

Theoretical scaling of the operational density limit in tokamaks and comparison to experimental data

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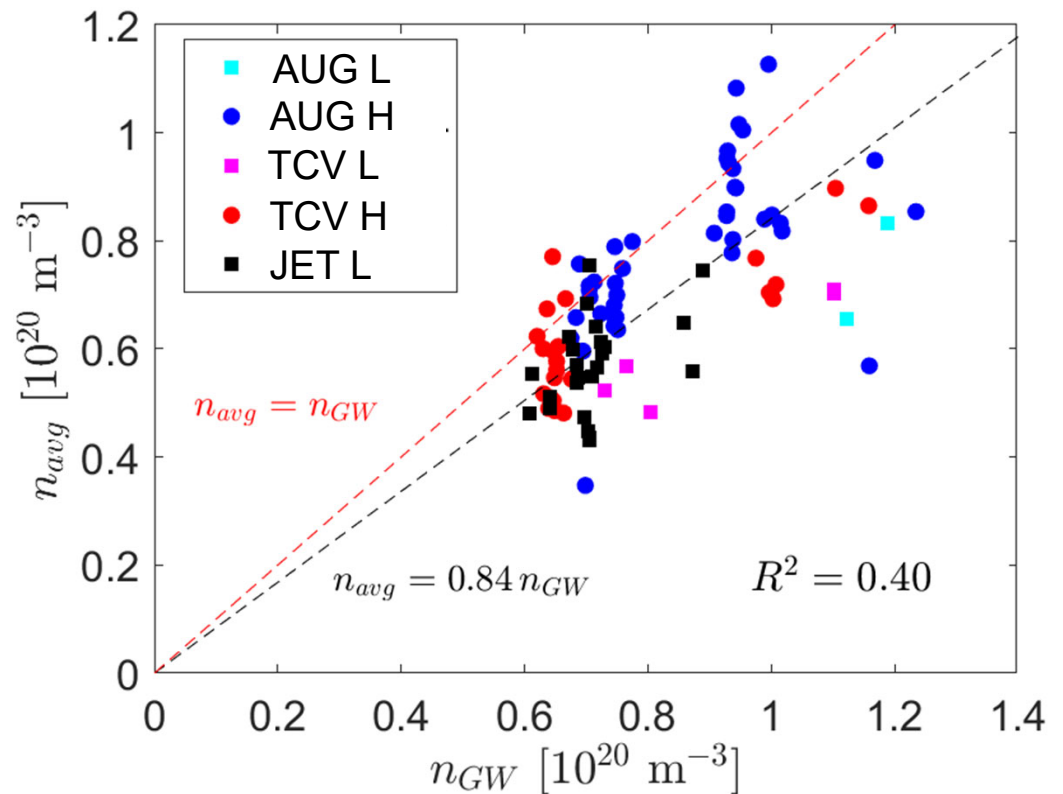
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EPFL Limited predictive capabilities of empirical Greenwald limit

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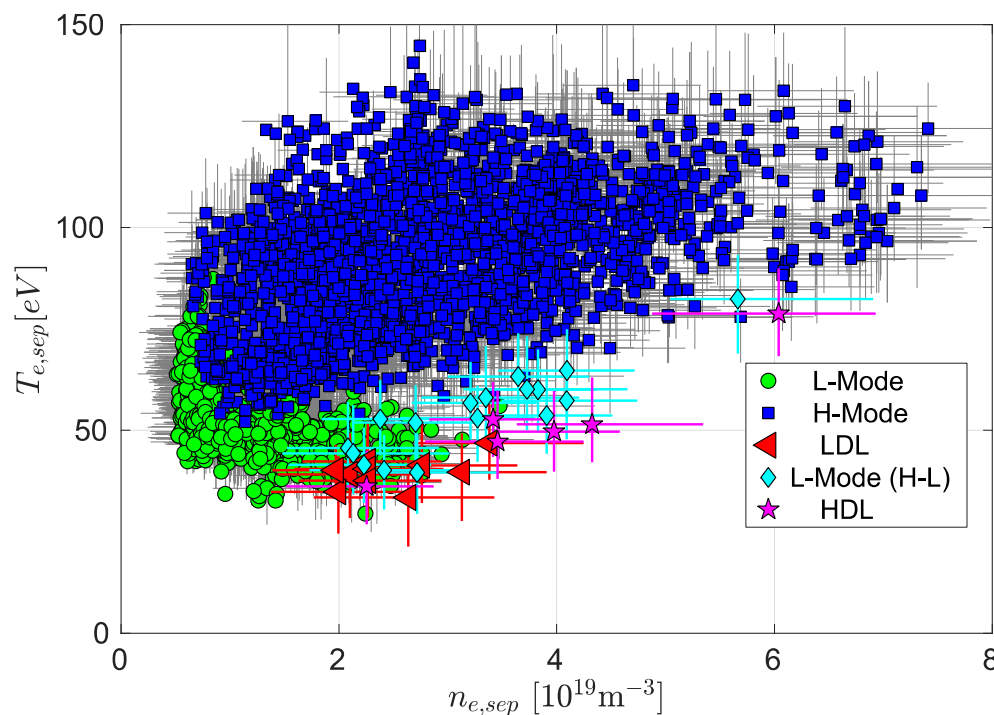
$$n_{GW} = \frac{I_p}{\pi a^2}$$



Maximum achievable density in real-time controlled discharges show hidden dependencies



Edge physics determines density limit



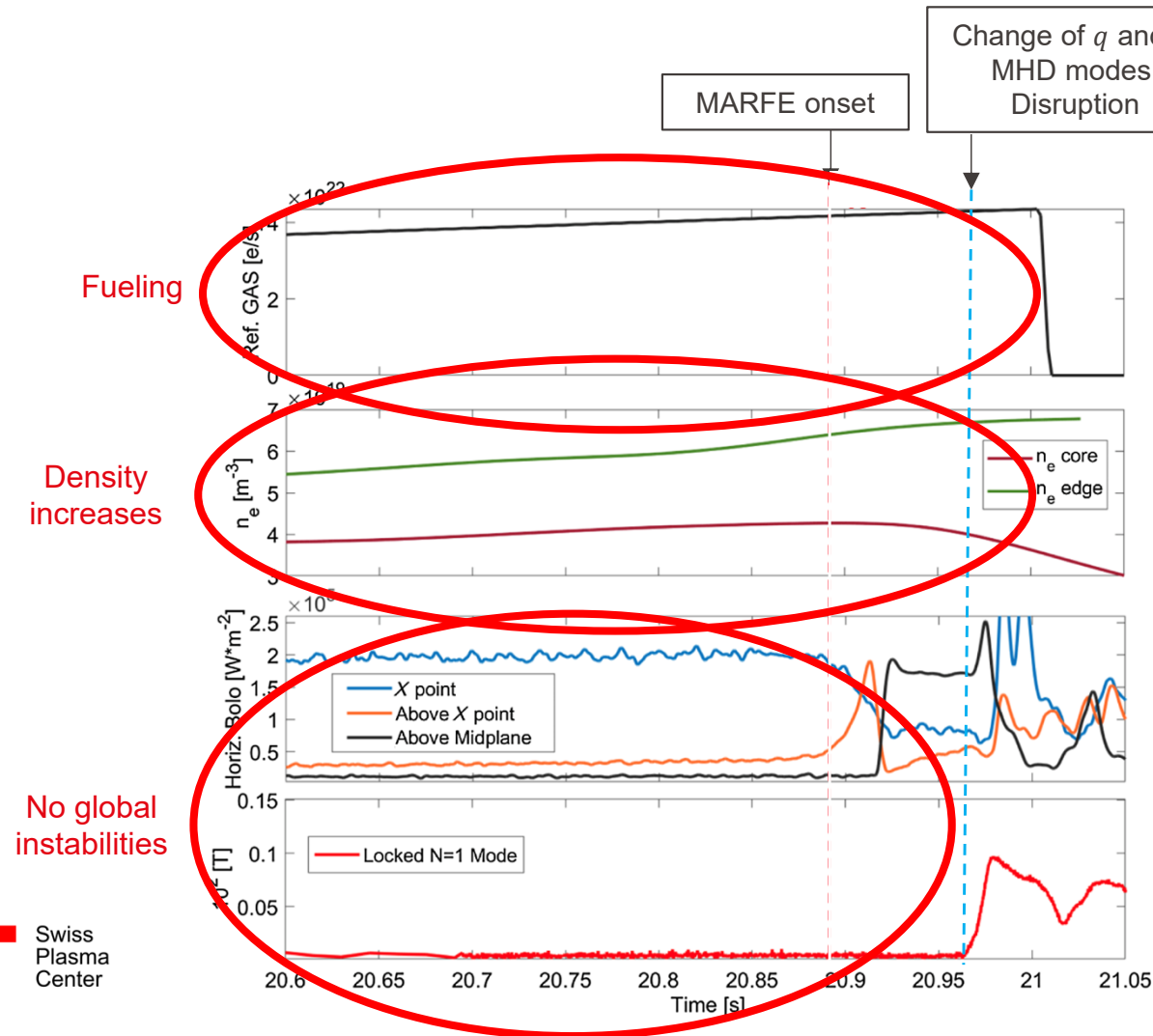
Manz et al., NF 2023

Two mechanisms, providing similar predictions for AUG [Manz et al., NF 2023] :

- Radiative collapse [Gates *et al*, PRL 2012; Zanca *et al* PRL 2017; Stroth *et al*, NF 2022].
- Enhanced turbulent transport [Rogers *et al*, PRL 1998; Eich *et al*, NF 2021; Brown *et al*, NME 2021; Singh *et al*, PPCF 2022].



MARFE onsets precedes disruption

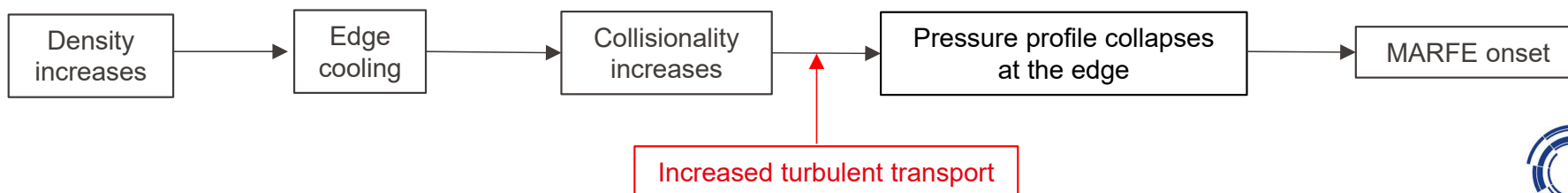
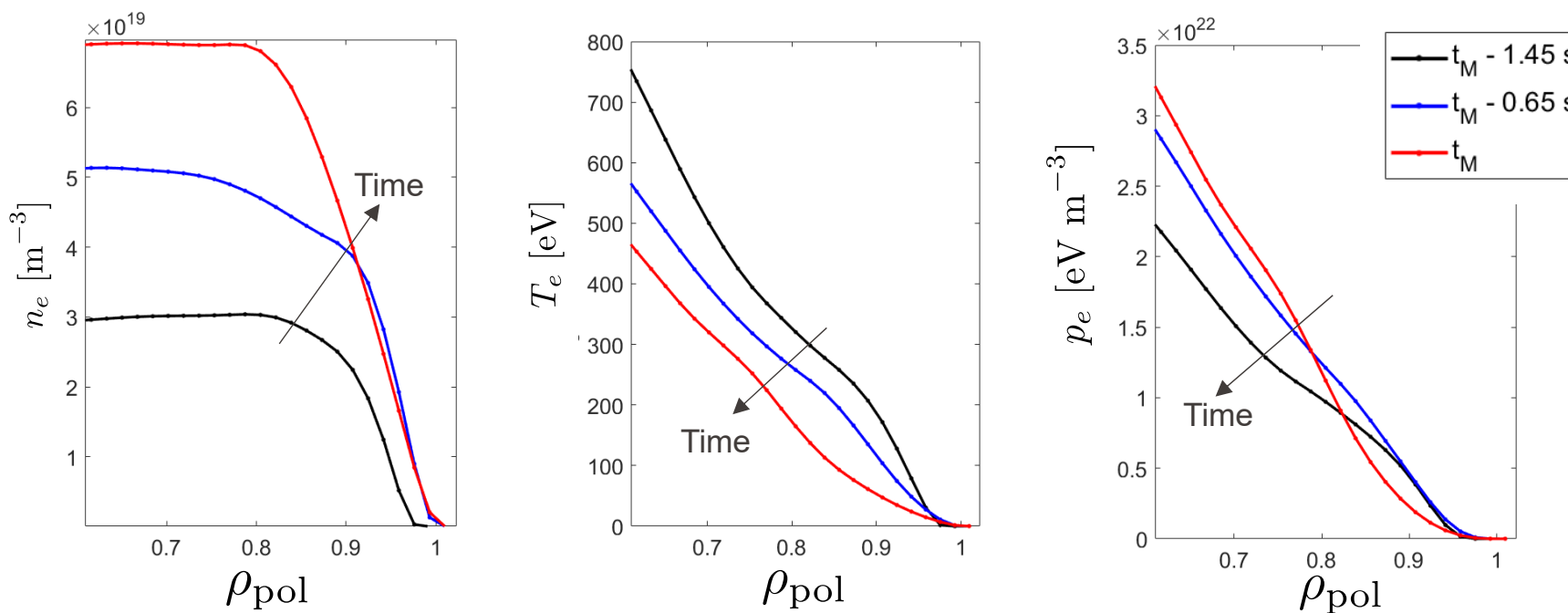


Phenomena triggering the MARFE are key to understand density limit

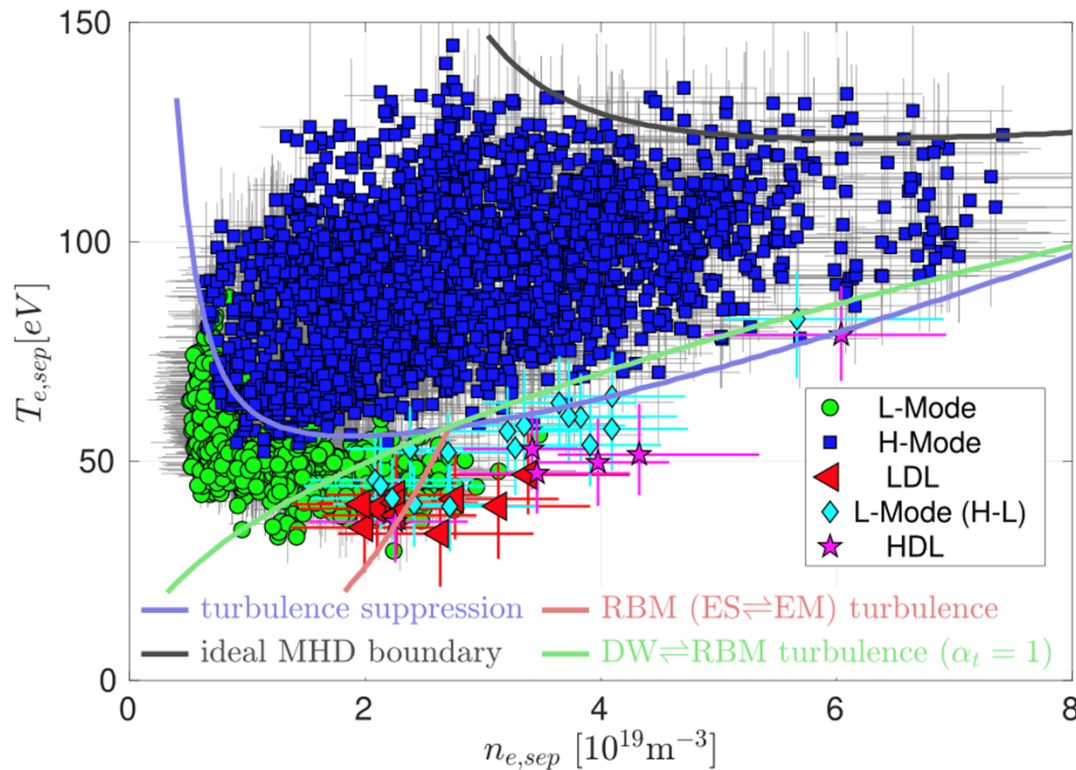
JET, #80823



Edge pressure gradient collapse precedes MARFE onset



Based on local edge parameters, AUG operational space explained in terms of transition between turbulent regimes



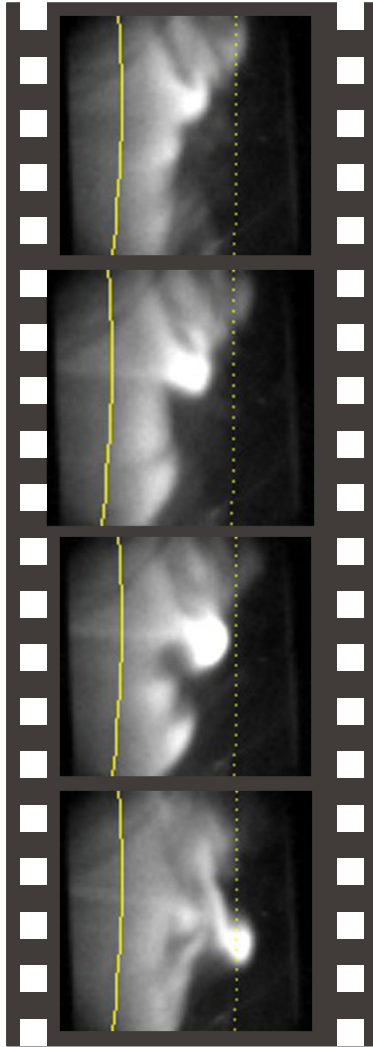
Manz et al., NF 2023

→ Need of boundary simulations

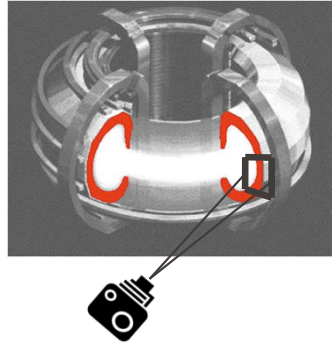


Properties of boundary turbulence

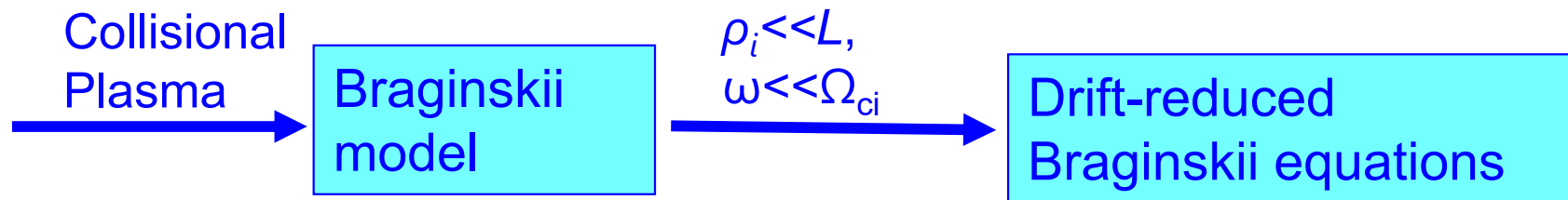
Courtesy of R. Maqueda, typical L-mode SOL



- $n_{fluc} \sim n_{eq}$
- $L_{fluc} \sim L_{eq}$
- Fairly collisional magnetized plasma (< 100 eV, $n_e \sim 10^{19} \text{ m}^{-3}$)
- Role of neutrals
- Sheath physics



A model to evolve boundary plasma turbulence



$$\frac{\partial n}{\partial t} + \underbrace{[\phi, n]}_{\substack{\text{E} \times \text{B} \\ \text{CONVECTION}}} = \underbrace{\hat{C}(nT_e) - n\hat{C}(\phi)}_{\substack{\text{MAGNETIC} \\ \text{CURVATURE}}} - \underbrace{\nabla_{\parallel}(nV_{\parallel e})}_{\substack{\text{PARALLEL} \\ \text{DYNAMICS}}} + \underbrace{n_n \nu_{\text{ion}}}_{\text{IONIZATION}} - \underbrace{n\nu_{\text{rec}}}_{\text{RECOMBINATION}} + \underbrace{S_n}_{\text{INJECTION}}$$

T_e, T_i, Ω (vorticity) $\rightarrow$ similar equations

$V_{\parallel e}, V_{\parallel i}$ $\rightarrow$ parallel momentum balance

$\nabla \cdot (n \nabla_{\perp} \phi) = \Omega - \tau \nabla_{\perp}^2 p_i$ $\rightarrow$ Poisson equation

$\nabla_{\perp}^2 \psi = j_{\parallel}$ $\rightarrow$ Ampère equation



EPFL A model to evolve boundary plasma turbulence

+ coupling with kinetic neutrals

$$\frac{\partial f_n}{\partial t} + \underbrace{\mathbf{v} \cdot \frac{\partial f_n}{\partial \mathbf{x}}}_{\text{STREAMING}} = \underbrace{-\nu_{\text{ion}} f_n}_{\text{IONIZATION}} - \underbrace{\nu_{\text{CX}} (f_n - n_n f_i / n_i)}_{\substack{\text{CHARGE} \\ \text{EXCHANGE}}} + \underbrace{\nu_{\text{rec}} f_i}_{\text{RECOMBINATION}}$$

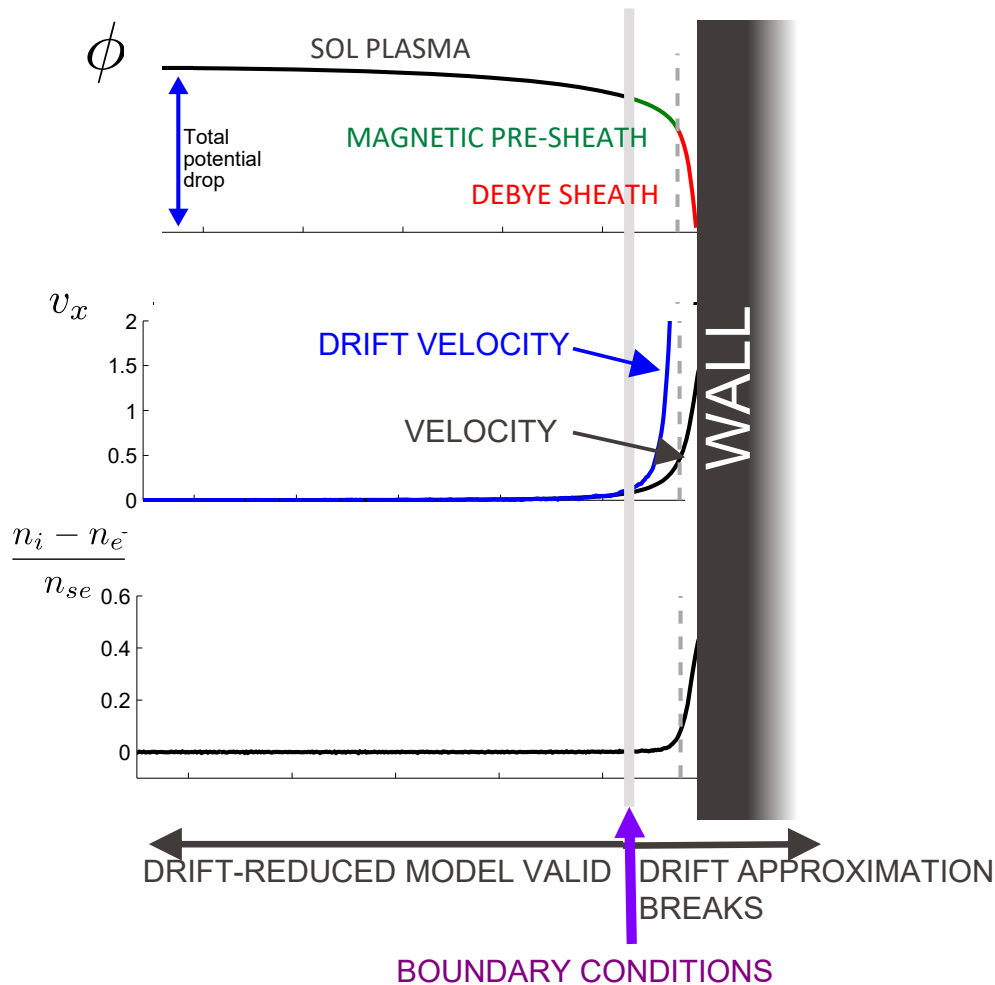
$$\nu_{\text{ion}} = n \langle v_e \sigma_{\text{ion}} \rangle \quad \nu_{\text{CX}} = n \langle v_{\text{rel}} \sigma_{\text{CX}}(v_{\text{rel}}) \rangle \quad \nu_{\text{rec}} = n \langle v_e \sigma_{\text{rec}} \rangle$$

Wersal & Ricci, NF 2015

We solve in 3D geometry, taking into account turbulent transport, ionization and charge exchange processes, and losses at the vessel

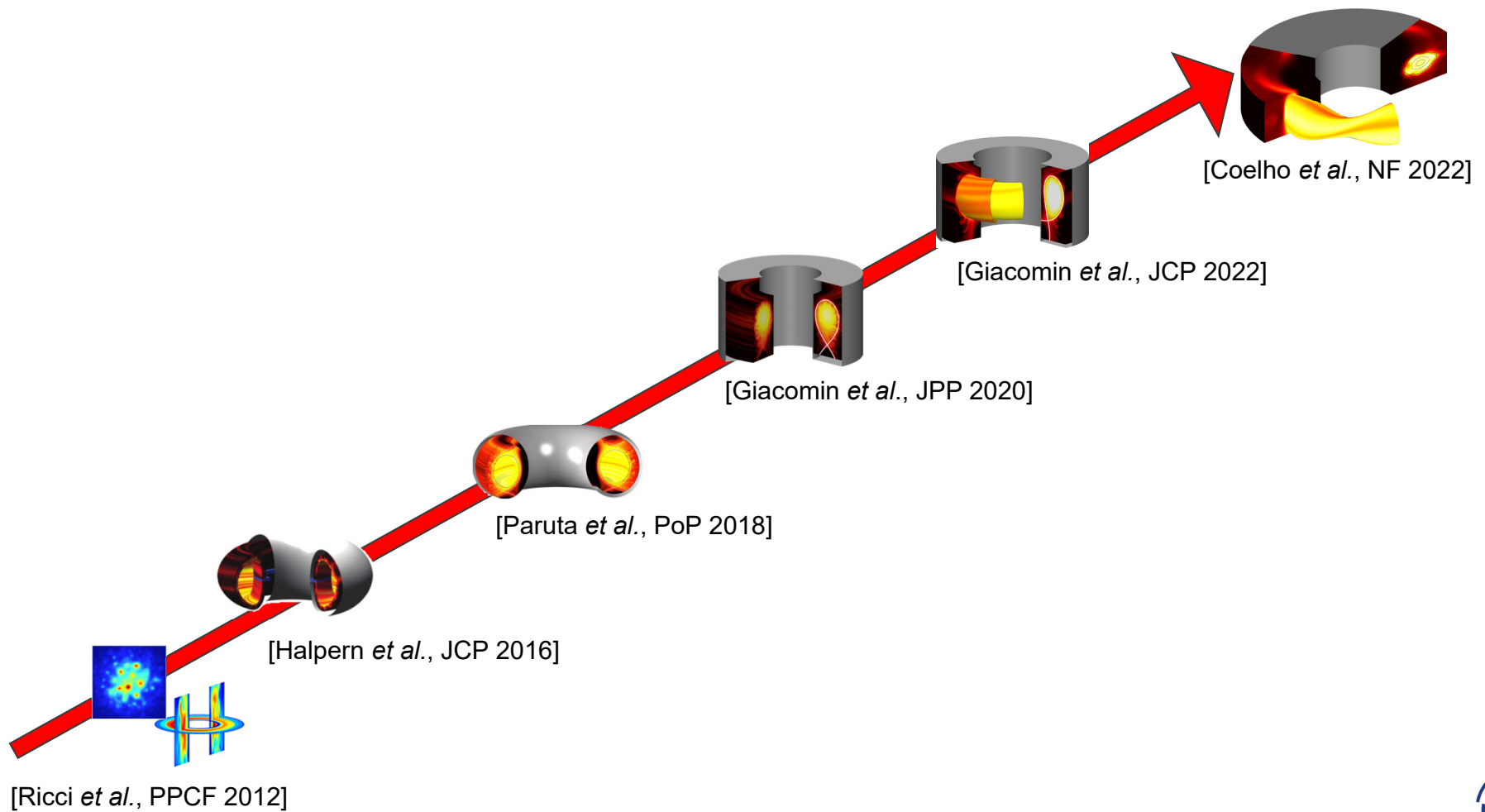


EPFL Boundary conditions at the plasma-wall interface



- Set of b.c. for all quantities, generalizing Bohm-Chodura
- Checked agreement with PIC kinetic simulations
- Neutrals: reflection and re-emission with cosine distribution

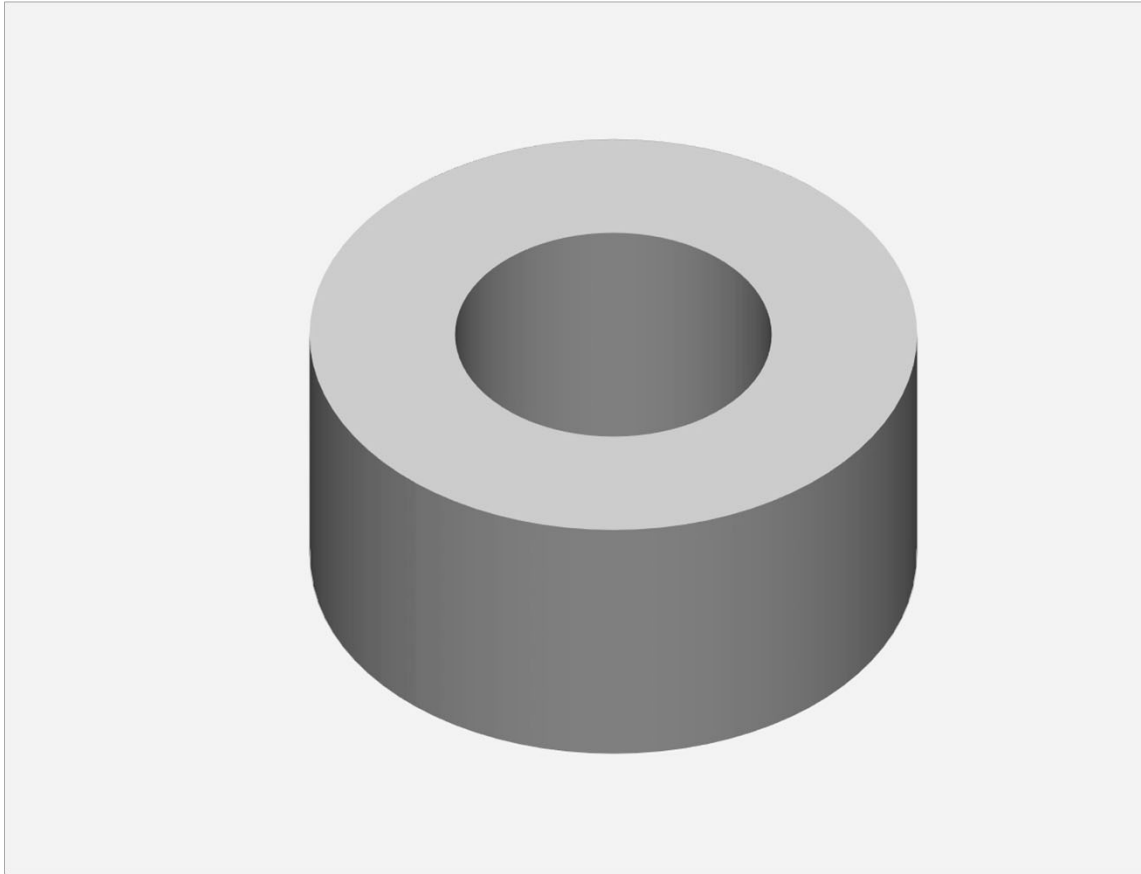
GBS: our simulation code



EPFL Turbulent simulations to investigate edge turbulent regimes

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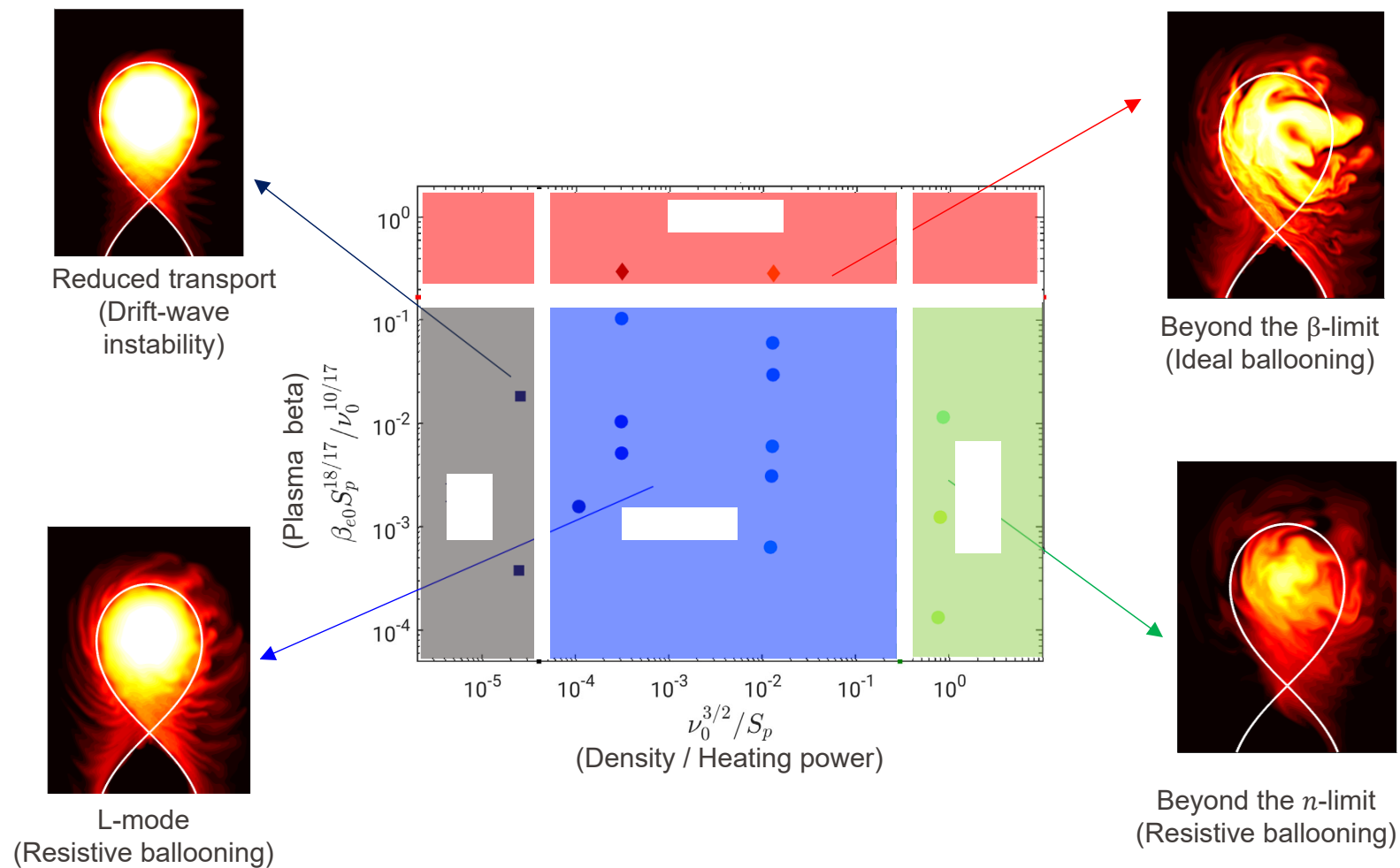
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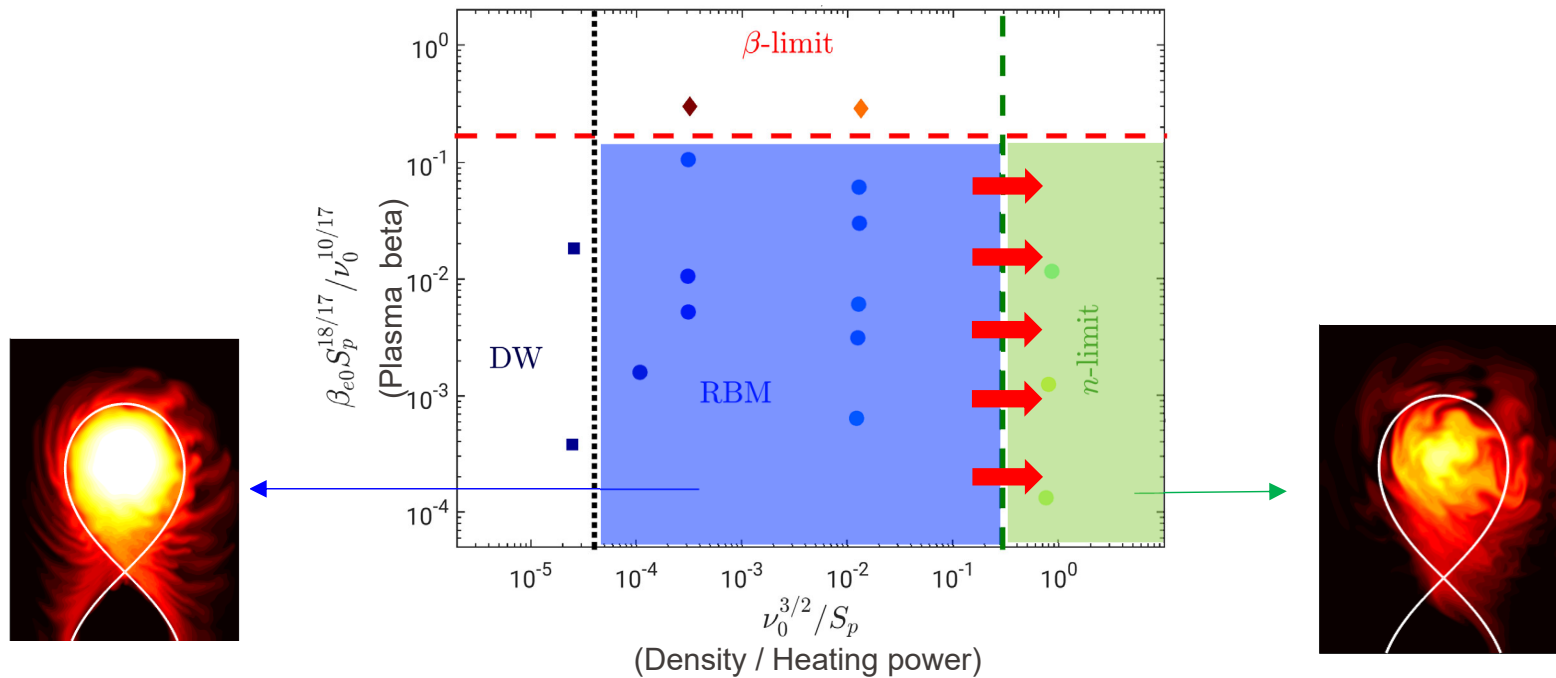
- Retain core-edge-SOL interplay
- No separation of equilibrium and fluctuating quantities
- Validated against experimental results [Oliveira, Body et al., NF 2022]



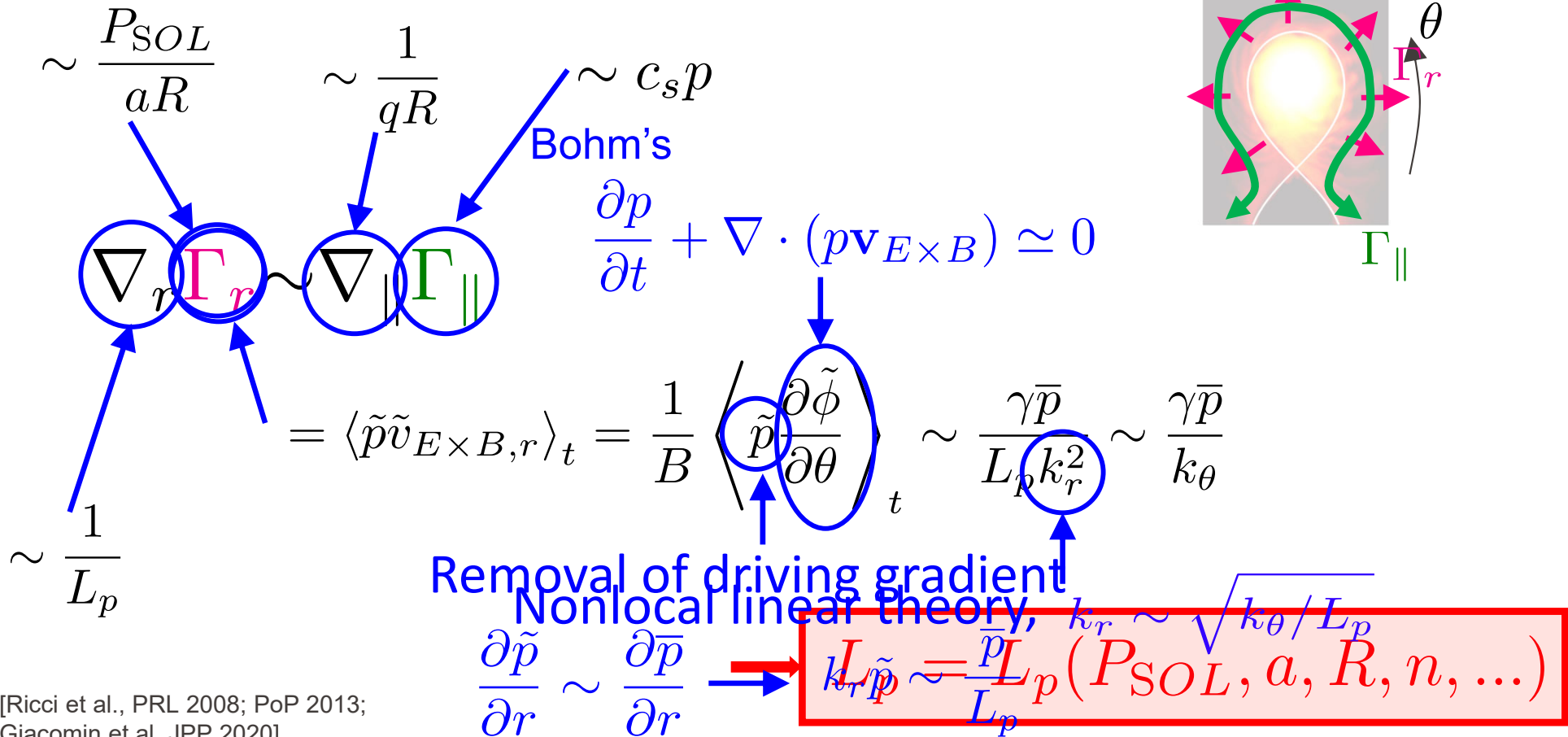
Four regimes of boundary turbulence



L-mode turbulence driven by resistive ballooning modes



SOL width: balance of perpendicular and parallel transport

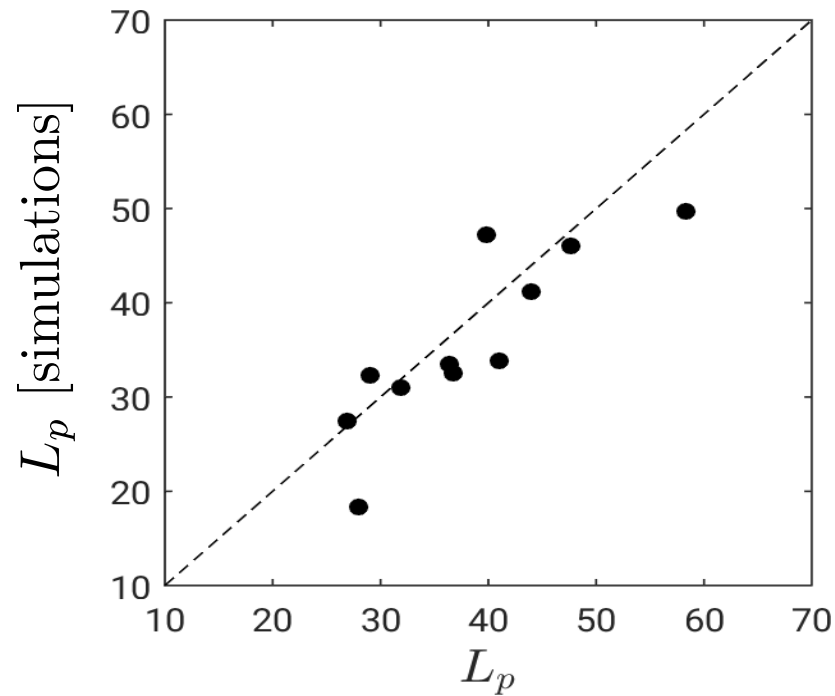


EPFL Good agreement between analytical L_p scaling and simulations

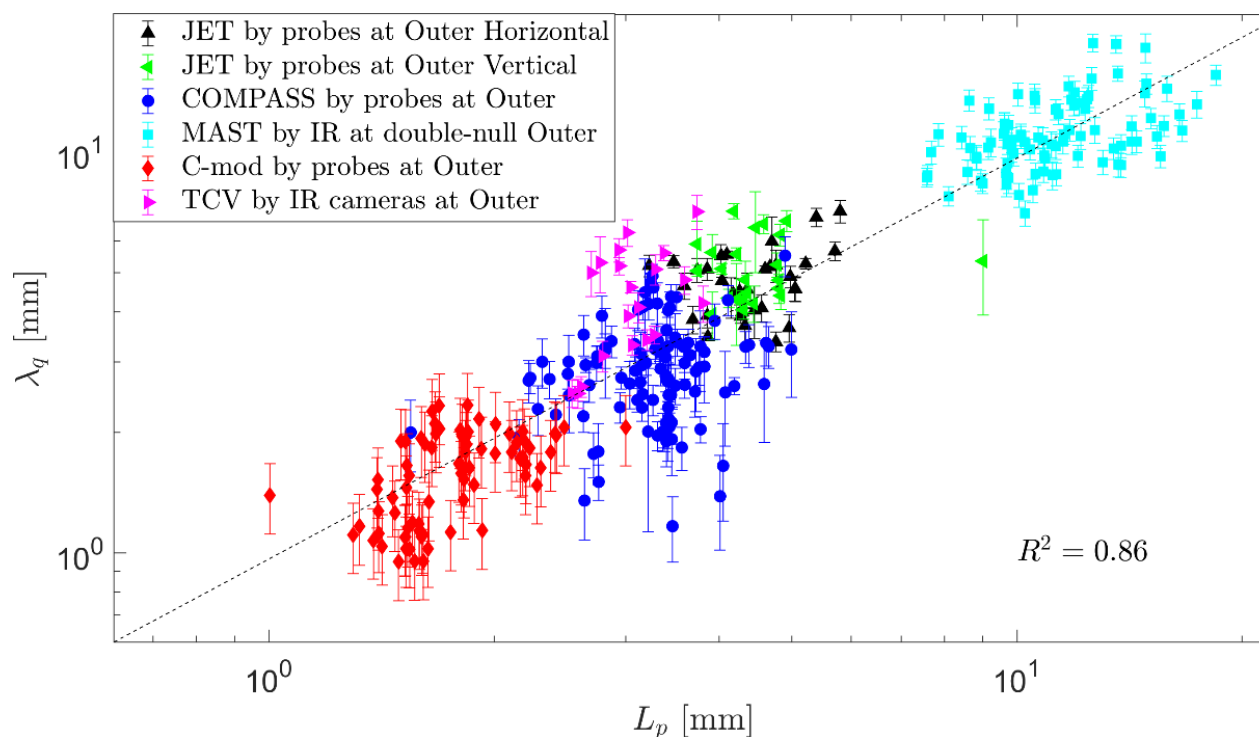
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$$L_p \simeq q^{12/17} R^{7/17} P_{\text{SOL}}^{-4/17} a^{12/17} (1 + \kappa^2)^{6/17} n^{10/17} B_T^{-12/17}$$



Good agreement between analytical estimate and multimachine database

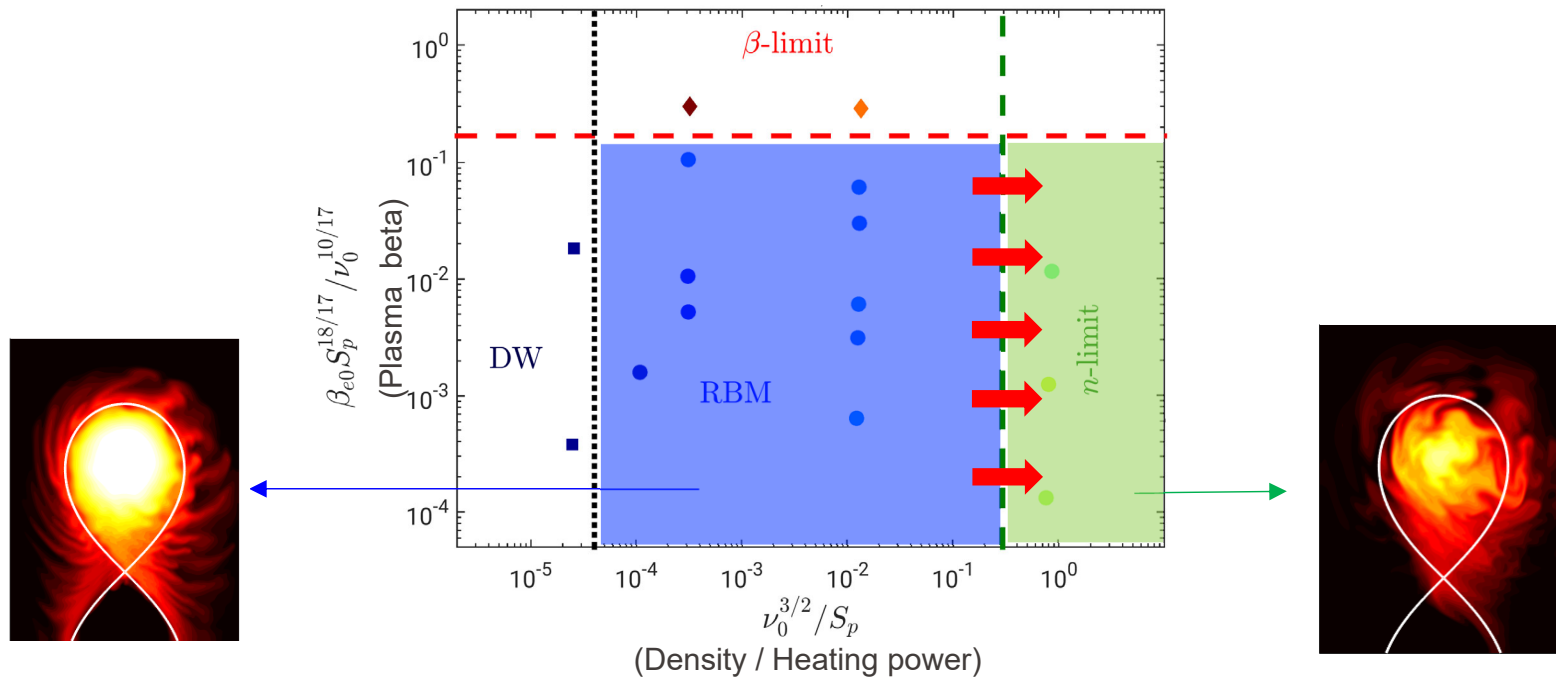


Reliable
understanding
of key
processes at
tokamak edge

Prediction for ITER L-mode: $\lambda_q \simeq 3.5$ mm



Transition to large transport at high density



Theoretical estimate of density limit based on operational parameters

$$\textcircled{L_p} = L_p(P_{\text{SO L}}, a, R, n, \dots)$$

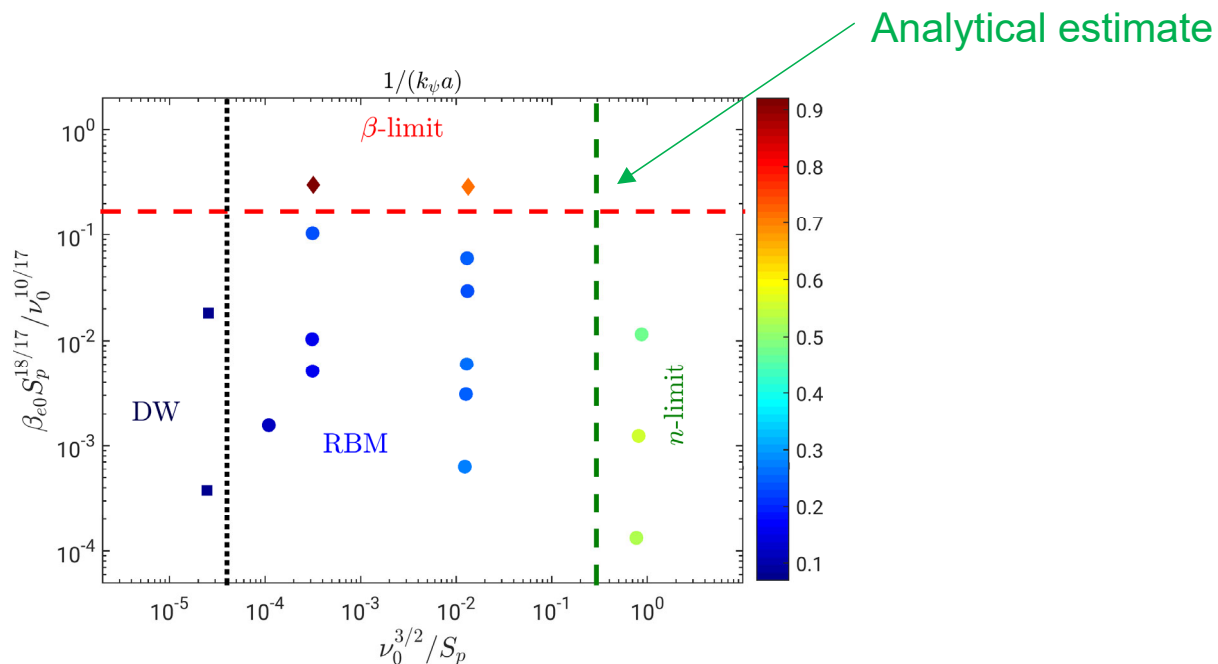
Collapse of edge pressure gradient

$$L_p \sim a$$

$$\Rightarrow n_{\text{lim}} = n_{\text{lim}}(P_{\text{SO L}}, a, R, \dots)$$



Good agreement between analytical and simulation results



No need of EM effects to access the density limit: electrostatic modes become large with collisionality



Density limits depends on I_p and a , but also on P_{SOL}

- Density limit in physical units:

$$n_{\text{lim}} = \alpha A^{1/6} a^{3/14} P_{\text{SOL}}^{10/21} R^{-43/42} q^{-22/21} (1 + \kappa^2)^{-1/3} B_T^{2/3}$$

α : Numerical coefficient rising from order of magnitude estimates and numerical factors

- Empirical Greenwald density limit:

$$n_{\text{GW}} = \frac{I_p}{\pi a^2}$$

- Density limit in terms of the plasma current:

$$n_{\text{lim}} \sim P_{\text{SOL}}^{0.48} R^{0.02} B_T^{-0.38} (1 + \kappa)^{-0.33} \frac{I_p^{1.05}}{a^{1.88}}$$

- Dependence on power observed in experiments [Bernert *et al*, PPCF 2014; Esposito *et al*, PRL 2008; Huber *et al*, JNM 2013]

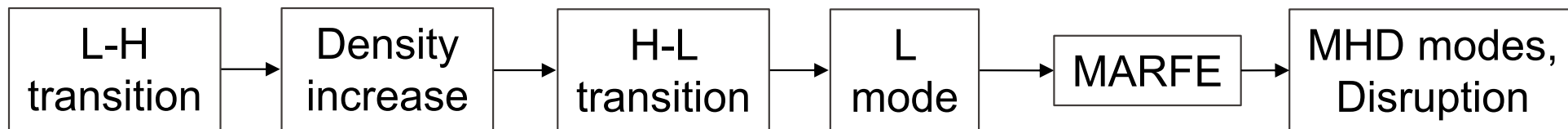


EPFL Comparison with density limit in AUG, TCV and JET, in two scenarios

Standard L-mode:



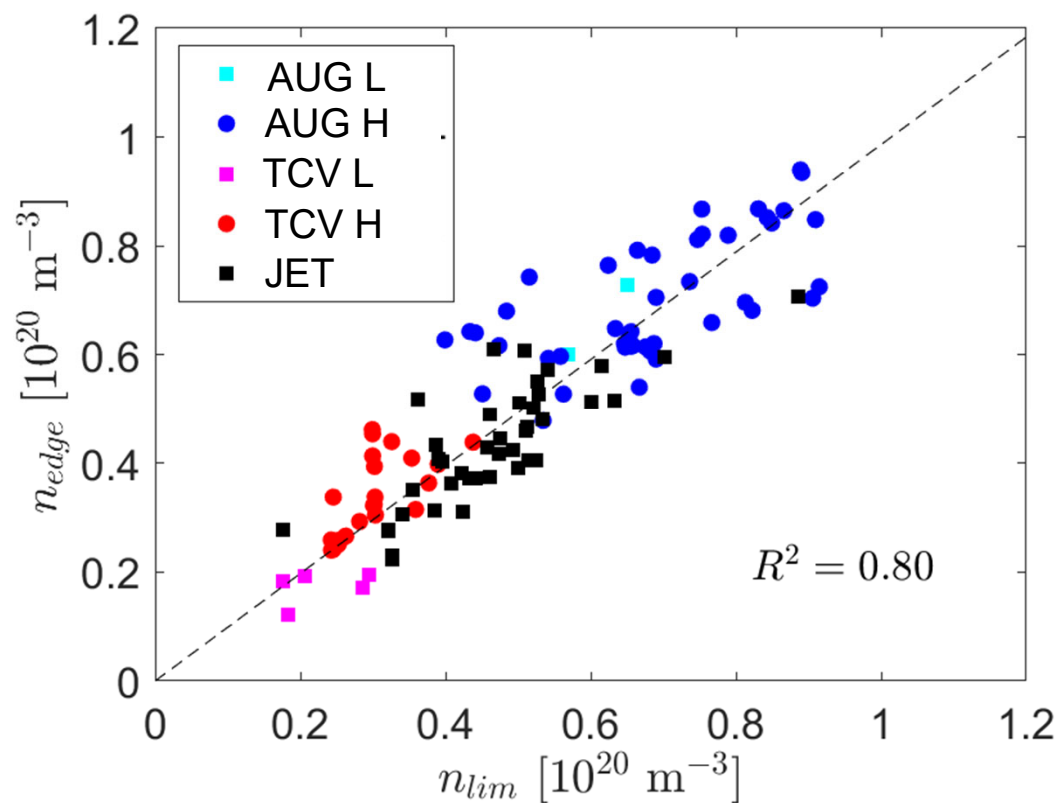
ITER-relevant H-mode:



Data range:

$n: 2 \times 10^{19} - 1.2 \times 10^{20} \text{ m}^{-3}, I_p: 0.1 - 2.5 \text{ MA}, B_0: 1.4 - 3 \text{ T}, P_{SOL}: 0.1 - 9$

Good agreement with experimental data

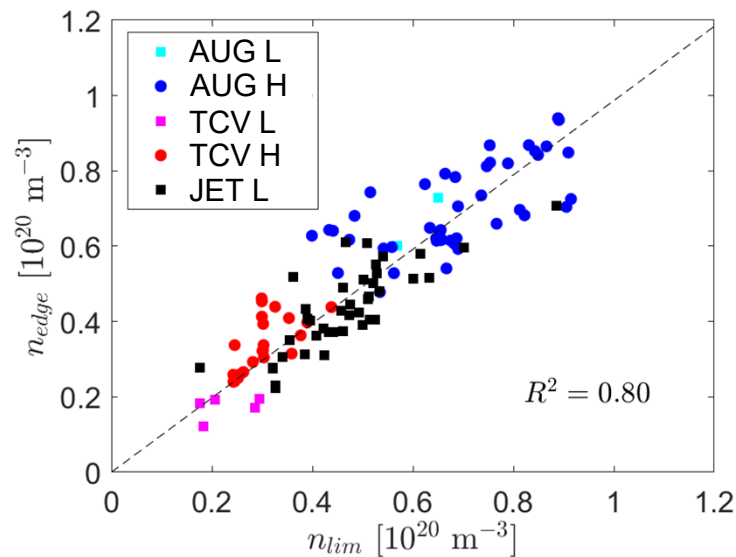


[Giacomin *et al.*, PRL 2022]

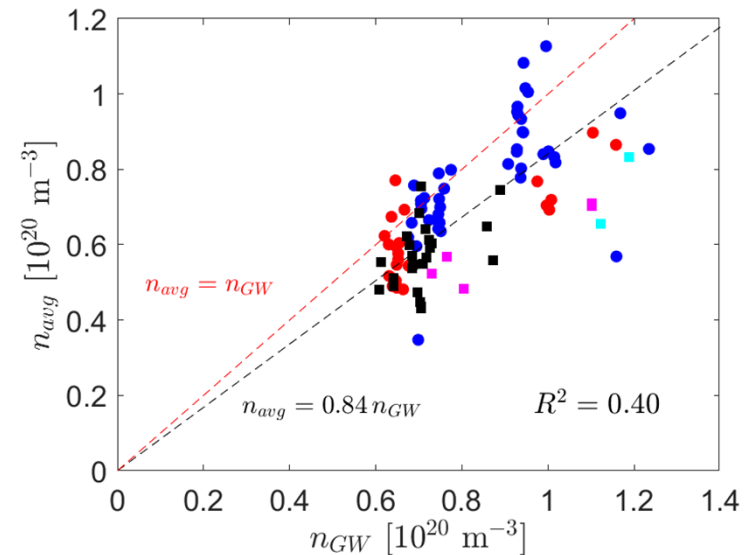


Significant improvement with respect to Greenwald

$$n_{\text{lim}} = \alpha A^{1/6} a^{3/14} P_{\text{SOL}}^{10/21} R_0^{-43/42} q^{-22/21} (1 + \kappa^2)^{-1/3} B_T^{2/3}$$



$$n_{\text{GW}} = \frac{I_p}{\pi a^2}$$



- Promising approach for real-time control in MAST-U [Berkery et al., PPCF 2023]
- Experimental campaign planned in DIII-D
- Prediction for ITER ($P_{\text{SOL}}=50 \text{ MW}$, $q=3$, $B_T=5.3 \text{ T}$): $n_{\text{lim}} \simeq 2.5 \times 10^{20} \text{ m}^{-3} > 2n_{\text{GW}}$

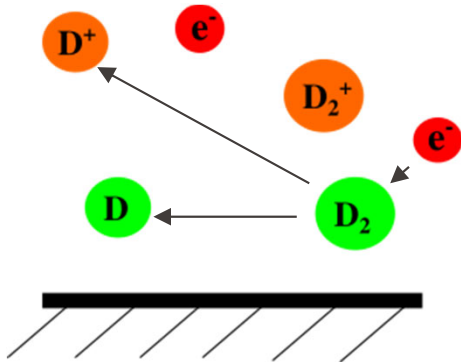


- Density limit set by edge dynamics
- Increase of density leads to higher collisionality, larger transport, triggering MARFE and disruption
- Analytical scaling provided show I_p and a dependence similar to Greenwald, but also P_{SOL} dependence
- Good agreement with AUG, JET and TCV discharges, as well as MAST-U
- Significantly larger safety margin than Greenwald in case of unintentional H-L transition in ITER
- Given possible role of other phenomena in setting density limit in tokamaks, further experimental investigations urgently needed.

EPFL Moving forward: multispecies simulation with detachment

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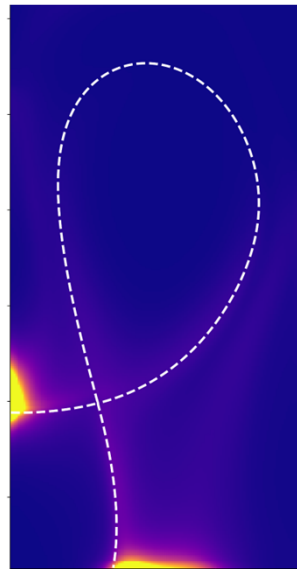
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A multispecies (D , D^+ , D_2 , D_2^+ , e^-) model allowed first simulations of highly-radiative (detached) scenarios

[Calado *et al.*, PoP 2022, NF 2022, Mancini NF 2023]

Ionisation source



Density increases,
ionization front moves,
heat flux to vessel reduced

Role in density limit?

Ionisation source

