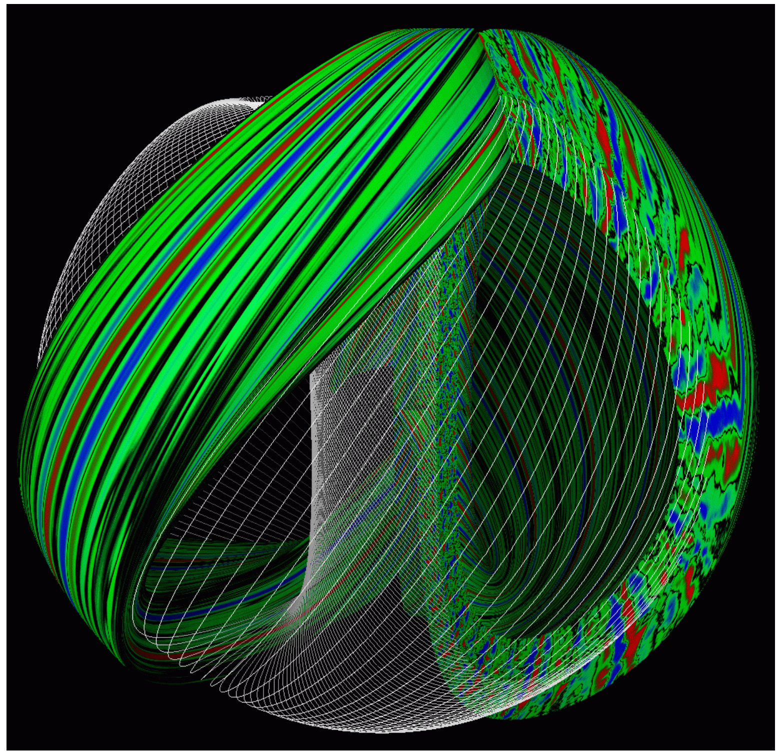
The Plasma Microturbulence Project

http://fusion.gat.com/theory/pmp/



Direct Numerical Simulation of Plasma Microturbulence

Presented at PPPL, August 3-4, 2001 by

G. W. Hammett (& B.I. Cohen) for W.M. Nevins, P.I.

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Computer Simulations —A Testbed for Understanding Turbulent Transport

Turbulent plasma transport is:

$\Rightarrow$ An important problem:

Size of an ignition experiment determined by fusion self-heating $\Leftrightarrow$ turbulent transport losses

$\Rightarrow$ A challenging problem:

Turbulence is the outstanding unsolved problem of classical physics

$\Rightarrow$ A terascale problem

Teraflop computers make high resolution simulation of the full set of fundamental equations possible

Computational Center for the Study of Plasma Microturbulence

- Development and applications of advanced gyrokinetic simulations, and comparisons to theory and experiment
- Development and deployment of shared software tools, including interfaces, diagnostics, and analysis tools
- Establishment of a *Summer Frontier Center for Plasma Microturbulence*
- Multi-institutional team: GA, LLNL, PPPL,UMD, CU, UCLA.   (P.I.=Bill Nevins)
- Project builds on experience and investment in Num. Tok. Turb. Project and leverages off OFES Theory base program.

Why is Simulation of Plasma Turbulence Important?

- Energy confinement is key problem in MFE
  - Confinement quality measured by $n\tau_E T$
  - Current experiments have achieved $n\tau_E T \sim 10^{21}$ keV-s/m^3
  - Burning plasma experiment requires $n\tau_E T \sim 10^{22}$ keV-s/m^3
  - Facility cost scales (roughly) with $n\tau_E T$
- Dominant energy loss mechanism in magnetic confinement devices is turbulent transport

$\Rightarrow$ Understanding turbulent transport would allow us to get more $n\tau_E T$ for the same dollars

- **Direct numerical simulation** of turbulence is a cost-effective and easily diagnosed proxy for very expensive experiments. Simulations facilitate understanding and are necessary to develop a predictive modeling capability.

The Plasma Microturbulence Project Has Produced Results

- Numerous invited talks at ‘00 & ‘01 APS-DPP, ‘00 IAEA, ‘01 TTF, and ‘01 Sherwood: Dimits, et al., IAEA ‘00; Dorland, IAEA ‘00; Lin et al., IAEA ‘00; Y. Chen, APS-DPP ‘00; Nevins, APS-DPP ‘00; Cohen, APS-DPP ‘01; Waltz, APS-DPP ‘01; Jenko, Sherwood ‘01; Leboeuf, Sherwood ‘01; Candy and Waltz, EPS ‘01; Jenko, EPS ‘01; Hallatschek TTF ‘01; etc.

- Numerous publications in refereed journals: Dorland, et al., PRL **85** (‘00); Rogers, Dorland, et al., PRL **85** (‘00); Y. Chen and Parker, PoP **8**, 441 & 2095 (‘01); Dimits, et al., Nuc. Fusion **41**, (‘01); Kim & Parker, J.Comp.Phys. **16** (‘00); Leboeuf, et al., PoP **7** (‘00); Lin and Chen, PoP **8** (‘01); Rettig, Leboeuf, et al., PoP **8**, (‘01); Snyder & Hammett, PoP **8** (‘01); etc.

- Experimental contributions: Budny (JET), McKee (DIII-D), Murakami (DIII-D) IAEA ’00, Kinsey (DIII-D) PRL ’01. Ernst (TFTR) PoP ’00, many others.

- The PMP has had the single largest allocation at NERSC for a few years.

The Physics Model

Magnetic Coordinates:

$$\boldsymbol{B} = \nabla\alpha \times \nabla\psi$$

Perturbed 5-D distribution function:

$$h_s = h_s(\psi, \alpha, \theta, \varepsilon, \mu)$$

Gyrokinetic equation:

$$\left(\frac{\partial}{\partial t} + \hat{\mathbf{b}} \cdot \times \nabla\Phi \cdot \nabla + v_{\|}\hat{\mathbf{b}} \cdot \nabla + i\omega_d\right)h = i\omega_*^T \Phi - q\frac{\partial F_0}{\partial \varepsilon}\frac{\partial \Phi}{\partial t}$$

where:

$$\Phi = J_0\left(\tfrac{k_\perp v_\perp}{\Omega}\right)\left(\phi - \frac{v_{\|}}{c}A_{\|}\right) + \frac{J_1\left(\frac{k_\perp v_\perp}{\Omega}\right)}{\frac{k_\perp v_\perp}{\Omega}}\frac{mv_\perp^2}{q}\frac{\delta B_{\|}}{B}$$

Reduced Maxwell's Equations

Electrostatic potential:

$$\nabla_\perp^2 \phi = 4\pi \sum_s q \int d^2v \left[q\phi \frac{\partial F_0}{\partial \varepsilon} + J_0\left(\tfrac{k_\perp v_\perp}{\Omega}\right)h \right]$$

$\delta B_\perp$:

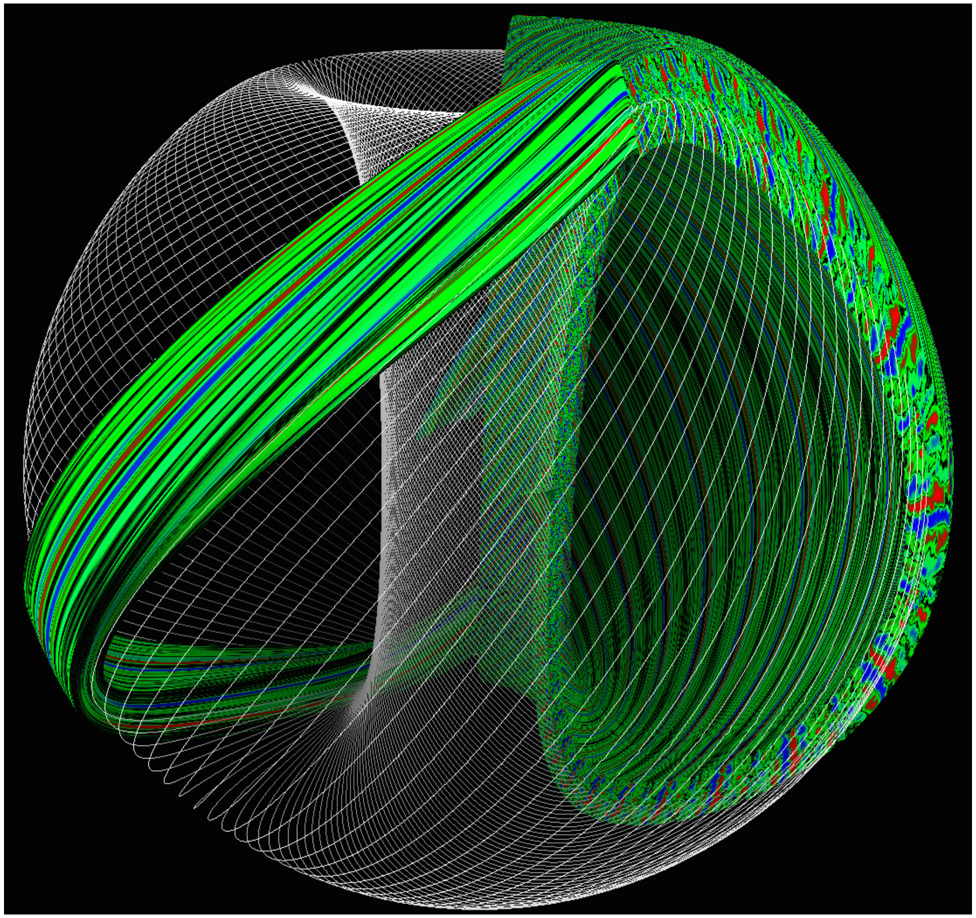
$$\nabla_\perp^2 A_{\|} = -\frac{4\pi}{c}\sum_s \int d^2v \;\; q v_{\|} J_0\left(\tfrac{k_\perp v_\perp}{\Omega}\right)h$$

$\delta B_{\|}$:

$$\frac{\delta B_{\|}}{B} = -\frac{4\pi}{B^2}\sum_s \int d^2v \;\; mv_\perp^2 \frac{J_1\left(\frac{k_\perp v_\perp}{\Omega}\right)}{\frac{k_\perp v_\perp}{\Omega}} h$$

Plasma Turbulence Simulation Codes Already Developed

- Builds on NTTP effort
- Realistic Geometry & efficient grids aligned with $\boldsymbol{B}$ ($k_{\parallel} << k_{\perp}$) :
  - Flux-tube codes
  - Global codes
- Efficient Algorithms
  - $\Rightarrow$ **Gyrokinetic—Continuum**
  - $\Rightarrow$ **Gyrokinetic—PIC**
- Demonstrated scaling to 100’s of processors



Plasma Microturbulence Project Relies on a Small Suite of Codes

- PMP code suite: 2x2 matrix of global and flux-tube codes using gyrokinetic Vlasov continuum and particle methods. Building shared back ends for diagnostics and visualization, shared front end for experimental data interfaces.

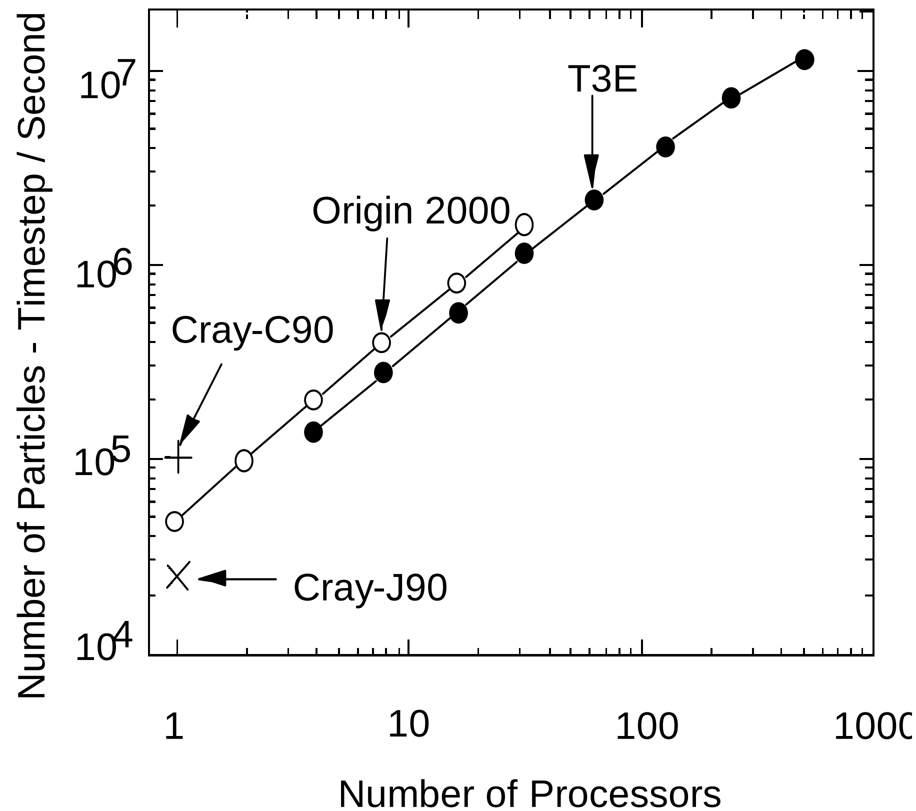
- Both global and flux-tube codes are needed. Flux-tube is more efficient for parameter studies, does *not* trip over problems of plasma particle and energy sources or profile relaxation, and more readily includes physics at scales less than the ion Larmor radius (e.g., ETG). Global (nonlocal) accommodates equilibrium profile variations and scaling wrt Larmor radius over minor radius nonperturbatively.

- Vlasov continuum and particle approaches have different computational advantages/disadvantages. Having two approaches has been vital for cross-checking results and error correction, and has provided opportunities for innovation and creativity.

Existing Codes (I)
Gyrokinetic Particle Codes

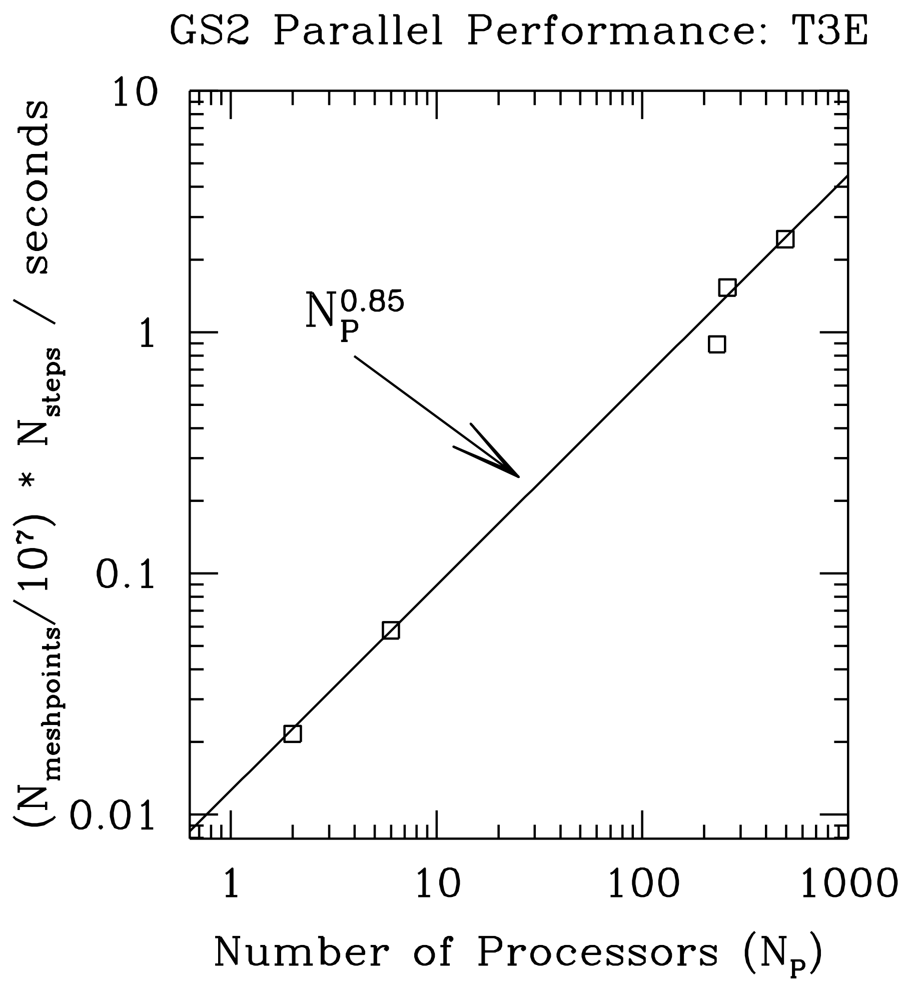
- Integrates GKE along characteristics
  - ⇒Many particles in 5-D phase space
  - ⇒Interactions through self consistent electric & magnetic fields

⇒Particles advanced in parallel



Existing Codes (II): 5-D Continuum Codes

- Solves GKE on a grid in 5-D phase space (multiple domain decomposition used)
- Eliminates discrete particle noise
- Linear physics is handled implicitly in GS2
  - ⇒ Kinetic electrons & electromagnetism have less impact on time step
- Global code GYRO is explicit, uses advanced CFD methods.



Under PSACI Auspices the PMP Proposal Was Approved to:

- **Explore new regimes of plasma microturbulence using existing and newly developed codes**
- **Develop advanced simulation algorithms for**
  - New generations of computers, e.g., IBM SP
  - New physics capabilities, e.g., kinetic electrons and electromagnetic fluctuations
- **Build advanced, shared diagnostics** to provide a bridge between simulation effort and theory & experimental communities

PMP physics focus: extend to kinetic electrons + electromagnetics

- Past decade: major progress on "Ion Temperature Gradient" (ITG) plasma turbulence in the electrostatic limit ($E = -\nabla\Phi(x,t)$, $\boldsymbol{B}$ = const), often w/ adiabatic/Boltzmann electrons $n_e = \exp(-q\Phi/T)$.
- Explains main trends in core of many experiments: marginal stability effects, turbulence suppression, self-generated zonal flows. But not sufficiently accurate for all plasma regimes, neglected electron heat and particle transport.
- Plasma Microturbulence Project major goal: extend to non-adiabatic electrons and fully electromagnetic fluctuations
  - Important at high β = (plasma pressure)/(magnetic pressure)
  - Needed for advanced fusion concepts
  - Hard: electrons are 60 times faster than ions, severe Courant condition
  - PIC numerical problems when $\beta > m_e/m_i$, recently solved with split-weight / fluid-kinetic hybrid algorithm

Plasma Microturbulence Project Addresses Scientific Issues

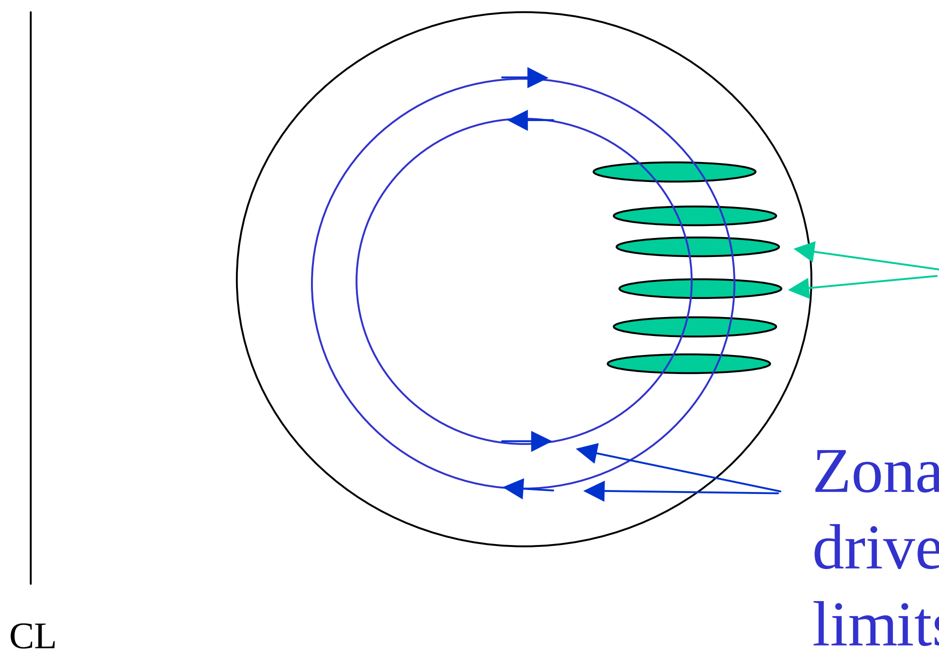
- Secondary instabilities, streamer and zonal flow dynamics
- Kinetic electrons and electromagnetic fluctuations
- Formation and dynamics of internal transport barriers
- The role of meso-scales in turbulent transport

$\Rightarrow$ Tractable models of turbulent transport

Plasma Microturbulence Project Deliverables

- ⇒ Mutually benchmarked, well diagnosed, electromagnetic, microturbulence codes (‘01-’02)
- ⇒ Advanced data analysis and visualization capability(‘01-’02)
- ⇒ Prototype national database for storing code output (working with fusion collaboratory, to be determined)
- ⇒ Better understanding of plasma microturbulence, detailed experimental comparisons (continuing)
- ⇒ SUMMIT shared electromagnetic+kinetic electron code (Fall ‘01)
- ⇒ GYRO adds electromagnetic capability (Fall ‘01)
- ⇒ Pace of code development is slowed compared to proposal because of reduced funding.

Studies of importance of “zonal flows”, secondary instabilities…



Primary instabilities, carry heat from center to edge

Zonal flows (on small scale, driven by secondary instabilities, limits the primary instabilities).

Why don’t zonal flows always grow to kill turbulence?

(enlarged view of small scale turbulence not to scale)

Physics Progress I: Secondary Instabilities

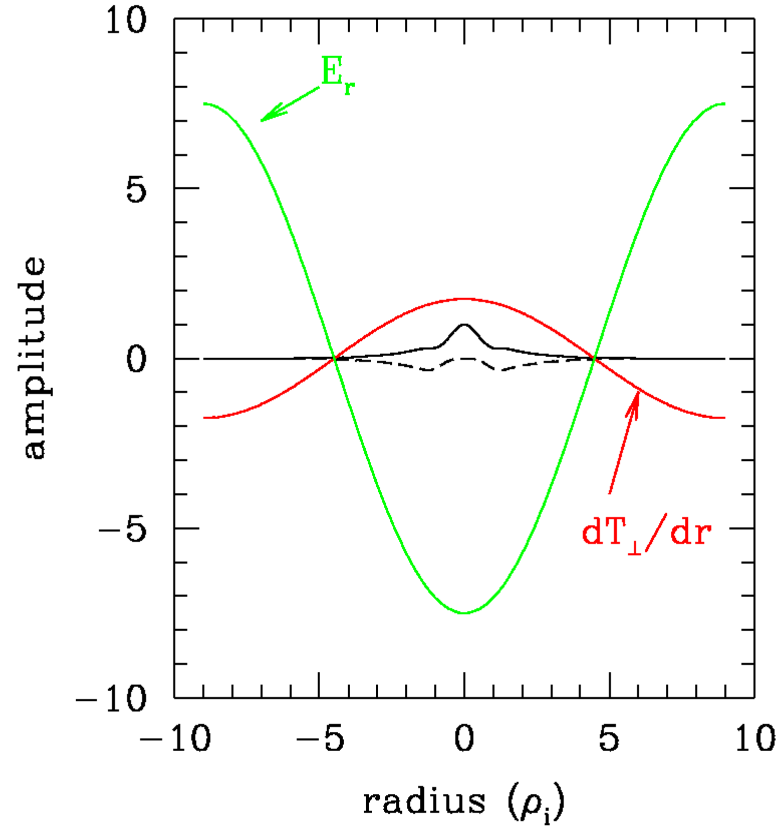
- Parasitic instabilities on zonal flows

  $\Rightarrow$ Limits zonal flow amplitude

  $\Rightarrow$ Increase in ITG turbulence and plasma transport

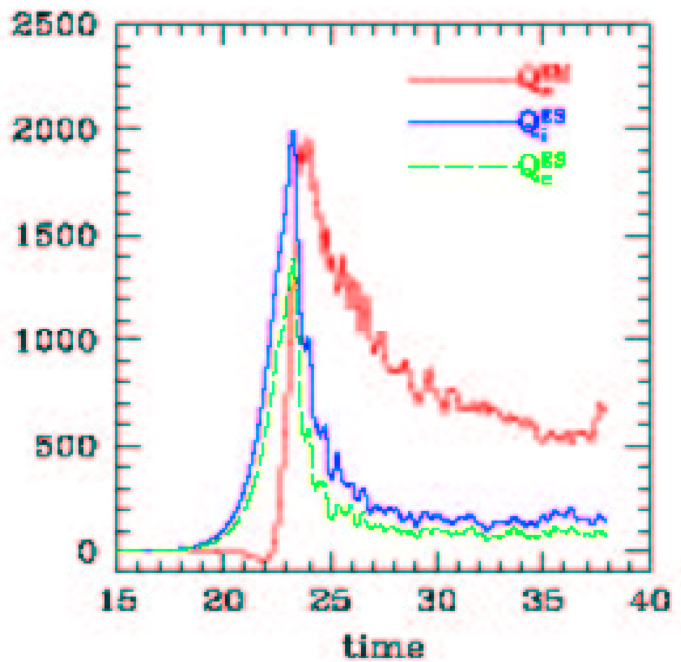
  $\Rightarrow$ Mechanism for 'Dimits shift'

- Talk by W. Dorland IAEA 2000, Rogers PRL 2000
- Also seen by Dimits in PG3EQ (Nevins, TTF '01)



Physics Progress II: GS2 Simulations of Electromagnetic ITG Turbulence

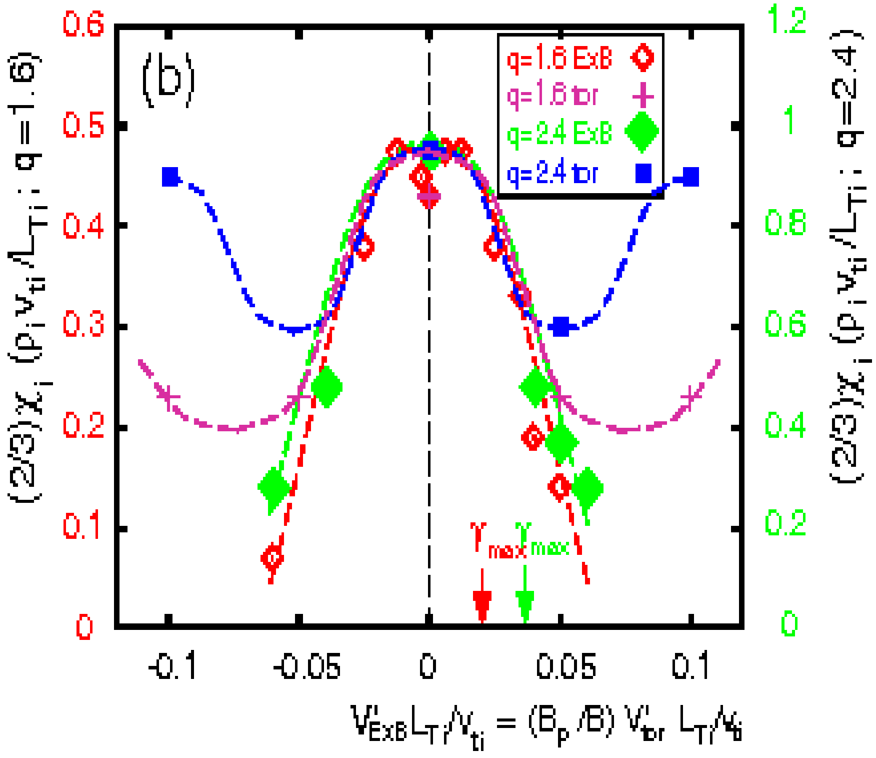
EM ITG modes can produce significant electromagnetic electron thermal flux.



- As β approaches ideal ballooning limit, character of ITG changes.
- Energy transport dominated by nonlinear magnetic flutter transport.

Physics Progress III: PIC Studies of ITG Turbulence

- Dependence of χ_i on T", Φ"
  - ⇒ Importance of ion radial force balance in initial state
- Dependence of χ_i on
  - – magnetic shear
  - – E×B shear
  - – Toroidal flow shear
  - ⇒ Significant departures fromWaltz-Dewar-Garbet transport reduction model
- A. Dimits at IAEA 2000 and TTF '01, PG3EQ flux-tube simulations

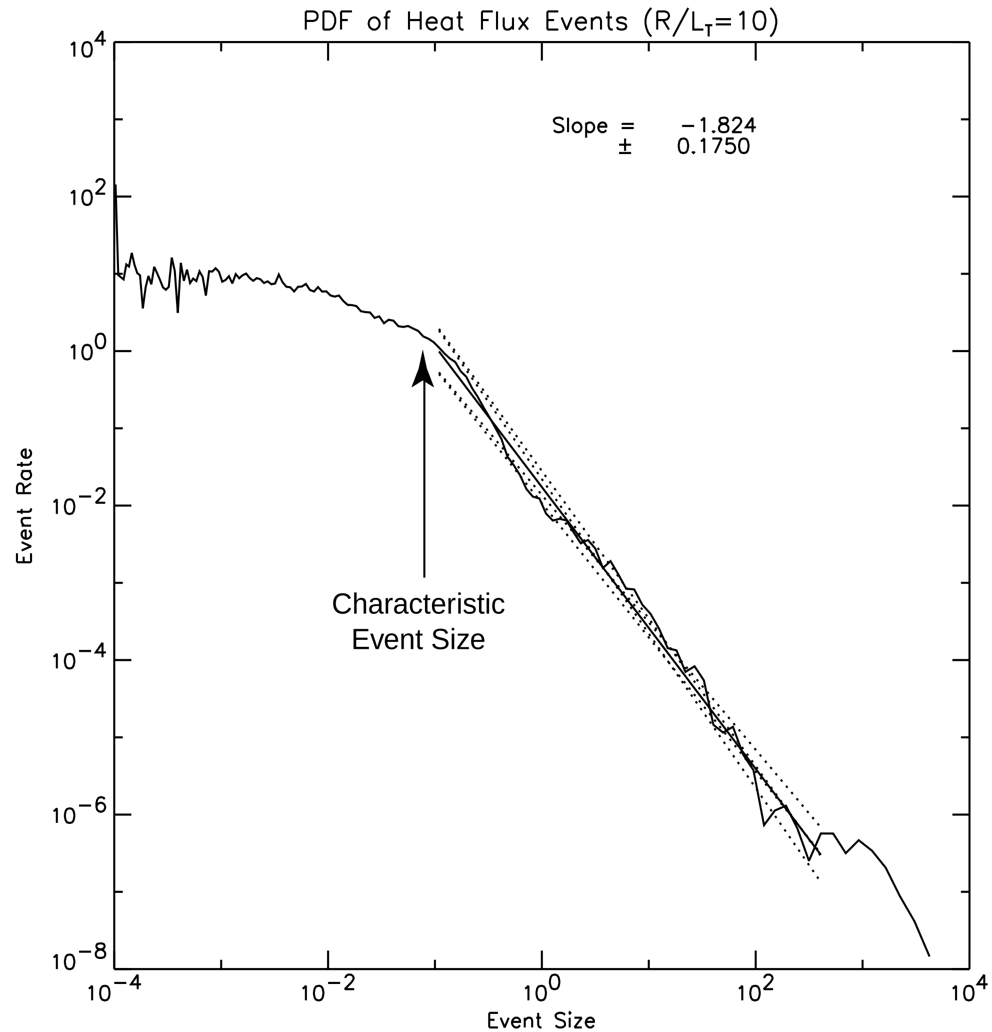


Physics Progress IV: SOC & Heat Pulse Analysis

- In analogy to Newman's work on SOC & transport:
  - Decompose heat flux into sum of 'heat pulses'
  - Probability Dist. Function: pulse rate vs. pulse size
  - $\Rightarrow$ PDF yields power law

$\Rightarrow$ Explanation of Bohm transport scaling?

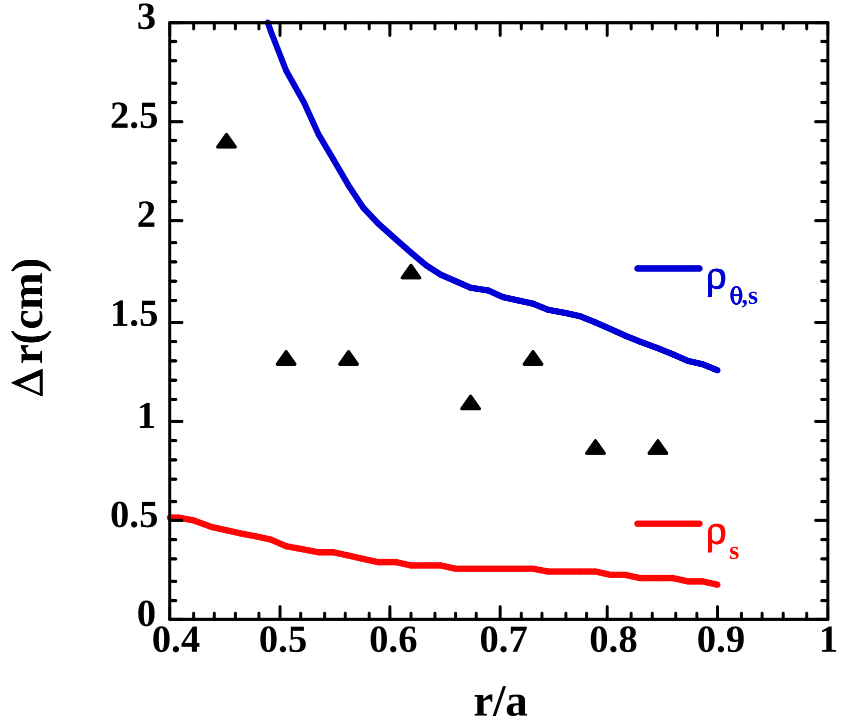
- Talk by Nevins at APS/DPP 2000



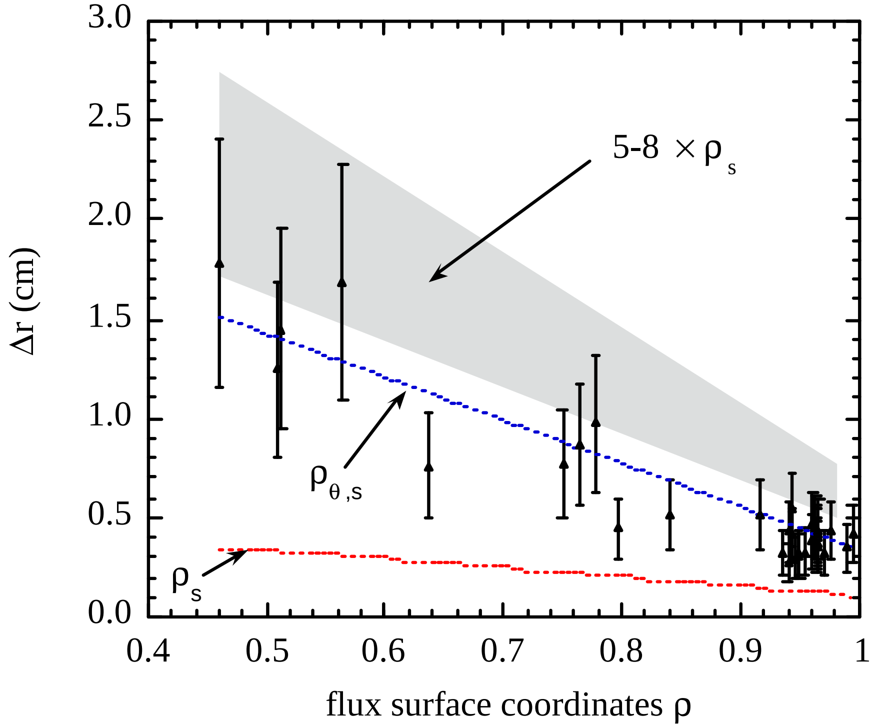
Physics Progress V: Comparing Global Gyrokinetic Particle Simulation To Experimental Observations

- Preliminary work looks like a promising foundation for future thrust of microturbulence effort: DIII-D Radial Correlation Lengths

Gyrokinetic Results (UCAN)



Reflectometry Results



Physics Progress VI: Zonal Flows

- ITG turbulence

  $\Rightarrow$ Zonal Flows

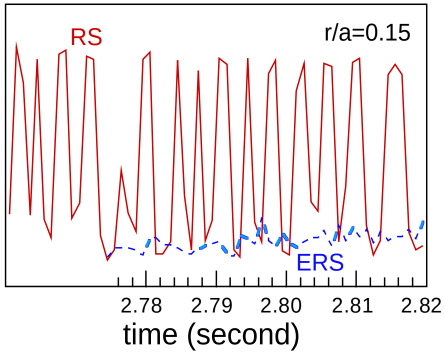
  $\Rightarrow$ Suppression of ITG turbulence

- ν_i damps zonal flows

  $\Rightarrow$ Bursting behavior

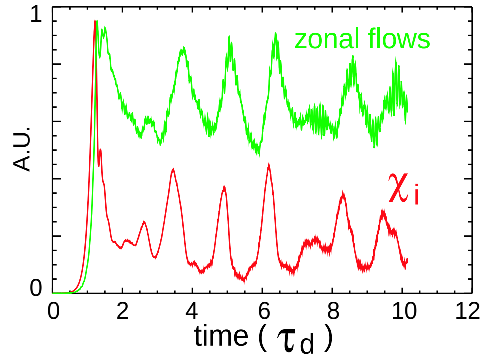
  $\Rightarrow$ Average transport ~ ν_i

- Talk by Z. Lin presented at IAEA 2000



[Mazzucato, et al., PRL, 1996]

large bursts of fluctuation in TFTR RS plasmas observed period ~ collisional flow damping time

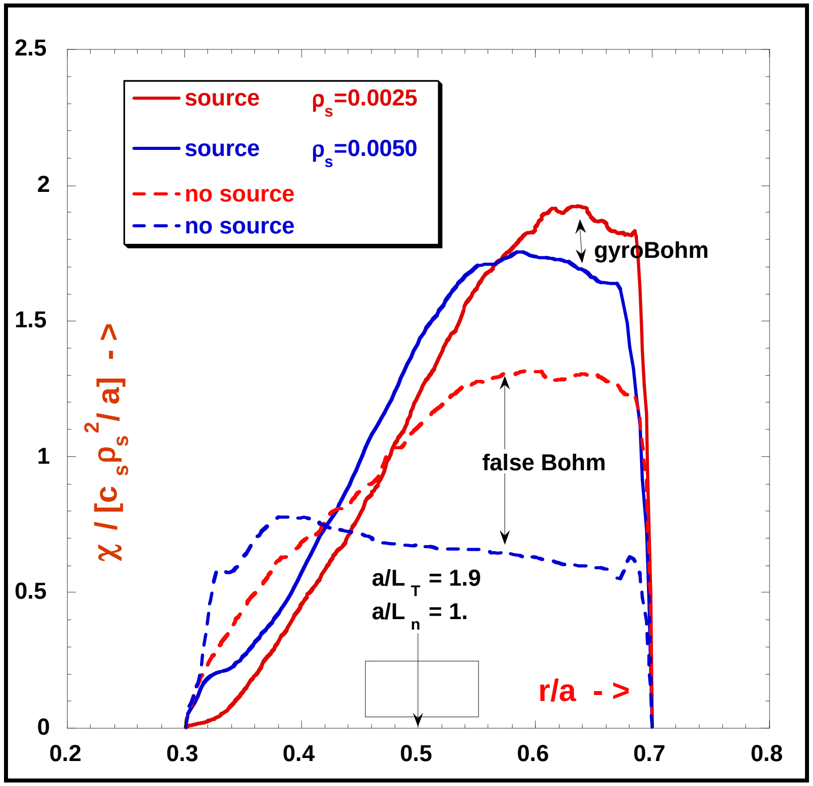


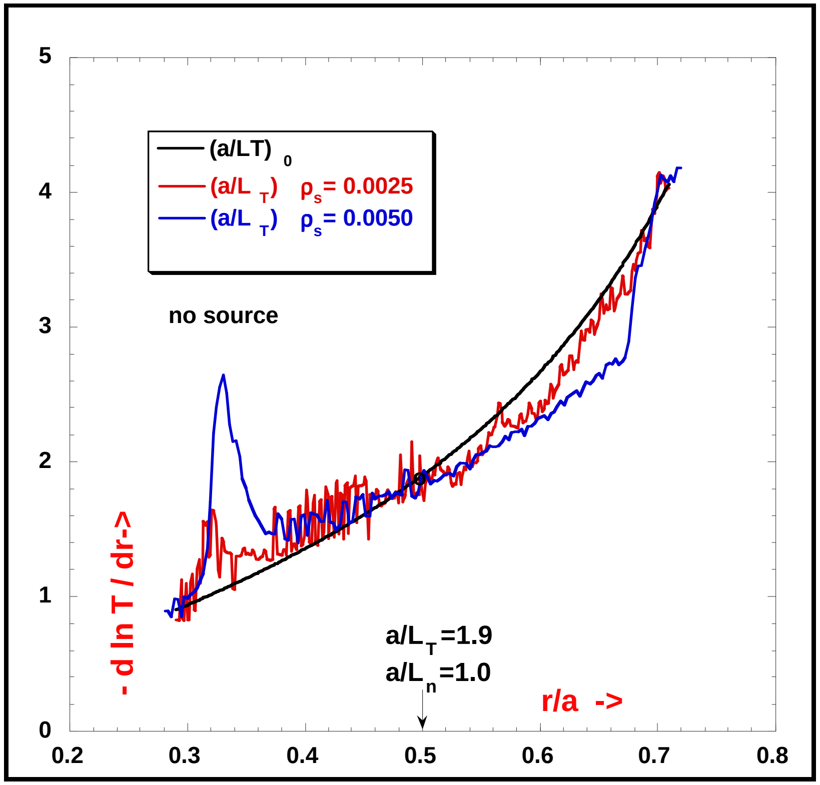
[Lin, et al., PRL, 1999]

collisional damping of zonal flows causes bursts of turbulent transport in gyrokinetic simulations

Physics Progress VII: Nonlocal Simulation of ITG Turbulence with Sources

- Inclusion of an adaptive source to maintain profiles in GYRO global simulations of ITG can restore gyro-Bohm levels of thermal transport.
- In absence of sources, small deviations from equilibrium profiles caused by n=0 perturbations can cause “false” Bohm transport.





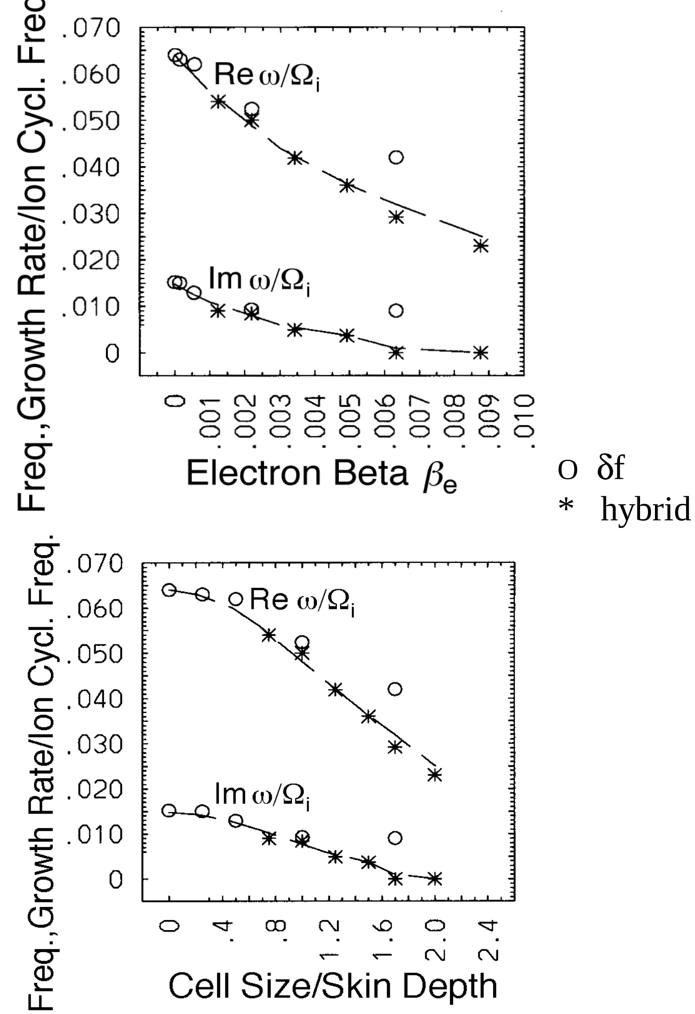
Kinetic Electrons and Electromagnetic Fluctuations

- Motivation:
  - Modeling of particle transport and electron thermal transport
  - Increased fidelity in modeling of ρ_i-scale turbulence [new sources of free energy, electromagnetic corrections]
  - Short wavelength turbulence and associated electron transport [$\rho_e \sim (m_e/m_i)^{1/2}\rho_i$ through $\delta_e = c/\omega_{pe} \sim (m_e/\beta m_i)^{1/2}\rho_i$]
- Status:
  - Fully electromagnetic gyrokinetic continuum codes exist [benchmarking of global/flux tube continuum codes in progress]
  - Electromagnetic, gyrokinetic PIC codes being developed based on the split-weight algorithm (Manuilskiy, W. Lee) combined with extended hybrid algorithm (Lin, L. Chen, Y. Chen, Parker, Cohen)
  - **Successful workshop at GA (July 24-26) on new methods and physics**
- Critical Issues:
  - Relaxed δ_e spatial resolution requirements in both continuum and PIC approaches for ITG and TEM applications.
  - Dominant electron dissipation in torus is likely from trapped electrons.

Progress on Kinetic Electrons I: Hybrid PIC Split-Weight Schemes in 2-1/2 D Slab

- Algorithm demonstrated in “2-1/2” D test problem
  - Simplified geometry
  - Reduced dimensionality
- Accurate linear physics required:
  - $\Rightarrow$ Δt resolution: $k_{\|} v_e \Delta t \leq O(1)$
  - $\Rightarrow$ Resolution of electron layer $[\ x_e \sim (m_e/m_i)^{1/2} L_s/L_n\ \rho_i\ ]$
- See Cohen et al., APS/DPP 2000 and 2001, Sherwood ‘01

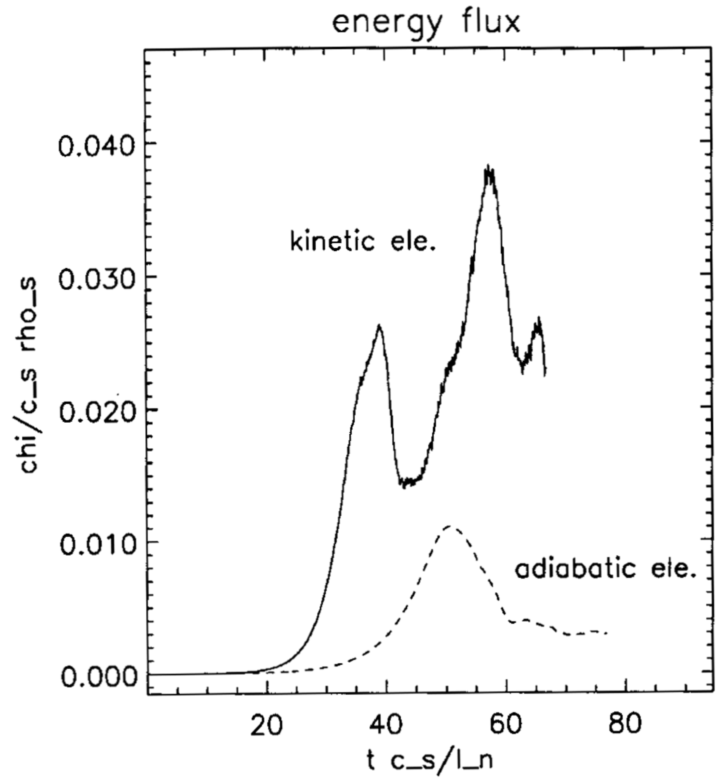
Collisionless Drift Wave



Progress on Kinetic Electrons II: Split-Weights in Field Line Coordinates

- 3-D electromagnetic gyrokinetic PIC (Y. Chen-Parker)
- Full drift kinetic electrons (i.e., ignores finite ρ_e)
- Accurate physics on ρ_i grid for
  - $\beta \leq 0.5\%$
  - $k_{||} v_{te} \Delta t \leq O(1)$
- Talk by Y. Chen at APS/DPP 2000 and PoP

With DIII-D H-mode parameters, χ_i is much higher with kinetic electrons.



What's Next with Kinetic Electrons and Electromagnetic Effects

- GS2 flux-tube continuum code has kinetic electrons and electromagnetics; increase physics throughput, benchmarks, and expand user base
- LLNL/CU/UCLA merging PG3EQ and TUBE with δB and kinetic electrons in a shared code (SUMMIT)
- Kinetic electrons working in GYRO global continuum code, and electromagnetic imminently
- Inclusion in GTC (a global GK-PIC code)
  - Kinetic electrons + electrostatics work. Electromagnetic next.
  - Collaboration with L. Chen, UC Irvine

Diagnostics & Visualization I: Interactive Data Analysis with GKV

- An object-oriented data analysis system with:
  - Correlation functions, cross correlation, bicoherence, etc.
  - Spectral density, cross spectra, bi-spectra, etc.
  - x-space ⇔ k-space transformations
  - Heat pulse analysis
  - Animations
  - … (more to come)

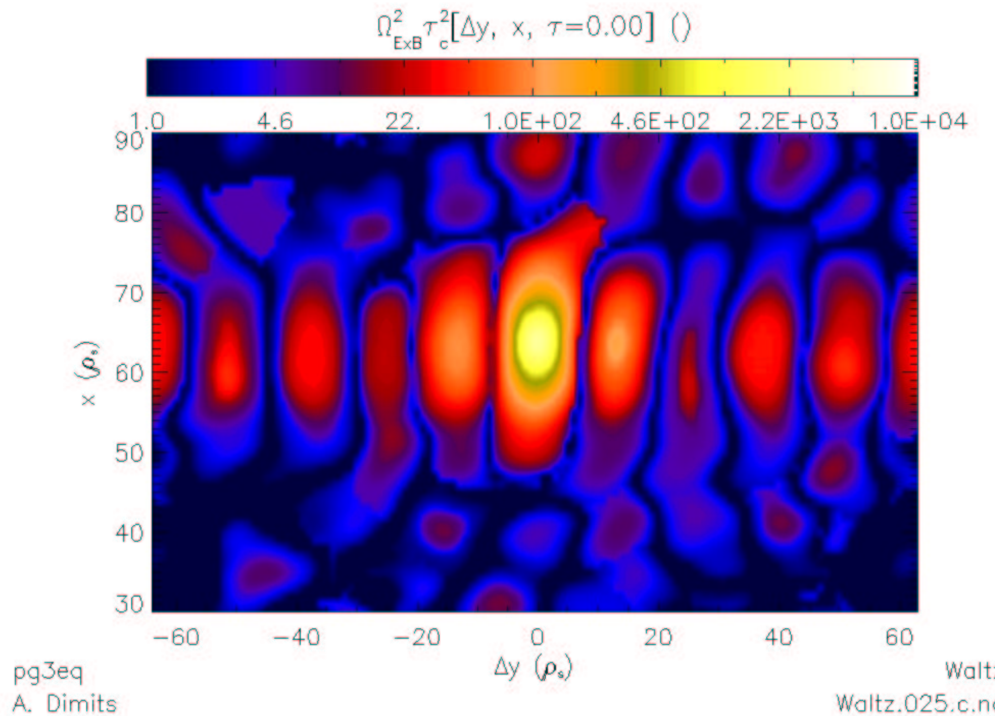
- GKV interfaces with:
  - Pg3eq (LLNL GK-PIC code)
  - GTC (PPPL GK-PIC code)
  - GS2 (U. of Md GK-C code)
  - UCLA GK-PIC code
  - BOUT (LLNL edge code)
  - … (more to come)

  - Nevins presentations at APS-DPP '00 and TTF '01

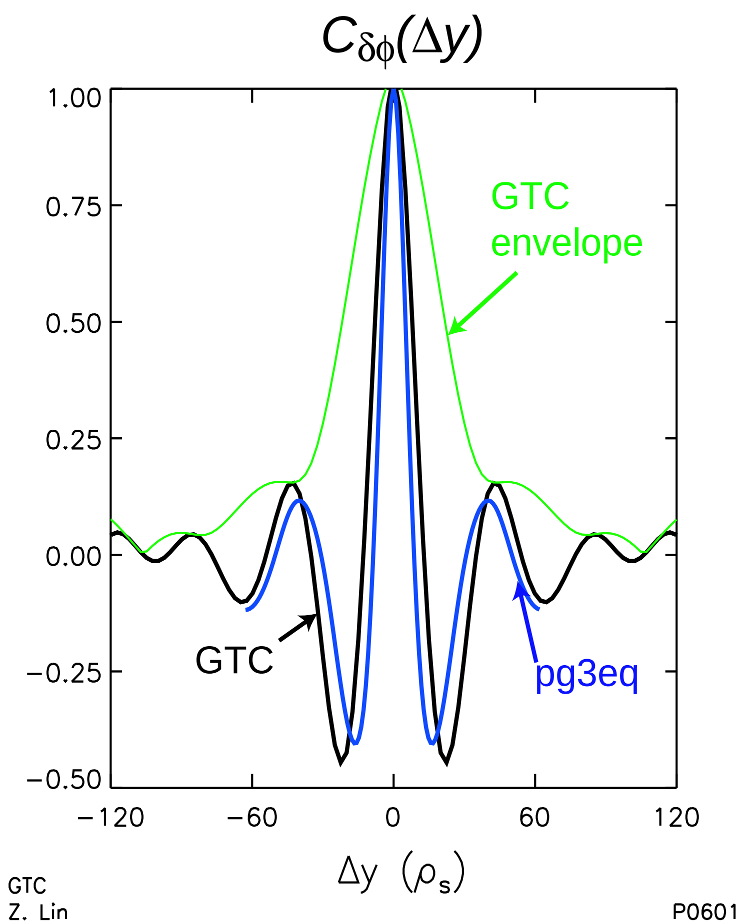
Data Analysis: The Bridge between Simulation and the Theory/Exp Communities

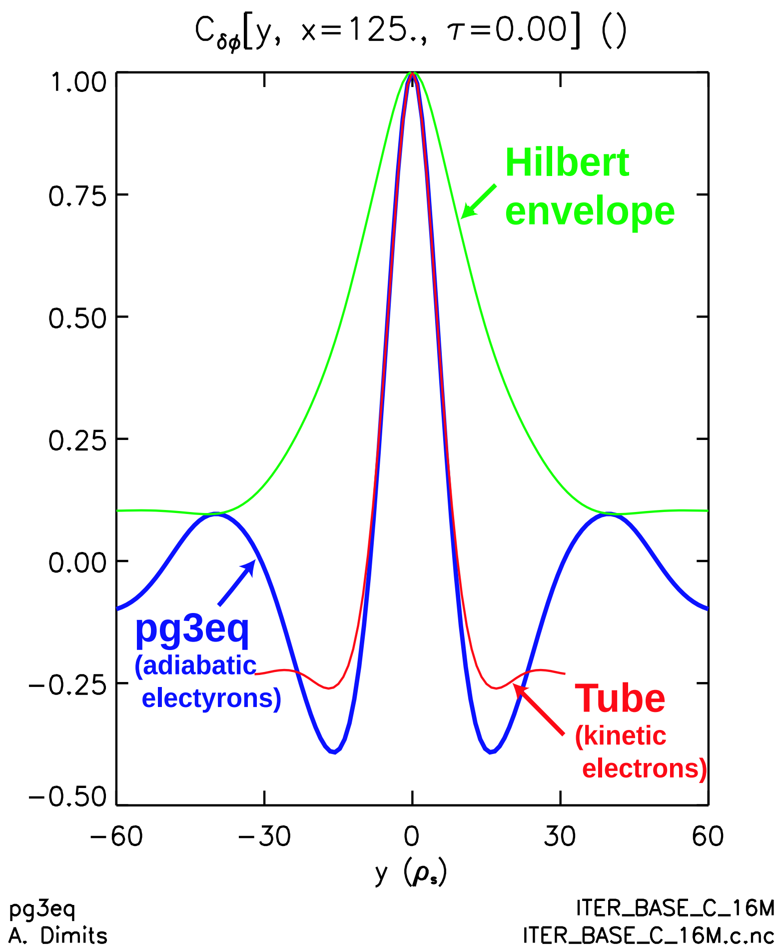
- Interactive Data Analysis with GKV
  - – Productive data exploration
  - ⇒ “Granularity”
    - Significant results few commands
    - Flexibility
  - – Standard analysis routines
    - Spectral density
    - Correlation functions
  - – Custom Analysis
    - Particle Trapping
    - Heat Pulse Analysis

Quantifying the Importance
Of particle trapping



Correlation Functions Calculated with GKV: Allows detailed cross comparisons of codes (and eventually with expt. fluctuation measurements)





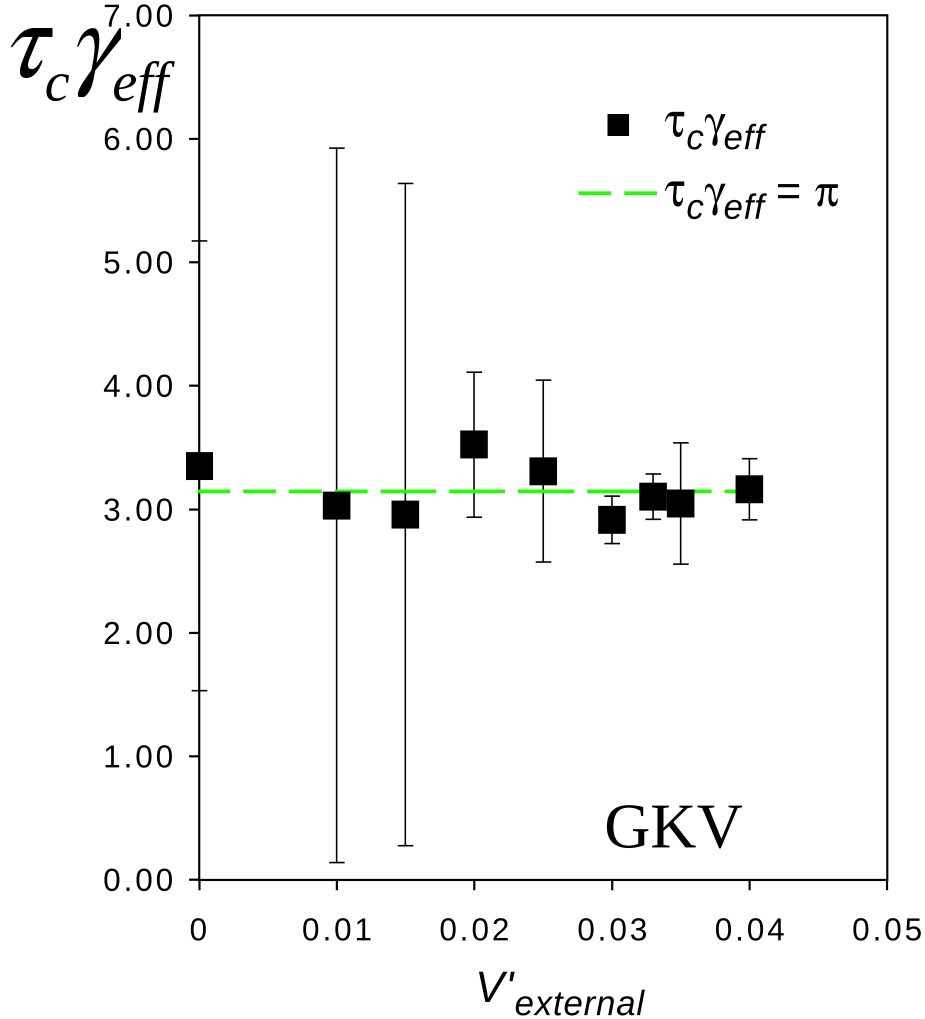
τ_c Determined by Effective $E{\times}B$ Shear

- Effective E×B Shearing Rate:
  - Contributions from $V'_{external}$ and zonal flows
  - Remove high-ω, high-k_x components of zonal flow

$$\gamma_{eff} = \frac{\Delta R}{\Delta y}\sqrt{V'^2_{external} + \left\langle V'^2_{zonal}\right\rangle_{\substack{\omega\tau_c<1 \\ k_r\Delta R<1}}}$$

- L-Mode simulation data shows

$$\tau_c \approx \frac{\pi}{\gamma_{eff}}$$

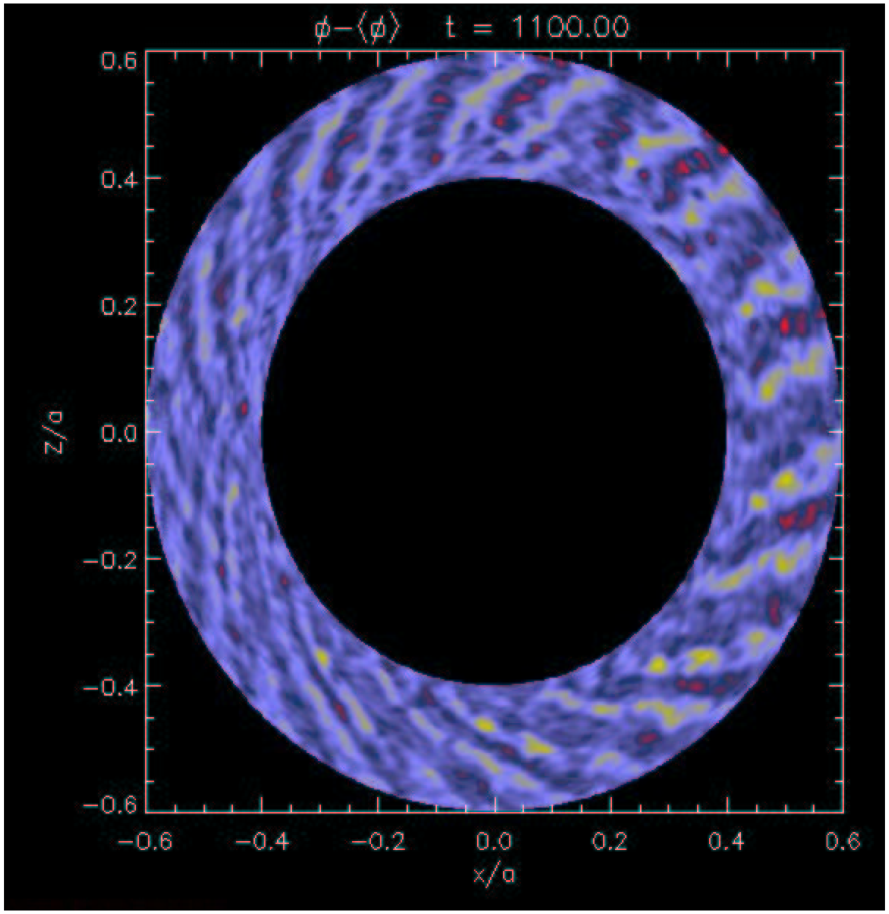


Data Analysis and Visualization II: Other Visualization Tools

- GYRO Visualization tools

- See invited talk by Waltz at APS/DPP 2001

  using a continuous stream of animations to illustrate the drift-ballooning modes and zonal flows in linear and fully developed states of ITG turbulence



Data Archiving

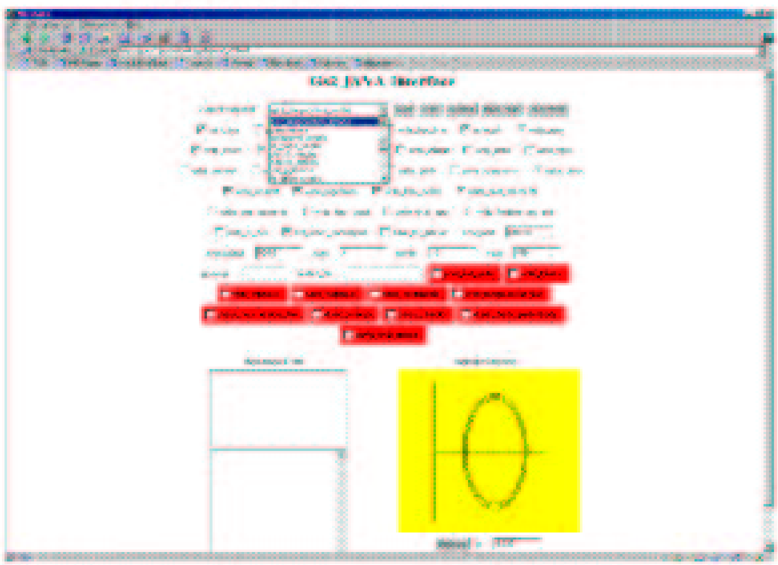
- A major issue in comparing results between codes is access to data
- Bill Dorland is working with Greenwald/Yuh (MIT) and Schissel (GA) on prototype system
  - Based on MDS Plus (data archiving system widely used by experimentalists)
  - Designing MDS Plus tree:
    - Input (grid params, physics params, transp run, …)
    - Output (record of what information was saved)
    - Raw data
- Data archiving effort will be expanded (in support of PMP and other PSACI projects)

GS2 User Community

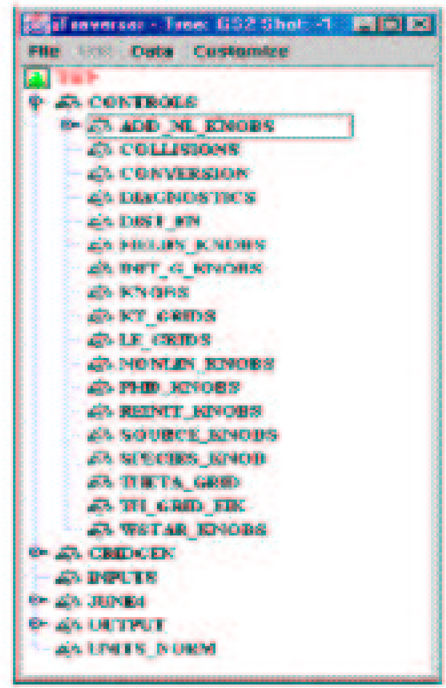
- **C. Bourdelle**, PPPL: NSTX
- **E. Belli**, PPPL: stellarator, NCSX
- **R. Budny**, PPPL: JET,transport bar.
- **S. Cowley**, Imperial College: tail of Goldreich-Sridhar cascade
- **A. Dimits**, LLNL: GK benchmarks
- **W. Dorland**, UMD: Collisional TEM, EM ITG/ETG, code support
- **D. Ernst**, PPPL: shear stab. models
- **P. Goswami**, UMD: dipoles, LDX
- **M. Greenwald**, MIT: MDS+ interface, C-Mod stability
- **K. Hallatschek**, IPP-Garch: particle transport and pinch analysis
- **G. Hammett**, PPPL: Advanced alg. development, benchmarking
- **F. Jenko**, IPP-Garch: ETG &TEM
- **M. Kotschenreuther**, IFS:Advanced alg. development, novel configs.
- **D. Mikkelsen**, PPPL: Experimental observ. of Dimits shift, C-Mod
- **B. Osborne**, UMD: Java interface
- **S. Parker and Y. Chen**, CU: collisionless TEM benchmarks
- **E. Quataert**, UC Berkeley: Astrophysics (β~1), black hole accretion disks
- **M. Redi, PPPL**: ITB formation in C-Mod
- **B. Rogers**, Dartmouth: EM turb. & reconnection
- **D. Ross**, FRC: Expt. Comparisons, DIII-D and C-Mod
- **A. Vinas**, NASA-Godd.: Solar wind
- **H. Yuh**, MIT: Stab. &Turb in C-Mod EDA modes

Java applet interface for GS2 inputs

- Java Applet facilitates GS2 input entry
  - Original program by Bryan Osborn (U. of Md.)
  - Modified to include MDS entry capabilities
    - Capable of retrieving GS2 input setups from any MDS server with GS2 tree
    - Centralized Java client will facilitate code maintenance, updates
    - It will be possible to submit runs with a web browser



- GS2 MDS tree created
  - Standard structure among multiples sites running GS2 simulations
    - It will be possible to submit runs with a web browser
    - Short implementation time for future sites
    - A Linux binary distribution of GS2 is available



What's Next for the Plasma Microturbulence Project?

- Continue and expand current efforts in:
  - Increasing interactions with experiments: collaborations with experimentalists and comparisons to data at DIII-D, C-MOD, JET, NSTX, LDX dipole, and stellarators
  - Develop and deploy single front and back end for flux-tube/global and continuum/PIC codes
  - Deploy PMP codes through the Fusion Collaboratory Project
  - Improved data analysis and visualization

    Exploit GKV and other PMP-shared diagnostics to compare simulations to one another and experiments -> more users
  - Code development and more physics in models
  - More physics results from existing codes
- The pace of these activities is slowed relative to the proposal's milestone schedule because of reduced funding. More money -> faster pace and convene Summer Frontier Center for a longer period.