Investigations of plasma turbulence in the edge of HSX, LHD and W7-AS

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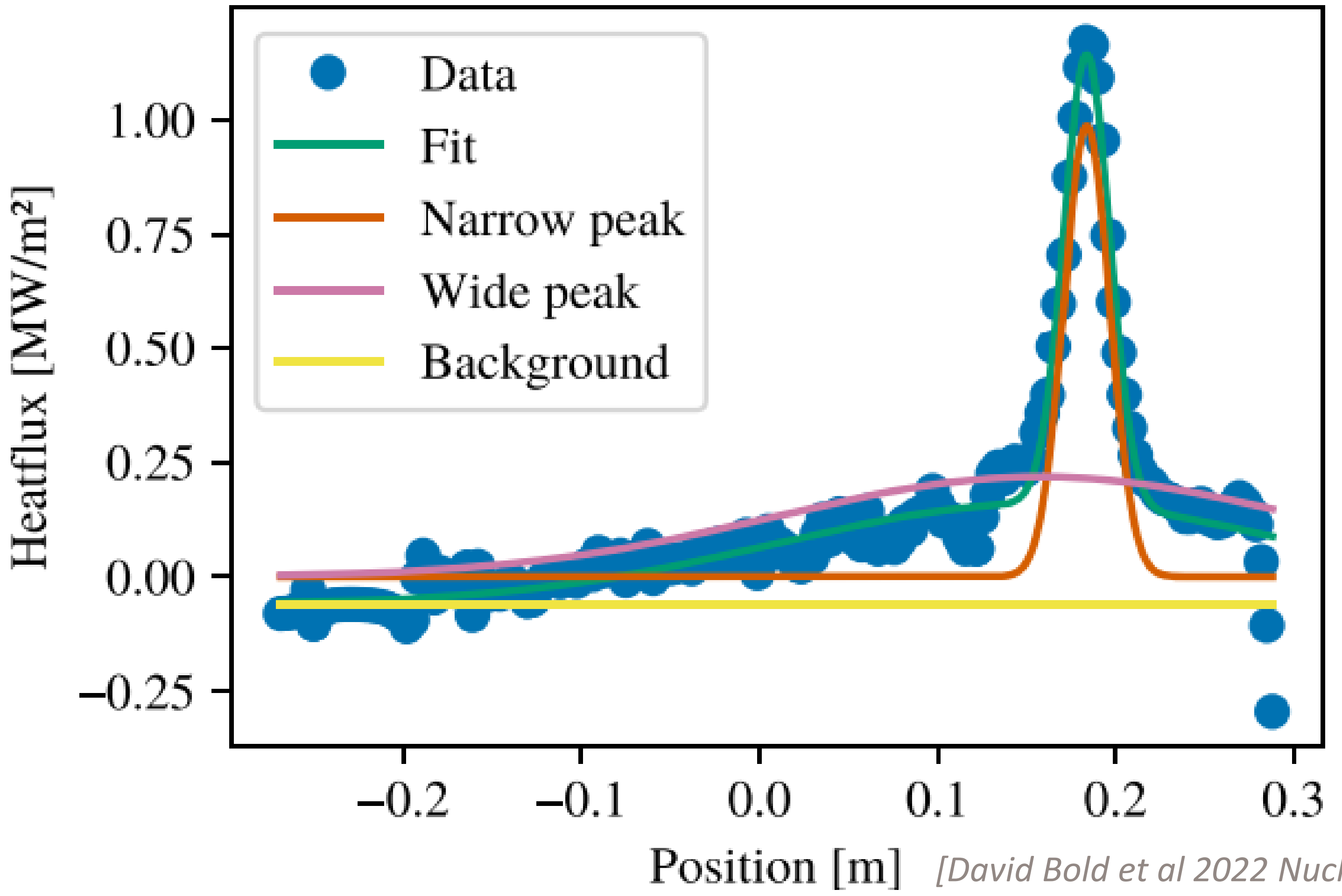
Understanding edge turbulence crucial in stellarators

- **Significant heat fluxes in the edge** of stellarators
- Perpendicular transport influences **peaks and spread of heat flux profile and SOL width**
- The **core plasma** is constrained by **boundary conditions established through edge turbulence**

Heat flux on target W7-X

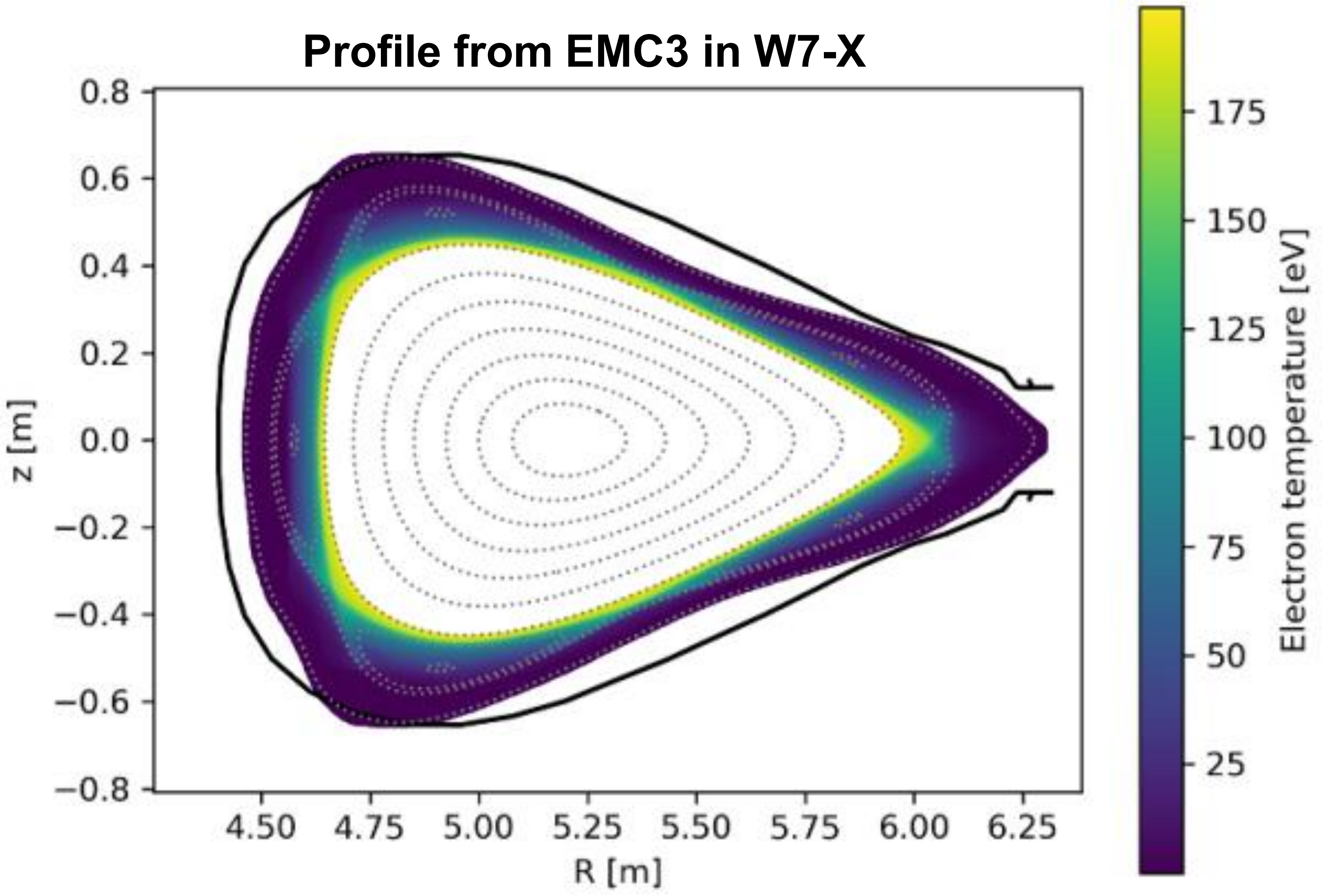


[David Bold et al 2022 Nucl. Fusion]

- **Inclusion of turbulence positively affecting the divertor design**
- **Include edge turbulence metrics in the stellarator optimisation loop** [M. J. Gerard et al, Nucl. Fusion 2023]

Current edge physics based on transport models

- Recent and past investigations are mainly based on **transport codes** *[Feng, Y., et al. Contributions to Plasma Physics (2004)]*
- Turbulent transport is modelled with **ad-hoc turbulent coefficients**
- **Use turbulent codes to inform transport codes.**



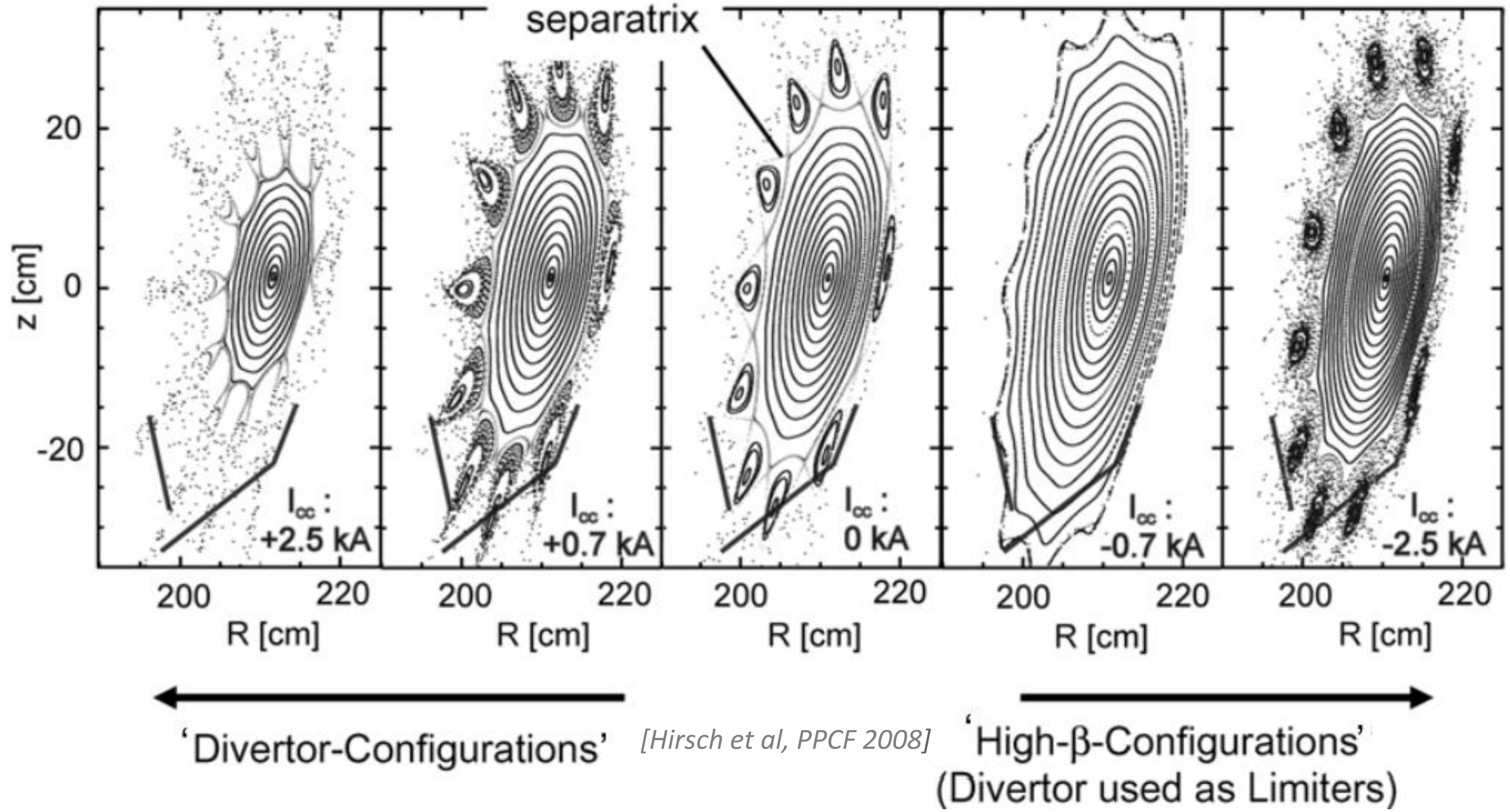
[David Bold et al 2024 Nucl. Fusion]

What makes the edge region challenging?

Simulating edge turbulence in stellarators is challenging

- **Edge complex magnetic structures**: magnetic islands, stochastic regions, X-points

W7-AS



[Hirsch et al, PPCF 2008]

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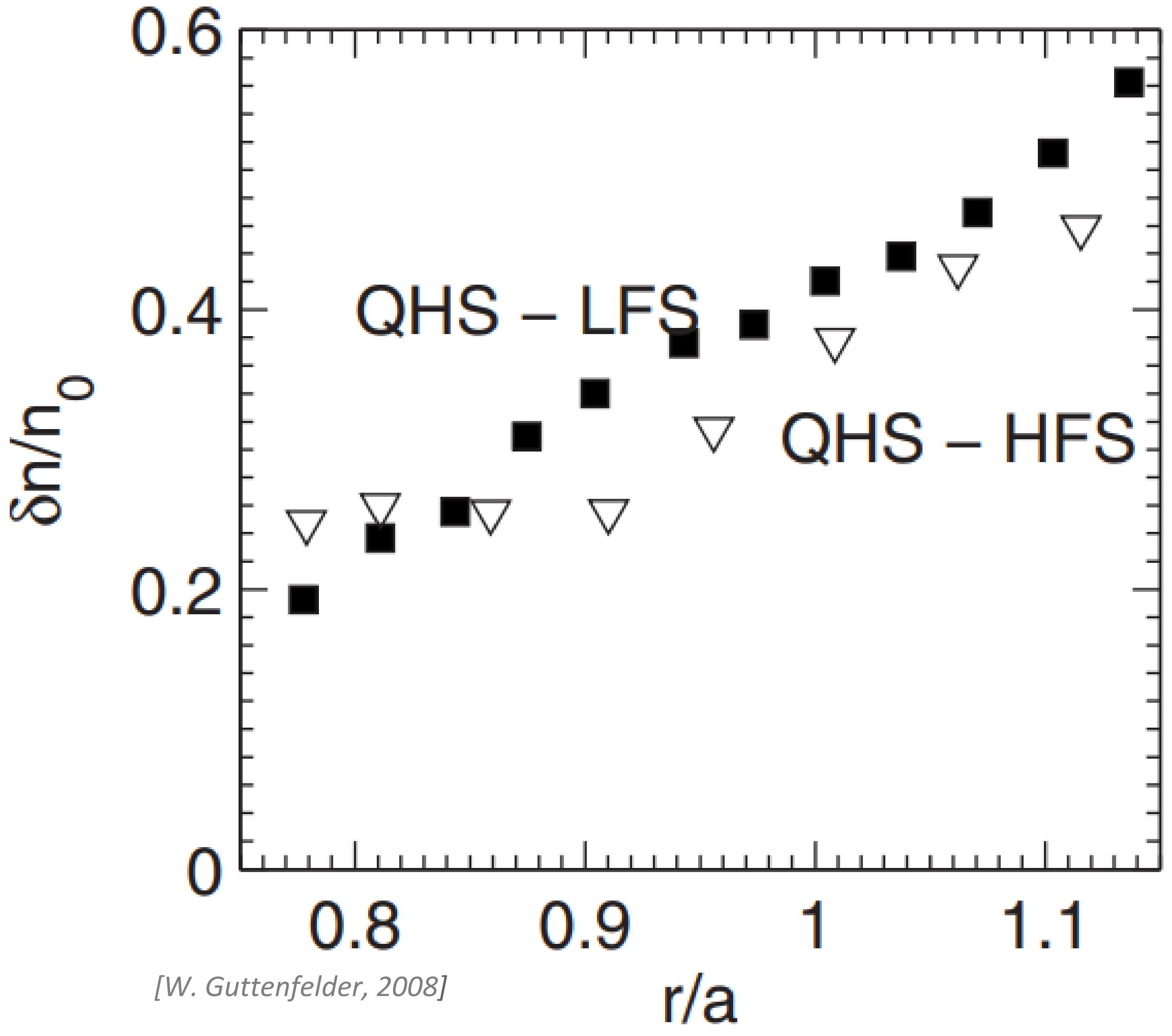
- **Large fluctuations levels:** no separation between **background and fluctuations**

HSX



[W. Guttenfelder, 2008]

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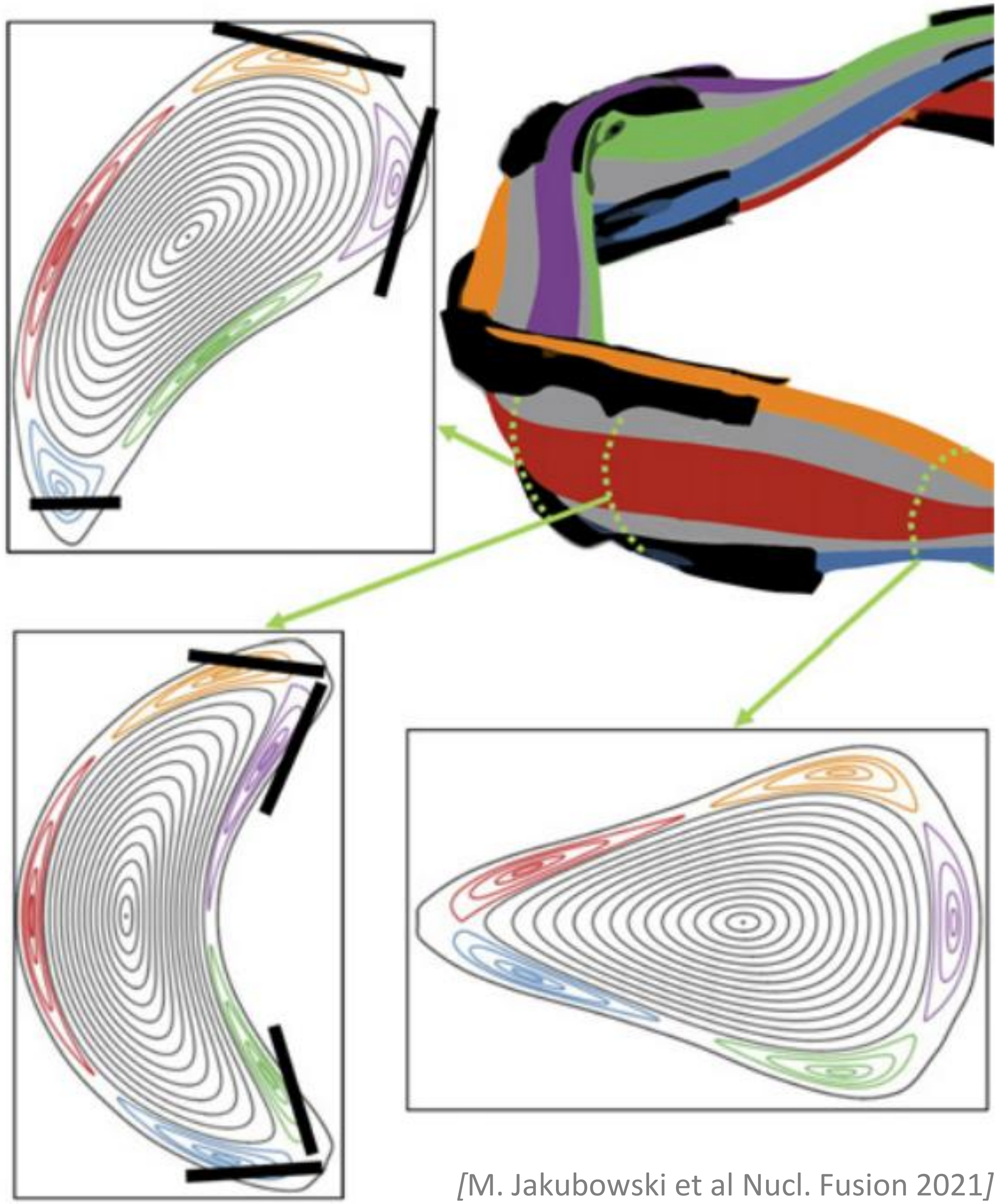

[M. Jakubowski et al Nucl. Fusion 2021]

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- **Edge complex magnetic structures**: magnetic islands, stochastic regions, X-points
- **Large fluctuations levels:** no separation between **background and fluctuations**
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- **Complex diverting structures**
- **Neutral dynamics**

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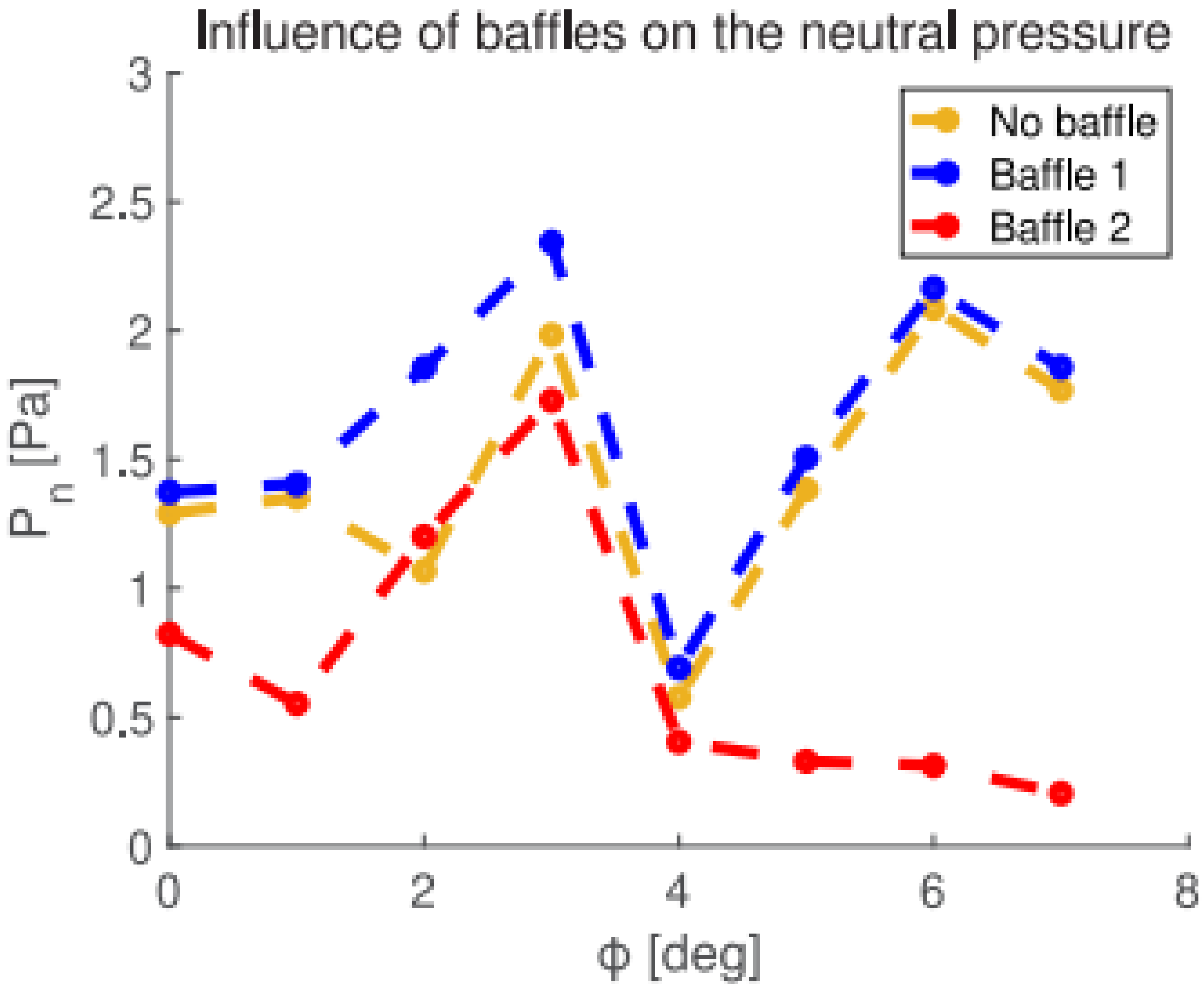

[D. Boeyaert et al Nl. Materials and Energy 2025]

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Simulating edge turbulence in stellarators is challenging

Main challenges in the edge region

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Simulation requirements

- **Flexible discretization scheme with non-flux-aligned coordinates**
- **No separation of equilibrium and fluctuating quantities**
- **Flux-driven**: sources generate gradients for turbulence driving
- **Global:** simulate the entire volume
- **Magnetic pre-sheath boundary conditions**
- **Coupling plasma and neutrals**

Drift-reduced Braginskii equations to simulate the boundary plasma turbulence

- Plasma edge is **highly collisional** $\rho_{L,i} k_\perp \ll 1$,$\lambda_{mfp} \ll L_\parallel$ use **two-fluid Braginskii model**
  [S. I. Braginskii. Reviews of Plasma Physics, 1965]

- **Turbulence time scale longer than** Ω_{ci}^{-1}**, drift-reduced approximation** *[A. Zeiler, (1999)]*

$$\mathbf{V}_e = \mathbf{V}_{E\times B} + \mathbf{V}_{de} + V_{\parallel e}\mathbf{b}, \quad \mathbf{V}_i = \mathbf{V}_{E\times B} + \mathbf{V}_{di} + \mathbf{V}_{pol} + V_{\parallel e}\mathbf{b}$$

- **Quasi-neutrality**: $n_e \sim n_i \sim n$,

$$\frac{\partial n}{\partial t} + \underbrace{\nabla \cdot \Gamma_{E\times B}}_{\mathbf{E}\times\mathbf{B}\ \text{convection}} + \underbrace{\nabla \cdot \Gamma_{di}}_{\text{diamagnetic convection}} + \overbrace{\nabla \cdot \Gamma_{pol}}^{\text{polarization convection}} + \underbrace{\nabla_\parallel \Gamma_\parallel}_{\text{parallel flow}} = \underbrace{\mathcal{S}_n}_{\text{source}}.$$

- **Electrostatic** perpendicular **electric field**: $\mathbf{E}_\perp = -\nabla_\perp \Phi$ solved with **Poisson**

- Similar equations for $V_{\parallel,e}, V_{\parallel,i}, T_e, T_i$ given by **momentum and energy conservation**

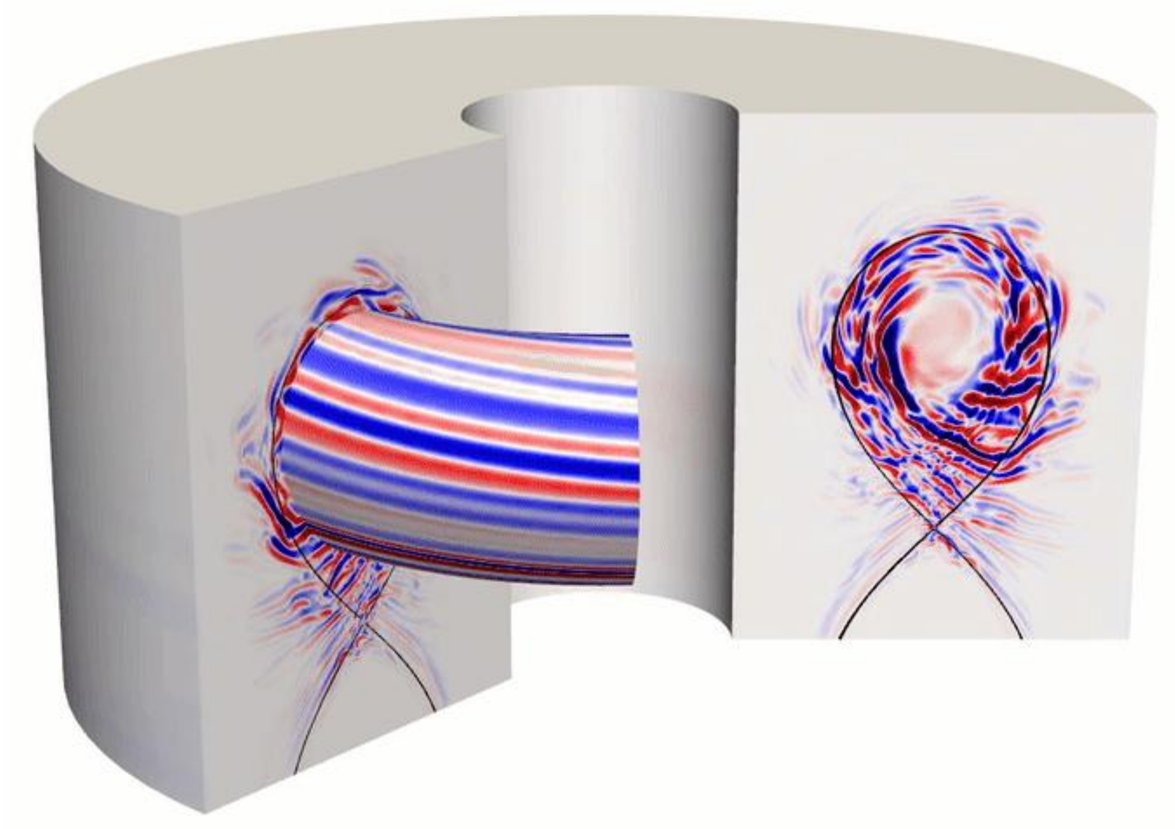
- **Charge conservation,** $\nabla \cdot (\mathbf{J}_\parallel + \mathbf{J}_{di} + \mathbf{J}_{pol}) = 0$

+ Neutral dynamics (not considered in the present work) *[D. Mancini et al Nucl. Fusion 2023]*

GBS solves the drift-reduced Braginskii equations

- GBS is **a two fluid, global, flux-driven code to simulate turbulence** evolving such equations in time in **a non-flux-aligned grid**
- **Coupled with a kinetic model for neutral dynamics**
  [D. Mancini et al Nucl. Fusion 2023]

TCV-like tokamak *[B. De Lucca et al EFTC 2025]*



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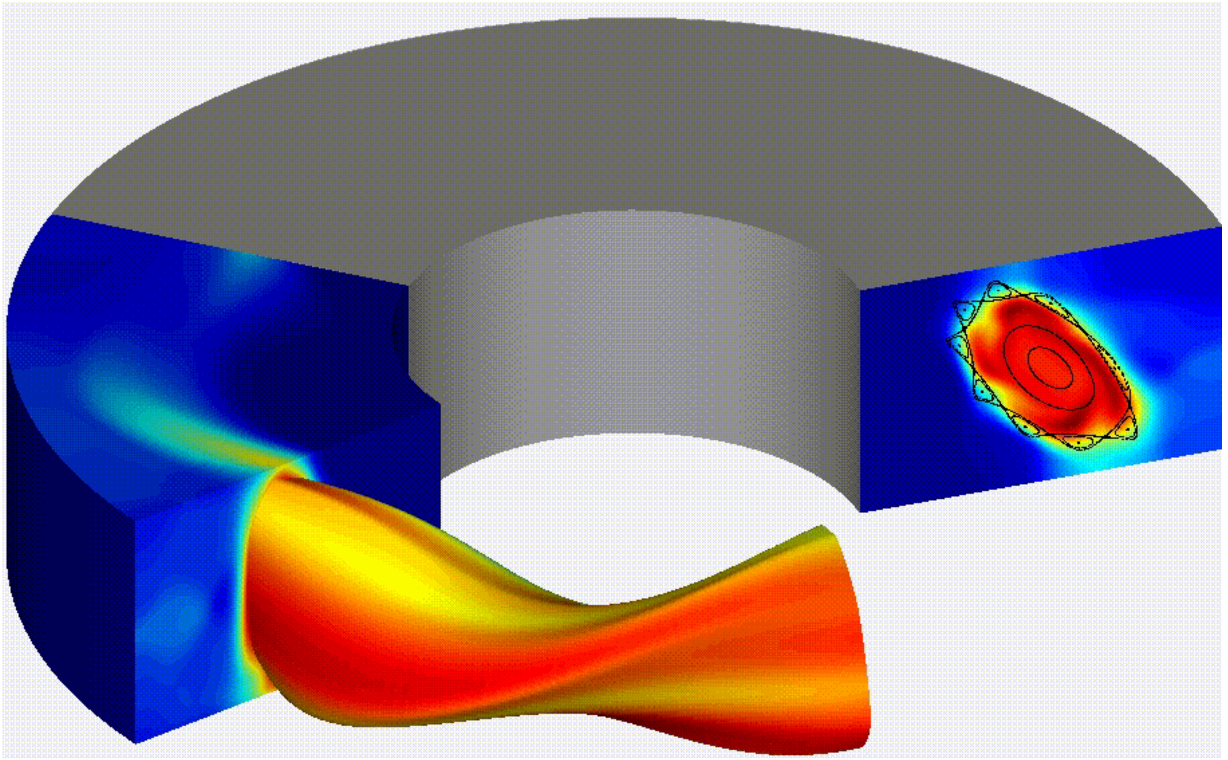
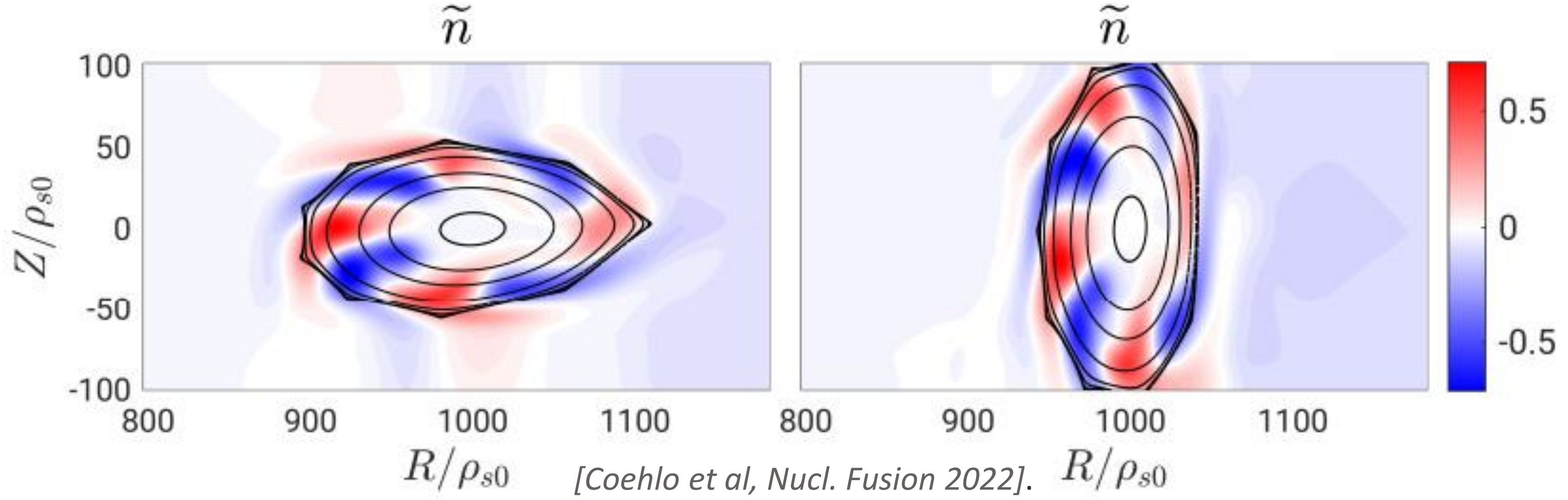
- GBS used in the past decade to simulate tokamaks *[Ricci et al. PPCF 2012, Giacomin et al. JCP 2022]*; **now it can simulate turbulence in 3D magnetic fields** *[Coehlo et al, Nucl. Fusion 2024]*.



[Coehlo et al, Nucl. Fusion 2024]

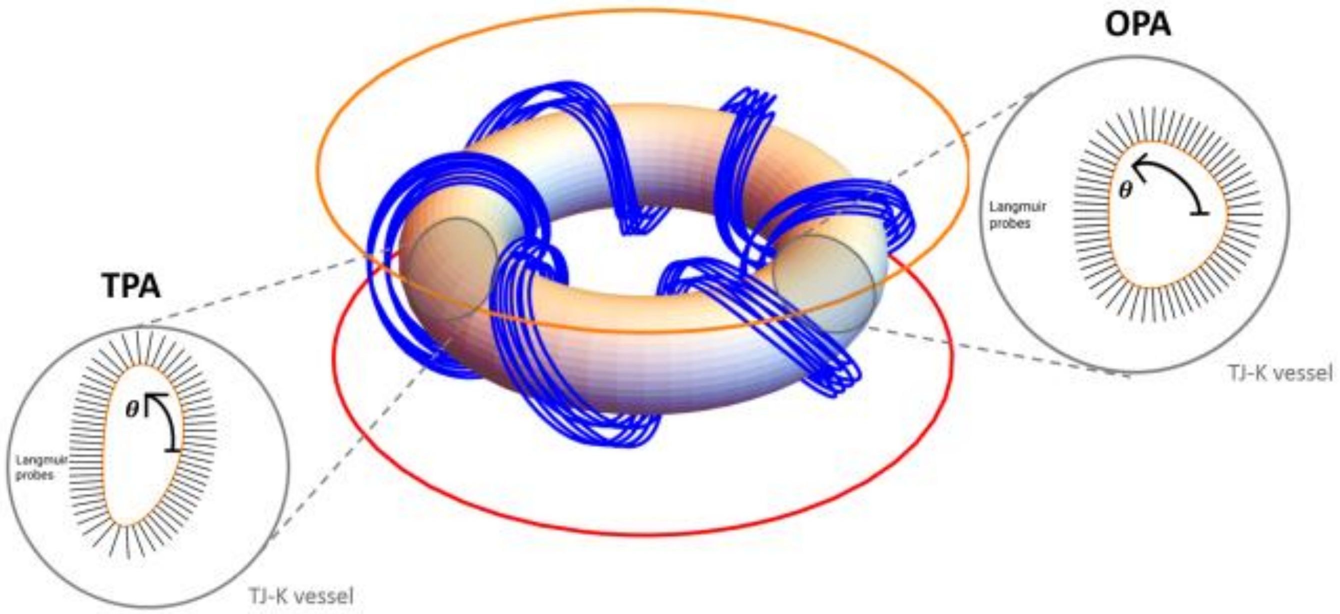
First-principles edge transport pioneered by the GBS group

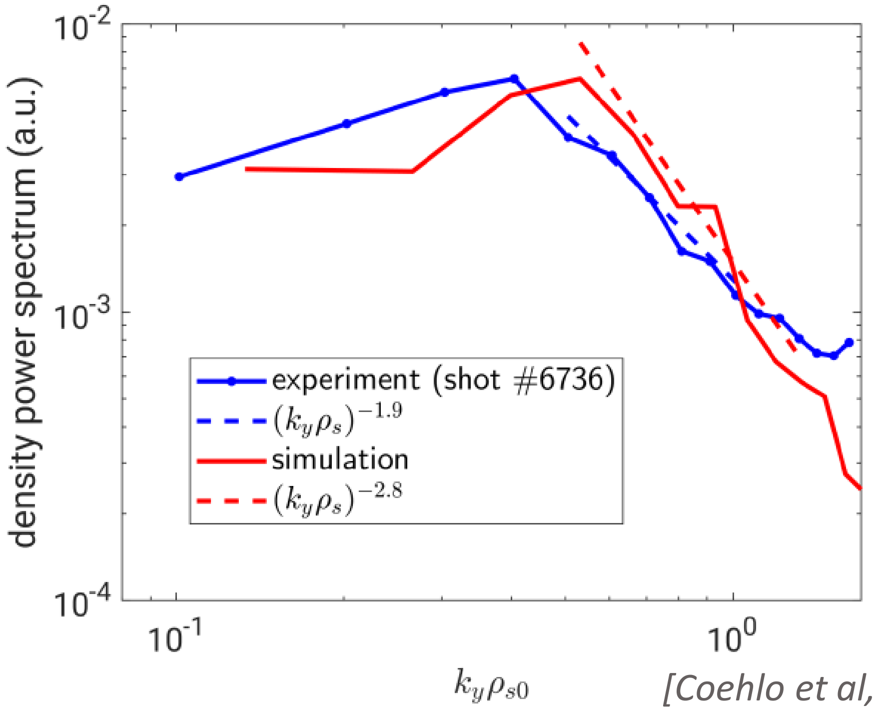
- **First global flux driven simulation** of a toy model stellarator



[Coehlo et al, Nucl. Fusion 2022].

- **Successful global quantitative validation in TJK**





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Stellarator edge turbulence gaining attention

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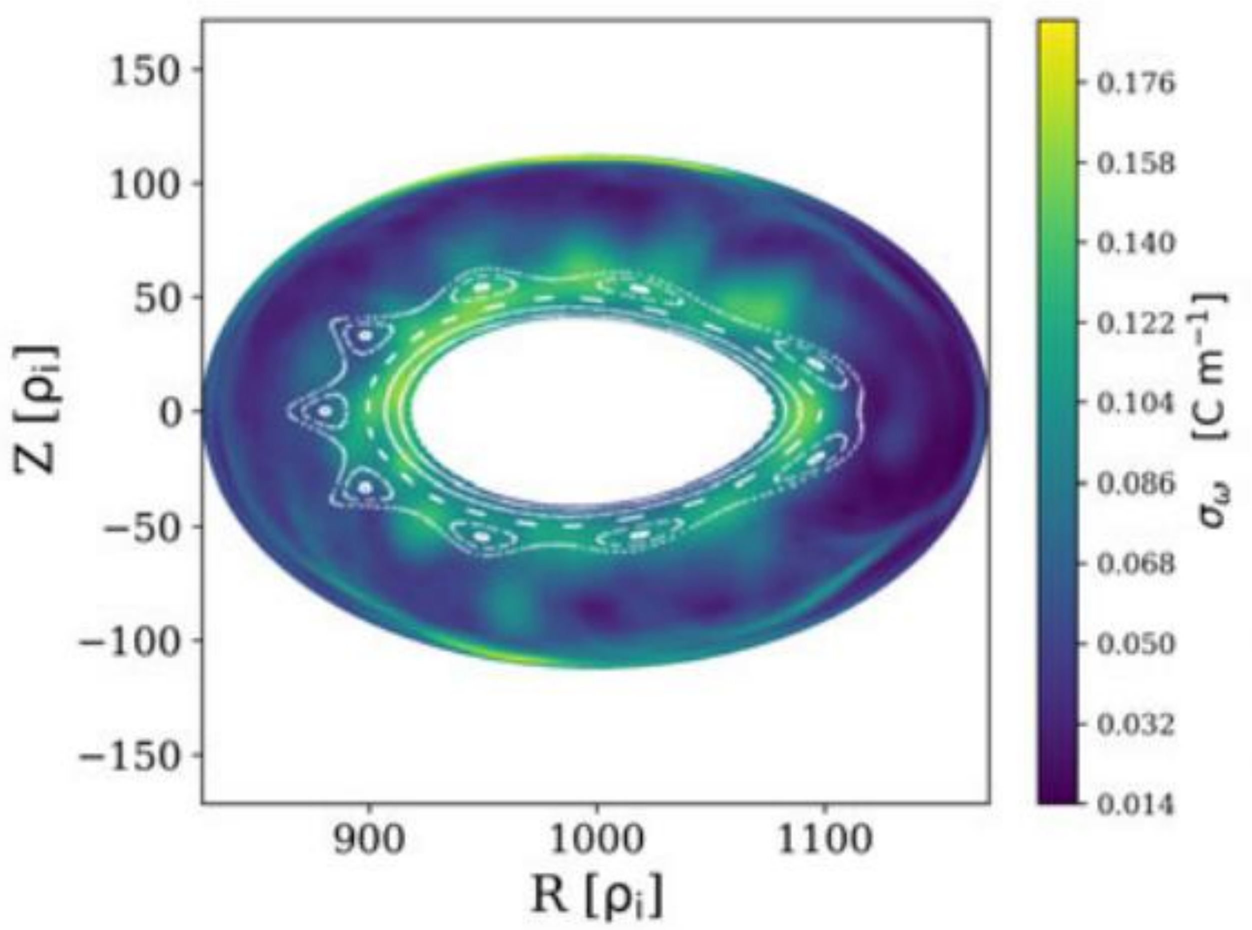
  - **Isothermal fluid model in BOUT++**



[B Shanahan et. al., JPP 2024]

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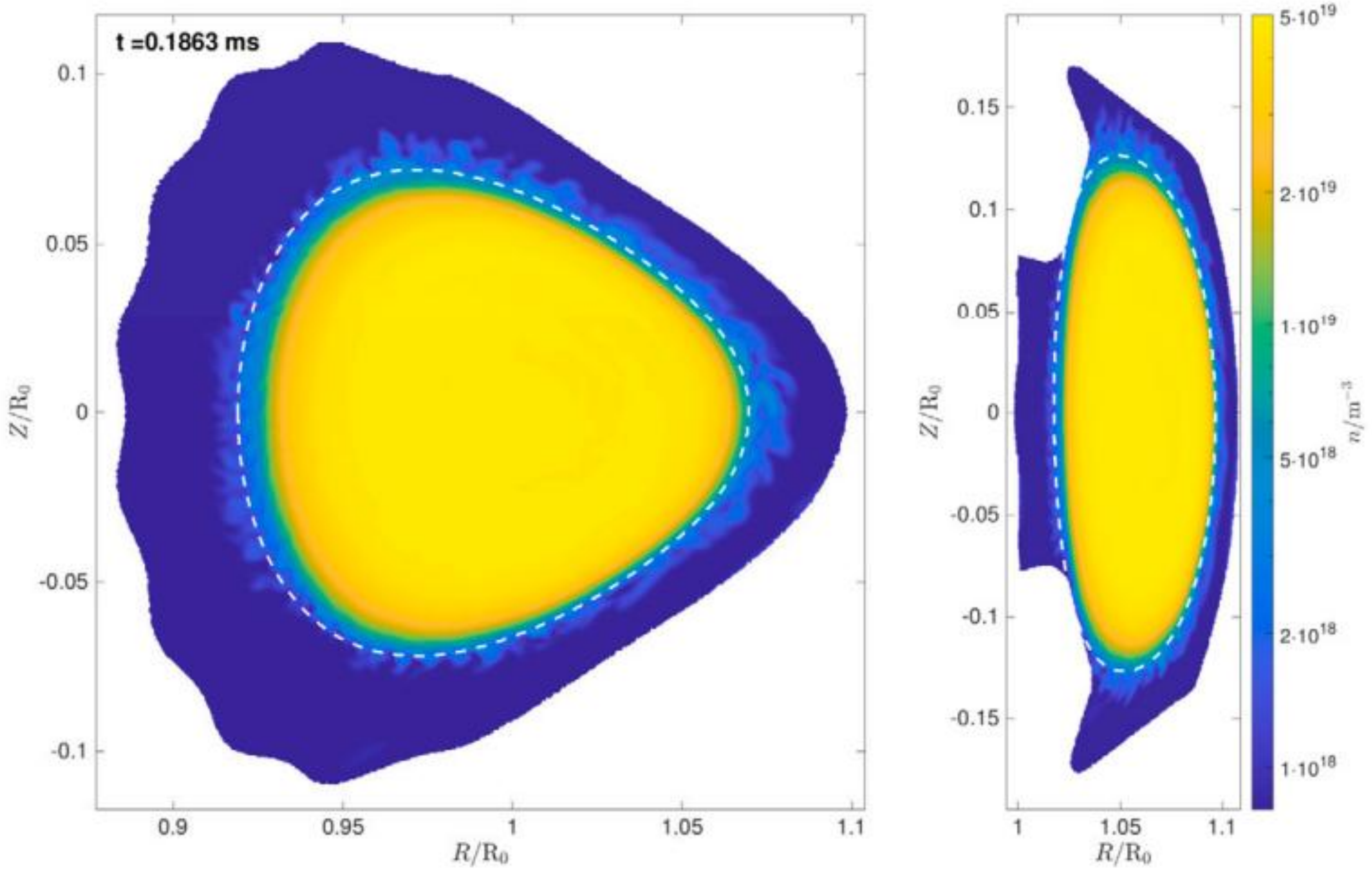
- Other groups followed **with different approaches**
  - **Isothermal fluid model in BOUT++**
  - **Plasma relaxation fluid model GRILLIX**



[A. Stegmeir et. al, JCP 2025]

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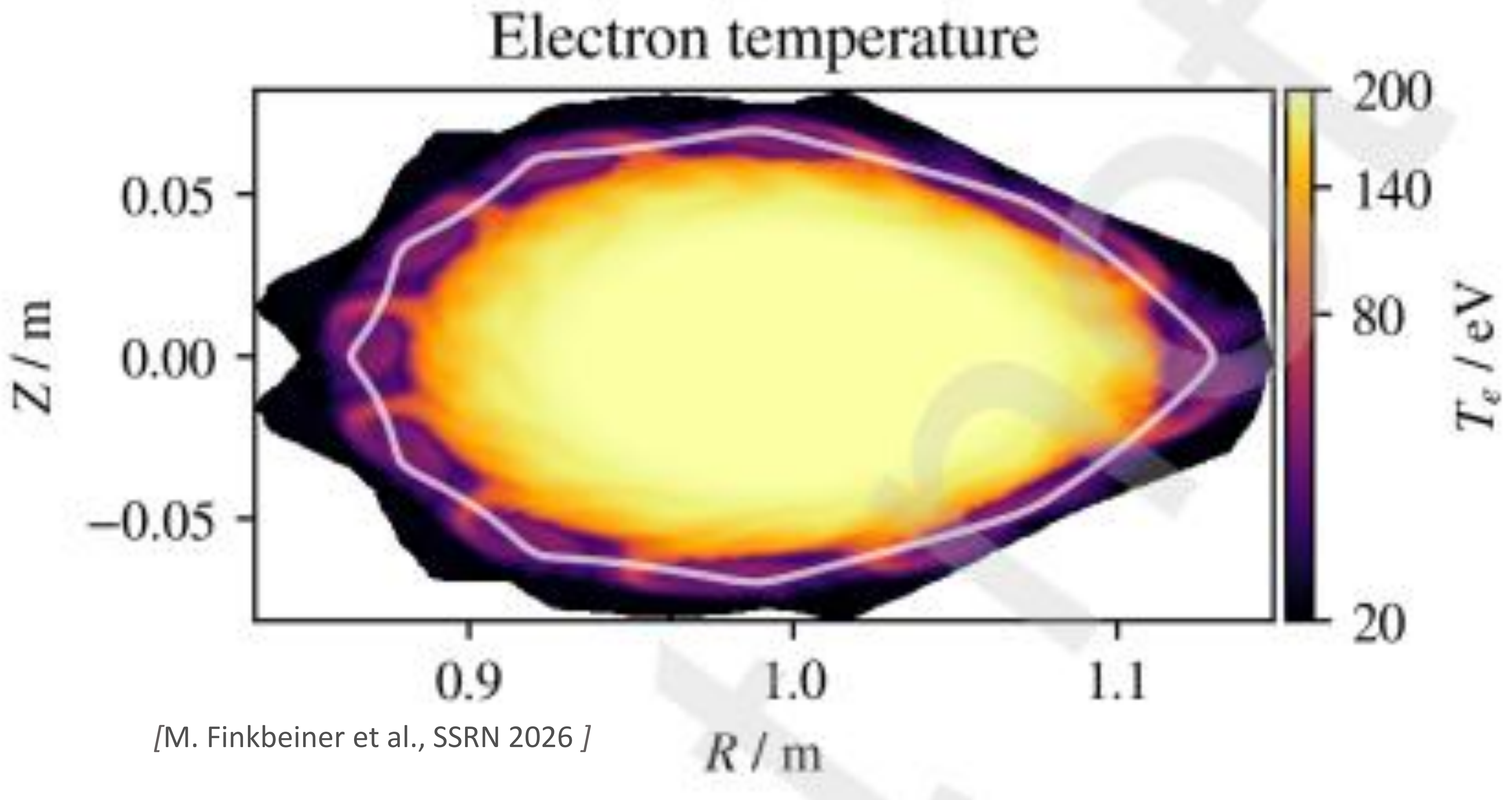
  - **Isothermal fluid model in BOUT++**
  - **Plasma relaxation fluid model GRILLIX**
  - **Plasma relaxation kinetic model GENE-X**



[M. Finkbeiner et al., SSRN 2026]

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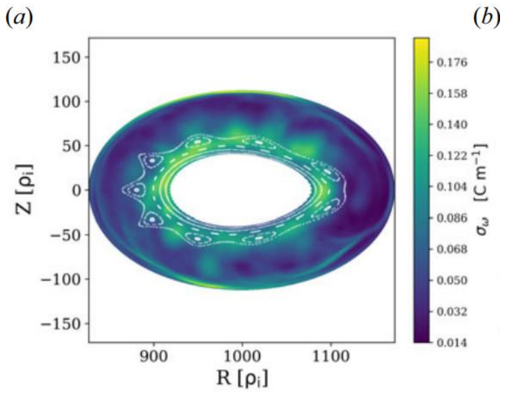
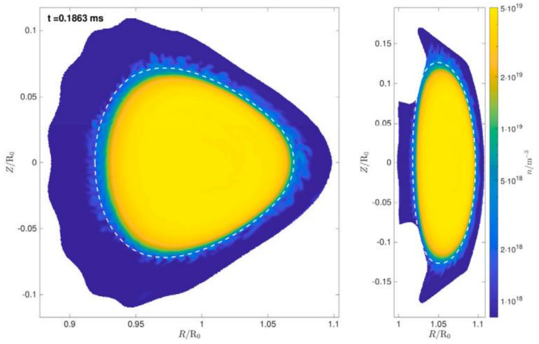
BOUT++



[B Shanahan et. al., JPP 2024]

GRILLIX



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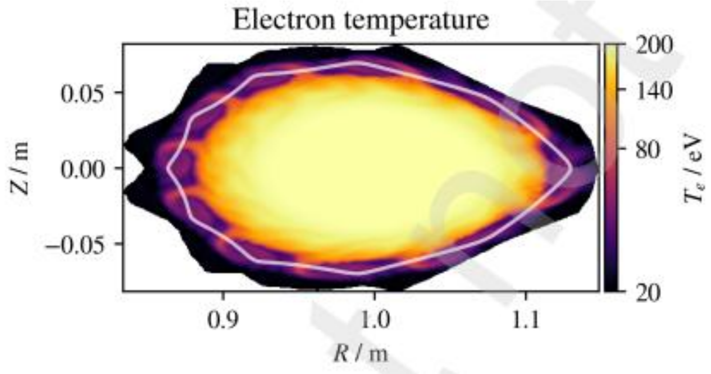
GENE-X



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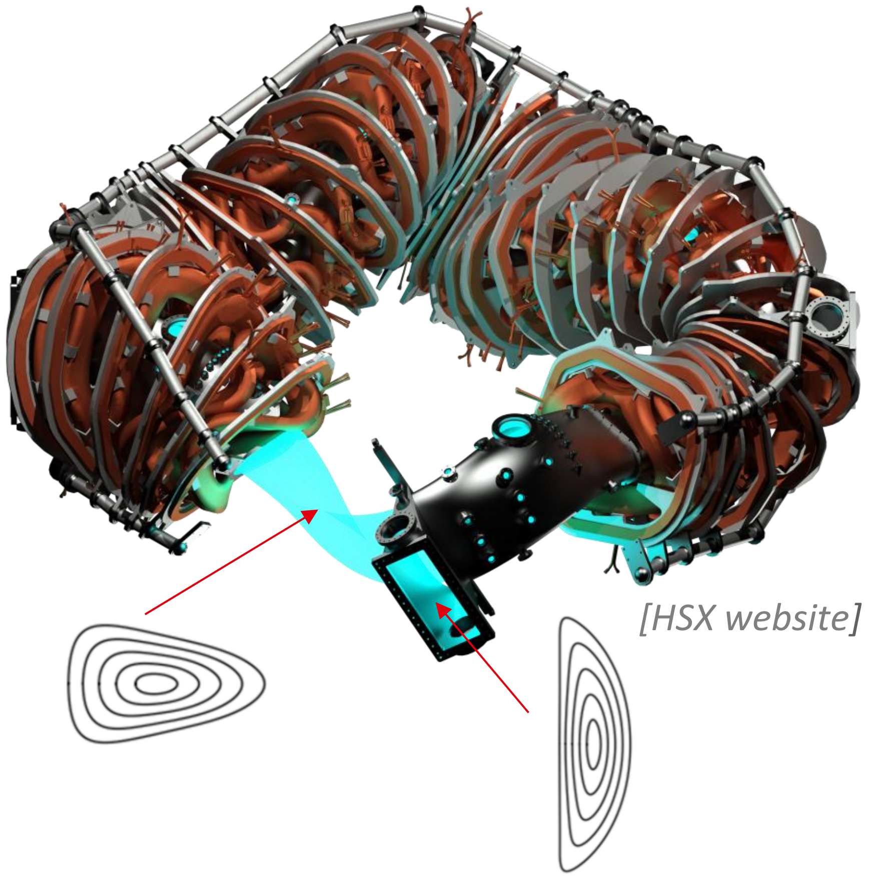
- Here we **examine and validate fusion-relevant machines**, to **understand the impact of three-dimensional geometries on edge turbulence**

GBS simulations of stellarators with different edge features

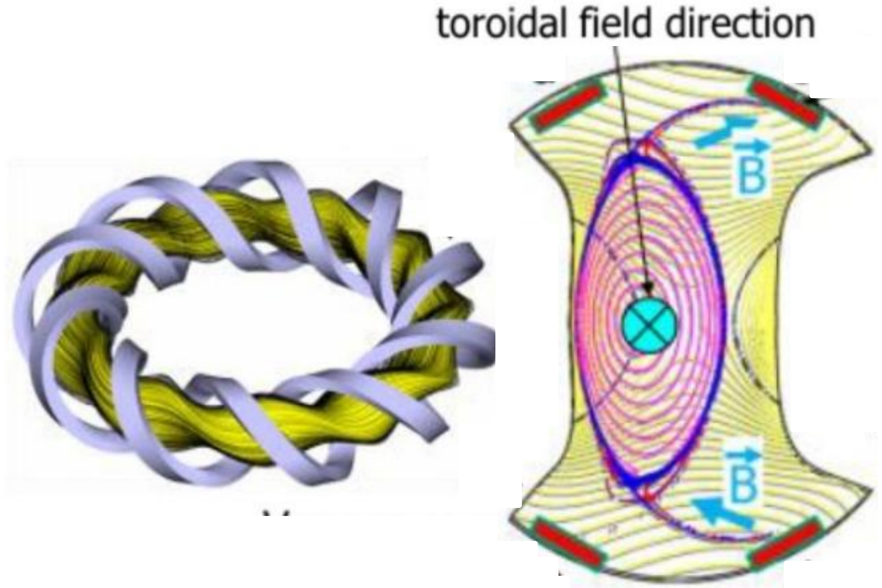
HSX



[HSX website]

Only **quasi-helically stellarator** in the world

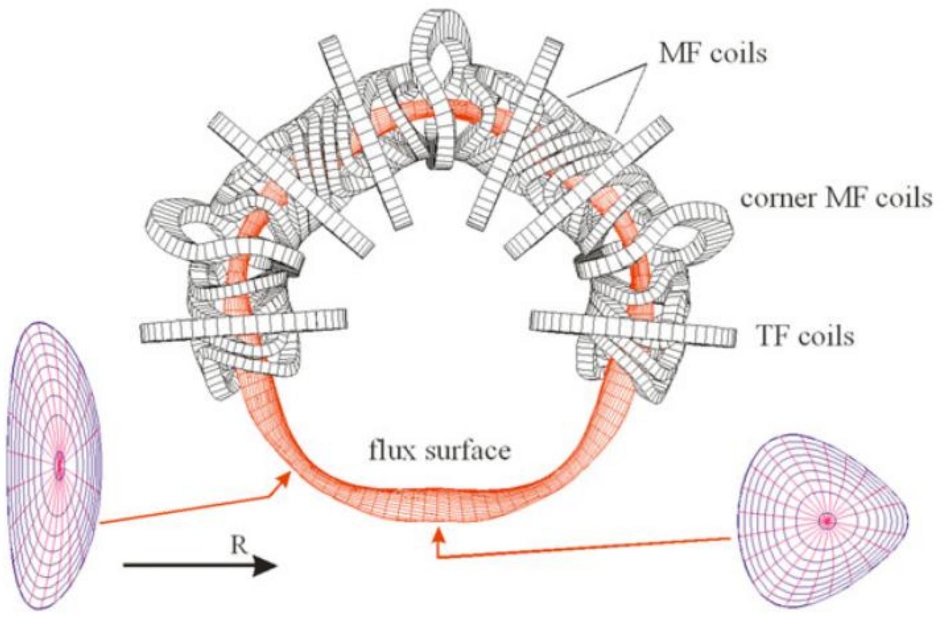
LHD



[S Masuzaki et al. Nuclear Materials and Energy 2019]

Largest **heliotron** stellarator in the world
Stochastic layer, X-point divertors

W7-AS



[Hirsch et al, PPCF 2008]

Predecessor of **W7-X sharing many features but smaller in size**

Auxiliary coil currents allowed **great flexibility in the edge topology**

GBS simulations of stellarators with different edge features

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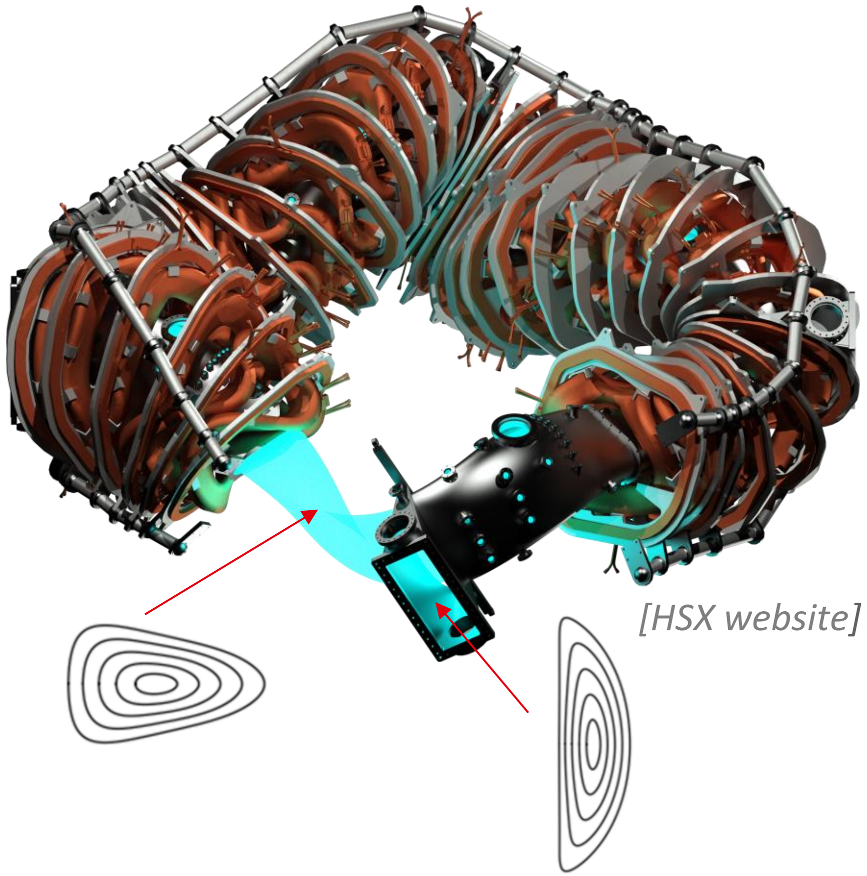

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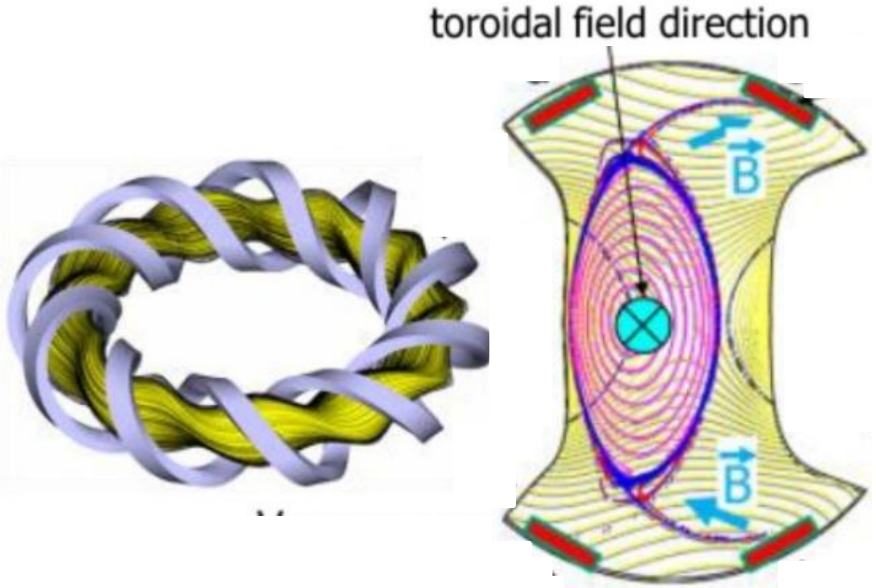

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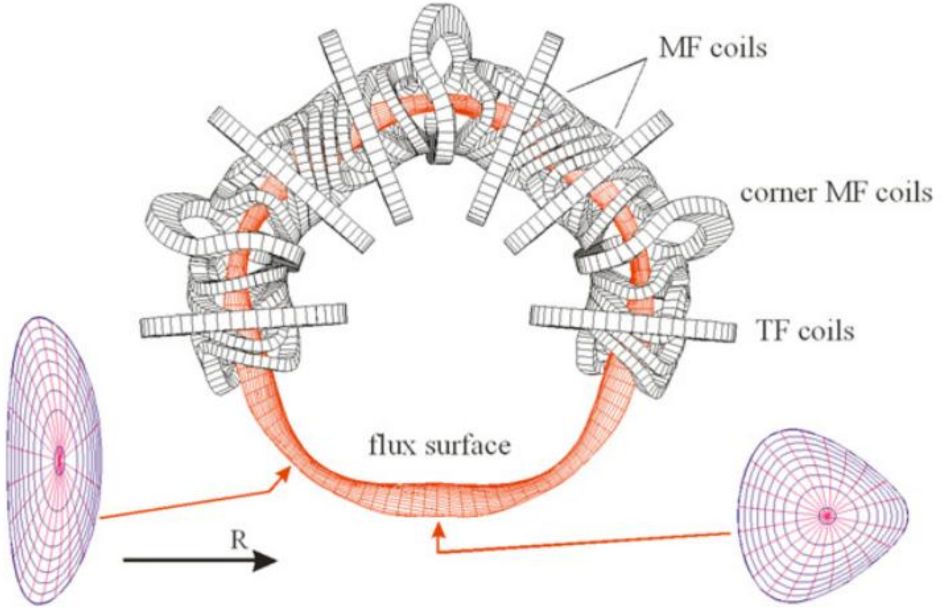

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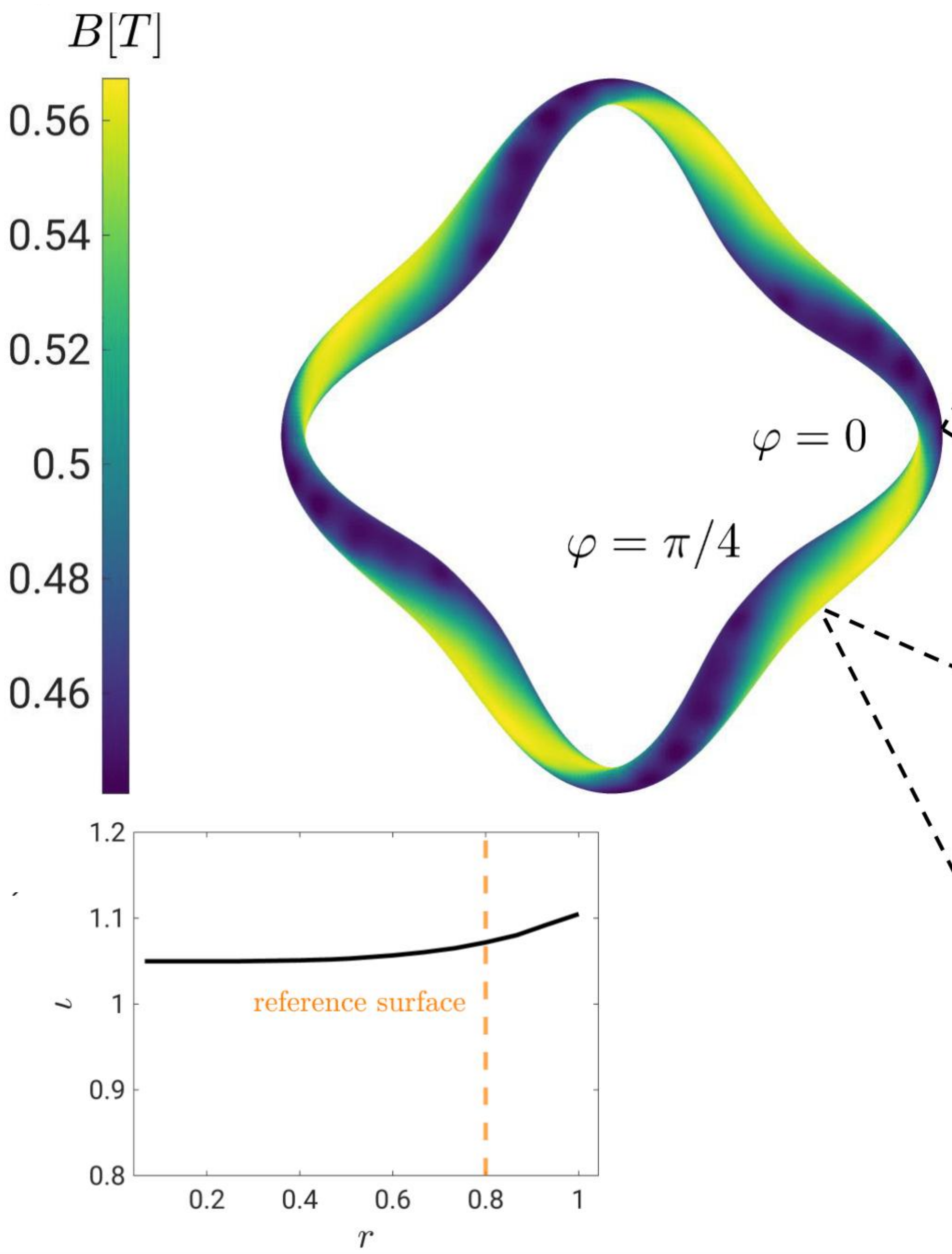
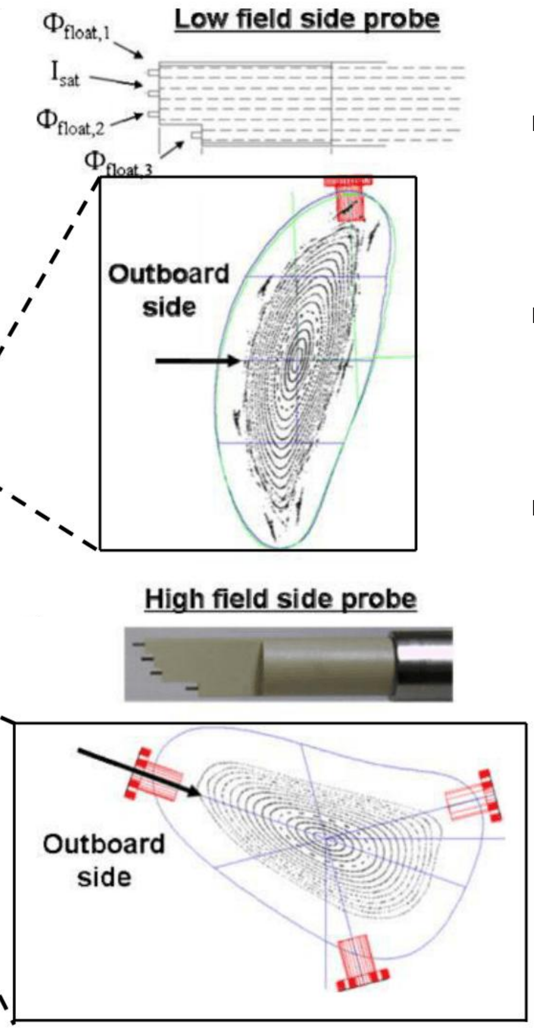
HSX, an ideal validation test bed





Phys. Plasmas 16, 082508 (2009)

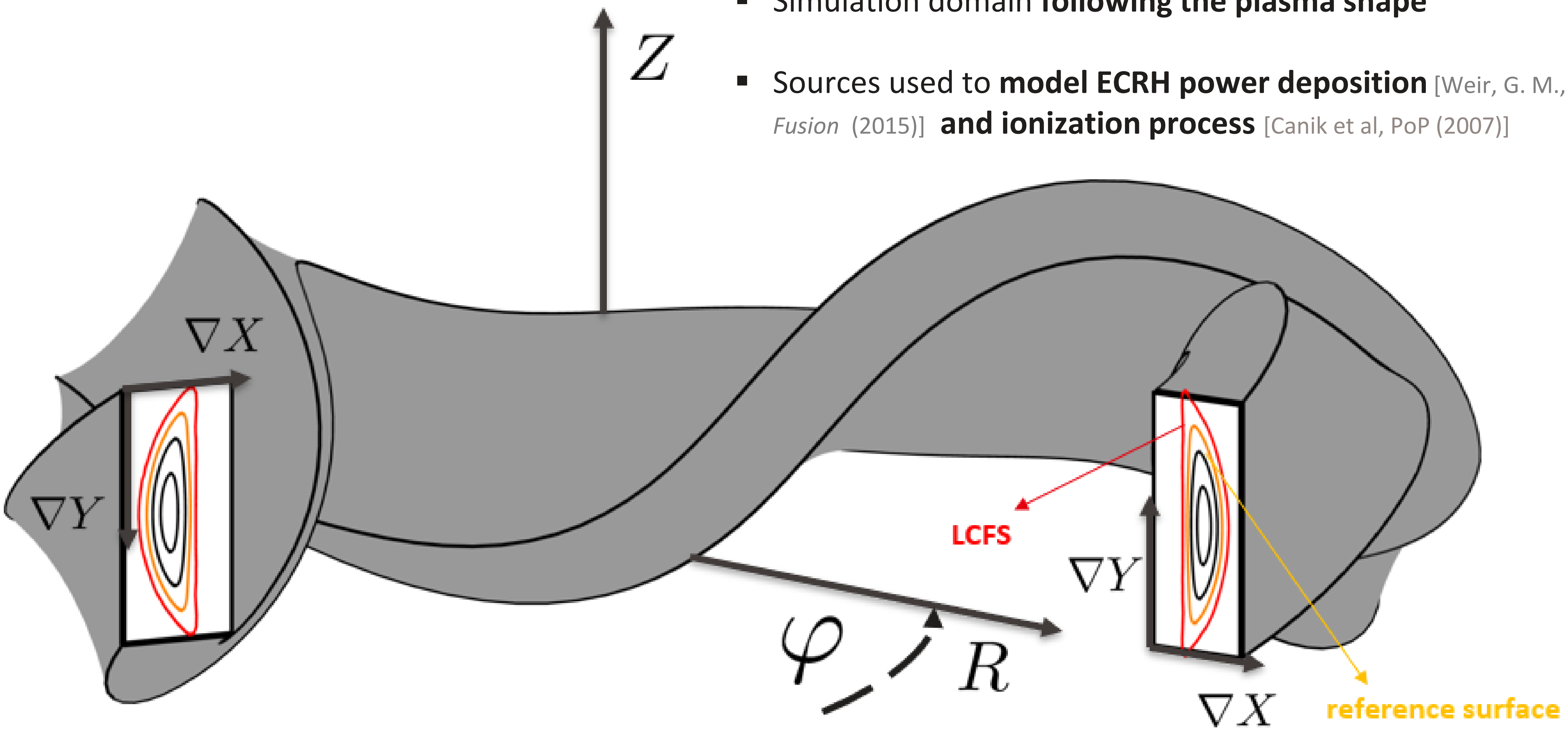
- **Simulate full-size machine with comparison to experiments** done by **W. Guttenfelder 2009**
- **Langmuir probes and Thomson scattering** diagnostic
- Turbulent properties compared at the **reference surface**

$$B_0 = 0.5\,T$$
$$n_0 = 10^{18}\,m^{-3}$$
$$T_e = 40\,eV$$
$$T_i = 20\,eV$$

[Z. Tecchiolli, submitted to Nucl. Fusion]

Simulation set up mimicking experimental conditions

- Simulation domain **following the plasma shape**
- Sources used to **model ECRH power deposition** [Weir, G. M., et al *Nuclear Fusion* (2015)] **and ionization process** [Canik et al, PoP (2007)]



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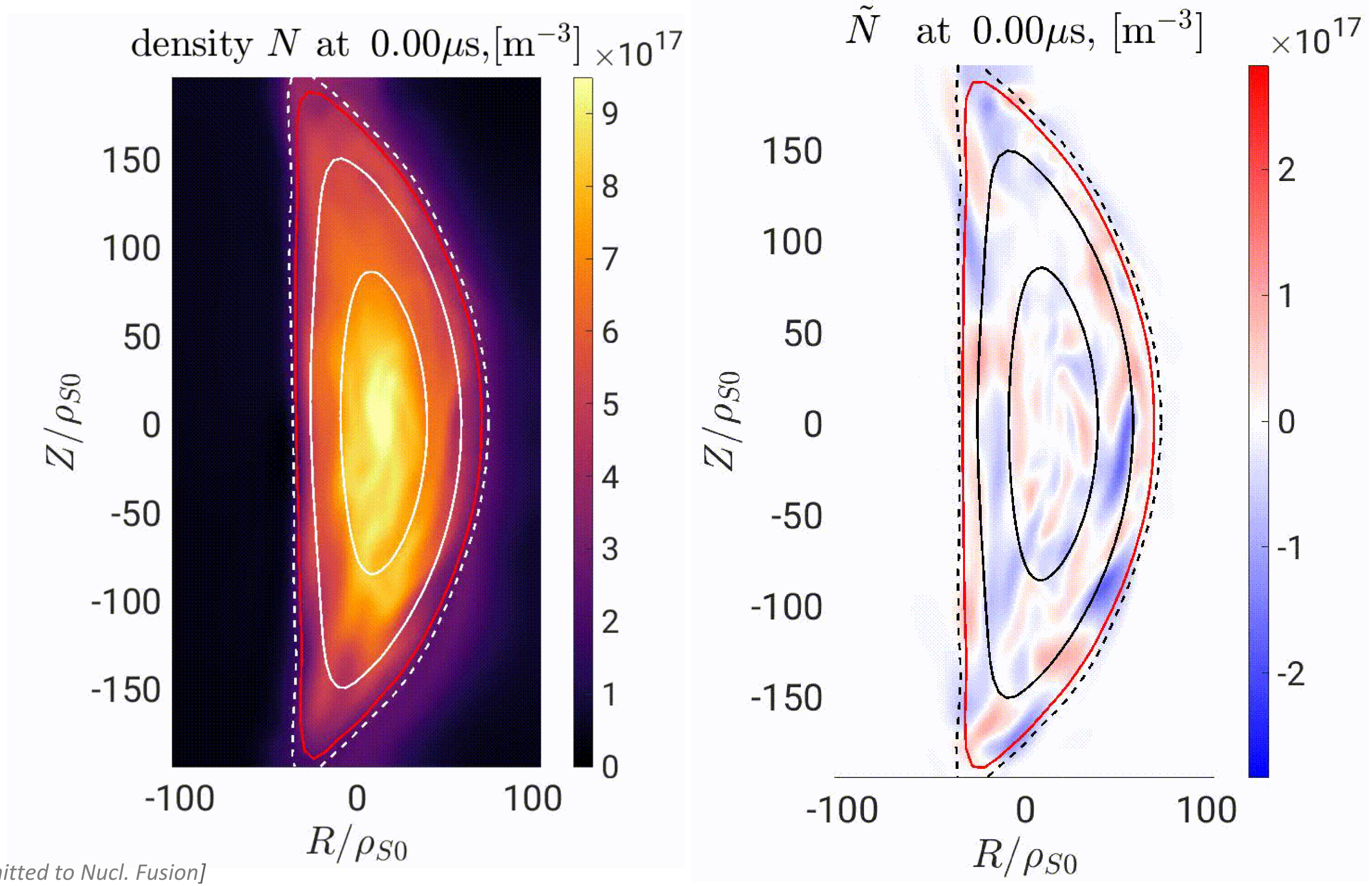
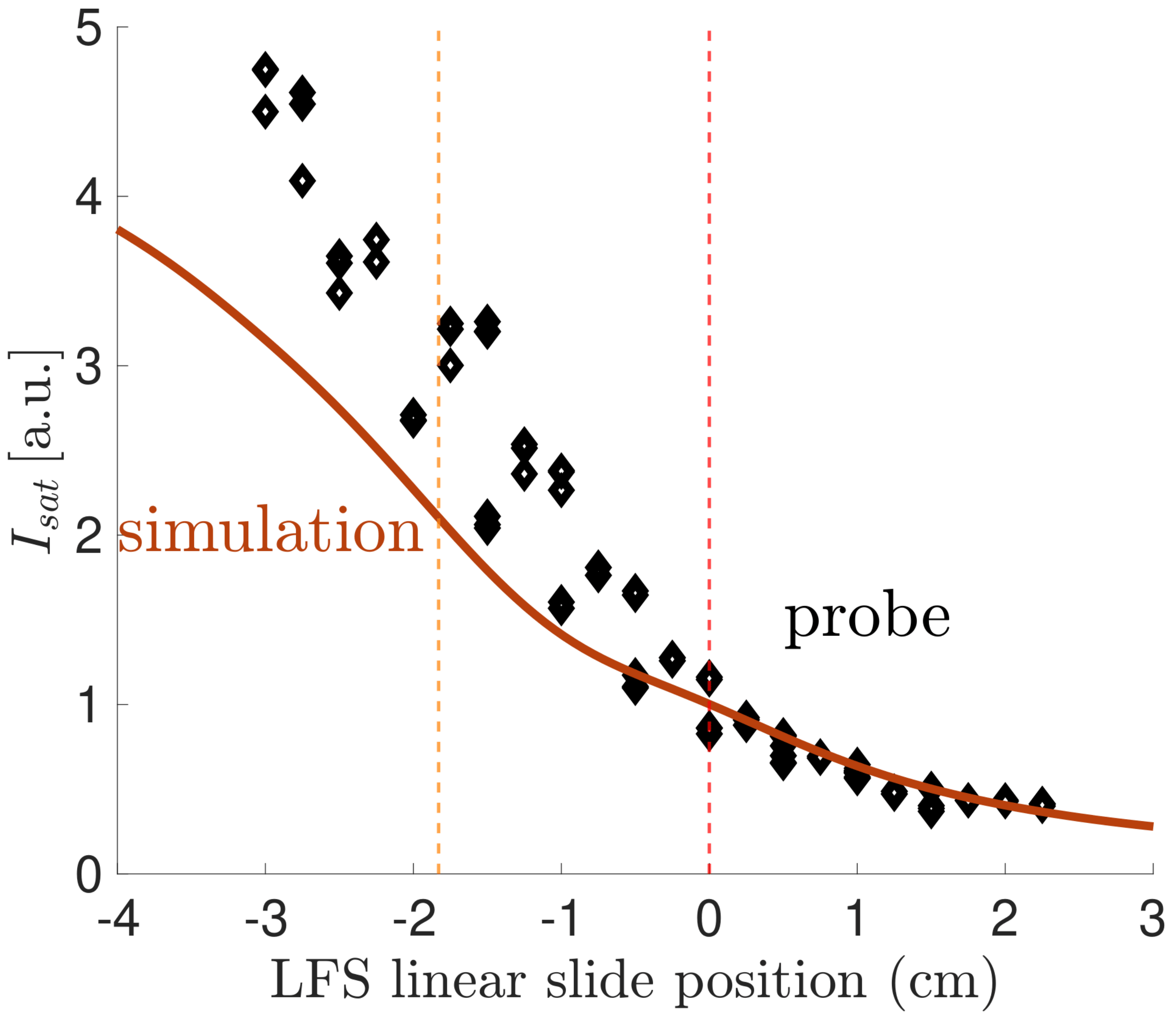
Steady-state plasma shows broad-band turbulence



[Z. Tecchiolli, submitted to Nucl. Fusion]

Probe measurements show good agreement



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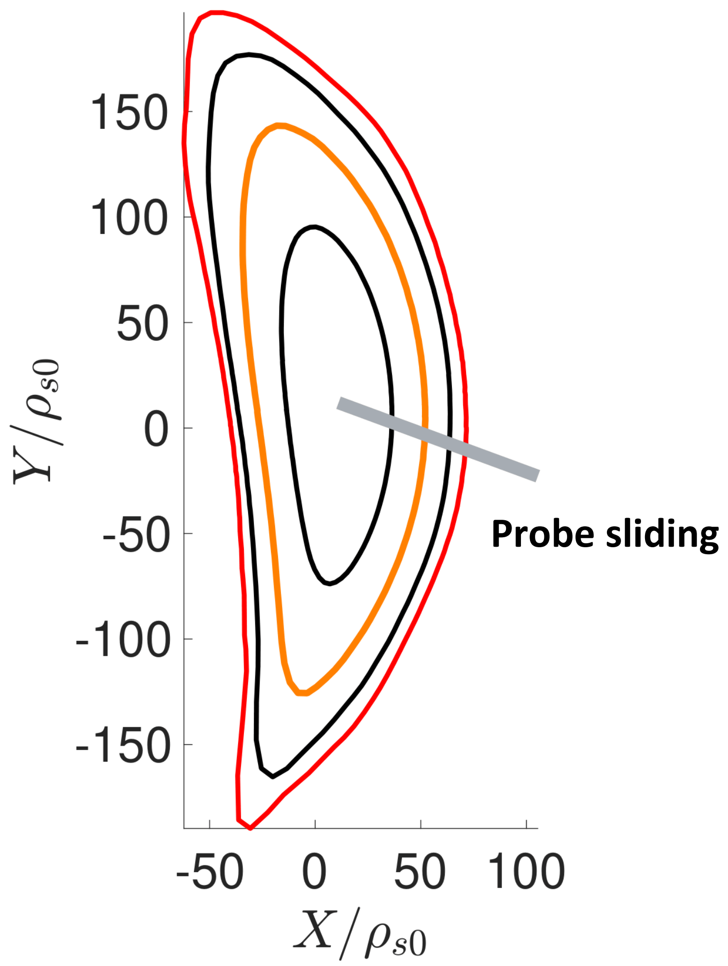
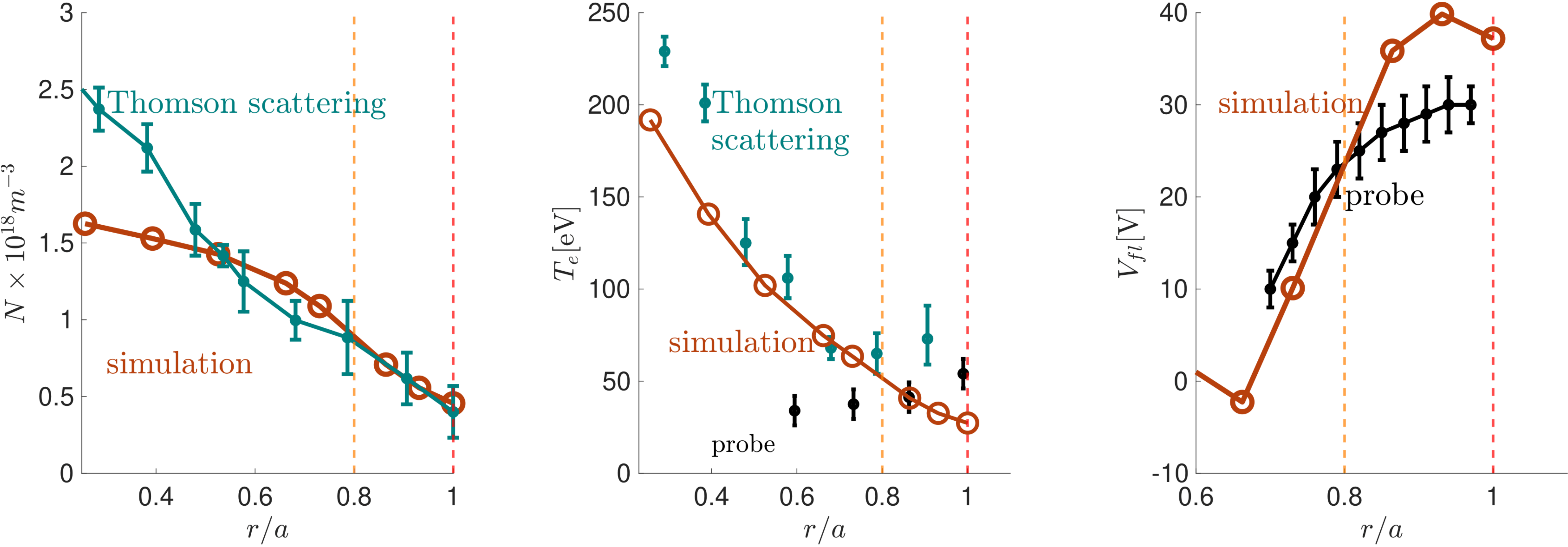
- Scaling length in the **SOL** $\sim 2\,cm$



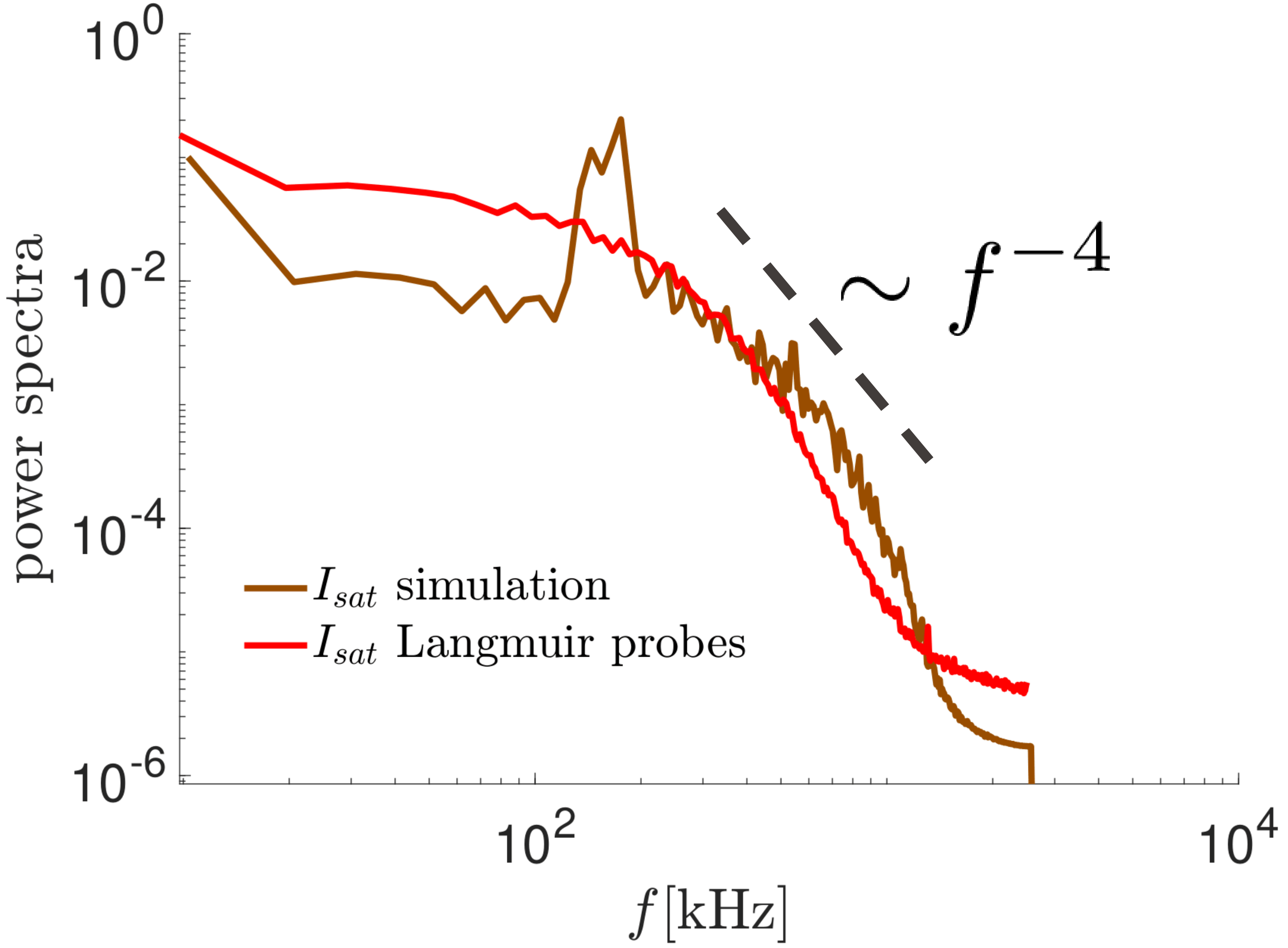
Average profiles show remarkable agreement

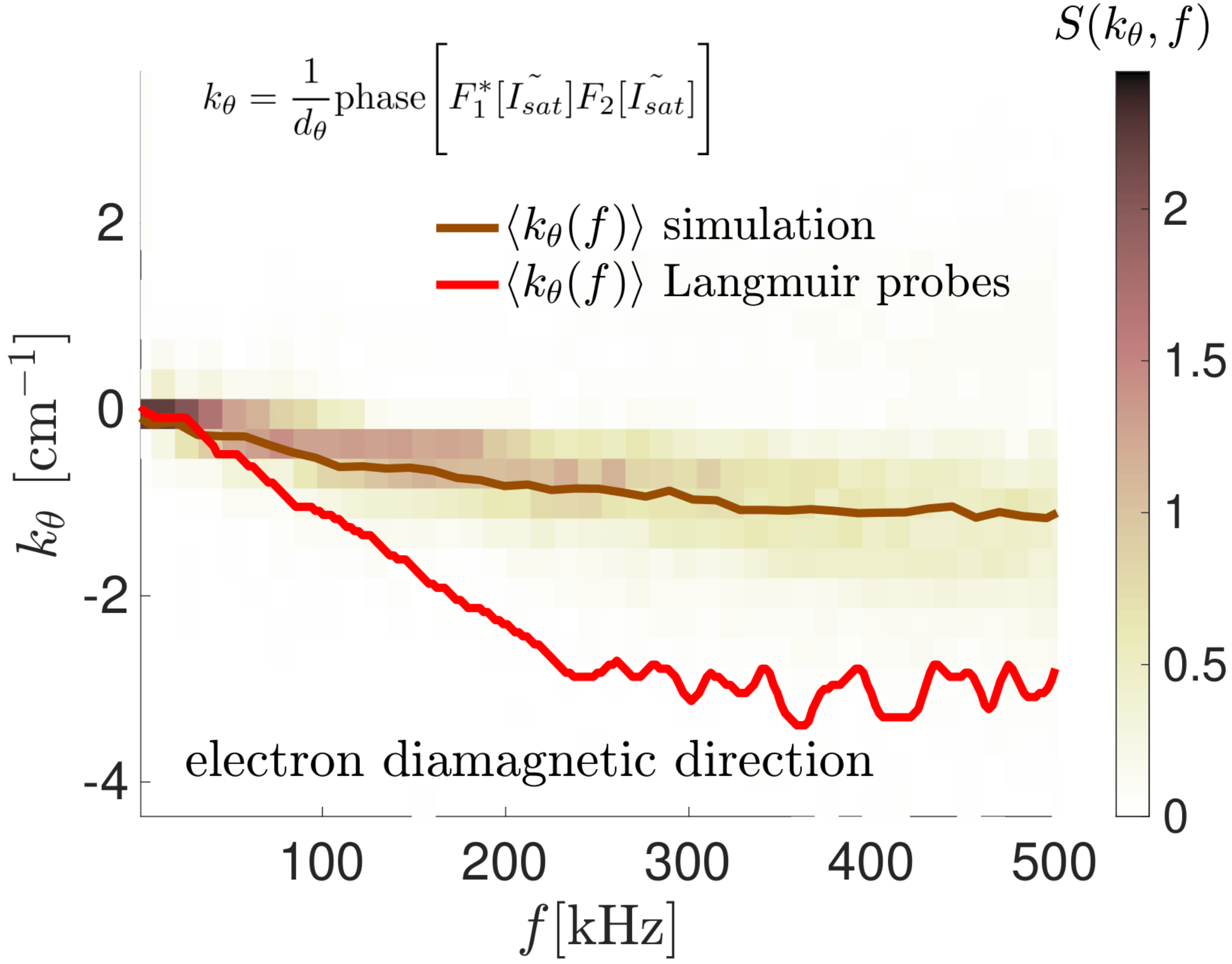


- **Negative edge radial electric field**

[Z. Tecchiolli, submitted to Nucl. Fusion]

Turbulent properties show reasonable agreement

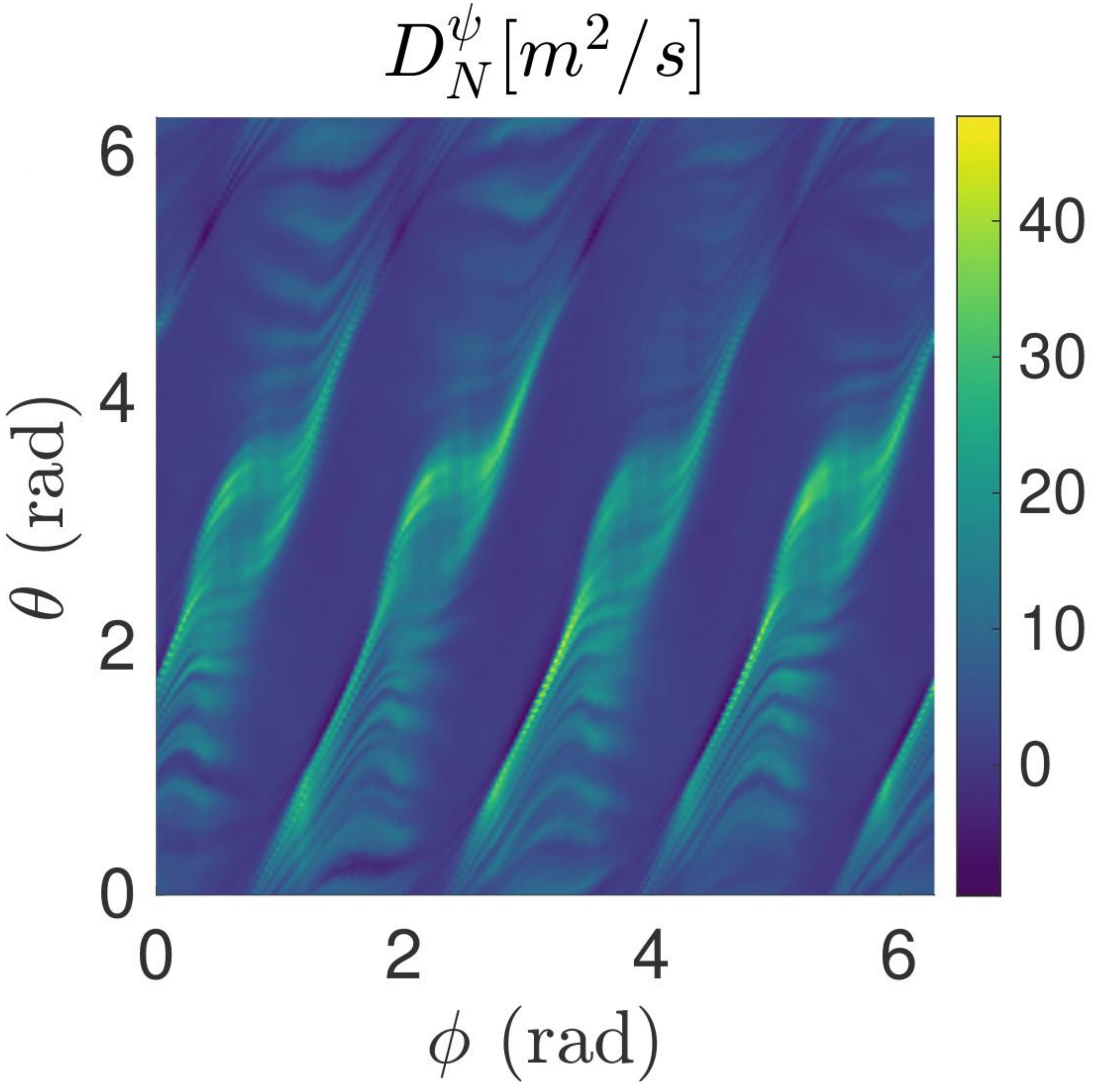


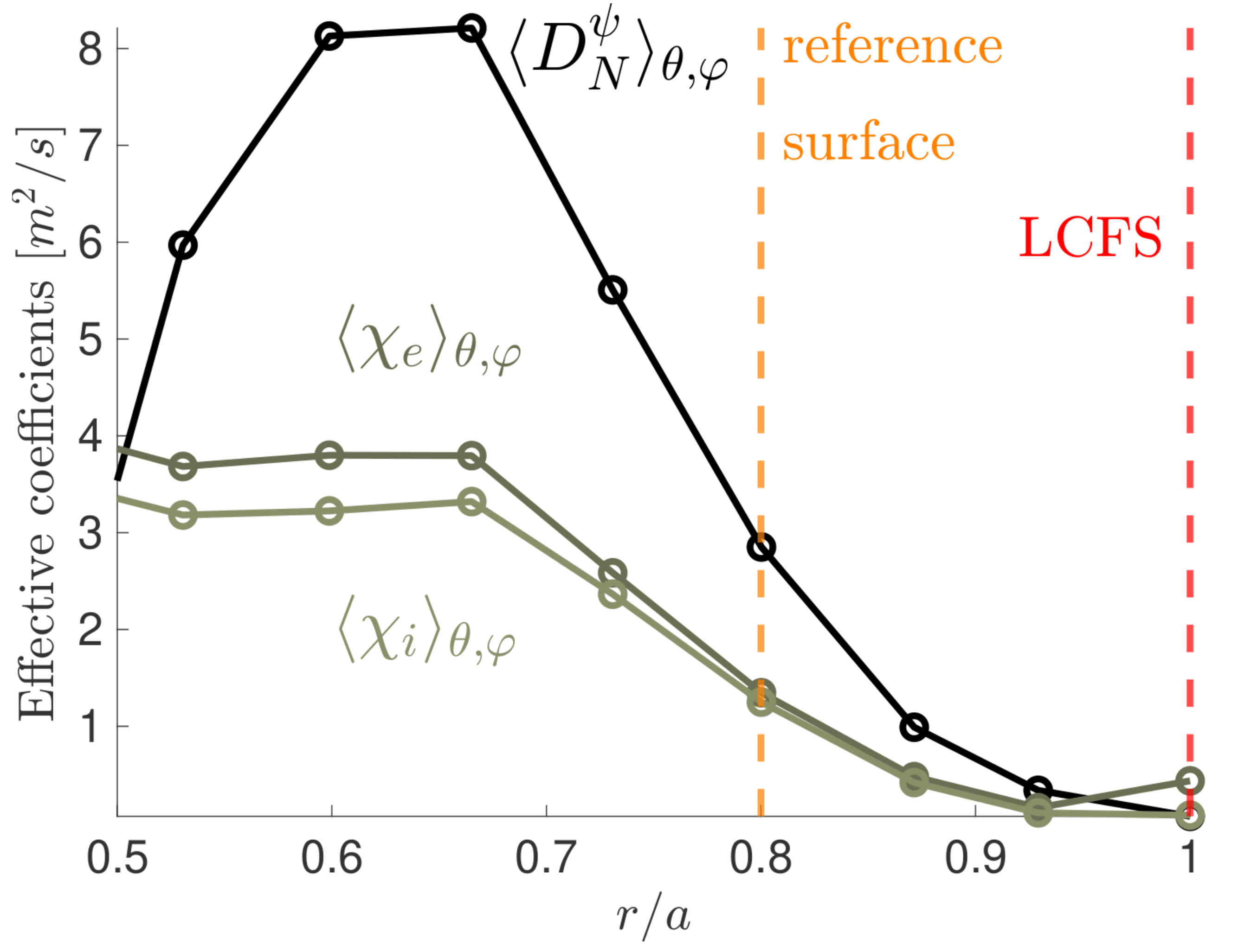


- **More energy** around $f \approx 200\,kHz$ **with cascade of** $\sim f^{-4}$
- **Poloidal correlation** $\rho_s\langle k_\theta\rangle \approx 0.12$ **and** $L_\theta \approx 6\rho_s$ **consistent with measurements of** $\rho_s\langle k_\theta\rangle \approx 0.14$ and $L_\theta \approx 7-8$

[Z. Tecchiolli, submitted to Nucl. Fusion]

3D first-principle effective diffusion coefficients





$$D_N^\psi = -\langle \tilde{\Gamma}_N^\psi \rangle_t / \langle \nabla N \cdot \mathbf{n}^\psi \rangle_t$$

$$\chi_{e,i}^\psi = -\langle \tilde{T}_{i,e} \tilde{V}_{E\times B}^\psi / \nabla T_{i,e} \cdot \mathbf{n}^\psi \rangle_t$$

- **Regions of negative particle transport**

[Z. Tecchiolli, submitted to Nucl. Fusion]

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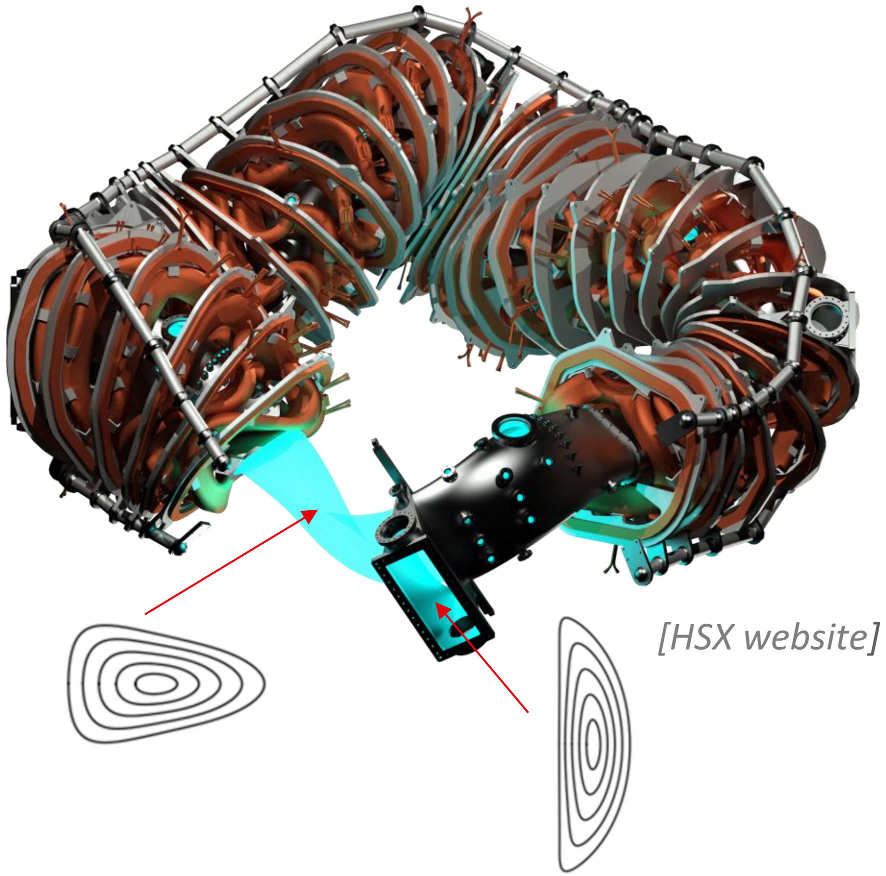

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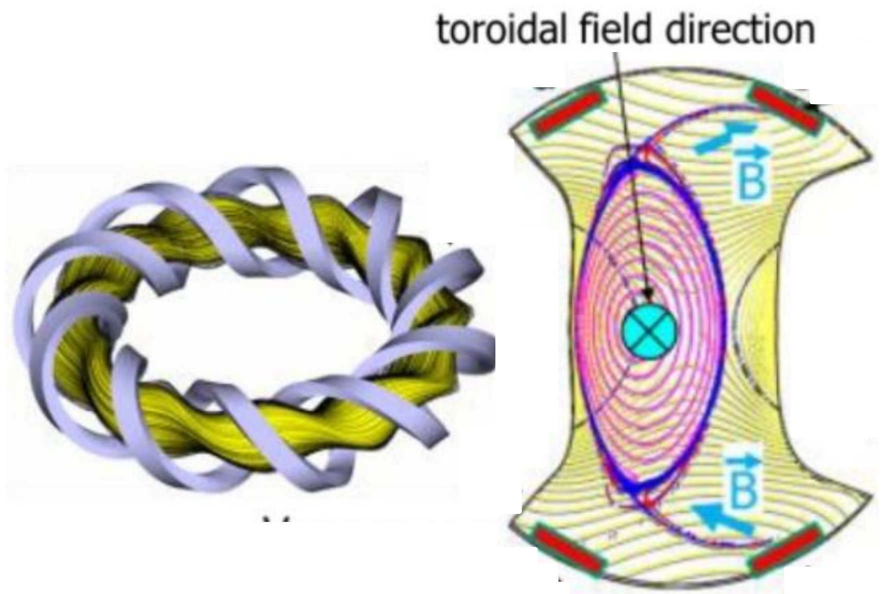

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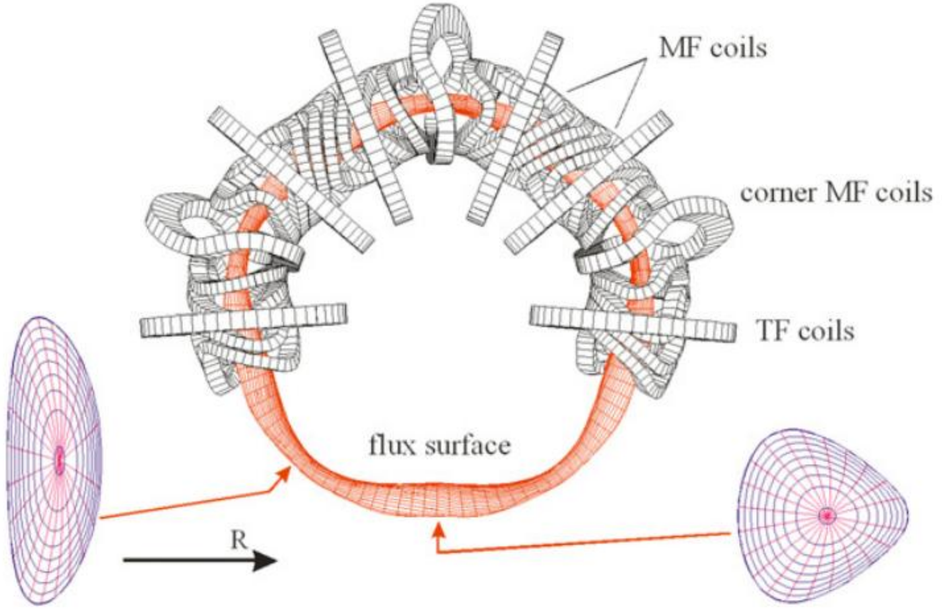


[Hirsch et al, PPCF 2008]

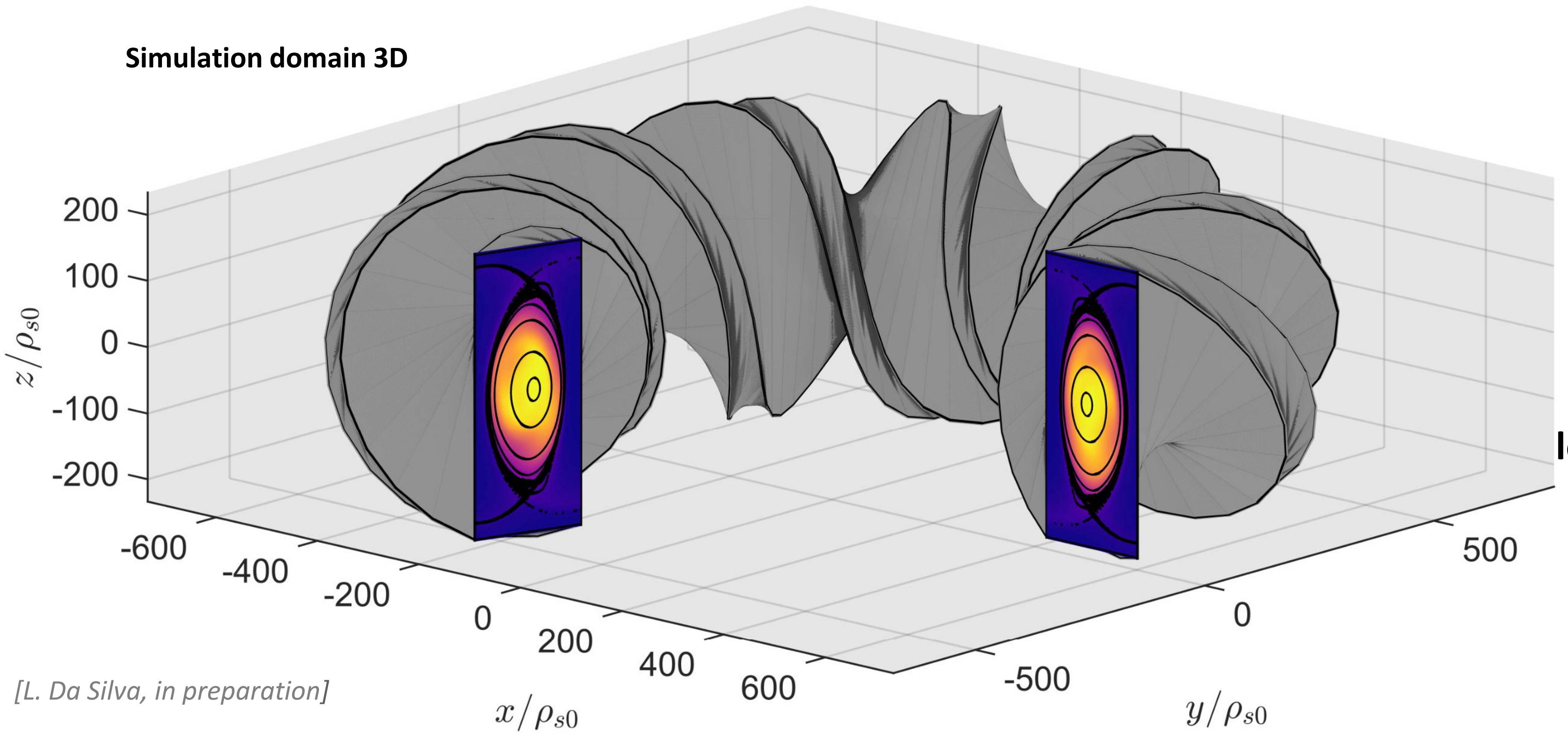
Predecessor of **W7-X sharing many features but smaller in size**

Auxiliary coil currents allowed **great flexibility in the edge topology**

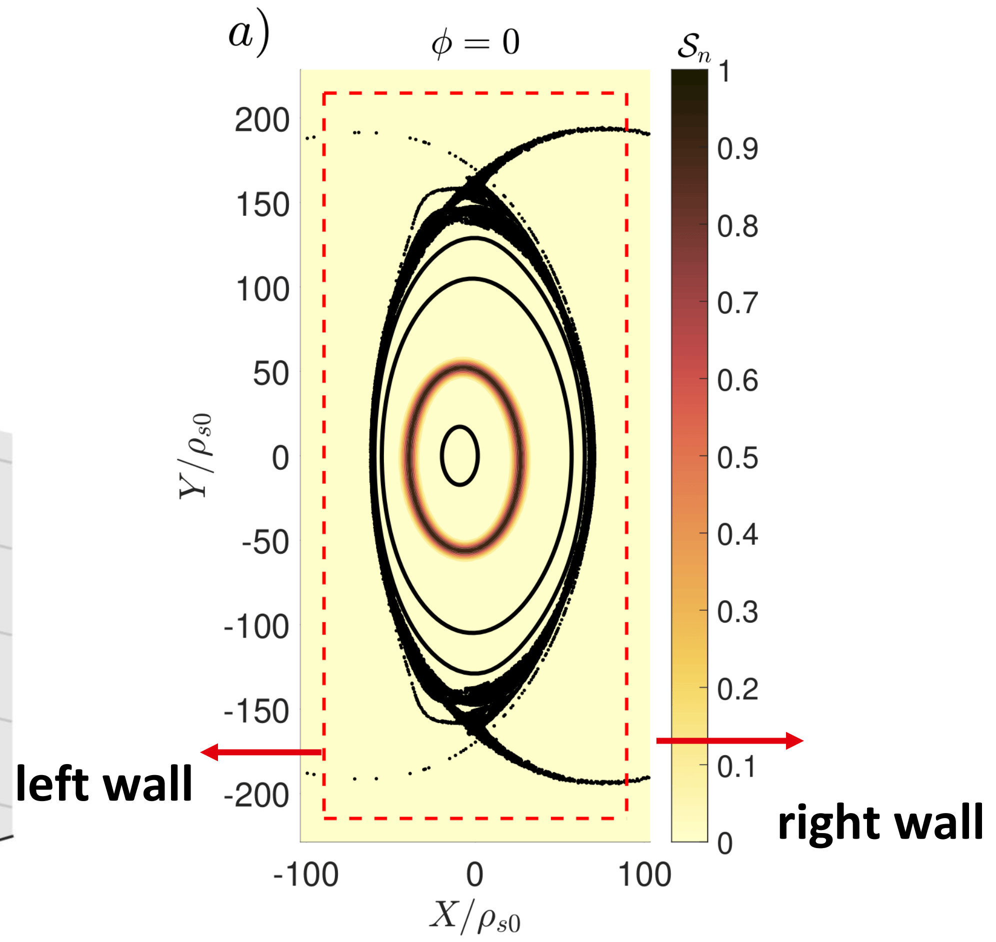
Simulating LHD for studying plasma dynamics in the chaotic divertor

- Simulation domain follows **the divertor plates geometry**
- Considering **1/3 of real size** for gaining computational time
- **Qualitative comparison** with experimental results

Simulation domain 3D

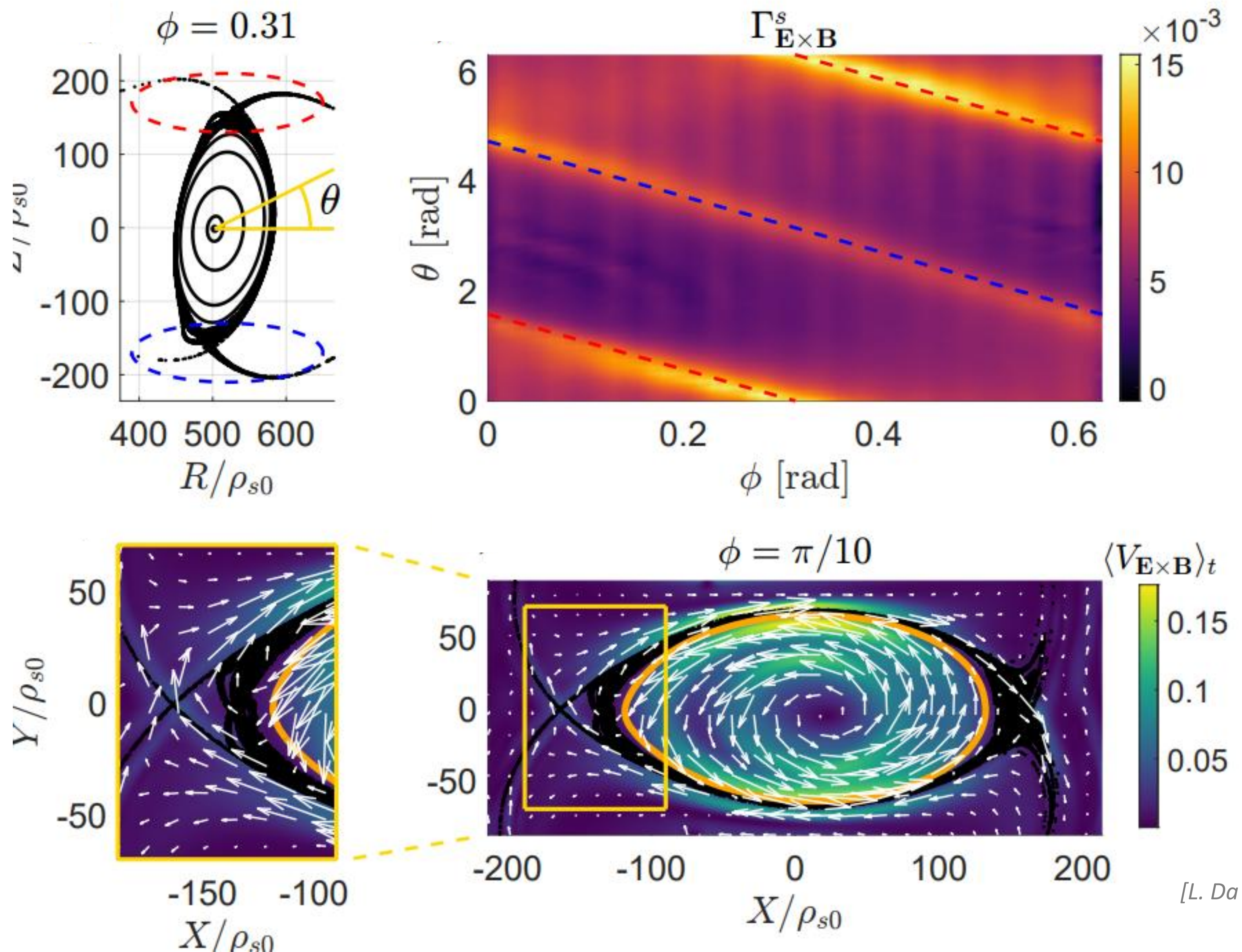


Simulation domain 2D



[L. Da Silva, in preparation]

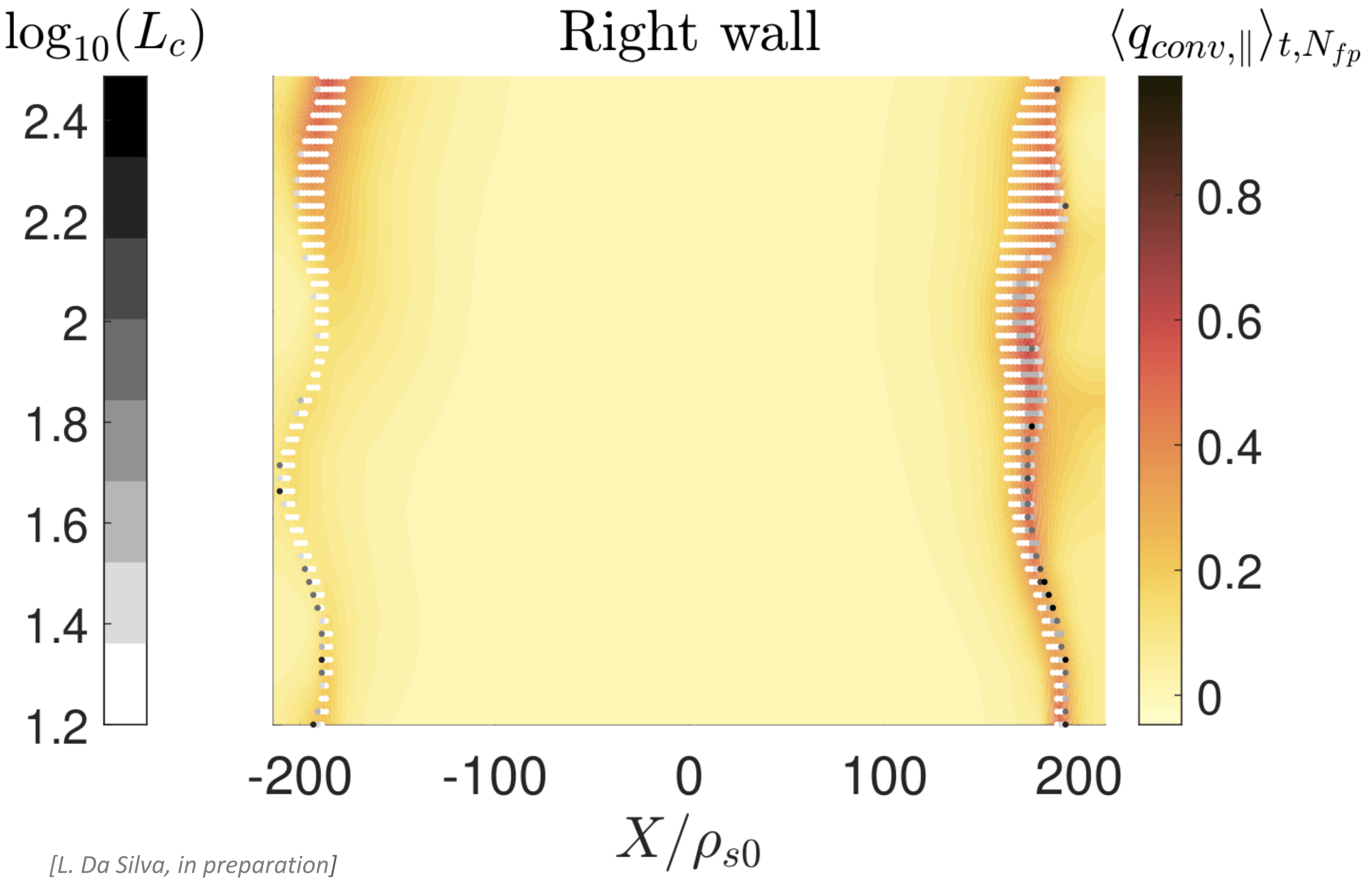
Self-consistent drifts produce asymmetries in divertors profiles



- $E \times B$ **creating L-R and T-B asymmetries** in profiles at the divertor plates
- Consequence of **self-consistently account for drifts**
- **Effect observed experimentally** [S Masuzaki et al. Nuclear Materials and Energy 2019]

[L. Da Silva, in preparation]

Asymmetries in the heat flux deposition on the divertor plates



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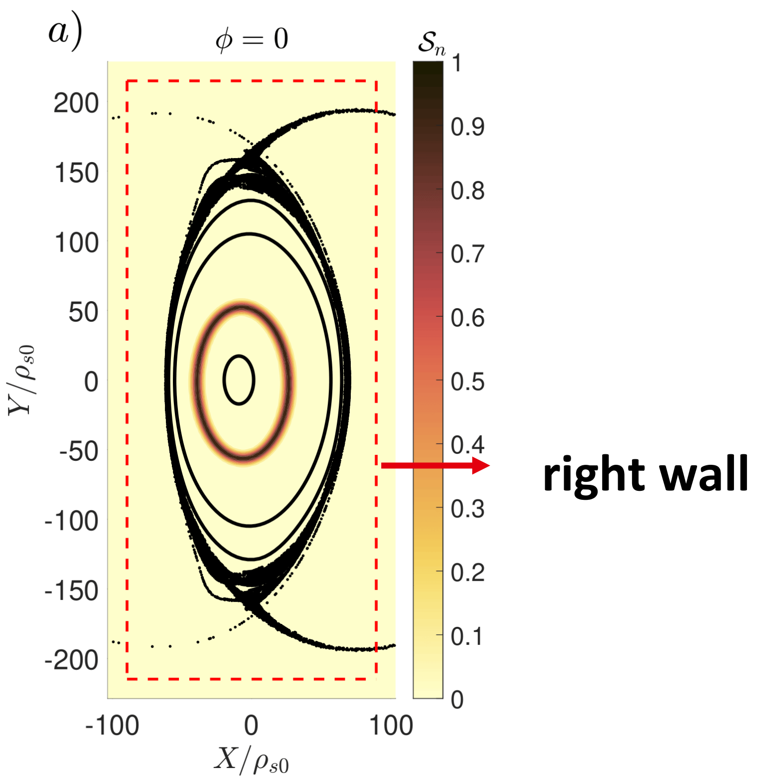
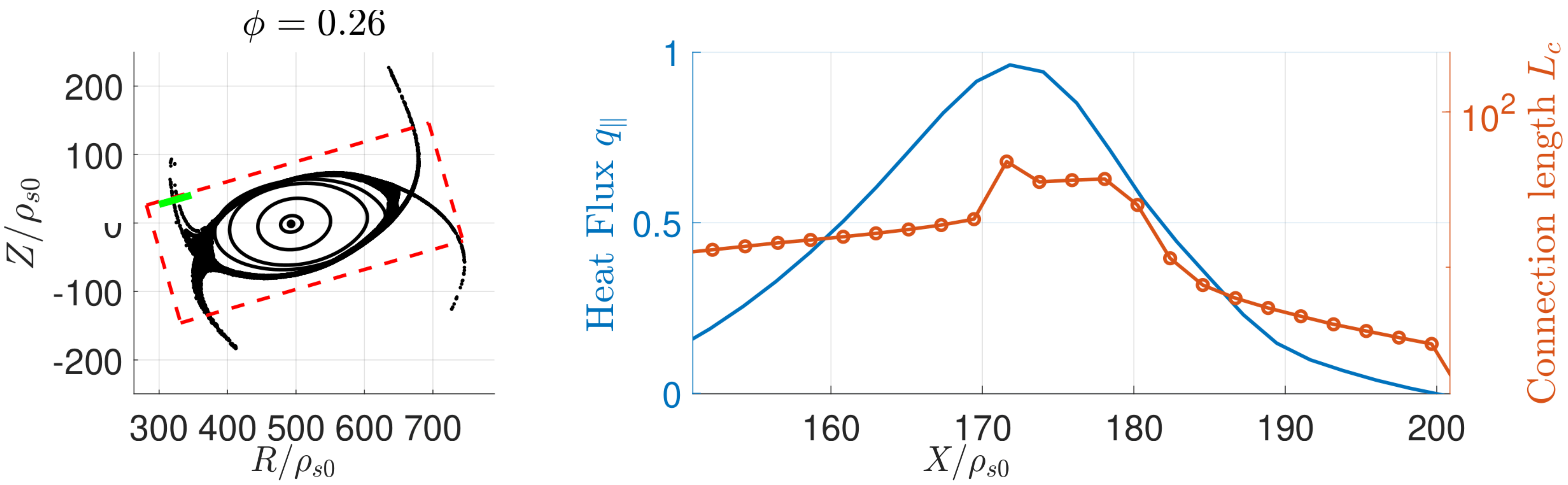
- **Heat flux deposition correlates with connection length**
- Heat profile **spreading due to turbulent effects** [M. Kobayashi et al. 2022 PRL]



Turbulence spreading broadens divertor heat load



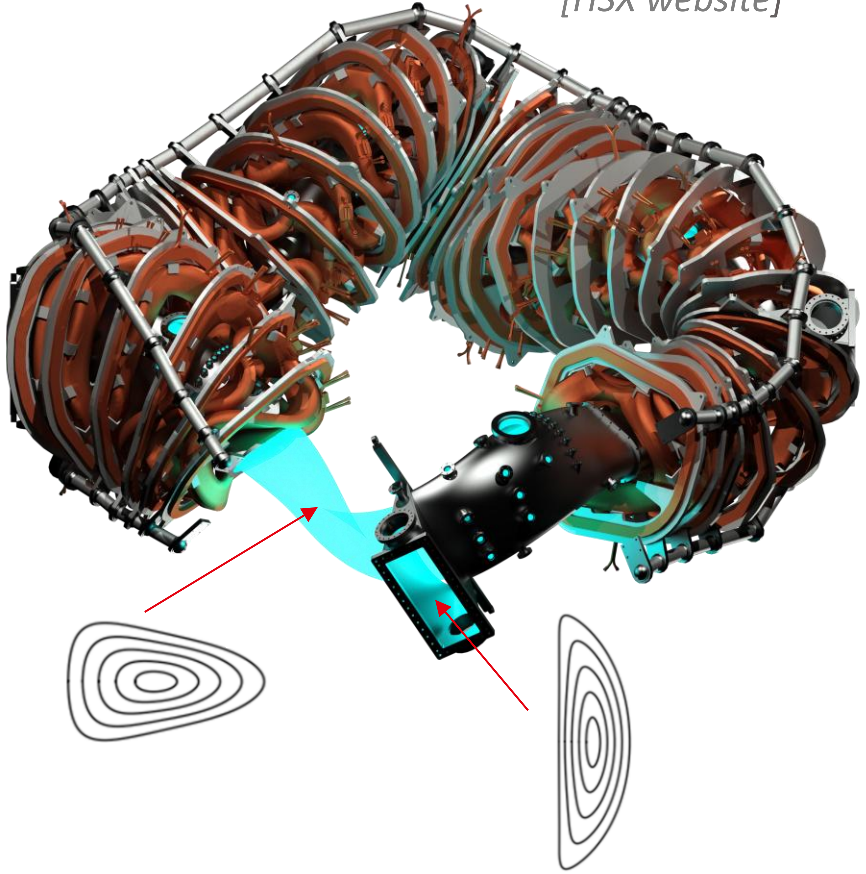
- $\lambda_q = 15\rho_s$ **consistent with experimental results of** $\lambda_q \approx 10 - 50\rho_s$ [M. Kobayashi et al. 2022 PRL]

[L. Da Silva, in preparation]

GBS simulations of stellarators with different edge features

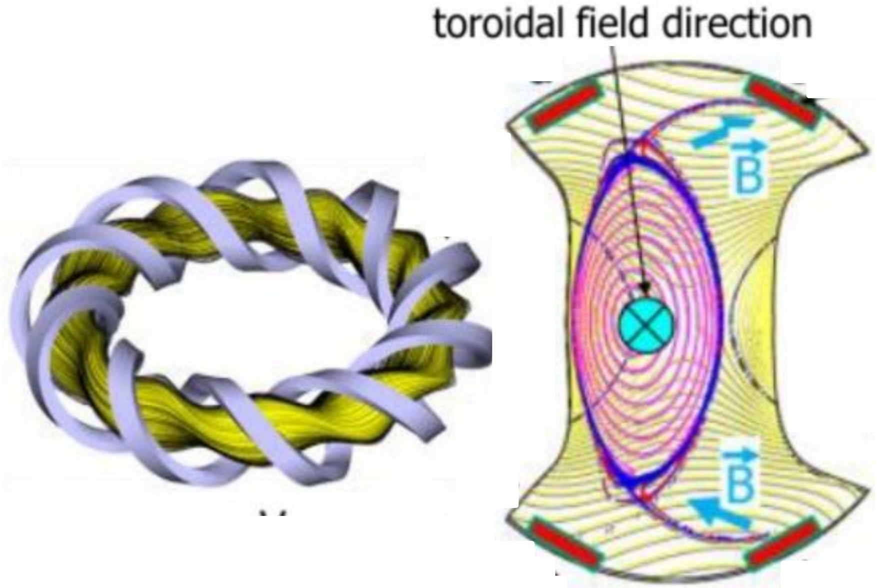
HSX

[HSX website]



Only **quasi-helically stellarator** in the world

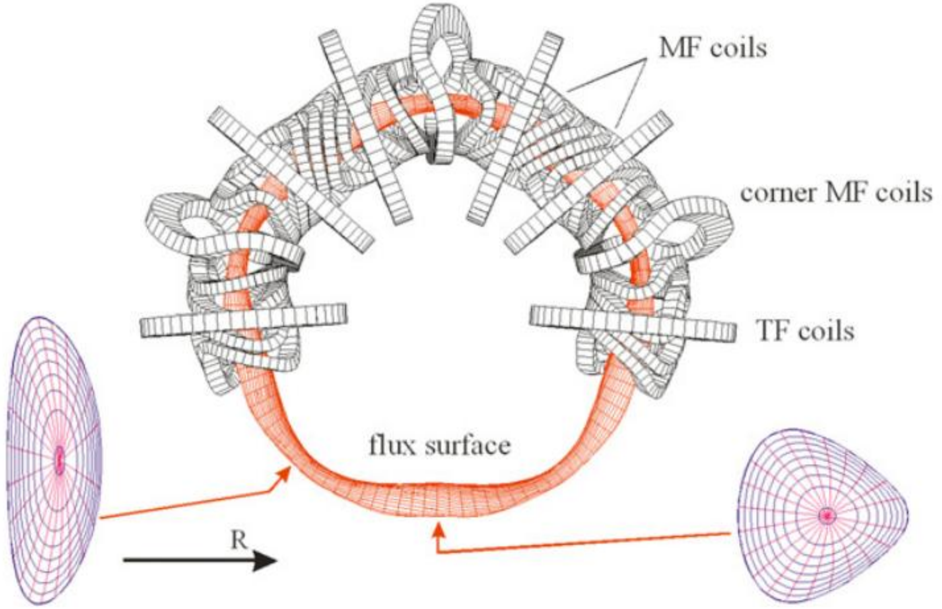
LHD



[S Masuzaki et al. Nuclear Materials and Energy 2019]

Largest **heliotron** stellarator in the world
Stochastic layer, X-point divertors

W7-AS

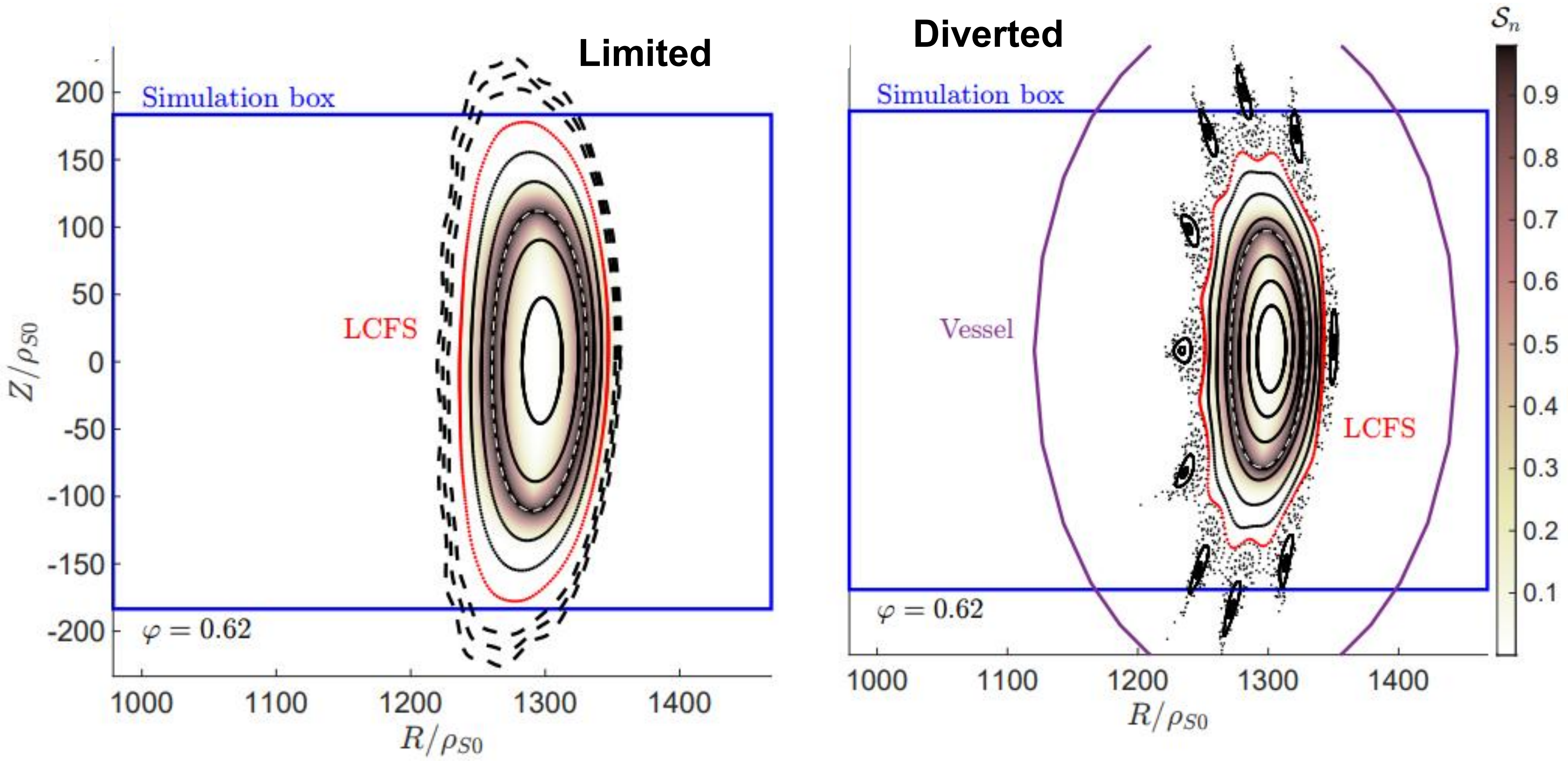


[Hirsch et al, PPCF 2008]

Predecessor of **W7-X sharing many features but smaller in size**

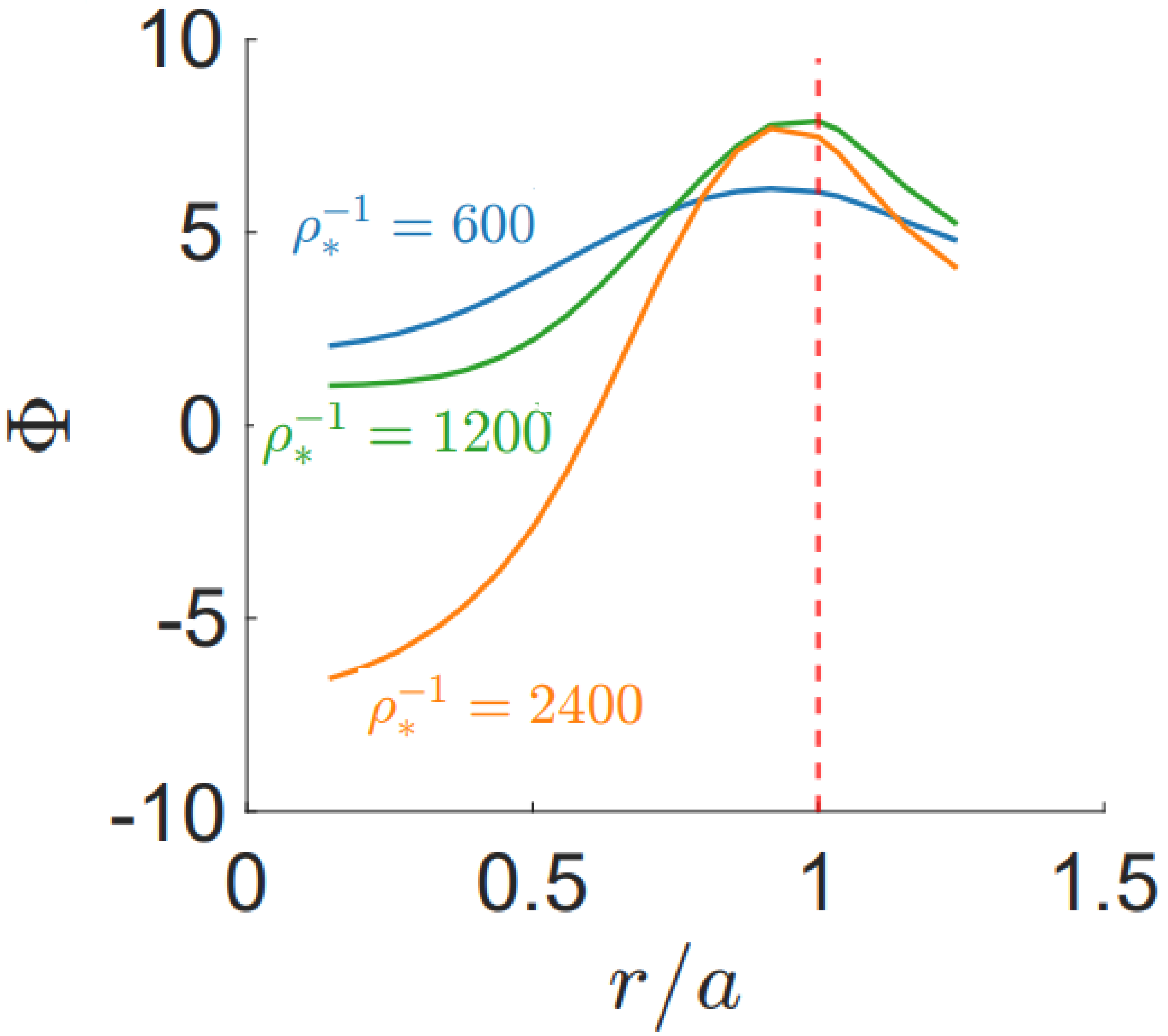
Auxiliary coil currents allowed **great flexibility in the edge topology**

Exploiting W7-AS flexibility for limited and diverted simulations



- **Limited configuration:** quarter-size $R_0/\rho_{s0} \sim 600$, half-size $R_0/\rho_s = 1200$, and full-size $R_0/\rho_{s0} \sim 2400$ with $\iota \sim 0.4$
- **Island-diverted configuration:** $R_0/\rho_{s0} \sim 2400$ **and** $\iota \sim 0.5$

Velocity shear layer at the last-closed flux surface

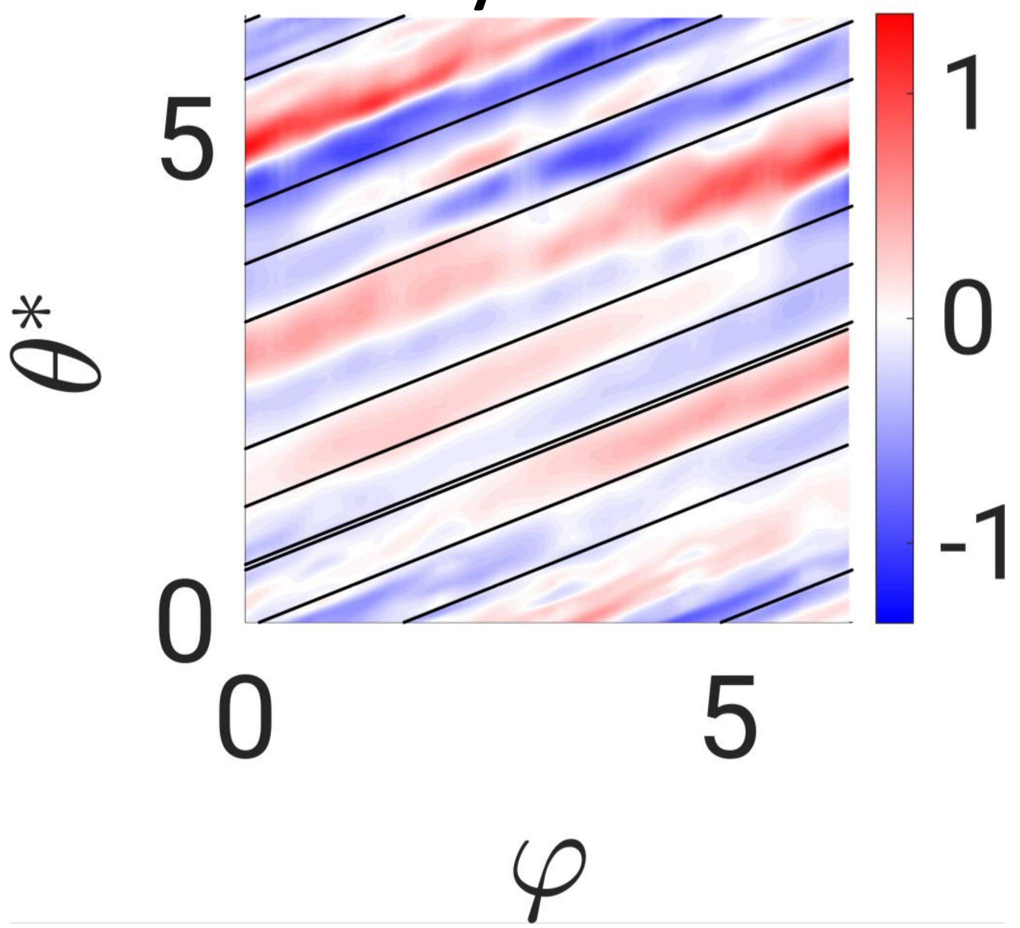


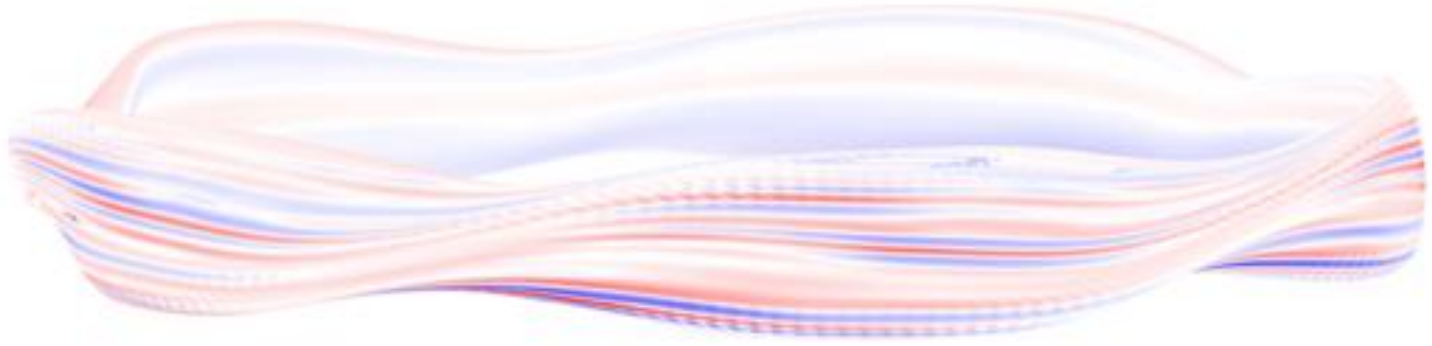
- **Negative radial electric field** in the **core** following $E_r \sim \partial_r P_i / N$ and **positive in the SOL** following $\Phi \sim \lambda T_e$, forming **layer shearing fluctuations** *[J Bleuel et al 2002 New J. Phys.]*

- $E \times B$ **main radial transport** mechanism *[M. Schubert et al. 2006]*

[Z. Tecchiolli, in preparation]

Field-aligned curvature-driven turbulence in the edge of W7-AS



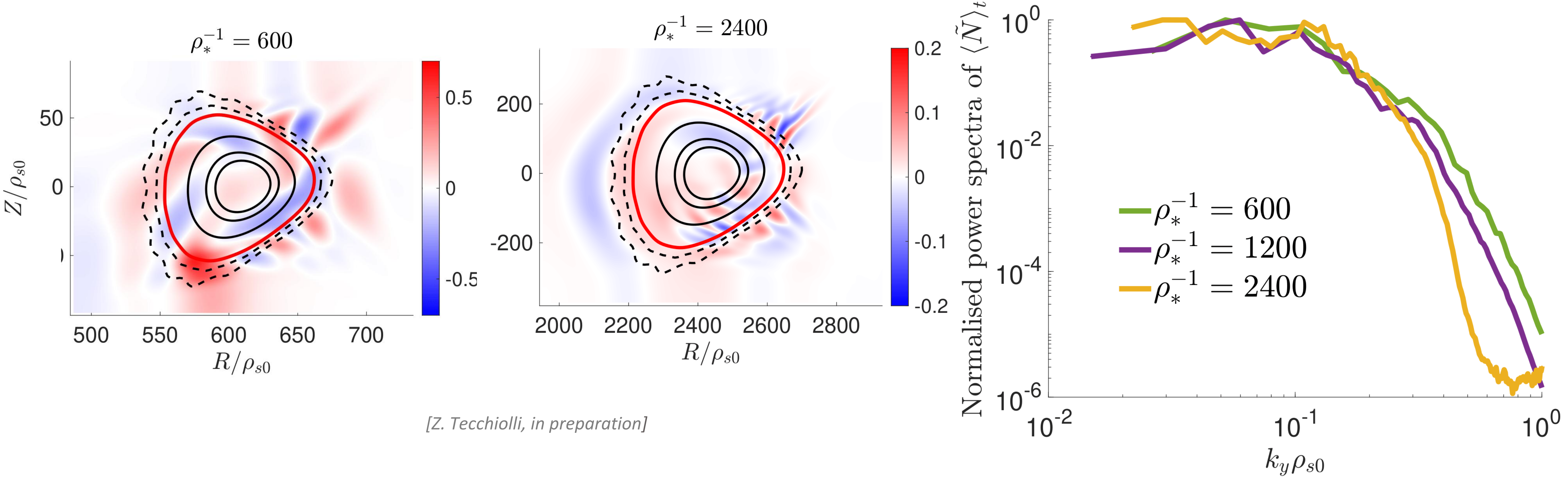


- **Field-aligned,** $k_{\parallel} \sim 0$ **, curvature driven,** $(\mathbf{b} \cdot \nabla \mathbf{b}) \cdot \nabla P$ turbulence
- Dominant mode number following $\iota \sim n/m$ where n **breaks the field periodicity of 5**
- **Importance of full torus simulations**

[Z. Tecchiolli, in preparation]

Similar poloidal size of fluctuating structure in size

Fluctuation levels

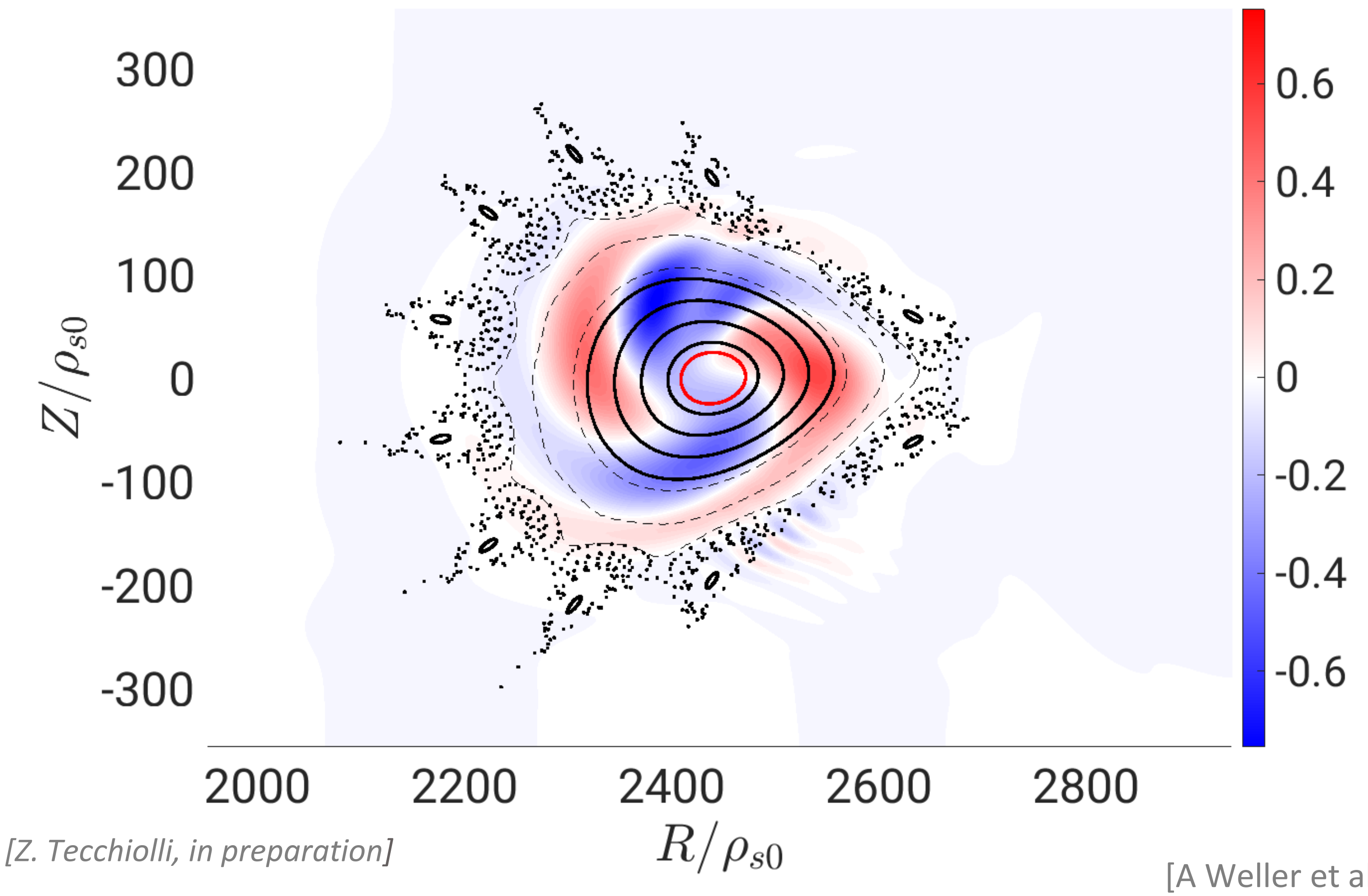


[Z. Tecchiolli, in preparation]

- **Poloidal size of fluctuating structure similar in** ρ_s **units among the different sizes**
- **Broader turbulent spectrum** compared to previous simulations and **consistent with experiments**[J Bleuel, et al. New Journal of Physics (2002)]

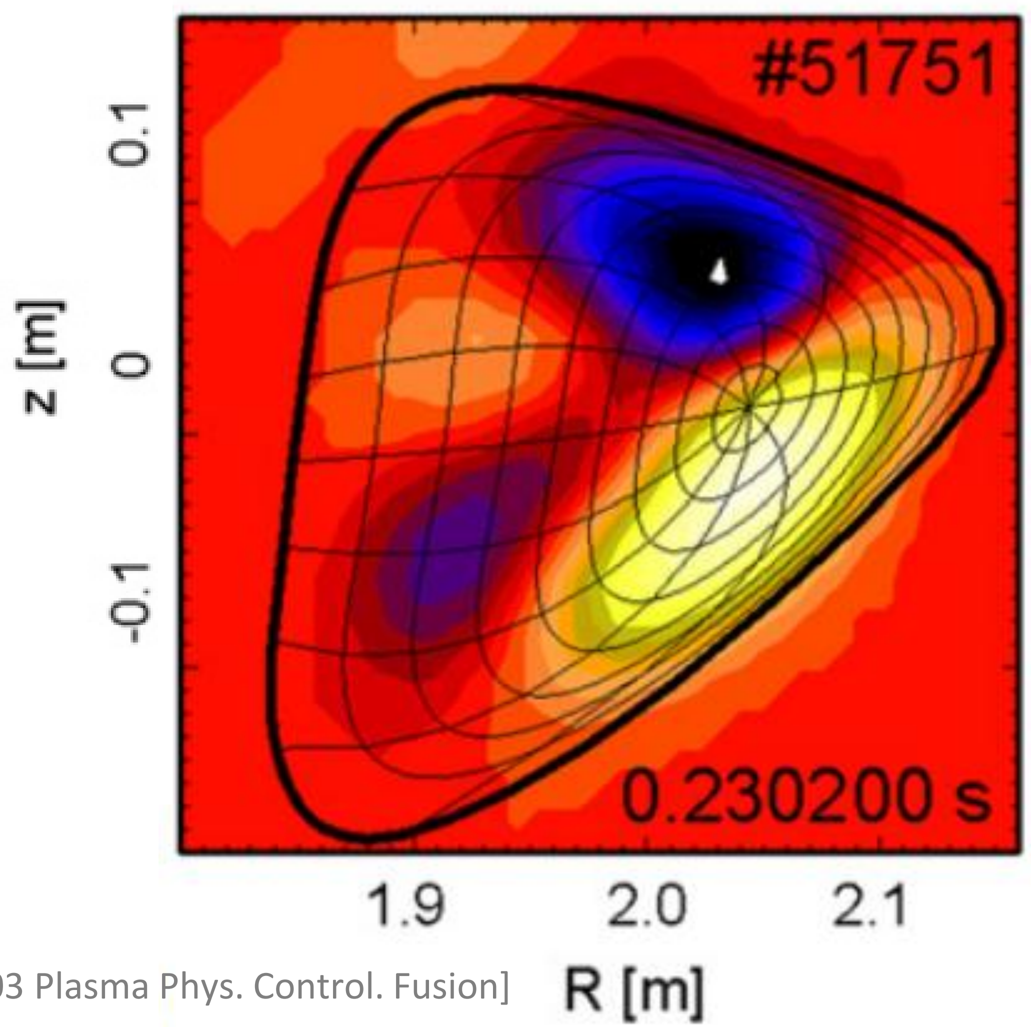
Global modes in the diverted configuration

Total density fluctuations



[Z. Tecchiolli, in preparation]

x-ray tomography



[A Weller et al 2003 Plasma Phys. Control. Fusion]

- **Global** $(m,n) = (2,1)$ **field-aligned instability** consistent with $\iota \sim 0.5$ and unstable Mercier condition for low-beta plasma in W7-AS
- **Study of SOL region still undergoing**

Conclusion: successful edge validation in W7-AS, LHD, and HSX provides a strong basis for further physical understanding

- Qualitative **validation** in **W7-AS and LHD**, combined with quantitative validation in **HSX**, indicates that the **drift-reduced Braginskii model represents a valid description for plasma physics in the edge of stellarators.**
- **Curvature-driven and field-aligned instabilities constitute the primary energy source** in the simulations considered. However, **plasma parameters** and **global electromagnetic effects** may significantly influence the resulting dynamics.
- **Substantial physics in the edge region remains to be explored**. Key areas include **neutral dynamics**, detailed characterization of **instabilities**, **saturation mechanisms**, **stochastic magnetic fields**, and **divertor geometries**.