Continuum Gyrokinetic Approach for Edge Kinetic Simulations

J. Candy

General Atomics, San Diego, CA

PSACI PAC Meeting

25 May 2006

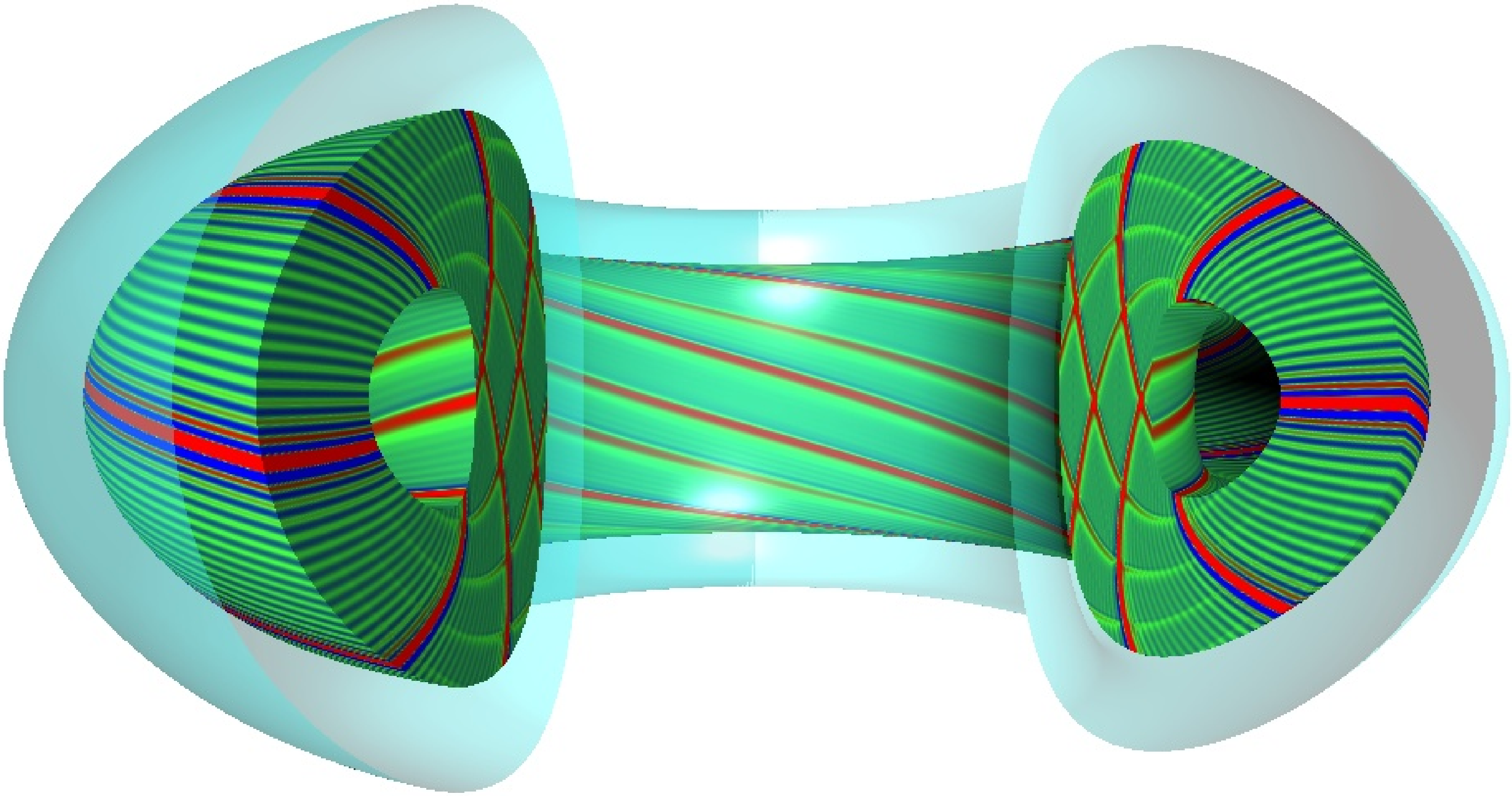
PPPL, Princeton, NJ

Acknowledgements: W. Dorland, W. Nevins, R. Cohen, M. Fahey, P. Worley, G. Hammett

Direct Numerical Simulation of Plasma Turbulence

GYRO simulations in Shaped Toroidal Geometry

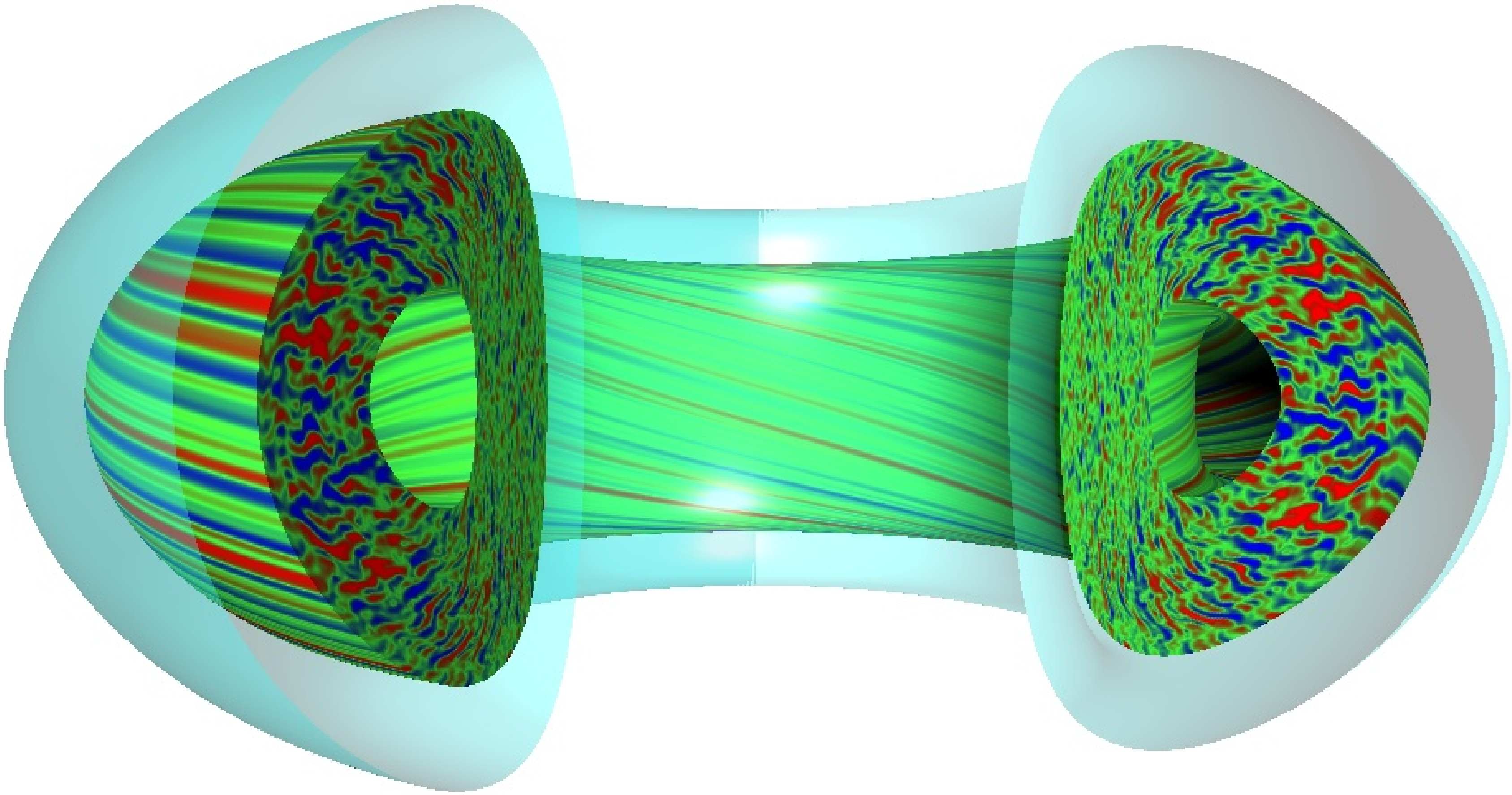
Linear phase of a plasma instability driven by ion temperature gradients



Direct Numerical Simulation of Plasma Turbulence

GYRO simulations in Shaped Toroidal Geometry

Nonlinear phase of a plasma instability driven by ion temperature gradients



Current Status of Continuum Codes

- GYRO and GS2:
  - dominate US fusion/transport research.
  - true production codes.
  - simulate real tokamak discharges [1, 2].
- Routinely simulate plasmas with **kinetic electrons**, **electromagnetic modes**, highly **noncircular shape**.
- All efforts to **VALIDATE** nonlinear GK simulations against **experimental results** have been carried out with these two **continuum** codes.
- GS2 is being used to simulate near-Earth and **astrophysical** plasma turbulence.

Worldwide Usage of GYRO and GS2

Eulerian codes are critical tools for fusion research

- **GYRO**

  General Atomics (Candy, Waltz, Kinsey, Staebler), **MIT** (Ernst, Bose), **UT Austin** (Bravenec), **PPPL** (Budny, Mikkelsen), **UCSD** (Estrada-Mila, Holland), **UCLA** (White, Carter, Wang, Plunk, Taylor), **CEA-France** (Bourdelle), **LLNL** (Nevins), **ORNL** (Fahey, Worley, Alam), **IPP-Germany** (Hallatschek)

- **GS2**

  Maryland (Dorland, Tatsuno, Barnes, Broemstrup, Gustafson, Schoeffler, Kirsch, Sobota, Hollingsworth, Goswami), **PPPL** (Hammett, Mikkelsen, Redi, Budny, Yuh, Hill), **MIT** (Ernst), **UT Austin** (Ross, Bravenec, Kotschenreuther, Pino), **Dartmouth** (Ricci, Rogers), **Berkeley** (Howes, Quataert), **SLU** (McCarthy), **Culham-UK** (Roach, Applegate), **IPP-Germany** (Jenko, Peeters, Angioni), **CEA** (Bourdelle), **Saskatchewan** (Joiner), **Columbia** (Pederson)

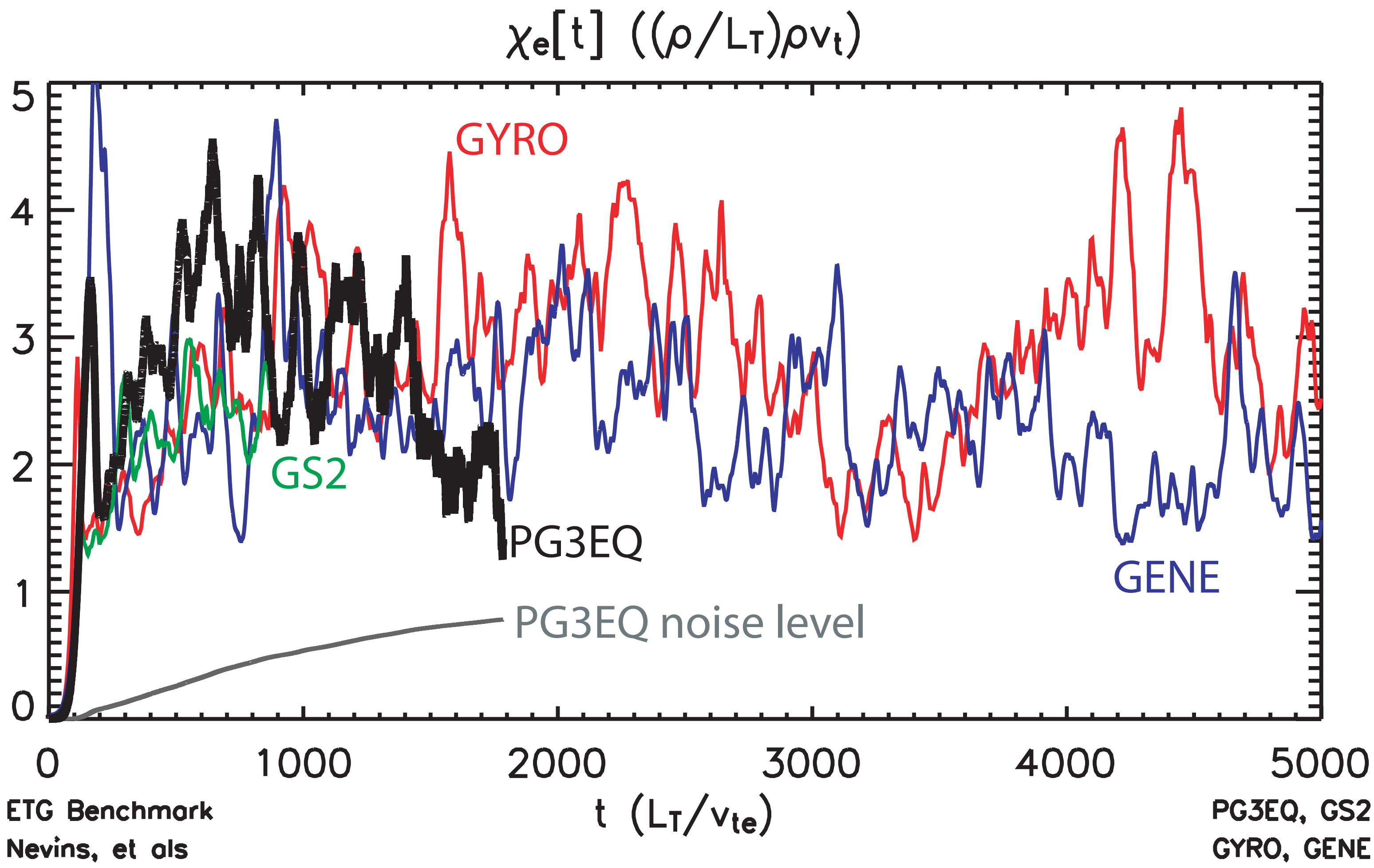
GYRO Platform Files for All Popular Machines

Enables unified make system, tools, batch submission

1. **General:** `PG_P3,PG_OPT64,IFORT_P3,IFORT_P4,G95,LF`
2. **NERSC**: `SEABORG,BASSI,JACQUARD`
3. **General Atomics**: `DROP`
4. **PPPL**: `PETREL,KITE`
5. **ORNL**: `EAGLE,CHEETAH,RAM,JAGUAR,PHOENIX`
6. **Unreleased**: PPPL Blue Gene, Cray XD1, Dawson (UCLA G5), Power3, Power4.

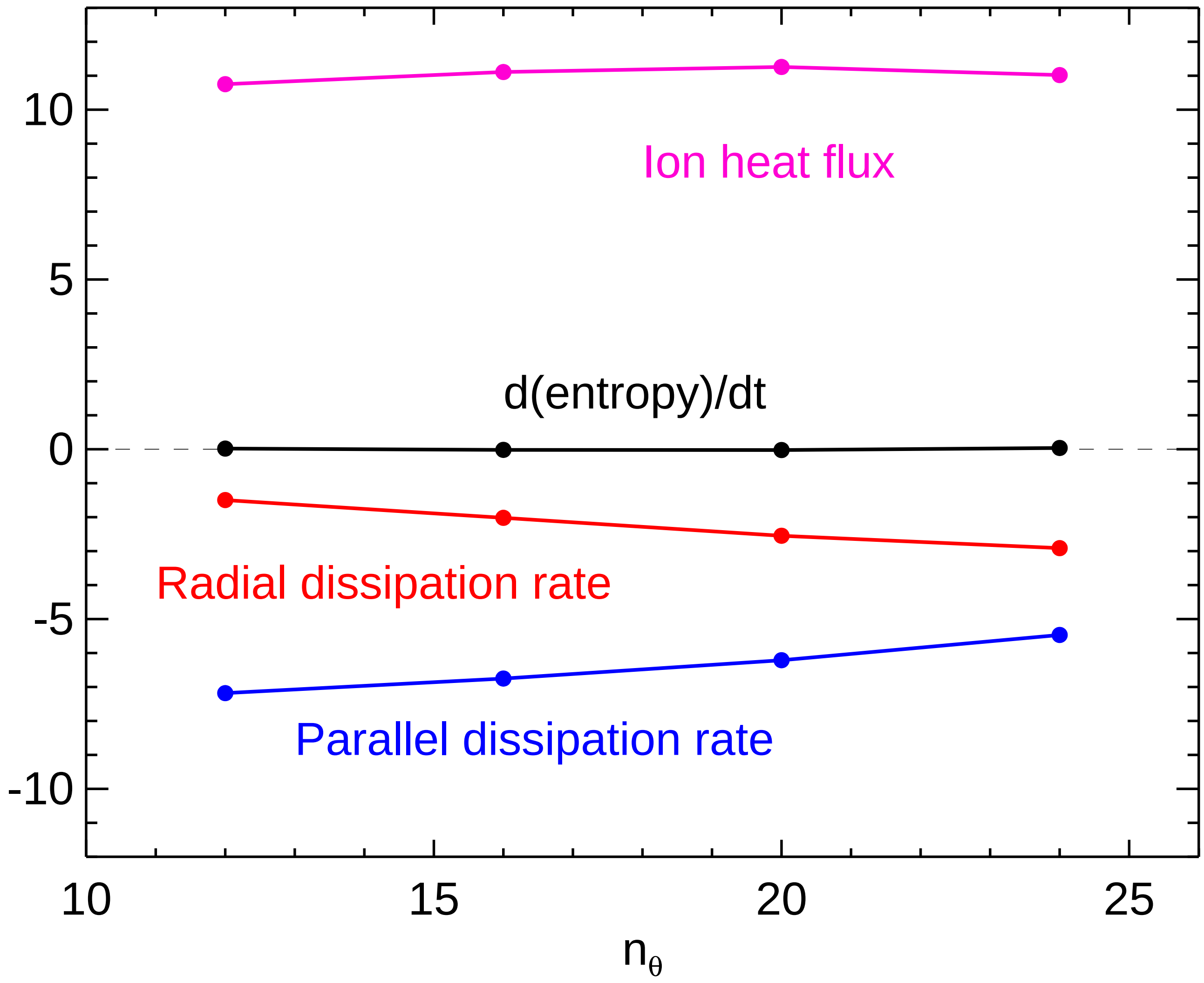
NOISE: Not an issue for continuum simulations

Phys. Plasmas 12 (2005) 122305



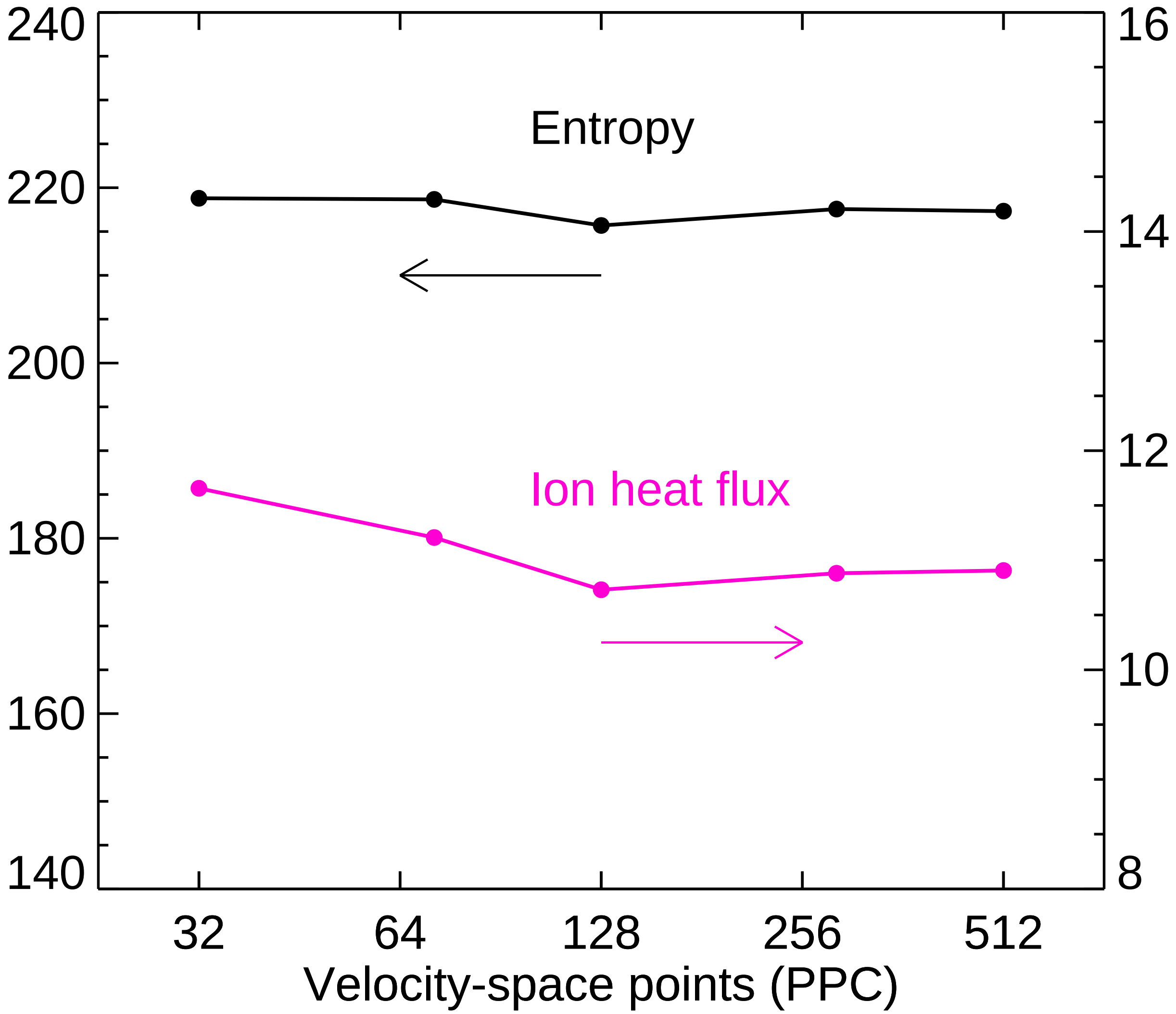
GRID DISSIPATION: Not an issue for GYRO

Phys. Plasmas 13 (2006) 032310



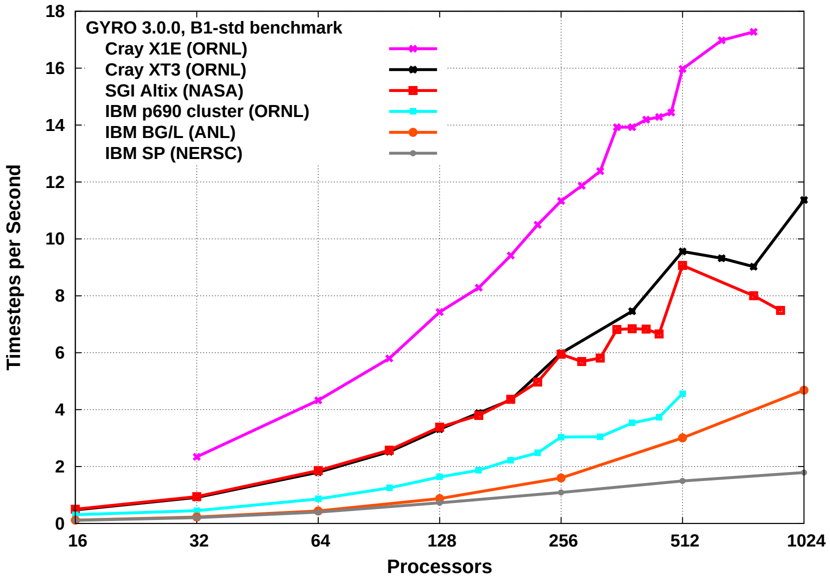
VELOCITY RESOLUTION: Not an issue for GYRO

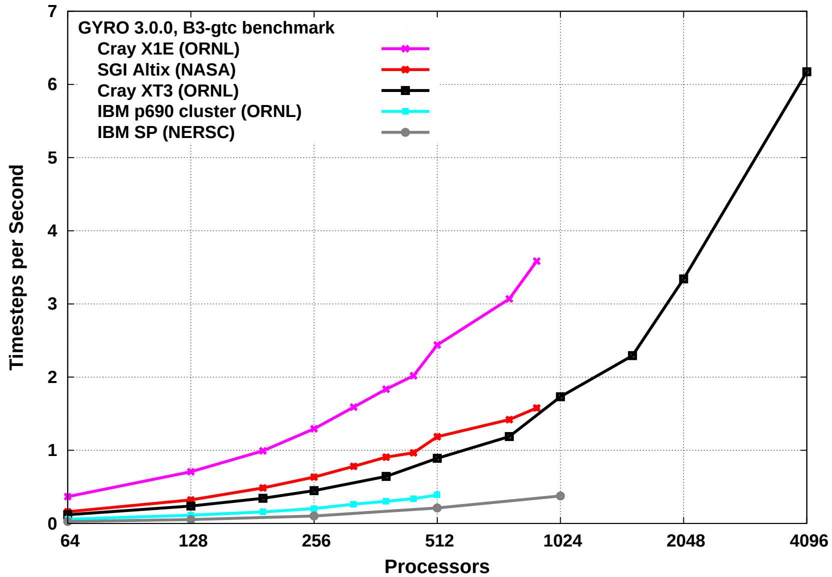
Phys. Plasmas 13 (2006) 032310

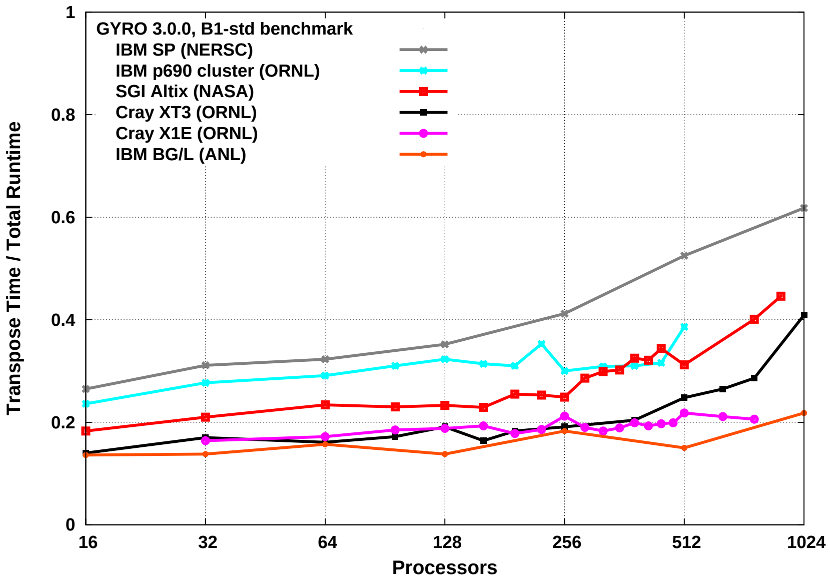


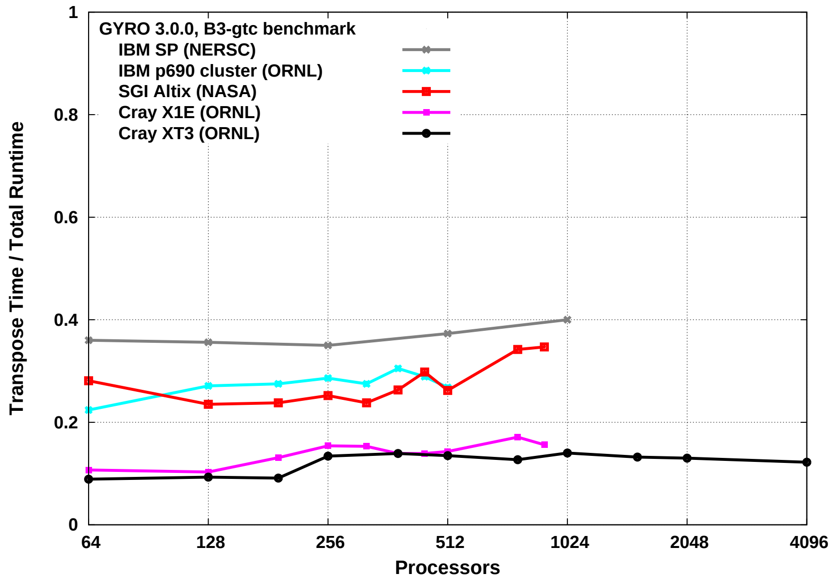
SCALING: GYRO Scales to Maximum Node Count

B1/B3 results courtesy Pat Worley (ORNL)



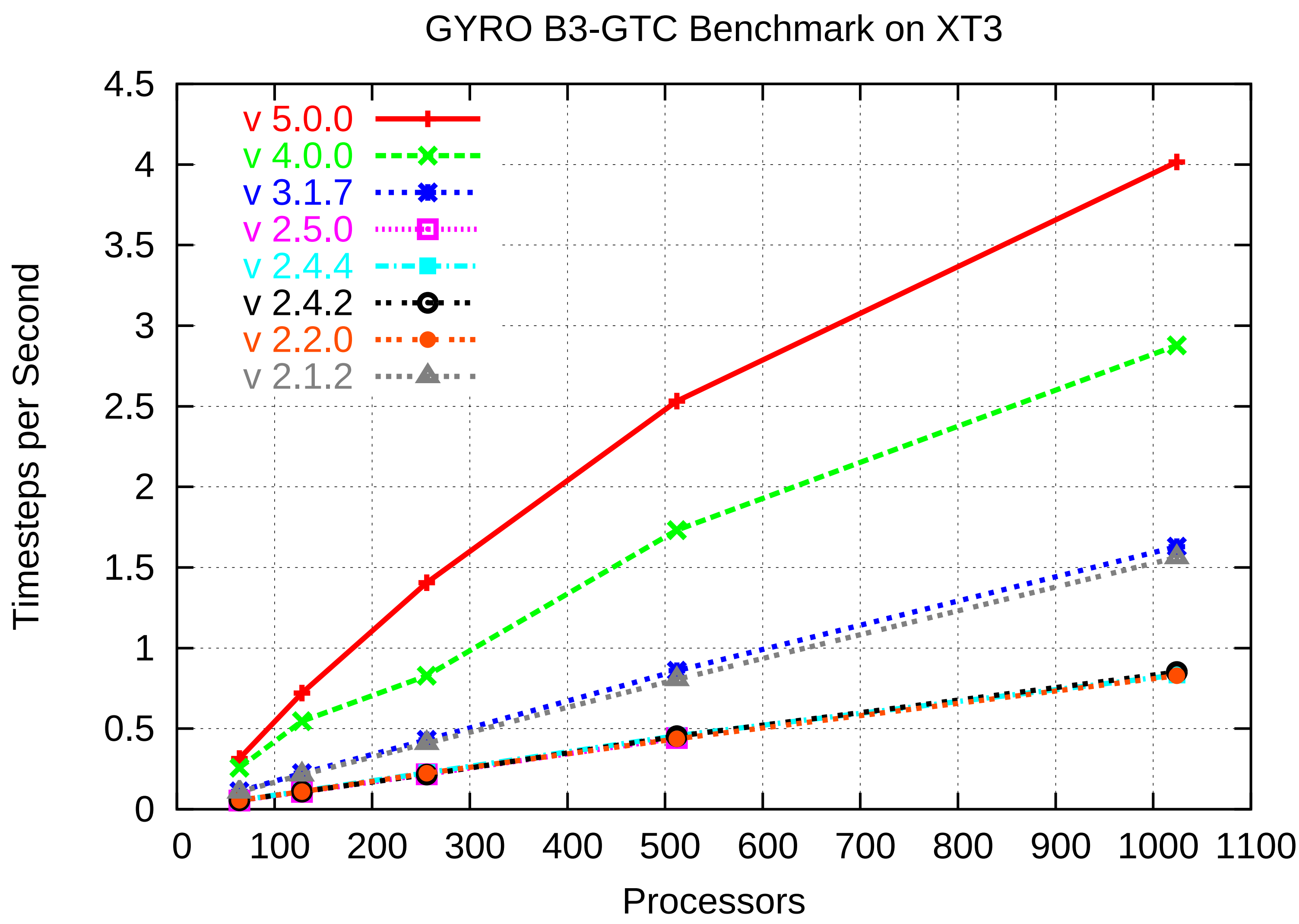






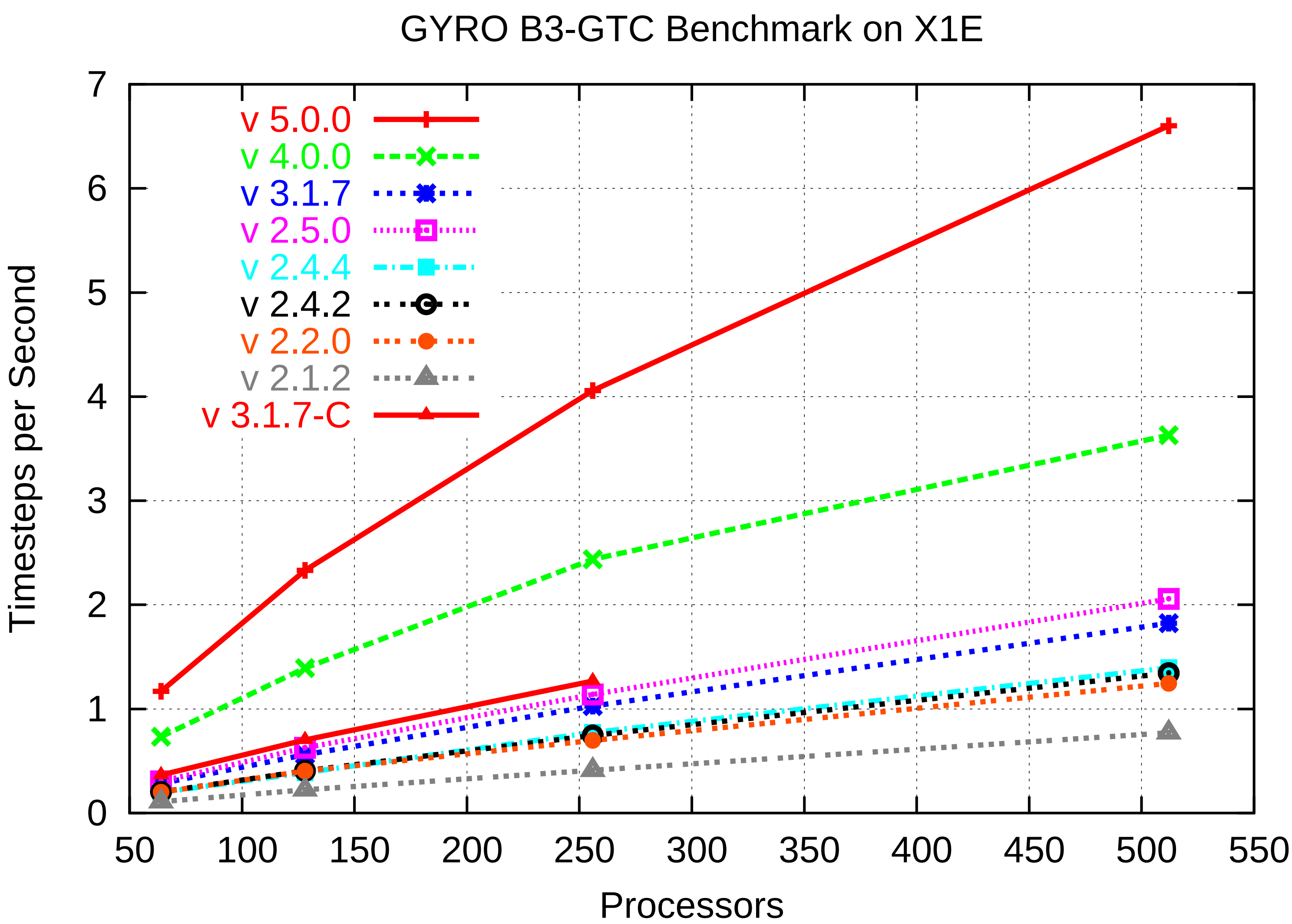
GYRO Performance Improvements (2003-2006)

B3 Results on Cray XT3 courtesy Mark Fahey (ORNL)



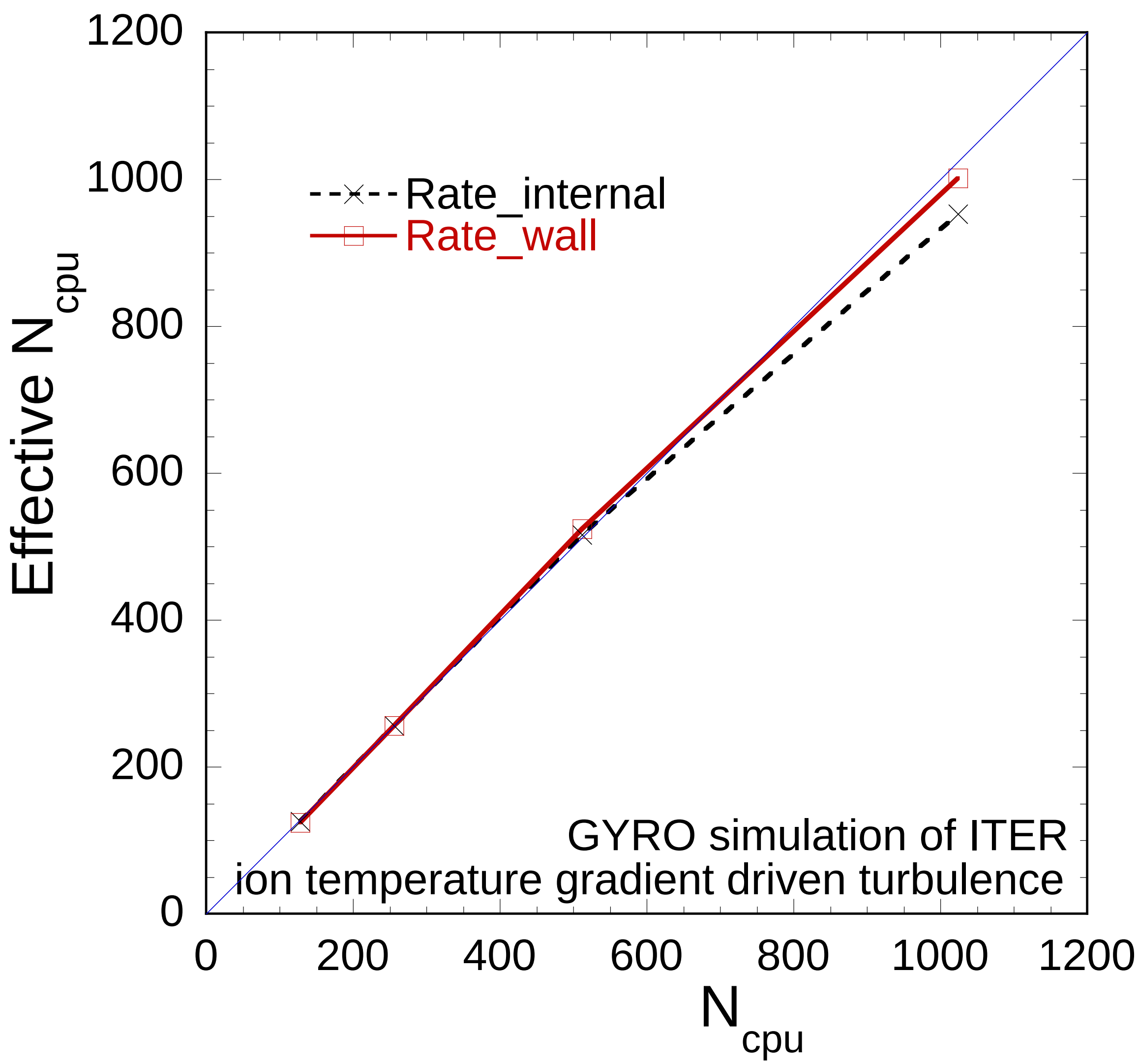
GYRO Performance Improvements (2003-2006)

B3 Results on Cray X1E courtesy Mark Fahey (ORNL)



GYRO Performance Data (2006)

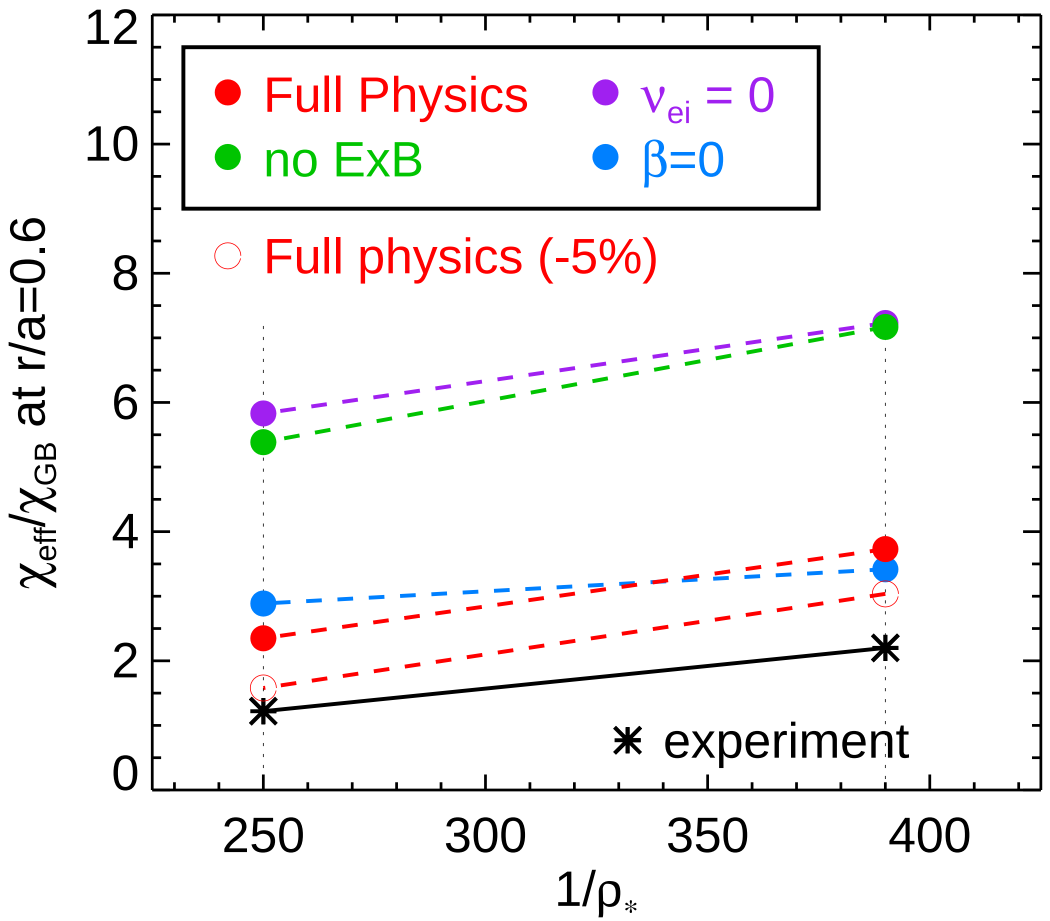
B4 Results on PPPL Blue Gene courtesy David Mikkelsen (PPPL)



Matched Experimental Power Flows in DIII-D Plasmas

Phys. Rev. Lett 11 (2003) 045001

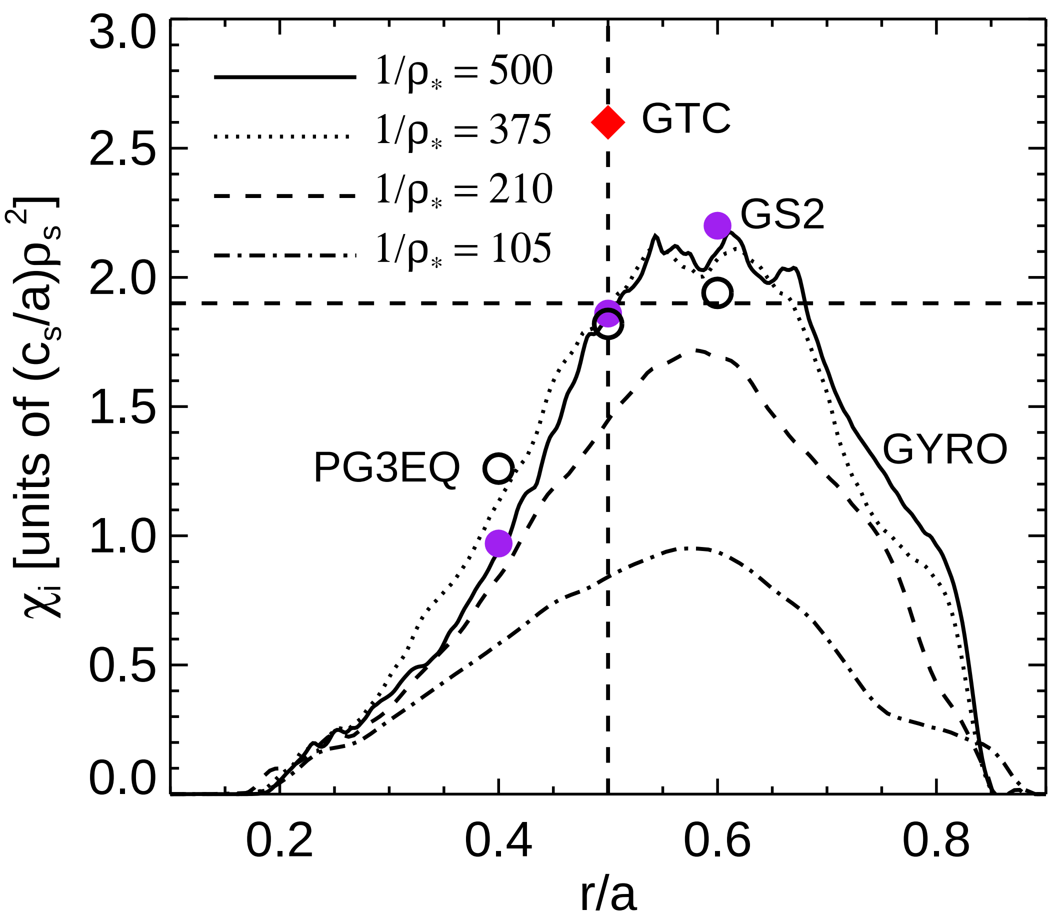
Most realistic gyrokinetic simulations ever published.



The Local Limit of Global Gyrokinetic Simulations

Phys. Plasmas 11 (2004) L25.

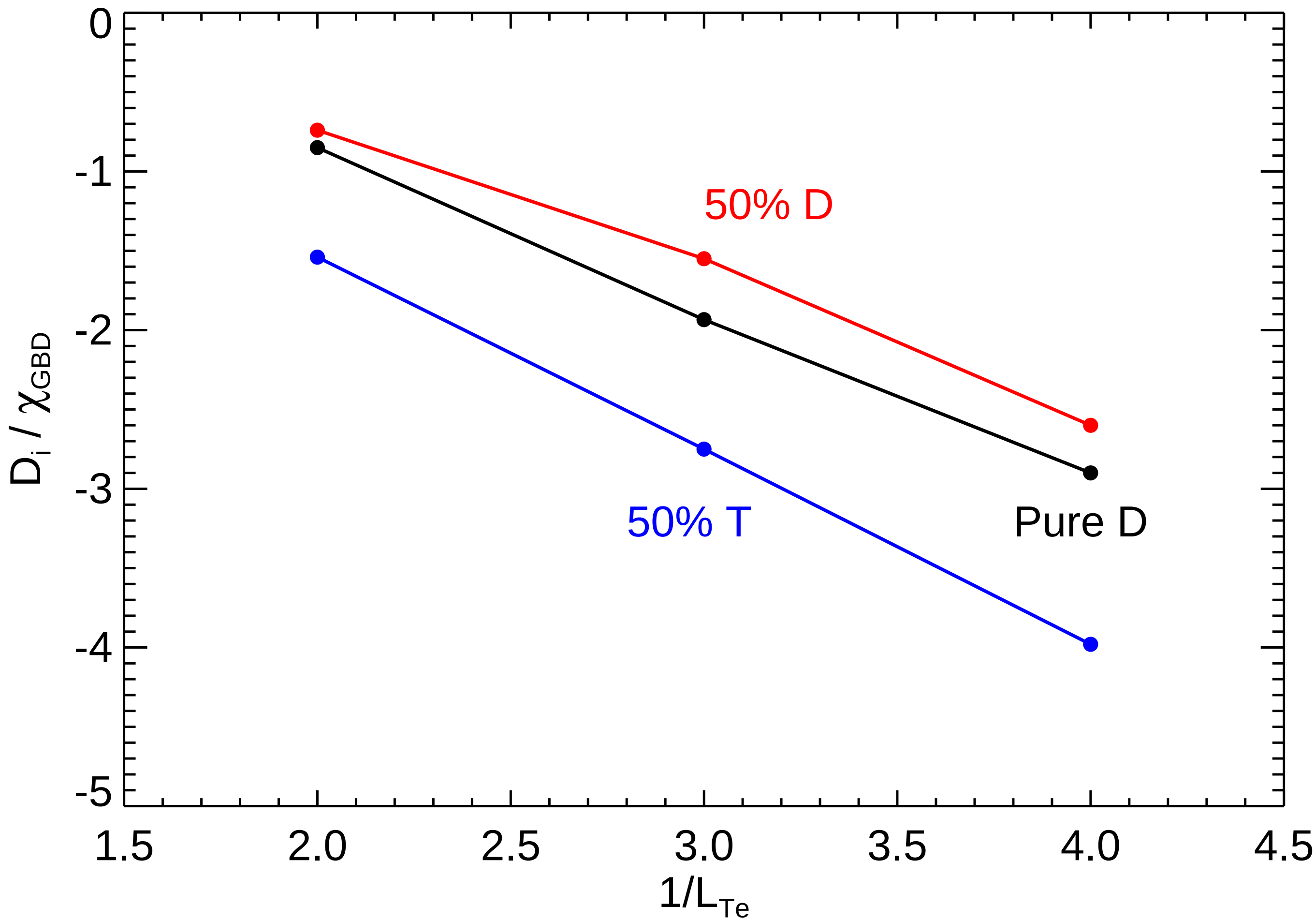
Local simulations are the rigorous limit of global simulations as $\rho_* \to 0$.



Systematic Gyrokinetic Study of Particle Transport

Phys. Plasmas 12 (2005) 022305

Deuterum-Tritium flow separation will occur in a reactor

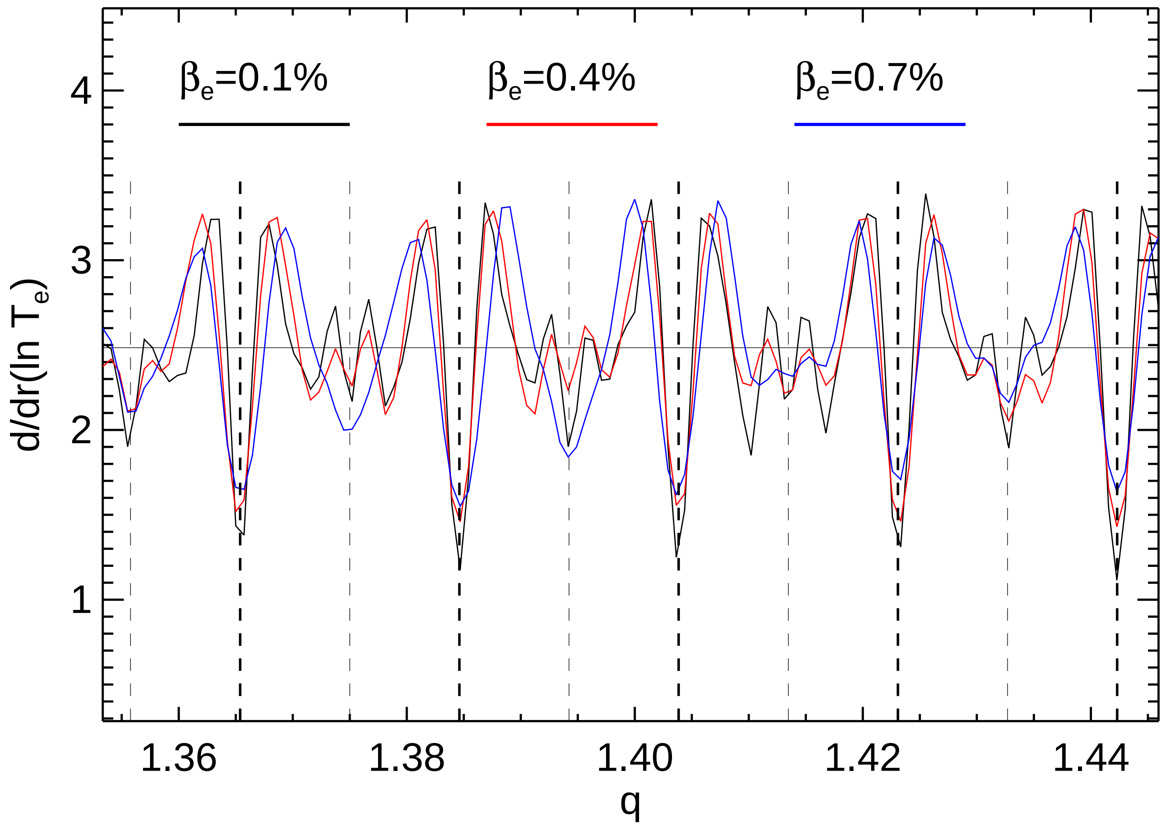


Electron Transport via Electromagnetic Fluctuations

Phys. Plasmas 12 (2005) 072307

Electrons are strongly resonant at rational magnetic surfaces

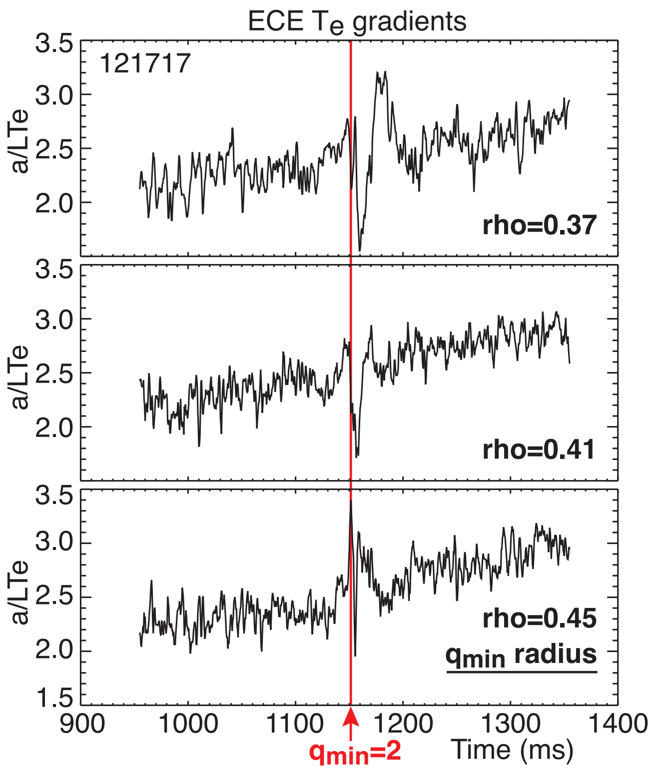
50% of electron transport is driven by magnetic-flutter at $\beta/\beta_{\text{crit}} = 0.6$.

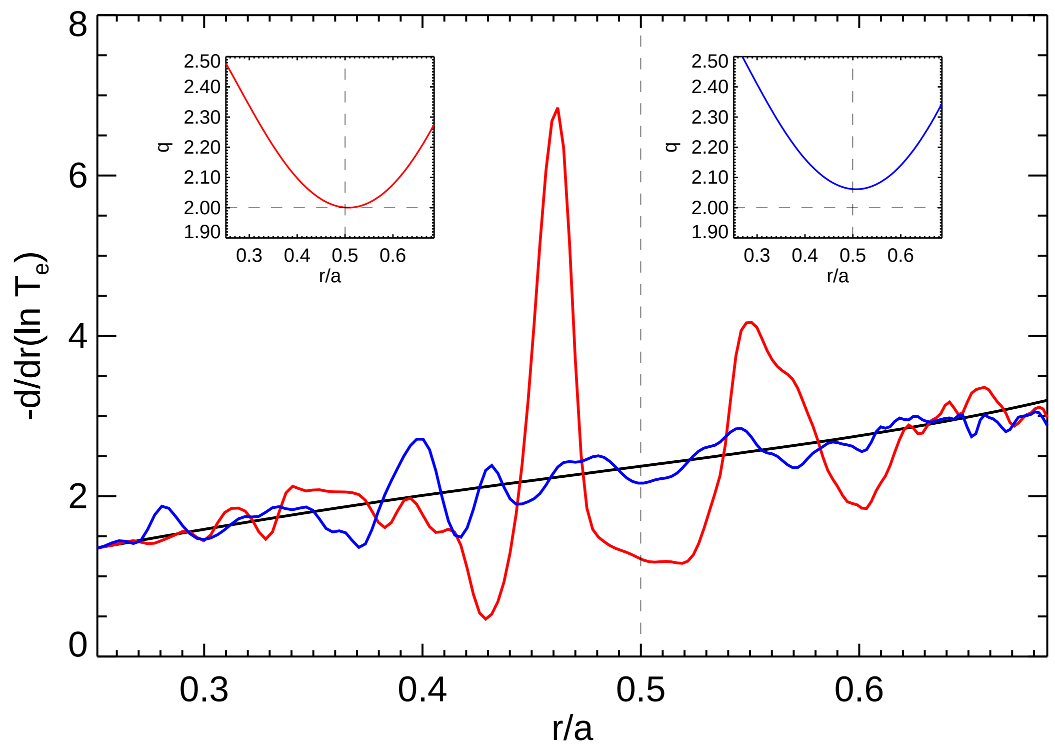


Electron Temperature Gradient Spike in DIII-D Experiment

Phys. Plasmas 13 (2006) 052301

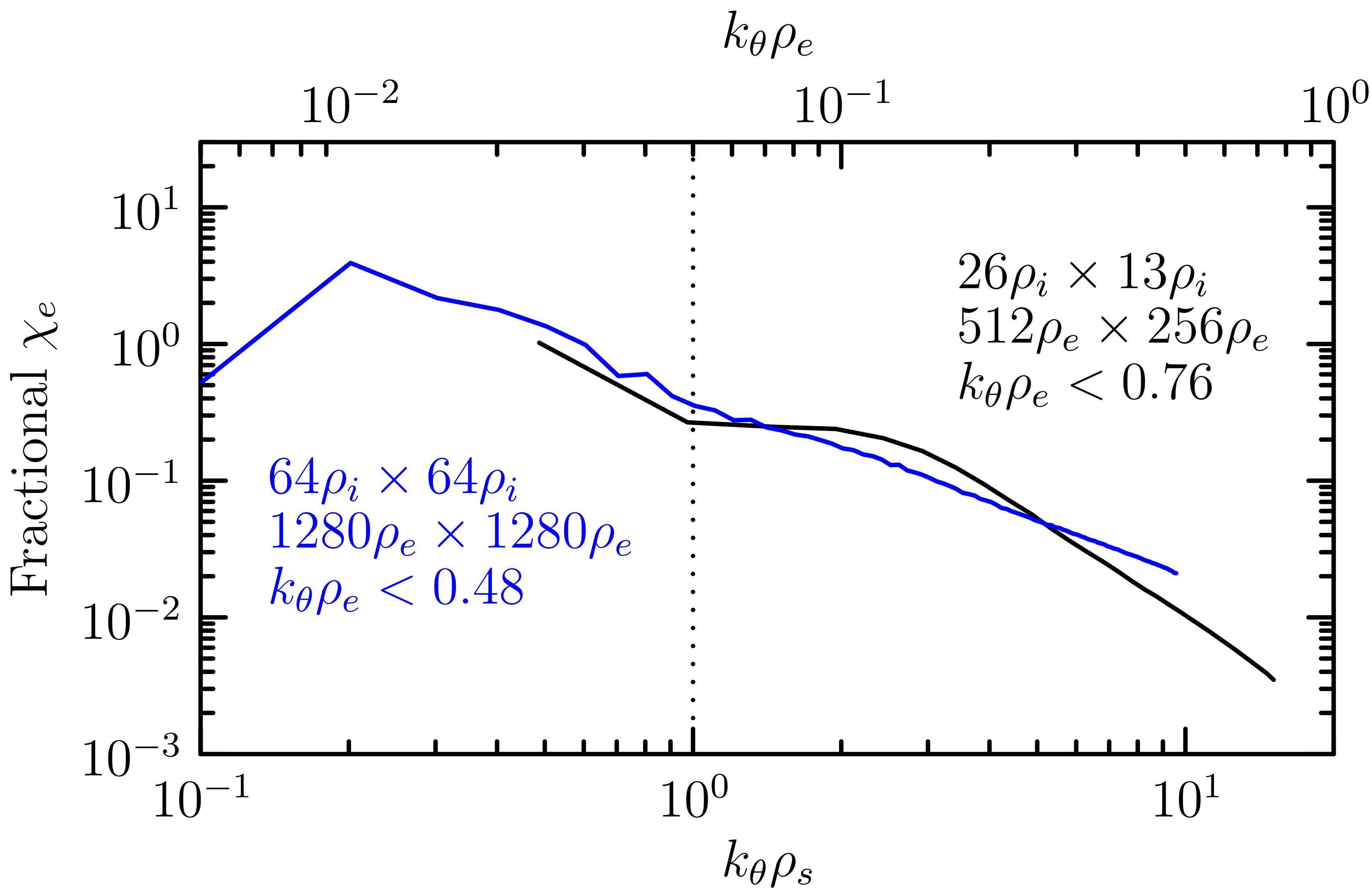
Appears at q=2; may trigger transport barrier (courtesy M. Austin)





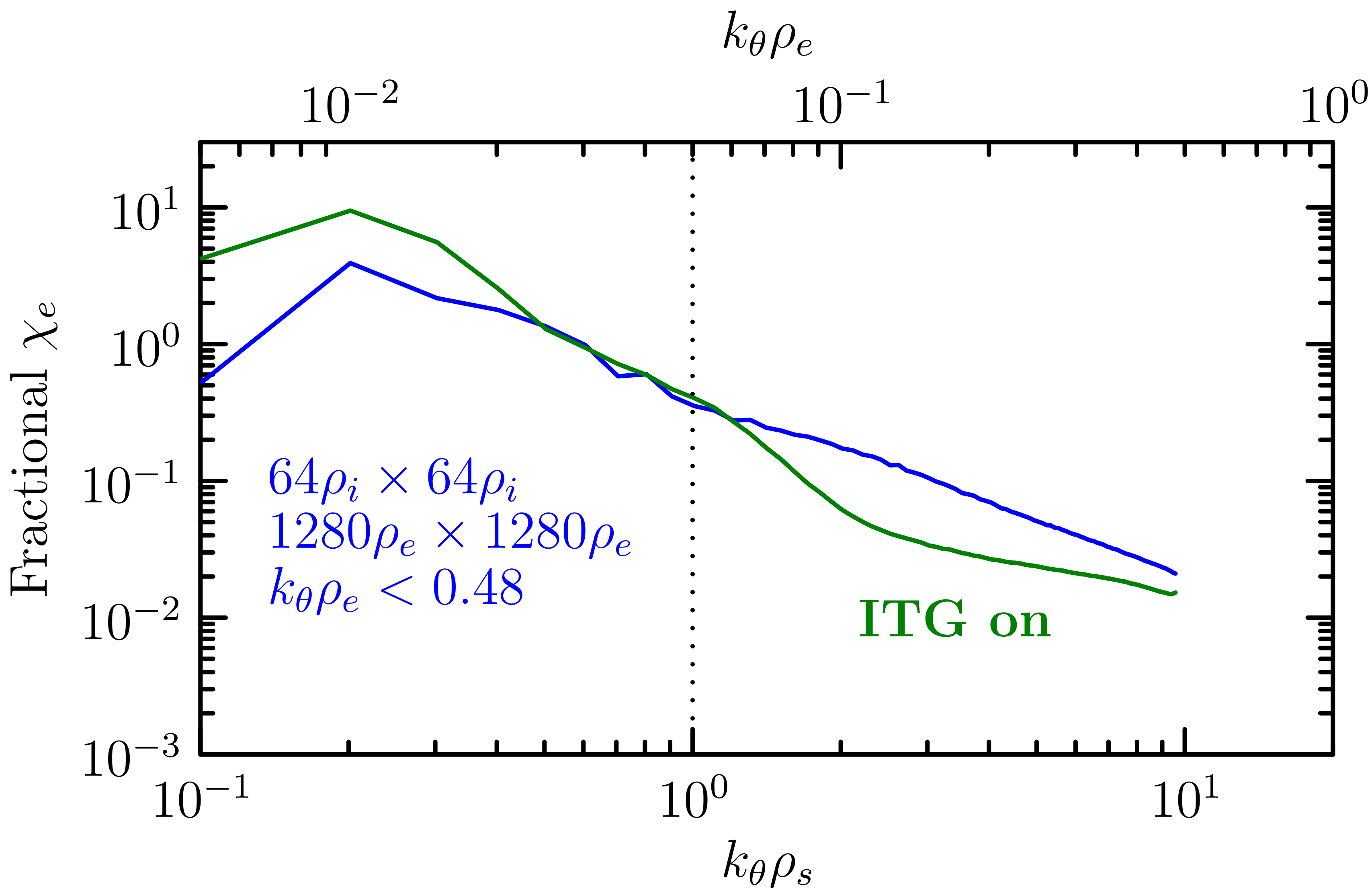
Coupled ITG/TEM-ETG Turbulence (INCITE Award)

Find spectral overlap (large vs. small box) when ion profiles are flat



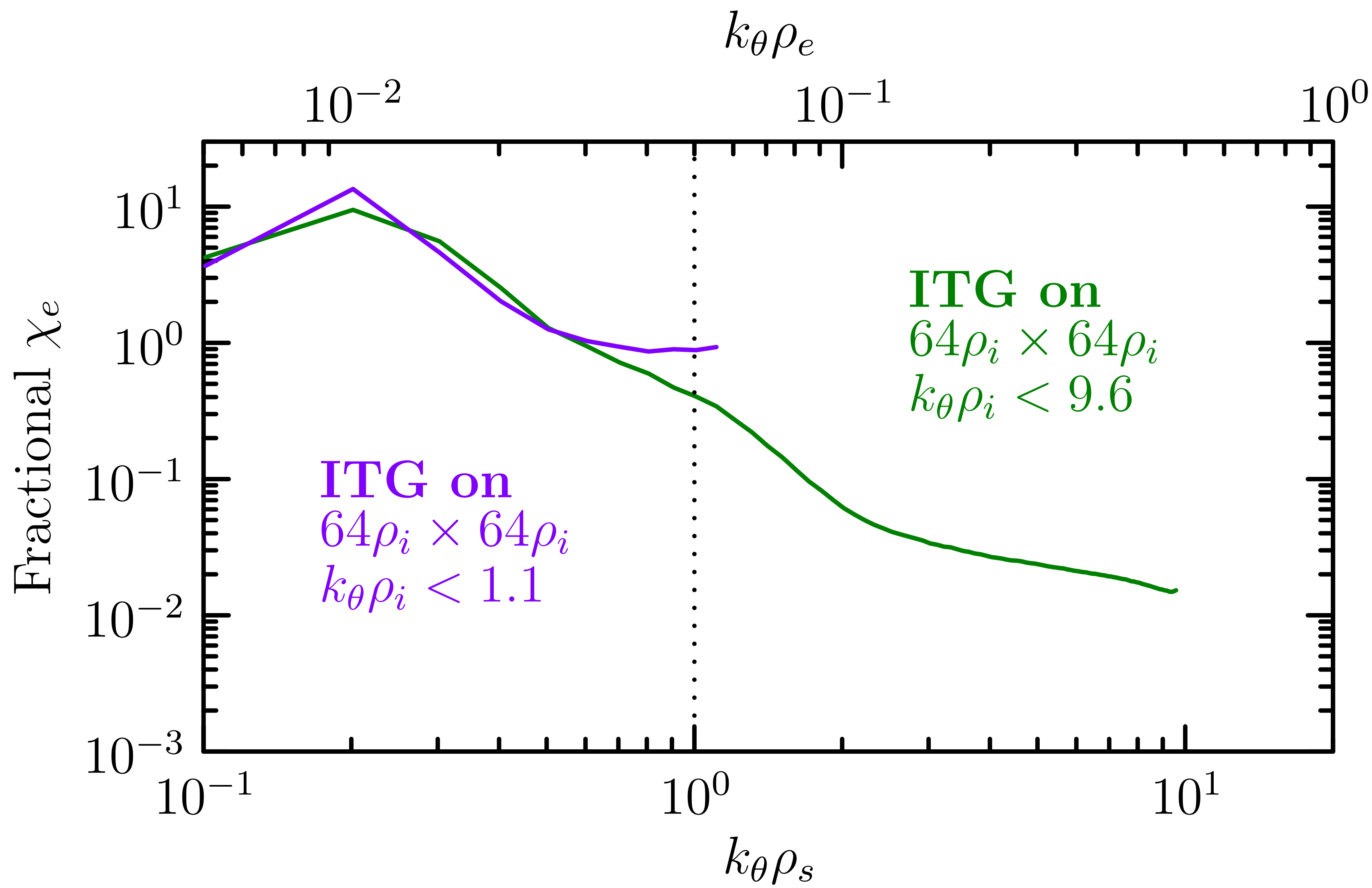
Coupled ITG/TEM-ETG Turbulence (INCITE Award)

Turning on ITG gives rise to decrease in short-wavelength transport



Coupled ITG/TEM-ETG Turbulence (INCITE Award)

Coarse grid leaves *lip* in electron heat transport



Endloss Studies with TEMPEST

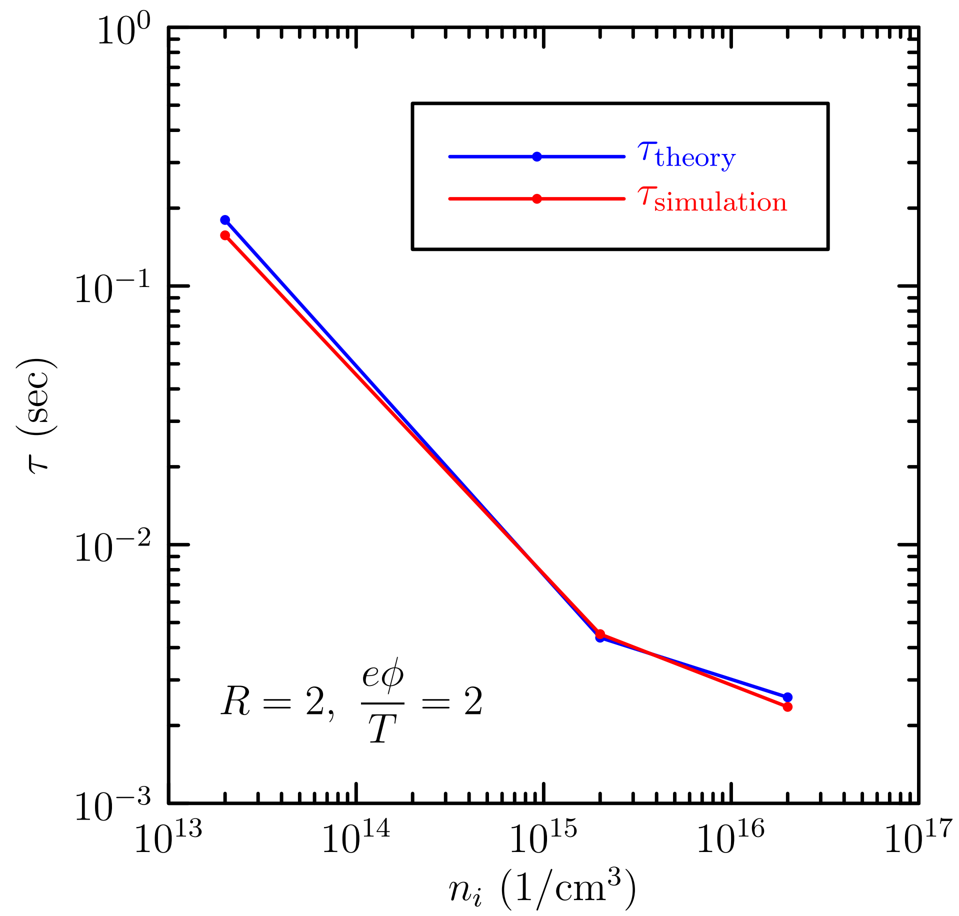
Velocity-space resolution requirements are shown to be modest

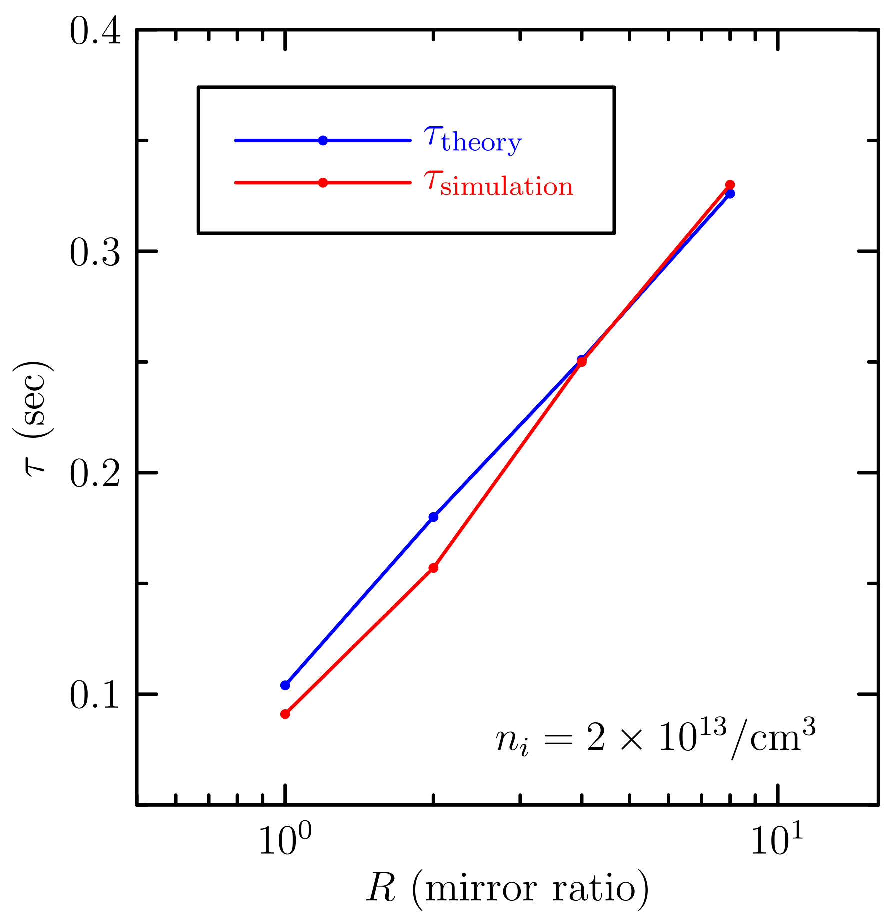
- Velocity-space **loss holes** are important for edge physics
  - Electron loss to divertor plates
  - Orbit loss of ions originating inside separatrix
- Tempest used to study endloss in combined magnetic and potential well
  - Fokker-Planck **collisions** and **parallel streaming**.
  - 3D study (2D velocity space).
  - Results show excellent **agreement with theory** over wide range of **potential, mirror ratio, collisionality**
- Modest v-space resolution requirements
  - plan to further reduce with v-space **adaptivity**.

Endloss Studies with TEMPEST

Simulations in close agreement with theory

First continuum simulations with full parallel motion (not bounce averaged)





Realistic Plasma Edge Simulation

New physics, greater computational challenges

- GK codes still fundamentally challenged in core.
  - high β, high s, steep gradients are problematic
- Must substantially generalize existing GK equations and simulation algorithms to properly simulate the edge:
  - New **nonlinearities**, comprehensive **collision** op.
  - Treat evolving **equilibrium** (begs issue of scale separation).
  - **Topology** change (open to closed field lines).
  - Must also work efficiently as a **core code**.
- True scope of challenges **not fully appreciated** now.

Success is very far off

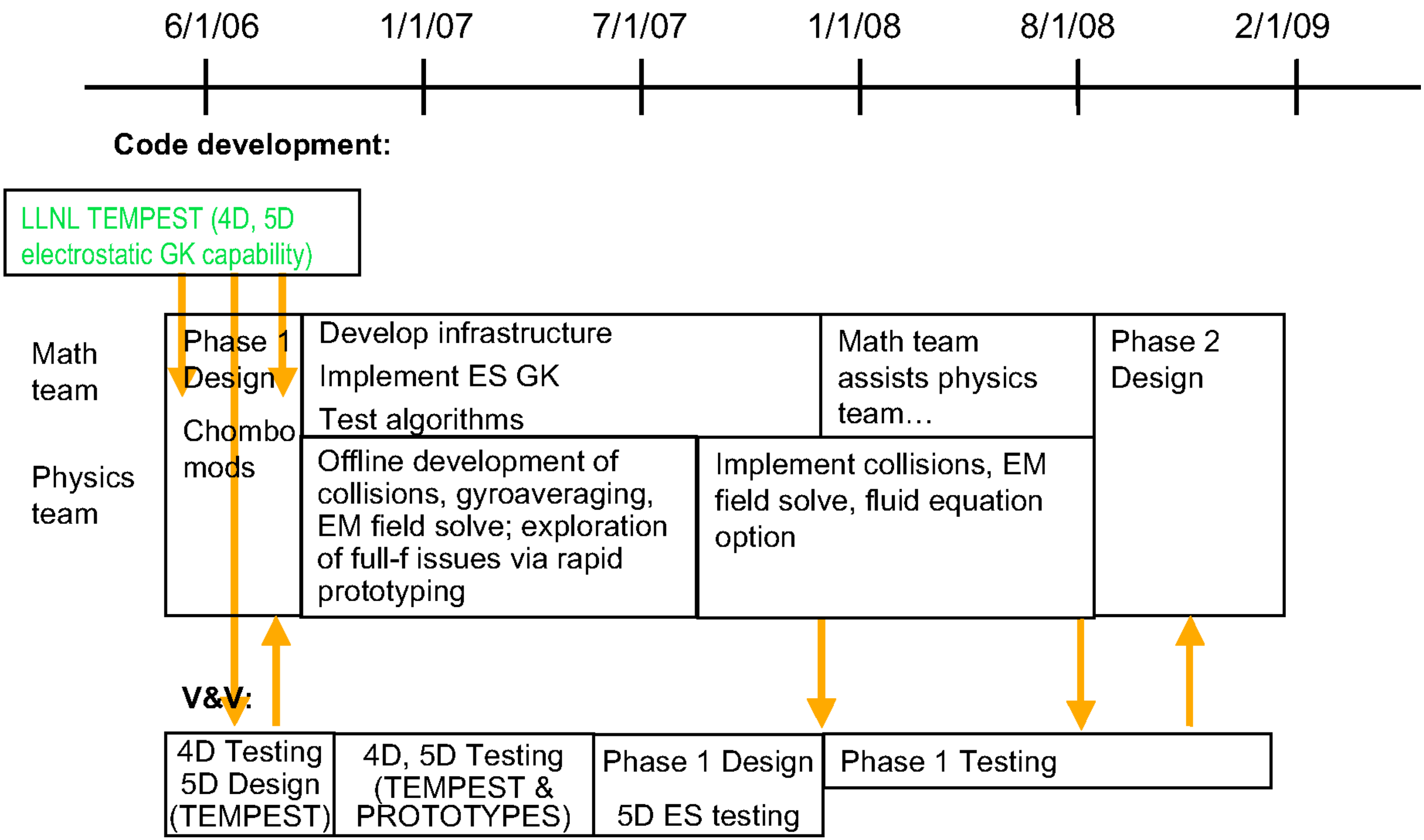
Edge Simulation Laboratory (ESL)

Bringing proven continuum methods to bear on edge gyrokinetics

- Project to develop 5D gyrokinetic code **valid in plasma edge**
  - OFES/OASCR base program activity.
  - Involves LLNL, GA, UCSD, LBNL, PPPL; **others welcome**.
- Use proven **Eulerian (continuum)** approach.
- Draw from continuum **knowledge base**: TEMPEST (LLNL), GYRO (GA).
- Code capability **goals**:
  - electromagnetic **(as in GYRO,GS2)**.
  - full divertor geometry **(as in TEMPEST,BOUT)**.
  - large-amplitude fluctuations: $\delta f/F \sim 1$ **(continuum $=$ noise-free)**.

Edge Simulation Laboratory (ESL) Roadmap

Tentative project timeline (2006-2009



ESL to Employ New Solvers for *Full F* Simulations

Finite Volume (FV) Techniques (Colella, Dorr)

- FV methods are good candidates for GK equation in **conservative form**:

$$\frac{\partial}{\partial t}(JF) + \frac{\partial}{\partial z_i}(\dot{z}_i JF) = 0$$

  - Enable manifestly **conservative discretization**.
  - **Average over spatial control volumes** to obtain a discrete equation for volume averages of JF.
  - **High-order** methods obtained by computing flux integrals to specified order
  - **Freestream preservation** (discrete divergence of a constant vector field is zero) is obtainable with minimal assumptions about the quadrature scheme
  - Can treat complex geometries: **multiblock mapped grids**, **embedded boundary discretiations**.

References

[1] D.W. Ross and W. Dorland. *Phys. Plasmas* **9**, 5031 (2002).

[2] J. Candy and R.E. Waltz. *Phys. Rev. Lett.* **91**, 045001–1 (2003).