Frank Jenko

Towards comprehensive global simulations of fusion plasmas

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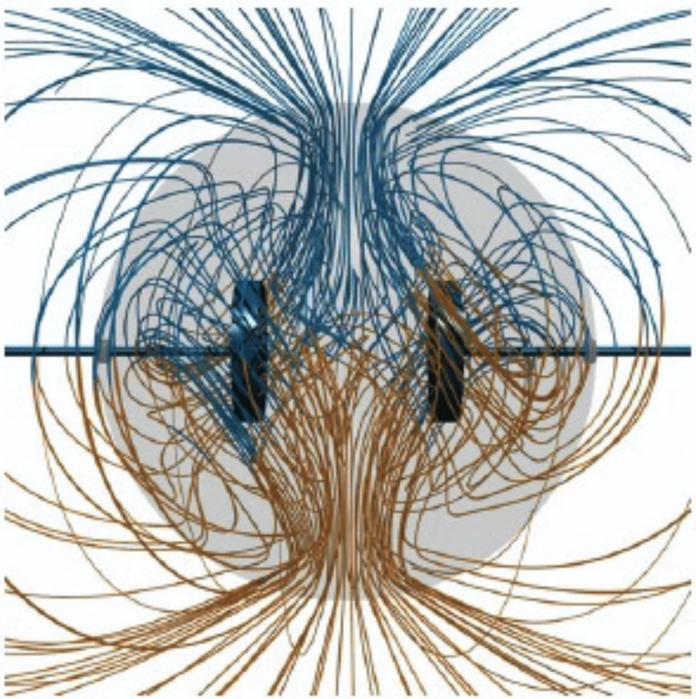
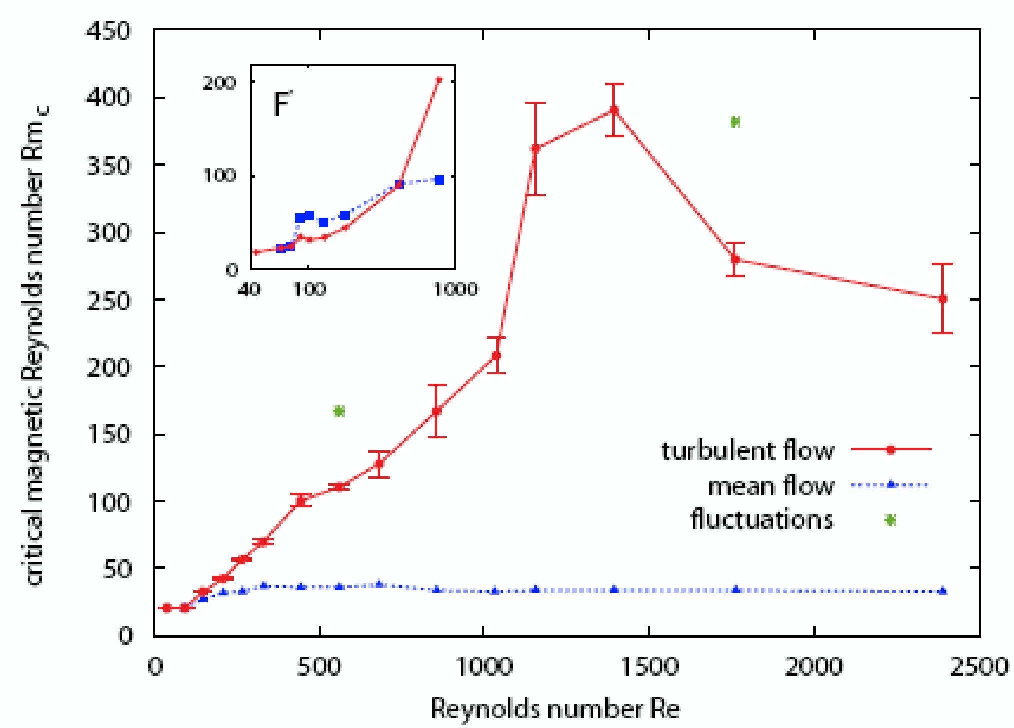
January 17, 2012

Liquid metal laboratory experiments



MHD simulations regarding the Madison Dynamo Experiment

Reuter, Jenko, and Forest, NJP 2011



Key question: What sets (or reduces) the critical magnetic Reynolds number?

Acknowledgements

Turbulence in Laboratory & Astrophysical Plasmas

Involved group members:

H. Doerk
T. Görler
D. R. Hatch
F. Merz
M. J. Pueschel
D. Told

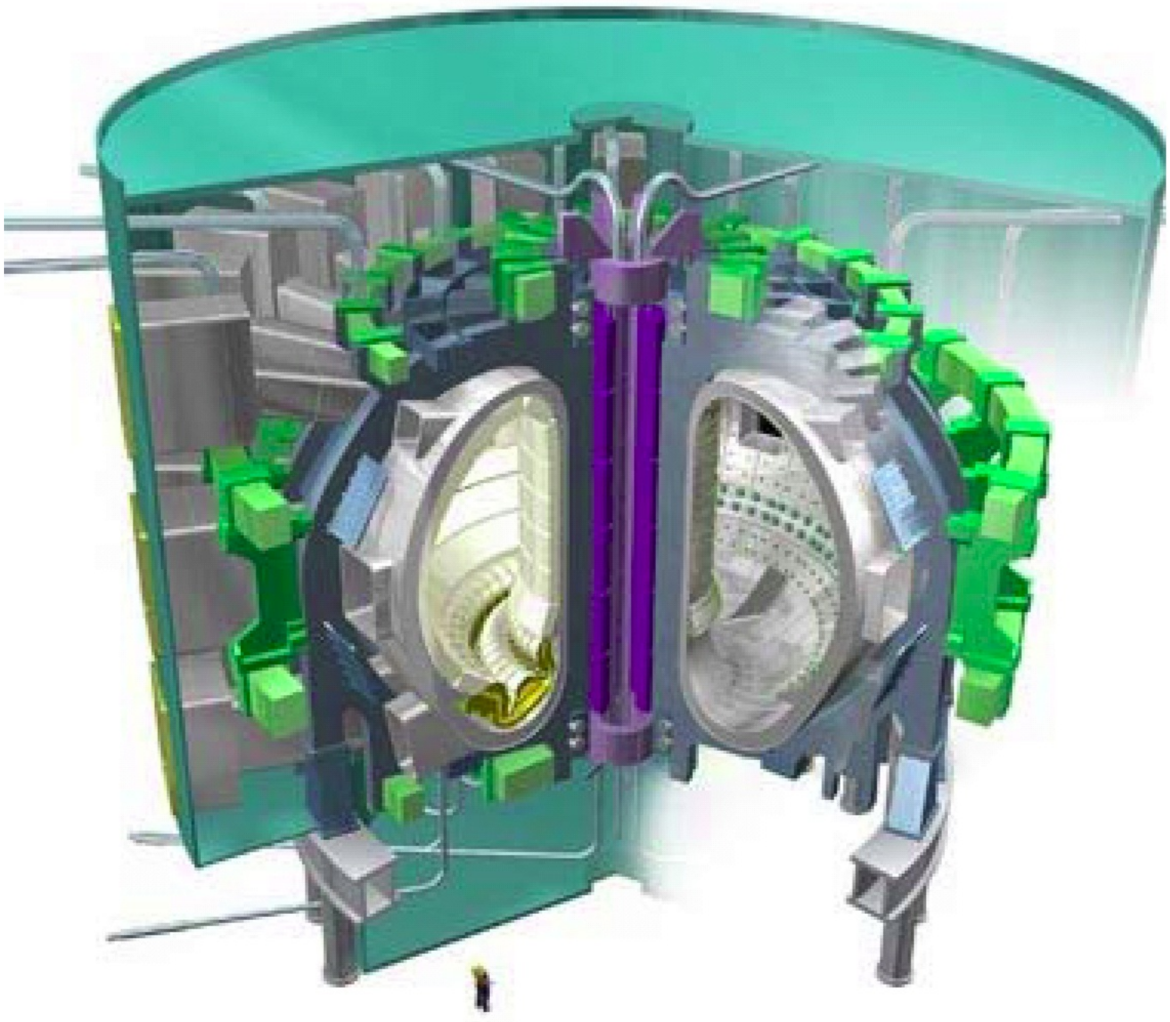
A rather complete list of papers and PhD theses can be found at:

www.ipp.mpg.de/~fsj

Many collaborators from various EU and US institutions, including:

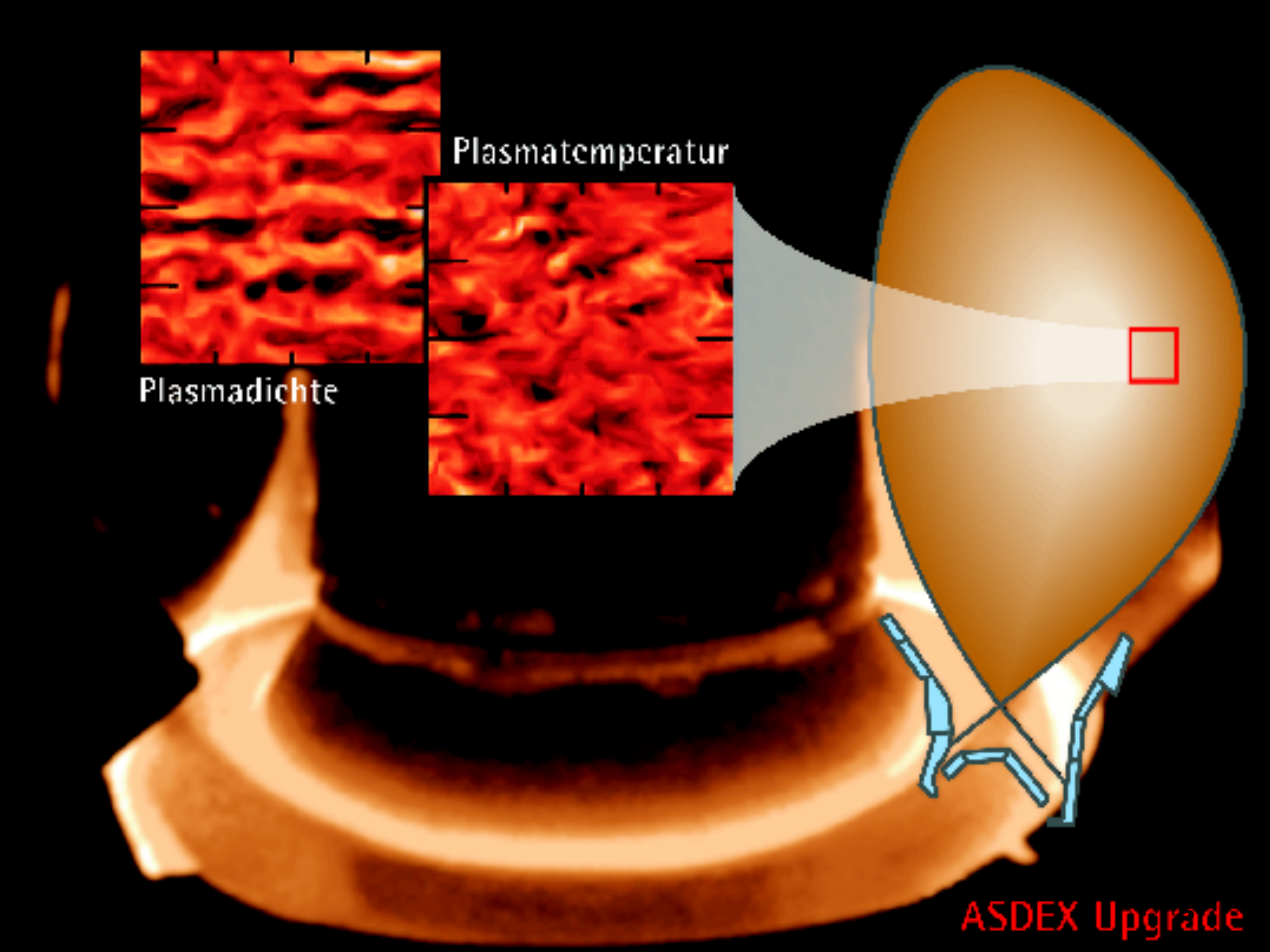
IPP Garching & Greifswald (incl. P. Xanthopoulos)
EPFL Lausanne
University of Wisconsin-Madison
PPPL

ITER: A crucial step towards DEMO

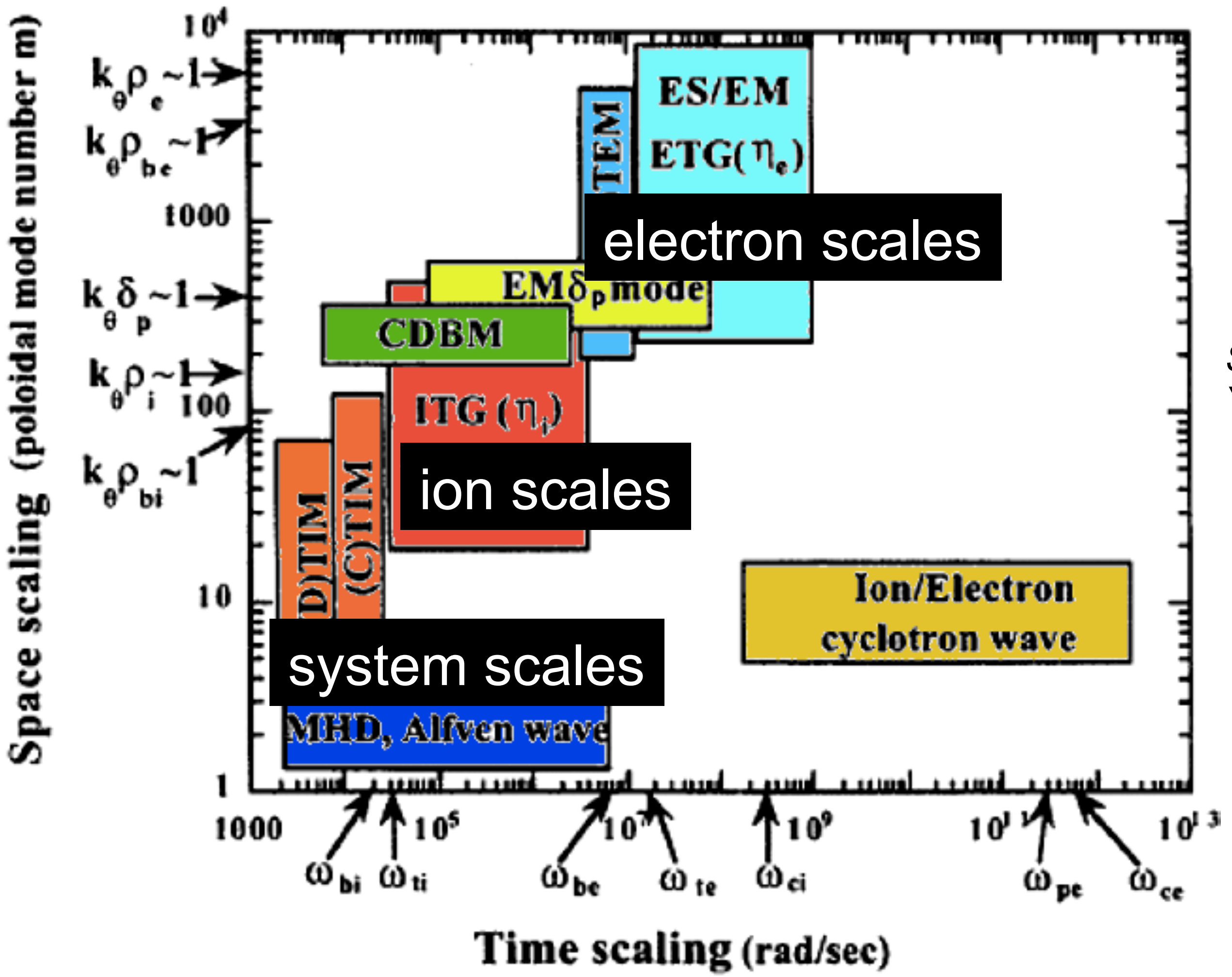


Goal: 500 MW of fusion power

Complex and expensive experiments call for strong theory program


Plasmatemperatur
Plasmadichte
ASDEX Upgrade

The multi-scale, multi-physics challenge



Source: Y. Kishimoto

Topics addressed in this talk

A few words about the GENE code

On the role of nonlocal effects and avalanches

Microtearing turbulence and field stochasticity

Small-scale turbulence in transport barriers

Turbulence optimization for stellarators

Some perspectives

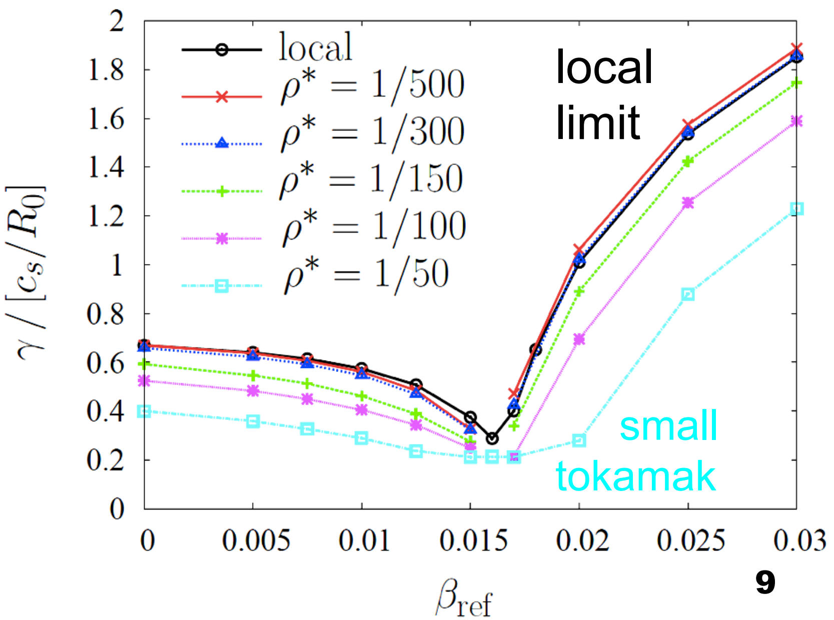
Extreme computing in support of ITER: The GENE code

The gyrokinetic Vlasov code GENE

GENE is a **physically comprehensive** Vlasov code:

- allows for multiple ion species and spatial scales, kinetic electrons & electromagnetic fluctuations, collisions, and external ExB shear flows
- is coupled to various **MHD equilibrium codes** (for tokamaks as well as stellarators) and two **transport codes**
- can be used as **initial value** or **eigenvalue** solver
- supports **local** (flux-tube or annulus) and **global** (full-torus), gradient-driven and flux-driven simulations

Many tests and benchmarks, e.g.:
Global electromagnetic ITG modes



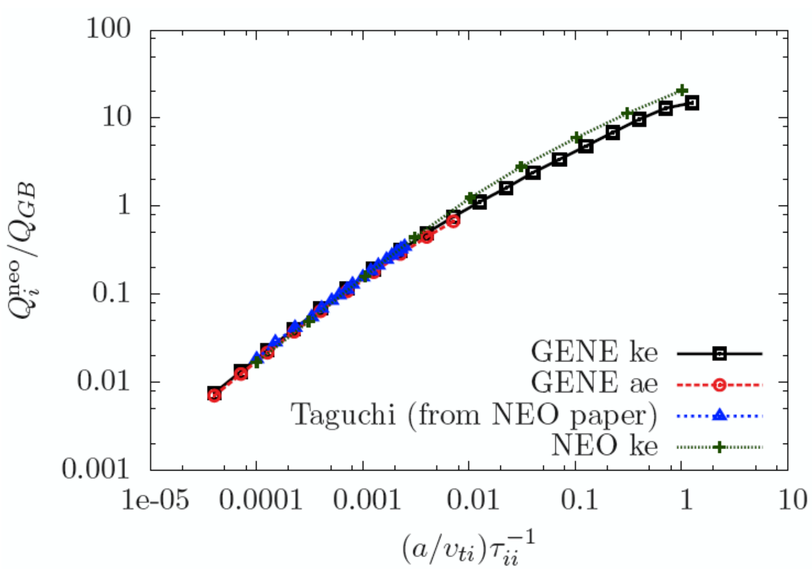
http://gene.rzg.mpg.de

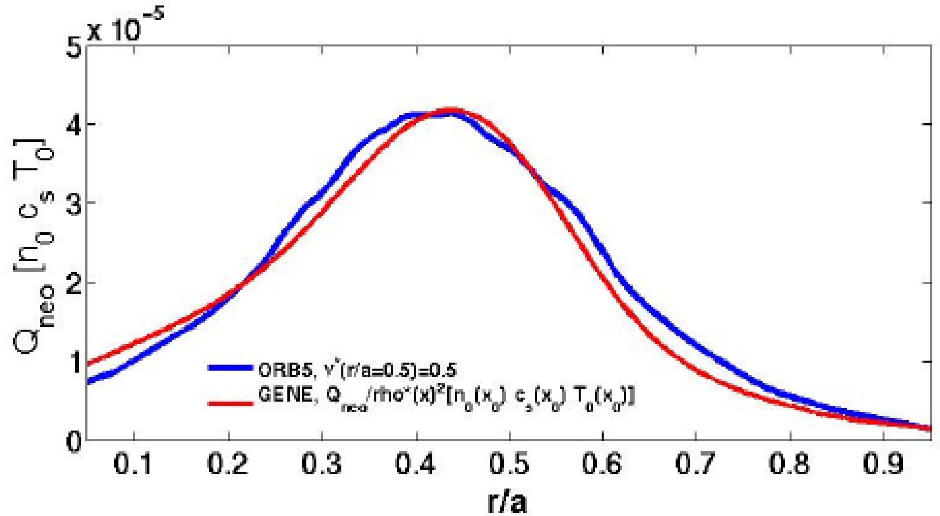
Benchmarking: Neoclassical transport

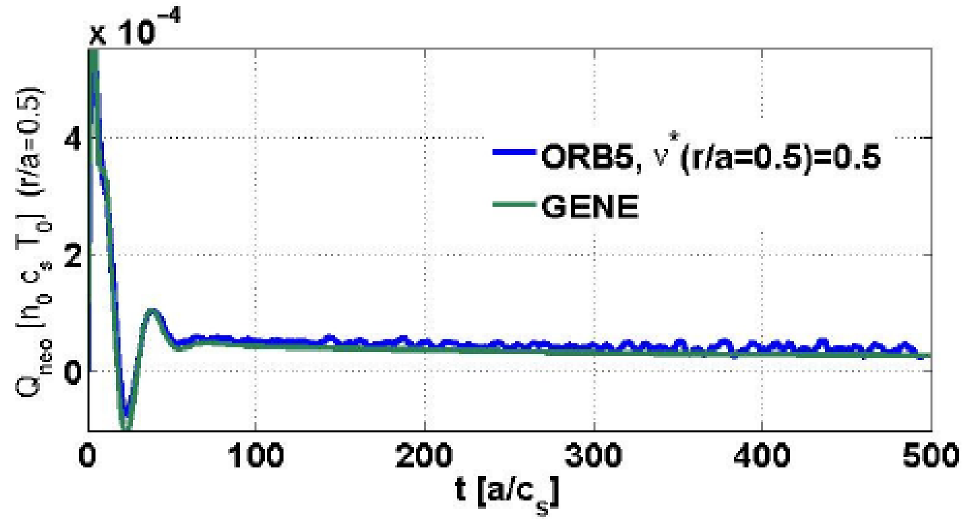
Neoclassical ion heat transport

- local simulations vs Taguchi
- global simulations vs ORB5

Doerk, Vernay *et al.*

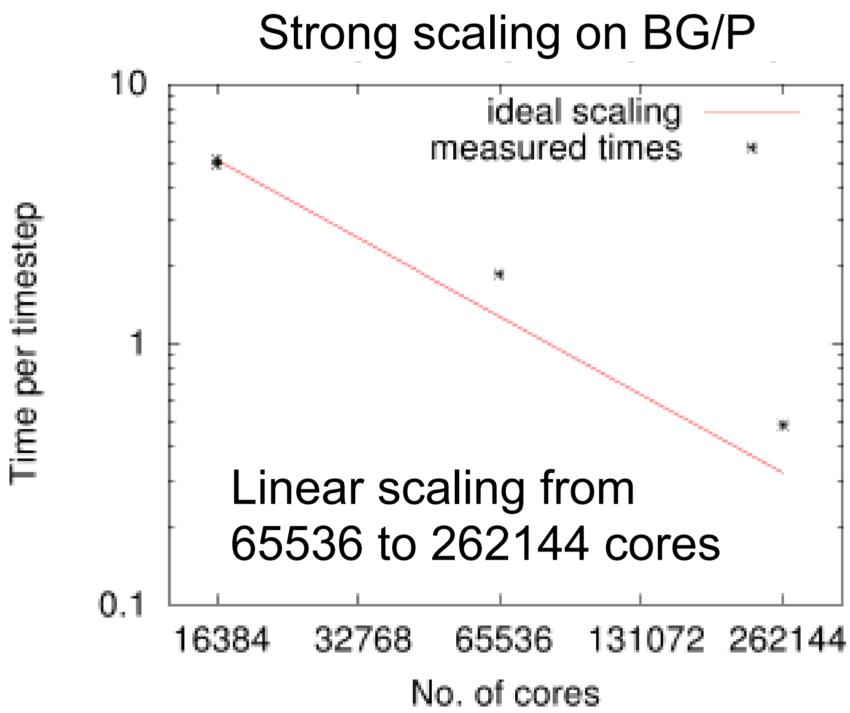






GENE: Parallel implementation

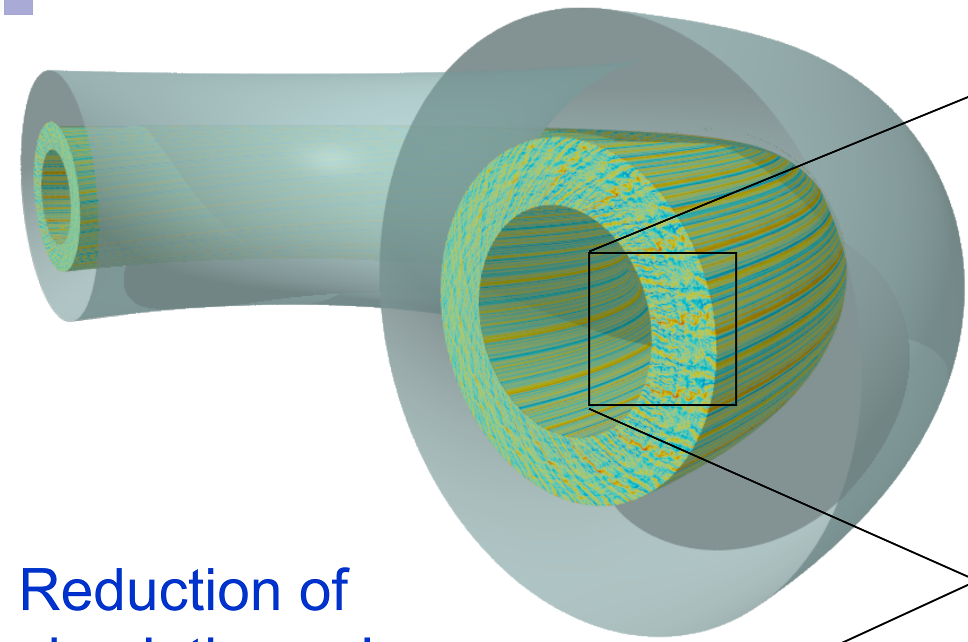
- code automatically adapts to chosen hardware & grid size (à la FFTW)
- efficient usage of petascale platforms

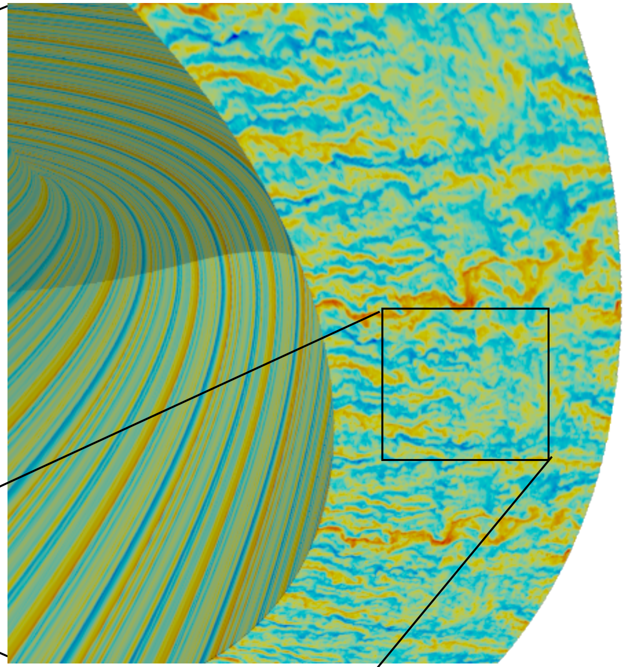


Close collaborations with experts in applied mathematics and computer science

However, since flux-driven global simulations scale as ρ_*^{-3} (or worse), large-scale devices cannot be tackled in a "brute-force" style

Main goal: Better physics understanding and problem reduction





Reduction of simulation volume:

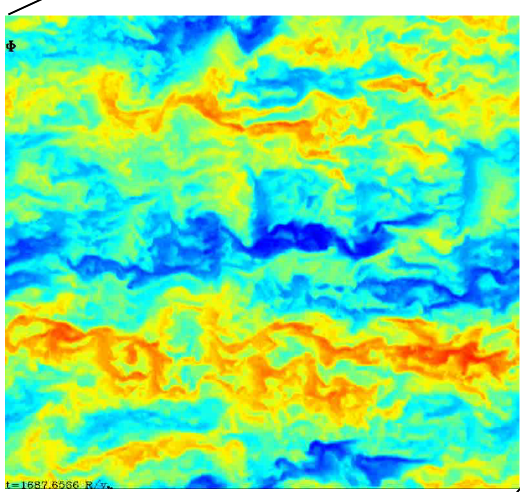
full torus

↓

annulus

↓

flux tube



Non-negligible contributions from sub-ion scales:

ETG modes and microtearing modes

Global Gyrokinetic Simulation of

Turbulence in

ASDEX Upgrade

GENE

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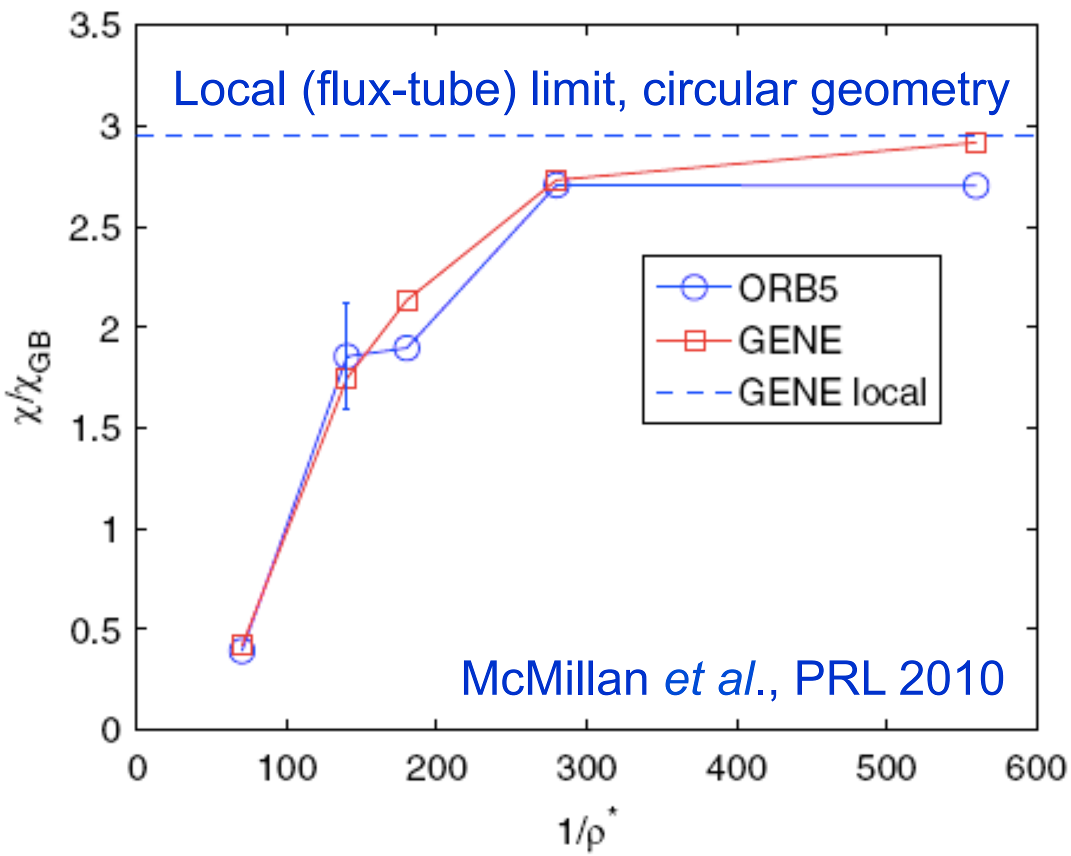
Nonlocal effects: ρ^* scaling and avalanches

Finite system size: Local limit recovered

Simulations of **gradient-driven ITG turbulence** (adiabatic electrons) with GENE and ORB5 show that the local limit is recovered, provided the geometry is treated consistently, settling a long-standing debate.



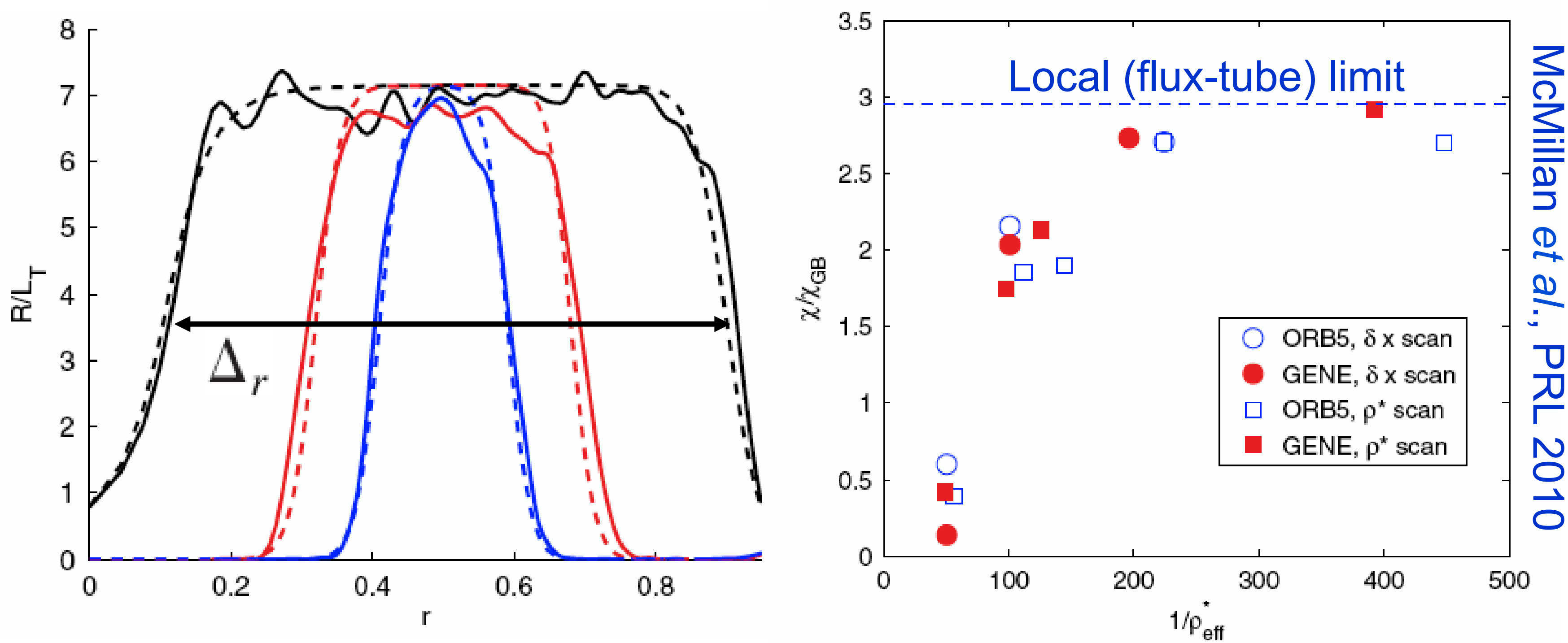
See also:

Candy et al., PoP 2004

Görler et al., JPCS 2010

Görler et al., PoP 2011

Finite system size: Profile shape matters



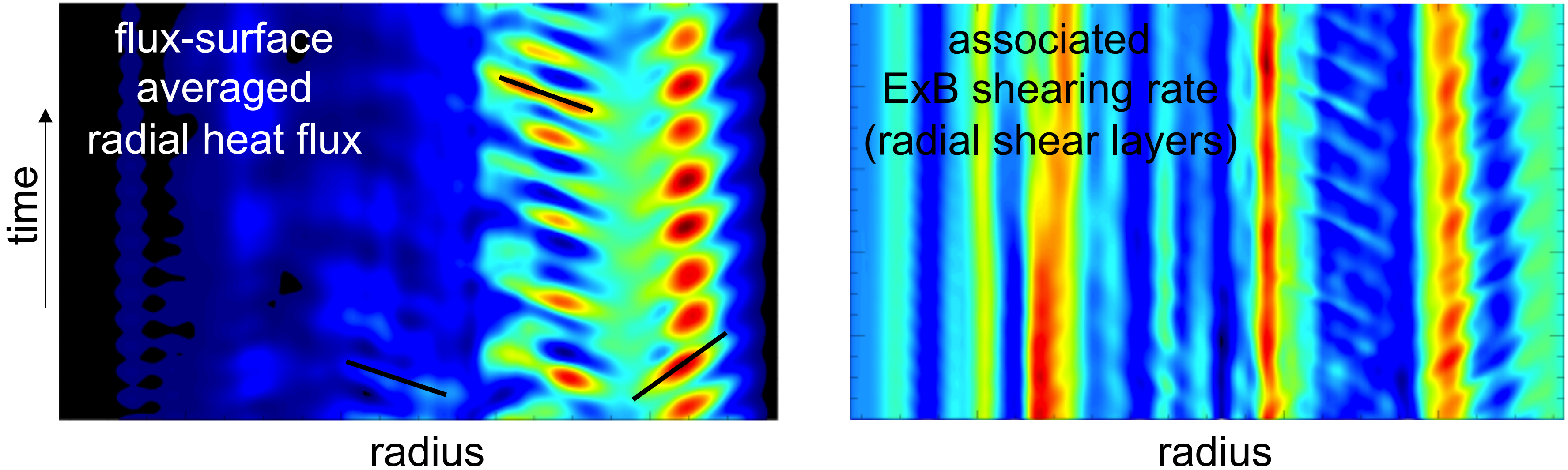
Both codes also show that it is the parameter

$$\rho^*_{\mathrm{eff}} = \rho^* / \Delta_r$$

which really matters – this should be kept in mind when dealing, e.g., with Internal Transport Barriers.

Can avalanches break gyro-Bohm?

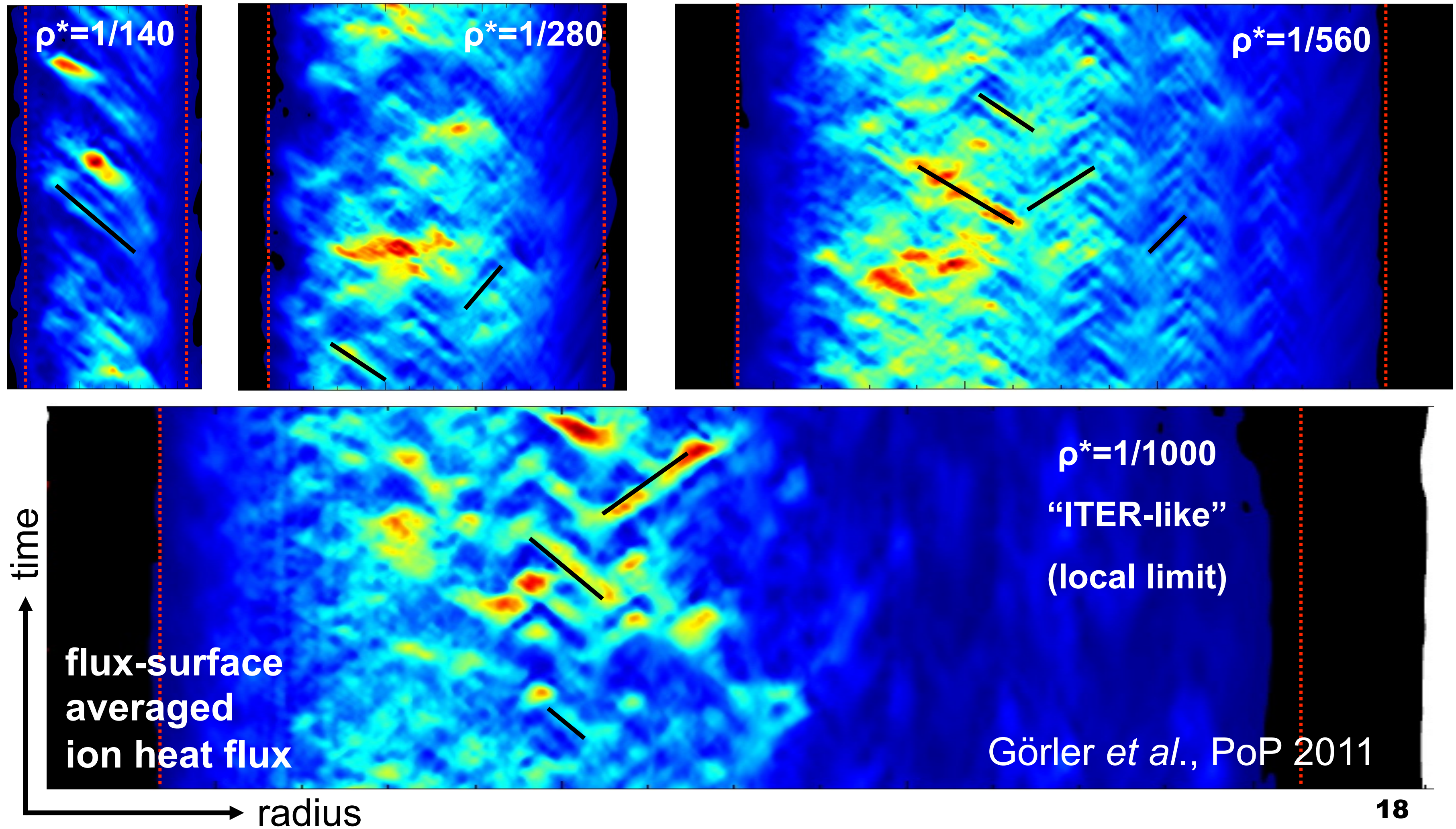
Global flux-driven simulations of ITG-ae turbulence with GENE (for $\rho^*=1/140$)



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

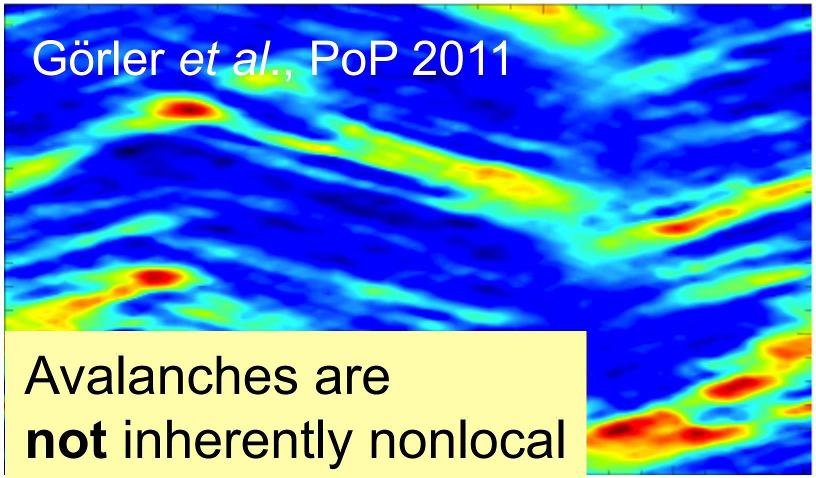
Heat flux avalanches are quasi-local

Global ITG turbulence simulations (adiabatic e) with GENE:
Radial extent and propagation speed do not depend much on ρ*

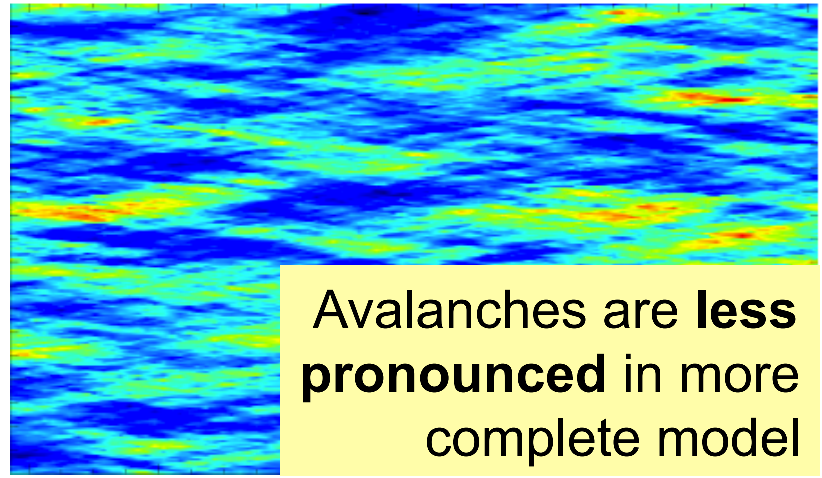


Better (local) models: Avalanches?!

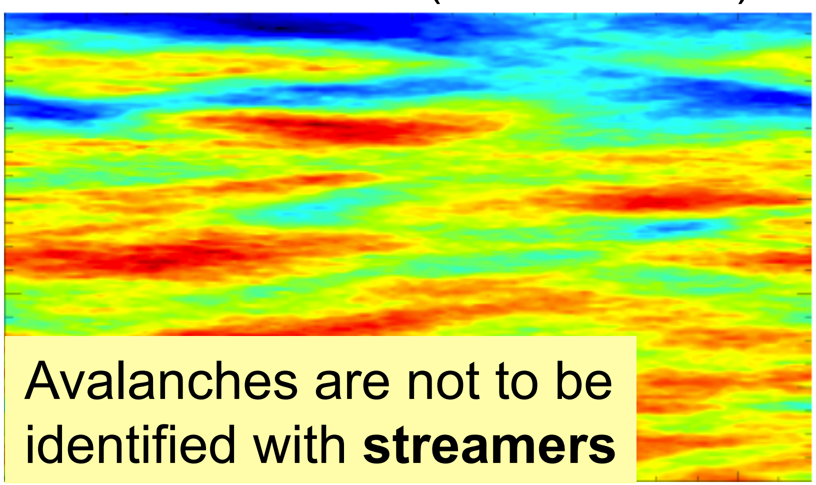
ITG turbulence (adiabatic electrons)



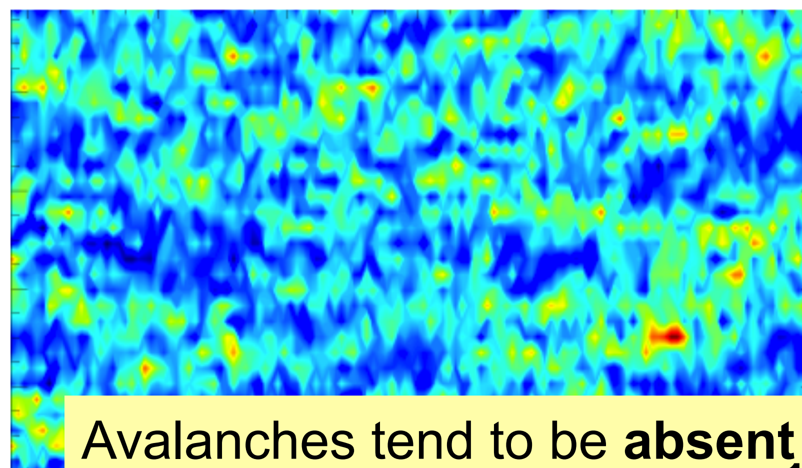
ITG turbulence (kinetic electrons)



ETG turbulence (adiabatic ions)



TEM turbulence



Summary “Nonlocal effects”

In sufficiently large machines, local simulations appear to be adequate – except for describing transport barriers.

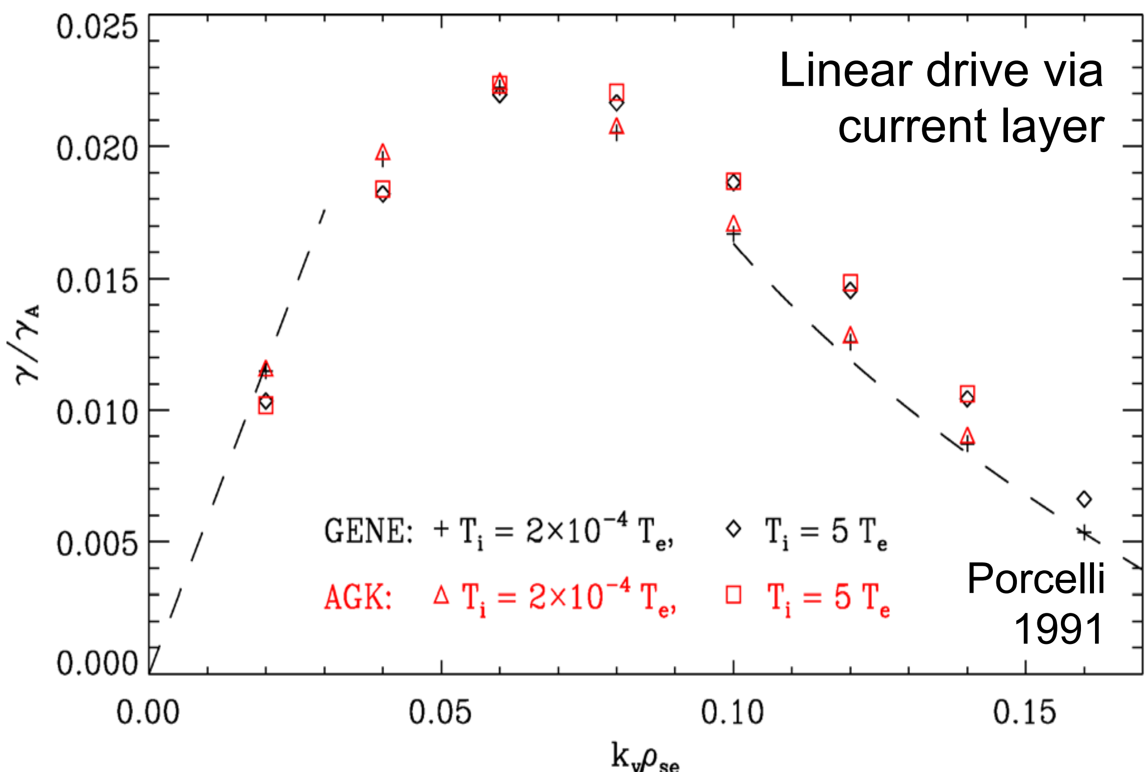
The latter seem to constitute very challenging multiscale problems, probably involving electron-scale physics.

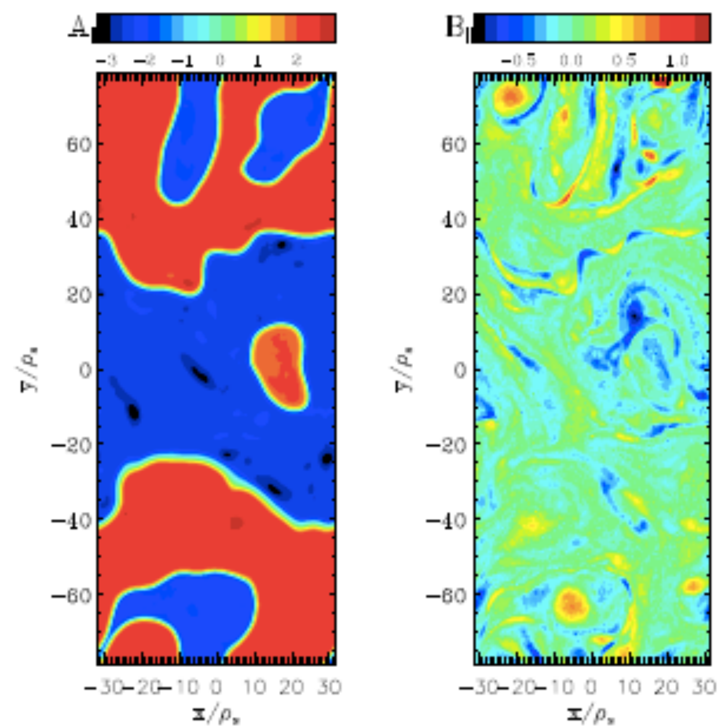
There are also other sub-ion-gyroradius scale effects…

Role of sub-ion-gyroradius scales: Field line stochasticity

GENE simulations of 2D reconnection

Magnetic reconnection in a strong guide field → use gyrokinetics
Extensive linear benchmarking (AGK code, Porcelli fluid model)
Decaying and driven nonlinear simulations (energy is conserved)





Pueschel *et al.*, PoP 2011

Some background on microtearing

Basic characteristics of microtearing modes:

- GK analogues of MHD tearing modes, but driven mainly by ∇T_e
- Exhibit tearing parity, giving rise to small-scale magnetic islands
- Heat transport is dominated by electron magnetic component

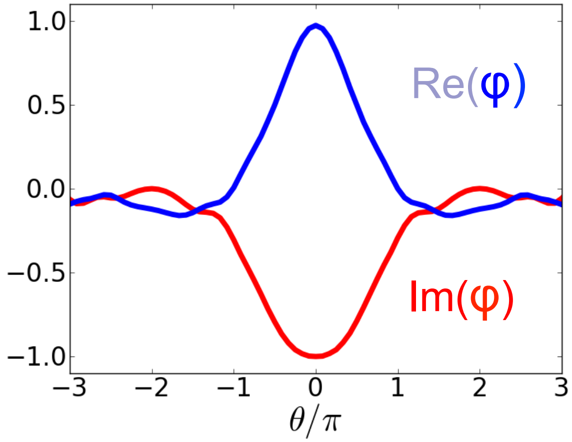
A brief history of microtearing modes:

- First discovered in the mid 1970's (Hazeltine, Drake, Chen, Callen)
- Maybe no microtearing modes in regular tokamaks (Connor 1990)
- Prediction of microtearing modes in STs (Kotschenreuther 2000)
- Simple transport predictions explain NSTX data (Wong 2007)
- Prediction of microtearing modes in regular tokamaks (Applegate 2007, Vermare 2008, Told 2008)
- First nonlinear microtearing simulations in (spherical) tokamaks (Doerk 2011, Guttenfelder 2011)

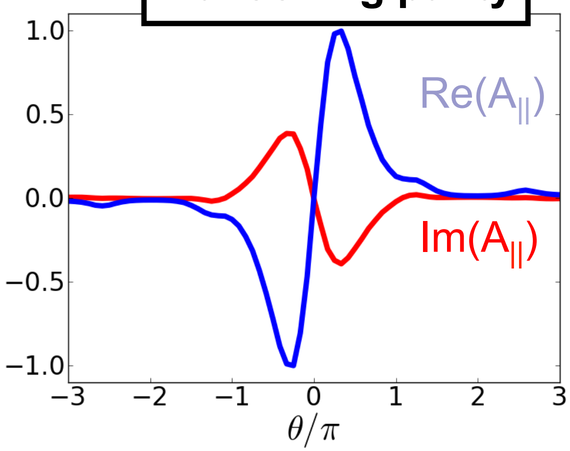
Here: GENE simulations of microtearing turbulence in regular tokamaks

Comparison of microinstabilities in ballooning space

ITG modes

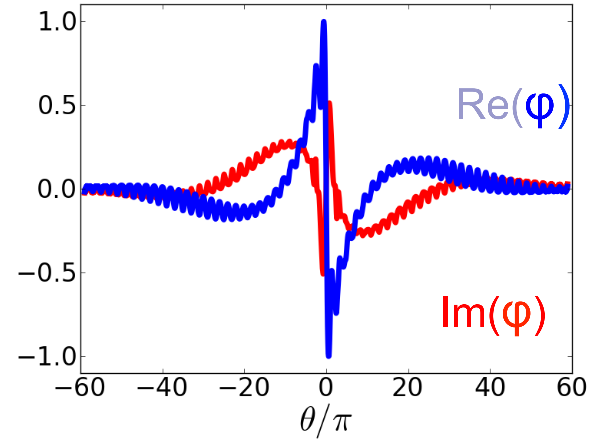


Ballooning parity

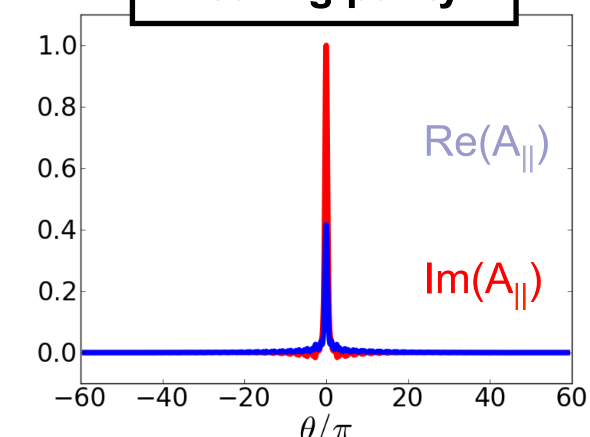


~**1-3** poloidal turns

Microtearing modes



Tearing parity

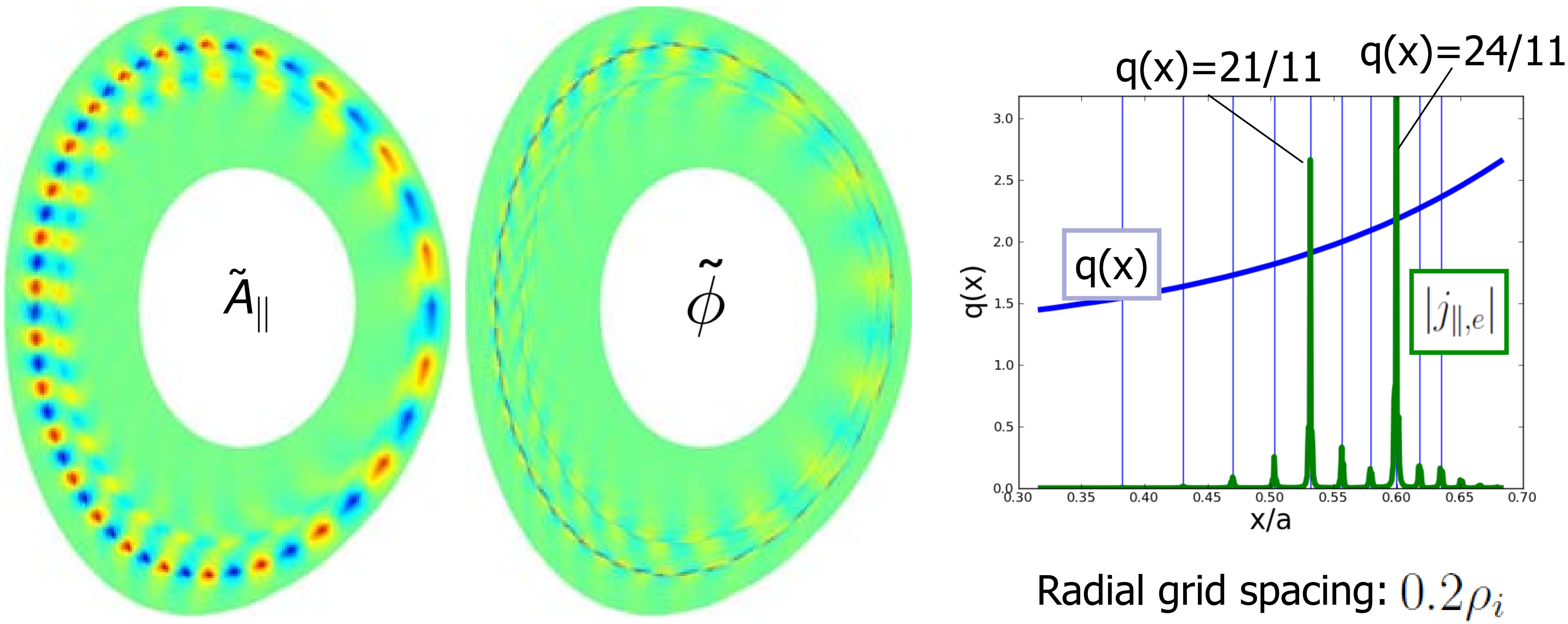


~**60** poloidal turns in φ

Microtearing modes show intrinsic multiscale features

Global linear simulations of ASDEX Upgrade #26459

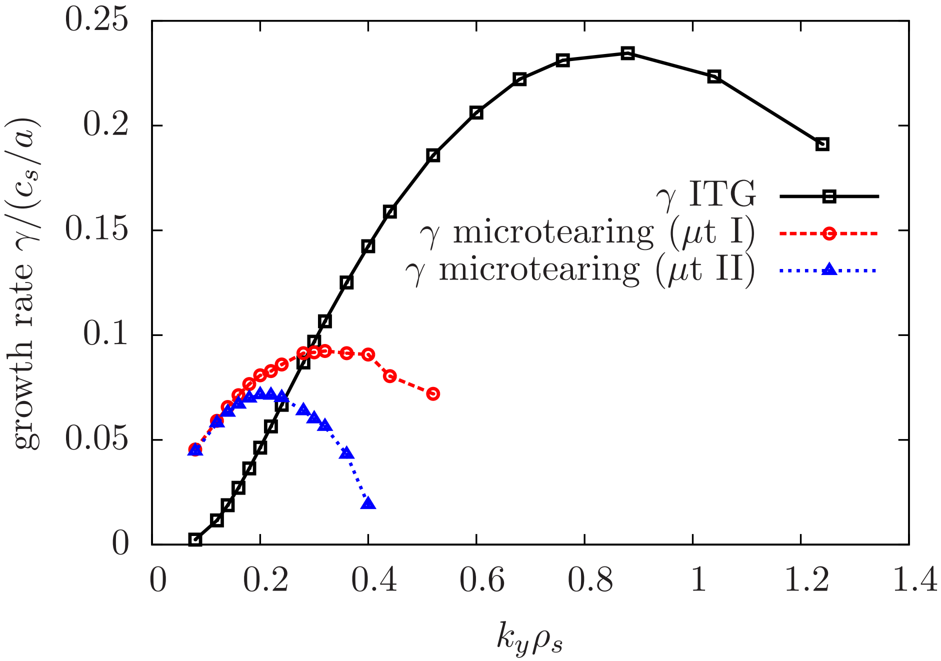
Contours of $A_{||}$ and Φ in the poloidal plane for n=11. The most unstable microtearing mode is localized at q=24/11.

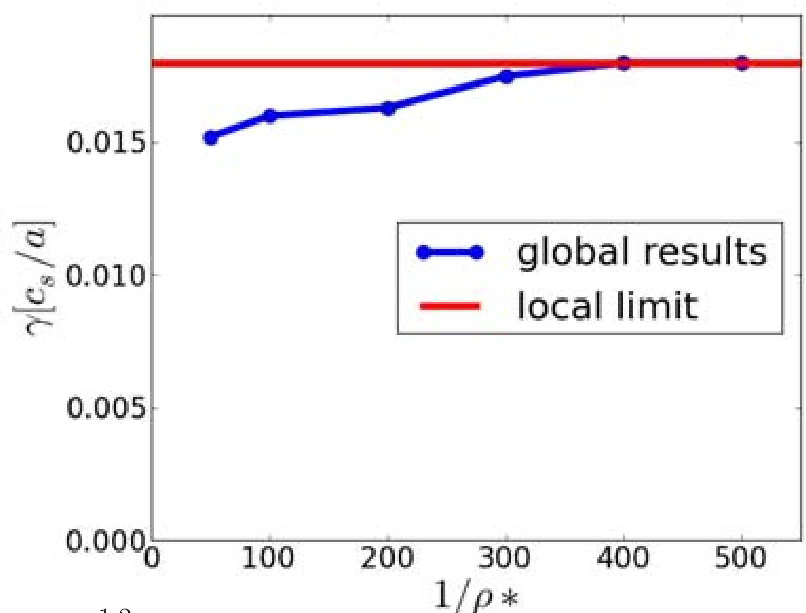


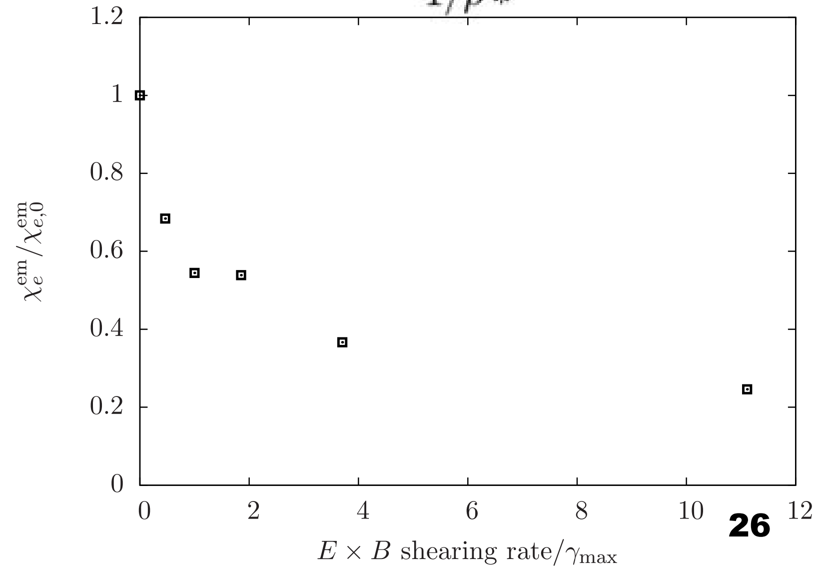
Radial grid spacing: $0.2\rho_i$

Microtearing instabilities expected to exist in AUG

ASDEX Upgrade #26459 (cont'd)



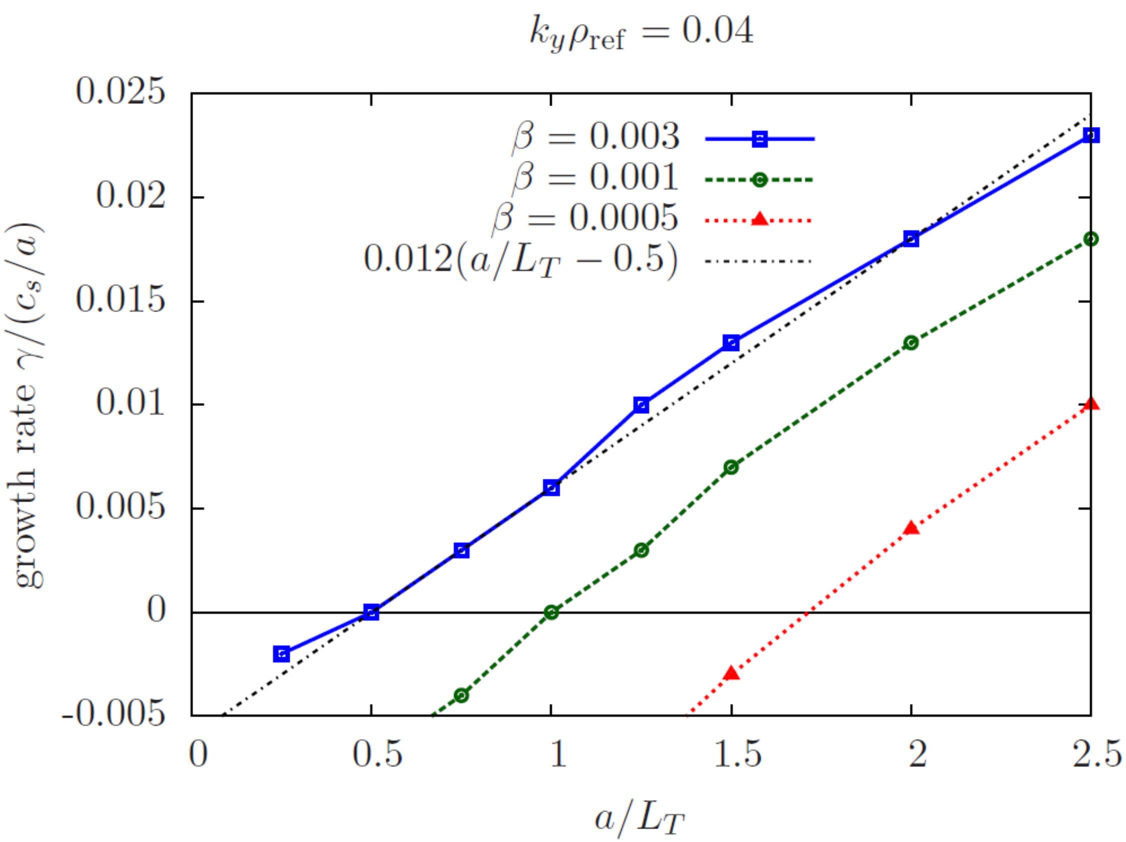




Microtearing modes at low k_y can coexist with ITG (or TE) modes; they react weakly to finite ρ* and ExB shear

Focus on local simulations!

Influence of electron temperature gradient and β_e



Experimental values:

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

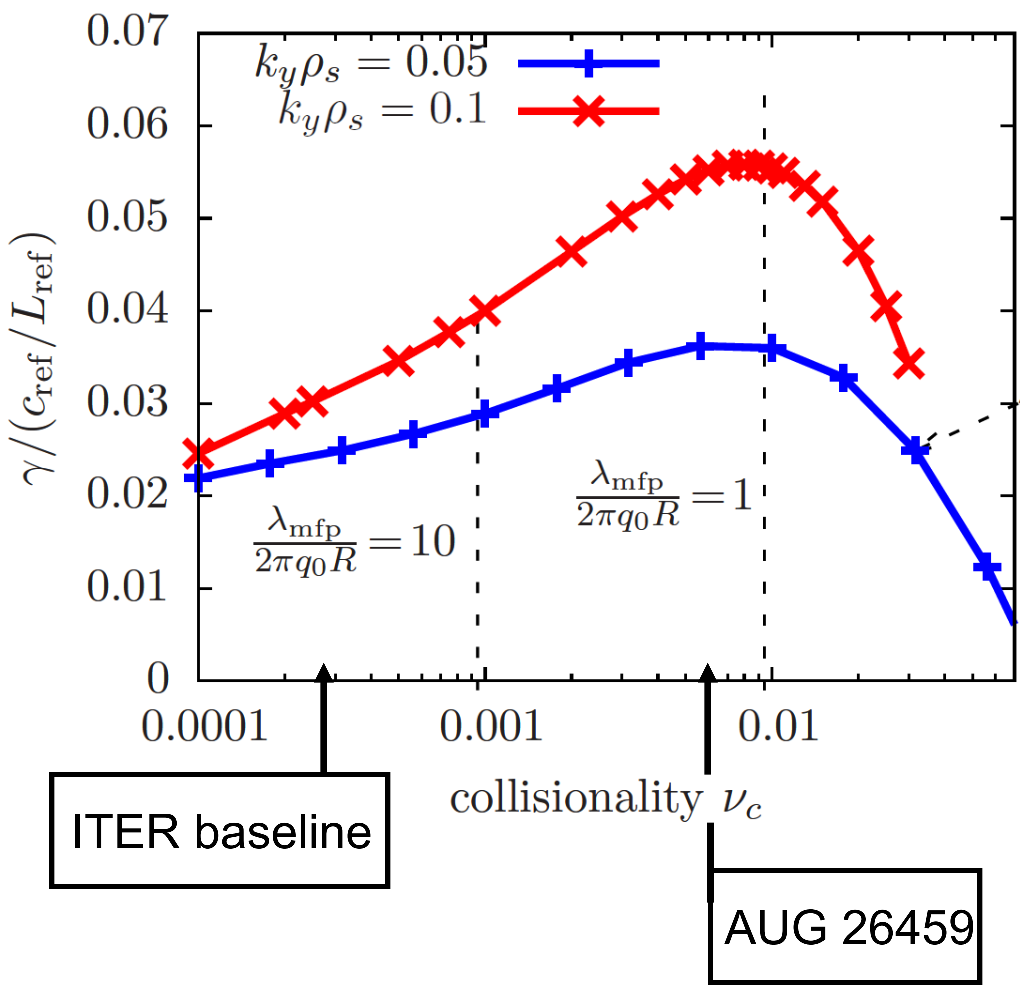
(well above threshold)

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

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

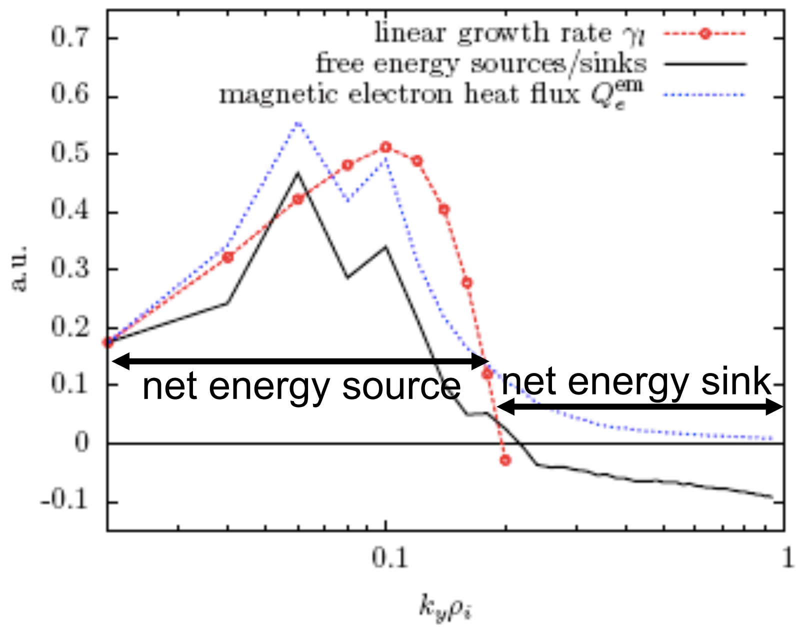
- Including **collisions** is **important**
- Growth rate depends on collision frequency only **moderately** (in agreement, e.g., with Applegate '07)
- Experiments are in the **semicollisional** to **collisionless** regime

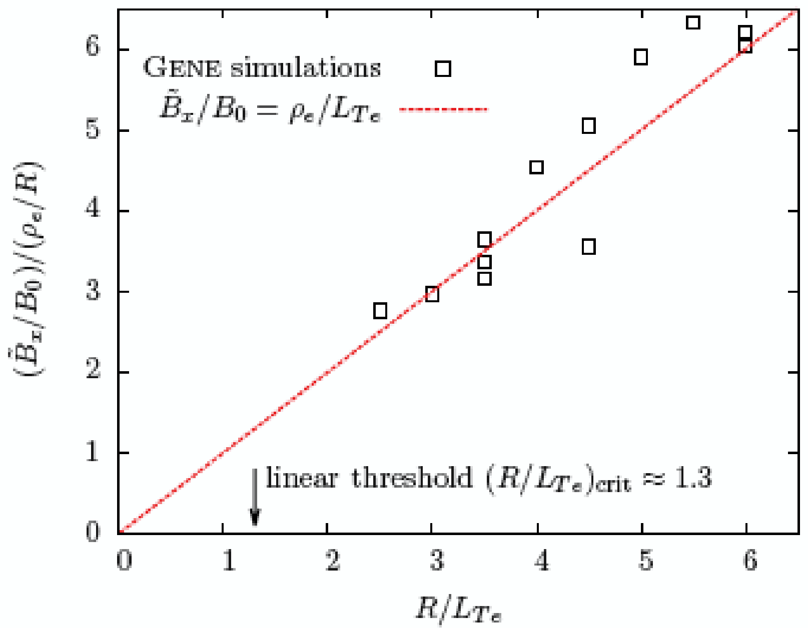
$\nu_c \sim n\, T^{-3/2}$ but:



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

Magnetic field saturation levels





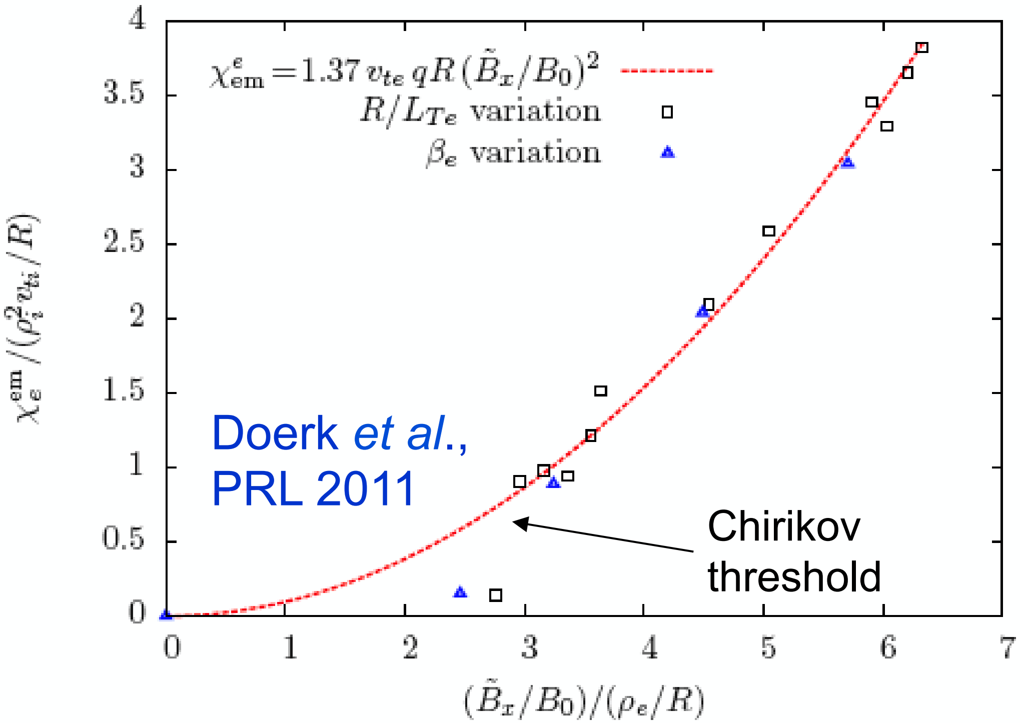
Parameter regime of interest here: $\gamma_l^{max} \propto (R/L_{T_e})^2 v_{ti}/R$

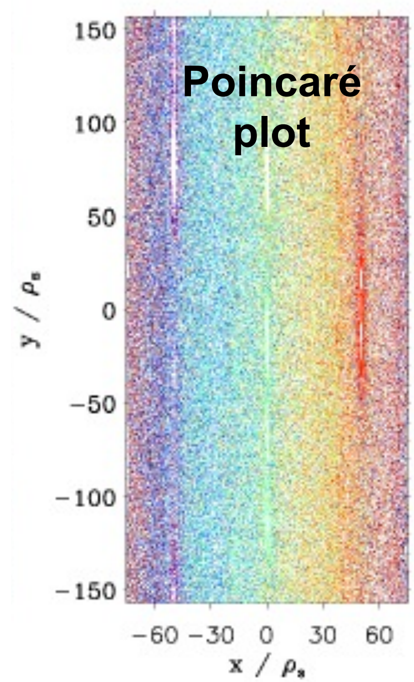
Dissipation of free energy at high k: $\gamma_{nl} = \chi_e^{em} k_{diss}^2 \qquad k_{diss} \gtrsim 0.2/\rho_i$

Balancing the two, one obtains: $\boxed{\tilde{B}_x/B_0 \sim \rho_e/L_{T_e}}$ (Drake 1980)

Doerk *et al*., PRL 2011

Magnetic electron heat transport





Magnetic electron heat diffusivity is well described by a Rechester-Rosenbluth model: $\chi_e^{em} \sim v_{te}\, L_c\, (\tilde{B}_x/B_0)^2$

…producing experimentally relevant transport levels (~m^2/s)

Summary “Field line stochasticity”

There is strong evidence that microtearing modes may contribute to the anomalous electron heat transport even in “standard” tokamaks like ITER.

Microtearing + ITG simulations are currently underway.

Further studies along these lines, including comparisons between theory and experiment, are called for.

Role of sub-ion-gyroradius scales: ETG turbulence in barriers

High-k turbulence and transport

Starting point: Stallard et al., PoP 1999

High-k ETG turbulence can induce significant electron heat transport:

$\boxed{\chi_e^{\mathrm{ETG}} \gg \frac{\rho_e^2 v_{te}}{L_{T_e}} \text{ is possible}^{a,b,c} \text{ (at positive shear)}}$

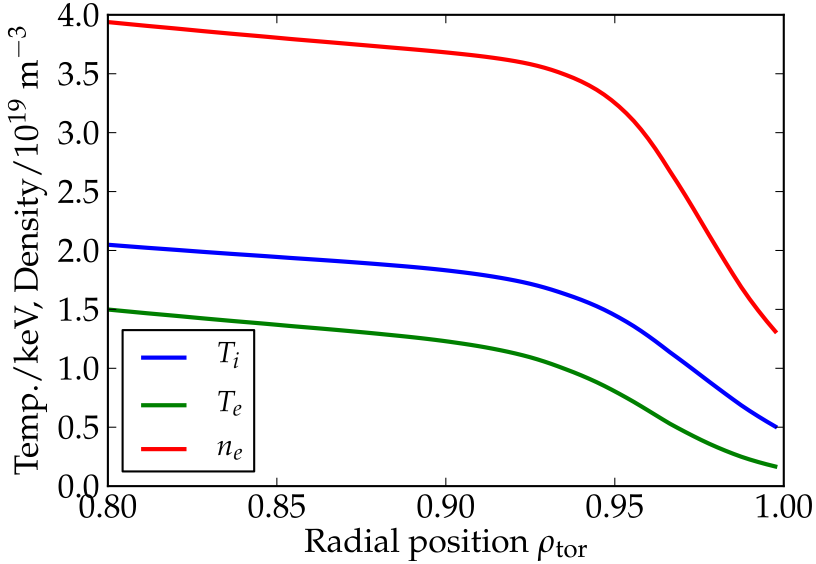
[a]Jenko et al., PoP 2000;
[b]Nevins et al., PoP 2006;
[c]Görler et al. PRL 2008

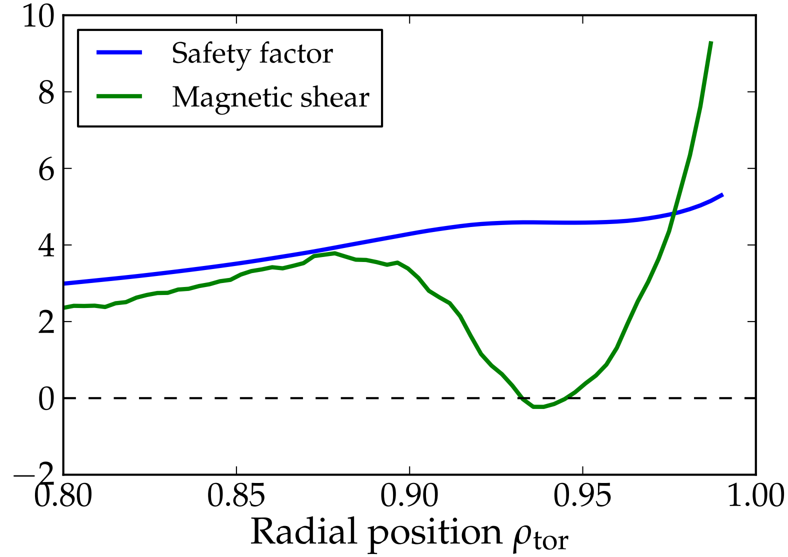
For comparison: $\chi_i^{\mathrm{ITG}} \approx 0.7 \frac{\rho_s^2 c_s}{L_{T_i}}$ (Cyclone base case, *exceeding experimental values*)

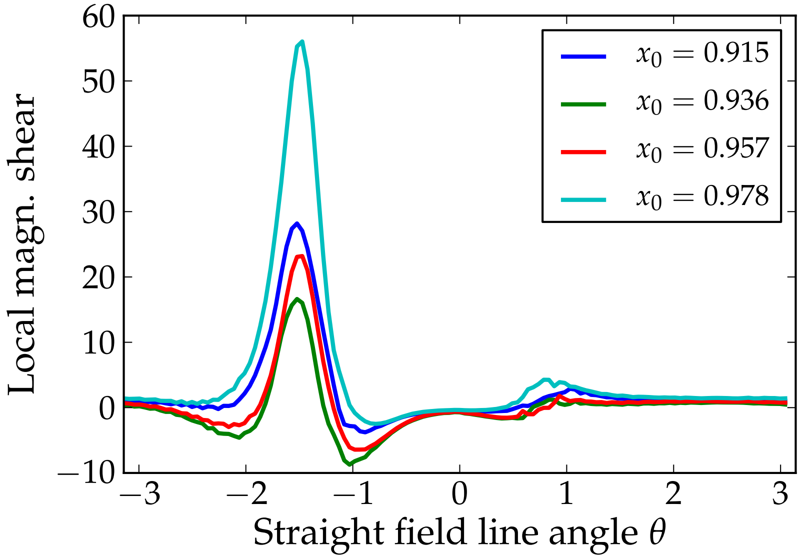
- About 10 (<1) such electron gyro-Bohms are sufficient to explain χ_e in the outer half (internal transport barrier) of various tokamak discharges[b]
- TGLF transport simulations of 32 DIII-D hybrid discharges: ion transport close to neoclassical, electron transport dominated by high-k ETG modes[d]
- For certain NSTX and MAST discharges, gyrokinetic ETG simulations yield χ_e's which are consistent with experimental values[e]

[d]Kinsey et al., APS 2009; [e]Roach et al., PPCF 2009

ASDEX Upgrade #20431 at t=1.82s



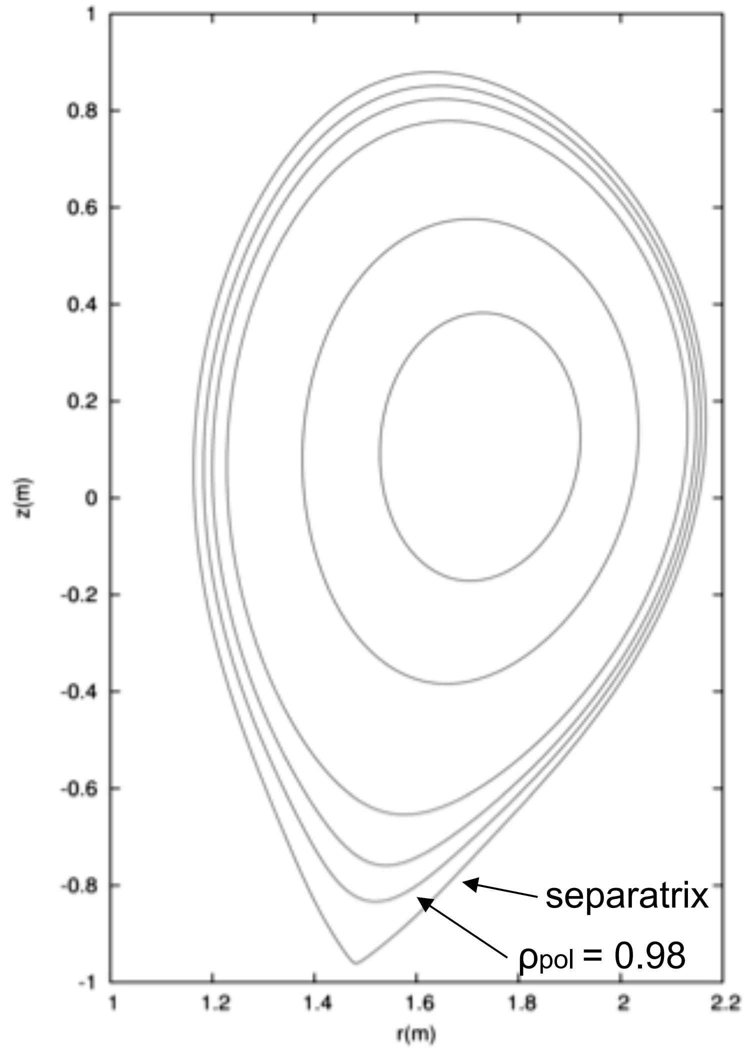


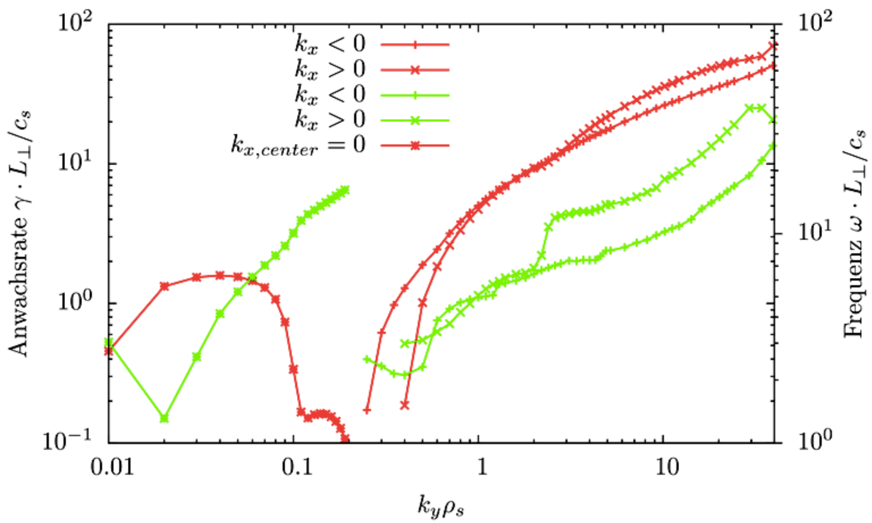


Metric coefficients extracted from MHD equilibrium via field-line tracing with the GIST code[a]

[a]Xanthopoulos et al., PoP 2009

GENE runs for AUG H-mode edge plasmas

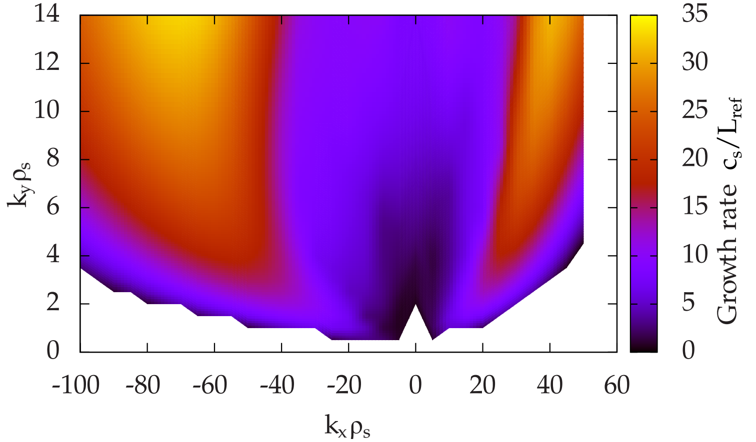




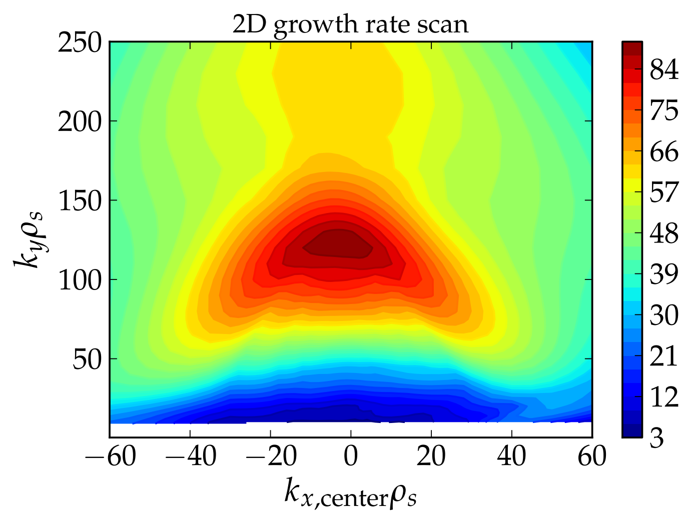
Edge transport barrier region:

- $k_y\rho_s < 0.1$ → ITG mode
- $k_y\rho_s \sim 0.15$ → microtearing mode
- $k_y\rho_s > 0.2$ → ETG mode

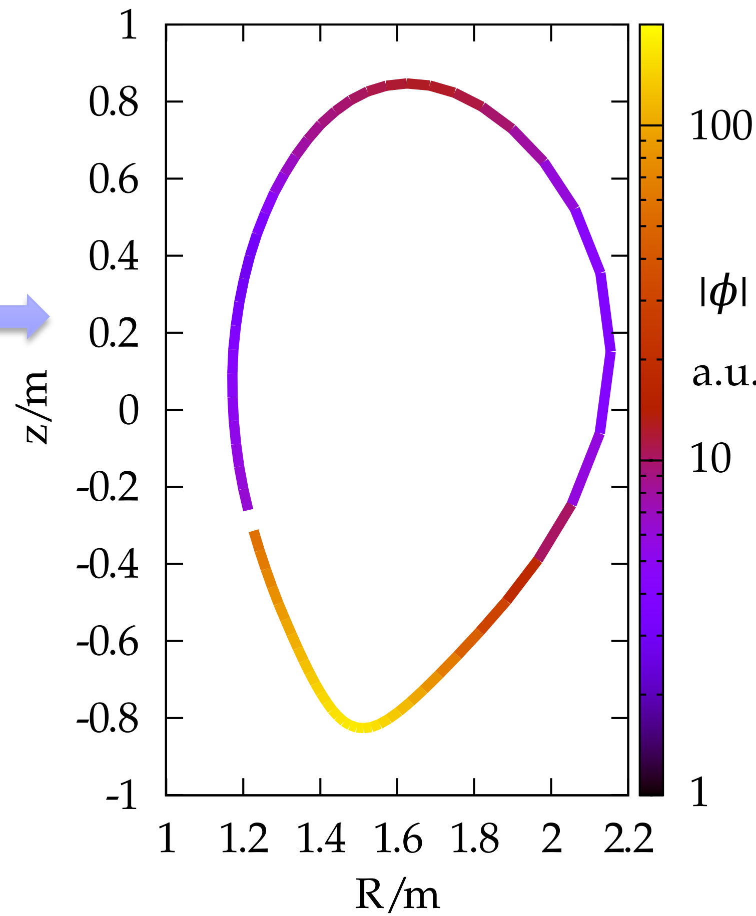
Linear stability of edge ETG modes



(a) 2D linear scan for low k_y wavenumbers. The ETG instability peaks at finite k_x values (off the outboard midplane).



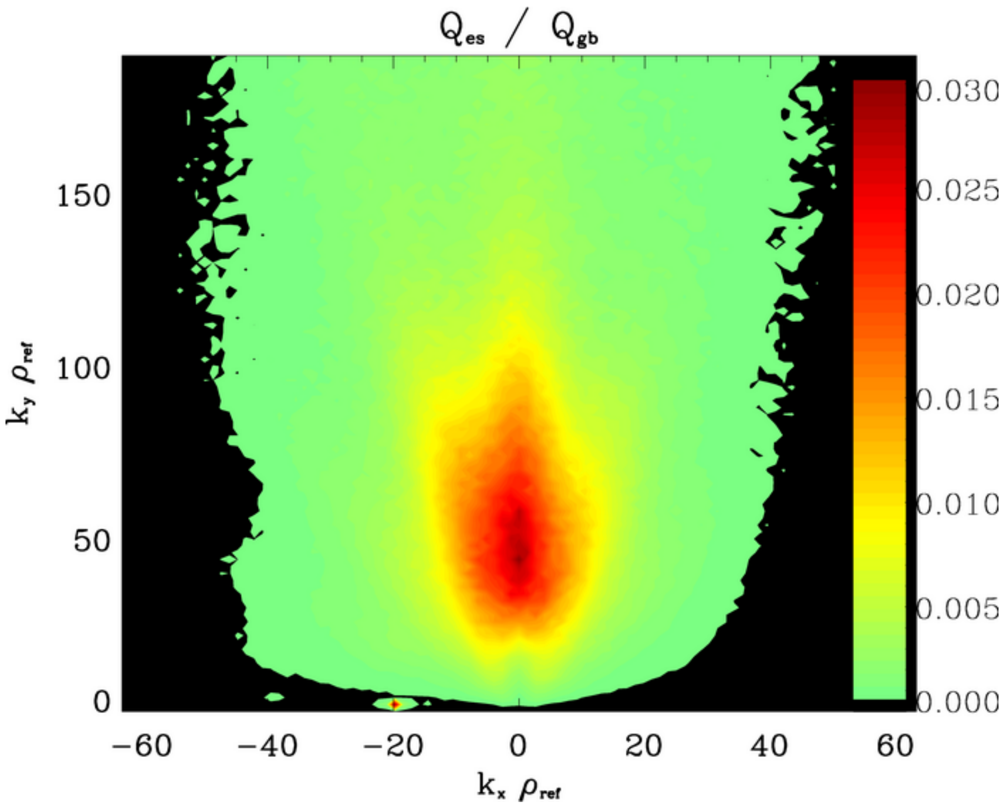
(b) 2D linear scan. For higher k_y modes, the ETG instability peaks again around $k_x = 0$ (close to the outboard midplane).



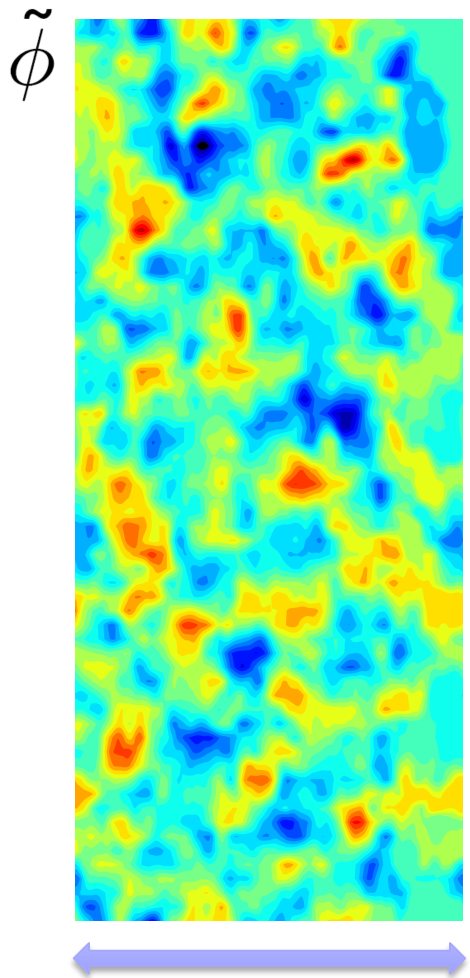
At low wavenumbers, ETG modes tend to peak near the X-point(s)

Properties of edge ETG turbulence

Electron heat flux spectrum in perpendicular wavenumber space



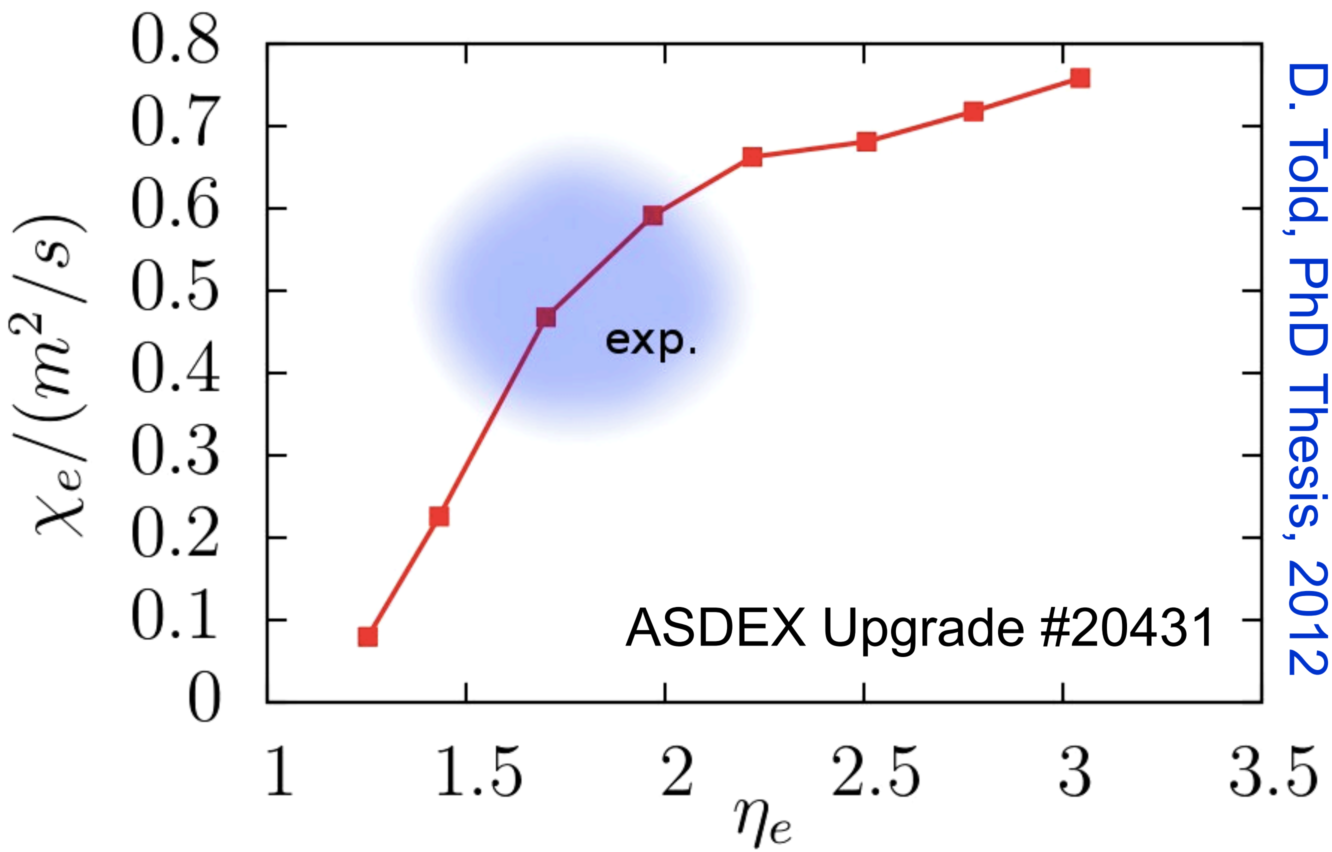
Significant ETG activity at $k_\perp \rho_i \gg 1$



$1.1\rho_s$ or $1.8\,\mathrm{mm}$

D. Told, PhD Thesis, 2012

Relevant ETG activity in edge barriers

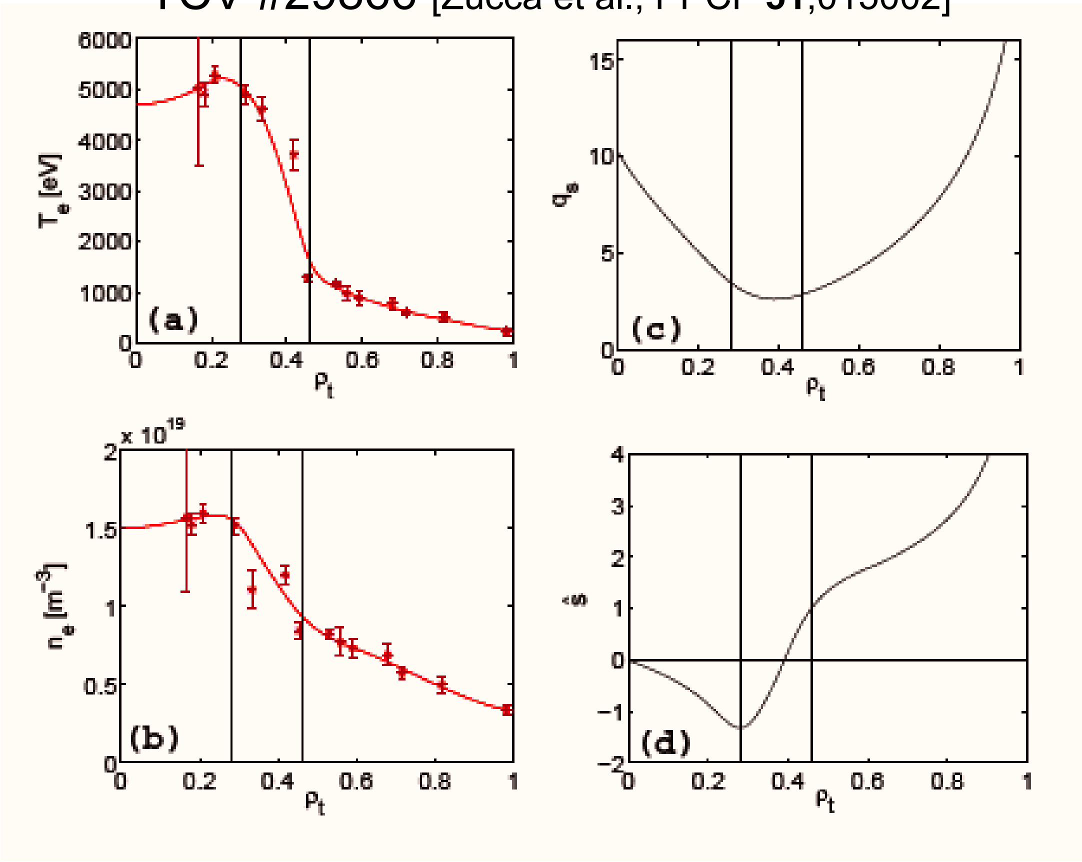


D. Told, PhD Thesis, 2012

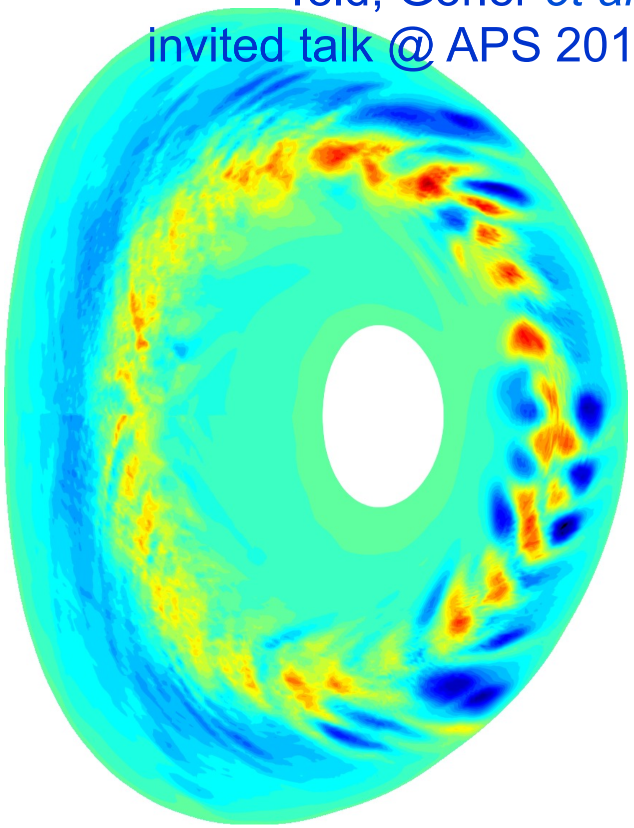
High-wavenumber ETG turbulence is able to explain the residual electron heat transport in H-mode edge plasmas

Global gyrokinetics: Established e-ITBs

TCV #29866 [Zucca et al., PPCF **51**,015002]

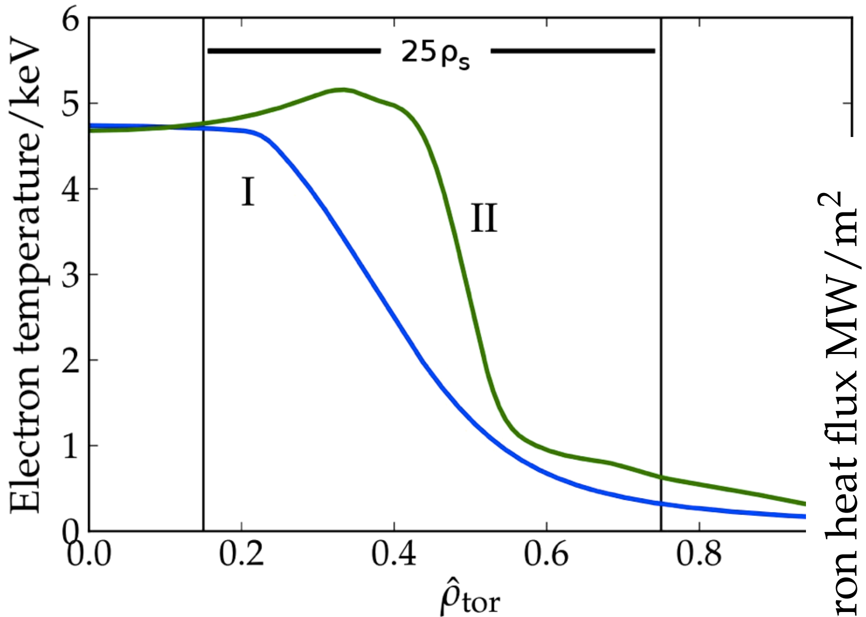


Told, Görler *et al.*, invited talk @ APS 2010



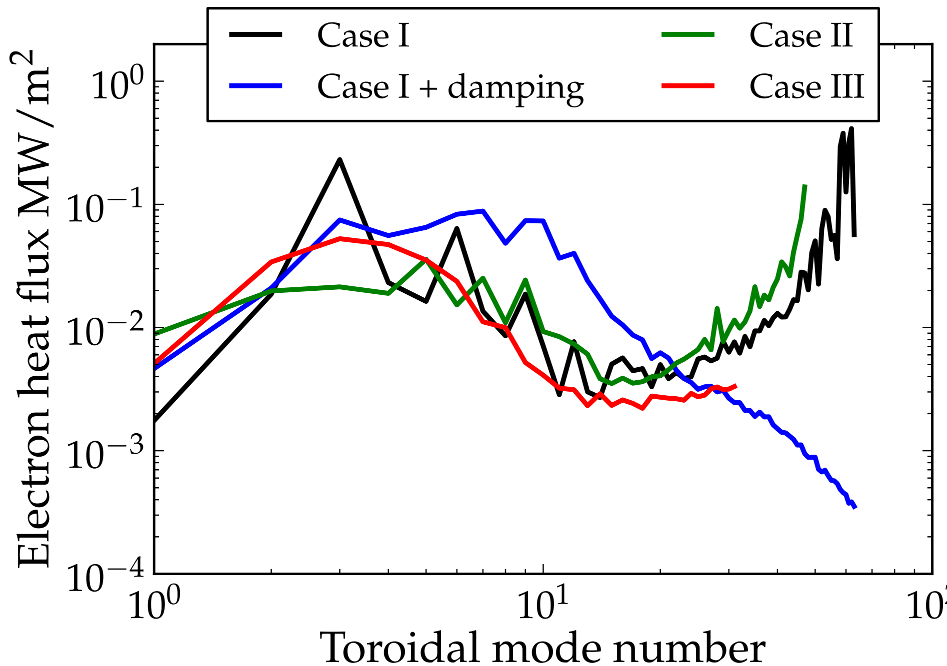
Global GENE simulations (with quite comprehensive physics) for e-ITBs in TCV tokamak “reproduce” experimental fluxes

Multiscale simulations of e-ITBs



I "relaxed" profile
II "nominal" profile

D. Told, PhD Thesis, 2012



GENE simulations suggest that the slope of the electron temperature profile is limited by the onset of ETG turbulence

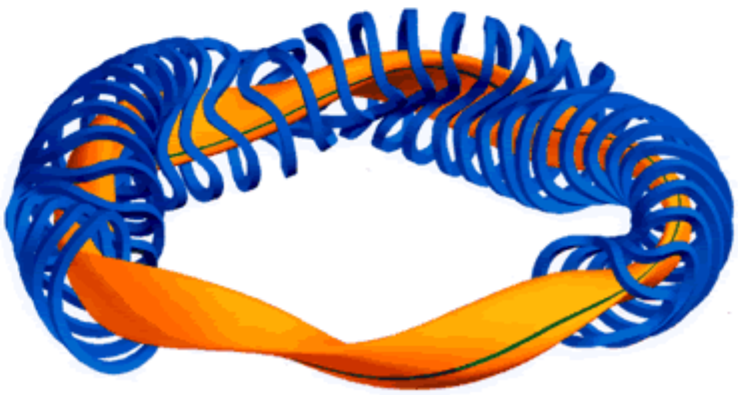
Summary “ETG turbulence”

There is clear evidence that ETG turbulence contributes to the residual turbulence in transport barriers.

Future multi-scale simulations will help determine the role of low-k, mid-k, and high-k regimes relative to each other.

Towards turbulence optimization in stellarators

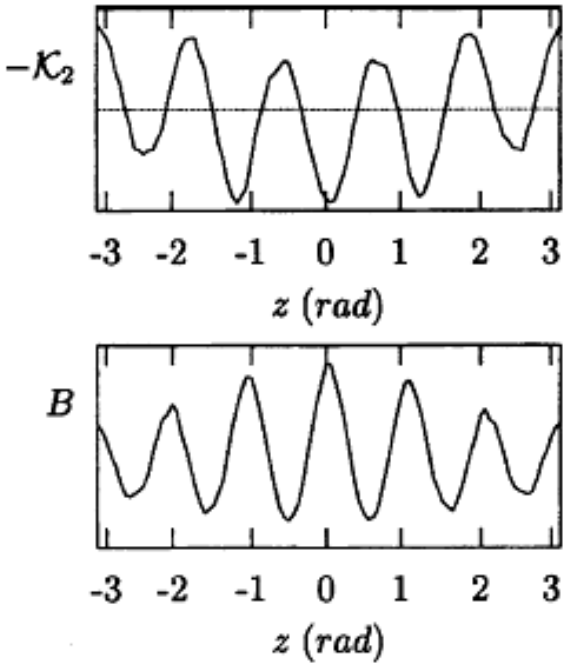
GENE simulations for stellarators



Wendelstein 7-X stellarator is optimized with respect to neoclassical transport

Does this imply turbulence optimization?

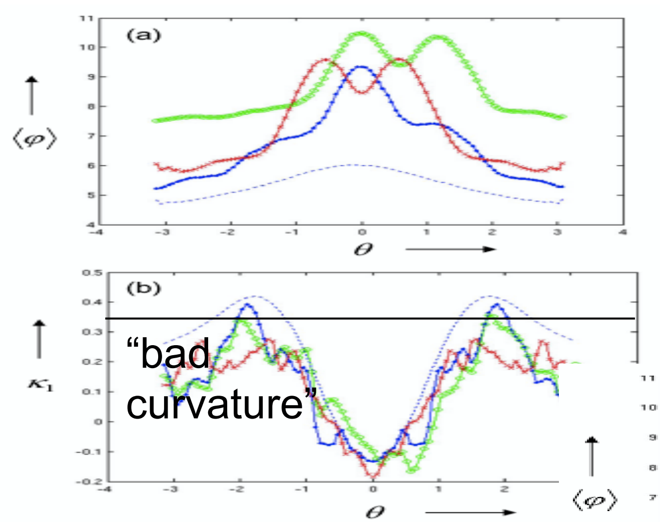
- GENE flux-tube simulations using field-aligned coordinates
- Geometric coefficients computed by GIST code from VMEC equilibria [Xanthopoulos *et al*., PoP 2009]
- Complicated parallel structure leads to costly simulations (>100 grid points)



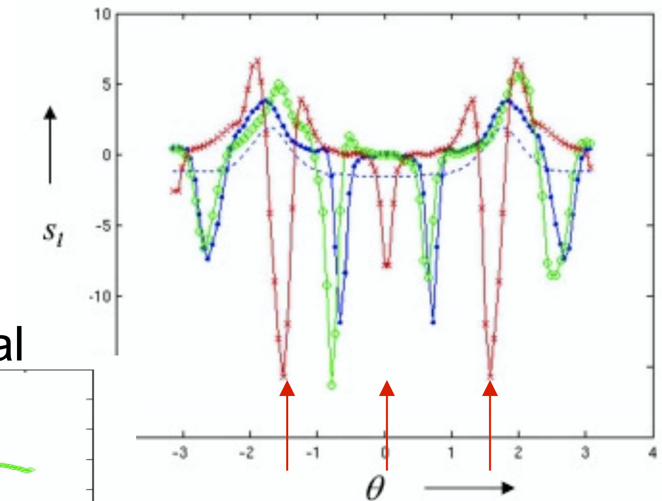
Microinstabilities in stellarators

Example: ITG modes (adiabatic electrons) in NCSX

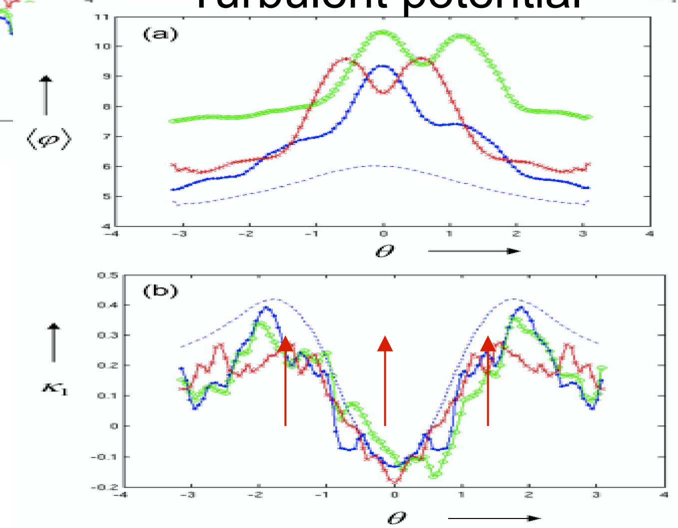
Radial curvature



Local magnetic shear



Turbulent potential



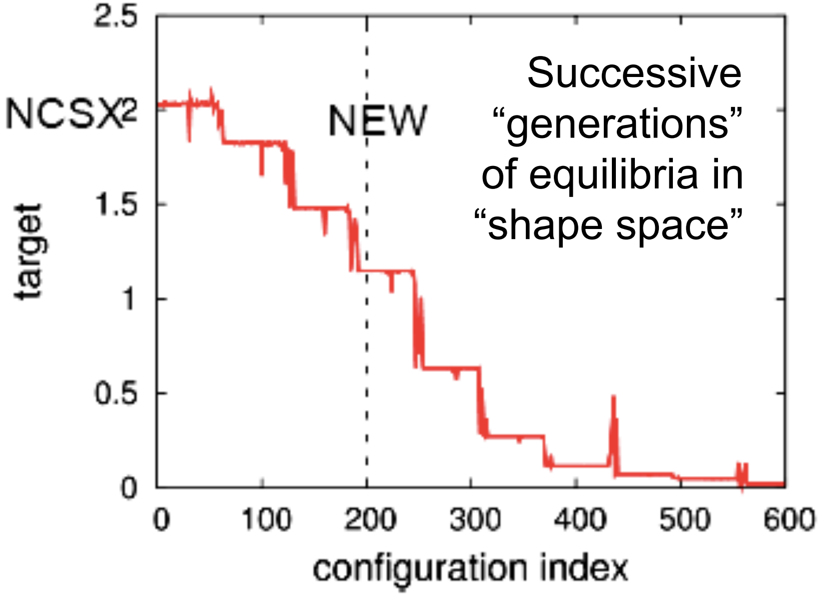
Bad curvature and local magnetic shear control the transport

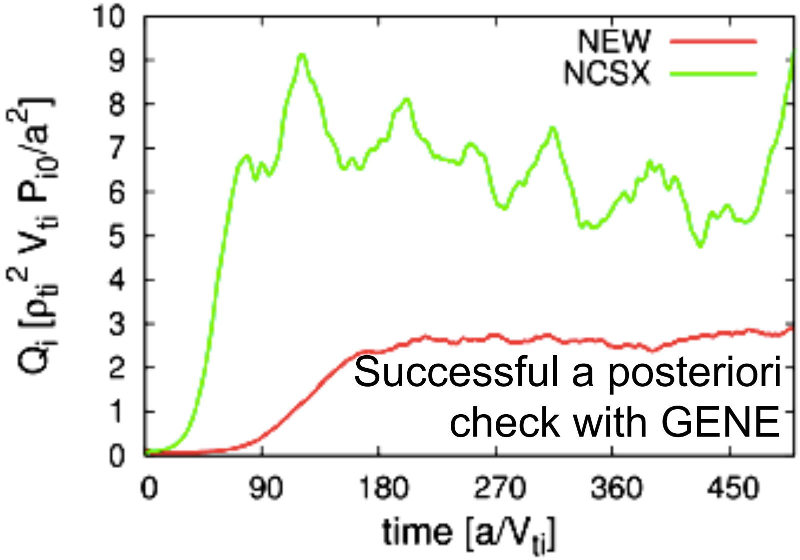
Mynick *et al*., PoP 2009

Geometry may also affect nonlinear saturation (e.g. ZFs) in subtle ways…

Including turbulence in optimization

Mynick *et al*., PRL 2010

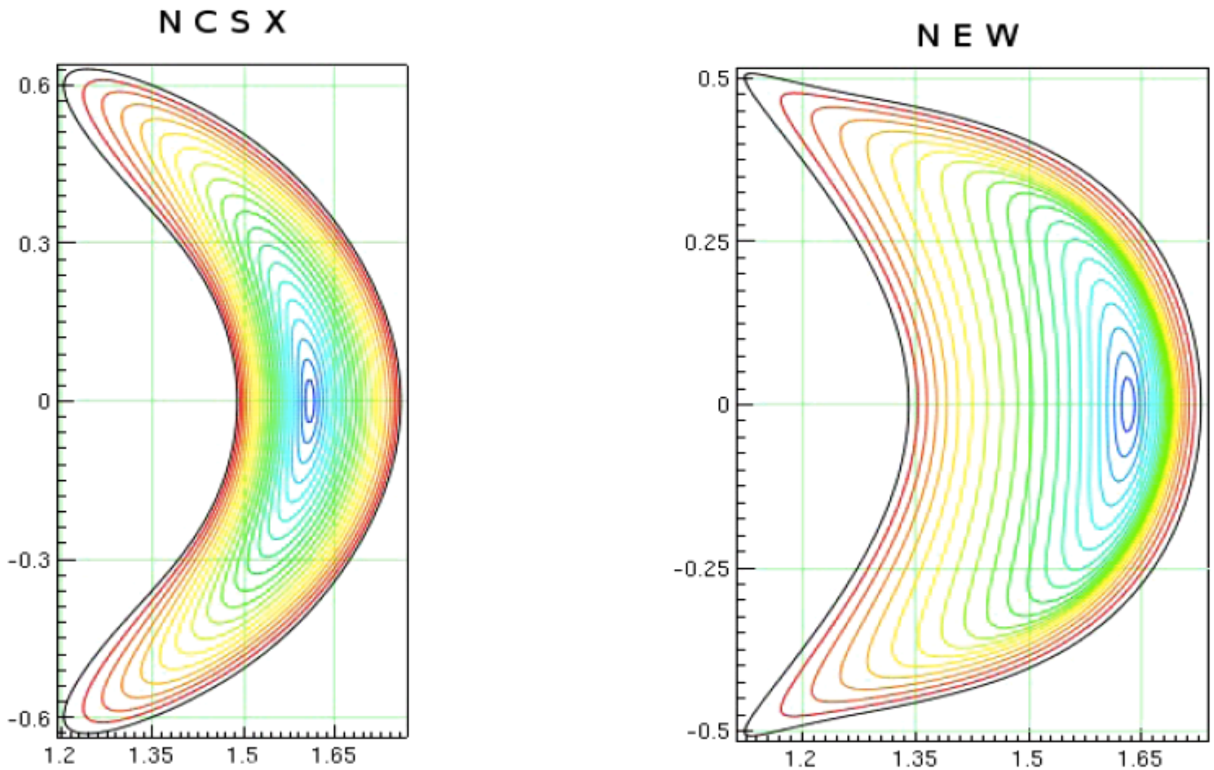




STELLOPT code seeks to minimize a cost function in "shape space" including a "proxy function" based on theory and GENE simulations

Starting from the standard NCSX configuration, a new configuration is determined which is characterized by reduced ITG-ae turbulence

Modification found by STELLOPT



Mynick *et al.*, PoP 2011

The NEW configuration displays outward shifted surfaces, corresponding to a deepening of the magnetic well (like finite β)

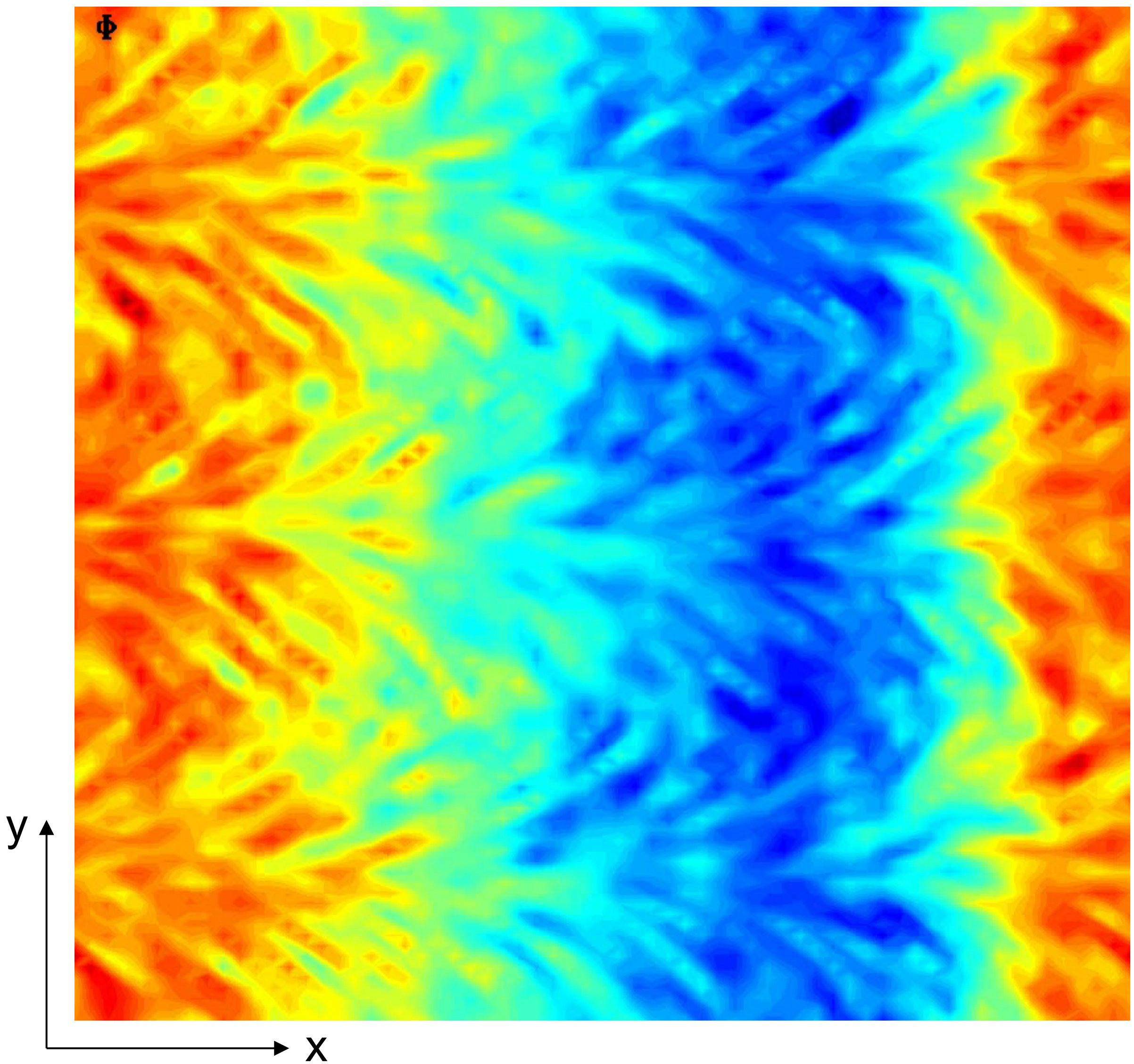
Summary “Turbulence in stellarators”

It is possible now to perform **local** gyrokinetic simulations of ITG / TEM / ETG turbulence in stellarators; extensions to nonlocal models are underway.

Stellarators offer many possibilities for 3D shaping as to minimize both neoclassical **and turbulent transport** (which, in general, is not the same, as it turns out).

Perspectives

Full flux surface stellarator runs



Magnetic geometry depends on z and y

Example: NCSX
(3-fold symmetry)

ITG turbulence
(electrostatic potential)

Next step:
Development of a
3D version of GENE

Told, Görler et al.
Bird, Xanthopoulos et al.

New frontier: Multiscale, multiphysics studies

- From the system size to the electron gyroradius
- Integration of turbulence, neoclassics, and MHD
- Incorporation of intrinsic / external 3D field effects

Goal:

Fundamental understanding and predictive capability for turbulence and nonlinear dynamics in fusion plasmas…

…via large-scale simulations in concert with novel theories and dedicated experiments