Features and perspectives of gyrokinetic turbulence in stellarators

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Contributions & Acknowledgments

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[Experiment] J. Alcuson, A. Dinklage, G. Fuchert, O. Grulke, N. Pablant

[Discussions] C. Beidler, J. Geiger, H. Maassberg, A. Mollen, H. Smith

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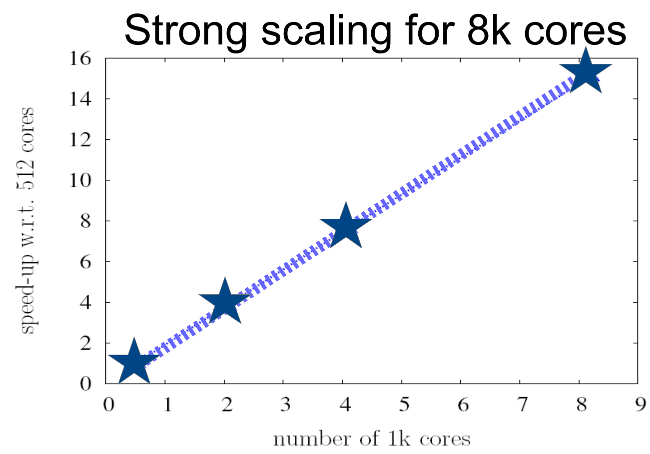
Outline

- **Where we stand & where to go**
- **Features of stellarator turbulence**
- **Turbulence optimization & control**
- **Applications to W7-X experiment**

Numerical tools @ IPP Garching & Greifswald

- **GENE: Gyrokinetic Electromagnetic Numerical Experiment**
  - Solves 5D NL system of GK equations
  - Runs on Hydra, NERSC, Marconi etc.
  - Open source www.genecode.org



- **GIST: Geometry Interface for Stellarators and Tokamaks**
  - Processes VMEC (or EFIT) equilibria, calculates geometry

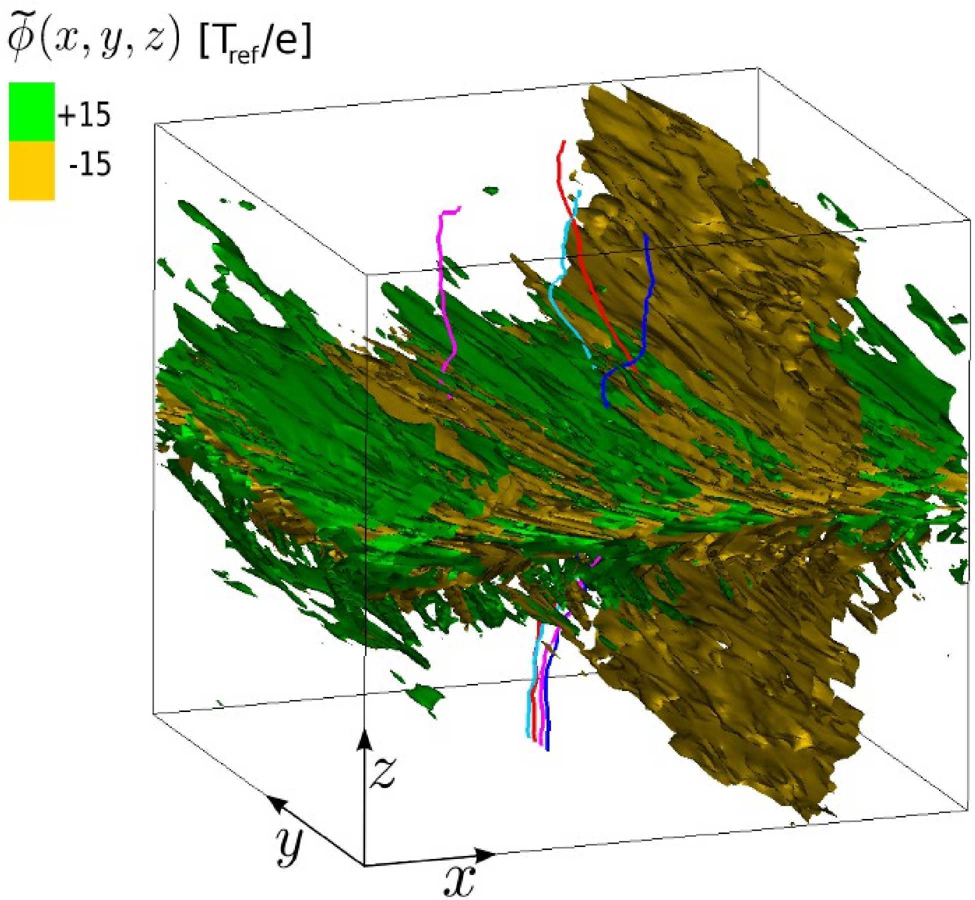
- **Visualization tools** (OpenGL, VisIt, Paraview)

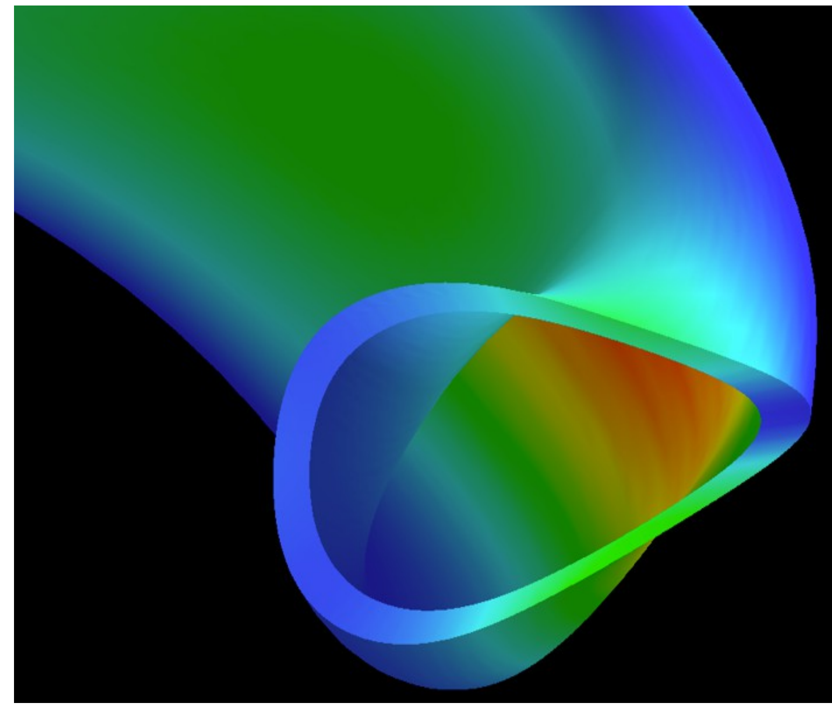
Lagrangian representation of turbulent flow fields

$$\dot{\mathbf{r}} = \mathbf{v}_{\mathrm{E\times B}} + v_\parallel \frac{\mathbf{B}}{B} = -\frac{\nabla\tilde{\phi}\times\mathbf{B}}{B^2} + v_\parallel\frac{\mathbf{B}}{B}$$

“boxed stellarator”

Apply result on W7-X geometry

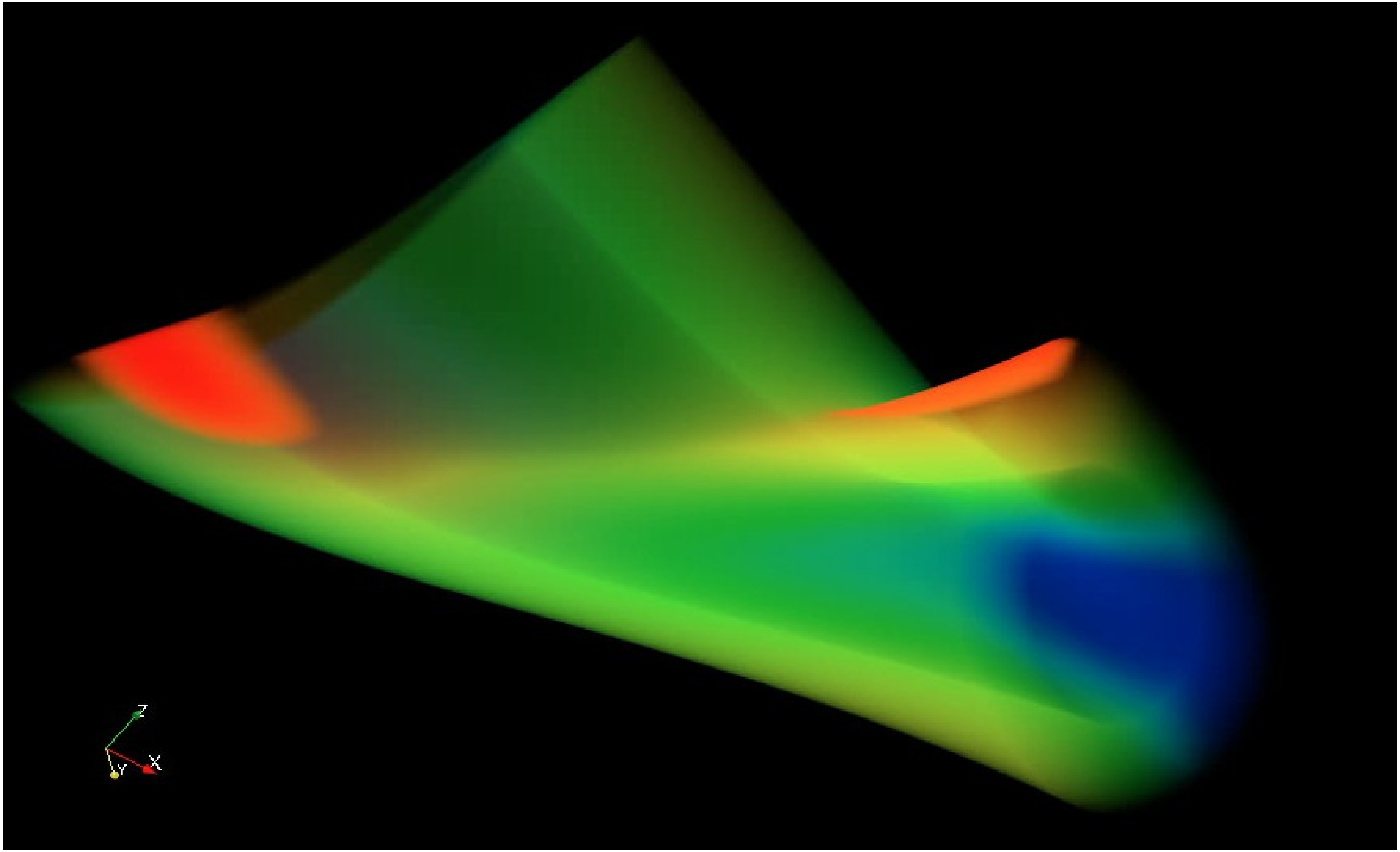




Alcuson et al., Phys. Plasmas 23, 102308 (2016)

Volume rendering* for global 3D GENE (OpenGL/Paraview)

*Artificial data. Gyrokinetics are expected from underway PhD project (Maurer et al.)



Operational status of GENE in 3D geometry

- **GENE treats the nonlinear GK system on a grid either**

  - **Local: flux tube geometry around a single field line**

or

  - **Surface-global: on a radially localized flux surface**

- **We address the following types of micro-turbulence:**

  - **Ion-Temperature-Gradient** (well understood)
  - **Trapped-Electron-Mode** (well understood)
  - **Kinetic-Ballooning-Mode** (ongoing PhD work)
  - **Electron-Temperature-Gradient** (recent results)

Gyrokinetic theory

- Perhaps the most elegant theory in plasma physics cast as **field theory**

- Dynamical system lives on tangent bundle TM (q^a, v^a) of a manifold M. The Lagrangian is expressed by a **1-form ω**

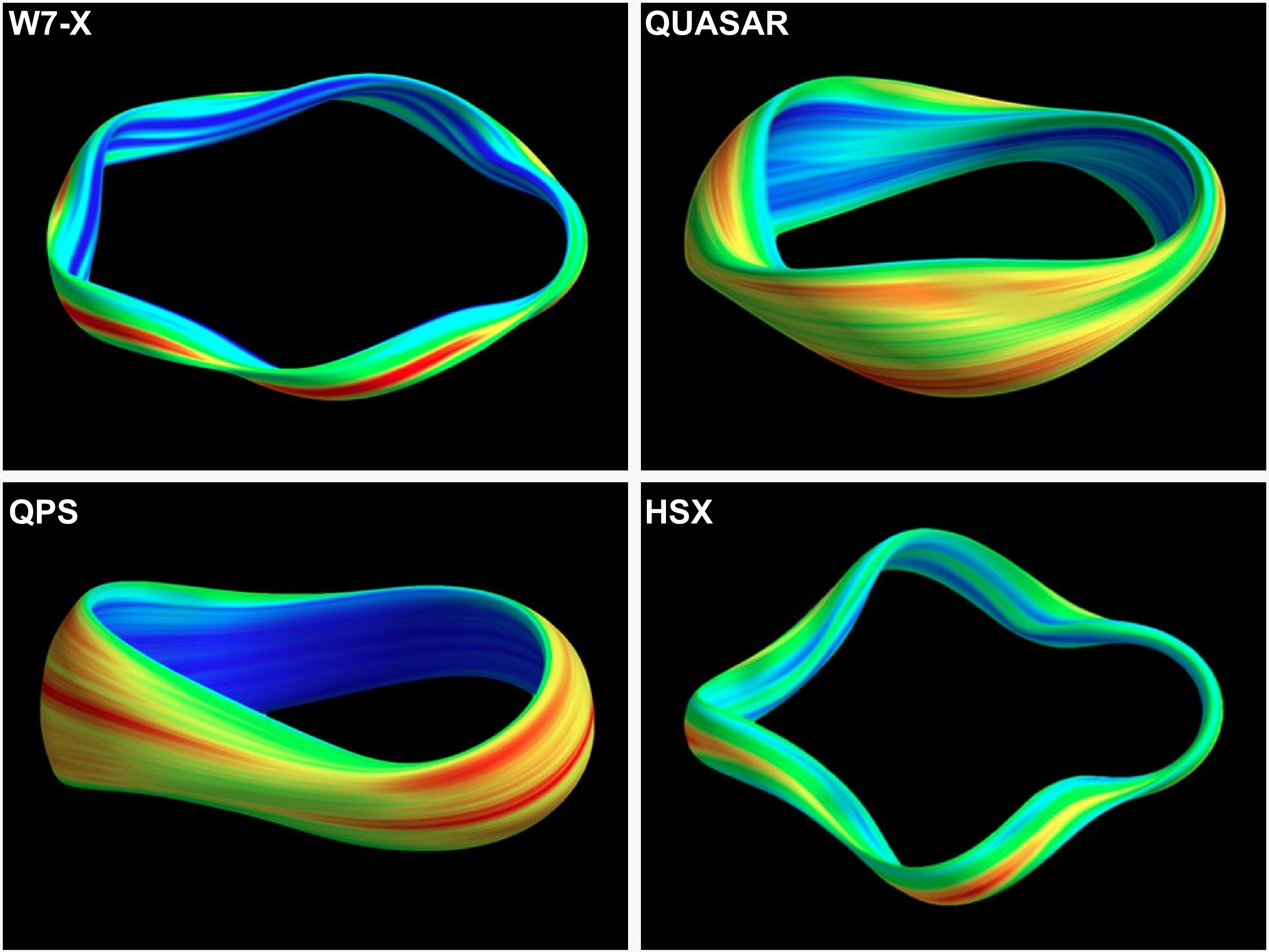
- An **invertible** (no loss of information) transformation is needed between positions (distribution function) and gyrocenters (perturbed fields)

- Find vector field G such that Lie derivative $\mathbf{L_G \omega}$ is free of fast gyration

- Perturbations: Exploit **small parameter** $\varepsilon=\rho/L$ to solve for each order

- "Pull back" the gyrocenter distribution in **Vlasov** equation (continuity) in particle coordinates to use in **Maxwell's** equations

Peta-scale ITG turbulence simulations in stellarators

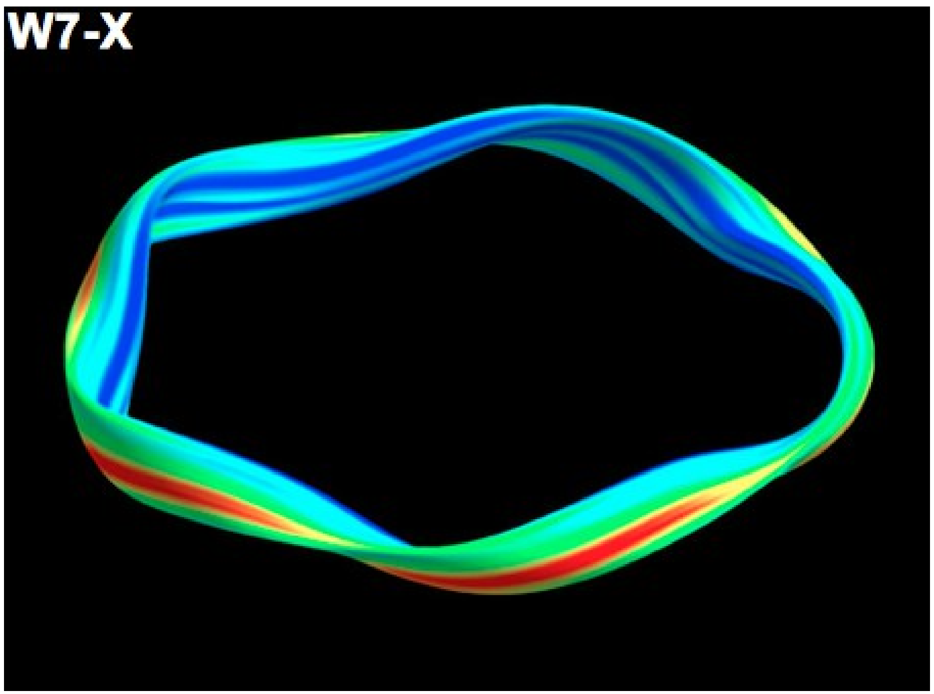


Central feature of 3D turbulence is poloidal localization

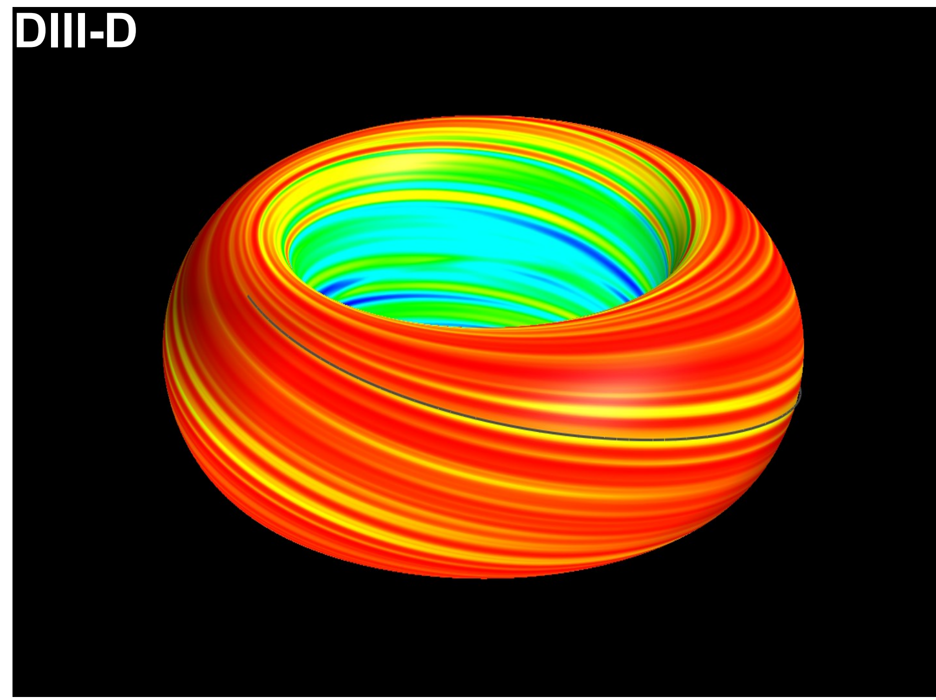
On a tokamak surface density **fluctuations cover the entire domain**

The stellarator tends to **localize ITG fluctuations** in a thin hot stripe

Turbulence localization has **remarkable implications** on turbulence

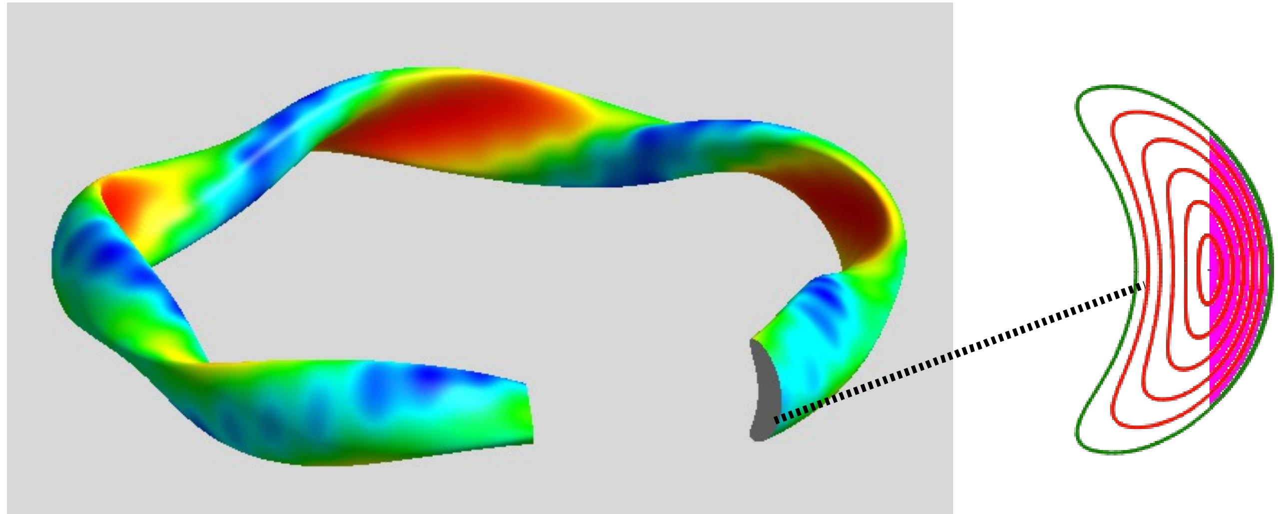


Xanthopoulos et al., Phys. Rev. Lett. 113, 155001 (2014)

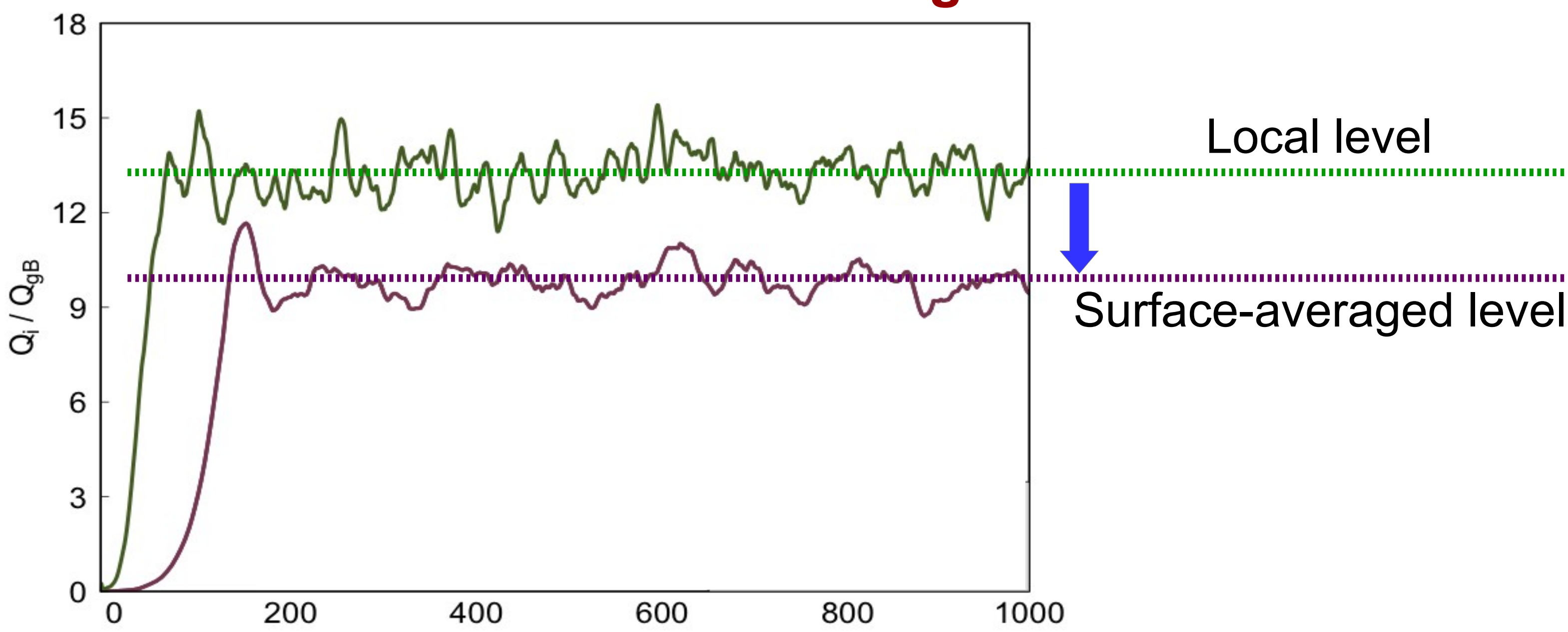


3D turbulence stabilization

- 3D shaping causes **increased local gradients** due to surface compression

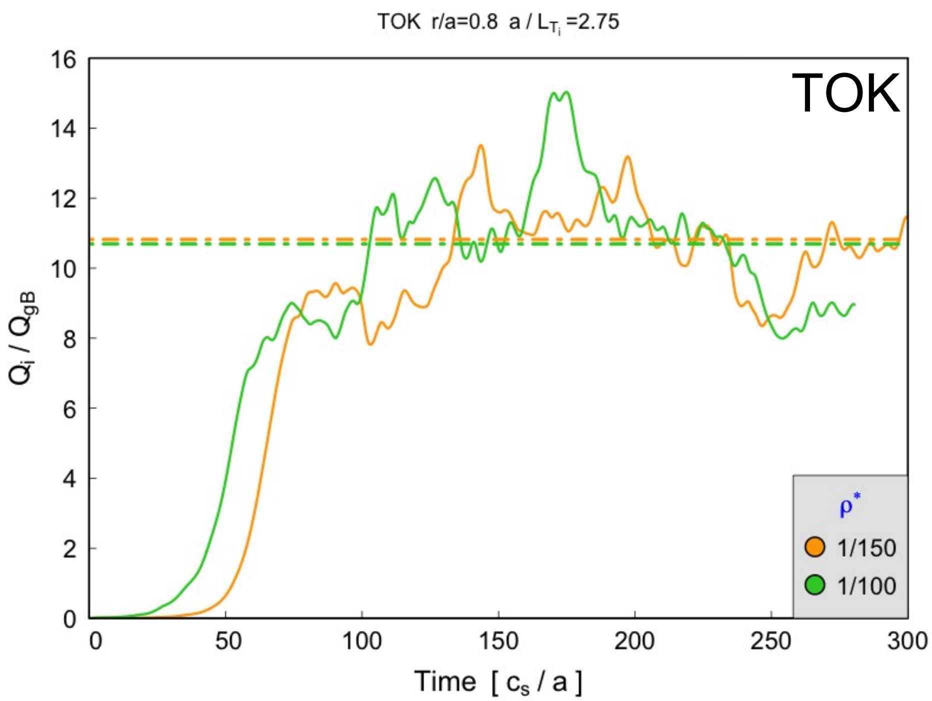


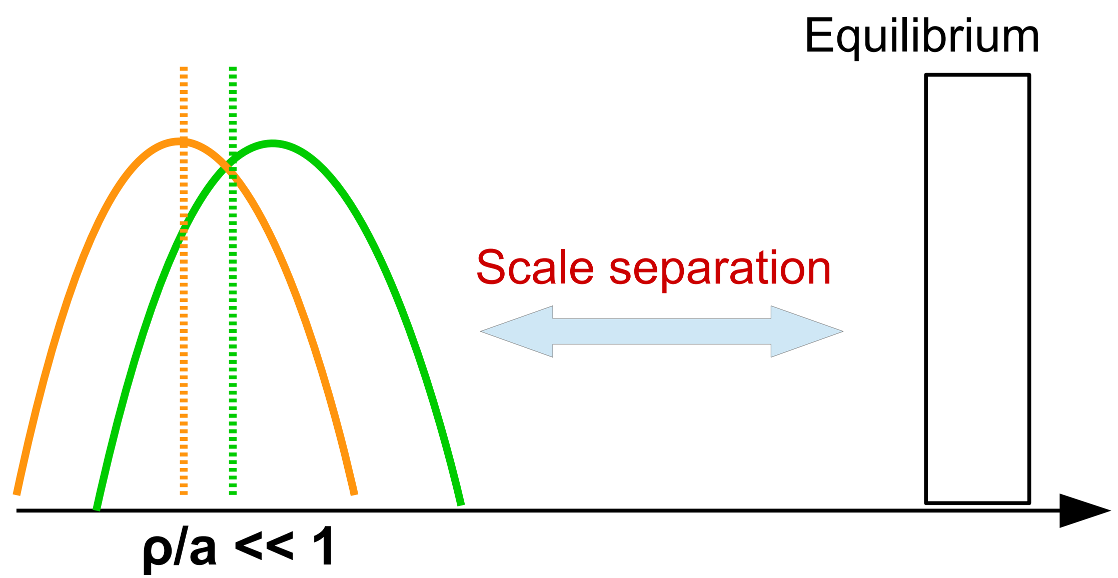
Thanks to localization of fluctuations: surface averaged level < local level



Xanthopoulos et al., Phys. Rev. X 6, 021033 (2016)

Tokamak turbulence insensitive to ρ* on surface





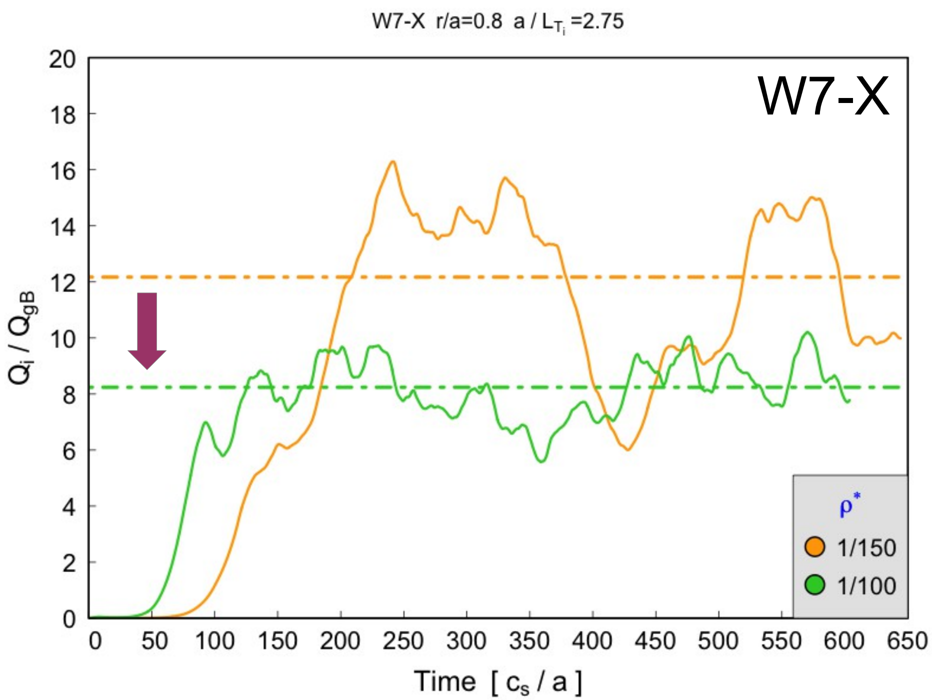
Examine dependence of ITG turbulence on normalized ion gyroradius **ρ/a=ρ***

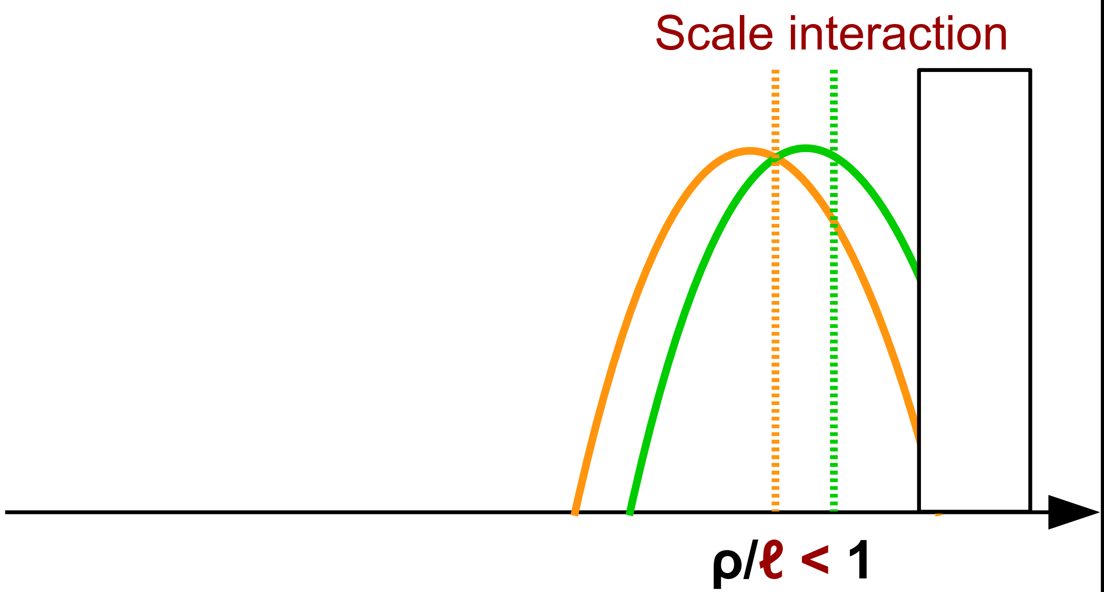
Vary ρ* in **flux-surface simulations** for stellarators and tokamaks (**no radial effects**)

For tokamaks, **no dependence** is observed for reasonably large ρ* (same heat levels)

Pronounced **scale separation** between equilibrium and turbulence scales

3D turbulence reacts on finite ρ*: Stabilization



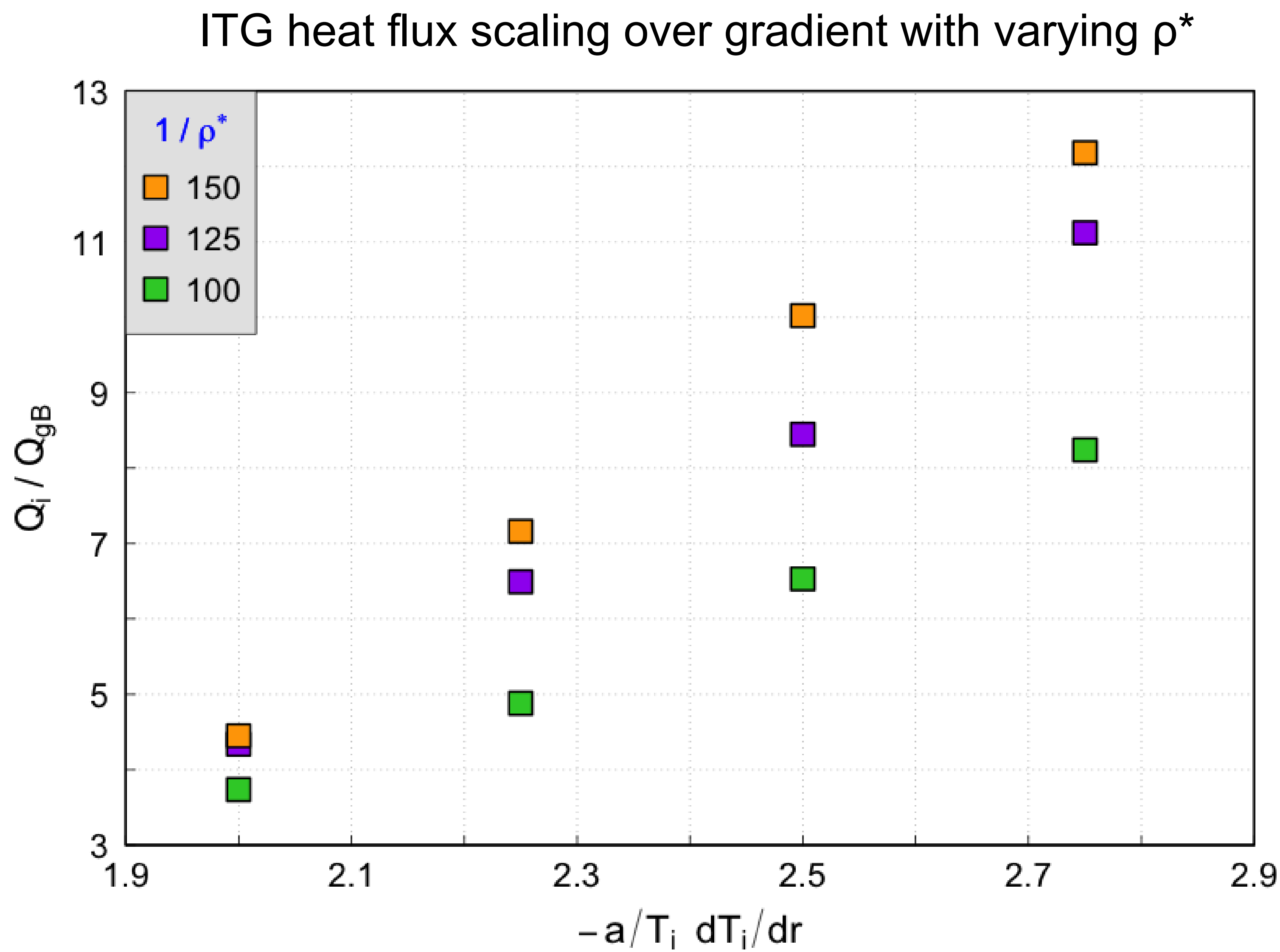


Localization of turbulence introduces an **effective length ℓ** much smaller than a

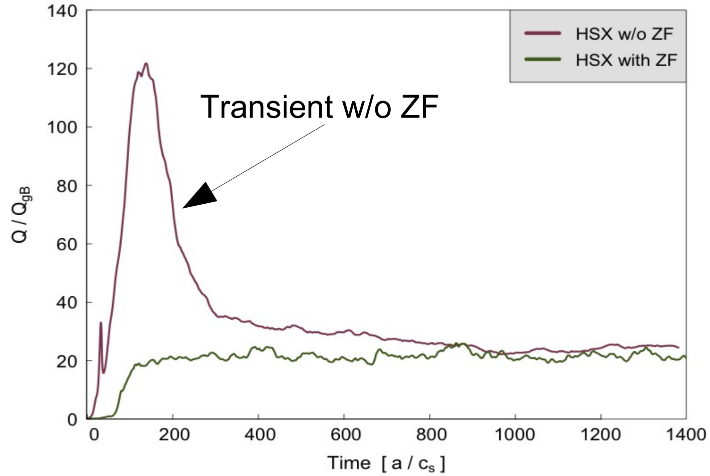
Therefore, $\boldsymbol{\rho^*_{eff}} = \rho^* \cdot a/\ell > \rho^*$. Equilibrium scales can interfere with turbulence

Mode falls onto “speed bumps” and gets **stabilized** (lower heat flux as ρ* increases)

3D turbulence reacts on finite ρ*: Stabilization

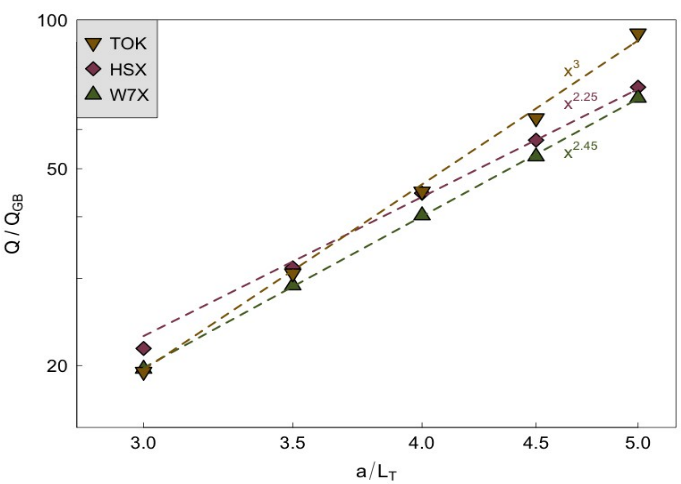


3D geometry reveals new “ZF free” saturation regime



- Zonal Flows have no impact on saturation of ITG turbulence in HSX
- Entirely opposite behavior compared to ITG saturation in tokamaks
- In tokamaks strong ZF shears toroidal branch apart and slab prevails

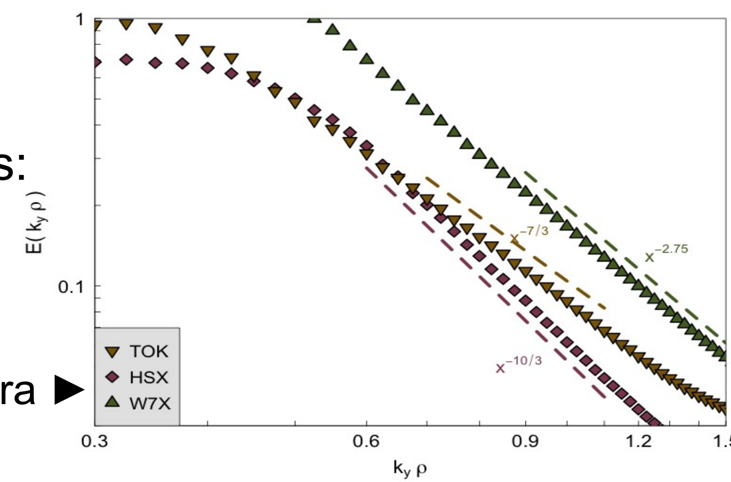
A new saturation regime found for 3D ITG where the toroidal branch persists in the absence of ZF



◀ Ion heat flux scaling

Comparing 3 configurations:
W7-X, HSX, TOK

Energy spectra ▶



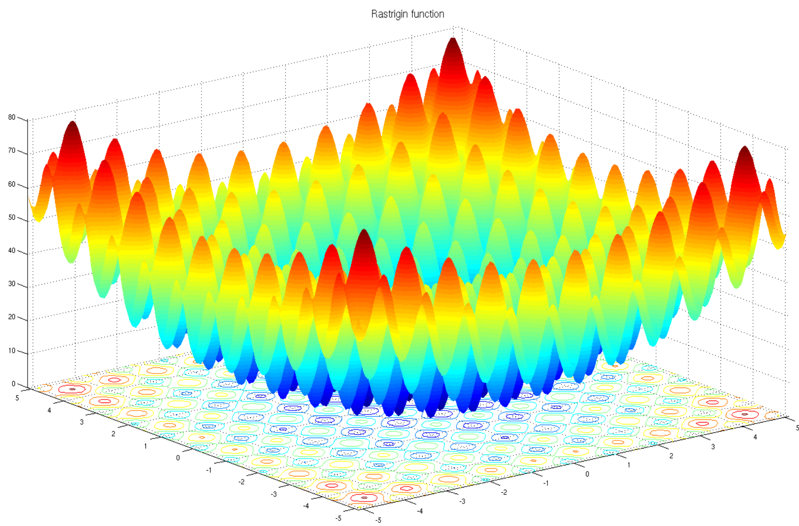
- Scaling in “**ZF dominated**” regime represented by **TOK**: Q ~ a/L_T^**3** and E ~ k_y^**(-7/3)**

  See also Barnes, Parra, Schekochihin PRL 107, 115003 (2011)
- Scaling in new “**ZF free**” regime represented by **HSX**: Q ~ a/L_T^**2.25** and E ~ k_y^**(-10/3)**

  Plunk, Xanthopoulos, Helander PRL 118, 105002 (2017)
- **Blending** of two regimes with intermediate power laws found in **W7-X**: Q ~ a/L_T^**2.45** and E ~ k_y^**(2.75)**

Use STELLOPT with Differential Evolution (stochastic global search)

Minimize Rastrigin (nonlinear multimodal) function



NP = 200 individuals evolve via strategy RAND2

$$X_{test} = X_i + F * (X_i - X_{rand})$$

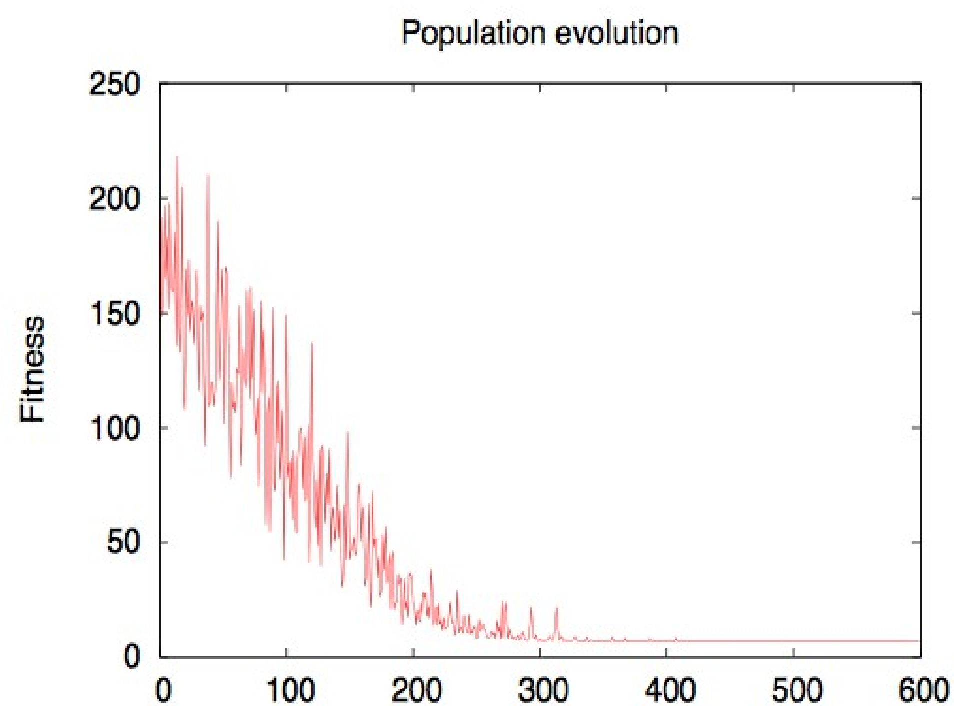
If X_{test} fitter than X_i → Replace X_i

Population-based: Many solutions evolving

Versatile: Plenty of different strategies

No guarantee for (optimum) convergence

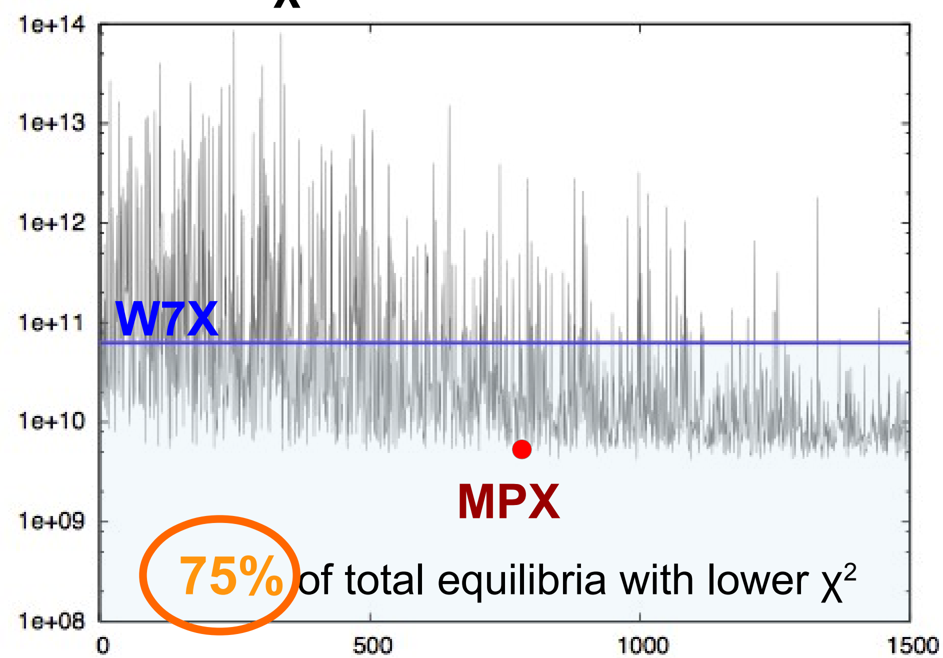
Sensitivity to parameters (lots of fiddling)



Minimize new ITG target function: **Curvature/distance$^{\lambda}$**

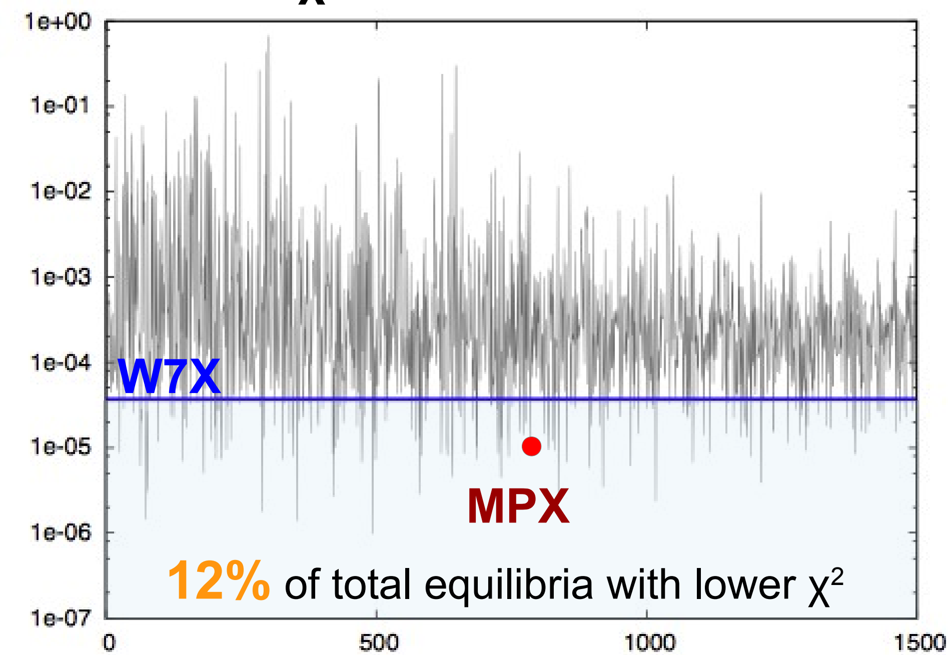
Starting from W7-X, we found configuration MPX with reduced ITG

χ^2 **for Turbulence**



Index of VMEC equilibrium

χ^2 **for Neoclassics**

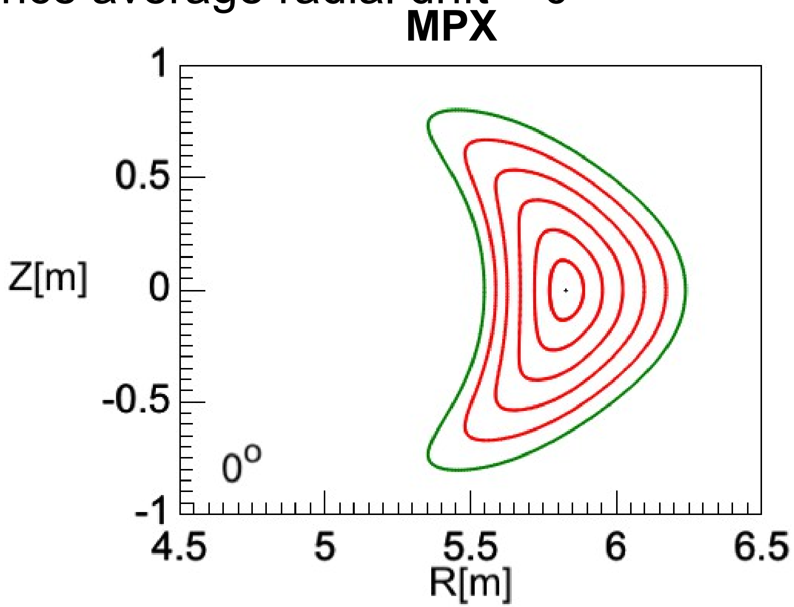


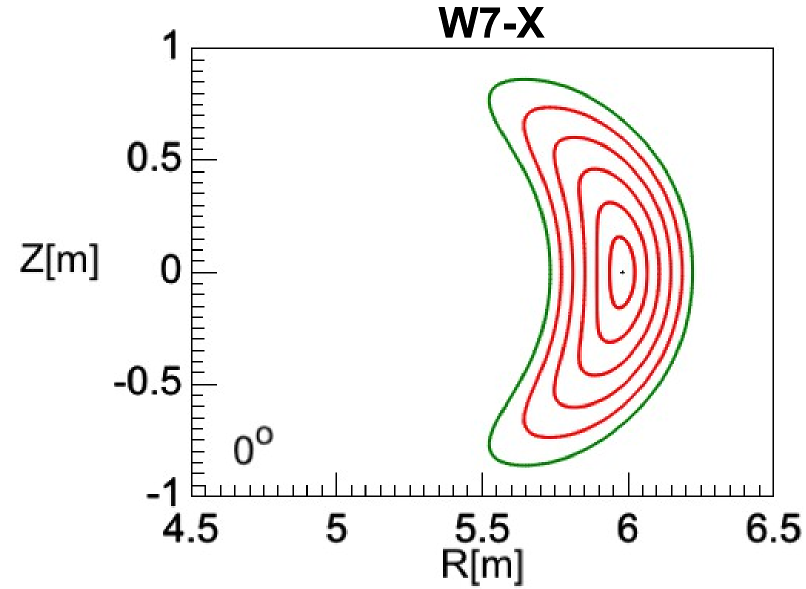
Index of VMEC equilibrium

Xanthopoulos et al., Phys. Rev. Lett. 113, 155001 (2014)

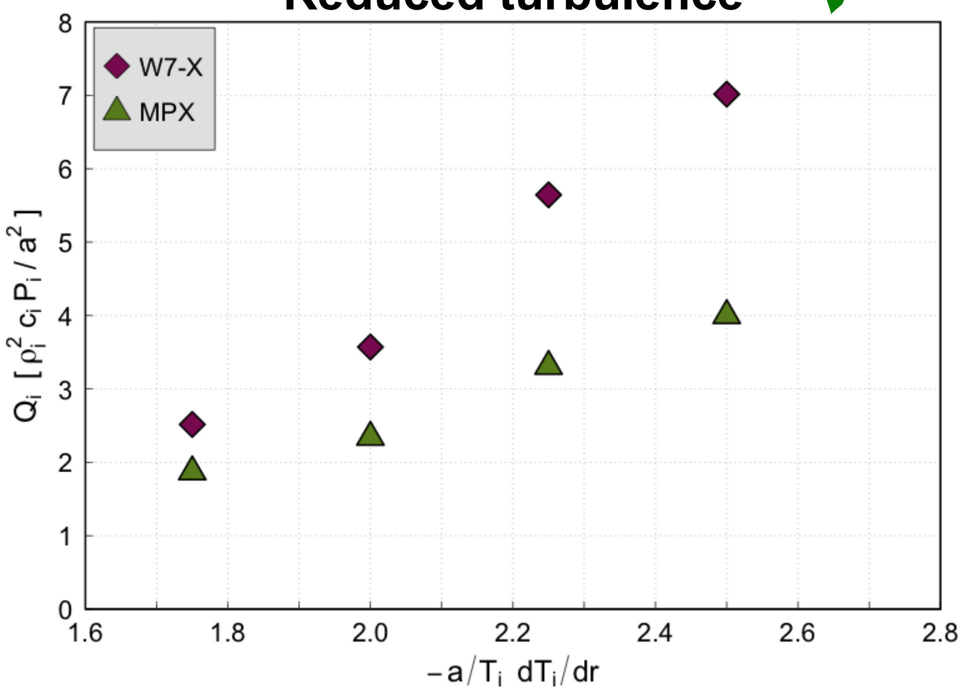
Evaluation of MPX quasi-omnigenous* equilibrium

*bounce average radial drift = 0

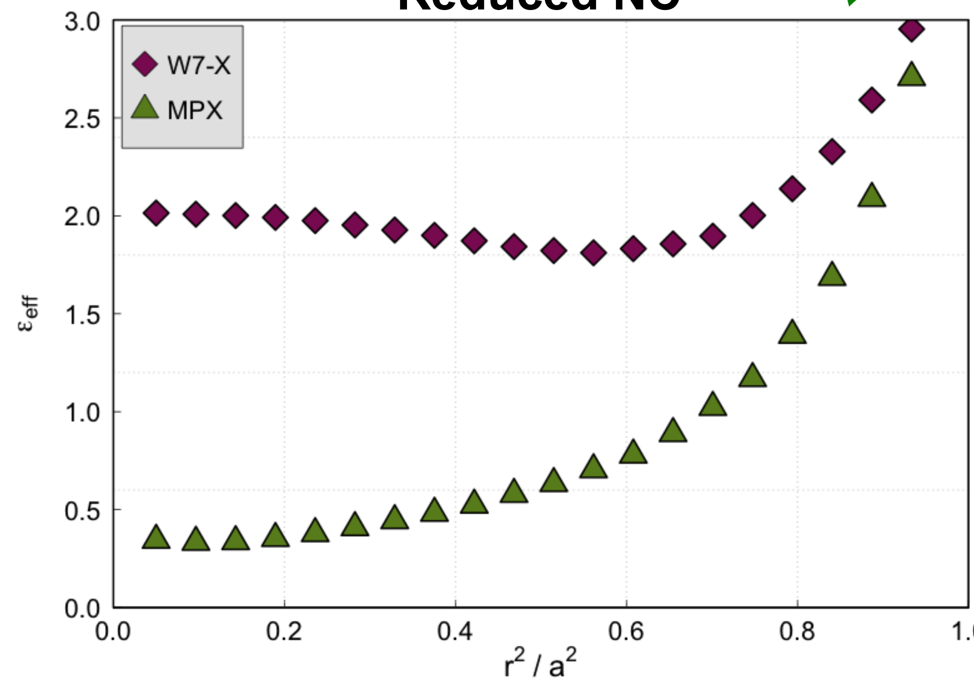




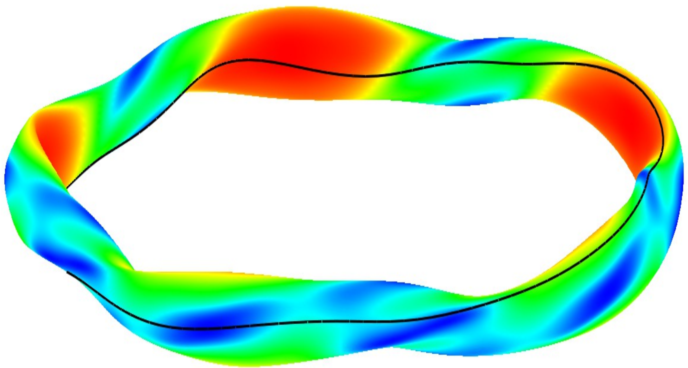
Reduced turbulence ✓

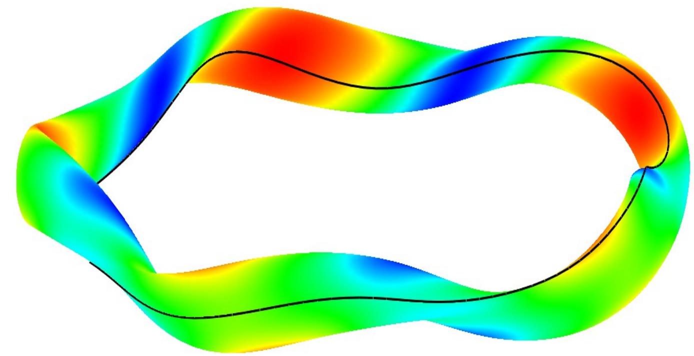


Reduced NC ✓



Identify elongation as critical geometric factor

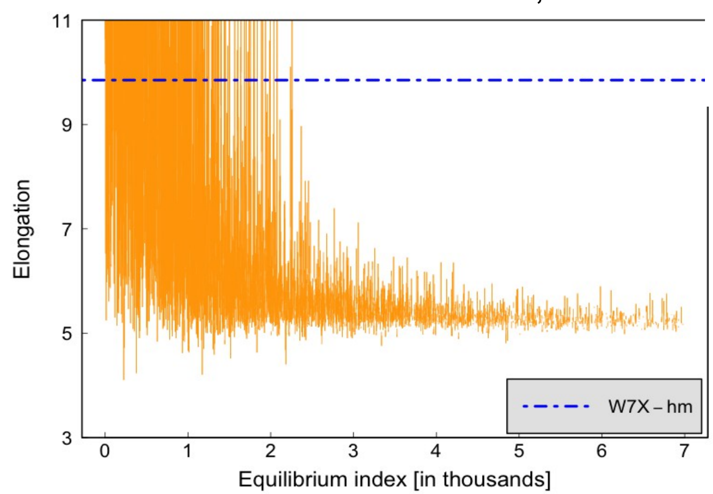


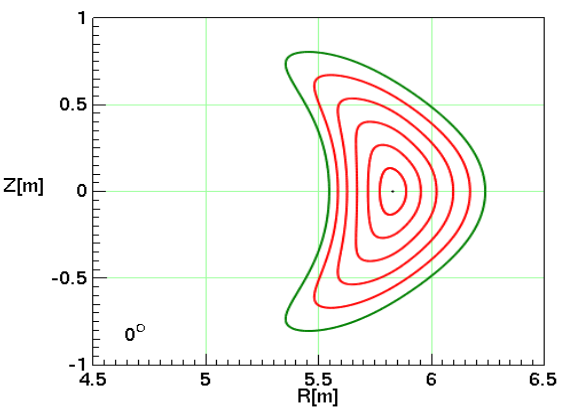


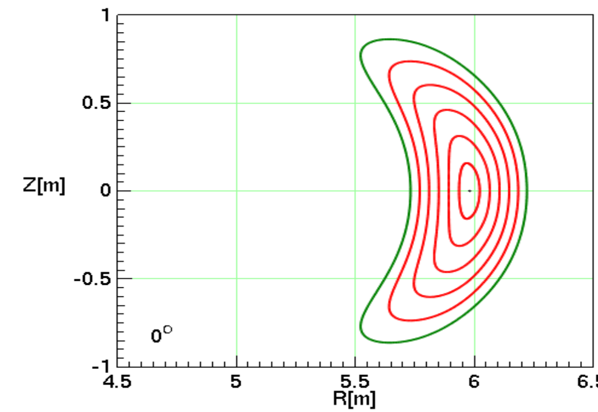
MPX

W7-X

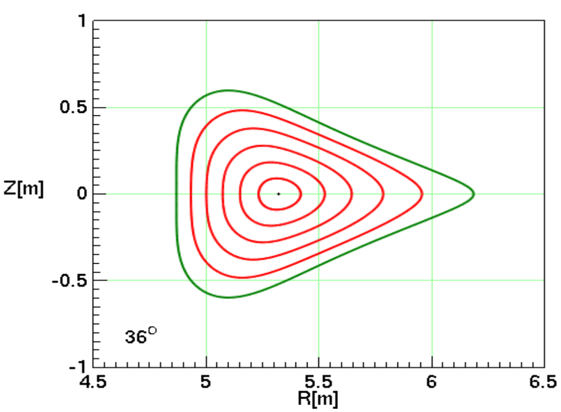
Elongation $(\varepsilon / b_{1,0})^2$

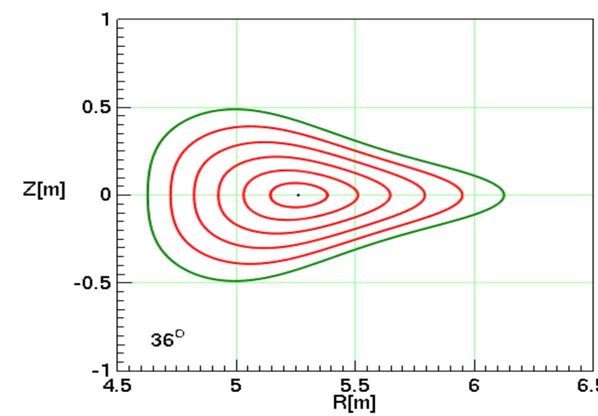






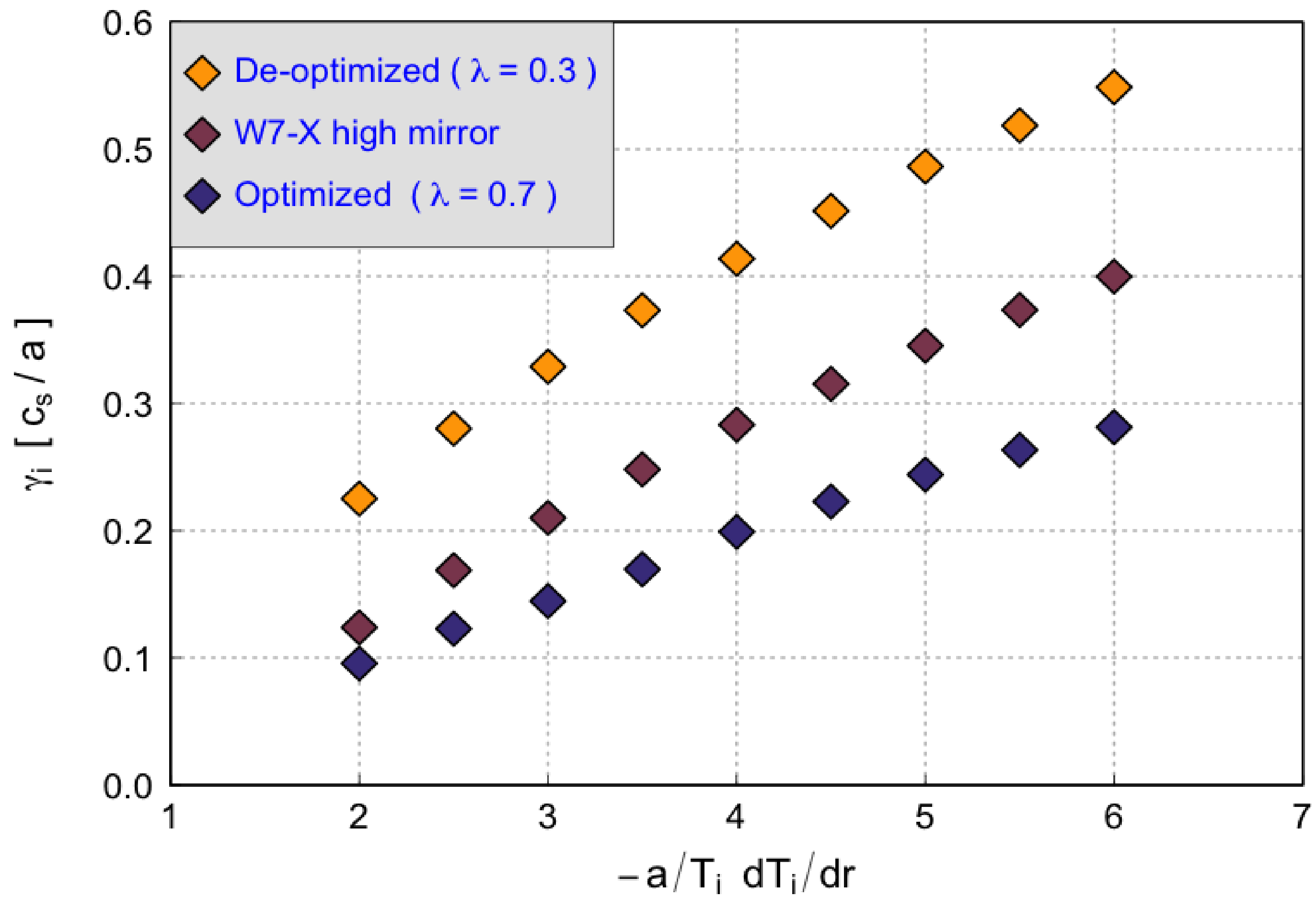
Reduced elongation





Controlling turbulence via free parameter

Varying the parameter λ we can optimize or de-optimize configurations

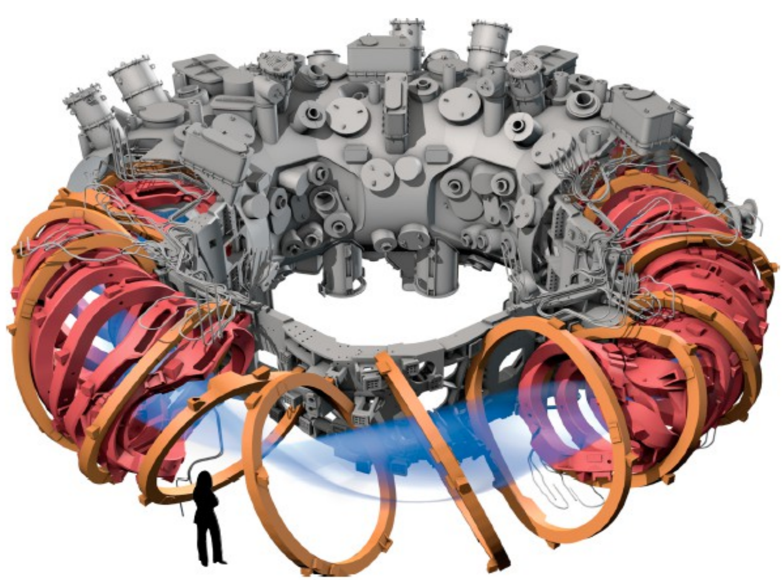


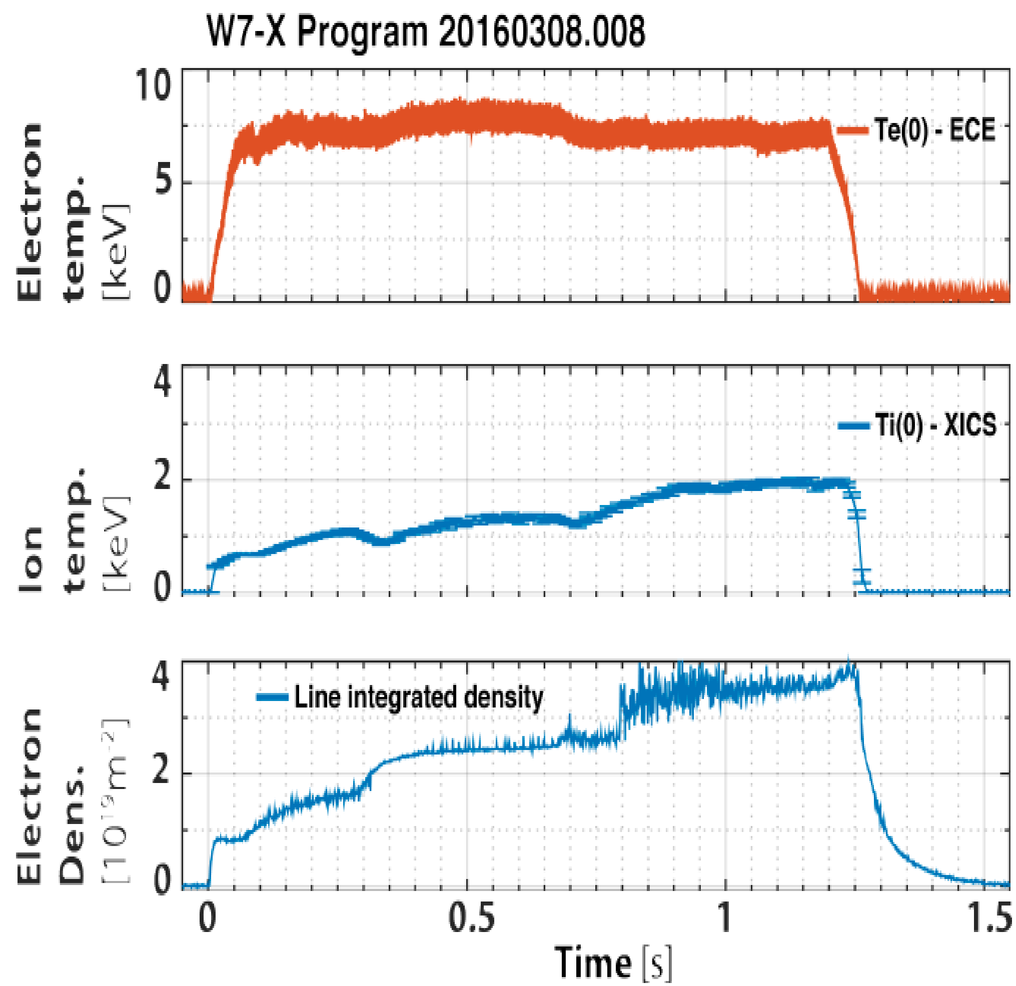
The initial W7-X campaign featured:

- Up to 4.3 MW of ECRH power.
- Graphite limiter configuration.
- Unshielded first wall
- 4 MJ injected power (administrative limit)

First plasma on December 10th, 2015

- 11 Weeks of plasma operations.
- 940 Experimental programs ("shots")
- 402 Dedicated physics scenarios ("shots")





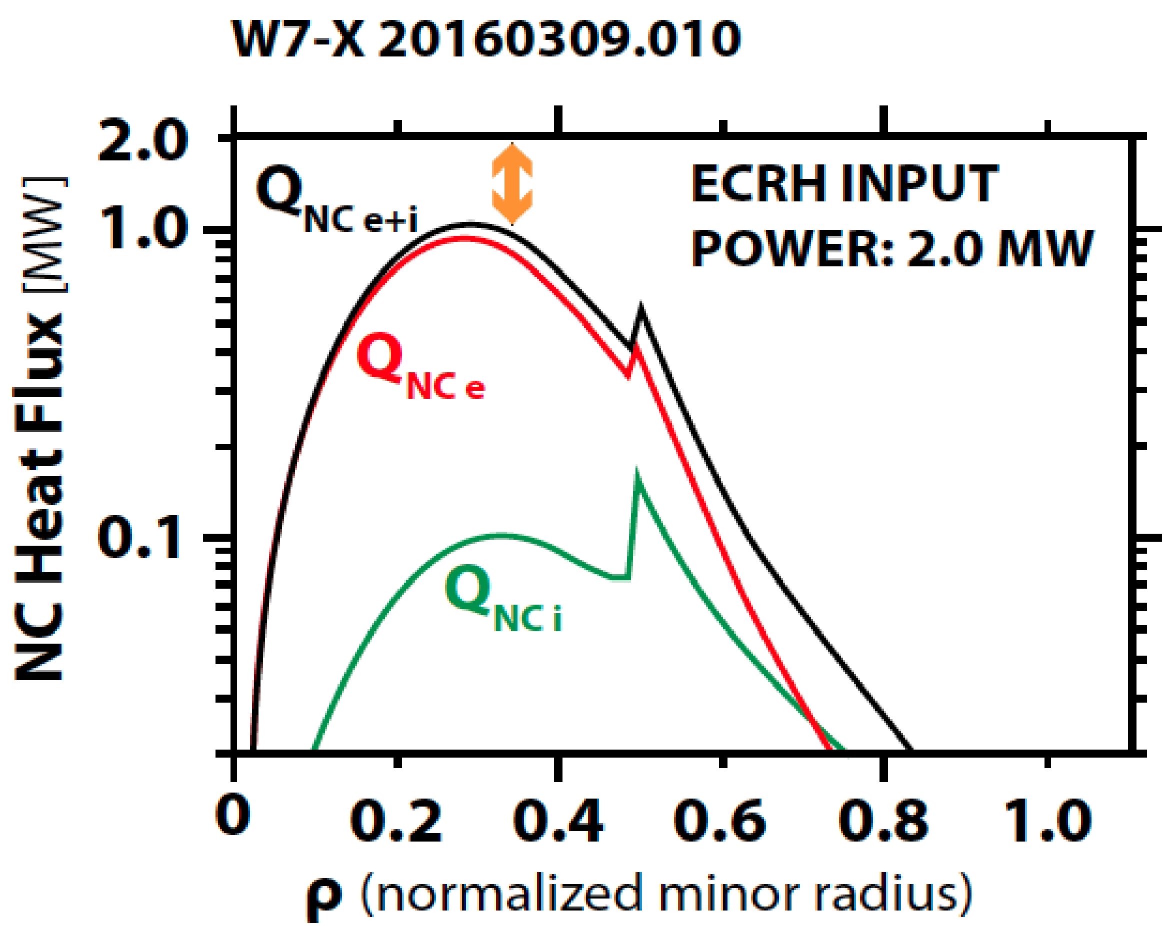
T_{eo} = 5 keV
T_{io} = 2.2 keV
n_{eo} = 3.5×10^{19} m^{-3}

4.0 MW of central ECRH heating
Stored energy: 0.4 MJ
Pulse length: 1.2 s

Pablant, submitted to PoP

Transport analysis for OP1.1

- **Transport is not adequately explained by NC physics**
  Only 50% of the total heat losses is predicted

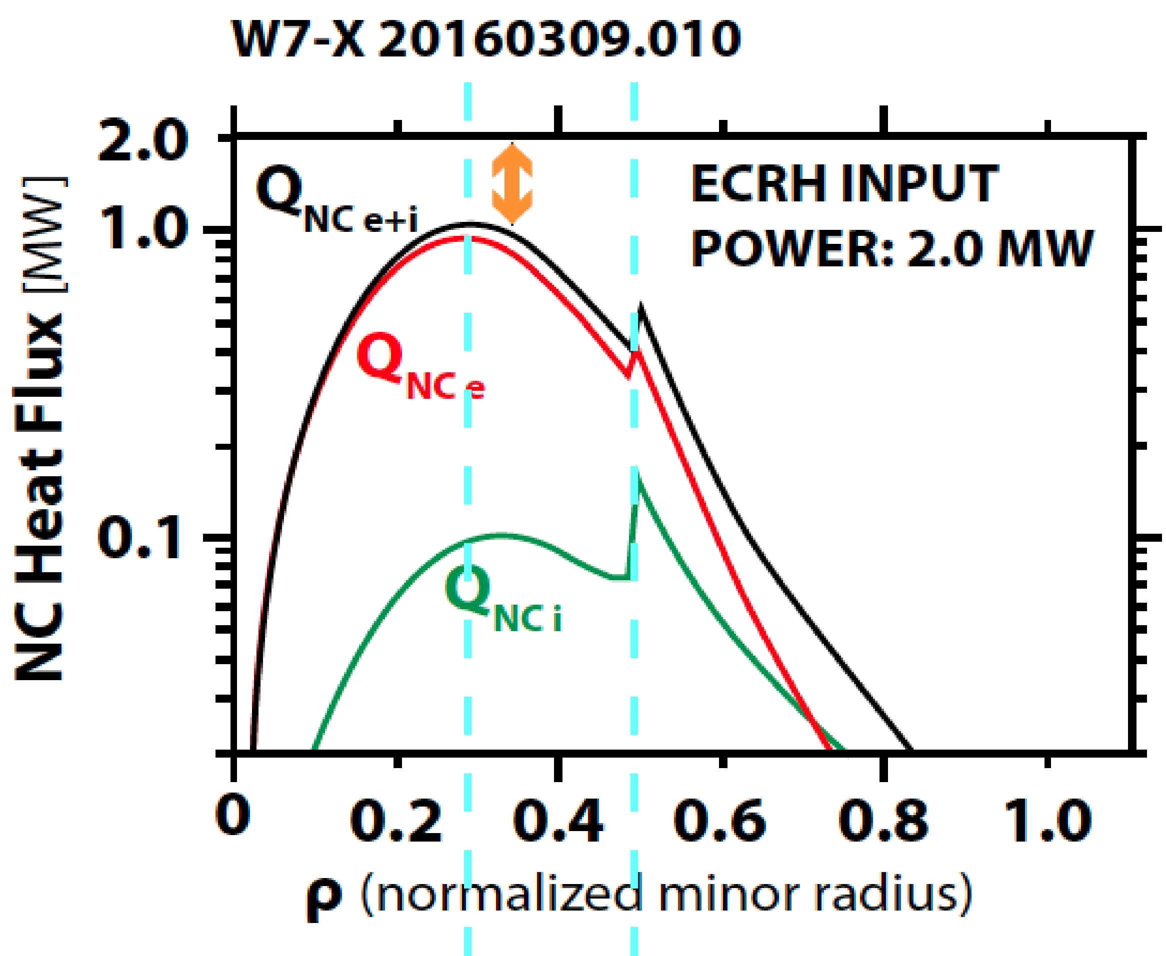


- **Challenge: Can turbulence explain (some of) the 50% gap?**
  Other plausible candidates: charge exchange and radiation losses

Transport analysis for OP1.1

- **Stellarator core (and beyond) is affected by ETG turbulence**

GENE simulations performed at distinct radii



$X_{ETG} \sim$ 0.5-2 m^2/sec

Conclusions

- Localization of fluctuations on flux surface is found in stellarators
- Local strong turbulence on surface is stabilized at zero ρ*
- Stellarator turbulence stabilizes as a reaction to finite ρ*
- New saturation regime discovered independent of zonal flows
- Optimization tools are developed including turbulence proxies
- Stellarator turbulence can be controlled without affecting optimization
- Power balance for W7-X core including ETG turbulence is under way

Highlights

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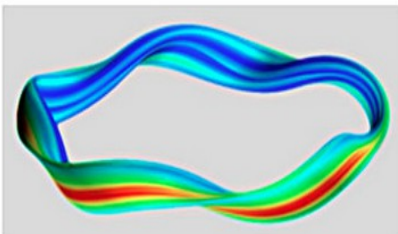

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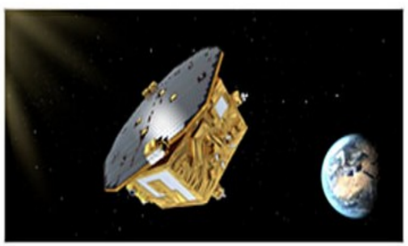

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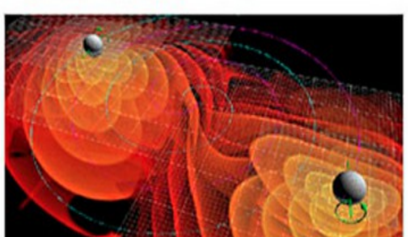

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Core Concept: Stabilizing turbulence in fusion stellarators

Adam Mann, *Science Writer*

A correction has been published

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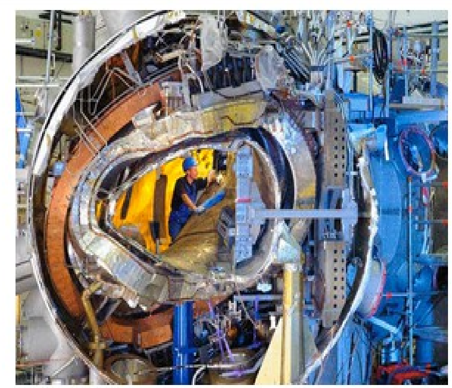
In the earliest days of the Cold War, physicists on both sides of the Iron Curtain raced to harness energy from nuclear fusion, which could, in principle, provide nearly limitless electricity. Innovative devices with names like pinch machines, levitrons, and superstators flourished, and for most of the 1950s it was unclear which would eventually prove most promising. But in 1968, at the Third International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Soviet scientists announced that their tokamak—which confined a thermonuclear plasma within a donut-shaped magnetic field—had achieved temperatures 10 times higher than any other experiment (1).



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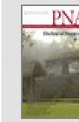
The interior of the Wendelstein 7-X stellarator. Visible are the plasma vessel, one of the stellarator coils, a planar coil, part of the support structure, and the cryostat together with a lot of cooling pipes and power supply lines. Photo by Wolfgang Filser and image courtesy of Max Planck Institute for Plasma Physics.

This Issue



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