

Gyrokinetic simulations: Recent achievements and new opportunities

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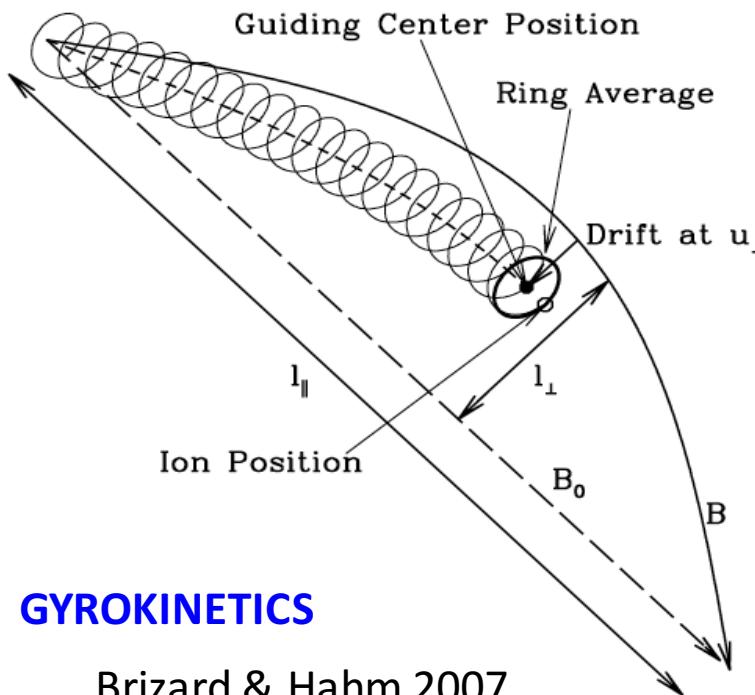
**18th European Fusion Theory Conference
Ghent, Belgium, October 7-10, 2019**

Fluid models don't work – use (gyro-)kinetics!

Hot and/or dilute plasmas are only **weakly collisional**: **6D Vlasov-Maxwell equations**

$$\frac{\partial f_\alpha}{\partial t} + \mathbf{v} \cdot \nabla f_\alpha + \frac{q_\alpha}{m_\alpha} \left[\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} \right] \cdot \nabla_v f_\alpha = 0 \quad \alpha = \text{particle species}$$

$f_\alpha = f_\alpha(\mathbf{x}, \mathbf{v}, t)$...from the Liouville equation via the BBGKY hierarchy



Strong background magnetic field:
Eliminate fast gyromotion; consider
slow dynamics of **guiding centers**

$$f = f(\mathbf{X}, v_{||}, \mu; t)$$

**Reduction of effort by
~12 orders of magnitude
(elimination of irrelevant
spatio-temporal scales &
reduction from 6D to 5D)**

$$\frac{\partial f}{\partial t} + \dot{\mathbf{X}} \cdot \frac{\partial f}{\partial \mathbf{X}} + \dot{v}_{||} \frac{\partial f}{\partial v_{||}} = 0$$

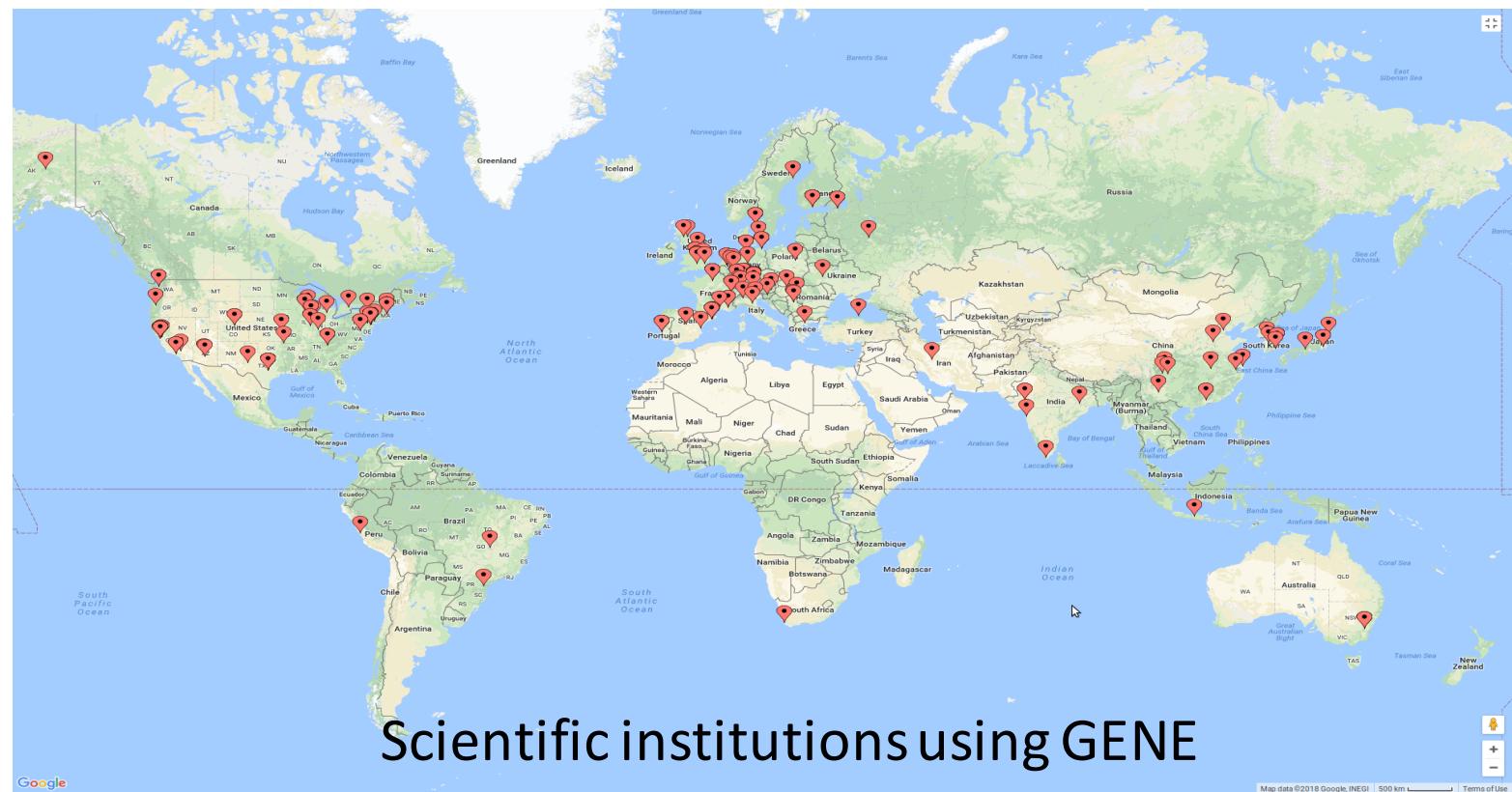
**Additional gain from using
field-aligned coordinates**

Gyrokinetic codes: GENE...



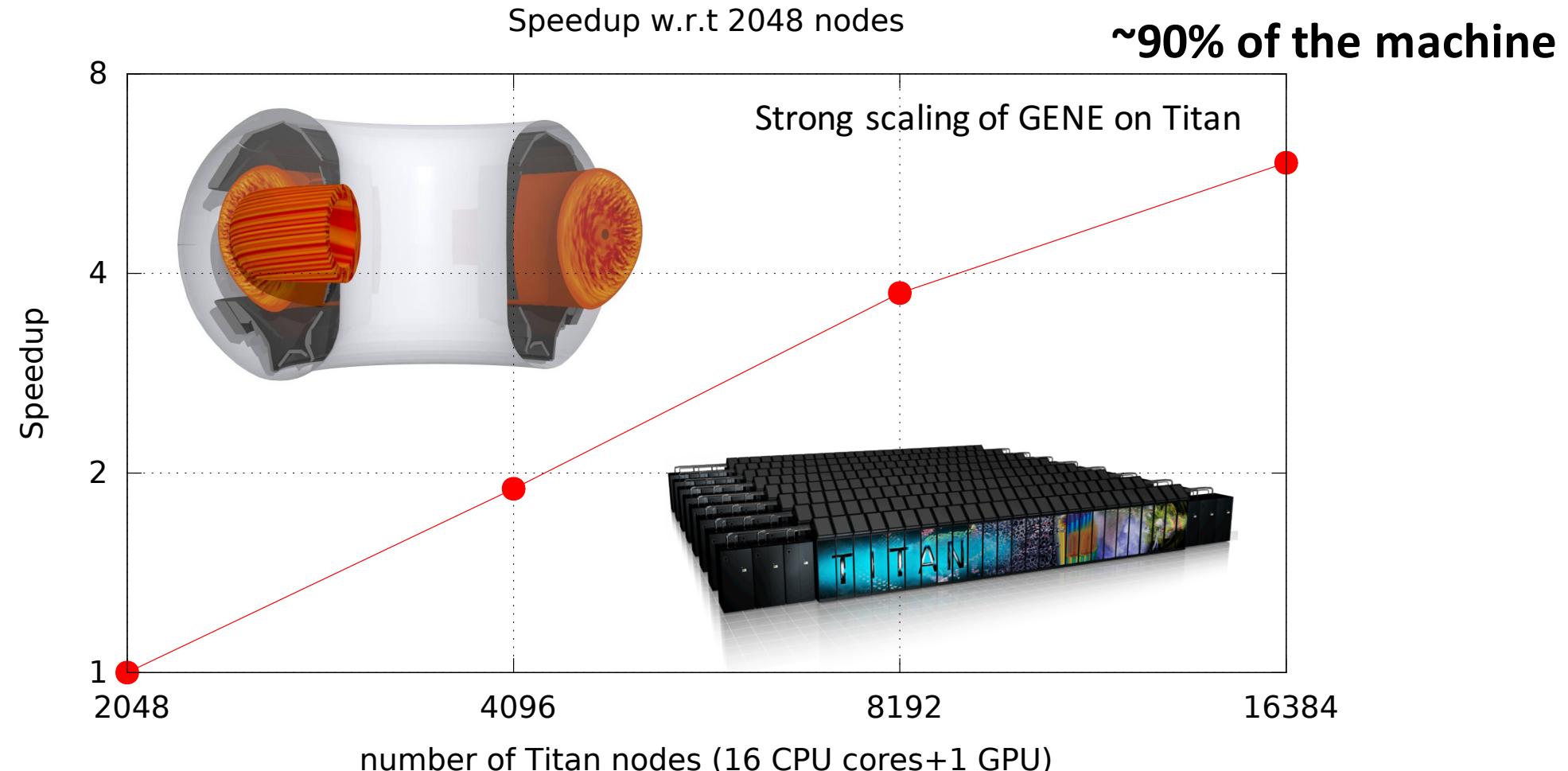
- First GENE publication: Jenko et al., Phys. Plasmas 2000
- Grid-based code with numerical methods like in **Computational Fluid Dynamics**
- GENE is a **family of codes**: flux-tube, global-tok, full-flux-surface, global-stell, SOL
- Open source policy;
world-wide user base:
genecode.org

Part of an ecosystem of
GK codes: ORB5, GYSELA,
ELMFIRE, EUTERPE, GKW,
GS2, GYRO, GTC, XGC, GKV,
GT5D etc.



Scientific institutions using GENE

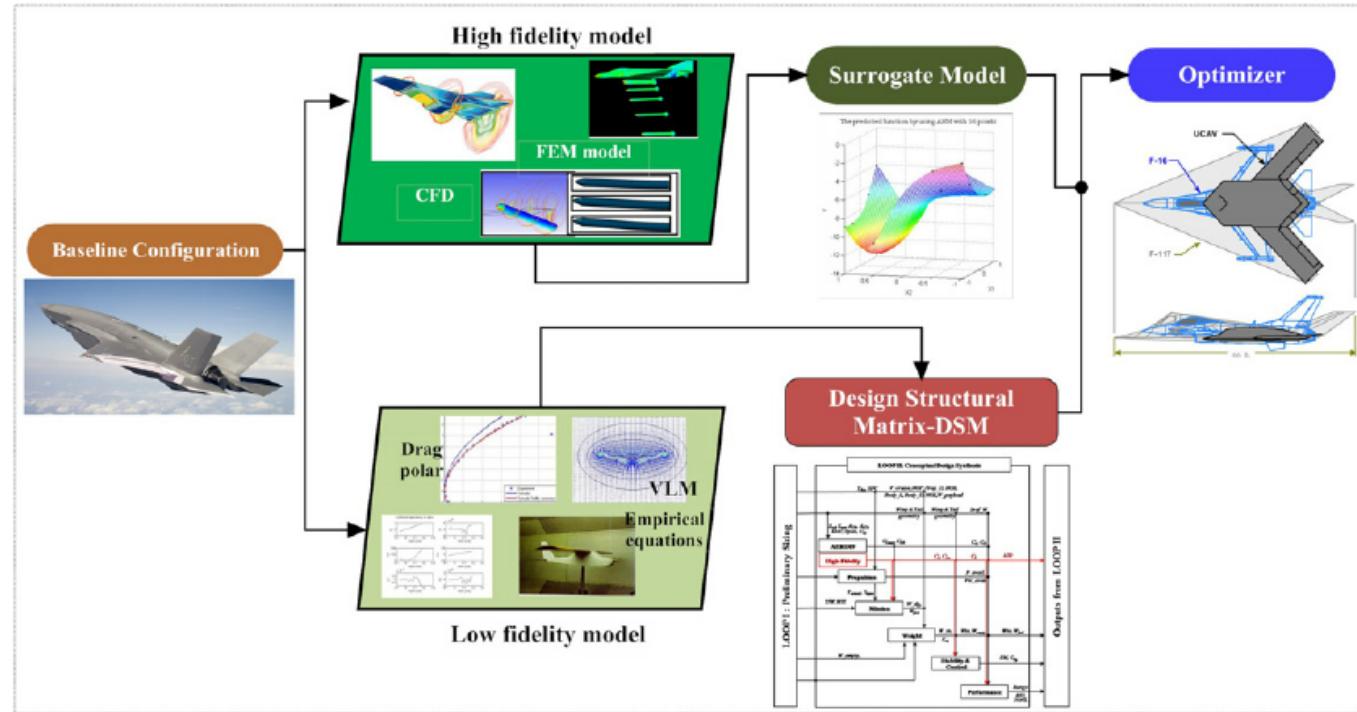
Gyrokinetics and supercomputing



Optimizing large-scale (GK) codes on pre-exascale systems may take person-years

Gyrokinetics within a multi-fidelity approach

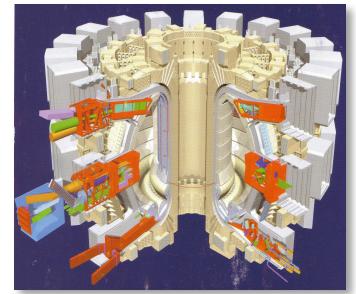
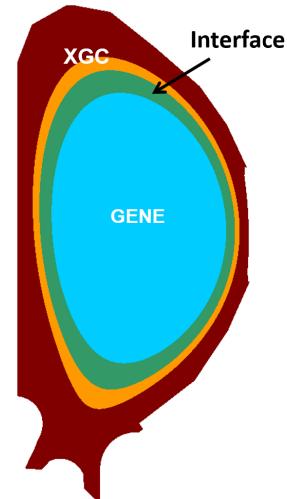
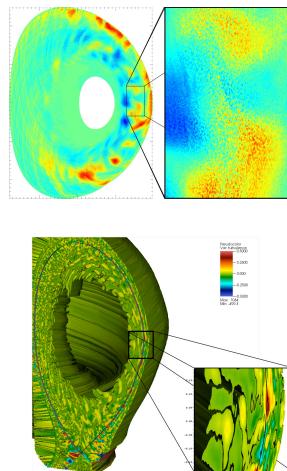
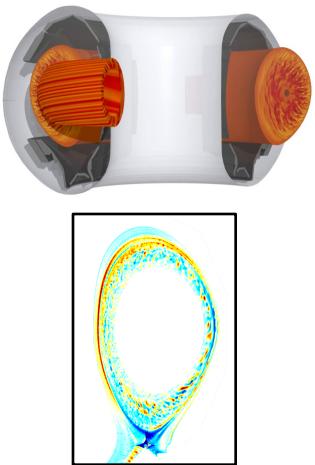
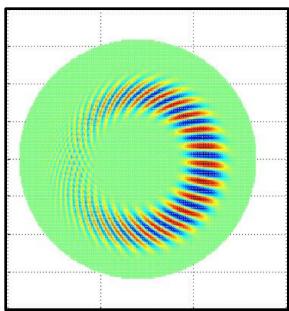
An example:



- High-fidelity models provide reliable **predictive capability**
- Lower-fidelity models foster **high-throughput computing**
- Both are needed – together

Towards a virtual fusion plasma: GK backbone

Increasing fidelity & modeling capability with increasing computing power



Gigaflops

Core: ion-scale electrostatic physics in simplified geometry

Teraflops

Core: adding kinetic electron electromagnetic physics in a torus

Edge: ion+neutral electrostatic physics in a torus

Petaflops

Core: adding electron-scale physics

Edge: adding kinetic electron electrostatic physics

Exaflops

Core-edge coupled studies of whole-device ITER, incl. turbulence, MHD instability, fast particles, heating, and plasma-wall interactions

Beyond

Whole device modeling of all relevant fusion science



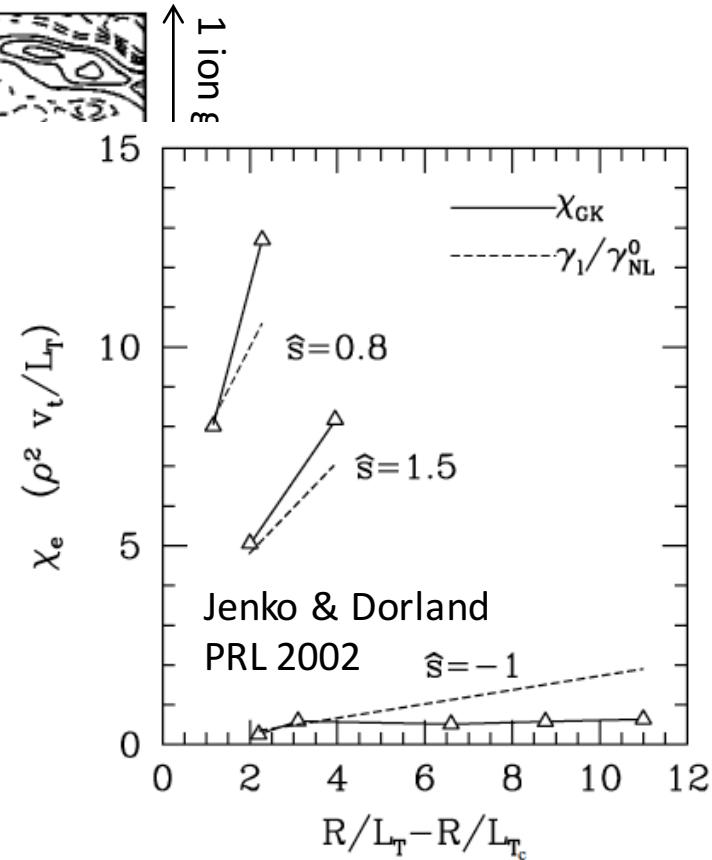
**Recent achievements (1st example):
Role of electron-scale turbulence**

ETG turbulence can be experimentally relevant

GENE: Experimental relevance of electron-temperature-gradient (ETG) driven turbulence



Jenko+ PoP 2000; Dorland+ PRL 2000



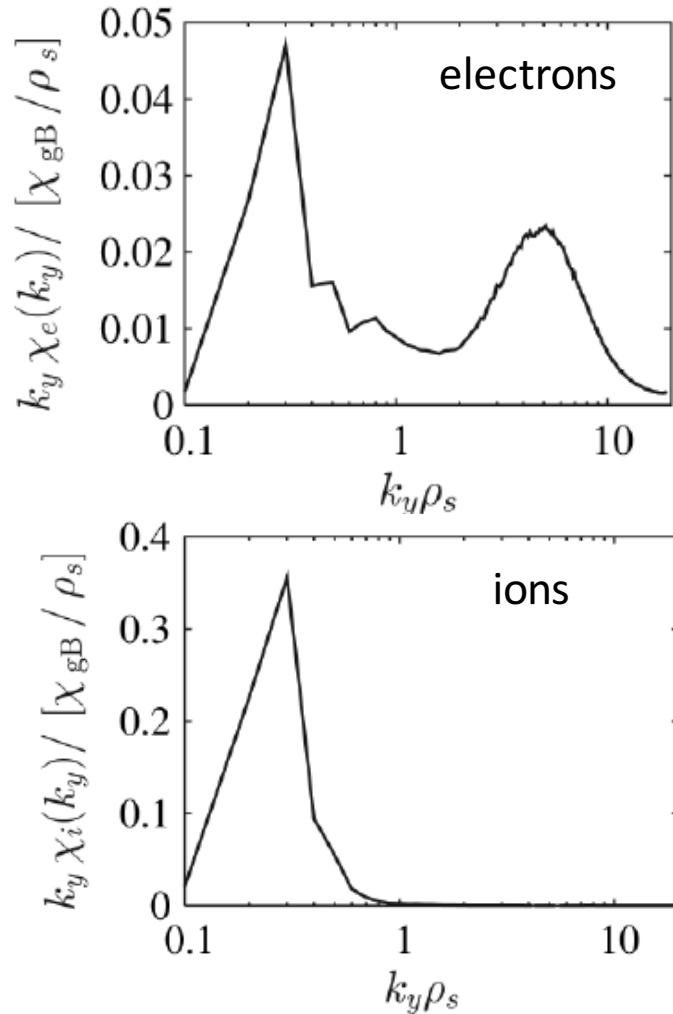
Intrinsic scalings (mixing length):

$$\chi_e^{ETG} \sim \frac{\rho_e^2 v_{th,e}}{L_{T_e}} \ll \chi_i^{ITG} \sim \frac{\rho_i^2 v_{th,i}}{L_{T_i}}$$

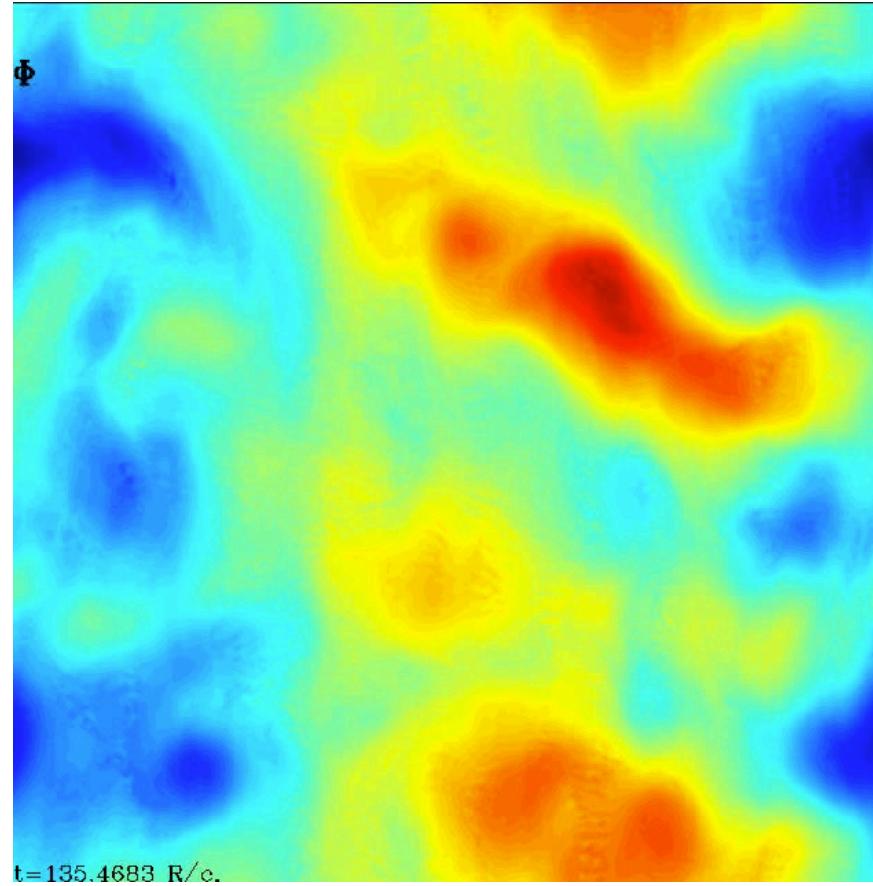
In the adiabatic electron/ion limit, linear ITG and ETG modes are isomorphic, but nonlinearly, this “symmetry” is broken!

Multi-scale turbulence: ITG-ETG interactions

Modified Cyclone Base Case parameters ($R/L_{Ti} = 5.5$)

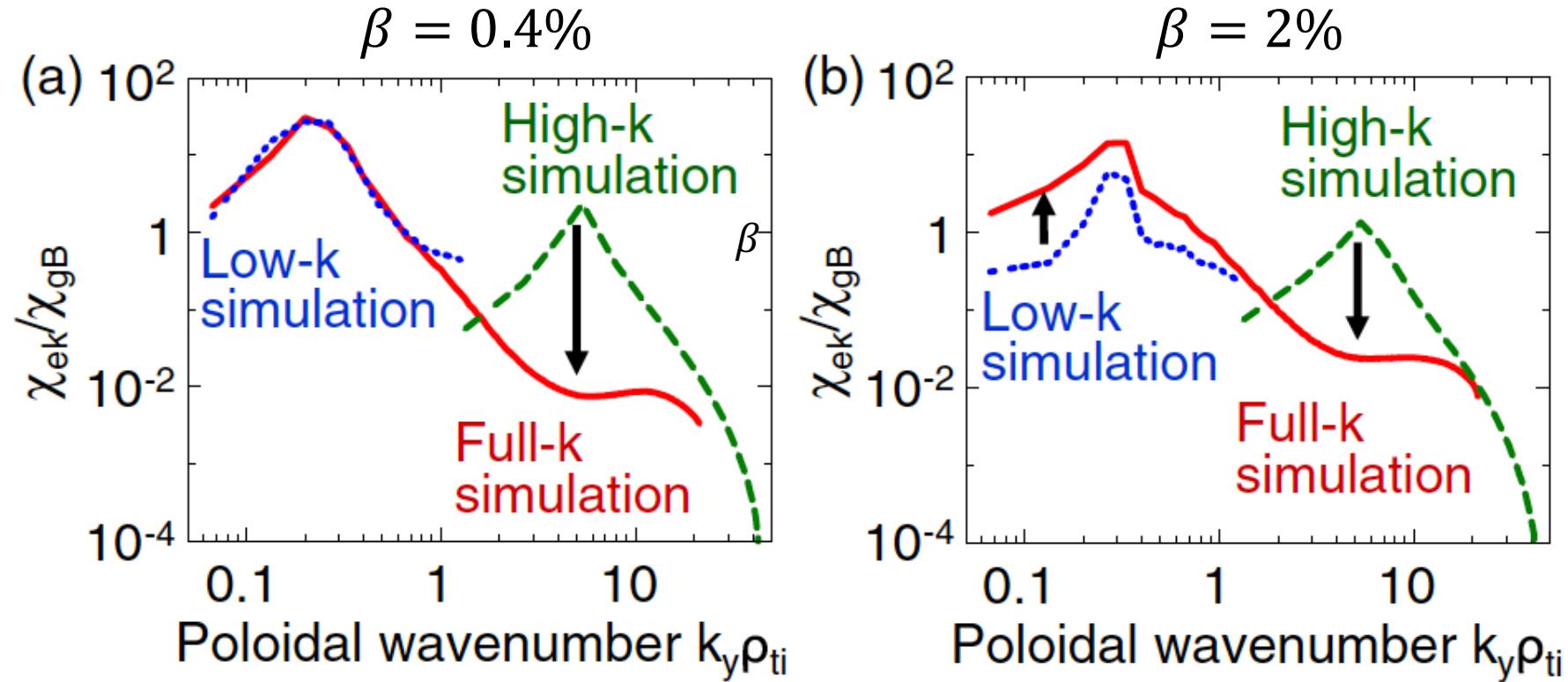


Görler & Jenko, PRL 2008



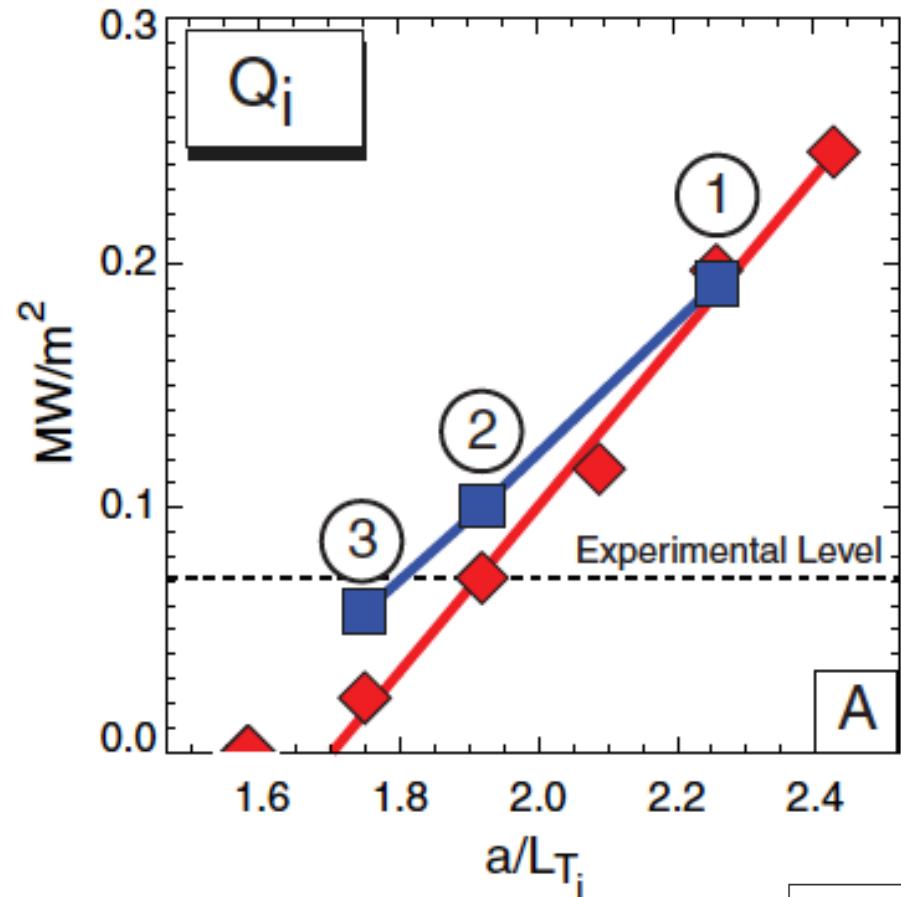
Multi-scale turbulence: ETGs affect ion scales

Maeyama+ PRL 2015

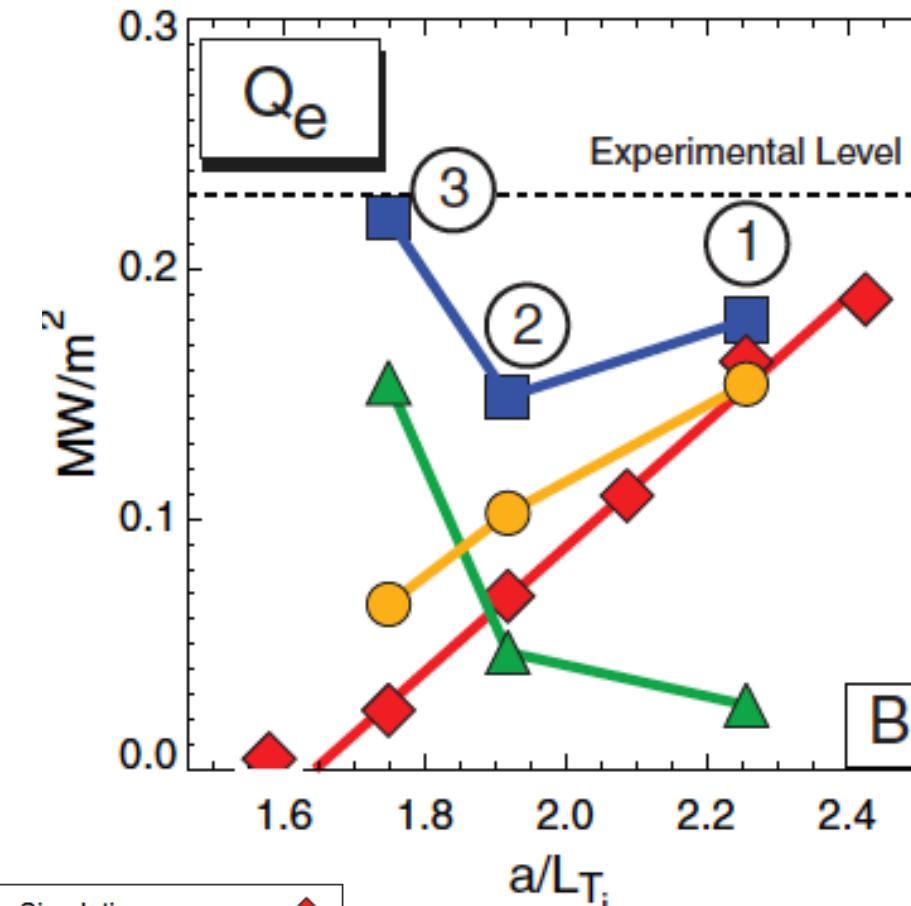


Close to marginality, ion-scale turbulence is enhanced
via damping of ion-scale zonal flows by ETG turbulence

Multi-scale turbulence: Flux matching of a C-Mod L-mode discharge

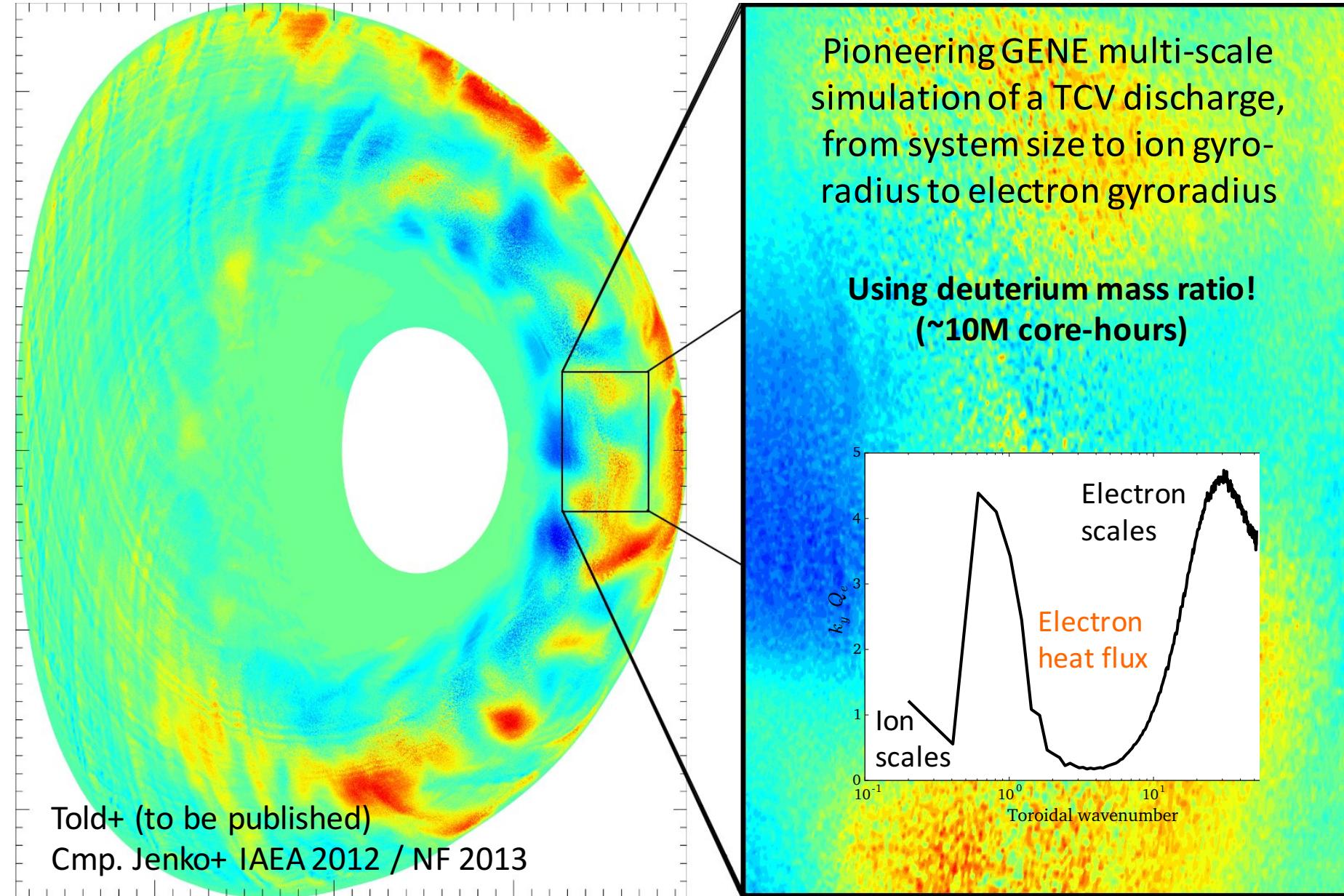


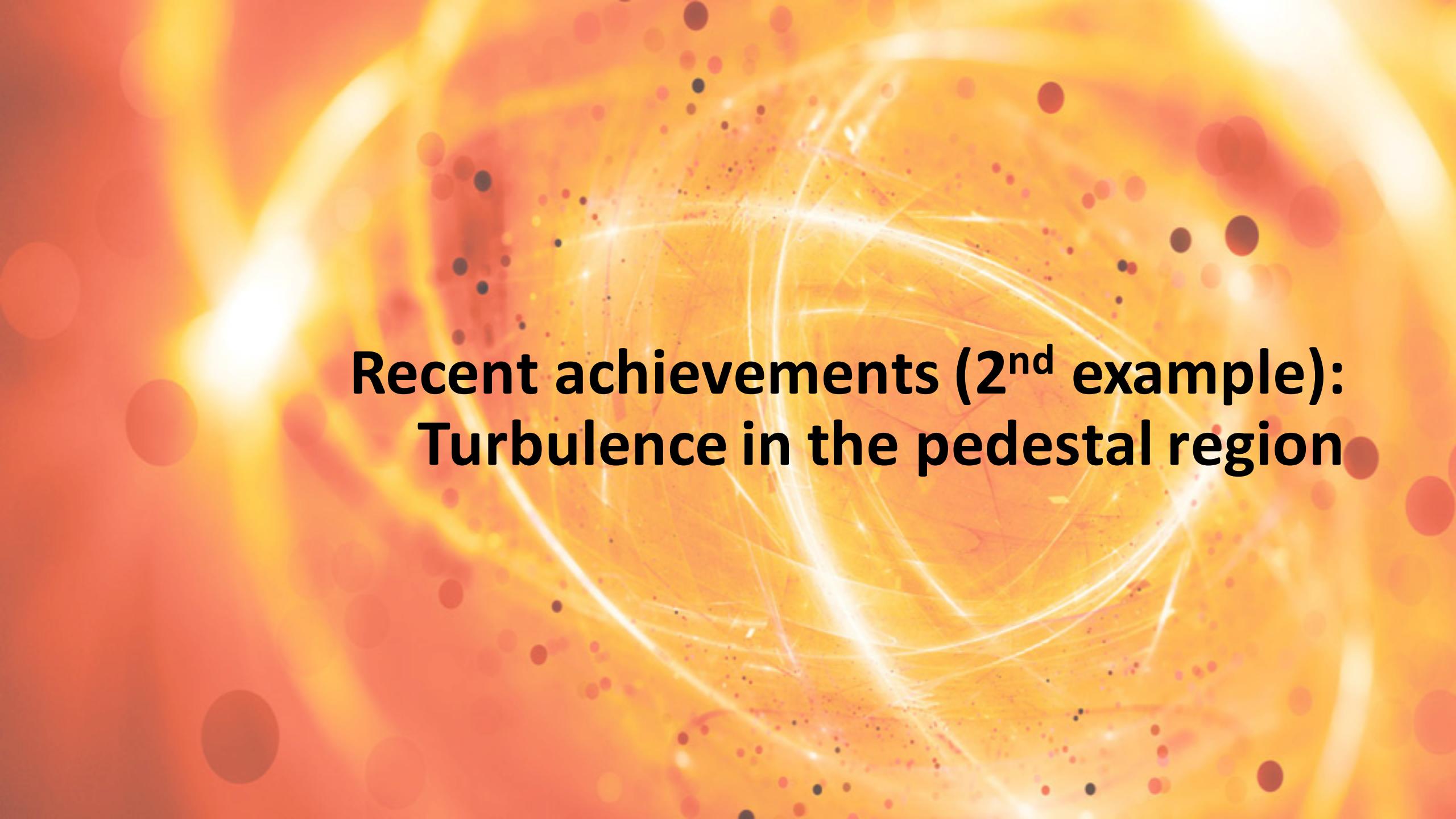
Howard+ NF 2016



Ion-Scale Simulation	Red Diamond
Multi-Scale Simulation	Blue Square
Multi-Scale Components	
High-k (ETG) Contributions	Green Triangle
Low-k (ITG) Contributions	Yellow Circle

Multi-scale turbulence in TCV-ITB discharge





**Recent achievements (2nd example):
Turbulence in the pedestal region**

Towards the edge / pedestal: Some challenges

Strongly shaped geometry

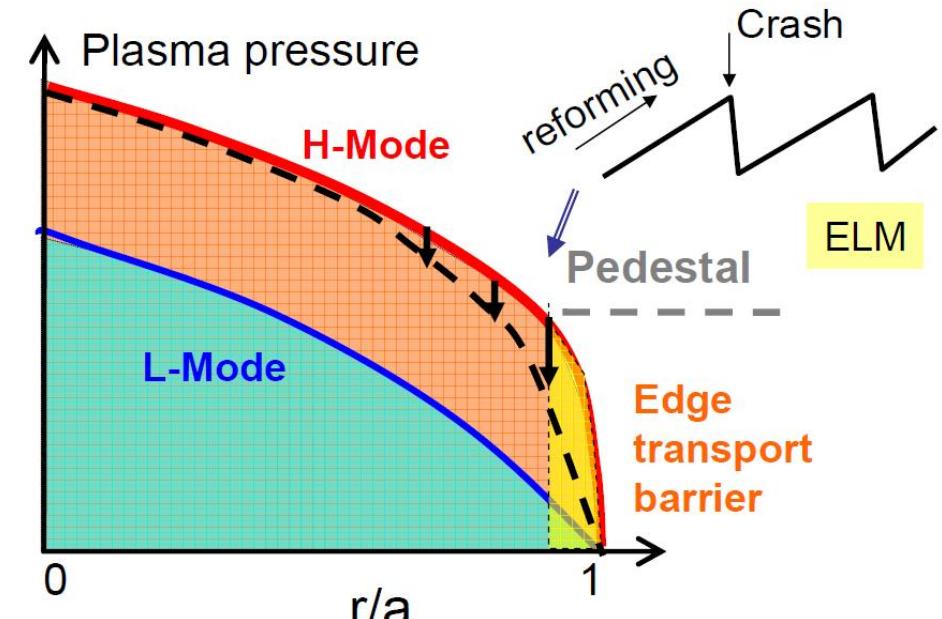
- Requires high resolution

Steep gradients

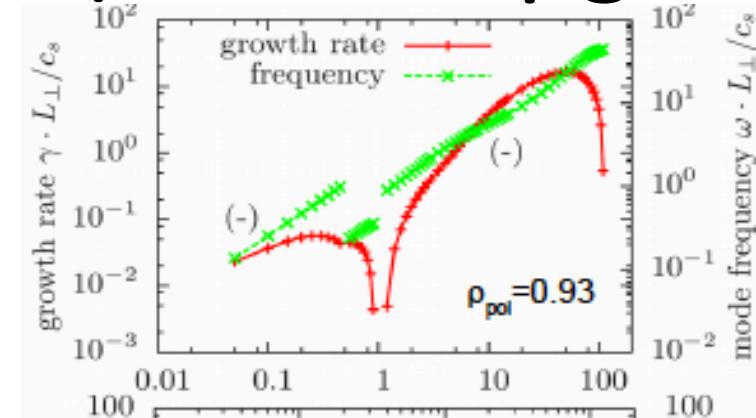
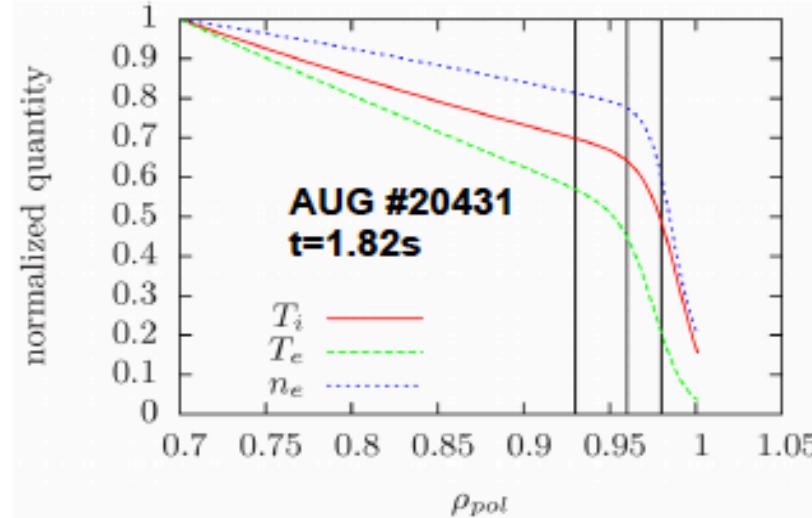
- Large zoo of microinstabilities

Breakdown of gyrokinetics?

- Stephens PoP 2017, On the limitations of gyrokinetics: Magnetic moment conservation
- Groselj ApJ 2017, Fully kinetic versus reduced-kinetic modeling of collisionless plasma turbulence
- Told NJP 2016, Comparative study of gyrokinetic, hybrid-kinetic and fully kinetic wave physics for space plasmas
- Muñoz PoP 2015, Gyrokinetic and kinetic particle-in-cell simulations of guide-field reconnection

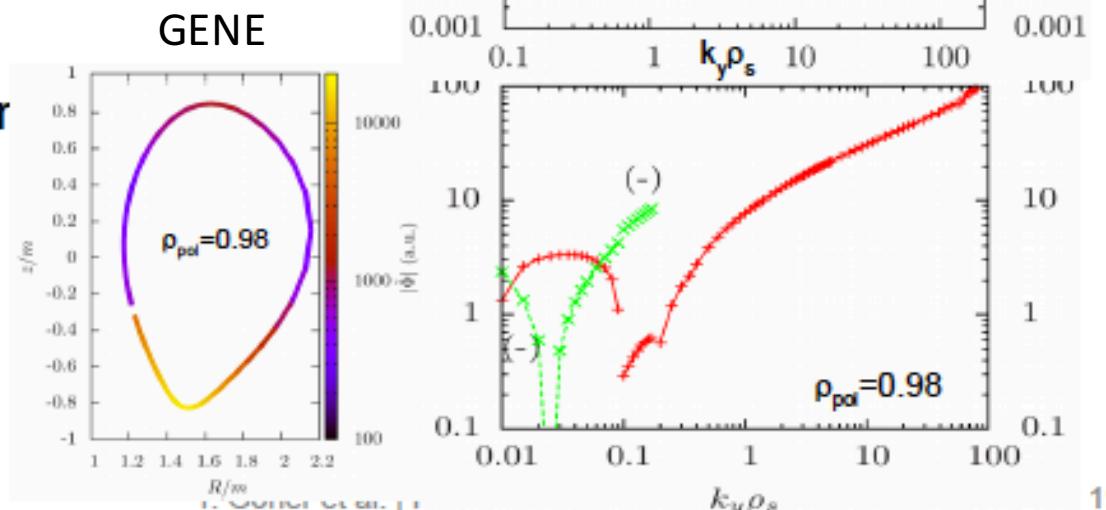


First GK pedestal simulations (ASDEX Upgrade)



Early study already revealed interesting insights:

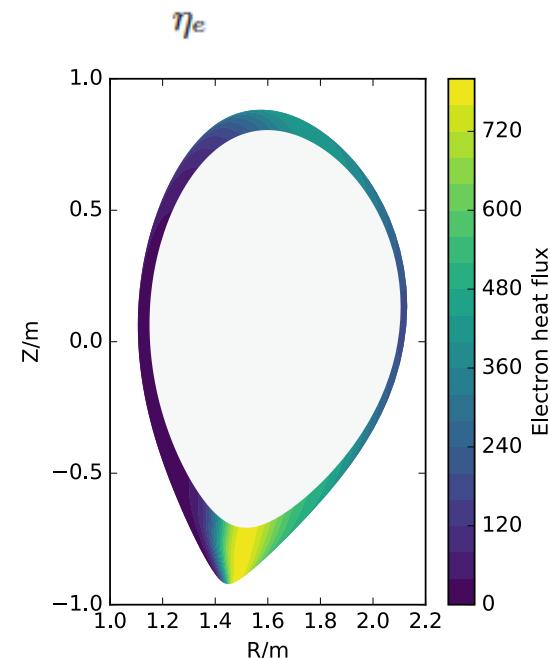
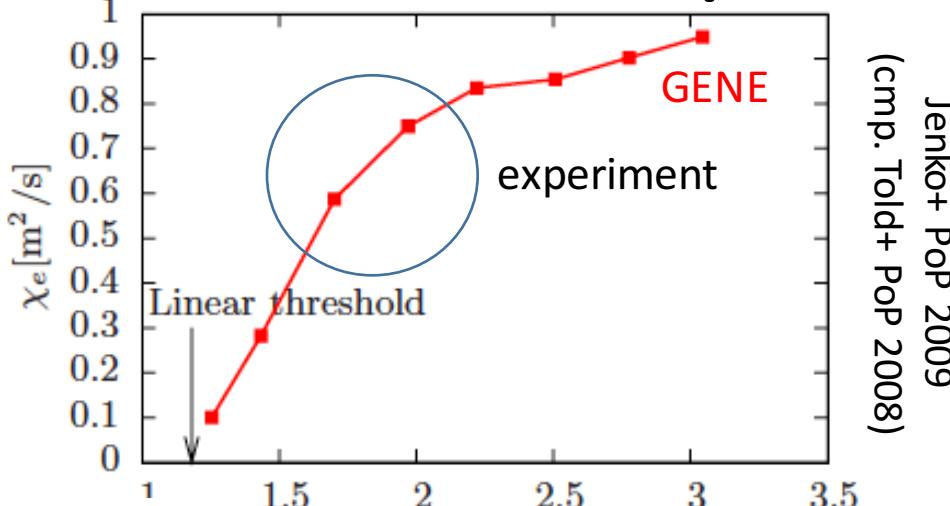
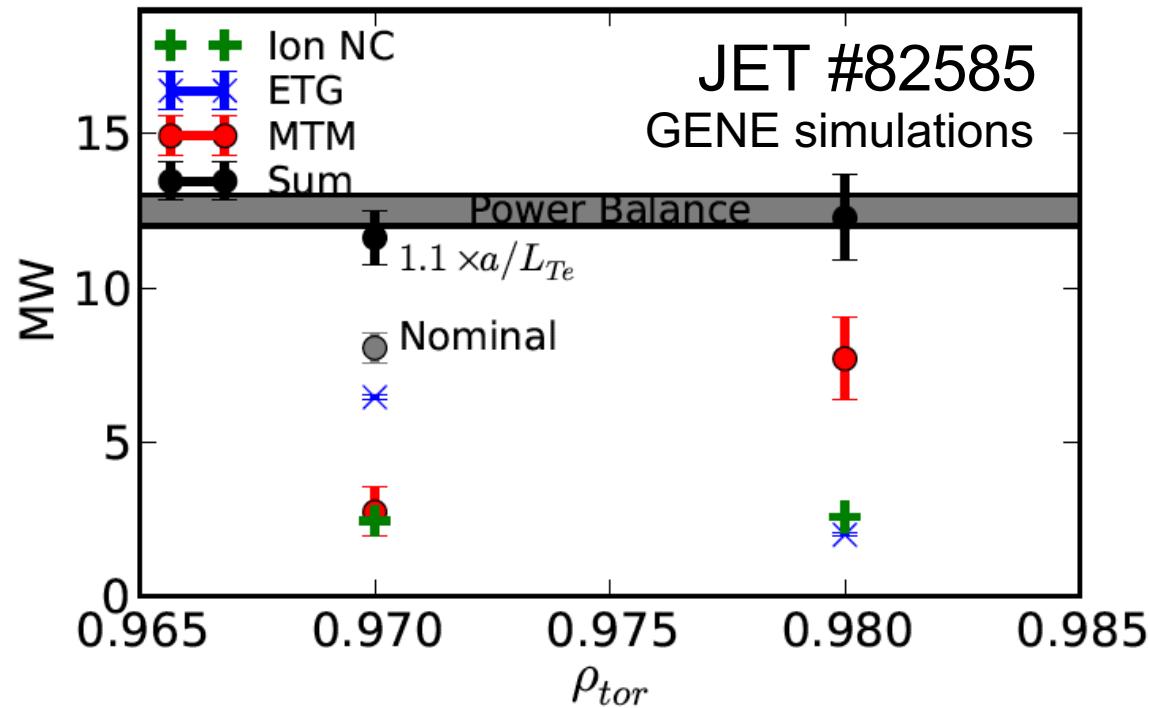
- micro-tearing mode excitations
- ETG-like instabilities up to rather large wavelengths
- Peaking near the X-point (large radial wavenumber)



ITER pedestal may differ from known pedestals

Dominant ion-scale microinstability in the **JET-ILW pedestal**: important role of microtearing modes, with additional contributions from electron scales and neoclassics

Hatch et al., NF 2016

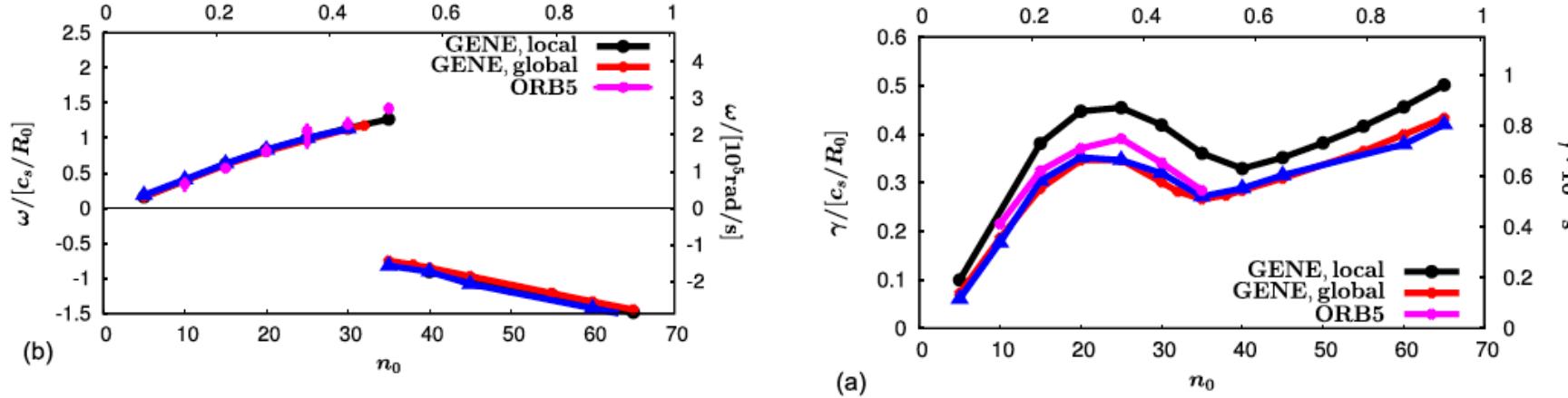


Recent achievements (3rd example): Verification, Validation & Uncertainty Quantification

Verification and validation

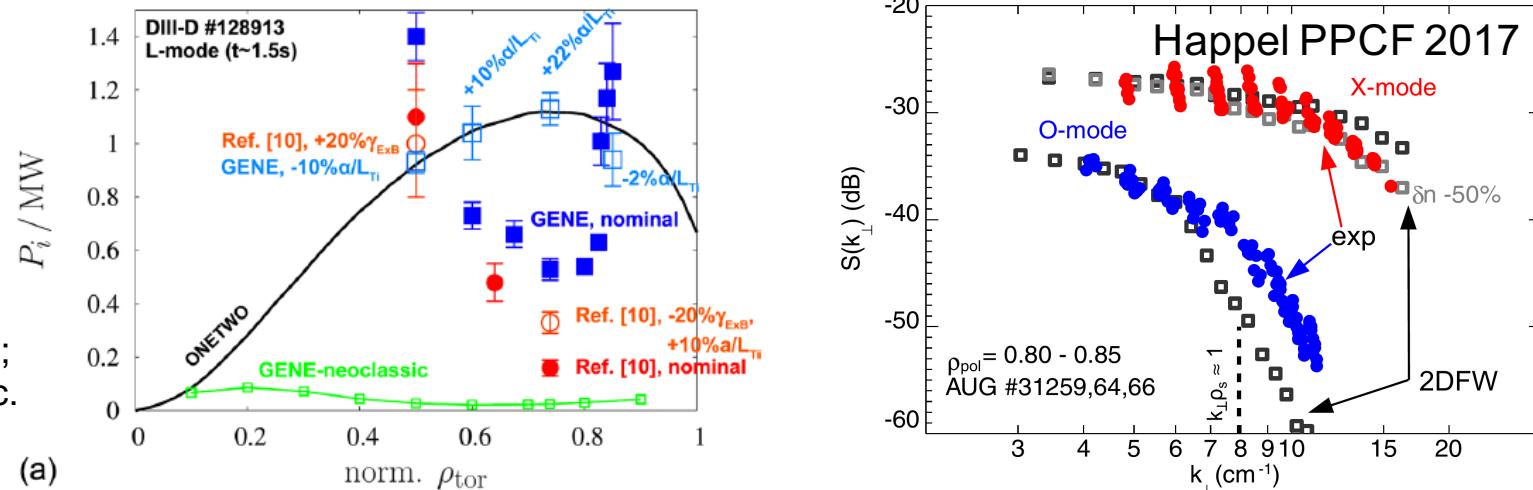
Code verification: Are we solving the equations right?

First benchmark of global electromagnetic GK codes [Görler PoP 2016]



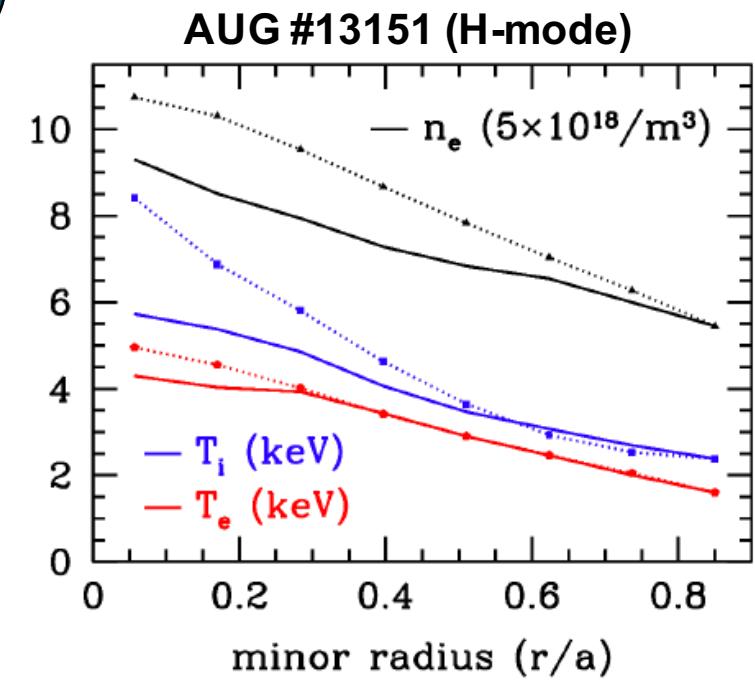
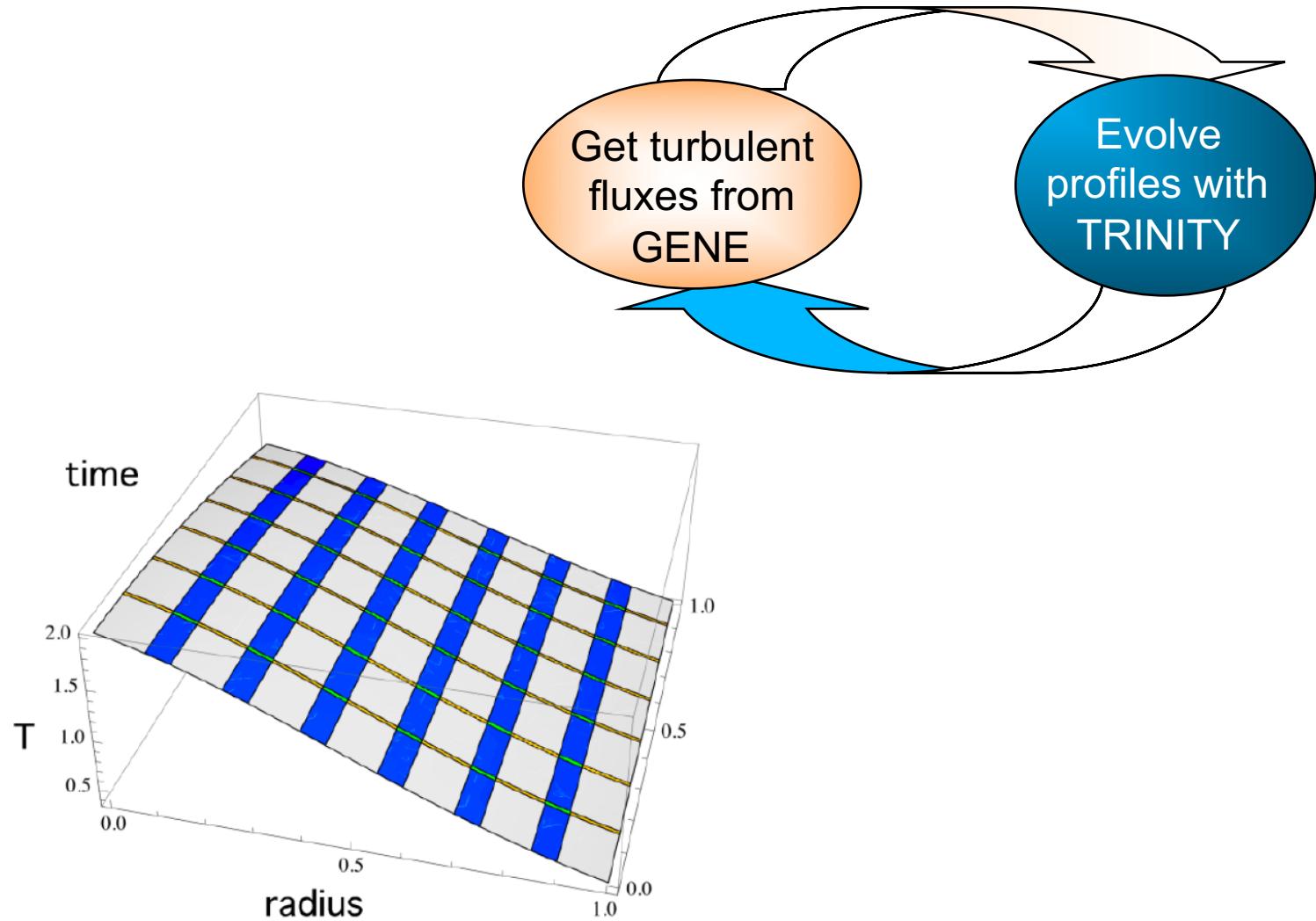
Code validation: Are we solving the right equations?

Can gyrokinetics describe outer-core L-mode plasmas? [Görler PoP 2014]

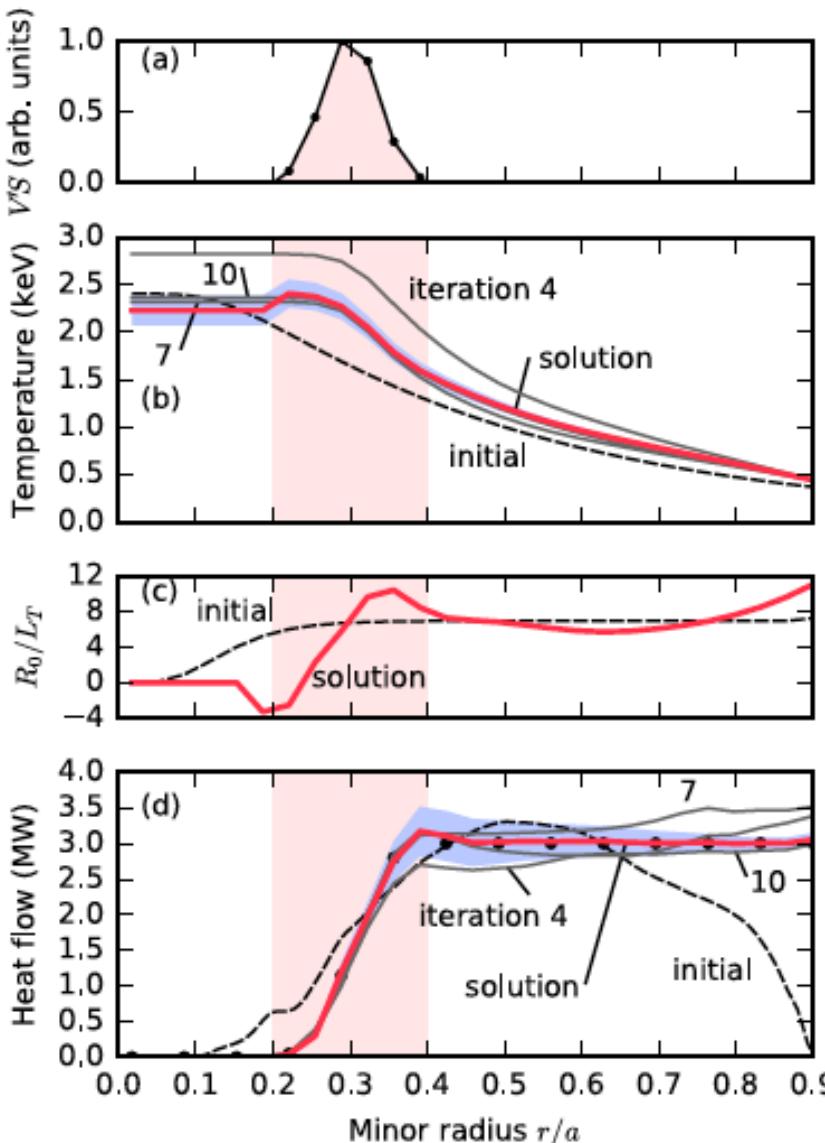


Cmp., e.g., Holland PoP 2009 & 2011;
Told PoP 2013; Navarro PoP 2015 etc.

Bridging turbulence and transport time scales



Extension to global gyrokinetic simulations



Global gyrokinetic code: GENE
Transport code: TANGO

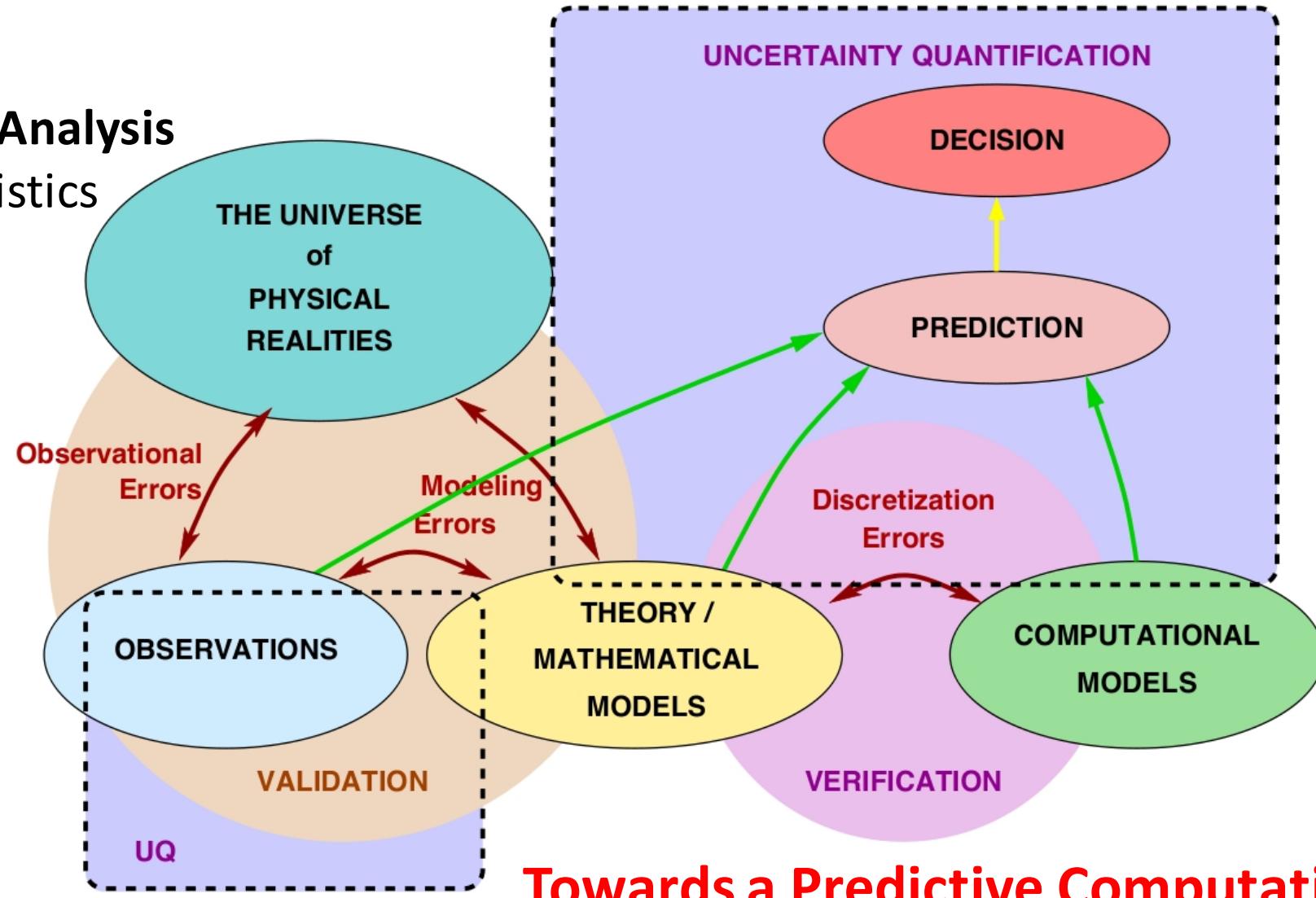
$$\frac{3}{2}V' \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} V' \hat{q} = V' S$$

$$\frac{3}{2}V' \frac{p_{m,l} - p_{m-1}}{\Delta t} + \partial_x [V' (-D_{m,l-1} \partial_x p_{m,l} + c_{m,l-1} p_{m,l})] = V' S_m$$

The crucial role of Uncertainty Quantification (UQ)

Example:

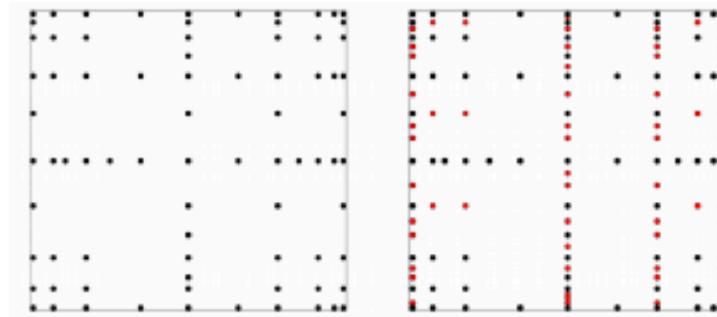
Integrated Data Analysis
via Bayesian statistics



Turbulence, transport, and UQ

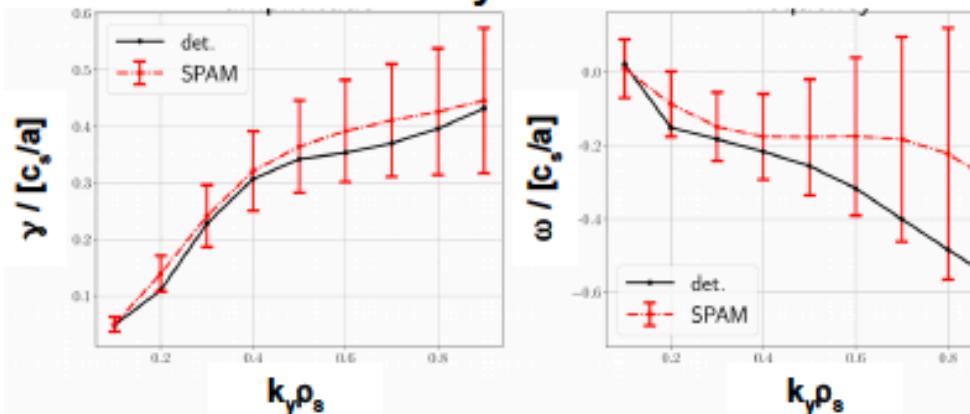
- clever approach needed to explore hyper-space/sensitivities w.r.t. physics inputs
- here: forward UQ study based on Sparse Pseudo-spectral Approximation Method (SPAM) [I.-G. Farcas et al.]
 - grid avoids internal aliasing error by construction, i.e. often found problem in sparse quadrature schemes
 - based on Leja points (nested & linearly increasing with dimensionality)
[A. Narayan and J. D. Jakeman, SIAM J. Sci. Comput. 36, A2952 (2014)]
 - a lot fewer grid points required
 - ultimately, application to turbulence

example illustration of a Leja grid for 2 stochastic inputs

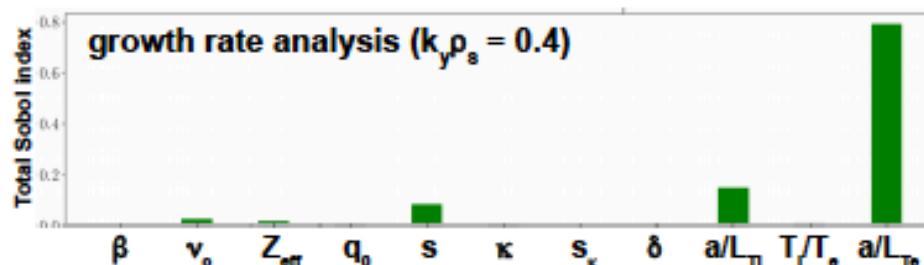


Standard 2D Leja grid (left), refined 2D Leja grid (red points, right)

11D linear study for AUG 33585



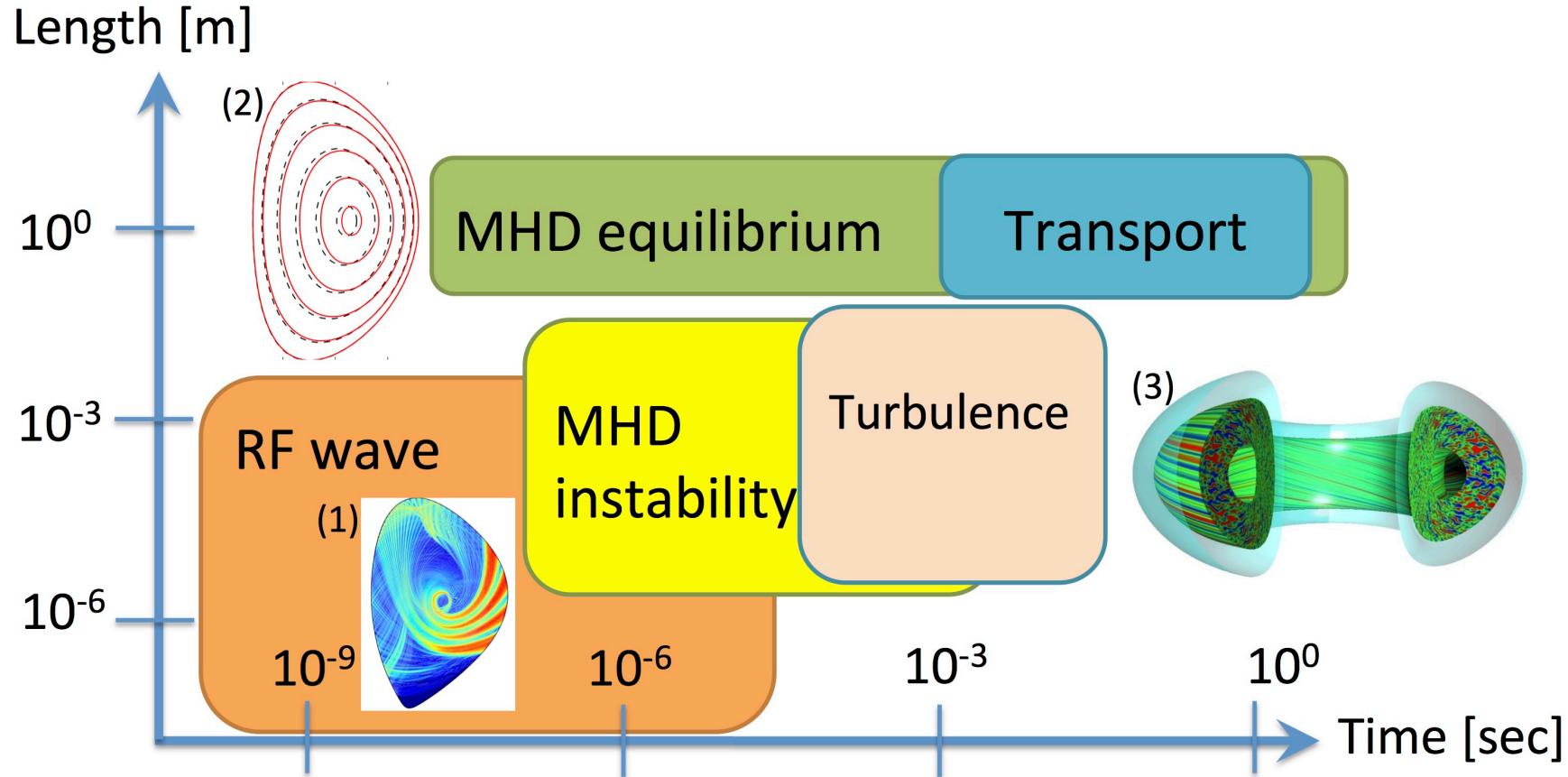
I.-G. Farcas et al., QUIET 2017, Trieste





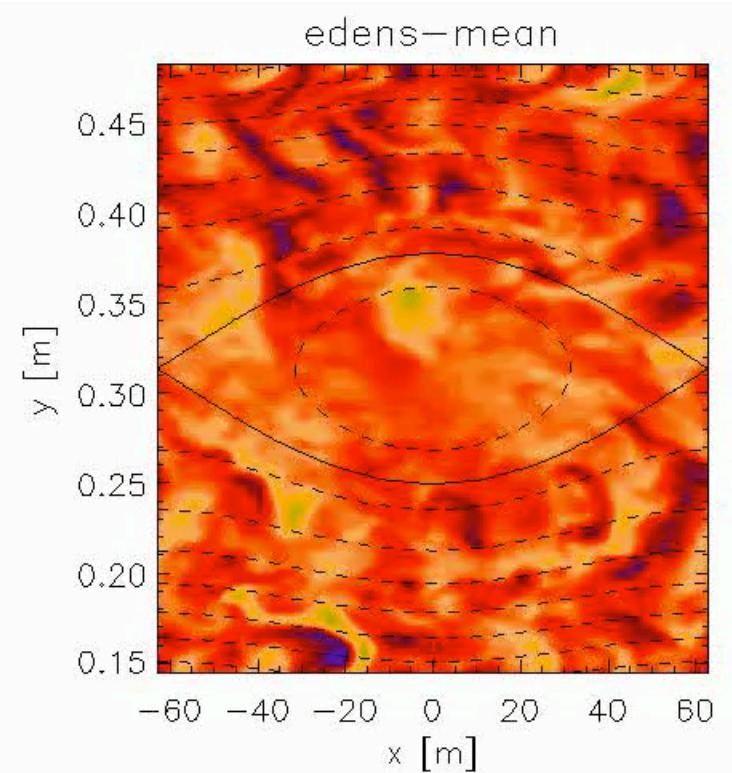
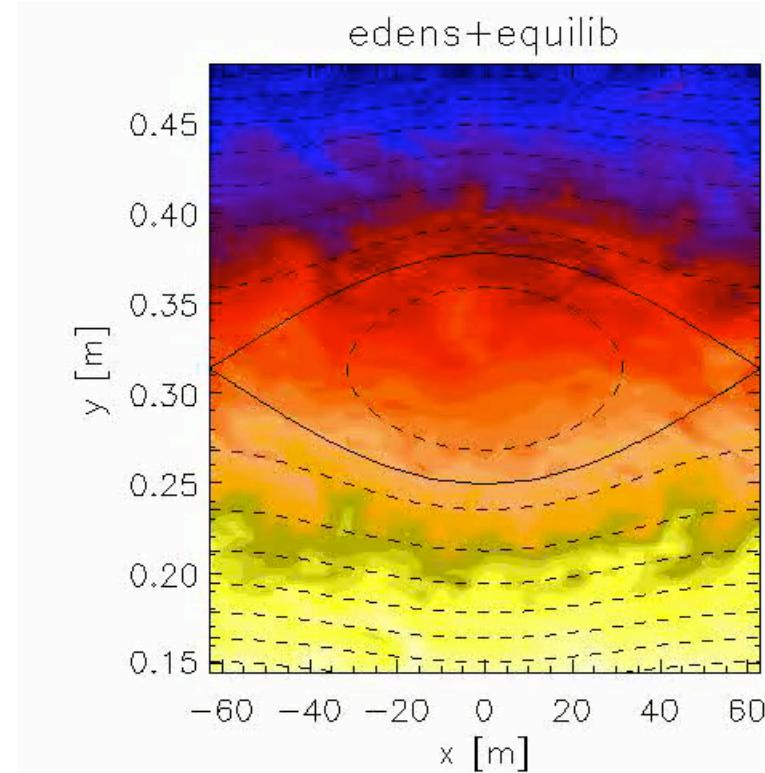
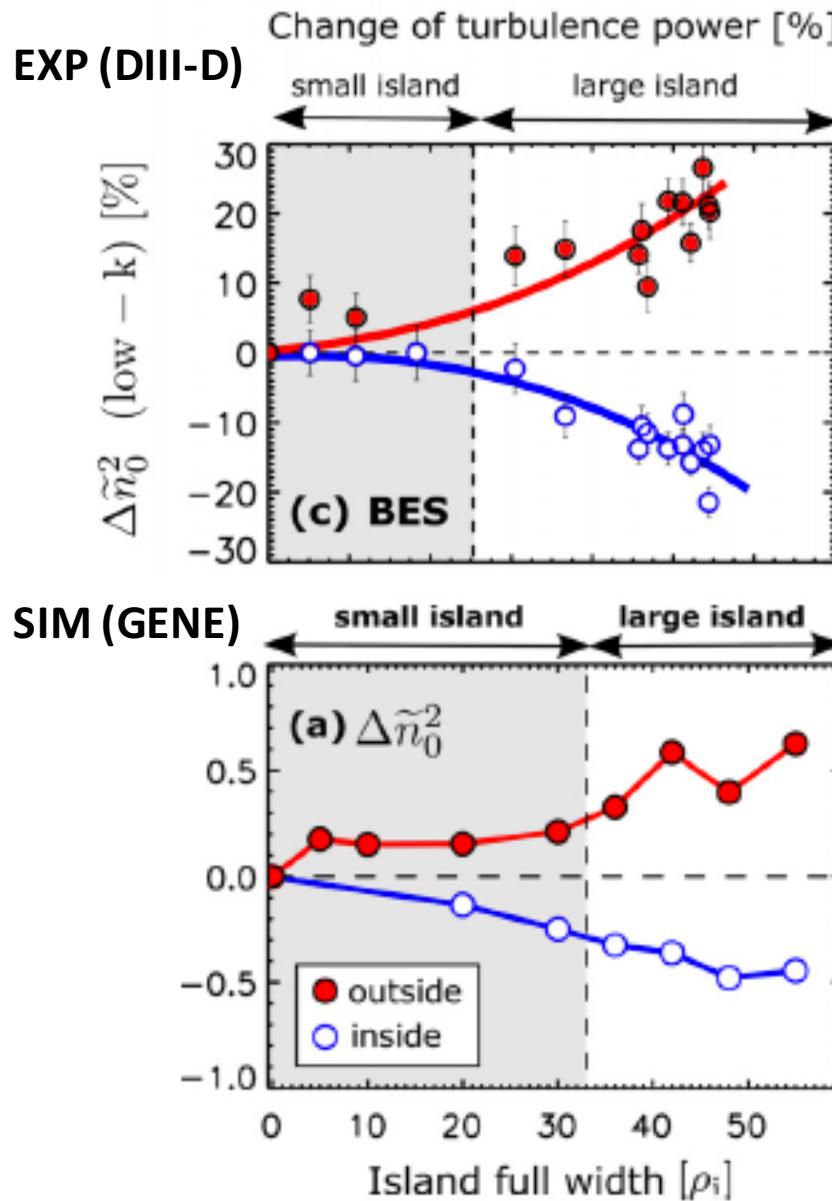
**New opportunities (1st example):
Connecting different physical processes**

The multiscale, multiphysics challenge



Many nonlinear interactions; we cannot use a simple “superposition principle”

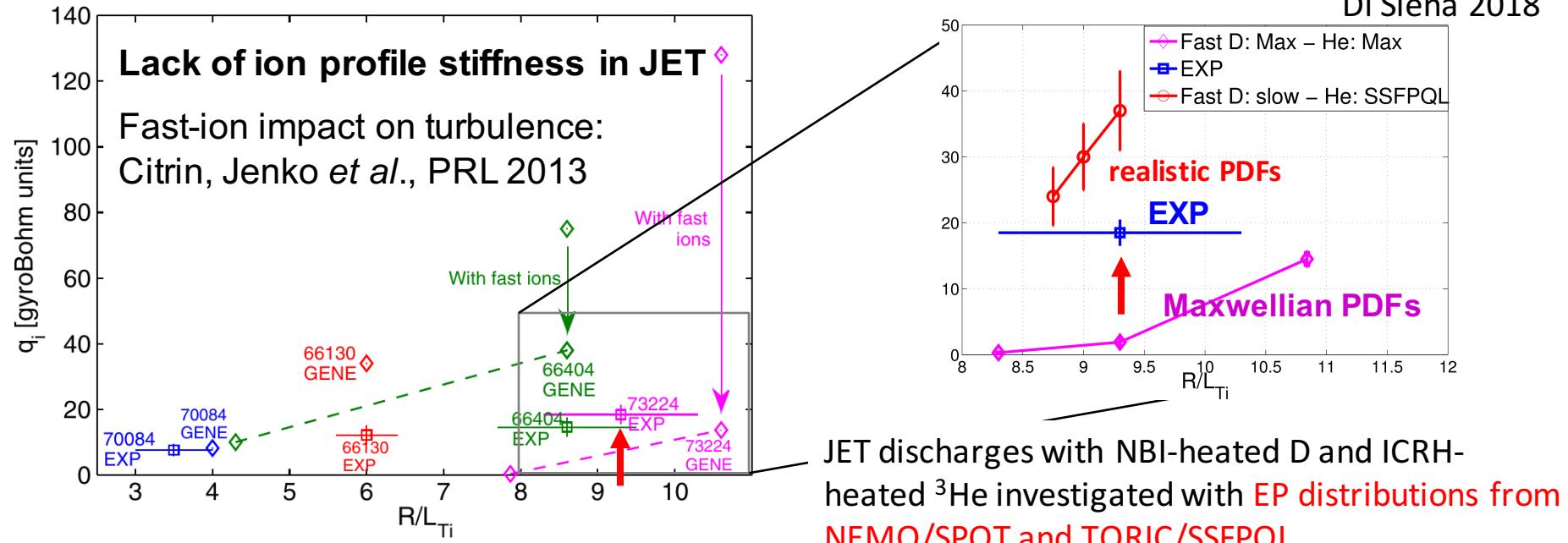
Turbulence in the presence of magnetic islands



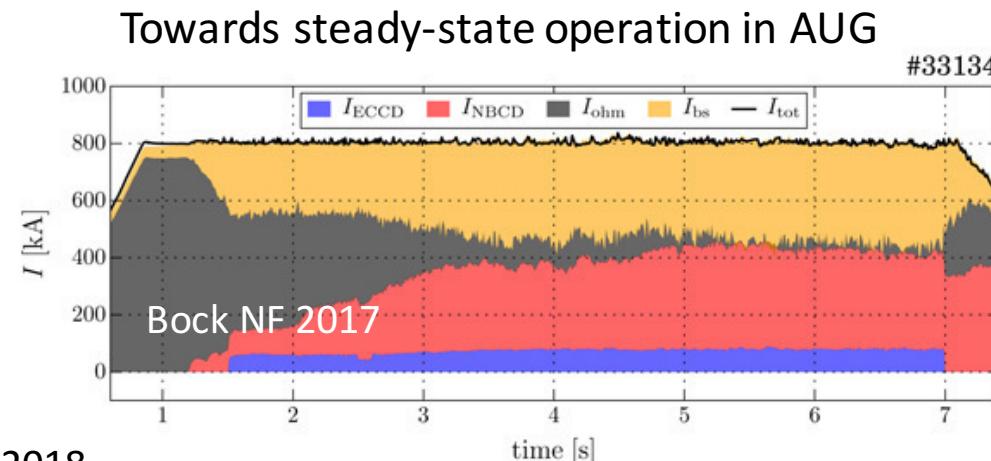
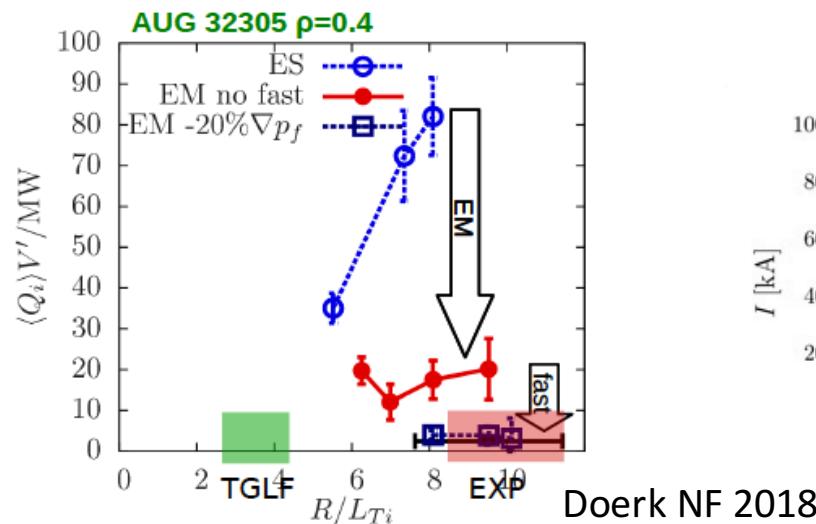
Bañón Navarro+ PPCF 2017
Bardóczi PoP 2017
(cmp. Hornsby+ PPCF 2016)

Turbulence in the presence of energetic particles

Di Siena 2018

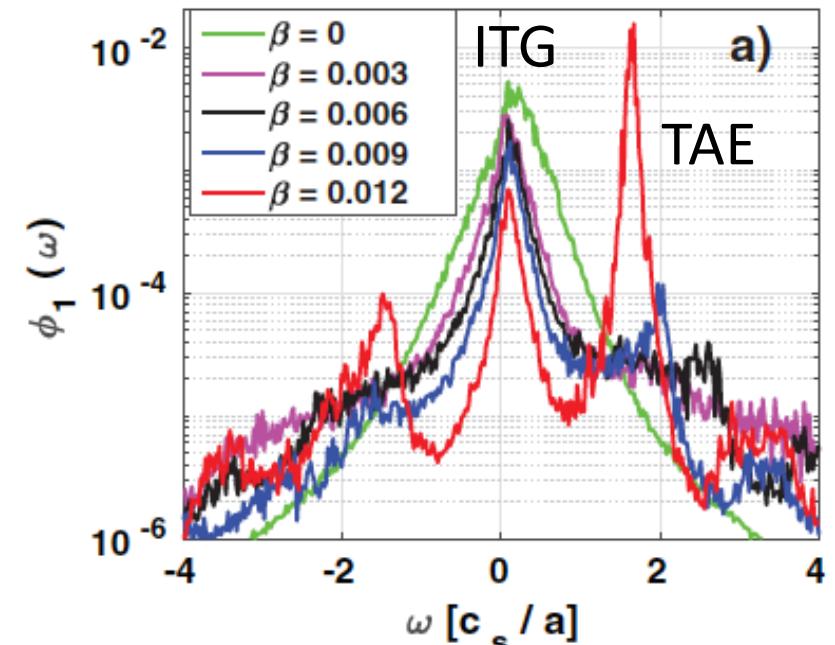
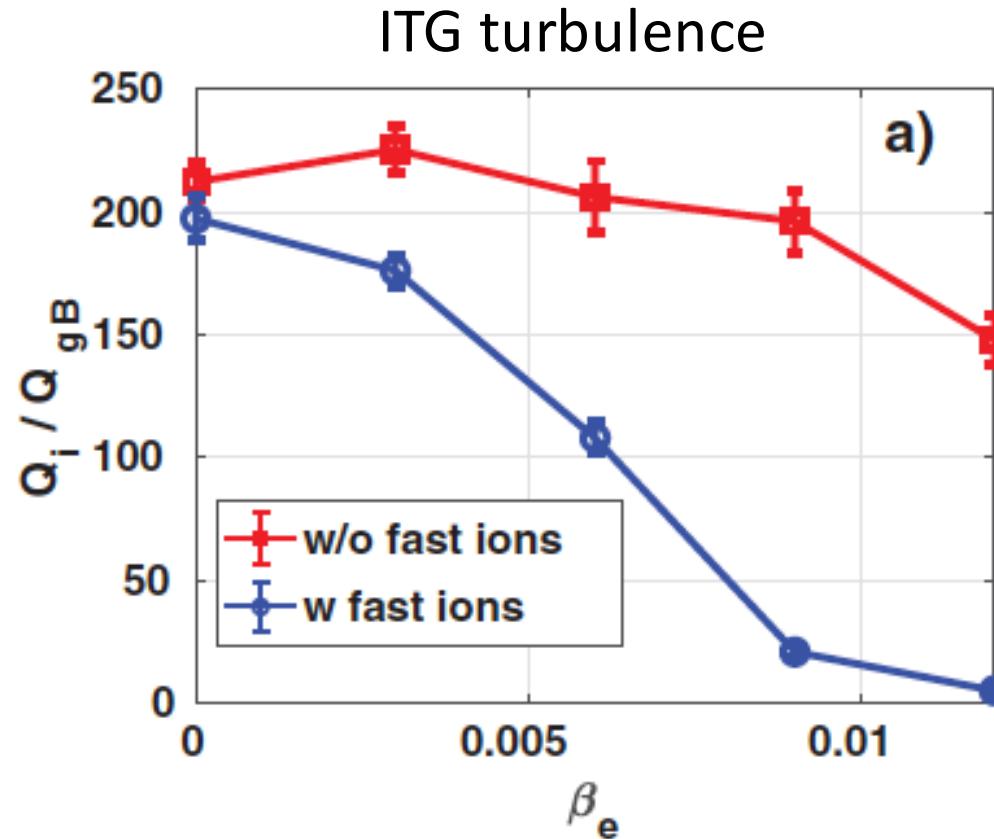


From JET to AUG advanced scenarios



Turbulence suppression by EP-driven modes

Di Siena et al. NF 2019

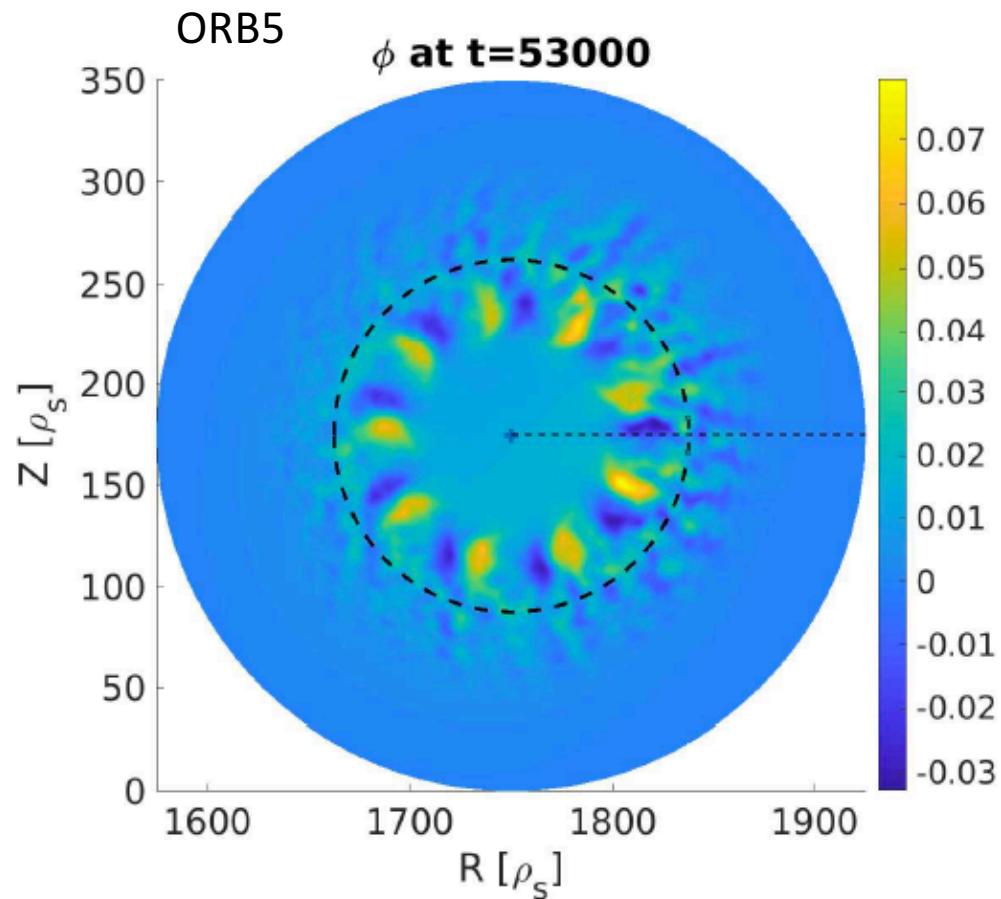


Linearly stable TAEs are nonlinearly excited by the ITG turbulence, leading to an enhancement of ZF activity and a suppression of the ITG turbulence

Interaction of Alfvénic modes and turbulence

Physics of energetic particles included in GK turbulence simulations;
both phenomena are treated on the same footing

Important step towards better understanding of burning plasmas



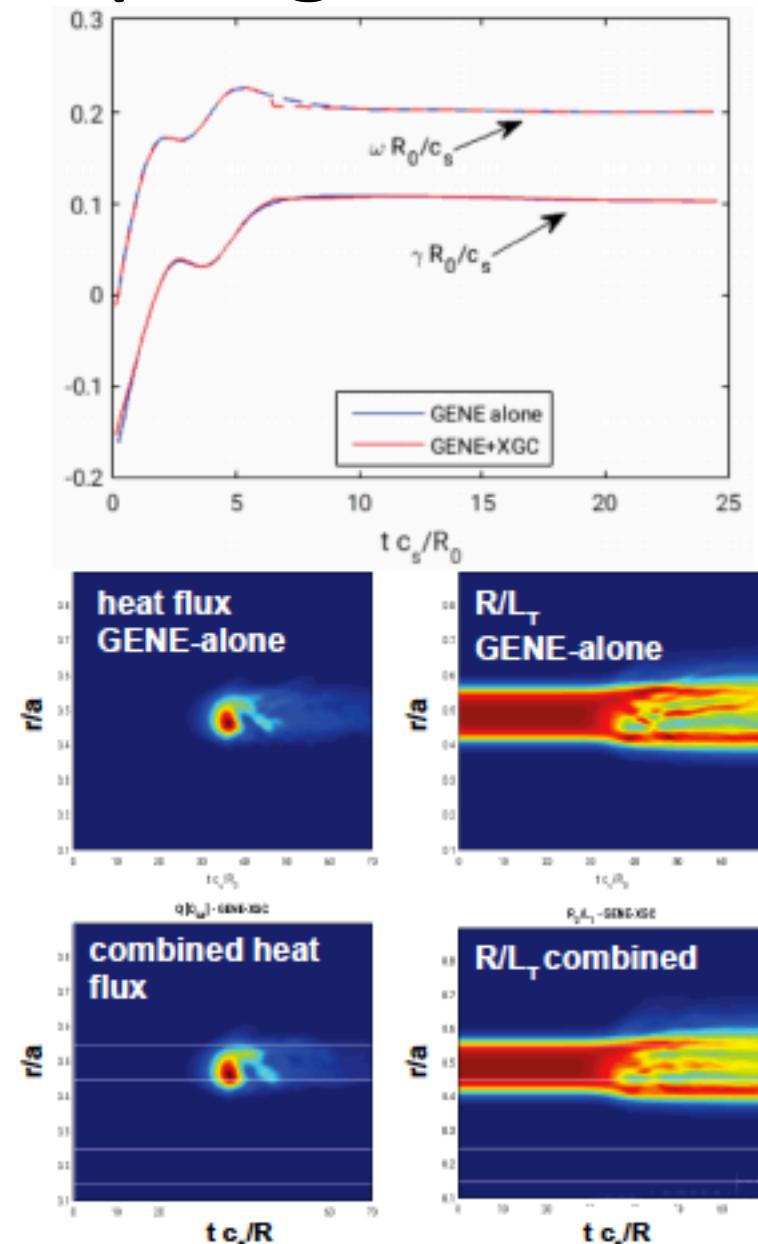
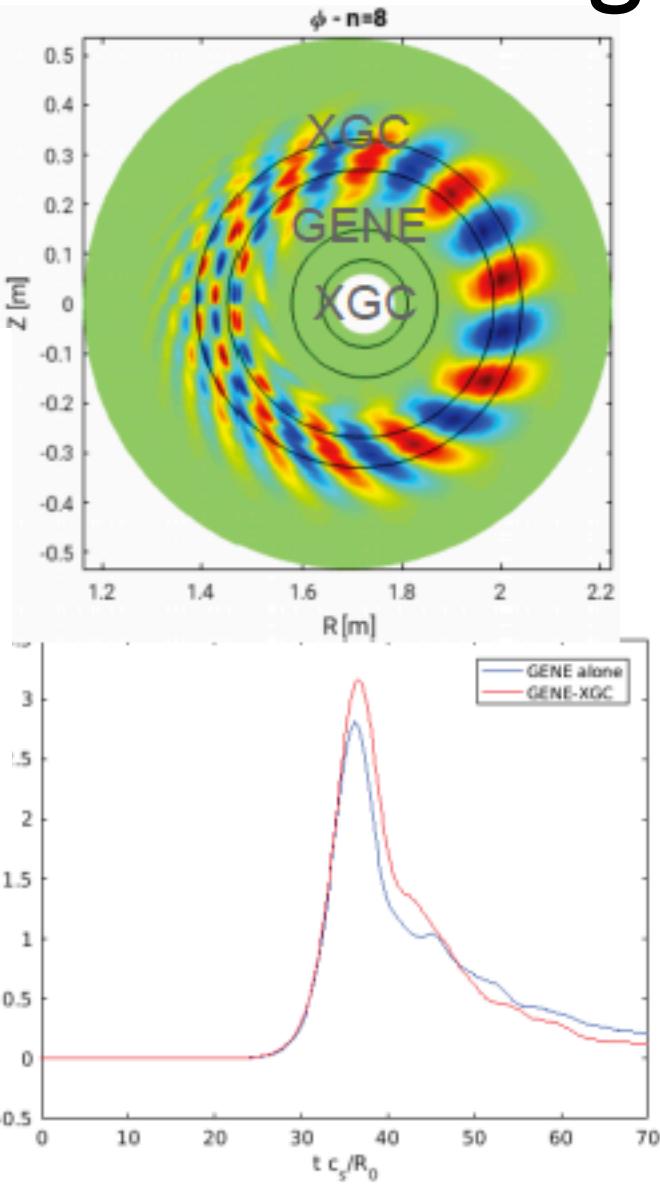
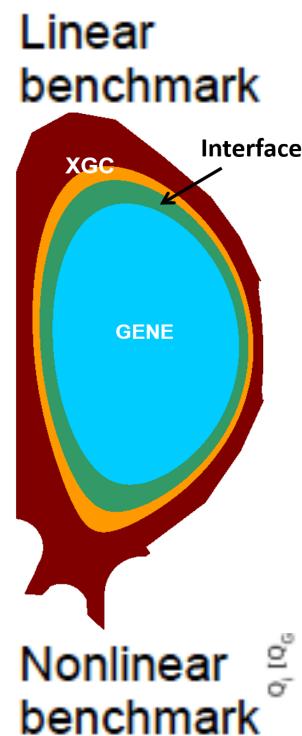
Poloidal cross section of a
Beta-induced Alfvén Eigenmode
(BAE) excited by an EP population
in the presence of ITG turbulence

A. Biancalani et al., to be published



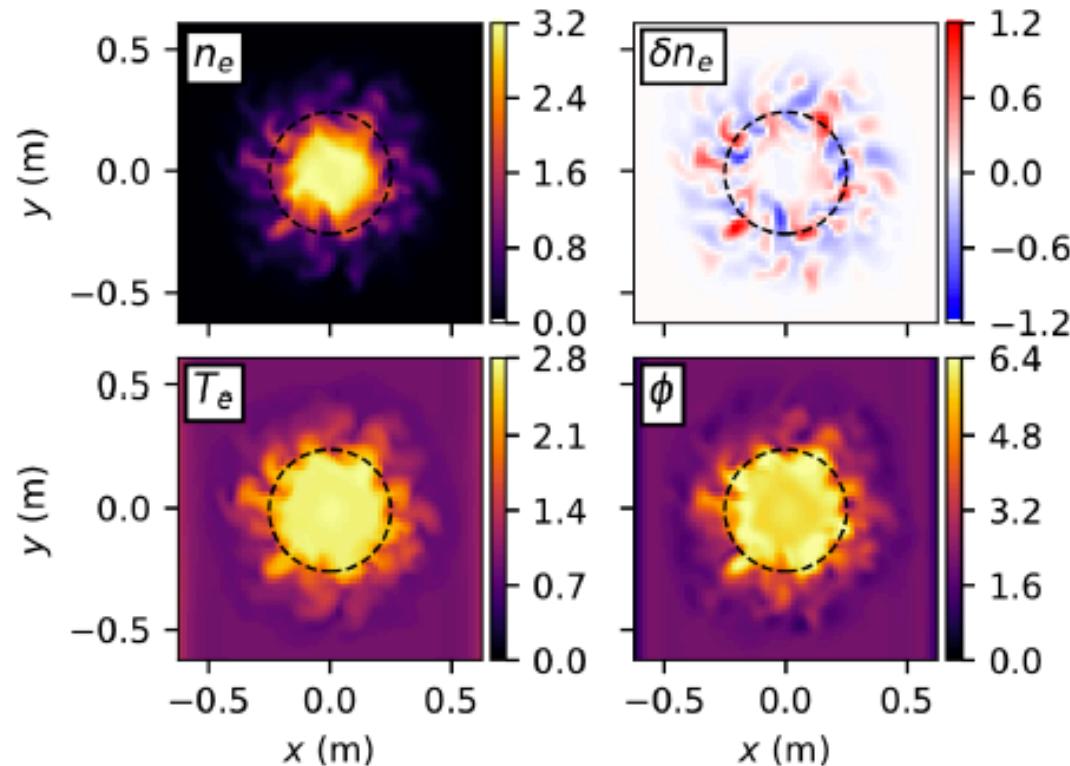
**New opportunities (2nd example):
Taking GK from the core into the SOL**

Whole-device modeling: Coupling GENE & XGC



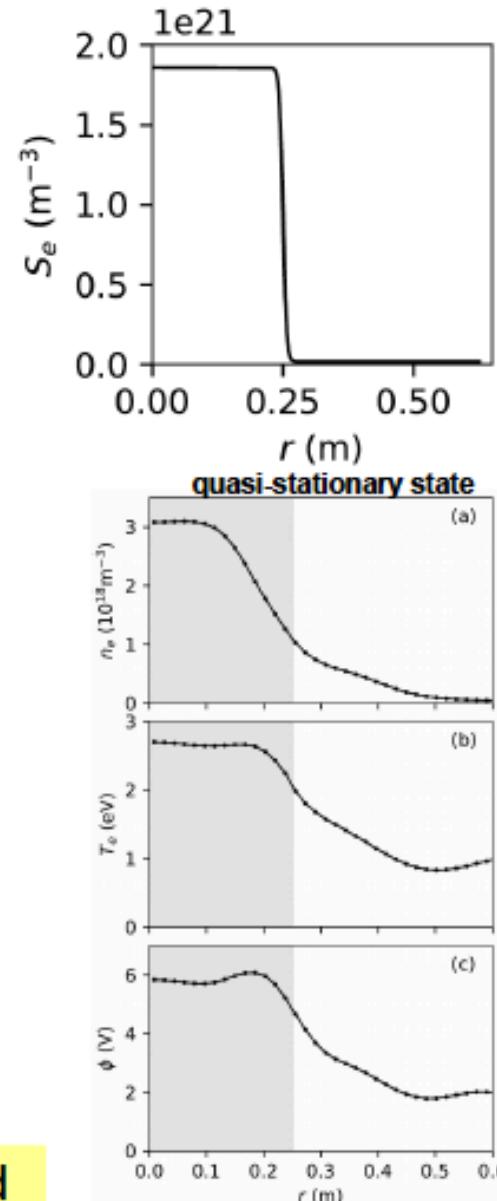
Full-f version of GENE for the SOL

- LAPD-like parameters [Rogers and Ricci, PRL (2010); Shi et al., JPP (2017)]
- two simplifications: reduced mass ratio ($m_i/m_e = 400$) and collisions ($0.01 v_{ee}/v_{ei}$ and $0.1 v_{ii}$)
- top-hat-like source (uniform along z) modeling ionization of neutrals by primary electrons



Pan et al., PoP 2018

Statistical features from exp. and previous sims reproduced



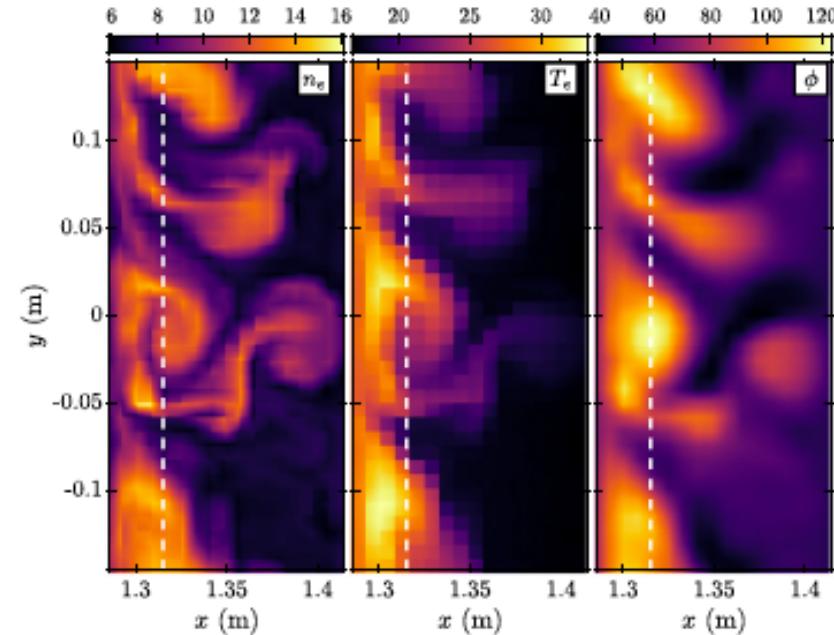
Some other efforts to take GK into the SOL

COGENT (M. Dorf et al.): Full-f grid-based code

Gkeyll (A. Hakim et al.): Full-f grid-based code

GYSELA-X (Y. Sarazin et al.): Full-f Semi-Lagrangian code

PICLS (M. Boesl et al.): Full-f PIC code



Shi et al., PoP 2019

Current status: 3D implementation



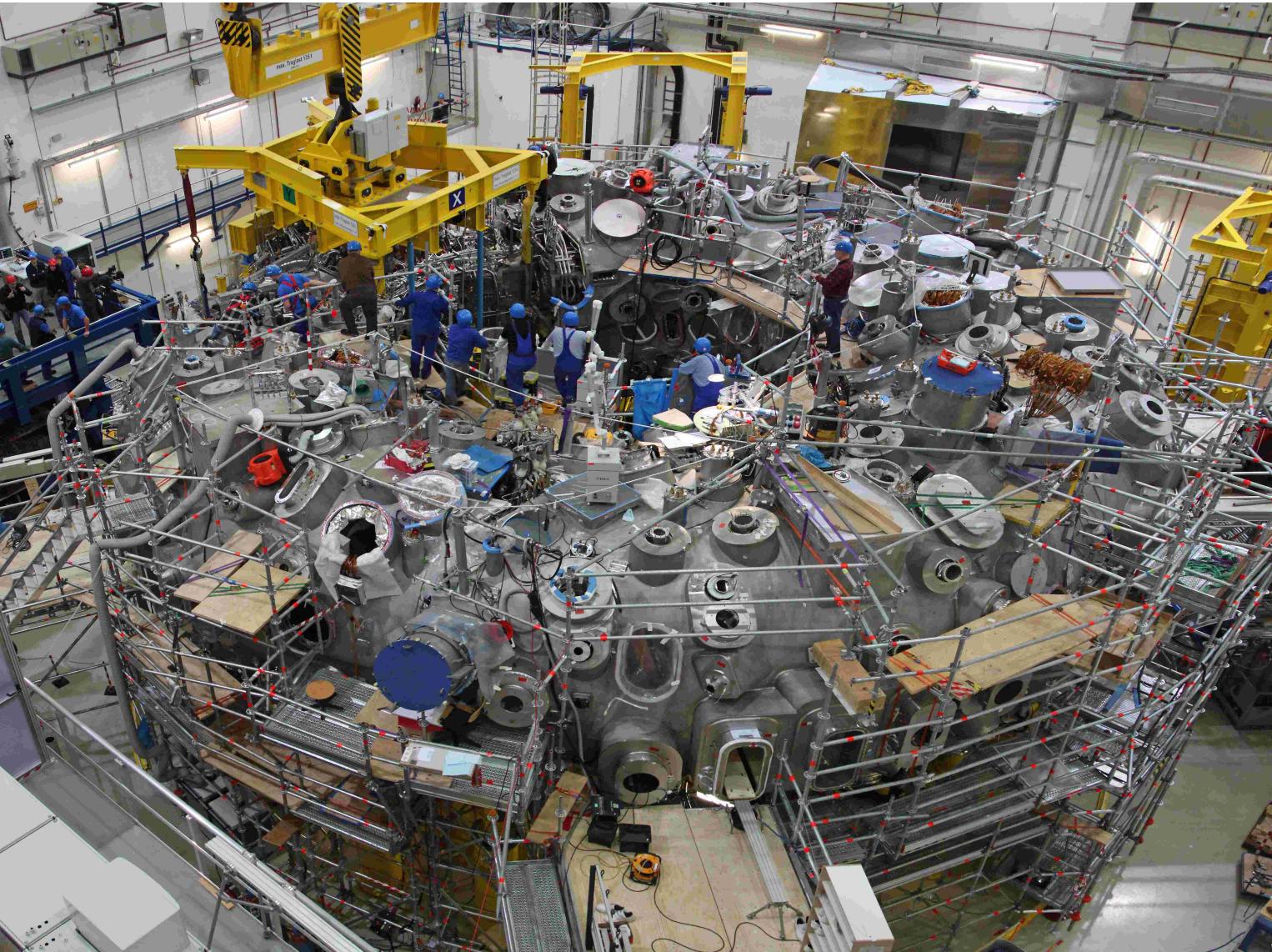


**New opportunities (3rd example):
“Transport-by-design” for stellarators**

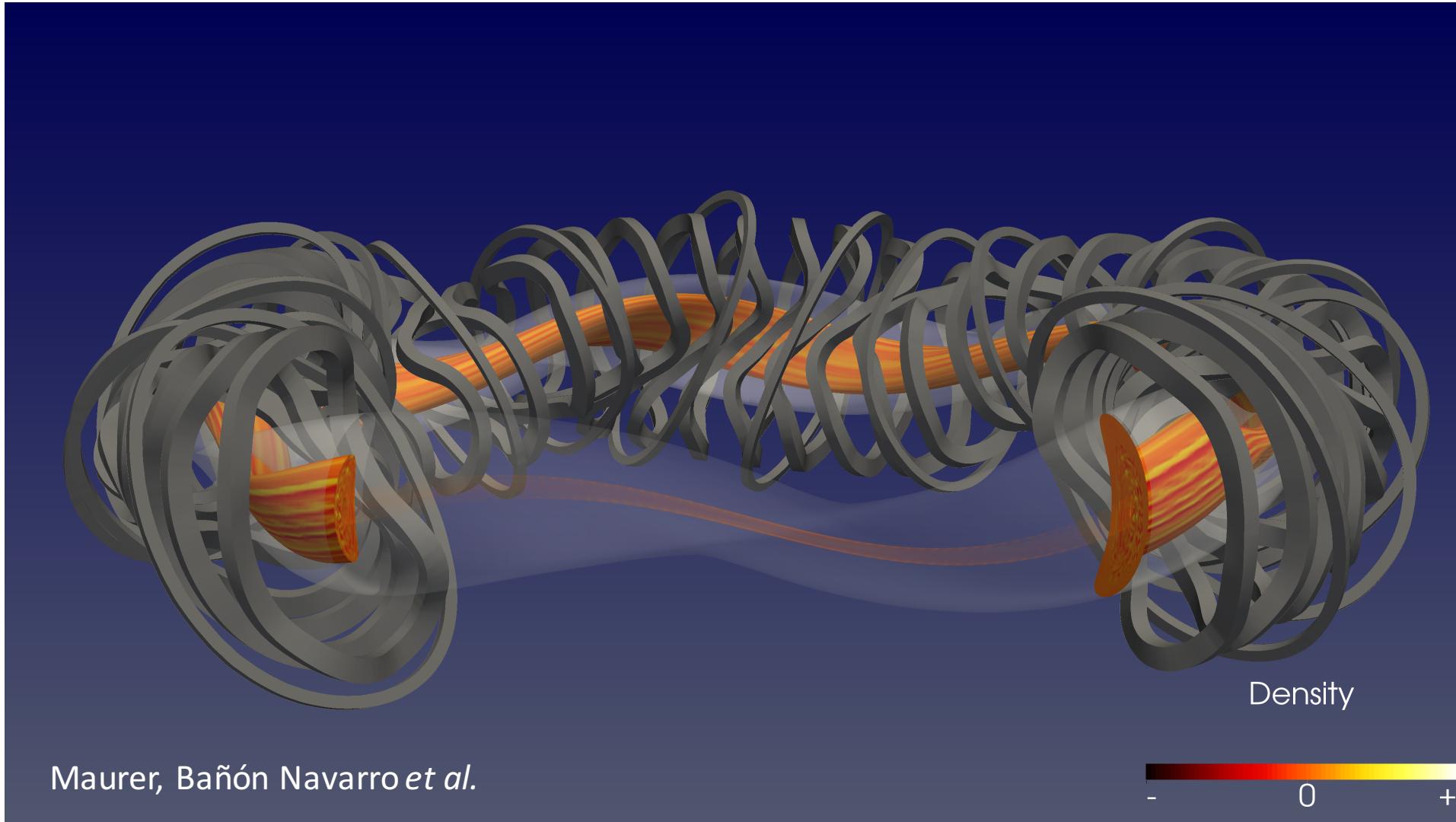
Optimized stellarators: Wendelstein 7-X (2015-)

Complex plasma shape, optimized via HPC

Next step: Take turbulence into account



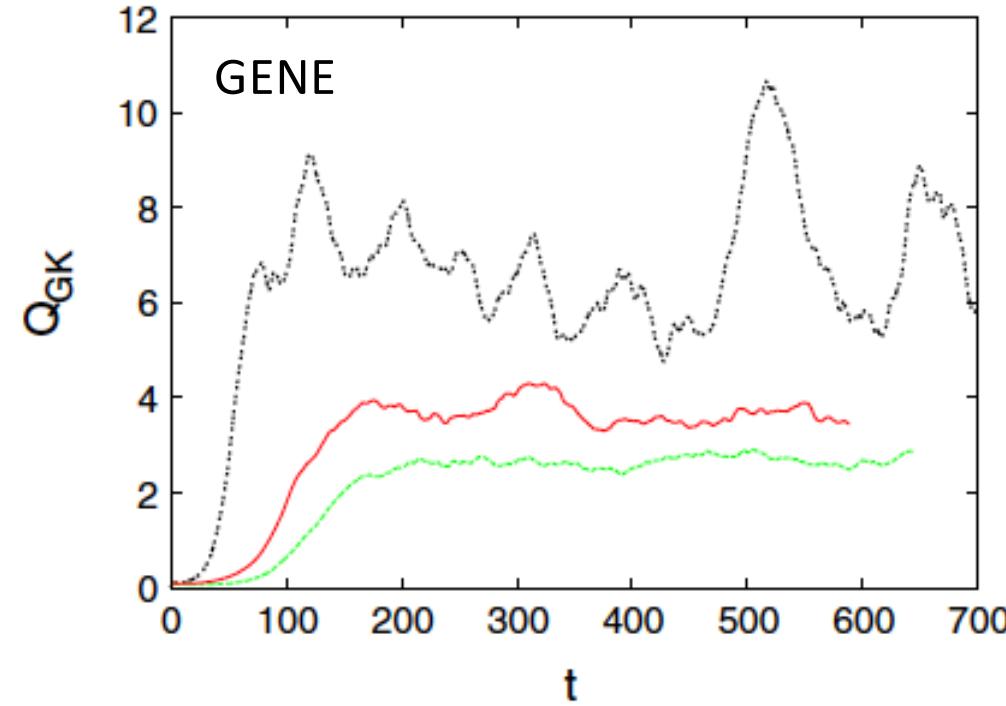
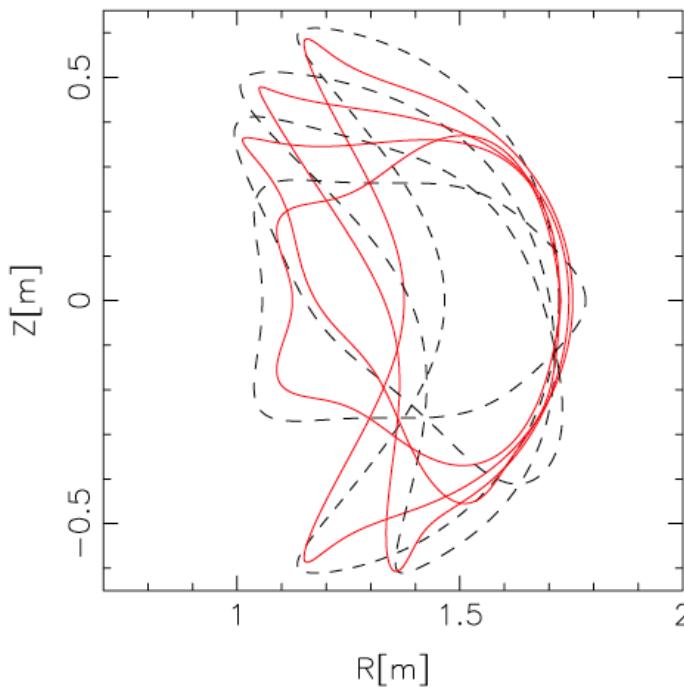
New GENE-3D code: Applications to W7-X



GENE-3D is a full-torus (“global”) gyrokinetic turbulence code for non-axisymmetric geometries like stellarators or perturbed tokamaks

Vision: “Transport-by-design”

Proof-of-principle: Magnetic geometries, optimized for turbulent transport via successive MHD equilibria, using simple “cost functions” and GK simulations



Mynick+ PRL 2010

Xanthopoulos+ PRL 2014

Terry+ PoP 2018

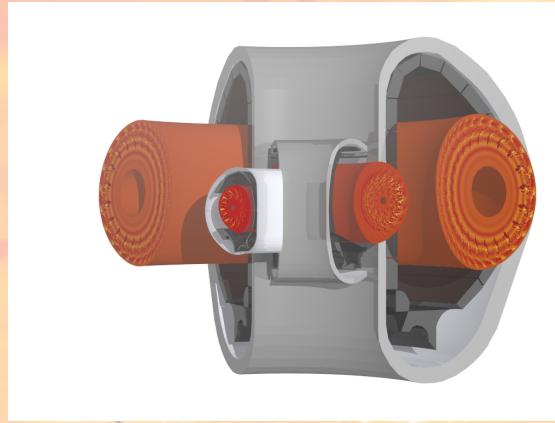
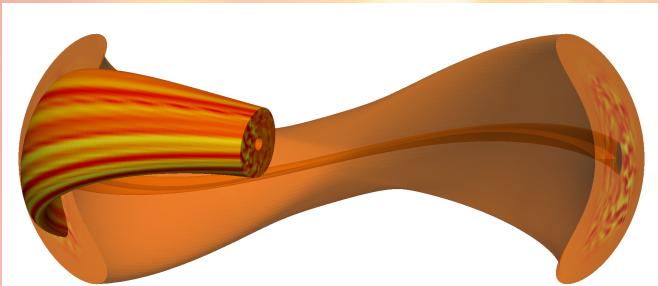
Hegna+ PoP 2018

Lobsien+ submitted to NF

The background of the image is a vibrant orange color with a subtle gradient. It features numerous small, semi-transparent circular particles in shades of red, orange, and yellow, some with a slight glow. Overlaid on this are several thin, white, curved lines that form a network or web-like pattern, radiating from the center towards the edges.

Outlook

The big picture



In recent years, enormous progress has been made in the area of computational gyrokinetics, increasingly **explaining experiments qualitatively and quantitatively**

New opportunities include the self-consistent description of different physical processes, the application of GK simulations to the SOL, and "transport-by-design" for stellarators (and tokamaks)

Overarching goal: Contribute to the **gradual development of a validated predictive capability ("virtual fusion plasma")**, helping to accelerate fusion energy research