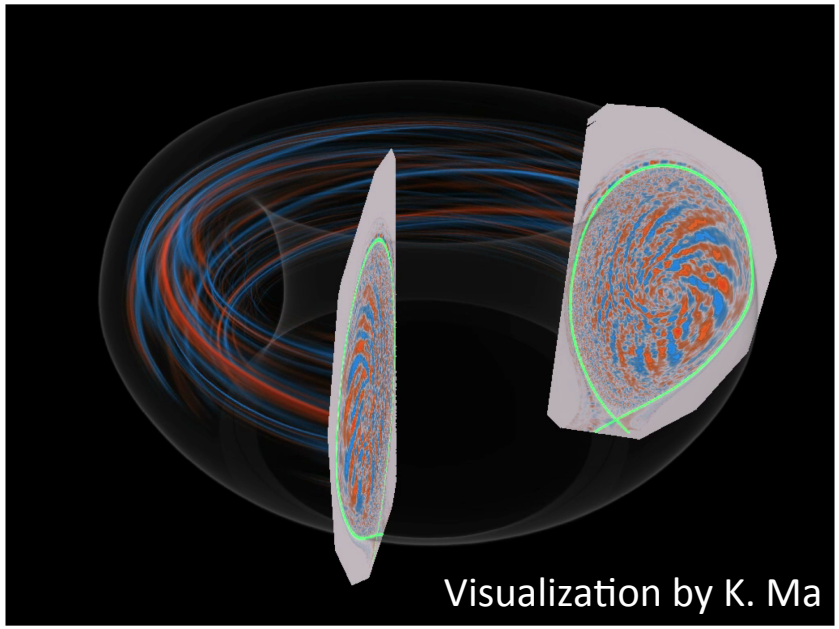
Core gradient region in full-f GK code XGC1 (Chang, et al)

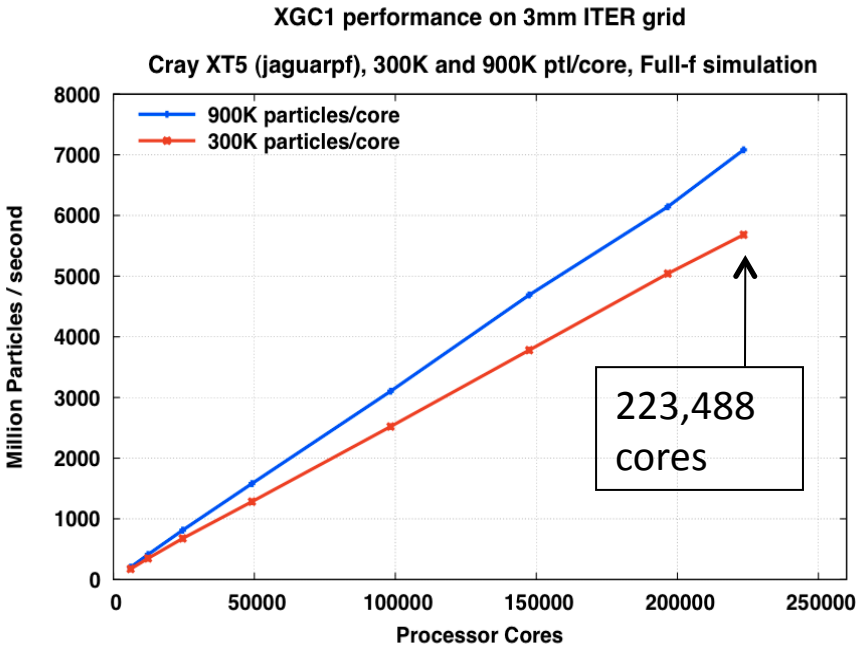
- **Simulation: global multiscale multiphysics approach, in diverted geometry**
  - **Neoclassical, turbulence, impurities, neutral particles, atomic physics, NBI**
    - Turbulence will include all the important electromagnetic modes (ETG will be handled on localized adaptive grids in multiscale)
  - **Edge neutral, impurity, atomic physics → pedestal neoclassical and turbulence → SOC in core gradient region, momentum transport**
  - Central flat core: neoclassical effects from potato orbits (beam interaction with electrons, thermal ions) → subcritical turbulence → core gradient region
- **Diagnostics**
  - **Radially distributed turbulence property: δn, δT, k, ω, V'_{ExB}, correlations**
  - **Effect of neutral gas puff, impurity radiation, pedestal T and n structure**
    - Weakly collisional pedestal in NSTX-U may separate T_i from T_e, make T_i profile broader than n, provoke ITG source with radial spreading, and interact with (mask) the ETG transport of NSTX
  - **Effect of beam ion density and energy on the turbulence property**
- **Code development**
  - **Current capability:**
    - Full-f ITG + neoclassical + neutral in diverted geometry
    - Full-f ITG+TEM turbulence in non-diverted geometry
    - Delta-f electromangetic turbulence in non-diverted geometry
  - **Near Future**: E&M turbulence + neoclassical + neutrals + impurities +NBI in diverted geometry, ETG is planned to be a longer term addition

Comprehensive gyrokinetic code XGC1
(Unique in the world fusion program)

- Diverted magnetic field geometry with material wall BD condition
- Includes magnetic axis: wall-to-wall simulation
  - Lagragian operation (particle time-advance) in cylindrical coordinates
  - Eulerian operation (field solver) in field-following coordinates
- Wall-recycling of neutral particle with atomic physics
- Multiscale simulation of neoclassical, turbulence, neutral particle, and atomic physics
- Aim for 24 hour simulation by utilizing HPC

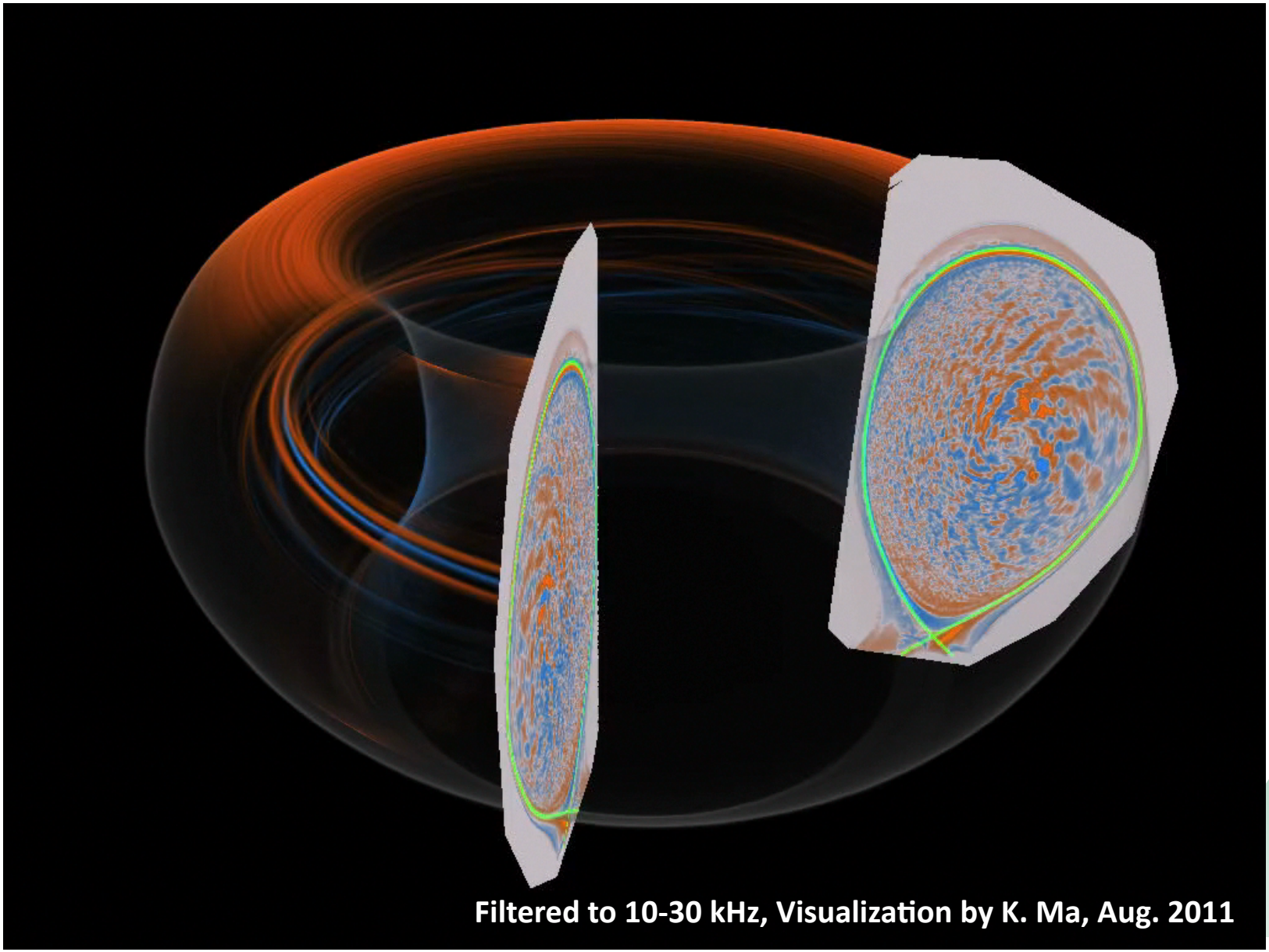


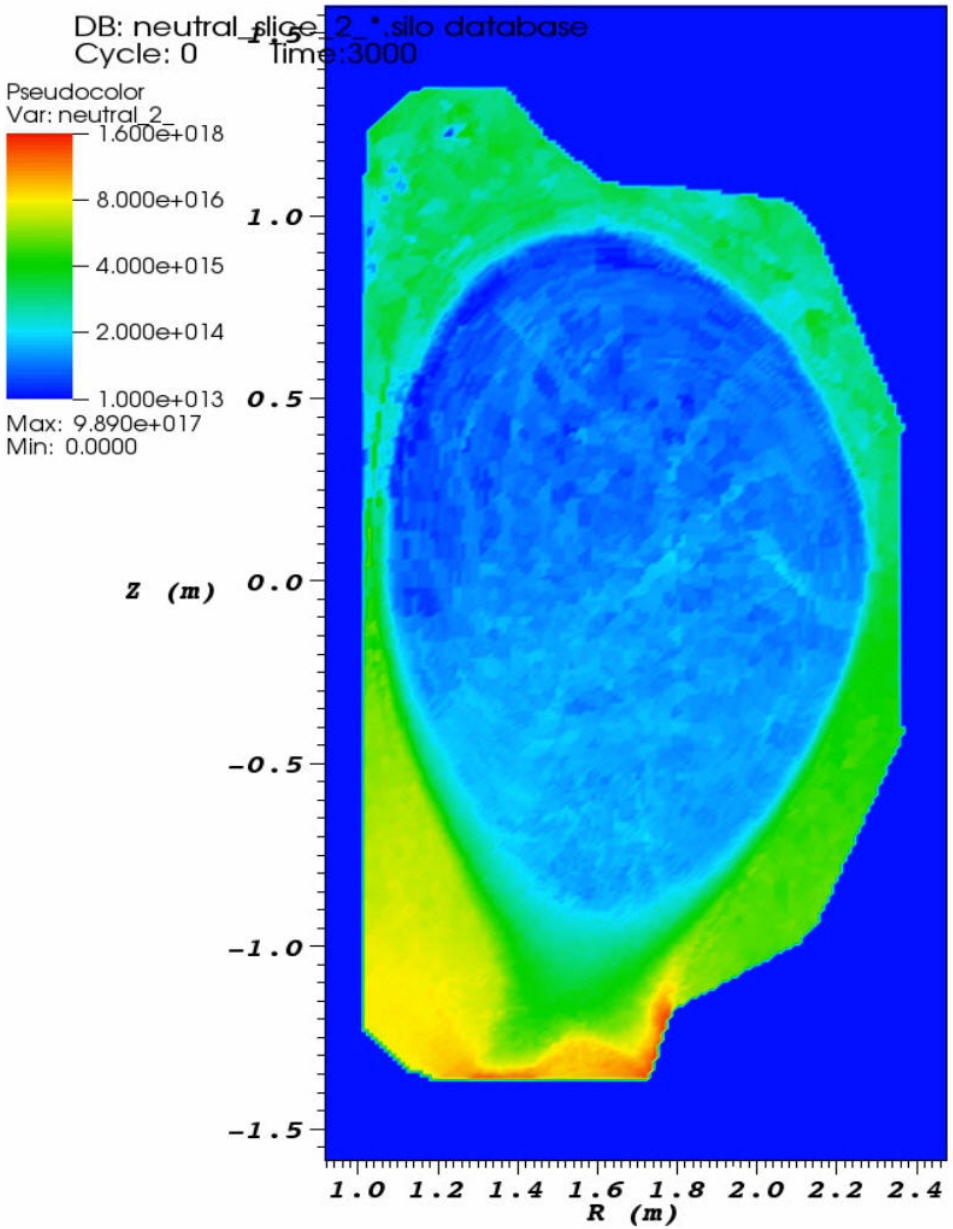
Ion turbulence fills the whole volume, but is confined by magnetic separatrix surface (green curve). DIII-D geometry is used.



XGC1 scales efficiently all the way to the maximal Jaguarpf capability, with MPI+ OpenMP. Routinely uses >70% capability.

Ion turbulence fills up the whole volume including central core, but is confined by magnetic separatrix surface (green curve). DIII-D geometry is used with monotonic q>1.



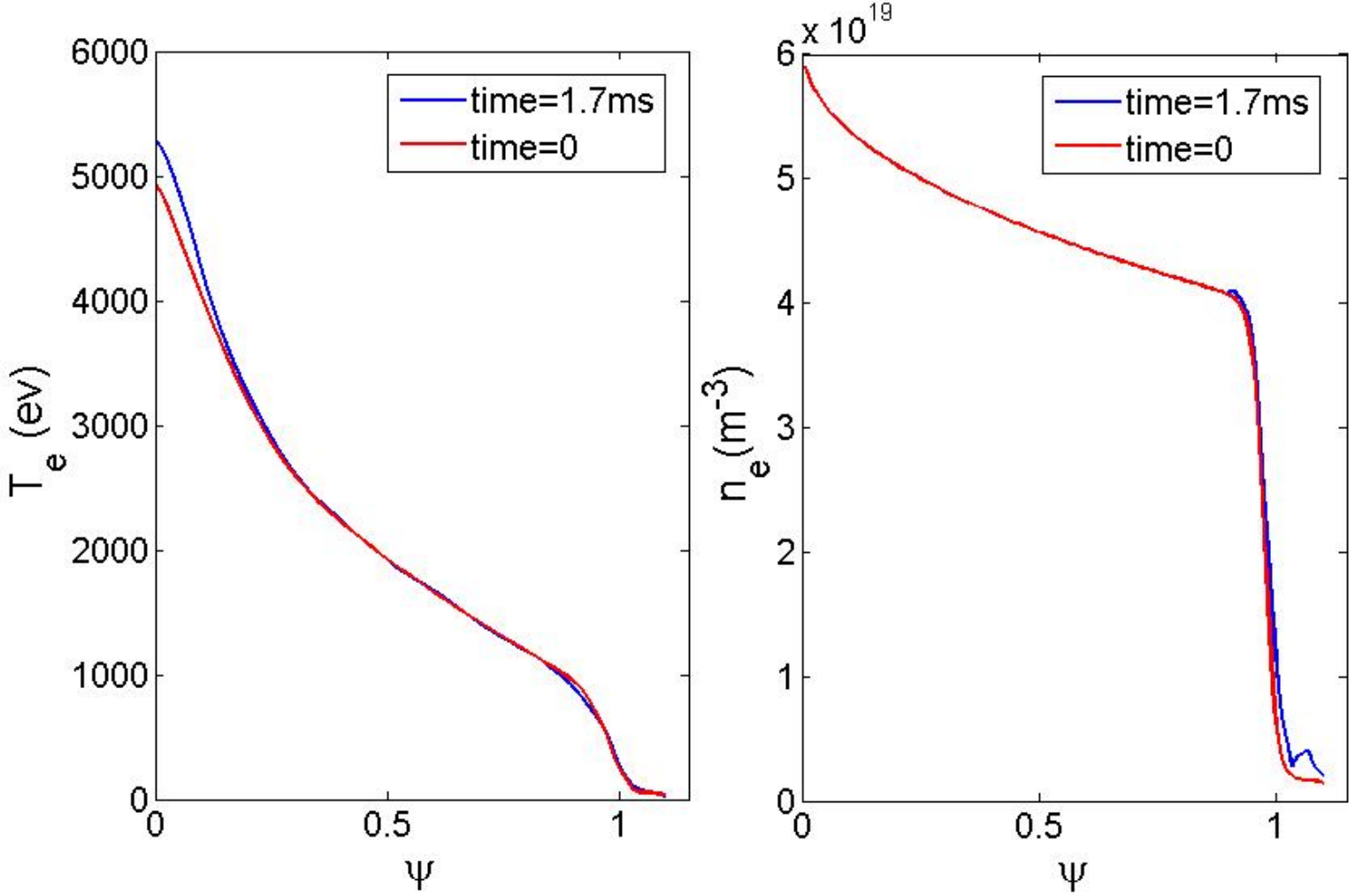


Neutral particle density distribution in realistic DIII-D edge geometry from XGC [simulation by D. Stotler].

Neutral particles interact with plasma in XGC0 and XGC1

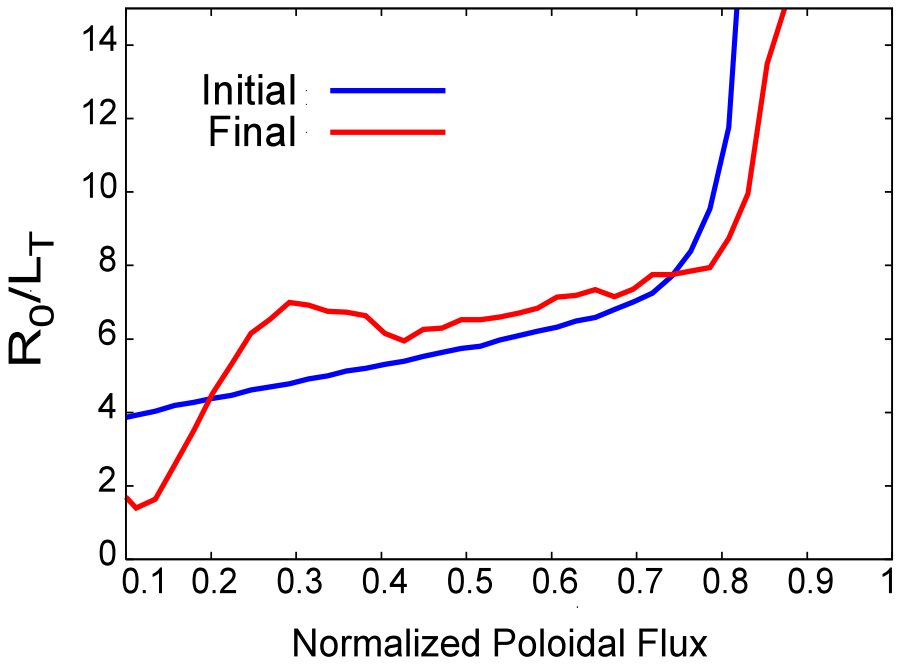
- Monte Carlo transport
- Wall recycling
- Ionization
- Charge exchange

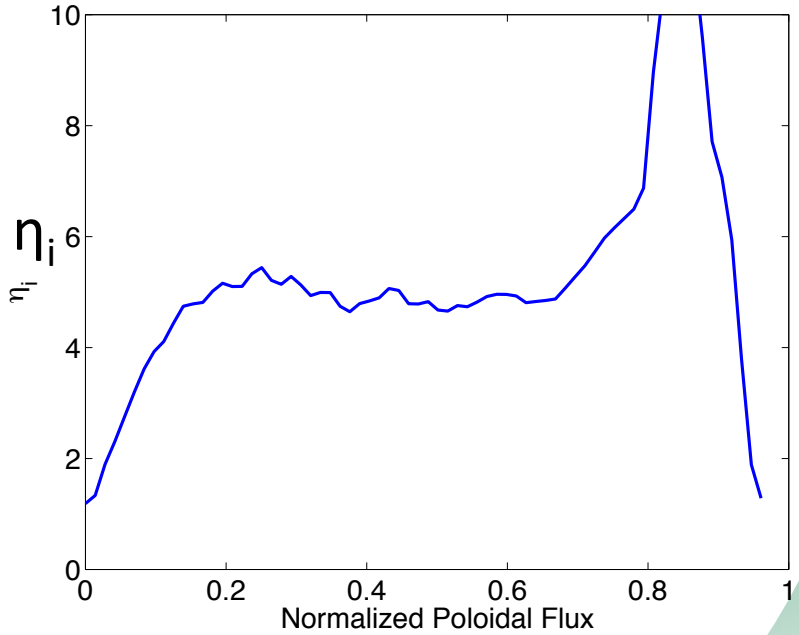
Neutral ionization and charge exchange in XGC1 (1.7 ms)



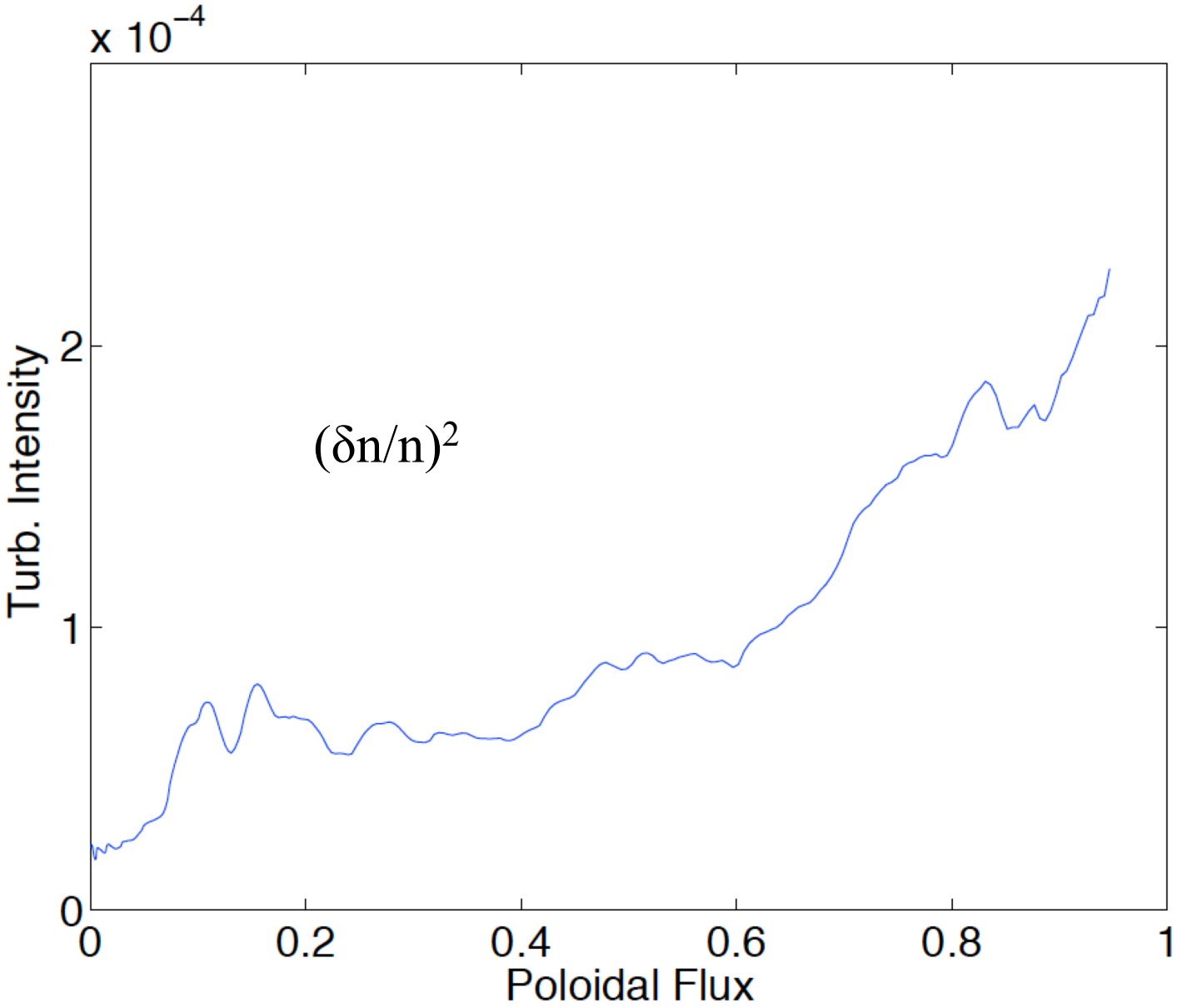
Final stiff T_i profile shows global SOC, but is super-critical at pedestal top, and is subcritical in the central core (Ψ_N<0.25) and in the density pedestal

- At pedestal top, ∇T_i remains moderate (ion orbit mixing effect forces T_i pedestal to be wider than n-pedestal), but ∇n_e is weak → Large η_i → super critical
- In the density pedestal, ∇T_i is moderate (neutral cooling and orbit mixing), but ∇n_e is very strong → small η_i → subcritical





Simulation by S. Ku



XGC1 shows for the first time that turbulence intensity $(\delta n/n)^2$ increases with minor radius, as observed in experiments.

Turbulence spreading into core flat region in full-f GK XGC1

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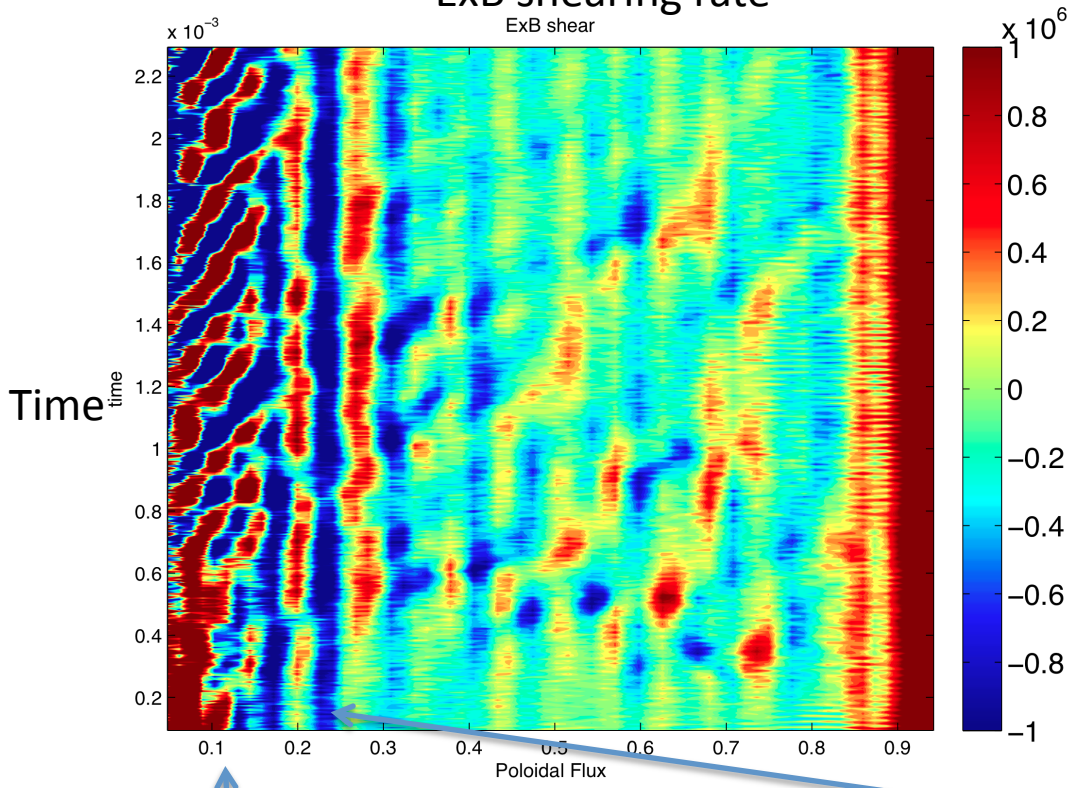
  - **Neoclassical, turbulence, impurities, neutral particles, atomic physics, NBI**
    - Turbulence will include all the important electromagnetic modes (ETG will be handled on localized adaptive grids)
  - **Edge neutral, impurity, atomic physics → pedestal neoclassical and turbulence → SOC in core gradient region → spreading into central core**
  - Central flat core: neoclassical effects from potato orbits (beam interaction with electrons, thermal ions) → subcritical turbulence
- **Diagnostics**
  - **Radially distributed turbulence property: δn, δT, k, ω, V'_{ExB}, correlations**
  - **Cold or hot pulse experiment to study spreading dynamics**
  - **Effect of beam ion density and energy on the width of the core flat region**
- **Code development**
  - **Current capability:**
    - Full-f ITG + neoclassical + neutral in diverted geometry
    - Full-f ITG+TEM turbulence in non-diverted geometry
    - Delta-f electromagnetic turbulence in non-diverted geometry
  - **Near Future**: E&M turbulence + neoclassical + neutrals + impurities +NBI in diverted geometry. ETG will be added when NSTX-U is in operation.

A spreading generated subcritical turbulence does not usually mean elevated anomalous transport

How can such a turbulence expel heat if the plasma is centrally heated?
→ Zonal flows builds high ways for avalanche process.

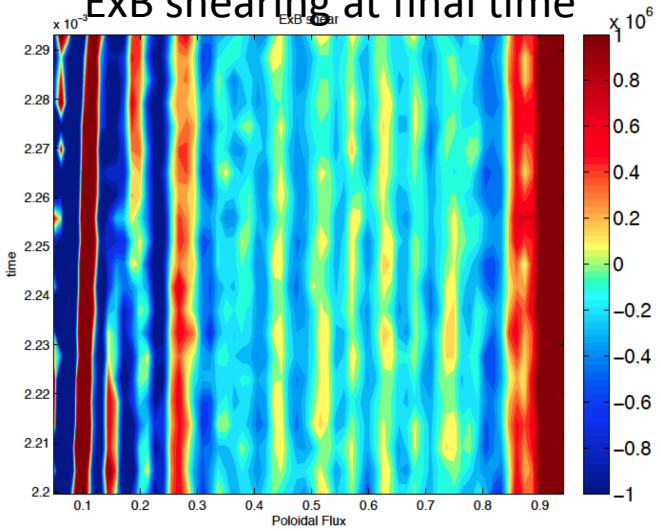
ExB shearing rate



Time

Poloidal flux (radius)

ExB shearing at final time

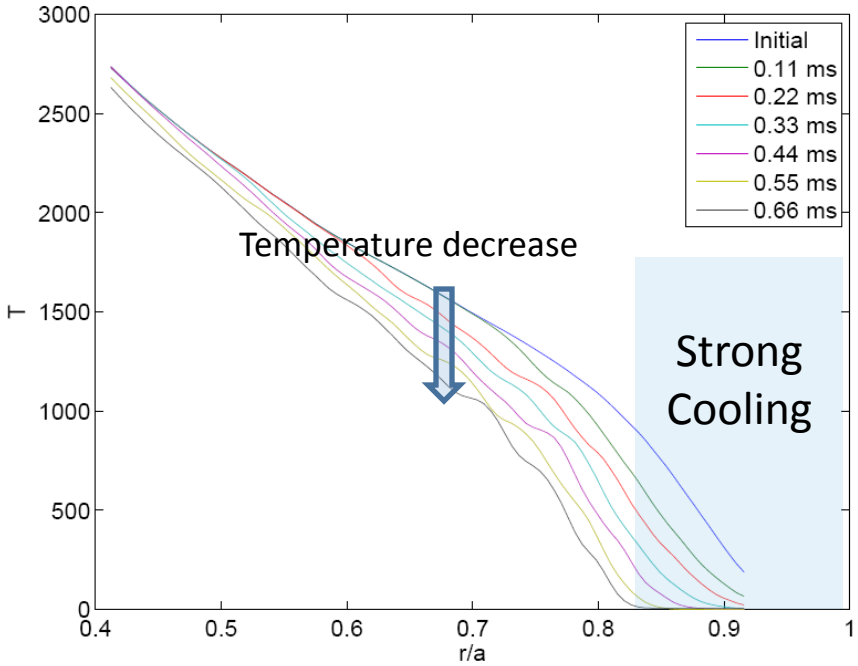


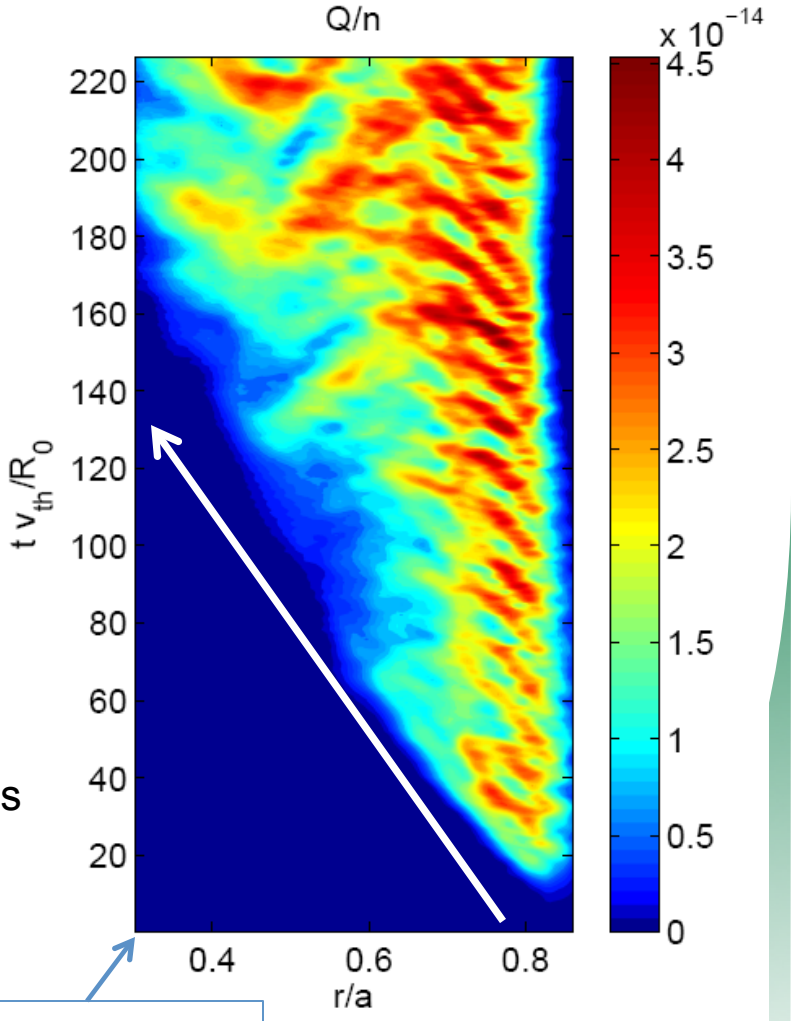
Zonal flows usually form staircase and reduce turbulence driven transport

Zonal flows form a “transport highway” in the subcritical central core to expel heat when central heating is present.

Sign of internal transport barrier formation at the boundary between sub and SOC regions

Simulation of cold edge pulse in XGC1p





- ITG turbulence in XGC1p
- Strong cooling at the edge after the plasma reaches quasi steady state.
- Cold pulse propagates inwards.
- Inward propagation of intensified turbulence

Simulation by S. Ku

Fully nonlinear collision operation

- We have both linear-based Monte Carlo operator and fully non-linear Fokker-Planck operator, at work in XGC0
- Chang-Hinton has been reproduced from nonlinear collisions within <20%