Theoretical scaling law for H-L back transition

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TSVV1 Progress Workshop, Sep 18-20, 2024

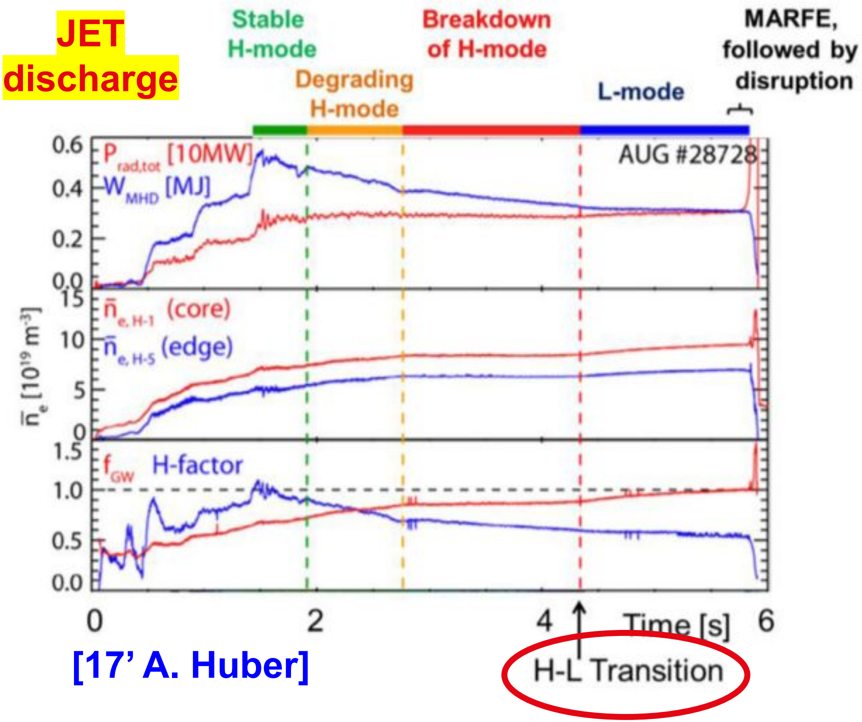
GBS Deliverables and milestones

Within the topic of TSVV1 regarding **the physics of the LH transition,**

- Explore boundary plasma turbulence phase space
- Scaling law: L-mode density limit, H-to-L backtransition
- EM physics in boundary plasma turbulence
- neutrals / impurities

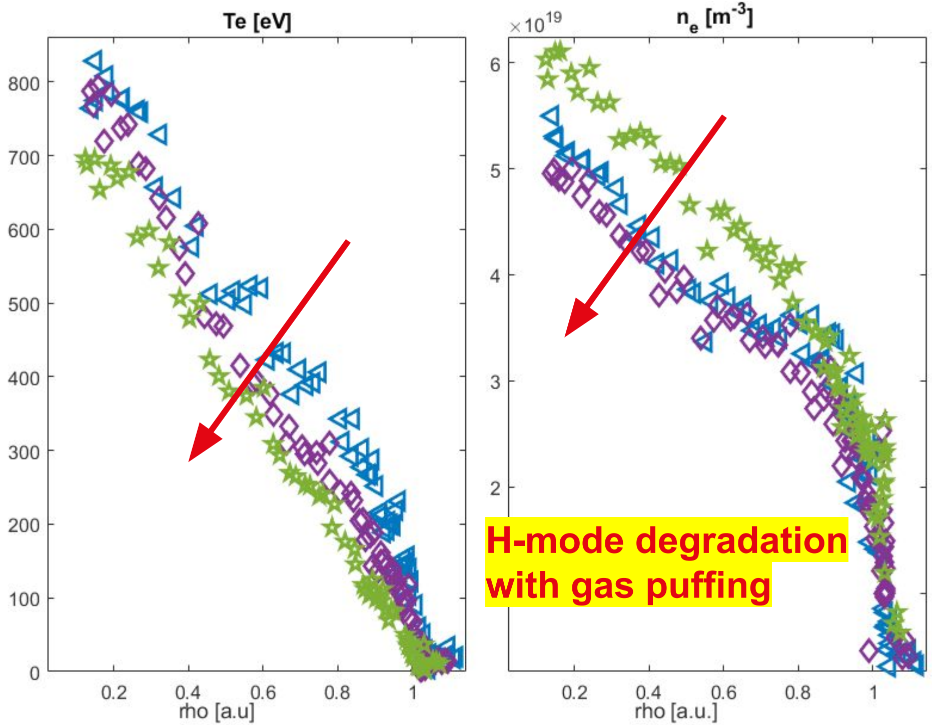
Most of them are already addressed or currently being addressed.

H-mode density limit (HDL) with increasing gas puffing



JET discharge

[17' A. Huber]



H-mode degradation with gas puffing

Increasing further density in H-mode leads to back transition to L-mode plasmas (or complete disruption). **Can we predict the density at which HL transition occurs?**

Different approaches for density limit

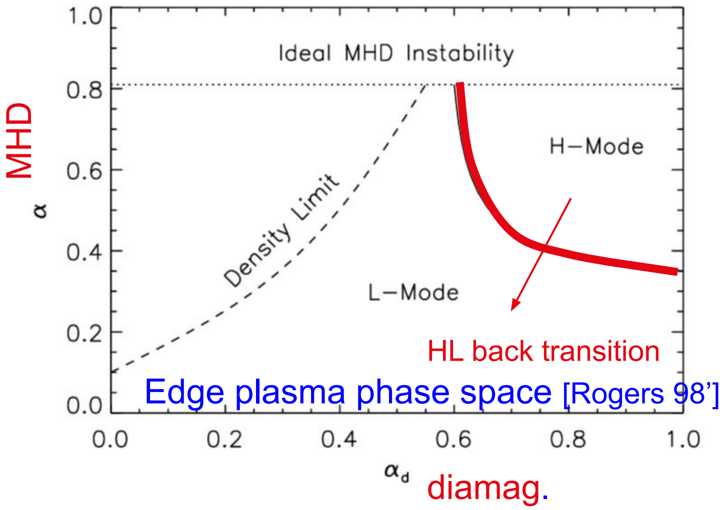
Various theoretical approaches

(1) Radiation **[Zanca 19' Stroth 22']**

(2) Collapse of the outer shear layer **[Singh 22']**

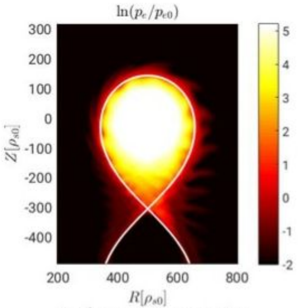
(3) Turbulence phase space **[Rogers 98' LaBombard 07' Giacomin 22' Manz 23']**

We associate the HL back transition with turbulence phase space



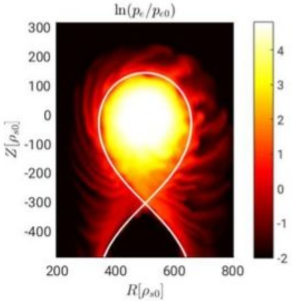
Edge plasma phase space [Rogers 98']

Phase space of edge turbulence

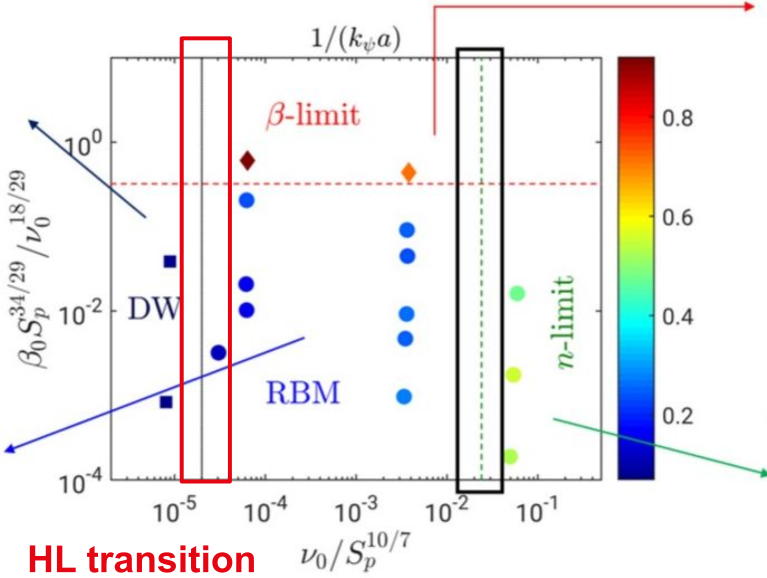


Drift-wave instability

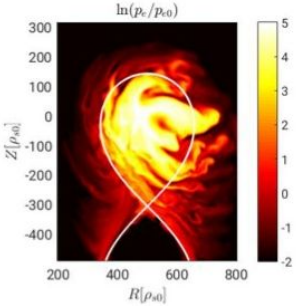
$$\frac{\tau_{E,DW}}{\tau_{E,RBM}} \simeq 1.5$$



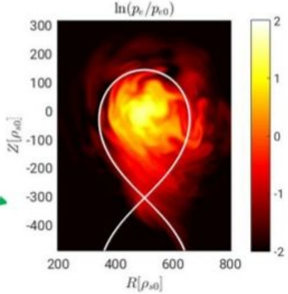
L-mode regime
Resistive ballooning instability



HL transition



Regime beyond the β-limit
Ideal ballooning instability



Regime beyond the n-limit
Resistive ballooning instability

GBS explored phase-space of edge plasma turbulence

The transition from DW to RBM is associated with the H-mode density limit, and extending it to include shaping effects (elongation, triangularity)

How shaping affects L- and H-mode density limits?

We associate the HDL with the boundary between **DW** and **RBMs**.

BMs are interchange instabilities driven by **pressure gradient + bad curvature**

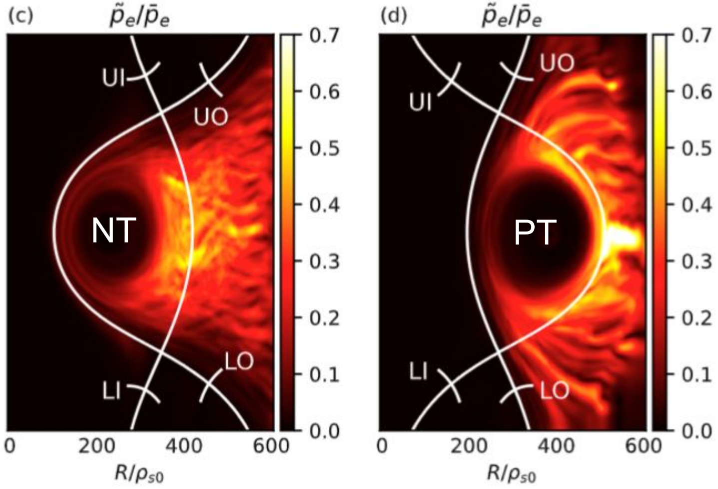
Shaping affects SOL turbulence via curvature -> it shifts the boundary between DW and RBMS

PT -> strong curvature & larger surfaces

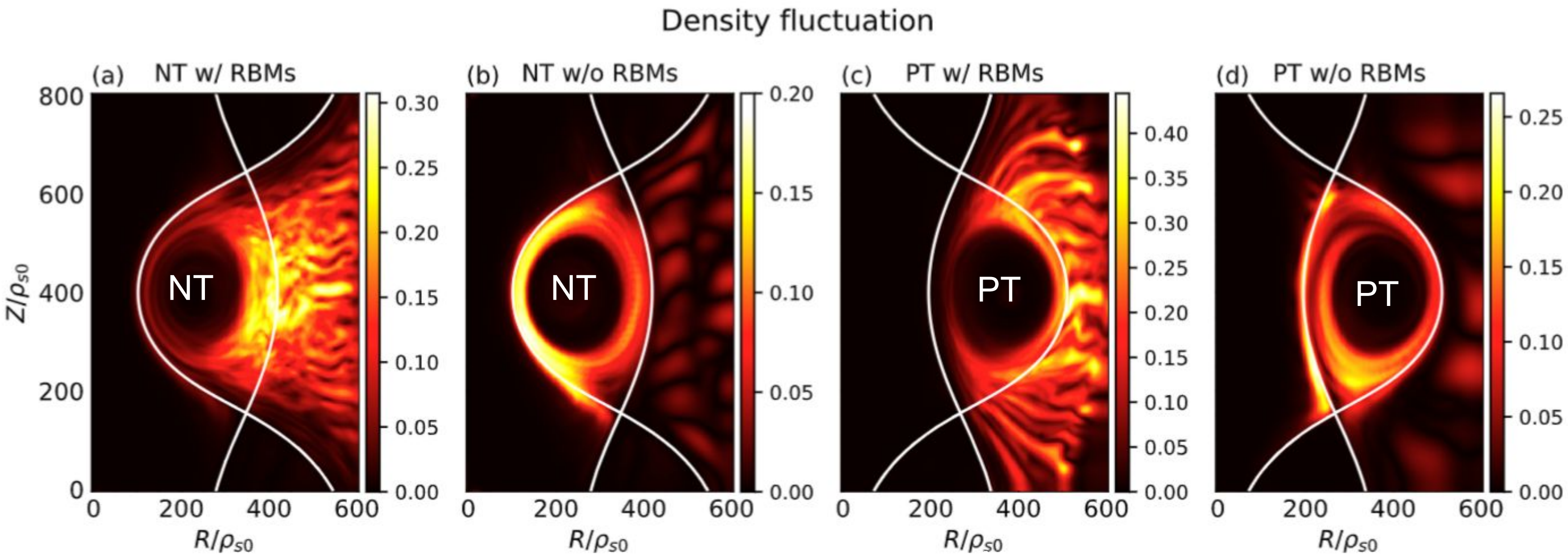
NT -> smooth curvature & smaller surfaces

In PT plasmas, particles stay longer in bad curvature region.

Thereby, reduced turbulence in NT.



Evidence that RBMs is related to NT plasma reduction



We artificially turned off the curvature operator in the vorticity equation.

45% fluctuation reduction in PT and 30% fluctuation reduction in NT.

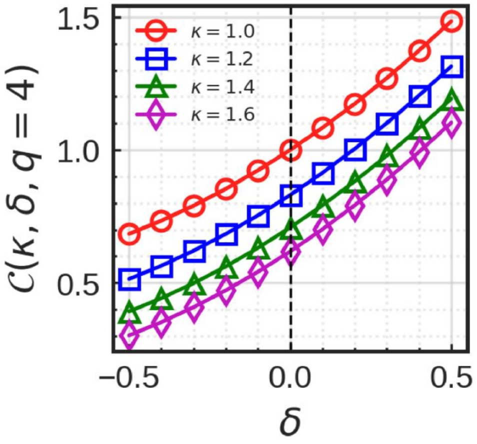
RBMs play more strongly in PT.

Reduced SOL-BMs turbulence in NT

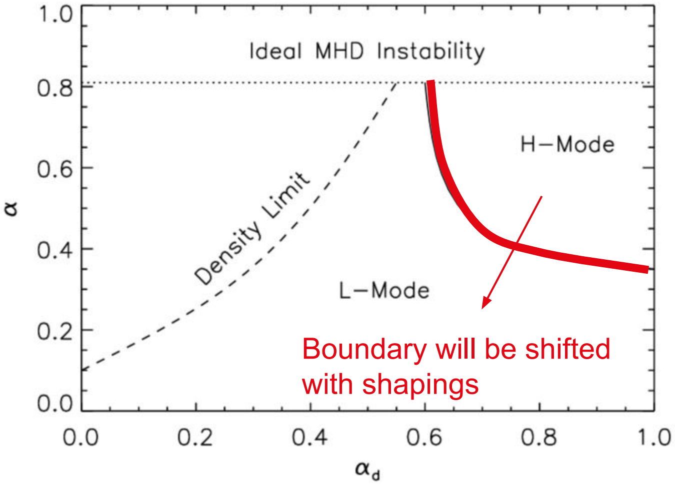
We relate the growth rate in RBMs with the analytical curvature operator.

This allows us to include shaping effects in boundary physics.

$$\gamma^2 = \gamma_{\mathrm{RBM}}^2 \frac{\mathcal{C}(\kappa,\delta,q)}{3},$$



Reduced curvature in NT

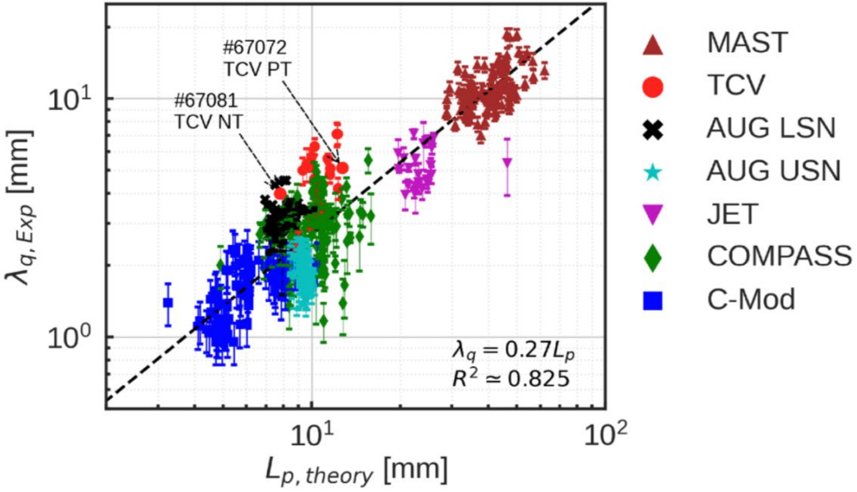


Boundary will be shifted with shapings

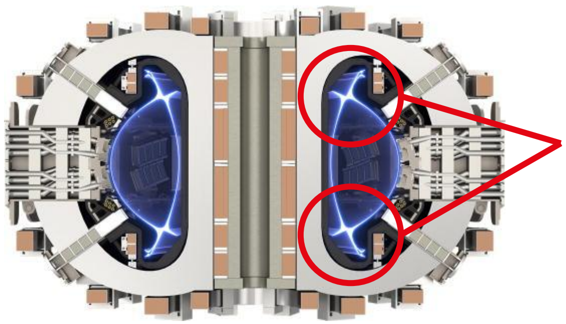
Ex1) NT leads to smaller size of λ_q due to reduced turb.

In NT plasmas, turbulence is reduced -> smaller size of power-decay length.

$$L_p \simeq 1.95\,\mathcal{C}(\kappa,\delta,q)^{9/17} A^{1/17} q^{12/17} R_0^{7/17} P_{\mathrm{SOL}}^{-4/17} n_e^{10/17} \times B_T^{-12/17} L_\chi^{12/17},$$



Ex2) Shaping affects up-down power asymmetry in DN

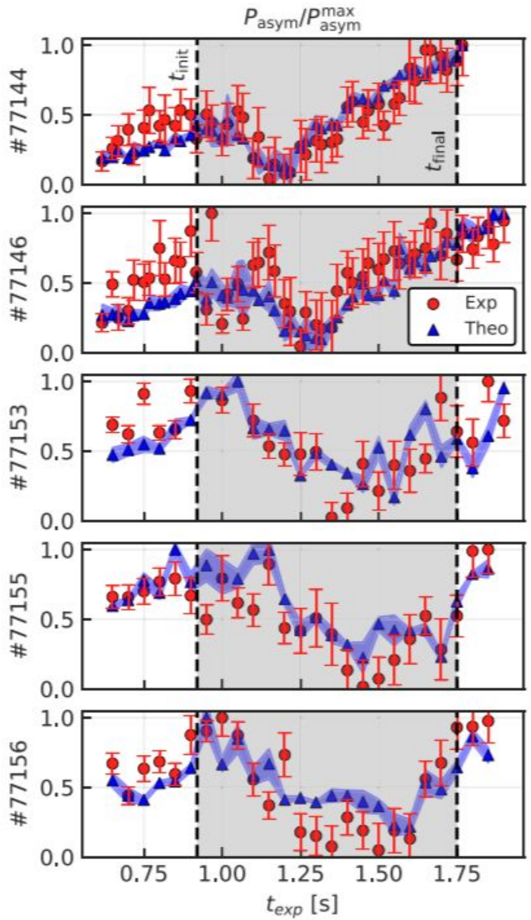


Power is not evenly distributed

$$|P_{\mathrm{LO}} - P_{\mathrm{UO}}| = P_{\mathrm{asym}} = P_{\mathrm{SOL}}\left[\alpha_{\mathrm{g}} + (1-\alpha_{\mathrm{g}})\,\alpha_{\mathrm{d}} K\right],$$

$$\alpha_{\mathrm{d}} \sim 1.14 A^{13/12} R_0^{-23/12} B_T^{-1} L_{\mathrm{p}}^{-11/12} P_{\mathrm{SOL}}^{2/3} n^{-7/6} q^{-1}.$$

$$L_{\mathrm{p}} \sim 1.95\,\mathcal{C}(\kappa,\delta,q)^{9/17} A^{1/17} q^{12/17} R_0^{7/17} P_{\mathrm{SOL}}^{-4/17} n^{10/17} B_T^{-12/17} L_\chi^{12/17}, \qquad (37)$$



Ex3) Reduced blob-wall interactions in NT

The two-region model is often used to describe blob dynamics.

This model uses the interchange drive as the blob generation mechanisms

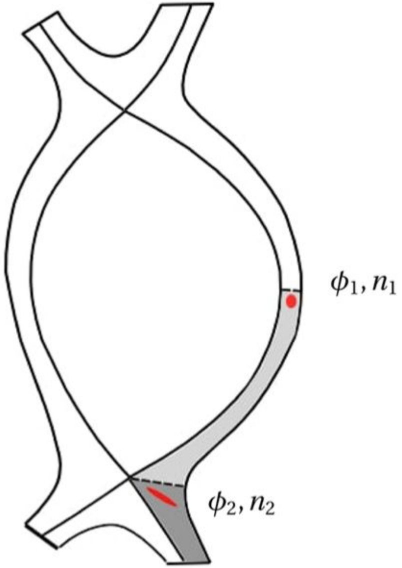
vorticity

$$\frac{\partial \omega_1}{\partial t} + \frac{R_0}{\rho_{s0}}[\phi_1, \omega_1] = \frac{1}{n_1}\nabla_\parallel j_{\parallel 1} + \frac{2T_1}{n_1}\boxed{\mathcal{C}(n_1),}$$

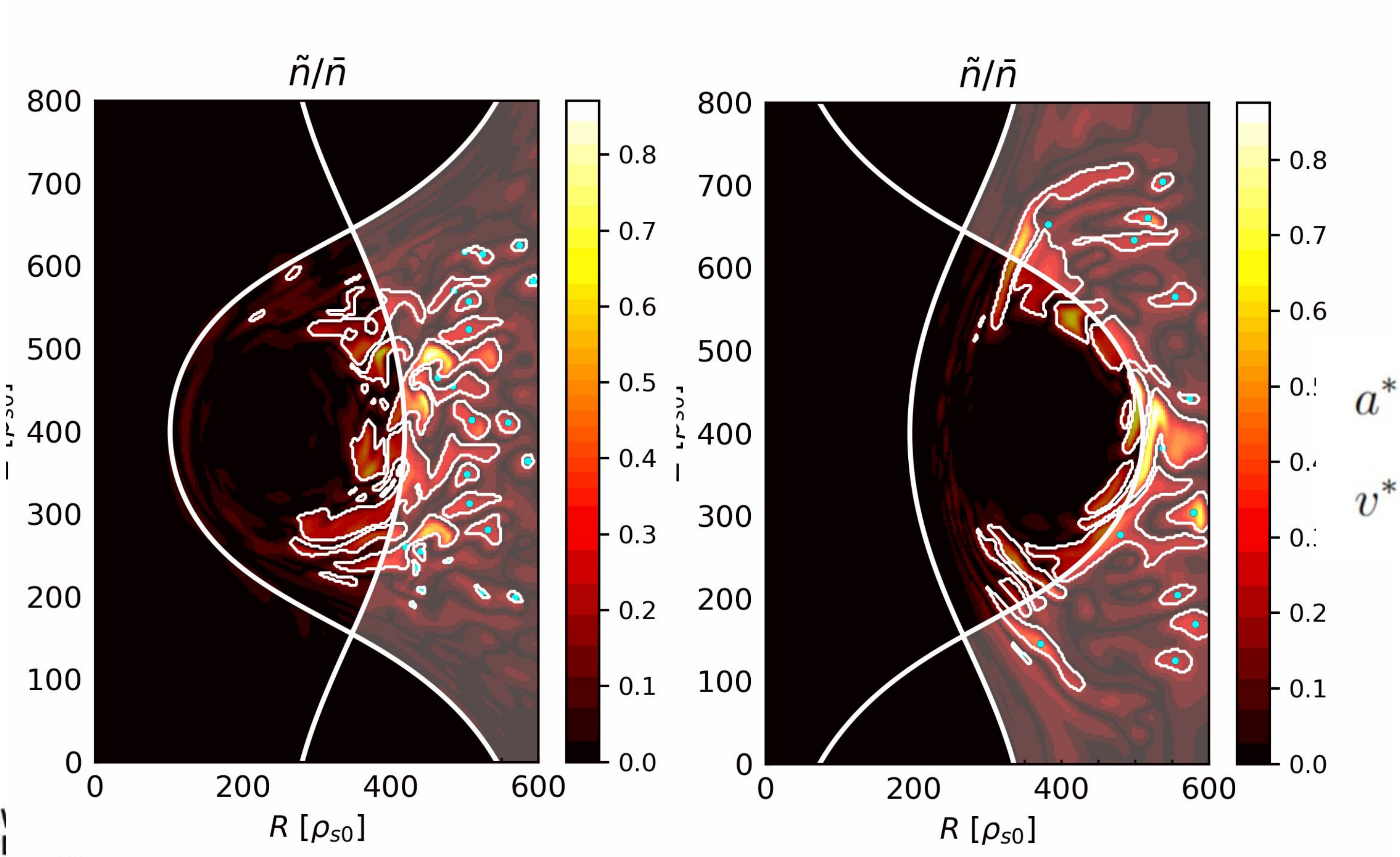
$$\frac{\partial n_1}{\partial t} + \frac{R_0}{\rho_{s0}}[\phi_1, n_1] = 0,$$

$$\frac{\partial \omega_2}{\partial t} + \frac{R_0}{\rho_{s0}}[\phi_2, \omega_2] = \frac{1}{n_2}\nabla_\parallel j_{\parallel 2},$$

$$\frac{\partial n_2}{\partial t} + \frac{R_0}{\rho_{s0}}[\phi_2, n_2] = 0,$$



Ex3) Reduced blob-wall interactions in NT



blob size

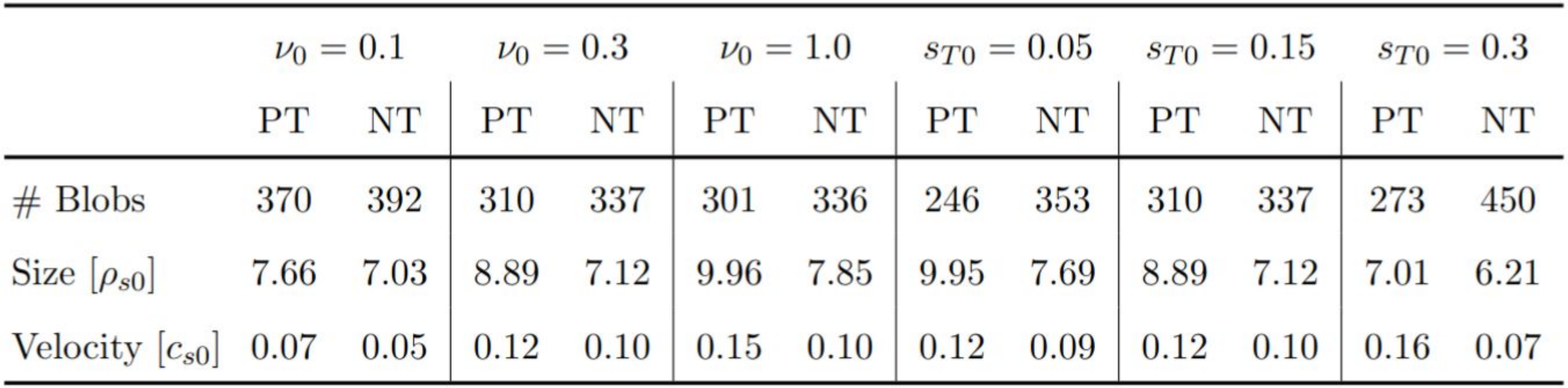
$$a^* \propto \mathcal{C}(q,\delta,\kappa)^{1/5} a^*_{\mathrm{ref}},$$

$$v^* \propto \mathcal{C}(q,\delta,\kappa)^{1/2} v^*_{\mathrm{ref}},$$

blob velocity

ref = scaling without shaping

Ex3) Reduced blob-wall interactions in NT



	$\nu_0 = 0.1$		$\nu_0 = 0.3$		$\nu_0 = 1.0$		$s_{T0} = 0.05$		$s_{T0} = 0.15$		$s_{T0} = 0.3$	
	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT
# Blobs	370	392	310	337	301	336	246	353	310	337	273	450
Size $[\rho_{s0}]$	7.66	7.03	8.89	7.12	9.96	7.85	9.95	7.69	8.89	7.12	7.01	6.21
Velocity $[c_{s0}]$	0.07	0.05	0.12	0.10	0.15	0.10	0.12	0.09	0.12	0.10	0.16	0.07

NT blobs are smaller and slower, but more numerous than PT blobs.

Plasma-wall interactions are reduced in NT plasmas.

Qualitative consistent with our theoretical scaling law.

Derivation of the HDL scaling law with shaping effects

The analytical expression of pressure gradient length, L_p, is known for DW/BM.

We suppose the HL back transition occurs when $L_{p,RB} \sim L_{p,DW}$

This leads to the following expression

$$
\begin{aligned}
n'_{\mathrm{HDL}} &\sim C_{\mathrm{geo}}^{-15/37} A^{8/37} P_{\mathrm{SOL}}^{19/37} a^{-19/37} q^{-36/37} R_0^{-22/37} B_T^{15/37} \\
&\sim C_{\mathrm{geo}}^{-15/37} A^{8/37} P_{\mathrm{SOL}}^{19/37} R_0^{14/37} B_T^{-21/37} \frac{I_p{}^{36/37}}{a^{91/37}}
\end{aligned}
$$

(NT allows larger density limit -> $f_{GW} \sim 2$ in DIII-D NT scenario)

We validate the above scaling law with TCV, AUG, and JET exp. datasets.

Validation of HL back transition

$$n'_{\mathrm{HDL}} \sim C_{\mathrm{geo}}^{-15/37} A^{8/37} P_{\mathrm{SOL}}^{19/37} a^{-19/37} q^{-36/37} R_0^{-22/37} B_T^{15/37}$$

Some shots deviates.

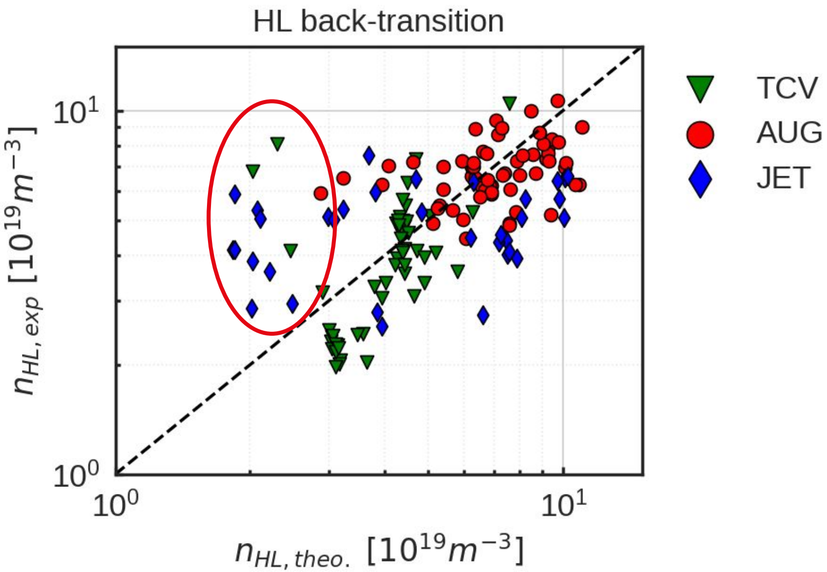
Reasons can be attributed to:

(1) measurements errors

(2) Impurity accumulation

(3) needs for proper time window

(4) etc…



A few discharges show some deviation.
A detailed investigation is ongoing.

Comparison with the other existing scaling laws

We compare different scaling laws with the same datasets.

$$n_{\mathrm{lim}}^{\mathrm{Bernert}} \propto P_{\mathrm{heat}}^{0.39} \cdot q_{\mathrm{cyl}}^{-0.59} B_{\mathrm{tor}}^{0.27} .$$

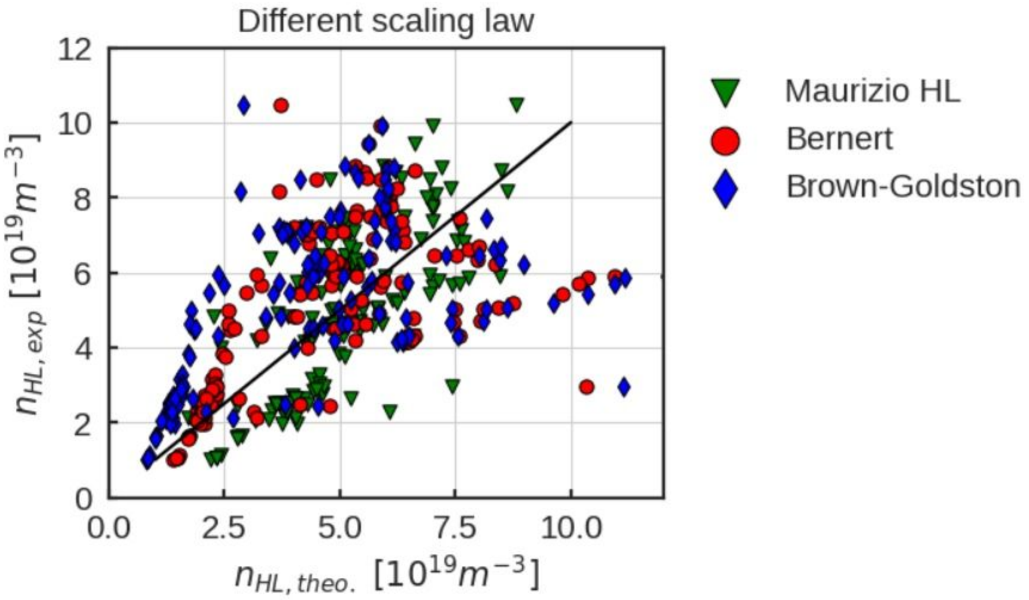
1. **Bernert scaling law.** This is empirical and derived on AUG datasets.

   It makes use of input heating power (P_{heat}) not power entering SOL (P_{SOL}), which means the radiation effect is not included

2. **Brown-Goldston model.** This law links the HL back transition with the collapse of shear rate.

$$n_{\mathrm{lim}}^{\mathrm{Brown\text{-}Goldston}} = 7.1 \cdot P_{\mathrm{SOL}}^{0.48} q_{\mathrm{cyl}}^{-0.9} B_{\mathrm{tor}}^{0.68} .$$

Comparison with the other existing scaling laws



The best-fitting pre-factor alpha for each model is computed using linear-regression method. When compared, Maurizio's HL law is found to works better than others.

Summary

- We want to predict the density at which the HL back transition occurs

- Theoretical scaling law is derived based on phase-space and is extended to include shaping effects

- Multi-machine validation is preliminary done showing an interesting results, but some shots needs to be investigated in detail

- There are still open questions, i.e., effects of EM, impurities, isotopes, etc..