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## European edge fluid modelling tools towards self-consistent reactor-relevant conditions

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### BACKGROUND

- Project gathering European expertise to progress towards **self-consistent fluid modelling of the edge plasma in reactor-relevant conditions** (EUROfusion TSVV3)
- Strategy: progressively incorporate in turbulence codes necessary ingredients to model divertor regimes

	Self-consist. $\perp$ transport	Neutrals	Impurities	Plasma and wall geom.	3D equilibria	Acceptable runtime
Mean-field		✓	✓	✓	~	~
Turbulence	✓					

- 4 edge turbulence codes involved: **FELTOR, GBS, GRILLIX, SOLEDGE3X**

### MODELS

Upstream development of models:

- revised **sheath BC** for highly collisional conditions: [D. Tskhakaya, in prep.]

$$M_{\parallel} = 1 + \chi - \sqrt{\chi^2 + 2\chi} \quad \chi = \frac{(v_{mt}(1-\alpha) + v_{ei})x_0}{2c_s \sin \theta}$$

- Landau **non-local closure** implemented in GRILLIX [C. Pitzal, submit. PoP]

- multi-temperature **collisional closure** [M. Raghunathan, PPCF 2022]

- gyro-fluid model** including collisions and reaction terms:

$$\Lambda_N = s_n - \Delta_{\perp} \left( \frac{ms_{p\perp}}{2qB^2} \right) - \nabla \cdot \left( \frac{ms_n \nabla_{\perp} \phi}{B^2} \right) \quad \Lambda_{mNU_{\parallel}} = s_{nu_{\parallel}}$$

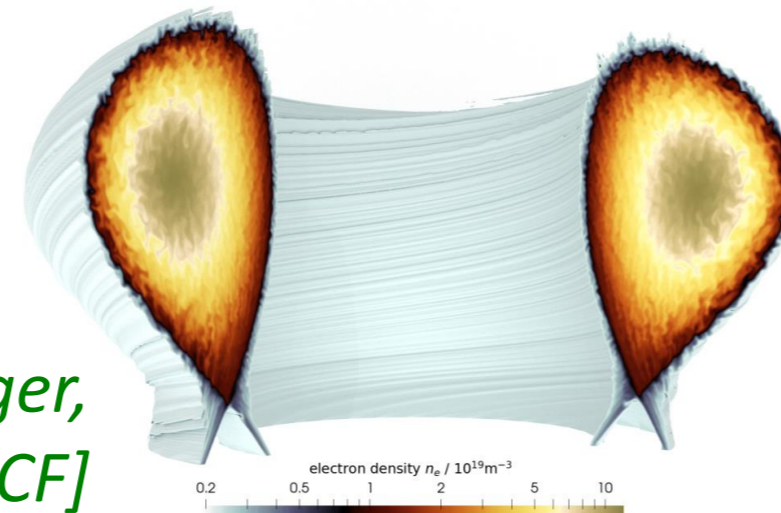
$$\Lambda_{P_{\perp}} = s_{p_{\perp}} - \Delta_{\perp} \left( \frac{ms_{r_{\perp}}}{2qB^2} \right) - \nabla \cdot \left( \frac{ms_{p_{\perp}} \nabla_{\perp} \phi}{B^2} \right) \quad \Lambda_{E_{\parallel}} = s_{e_{\parallel}} \quad [M. Wiesenberger, J. Phys.: Conf. Series 2022]$$

### COMPLIANT PLASMA AND WALL GEOMETRIES

#### ARBITRARY AXISYMMETRIC PLASMA GEOMETRY

All codes compliant with arbitrary axisymmetric magnetic geometries but with different technical choices

[M. Wiesenberger, submitted to PPCF]

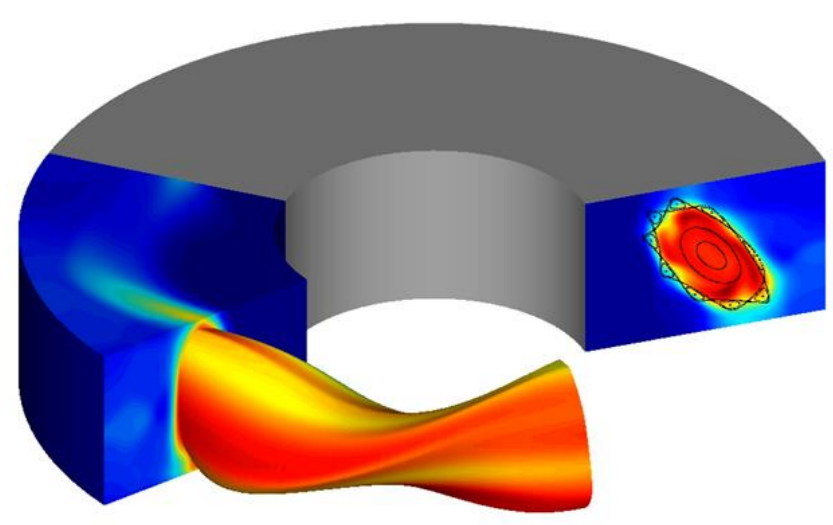


Code	Poloidal grid type	Grid alignment	Poloidal discretization	Parallel / toroidal discretization
FELTOR	Structured, Cartesian	None	Discontinuous Galerkin	FCI
GBS	Structured, Cartesian	None	Finite Differences	Finite differences
GRILLIX	Unstructured, locally Cartesian	None	Finite Differences	FCI
SOLEDGE3X	Locally structured, curvilinear	Flux-surface	Finite Volumes	Finite volumes

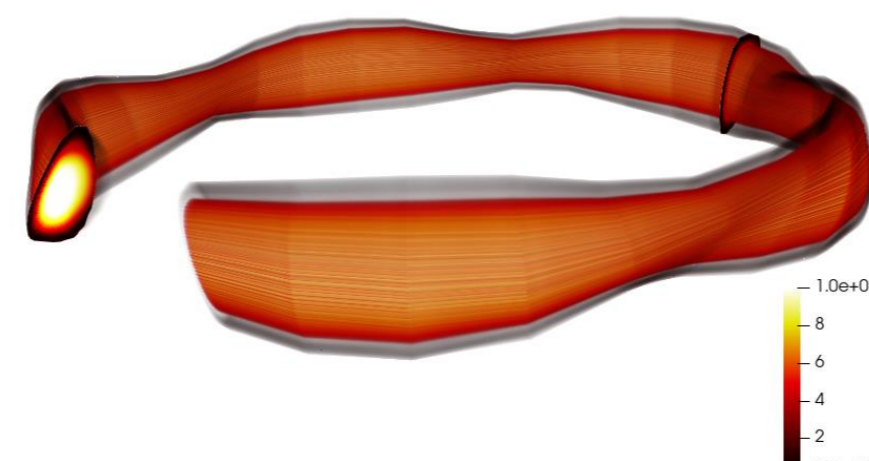
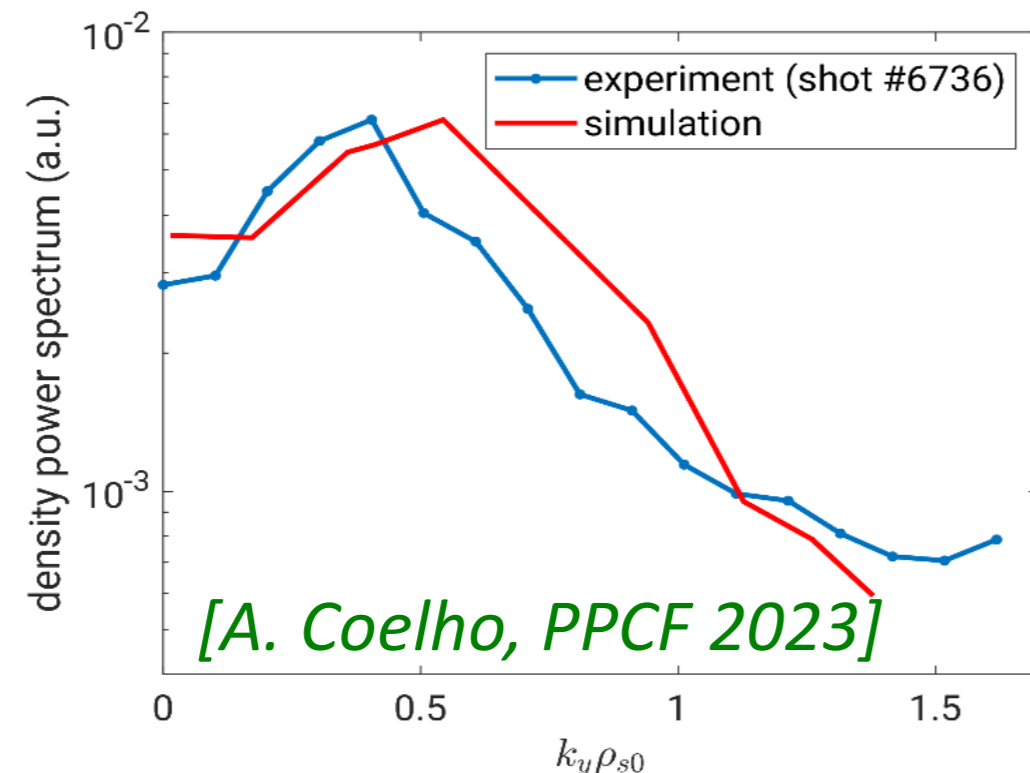
#### 3D MAGNETIC EQUILIBRIA

GBS and GRILLIX extended to 3D magnetic equilibria

- GBS confronted to TJ-K experiment, W7-AS proof-of-principle in GRILLIX



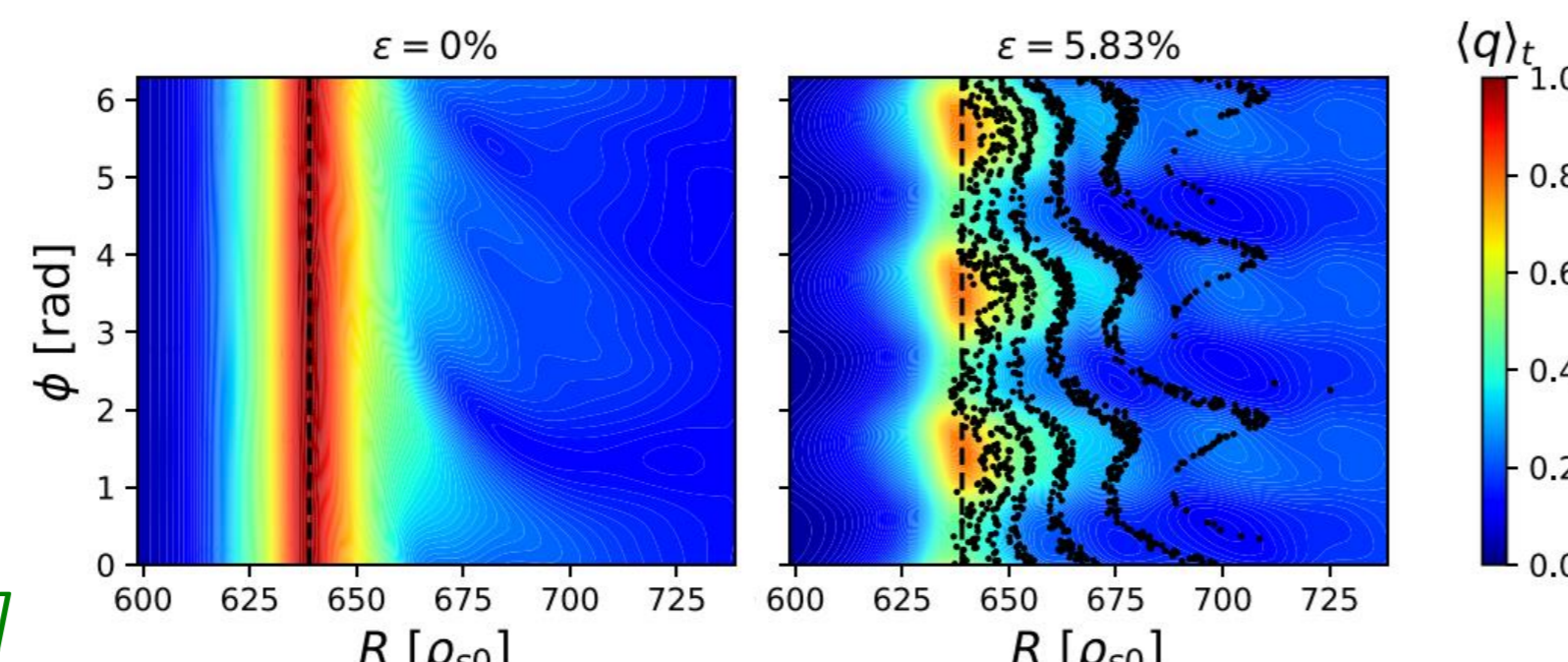
[A. Coelho, NF 2022]



[W7-AS geometry with GRILLIX]

- 3D turbulence with RMPs in GBS
  - RMPs impact turbulence but not transport level
  - 2D divertor heat flux pattern smoothed by turbulence

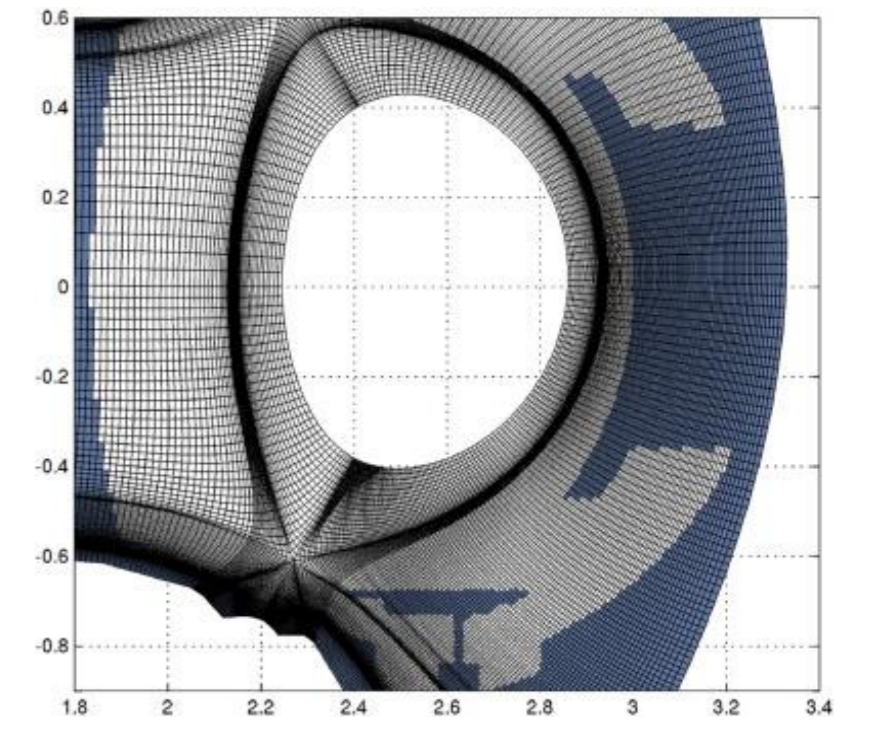
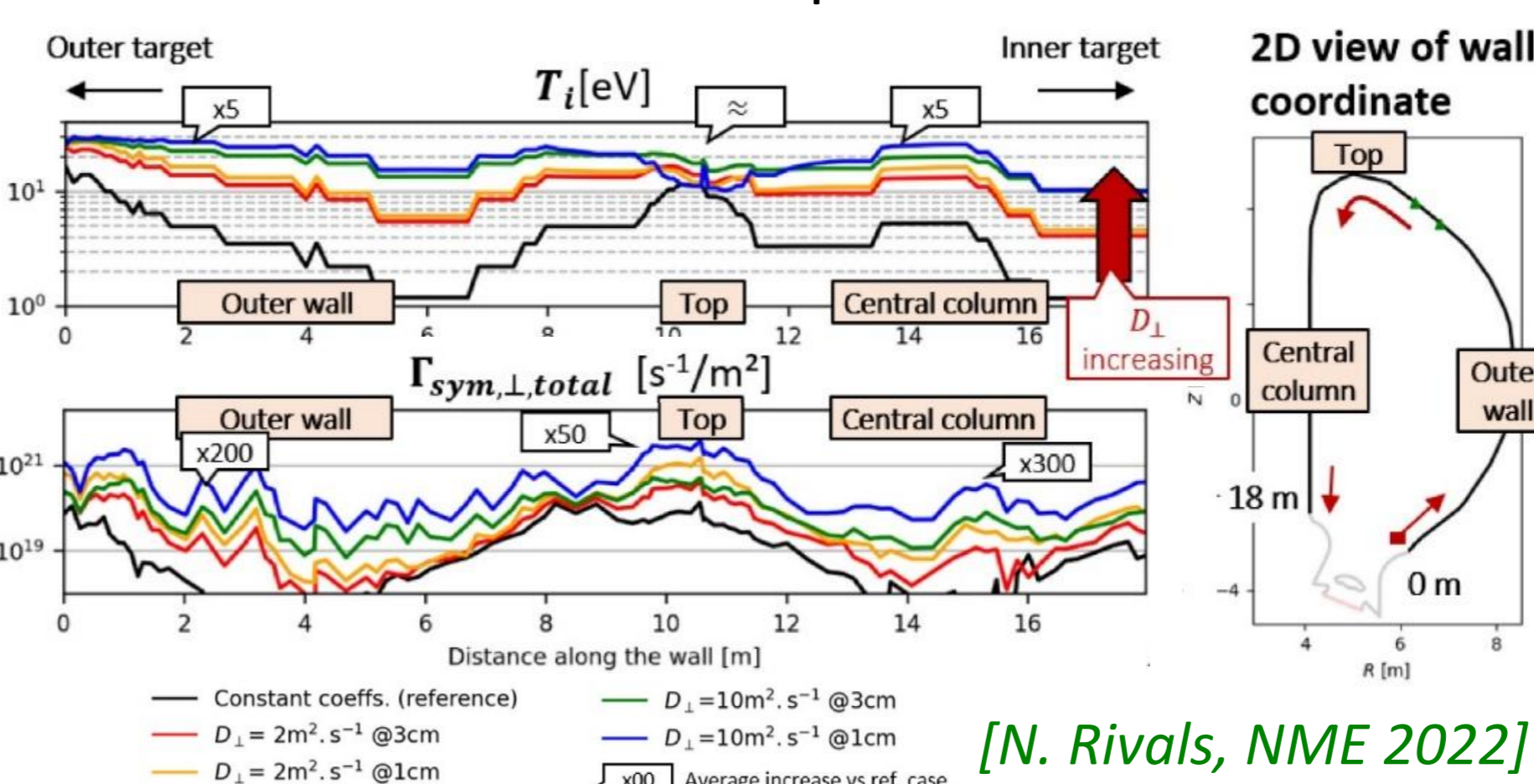
[T. Boinnard, NF 2023]



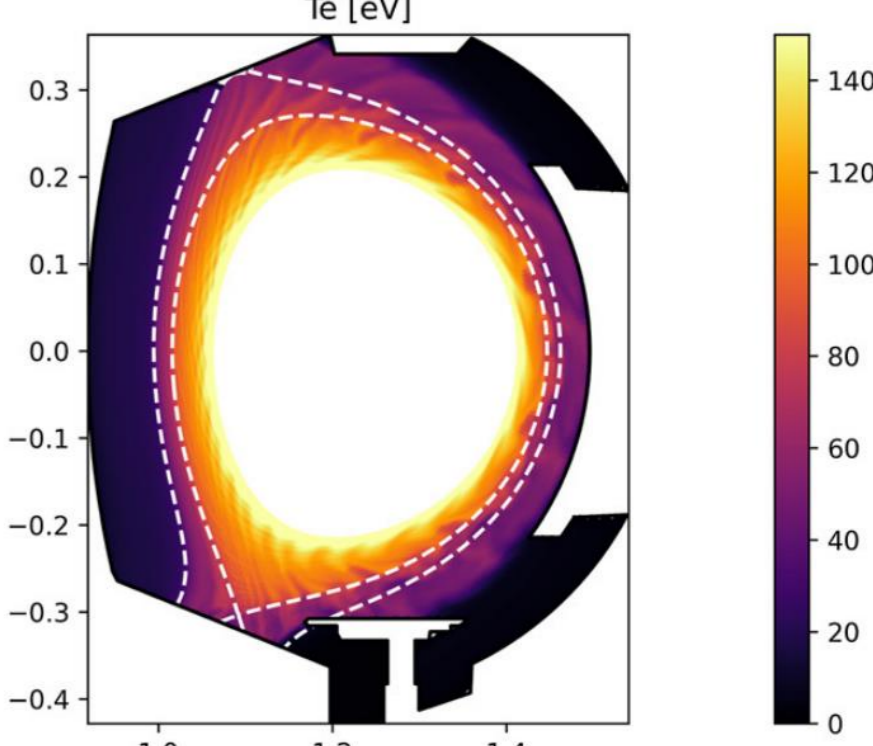
### CAPTURING ACCURATELY THE WALL GEOMETRY

Major challenge but mandatory for accurate density regimes

- Immersed boundaries in SOLEDGE3X, GRILLIX, FELTOR
- Combined with penalization in GRILLIX (non-local wall?) [A. Stegmeir, CPC 2023]
- Combined with curvilinear grid in SOLEDGE3X
- SOLEDGE3X simulations up-to-the-wall in WEST & ITER

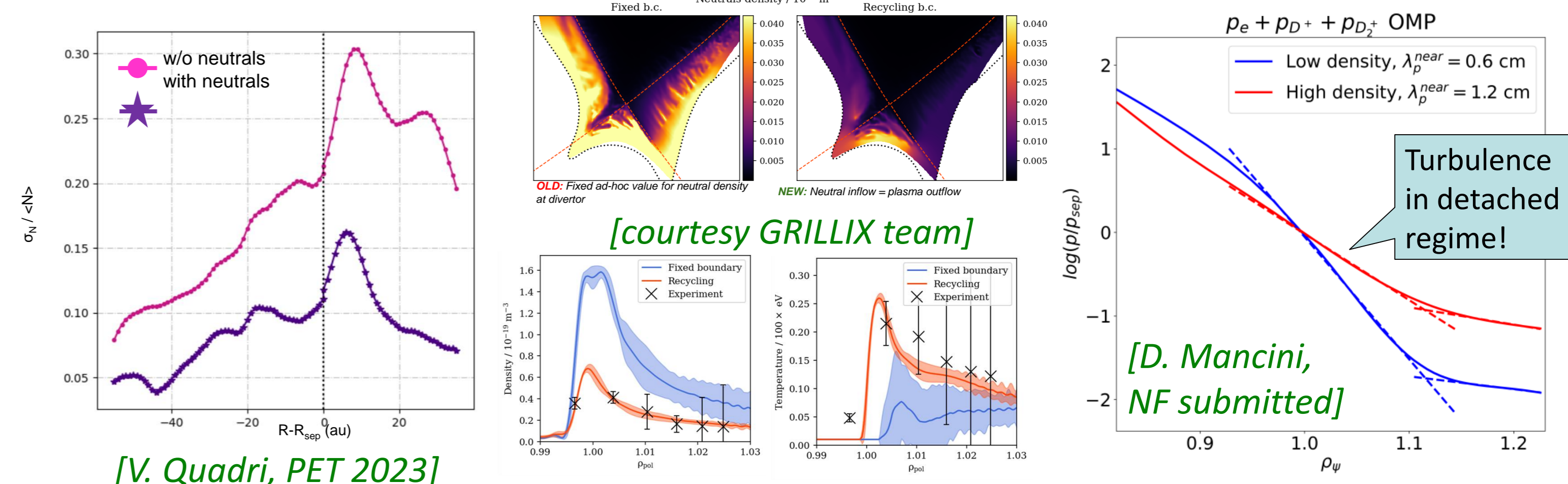


[H. Bufferand, NF 2021]

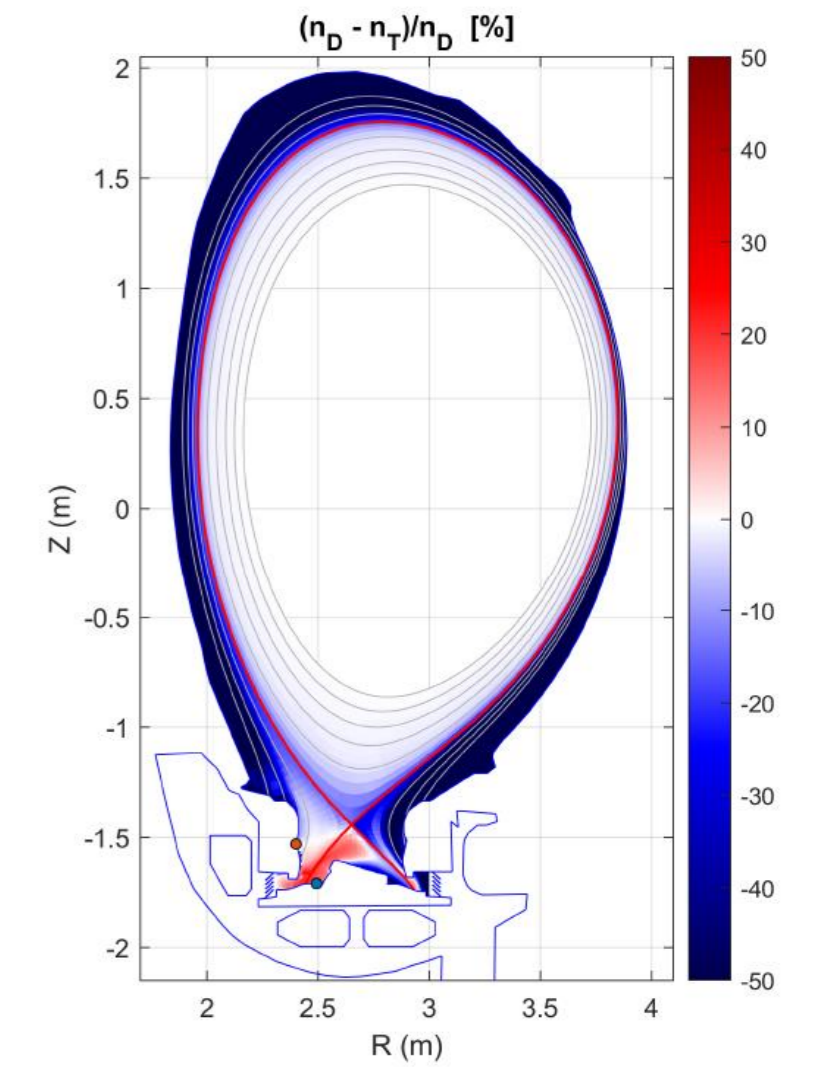
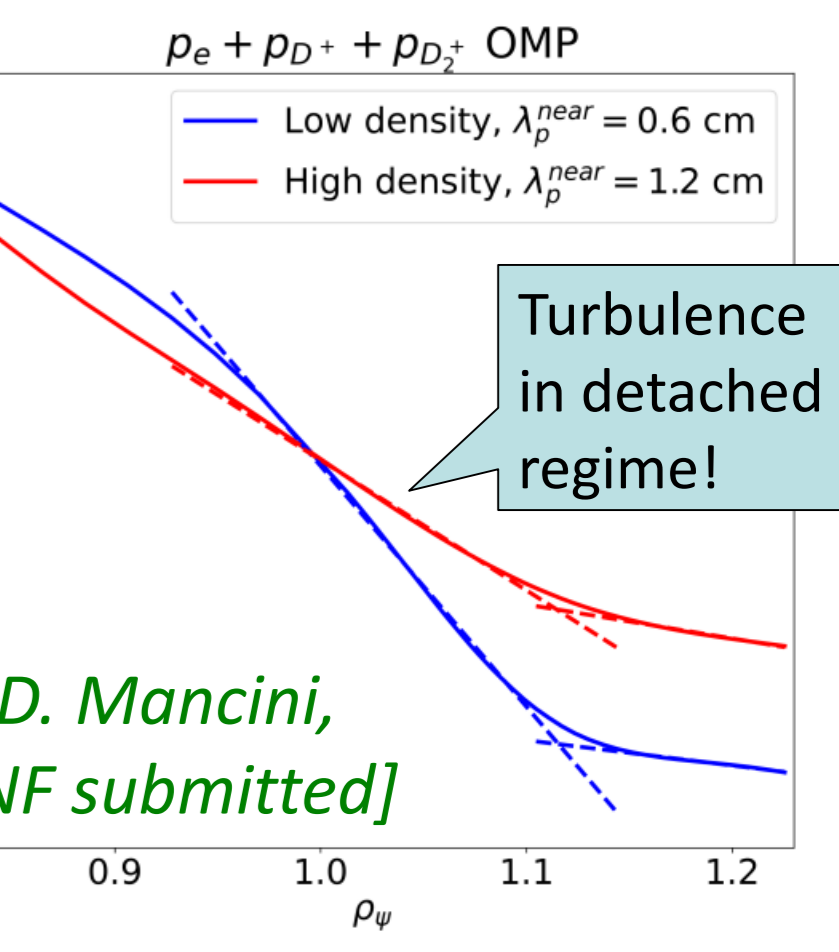


### NEUTRALS AND MULTISPECIES PHYSICS

- GBS, GRILLIX and SOLEDGE3X feature self-consistent neutrals models
  - kinetic (method of characteristics) in GBS
  - kinetic (EIRENE) in SOLEDGE3X, but limited to 2D or low resolution 3D
  - fluid (CX-dominated model) in GRILLIX and SOLEDGE3X [N. Horsten, NF 2017]
- Significant impact of neutrals on turbulence and transport in the edge plasma



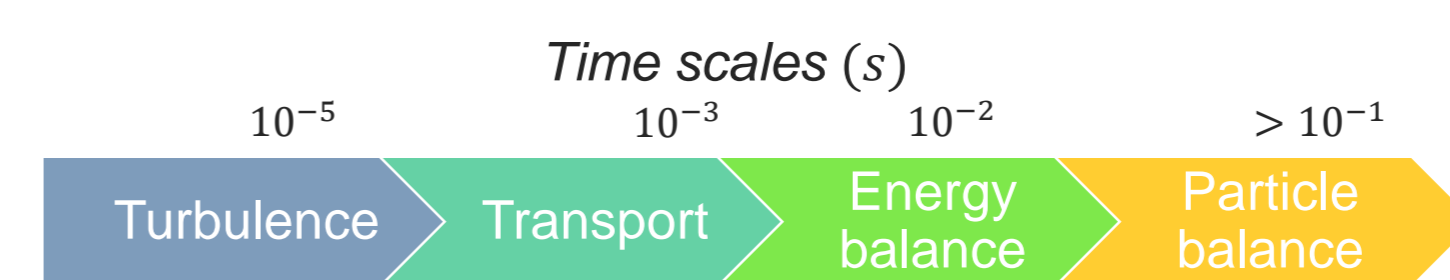
- Zhdanov closure (non trace impurities) implemented in GBS and SOLEDGE3X:
  - Applied to D-T-Ne cases => D/T imbalance in divertor [H. Bufferand, PPCF 2022]
  - Extension to 3D turbulence raises questions on tractability of numerical algorithm
- Common validation against dedicated TCv pulse in high-density regime started



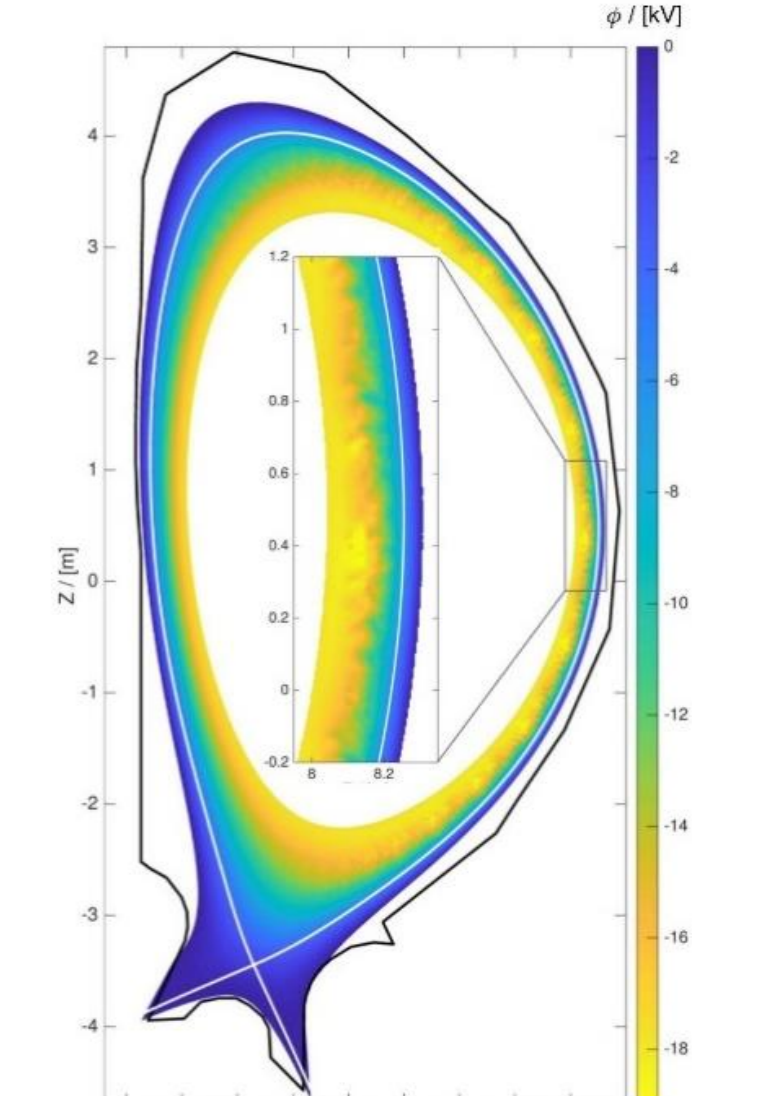
### UPSCALING SIMULATIONS

- Strong effort invested in parallel towards upscaling simulations to reactor size
  - Effort centered on linear solvers and GPU-ization
  - ITER size case in GRILLIX [A. Stegmeir, CPC 2023]
- Impact of neutrals possibly challenging:

$$\tau_{eq,n} \approx \frac{\tau_{transp}}{1-R} \quad R_E \sim 25\% \quad R_n > 99\%$$



- need scheme to accelerate convergence (e.g., [E. Kaveeva, NF 2018])



[ITER size case with GRILLIX]



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