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Finite-size effects in plasma microturbulence

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Gyrokinetics for ITER II
WPI, Vienna
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Overview

- The Vlasov code GENE – local and global
- Linear and nonlinear investigations of finite-size effects
- Heat flux avalanches
- Conclusions

The gyrokinetic Vlasov code GENE

Theoretical framework: Gyrokinetic theory

(fusion plasmas are *hot* and *dilute* and thus *collisionless*)

- <u>Main idea:</u> use a reduced, gyroangle independent description

Gyrokinetic Vlasov equation

$$\boxed{\frac{\partial f_\sigma}{\partial t} + \dot{\mathbf{X}} \cdot \nabla f_\sigma + \dot{\mu} \frac{\partial f_\sigma}{\partial \mu} + \dot{v}_\parallel \frac{\partial f_\sigma}{\partial v_\parallel} = 0}$$

with gyrocenter position $\mathbf{X}$

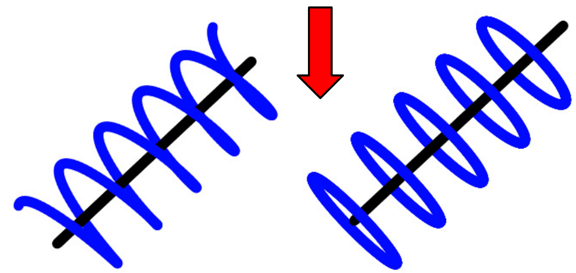
$$\begin{aligned}
\dot{\mathbf{X}} &= v_\parallel \mathbf{b}_0 + \frac{B_0}{B_{0\parallel}^*}\left(\frac{v_\parallel}{B_0}\bar{\mathbf{B}}_{1\perp} + \mathbf{v}_\perp\right) \\
\mathbf{v}_\perp &\equiv \frac{c}{B_0^2}\bar{\mathbf{E}}_1 \times \mathbf{B}_0 + \frac{\mu}{m_\sigma \Omega_\sigma}\mathbf{b}_0 \times \nabla B_0 \\
&\quad + \frac{v_\parallel^2}{\Omega_\sigma}(\nabla \times \mathbf{b})_\perp
\end{aligned}$$

parallel velocity $v_\parallel$

$$\dot{v}_\parallel = \frac{\dot{\mathbf{X}}}{m_\sigma v_\parallel} \cdot (q_\sigma \bar{\mathbf{E}}_1 - \mu \nabla B_0))$$

and magnetic moment μ

$$\dot{\mu} = 0$$



Gyrokinetics: reduced description
("charged rings")

Poisson equation

$$\boxed{\begin{aligned}
-\nabla^2 \phi(\mathbf{x}) &= 4\pi \sum_\sigma q_\sigma n_\sigma \\
&= 4\pi \sum_\sigma q_\sigma \int \delta(\mathbf{X} + \mathbf{r} - \mathbf{x}) T^* f_\sigma \frac{B_{0\parallel}^*}{m_\sigma} \mathrm{d}^3 X \mathrm{d}v_\parallel \mathrm{d}\mu \mathrm{d}\theta
\end{aligned}}$$

Ampère's law

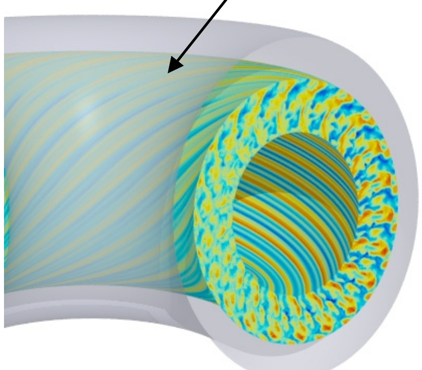
$$\boxed{\begin{aligned}
-\nabla^2 A_\parallel(\mathbf{x}) &= \frac{4\pi}{c} j_\parallel \\
&= \frac{4\pi}{c} \sum_\sigma q_\sigma \int \delta(\mathbf{X} + \mathbf{r} - \mathbf{x}) v_\parallel T^* f_\sigma \frac{B_{0\parallel}^*}{m_\sigma} \mathrm{d}^3 X \mathrm{d}v_\parallel \mathrm{d}\mu \mathrm{d}\theta
\end{aligned}}$$

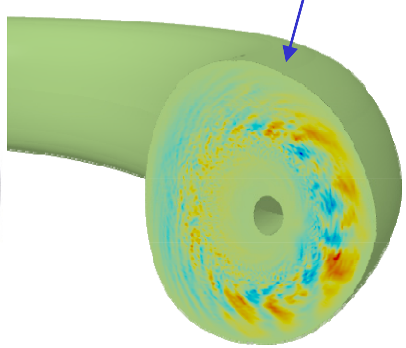
→ see, e.g., [Brizard & Hahm, Rev. Mod. Phys, 2007]

The gyrokinetic code GENE

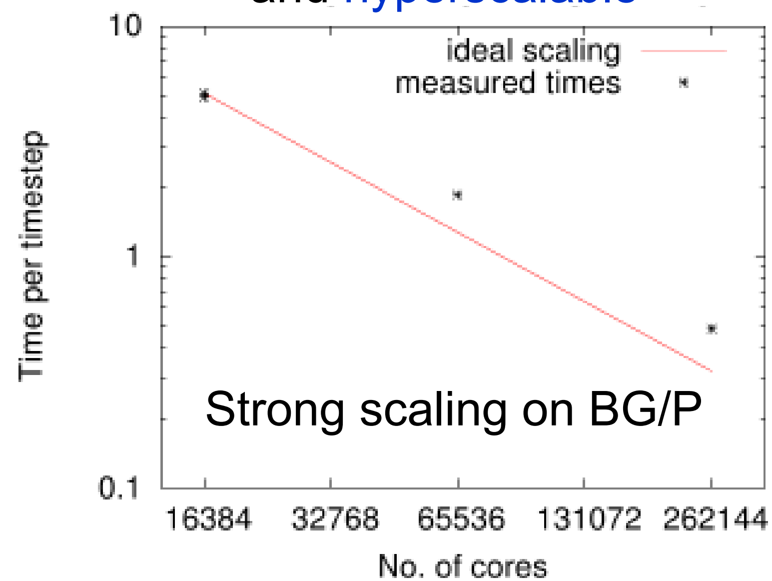
GENE is a physically comprehensive Vlasov code:

- allows for kinetic electrons & electromagnetic fluctuations, collisions, and external ExB shear flows
- is coupled to various MHD codes and the transport code TRINITY
- can be used as **initial value** or **eigenvalue** solver
- supports **local** (flux-tube) and **global** (full-torus), gradient- and flux-driven simulations





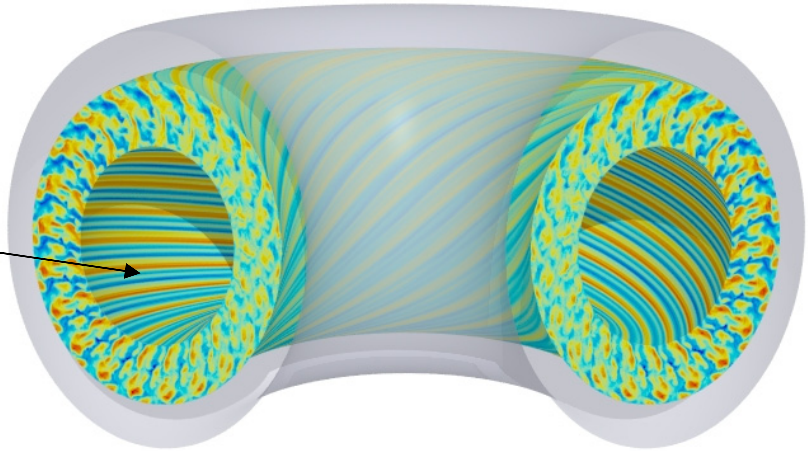
GENE is well benchmarked and hyperscalable



Concepts used within GENE

- GENE is a *Eulerian* code; thus solving the 5D (δf-splitted) distribution function on a fixed grid

- field-aligned coordinate system to exploit the high anisotropy of plasma turbulence



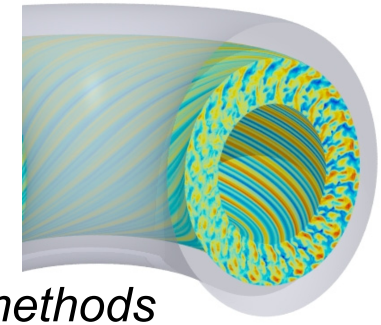
gene.rzg.mpg.de

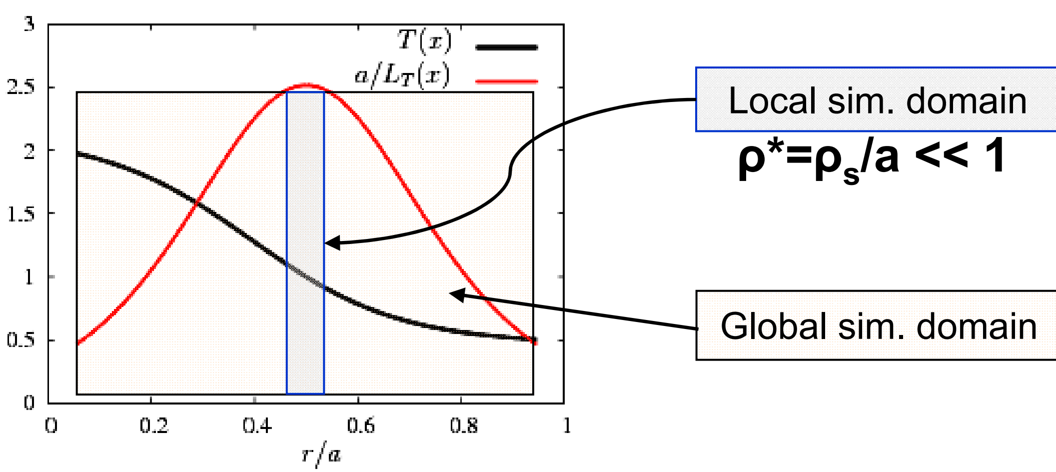
- the differential operators are discretized via a combination of spectral, finite difference, and finite volume methods

- the time stepping is done via a (non-standard) explicit Runge-Kutta method

Local vs. global GENE

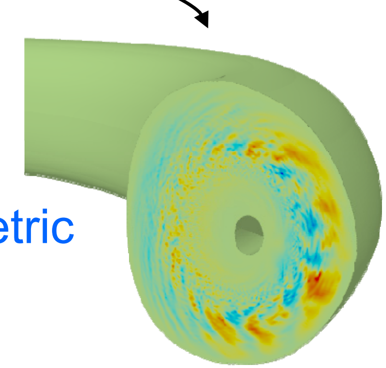
- **Local:** in the radial direction
  - Simulation domain small compared to machine size; thus, *constant* temperatures/densities and *fixed* gradients
  - Periodic boundary conditions; allows application of *spectral methods*





$\rho^* = \rho_s/a << 1$

- **Global:** adding nonlocal features in the *radial* direction
  - Consider full temperature & density profiles; radially varying metric
  - Dirichlet or v. Neumann boundary conditions
  - Heat sources & sinks



Local vs. global GENE – numerical point of view

Local approach:

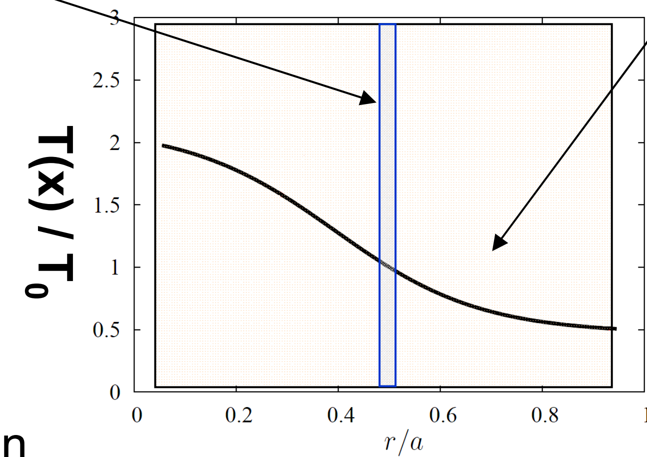
Spectral methods

- derivatives:

$$\frac{\partial f}{\partial x} \rightarrow \mathrm{i}k_x f(k_x)$$

- Gyroaverage & field operators can be given analytically:

$$\langle \phi(\mathbf{x}+\mathbf{r})\rangle = \sum_{\mathbf{k}_\perp} J_0(k_\perp \rho)\phi(\mathbf{k}_\perp, z)\mathrm{e}^{\mathrm{i}\mathbf{k}_\perp \mathbf{x}}$$



Global approach:

- derivatives: finite difference scheme, typically 4th order

- Use interpolation schemes for gyroaverage & field operators

$$\langle \phi_1(\mathbf{X}+\mathbf{r})\rangle = \sum_{k_y} \mathrm{e}^{\mathrm{i}k_y Y}\,\mathcal{G}(X,k_y,z,\mu)\cdot\phi_1(X,k_y,z)$$

with gyromatrix $\mathcal{G}_{in}(x,k_y,z,\mu)$

$$= \frac{1}{2\pi}\int_0^{2\pi} \boxed{\Lambda(x_{(i)} - r^x(\theta))}\,\mathrm{e}^{-\mathrm{i}k_y r^y(\theta)}\,\mathrm{d}\theta$$

local polynomial base (coarse grid values can directly be extracted)

Why global?

- Cover a larger radial domain (instead of using several flux tubes)

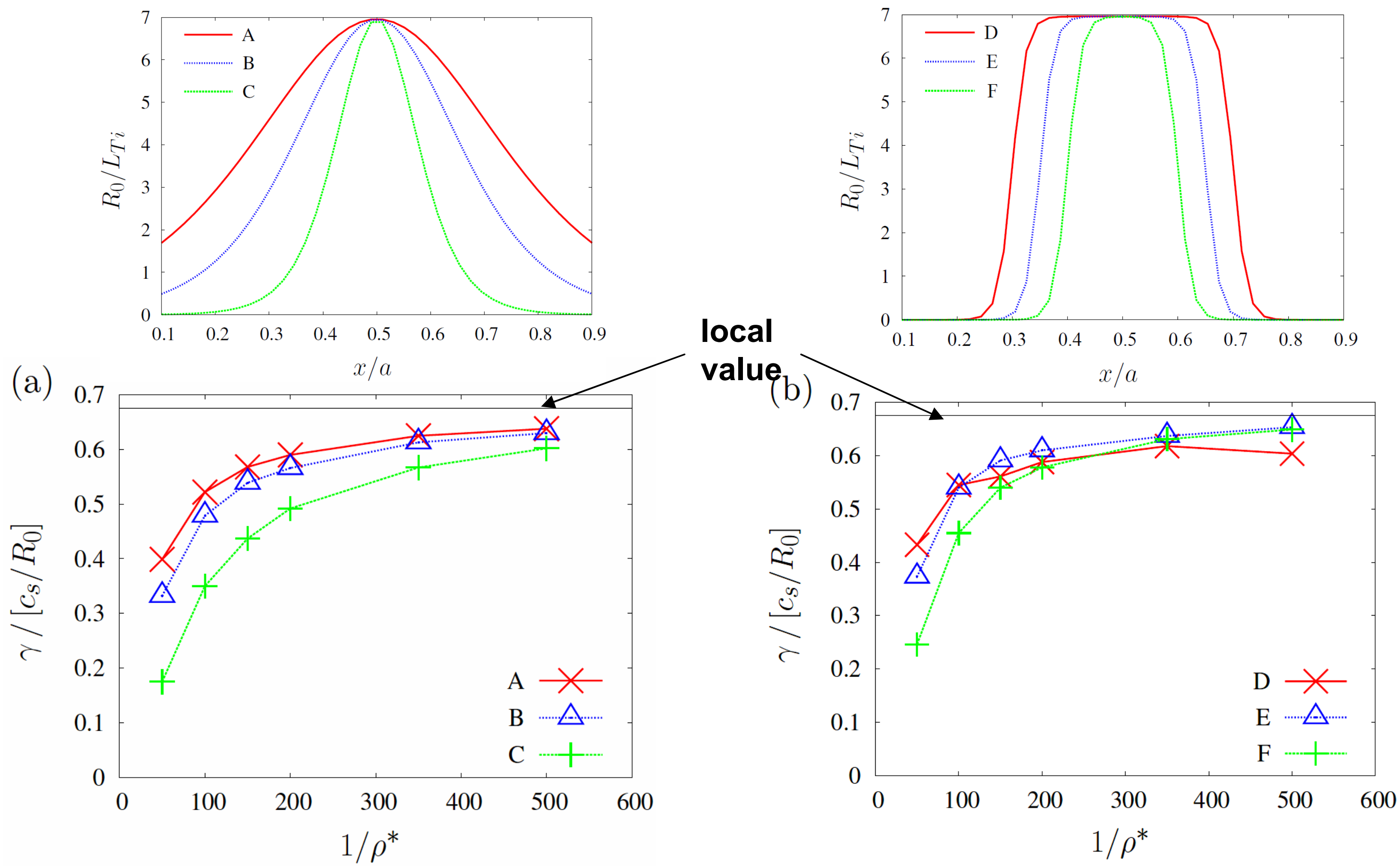
- Check validity of local simulations:
  - When do meso-/large scale events, i.e. avalanches or turbulence spreading, occur?

  - Do they affect the transport scaling?
    - "machine-size" events: Bohm scaling $\chi_B = cT/eB$
    - Gyroradius scale turbulence: Gyro-Bohm scaling $\chi_{\mathrm{GB}} = \rho^* \chi_B$

  - Re-assess earlier results by [Z. Lin et al., PRL, 2002] and [Candy et al., PoP 2004]

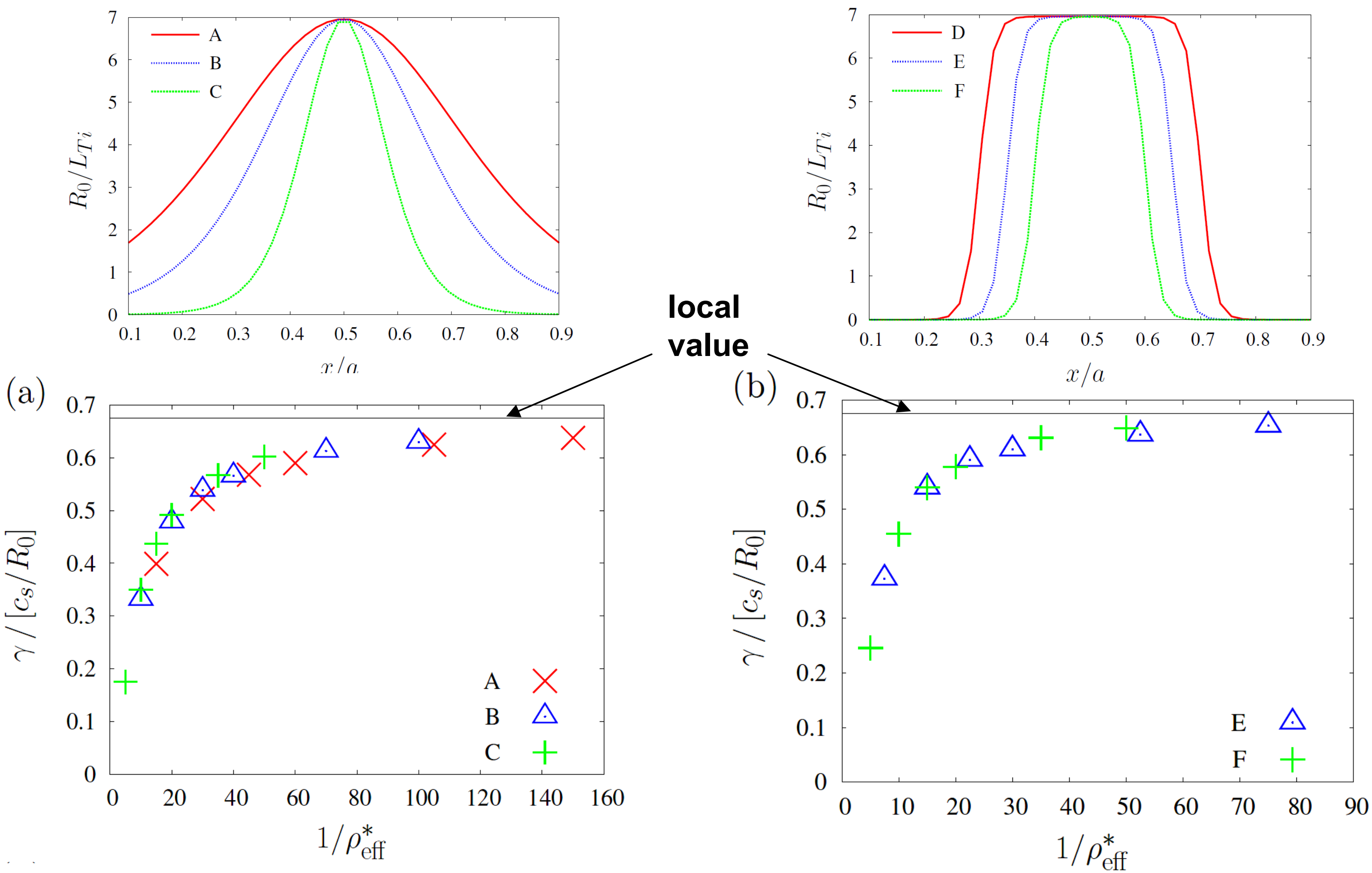
- Allow for flux-driven simulations

Local limit test ($\rho^* \rightarrow 0$) with L_x/a =const. for 2 profile types



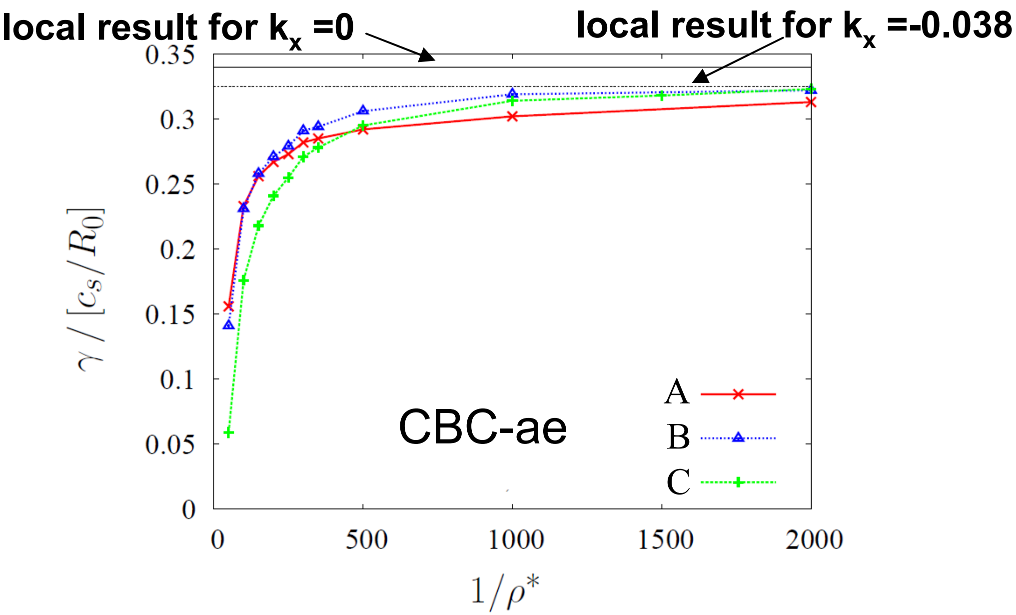
- Here: CBC-like parameters with kinetic electrons at $k_y\rho_s \sim 0.3$
- The global results do approach the local limit

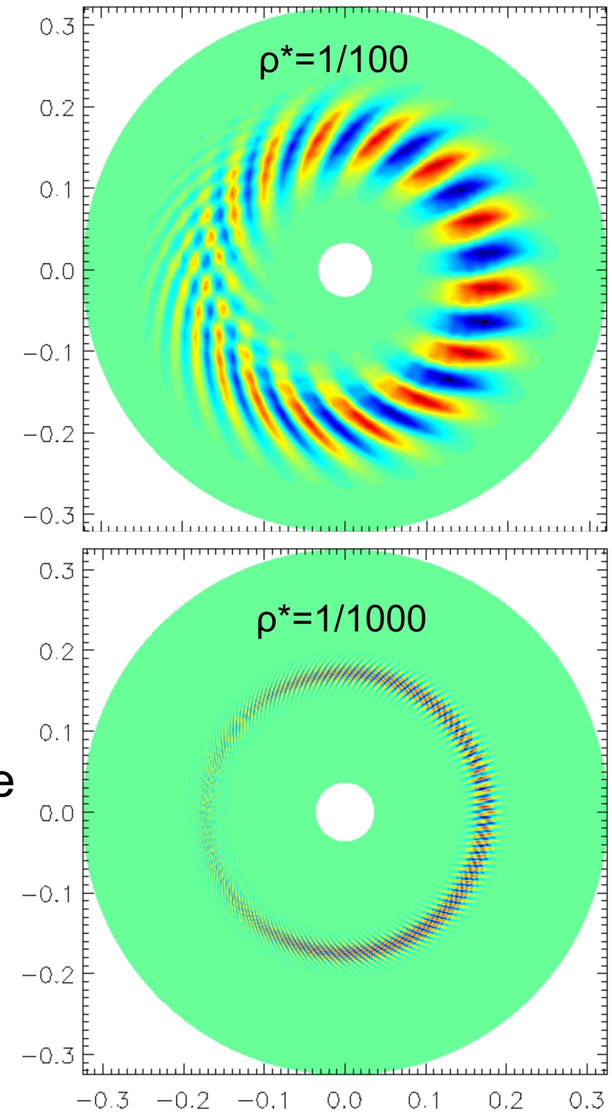
Local limit test ($\rho^* \rightarrow 0$) with **L_x/a =const.** for 2 profile types



- The profile shape (linear driving region) matters!
- Data points align with $\boxed{\rho^*_{\mathrm{eff}} = \rho^*/\Delta_r}$

Why convergence towards the local limit?

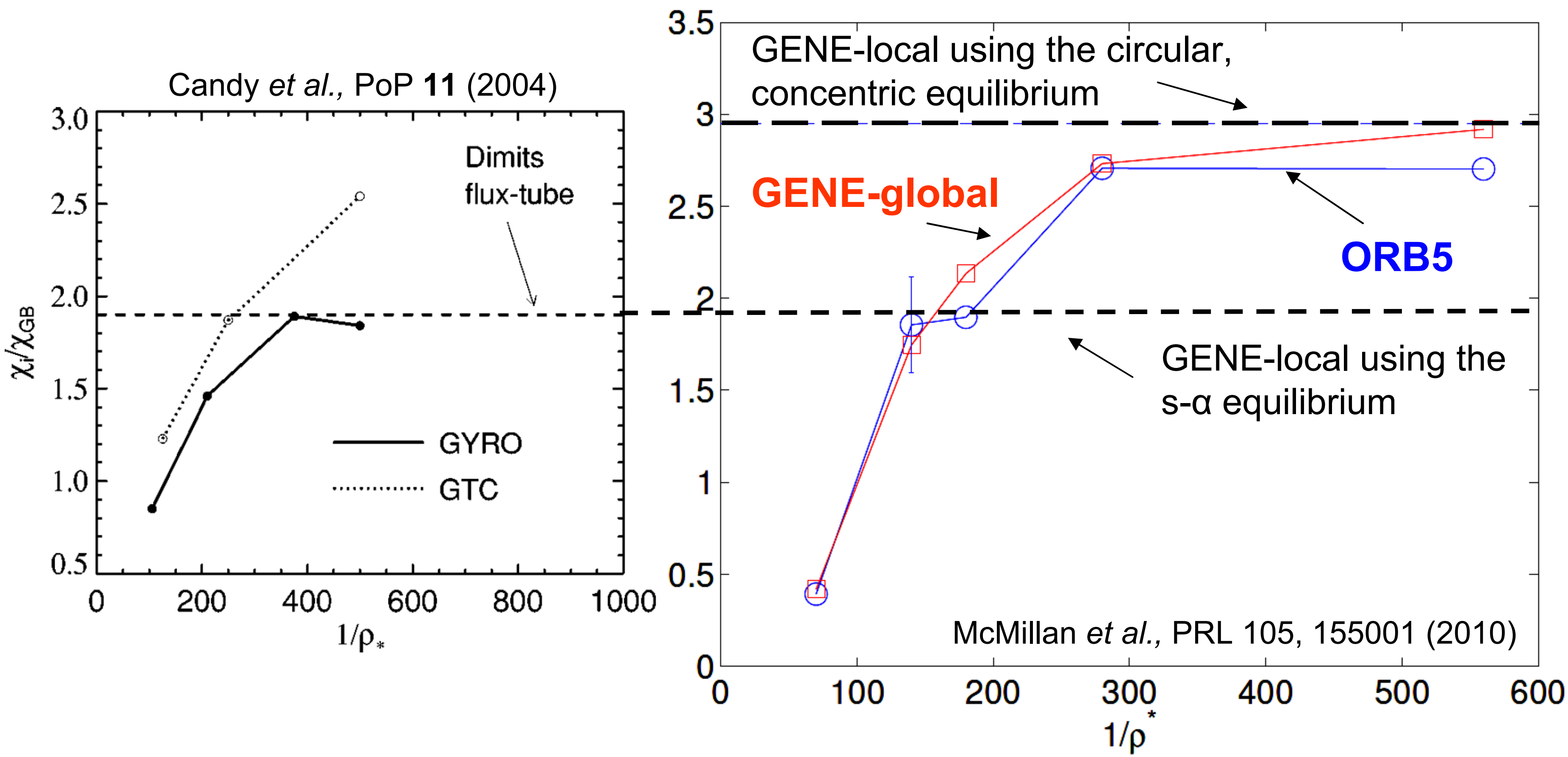




- Cowley et al., Phys. Fluid B '91:
  eddy size $\sim \sqrt{\rho_s L_T}$ $\rightarrow$ effective gradient drive

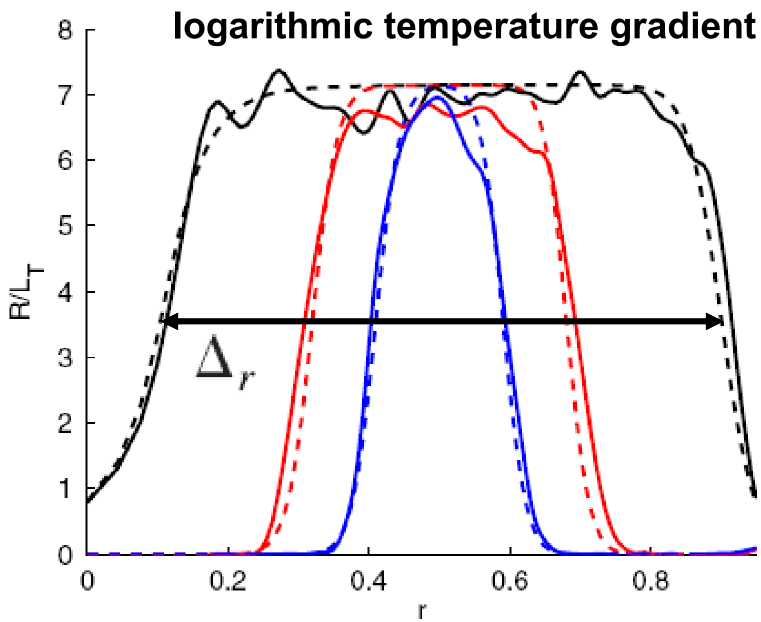
- However, finite offset might exist due to profile shearing which imposes a finite tilt in ballooning angle (finite k_x)

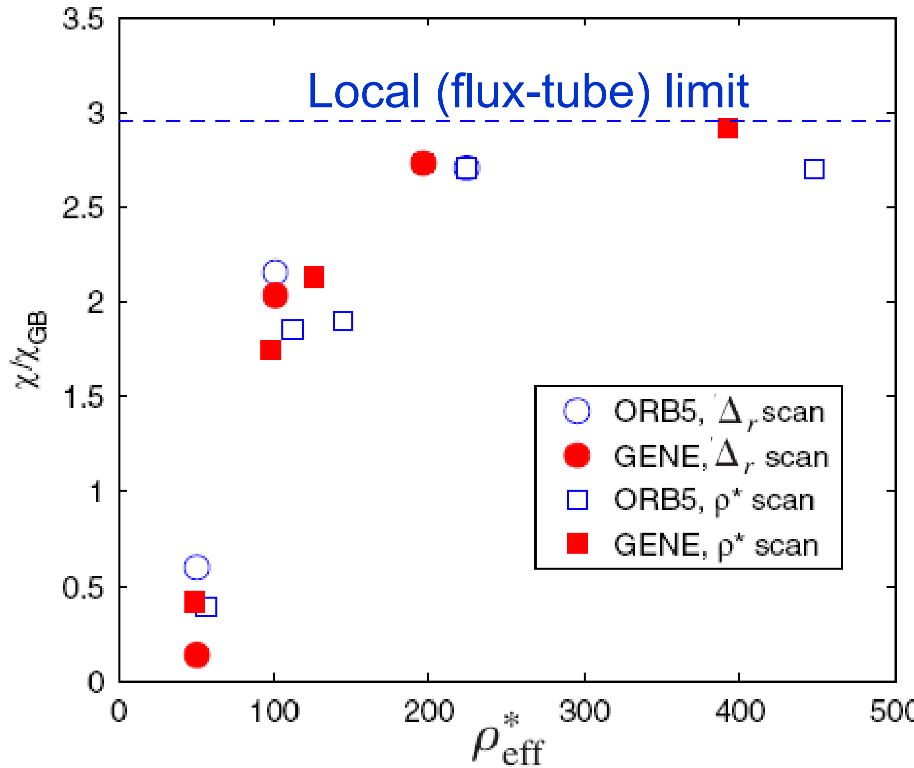
Nonlinear investigation of finite size effects



- ORB5 (Lagrangian) and GENE (Eulerian) agree if the **same geometry** model is used → long lasting controversy probably resolved
- Both, GENE and ORB5 converge towards the local limit
- Deviations (global/local) < 10% at $\rho^* < 1/300$

Finite system size: Profile shape matters





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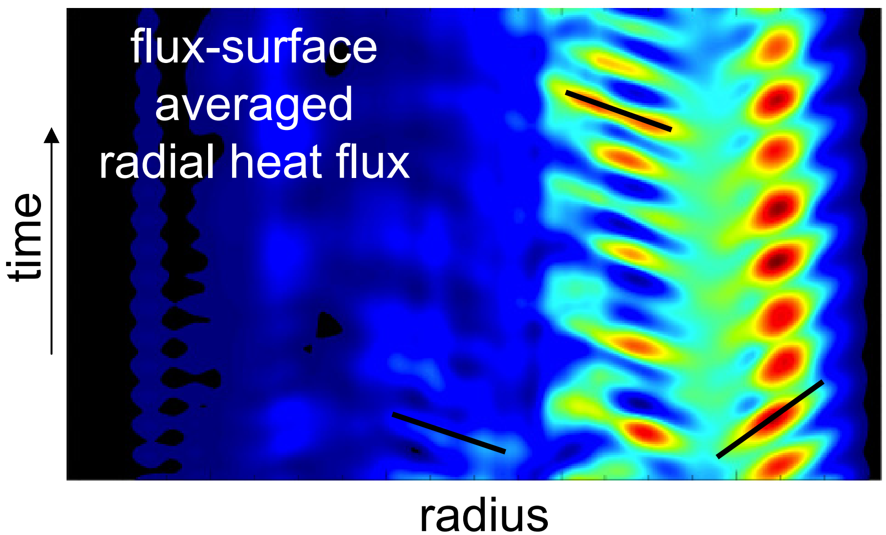
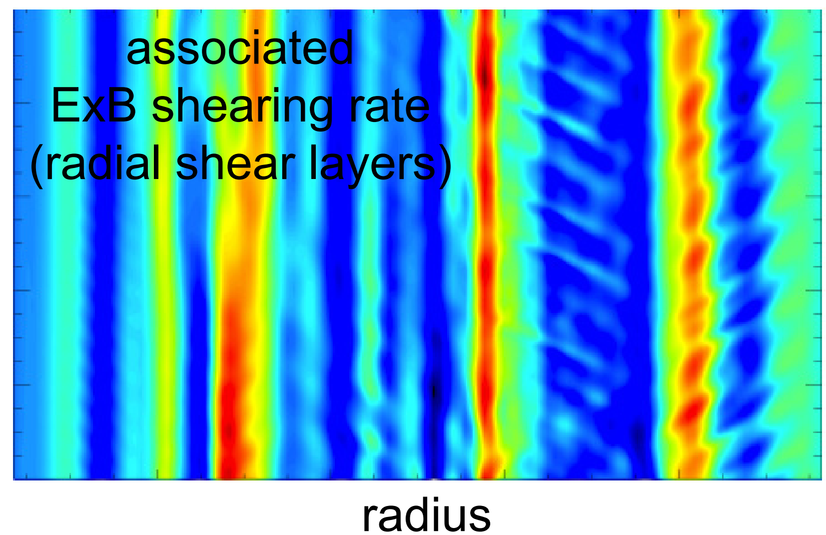
- Both codes also show that it is the parameter $\boxed{\rho^*_{\rm eff} = \rho^*/\Delta_r}$ which really matters – this should be kept in mind when dealing, e.g. with Internal Transport Barriers
- Scaling cannot be explained with profile shearing (only weak Δ_r dependence)
- Turbulence spreading, **avalanches**?

Can avalanches break gyro-Bohm scaling?

Global ***flux-driven*** simulations of ITG-ae turbulence with GENE (for $\rho^*=1/140$)



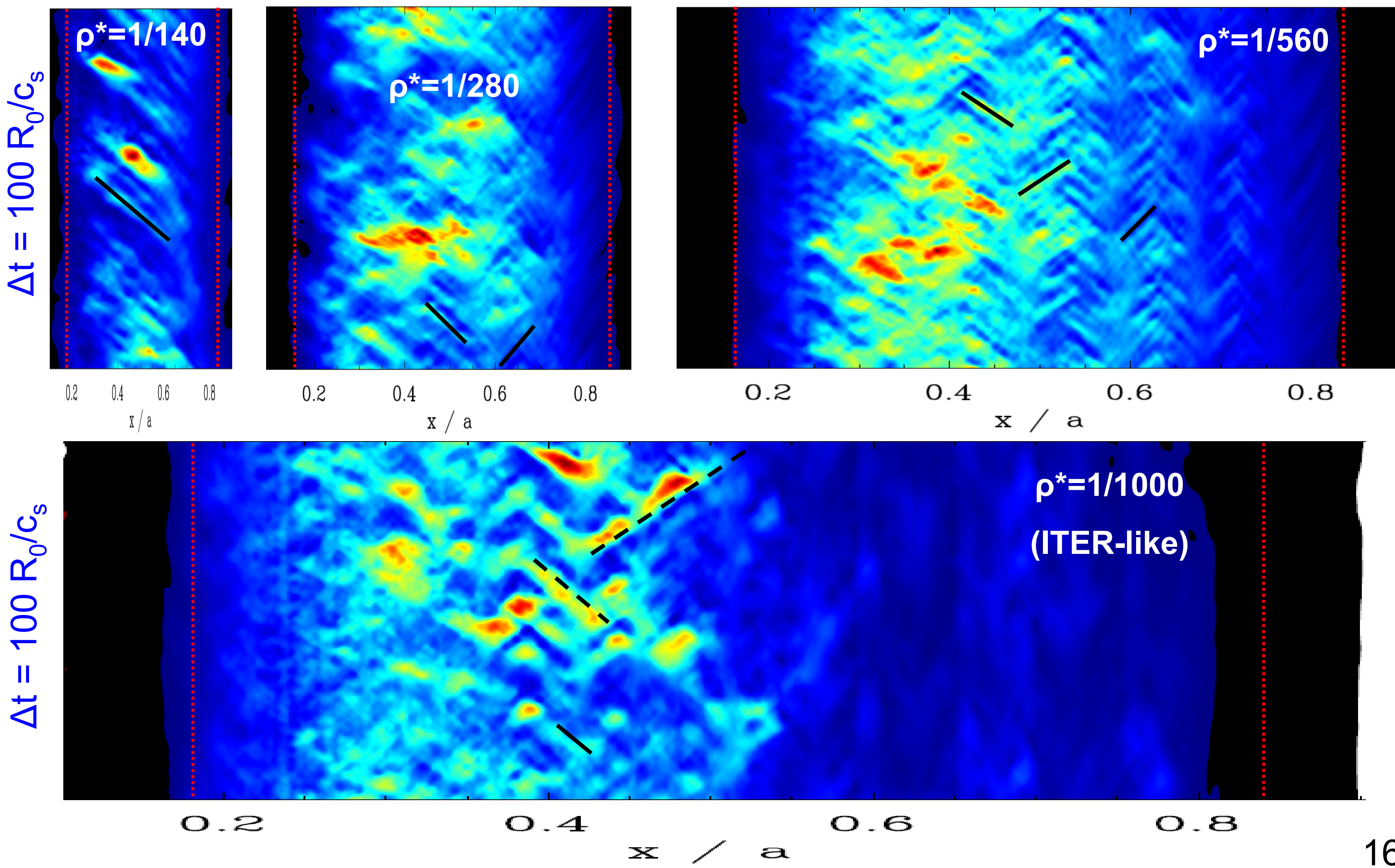


- avalanches are “mesoscale”; radial extent ~20-40 ρ_i
- their propagation speed is found to be ~$\rho^* v_{ti}$
- propagation direction is correlated with sign(ω_E)
- importance of low-frequency zonal flows & mean flows

Same phenomenology as, e.g., McMillan (PoP 2009)

Heat flux for global, gradient-driven ITG-ae

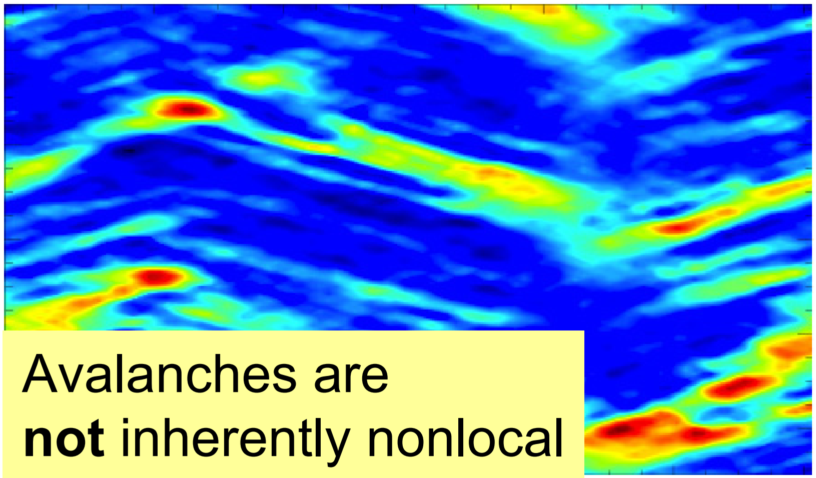
Radial extent and propagation velocities do not depend much on ρ*



Interesting insights from local simulations

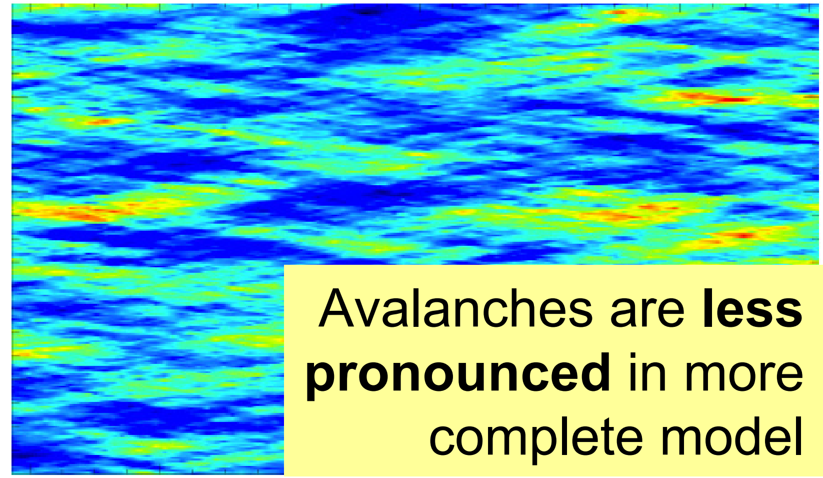
ITG turbulence (adiabatic electrons)

$\Delta t = 100\ R_0/c_s$



Avalanches are **not** inherently nonlocal

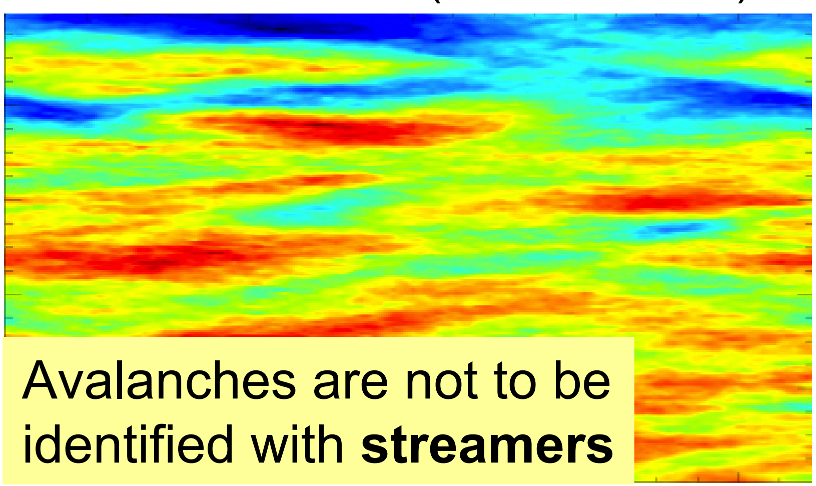
ITG turbulence (kinetic electrons)



Avalanches are **less pronounced** in more complete model

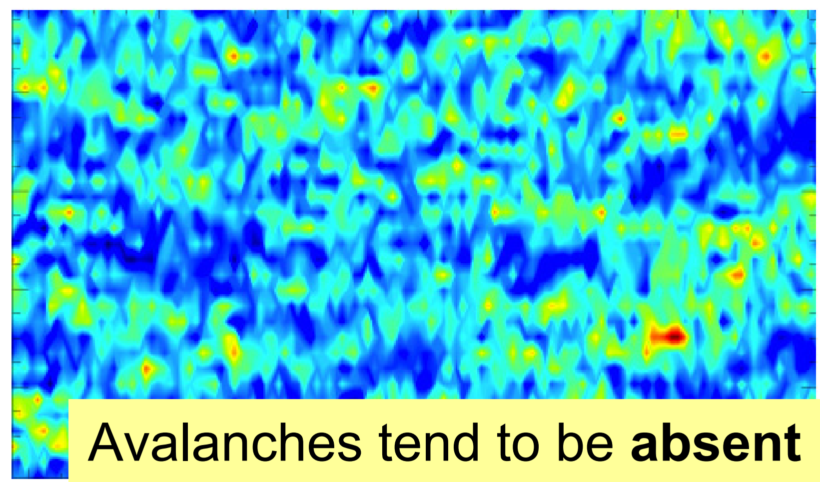
ETG turbulence (adiabatic ions)

$\Delta t = 100\ R_0/c_s$



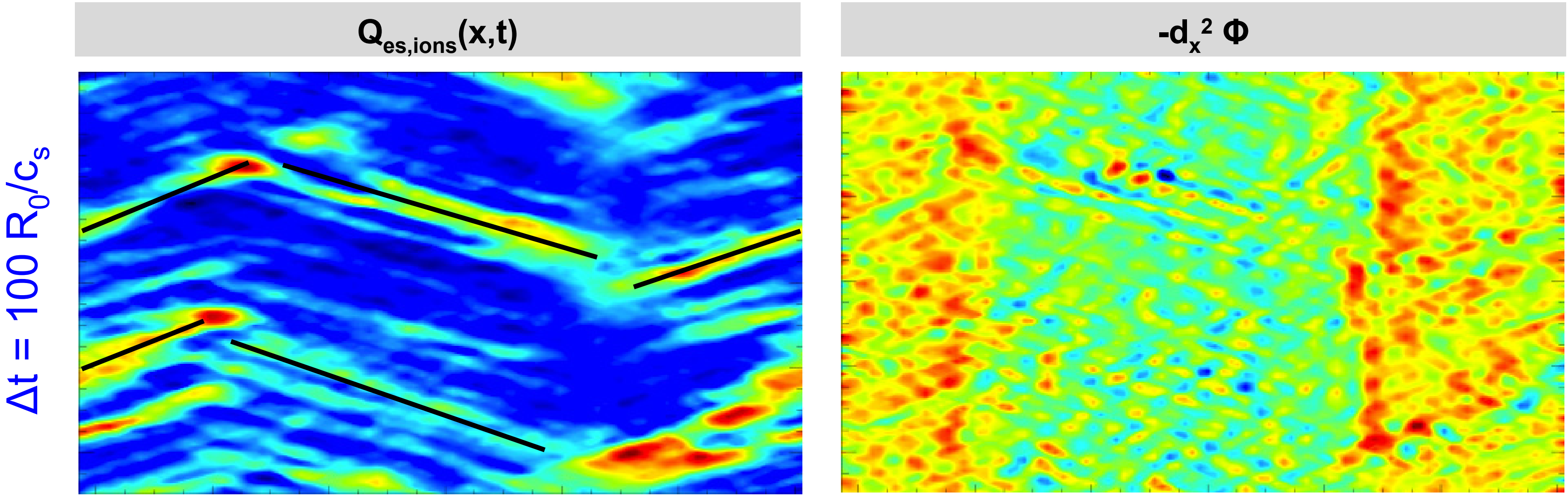
Avalanches are not to be identified with **streamers**

TEM turbulence

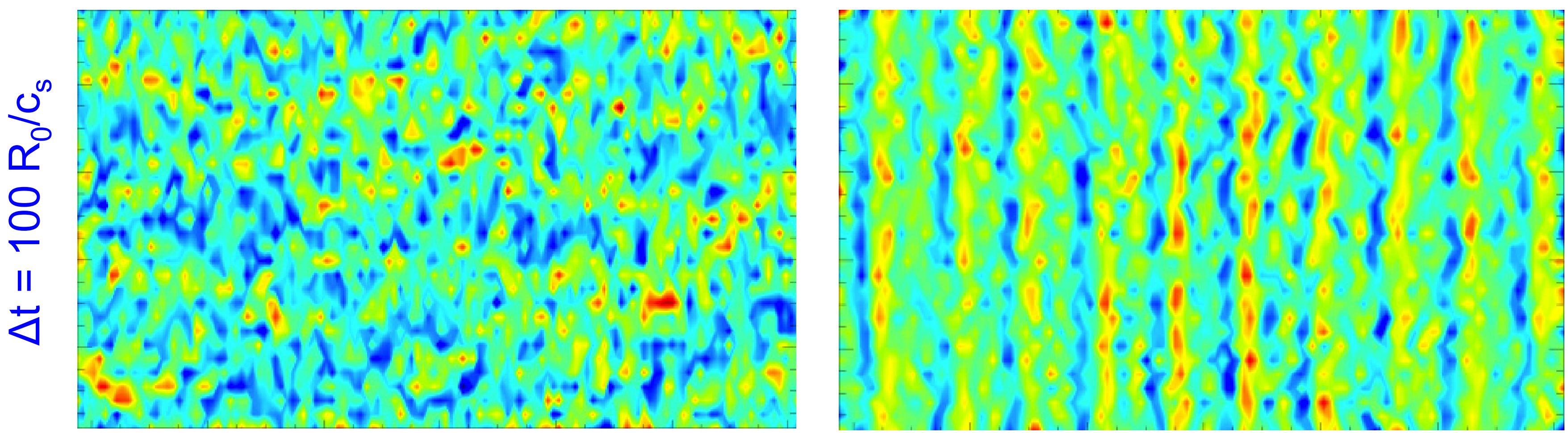


Avalanches tend to be **absent**

Local gradient-driven ITG-ae



Local gradient-driven TEM



Conclusions

Summary

- GENE has been extended to a nonlocal code; various sources/sinks allow for flux- and gradient driven types of operation
- Transition from nonlocal to local turbulence ($\rho^* \rightarrow 0$) has been revisited cooperatively via Lagrangian & Eulerian codes; linear driving region important
- Heat flux avalanches seem to be mesoscale (ρ_i-related) phenomena and are found not to break the gyro-Bohm scaling
- Applications to ITBs and Edge $\rightarrow$ Daniel's talk