Electron Thermal Transport in Tokamaks: ETG or TEM Turbulence?

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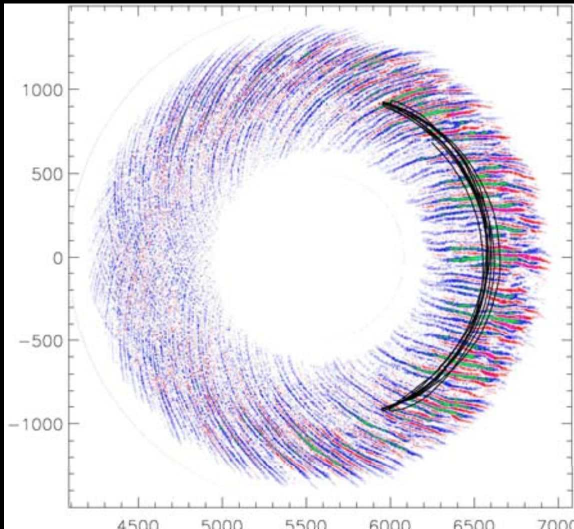
Electron Temperature Gradient (ETG) Turbulence

- Experimental search for origin of electron transport: inconclusive evidence
  - Ion scale (ρ_i): TEM/ITG
  - Collisionless skin depth (c/ω_{pe}): CDBM or electromagnetic ETG
  - Electron scale (ρ_e): electrostatic ETG
- ETG diagnostics being installed on DIIID, NSTX, CMOD, …
- ETG turbulence simulations: contradictory results
  - Flux-tube simulations: electrostatic streamers drive large electron transport *[Jenko et al, PoP2000; Dorland et al, PRL2000]*
  - Streamer size is comparable to simulation box size, violating fundamental assumption of flux-tube simulation using radially periodic boundary condition
  - Radially nonlocal fluid simulations: transport an order of magnitude smaller *[Labit & Ottaviani, PoP2003; Li & Kishimoto, PoP2004]*

Key Issues in ETG Turbulence

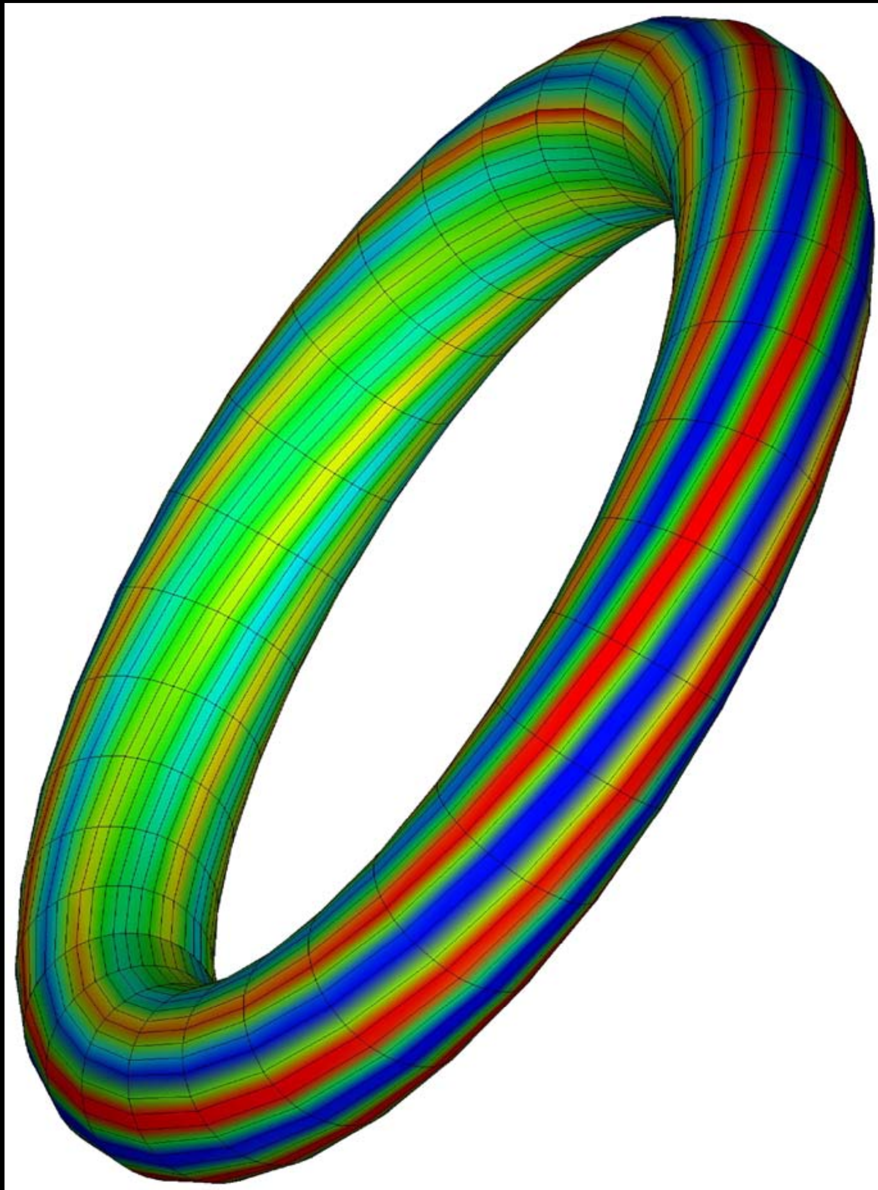
- Flux-tube gyrokinetic continuum simulation *[Dorland & Jenko, 2000]*
  - Electrostatic streamers drive large electron transport when magnetic shear s>0
  - Saturation via a Kelvin-Helmholtz type 2nd instability
- Unresolved issues in ETG turbulence
  - Correlation between streamer size and transport level
  - Saturation mechanism
- Global gyrokinetic particle simulation *[This paper]*
  - Streamers do not drive large transport: nonlinear particle dynamics
  - Saturation via nonlinear toroidal coupling: nonlocal interaction in *k*-space



ETG streamers

Gyrokinetic Toroidal Code (GTC) Simulation

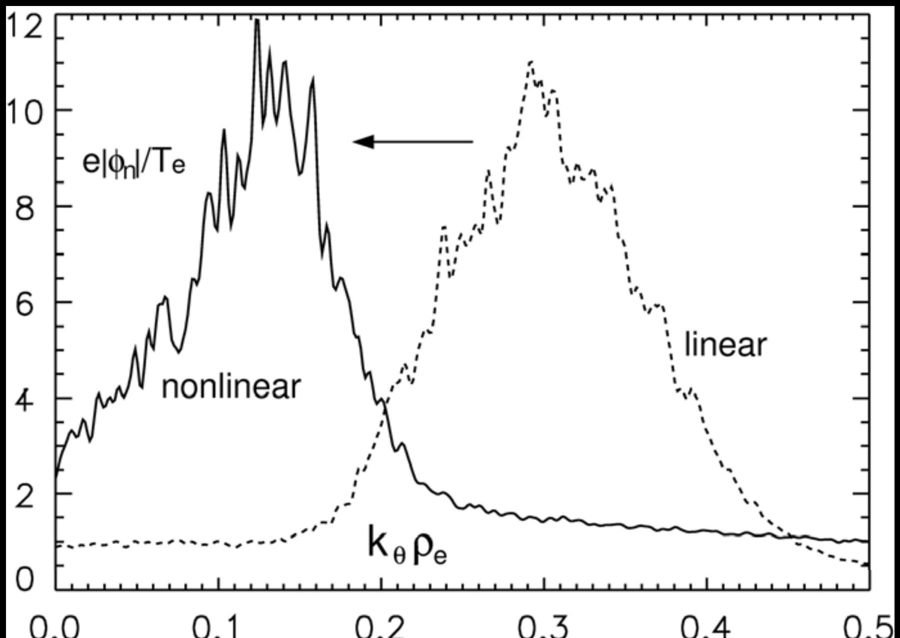
- GTC global field-aligned mesh: efficient for toroidal eigenmode
  - Reduces computation by $n \sim 10^3$
  - Respects physical periodicity
  - Keeps radial variations of $q(r)$
- Gyrokinetic particle-in-cell approach
  - Efficient sampling of 5D phase space
- Massively parallel computing
  - Device size up to DIIID
  - All ETG modes $n = 0 \sim 10^3$
- Resources: US DOE SciDAC
  - GPS Center (PI: W. W. Lee)
  - GTC Team (team leader: Z. Lin): PPPL, UCI, UCLA & Columbia U.

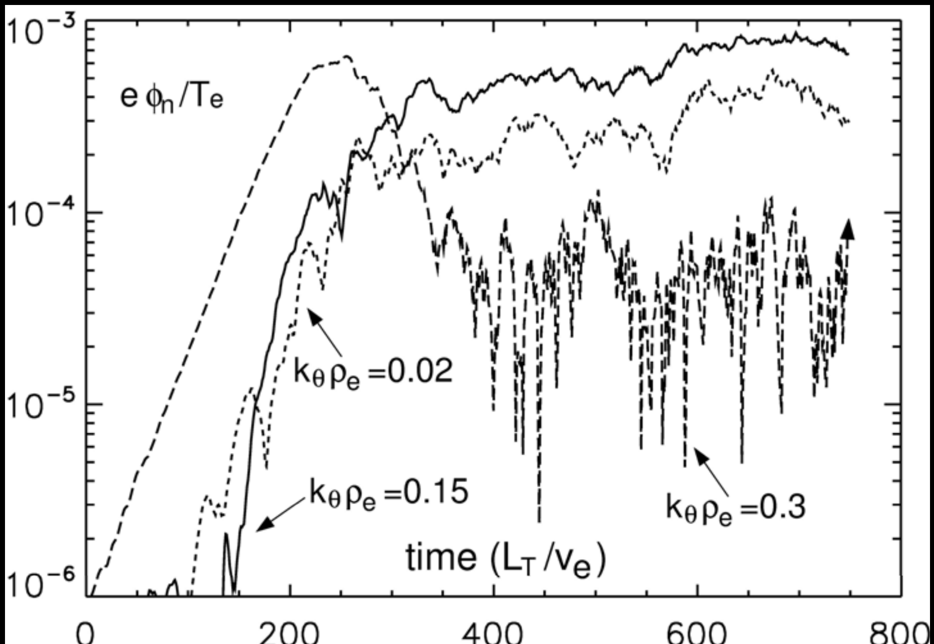


GTC mesh

ETG Turbulence Structure Nonlinearly Generated

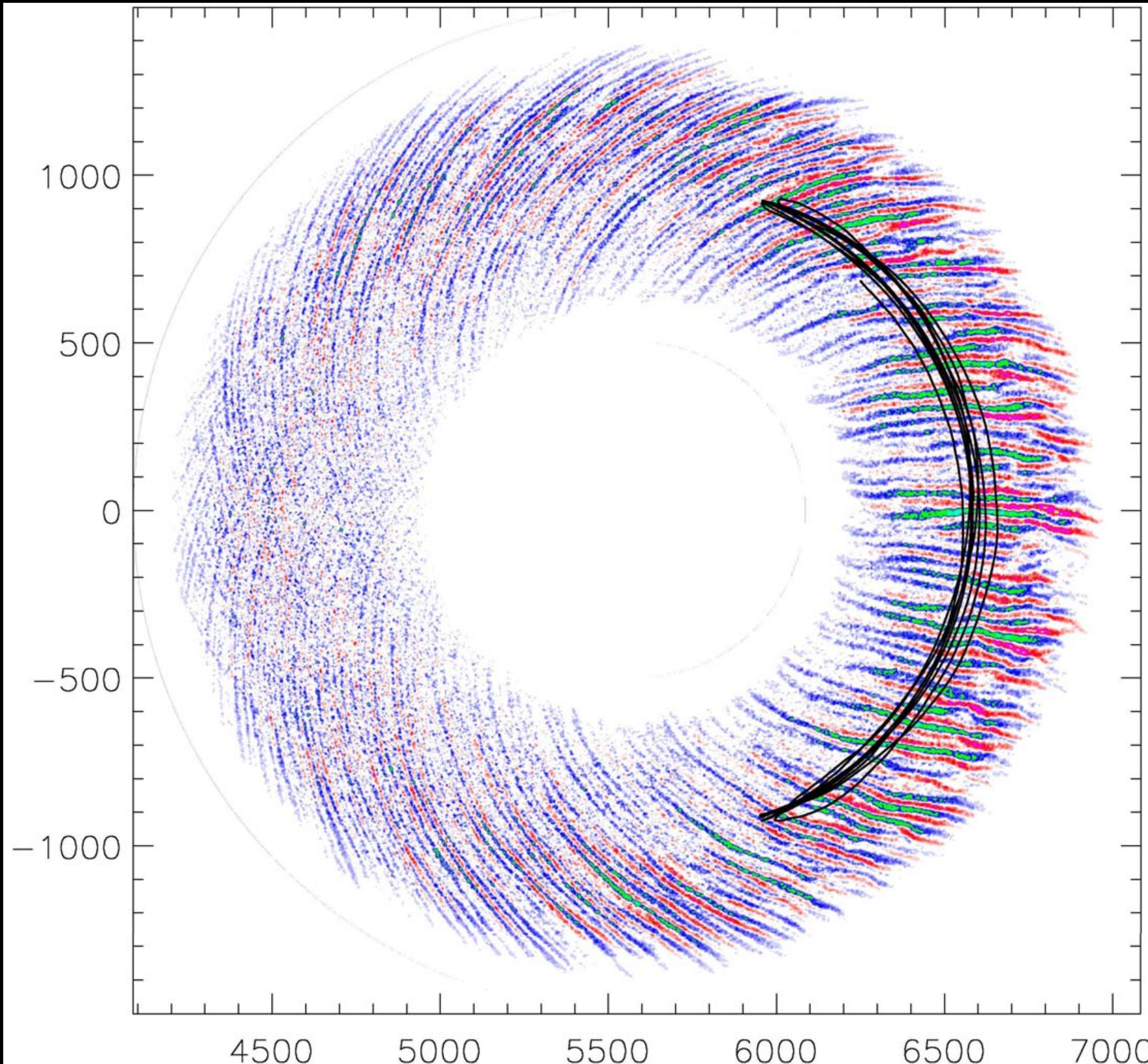
- Poloidal spectrum down shifts from linear $k_\theta\rho_e$~0.3 to nonlinear $k_\theta\rho_e$~0.12
  - Over 10 linear growth times
- Energy containing modes grow faster than linearly most unstable modes
  - Saturation via nonlinear mode coupling
  - Streamers nonlinearly generated
- Low-*n* modes driven up first before energy containing modes
  - Nonlocal interaction in *k*-space: not inverse cascade *[Hasegawa & Mima, PRL1977]*





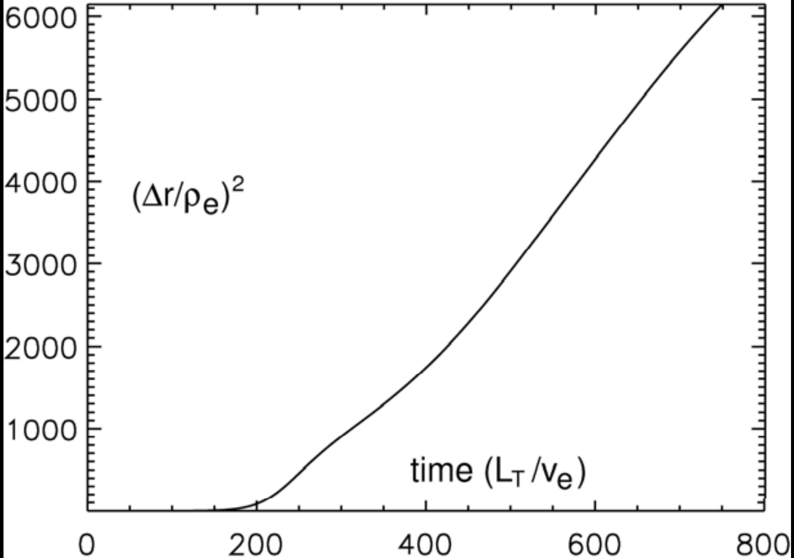
ETG Streamer Size >> Electron Radial Excursion

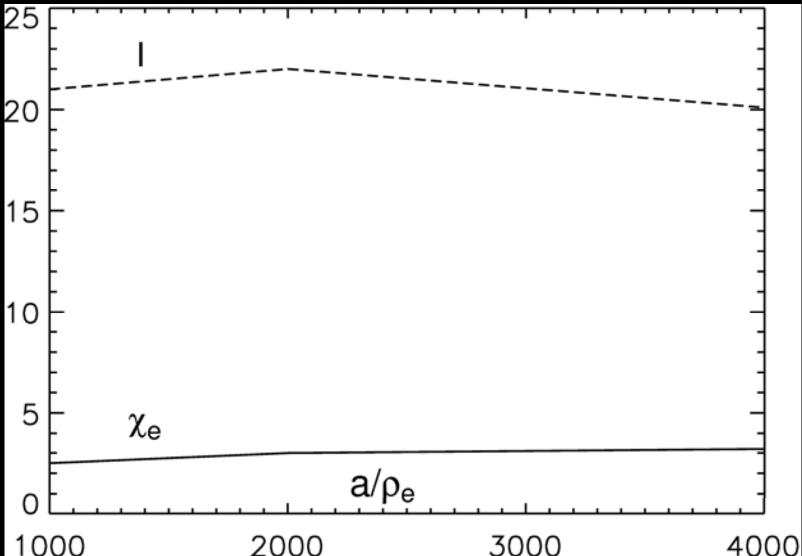
- Streamers at $t=20/\gamma_0$ after saturation
- Streamer size scales with device size
- Eddy turnover time $\tau \sim 17/\gamma_0$
  - $\gamma_{nl} << \gamma_0$
- Electron orbit during $20/\gamma_0$
- Small perturbation to parallel motion



ETG Streamers Do Not Drive Large Transport

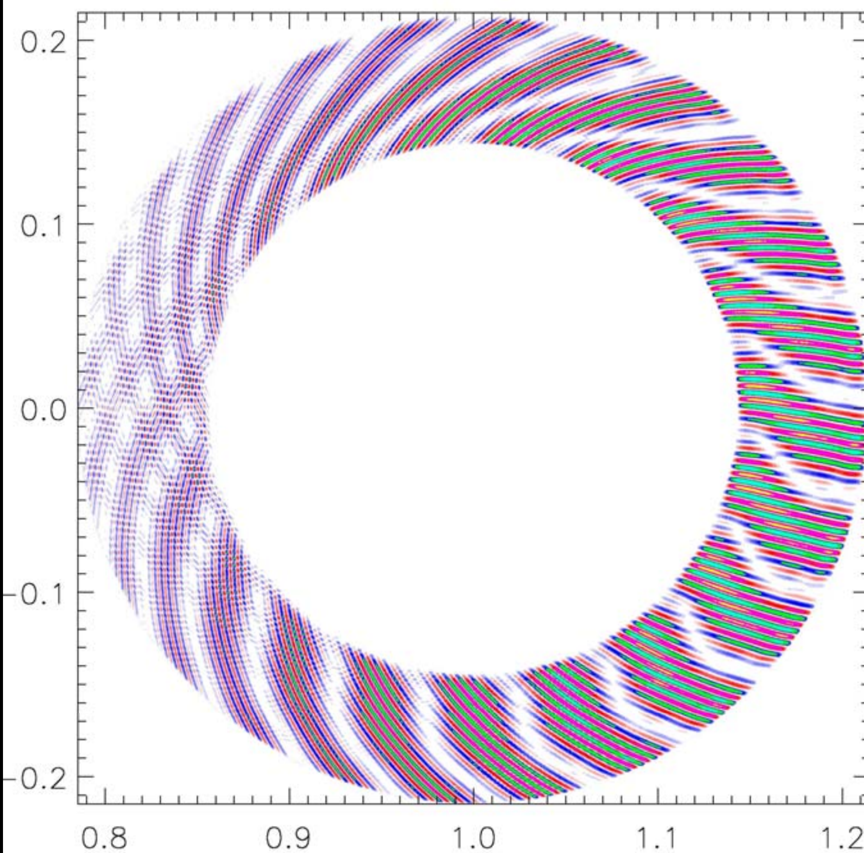
- Electron radial excursion is diffusive: $\Delta r \sim 80\rho_e$ for $\Delta t=20/\gamma_0$
- Intensity and transport independent of streamer size: gyroBohm scaling
  - $\chi_e = 3.2\ \chi_{GB}$ << flux-tube or experimental value
- Particles do not rotate around streamers
  - Radial diffusions cause loss of parallel resonant condition $\omega - k_{||}v_{||}=0$ due to $q(r)$
- "Mixing length theory" does not properly describe collisionless plasmas
  - Plasma turbulence: particles ≠ velocity field (streamers)
  - Fluid turbulence: fluid element = velocity field





Nonlinear Toroidal Coupling

- Three forms of nonlinear interaction of toroidal eigenmodes
  - Coupling of two eigenmodes: nonlinear toroidal coupling
  - Coupling to (0,0): zonal flow generation
  - Coupling to (0,1): parallel mode structure
- Zonal flow dominates in ITG/TEM: primary balances 2nd instability
  - E X B drift nonlinearity $\gamma_{nl} \sim \gamma_0$
- ETG: nonlinear toroidal coupling
  - Polarization drift nonlinearity $\gamma_{nl} << \gamma_0$
  - Single mode saturates: higher amplitude
- Parallel streamers cannot couple in slab geometry
  - $\boldsymbol{k_1 \times k_2 = 0}$ since $\boldsymbol{k_1 // k_2}$
- Toroidal streamers can couple
  - $k_r = s\theta k_\theta$: localized m-harmonics



Two ETG modes

Spectral transfer via Nonlinear Toroidal Coupling

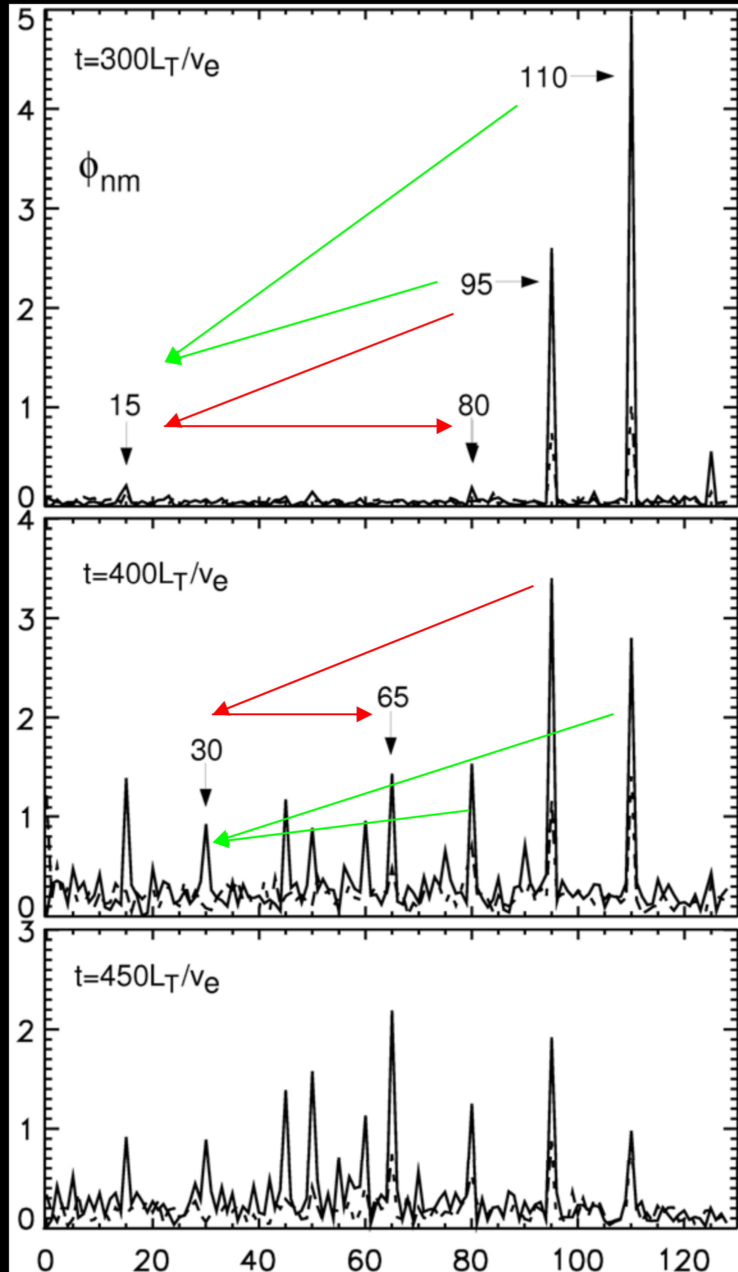
- Generation of low-*n* quasi-mode

  $$(n_1,m_1)+(n_2,m_2)\Rightarrow(\Delta n,\Delta m)=(n_2-n_1,m_2-m_1)$$

- Energy transfer to nonlinear streamers

  $$(n_1,m_1)+(\Delta n,\Delta m)\Rightarrow(n_1-\Delta n,m_1-\Delta m)$$

- Transfer facilitated by low-*n* quasi-mode
  - Nonlocal in *k*-space, “Compton Scattering”
  - $\lambda_{||}$~$qRn^{1/2}$: no ballooning structure
- Streamers are nonlinearly generated
  - $\lambda_{||}$~qR
- Need to keep all toroidal modes



Nonlinear Gyrokinetic Theory of ETG Saturation

- Nonlinear gyrokinetic equation + quasi-neutrality condition

$$\frac{e}{T_e}\frac{\partial}{\partial t}L_k\delta\phi_k = \alpha_e \frac{c}{B}\rho_e^{\,2}(\vec{k}'_\perp \times \vec{k}''_\perp)\cdot\vec{e}_\parallel (k'^{\,2}_\perp - k''^{\,2}_\perp)\delta\phi_{k'}\delta\phi_{k''}$$

- Generation of low-*n* quasi-mode: contribution from all unstable modes

$$(\frac{\partial}{\partial t}+\gamma_l)\,|a_l(t)| = 4(\hat{\alpha}_e/\tau)q'_s\int k_{\theta n}^{\,3} I_n dn$$

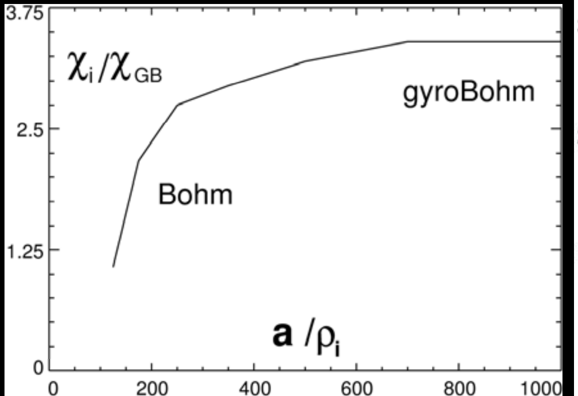
- Dynamics of unstable modes: free streaming in *n*-space $v_n(a_l)<0$

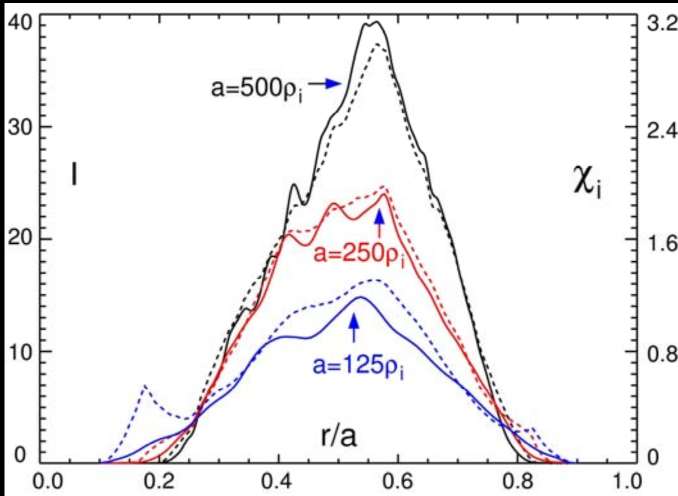
$$(\frac{\partial}{\partial t}-2\gamma_n)I_n + v_n(a_l)\frac{\partial}{\partial n}I_n = 0$$

- Theory confirms qualitatively GTC simulations of nonlinear coupling
  - Spectral transfer to nonlinear streamers via nonlinear toroidal coupling
  - Spectral transfer facilitated by low-*n* quasi-mode: $k_\parallel \sim 0$ and high k_r
  - Nonlinear toroidal coupling controls poloidal spectrum

Turbulence Eddy Size vs Transport Scaling

- ETG: radial streamers & gyroBohm transport scaling
- ITG: isotropic eddy & transition from Bohm to gyroBohm *[Lin et al, PRL2002]*
- Contradict "mixing length" & "local conjecture" *[Lin et al, IAEA2002]*
- Transport driven by local intensity *[Lin & Hahm, PoP2004; PRL1999]*
- Intensity not always determined by eddy size
  - ETG: nonlinear toroidal coupling *[this talk]*
  - ITG: spreading *[Hahm et al, PPCF2004; Chen et al, PRL2004; Zonca et al, PoP2004]*
- Transport process de-couples from saturation mechanism
  - Transport: wave-particle interaction
  - Fluctuation: wave-wave coupling

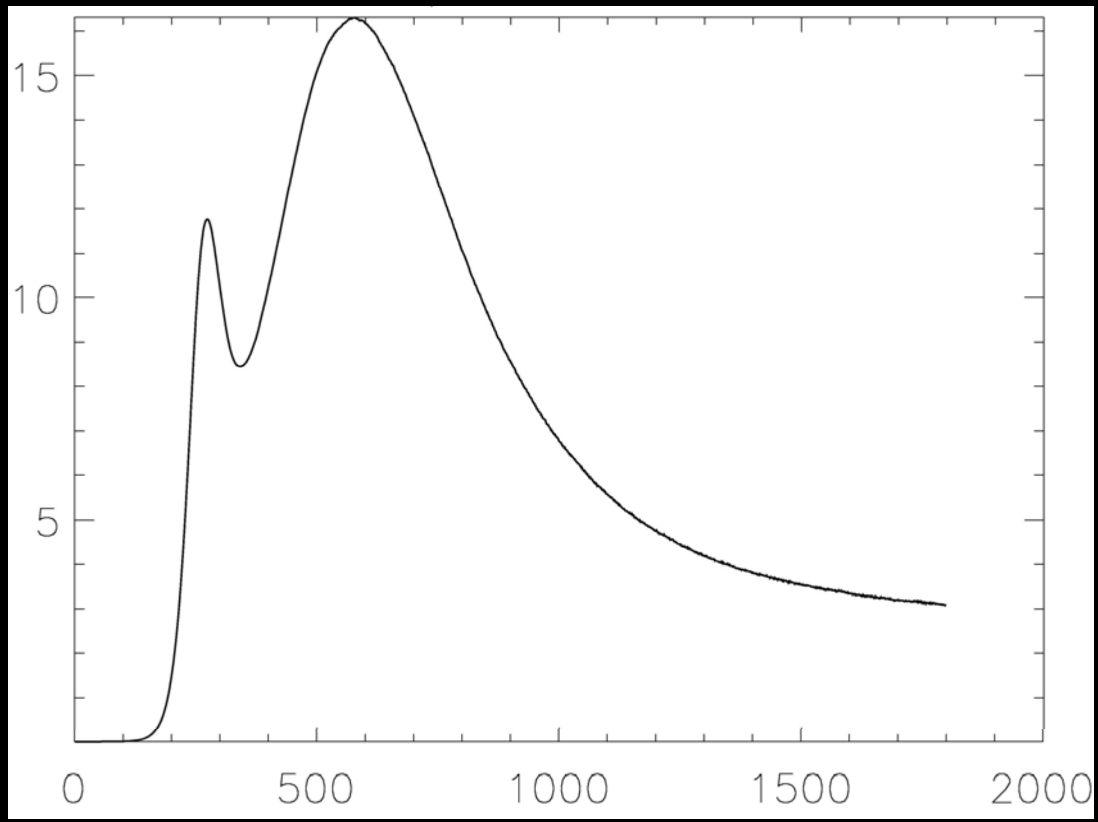




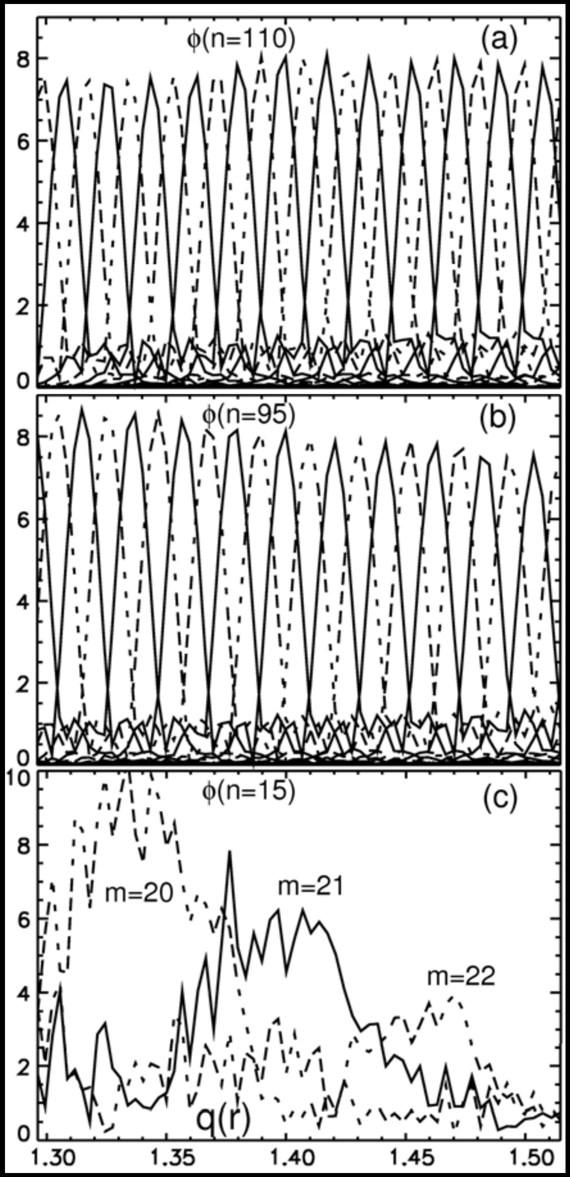
Conclusion

Global gyrokinetic particle simulation and nonlinear gyrokinetic theory

- ETG transport is well below experimental χ_e, or flux-tube results
- ETG instability saturates via nonlinear toroidal coupling
- Our results are in contrast to recent finding of flux-tube simulations that ETG is responsible for electron thermal transport in tokamaks



15
10
5
0
500
1000
1500
2000



ϕ(n=110)
(a)
ϕ(n=95)
(b)
ϕ(n=15)
(c)
m=20
m=21
m=22
q(r)