Global Gyrokinetic Simulation of Electron Temperature Gradient Turbulence and Transport in NSTX Plasmas

NSTX

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IAEA FEC 2010 Conference, Oct 11-16, 2010, Daejon, Korea

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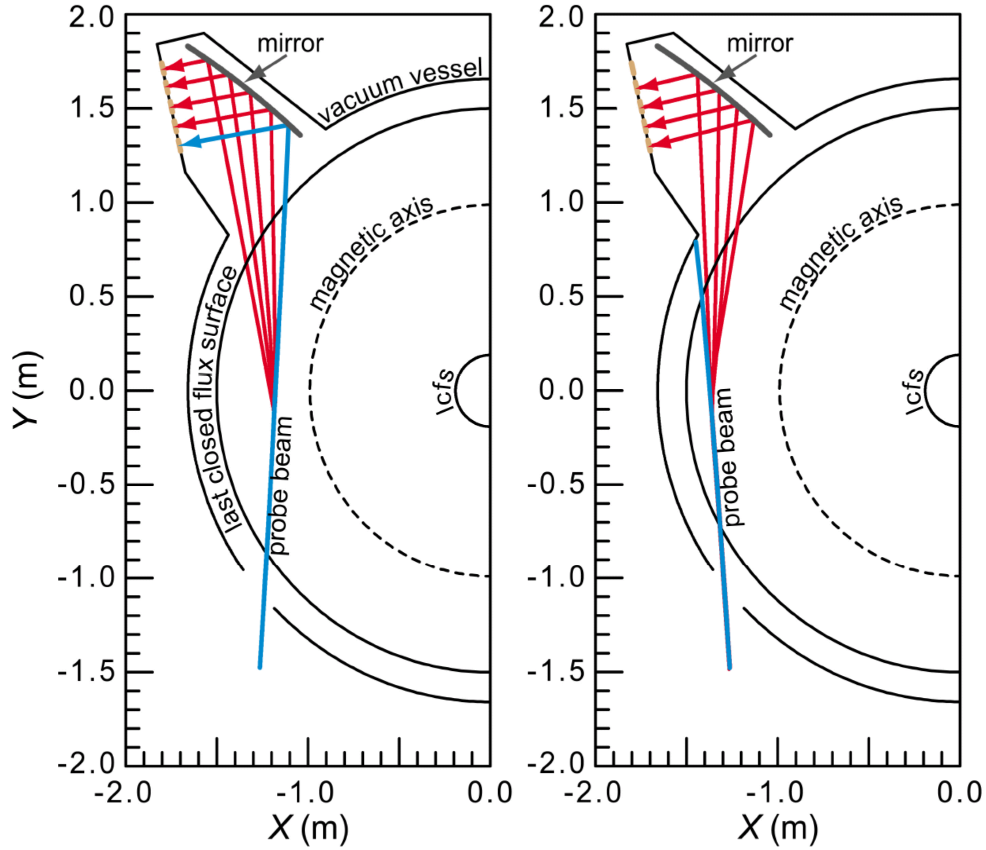
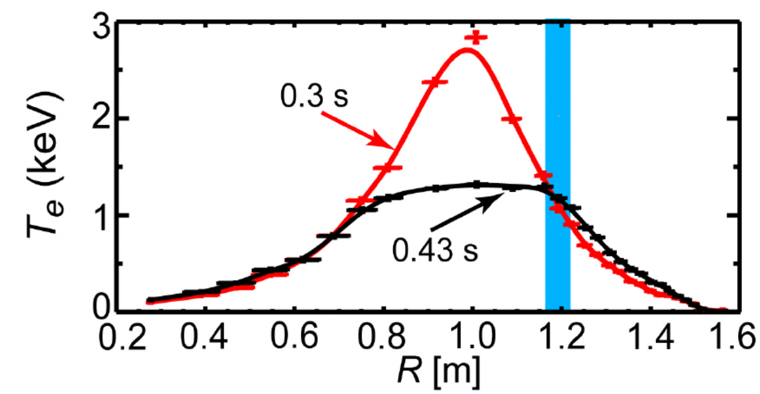
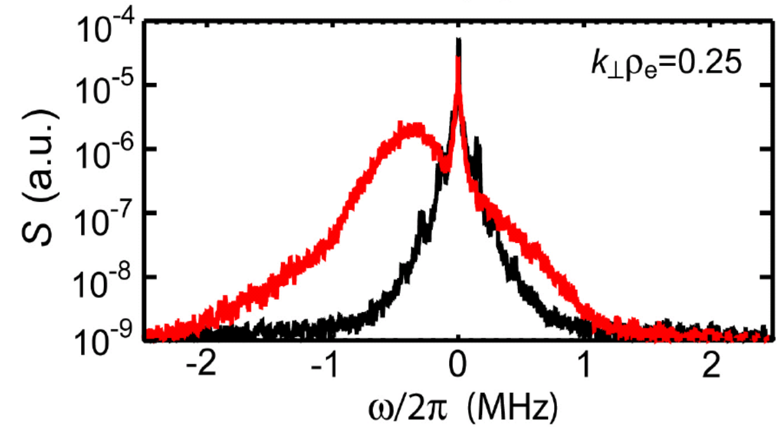
Motivation: Measurements of high-k fluctuations in NSTX

- Coherent tangential scattering of EM waves
- *Mazzucato et al., Nuclear Fusion* **49** No 5, 055001 (May 2009)

NSTX

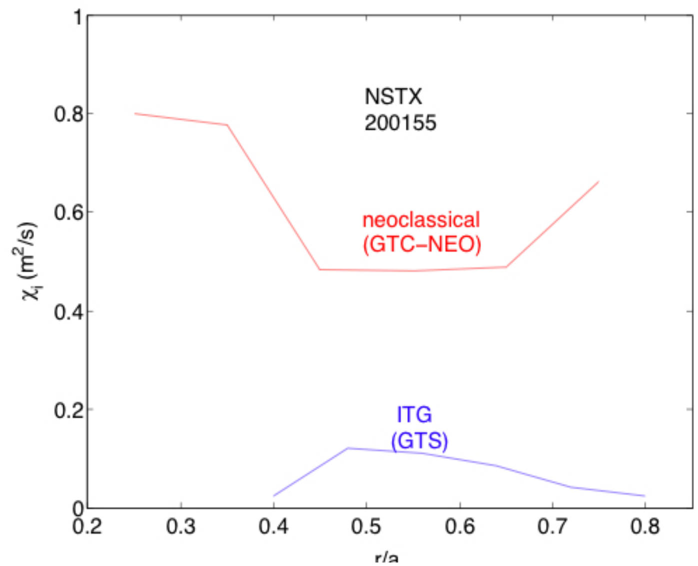


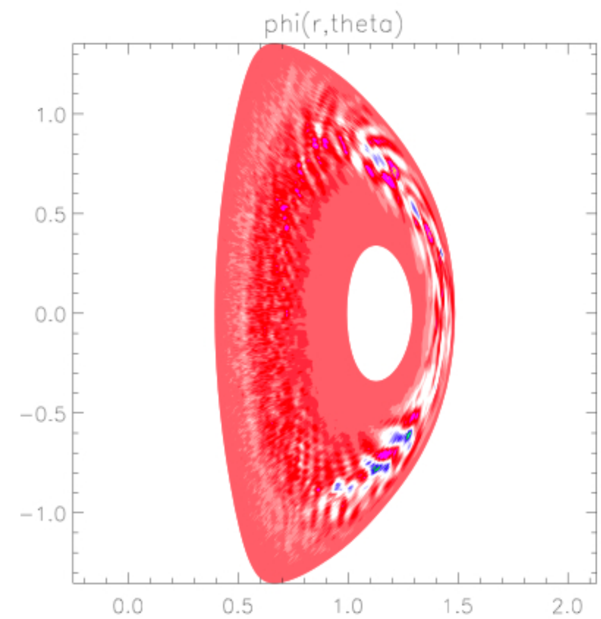




NSTX offers a unique platform to study electron transport

- Transport in NSTX is dominated by electron transport
- Strong E x B flow shear largely suppress low-k fluctuations
- ITG is a minor player
- Ion transport is close to neoclassical level
- Plasma transport has strong geometry dependence



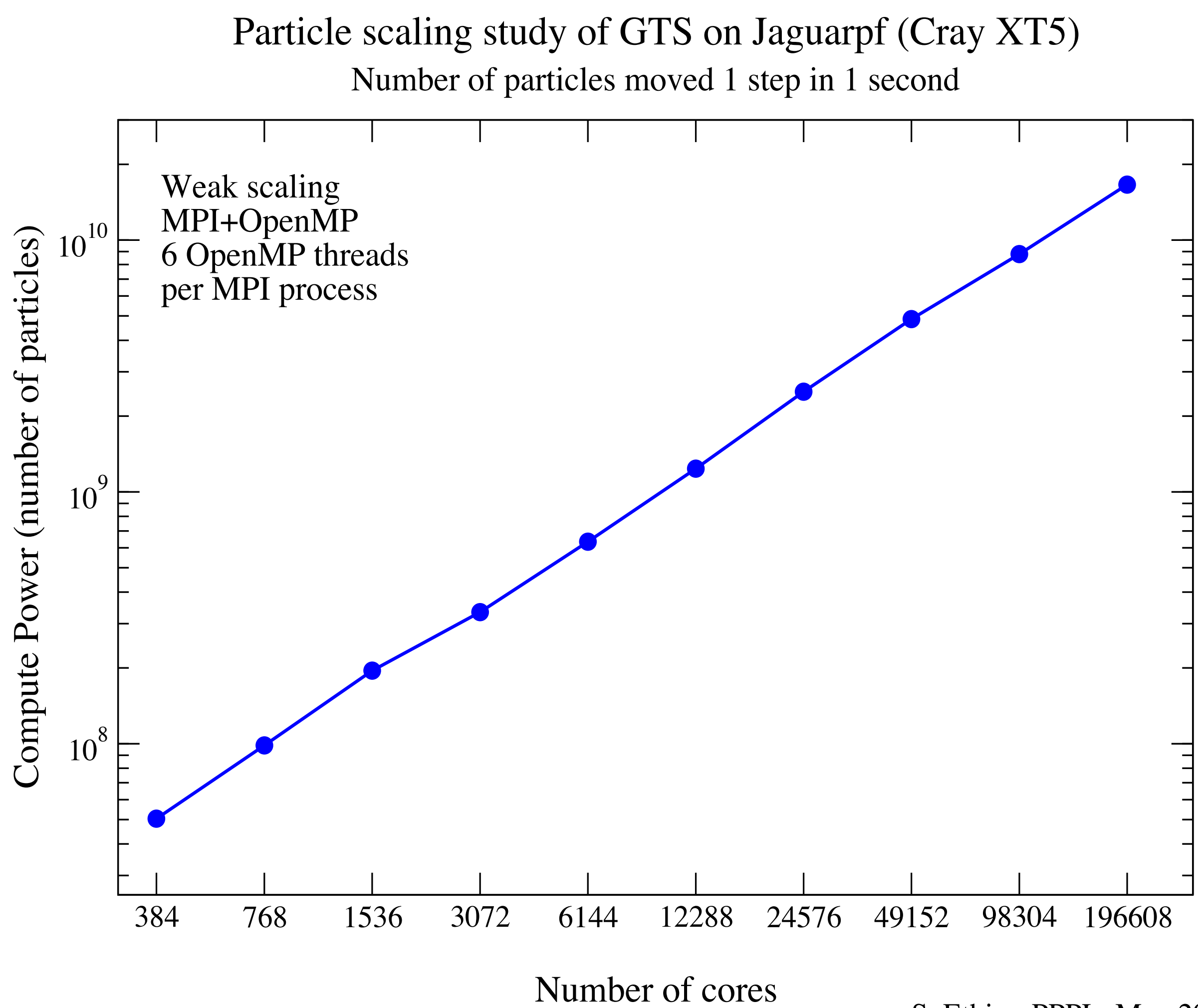


The Gyrokinetic Tokamak Simulation code (GTS)

- Generalized gyrokinetic simulation model
- Particle-in-cell approach; global simulation (Wang et al., PoP'06)
- Turbulence fluctuations are perturbations on top of neoclassical equilibrium
- Full kinetic electrons: drift kinetic for ITG, TEM etc.; gyrokinetic for ETG
- Linear Coulomb collisions conserving particles, momentum and energy
- {$<n(r,t)>$, $T(r)$, $\Phi_0(r)$, *and* $\omega_t(r)$} ➔ turbulence & transport (energy, particles, momentum flux
- Interfaced with MHD equilibrium codes and experimental data base (via TRANSP)
- Refine MHD equilibrium using JSOLVER with TRANSP profiles
- Interfaced with Neoclassical via GTC-NEO (Wang et al,. CPC'04)
  - GTC-NEO ➔ Neoclassical equilibrium f_0, Φ_0 and transport
  - Non-local physics associated with large ion orbits and steep gradients
- Use of PETSc parallel library to solve the field quantities
- High Performance parallel I/O with ADIOS (Adaptable I/O library, ORNL)

GTS is a massively parallel code

- 3 levels of parallelism on modern day supercomputers
  - 1D domain decomposition in the toroidal direction (MPI)
  - MPI-based particle distribution within each domain
  - Fine-grain loop-level parallelism implemented with OpenMP



S. Ethier, PPPL, May 2010

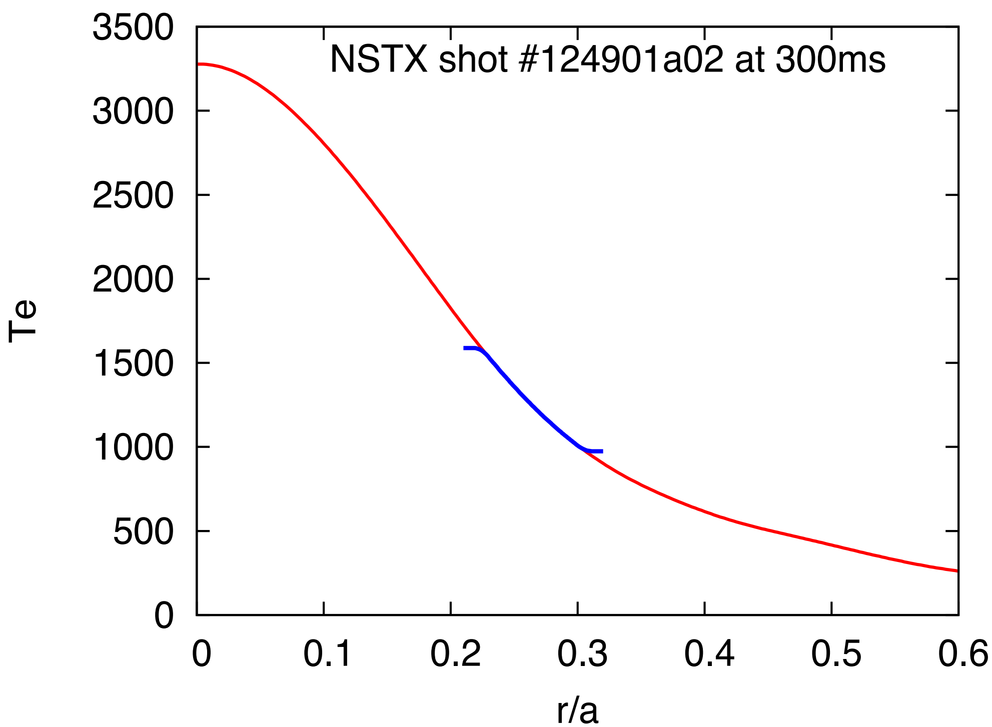
ETG simulation model and parameters

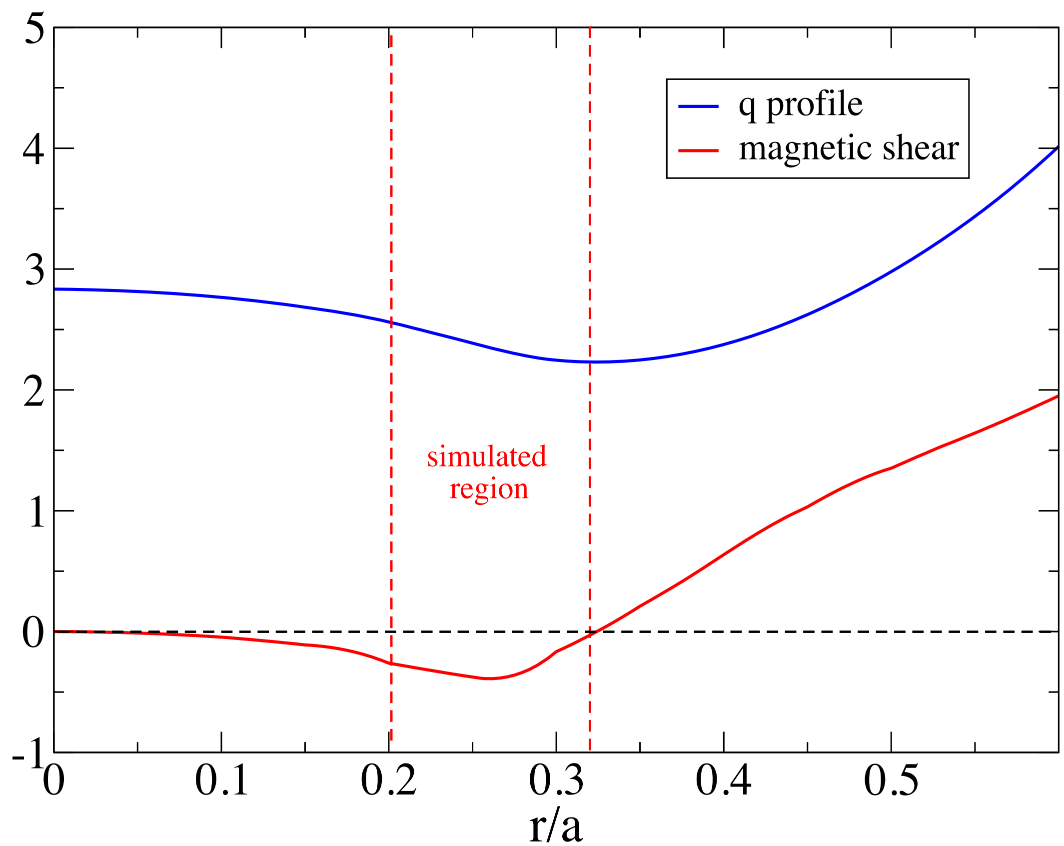
- Adiabatic ions (neglecting coupling with low-k fluctuations)
- Global simulation covers ~ 450ρ_e and full toroidal and poloidal regions
- Grid size in perpendicular directions ~ ρ_e
- Real electron mass
- Simulation of NSTX shot #124901 at 300 msec
- Plasma parameters read into GTS from TRANSP run of shot 124901
- Working gas is helium (Z_{eff} = 2)
- Simulations carried out at NCCS/ORNL on Jaguar and Jaguarpf
- 22.6 billion particles, 400 million grid points
- Simulations used 31232, 65536, and 98304 cores for 48 hours

Image courtesy of the National Center for Computational Sciences, Oak Ridge National Laboratory

Profiles of electron temperature and magnetic shear used as input for simulations

- Weak reverse shear in the simulated region
- Not enough to completely suppress ETG





Characteristics of simulated ETG turbulence

- Slowly growing, nonlinearly generated zonal flows display fine radial structures
- Experimental identification of streamers to validate nonlinear ETG simulation models and to understand effects of multi-scale coupling
- Calculated χ_e ~ 0.2 – 0.3 m^2/sec – too low for this case close to ETG marginality (estimated experimental χ_e = 1.2 ±50%)
- Tested for sensitivity to experimental errors in plasma profiles: gradient Te increased by 20% leads to about 2X increase in growth rate and saturated flux

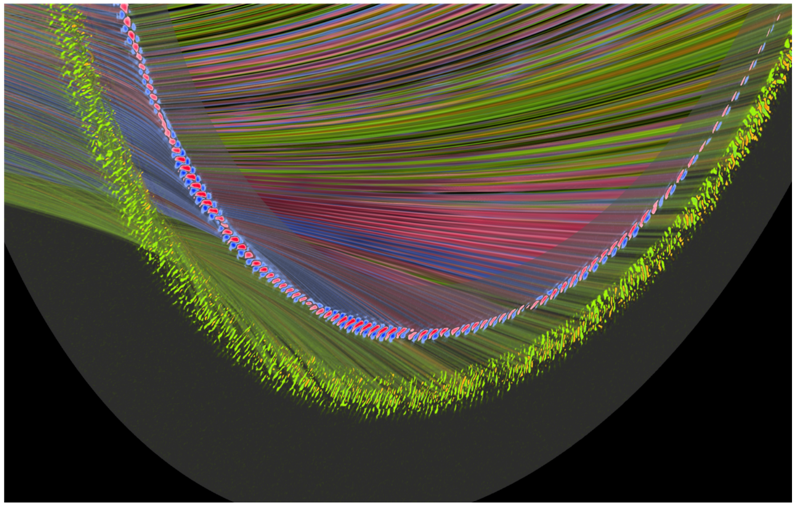
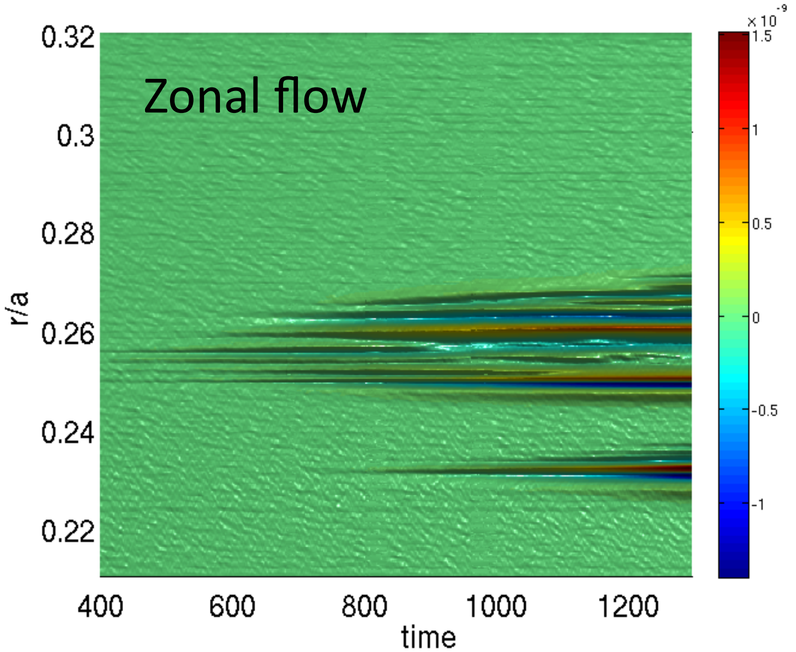
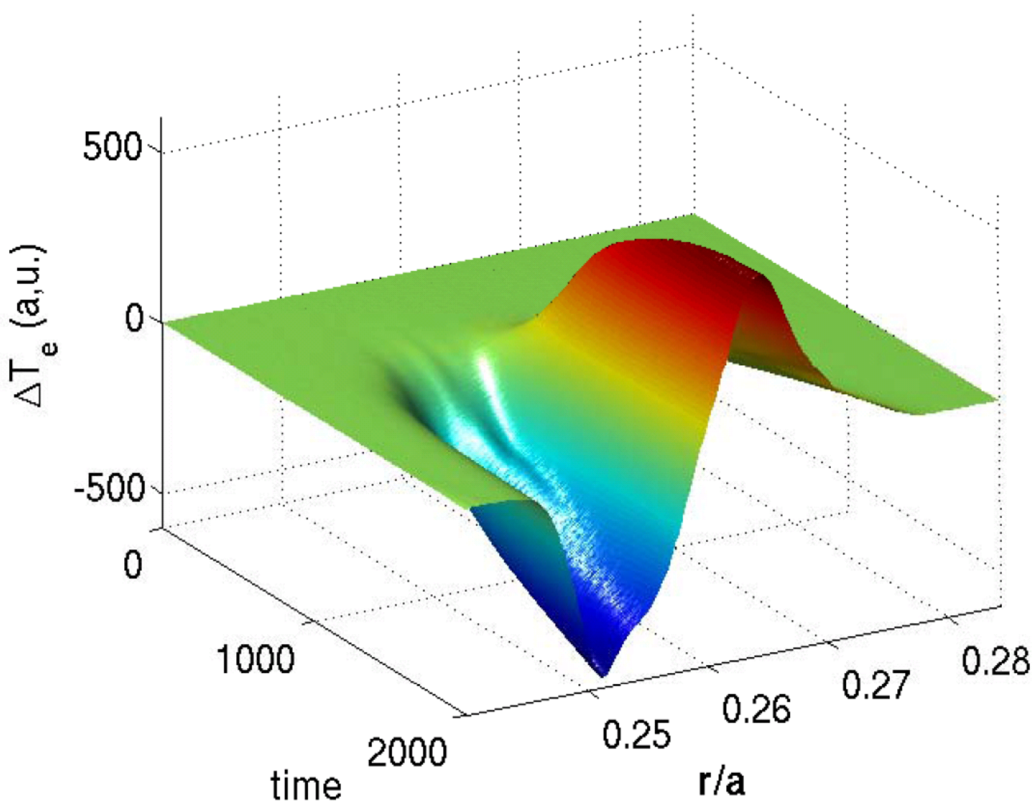


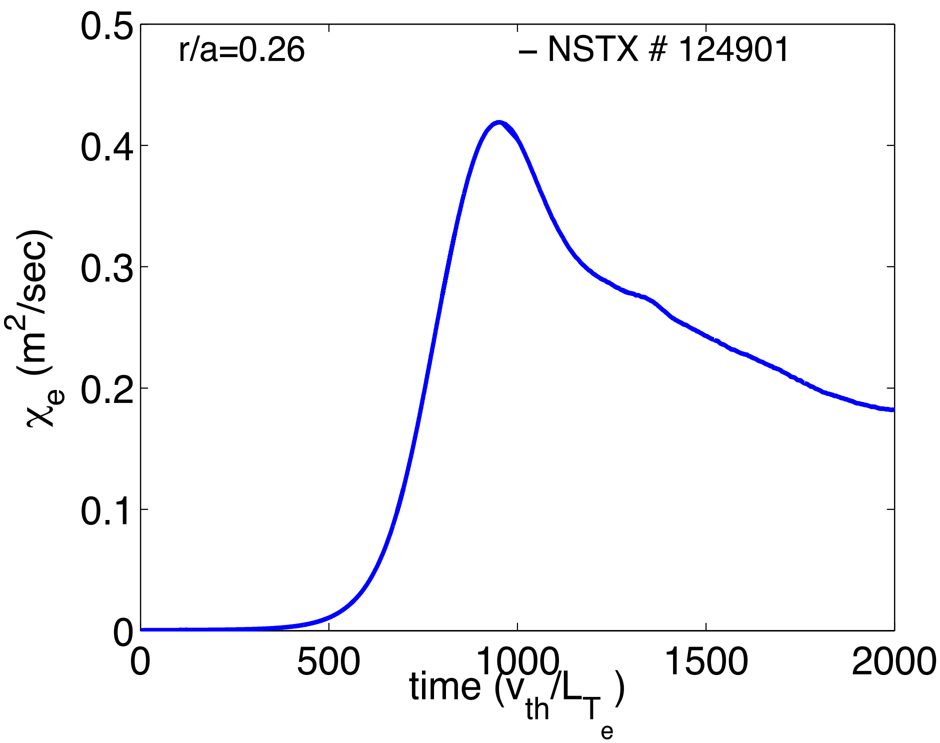
Image generated by Kwan-Liu Ma (P.I.), Chad Jones, and Chris Ho of UC Davis, as part of the SciDAC Ultrascale Visualization Institute



ETG-driven transport causes considerable relaxation of T_e profile during simulation

- Effective driver ($\nabla T_{e0} + \langle \delta T_e \rangle_{\delta f}$) decreases → q_e drops with time





Anti-relaxation scheme implemented to maintain a constant gradient drive

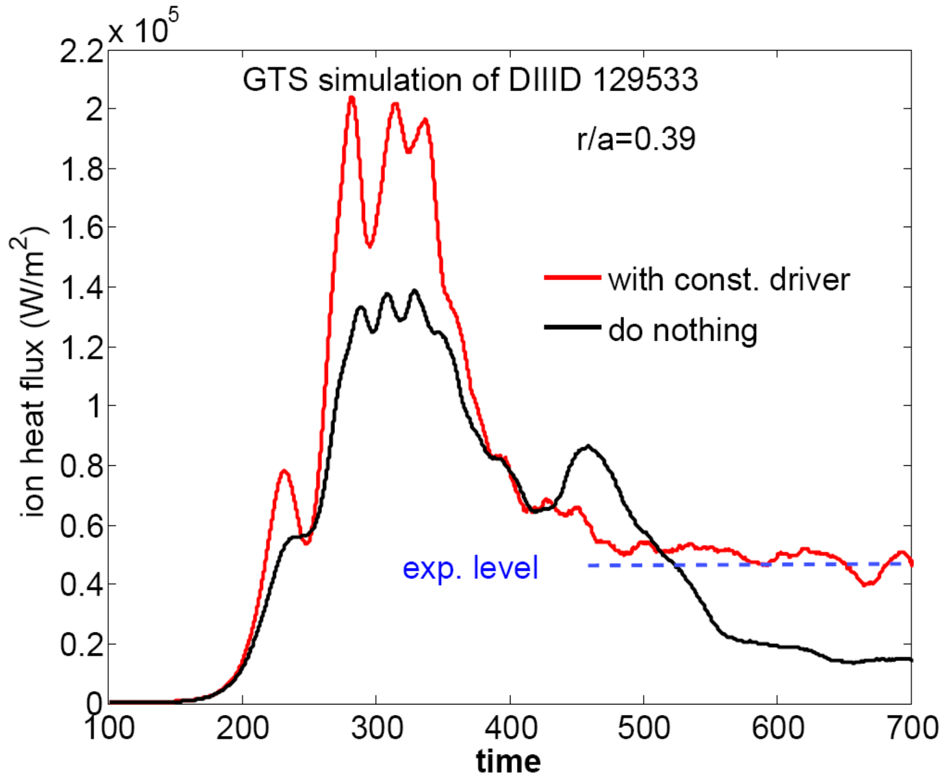
- Compensate for the effect of evolving δf :

  → $D\delta f/Dt = -\{\mathbf{v}_E.\nabla f_0 - v_E.\nabla\delta f_0 + \ldots\}$

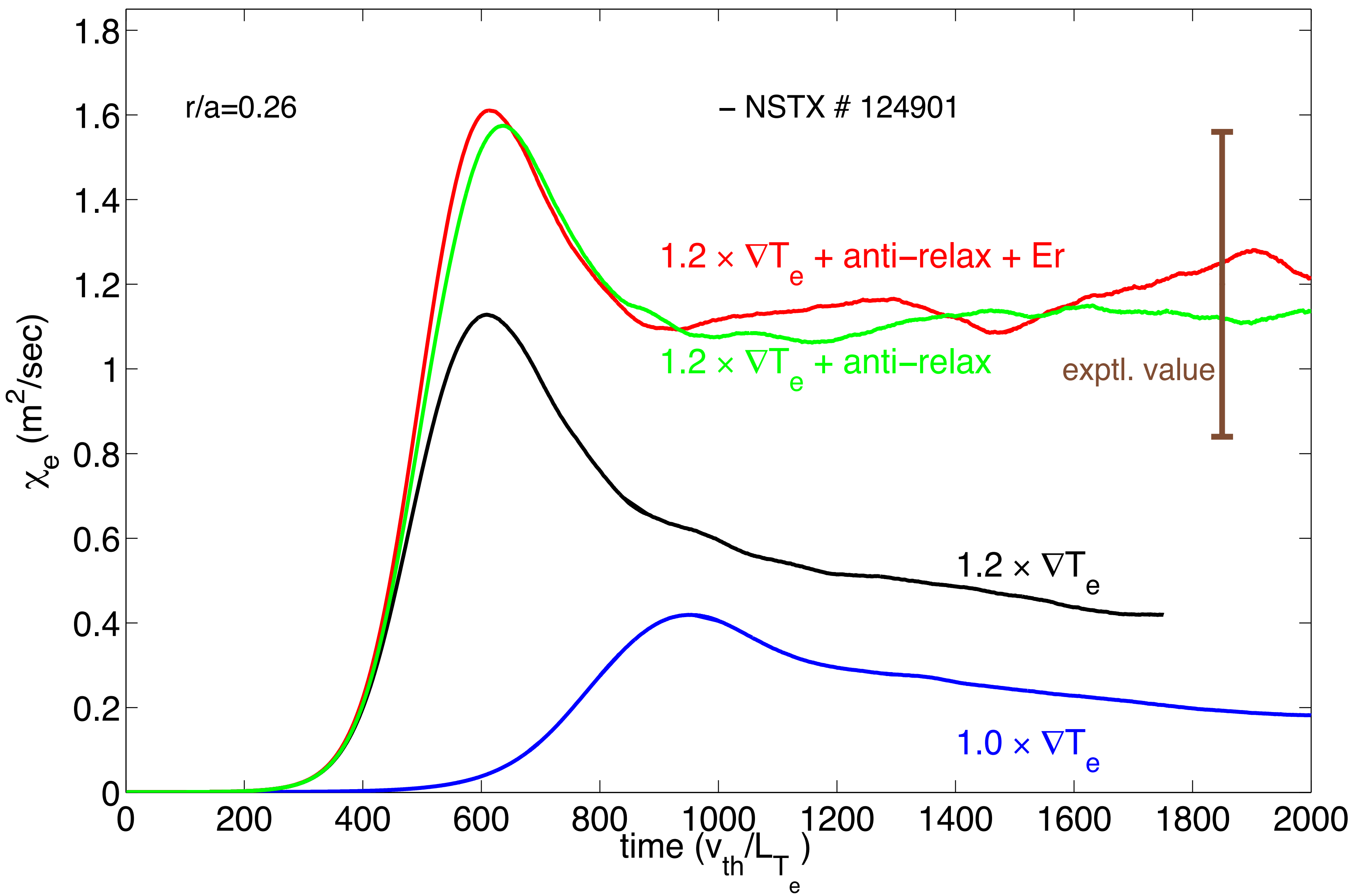
  where $\delta f_0 \approx (mv^2/(2T_0) - 3/2)(\langle\delta T\rangle/T_0) f_0$

  with $\delta T = (1/3n)\int d\mathbf{v}mv^2\delta f$

- Validation of anti-relaxation scheme for ITG-driven ion transport against DIII-D discharge: matches experimental value of heat flux



Time evolution of electron heat conductivity and comparison with experimental value



ETG drives a significant fraction of the electron transport in NSTX

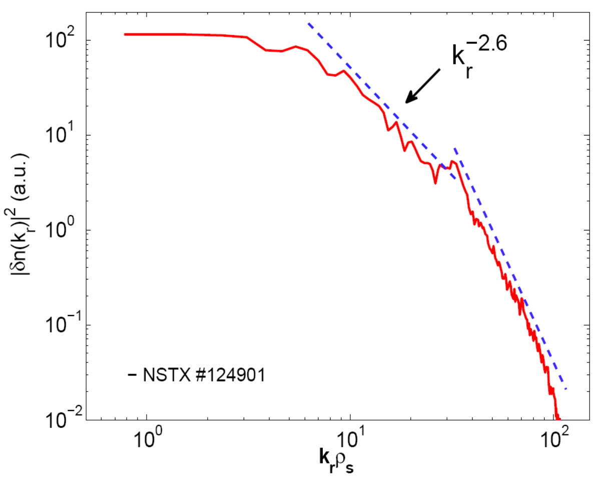
PPPL THEORY COMPUTATION

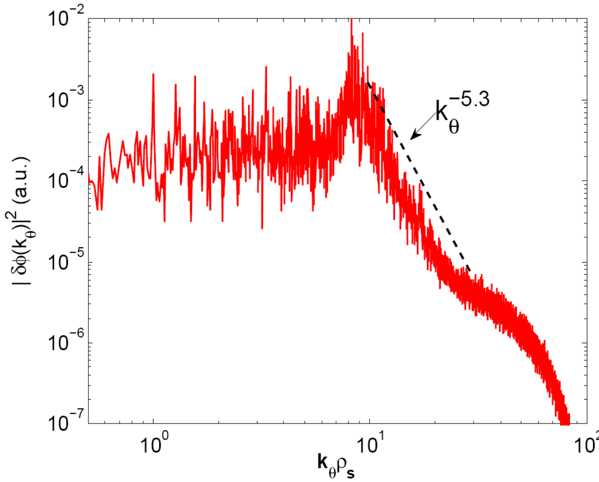
- Eliminating the influence of profile relaxation seems essential for achieving steady-state in collisionless ETG simulations
- Increasing the temperature gradient within experimental uncertainties brings the steady-state value of the heat conductivity to the experimental level
- A value of χ_e ~ 1.2 is obtained with the constant drive and the uncertainties over local plasma profiles, indicating that ETG can be a major contributor to the electron heat transport
- Adding the equilibrium electric field **Er** (equilibrium ExB shear), as calculated by the GTC-NEO code, has little impact on the results of the simulation.

Comparable density fluctuation spectra between simulation and experiment

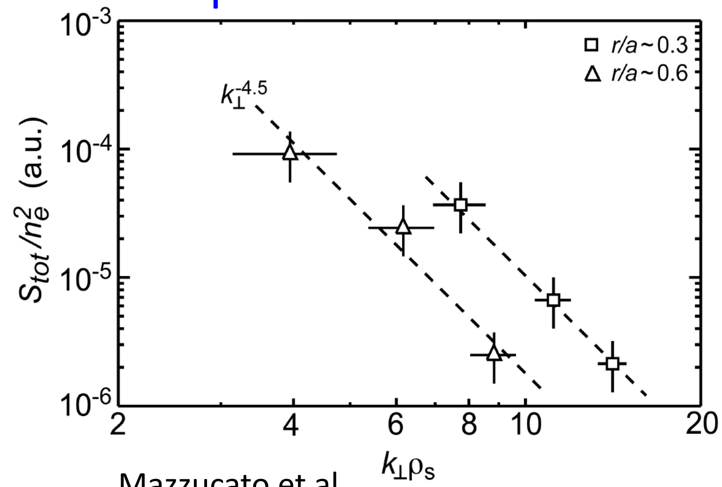
- Exponential power -2.6 (in k_r spectrum) and -5.3 (in k_θ) in simulation compared to -4.5 of $k_\perp$ spectrum in experiments
- Ray-tracing calculation (by F. Poli) suggests the need for a more comprehensive synthetic diagnostic that takes into account the beam trajectories and experimental uncertainties

simulation





experiment

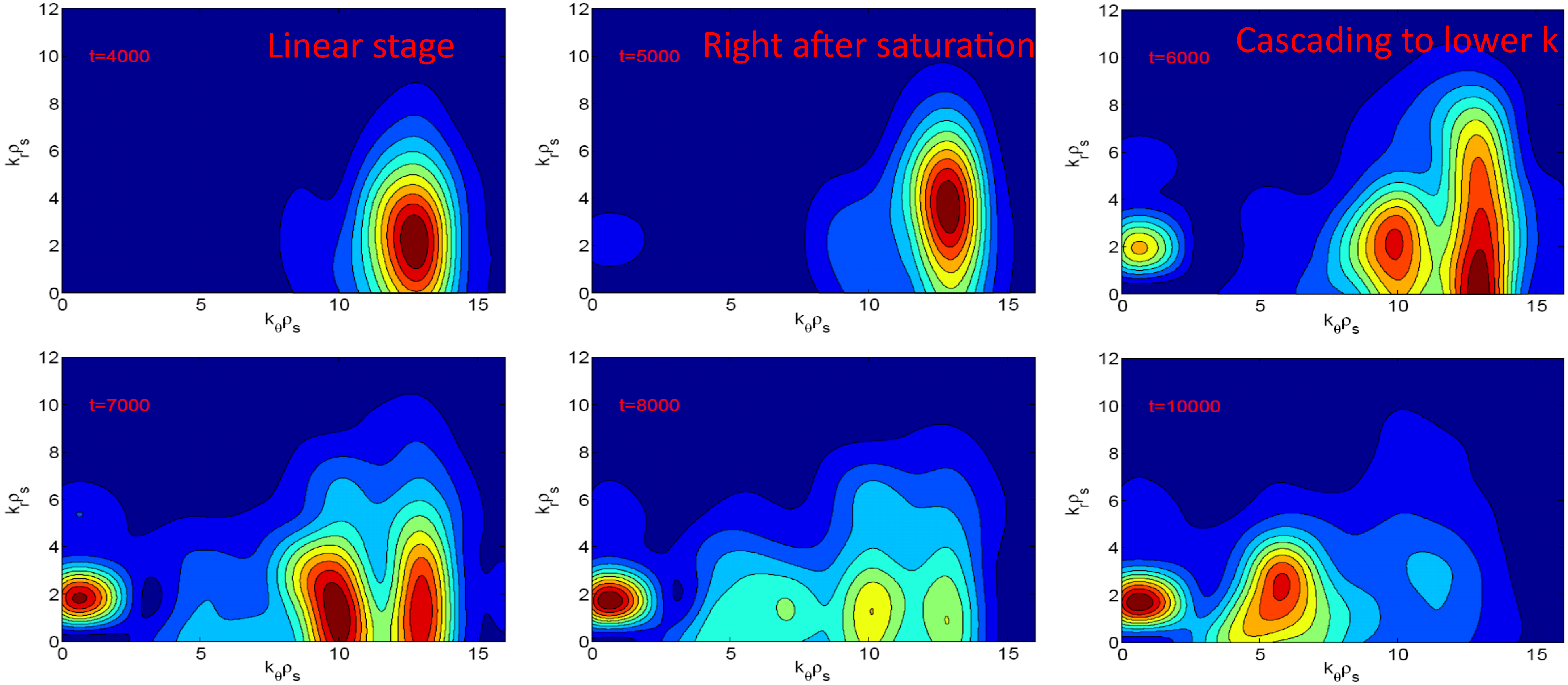


Mazzucato et al.,
Nucl. Fus. 49, 055001 (2009)

Strong nonlinear energy coupling in spectral dynamics

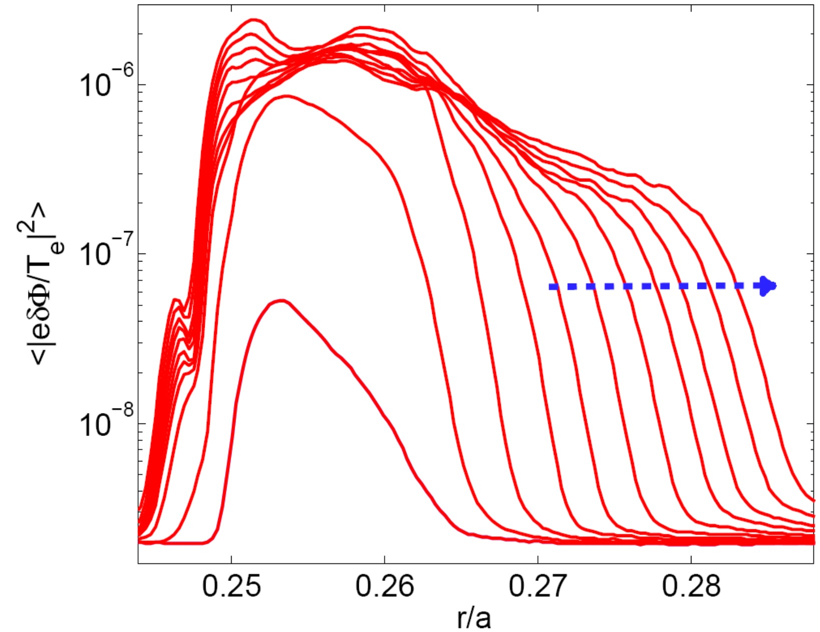
PPPL THEORY COMPUTATION

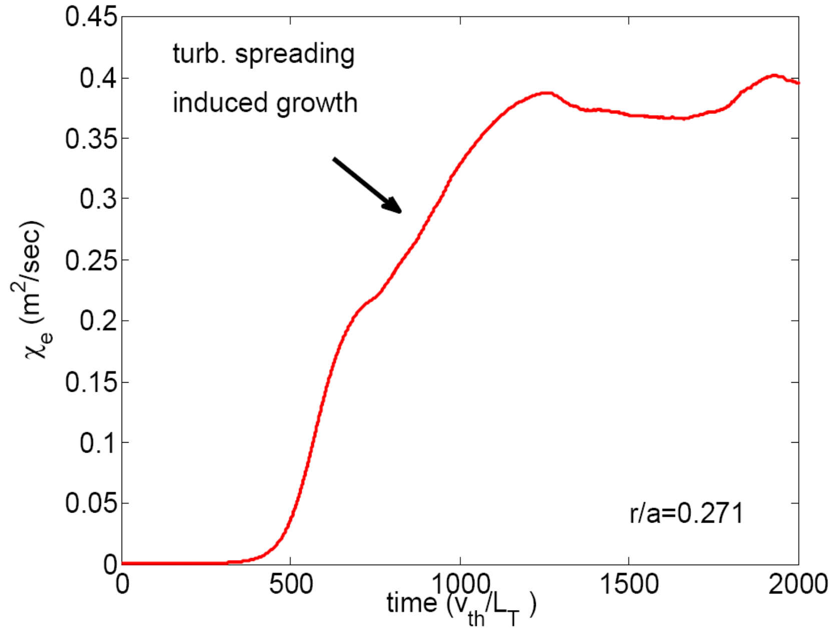
- Strong spectrum anisotropy: $k_\theta >> k_r$
- Nonlinear streamer generation
- Strong energy coupling to e-GAM
- e-GAM & zonal flow damping important



ETG turbulence spreads

- Ballistic outward spreading (to positive magnetic shear region)
- How fast: ~ (1 – 2) x 10^{-3} c_s
  How far: ~ a few tens of ρ_e
- Little inward spreading due to reversed magnetic shear
- Results are for the case with anti-relaxation and 20% increase in Te gradient



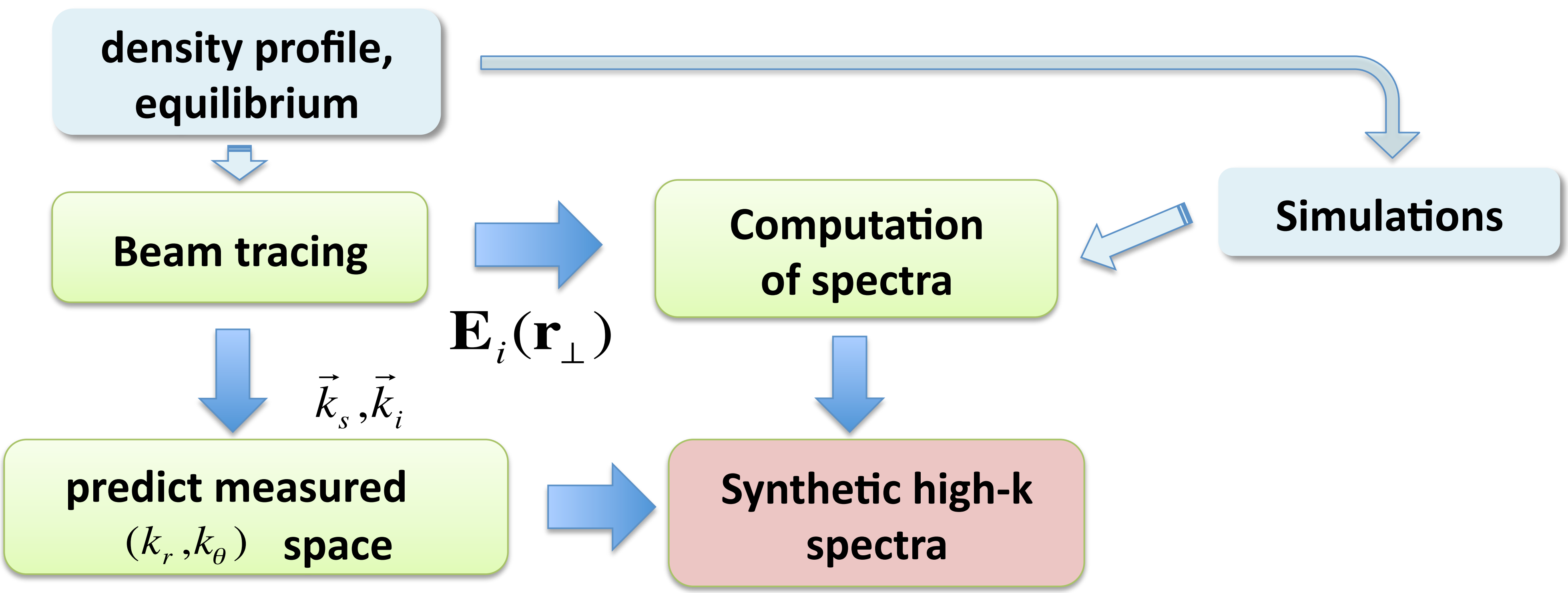


Development of a comprehensive synthetic diagnostic of high-k measurement

$$\mathbf{E}_s(\nu_s) = \frac{r_e}{x} e^{i\mathbf{k}_s\cdot\mathbf{x}} (\hat{s}\hat{s} - \mathbf{1}) \cdot \int_{T'} dt' \int_V d^3r' \, \mathbf{E}_i(\mathbf{r}_\perp)\, e^{i(\omega t' - \mathbf{k}\cdot\mathbf{r})}\, \tilde{n}(\mathbf{r}', t')$$

Direction & amplitude of k_s

Fourier Transform of density fluctuations weighted by the beam intensity



[F. Poli et al, Phys. Plasmas, in press]

Use the collection efficiency to construct a filter (k_r,k_θ) for the spectra

The detection relative efficiency depends on:

- scattering angle
- change in the magnetic field direction

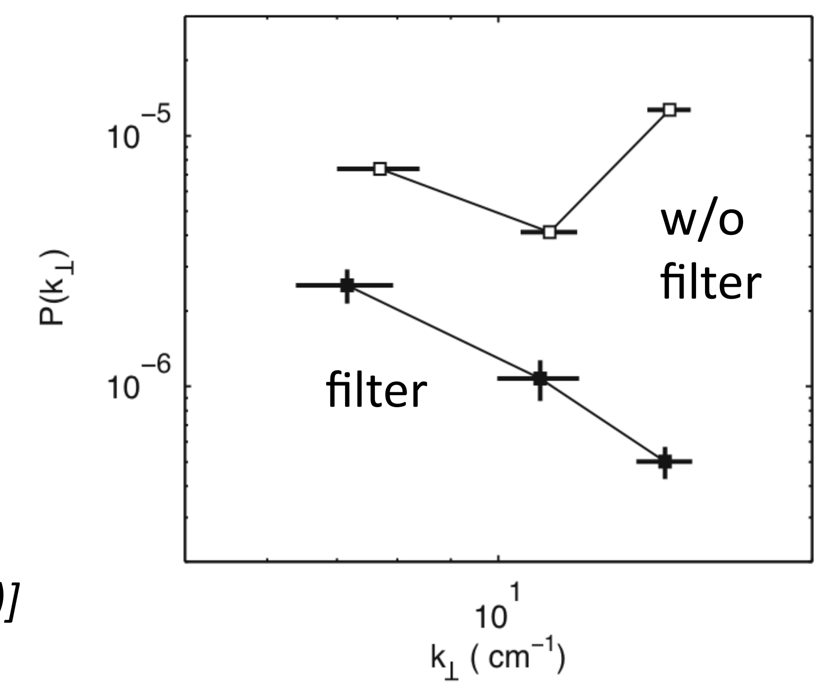
Collection efficiency

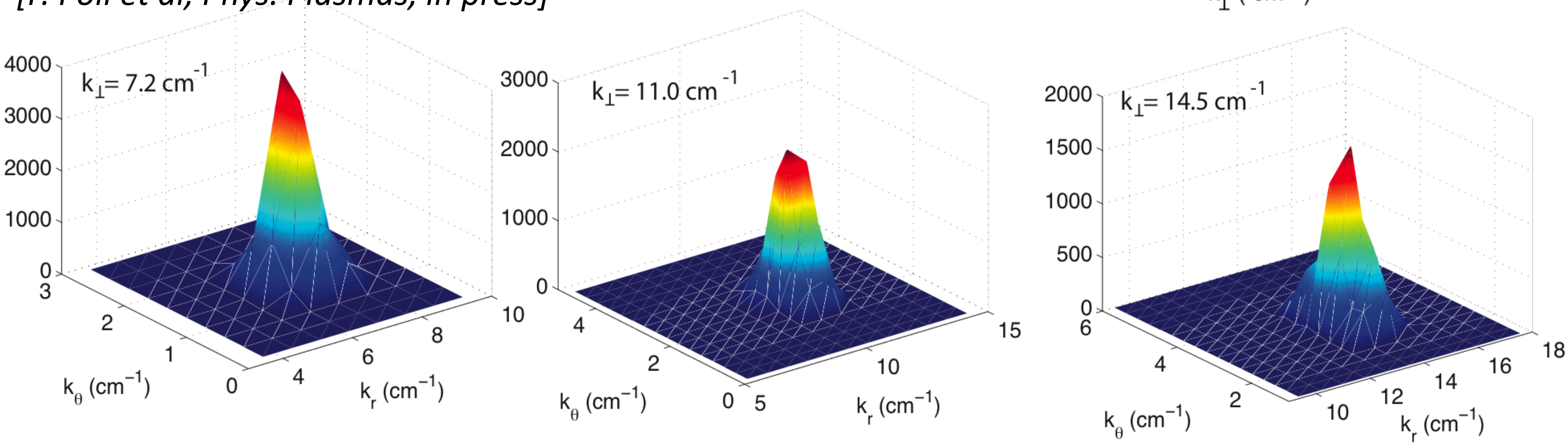
$$F \approx \exp(-k_i^2\alpha^2/2a^2)$$

$$\cos\alpha = \cos(\theta-\theta_0) - 2\sin\theta_0\sin\theta\sin^2(\delta\phi/2)$$

*[E. Mazzucato, Plasma Phys. Control Fusion **48** 1749 (2006)]*

[F. Poli et al, Phys. Plasmas, in press]





Summary and remarks

- First global, nonlinear ETG simulations for realistic discharges carried out for direct validation against experimental measurements in NSTX
- Qualitative agreement with experiment in density fluctuation spectrum
- ETG contribution to electron transport may be significant within plasma profile uncertainties
- Eliminating influence of profile relaxation is crucial in simulations
- Impact of E_r equilibrium electric field on ETG transport seems to be low
- Highly remarkable nonlinear spectral dynamics: strong spectrum anisotropy with $k_r << k_\theta$; strong energy coupling to e-GAM; long term zonal flow effect ...
- ETG turbulence spreading and effect identified
- Ongoing work:

  → effects of collisions on zonal flow and e-GAM damping and their influence on steady state spectrum and turbulence level

  → Development of a comprehensive synthetic diagnostic

Acknowledgements

- This work was supported by U.S. DOE Contract No. DE-AC02-09CH11466, by the SciDAC project for Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas, and by the UK EPSRC (F. M. Poli at U. of Warwick)
- This research used resources of the National Center for Computational Sciences at Oak Ridge National Laboratory, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.
- Thanks to Scott Klasky and ADIOS team (ORNL/NCCS), Mark Adams (Columbia U. -- PETSc solver), Kwan-Liu Ma, Chad Jones, and Chris Ho (U.C. Davis – SciDAC Institute for Ultrascale Visualization).