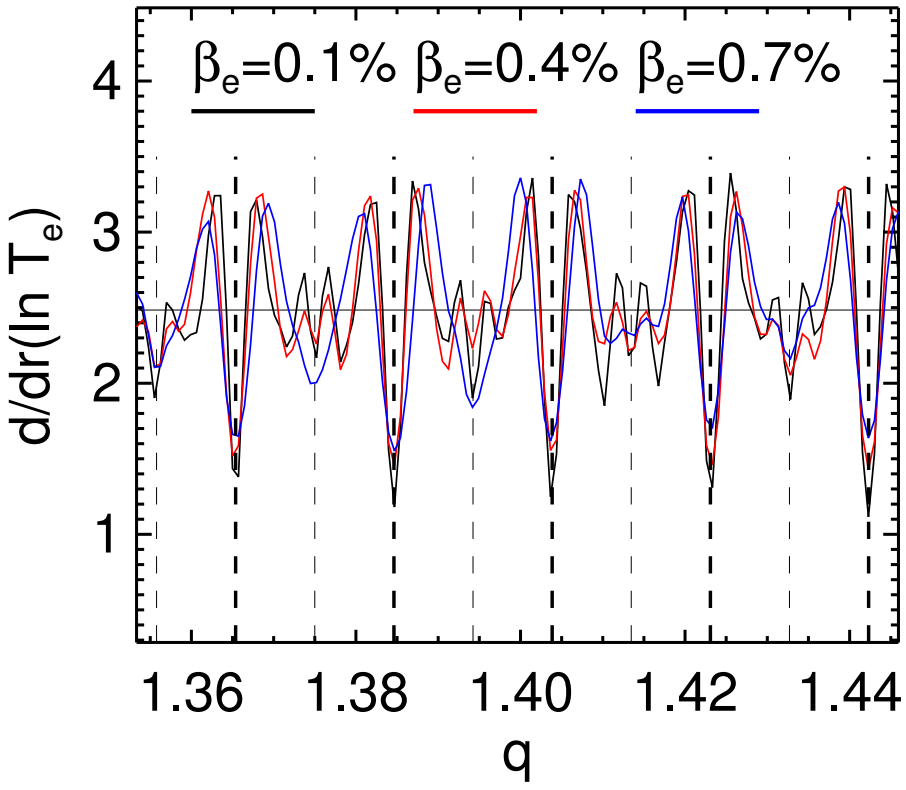


Electron Transport via Electromagnetic Fluctuations

Phys. Plasmas **12** (2005) 072307.

Electrons are strongly resonant at rational magnetic surfaces. Also, 50% of electron transport is driven by magnetic-flutter at $\beta/\beta_{\rm crit} = 0.6$**.**

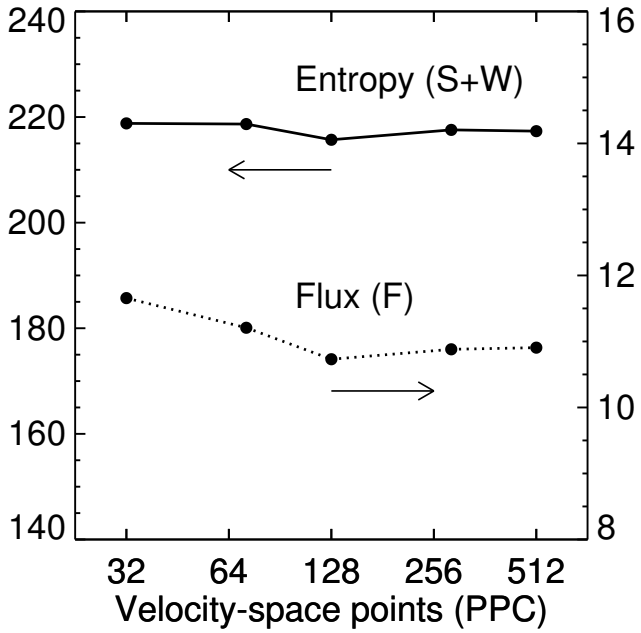
Done exclusively on the X1.



The Connection between Entropy, Upwind Dissipation, Velocity-Space Resolution and Steady-States of Turbulence

Submitted to Phys. Plasmas.

Study performed to clarify various misconceptions and misunderstandings about Eulerian methods. Results show that there is no missing velocity-space structure in GYRO.

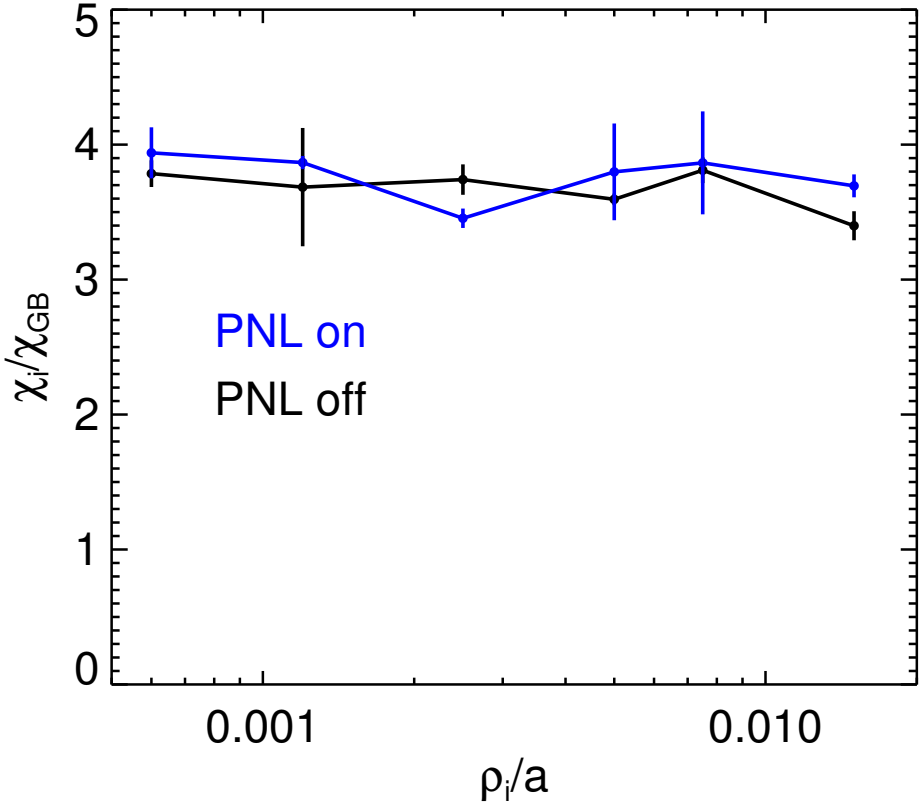


GYRO velocity-space integration is extremely accurate, and simulations are noiseless

Demonstration that the Parallel Nonlinearity is Negligible

Even at unphysically large values of $\rho_* = \rho_i/a$, no effect of the PNL is observed. This result is essentially a requirement of the gyrokinetic ordering.

Unlikely that current codes could treat the term accurately if it was important.

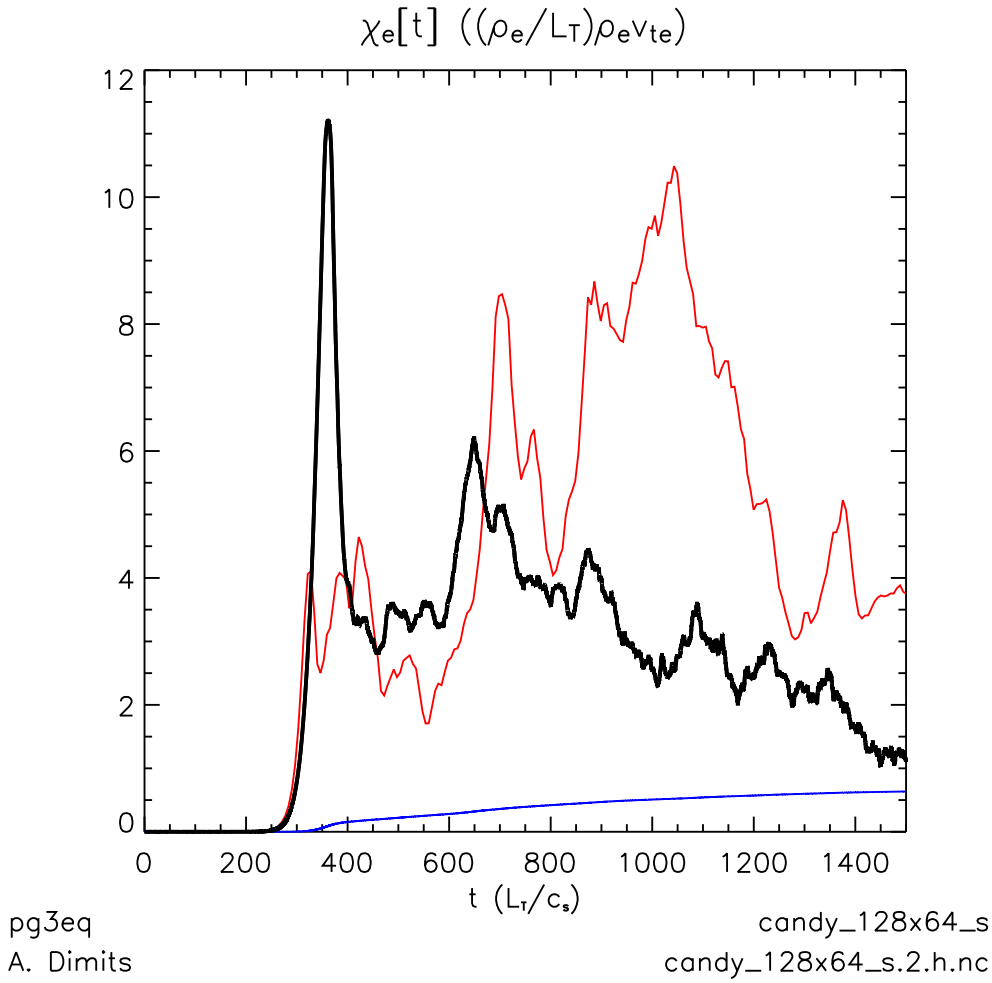


Benchmarking Eulerian verus PIC codes on ETG Simulations (adiabatic ion dynamics)

Submitted to Phys. Plasmas.

PIC Simulations of ETG are dominated by discrete particle noise in "strong transport" regime. Benchmarking effort show perfect intercode agreement when noise is under control.

GYRO (Eulerian, red) versus PG3EQ (PIC, black). Blue curve shows the "pure noise" diagnostic.



Summary of Results and Requirements

- Most of the previous simulations/publications were done using

  only 16-64 MSPs

- GYRO algorithms are **powerful** enough to make most ITG-only, ITG-TEM, or ETG-only studies quick and easy

- Each publication typically presents from **10 to 100 simulations**

Are there problems for which 64 MSPs are not enough?

The Future: Fully-Coupled ITG-ETG Studies

- We want to attempt

  simulation of ETG turbulence embedded in ITG turbulence

- Preliminary testing on **640 X1E MSPs** shows
  - $\mu \doteq \sqrt{m_i/m_e} = 20$ works with $0 \leq k_\theta \rho_e \leq 0.3$
  - implies that $\mu = 30$ runs with $0 \leq k_\theta \rho_e \leq 0.6$ are feasible
  - cost scales roughly as $\mu^{3.5}$

The Future: Fully-Coupled ITG-ETG Studies

This is our INCITE proposal; it will be described in detail at a talk at ORNL on Wednesday