# Gyrokinetic Simulations

D. R. Hatch

ICTP May 14, 2026

# Outline

## Talk 1: Introduction to gyrokinetic model

## Talk 2: overview of activities using gyrokinetic

Foundations—ITG instability, saturation
A taste of various topics—no claim to exhaustive references, etc.
Material is mostly from the broader community (a little from our group)

## Talk 3: Transport Barriers II

Foundations—pedestal, turbulence suppression
Building on excellent talks from Prof. Mahajan, Prof. Kim.
More focused on research from our group (UT-IFS). At the 'research frontier'.

# Many Non-Fusion Applications

- Foundation for space and astrophysical turbulence
  - G. G. Howes et al. *ApJ*, (2006).
  - A. A. Schekochihin et al. *ApJS*, (2009).
  - Kunz et al. JPP, (2018).
- Solar wind turbulence
  - G. G. Howes, et al. *Phys. Rev. Lett.*, (2011).
  - J. M. TenBarge et al. *Physics of Plasmas*, (2012).
  - D. Told et al. *Phys. Rev. Lett.* (2015).
  - Groselj et al. App J. (2017).
- Magnetic reconnection
  - J. M. TenBarge, et al. *Physics of Plasmas (*2014).
  - M. J. Pueschel,, et al. *ApJS*, (2014).
- Fundamental turbulence
  - Tatsuno *et al. Phys. Rev. Lett. (2009)*
  - Banon-Navarro et al. *Phys. Rev. Lett. (2011,2016)*
  - Teaca *et al. Phys. Rev. Lett. (2012)*
  - Hatch *et al. Phys. Rev. Lett. (2011,2013)*
- Codes
  - AstroGK (based on fusion code GS2)
  - GENE
  - Others

# Gyrokinetic Codes

Gyrokinetics is enormously simplified an optimized in comparison with full 6D kinetics.

But it is still computationally demanding.

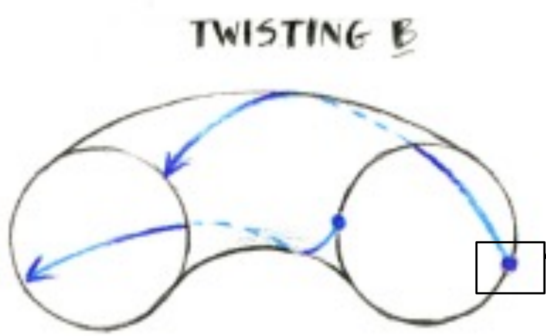
Advances in computing: we can now do some interesting things with GK with modest resources

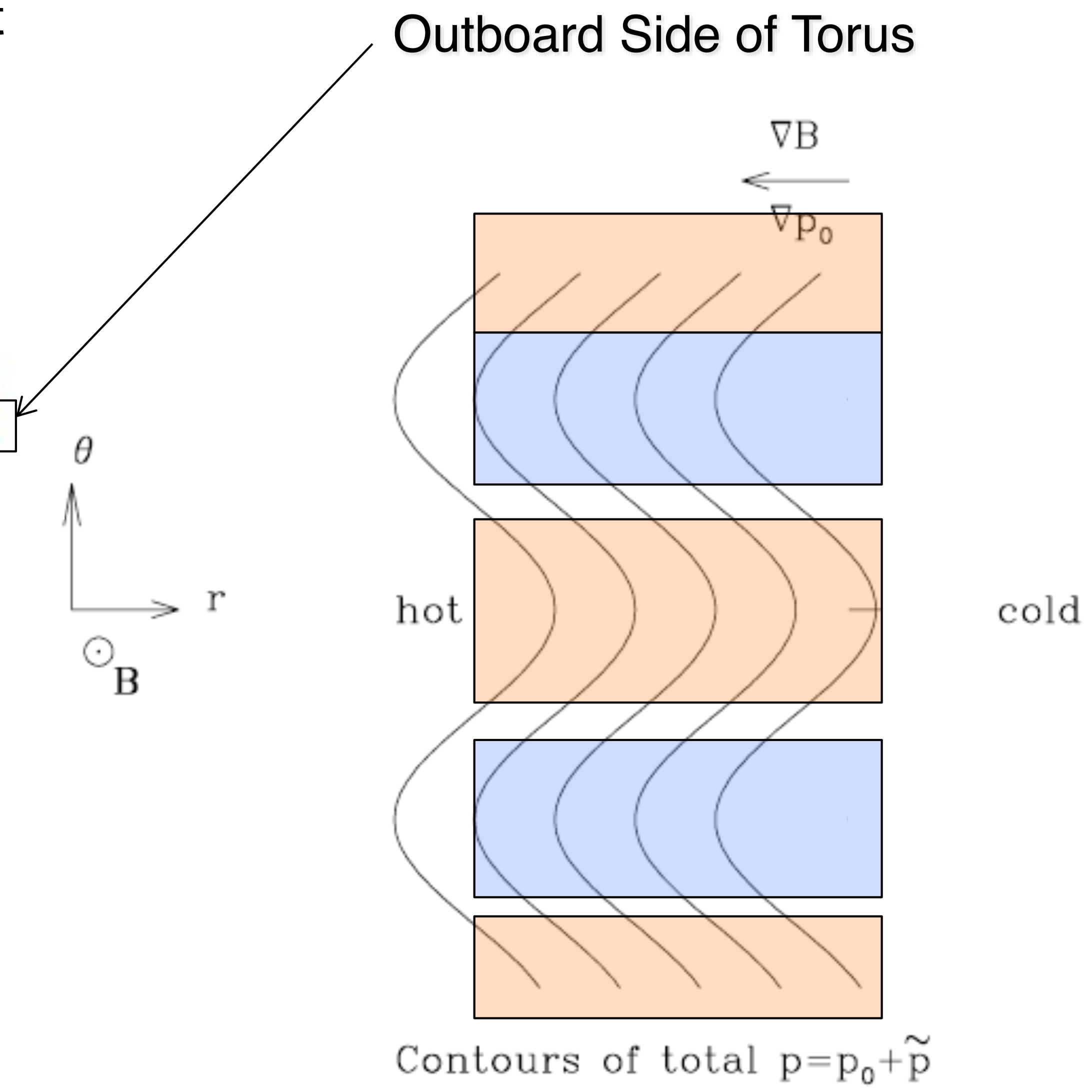

| Name | Model | [illegible] | ity |
|---|---|---|---|
| GENE | Continuum Delta-$f$ GK | [illegible] | [illegible] |
| CGYRO | Continuum Delta-$f$ GK | Core | 5 |
| GX | Moment-based Delta-$f$ GK | Core | 5 |
| GENE-X | Continuum Full-$f$ GK | Core & SOL | 5 |
| XGC | PIC Full-$f$ GK | Core & SOL | 4 or 5 |
| Gkeyll | Continuum Full-$f$ GK | Core & SOL | 4 or 5 |

https://genecode.org/
https://gx.readthedocs.io/en/latest/
https://gkeyll.readthedocs.io/en/latest/
https://genexcode.org/

# ITG Instability

Ion Temperature Gradient
Instability (ITG)



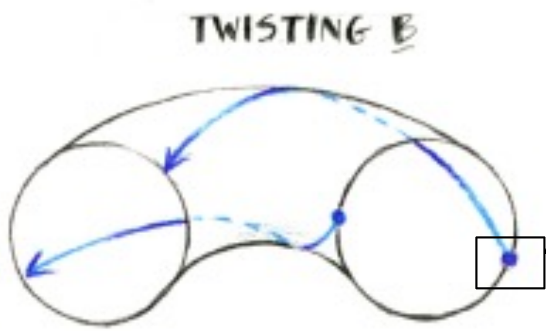




$$v_d = \frac{\frac{1}{2} m_j {v_\perp}^2}{q_j B} \frac{B \times \nabla B}{B^2}$$

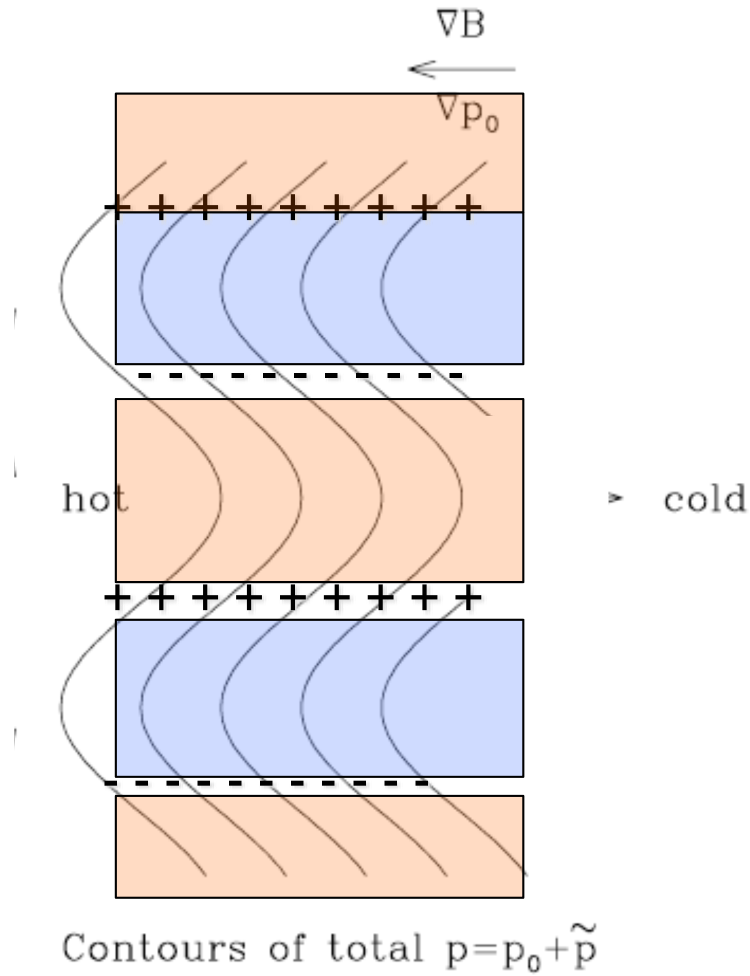
Mike Beer - Thesis

# ITG Instability

Ion Temperature Gradient Instability (ITG)




Outboard Side of Torus

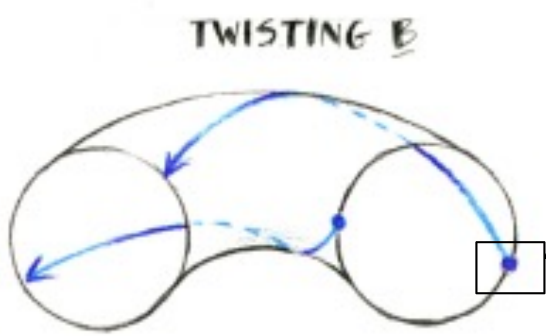




$$v_d = \frac{\frac{1}{2} m_j v_\perp^{\ 2}}{q_j B} \frac{B \times \nabla B}{B^2}$$

$$v_E = \frac{E \times B}{B^2}$$

# ITG Instability

Ion Temperature Gradient Instability (ITG)

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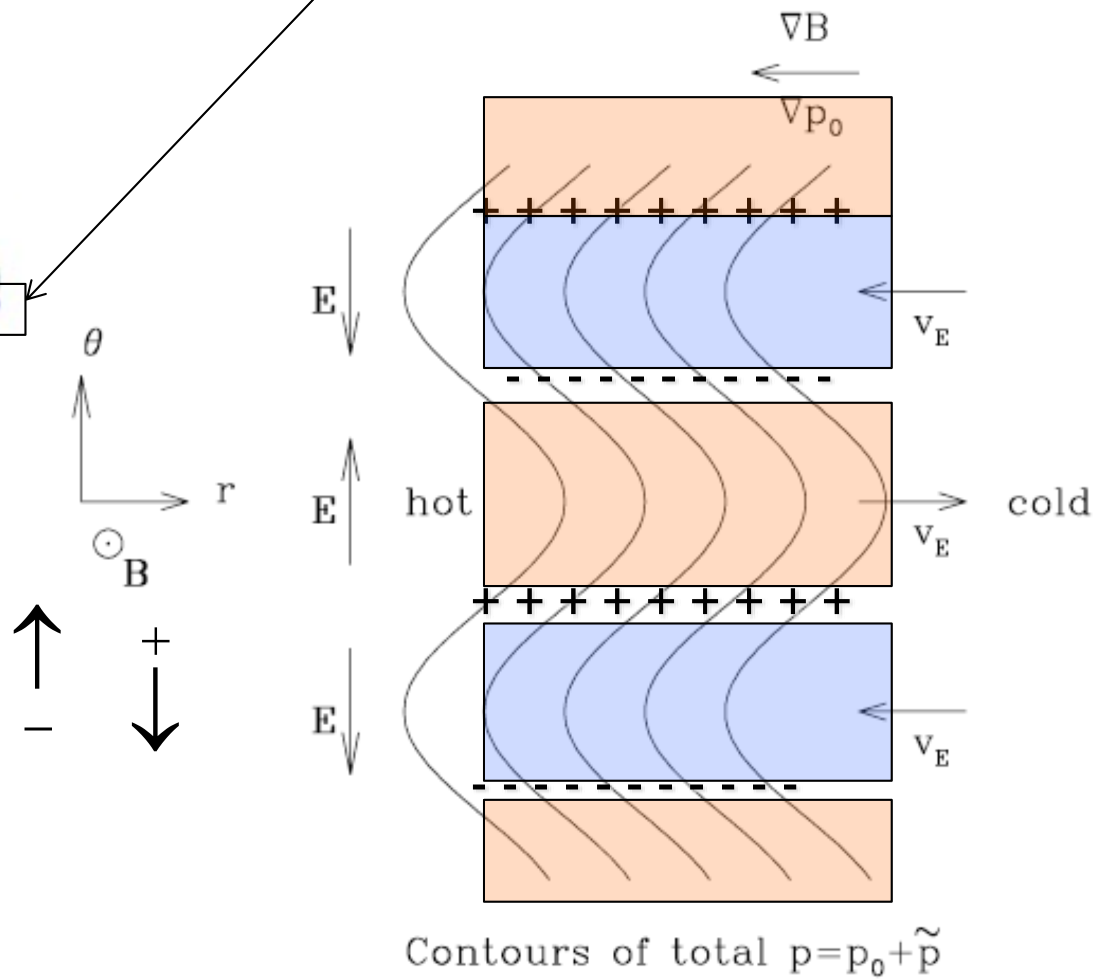


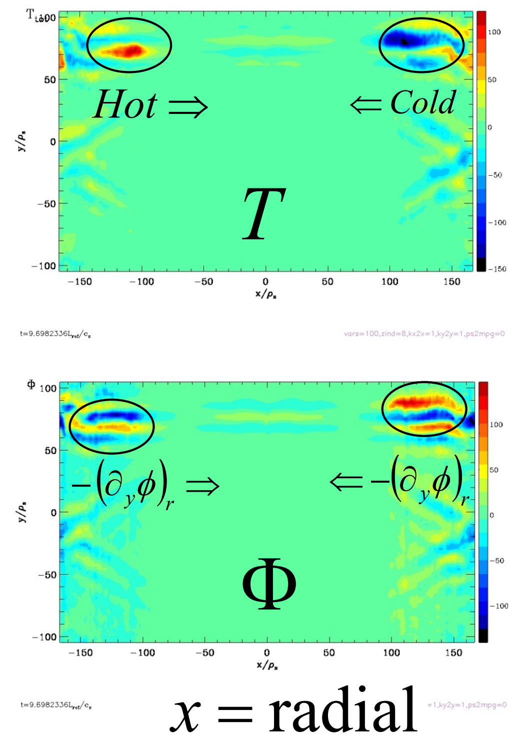

$$v_d = \frac{\frac{1}{2} m_j v_\perp^2}{q_j B} \frac{B \times \nabla B}{B^2}$$

$$v_E = \frac{E \times B}{B^2}$$

# Heat Flux

$$Q \equiv \nabla\psi \cdot \int d^3\mathbf{v}\frac{mv^2}{2}\left(\mathbf{v}_\chi \delta f_1 + \mathbf{v}_B\langle f_1\rangle + \boldsymbol{\rho} C[\boldsymbol{\rho}\cdot\nabla f_0]\right),$$

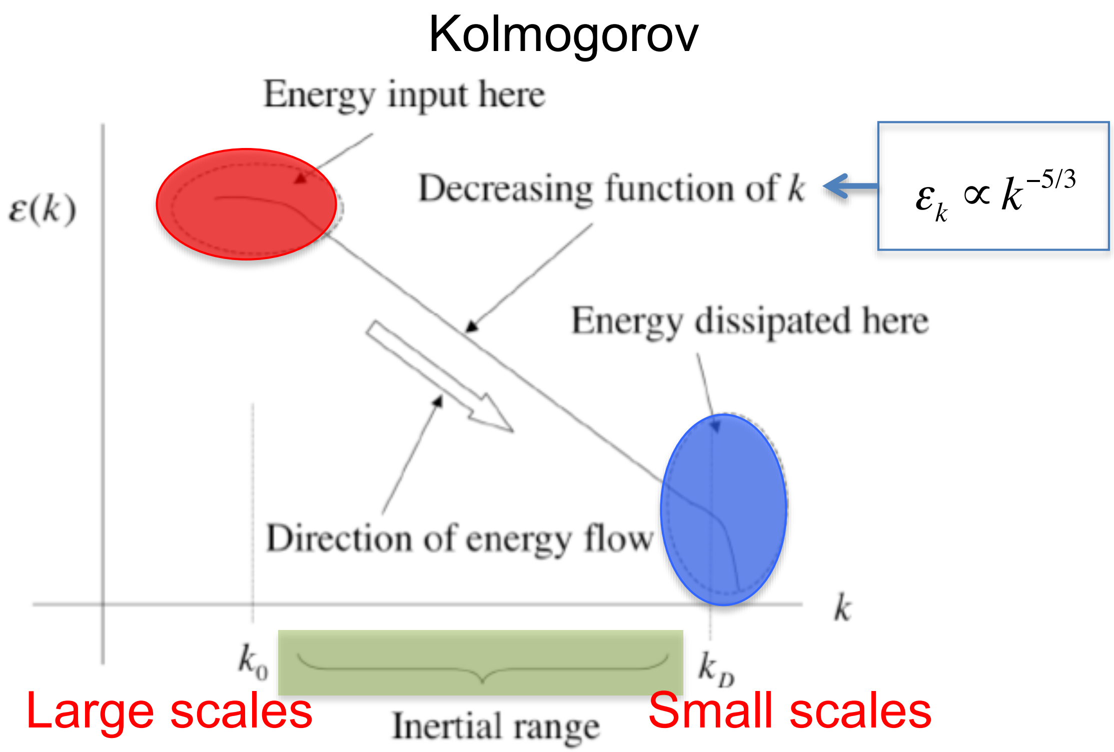
- **Turbulent** transport
- Advection of temperature fluctuations by velocity fluctuations
- Dominant transport mechanism in fusion devices



# Fundamental Turbulence Paradigm

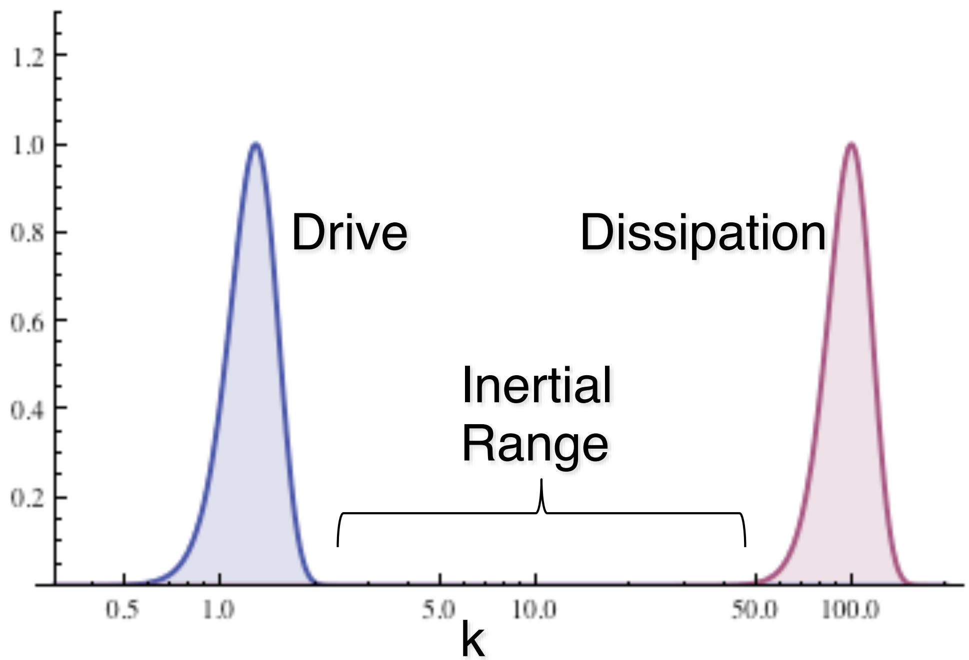
$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} - \frac{1}{\mathbf{Re}} \nabla^2 \mathbf{u} = \mathbf{g}$$

Turbulence:
Energy
1. Injection
2. Redistribution
3. Dissipation



# Fluid Turbulence - Saturation

Hydrodynamic turbulence:
Navier Stokes equation ➔ Kolmogorov picture:




1. Energy drive at large scales.
2. Conservative nonlinear energy transfer through inertial range of scales.
3. Dissipation at small scales.

**Saturation ➔ Energy drive at large scales balances with dissipation at small scales.**

# Dissipation mechanisms

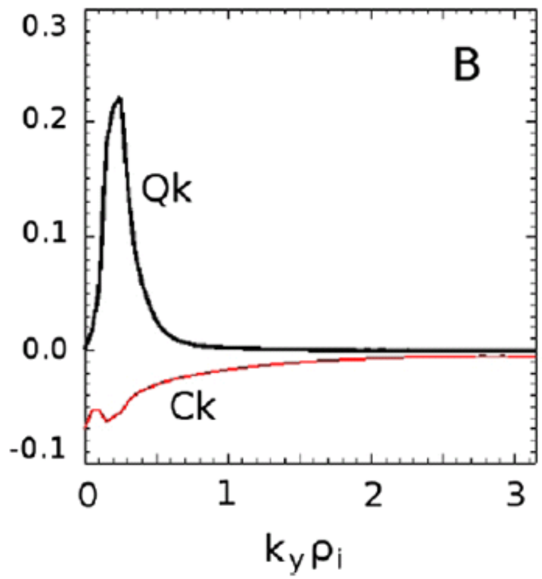
Dissipation in fluid turbulence: $\frac{1}{\mathrm{Re}}\nabla^2 u$

Re=large➔small scale dissipation

Dissipation in kinetic plasma turbulence: $\propto \upsilon \nabla_{\mathrm{v}}{}^2 f$

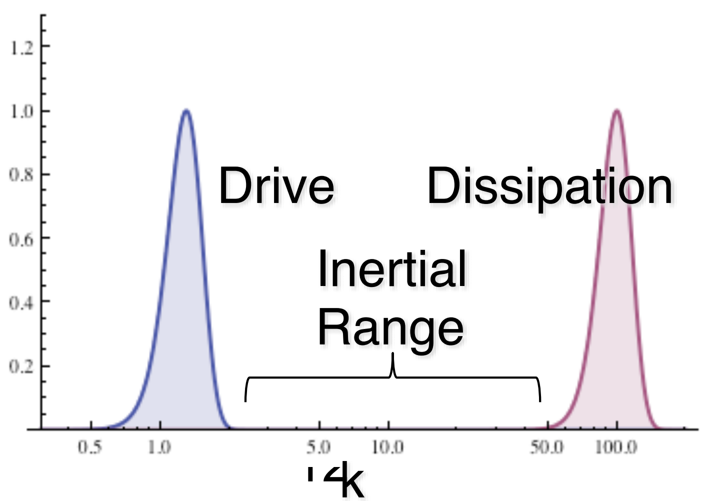
$\upsilon$ =small➔small scale dissipation in **velocity space**

# Dissipation in gyrokinetic ITG turbulence

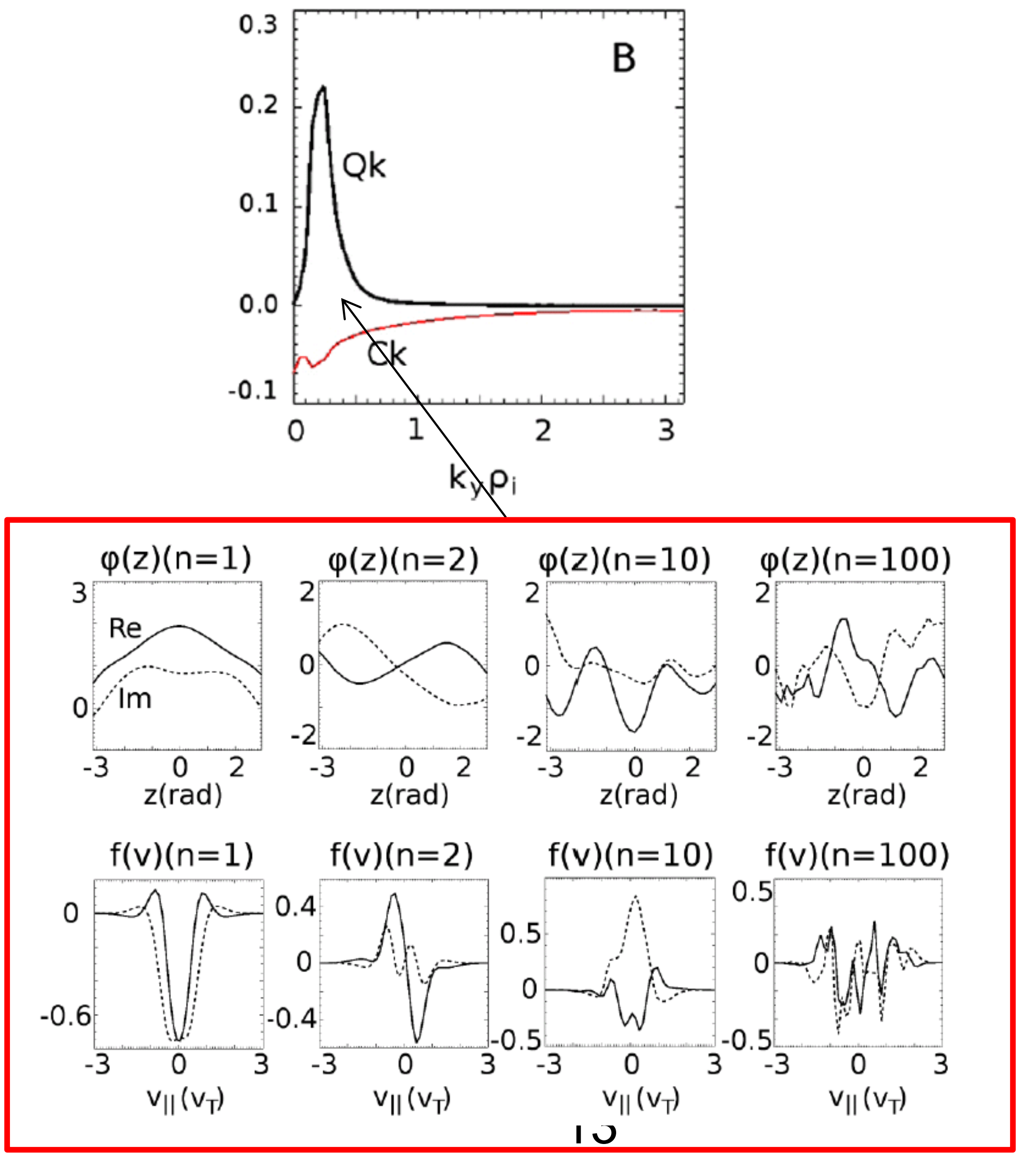



Q=gradient drive
C=collisional dissipation

**Contrast:**



# Dissipation in gyrokinetic ITG turbulence



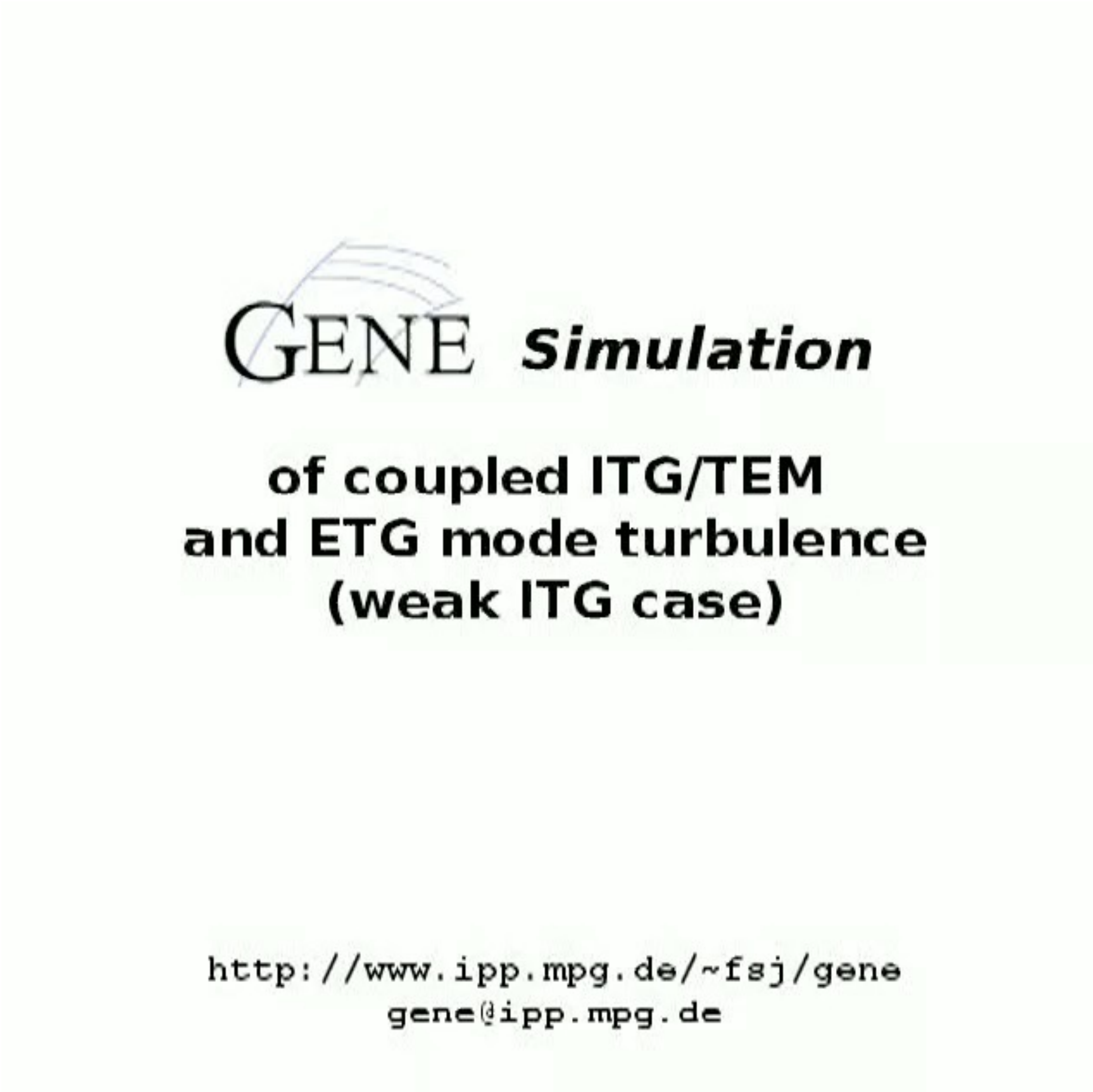

Q=gradient drive
C=collisional dissipation

**Small scales develop in velocity space even at drive scales in real space.**
**➔Scale range of drive and dissipation overlap!**
**D. R. Hatch et al. PRL, 2011.**

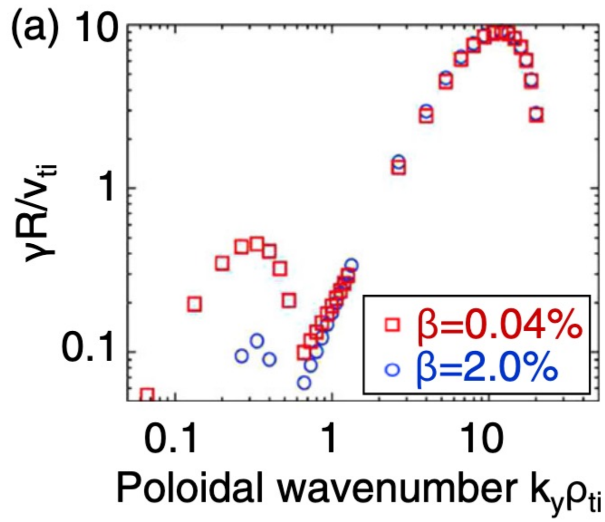
(Also a cascade at higher k
Banon Navarro, PRL, 2011.
See also Hatch et al. PRL 2013)

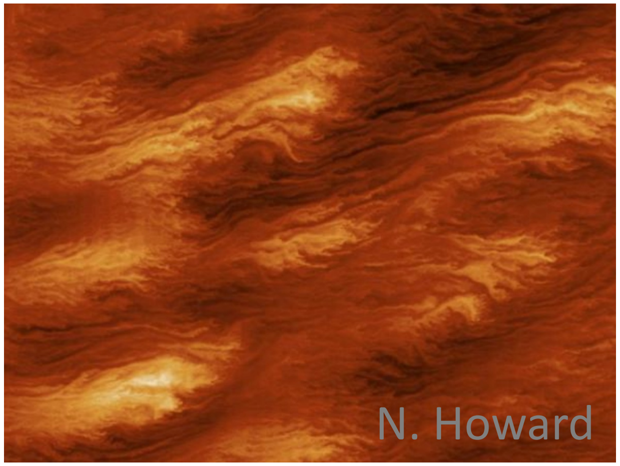
# Gyrokinetics: Major Research Activities

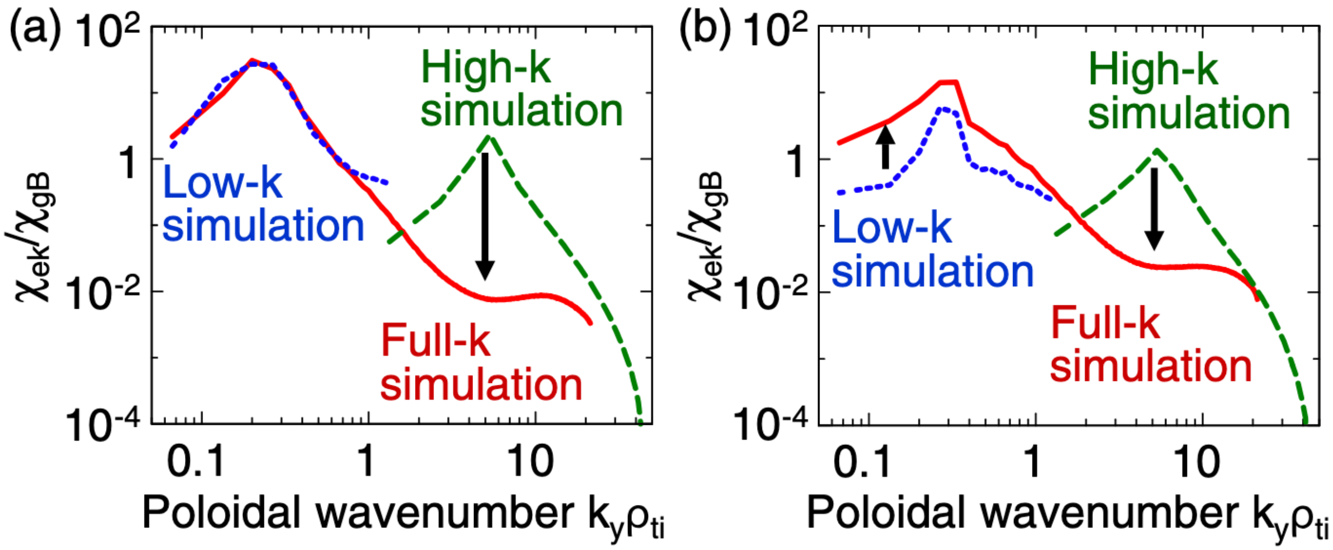
# Multiscale (ion-electron scale) Gyrokinetic Turbulence



# Multiscale (ion-electron scale) Gyrokinetic Turbulence



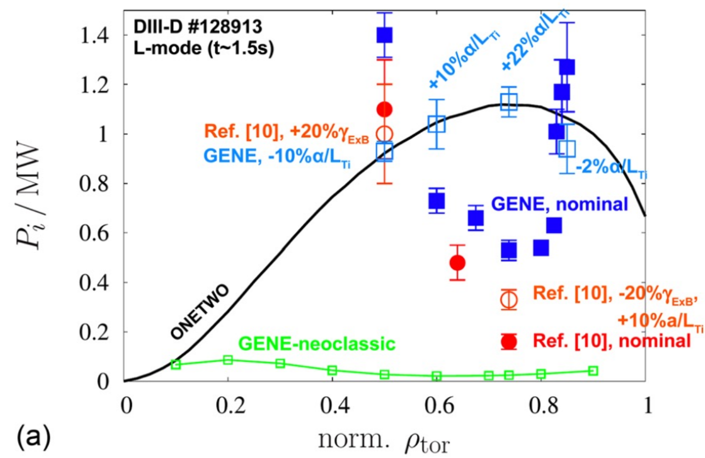



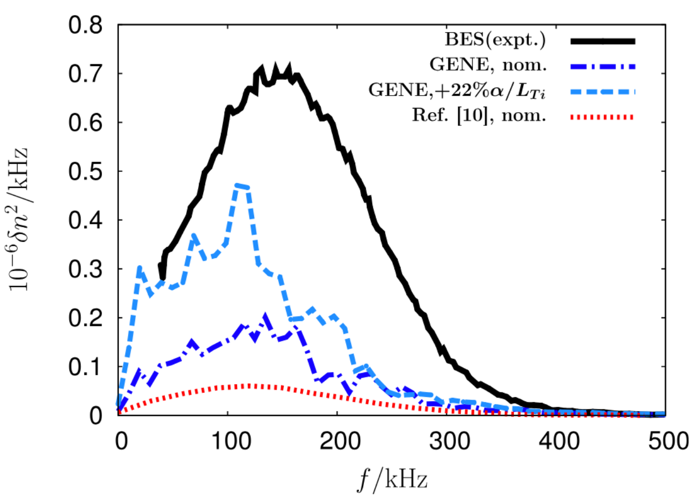

Maeyama et al. PRL 2015

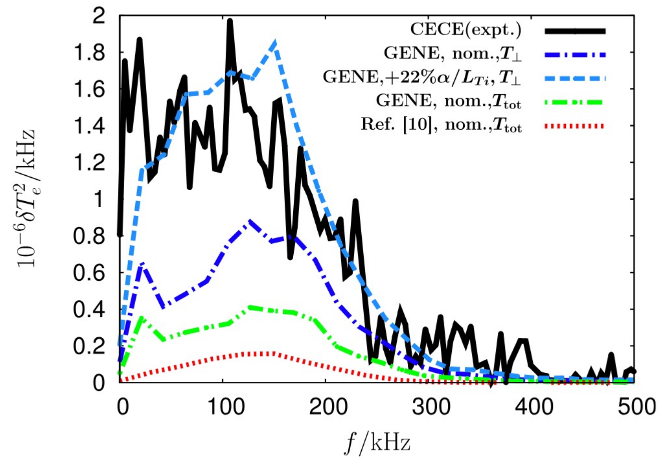
# Validation of GK Turbulence

Comparisons between GK simulations and experiments find increasingly good agreement.

-'Flux Matching'
-Fluctuation diagnostics




Goerler et al. PoP 2014

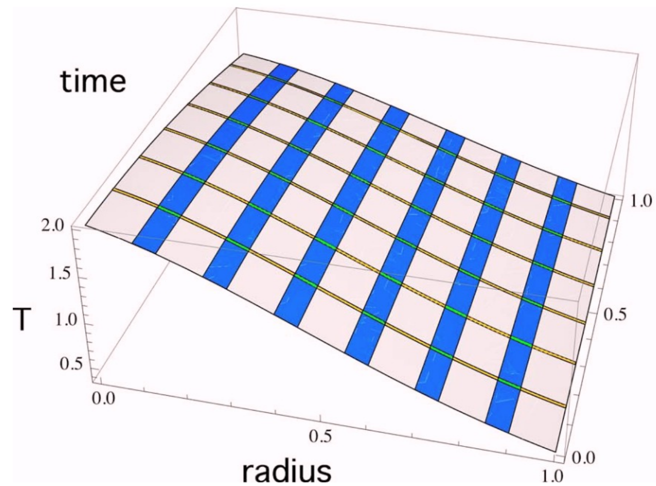
# Inverting the problem: Going from sources to profile predictions

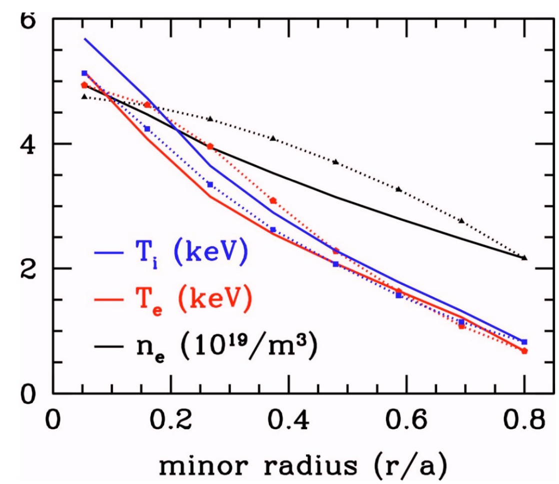
$$\frac{\partial n_s}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \psi}(V'\overline{\langle \Gamma_s \rangle}) = \overline{\langle S_n \rangle},$$

$$\frac{3}{2}\frac{\partial p_s}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \psi}(V'\overline{\langle Q_s \rangle})$$

$$= -\overline{\langle H_s \rangle} + \frac{3}{2} n_s \sum_u \nu_{su}^{\varepsilon}(T_u - T_s) + \overline{\langle S_p \rangle},$$

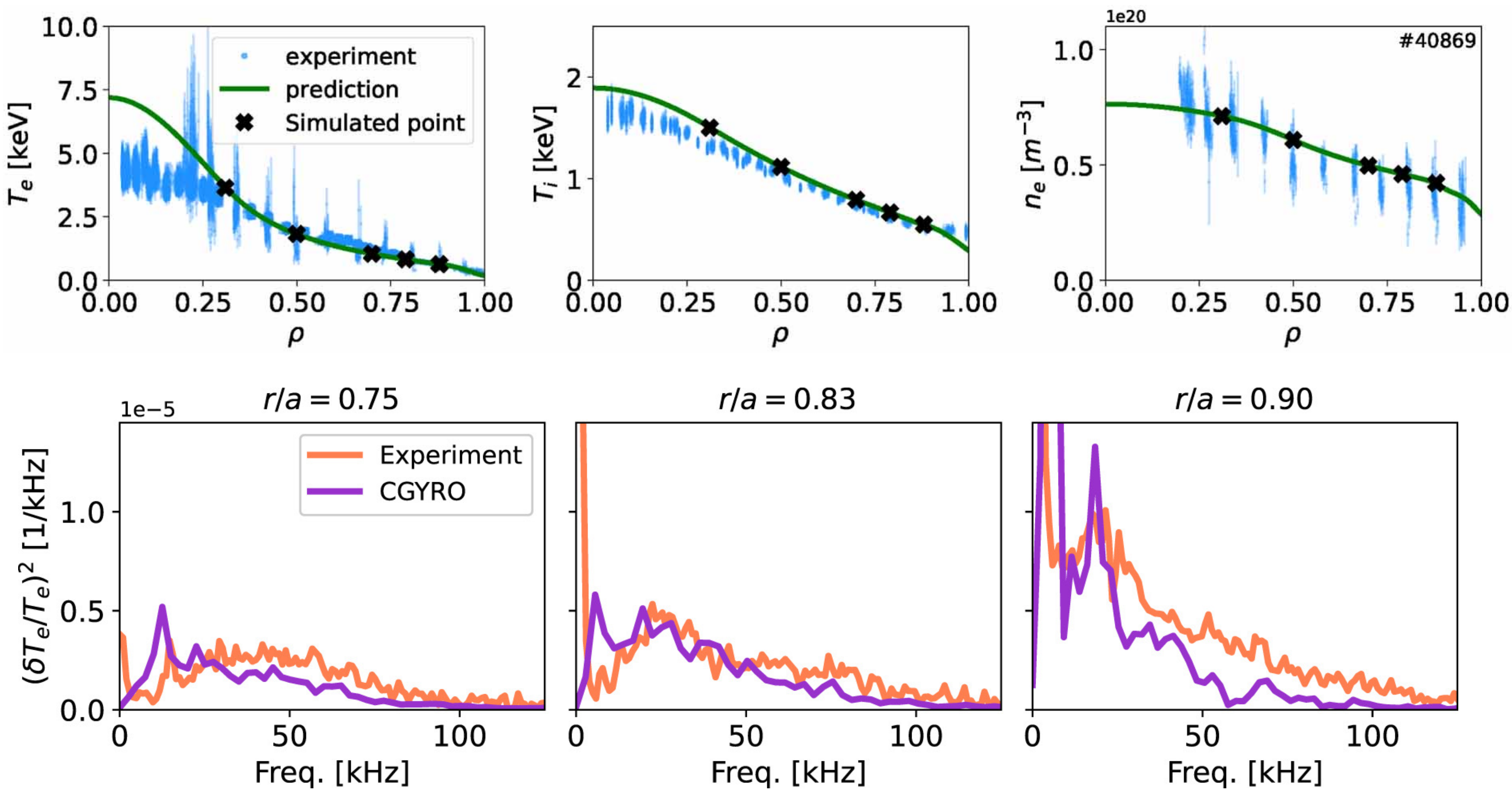
$$Q \equiv \nabla\psi \cdot \int d^3\mathbf{v} \frac{mv^2}{2}(\mathbf{v}_\chi \delta f_1 + \mathbf{v}_B \langle f_1 \rangle + \boldsymbol{\rho} C[\boldsymbol{\rho}\cdot\nabla f_0]),$$




Barnes et al. PoP 2010

# Validation via Profile Prediction



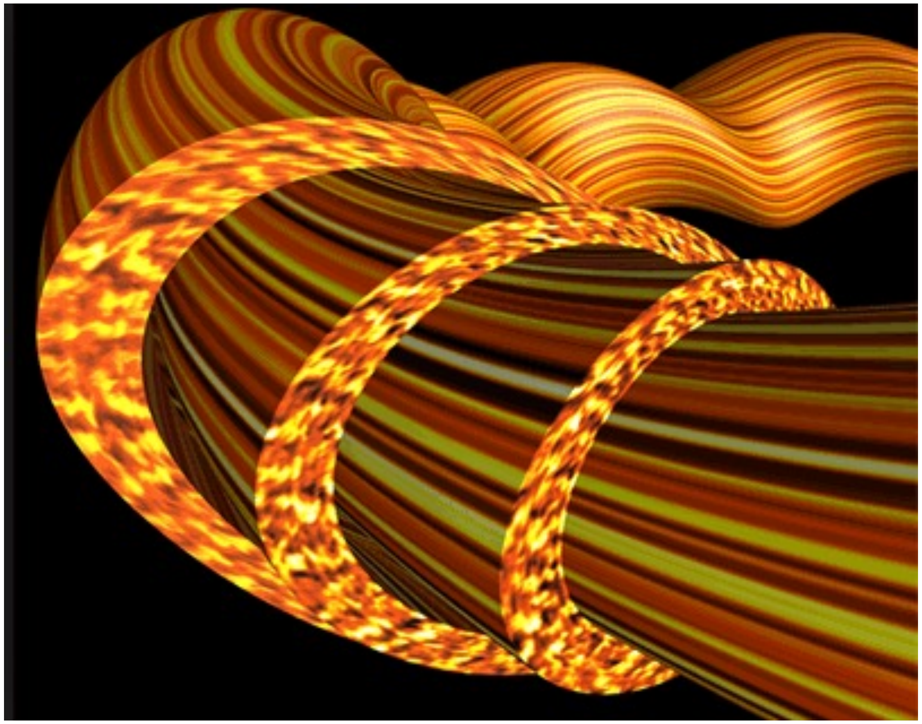

Bielajew et al. NF 2025

# Gyrokinetics for Stellarator Turbulence

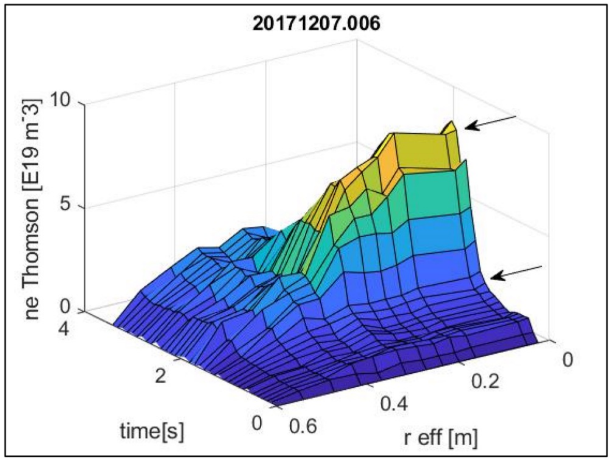
Challenges of 3D equilibrium

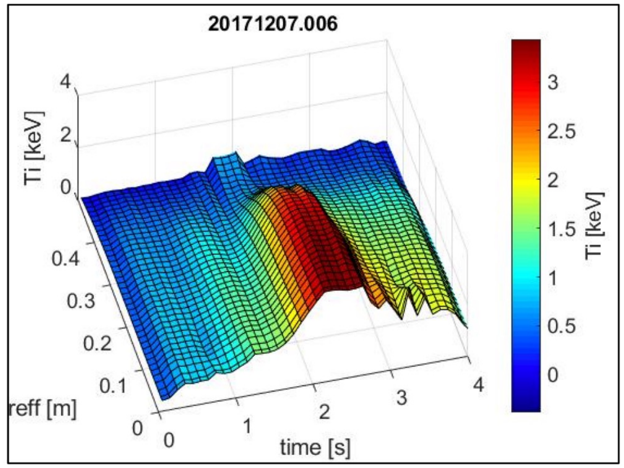
But GK is capable of modeling stellarator turbulence

-Flux tube
-Full flux surface

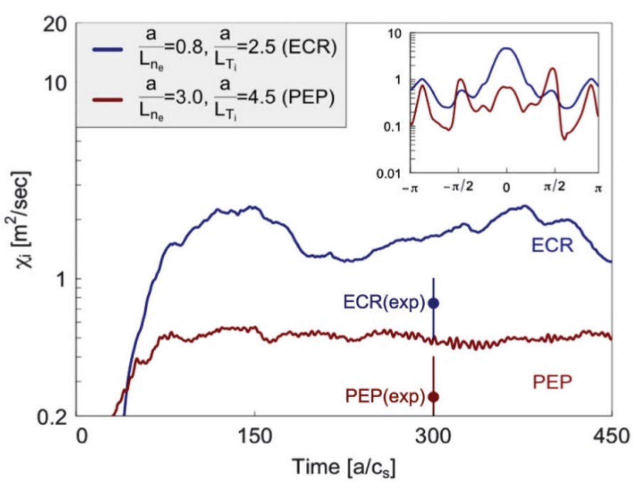


# 'Unclamping' of Ti profile in W7X



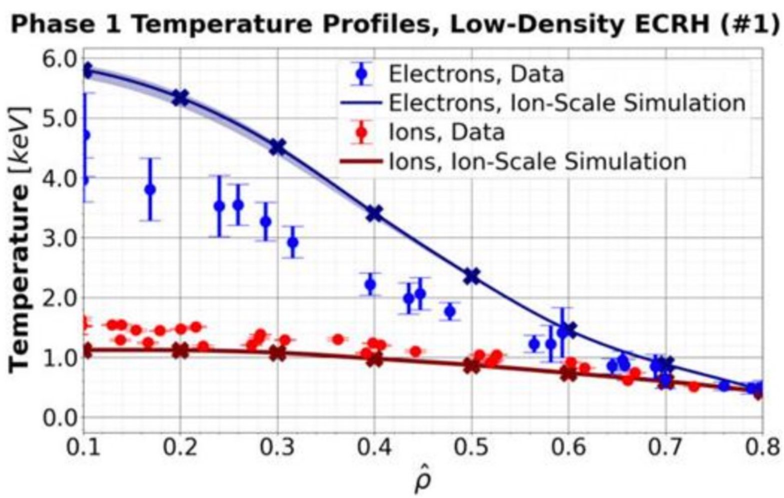

Baldzuhn et al. PPCF 2020

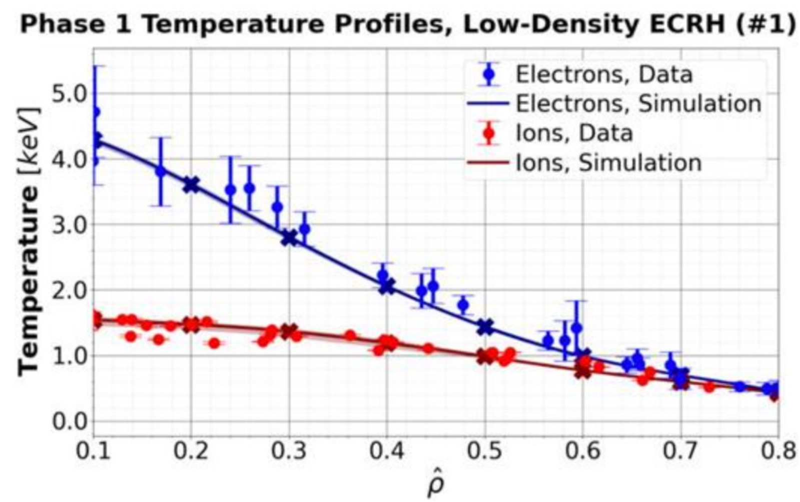



Gyrokinetic simulations show a reduction in transport as density gradient increase (more in next lecture!).

Xanthapolous et al PRL 2020

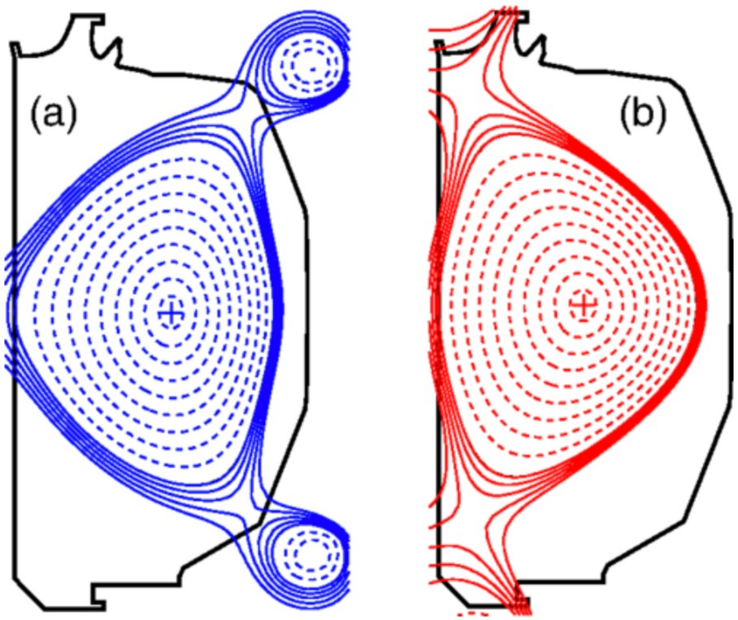
# GK Modeling W7X profiles



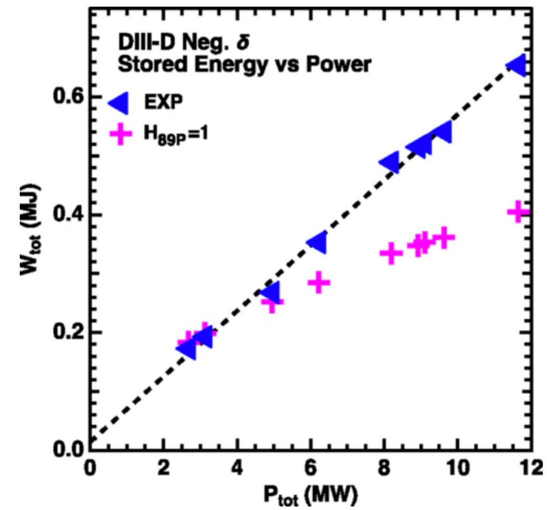



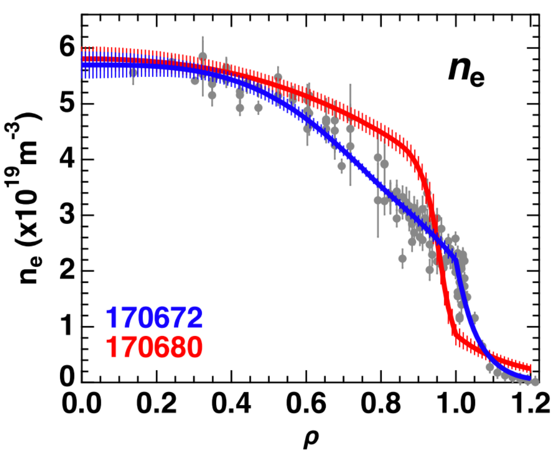

D. A. C. Agapito Fernandez et al. PoP 2025

# Alternative to H-mode?: Negative Triangularity

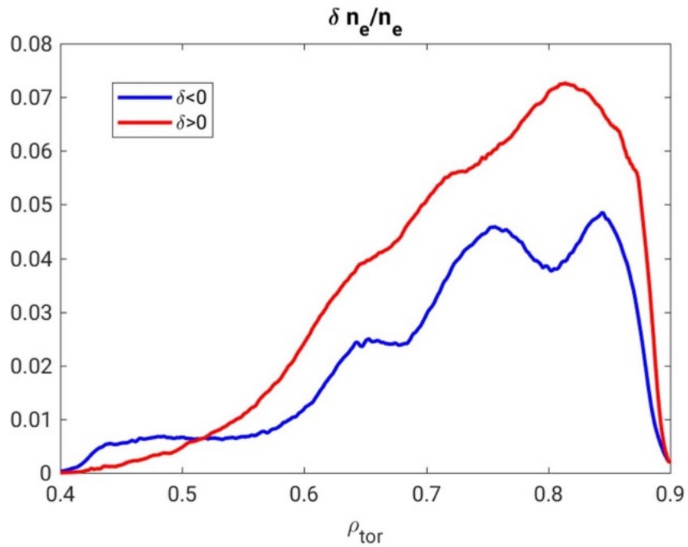


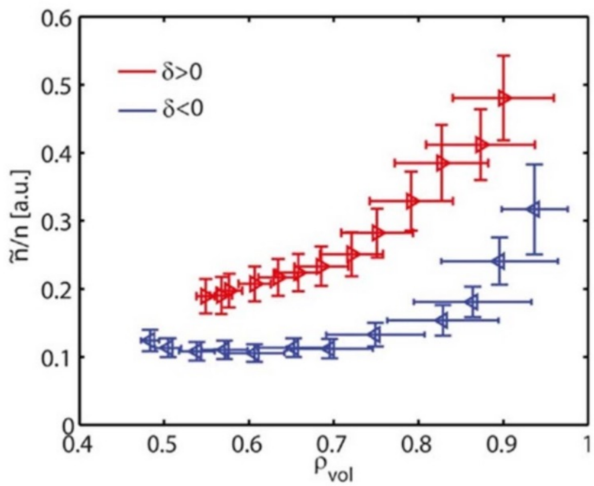

Austin et al. PRL 2019



# GK analysis of negative triangularity

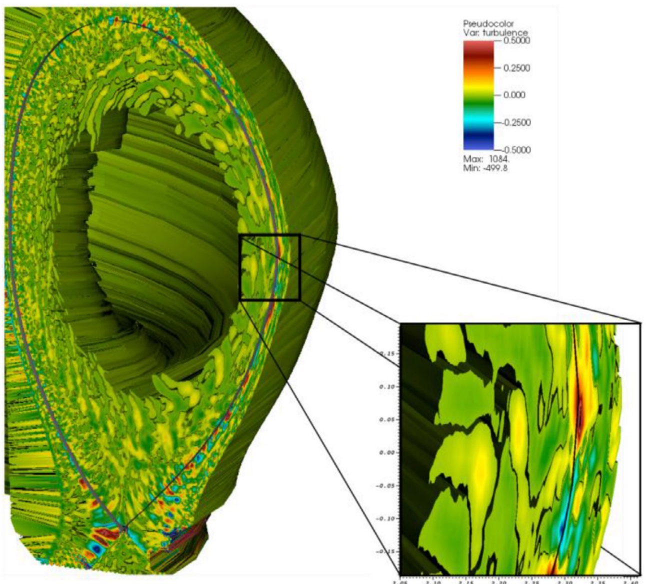


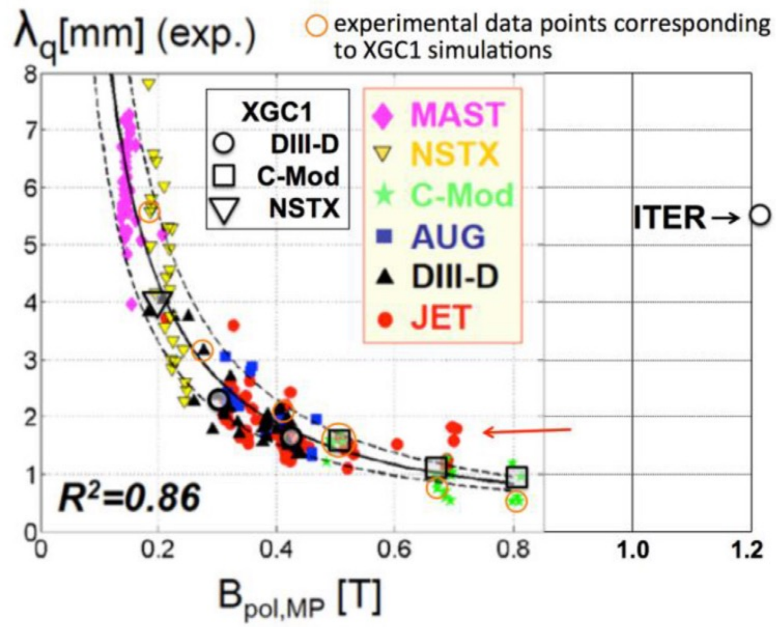




Merlo et al. PPCF 2021

# Gyrokinetic Predictions of Future Devices

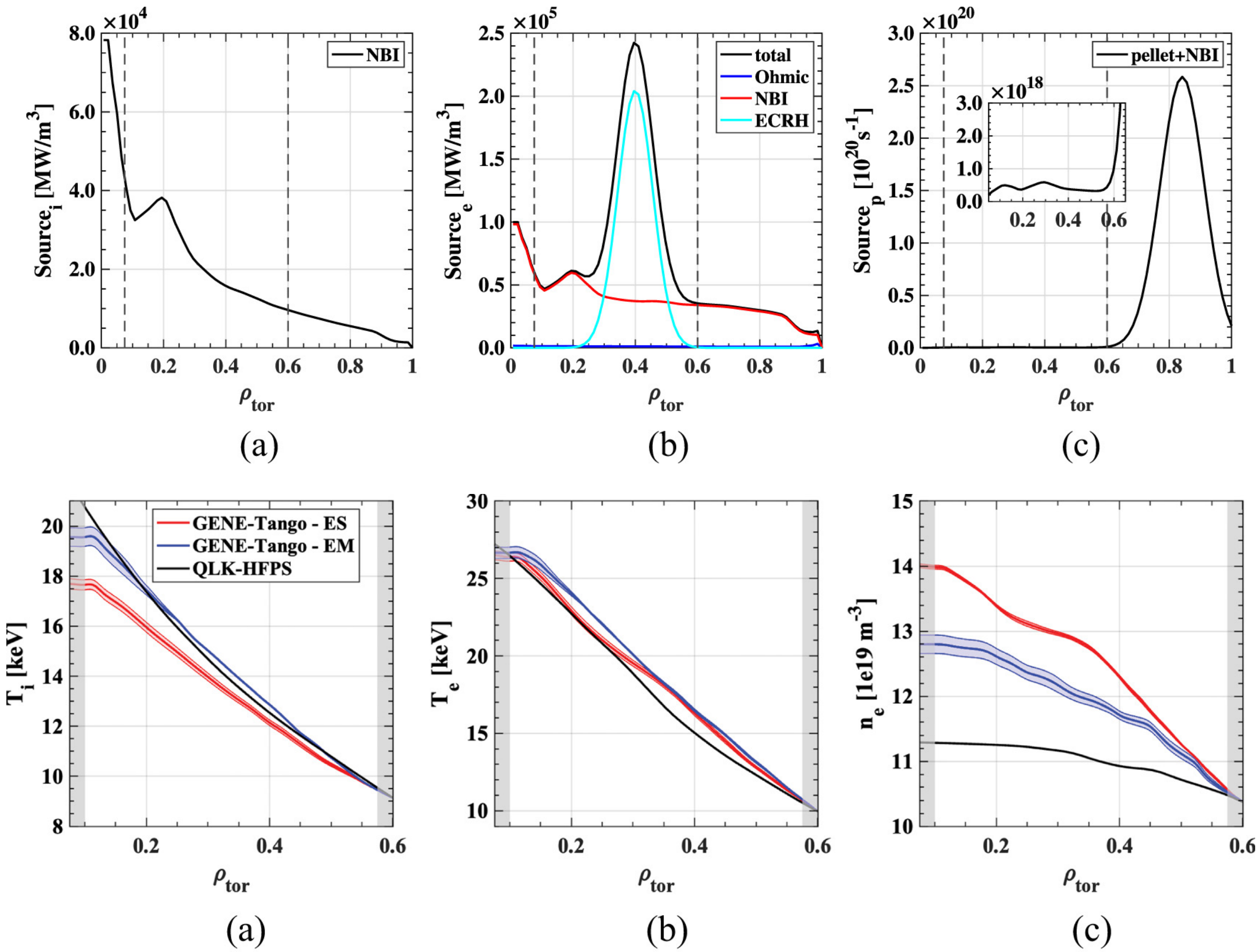
# GK Prediction of ITER SOL Width





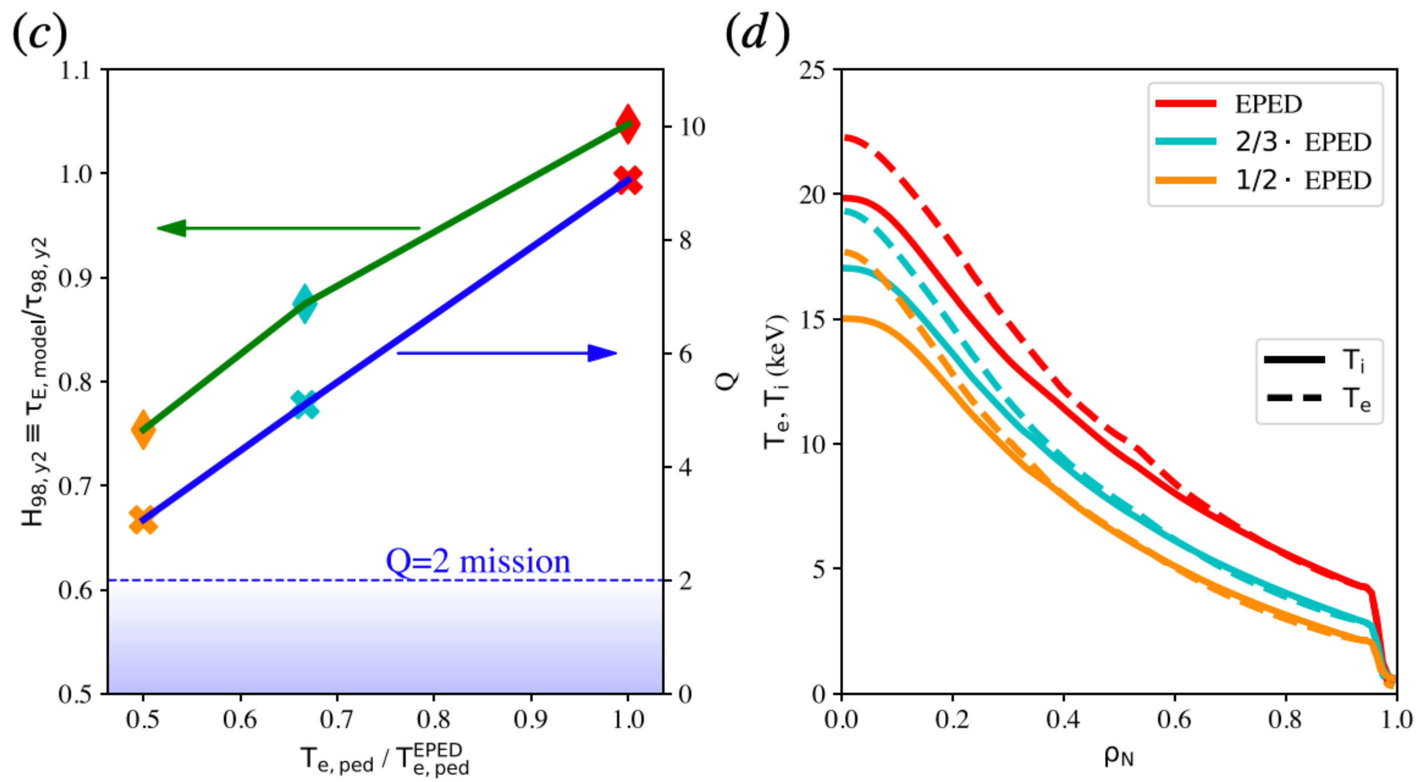

Chang et al. NF 2017

# GK Prediction of ITER profiles



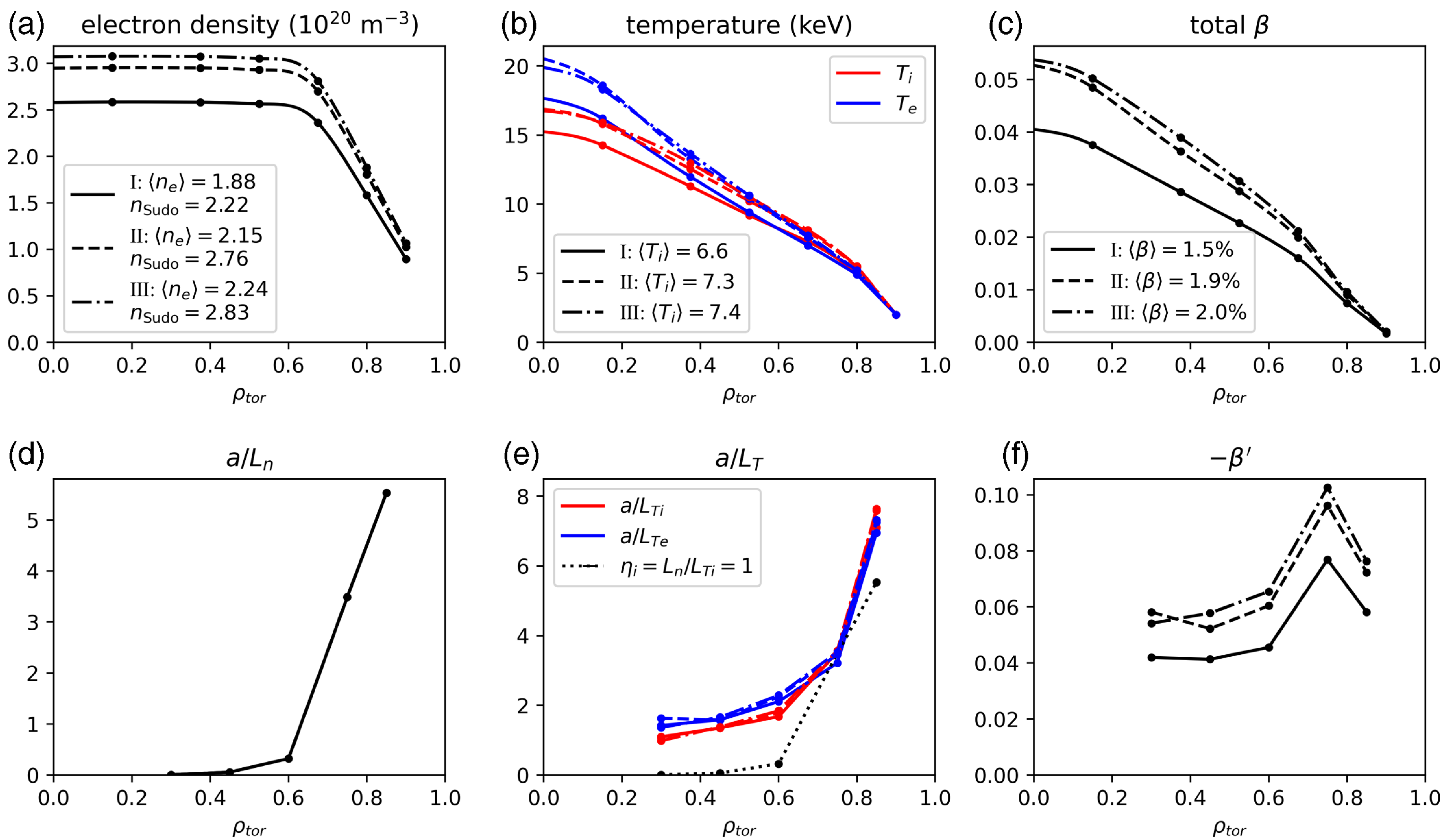

Di Siena et al. NF 2026

# GK Prediction of SPARC Performance



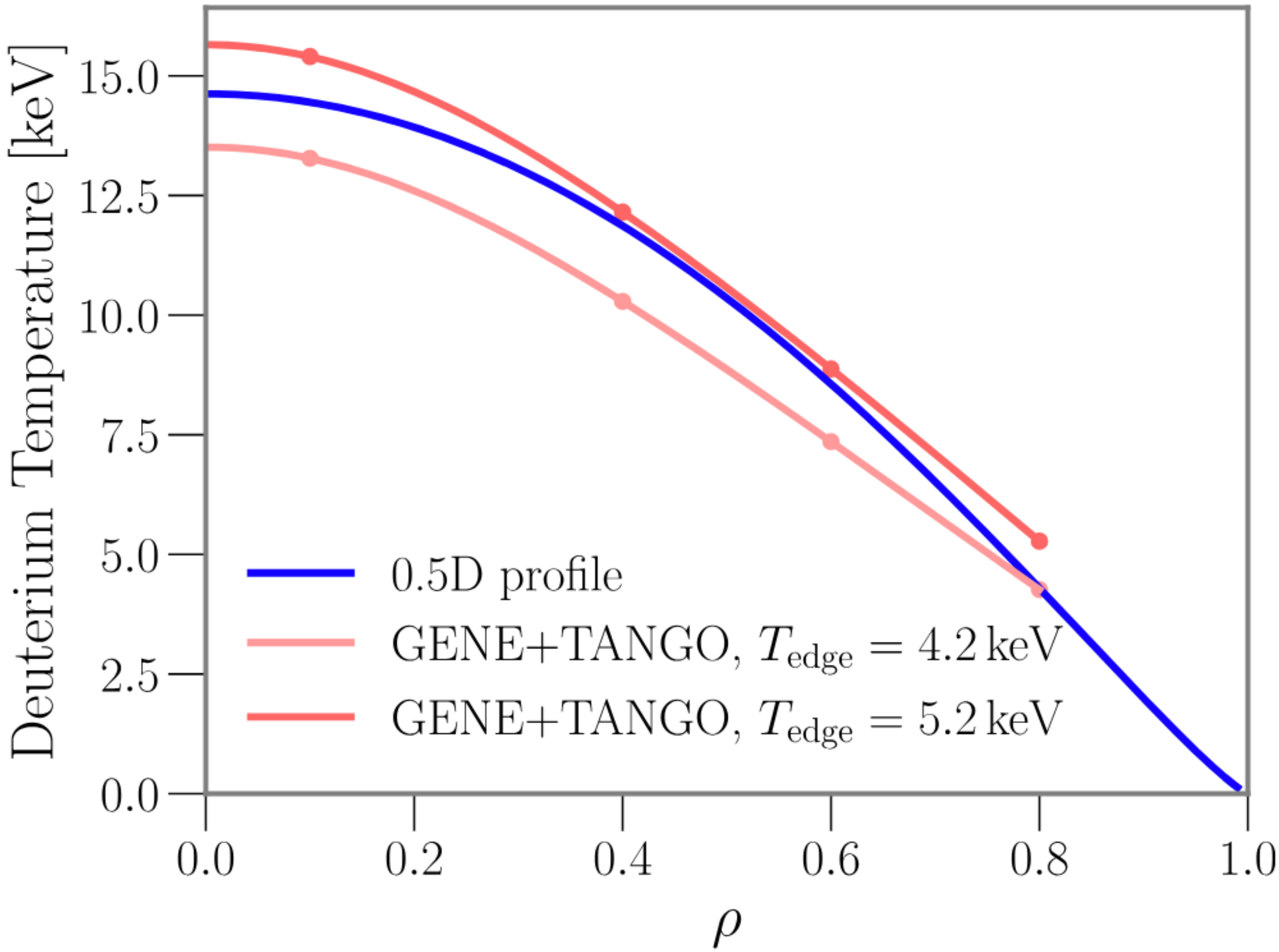

P. Rodriguez Fernandez et al. JPP 2020

# GK Prediction of Infinity 2 Performance



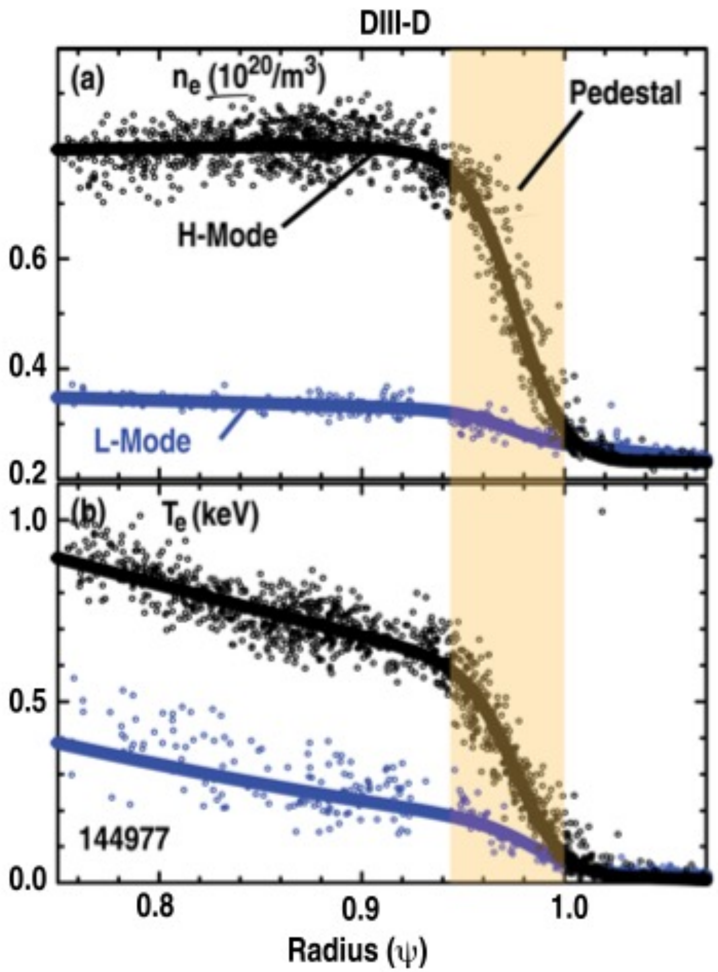

Guttenfelder et al. JPP 2025

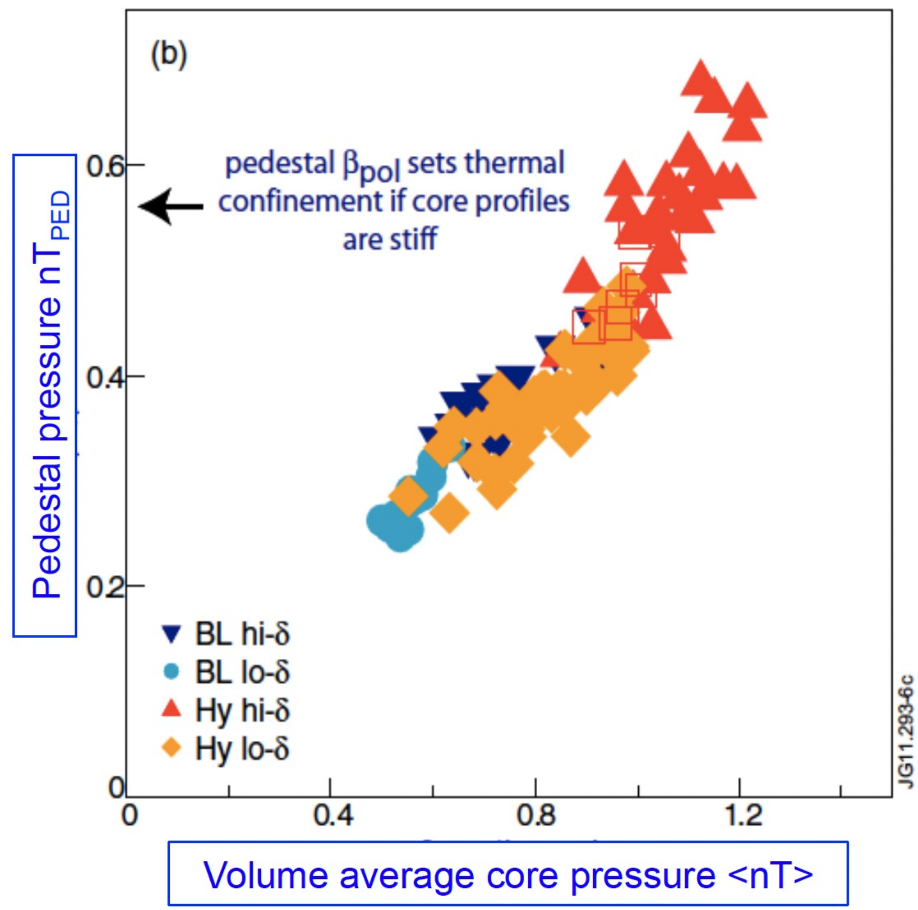
# GK Prediction of Infinity 2 Performance



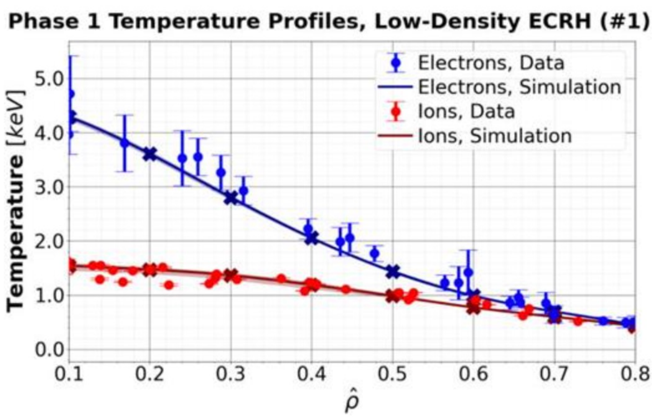

Lion et al. FED 2025

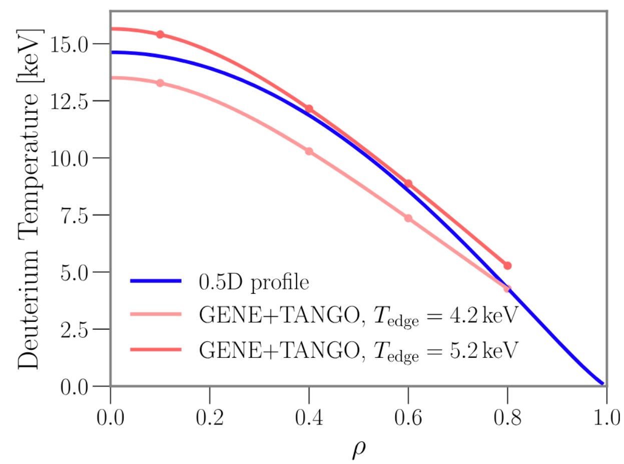
# The Elephant in the Room: Pedestal Boundary Condition + Profile Stiffness

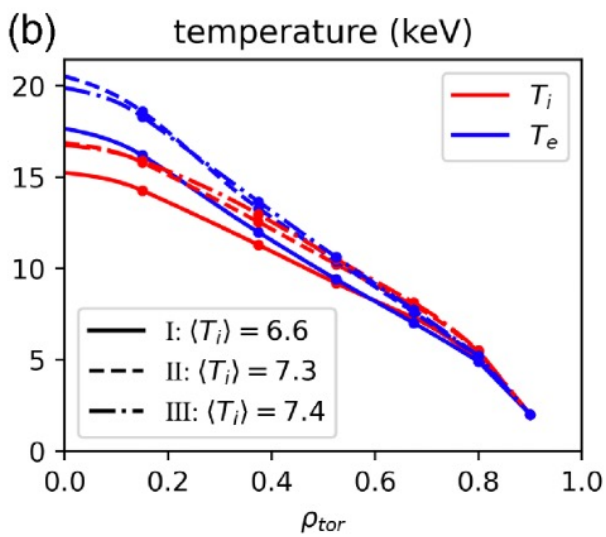


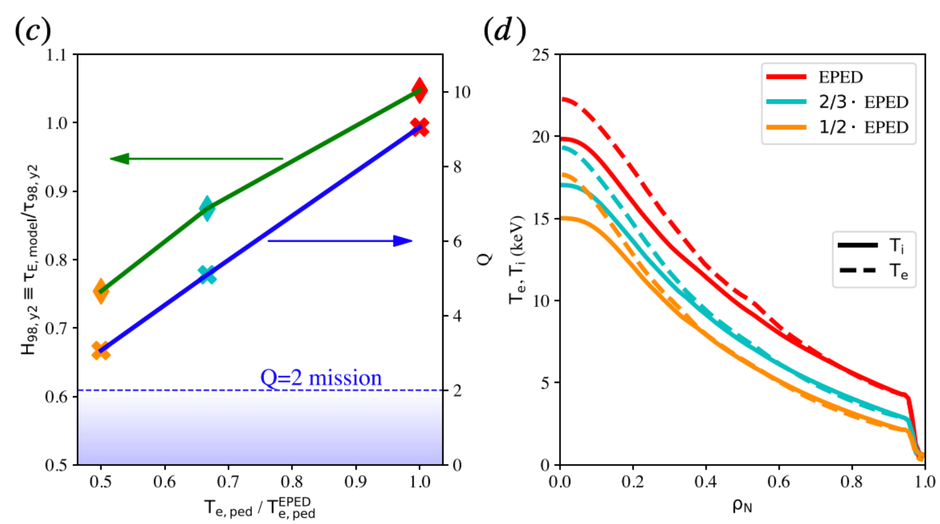



# All Core Profile Predictions Use
# (1) Experimental data or
# (2) A simple model
# For the Pedestal B.C.



All Core Profile Predictions Use
(1) Experimental data or
(2) A simple model
For the Pedestal B.C.

Core confinement depends almost entirely on the pedestal

We cannot currently make GK transport-based predictions of the pedestal! (More in next talk)