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Progress towards a numerical tokamak

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Universität Ulm

Advanced Workshop on “Fusion and Plasma Physics”
October 3 – 14, 2011
Trieste, Italy

Some introductory remarks

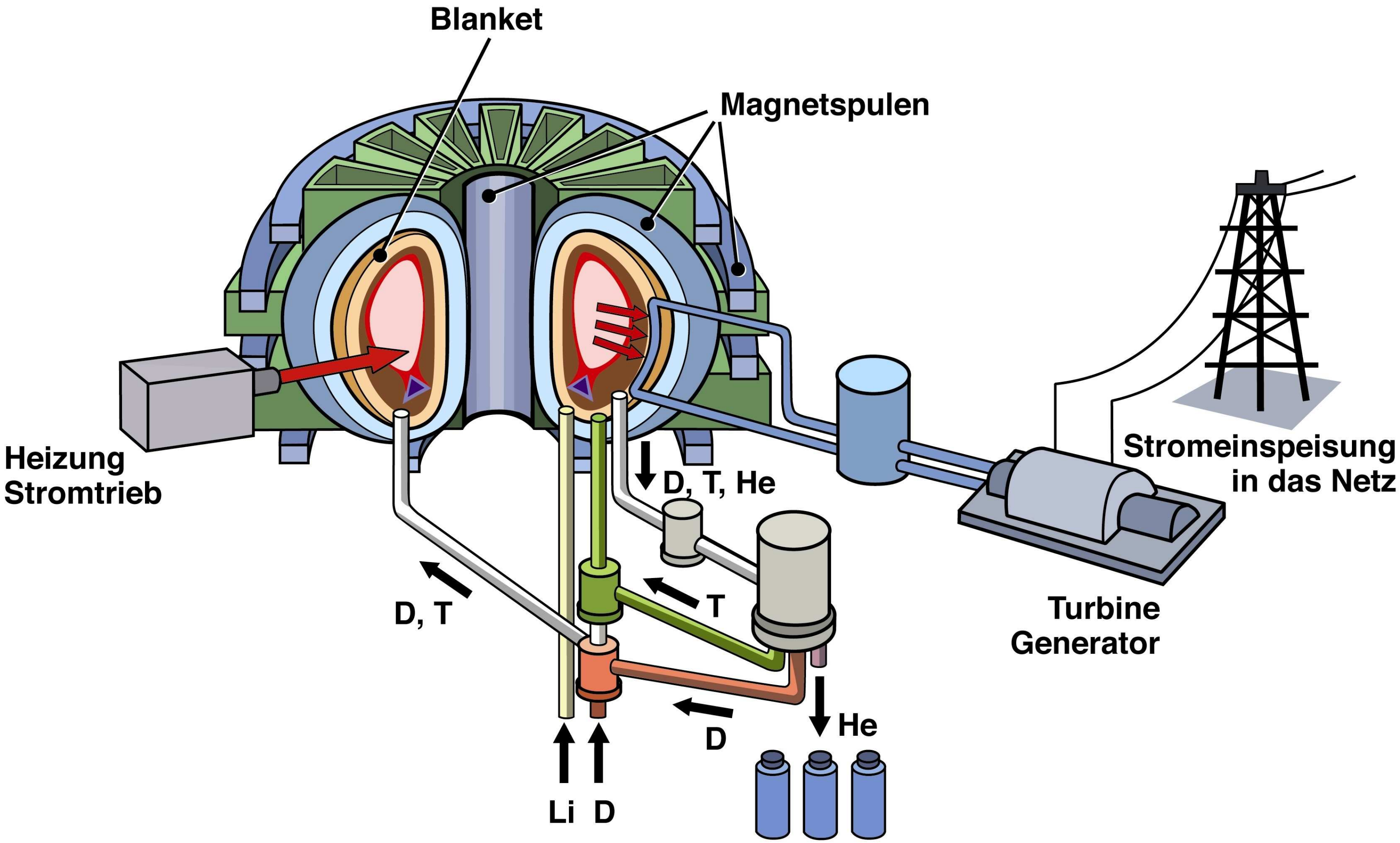
Building on the previous two lectures, it is finally time to address some key issues concerning the ITER project

I will attempt to present the material in an accessible way

Please feel free to interrupt me if you have a question

ITER and the quest for fusion energy

Schematic of a fusion power plant



Fusion research: Towards ignition

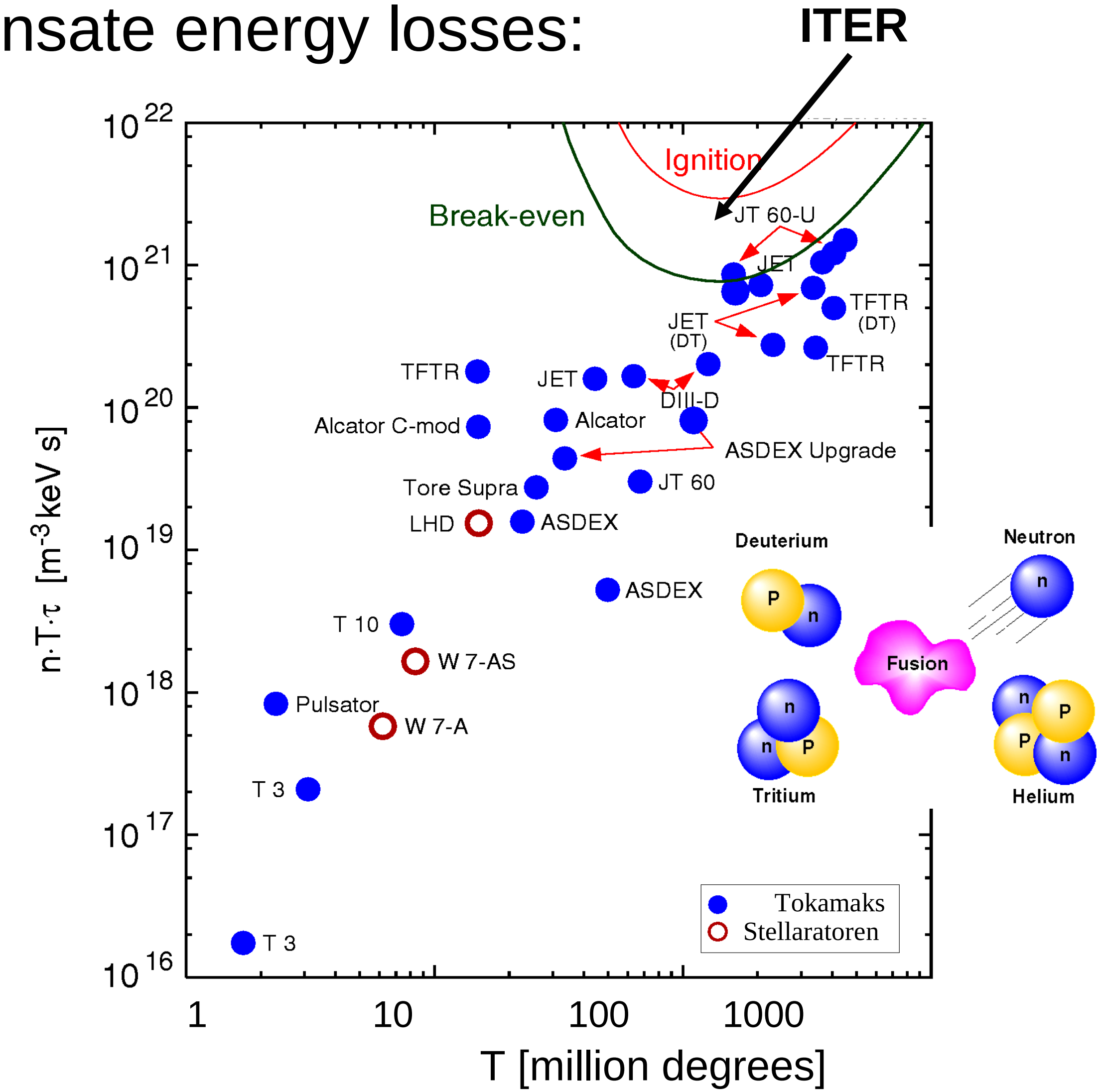
α heating must compensate energy losses:

- **Electromagnetic radiation**
- **Turbulent transport**

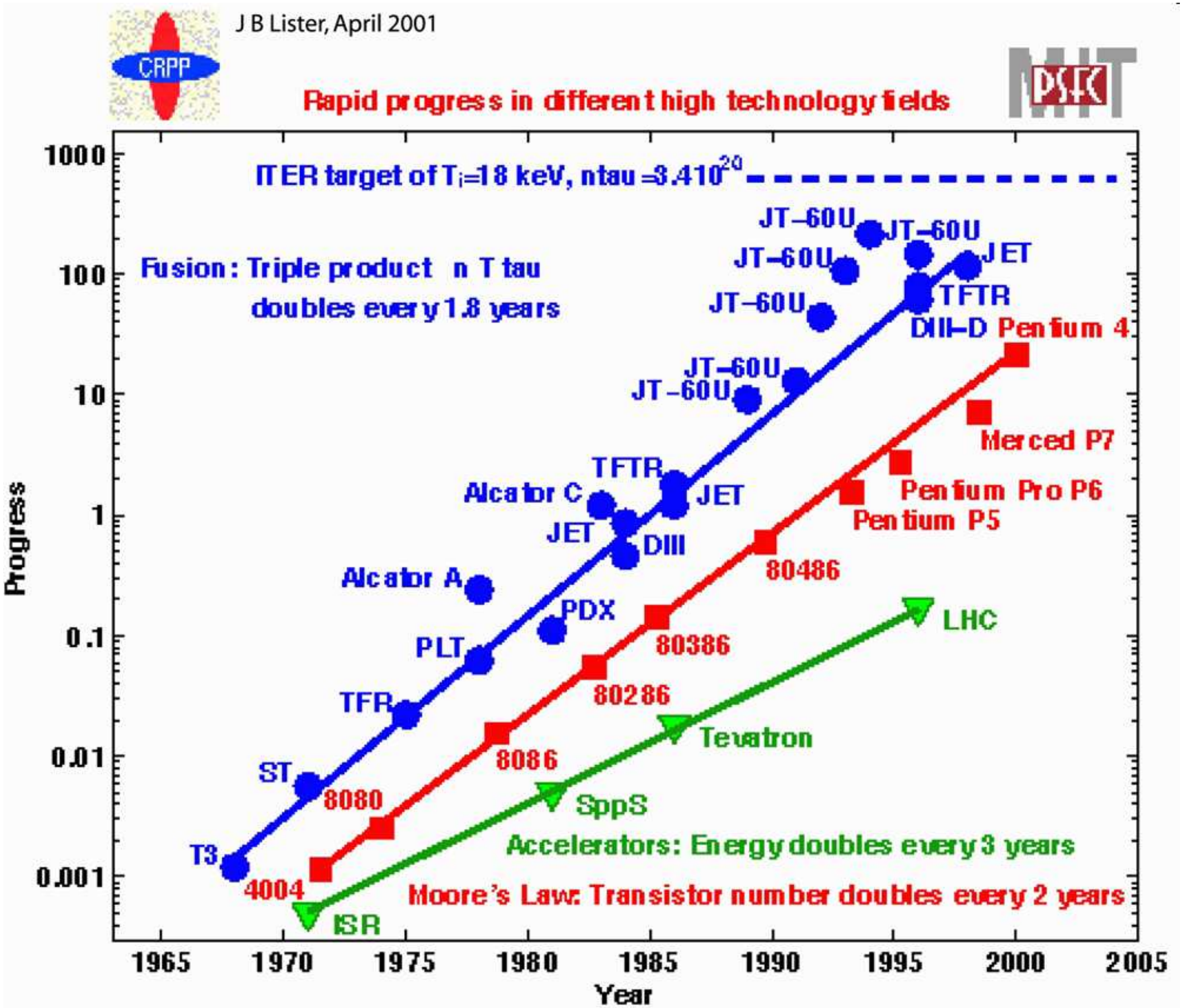
Key requirements:

- **Large central pressure (limited by onset of large-scale instabilities)**
- **Large energy confinement time (limited by small-scale instabilities, i.e. turbulence)**

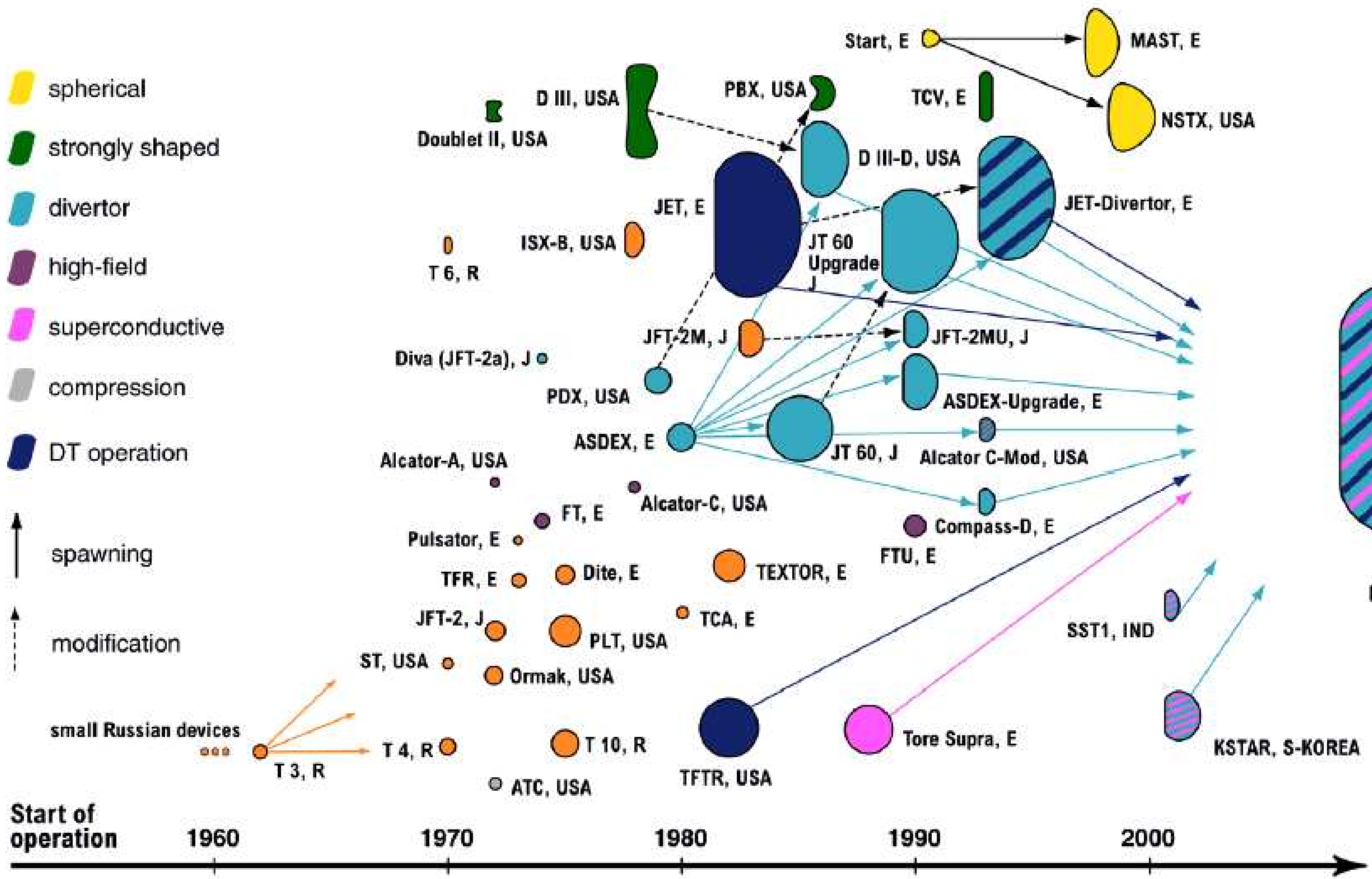
$$\tau_E = E_{plasma} / P_{loss}$$



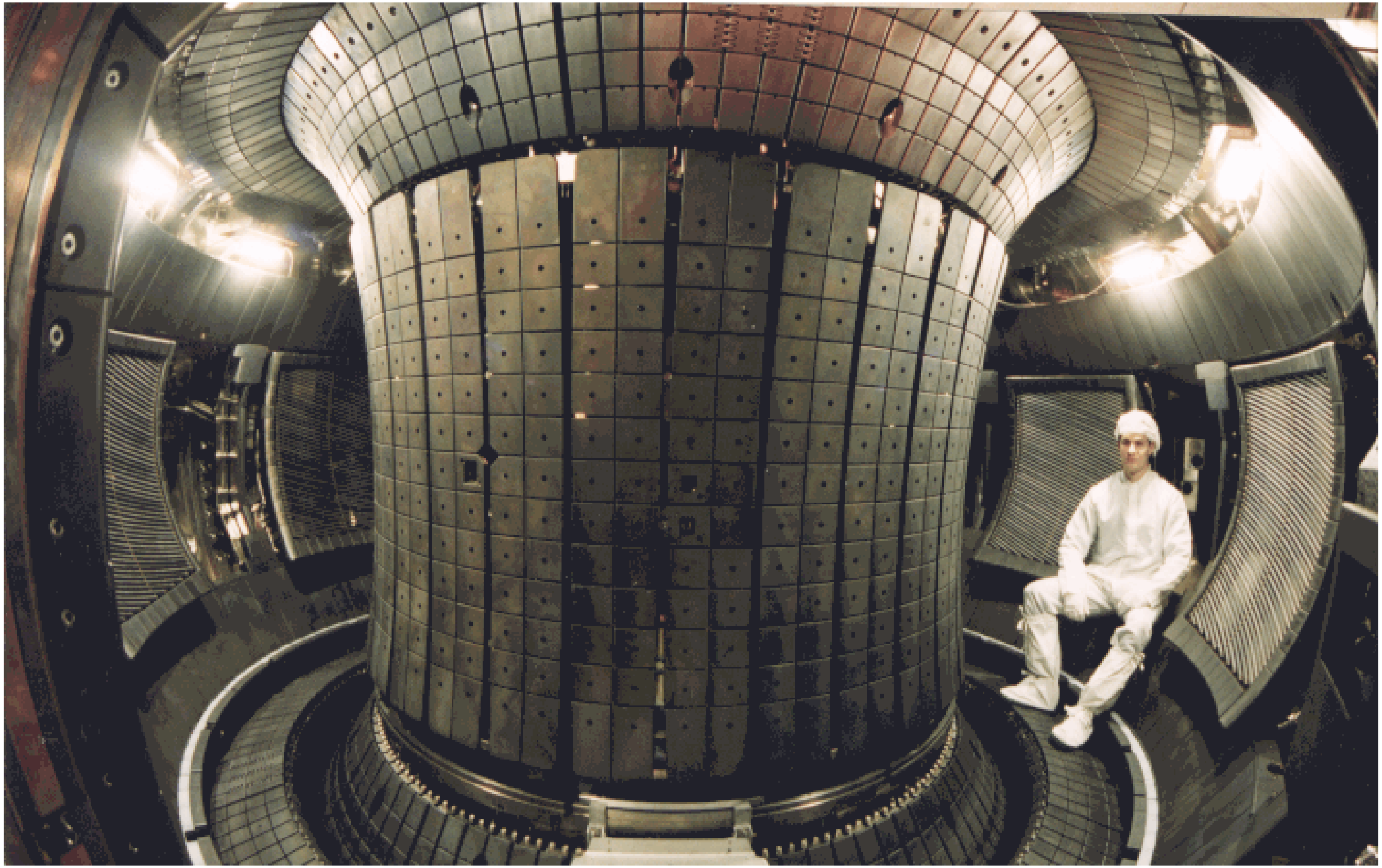
Progress in fusion



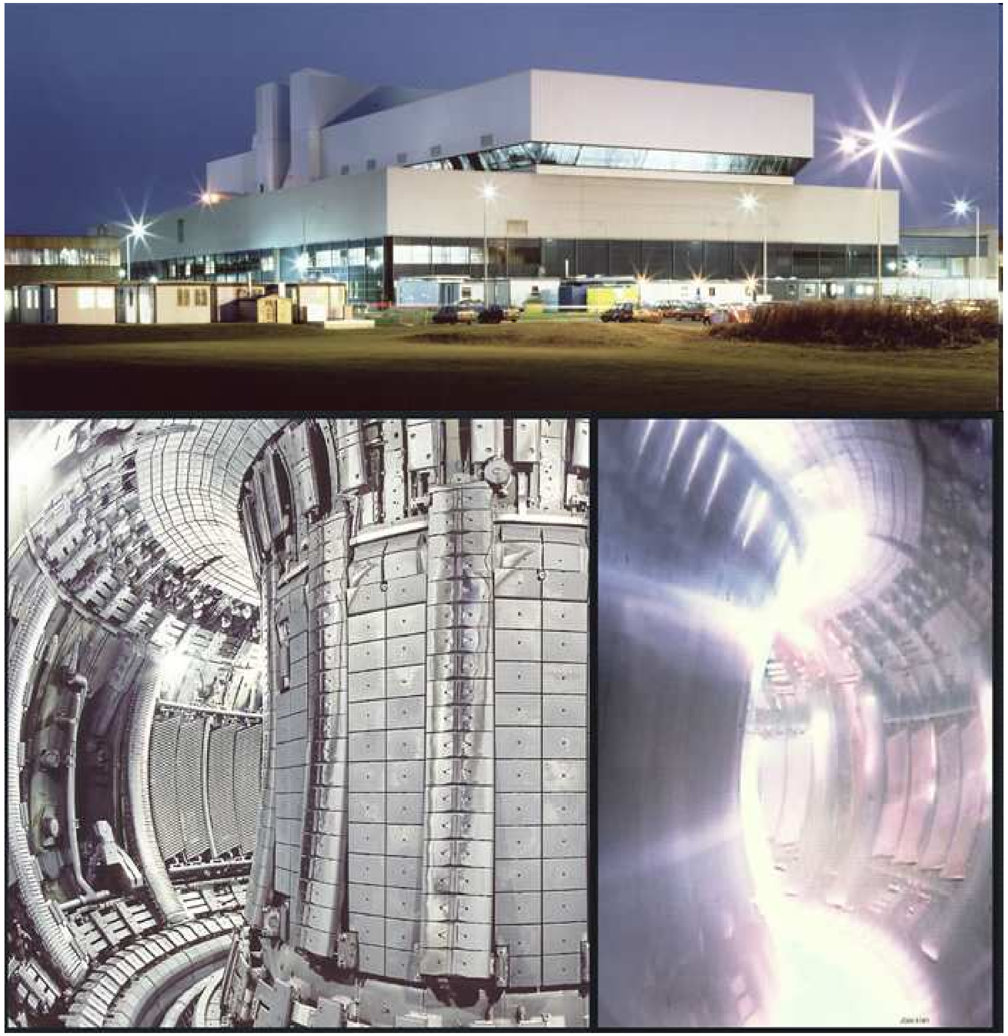
Development of the tokamak line



“ASDEX Upgrade” at IPP Garching



JET – The world's largest tokamak

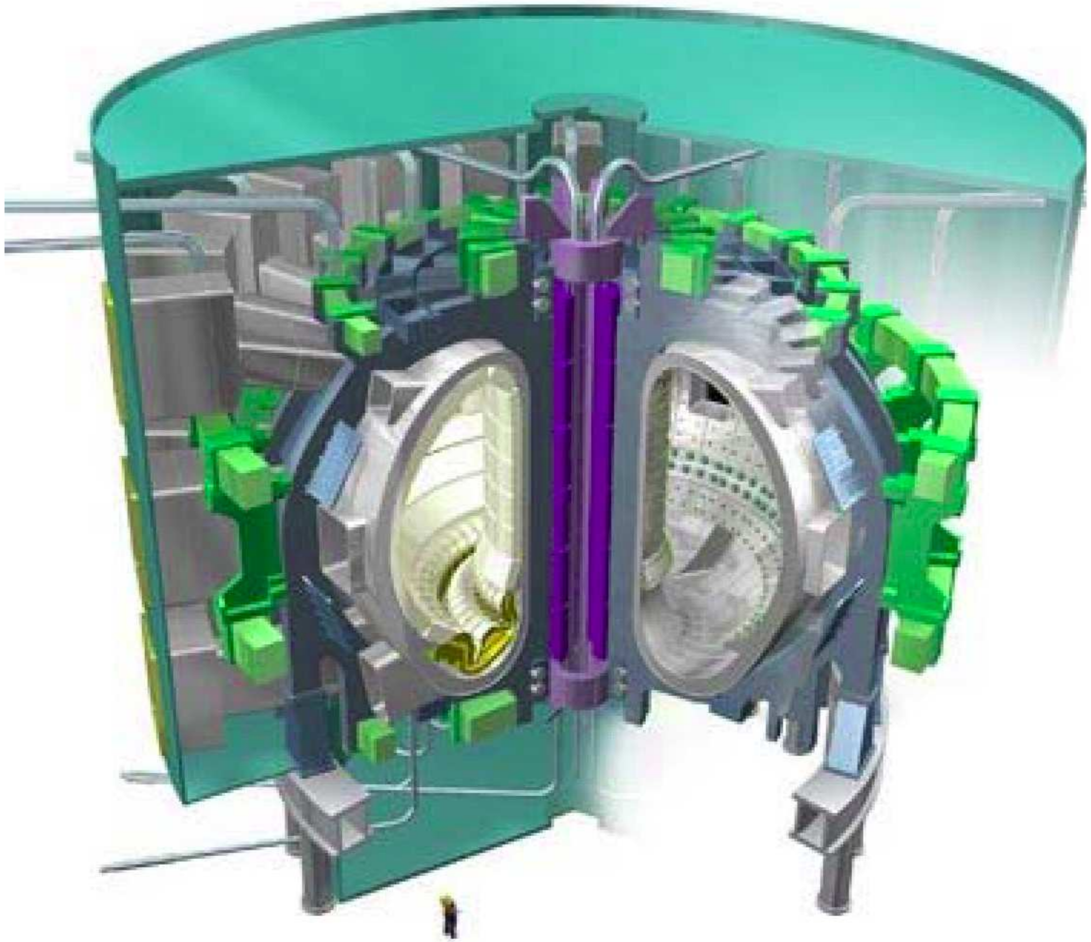


Joint **E**uropean **T**orus

Located near Oxford, UK

World record: 16 MW
of fusion power (1997)

ITER: The final step towards DEMO (a demonstration fusion power plant)



ITER is one of the biggest and most challenging scientific projects of mankind

Goal: 500 MW of fusion power

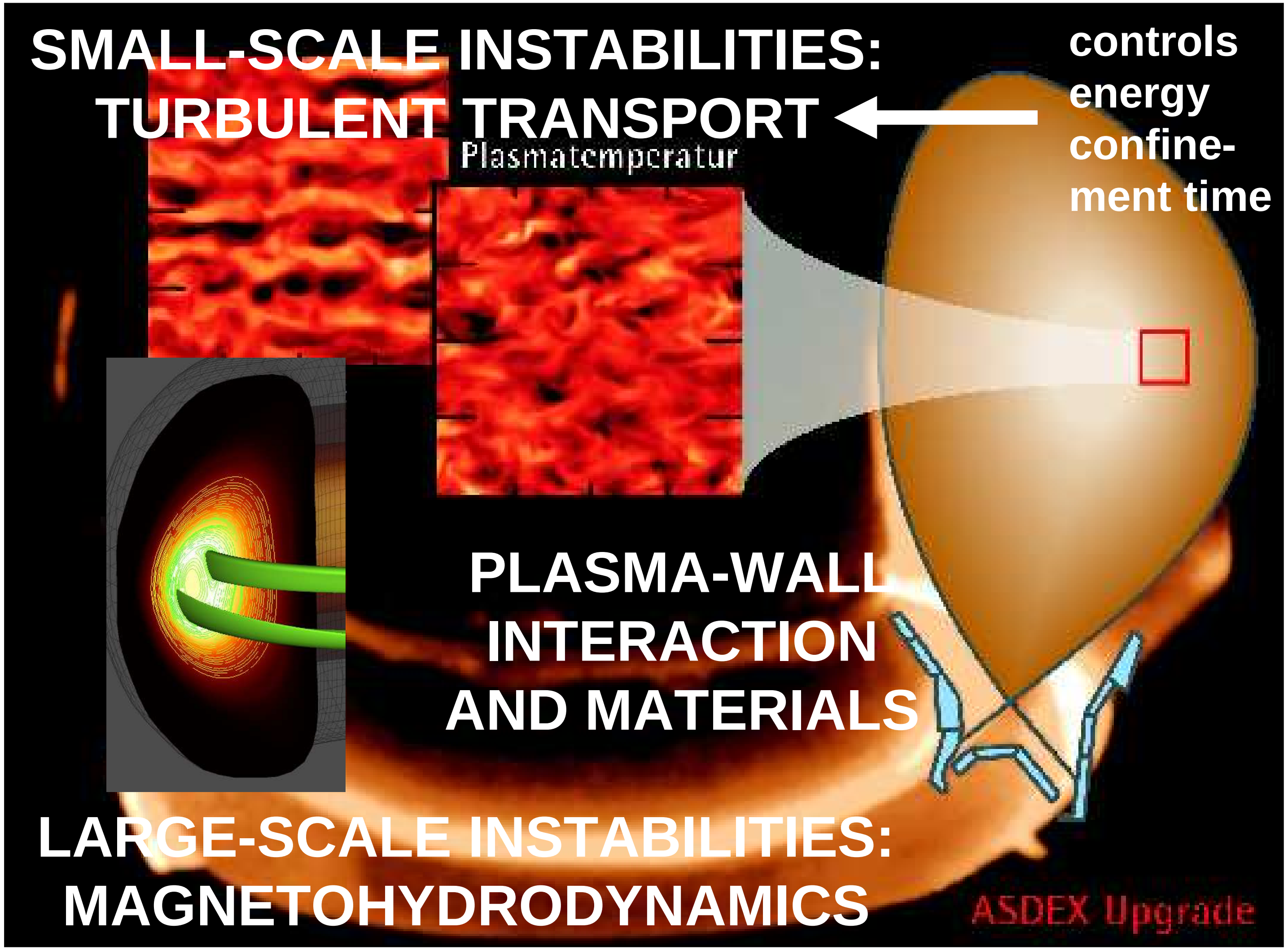
www.iter.org

The resources for fusion energy are practically unlimited

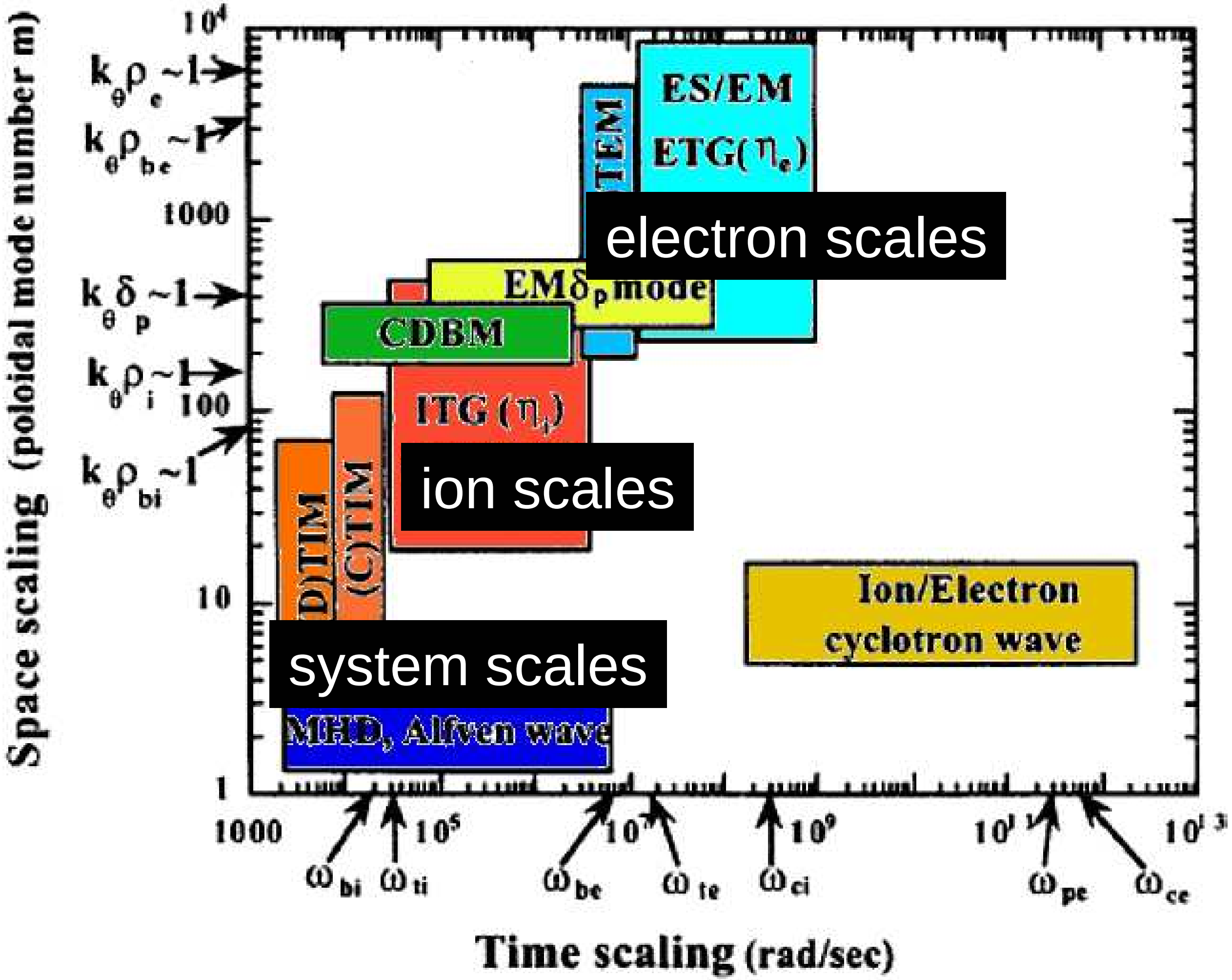
Deuterium in a bath tub full of water and Lithium in a used laptop battery suffice for a family over 50 years

Basic research in support of ITER

Three key themes of fusion physics

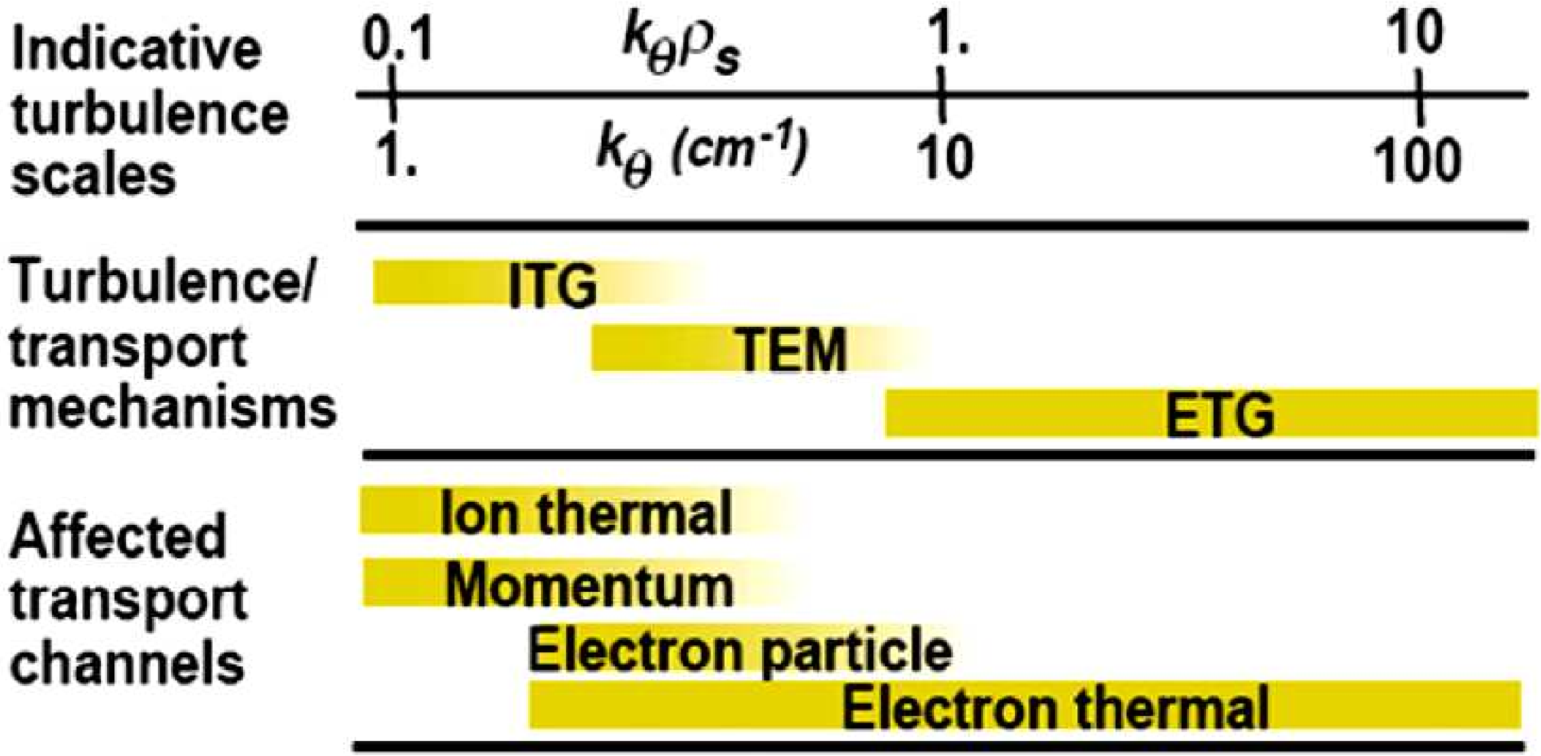


The multi-scale challenge



Source:
Y. Kishimoto

Multiple scales in Plasma microturbulence



Doyle et al.

- **ITG/TEM and ETG scales separated by** $\sqrt{\frac{m_i}{m_e}}$
- **TEM may transition smoothly to ETG**

High-k turbulence GENE simulations

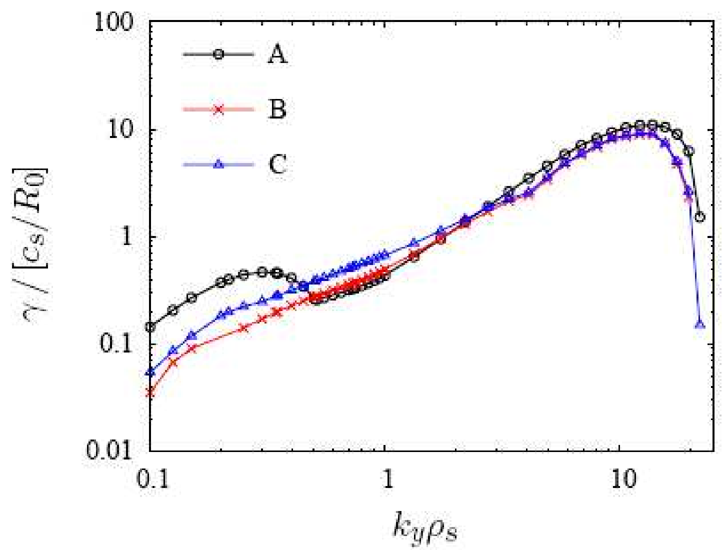
(Pure) ETG turbulence can induce significant electron heat transport:

$\chi_e^{ETG} \gg \frac{\rho_e^2 v_{te}}{L_{T_e}}$ is possible (Jenko, Dorland, Rogers & Kotschenreuther, PoP 2000)

For comparison: $\chi_i^{ITG} \approx 0.7 \frac{\rho_s^2 c_s}{L_{T_i}}$ (Cyclone base case)

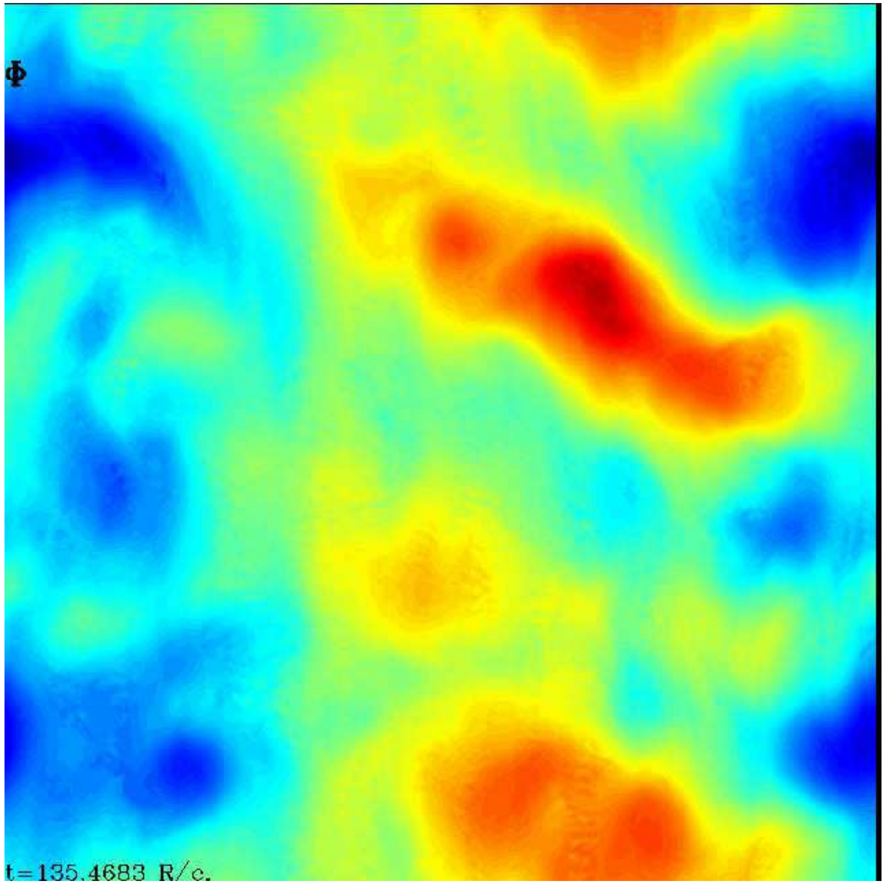
Confirmed, e.g., by (Idomura *et al*., NF 2005), (Nevins *et al.,* PoP 2006), and (Bottino *et al.,* PoP 2007)

ETG turbulence in concert with longer wavelengths (ITG, TEM etc.)?



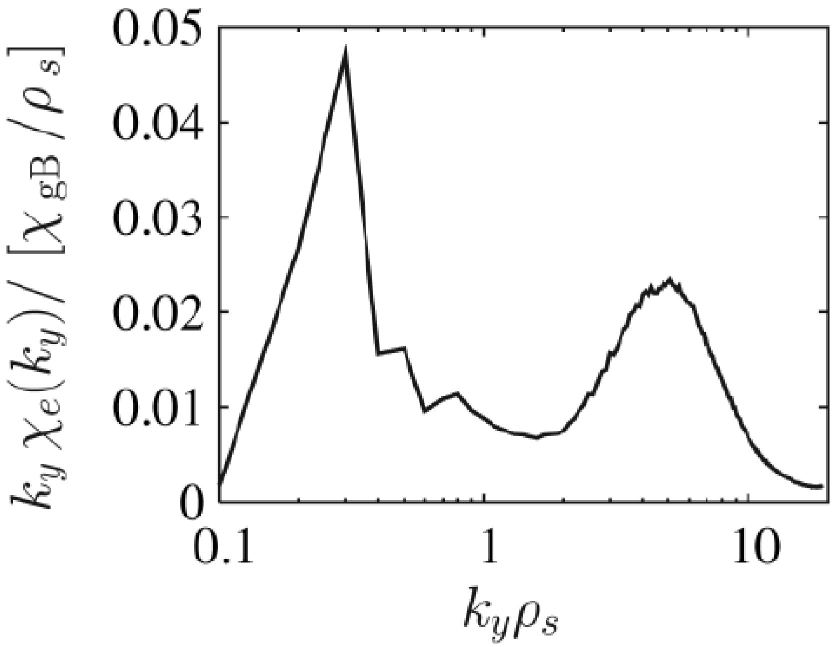
Coexistence of ITG and ETG modes

box size: ~64 ρ_i resolution: ~2ρ_e



Reduced mass ratio (400), but still > 100,000 CPU-h.

[Görler & Jenko, PRL 2008]



<u>ITG/TEM/ETG turbulence</u>: Large fraction of electron heat transport is carried by electron scales (cmp. recent experiments).

High-k turbulence in NSTX

Mazzucato et al., PRL 2008
Smith et al., PRL 2009

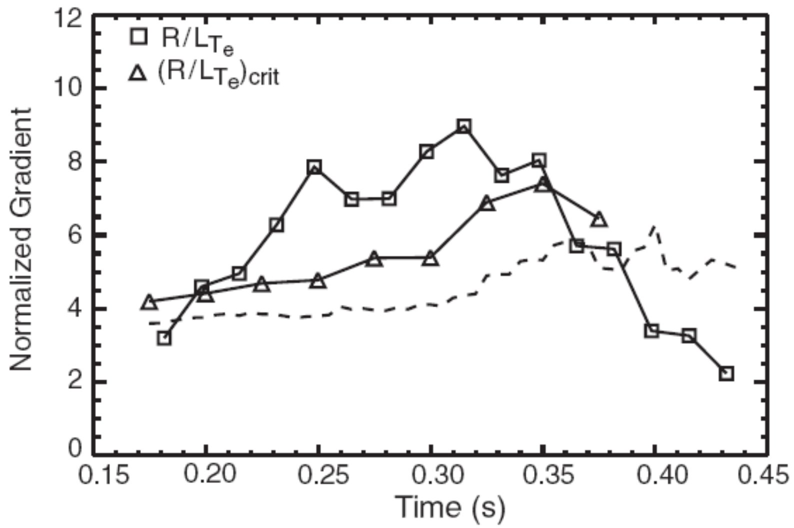


FIG. 7. Time evolution of measured gradient R/L_{T_e} (squares) and GS2 critical gradient $(R/L_{T_e})_{\rm crit}$ for the onset of the ETG mode (triangles). The dashed line is the critical gradient from Ref. [19].

ETG modes are linearly unstable

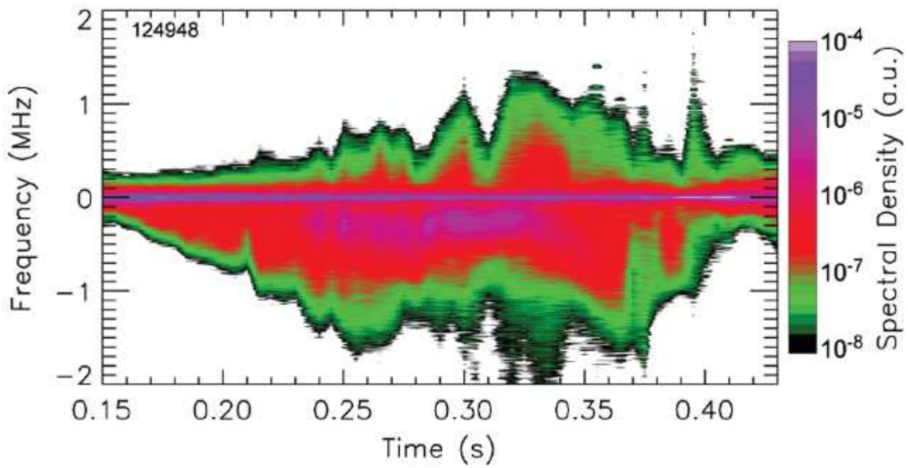
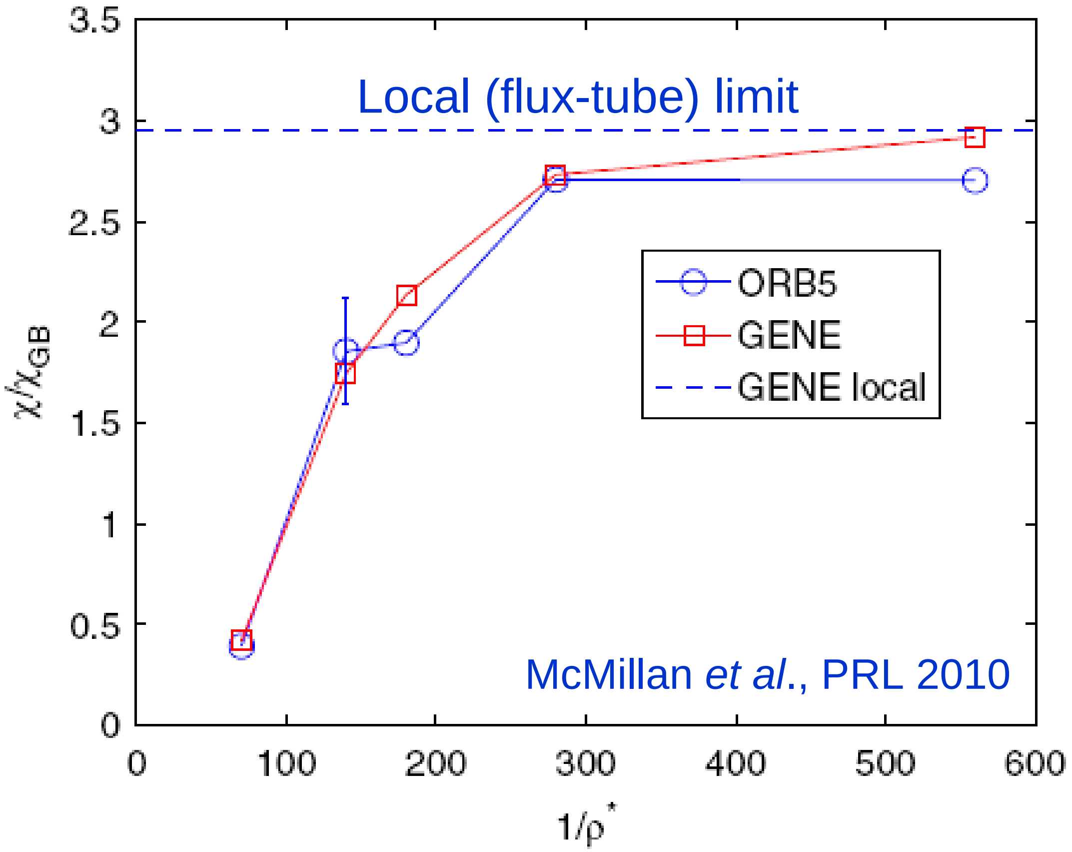


FIG. 3 (color). Logarithmic contour plot of spectral density of fluctuations with $k_\perp \rho_e = 0.2$–0.4 at $R = 1.2$ m. Negative frequencies correspond to wave propagation in the electron diamagnetic direction.

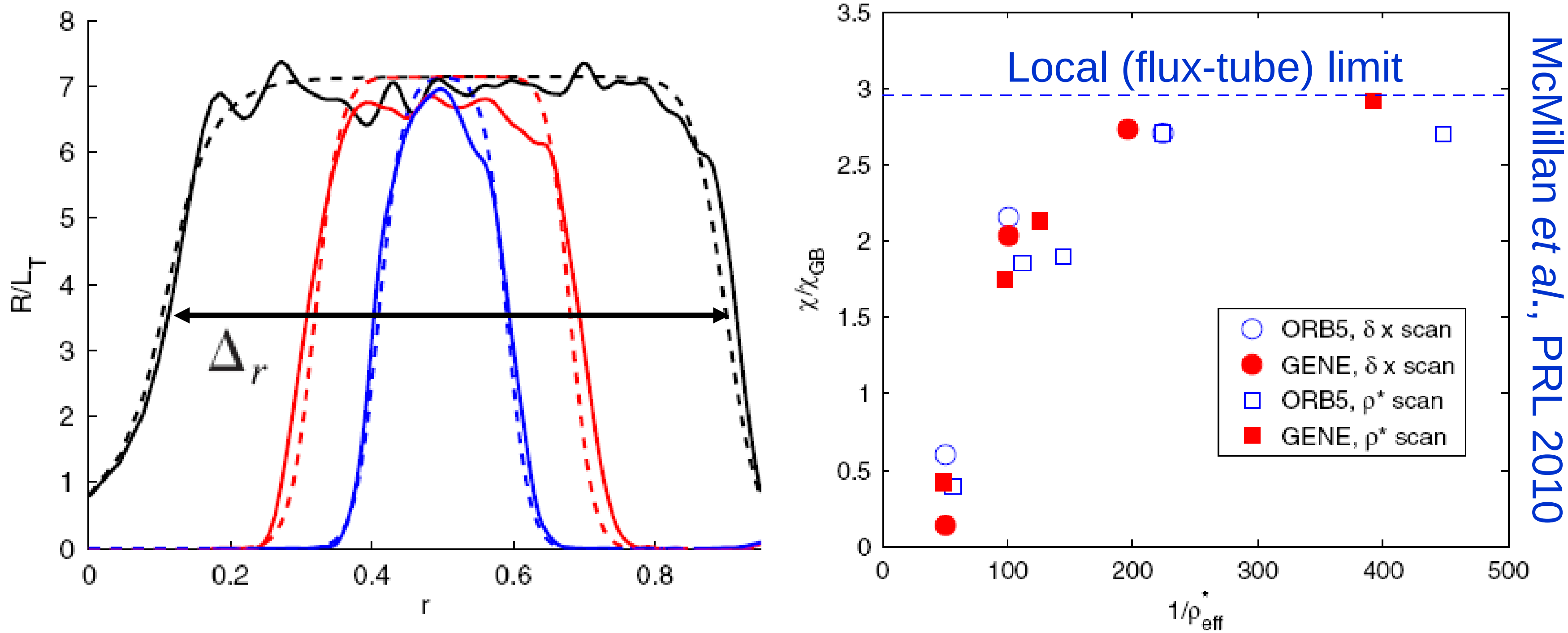
High-frequency density fluctuations are detected; their amplitude is correlated with the threshold distance

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.



Finite system size: Profile shape matters



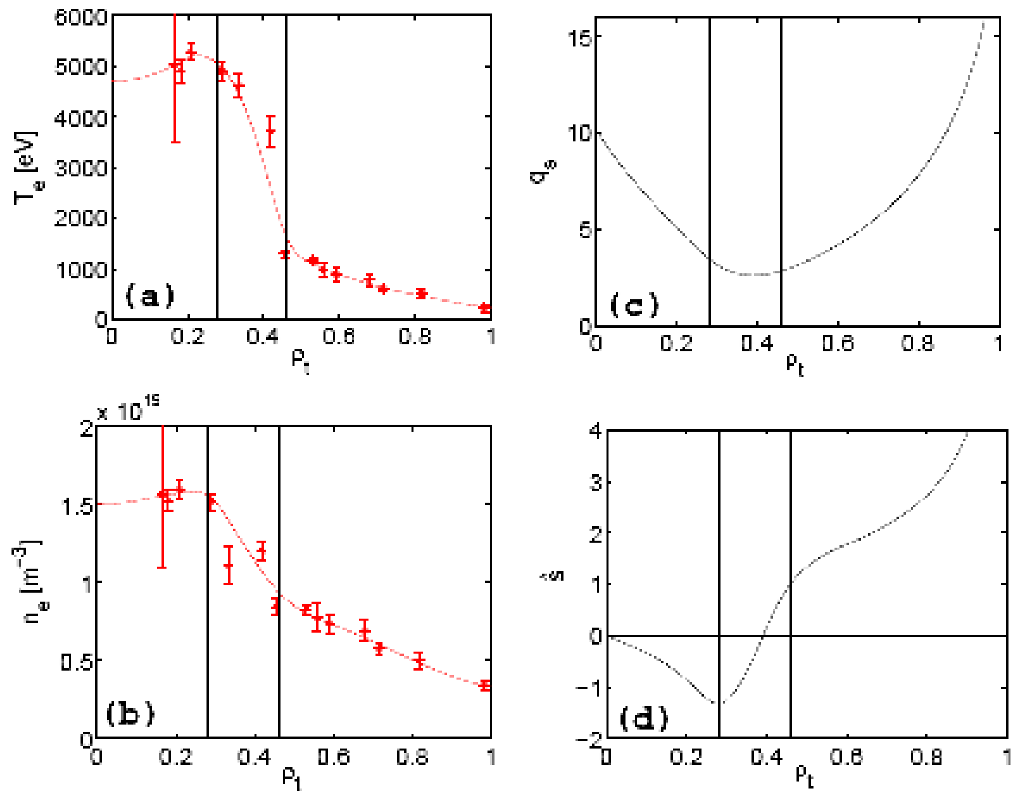
Both codes also show that it is the parameter

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

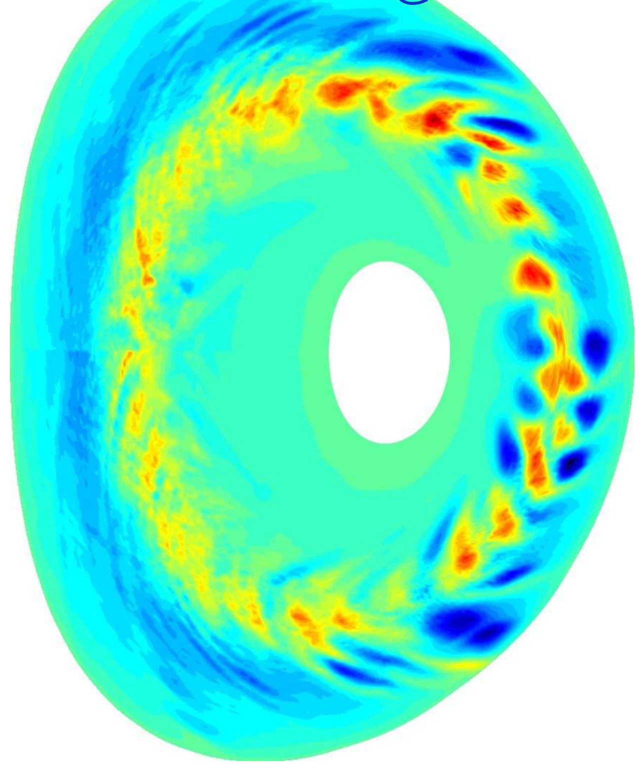
which really matters – this should be kept in mind when dealing, e.g. with Internal Transport Barriers.

Global gyrokinetics: Established e-ITBs

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



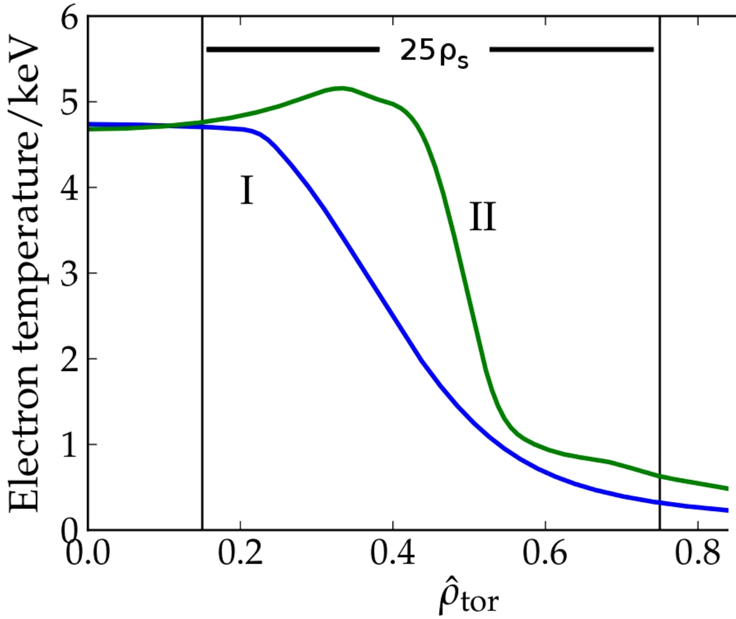
Told, Görler *et al.*,
invited talk @ APS 2010



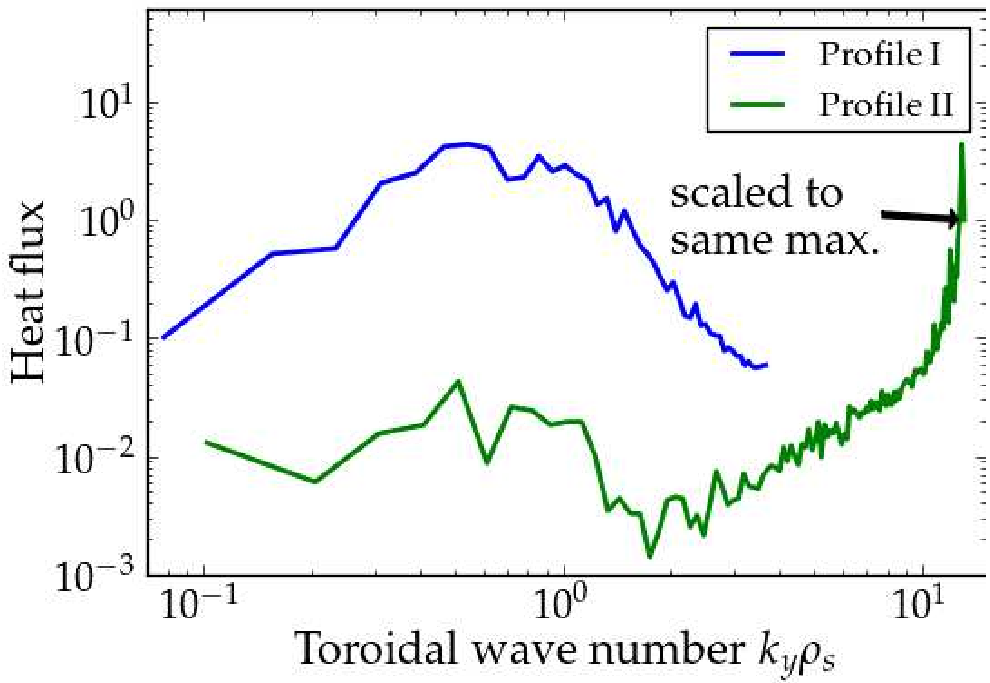
Global GENE simulations (with quite comprehensive physics) for e-ITBs in TCV tokamak “reproduce” experimental fluxes

Multiscale simulations of e-ITBs

Told, Sauter *et al*.

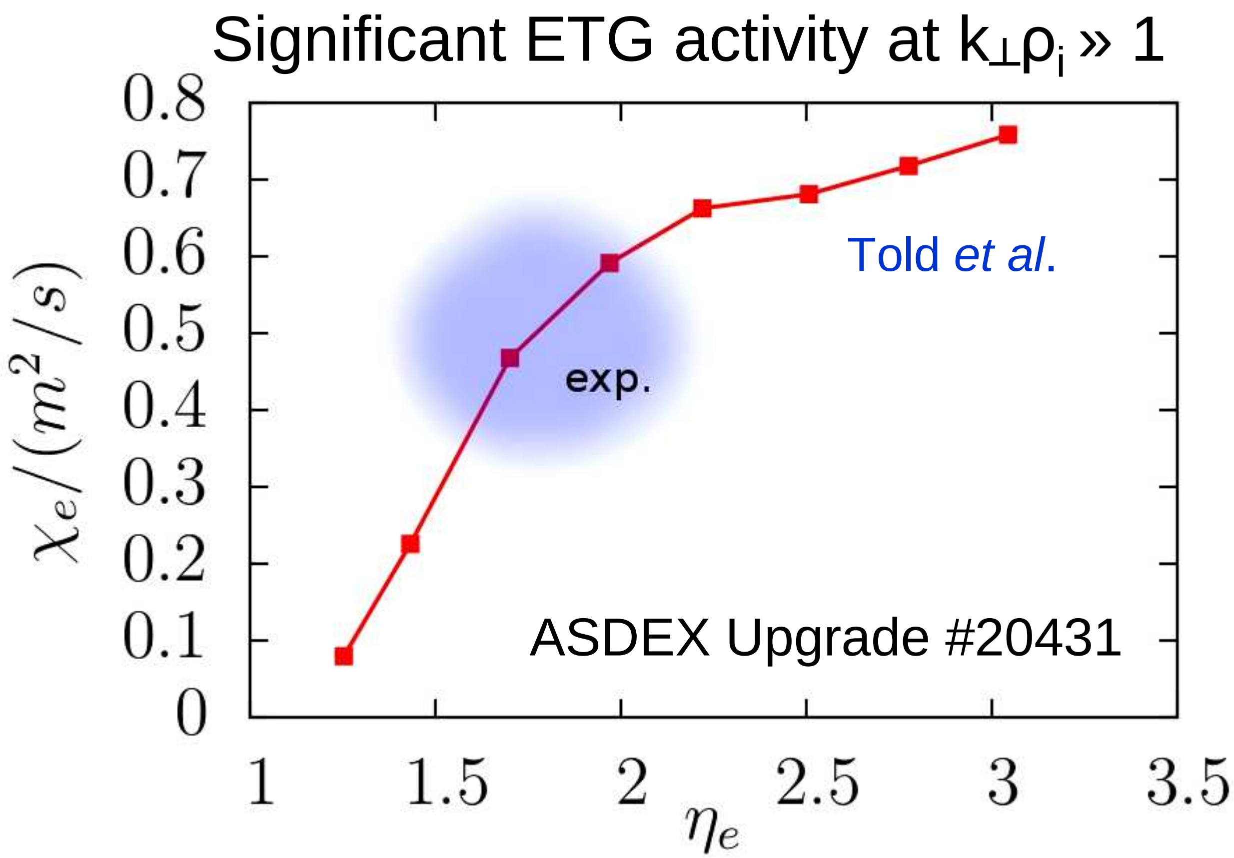


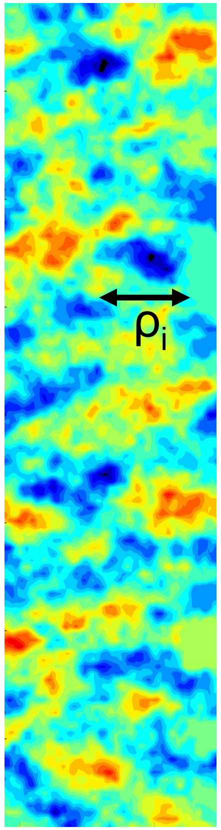
I “relaxed” profile
II “nominal” profile



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

High-k gyrokinetics for edge barriers





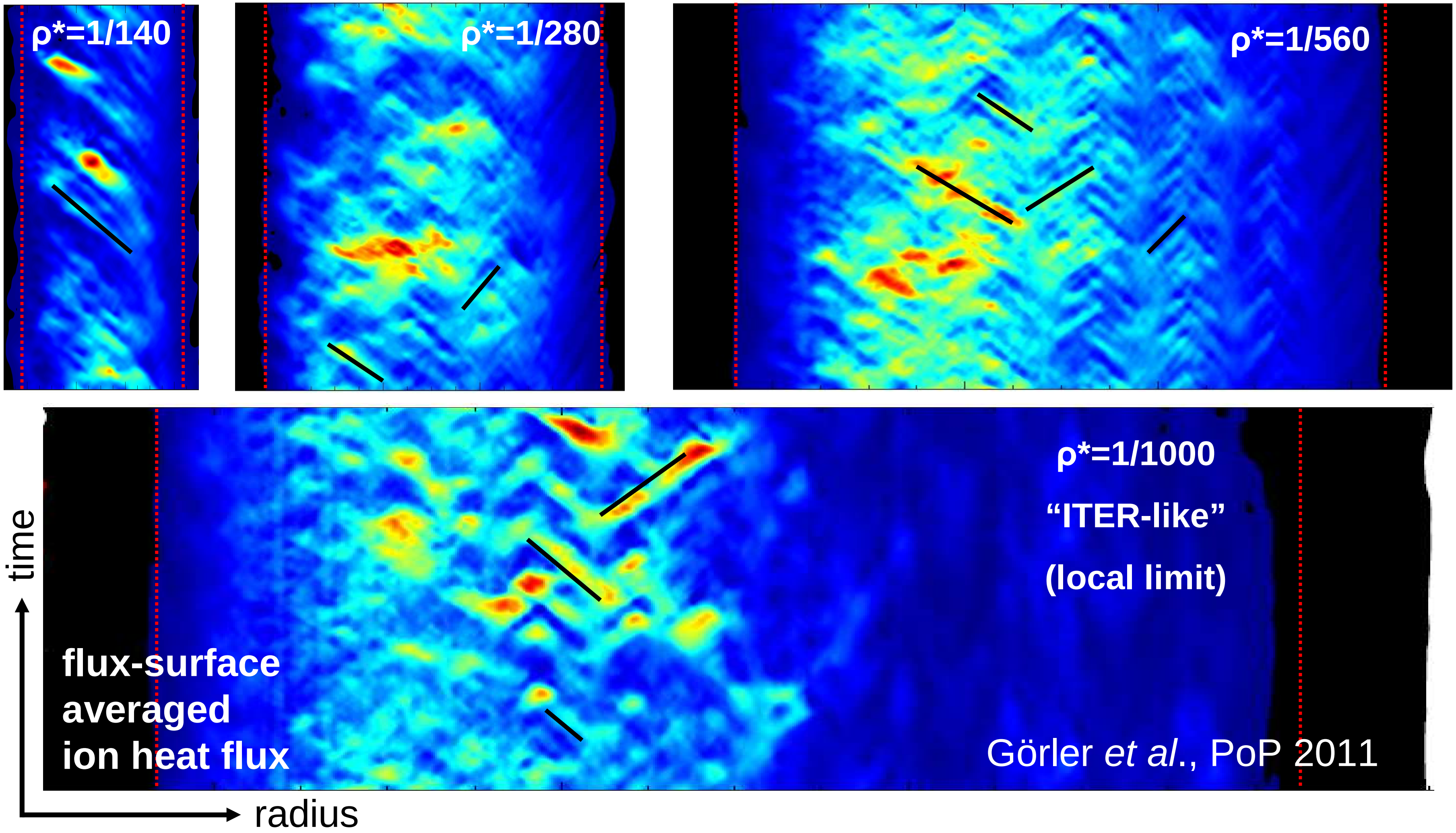
Φ contours on the outboard side

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

Turning now back to the question of core transport…

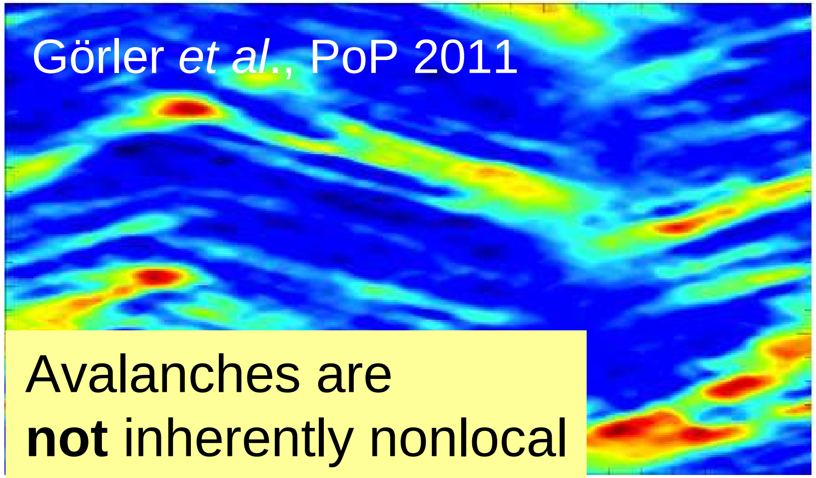
Heat flux avalanches are quasi-local (!)

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

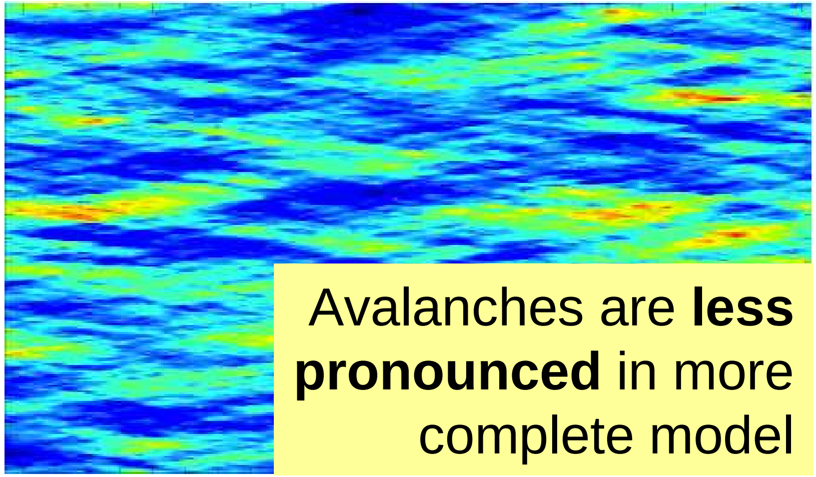


Weak / no avalanches in “better” models

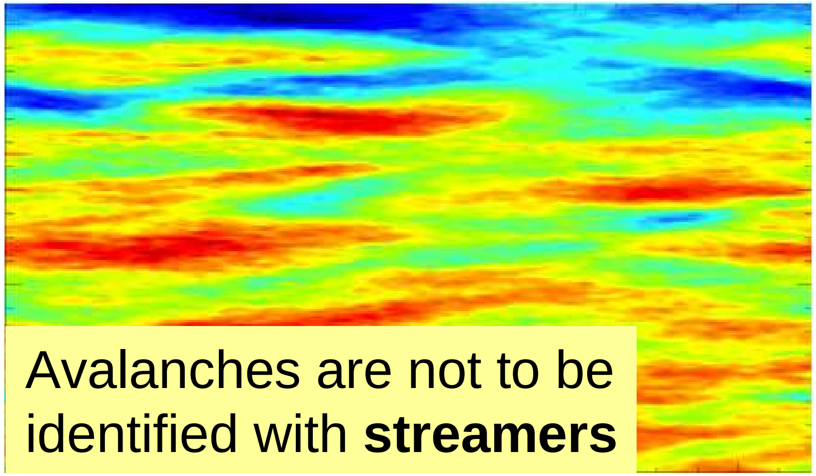
ITG turbulence (adiabatic electrons)



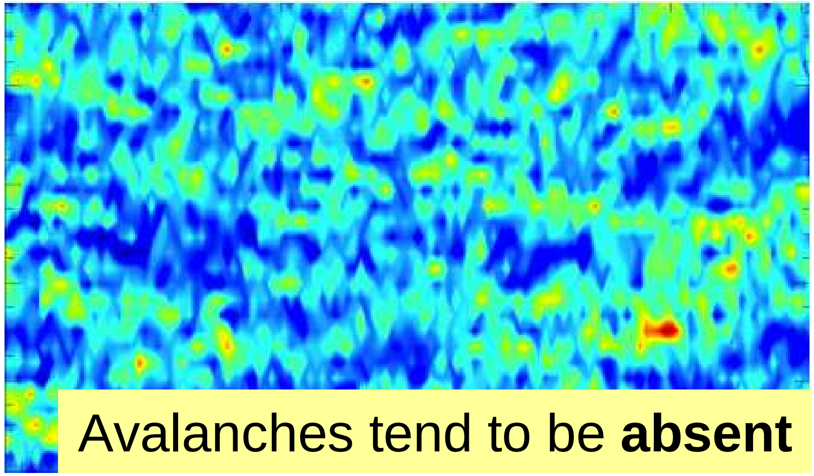
ITG turbulence (kinetic electrons)



ETG turbulence (adiabatic ions)

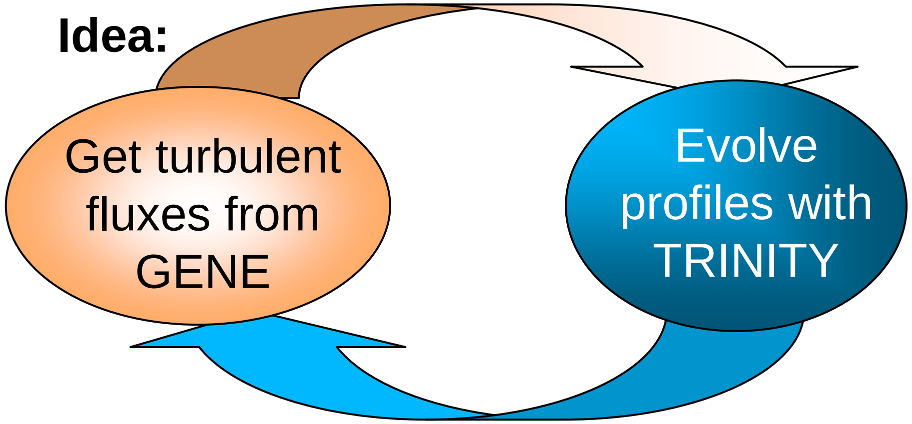


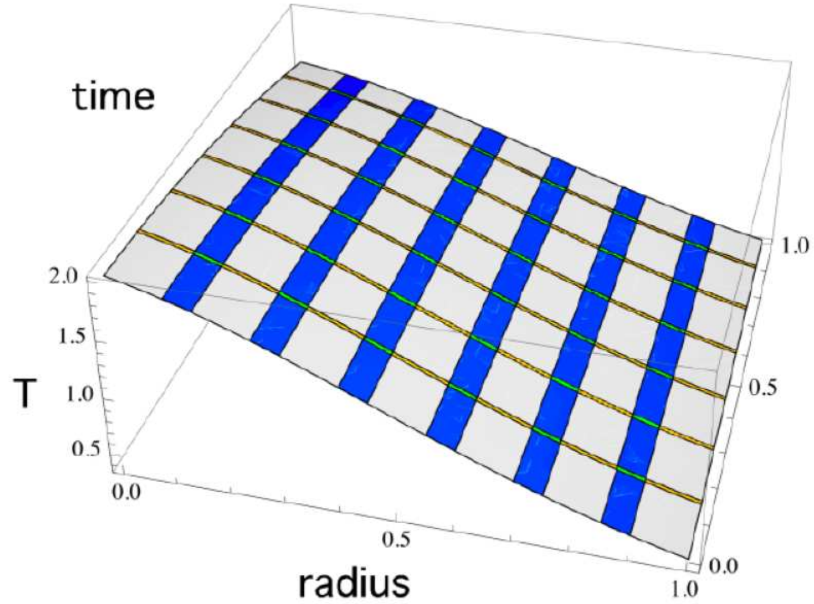
TEM turbulence



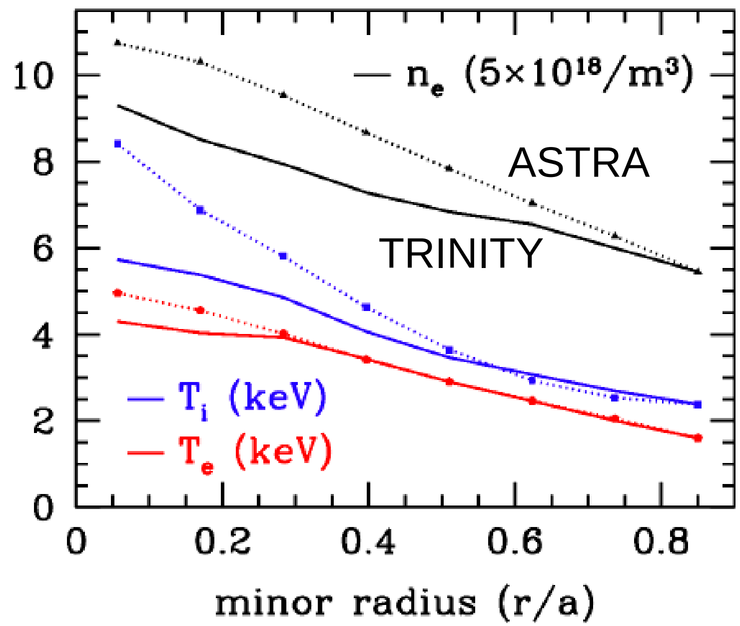
Coupling GENE and TRINITY

Idea:





AUG #13151 (H-mode)



Barnes *et al.*, PoP 2010

Observed deviations possibly due to:

- *shear flow effects*
- *uncertainties in q profile*

Computational cost much lower than for (flux-driven) global simulations

Final remarks

The new frontier: Multiscale gyrokinetics

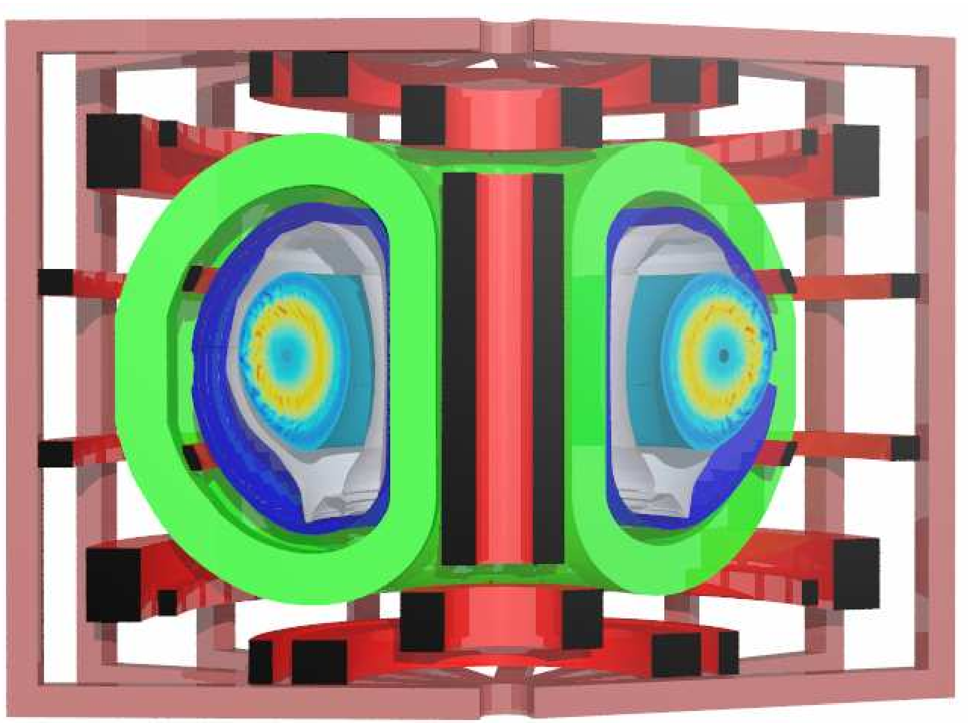
- From the system size to the electron gyroradius
- Integration of turbulence, neoclassics, and MHD

Vision:

Predictive capability for tokamaks (as well as other fusion devices)

Outstanding open problem:

Physics of transport barriers



ASDEX Upgrade

More info: http://gene.rzg.mpg.de