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Global fluid simulations of plasma turbulence in diverted stellarators

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The effect of 3D fields on boundary turbulence is an outstanding question

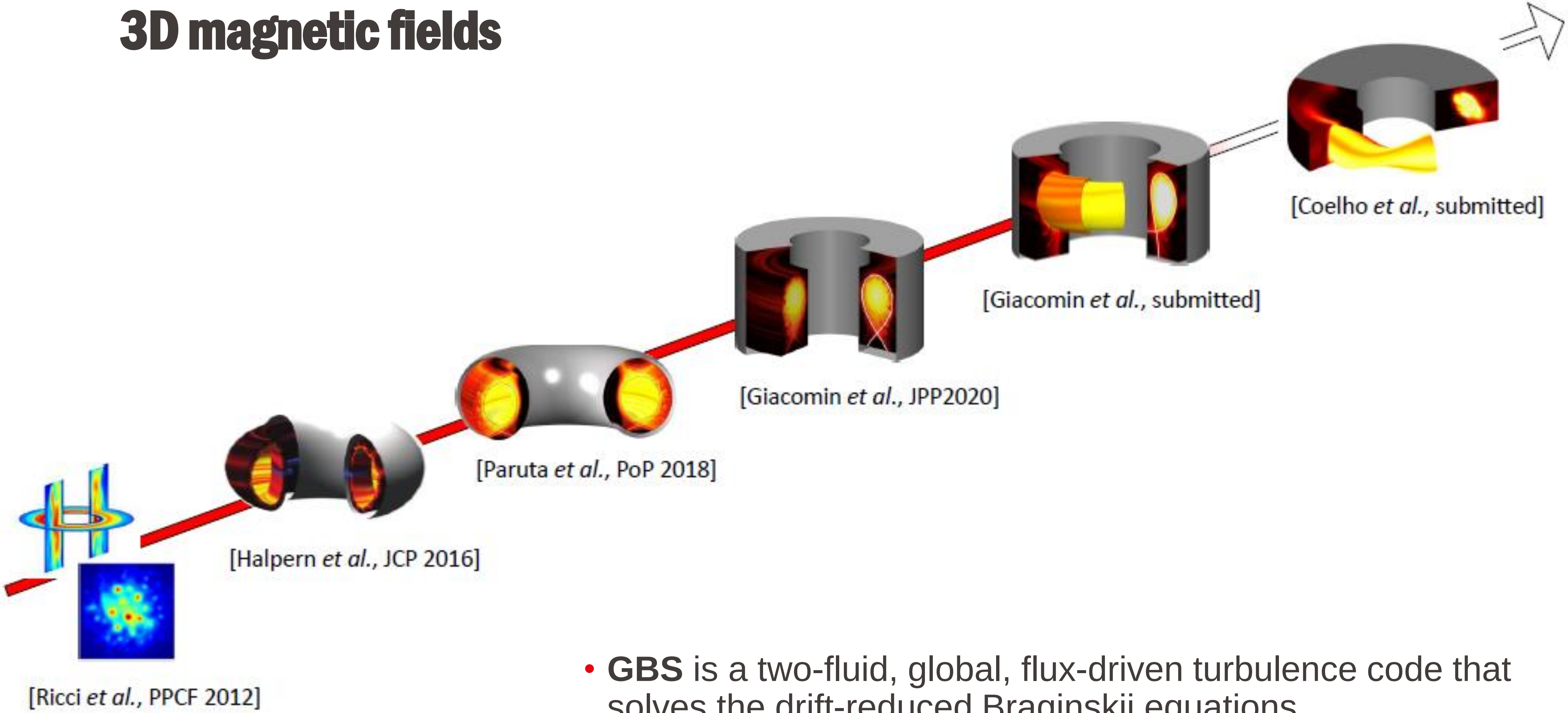
- **Tokamak boundary**: broad-band turbulence and blobs

- **ITER/DEMO:** Effect of RMPs on SOL turbulence and divertor heat loads are important**;** first-principle modelling still needed

- **W7-X boundary:** filaments bound to their flux surface [Killer 2021]
  quasi-coherent modes [Zoletnik 2020]

- In the **boundary**: collisionality may be high and turbulence time-scales longer than ω_{ci}^{-1}
  - fluid drift-reduced Braginskii equations [Zeiler, 1999]

GBS code can now simulate turbulence in 3D magnetic fields



- **GBS** is a two-fluid, global, flux-driven turbulence code that solves the drift-reduced Braginskii equations

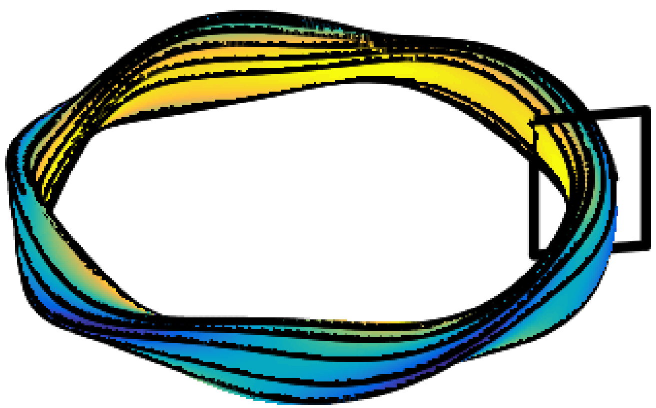
GBS solves the drift-reduced Braginskii equations

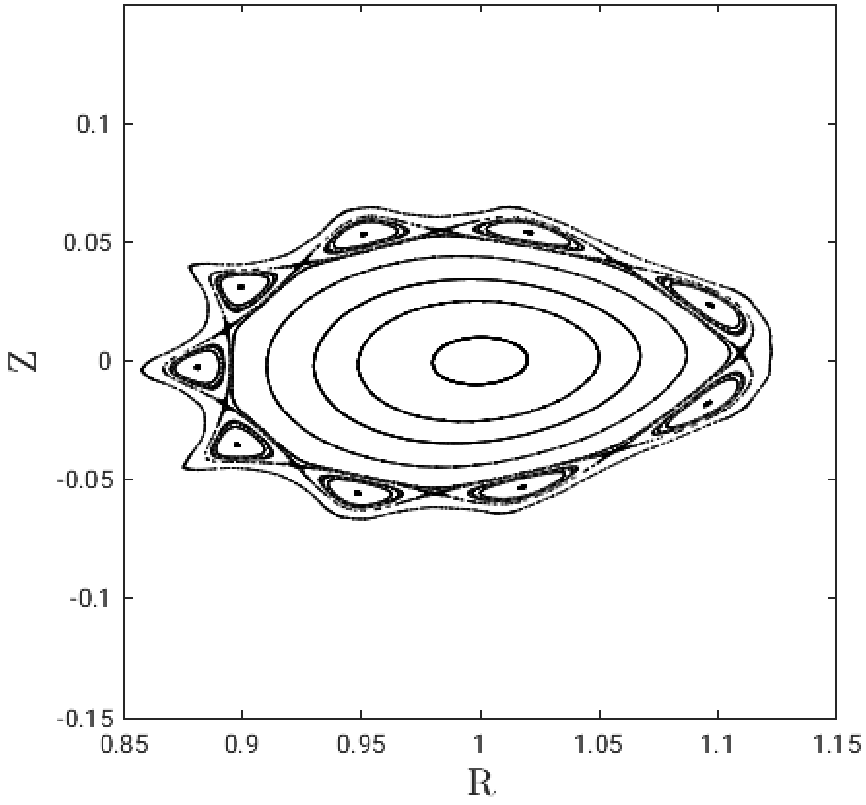
- Set of equations for $\mathrm{n}, \mathrm{T_e}, \mathrm{T_i}, \mathrm{V_{\parallel e}}, \mathrm{V_{\parallel i}}, \omega, \phi$
  - Density (n) equation:

$$\frac{\partial n}{\partial t} + \nabla \cdot \mathbf{\Gamma}_{\mathrm{ExB}} + \nabla \cdot \mathbf{\Gamma}_{\mathrm{dia}} + \nabla \cdot \mathbf{\Gamma}_{\parallel e} = \mathcal{S}_n$$

  - Electron and ion temperatures (T_e, T_i) equations: energy conservation
  - Parallel electron and ion velocities ($V_{\parallel e}, V_{\parallel i}$): parallel force balance
  - Electrostatic potential (Φ): obtained from vorticity (quasi-neutrality)

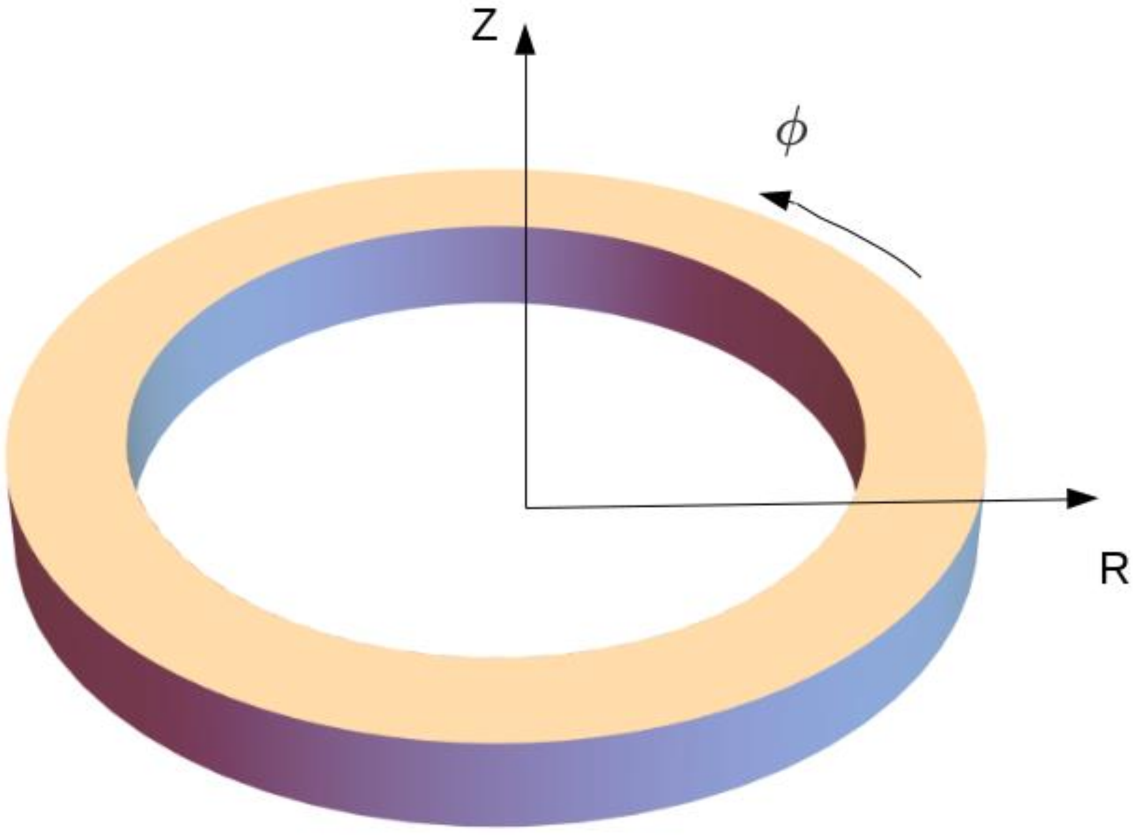
We simulate a 5-field period stellarator with a 5/9 chain of islands

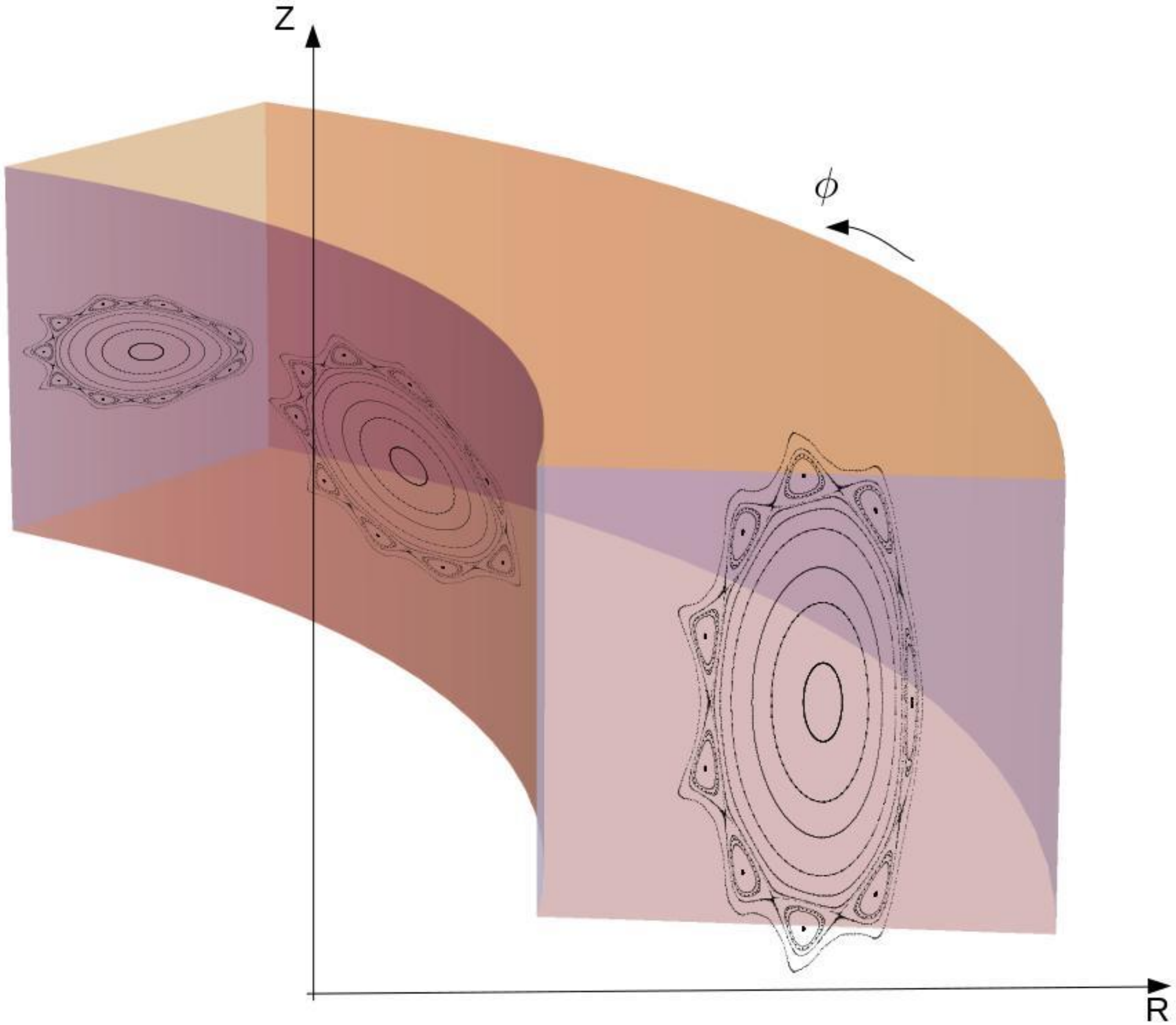




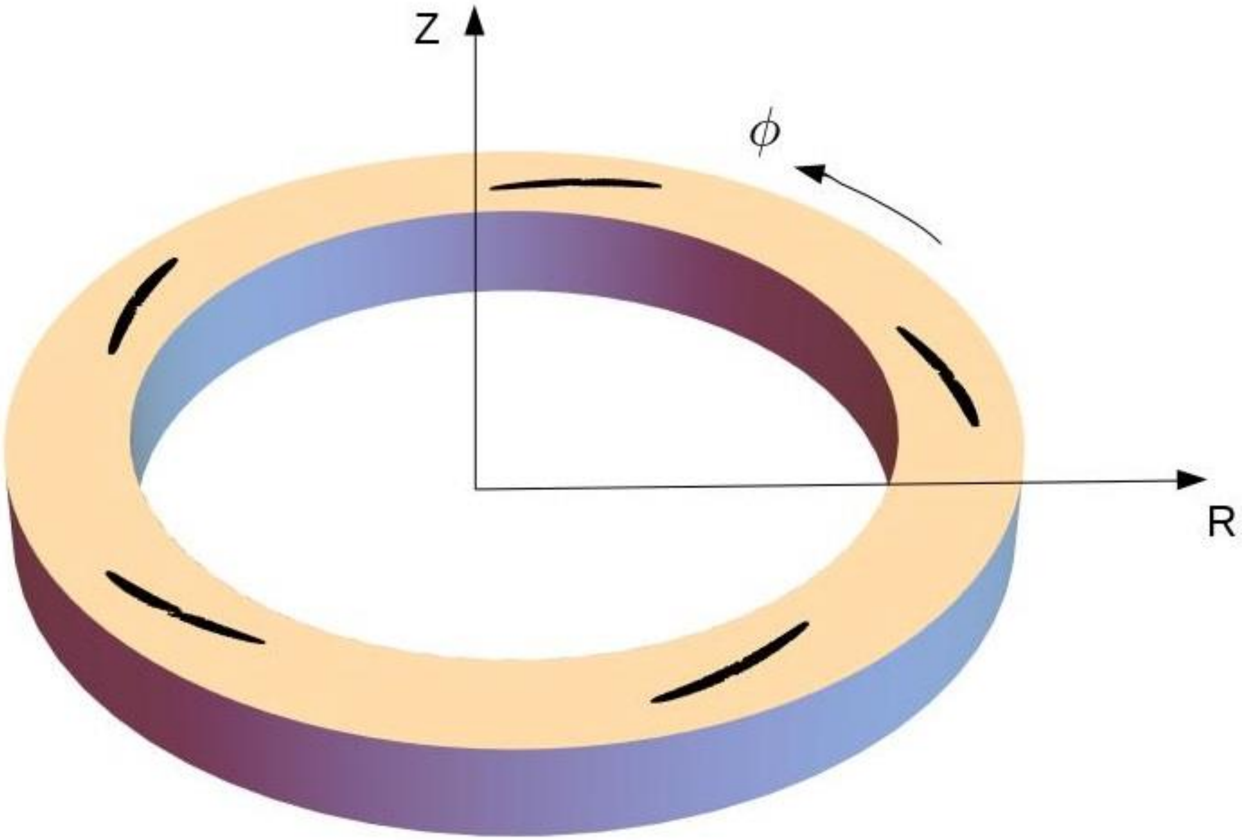
- Magnetic field is an analytical solution in vacuum [Dommashck 1986]

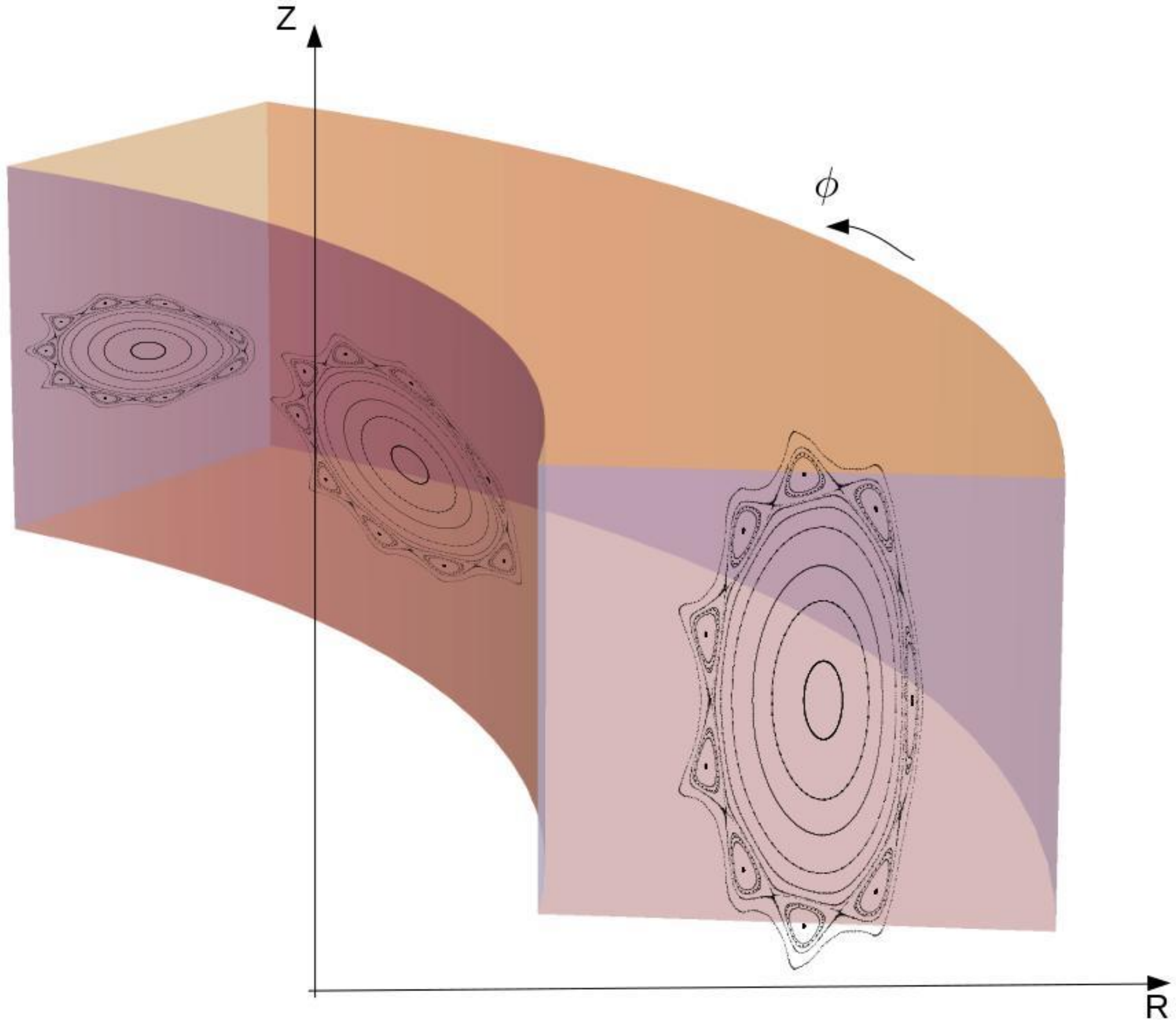
GBS domain boundary intersects divertor islands



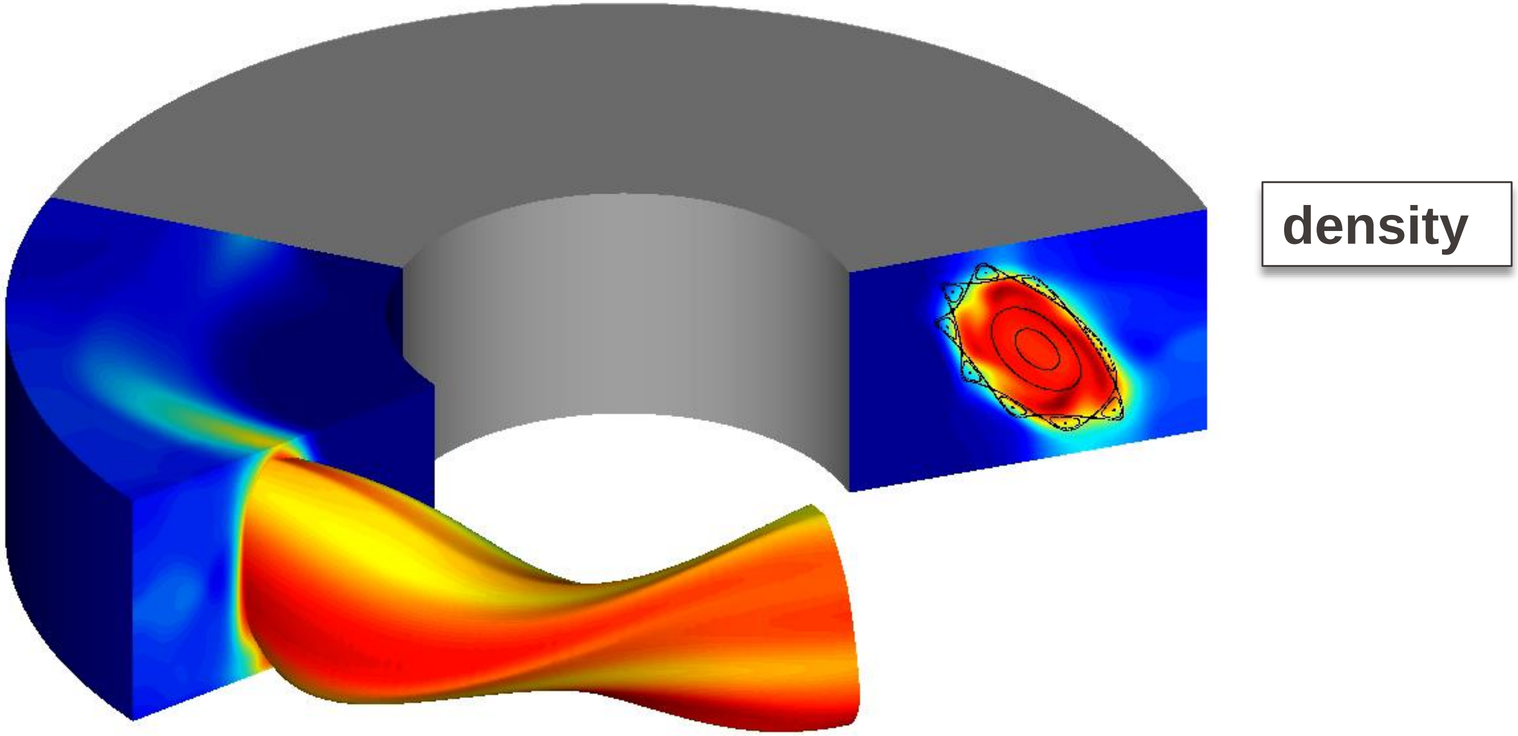


GBS domain boundary intersects divertor islands



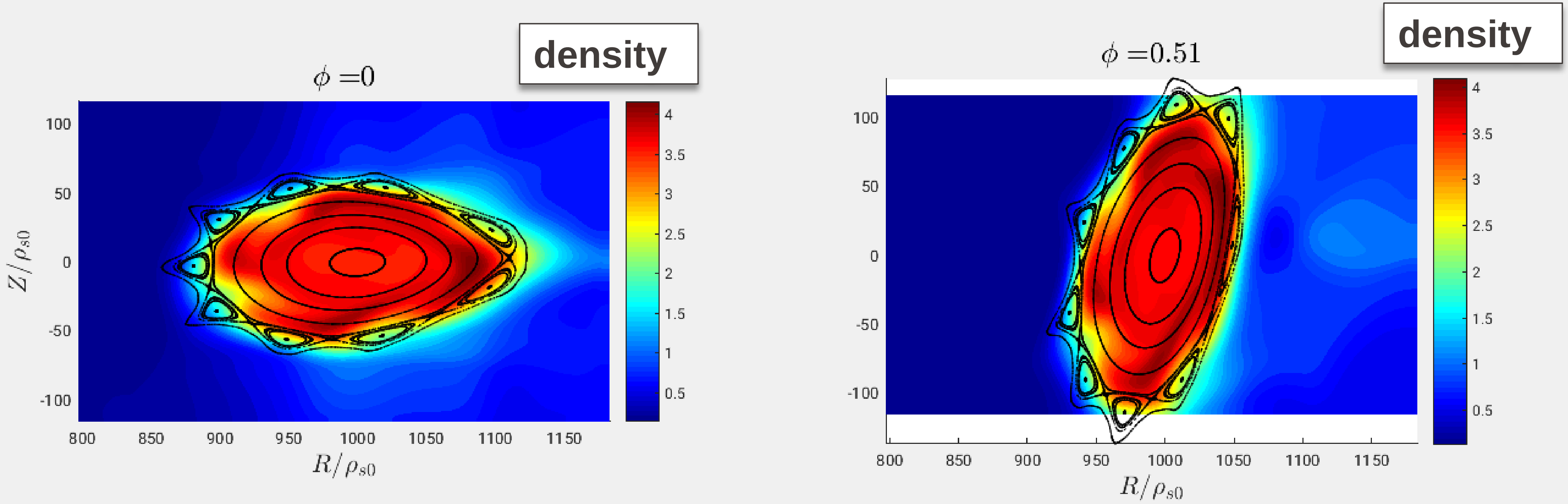


Global fluid simulation of diverted stellarator



- No separation between equilibrium and fluctuating quantities
- Density and temperature sources generate the gradients that drive turbulence

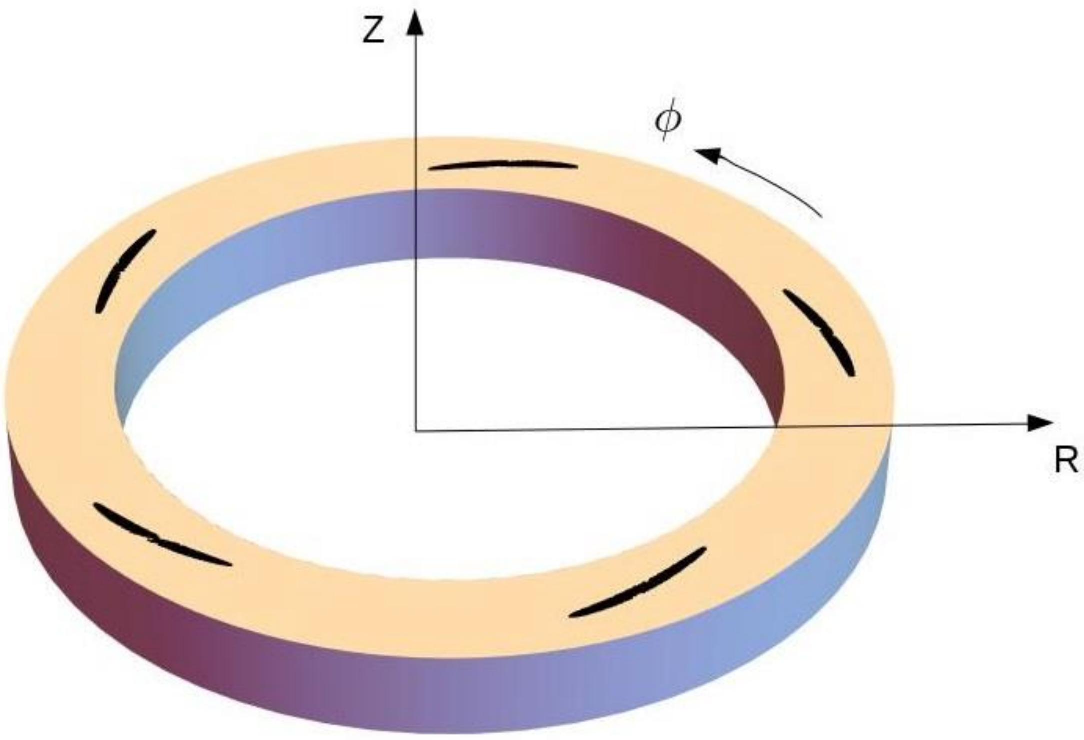
Steady-state of simulation dominated by coherent mode

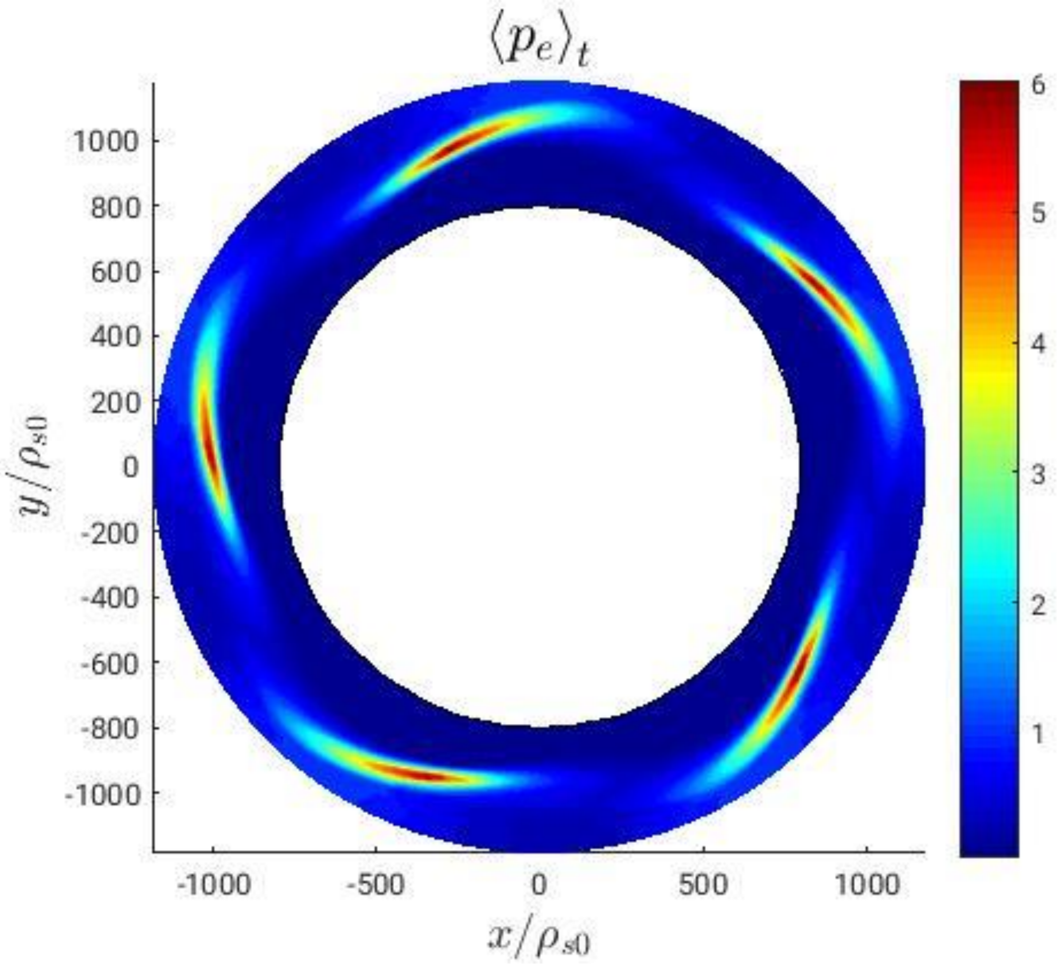


- An m=4 mode dominates the global dynamics
- Mode rotates with ~ ion diamagnetic frequency
- No broad-band turbulence
- Radial turbulent transport due to $< \tilde{\Gamma}_{\text{ExB}} >_t = < \tilde{n}\tilde{V}_{\text{ExB}} >_t$ balances source

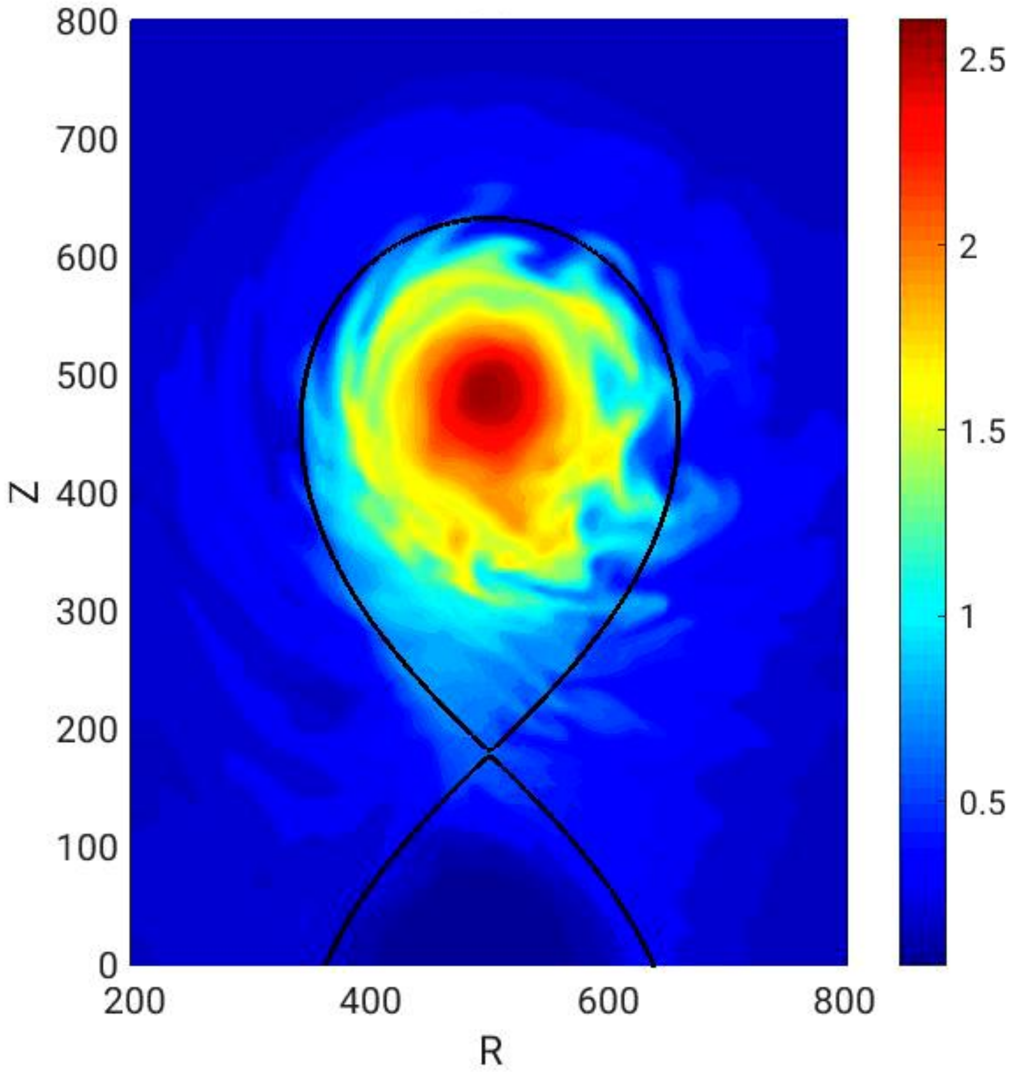
Effectiveness of the island divertor

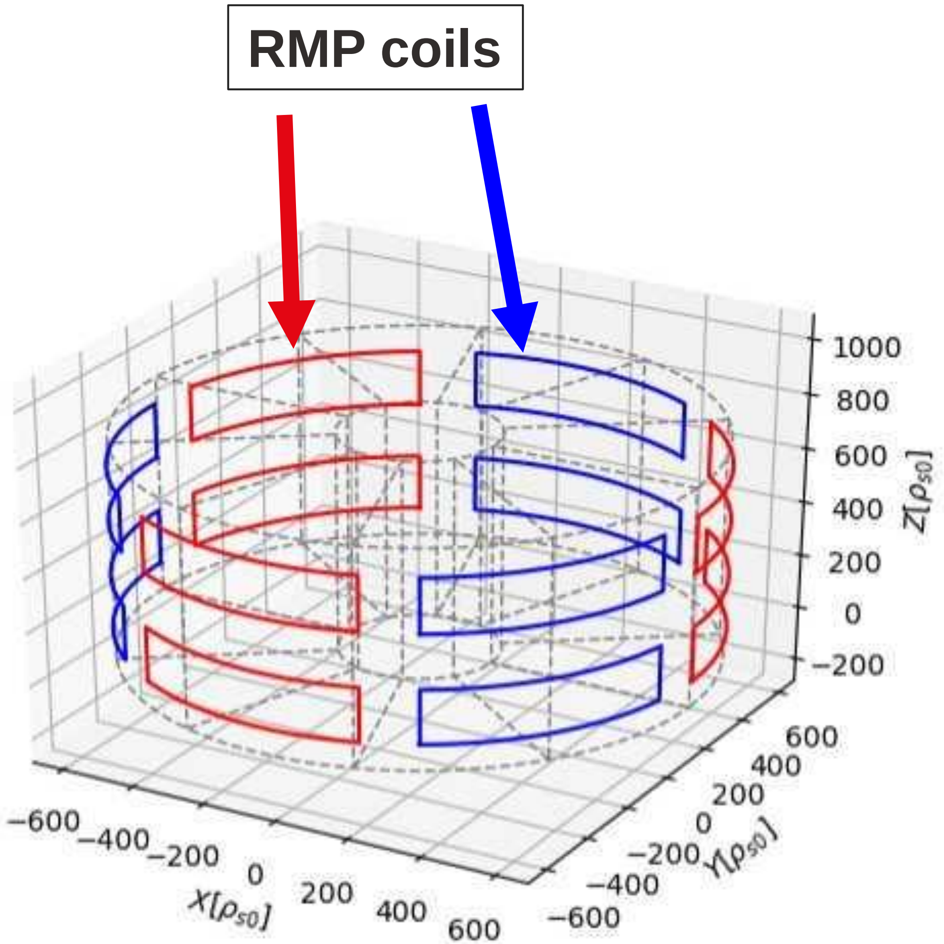
- On the **TOP** of the simulation box, pressure is maximum where field lines strike:





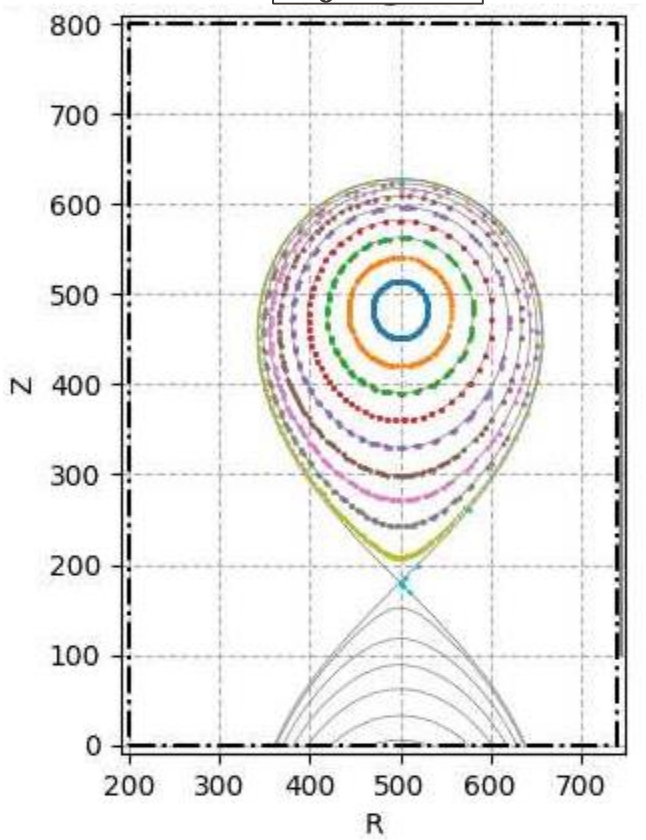
Leveraging stellarator simulations we are now implementing 3D effects in tokamaks



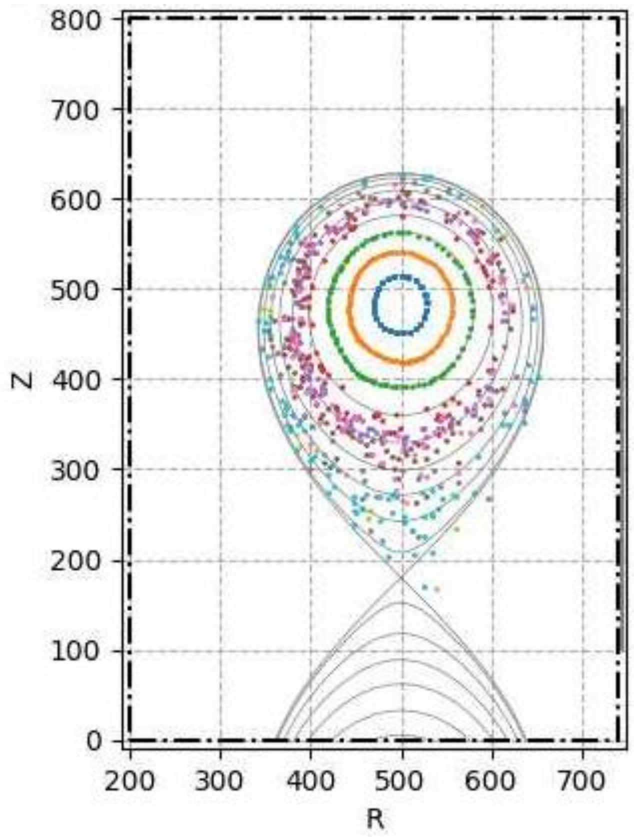


Poincaré plots with increasing amplitude of perturbation

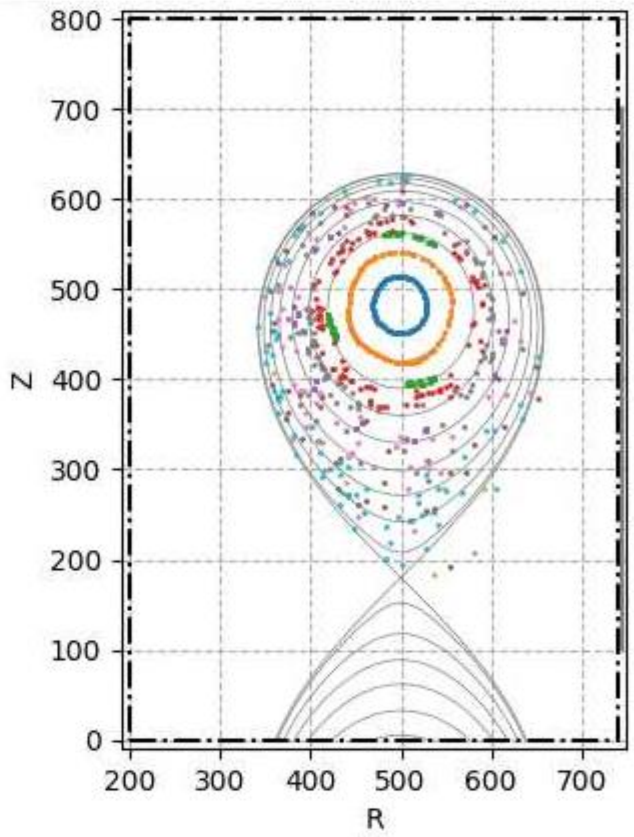
$\frac{\delta B}{B_0} = 0\%$



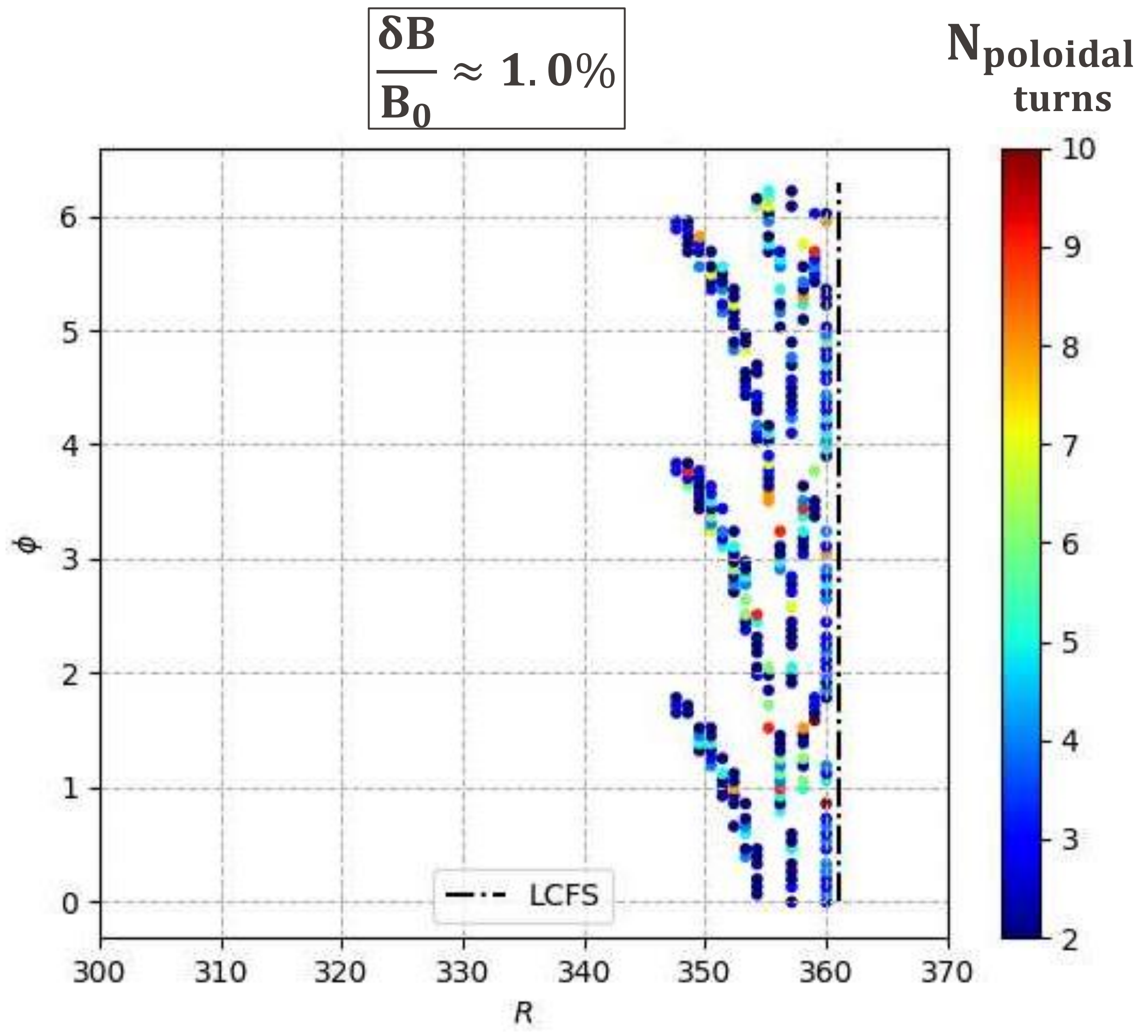
$\frac{\delta B}{B_0} \approx 1.0\%$

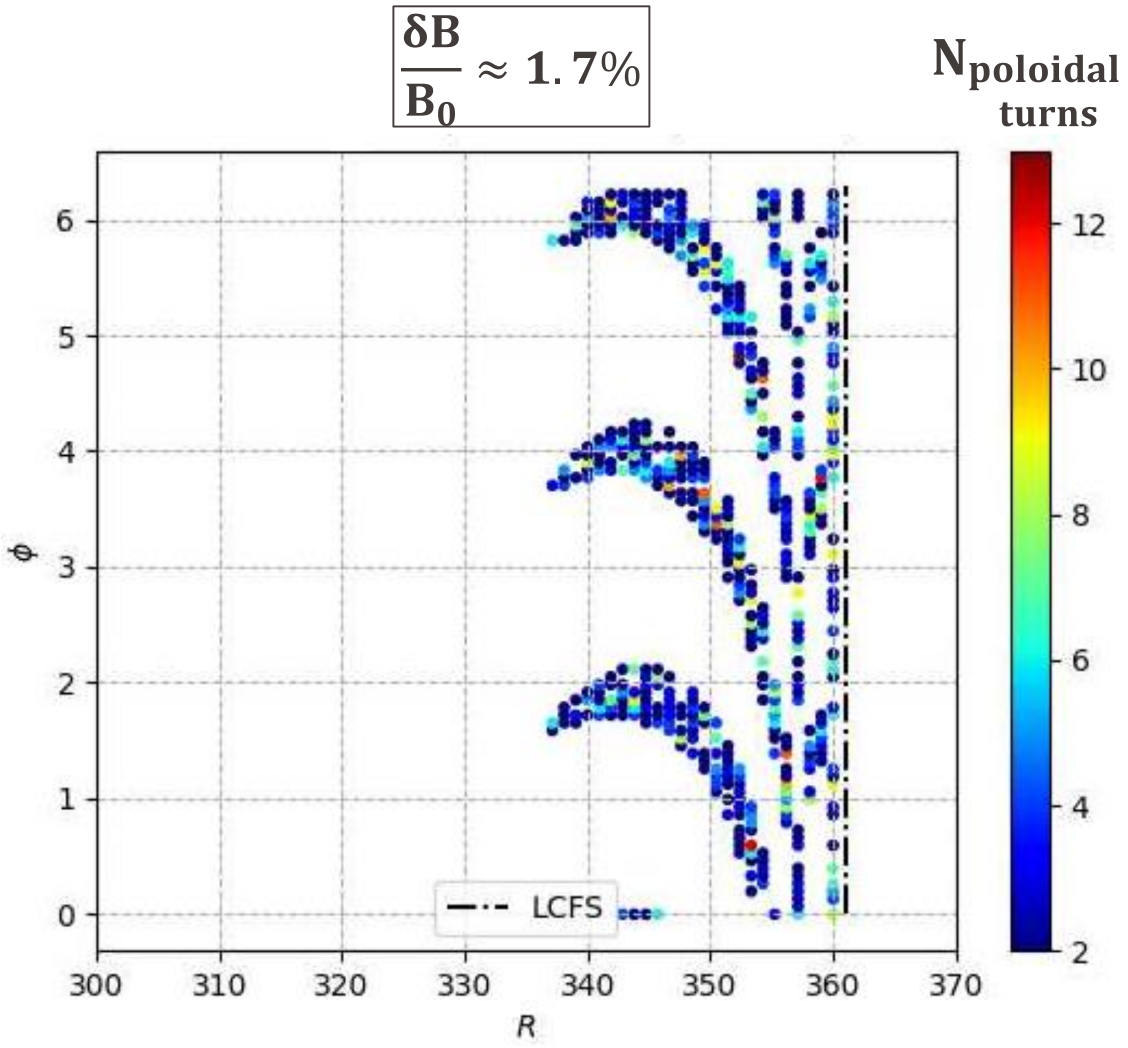


$\frac{\delta B}{B_0} \approx 1.7\%$



Footprints on the left divertor plate





Conclusions & Future Work

- 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**
- **3D effects** are important on boundary turbulence
- Starting to study the **impact of RMPs** on the boundary turbulence