ASDEX Upgrade

Max-Planck-Institut für Plasmaphysik

Gyrokinetic Turbulence in Tokamaks and Stellarators

Frank Jenko

IPP, Germany

Acknowledgements:

P. Xanthopoulos, F. Merz, T. Görler, M. Pueschel, D. Told;

A. Boozer, G. Hammett, D. Mikkelsen, M. Zarnstorff,

H. Sugama, T. Watanabe

18th International Toki Conference; December 10, 2008

Outline

A very brief review of some recent (tokamak) gyrokinetic results – for more details, see, e.g., E.J. Doyle *et al*., "Progress in the ITER physics basis", Ch. 2, Nuclear Fusion **47**, S18 (2007)

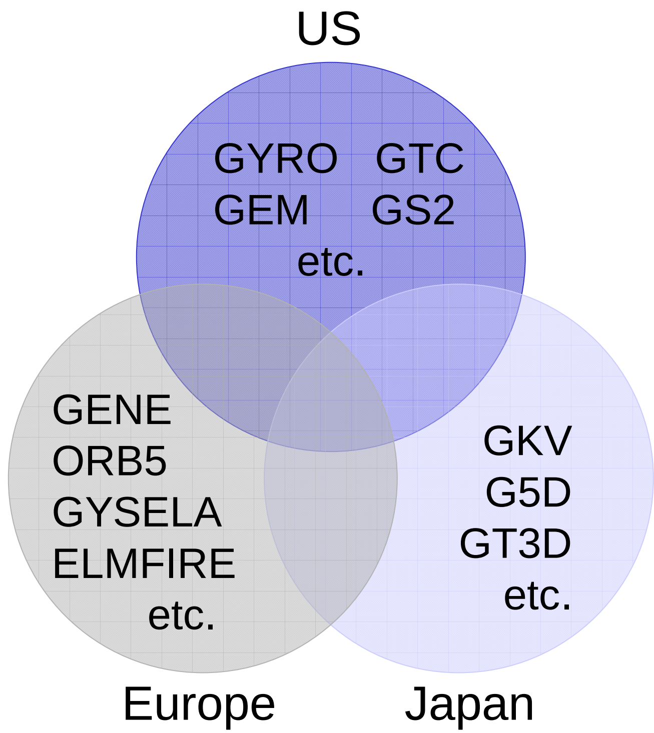
Some recent gyrokinetic turbulence simulations for:

- LHD
- NCSX
- W7-X

Long-term goal: Explore potential for systematic optimization of turbulent transport in stellarators

State of the art in nonlinear gyrokinetics

- Gyrokinetics has emerged as the standard approach to tokamak core turbulence
- Experimental comparisons are rather promising
- Extensions to tokamak edge and stellarator are underway
- Variety of gyrokinetic codes is being used and (further) developed, differing both in physics and in numerics



Gyrokinetic stellarator codes in production

GS2 (Mikkelsen, Dorland *et al.*); GOBLIN (Yamagishi *et al.*)

- Comprehensive physics (multispecies, finite beta, collisions etc.)
- Flux tube geometry

GKV (Watanabe, Sugama *et al.*)

- Adiabatic electrons, model geometry
- Flux tube geometry
- Under further development

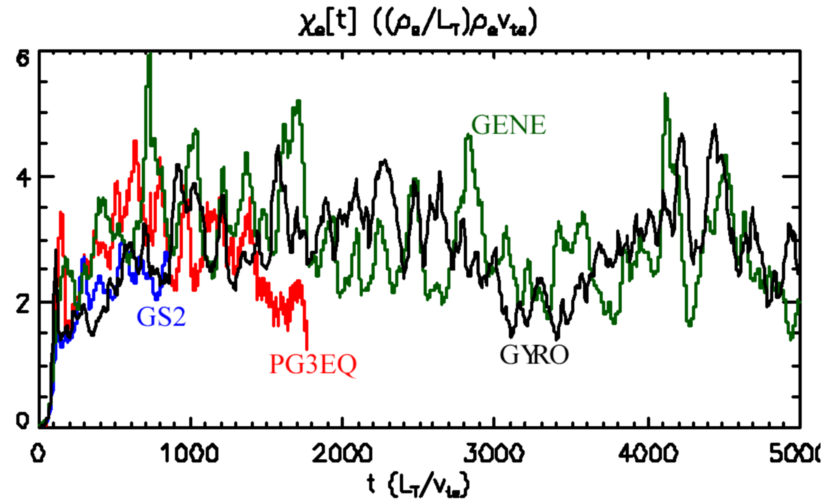
GENE (Jenko, Xanthopoulos, Merz *et al.*)

- Comprehensive physics (multispecies, finite beta, collisions etc.)
- Flux tube or global (tokamak) geometry; includes eigenvalue solver
- Under further development
- Freely available via www.ipp.mpg.de/~fsj/gene

Code benchmarking efforts

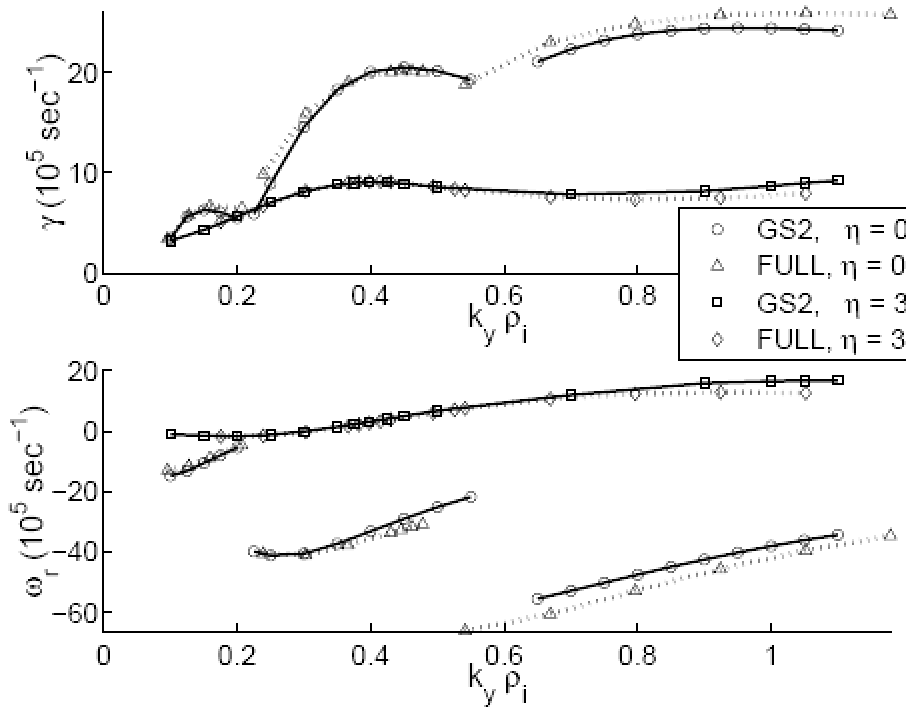
- Are we solving the equations right?
- Such efforts tend to be a bit painful but are necessary
- Examples below: Nevins *et al*., PoP 2006 & 2007; Belli *et al*.
- Another recent example: Falchetto *et al*., PPCF 2008

Nonlinear tokamak ETG case



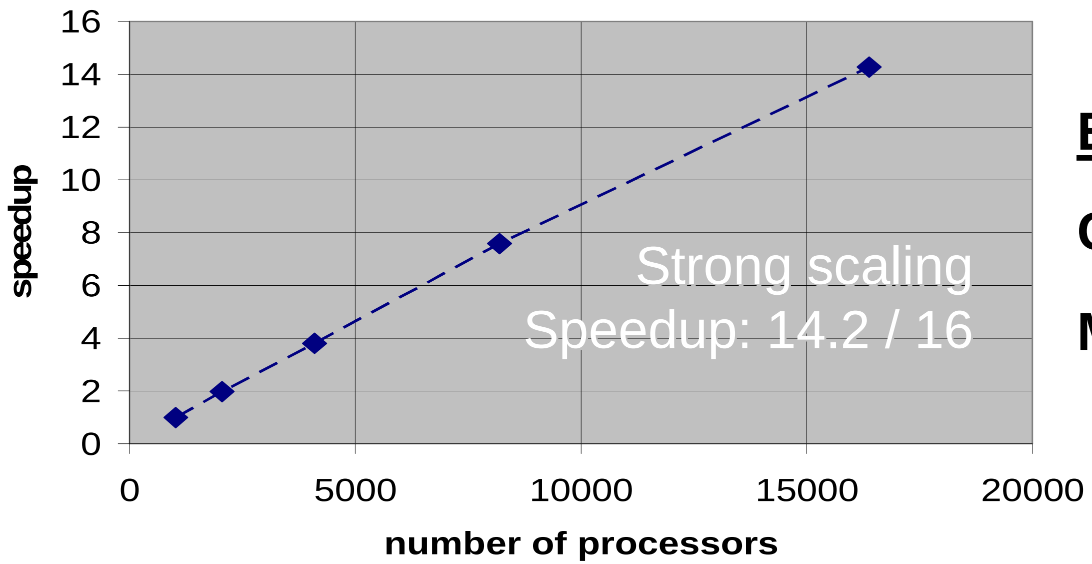
See poster P1-18 by D. Mikkelsen; P. Xanthopoulos *et al*., PoP 12/2008

Linear stellarator (NCSX) case



Massive parallelism

- Many codes scale well up to thousands of cores
- Both particle and grid-based codes can deal with massive parallelism
- Assistance by computer experts can be helpful



Example

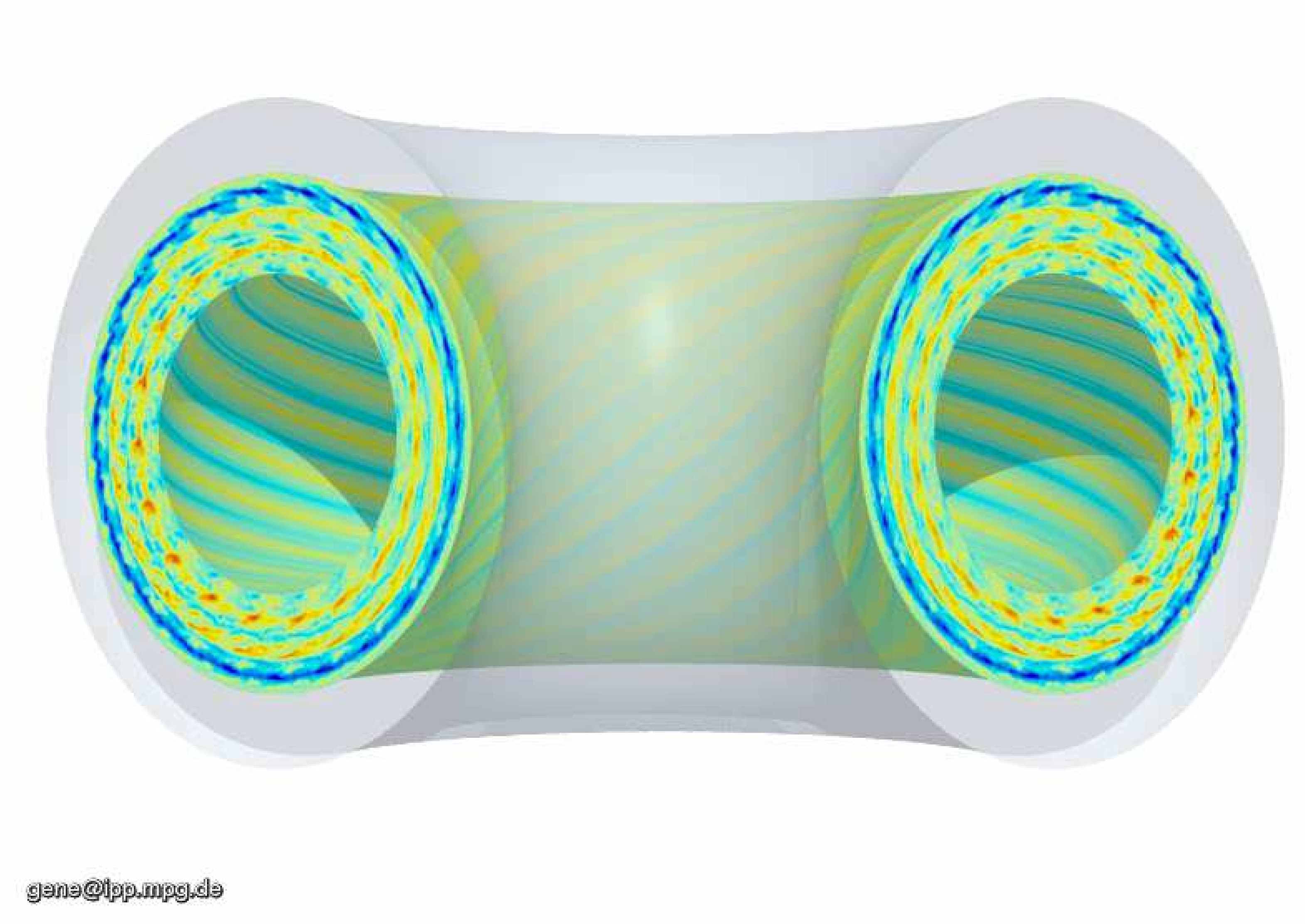
Code: GENE

Machine: BlueGene/L

The community is prepared for computers with more than 10k cores.
Further efforts are needed on the way towards PFlop/s computing.

Tokamak simulations

Gyrokinetic simulations for tokamaks



www.ipp.mpg.de/~fsj/gene

Physics issues

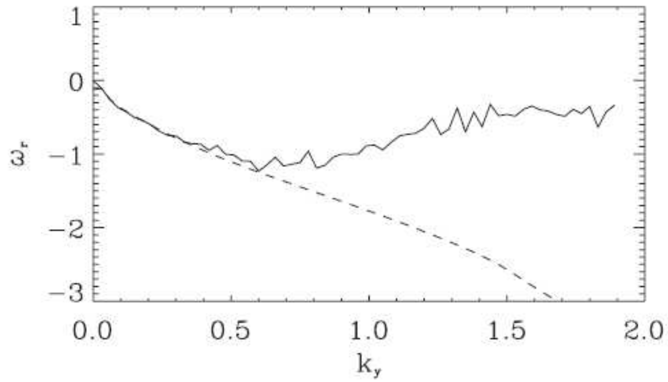
- Our physical understanding of microturbulence is still fragmentary at present

- Open questions (selection):

  1. Nonlinear saturation and mode interference
  2. Validity of quasilinear theory
  3. Impact of finite β effects in (improved) H-modes
  4. Role of sub-ion-gyroradius scales
  5. Interactions between turbulence, neoclassics, MHD
  6. Predictive *ab initio* modeling of core plasmas and transport barriers

- Close interactions between theory, simulation, and experiment are called for

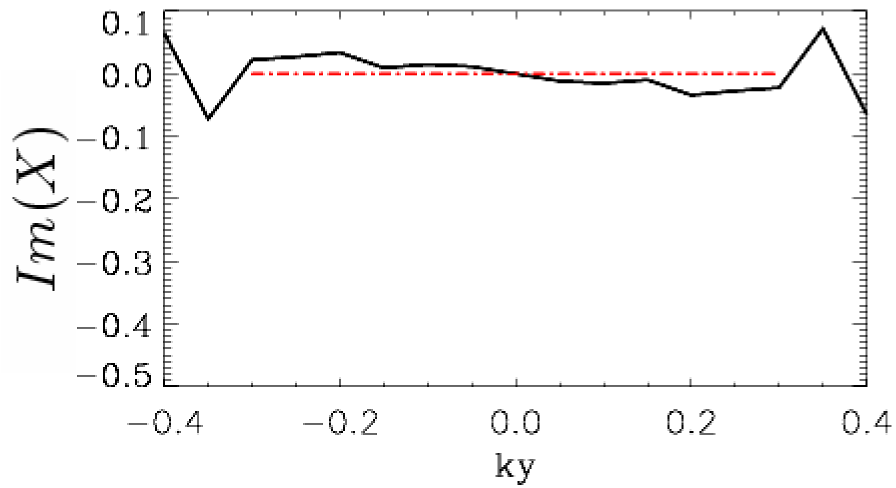
Nonlinear saturation of TEM turbulence

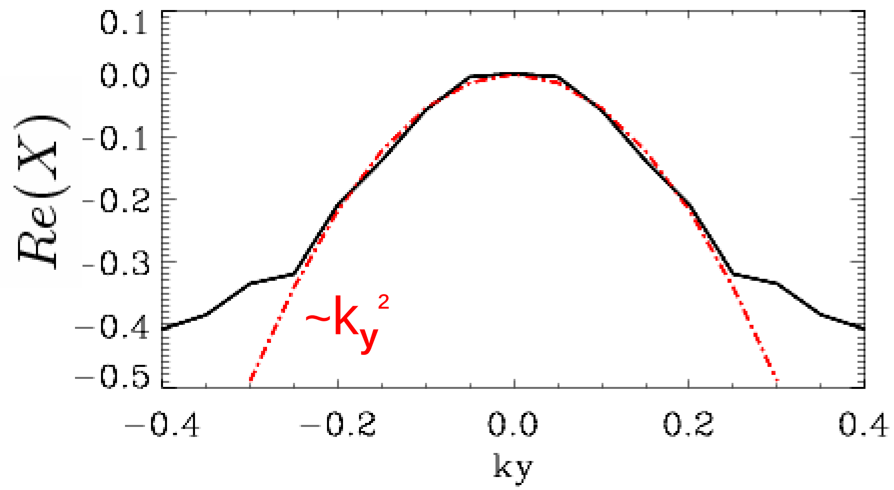


<u>Statistical analysis of NL GENE runs:</u>

- No significant shift of cross phases and frequencies w.r.t. linear ones
- Low ky: nonlinearity ~ eddy diffusion **[Merz & Jenko, PRL 2008]**

$$\mathcal{N}l[g] \simeq D(-k_\perp^2)g = D\nabla_\perp^2 g$$



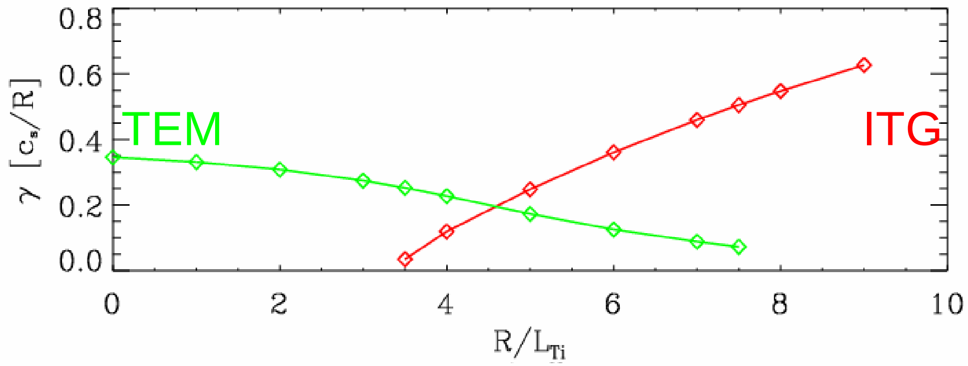


This is in line with various theories, including Resonance Broadening Theory (Dupree), MSR formalism (Krommes), Dressed Test Mode Approach (Itoh).

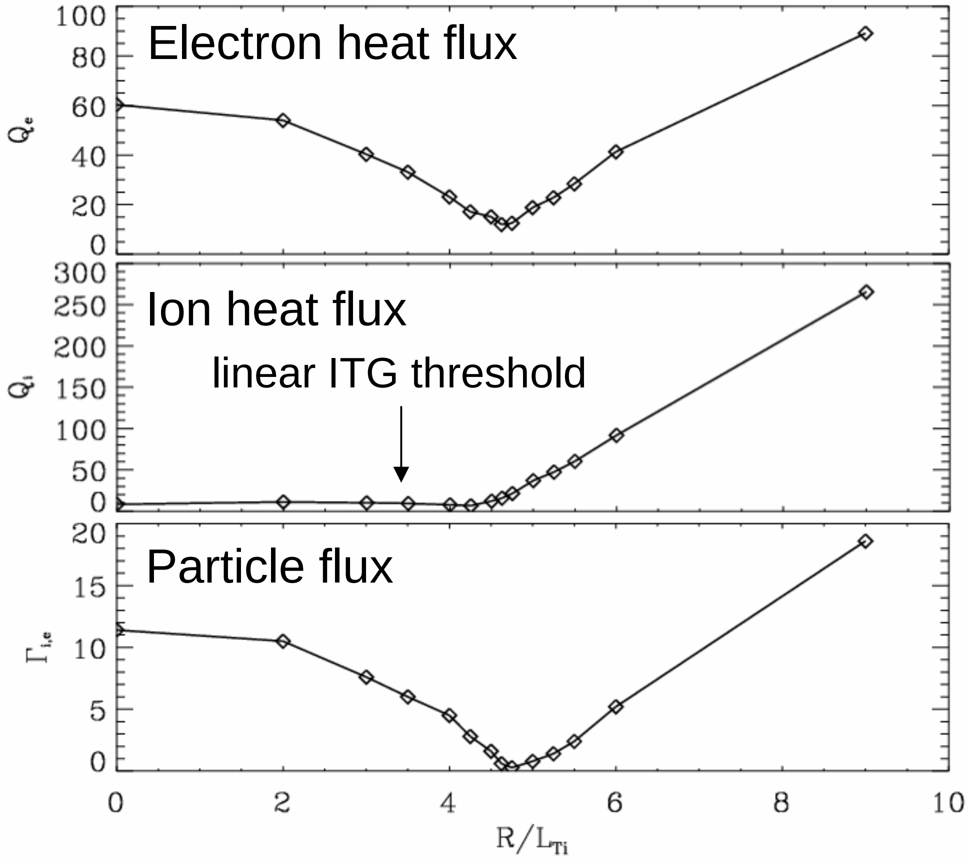
Destructive ITG/TEM interference

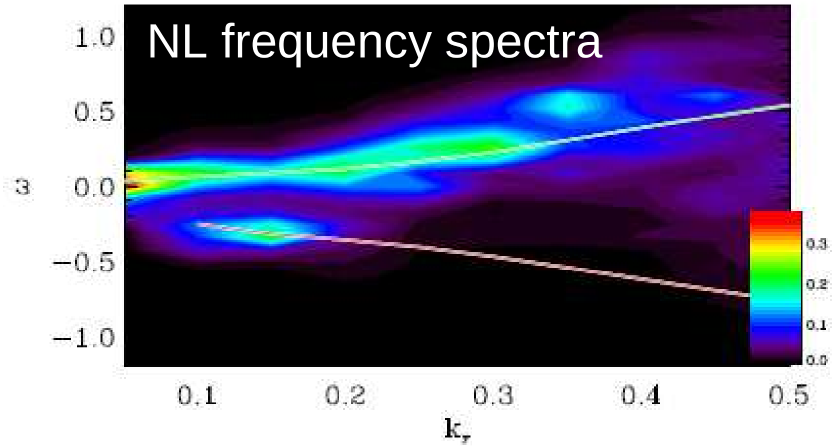
[F. Merz, PhD Thesis 2008]

- Linear growth rates (k_y=0.25), using GENE as an EV solver

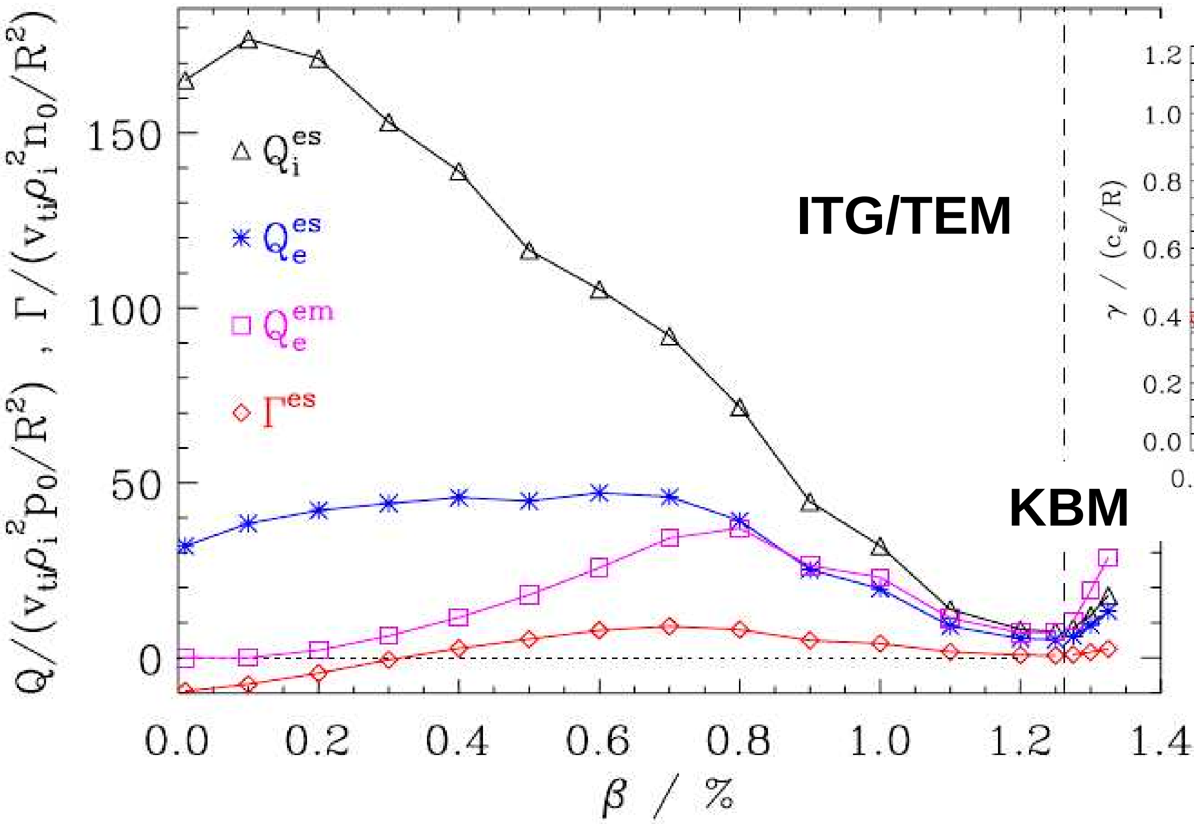


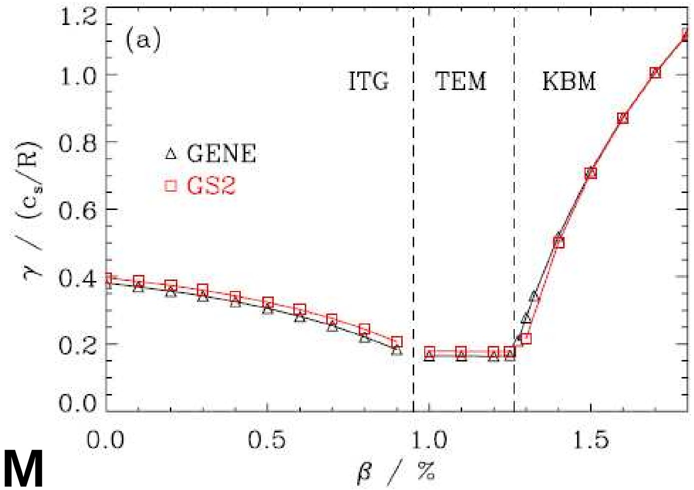
- TEM regime: Electron heat flux is suppressed, not increased
- ITG regime: Nonlinear upshift of critical R/L_{Ti}
- Nonlinear ITG/TEM coexistence





Gyrokinetic turbulence at high beta

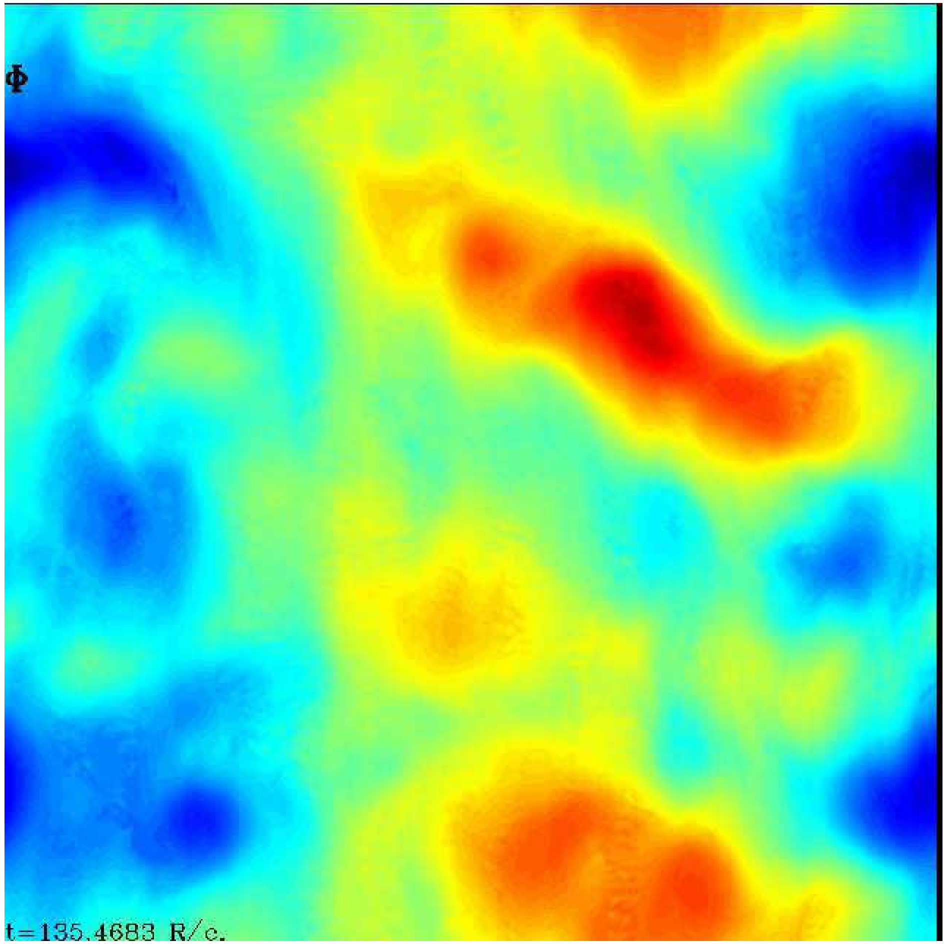


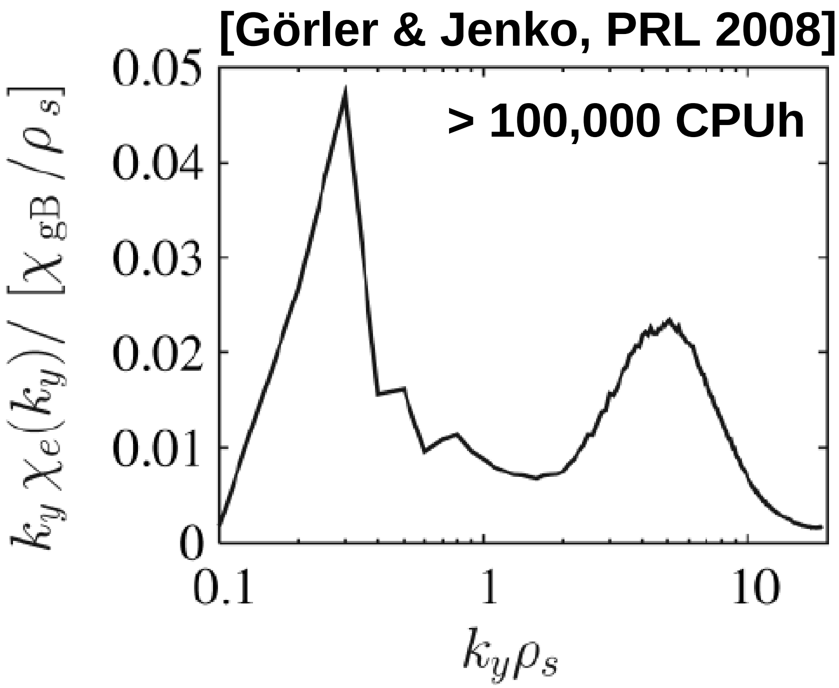


Finite-beta Cyclone Base Case simulations with the GENE code
[Pueschel *et al*., PoP 2008]

Nonlinear drop clearly exceeds (quasi-)linear expectations; this is likely to be due to destructive ITG/TEM interference.

Role of sub-ion-gyroradius scales

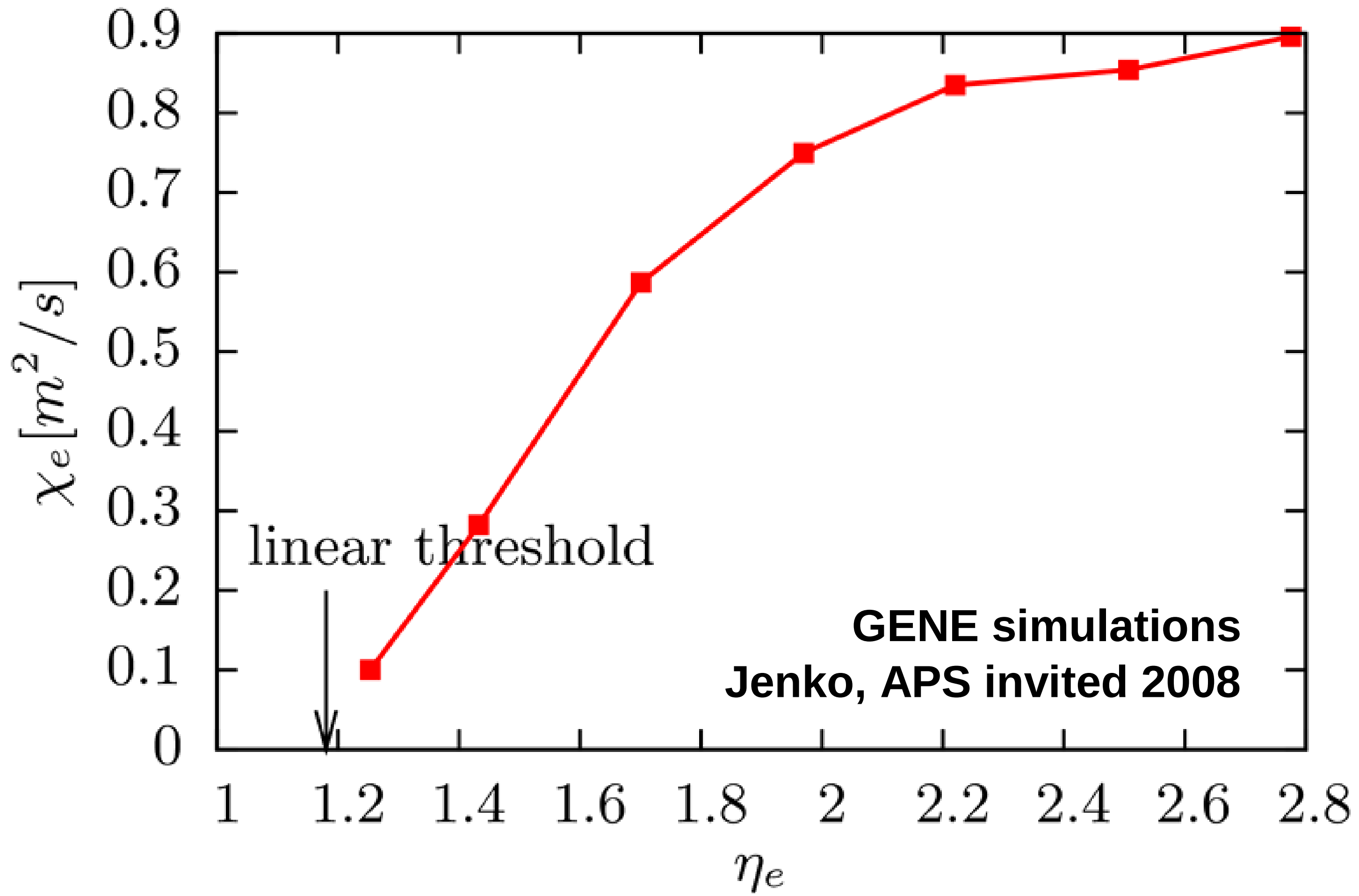




Mazzucato *et al*., PRL 2008
Smith / Yuh, APS invited 2008
Schmitz, APS invited 2008

<u>GENE simulations of ITG/TEM/ETG turbulence</u>: Large fraction of the electron heat transport is carried by the electron scales.

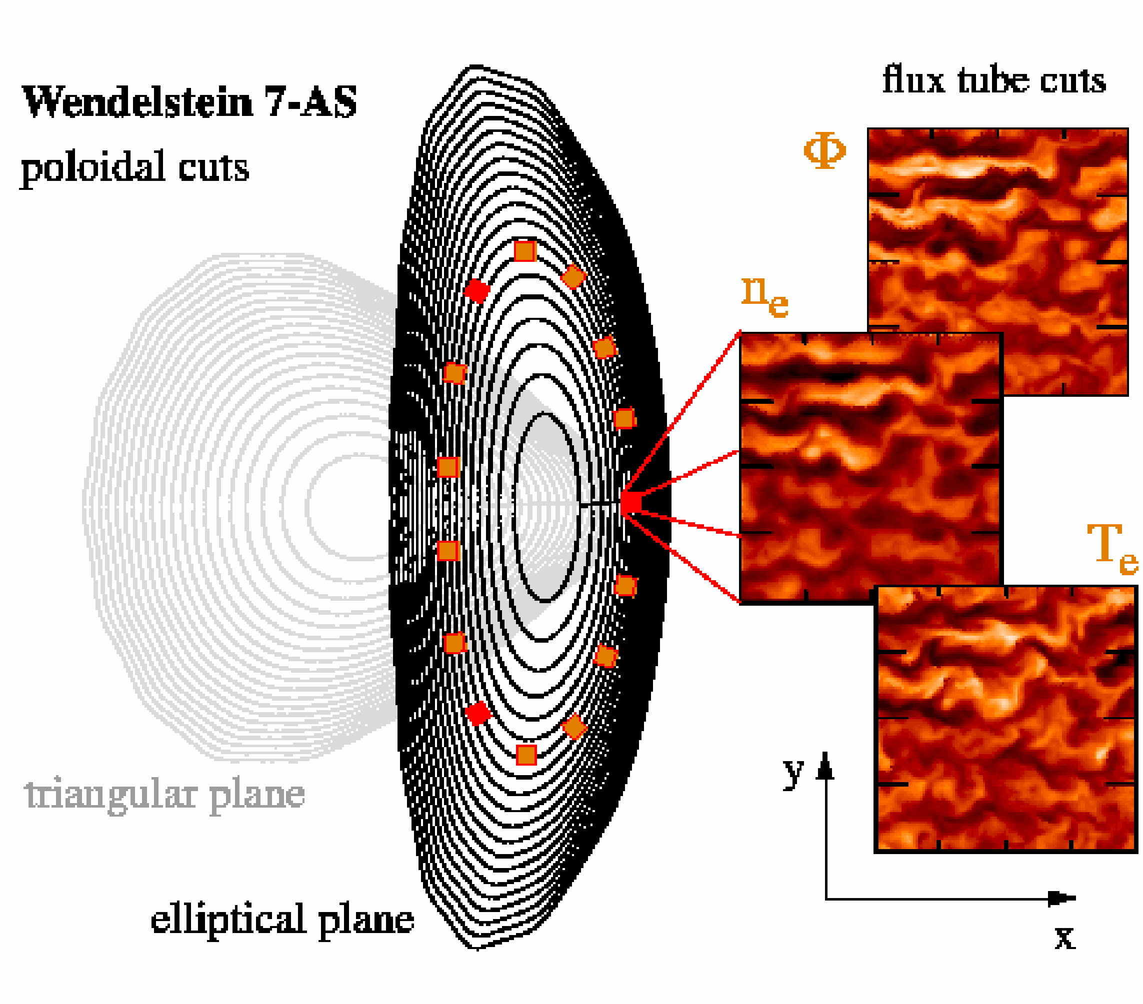
Electron heat diffusivity from edge ETG



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

Stellarator simulations

Gyrokinetic simulations for stellarators



Jenko & Kendl, NJP & PoP 2002

Linear simulations

Rewoldt *et al*. 1999
Kuroda *et al*. 2000
Kendl 2001 & 2004
Jenko & Kendl 2002
Rewoldt *et al*. 2002 & 2005
Lewandowski 2003
Kornilov *et al*. 2004 & 2005
Yamagishi *et al*. 2007
Xanthopoulos & Jenko 2007

Nonlinear simulations

Jenko & Kendl 2002 & 2002
Xanthopoulos *et al*. 2007
Watanabe *et al*. 2007 & 2008

Stellarator-specific issues

- Fairly (physically) comprehensive flux tube simulations in real 3D MHD equilibria are becoming feasible

- Nonlocal codes to be developed; computational cost will be very substantial, however

- Open questions (selection):

1. Similarities and differences w.r.t. tokamak turbulence?
2. Impact of 3D shaping on linear properties of various microinstabilities and their nonlinear saturation mechanisms?
3. Potential for systematic optimization of turbulent transport in stellarators (long-term goal)?

Some recent GKV results on LHD core turbulence

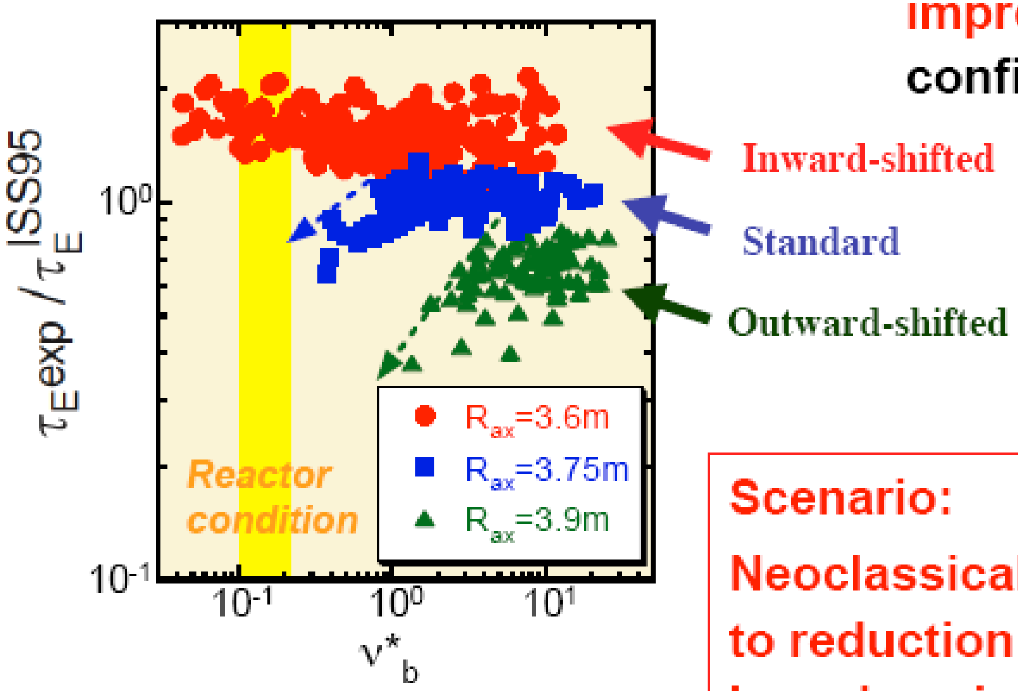
(using non-axisymmetric model equilibria)

Studies by H. Sugama and T. Watanabe

Results from LHD experiments

For low collisionality, better confinement is observed in the inward-shifted magnetic configurations, where lower neoclassical ripple transport but more unfavorable magnetic curvature driving pressure-gradient instabilities are anticipated.

Anomalous transport is also improved in the inward shifted configuration.



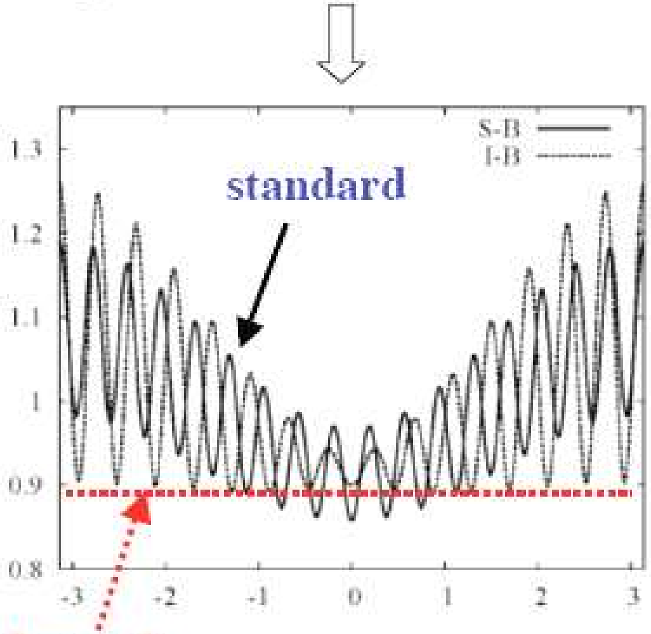
H. Yamada *et al.* (PPCF2001)

Scenario:

Neoclassical optimization contributes to reduction of anomalous transport by enhancing the zonal-flow level.

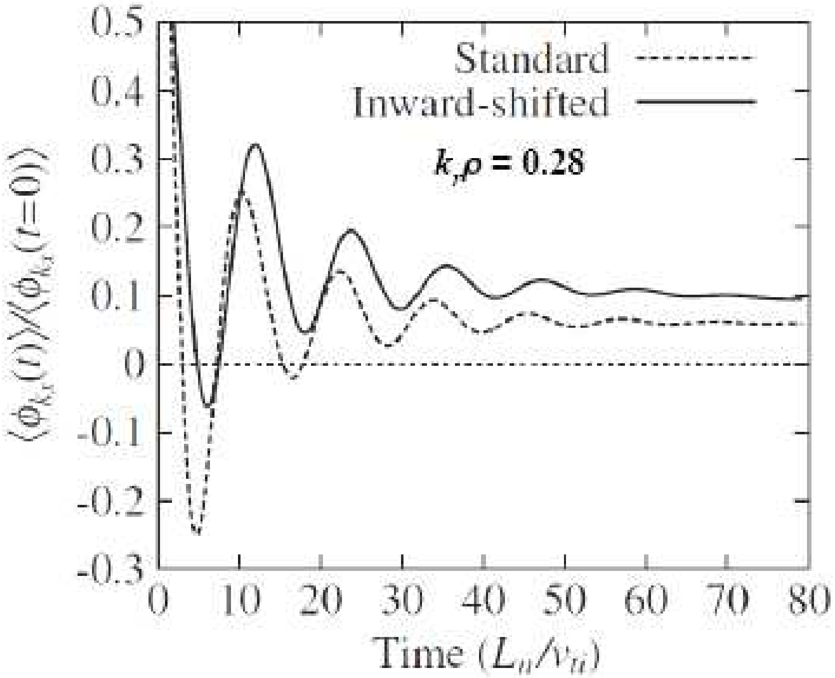
Standard and inward-shifted configurations

|*B*| along the fieldline on the magnetic surface at $r = 0.6\,a$



Inward
⇨ smaller neoclassical transport

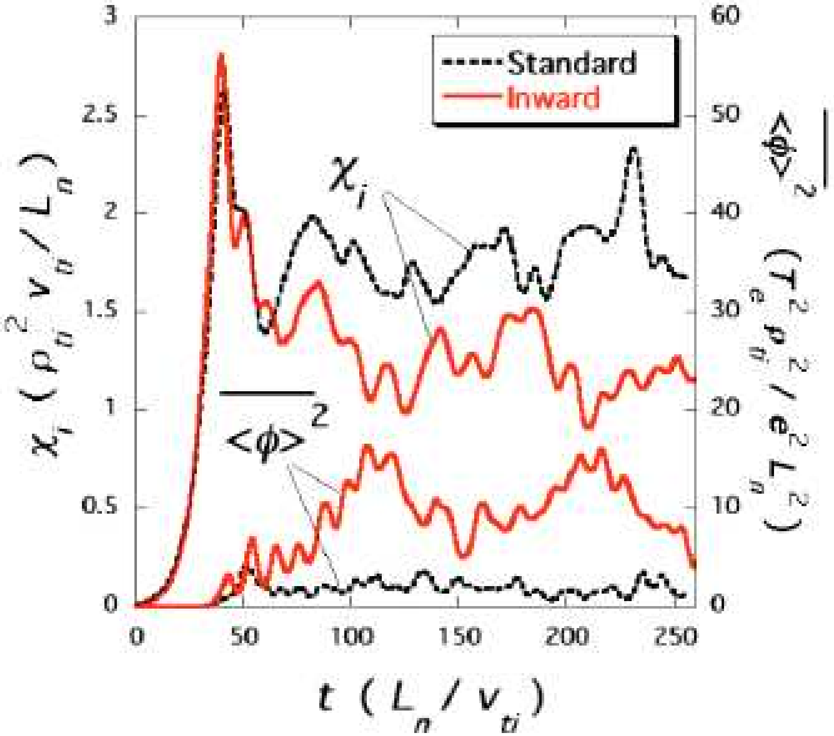
Time evolution of zonal-flow potential



Larger residual zonal flow is found for the inward-shifted case.

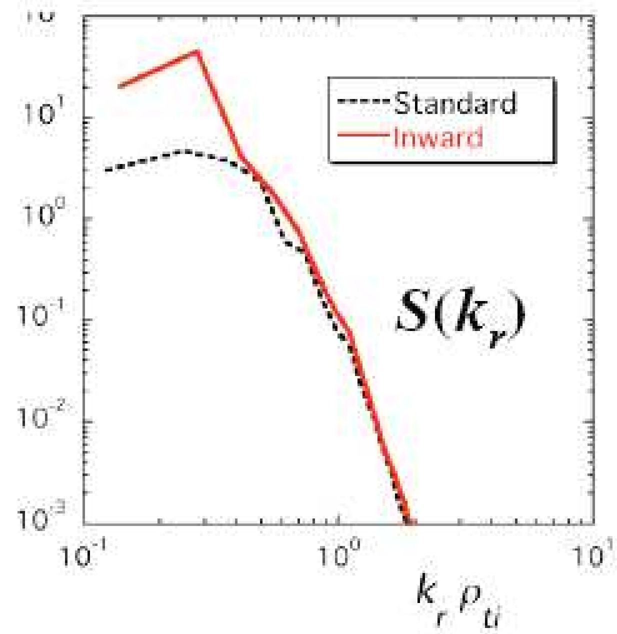
Adiabatic ITG turbulence simulations

Smaller χ_i and larger zonal flows are found in the saturated turbulent state for the inward-shifted configuration than for the standard one !



Turbulent thermal diffusivity and squared zonal-flow potential

$$\overline{\langle\phi\rangle^2} = \int_0^\infty S(k_r)dk_r$$

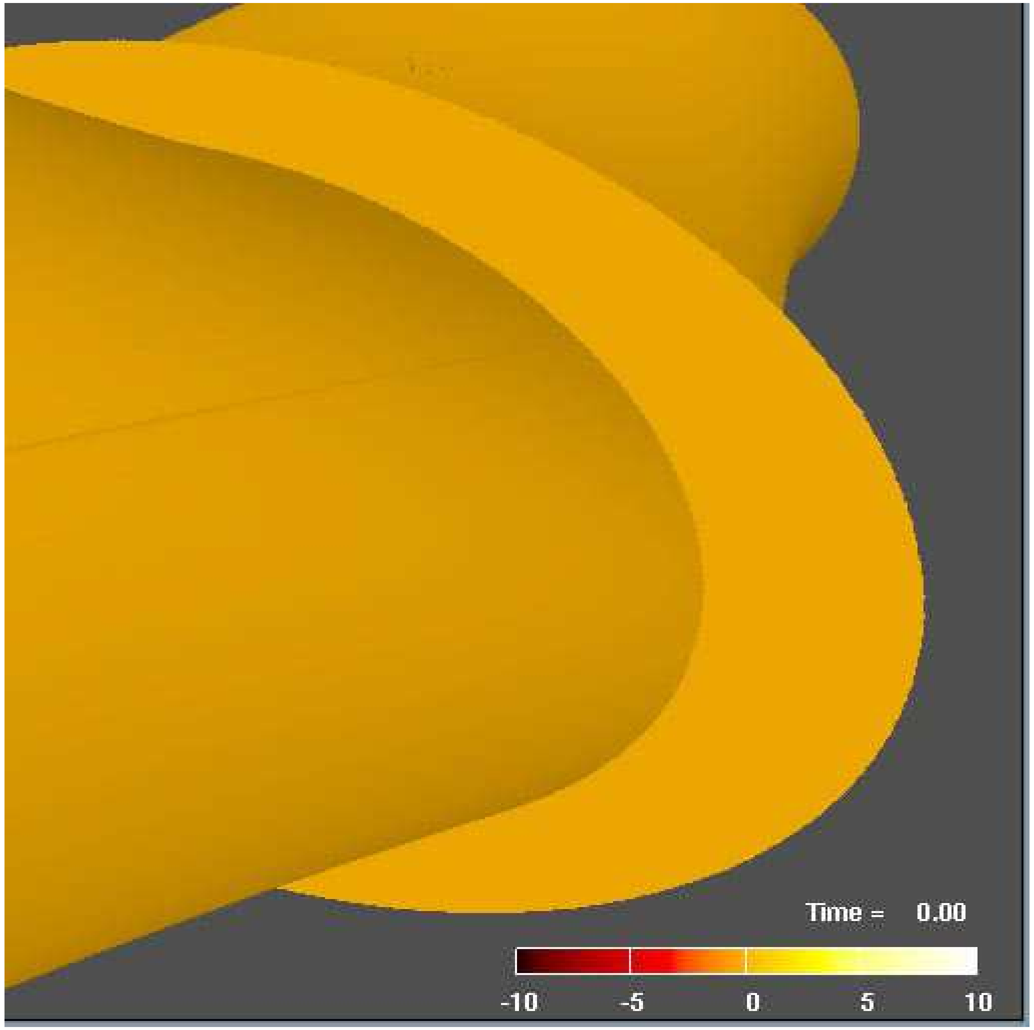


k_r spectrum of zonal-flow potential (averaged over $60 < t < 250$)

Watanabe, Sugama & Ferrando, PRL(2008), Sugama, Watanabe & Ferrando, PFR(2008)

Zonal flow dynamics in ITG-ae simulations

Contours of potential fluctuations (Inward-Shifted Case)



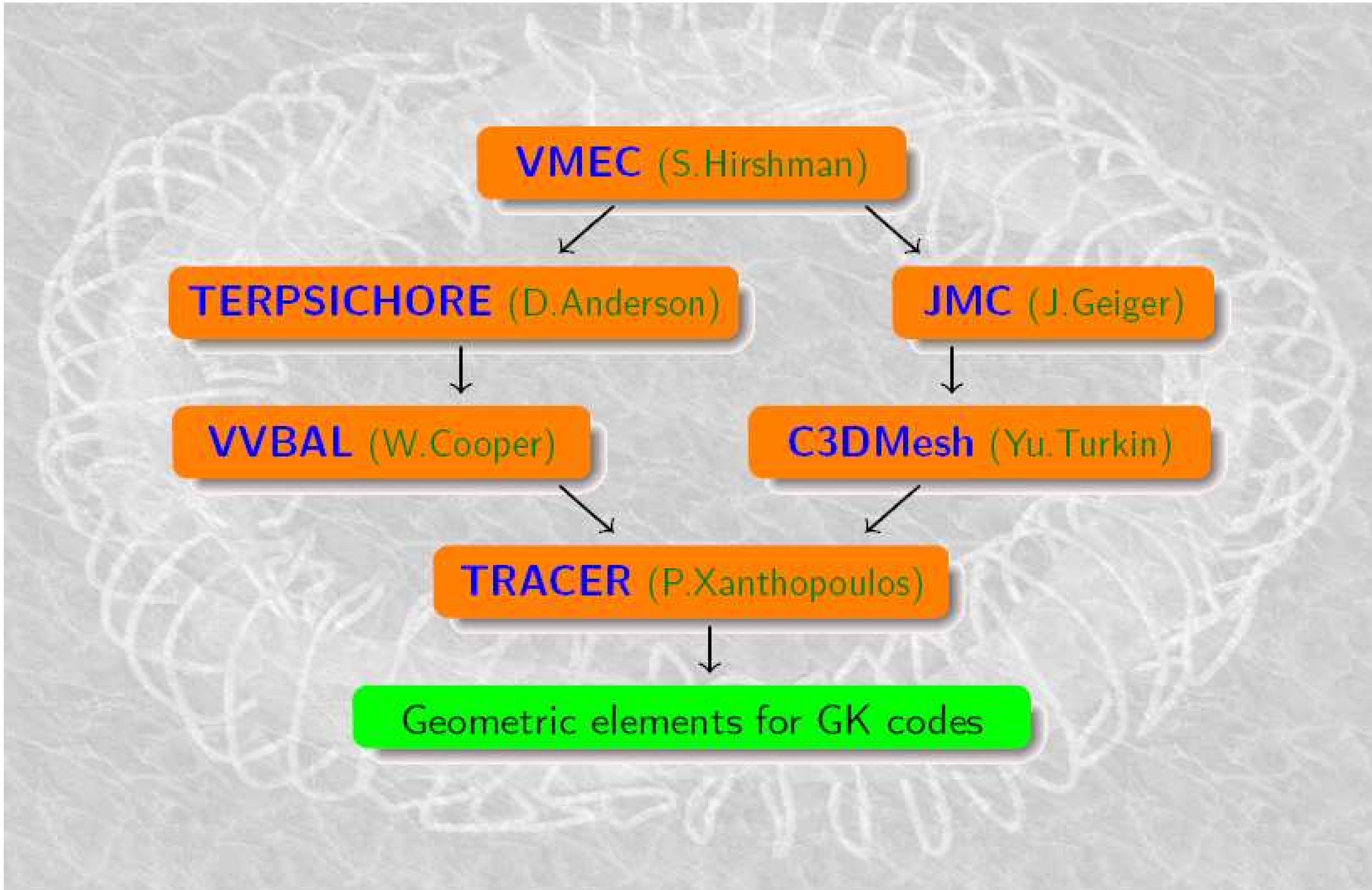
Sugama, APS invited 2008

Some recent GENE results on NCSX and W7-X core turbulence

(using real non-axisymmetric equilibria)

Geometry Interface for Stellarators/Tokamaks

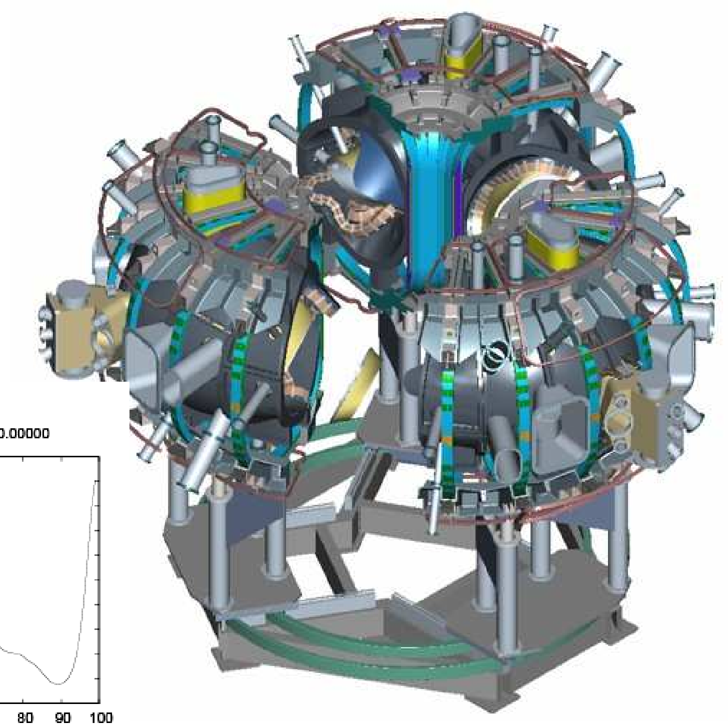
Author: P. Xanthopoulos (thanks to W. A. Cooper)
Goal: Local simulations for non-axisymmetric devices

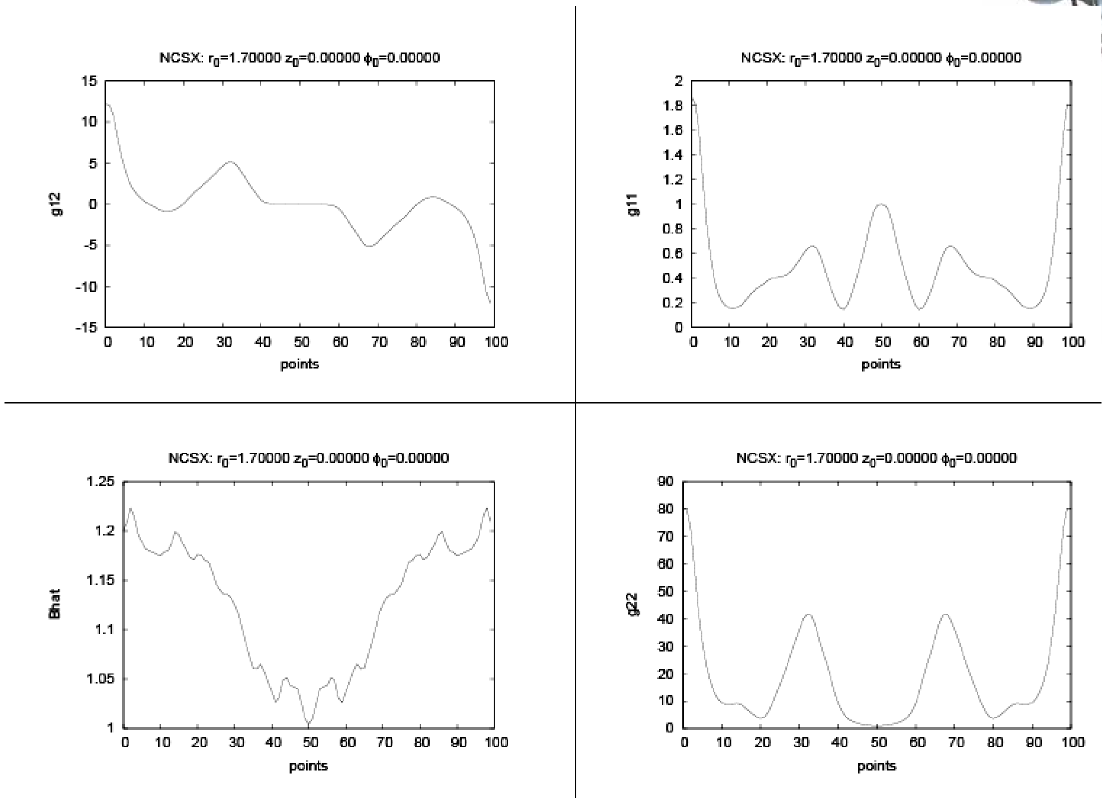


First example:

NCSX

Geometric coefficients for NCSX

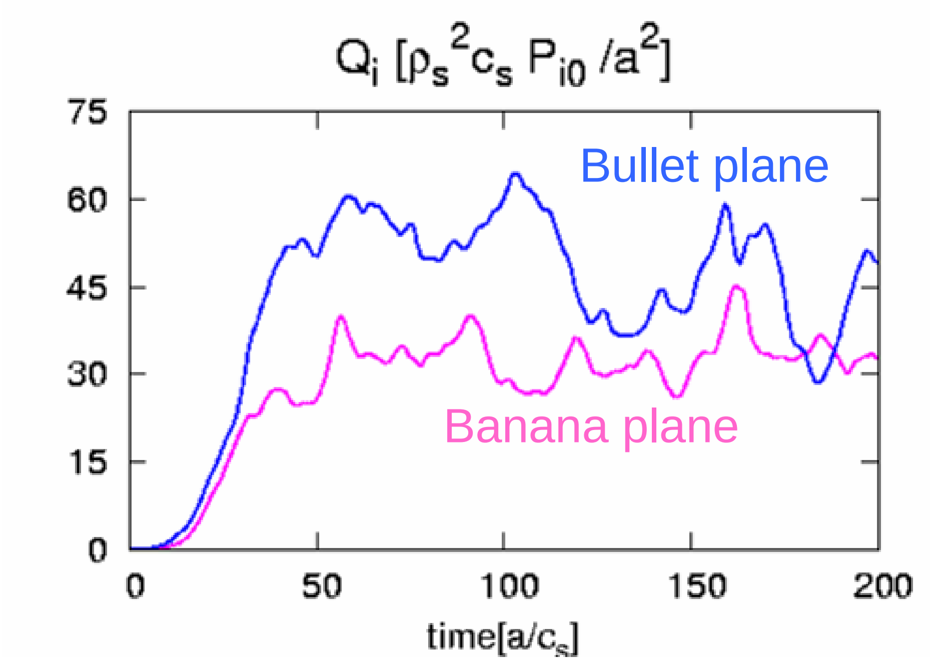


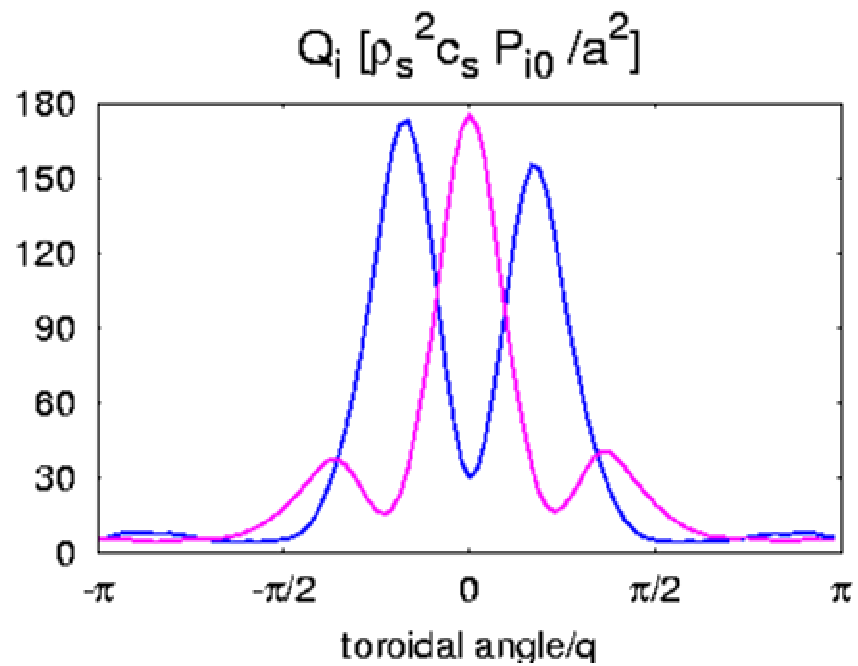


[Xanthopoulos & Jenko, PoP 2006]

Adiabatic ITG turbulence in NSCX

Two different flux tubes on the same magnetic surface:
The turbulent transport differs by a few 10%;
moreover, the parallel mode structures differ.

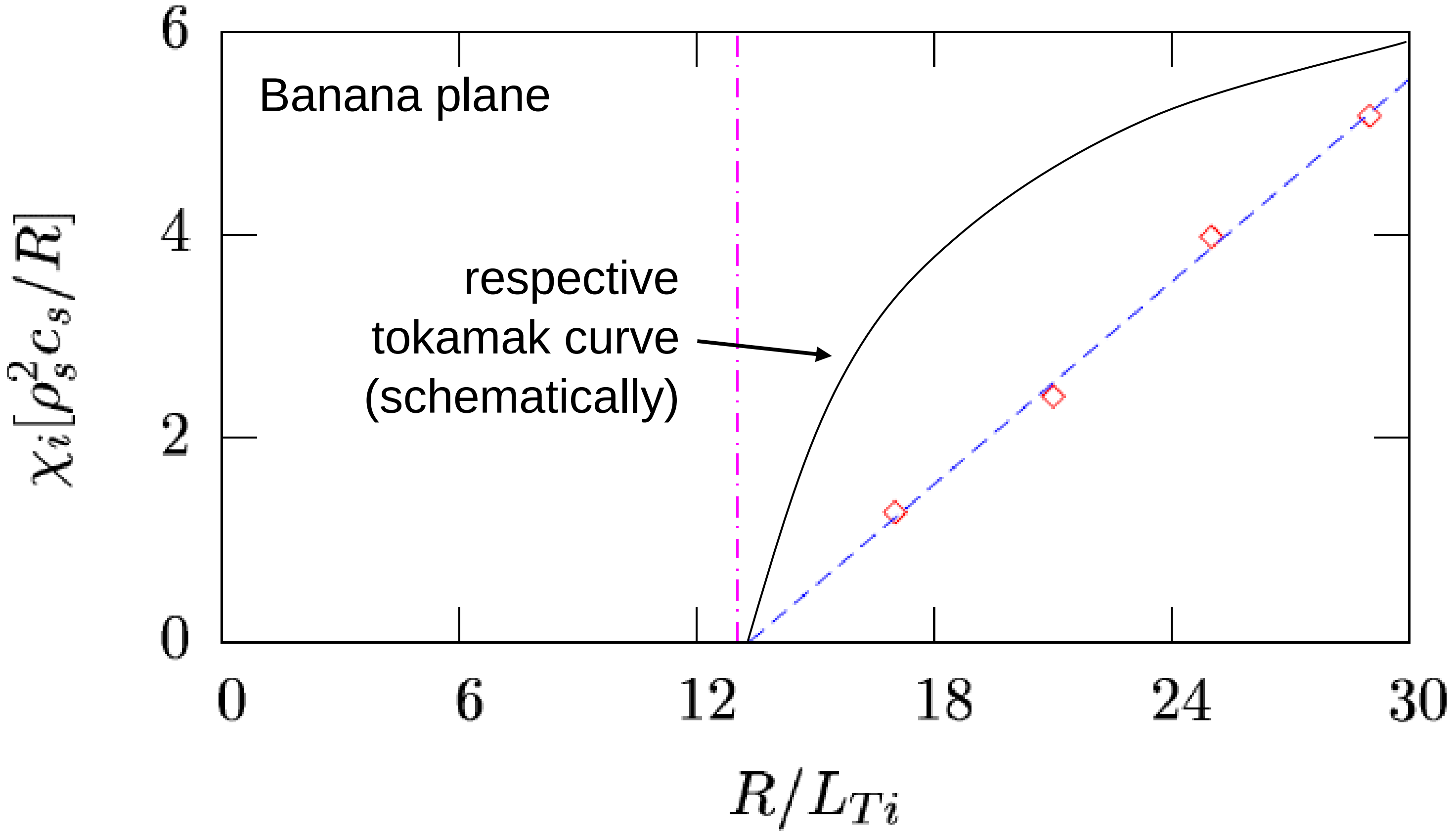




Critical gradients also differ; softening of turbulence onset!

Flux-gradient relationship (adiabatic ITG modes)

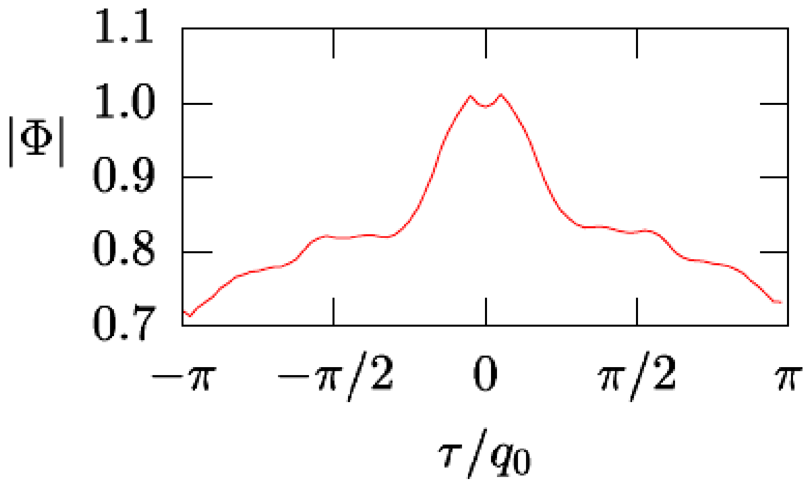
- Offset-linear scaling for χ – not Q
- **Moderate profile stiffness**

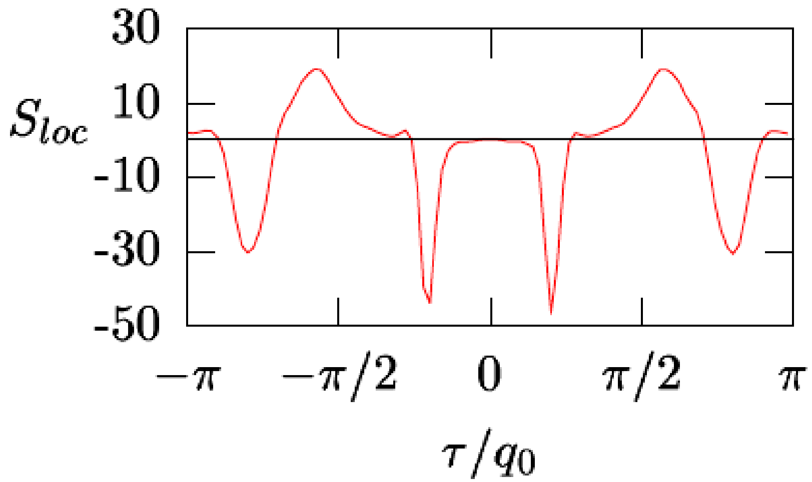


Parallel mode structure and linear threshold

NCSX exhibits strong ballooning controlled by localized bad curvature and local shear.

Example (*nonlinear* GENE simulation):





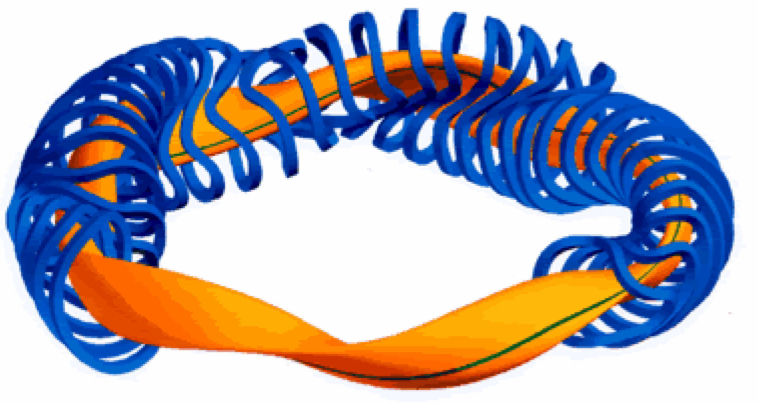
Linear thresholds of NCSX, W7-X, AUG, DIII-D are similar, but they can be increased by increasing the effective $k_\parallel$

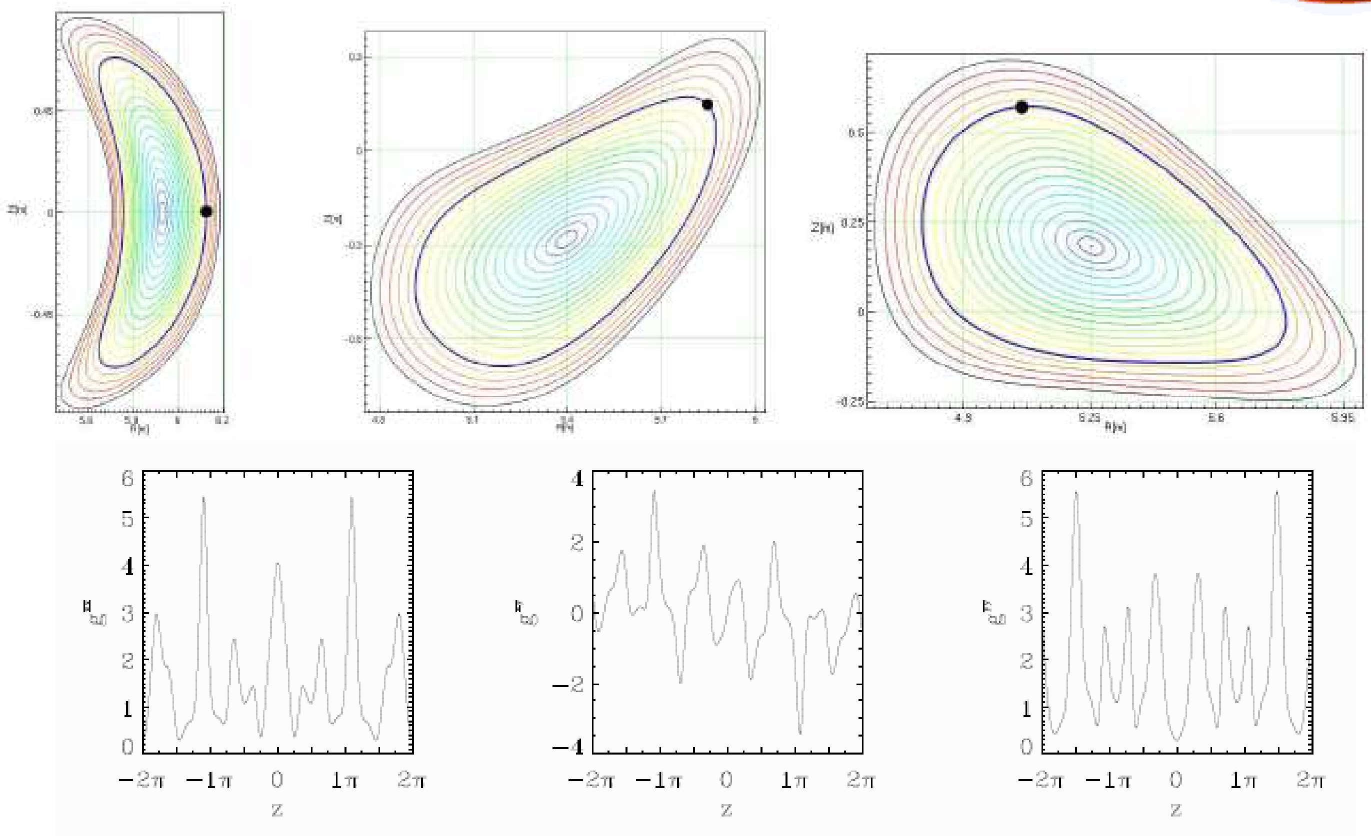
Second example:

Wendelstein 7-X

Geometric coefficients for W7-X

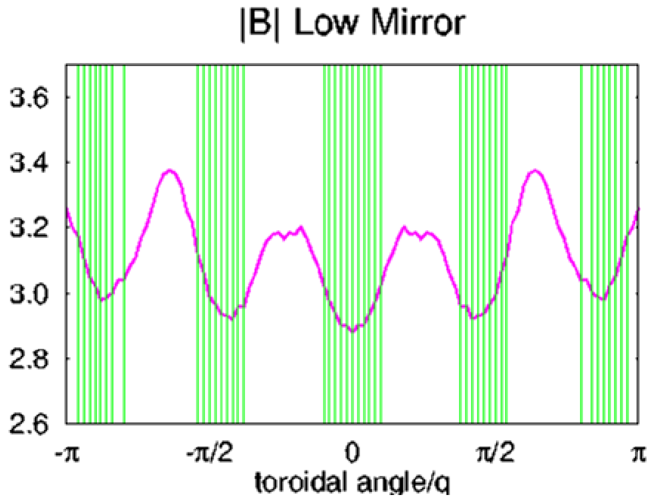
Wendelstein 7-X stellarator: optimized with respect to neoclassical transport



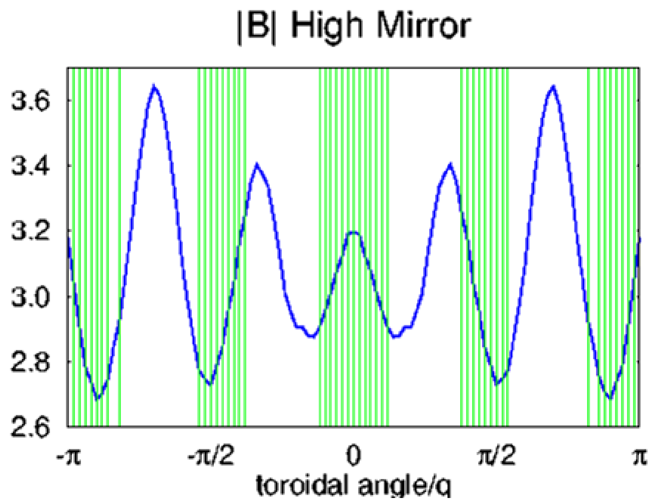


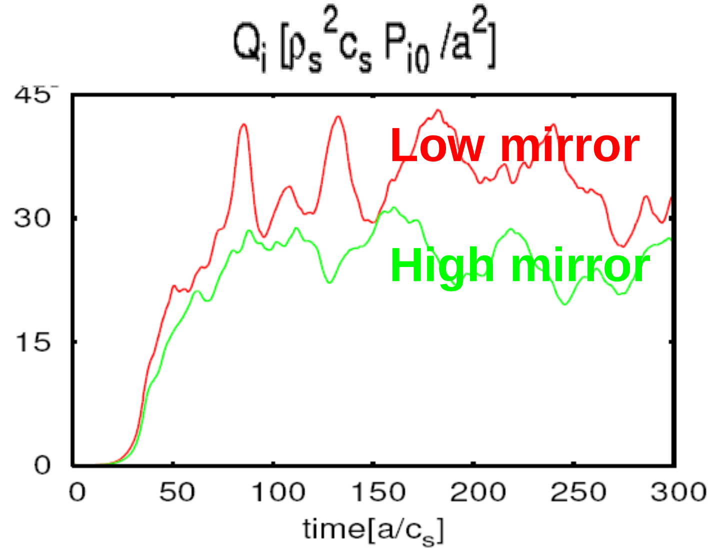
[Xanthopoulos & Jenko, PoP 2006]

ITG-ae turbulence: Subtle geometric effects



Bad curvature regions





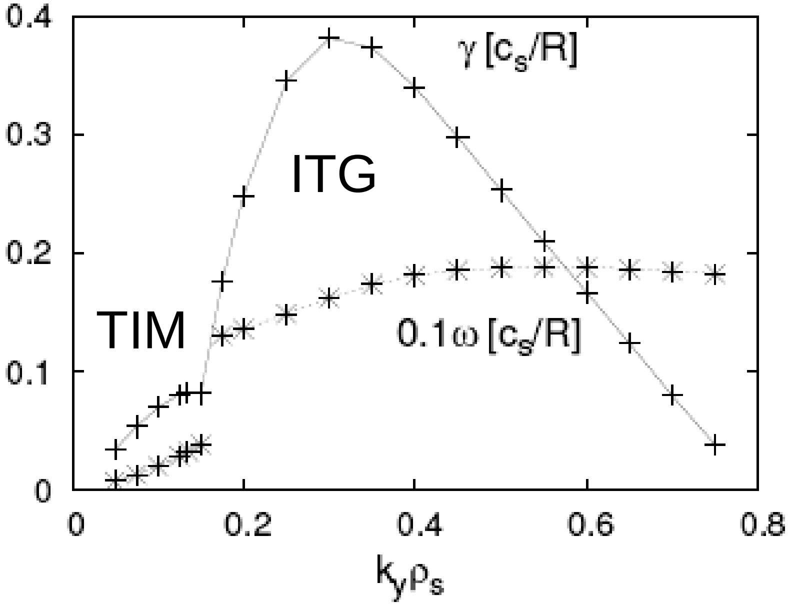
Two configurations which are geometrically virtually identical yield clearly differing results – although the <u>linear physics is almost the same</u>; there must be <u>geometric control of the NL saturation mechanism</u>

Nonlinear ITG/TIM coexistence

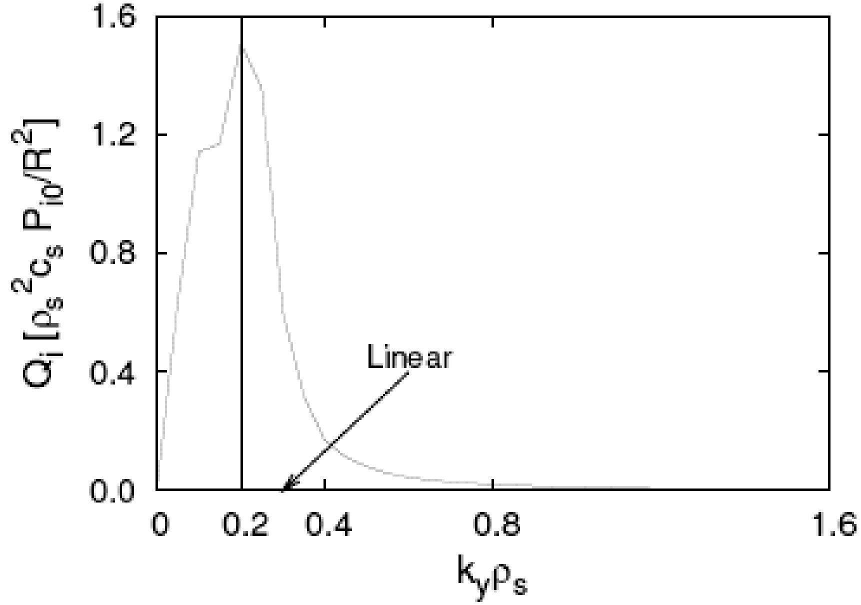
IPP

GENE simulations for W7-X (close to the magnetic axis; adiabatic electrons):
Trapped ion modes and ITG modes coexist linearly and nonlinearly.

Linear growth rate spectrum



Nonlinear transport spectrum

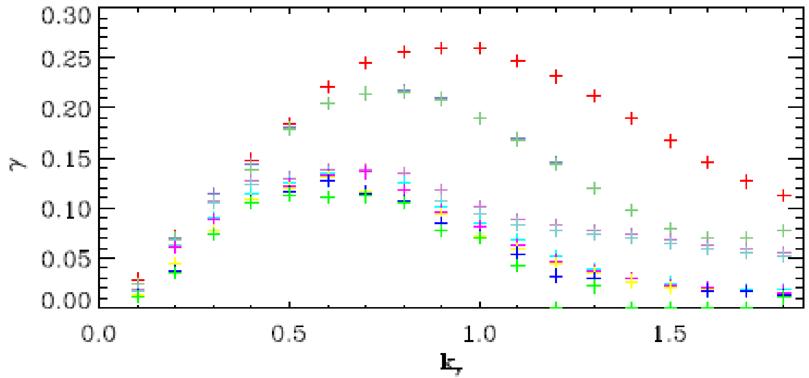


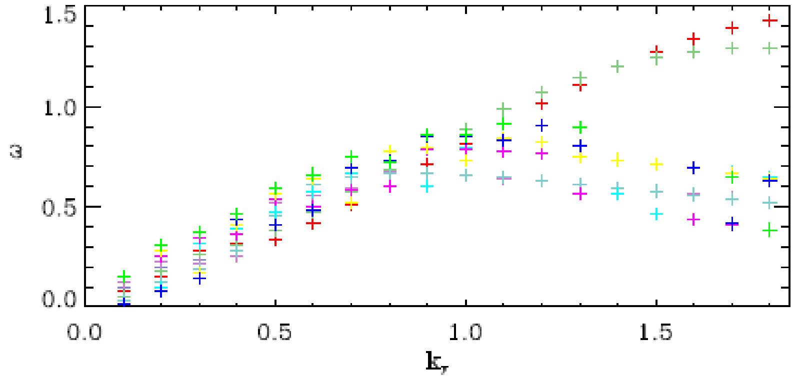
[Xanthopoulos, Merz, Görler & Jenko, PRL 2007]

Destructive interference phenomena?

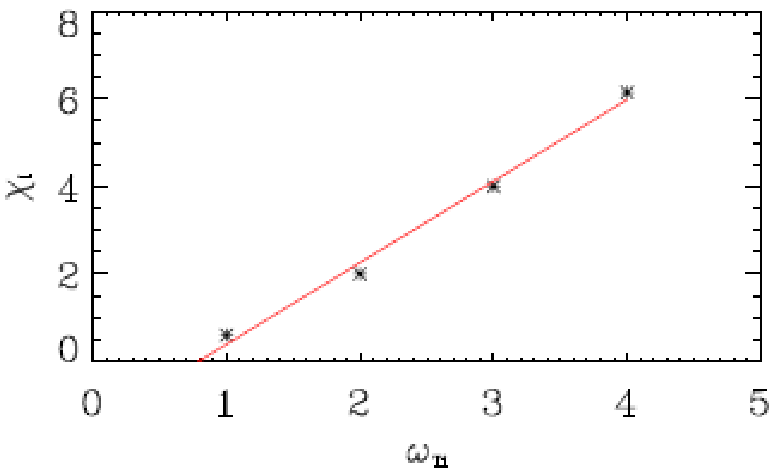
ITG turbulence in W7-X (adiabatic electrons)

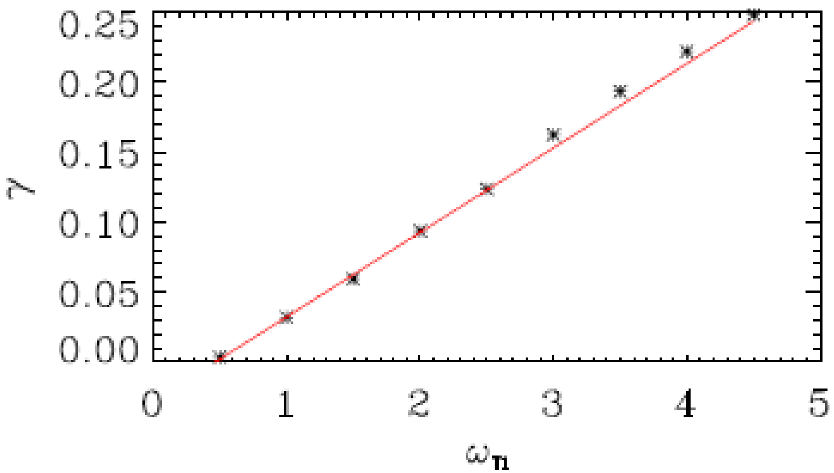
Many modes are unstable, with similar growth rates.





Nonlinear runs exhibit strong ZF activity, 35% Dimits shift.

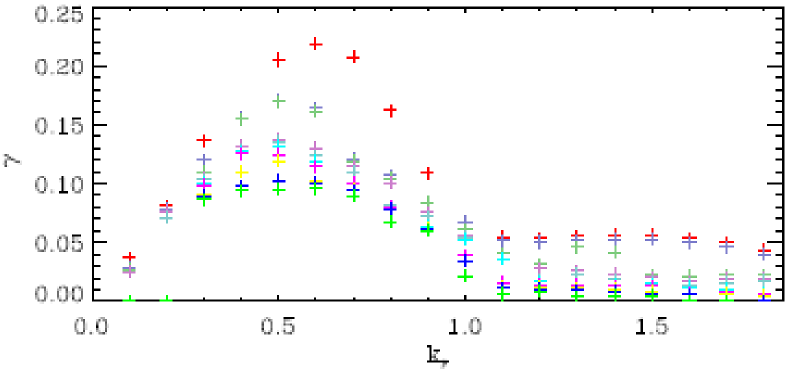


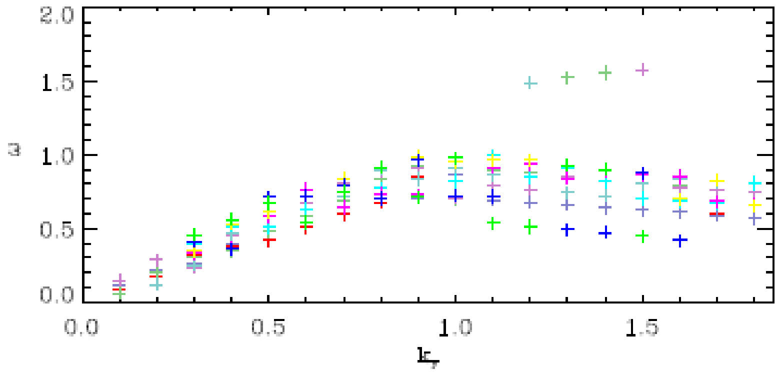


[F. Merz, PhD Thesis 2008]

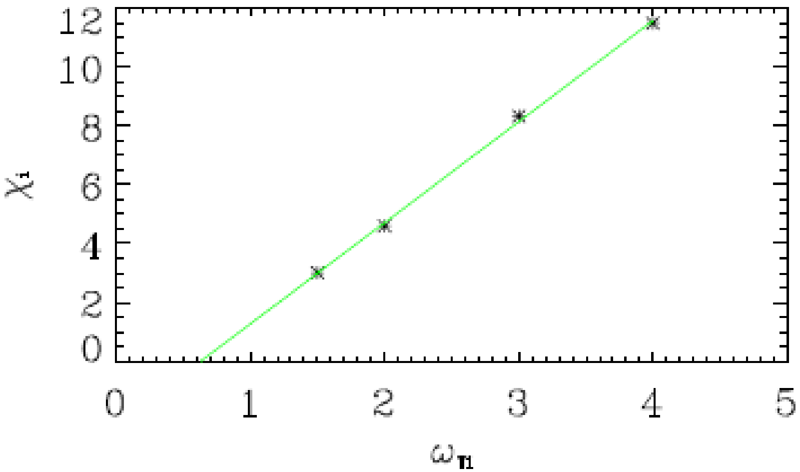
ITG turbulence in W7-X (kinetic electrons)

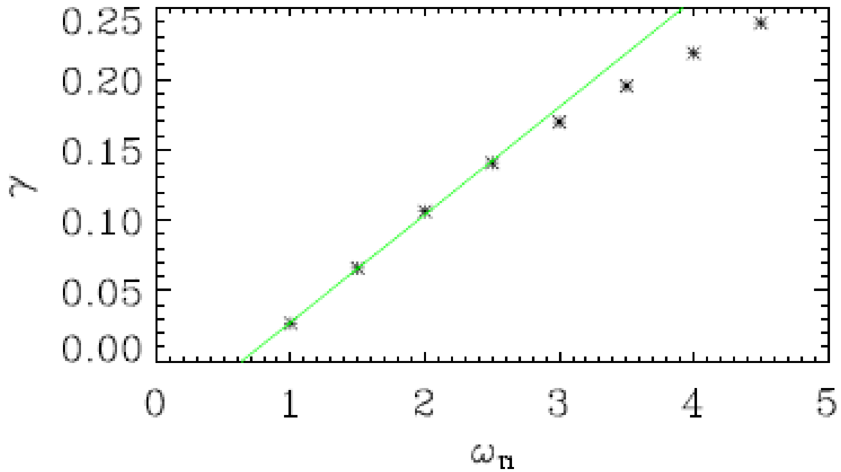
Many modes are unstable, with similar growth rates.





Nonlinear runs exhibit weak ZF activity, no Dimits shift.

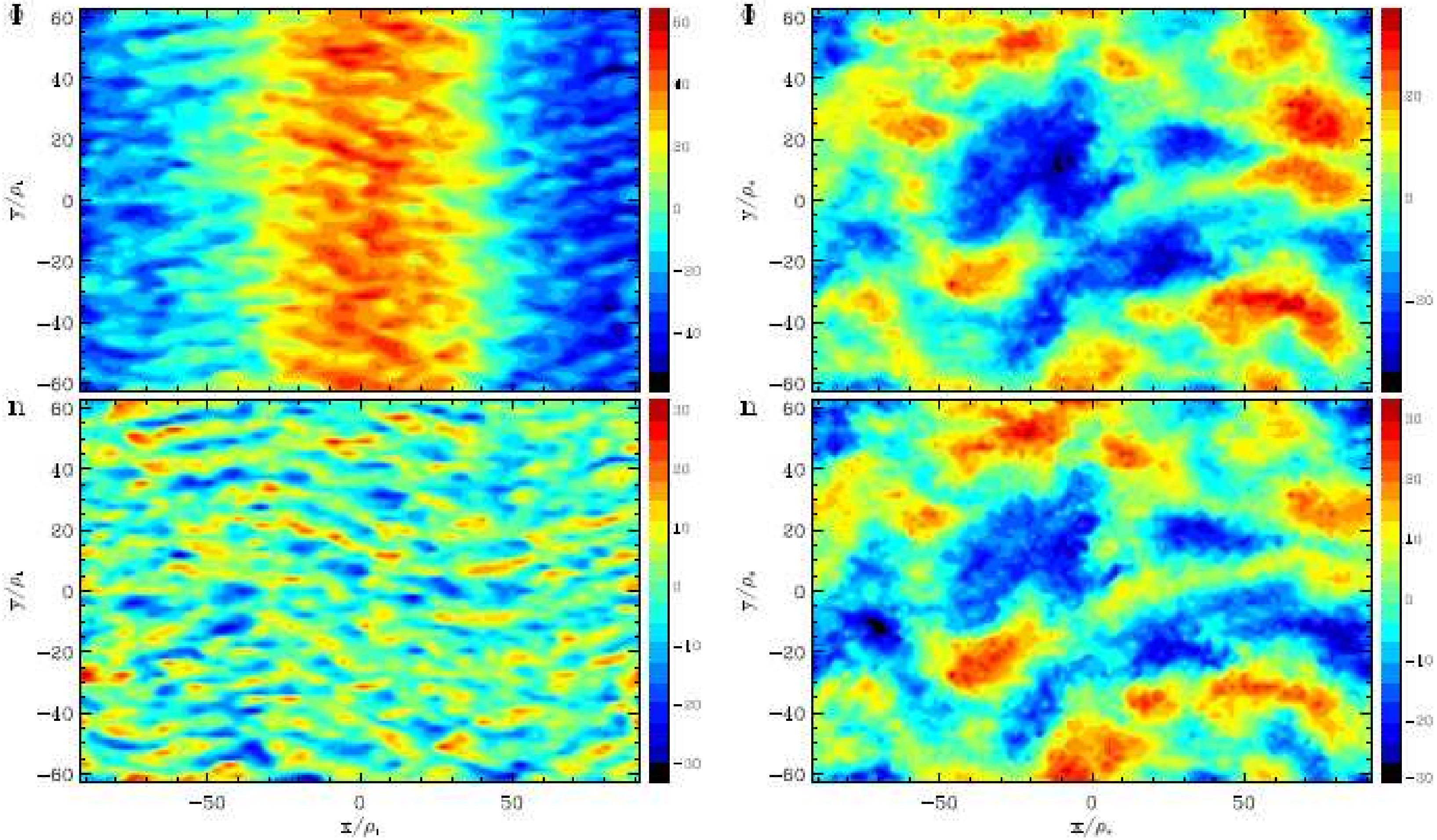




[F. Merz, PhD Thesis 2008]

ITG turbulence in W7-X: Role of zonal flows

Adiabatic electrons **Kinetic elec**

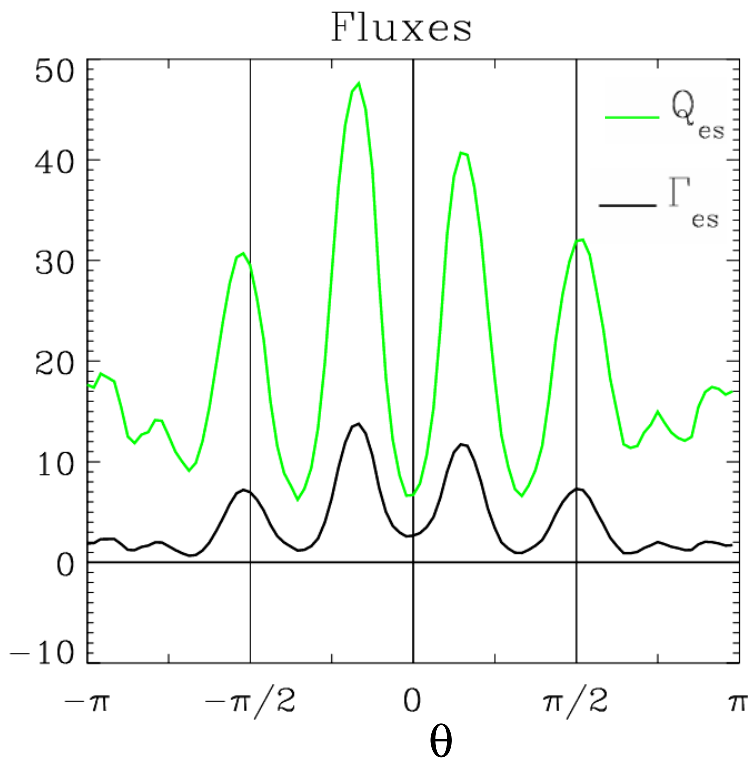


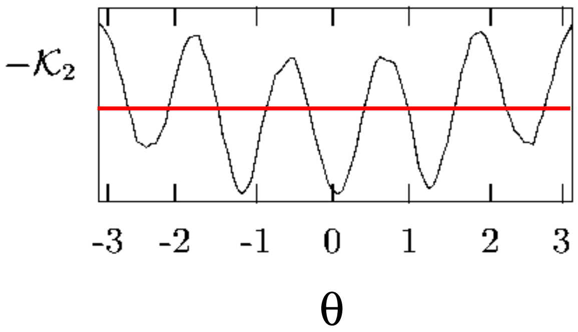
[F. Merz, PhD Thesis 2008]

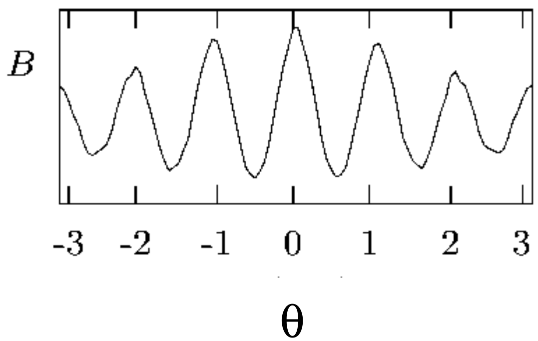
Like in tokamaks, kinetic electrons reduce the impact of zonal flows.

Properties of TEM turbulence in W7-X

- Parallel stucture: Transport reflects the structure of the magnetic wells
- Regions where bad curvature and magnetic wells overlap dominate transport







- Side remark: Nonlinear and linear mode structure are quite similar; zonal flows are weak
- Potential for turbulence control

Conclusions

<u>Gyrokinetic simulations for stellarators:</u>

- Comprehensive (local) gyrokinetic turbulence simulations are becoming feasible; nonlocal codes to be developed

- In principle, 3D shaping allows for fine-tuning:
  - linear drive of microinstabilities
  - nonlinear saturation (e.g., zonal flow physics)
  - destructive interference

  These changes affect critical gradients and turbulence onset

- Potential for systematic optimization of turbulent transport needs to be explored in more detail in the future