

GBS update: simulation of the HSX stellarator and experimental comparison

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⁵Gauss Fusion GmbH, Garching bei München, Germany,

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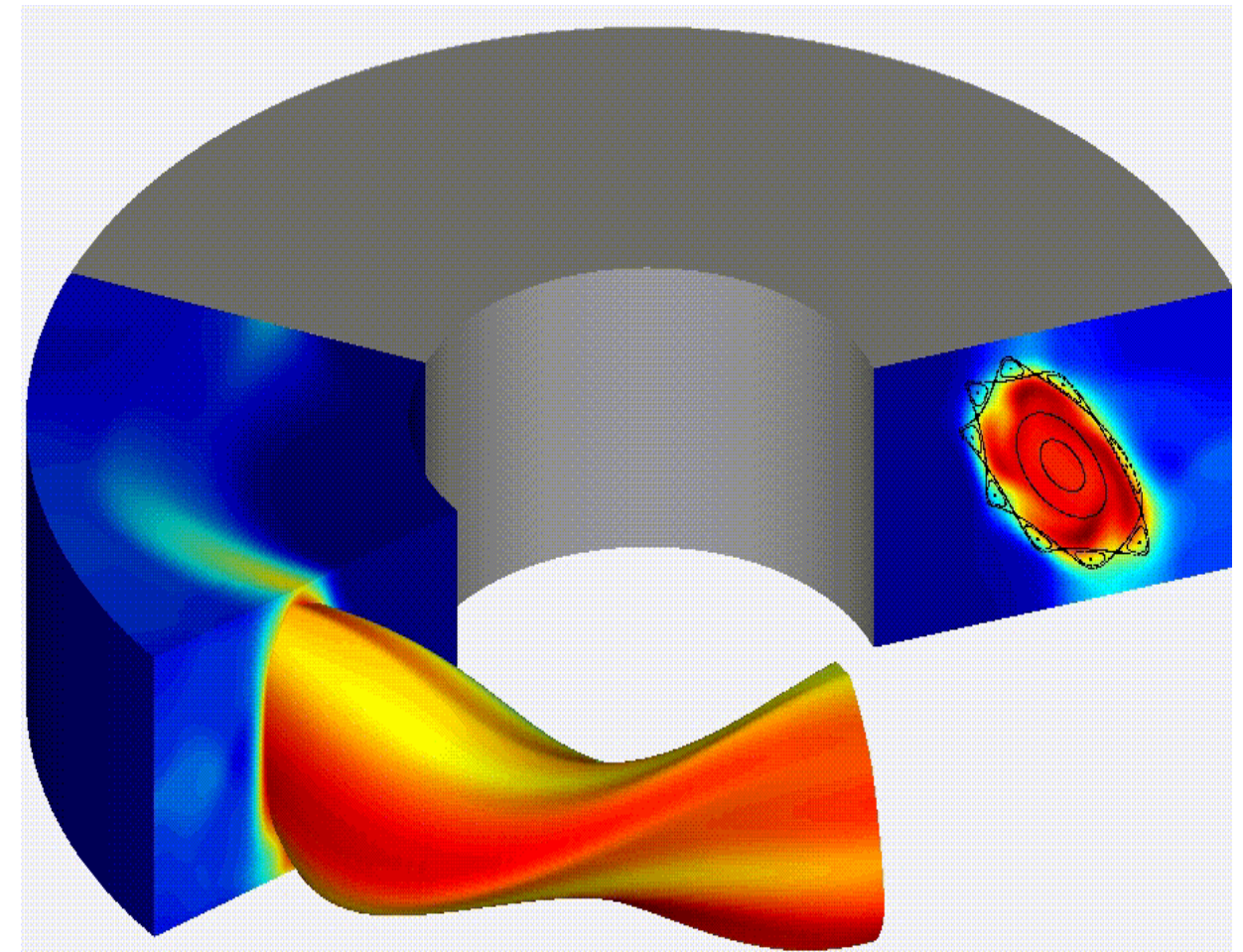
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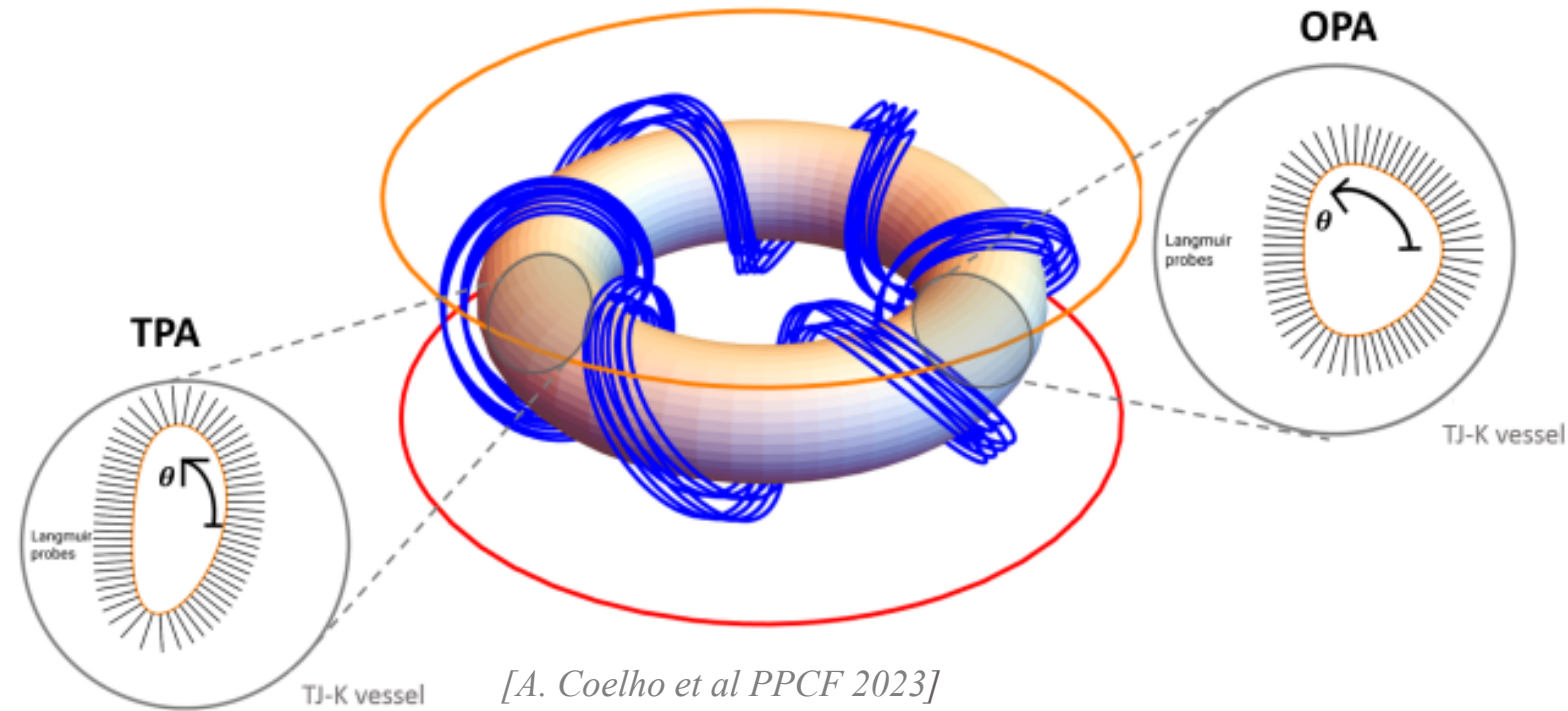
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- Wall = Simulation boundary with **magnetic pre-sheath boundary conditions** [Loizu et al PoP 2013]

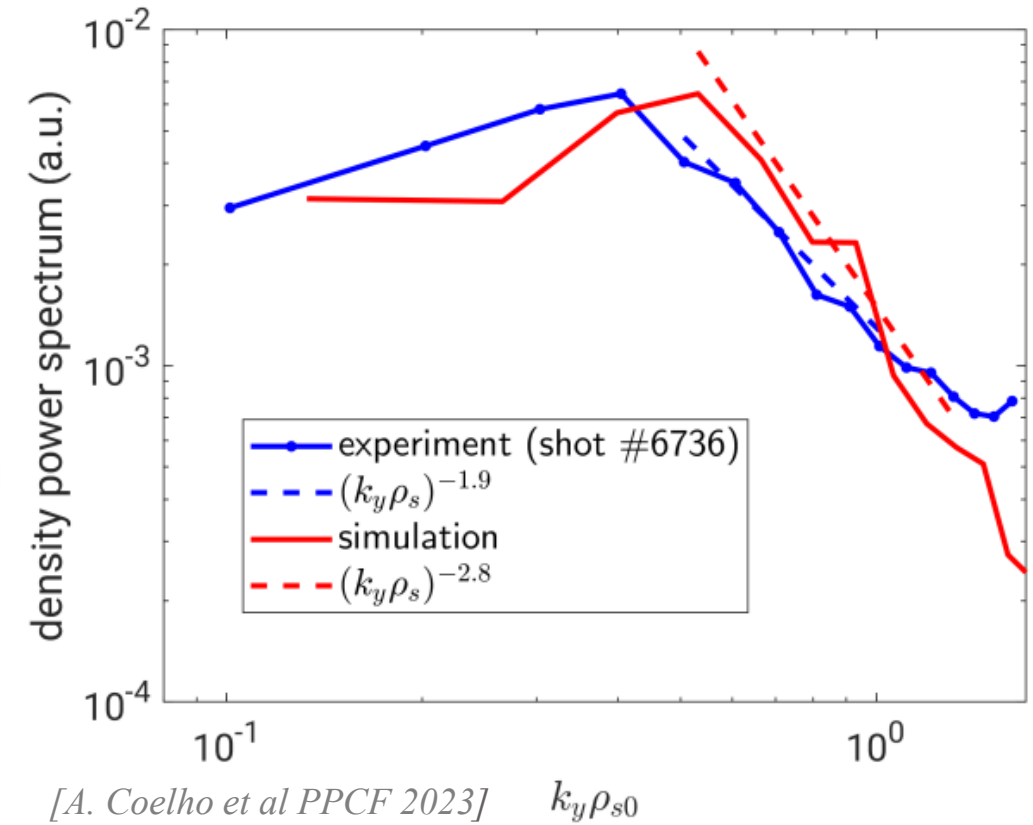
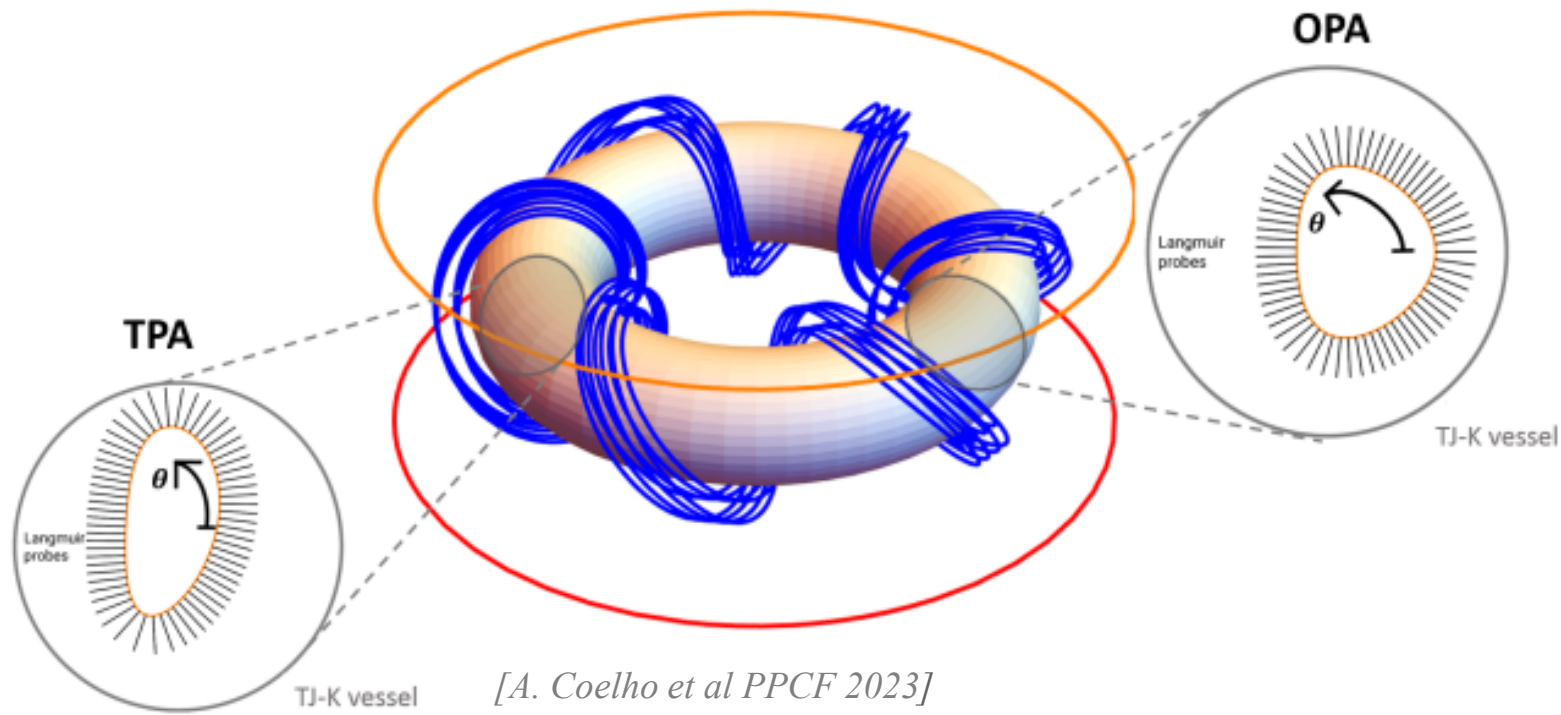
Quasi-steady-state given by **balance of sources, turbulence and sheath losses**



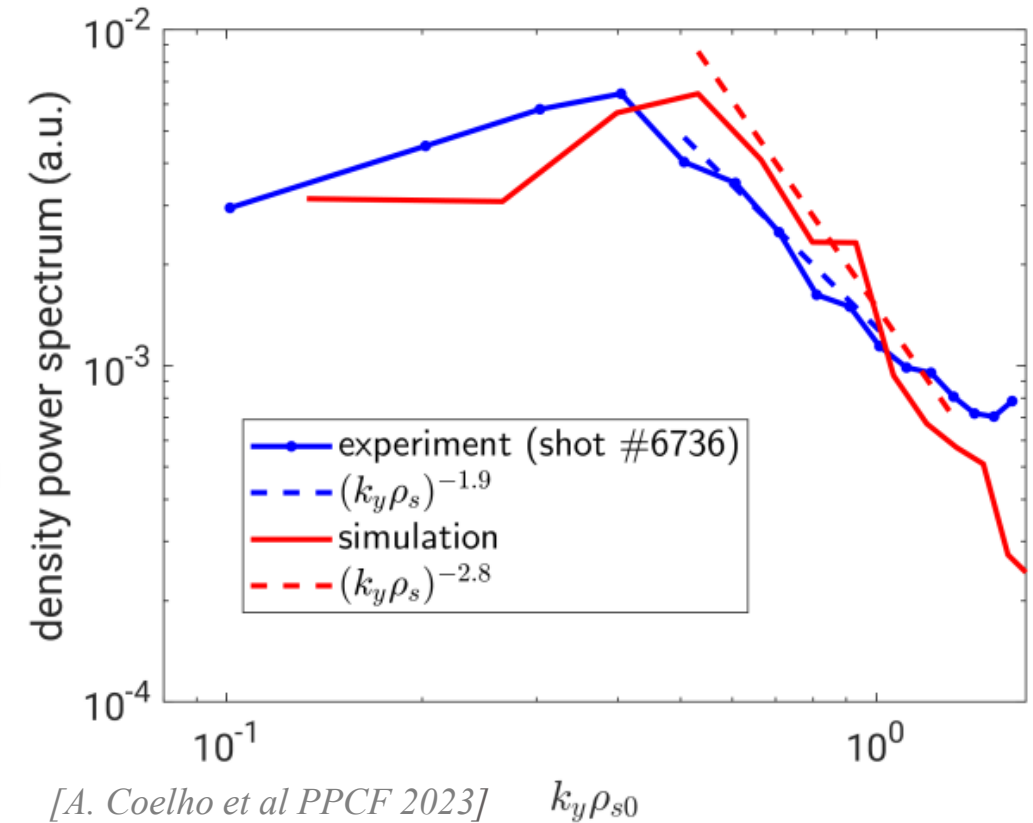
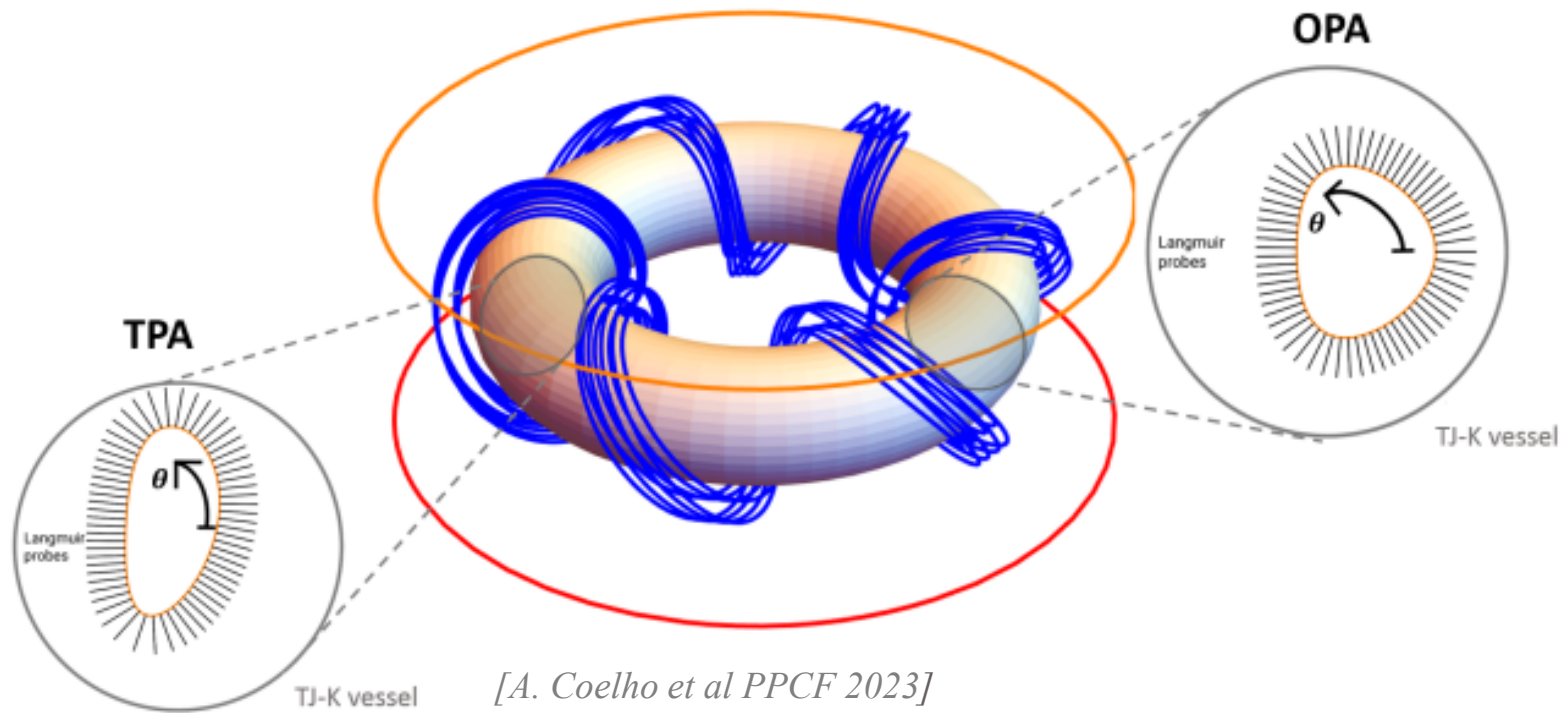
[Coelho et al, Nucl. Fusion 2024]



- **Model valid in full device** (except neutral physics not included)



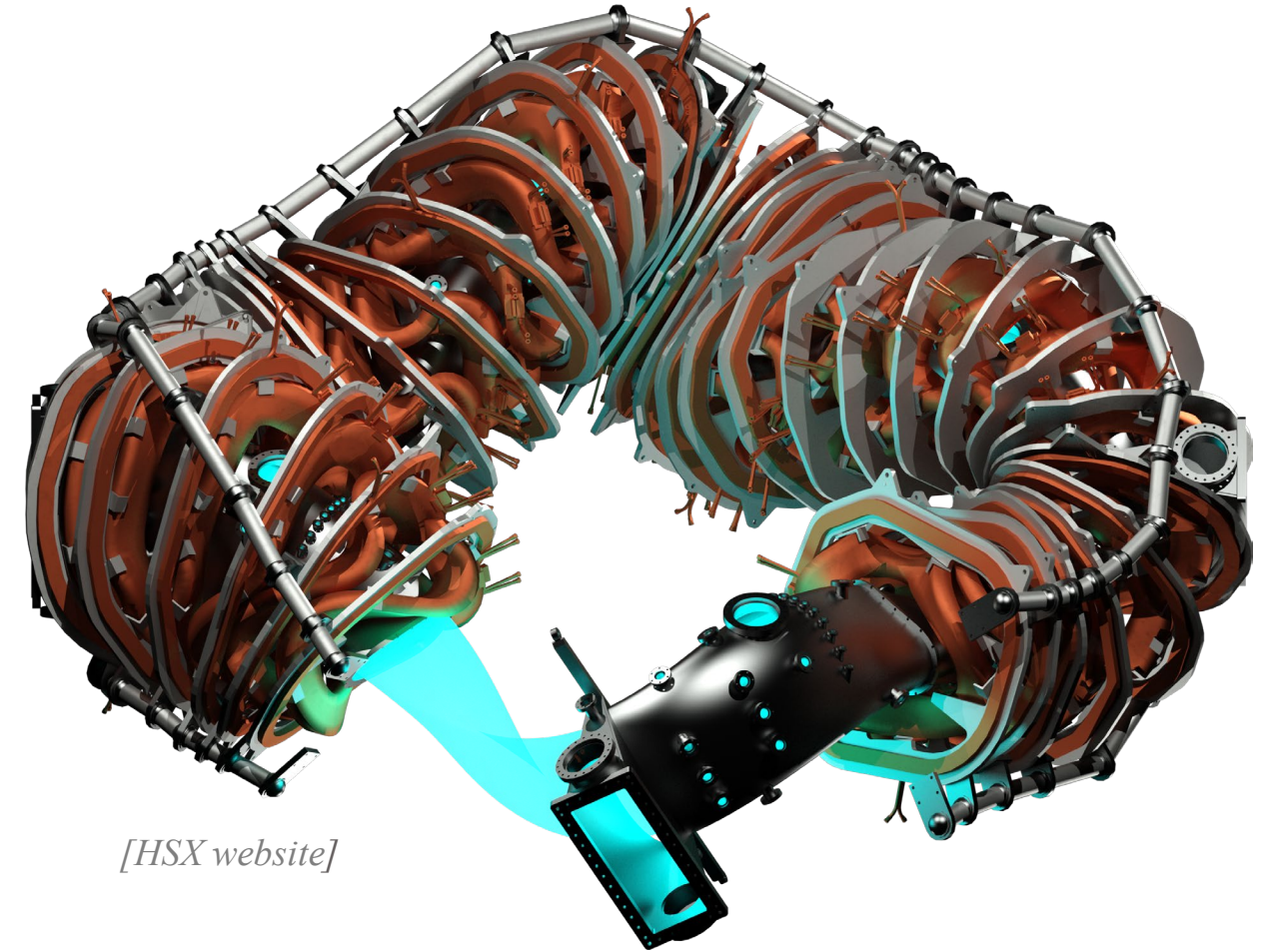
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**Here, we scale
up in size and
relevance**

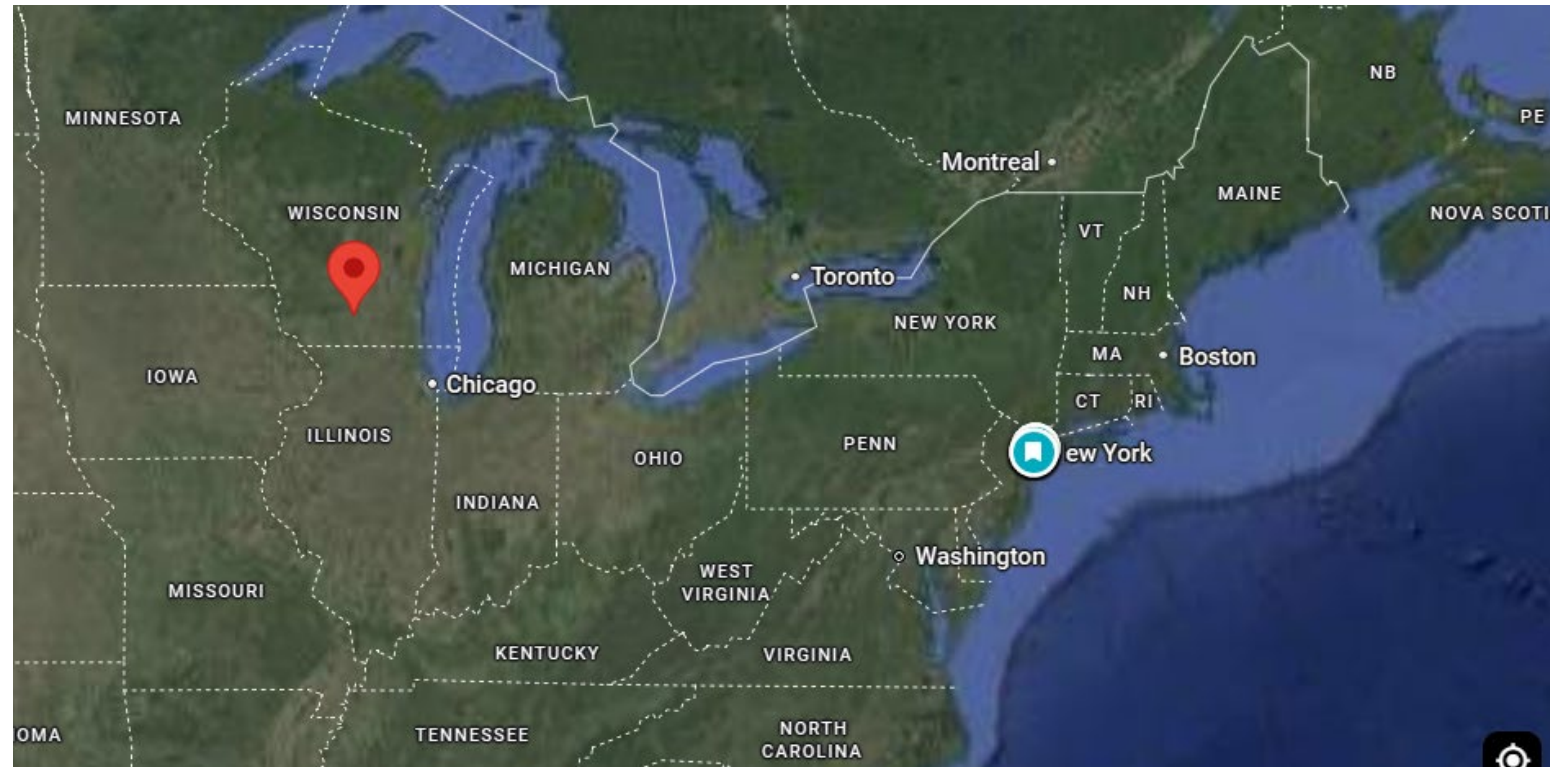
HSX



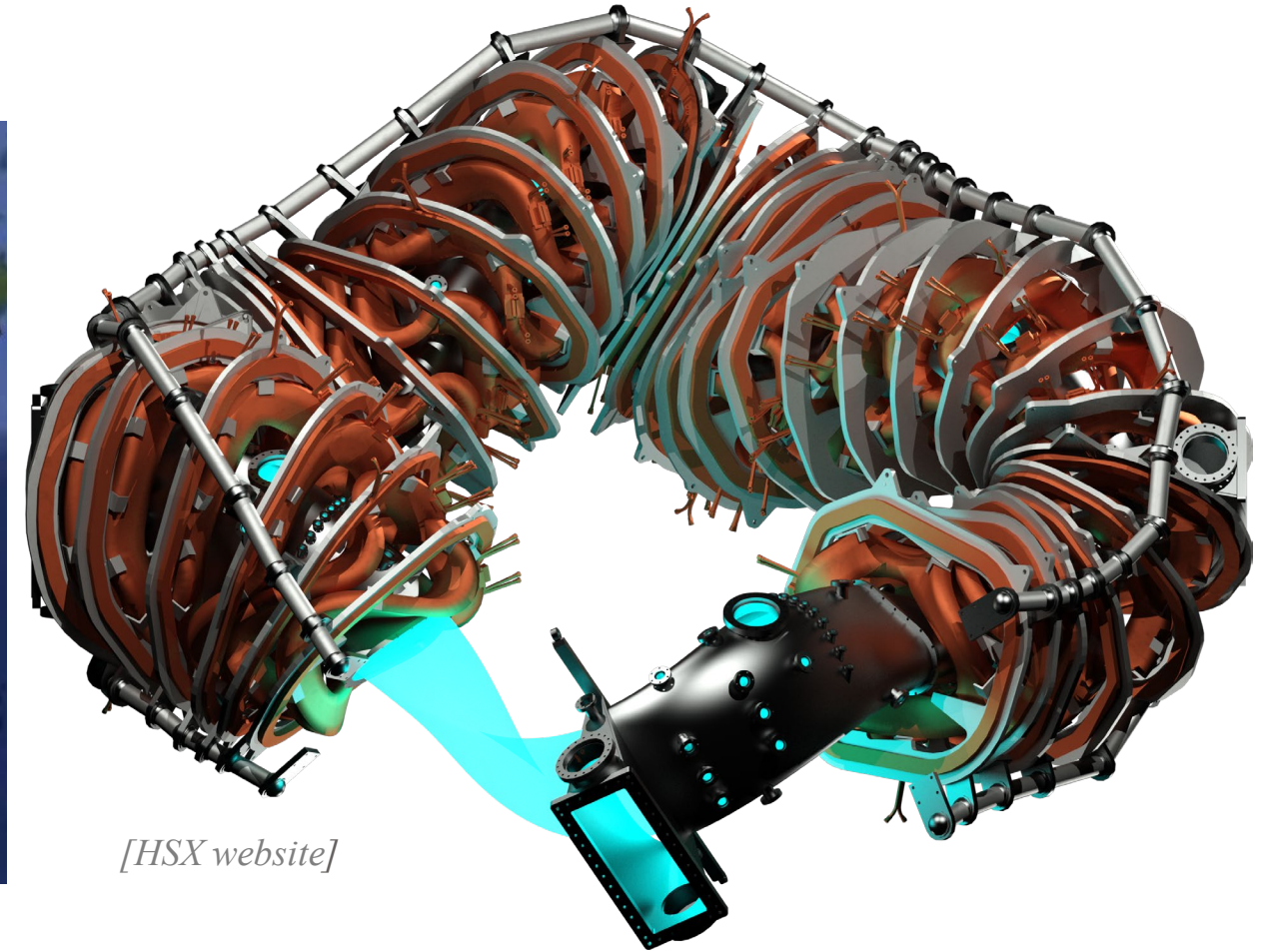
[HSX website]

EPFL HSX, an ideal validation test bed

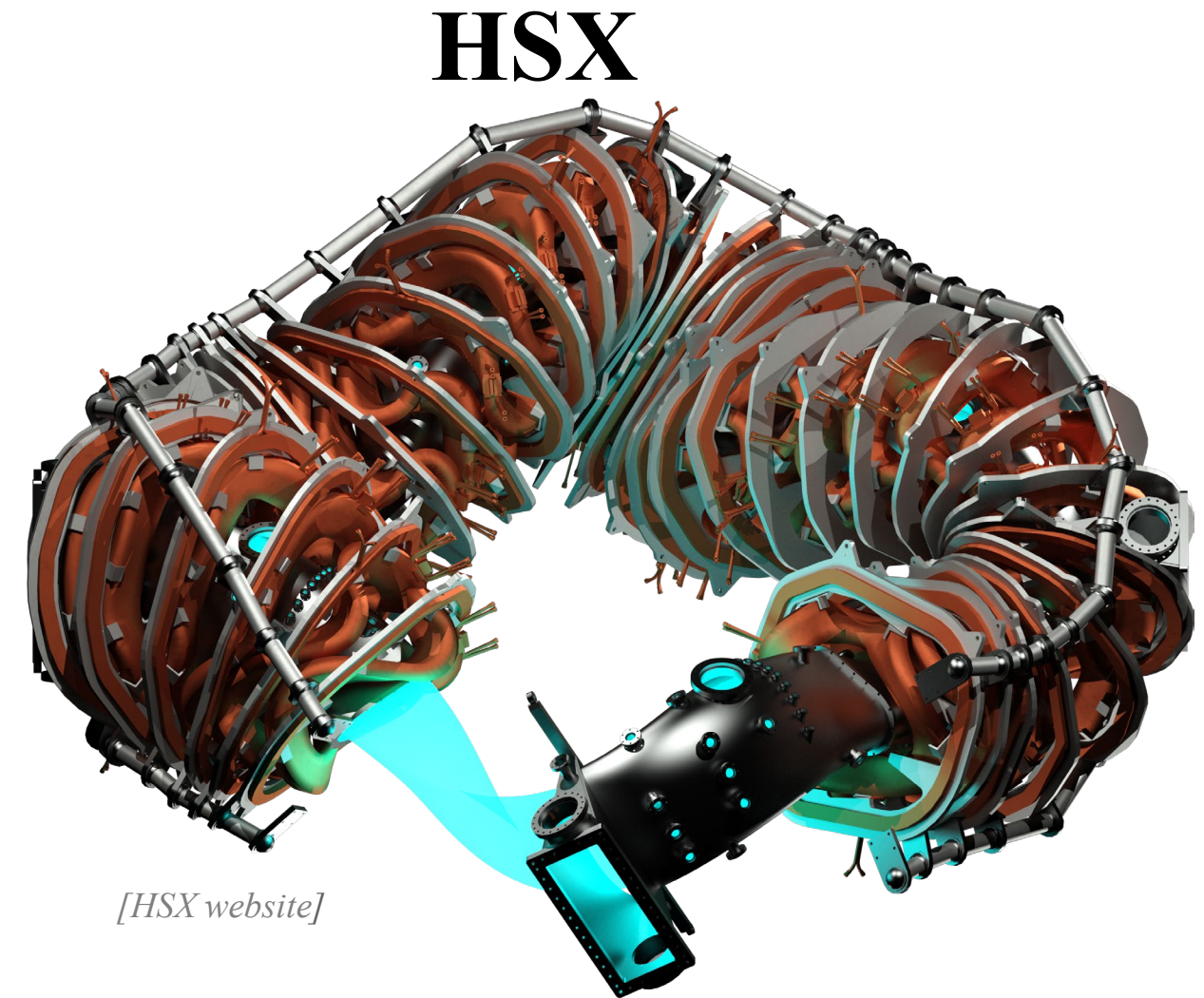
Located at Madison, Wisconsin, USA



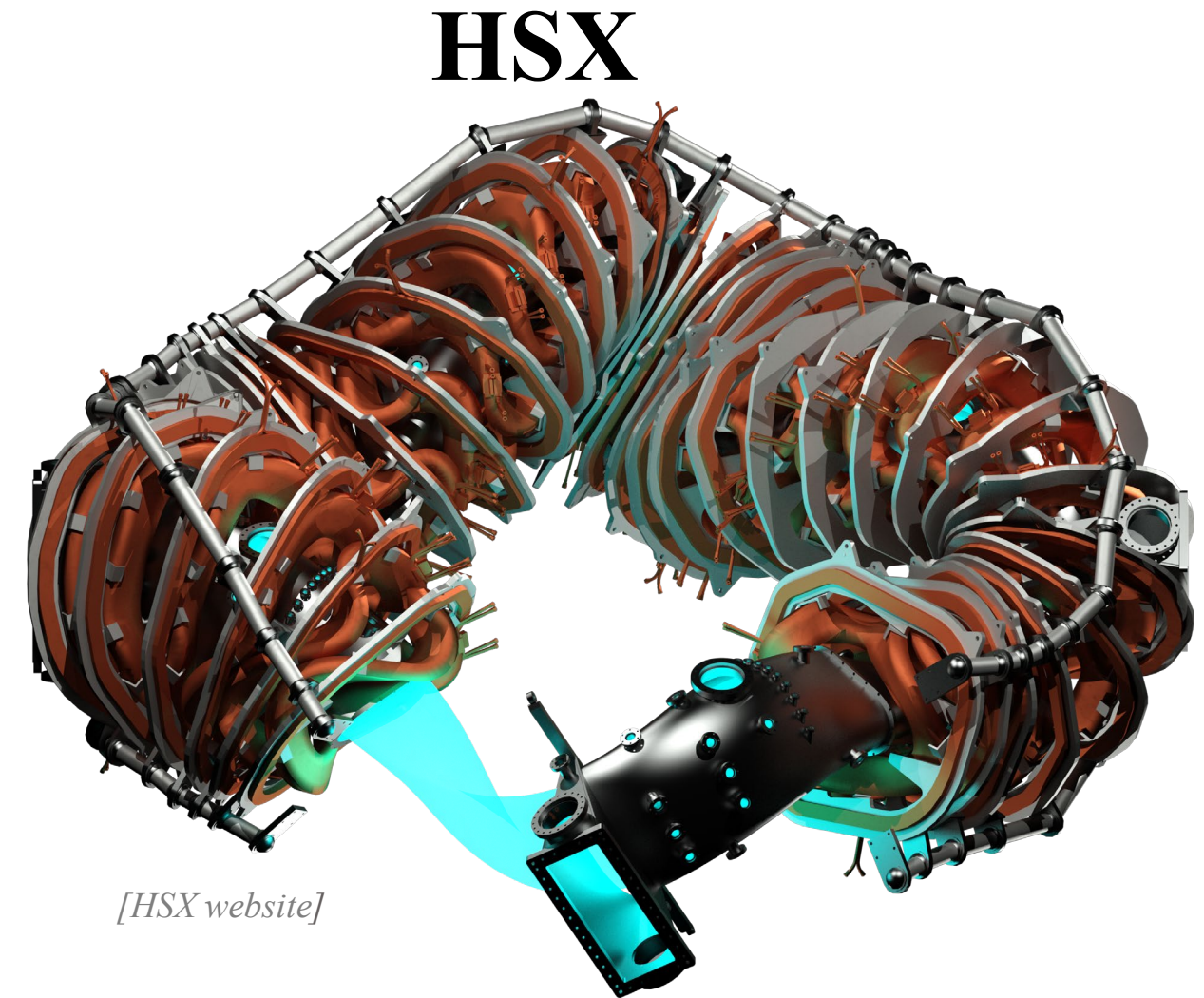
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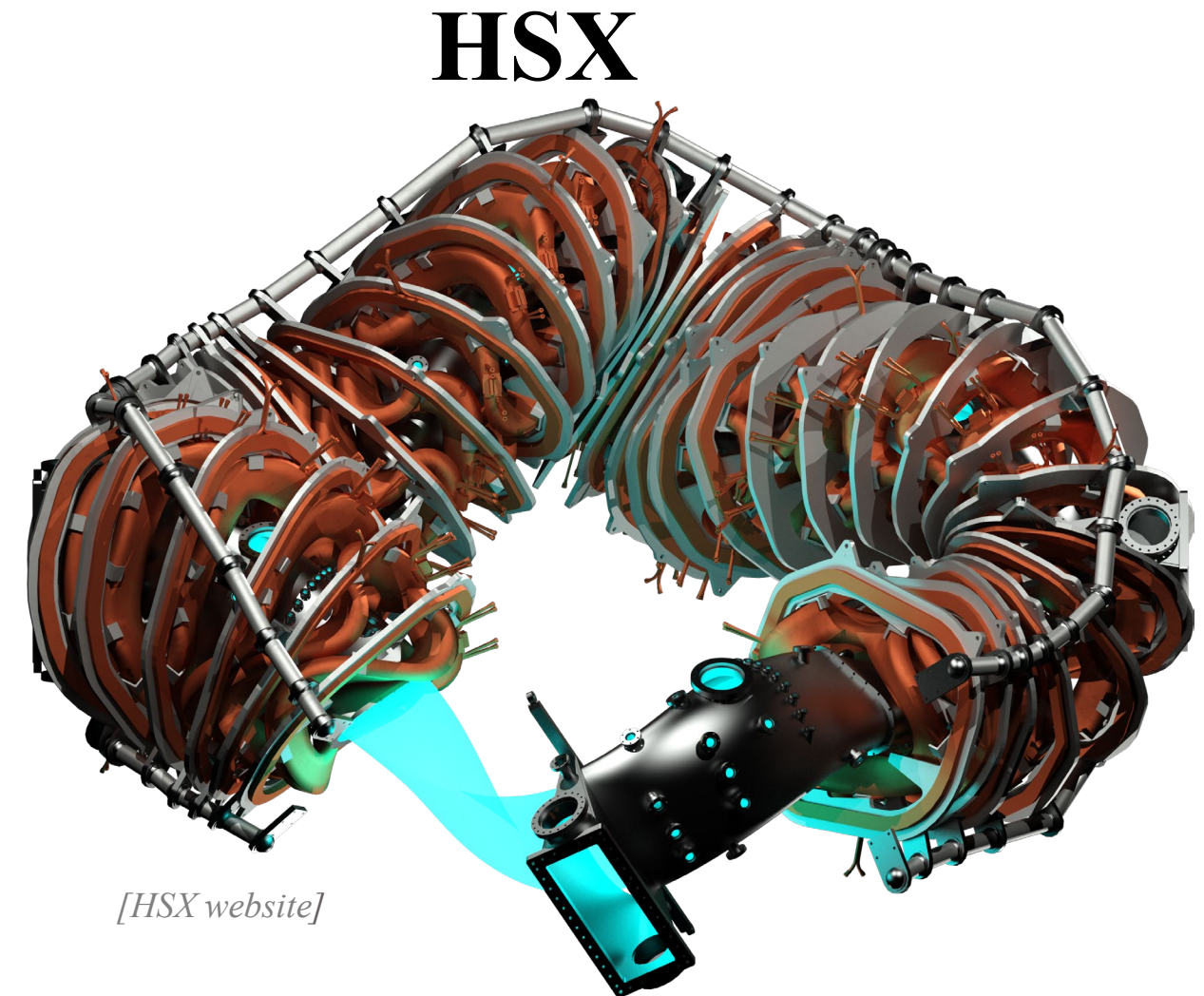
- **Quasi-helically-symmetric stellarator**
 $\Rightarrow$ Effects of quasi-symmetry in the edge



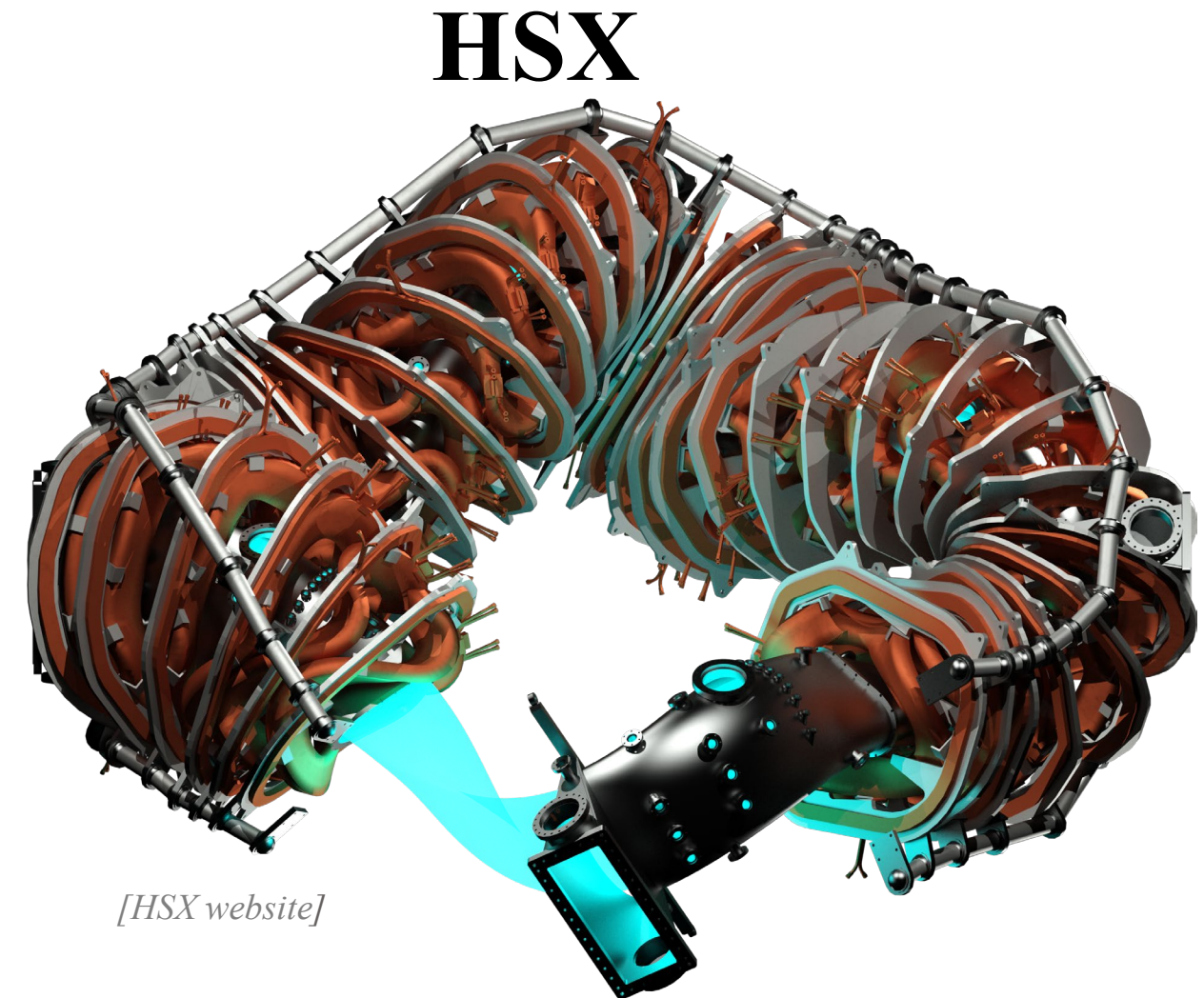
- **Quasi-helically-symmetric stellarator**
 $\implies$ Effects of quasi-symmetry in the boundary
- **Effective collisionality $\nu^* \sim 1$**
 $\implies$ Drift-reduced Braginskii modelling valid



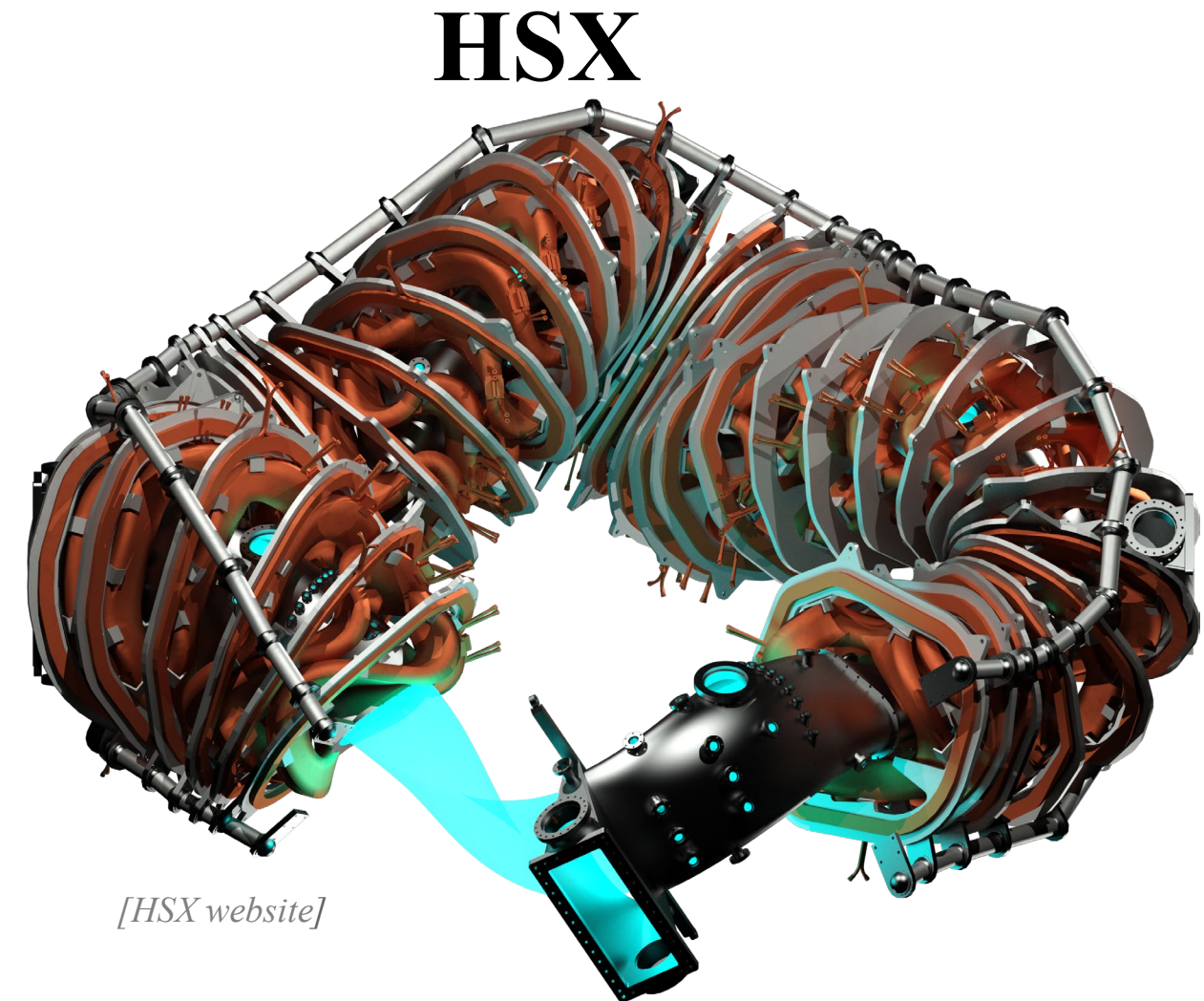
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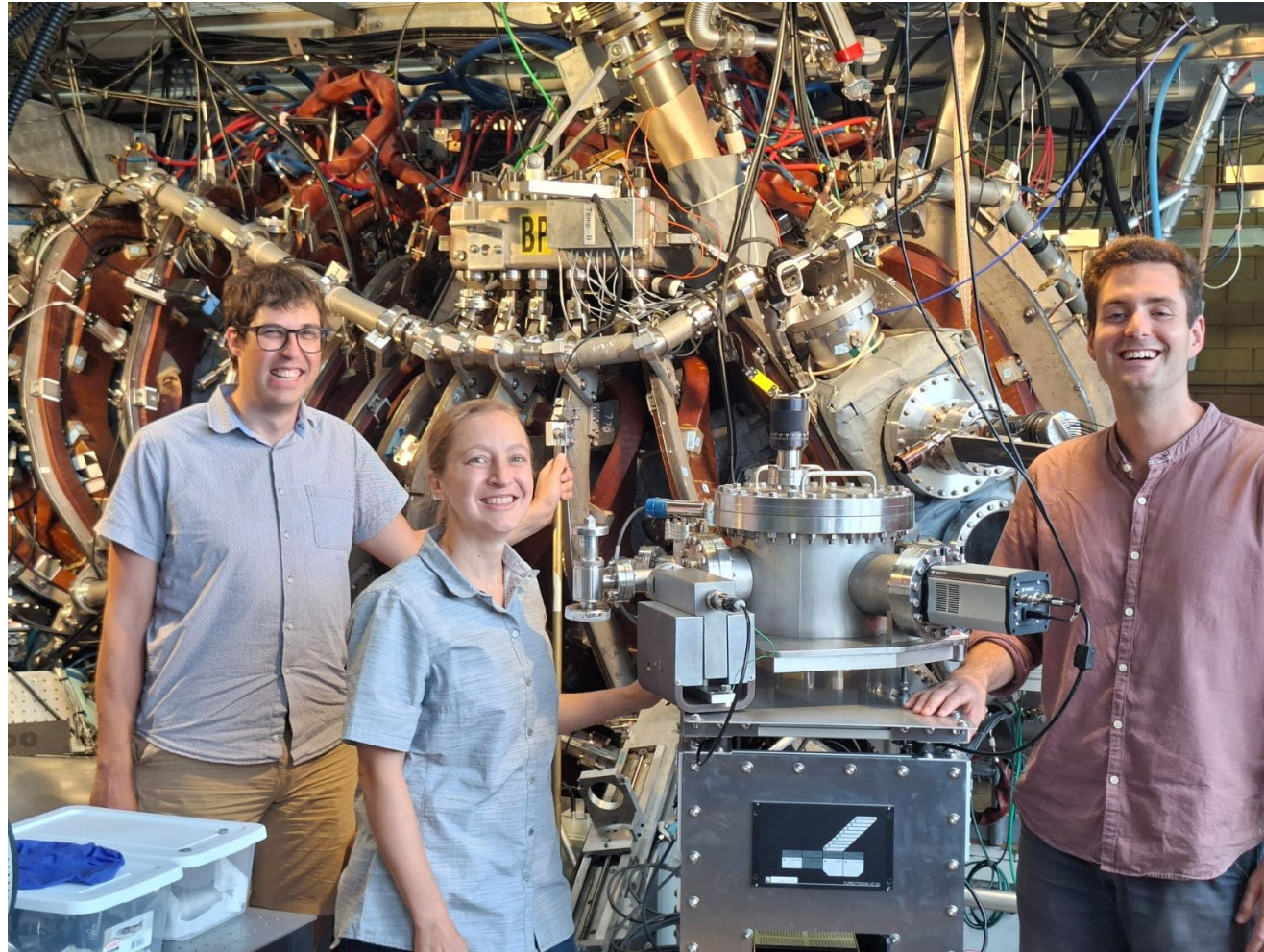


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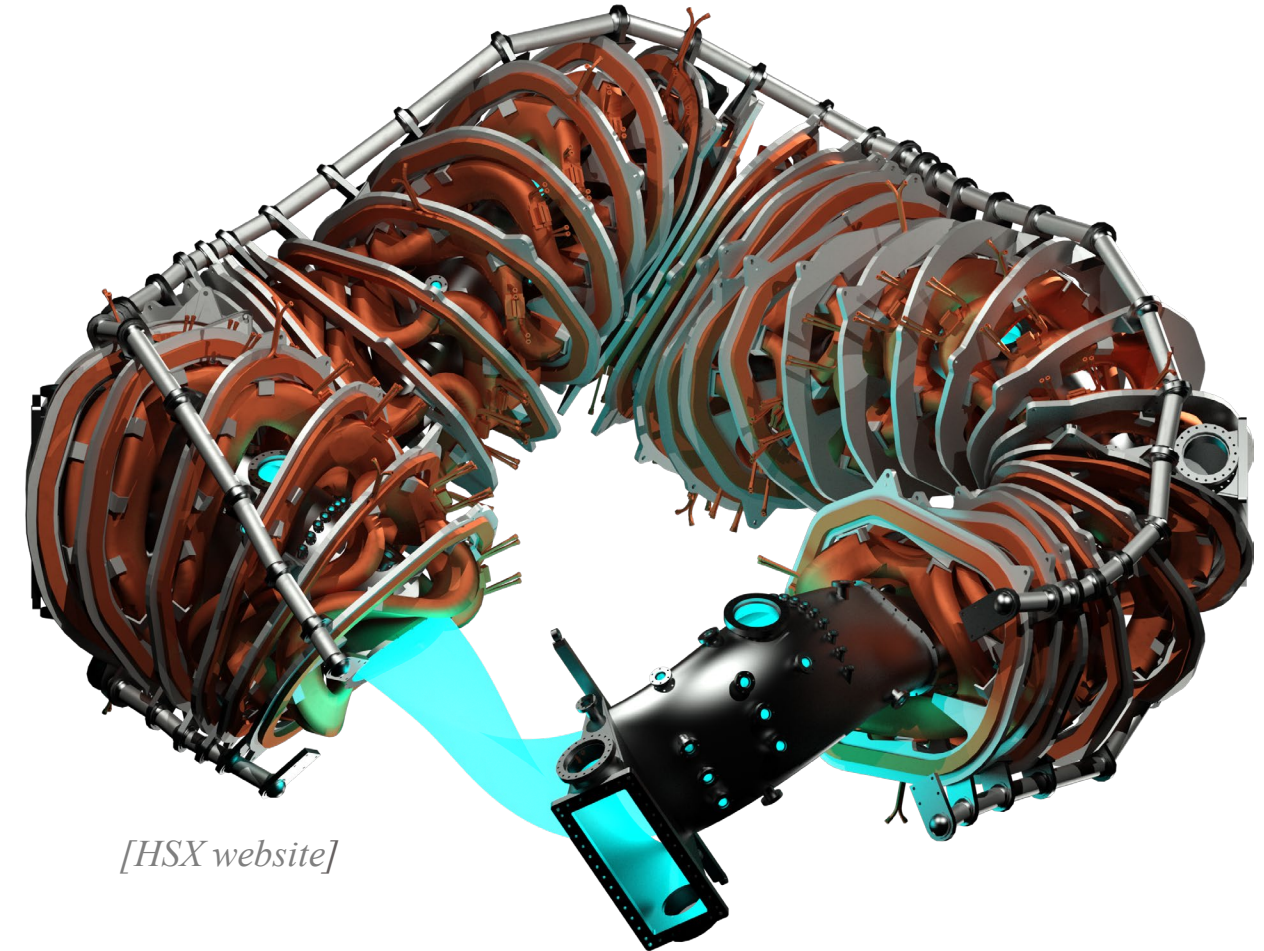
HSX represents the next step for understanding and validating plasma boundary turbulence

EPFL HSX, an ideal validation test bed

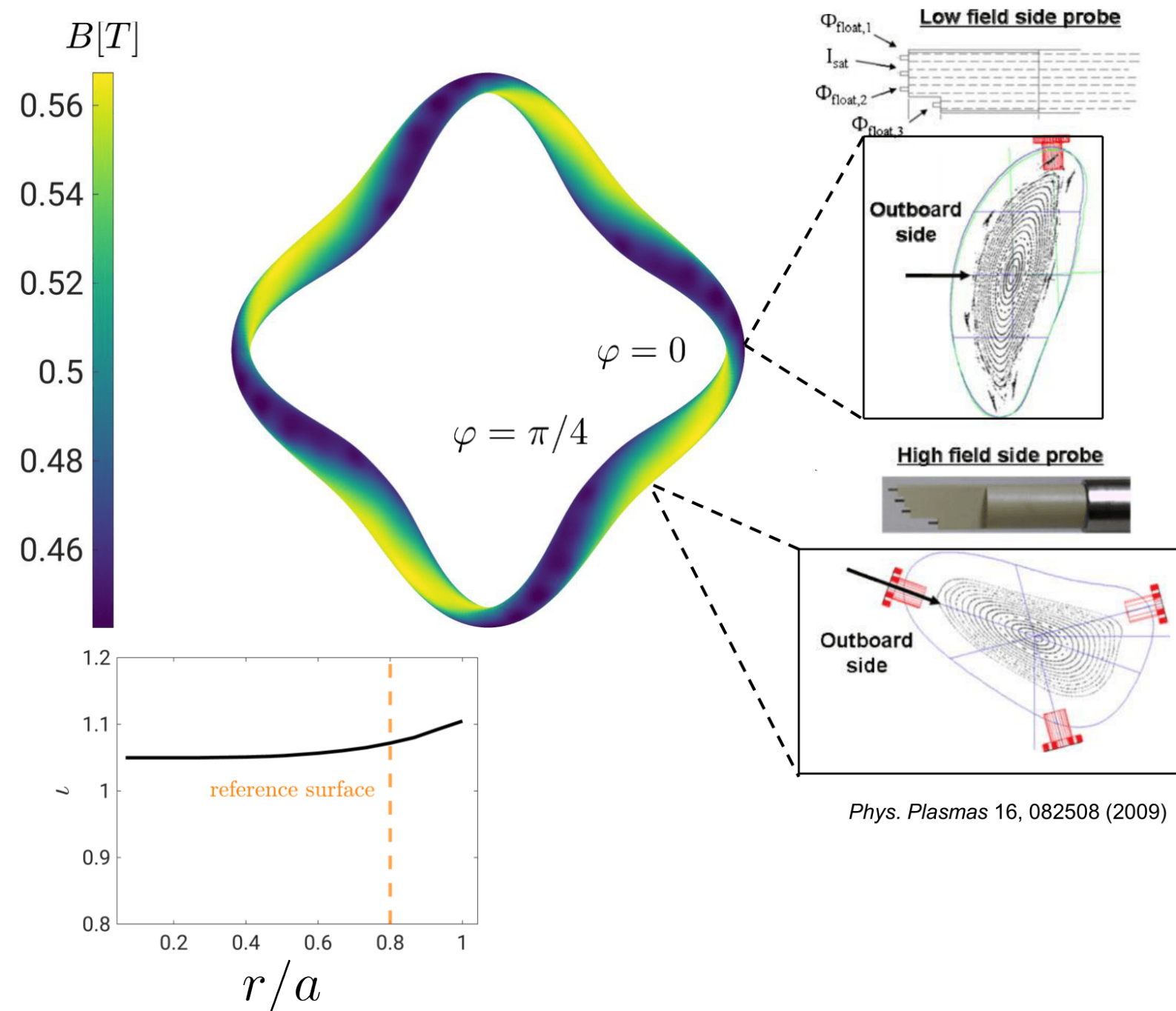


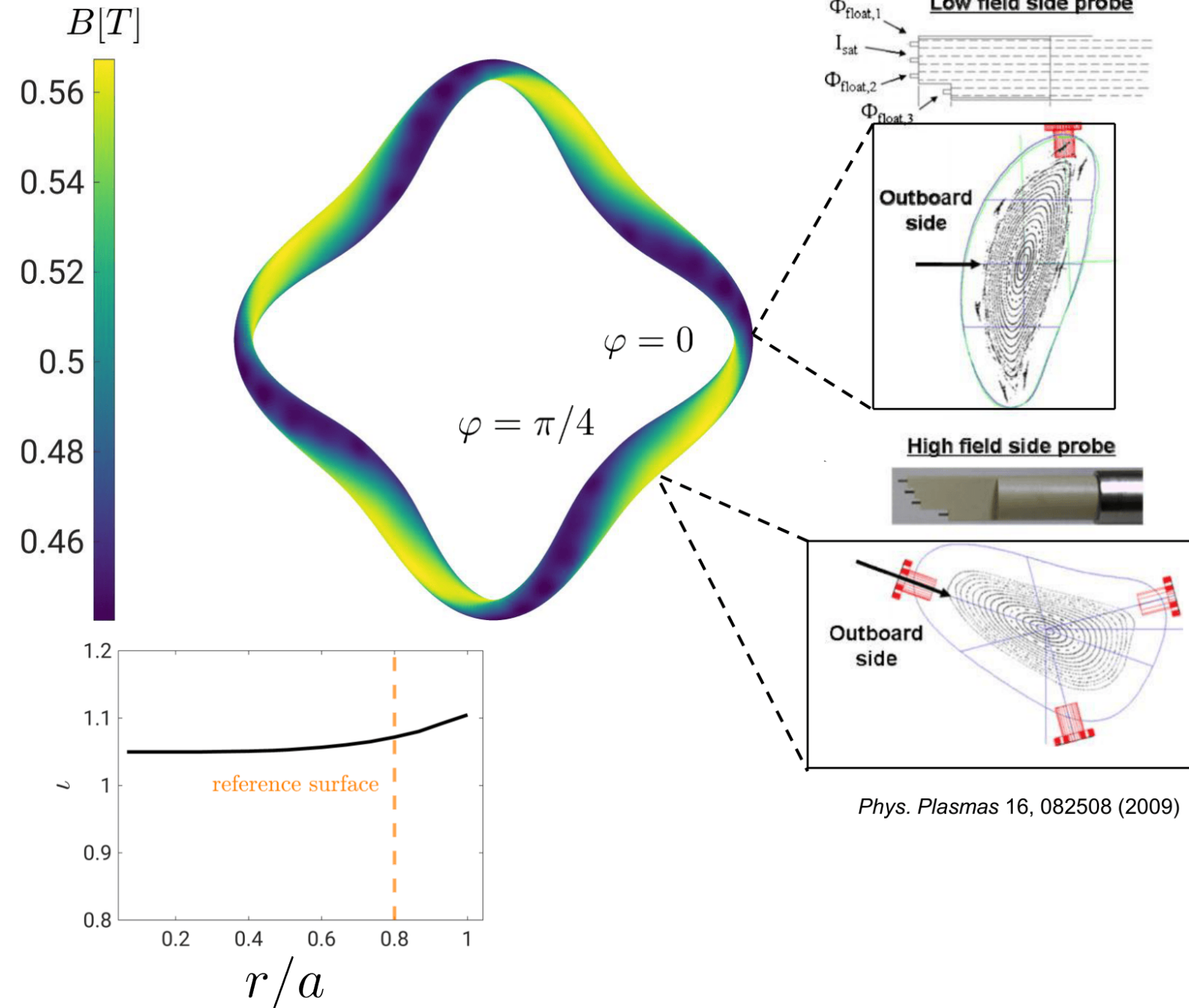
[EPFL-UW collaboration on the 20.07.2026]

HSX



[HSX website]





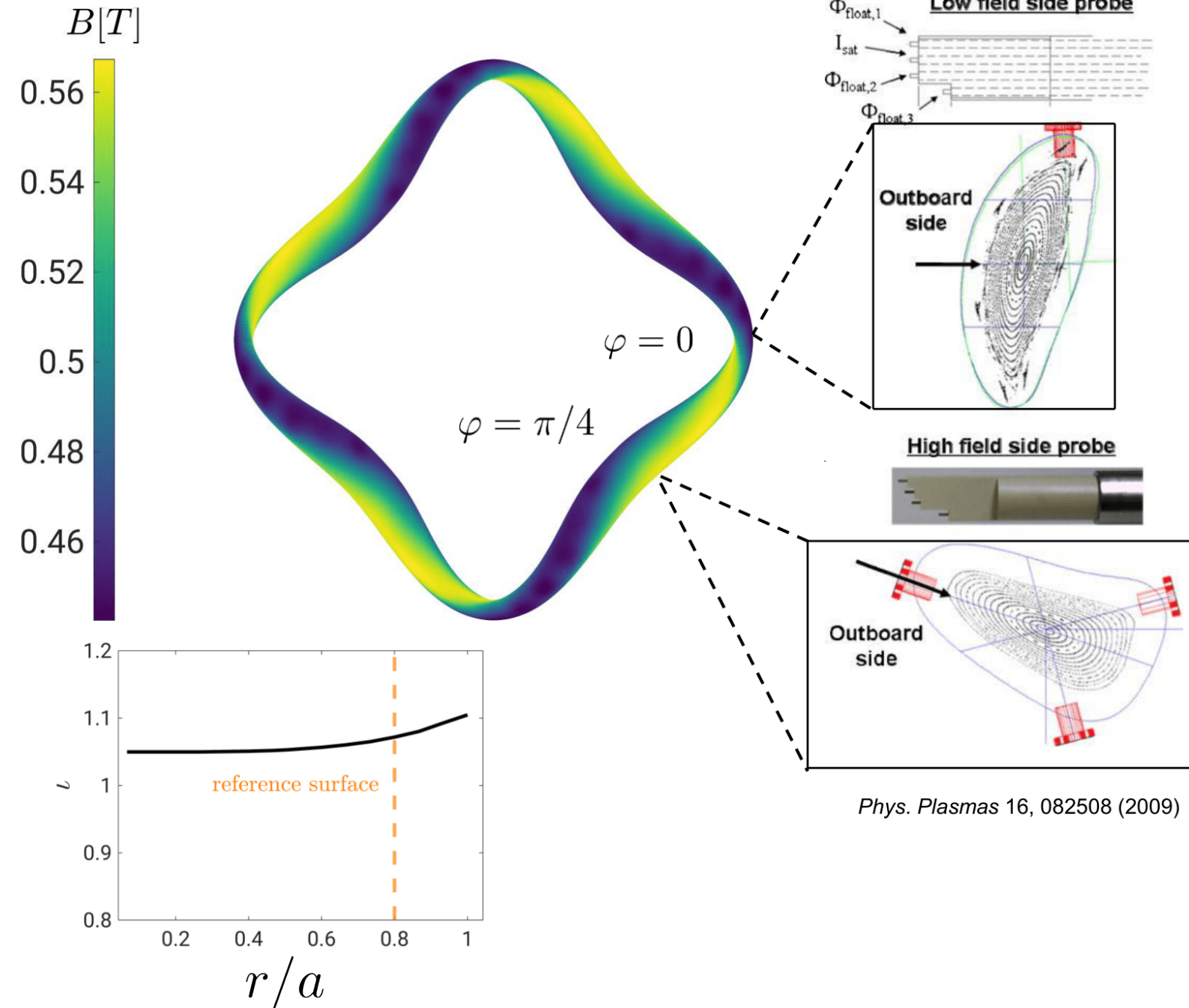
- Simulate full-size machine with comparison to experiments done by W. Guttenfelder (2009)

$$B_0 = 0.5 \text{ T} \quad \beta \approx 0.08\%$$

$$n_0 = 10^{18} \text{ m}^{-3}$$

$$T_e = 40 \text{ eV}$$

$$T_i = 20 \text{ eV}$$



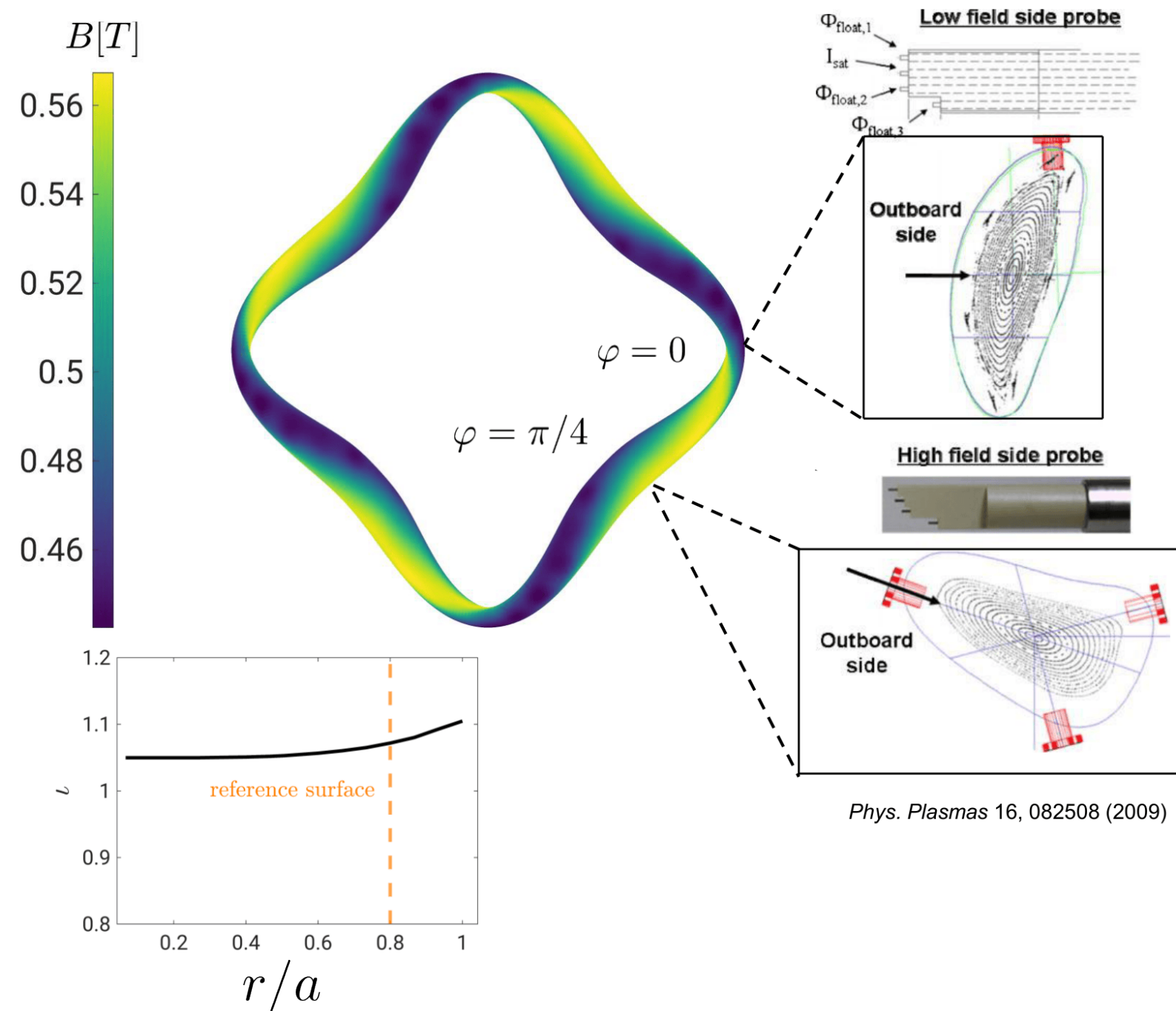
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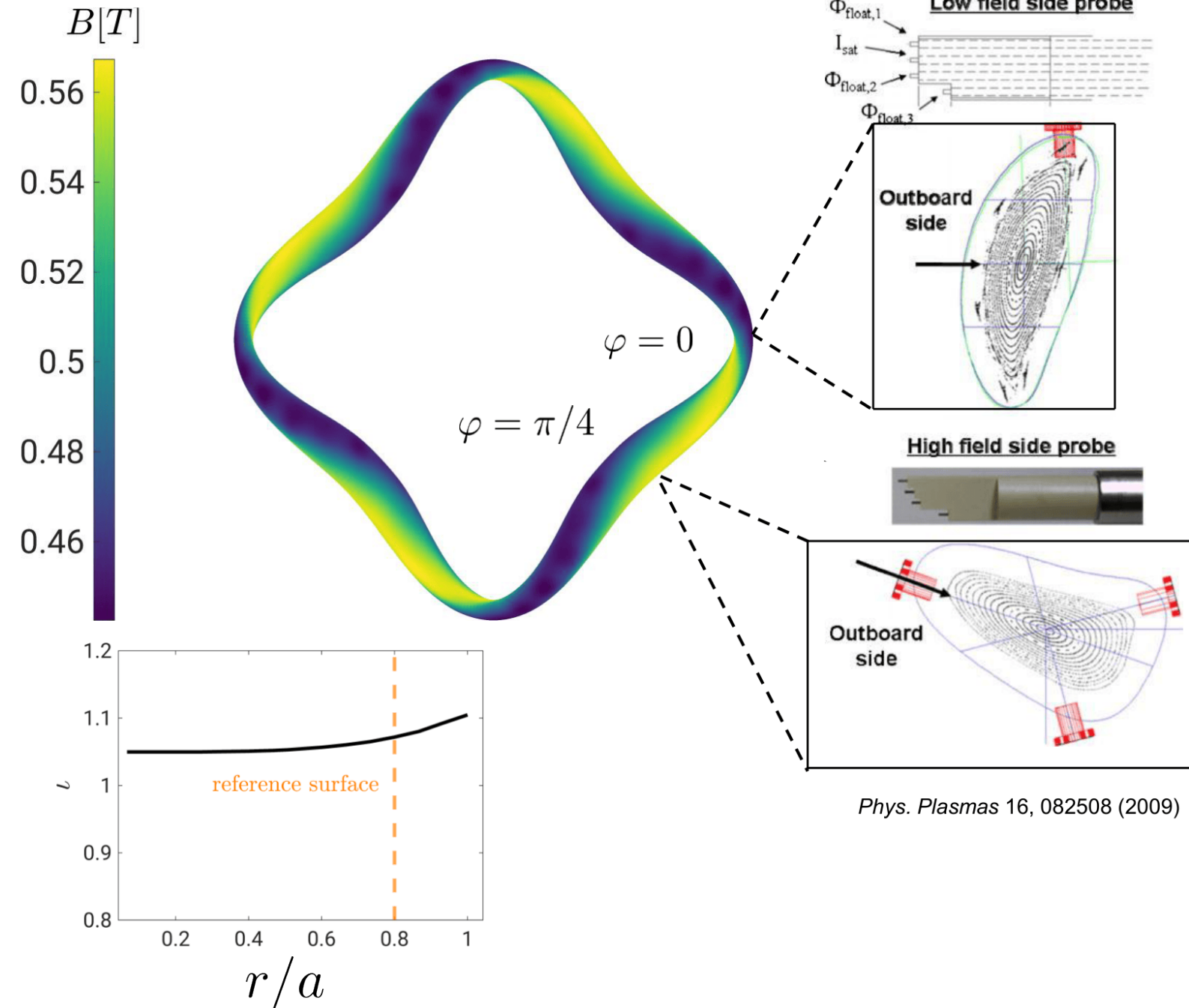
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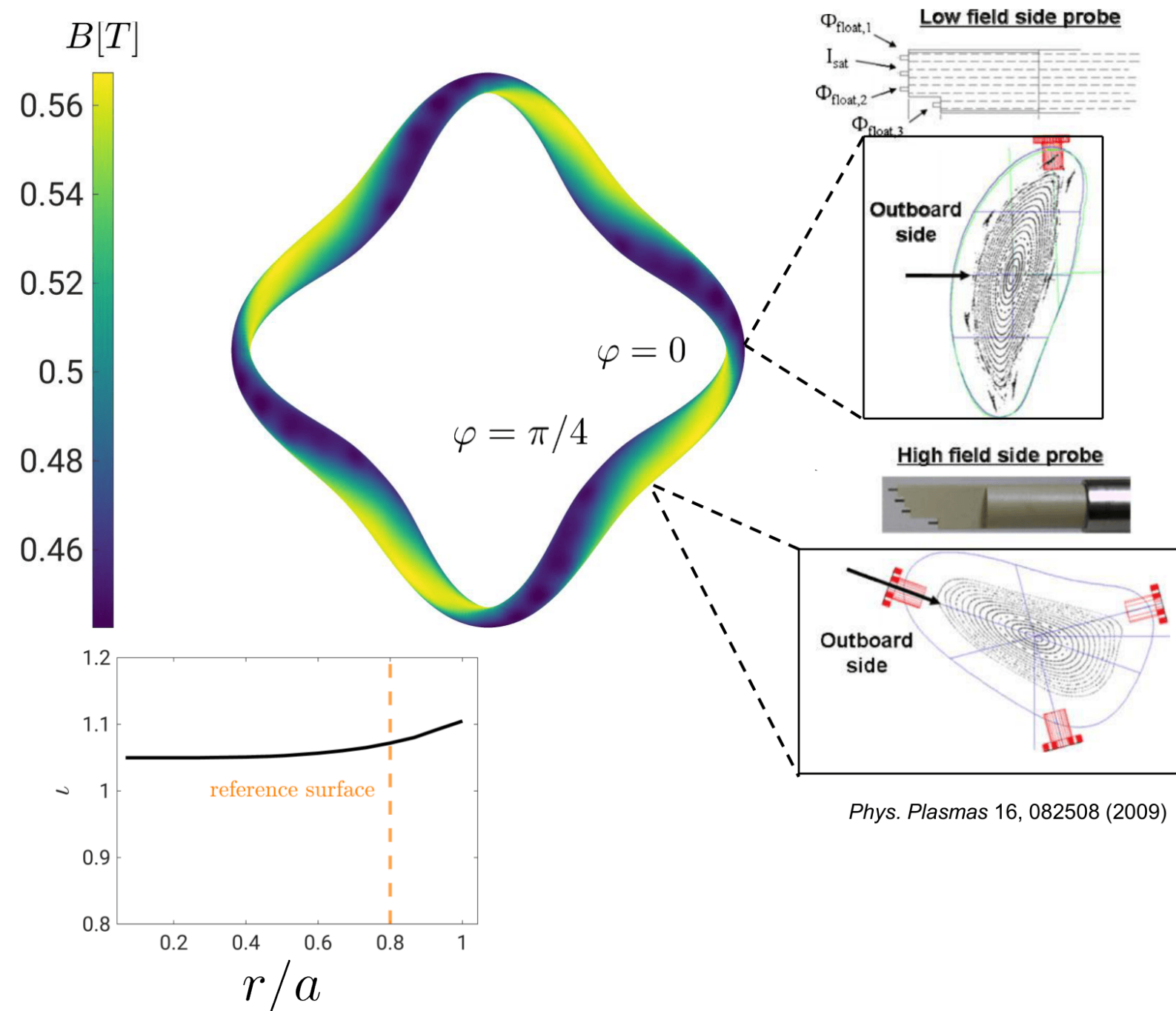
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- Electrostatic simulations

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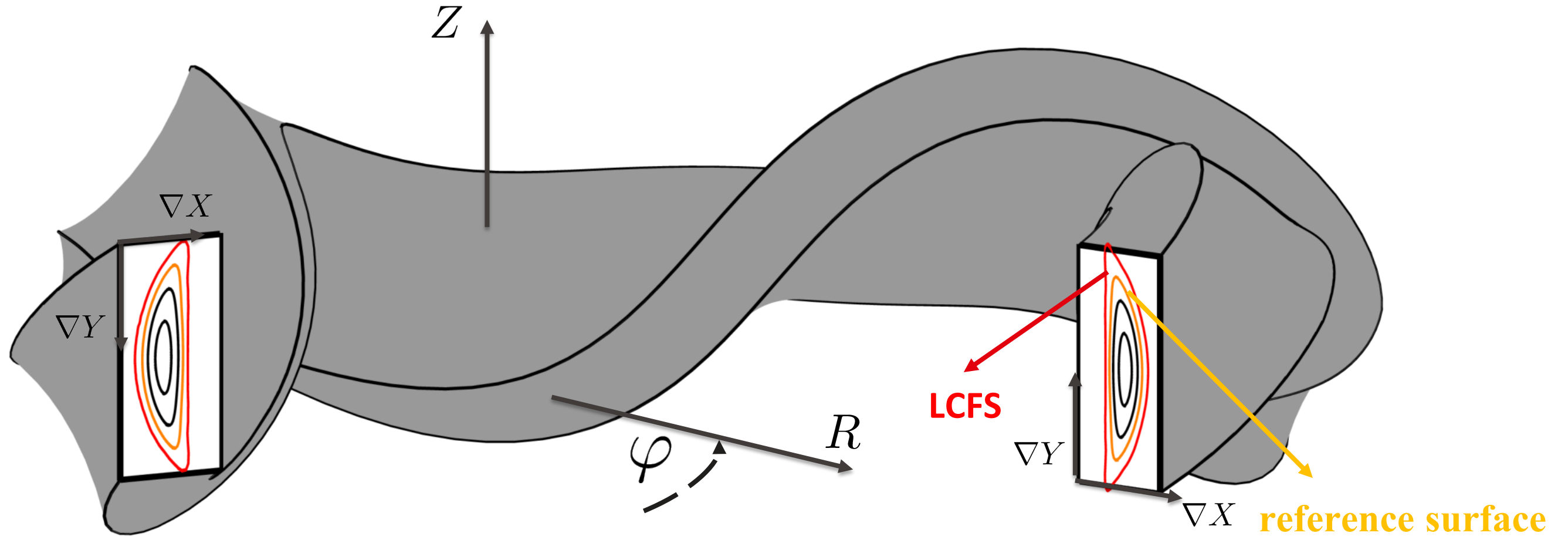
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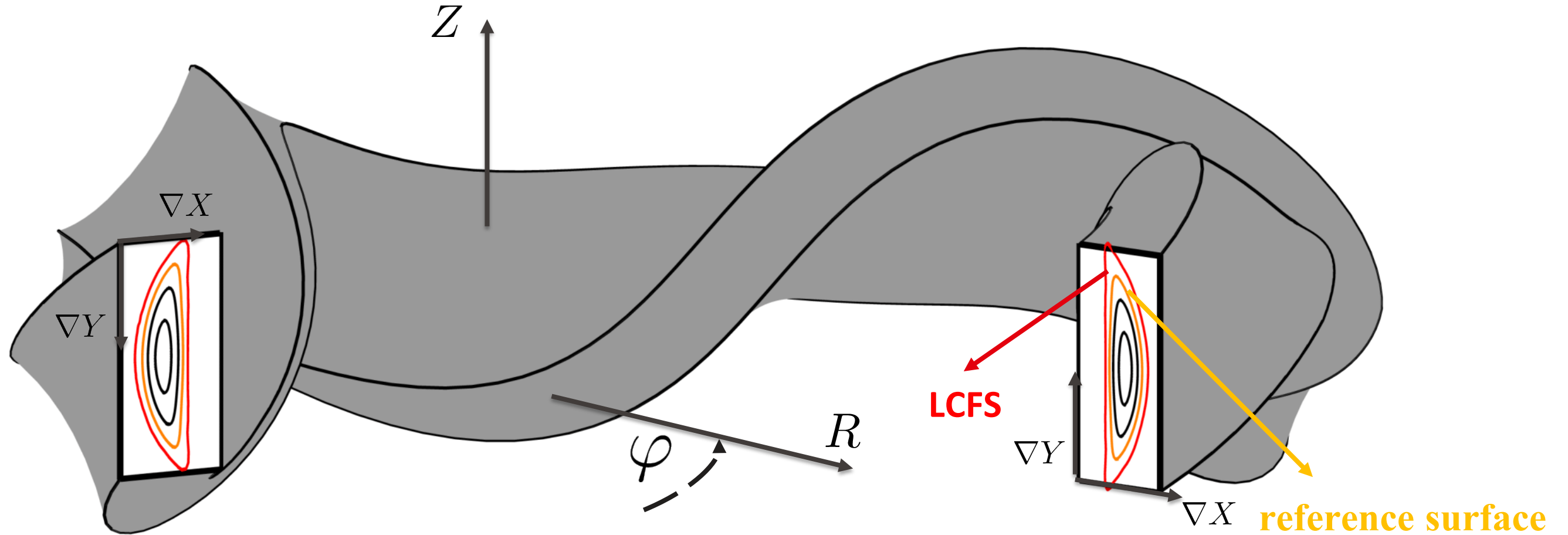
- Results extensively presented in Tecchioli, Z., et al. "Boundary turbulence simulations of the optimized HSX stellarator and comparison with experiments." *Nuclear Fusion* 66.7 (2026): 076051.



$$X = (R - R_c(\varphi)) \cos(\tau_b \varphi) + (Z - Z_c(\varphi)) \sin(\tau_b \varphi),$$

$$Y = -(R - R_c(\varphi)) \sin(\tau_b \varphi) + (Z - Z_c(\varphi)) \cos(\tau_b \varphi)$$

φ toroidal angle

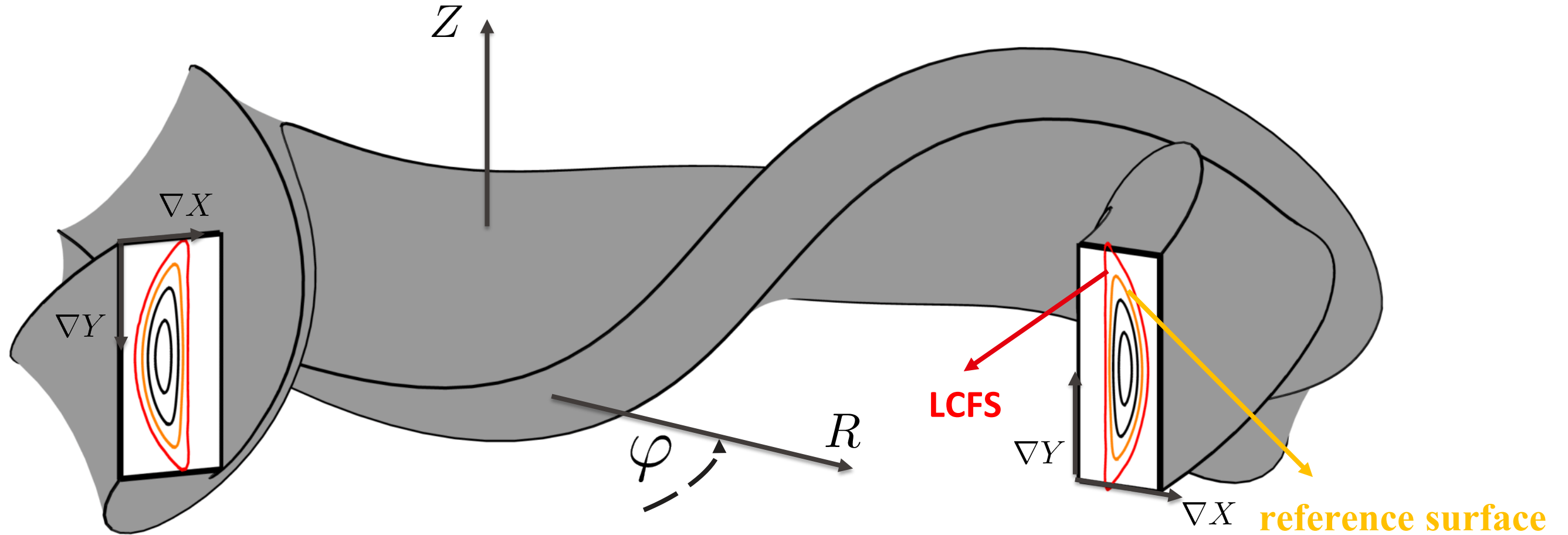


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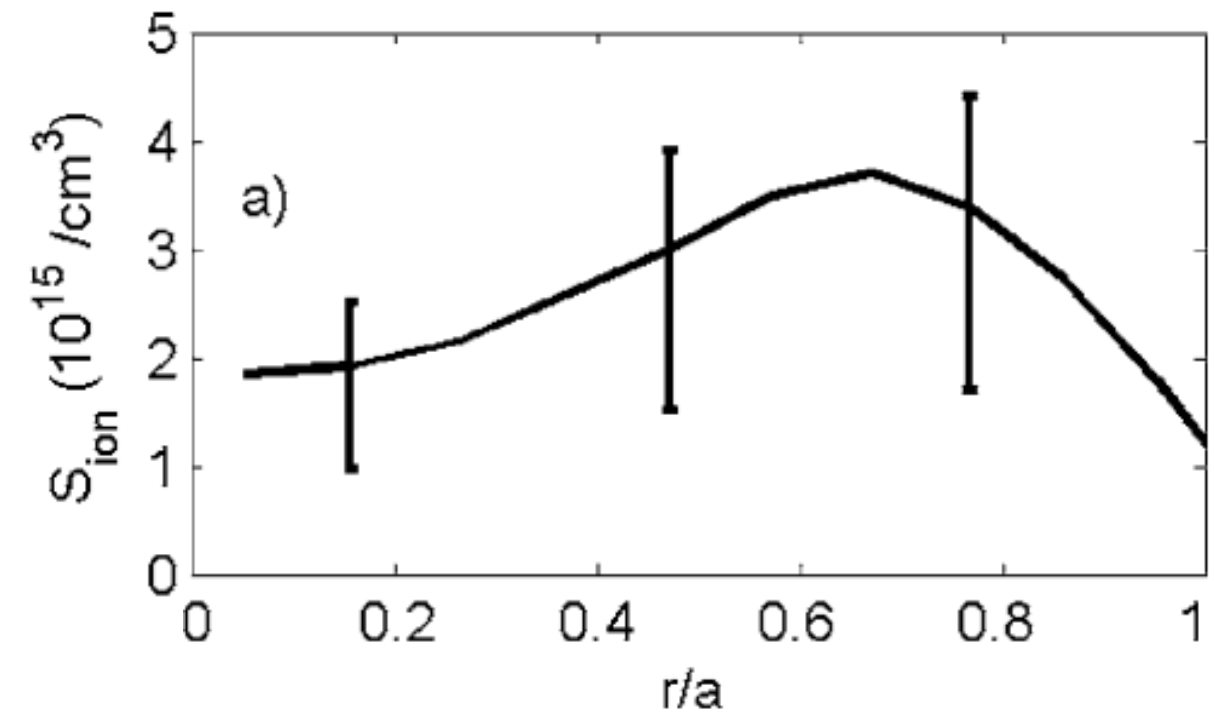
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- **Limited Configuration**

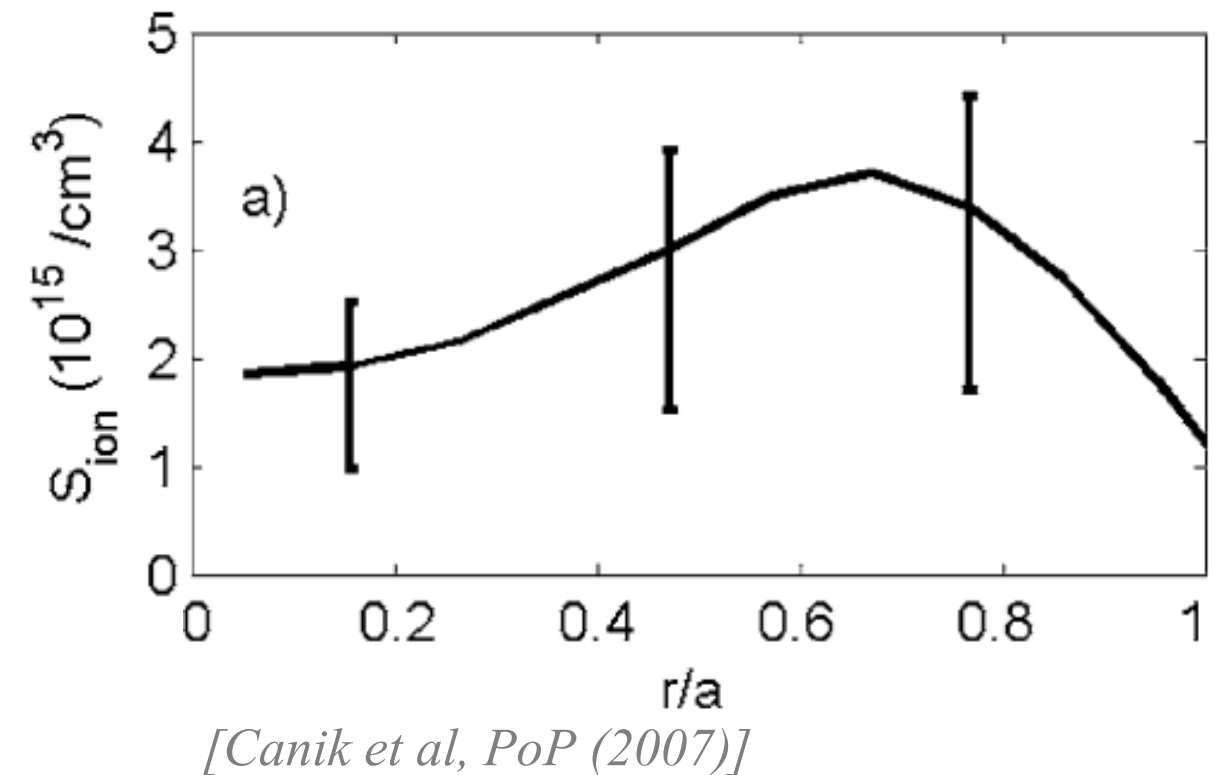
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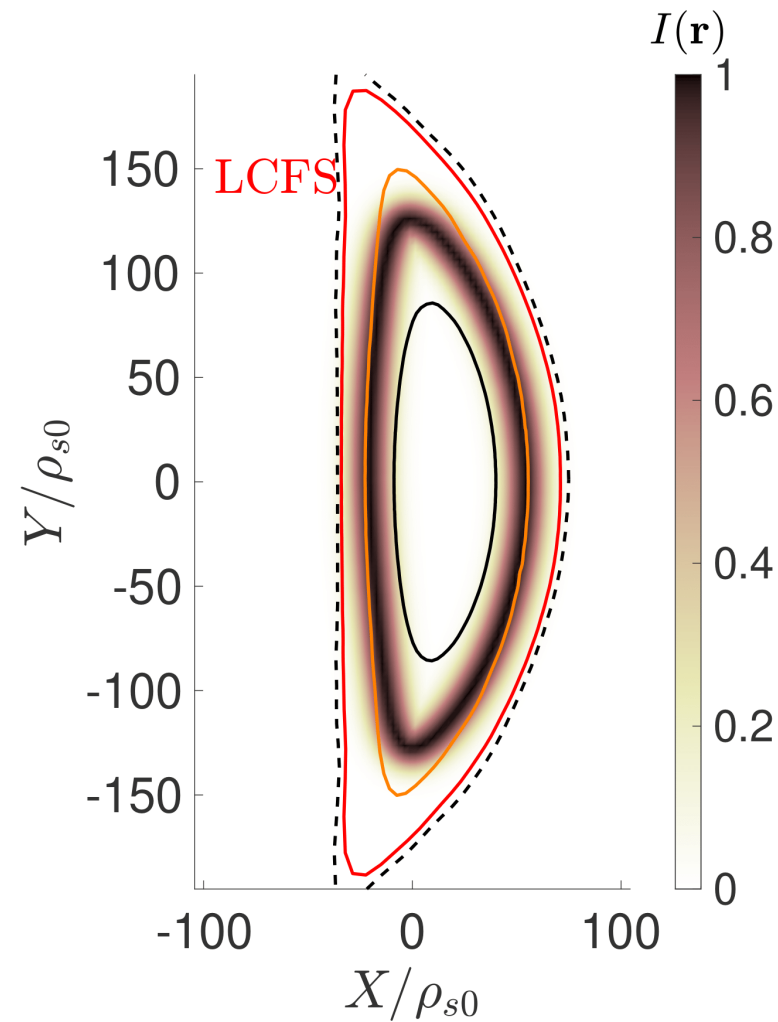


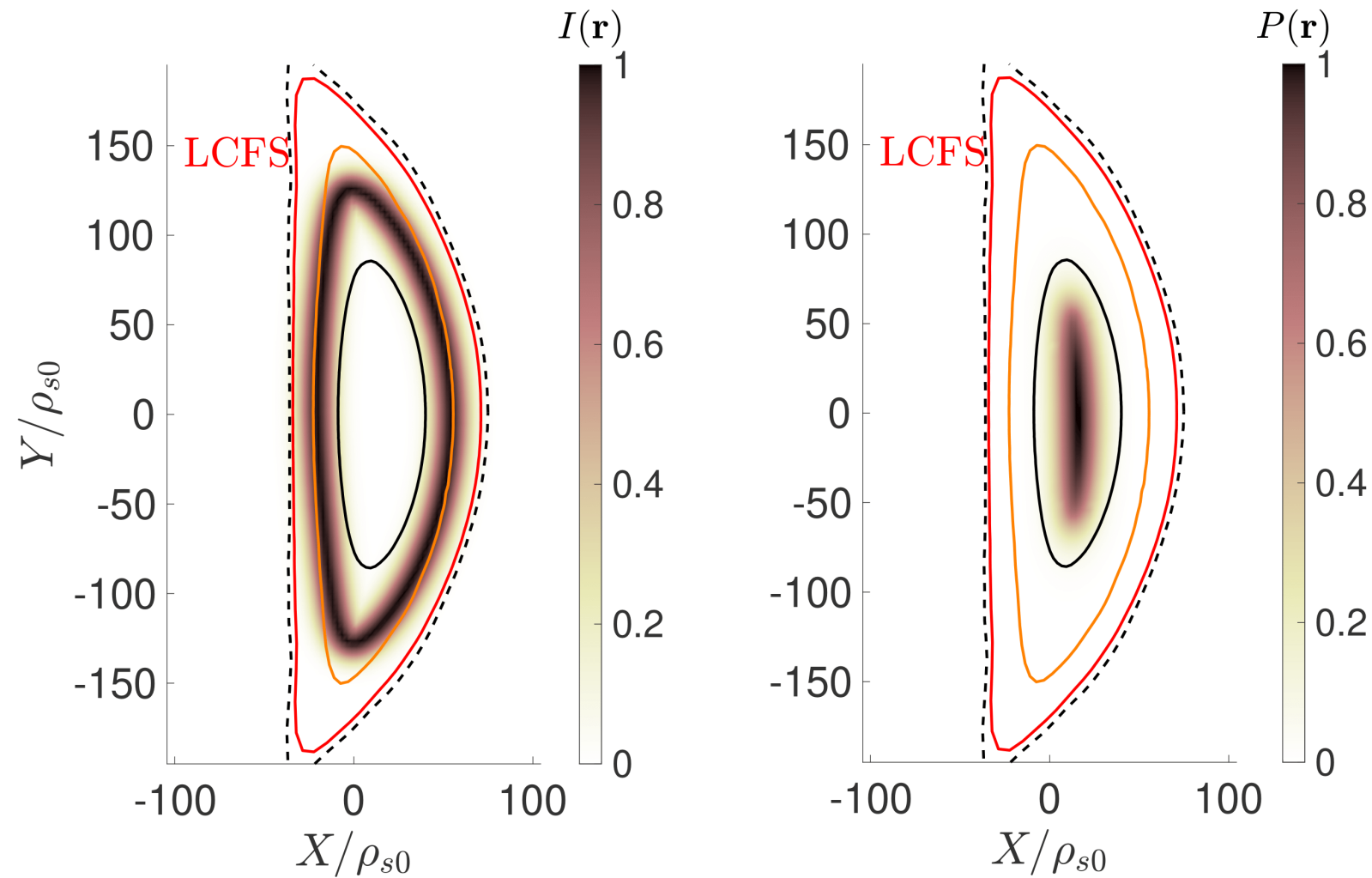
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- From the relatively small machine size and lower temperatures, **neutrals are present in the HSX edge**
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- As first ever turbulent simulation of HSX boundary, **we do not evolve neutrals, yet we consider experimentally relevant ionization sources** [*Canik et al, PoP (2007)*]

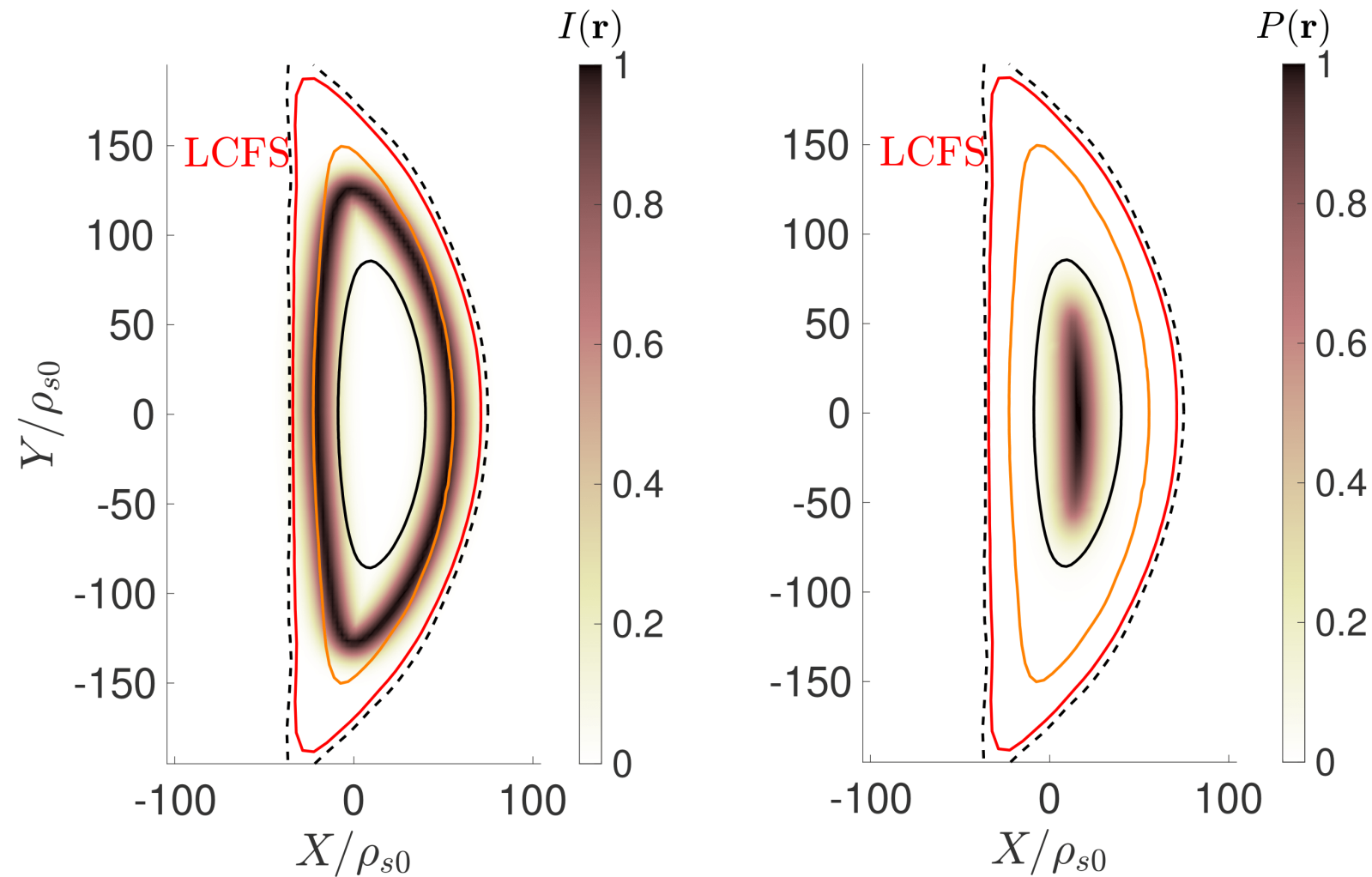


- **Flux-aligned density source $I(\mathbf{r})$**
to model neutral ionization [Canik et al,
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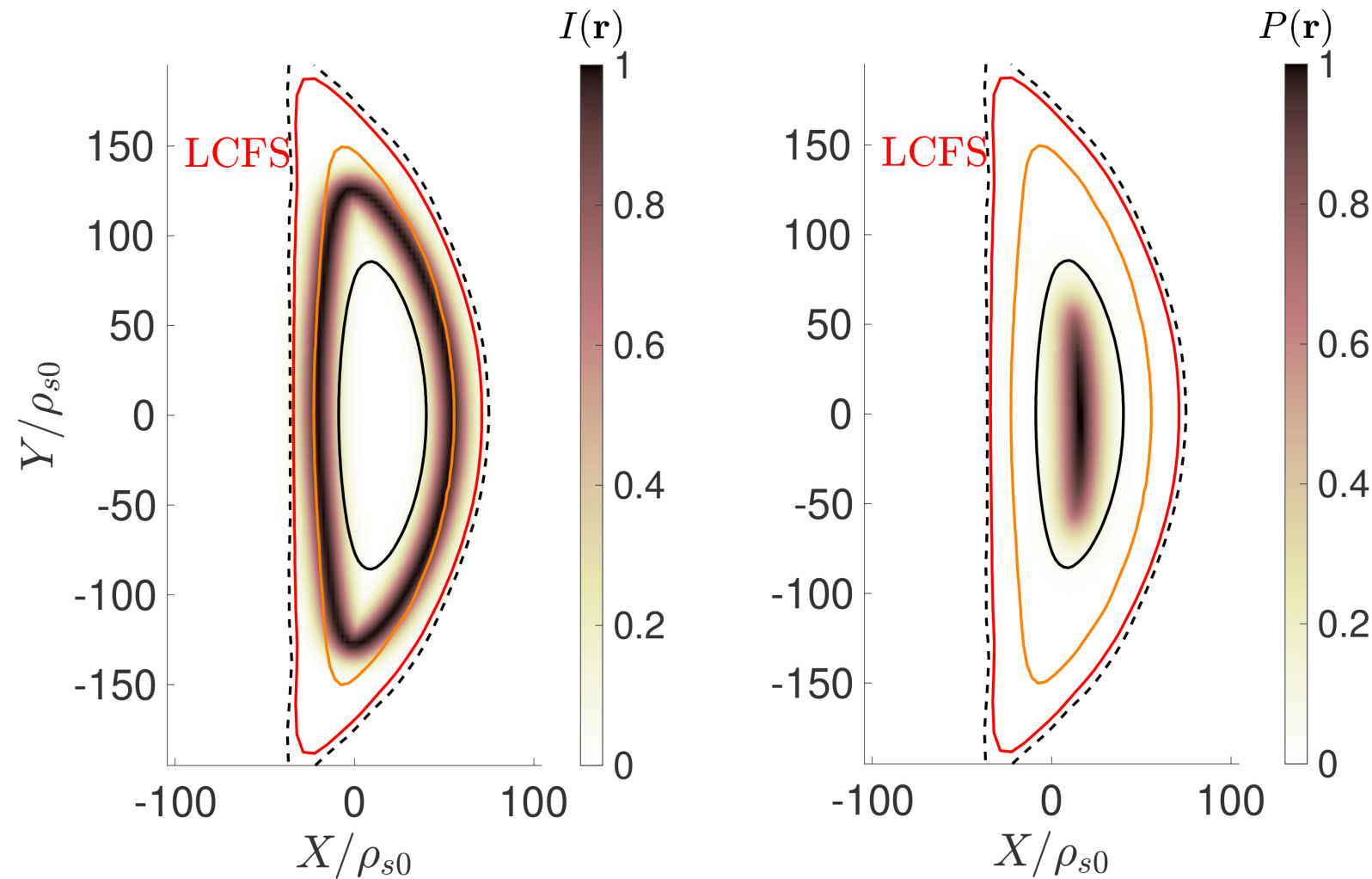




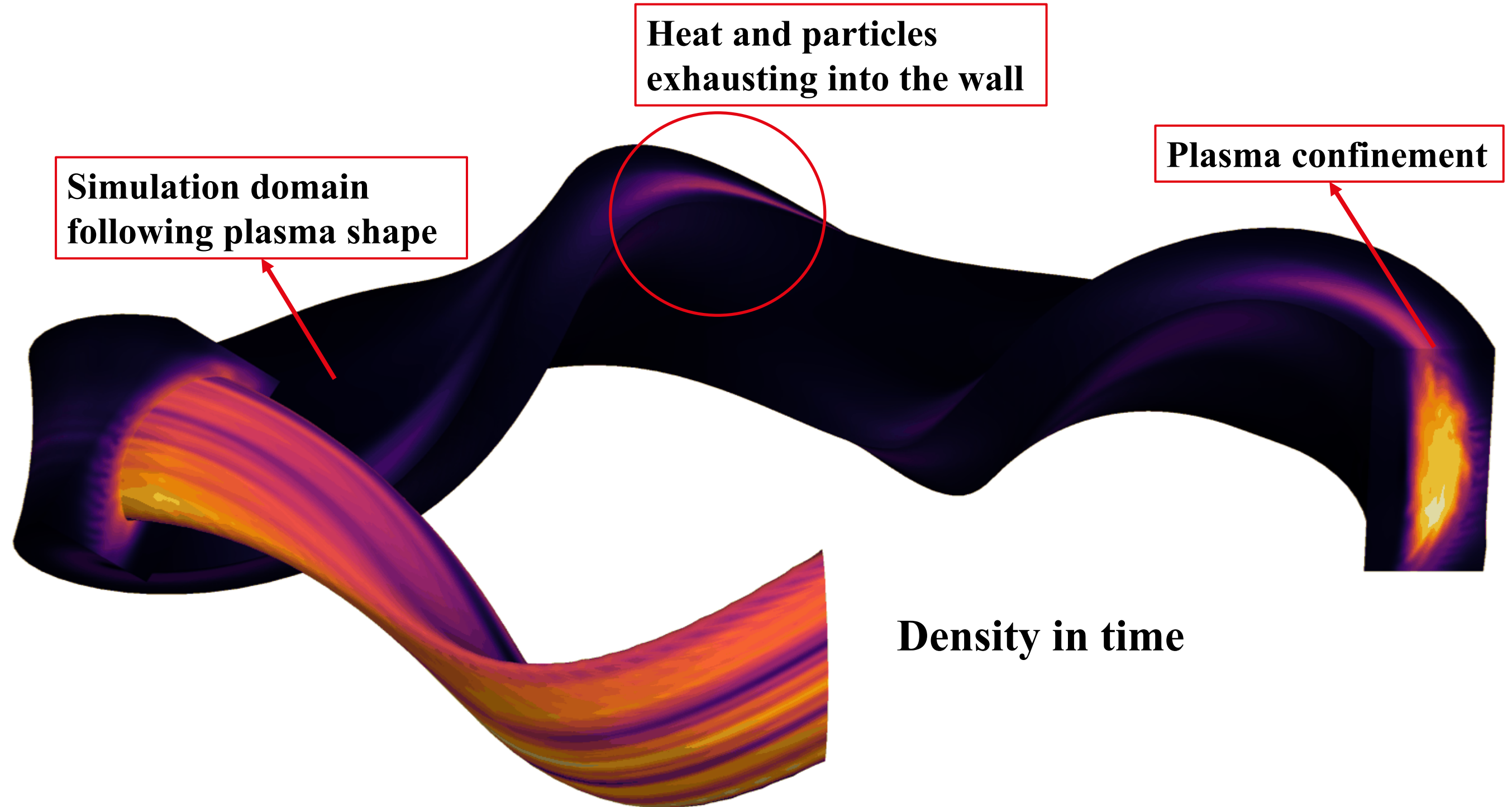
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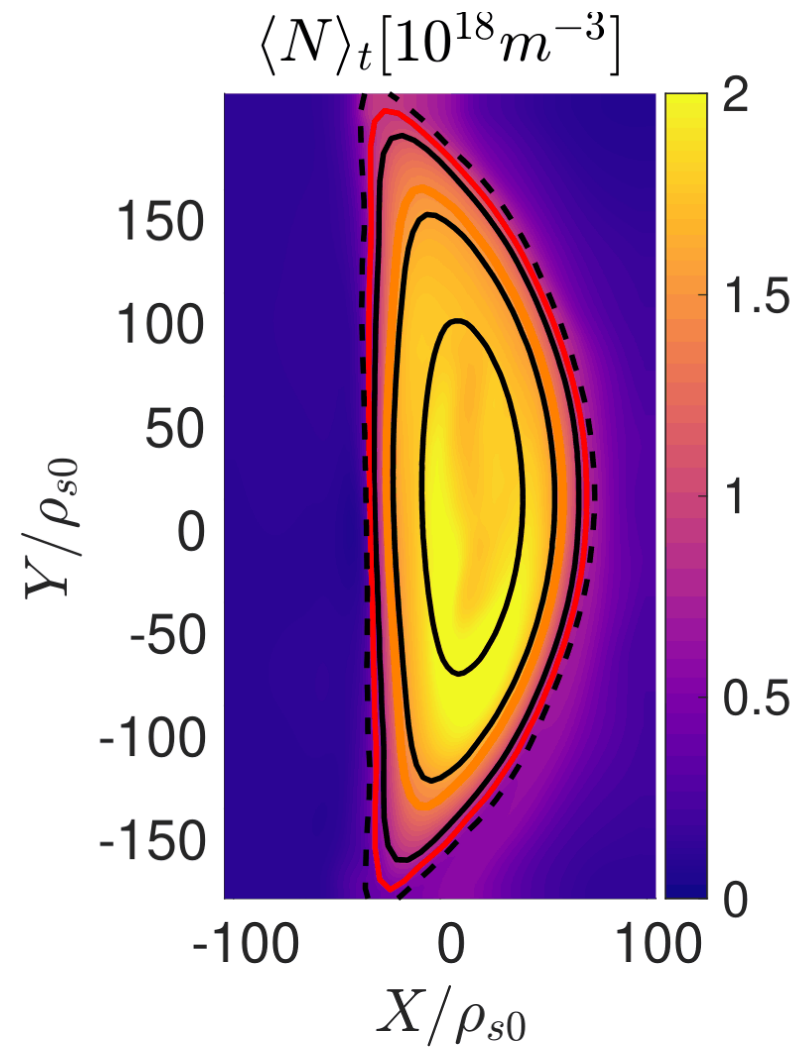


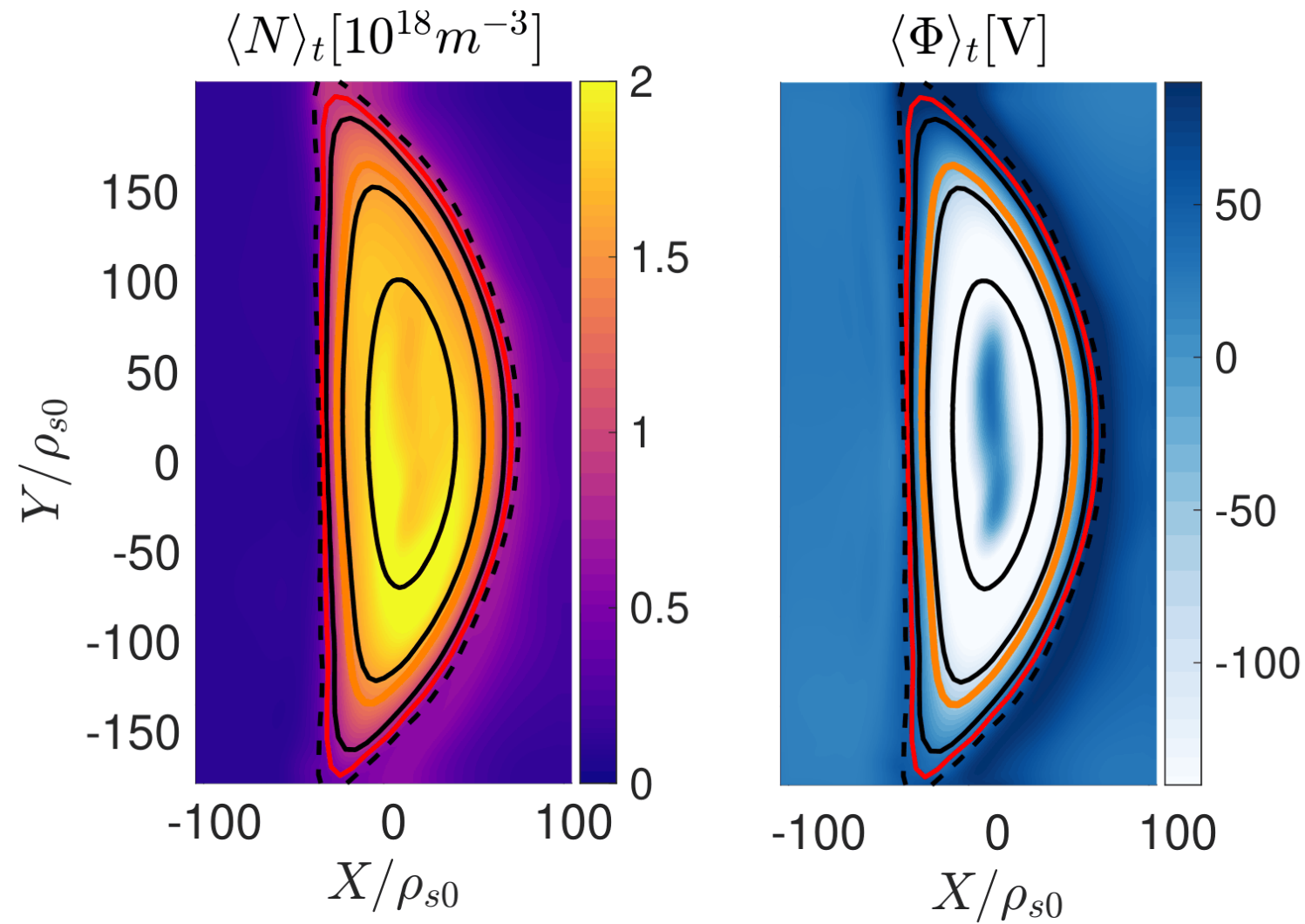
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- **Ions not directly heated** but energy transferred via **collisions**
 $2.61\nu(T_e - \tau T_i)N$



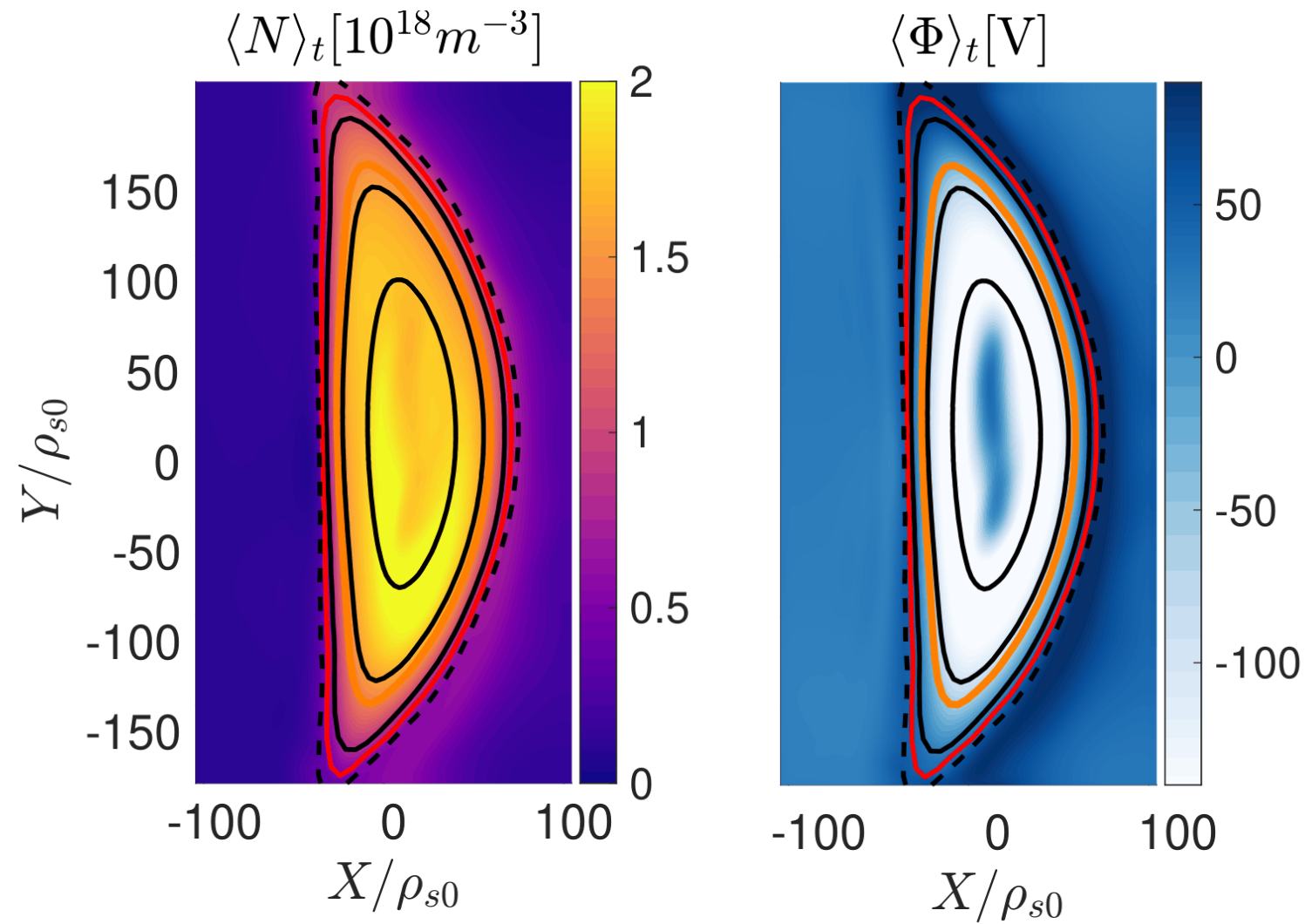
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- **Peak sources profiles controlled**
such that $N \approx N_0$ $T_e \approx T_{e0}$



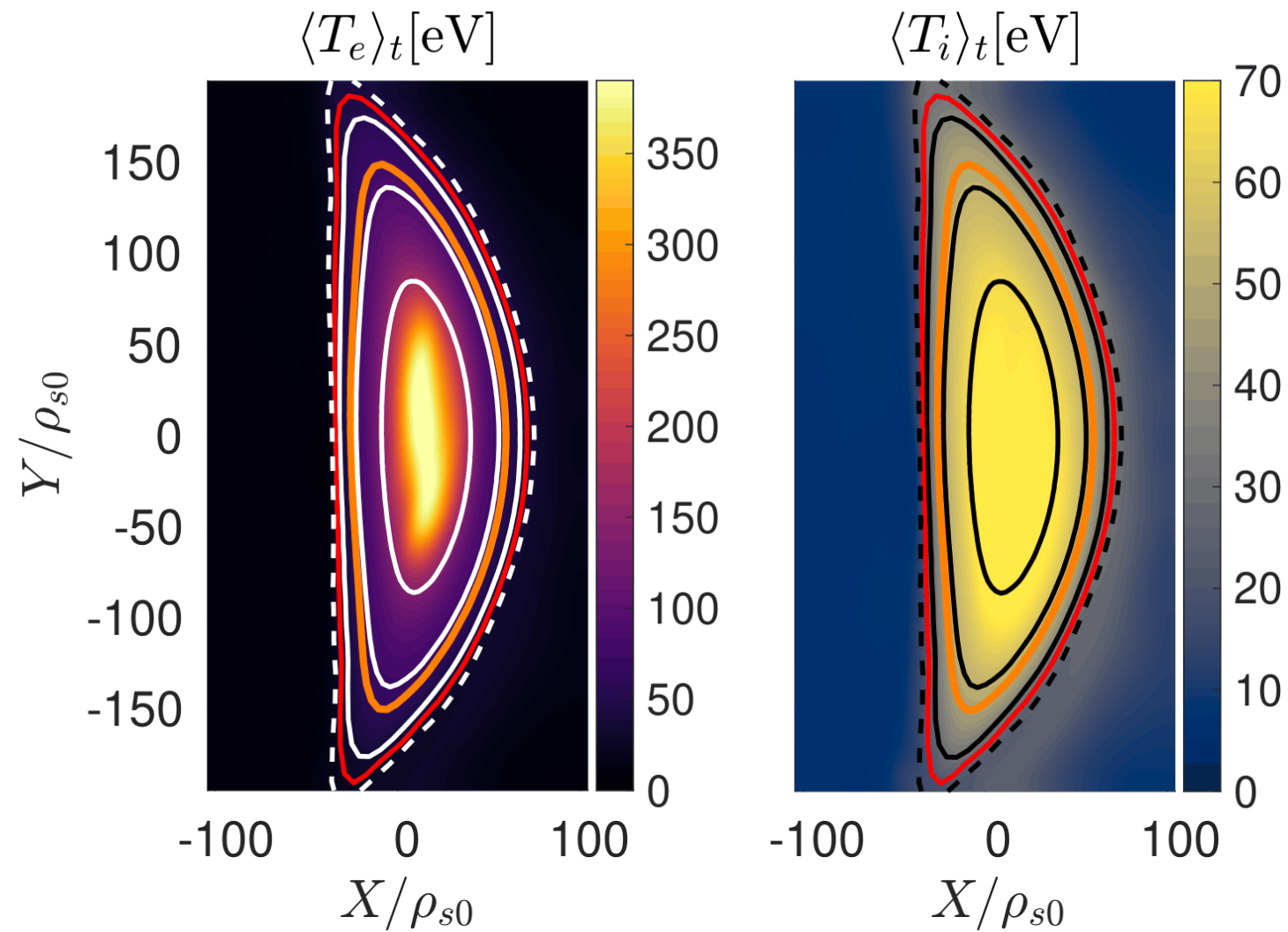




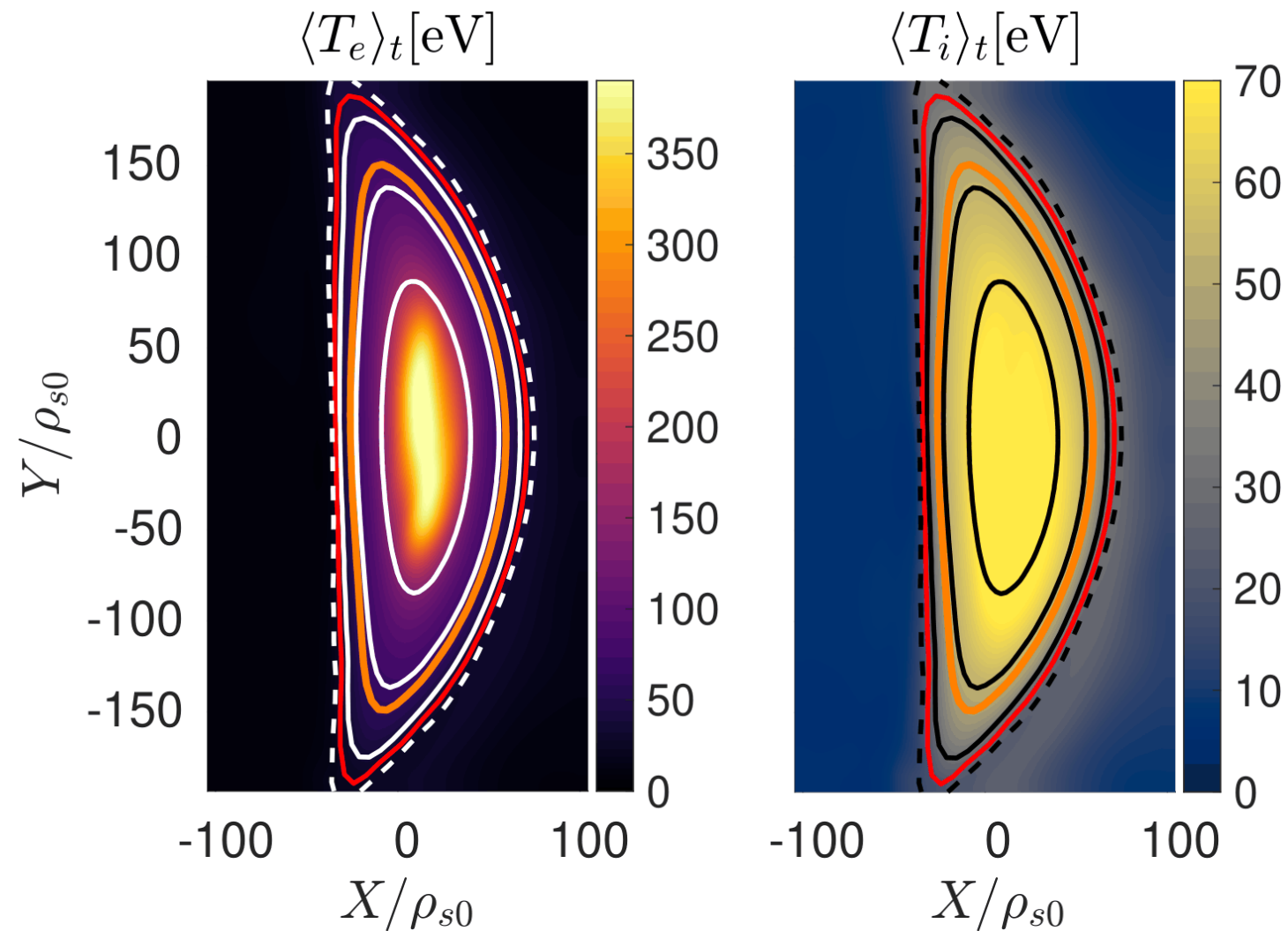
- **Negative radial electric field in the confined region $E_r \sim \partial_r P$**



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- **Positive radial electric field in the SOL with $\Phi \sim \lambda T_e$ and $\lambda \sim 3$**

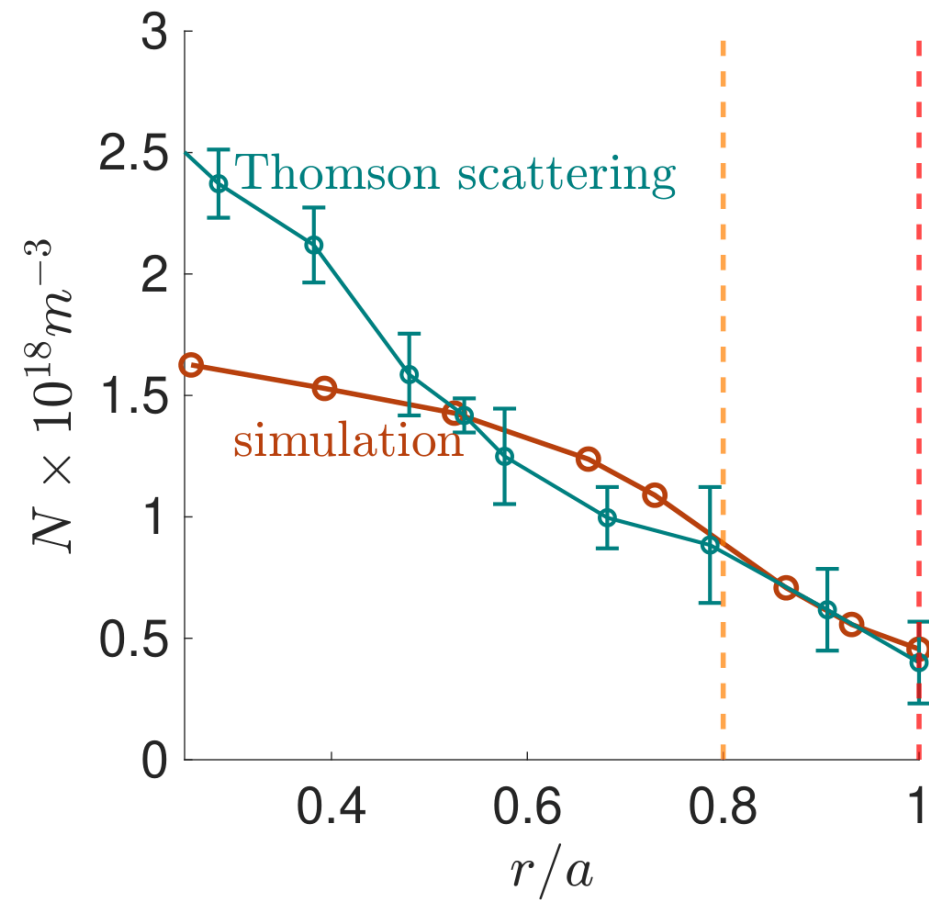


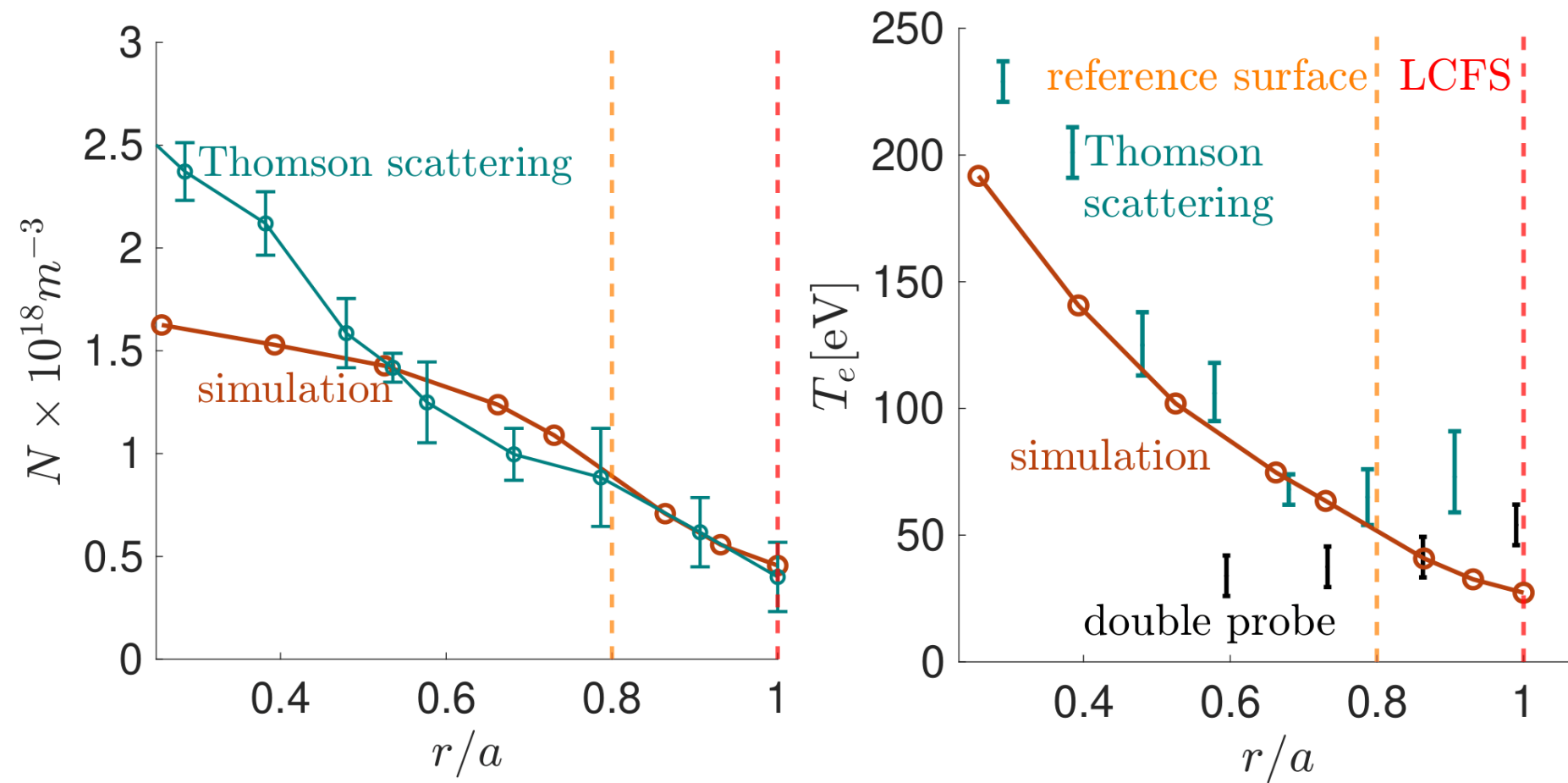
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- Small ion temperature gradient compared to electron one.

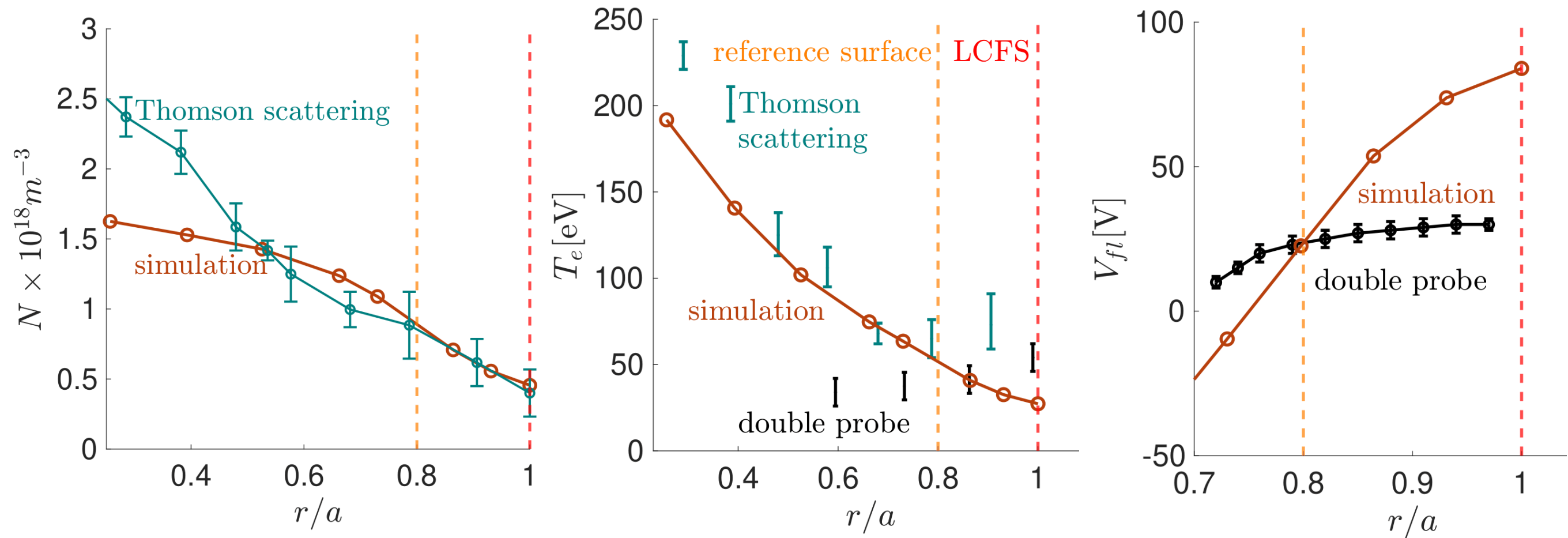


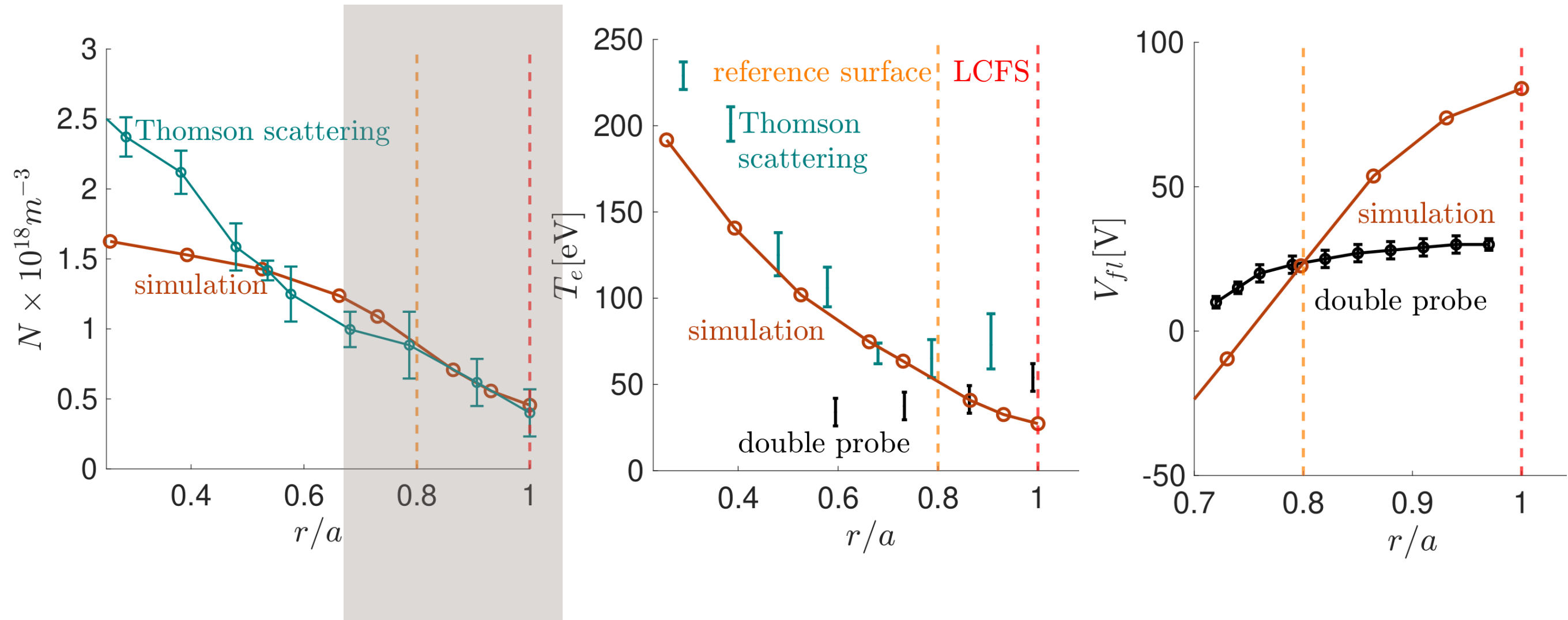
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Are these time-averaged profiles consistent with experiments?

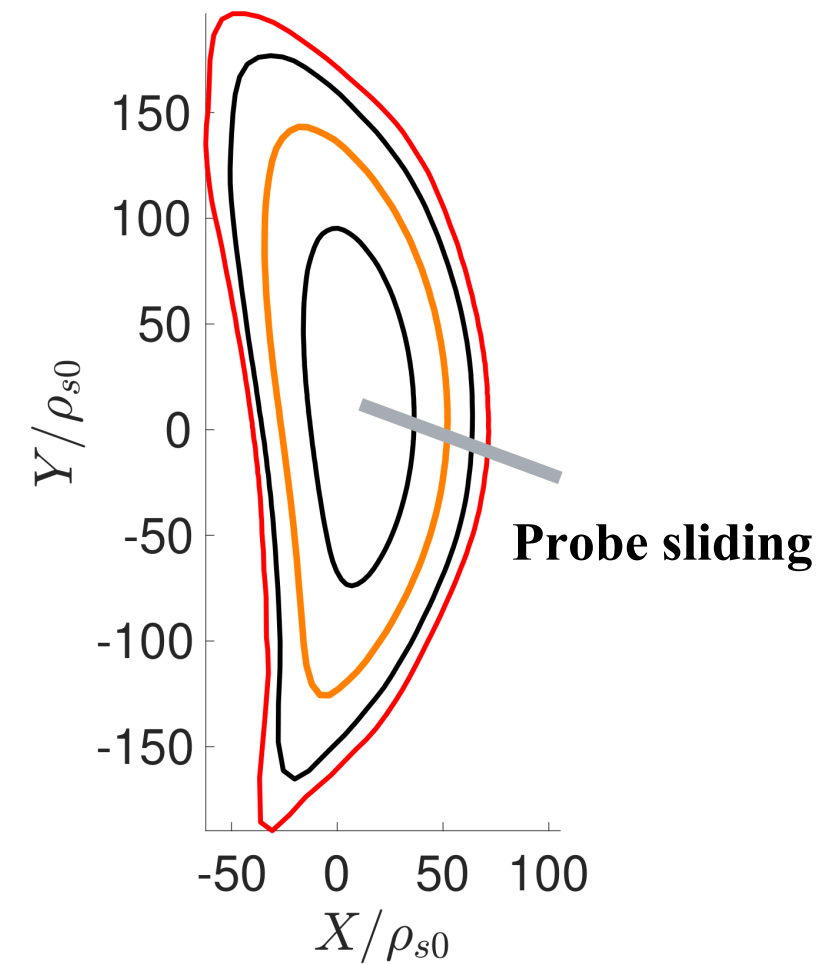


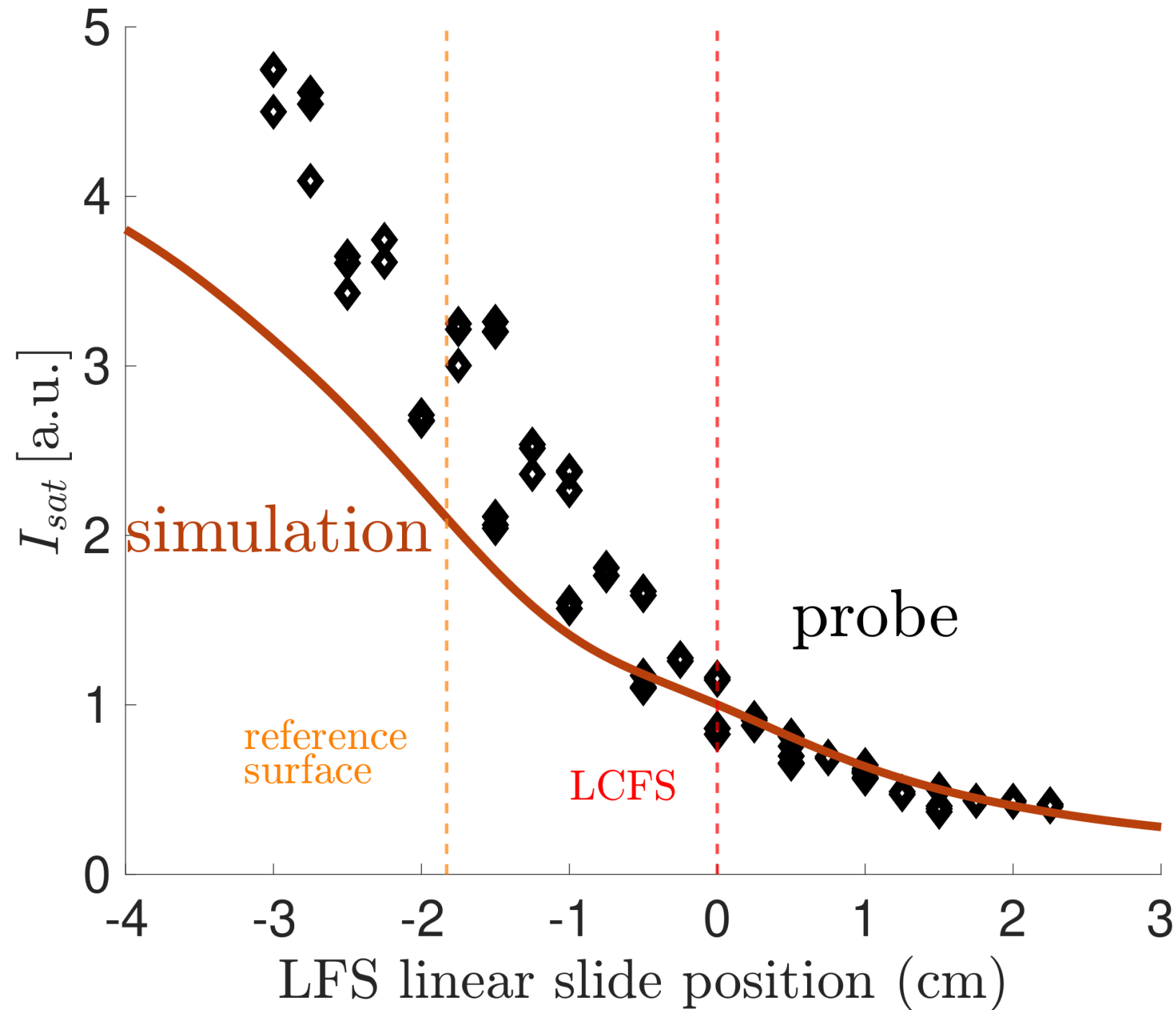




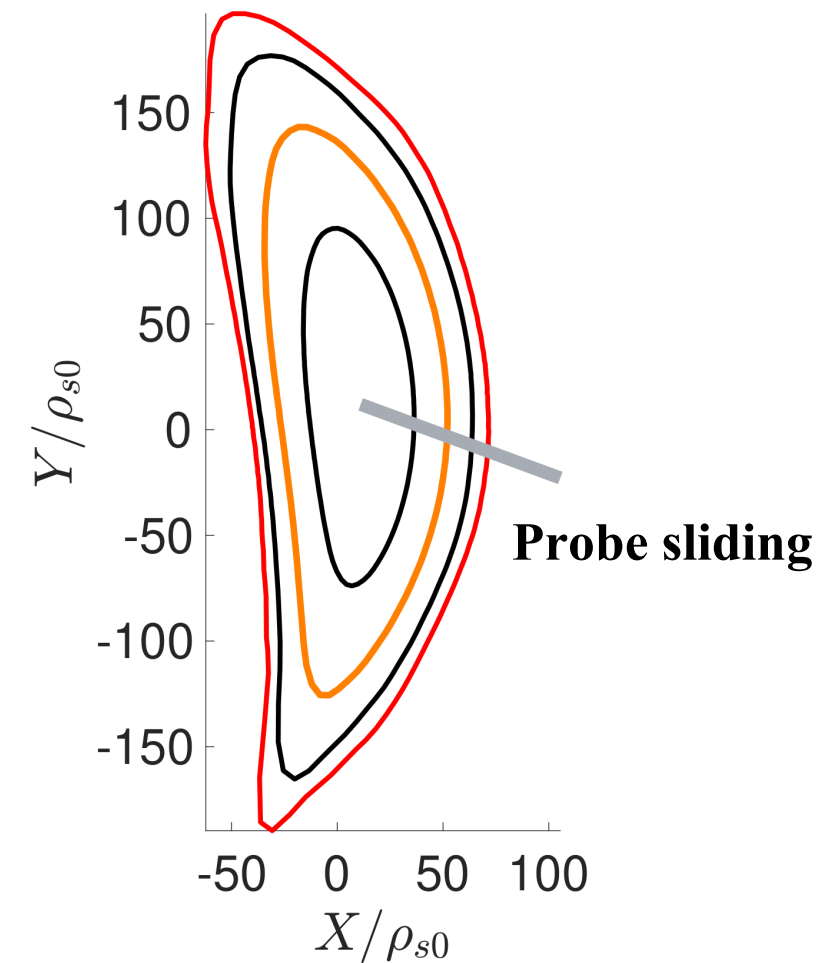


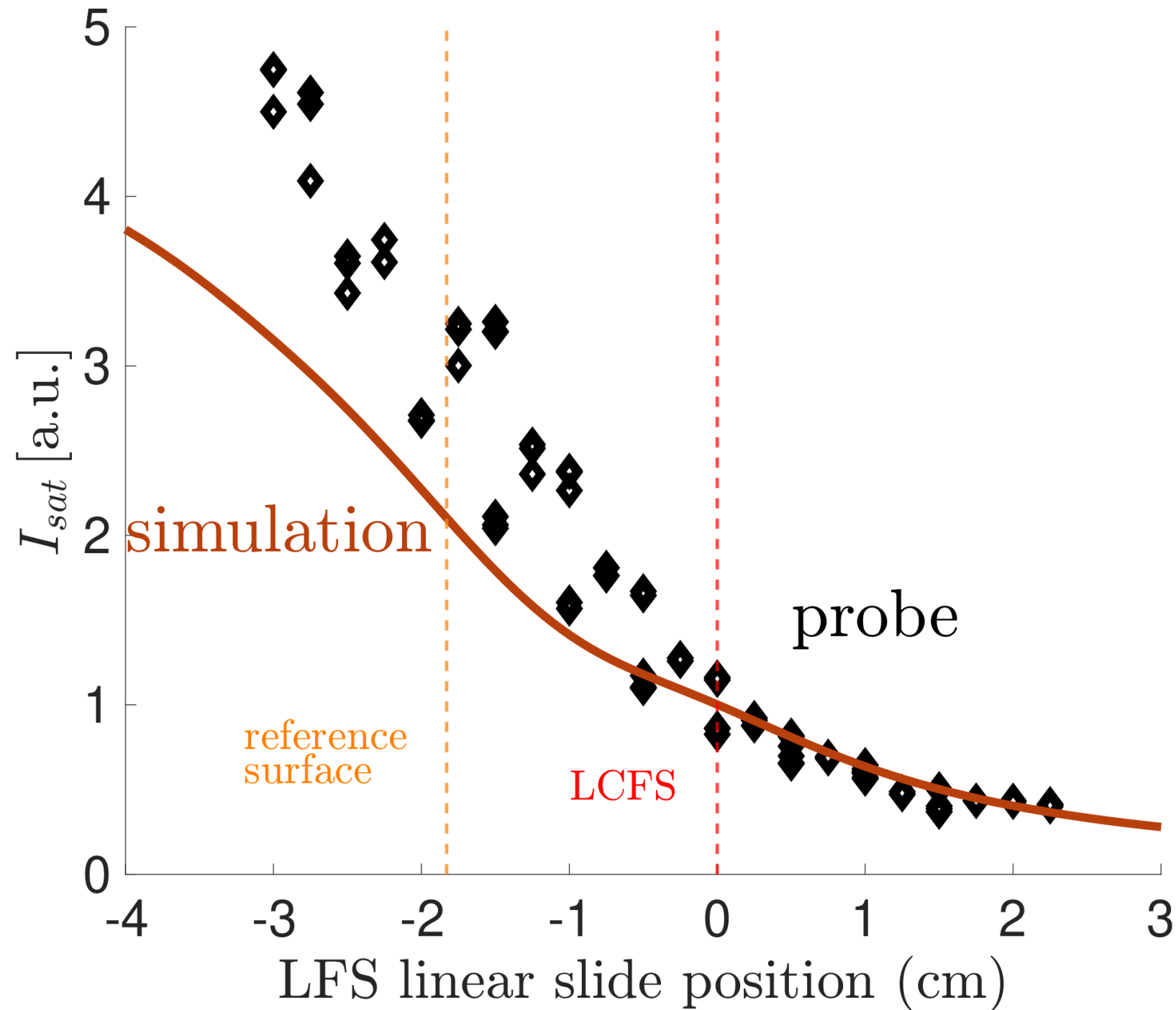
Closer look at the **edge region** using probe measurements





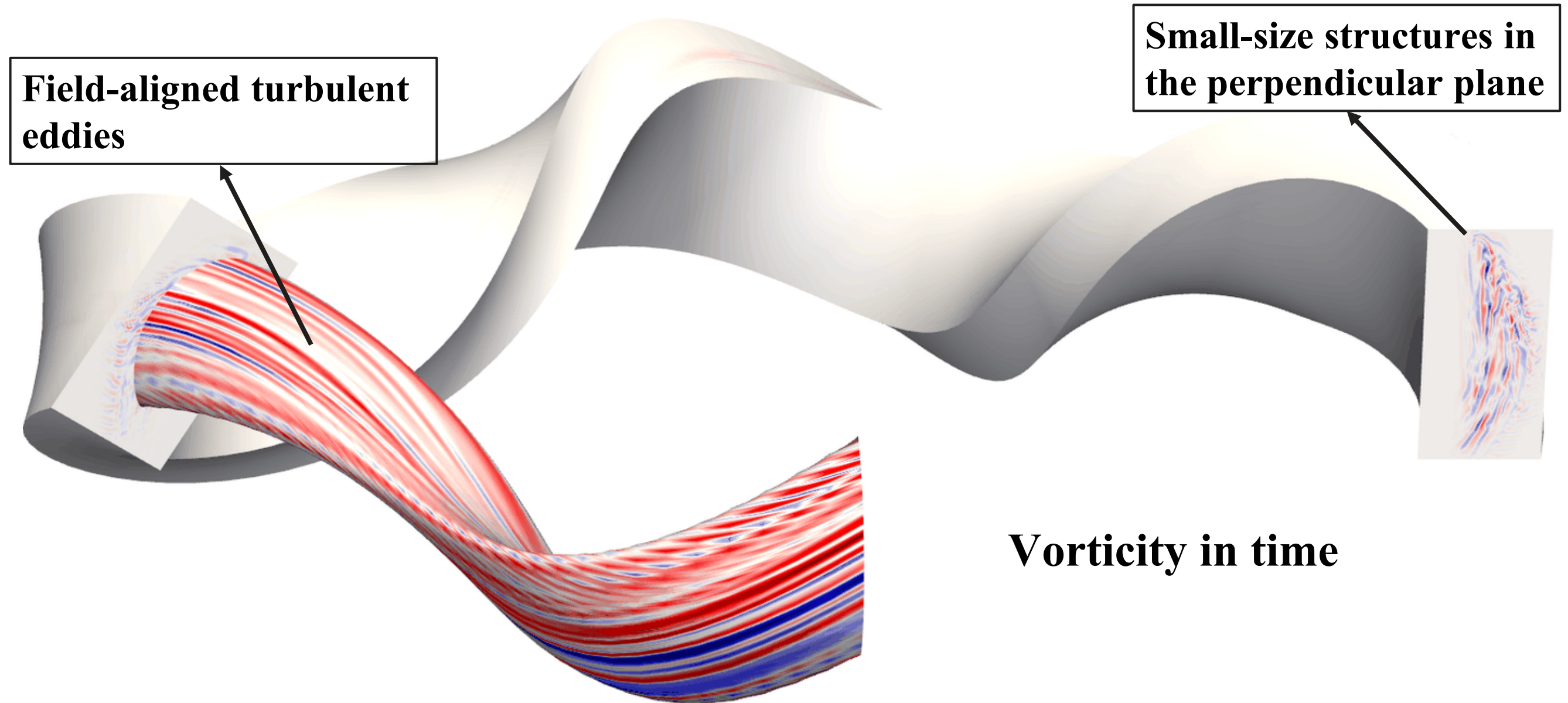
- Scaling length in the SOL ~ 2 cm



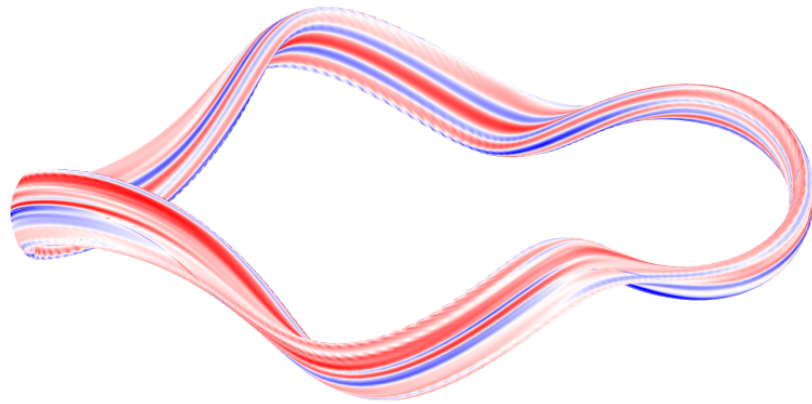


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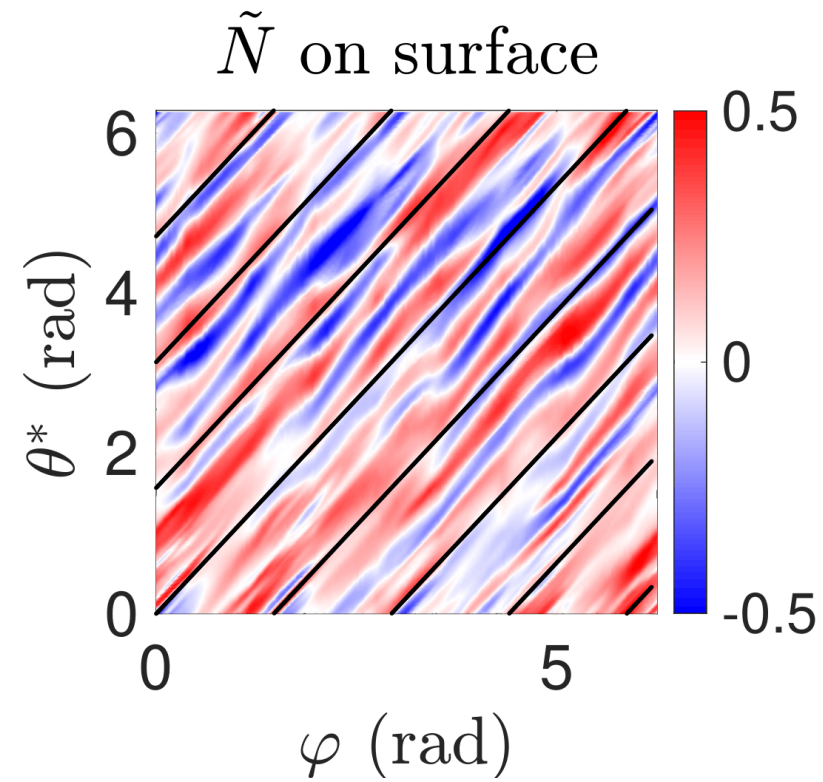
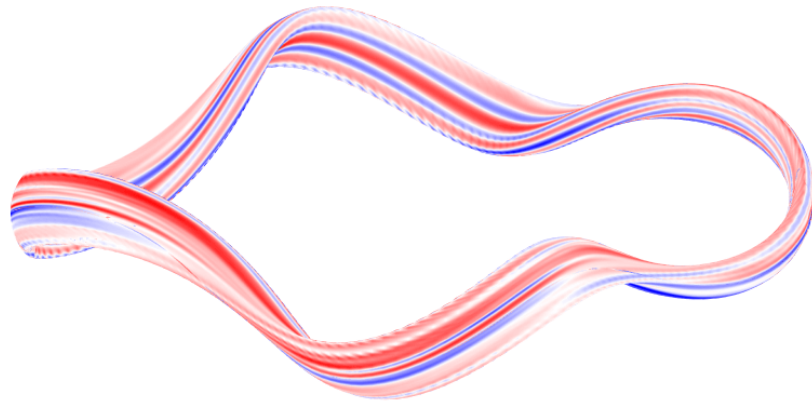
What about the nature and properties of fluctuations?



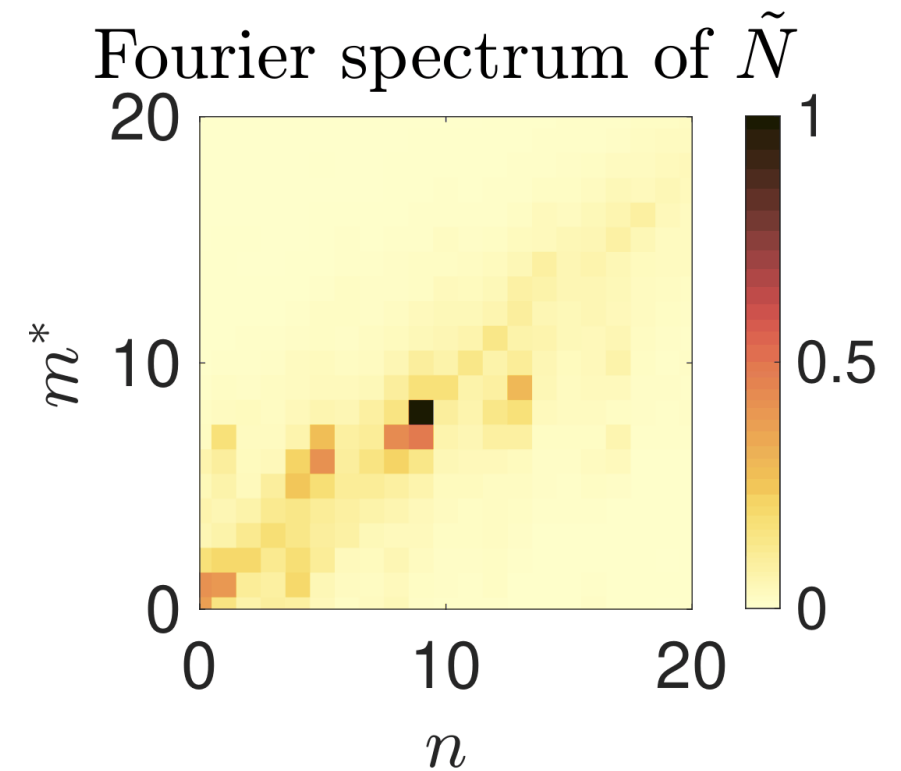
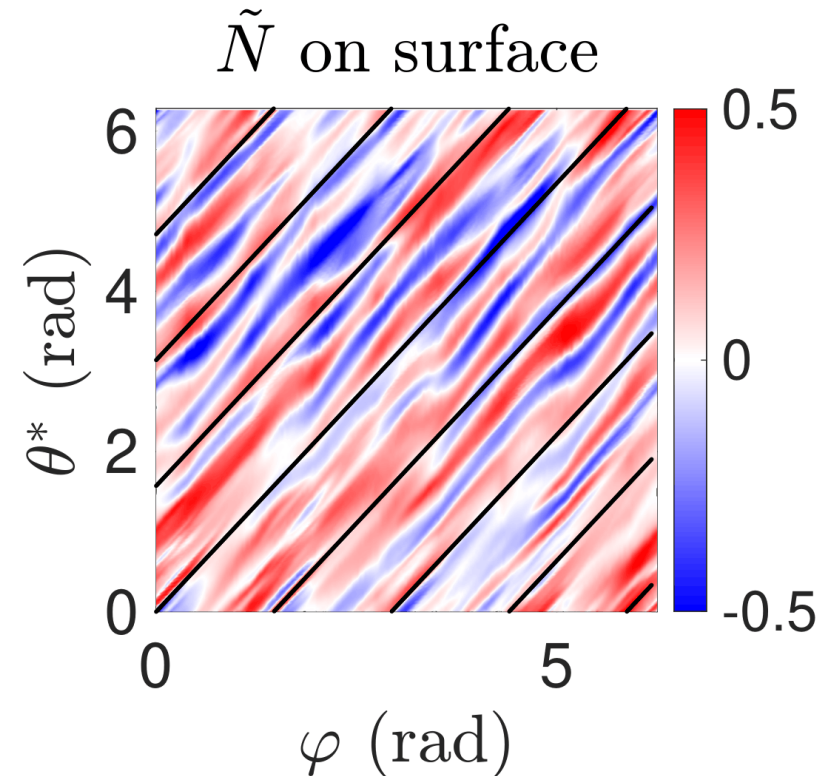
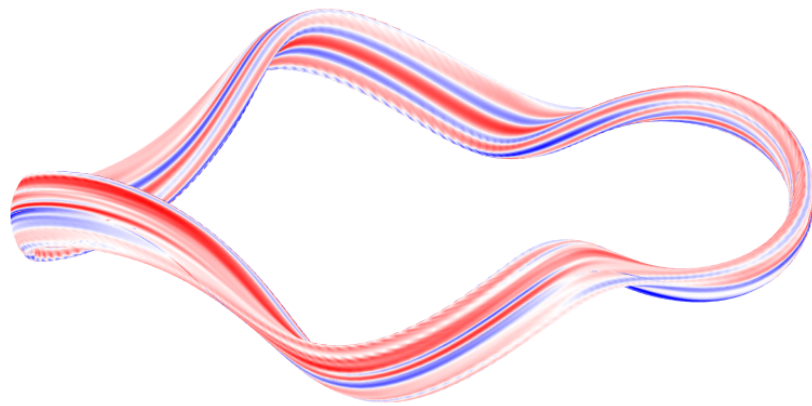
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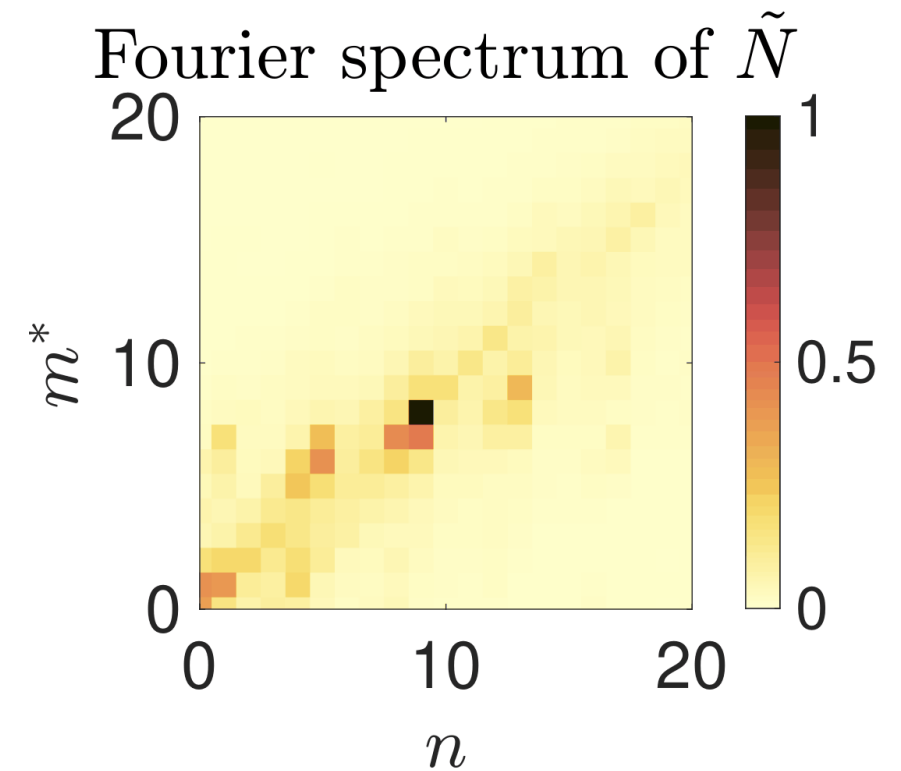
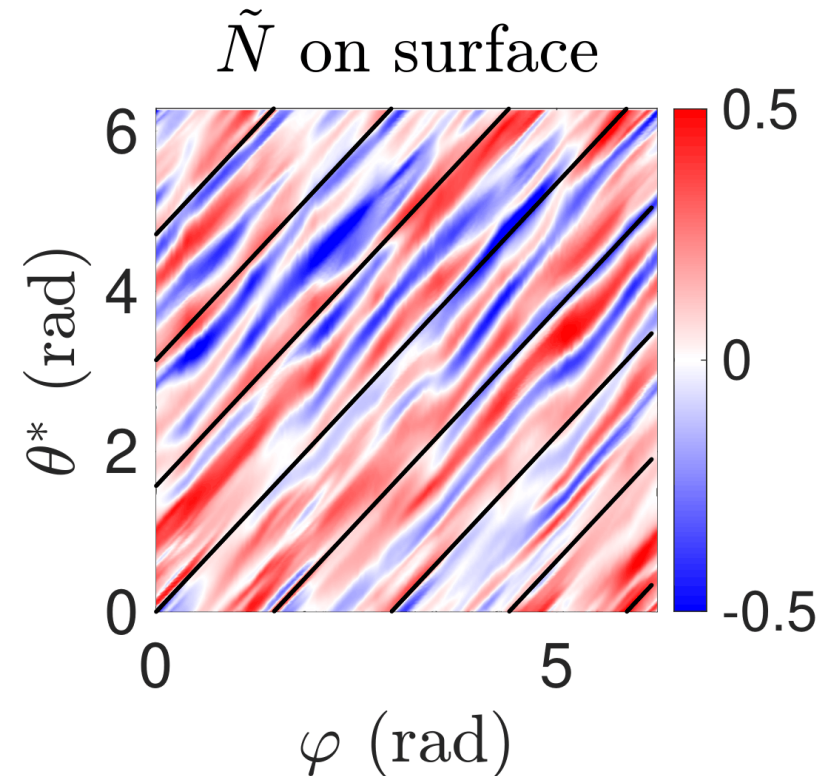
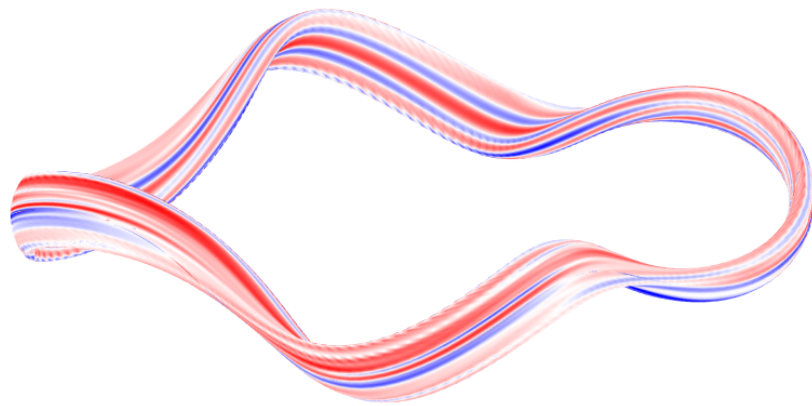


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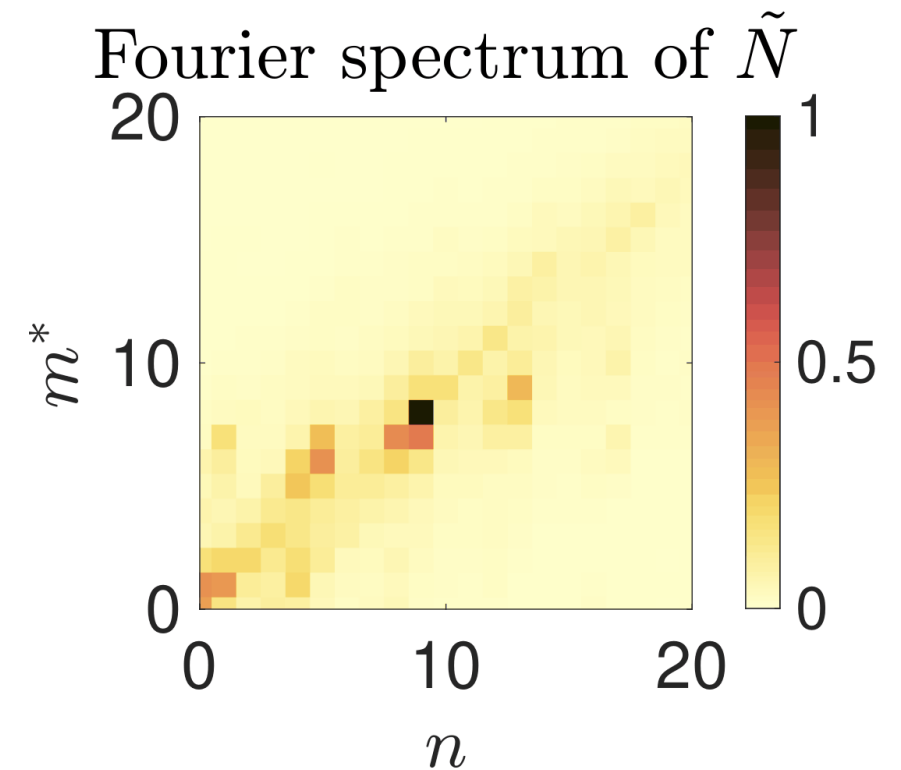
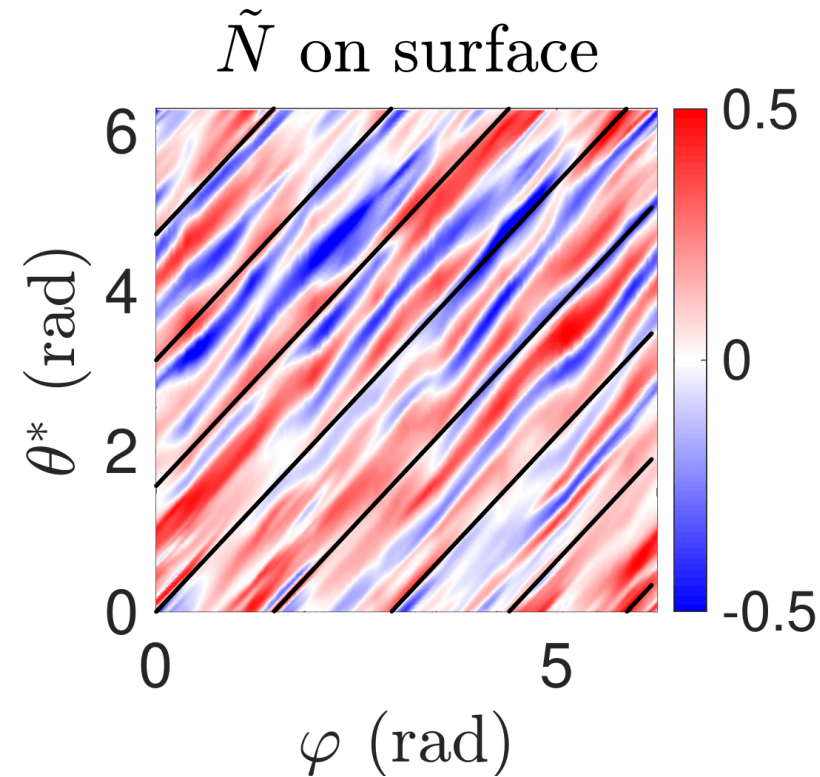
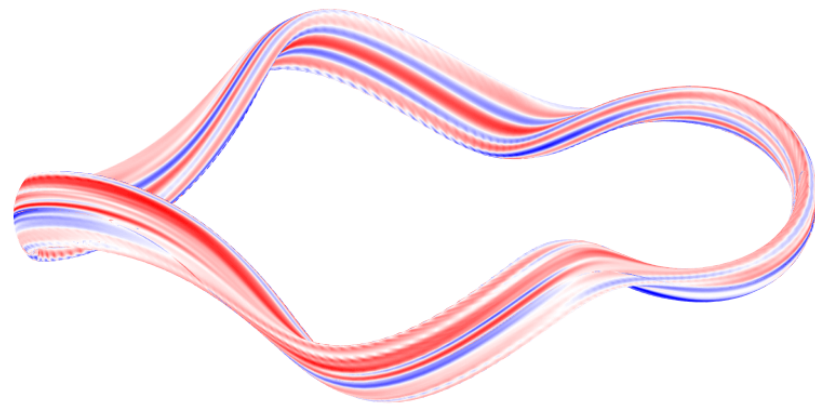
- **Turbulence is minimizing** $k_{\parallel} \sim n - \iota m$ with $\iota = 1.06$ and dominant $(n, m) = (9, 8)$
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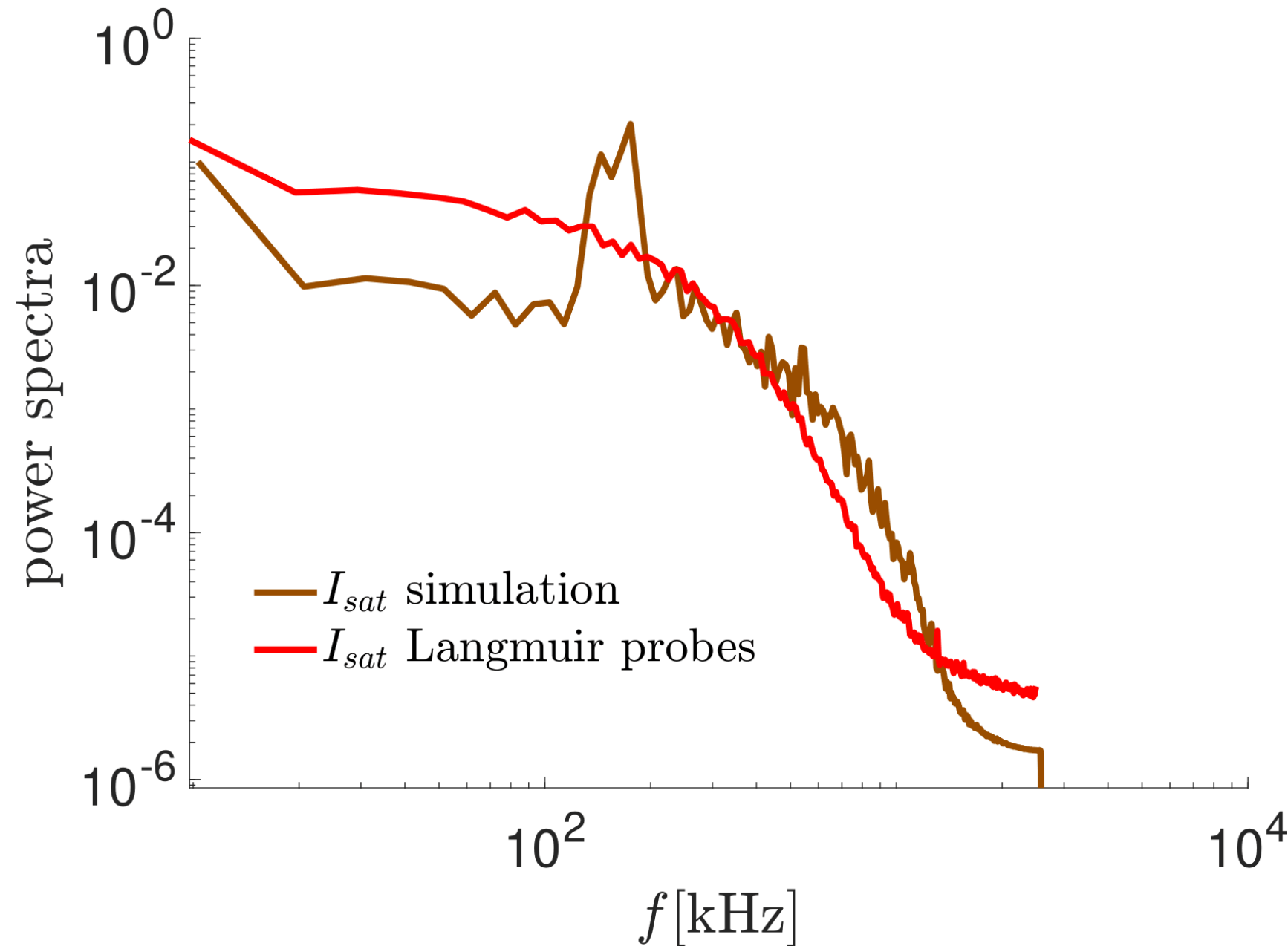
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- **Turbulence driven by pressure-driven curvature instability, consistent with a quasi-linear theory** by T. Rafiq et al (PoP 2010)

$$\tilde{N} = N - \langle N \rangle_t$$

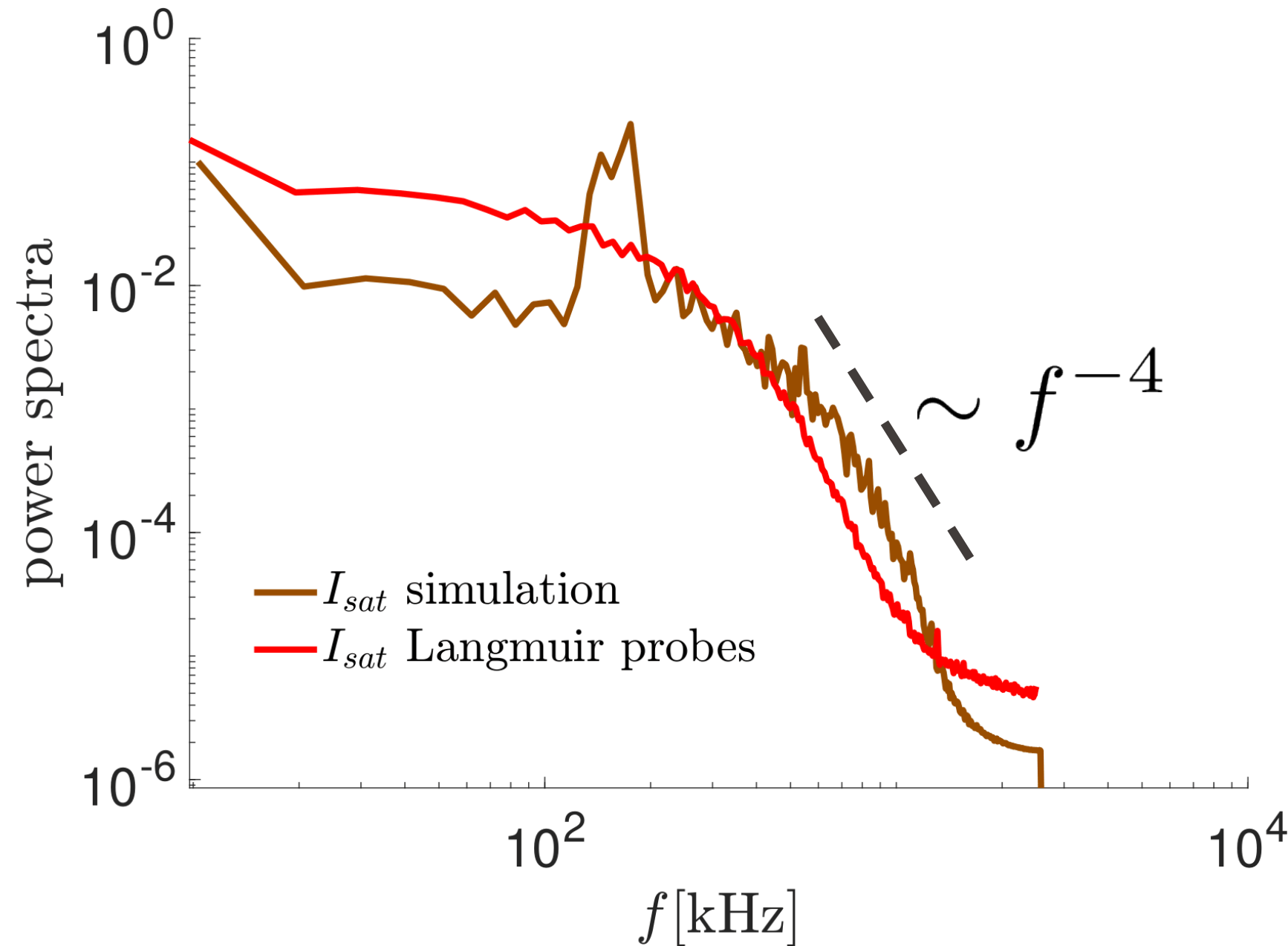


- **Turbulence is minimizing** $k_{\parallel} \sim n - \iota m$ with $\iota = 1.06$ and dominant $(n, m) = (9, 8)$ breaking field periodicity
- **Turbulence driven by pressure-driven curvature instability, consistent with a quasi-linear theory** by T. Rafiq et al (PoP 2010)

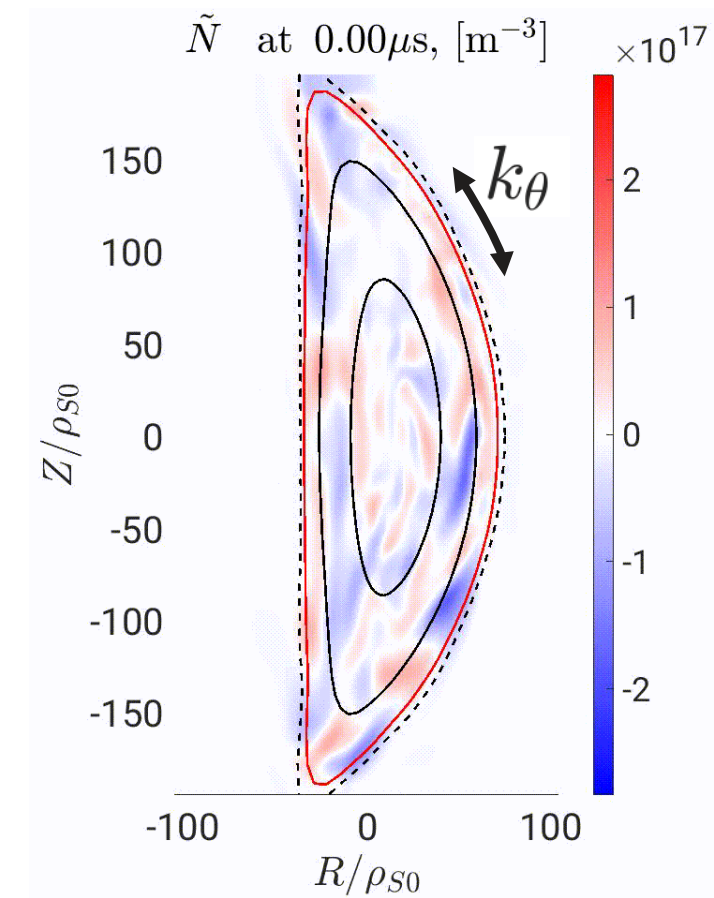
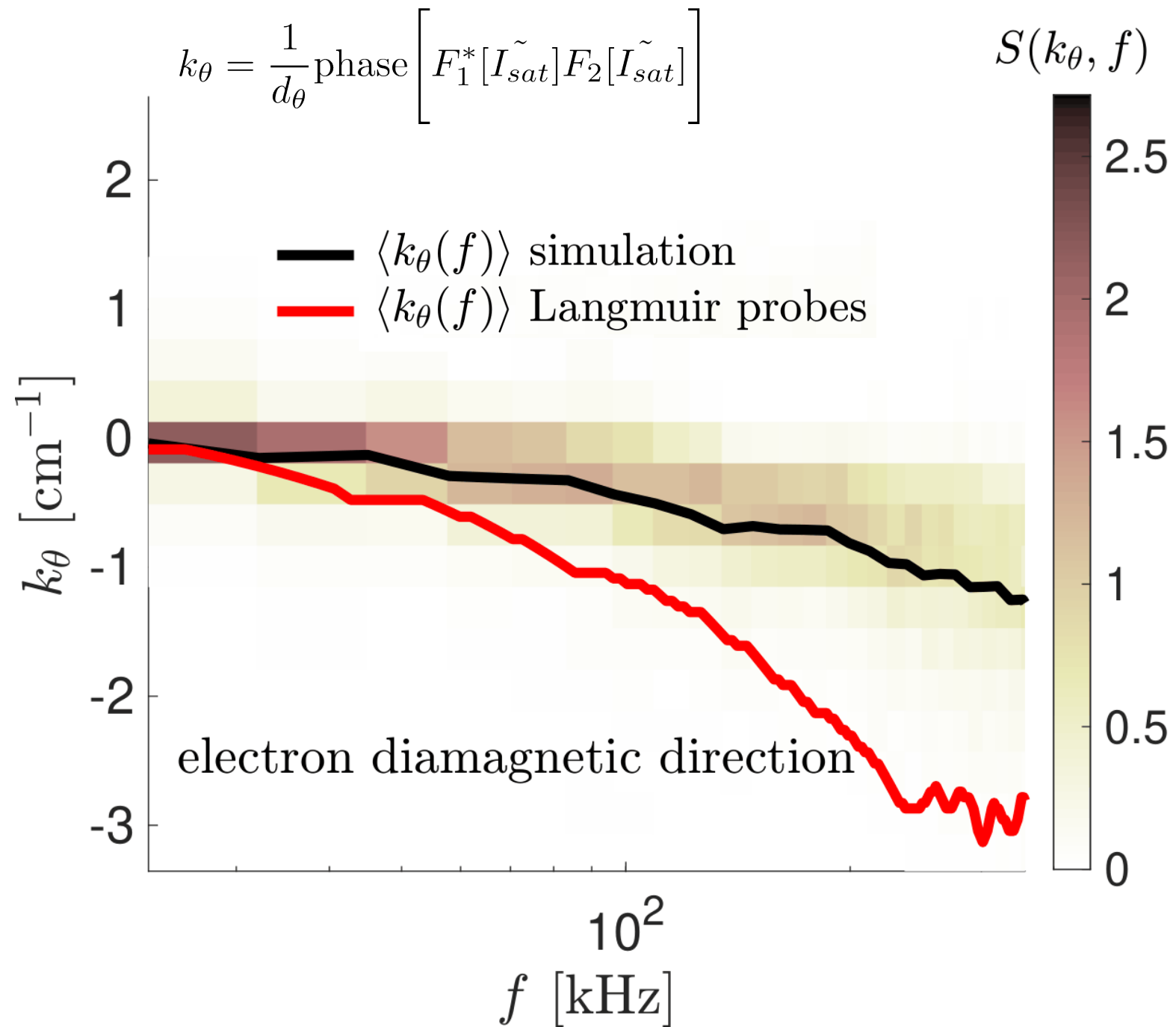
Are these results consistent with turbulent measurements?

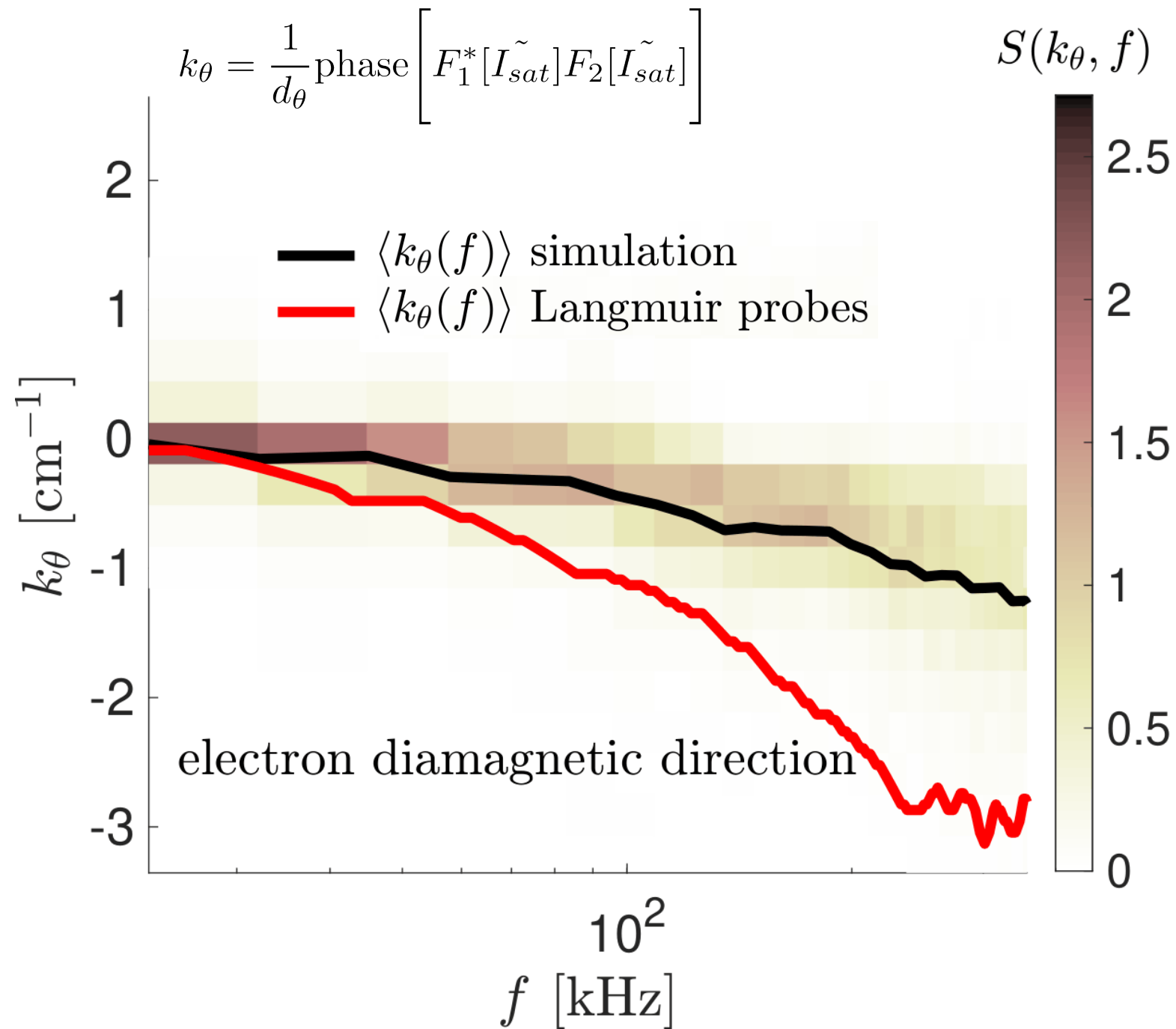


- **Peak** in the simulation at $f \approx 200 \text{ kHz}$ **not present in experiments**

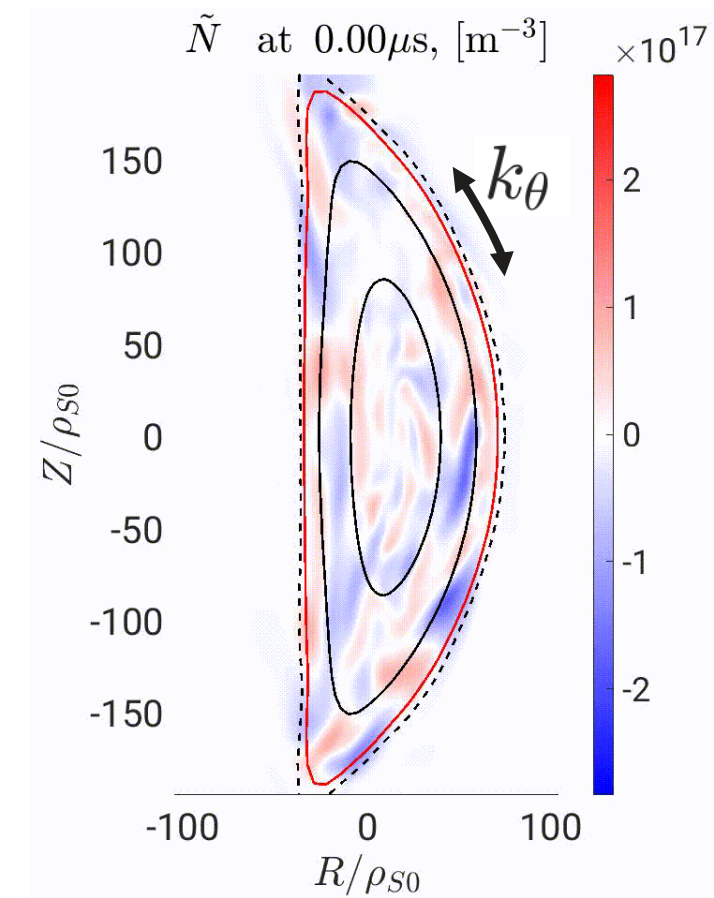


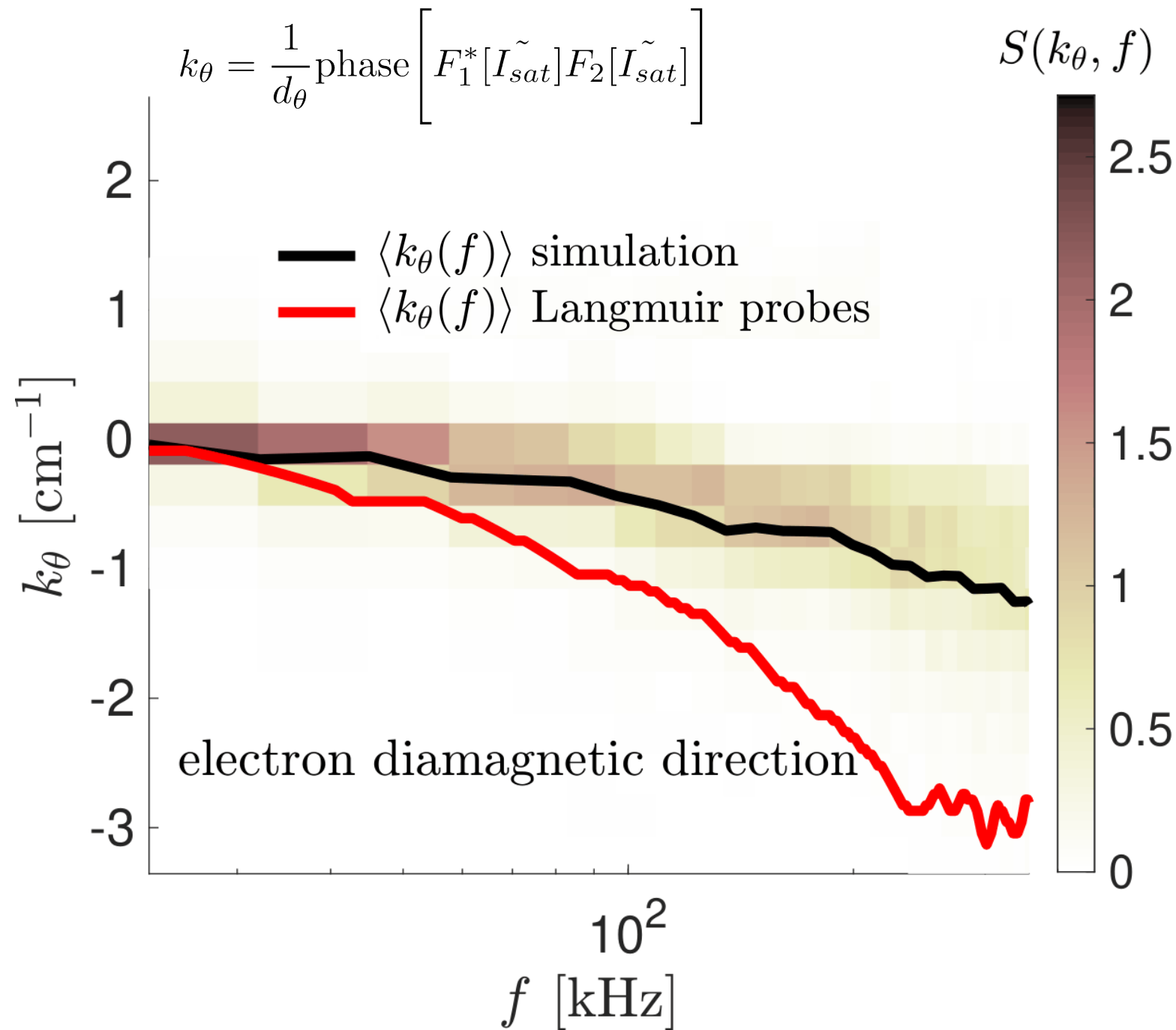
- **Peak** in the simulation at $f \approx 200 \text{ kHz}$ **not present in experiments**
- **Energy cascade of** $\sim f^{-4}$





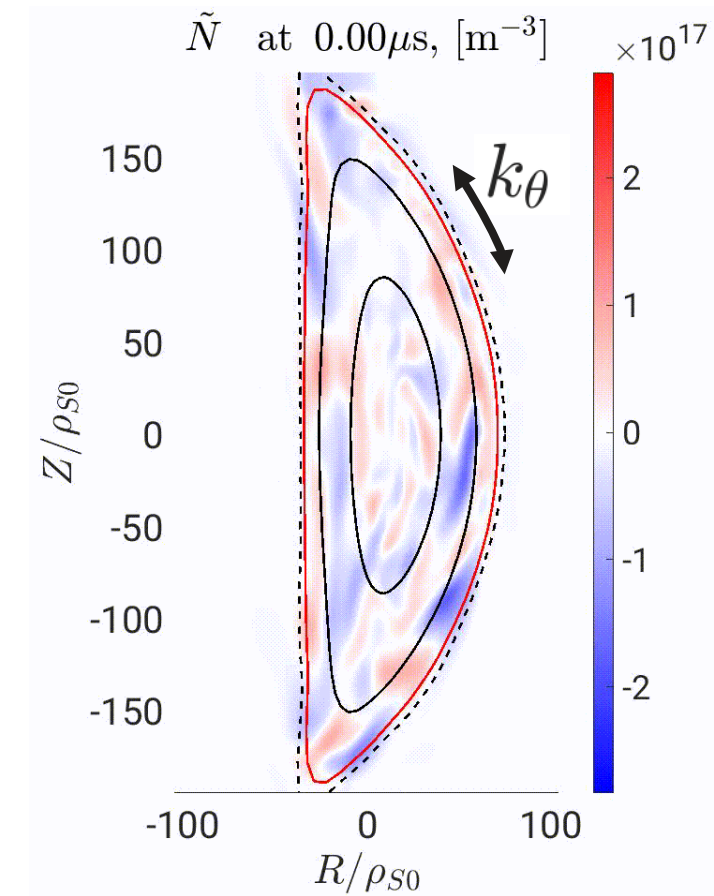
- **Compatible** $\langle k_\theta(f) \rangle$ for $f \lesssim 100$ kHz
- **Difference of factor 3** for $f \gtrsim 200$ kHz

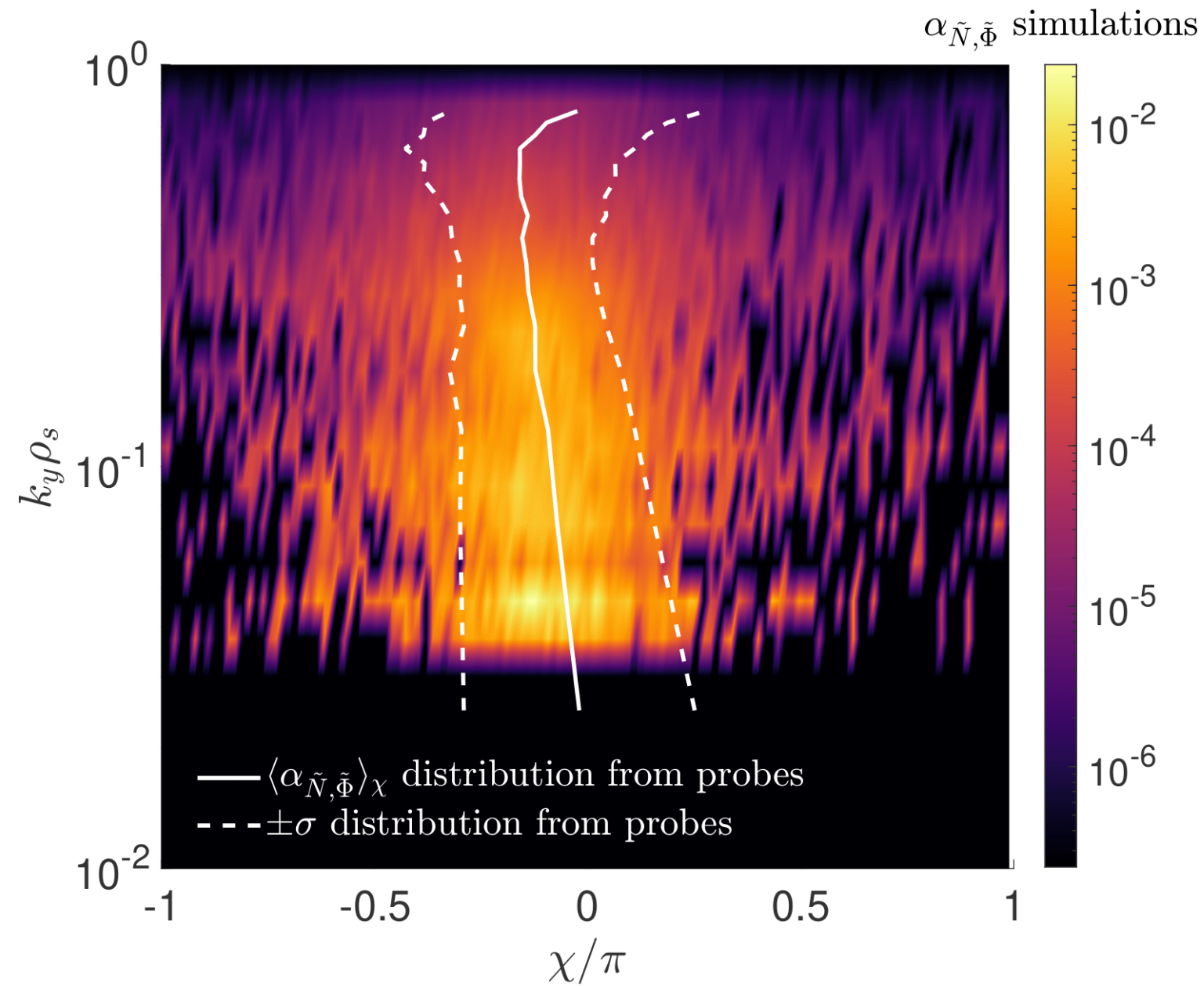


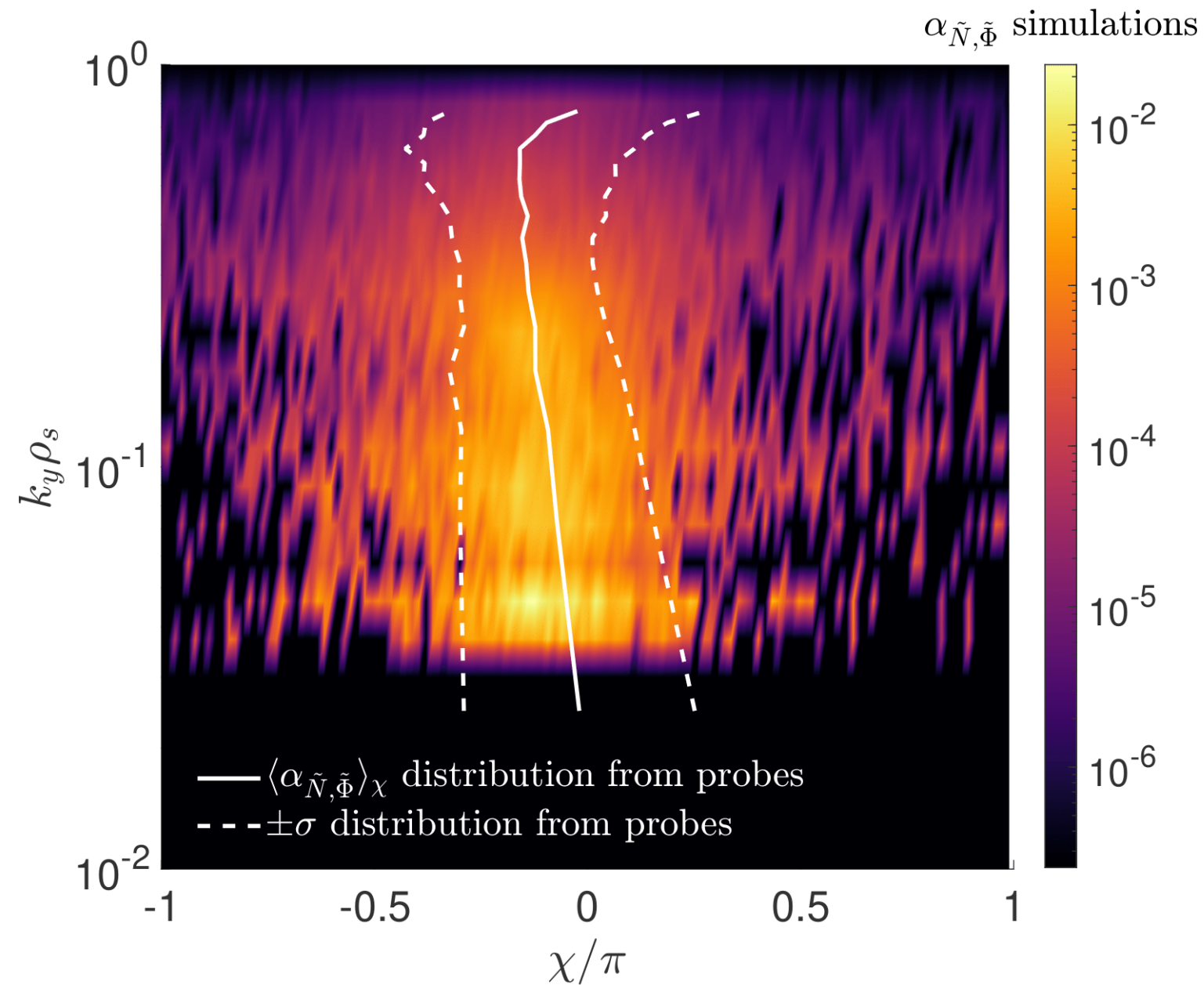


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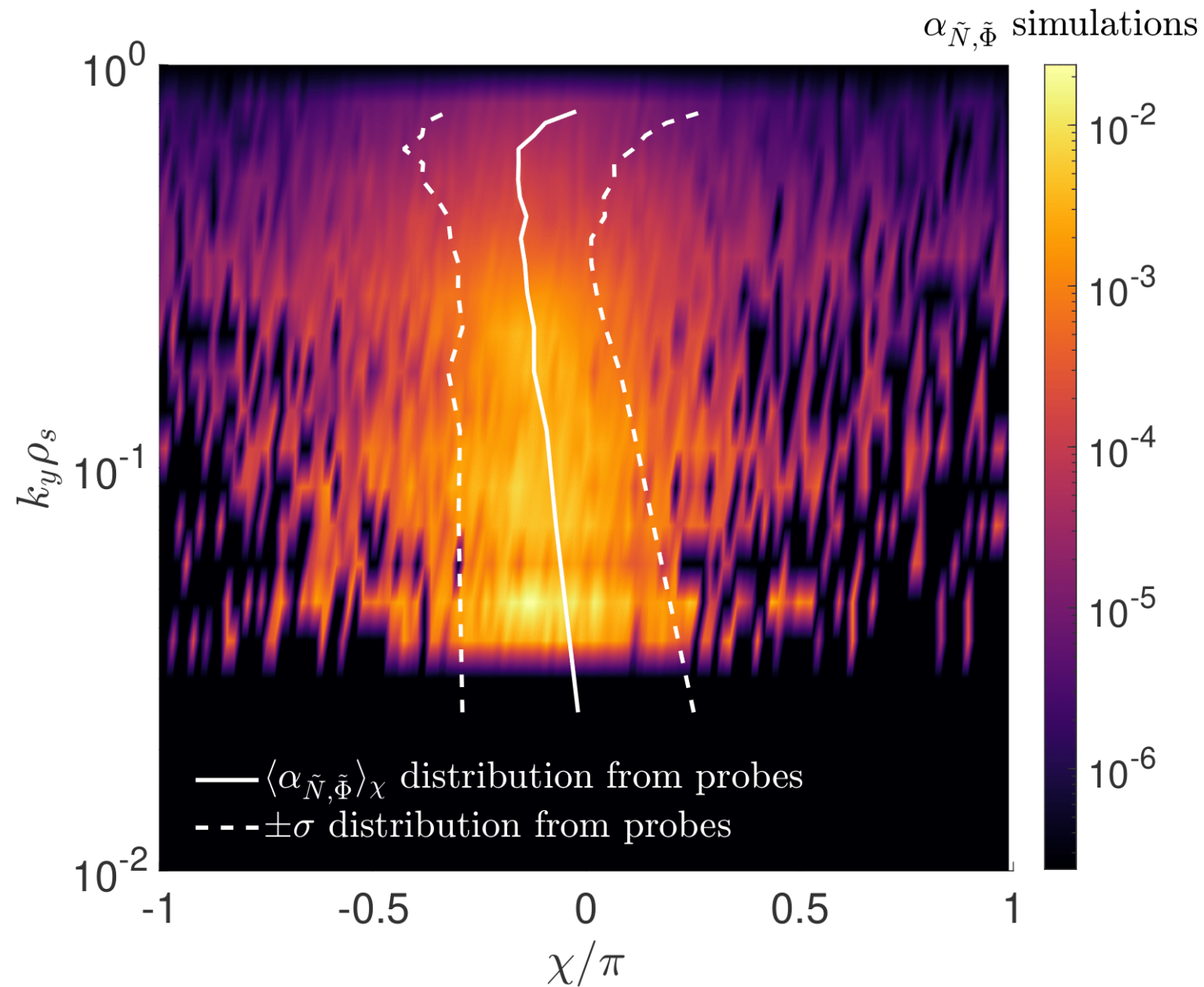
	Experiment	Simulation
$\rho_s \langle k_\theta \rangle$	0.14	0.12
$\rho_s \Delta k_\theta$	0.16	0.2



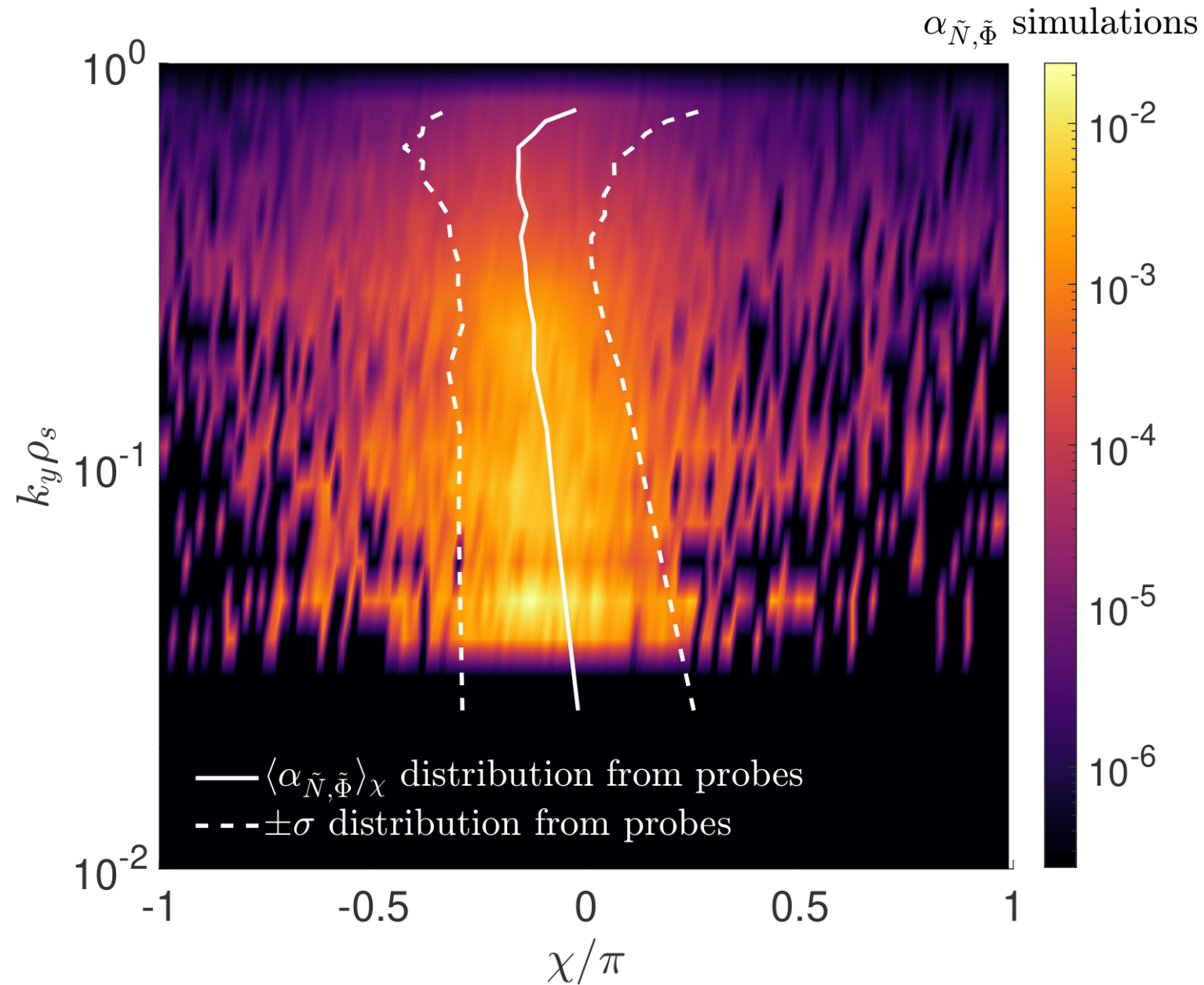




■ **Distribution peaking at $\chi/\pi \approx 0.1$**

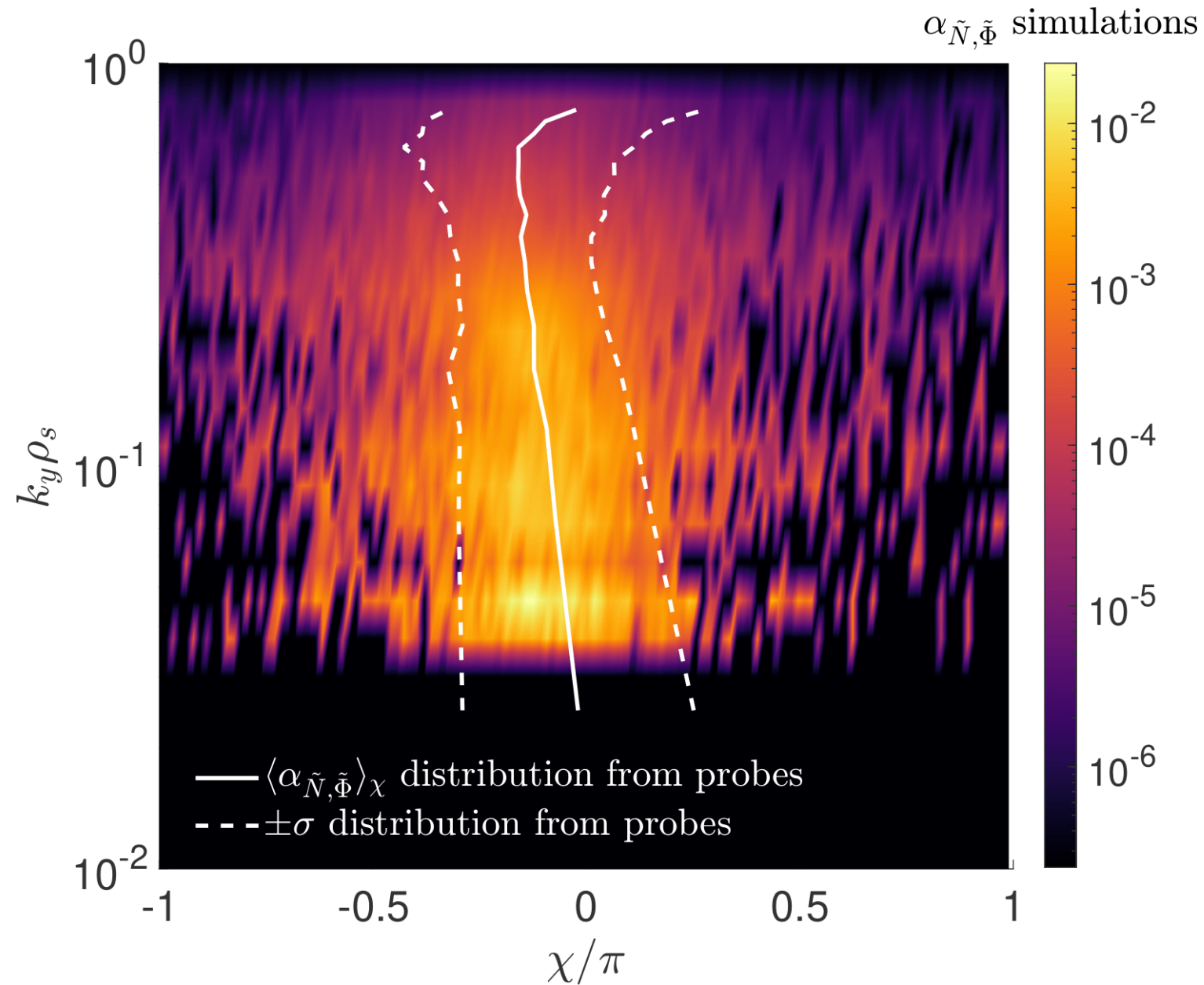


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$$\chi_{\tilde{N}, \tilde{\Phi}} = \arctan \left[- \frac{\rho_*^{-1} k_y}{L_n} \frac{\nu}{k_{\parallel}^2} \right]$$

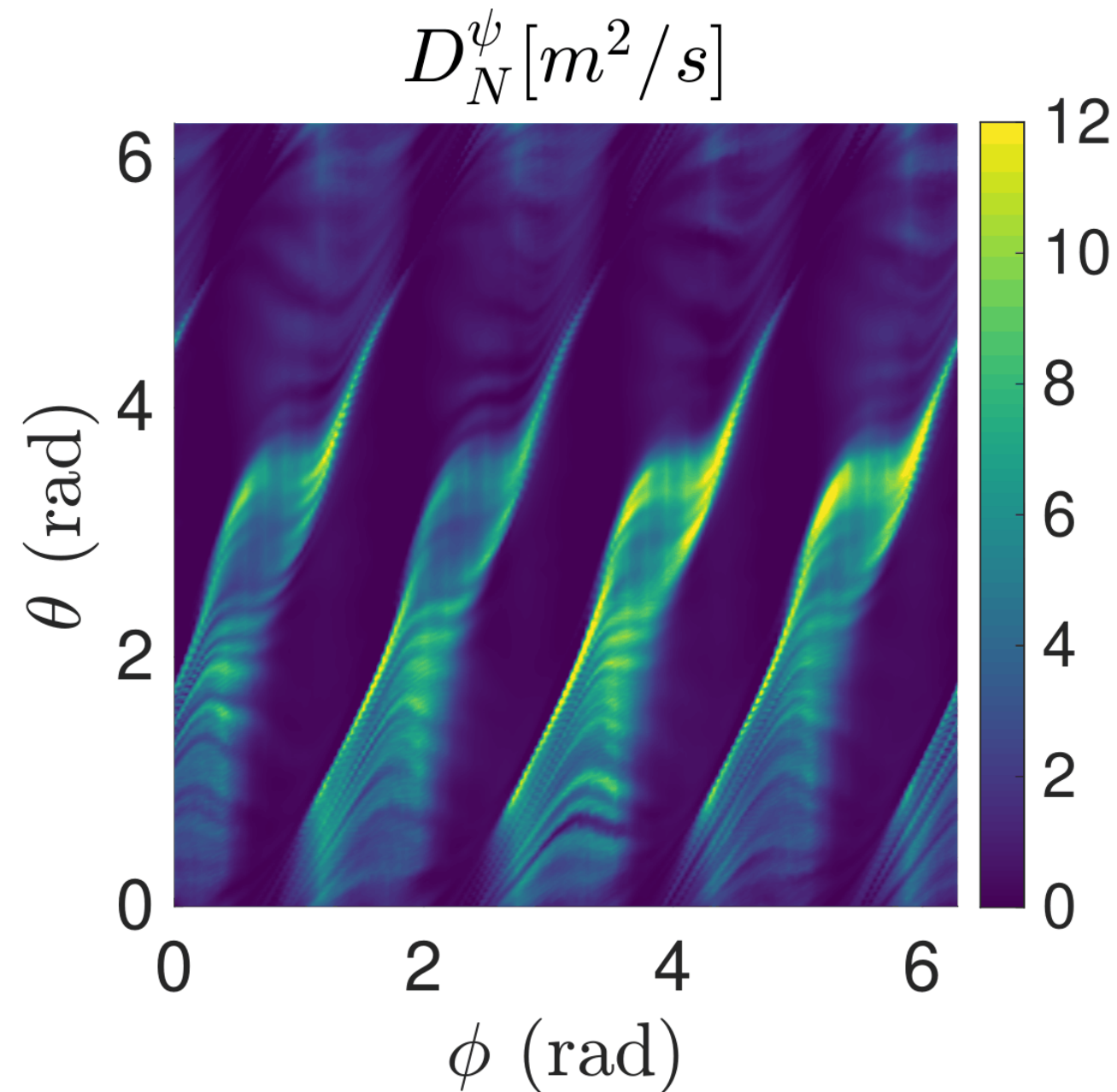


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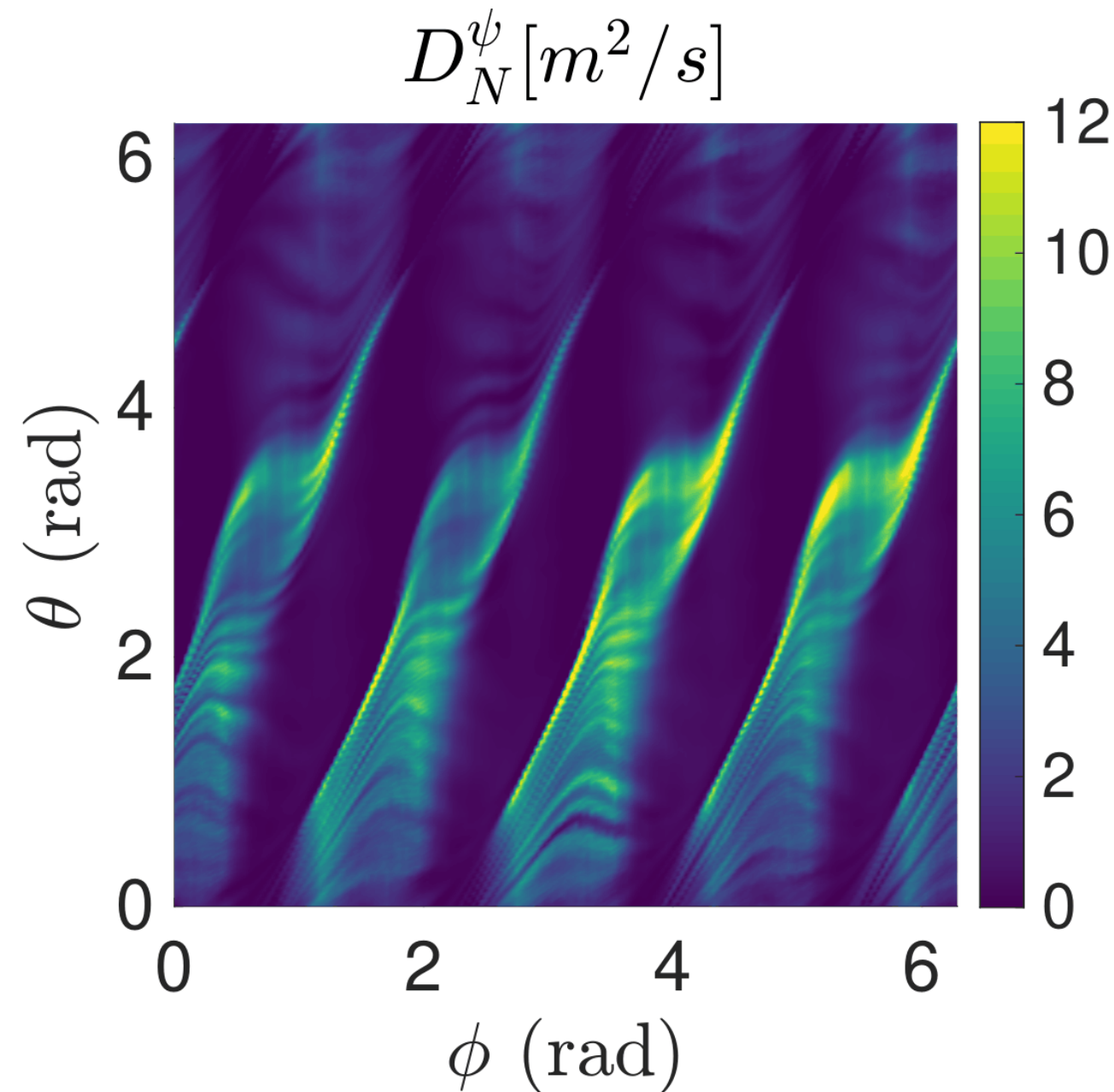
- **In the HSX case, $|\chi_{\tilde{N}, \tilde{\Phi}}|/\pi \sim 0.16$**

- Radial transport predominately caused by the $E \times B$ turbulent part



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

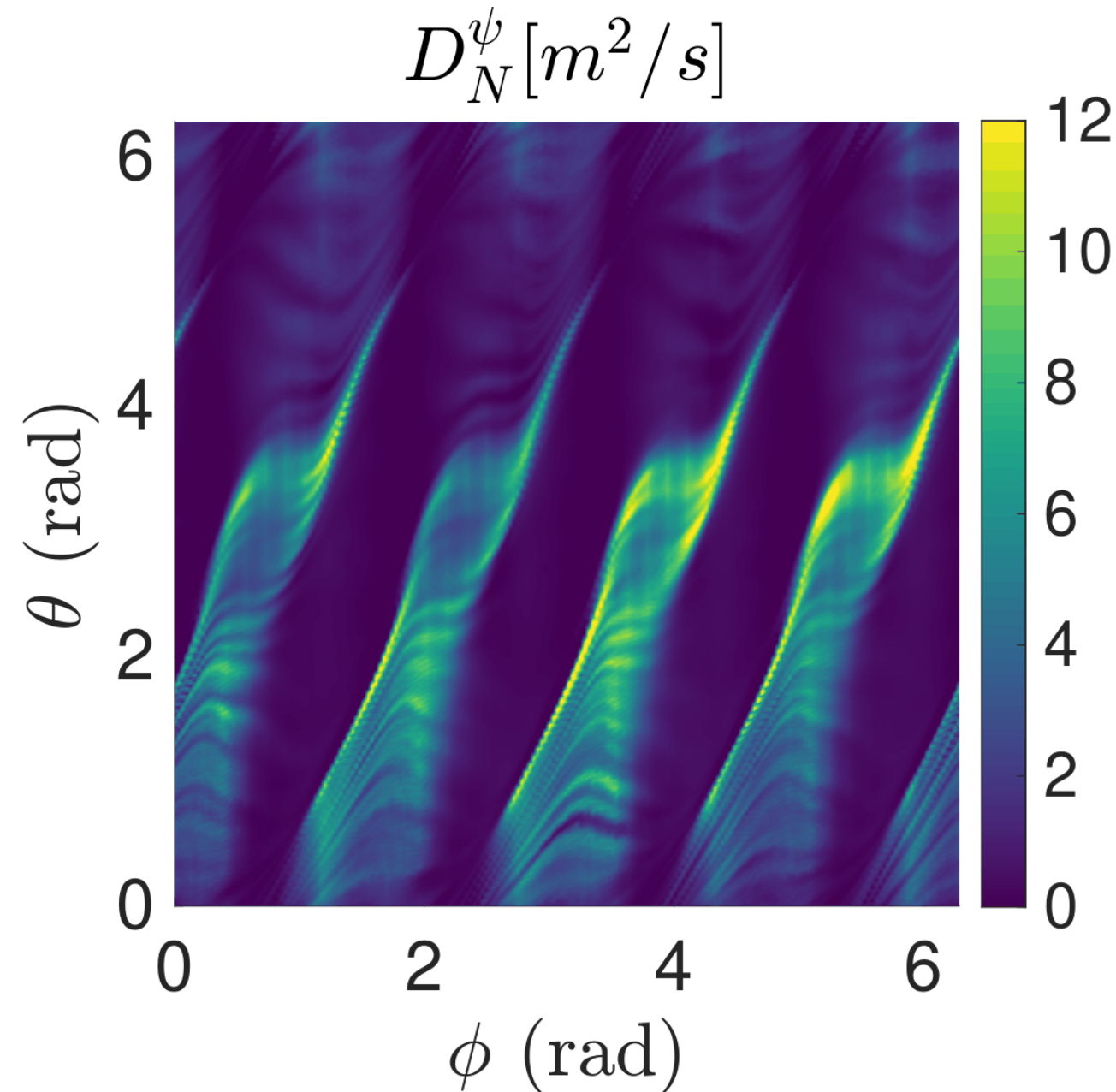
$$\chi_{e,i}^\psi = -\langle \tilde{T}_{i,e} \tilde{V}_{E \times B}^\psi / \nabla T_{i,e} \cdot \mathbf{n}^\psi \rangle_t$$



- Regions of negative particle transport

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- Regions of negative particle transport
- Ongoing collaboration with UW-Madison to test these profiles in EMC3-EIRENE

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Overall good agreement between GBS and measurements in the boundary of HSX

- **First-ever boundary turbulent simulation of a quasi-symmetric stellarator**
- Simulated average profiles and turbulent properties show **reasonable agreement** with the measurements
- **Field-aligned turbulence** is found to be driven by **curvature-driven modes**
- The computations of D_n^ψ and $\chi_{i,e}^\psi$ holds value for providing, for the first time in stellarators, **first-principle evaluations for transport codes**
- **Including neutrals dynamics, more realistic wall geometry, and improved boundary conditions represents the next steps in studying HSX plasmas in the boundary**
- More details are provided in recently submitted paper to *Nuclear Fusion*

BACKUP SLIDES

Zeroing out the turbulence drive to determining the leading mechanism

$$-\rho_*^{-1}[\Phi, \omega]/B$$

$$C(p_e + \tau p_i)$$

$$-\nabla_{\parallel} p_e / N - 0.71 \nabla_{\parallel} T_e$$

