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with T. Görler, D. Told, D. Hatch, M. Pueschel

Nature and role of microtearing turbulence in conventional tokamaks

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N^th Vienna meeting (N»1, thanks to Alex)
March 19th-30th, 2012

Outline of the talk

- **Historical context**
- Studies of the linear microtearing **instability**
  - expect existence in conventional tokamaks?
  - what are the critical plasma parameters?
- Nonlinear dynamics: microtearing **turbulence**
  - magnetic fluctuation amplitudes?
  - role of magnetic stochasticity?
- Microtearing modes in **finite** β **ITG/TEM** turbulence

A brief history of microtearing research

- **1973:** Small magnetic perturbations can lead to **stochastic fields** and **enhanced electron heat flux** ($\tilde{B}/B_0 \sim 10^{-4}$) [Stix]
- **1975-77:** Microtearing modes driven by ∇T_e are a **possible source** [Hazeltine et al., Drake et al., Chen et al.]
- **1980s and 1990s:** Linear theory of microtearing modes [Catto, Connor, Cowley, Drake, Hassam, Hastie, …]
- **Since 2000:** Linear gyrokinetic simulations; microtearing modes responsible for electron heat flux in **spherical tokamaks**? [Kotschenreuther et al., Redi et al., Applegate et al.]
- **2007/08:** Microtearing modes also in **medium aspect ratio tokamaks**? [Applegate et al., Vermare et al., Told et al.]
- **2010/11: Nonlinear gyrokinetic microtearing** simulations point to relevance for NSTX [Guttenfelder] and AUG (as well as ITER) [this work]

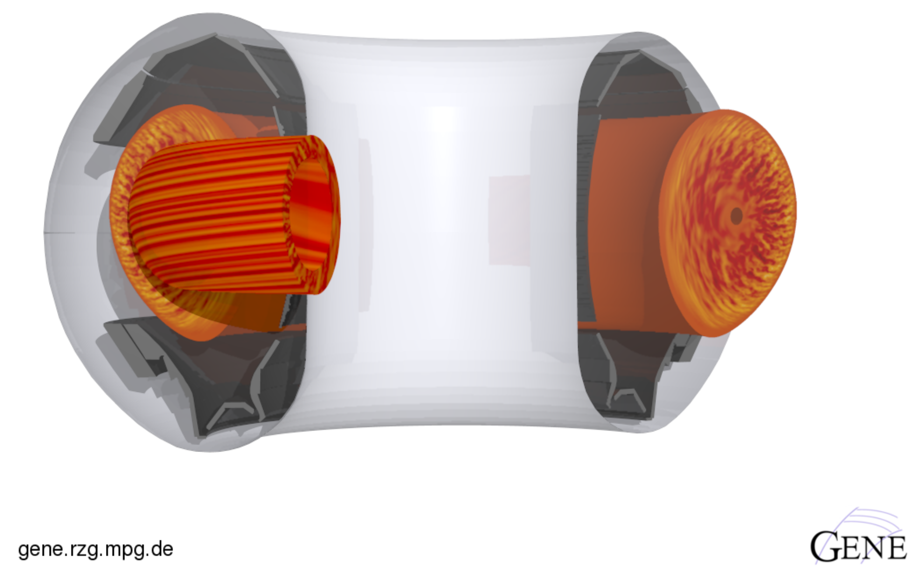
Scope of this work

Key questions:

- Properties of **linear microtearing instabilities**
- Electromagnetic **heat transport** due to microtearing turbulence
- **Nonlinear saturation** mechanism

Strategy:

- **Gyrokinetic simulations**
- Influence of **plasma parameters** (temperature gradient, beta, collisions…)
- Comparison to **analytical models**



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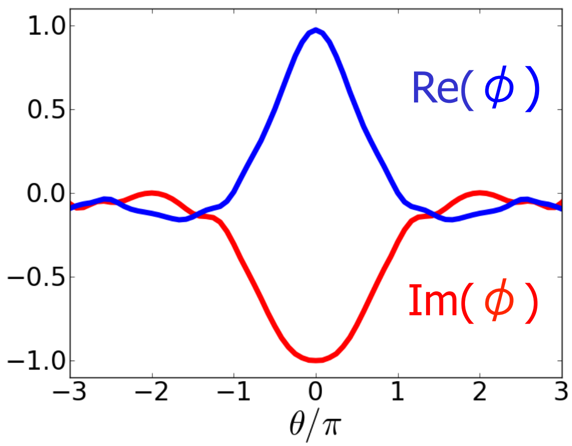
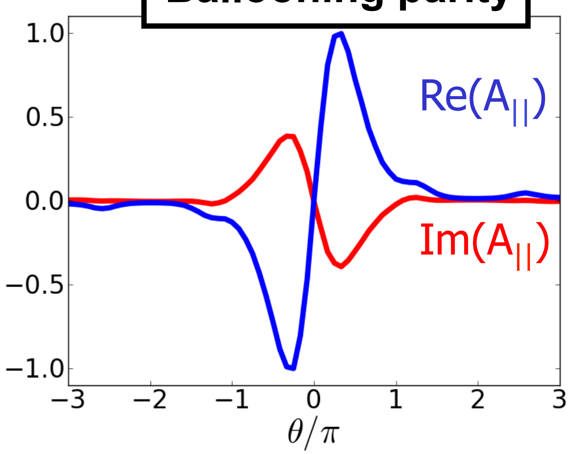
Studies of the linear microtearing instability

Comparison of microinstabilities in ballooning space

ITG modes (Ion Temperature Gradient)

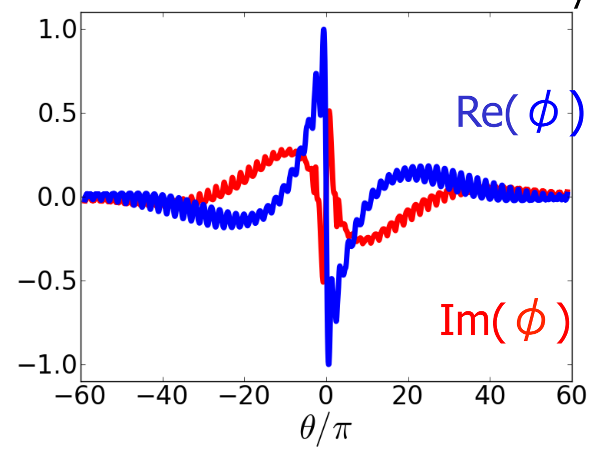


Ballooning parity

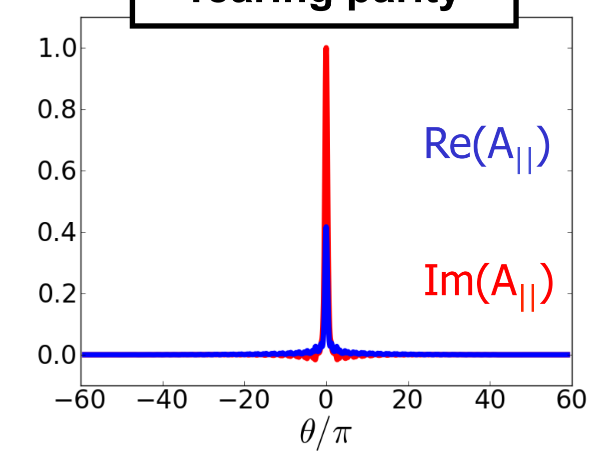


- Fields within ~**1-3** poloidal turns

Microtearing modes (k_y=0.12)



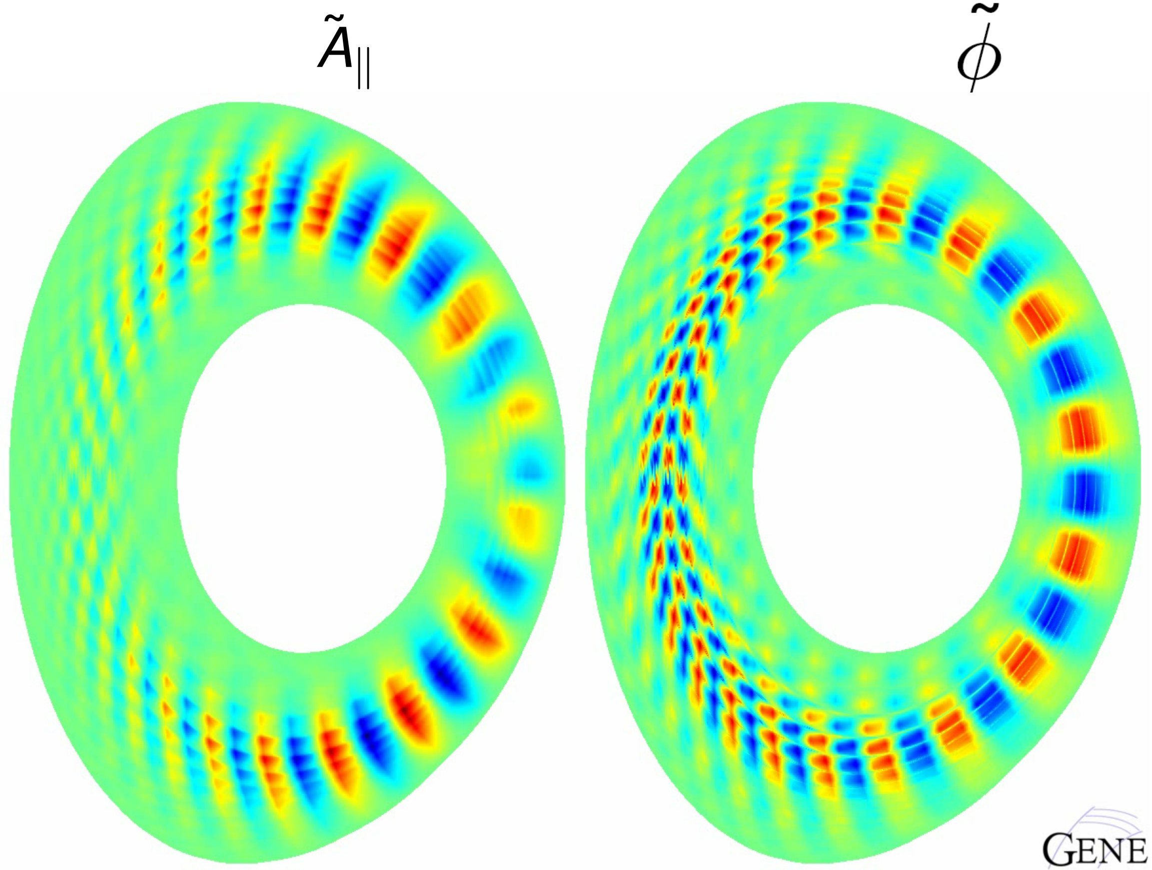
Tearing parity



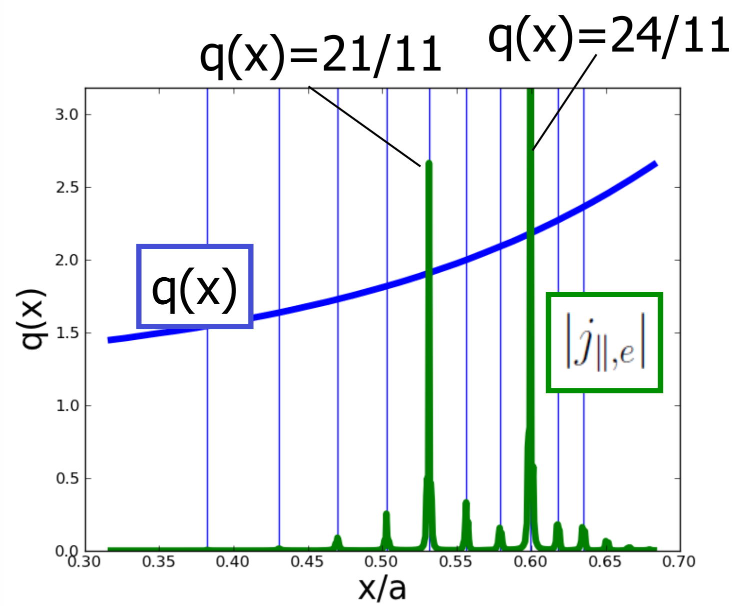
- ~**60** poloidal turns in ϕ (not $A_{||}$)

Microtearing modes: intrinsic multiscale features in x-y

Global linear simulations of ASDEX Upgrade shot 26459



Thanks to
M. Dunne and D. Told (equilibrium)
P. Schneider and M. Dunne (T_e,T_i,n)



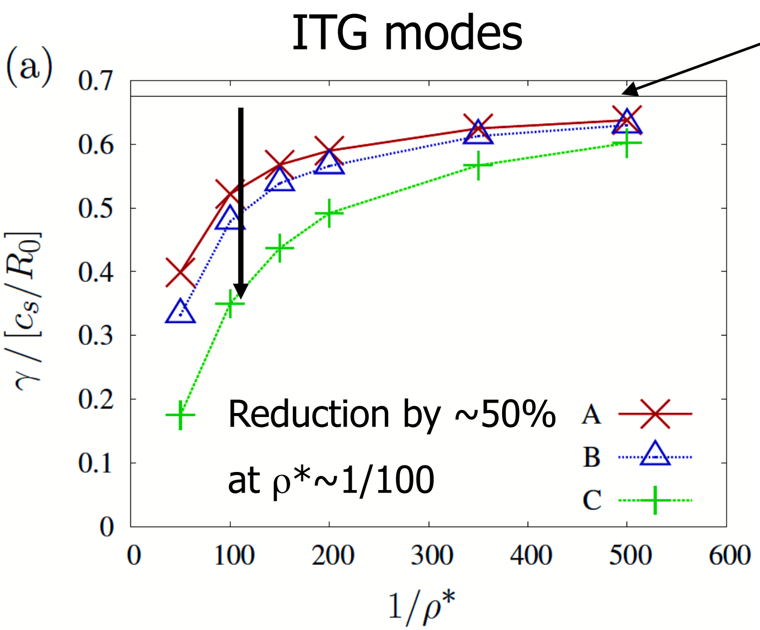
Radial grid spacing: $0.2\rho_i$

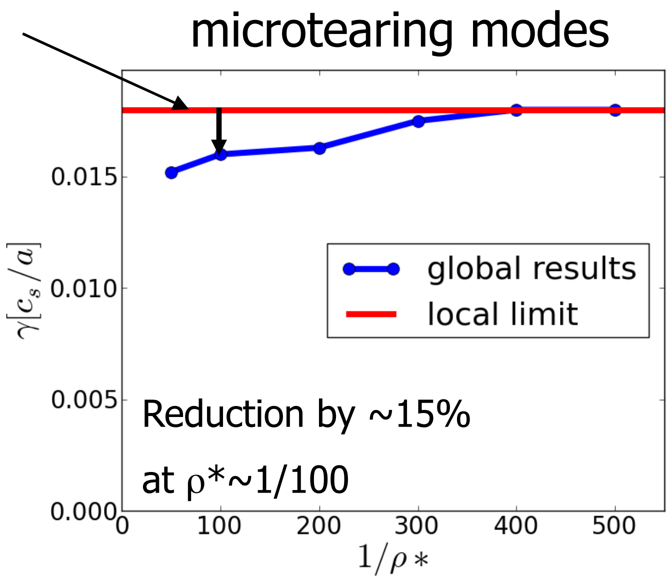
Microtearing instabilities expected to exist in AUG

System size effects

ρ^* scan ($\rho^*=\rho_i/a$):

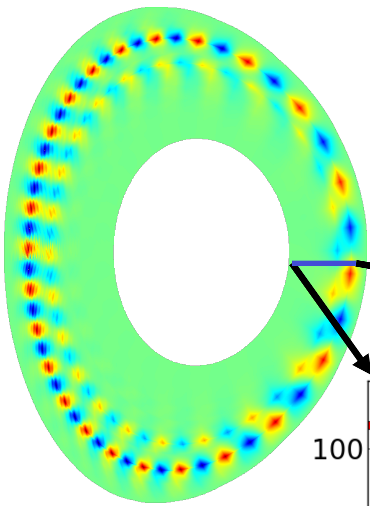
- Even for $\rho^*\sim 1/100$, the local results are fairly accurate
- $k_y\rho_i=0.12$ is n=1 for $\rho^*=1/50$
- More toroidal mode numbers are microtearing unstable in larger tokamaks



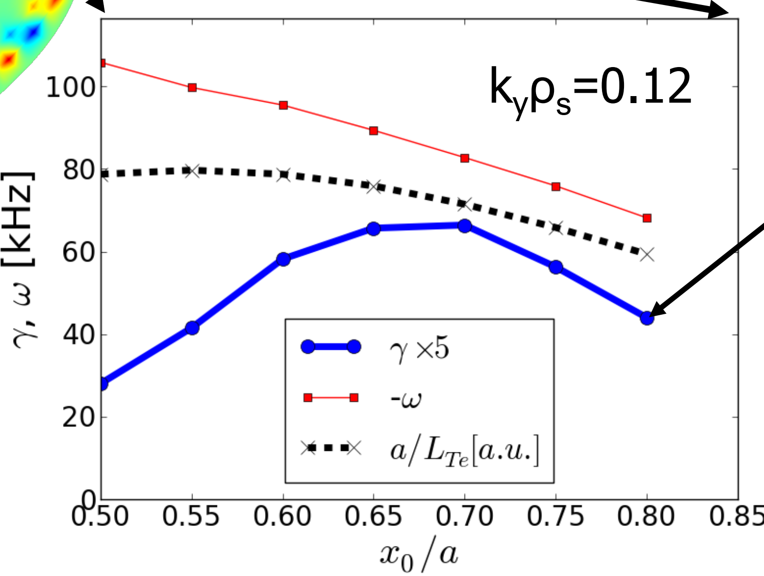


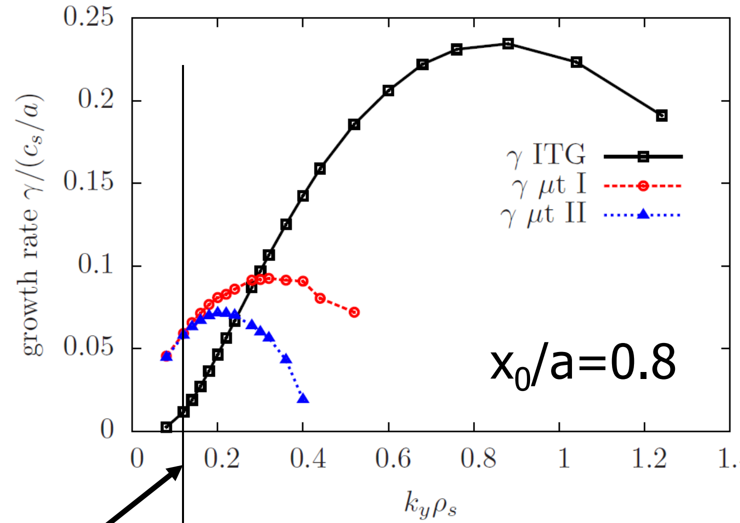
Linear modes are well described in the local approximation

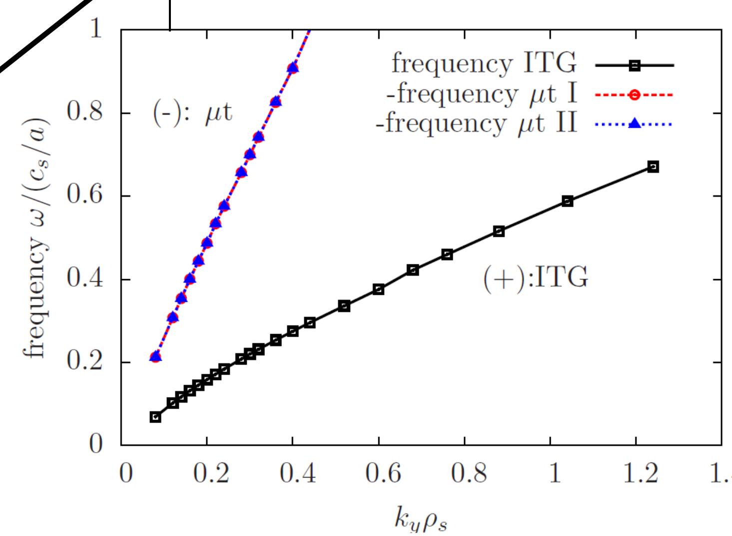
Growth rate spectra involving microtearing modes



ASDEX Upgrade shot 26459
- Lower wavenumber part is dominated by **microtearing**
- Frequency jump at transition to **ITG**

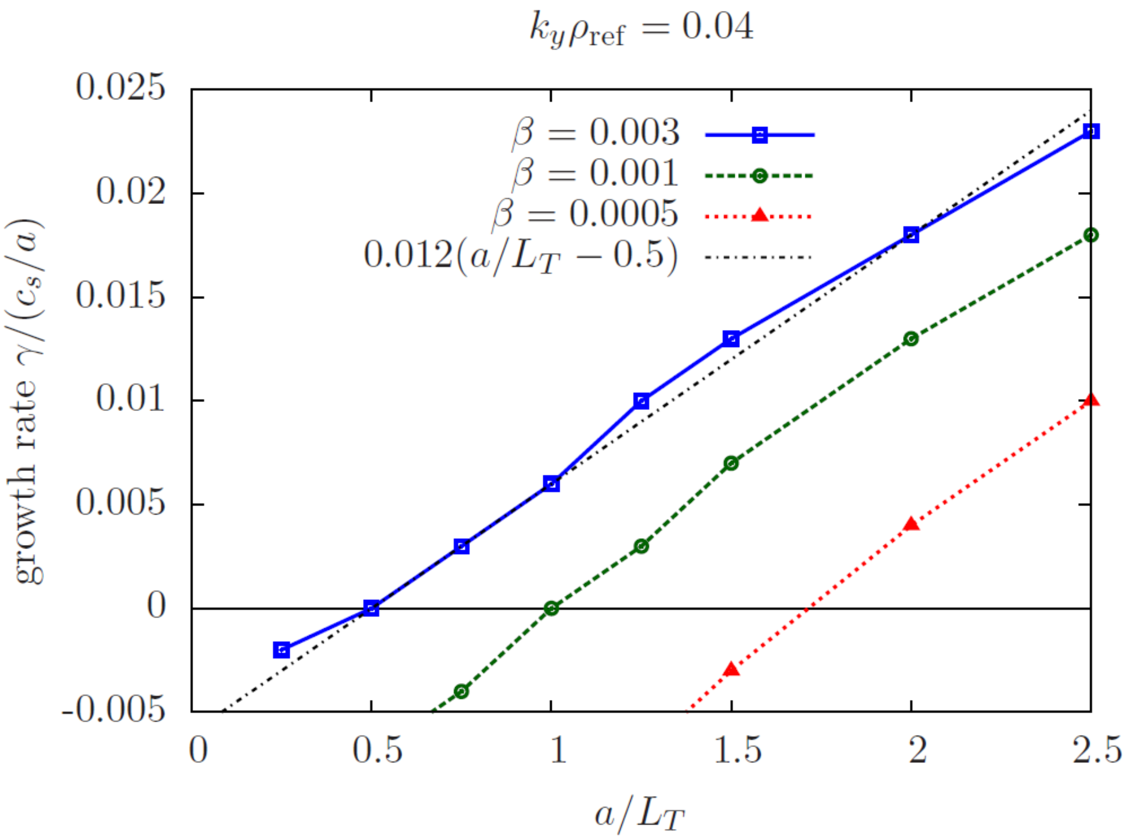






Microtearing modes peak at low k_y, coexist with ITG

Influence of electron temperature gradient and β_e



Experimental values:

- ρ_{tor}=0.8
- a/L_{Te}~2.2
- β_e~0.003

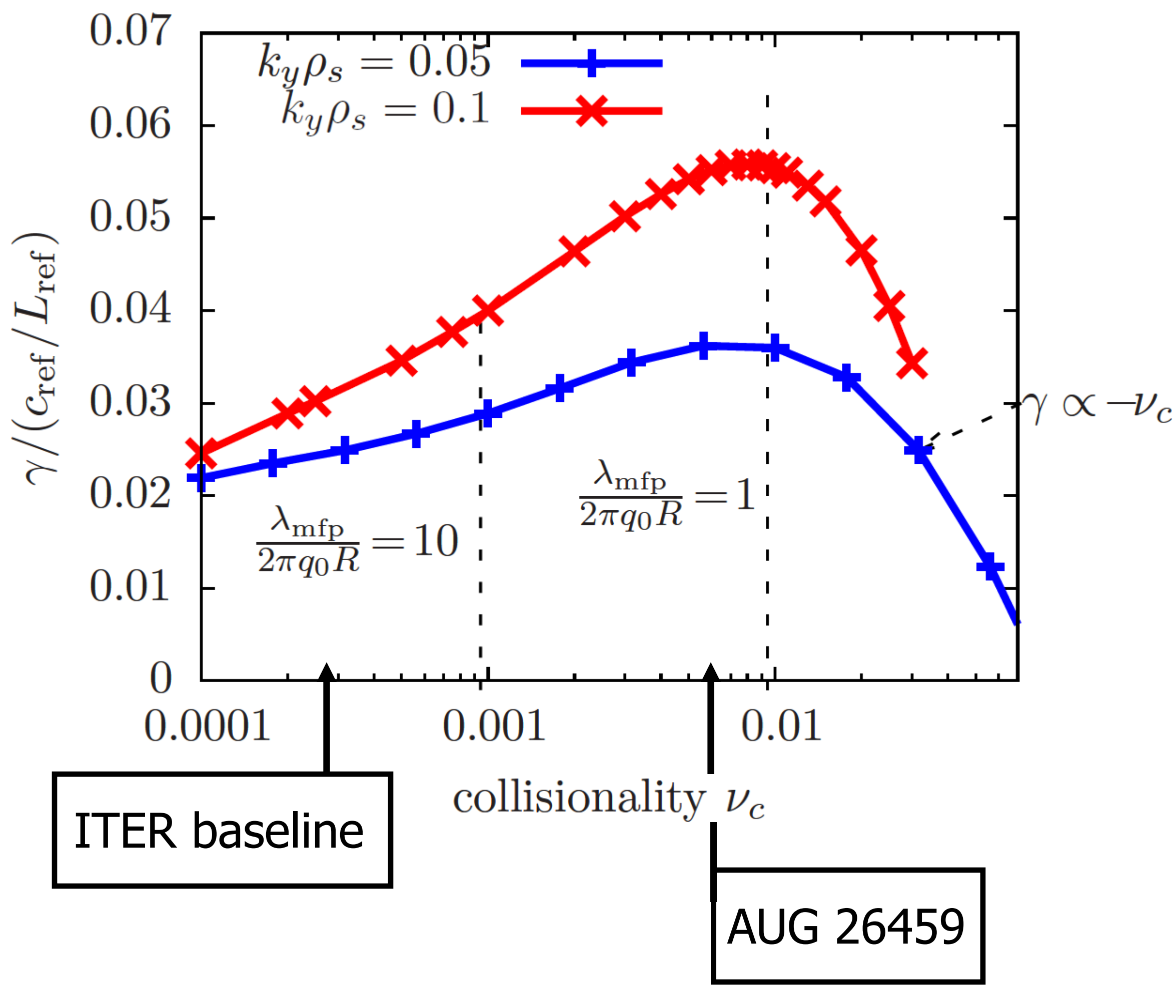
(well above threshold)

a/L_{Te} and β_e are critical plasma parameters

Collisional effects (a/L_{Te} and β kept constant)

- Including **collisions** is **important**
- Growth rate depends on collision frequency only **moderately** (in agreement, e.g., with Applegate '07)
- Experiments are in the **semicollisional** to **collisionless** regime

$\nu_c \sim n\, T^{-3/2}$ but:



Microtearing modes can also be present in hot (core) plasmas

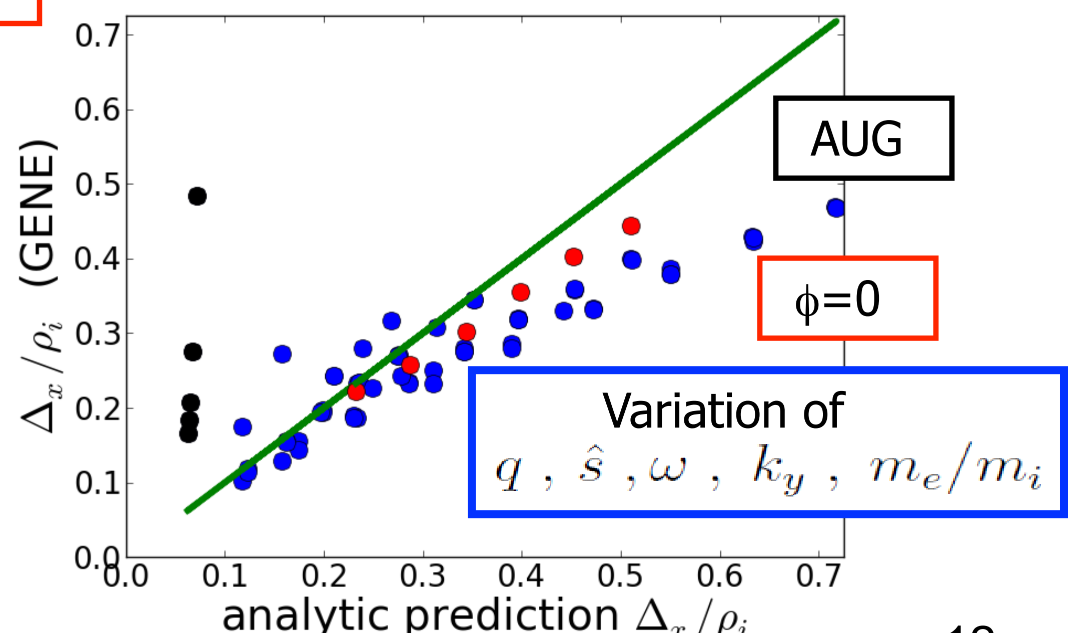
Thin current layers at resonant flux surfaces

Model of Drake (1977):

$\mathbf{k}_{||} = 0$ at rational flux surface $\mathbf{x} = 0$:
Nonadiabatic electron response until $\mathbf{k}_{||}\mathbf{v}_{te} \approx \omega$
with $\mathbf{k}_{||} \approx \mathbf{k}_y \mathbf{x}/\mathbf{L}_s$ and $\mathbf{L}_s = \mathbf{q}\mathbf{R}/\hat{\mathbf{s}}$

$$\Delta_x/\rho_i = \frac{q}{\hat{s}} \frac{k_y \rho_s}{\omega/(c_s/R)} \sqrt{\frac{m_e}{m_i}}$$

GENE simulation results



Current layers are thin:

$$\Delta_x = 0.1 - 0.5\rho_i$$

(requires proper treatment)

Nonlinear dynamics: Microtearing turbulence

Turbulent electron heat flux spectrum

Simulation setup:

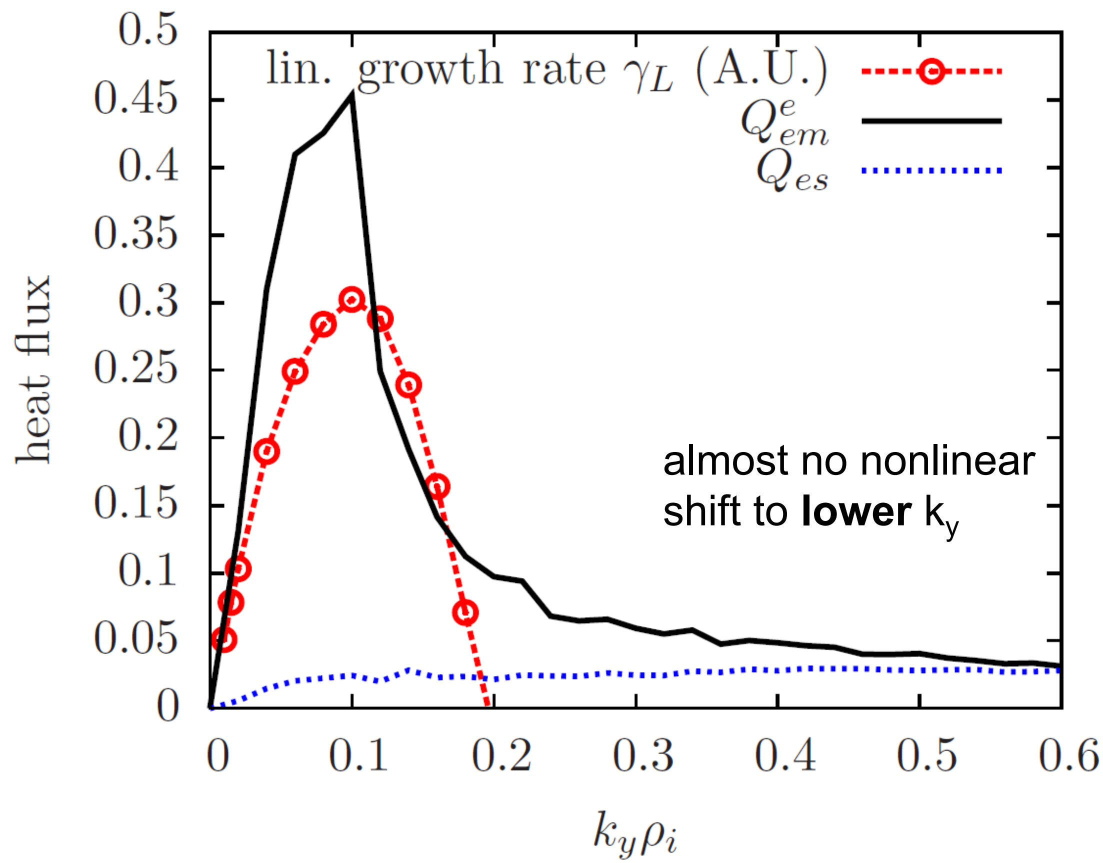
- **sufficiently large radial box**
- **high radial resolution**

384x64x24x32x16 grid points
in 5D (x,y,z,$v_{||}$, μ) phase space

Very challenging simulations!

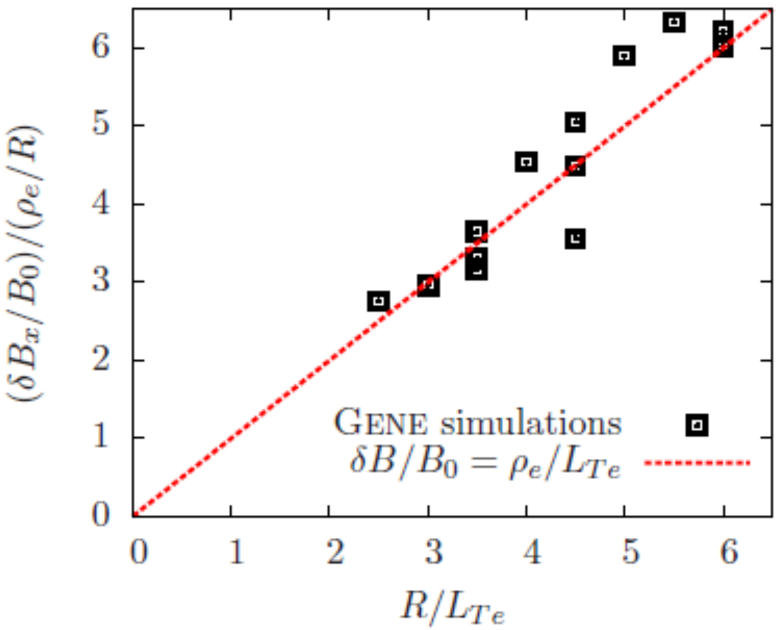
Simplifications:

- **ITG** drive switched **off**
  (avoid multimode drive)
- **Circular** magnetic geometry
  [Lapillonne et al. 2009]
  (allow for maximum flexibility)



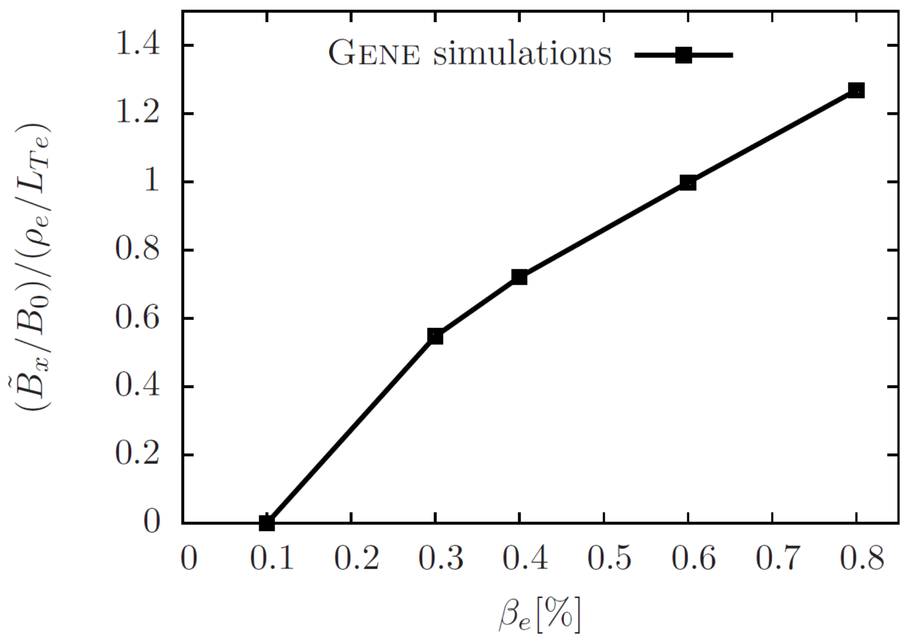
Heat flux is dominated by magnetic component at low k_y

Magnetic fluctuation level in microtearing turbulence



Model by Drake (1980):

$$\tilde{B}/B \sim \rho_e/L_{Te}$$

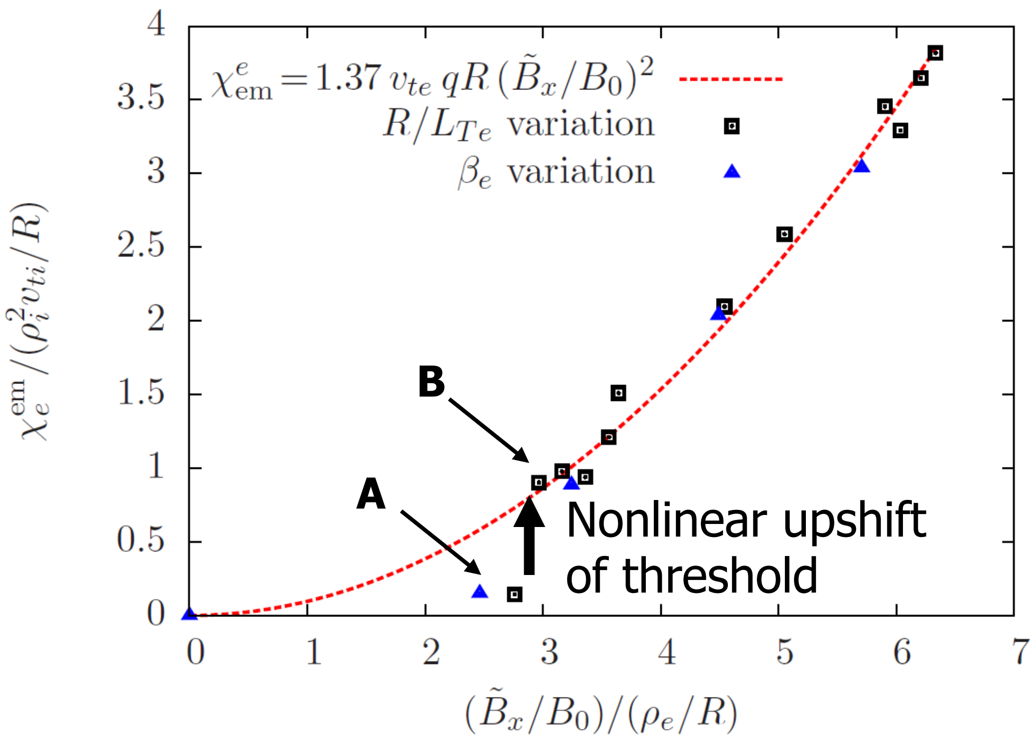


R/L_{Te} scaling

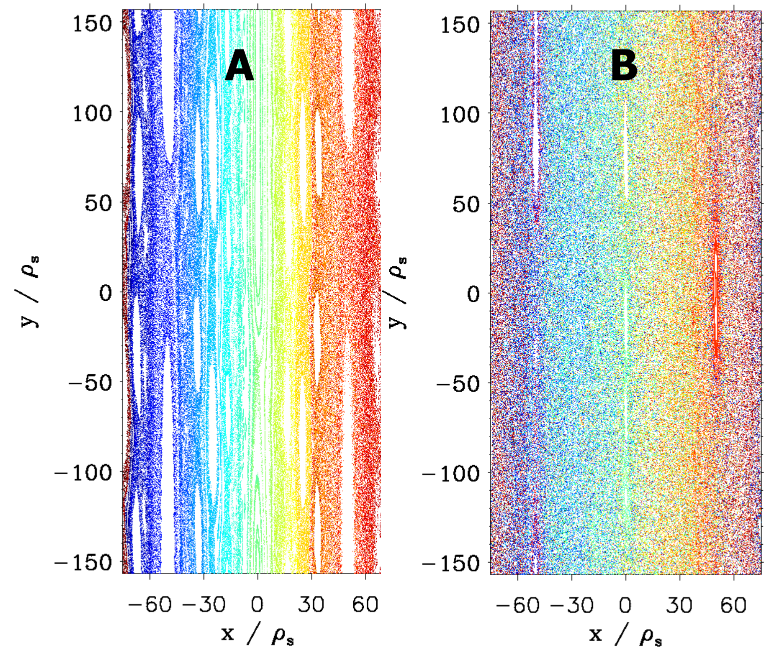
- "scatter": reduction of the nominal **resolution** by a factor of 2-3 in various phase-space dimensions
- Other parameters like β are important

Drake's formula yields good estimate, but neglects β effects etc.

The role of magnetic stochasticity



Poincare plot of magnetic field lines



Diffusivity model:

$$\chi_e^{em} = v_{te} D_M$$

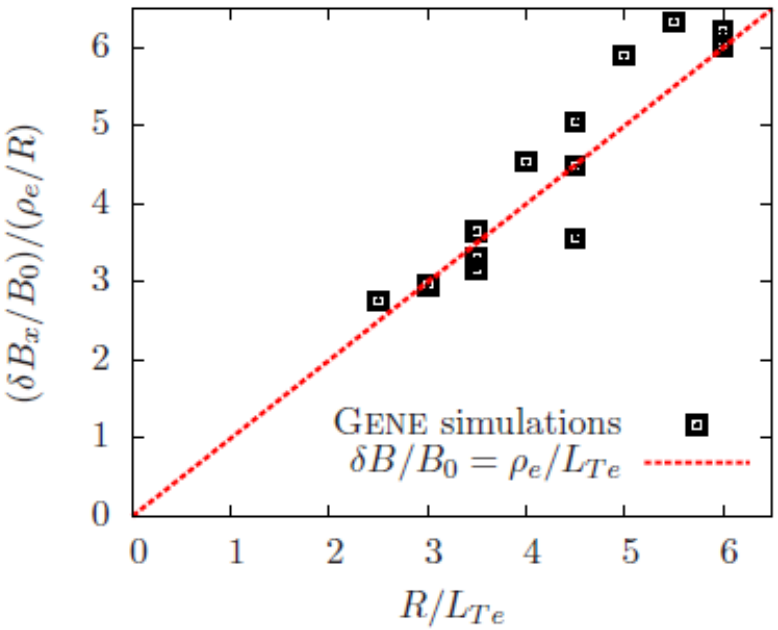
$D_M = L_C(\delta B/B_0)^2$ (quasilinear result)

use $L_C = qR$ as correlation length

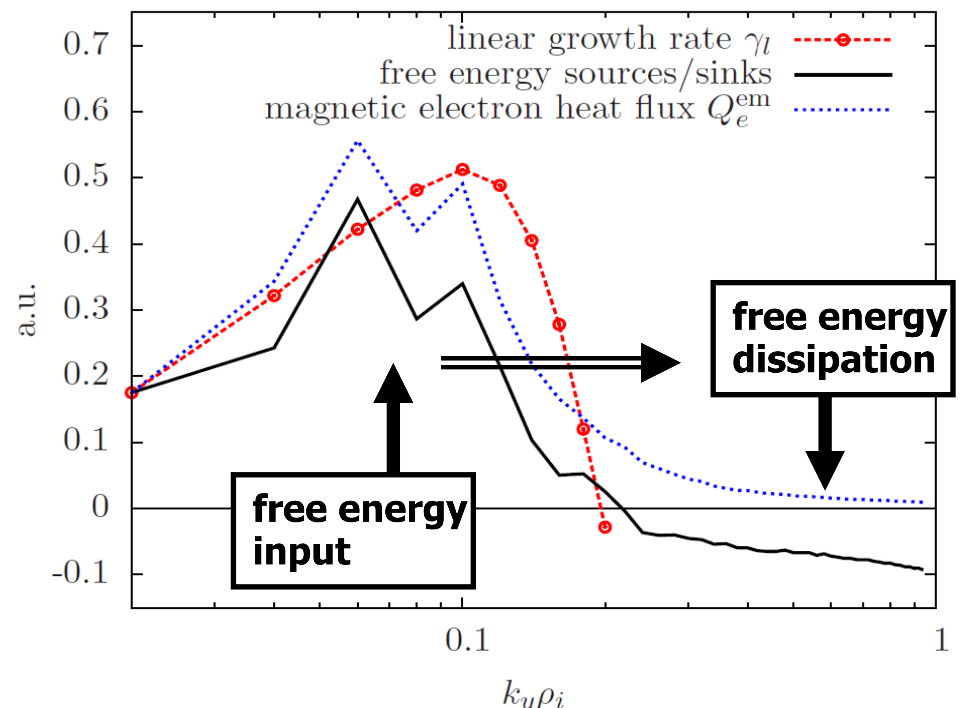
$$\chi^e_{em} = 1.37 qR v_{te} (\tilde{B}_x/B_0)^2$$

- **Effective threshold** for onset of strong transport (**A** to **B**)
- In stochastic cases **(B)**, GENE results confirm test-particle models (e.g. Liewer 1985, collisionless case)

Nonlinear saturation of microtearing turbulence



Model by Drake (1980): $\tilde{\mathbf{B}}/\mathbf{B} \sim \boldsymbol{\rho}_e/\mathbf{L}_{\mathbf{Te}}$
(based on dissipation at **low** wavenumbers)



In the accessible parameter range:

Linear drive: $\gamma_l^{max} \propto (R/L_{T_e})^2 v_{ti}/R$

Free energy sink at $k_{diss} \gtrsim 0.2/\rho_i$

Balance: $\gamma_{nl} = \chi_e^{em} k_{diss}^2$ → $\tilde{\mathbf{B}}/\mathbf{B} \sim \boldsymbol{\rho}_e/\mathbf{L}_{\mathbf{Te}}$

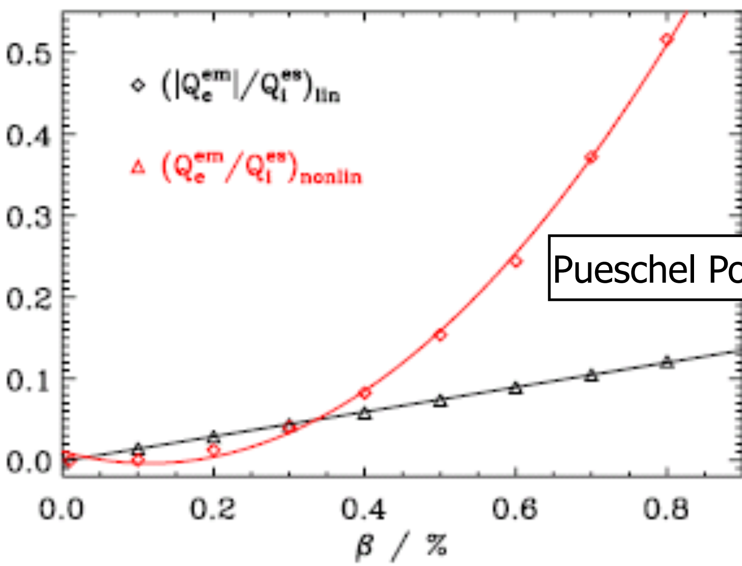
Free energy transfer to medium k_y, where it is dissipated

Microtearing modes in finite β ITG/TEM turbulence

Detailed account: D. Hatch (next week)

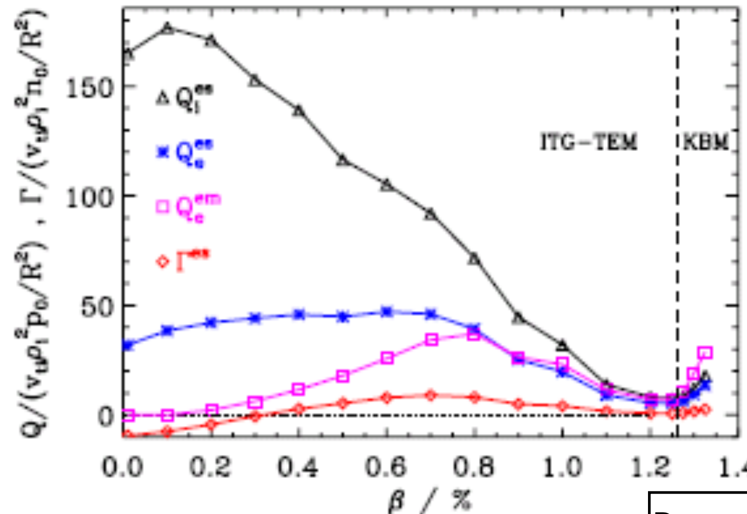
Motivation: Recent results on finite β turbulence

- Electron **magnetic heat transport** can approach (or even surpass) electrostatic transport as β **increases** [Candy PoP '05, Pueschel PoP `08]
- Magnetic transport violates quasilinear theory – β^2**-scaling**

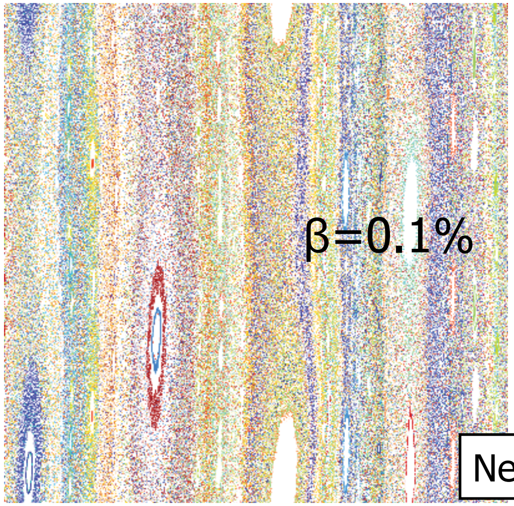


Pueschel PoP '08

- Observation of near-ubiquitous **magnetic stochasticity** – even at low values of β (Nevins PRL '11, Wang PoP '11)



Pueschel PoP '08



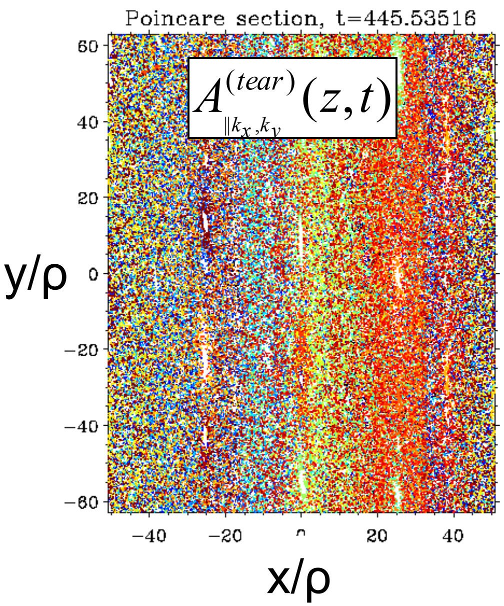
Nevins PRL`11

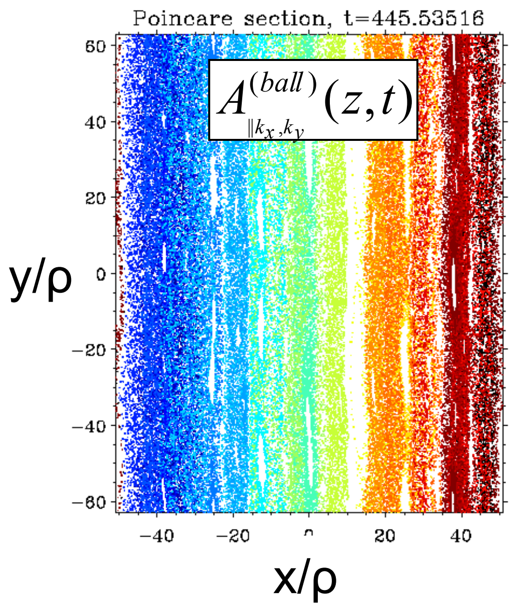
...needs an explanation!

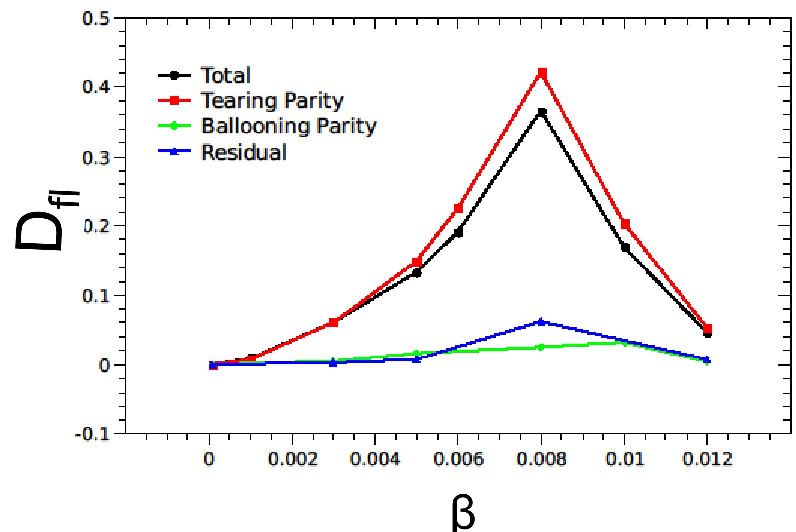
What is the reason for magnetic stochasticity?

- **Ballooning parity** modes: no reconnection/stochastic fields
- **Tearing parity** modes allow reconnection
- Analysis: **POD** of vector potential (optimal basis) : $A_{\|k}(z,t) = \sum_n A_{\|k}^{(n)}(z) h_k^{(n)}(t)$
- First two modes (ballooning and tearing) plus residual modes

$$A_{\|k_x,k_y}(z,t) = A_{\|k_x,k_y}^{(ball)}(z,t) + A_{\|k_x,k_y}^{(tear)}(z,t) + A_{\|k_x,k_y}^{(res)}(z,t)$$



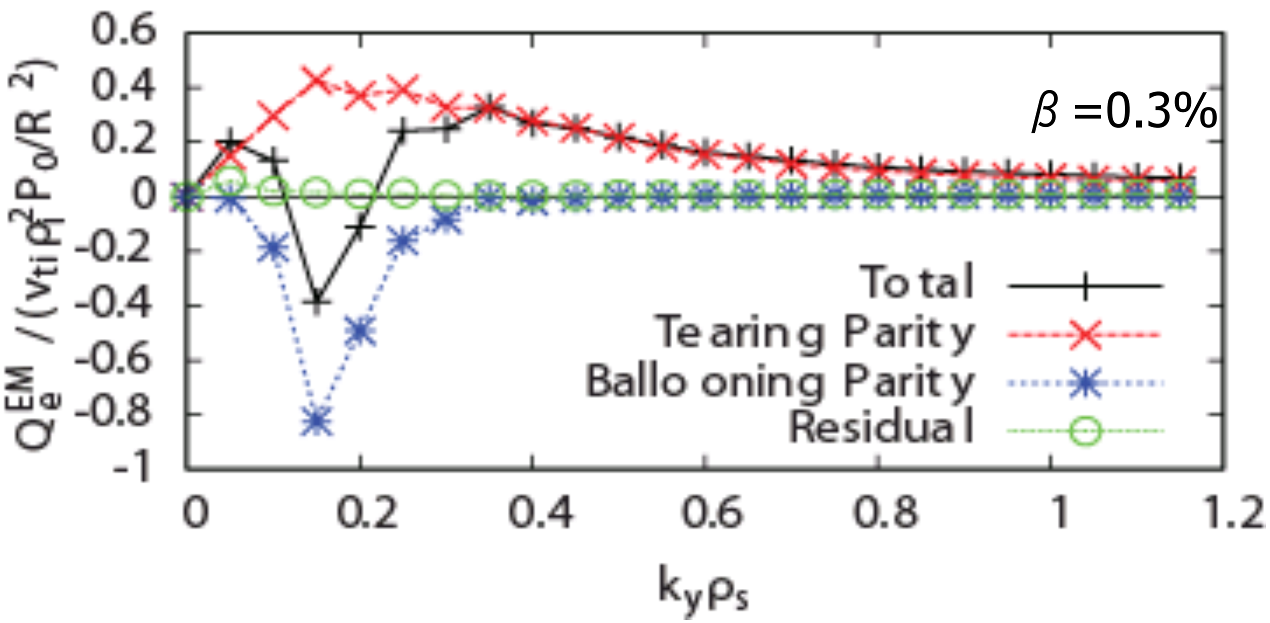




$$D_{fl} = \lim_{l \to \infty} \frac{1}{l} \left\langle \left| r_i(l) - r_i(0) \right|^2 \right\rangle$$

Tearing component causes stochasticity

Magnetic transport – superposition of ITG and tearing



$$Q_e^{EM(tot)} = q_{\|} B_x$$

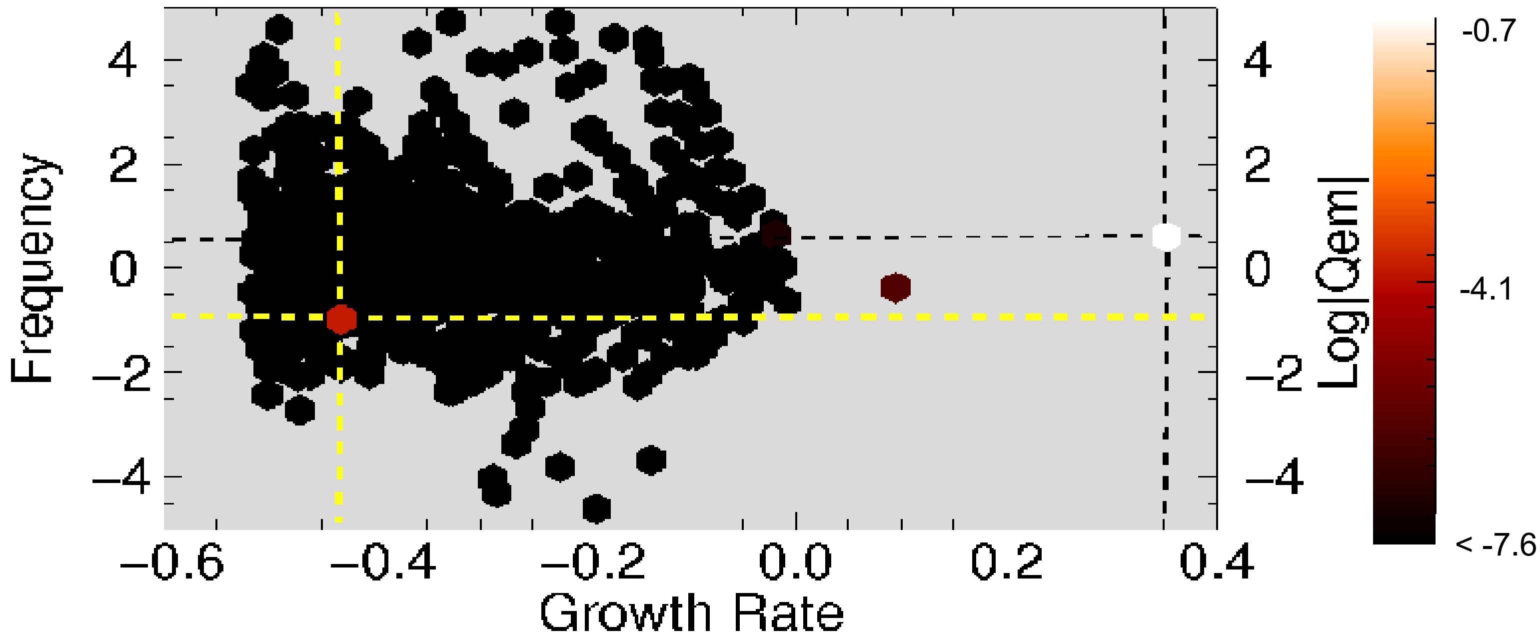
$$Q_e^{EM(tear)} = q_{\|} B_x^{(tear)}$$

$$Q_e^{EM(ball)} = q_{\|} B_x^{(ball)}$$

$$Q_e^{EM(res)} = q_{\|} B_x^{(res)}$$

- **‘Dip’** in the magnetic **electron heat transport spectrum** (at k_y of electrostatic transport peak) [Candy, PoP`05]
- **Understood** by attributing transport to **ballooning** and **tearing** part of $\mathbf{B_x}$
- Stochastic transport **explains** $\mathbf{Q_e^{EM}} \sim \beta^2$

Origin of the magnetic electron heat transport



- GENE eigenmode solver finds **all gyrokinetic eigenmodes**
- Nonlinearly evolved **distribution function projected** onto 1000 orthogonalized linear eigenmodes ($k_y\rho_i$=0.2,$k_x\rho_i$=0)
- **One damped eigenmode dominates**, has properties of **microtearing mode**
- Analysis of nonlinear transfer: **Excitation via coupling to zonal modes**

Nonlinearly excited microtearing mode causes electromagnetic heat flux

Summary & Outlook

Summary & Outlook

- **Microtearing modes** are expected to exist in **ASDEX Upgrade** and presumably also in other medium-aspect-ratio tokamaks like **ITER**
- Nonlinear gyrokinetic simulations establish microtearing as a **candidate** to explain **electron heat flux** in outer core of tokamaks: χ^{e}_{em}**~1m²/s**
- **Magnetic stochasticity** occurs when magnetic fluctuation amplitude exceeds an **effective threshold (in analogy to Dimits shift)**
- **Nonlinearly excited (linearly stable) microtearing modes** cause stochasticity and magnetic electron heat flux in **ITG turbulence**
- Underway: Microtearing + ITG turbulence (preliminary result: coexistence!)

References:

- **Doerk et al., PRL 2011**
- **Doerk et al., APS / PoP**
- **Hatch et al., submitted**