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# Global fluid simulations of plasma turbulence in diverted stellarators

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# Introduction

- Recent **W7-X experiments** showed significant differences with respect to tokamaks:
  - Filaments bound to their flux surface [Killer, 2021]
  - Fluctuations normally distributed (local origin)
- Stellarator turbulence simulations still in its infancy:
  - Gyrokinetic $\delta f$ codes (GENE-3D, Stella, XGC-S, …) – study the core
  - Fluid code BOUT++ simulated edge filaments in a rotating ellipse [Shanahan, 2019]

# GBS solves the drift-reduced Braginskii equations

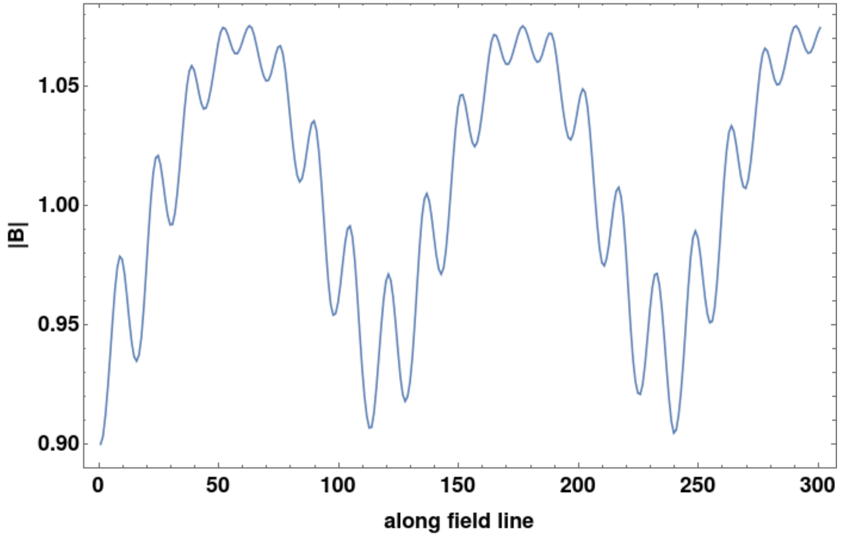
- Set of equations for $n, T_e, T_i, V_{\parallel e}, V_{\parallel i}, \omega, \phi$
    - Electrostatic simulations
    - Boussinesq approximation
    - No neutrals

# GBS solves the drift-reduced Braginskii equations

- Geometrical operators:

$$[\boldsymbol{\phi}, \mathbf{u}] = \mathbf{b} \cdot [\nabla\phi \times \nabla u] \qquad \boldsymbol{\nabla}_{\parallel}\mathbf{u} = \mathbf{b} \cdot \nabla u \qquad C(u) = \frac{B}{2}\left[\nabla \times \frac{\mathbf{b}}{B}\right] \cdot \nabla u \qquad \nabla_{\perp}^{2} u = \nabla \cdot [(\boldsymbol{b} \times \boldsymbol{\nabla u}) \times \boldsymbol{b}]$$

**Expansion parameters:** $\delta = \frac{B_p}{B}$ ; $\sigma = \frac{l_{\perp}}{l_{\parallel}}$ ; $\Delta = \frac{B_{max} - B_{min}}{B}$



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$$[\phi, u] = \frac{\partial \Phi}{\partial Z}\frac{\partial u}{\partial R} - \frac{\partial \Phi}{\partial R}\frac{\partial u}{\partial Z}$$

$$\nabla_{\perp}^{2}u = \frac{\partial^2 u}{\partial R^2} + \frac{\partial^2 u}{\partial Z^2}$$

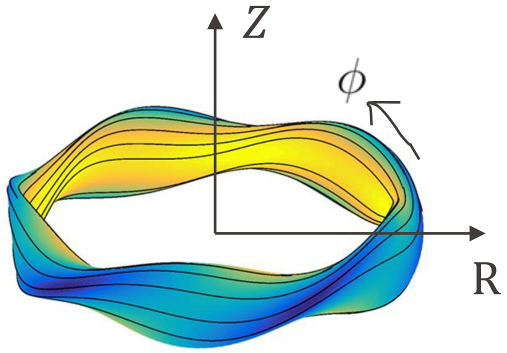
# Stellarator with an island divertor

$$\nabla \times \mathbf{B} = 0 \rightarrow \mathbf{B} = \nabla V$$

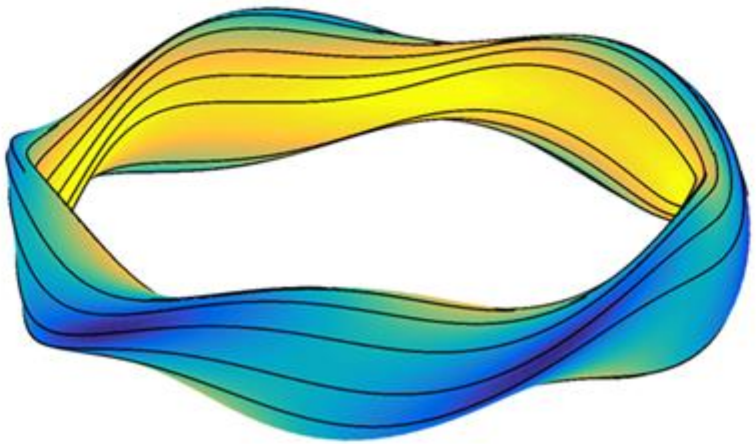
$$\nabla \cdot \mathbf{B} = 0 \rightarrow \nabla^2 V = 0$$

- Dommaschk potentials [Dommaschk, CPC 1986] are a solution of Laplace's equation in a torus:

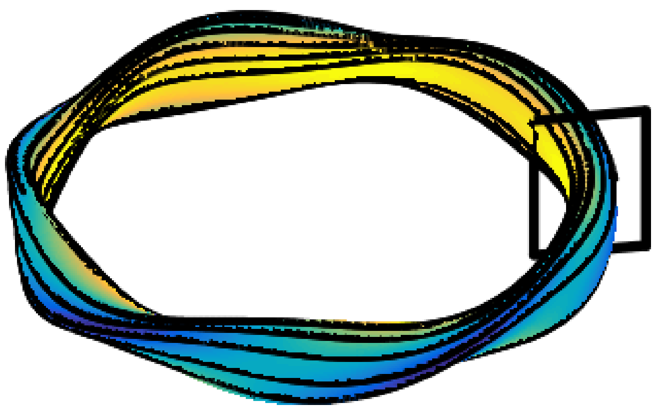
$$V(R, \phi, Z) = \phi + \sum_{m,l} V_{m,l}(R, \phi, Z)$$

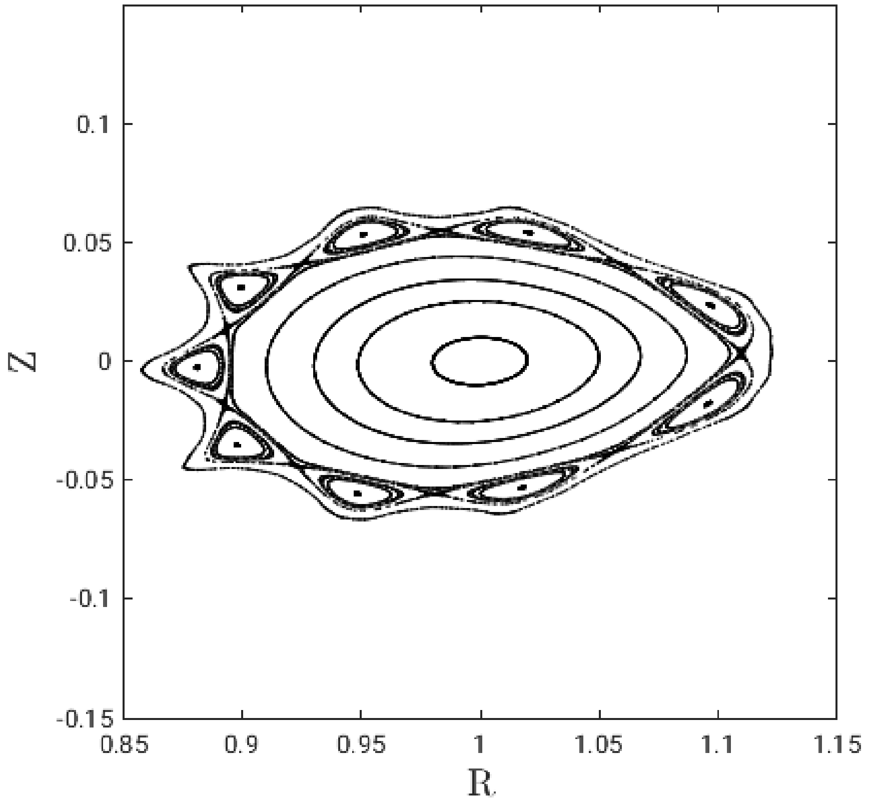


# We simulate a 5-field period stellarator...



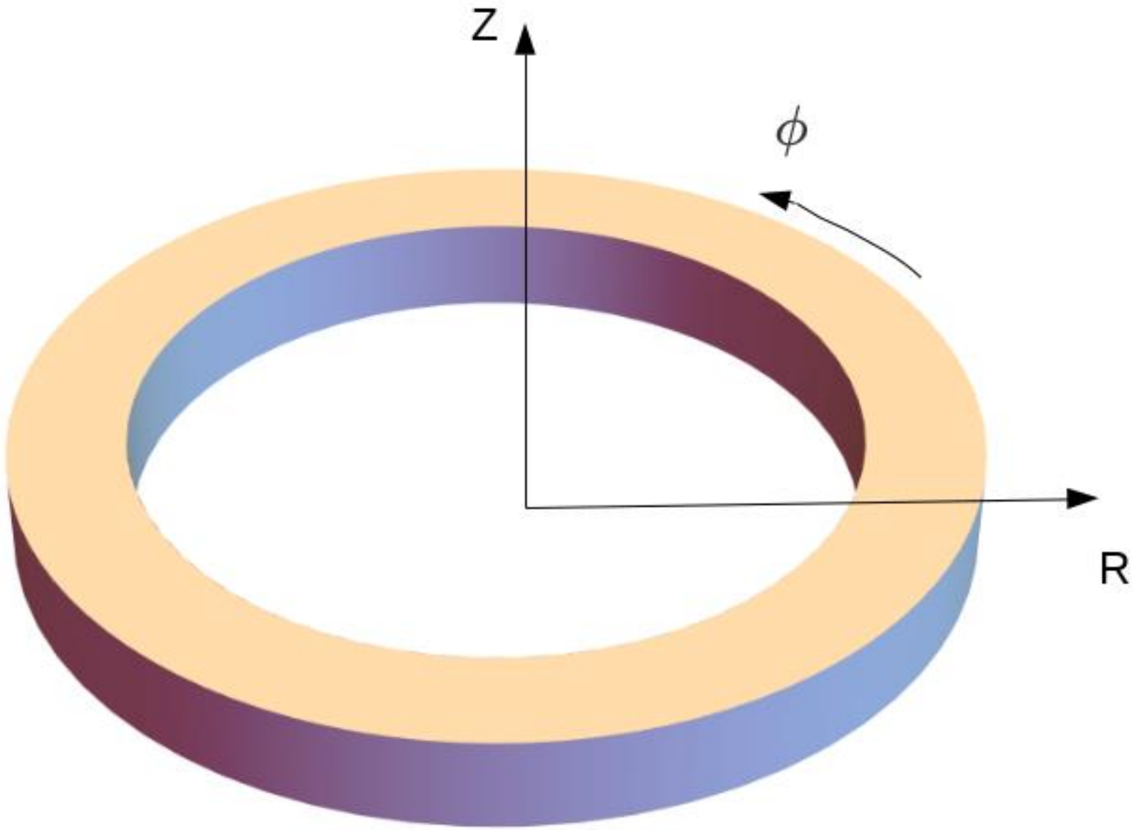
# We simulate a 5-field period stellarator... with a 5/9 chain of islands

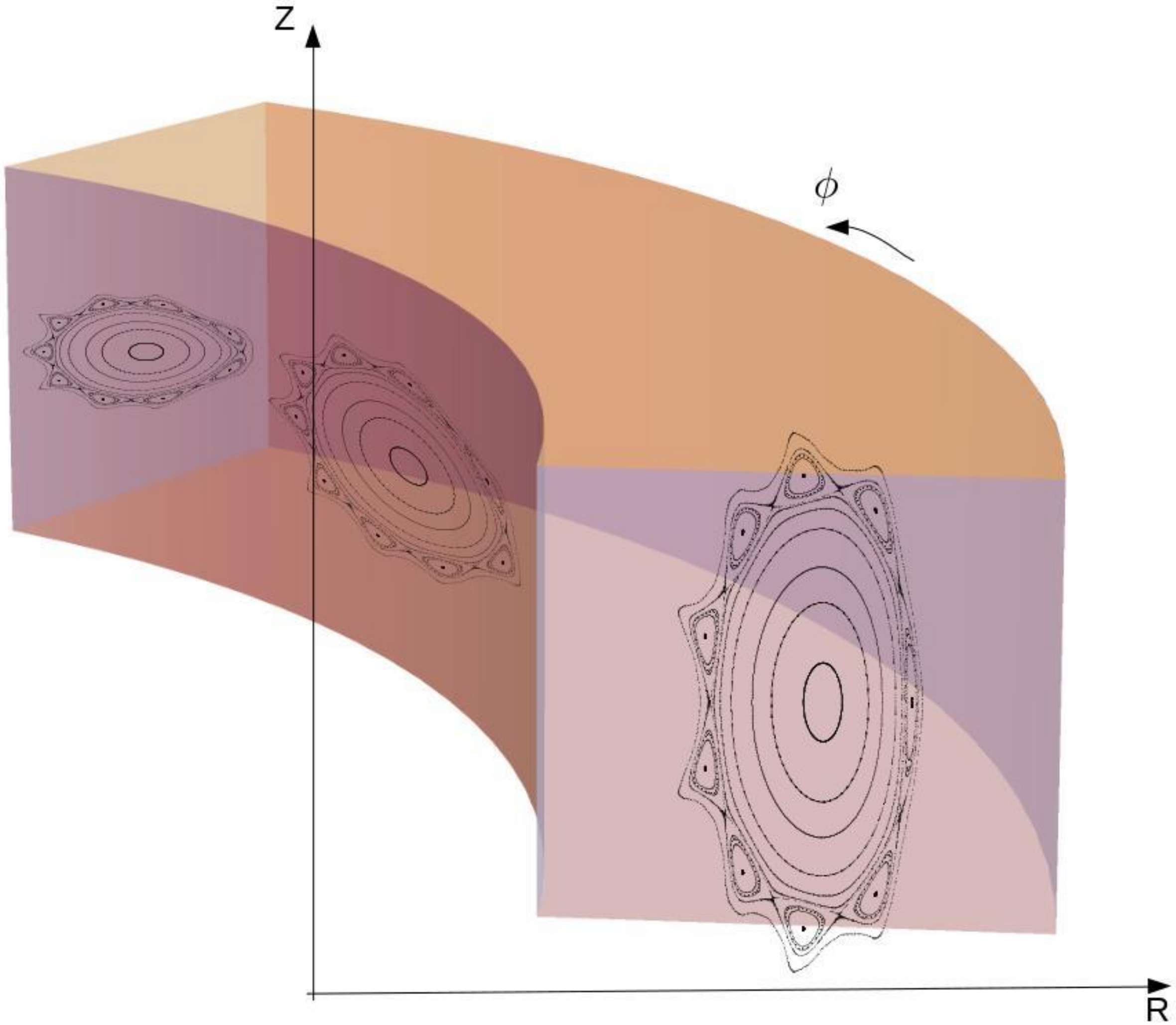





- All rotational transform from rotation of the ellipses

# GBS domain boundary intersects divertor islands



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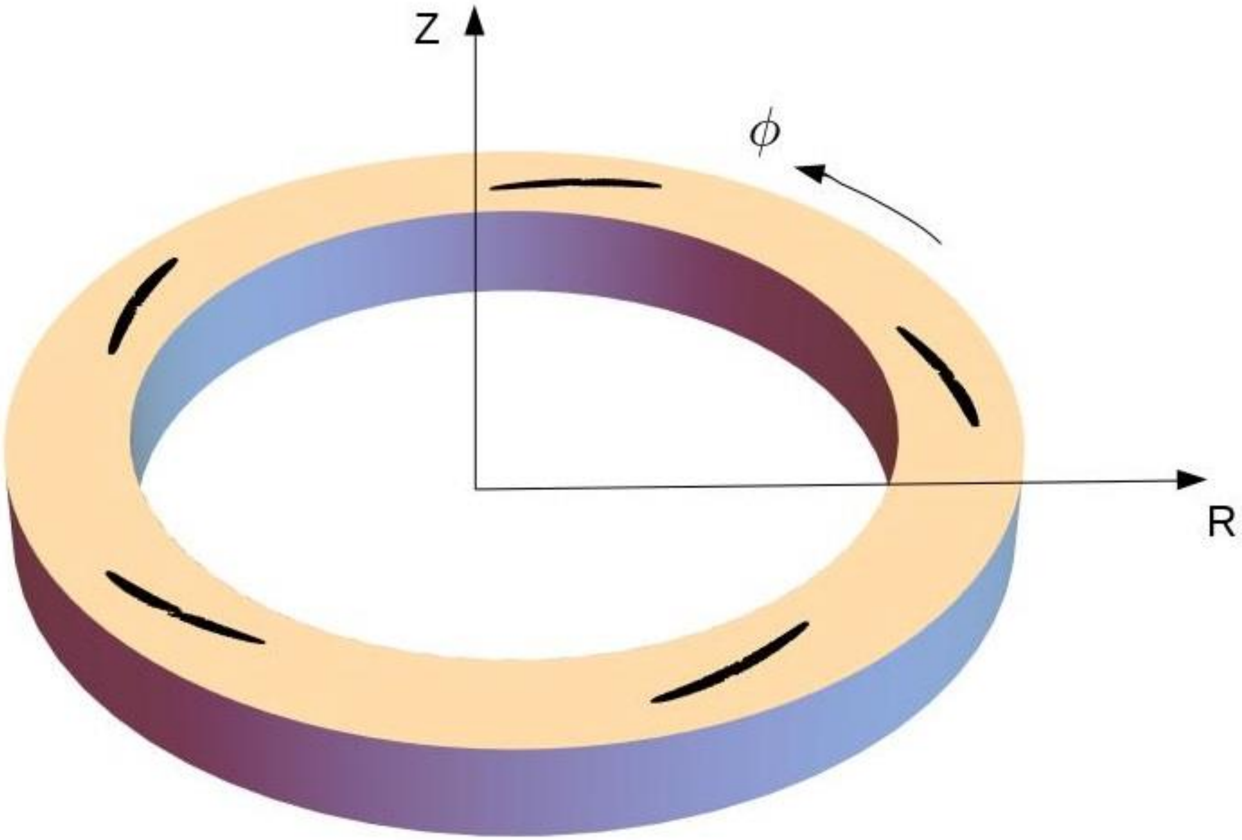
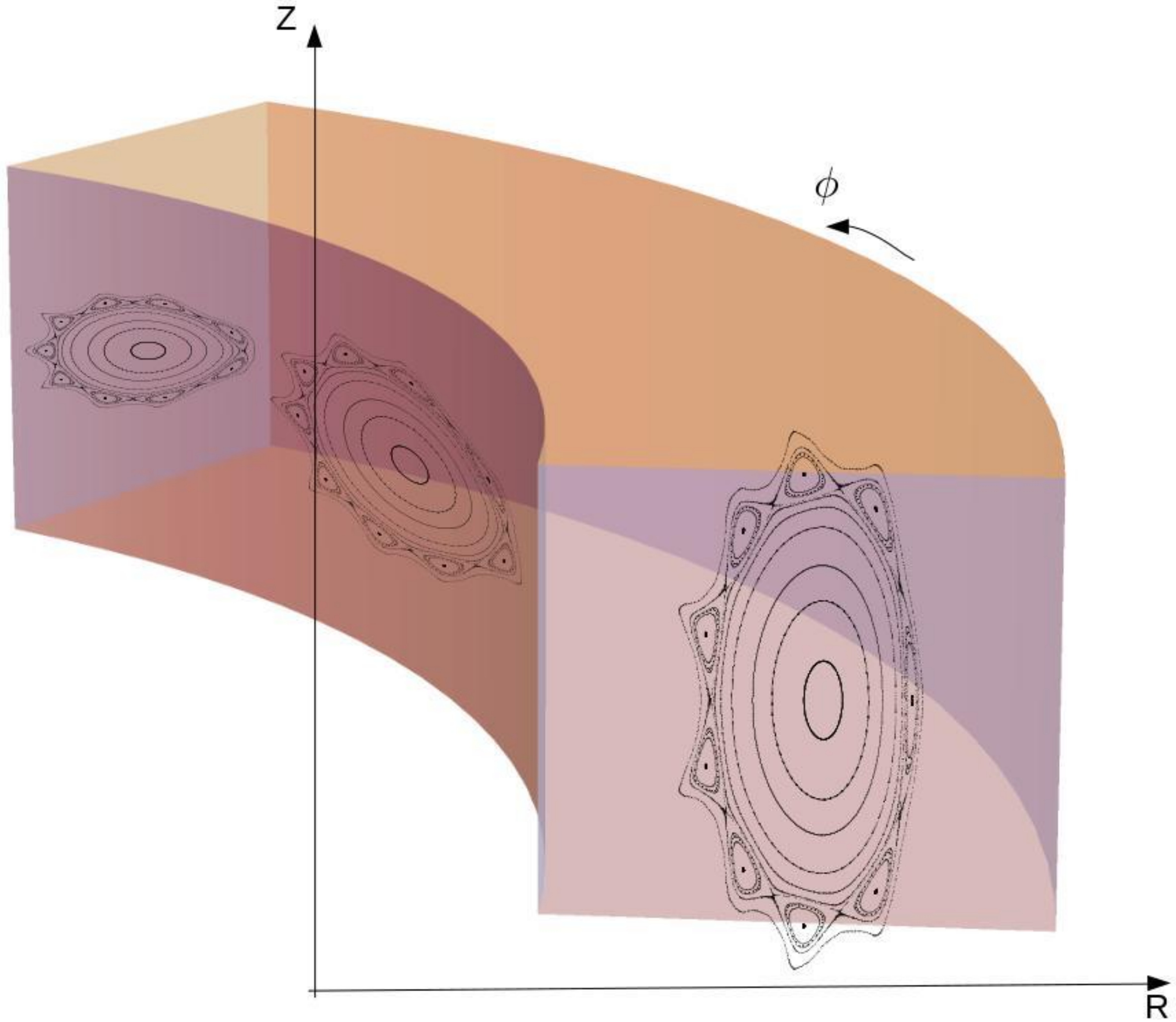
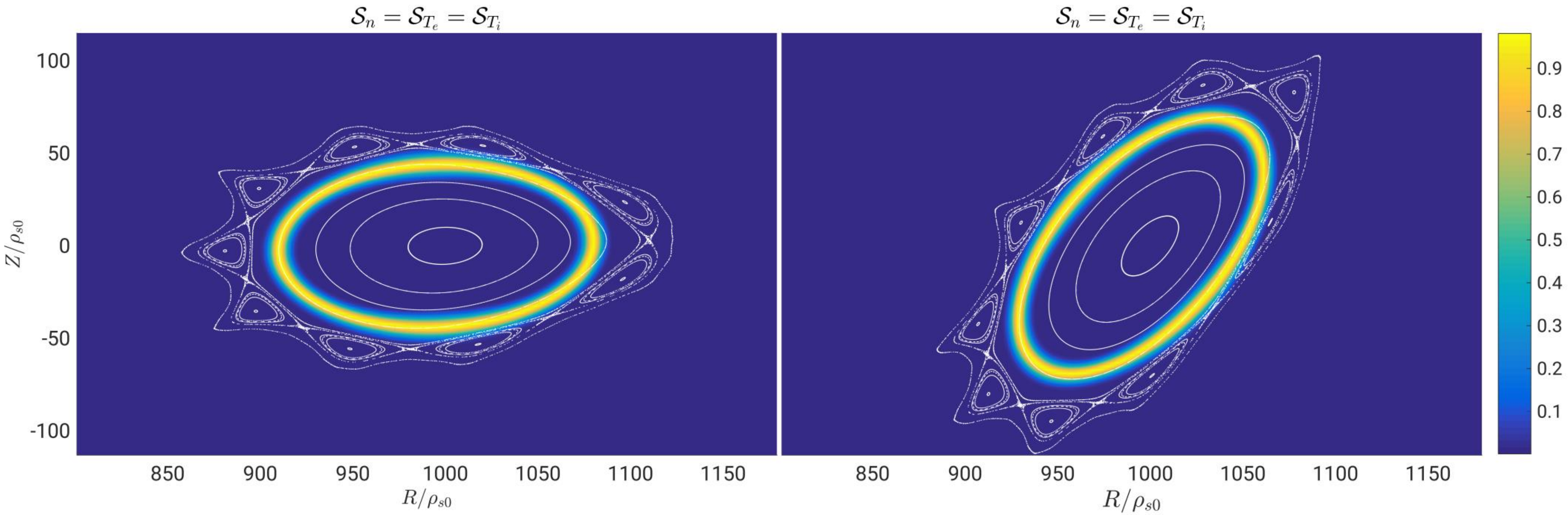


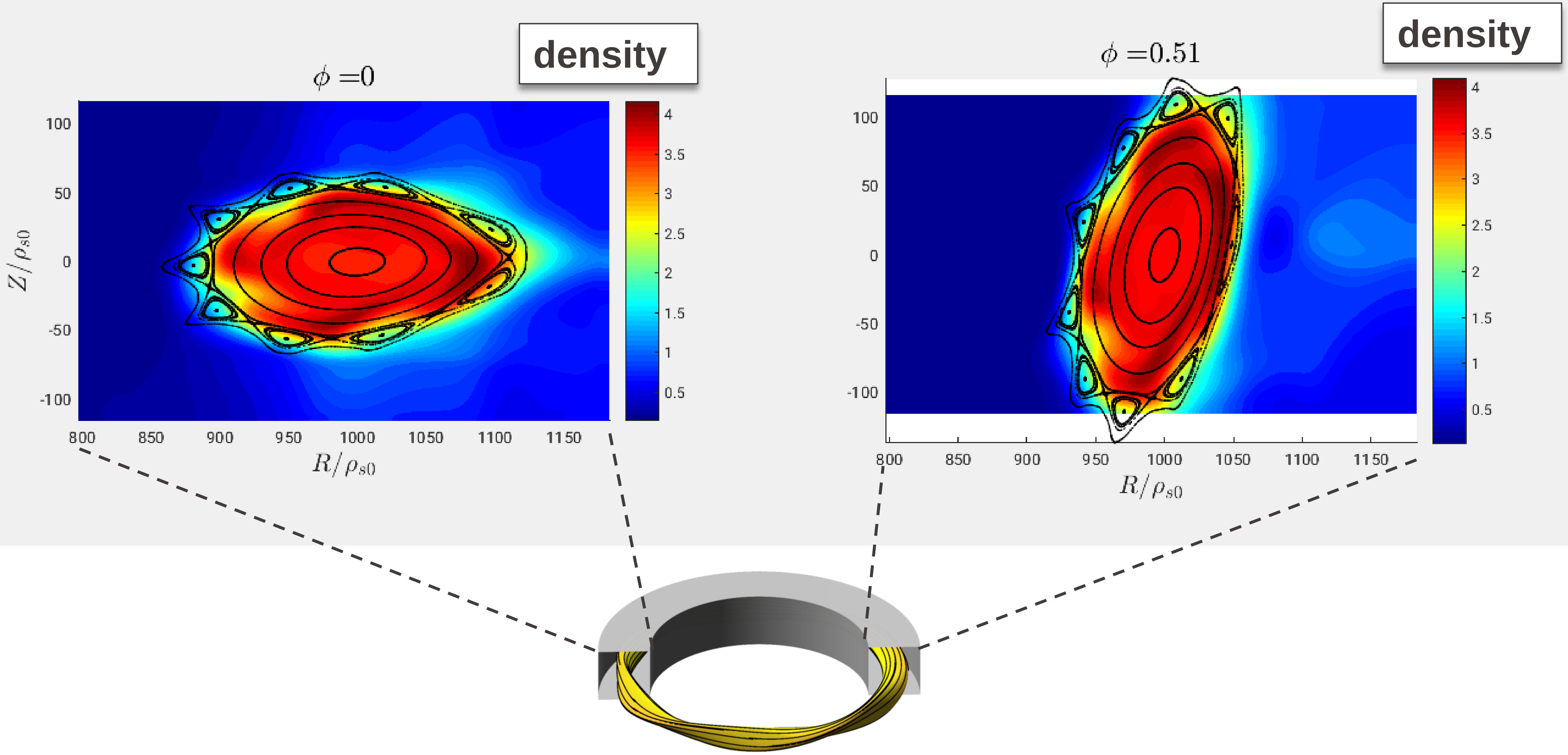



# Source for density and temperature localized around a magnetic surface

- Simulation doesn't strongly depend on the sources' profile



# Steady-state of simulation dominated by coherent mode



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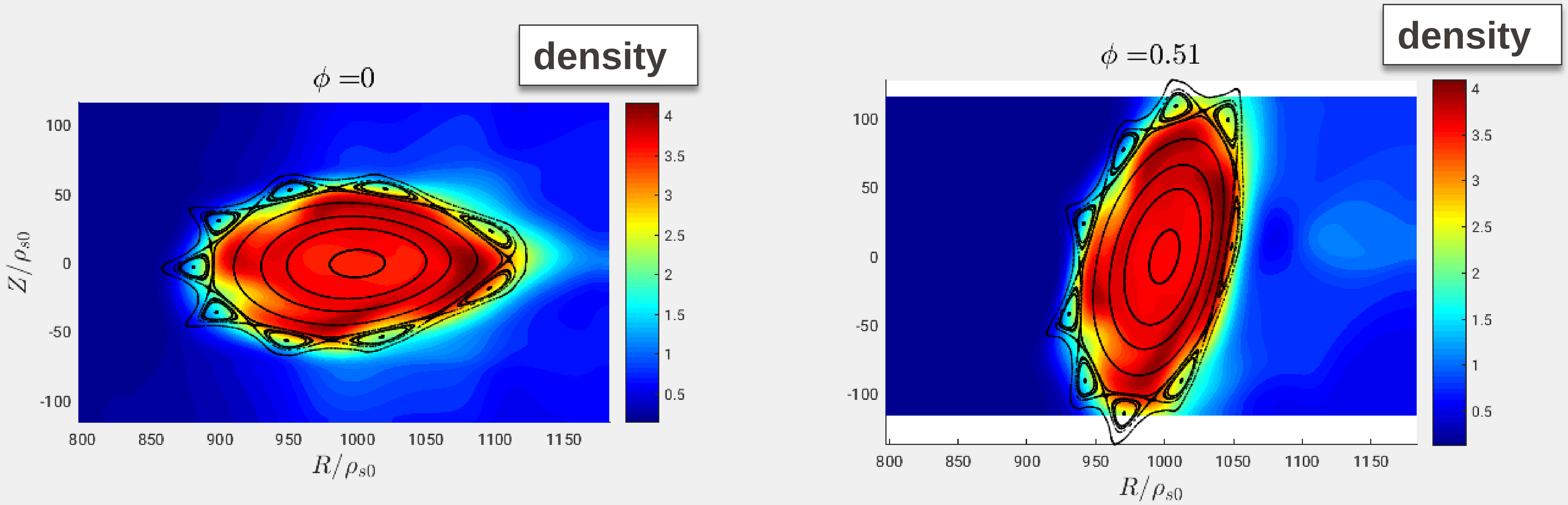
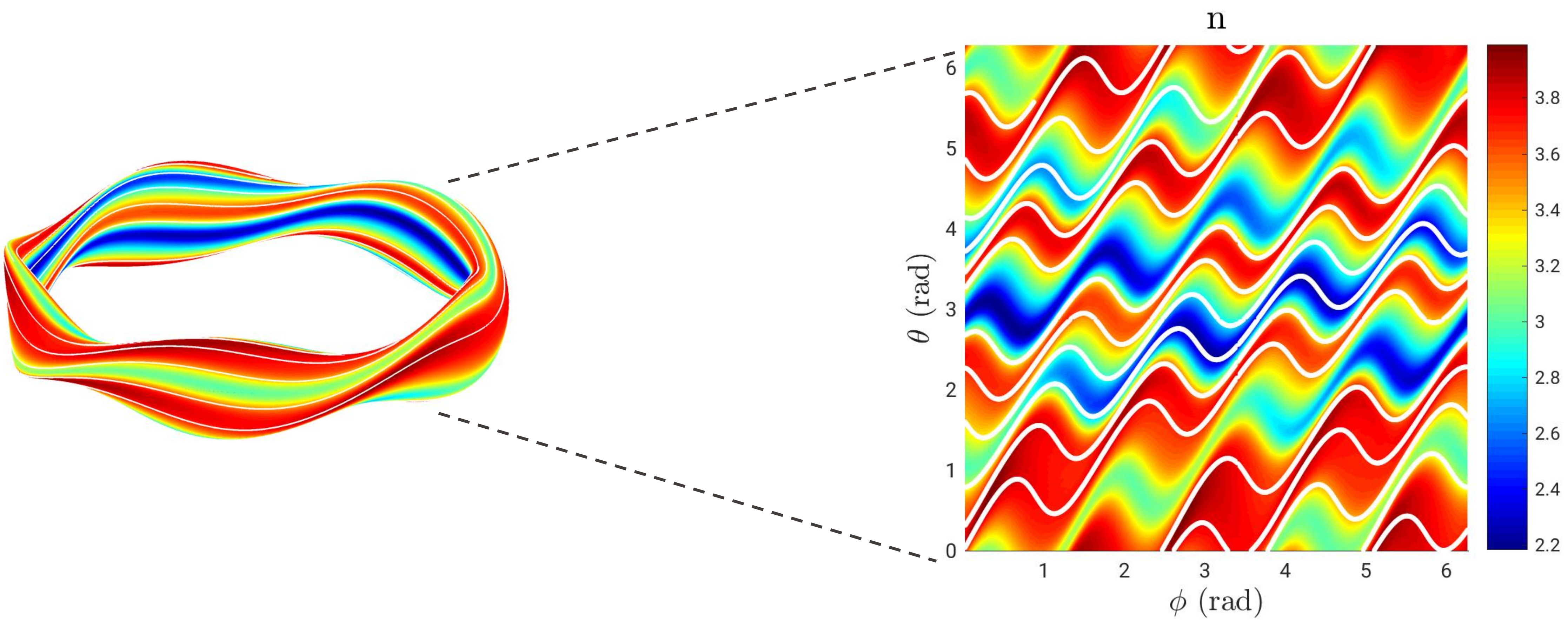
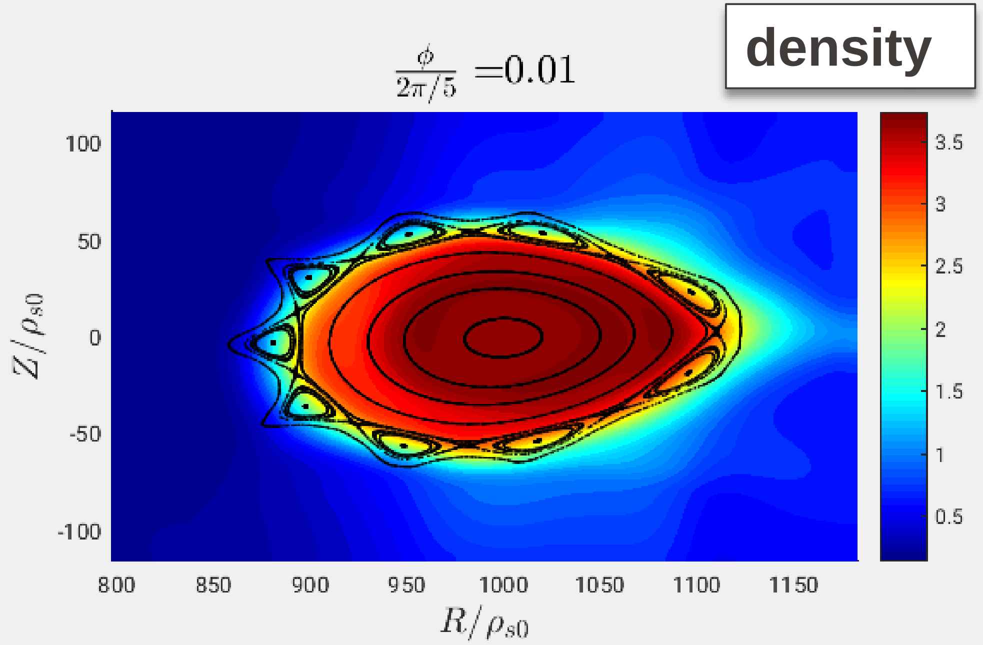


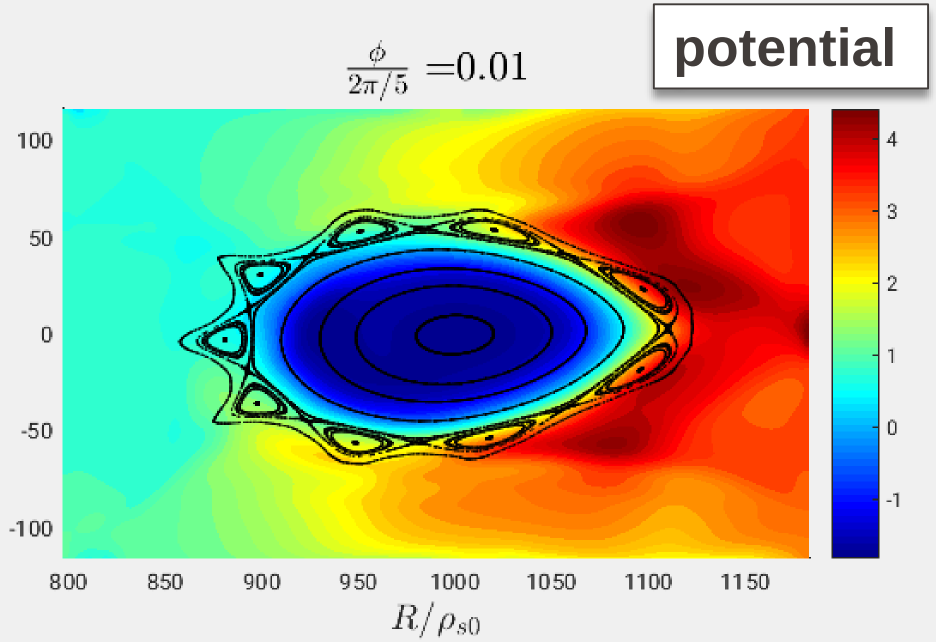

- An m=4 mode dominates the global dynamics
- Mode rotates with ~ ion diamagnetic frequency
- No broad-band turbulence
- Radial turbulent transport due to $< \tilde{\Gamma}_{\mathrm{ExB}} >_t = < \tilde{n}\tilde{V}_{\mathrm{ExB}} >_t$ balances source

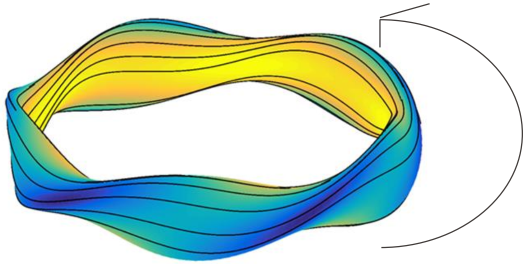
# Mode is field-aligned



# Equilibrium profiles

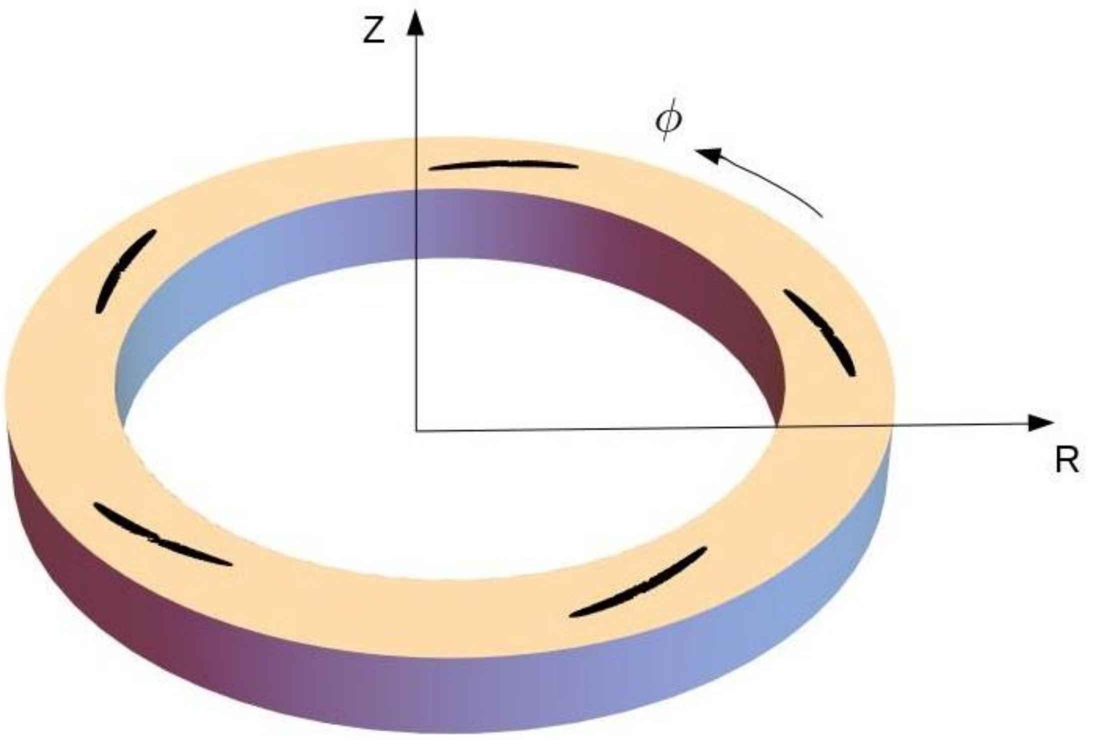


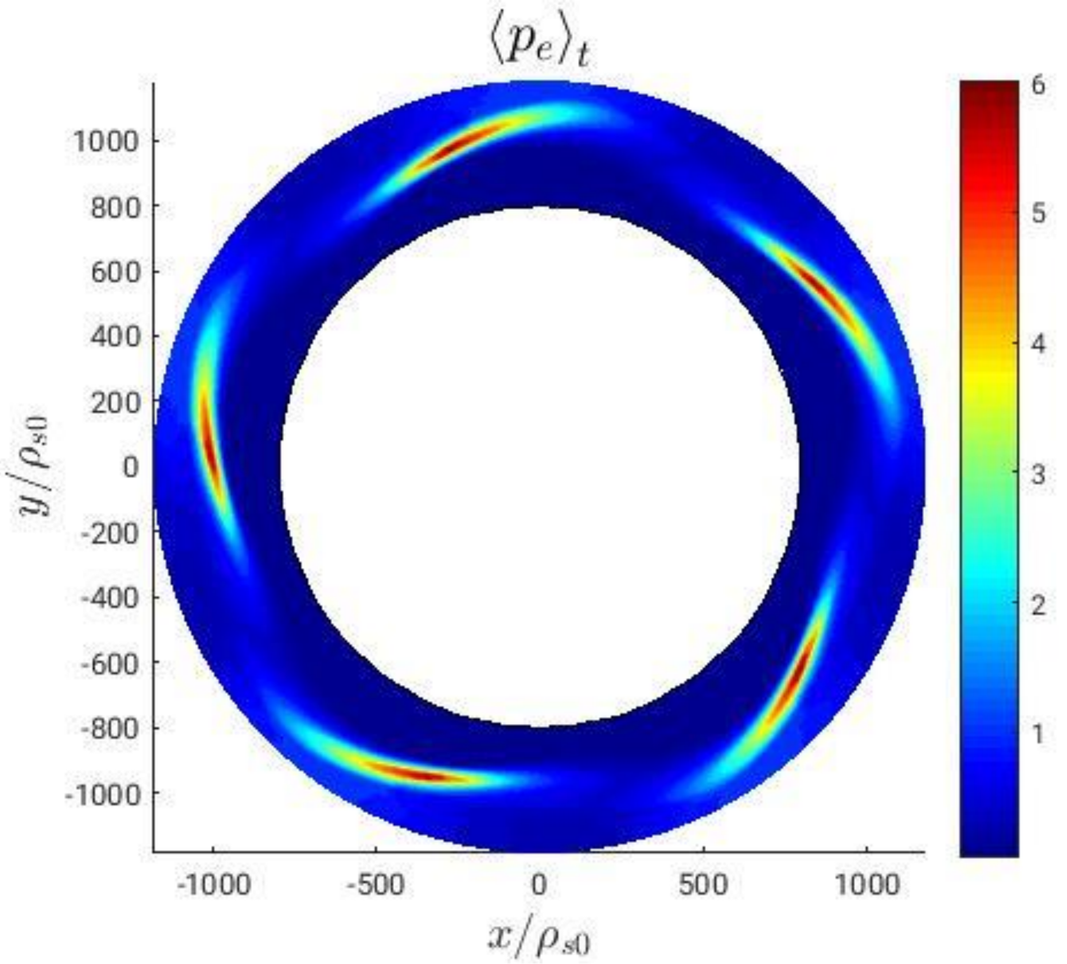



# Effectiveness of the island divertor

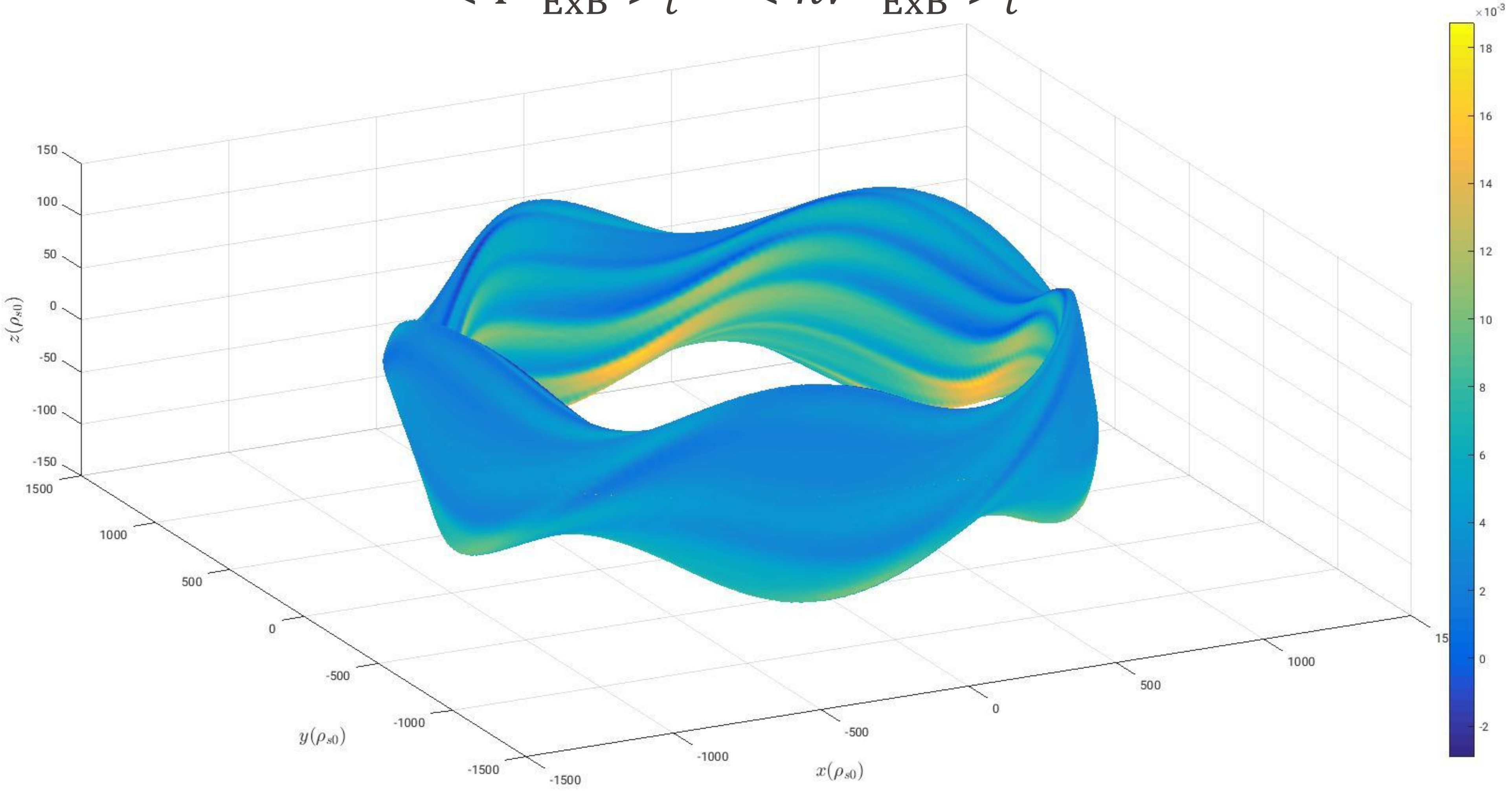
- On the **TOP** of the simulation box, pressure is maximum where field lines strike:



# Asymmetry of ExB-flux between HFS/LFS

$$< \widetilde{\Gamma^{r}}_{\mathrm{ExB}} >_t = < \tilde{n}\widetilde{V^{r}}_{\mathrm{ExB}} >_t$$



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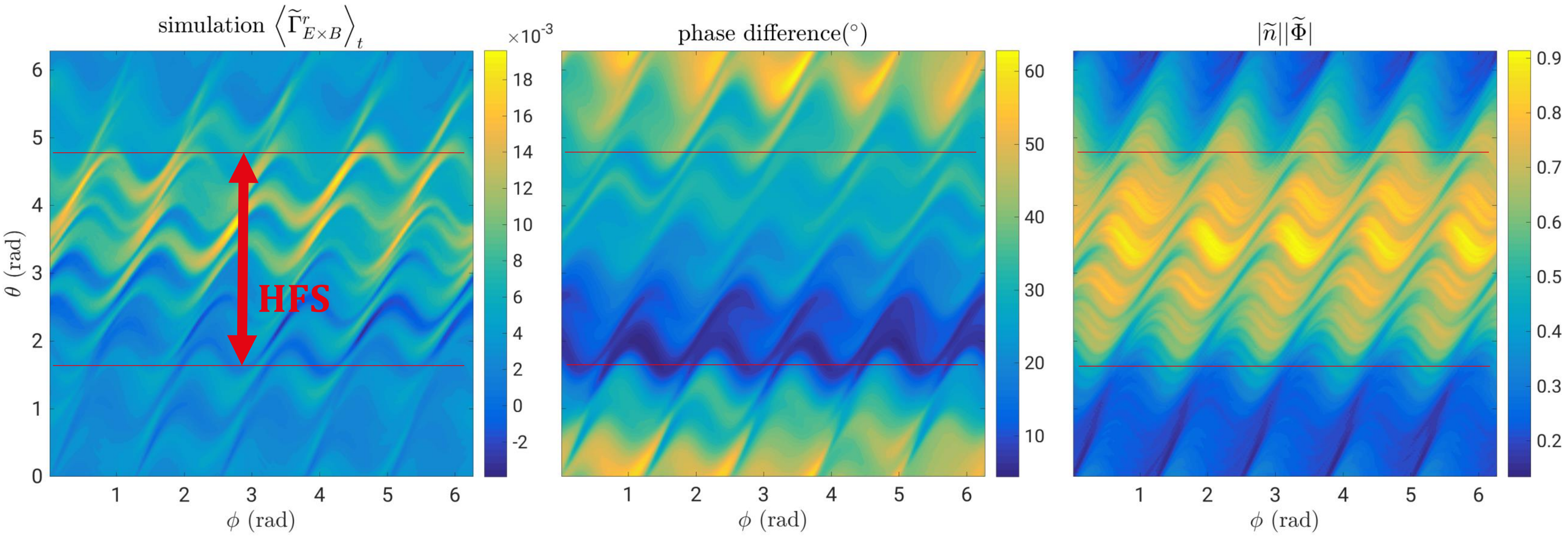


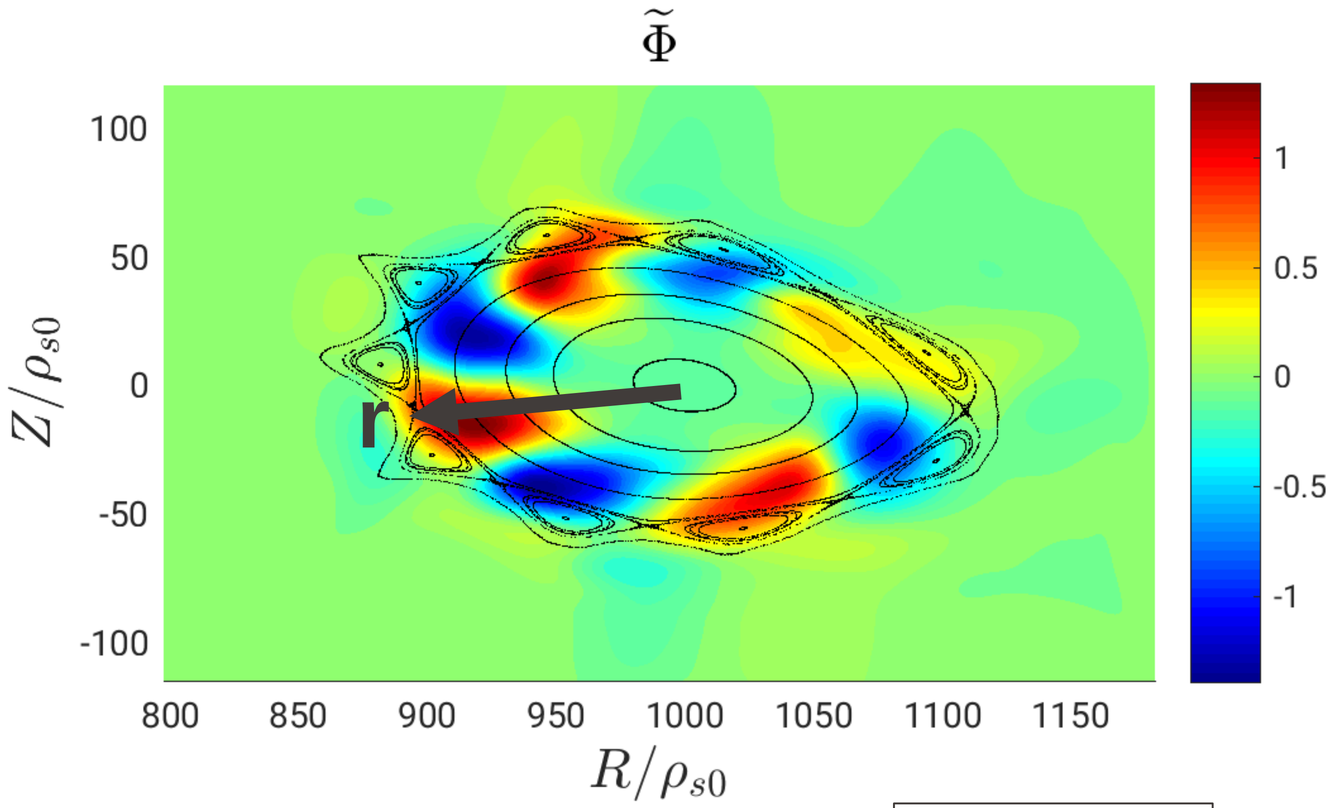
# Understand the mode with non-local linear theory

- Linearize GBS equations by assuming quantities vary as:

$$n = n_0(r) + \tilde{n}(r)e^{j(m\theta+n\phi)}e^{\gamma t}$$

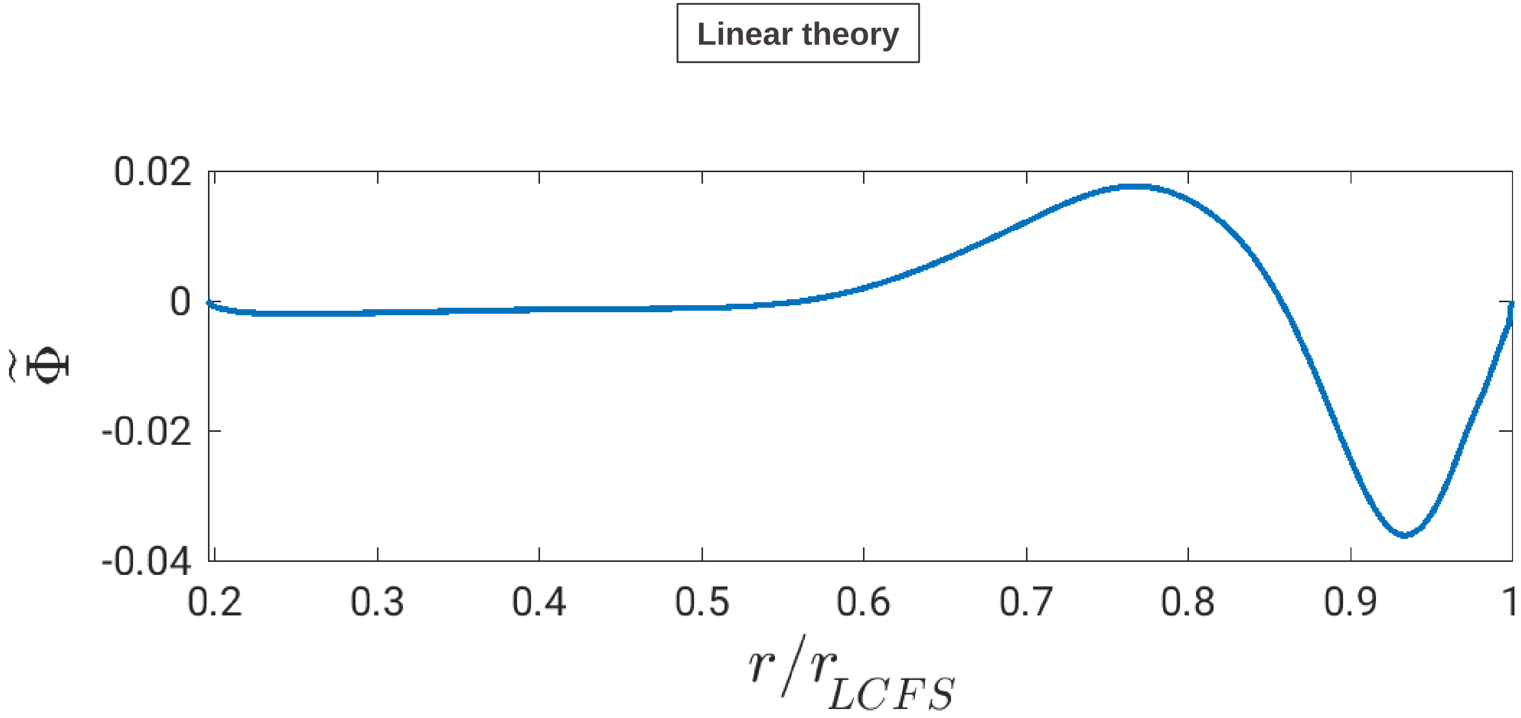
$m = 4$

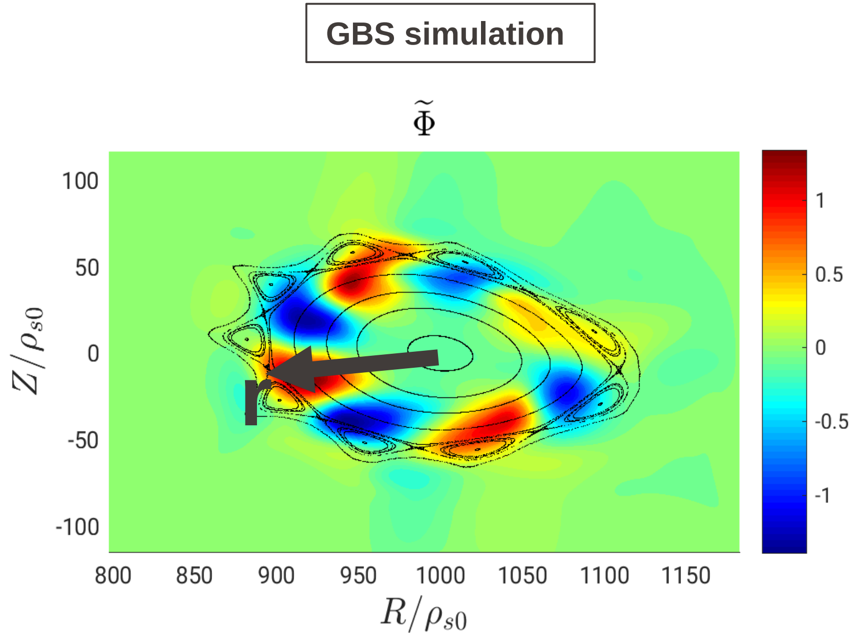
$n = 5$




GBS simulation

# Linear theory predicts the observed mode



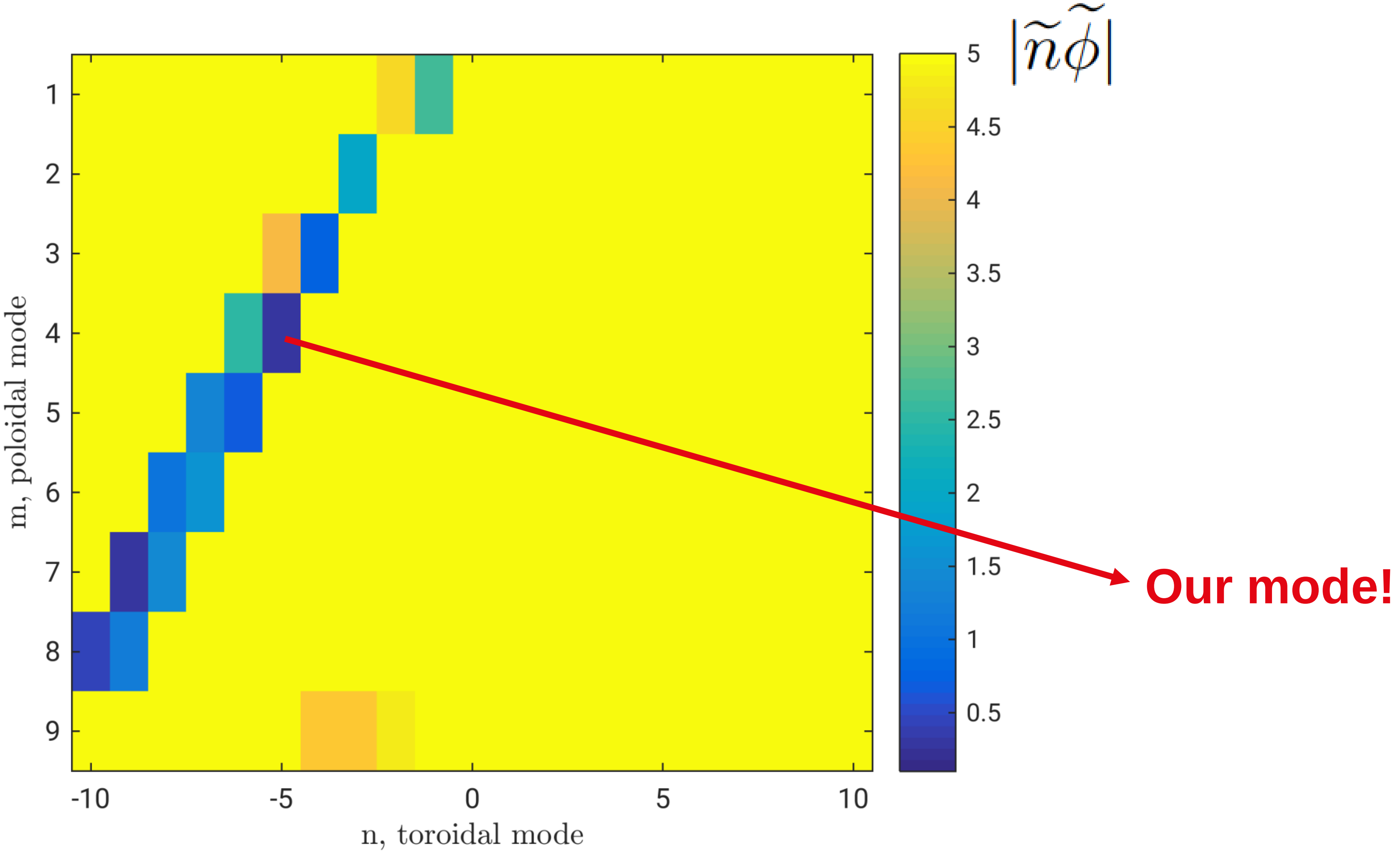
# Is the linear mode able to transport the same $\Gamma_{ExB}$?

$$\Gamma^c = \frac{k_y}{2B} |\widetilde{n\phi}| \sin(\delta_{\Phi-n})$$

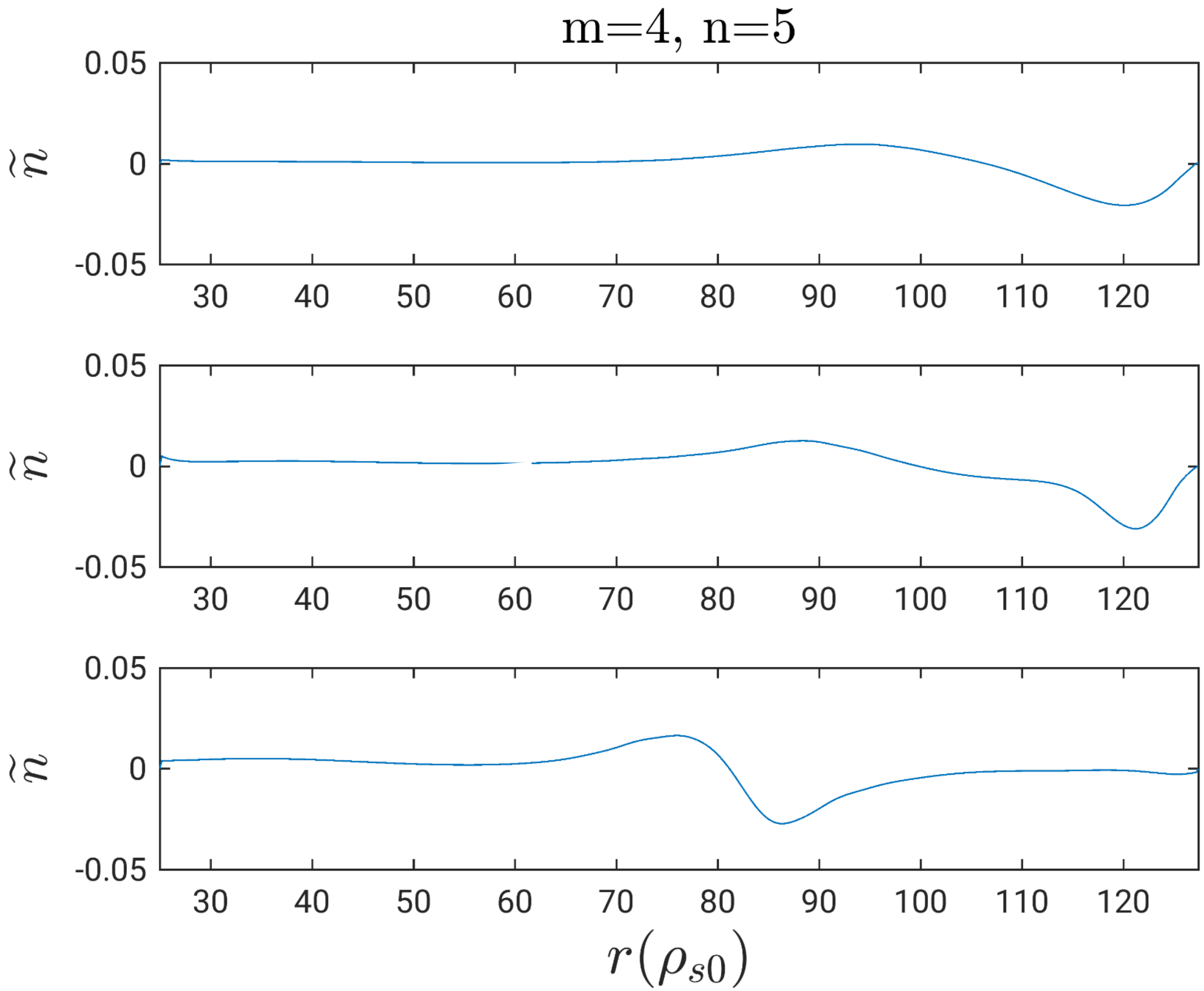
$$\int_{\partial\Omega} \Gamma^c dS = \int_{\Omega} \mathcal{S}_n \rho_* dV$$

$$|\widetilde{n\phi}| \sim \frac{2B}{k_y} \frac{\int_{\Omega} \mathcal{S}_n \rho_* dV}{\int_{\partial\Omega} dS} \frac{1}{\sin(\delta_{\Phi-n})}$$

# Linear mode is able to transport the same $\Gamma_{ExB}$



# Nature of the linear mode: balloning




**No drift-waves drive**

**($\nabla_{\parallel} p_e = 0$ in $V_{\parallel e}$ eq.)**

**No ballooning drive**

**(curvature(p)=0 in vorticity eq.)**

# Conclusions

- First global fluid simulations of a **stellarator** have been performed with **GBS code**
- Unlike tokamak experiments/simulations, **no broad-band turbulence nor blobs** were observed. Instead, a low **poloidal mode (m=4) dominates transport**
- Linear theory points to **ballooning mode**
- Is this coherent mode a property of the configuration used?

# Technical difficulties

- Number of grid points in toroidal direction (Nphi=200) -> dt ~ 3e-6

- Broad parameter space in the magnetic field configuration

- Difficult to predict what happens in the stochastic region. Regions of very small connection length. Density may decrease quickly

- Boundary conditions. Difficult to run with magnetic BC on density and vorticity. Instead:

$$\partial_s n = 0 \quad \text{and} \quad \omega = 0$$