Overview of transport modeling for SPARC H-modes: sensitivity of fusion performance to physics inputs

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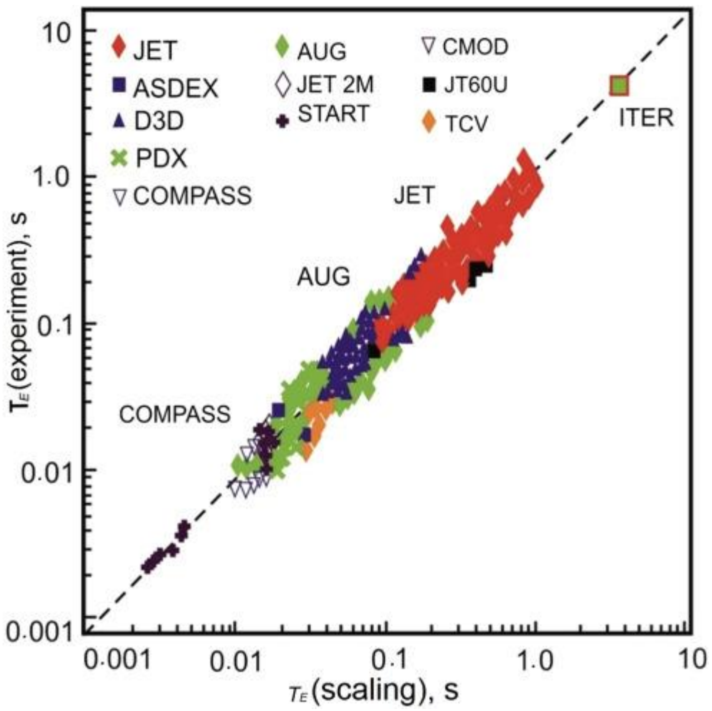
INTRODUCTION

What do we expect in future machines?

- Needs for extrapolations/predictions



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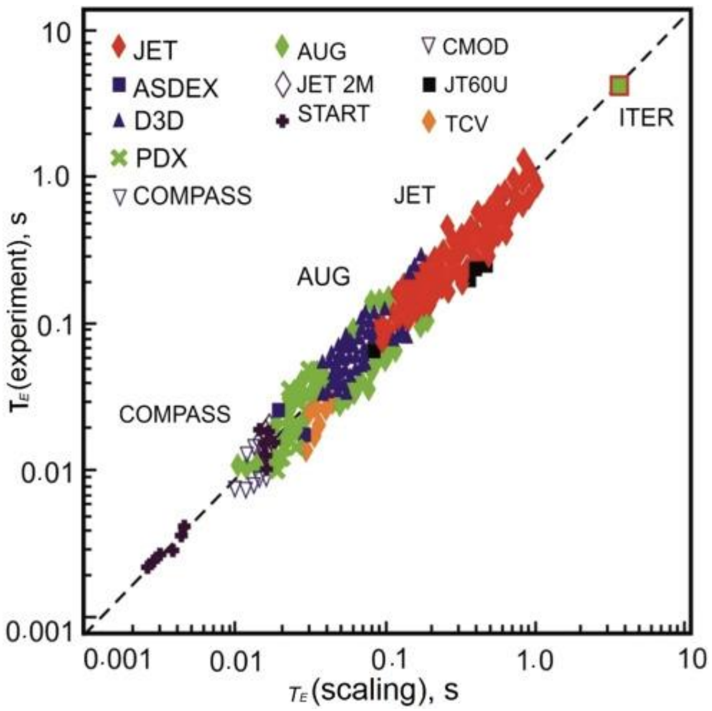
- Important predictions for future machines success → P_{fus} and Q



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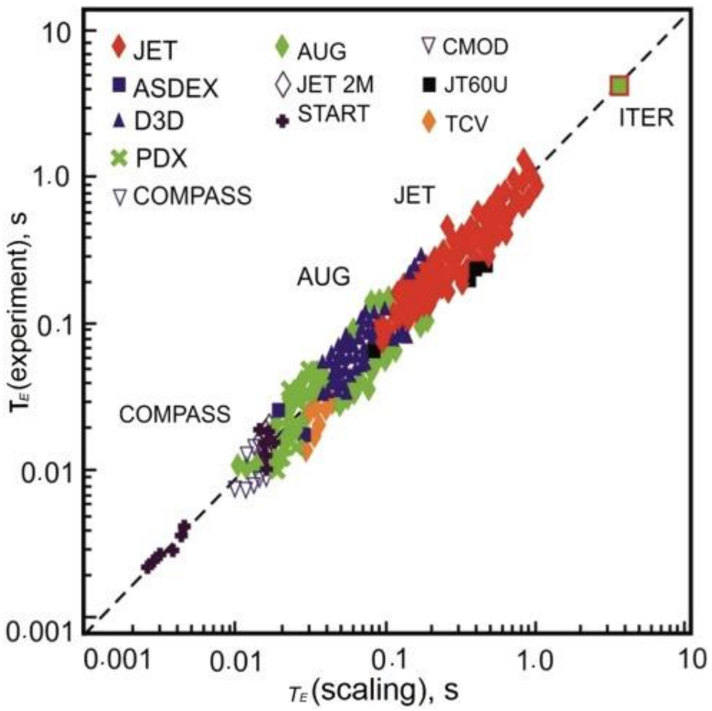
  - ➢ Are they realistic?
  - ➢ Can they be operationally controlled?
  - ➢ How strongly do they affect performance?



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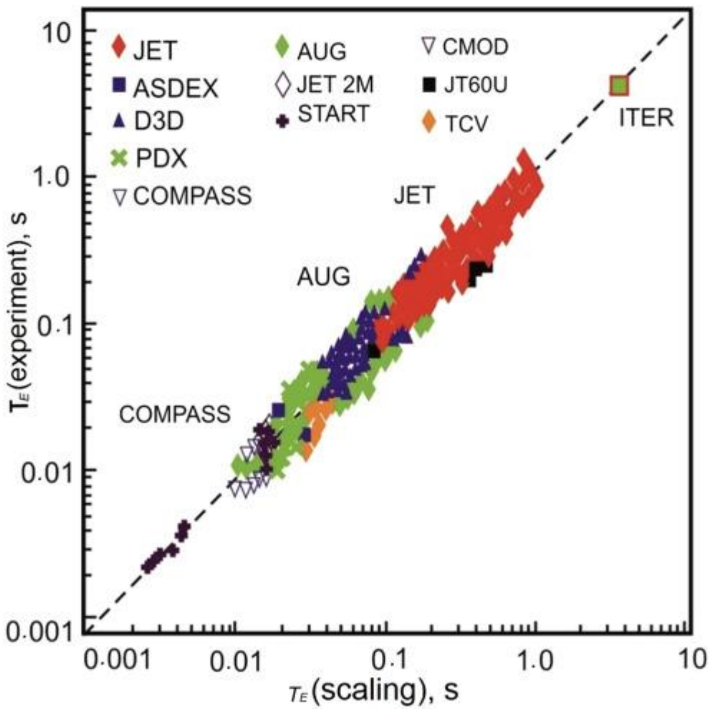

GOAL → Study effect of varying input assumptions on fusion performance

Sensitivity study performed for 3 SPARC H-modes

Reference H-mode, to reach high P_{fus} and Q ← **B=12T, I_p=8.7MA (PRD)**

B=8T, I_p=5.7MA (H8)

B=12T, I_p=6.5 MA (H12)

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Integrated Modeling of SPARC H-mode Scenarios: Exploration of the Impact of Modeling Assumptions on Predicted Performance

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[1]MIT Plasma Science and Fusion Center, 167 Albany St, Cambridge, MA 02139, USA
[2]Max Planck Institut fuer Plasma Physik, Boltzmannstrasse 2, Garching bei Muenchen, 85748, Germany

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November 2024

Abstract. In this paper an extensive database of SPARC H-modes confinement predictions has been provided, to assess its variability with respect to few input assumptions. The simulations have been performed within the ASTRA framework, using the quasi-linear model TGLF SAT2, including electromagnetic effects, for the core transport, and a neural network trained on EPED simulations to predict the pedestal height and width self-consistently. The database has been developed starting from two SPARC H-mode discharges (12.2 T, i.e. Primary Reference Discharge or PRD, and 8 T, i.e. reduced field) and permuting 4 input parameters (W concentration, DT mixture concentration, temperature ratio at top of pedestal and deviation of pedestal pressure from the EPED prediction), to perform a sensitivity study. For the PRD a scan of auxiliary input power (ion cyclotron heating) has been performed up to 25MW, to keep highly radiative plasmas above the LH power threshold as predicted by Martin and Schmidtmayr power scalings. A scan of pedestal density has then been performed for both PRD and 8T databases. p_{top}/p_{EPED} and T_i/T_e at top of pedestal showed the biggest impact on the fusion gain. Significant variation is observed across the database, highlighting the importance of sensitivity studies. Below a certain W concentration, the 12T database shows that $Q > 5$ is consistently achieved for full-field H-modes with 11 MW of auxiliary power, and values of $Q > 2$ are assured when increasing the input power to keep the plasma in H-mode. The 8T database demonstrates that SPARC can access a $Q > 1$ operational window with low W concentration, making it a potentially interesting scenario for obtaining breakeven conditions.

submitted to NF, published on arXiv (arXiv:2502.00187)

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Explored in this presentation

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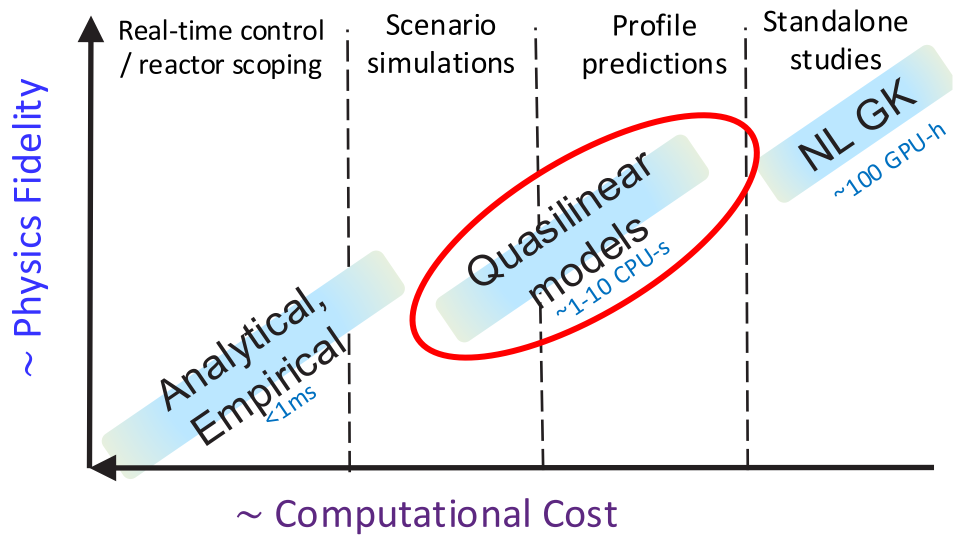

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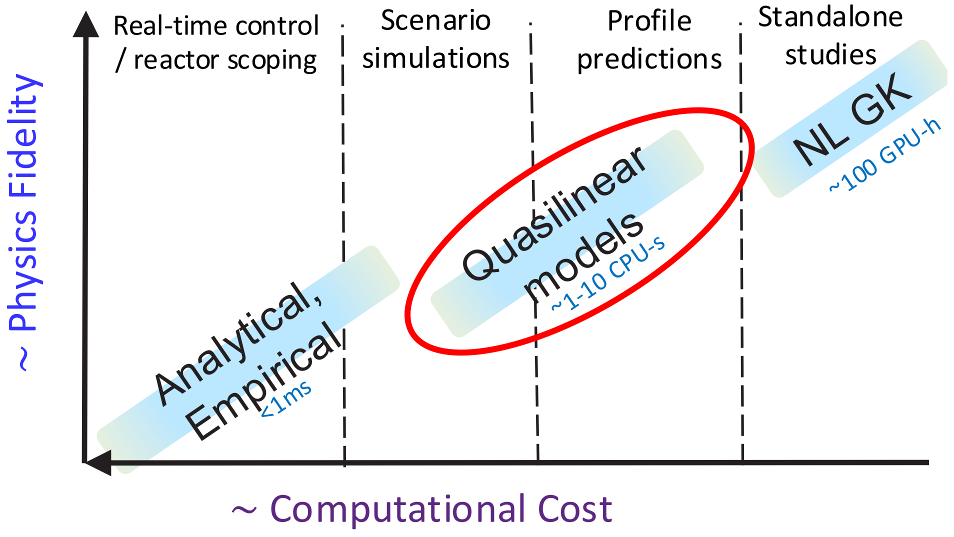

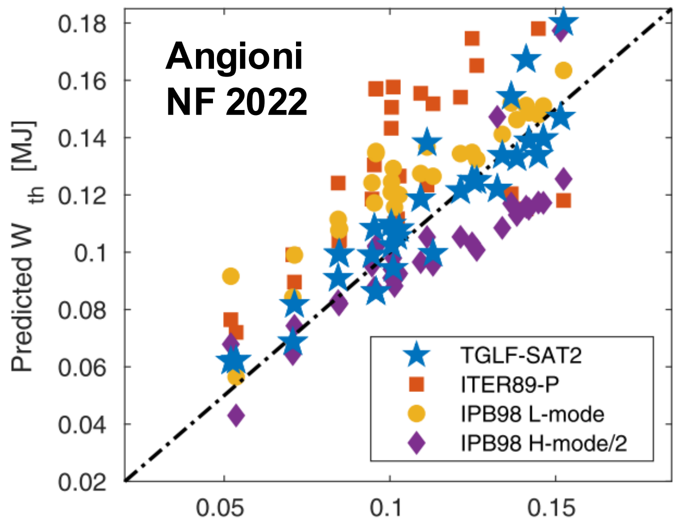

[1] G.M. Staebler *et al* 2021 *Nucl. Fusion* **61** 116007

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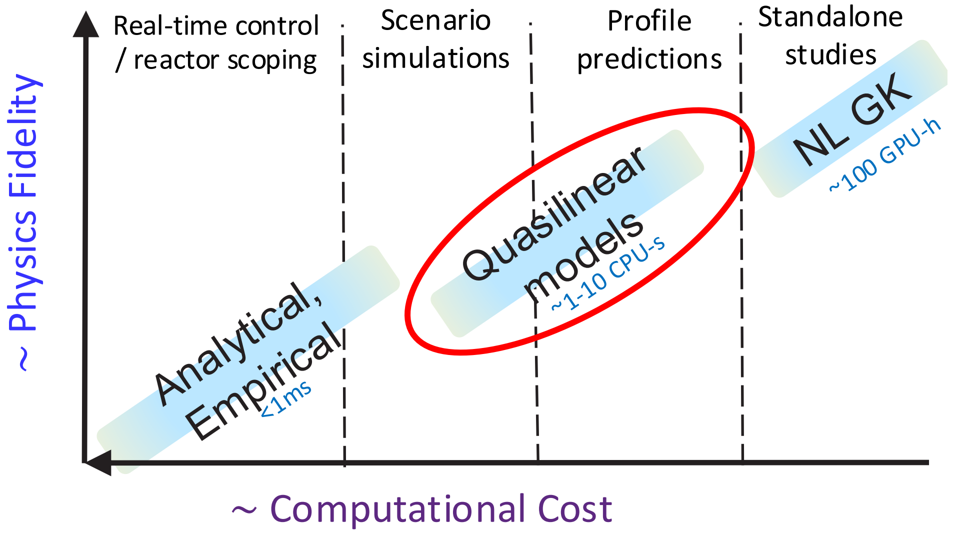
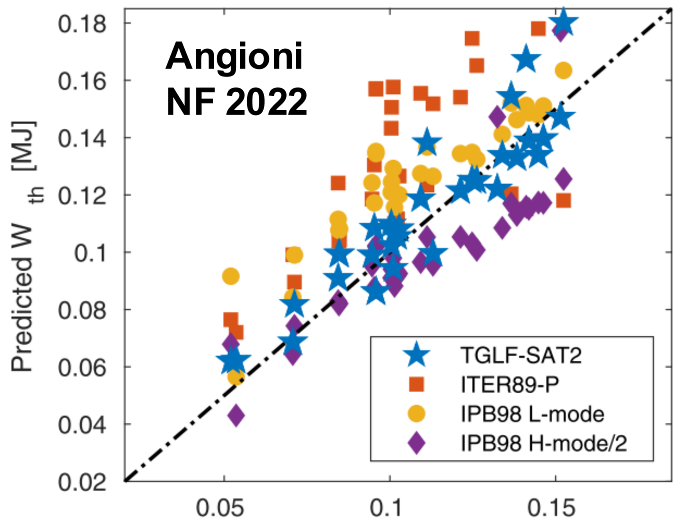
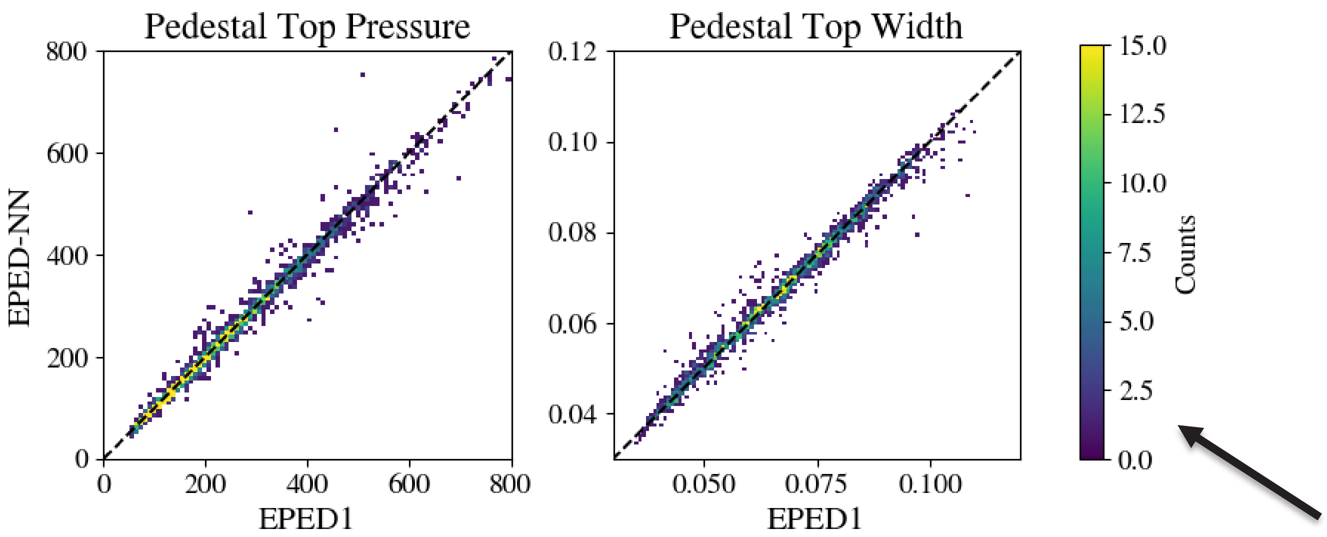
❖ Pedestal stability → NN derived from EPED [2] for SPARC H-modes







[J. Hall, P1 Tuesday]

[1] G.M. Staebler *et al* 2021 *Nucl. Fusion* **61** 116007 [2] P.B. Snyder *et al* 2011 *Nucl. Fusion* **51** 103016

TGLF and EPED-NN coupled in ASTRA

1. Integrated Modeling: 1.5D flux-matching transport solver → ASTRA [3]

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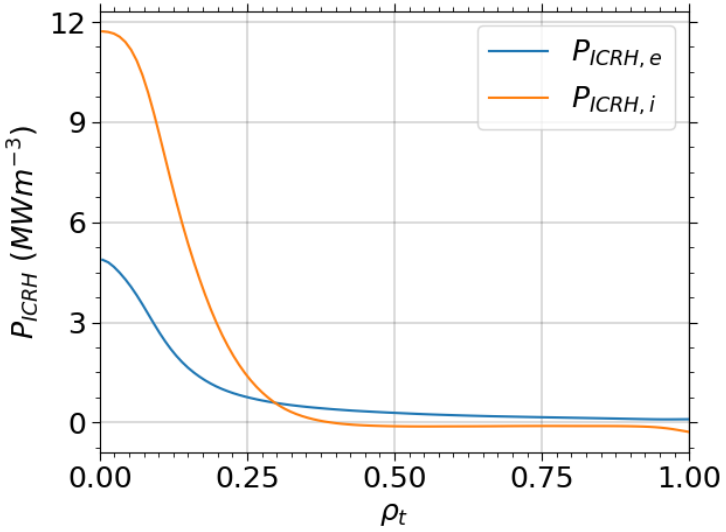

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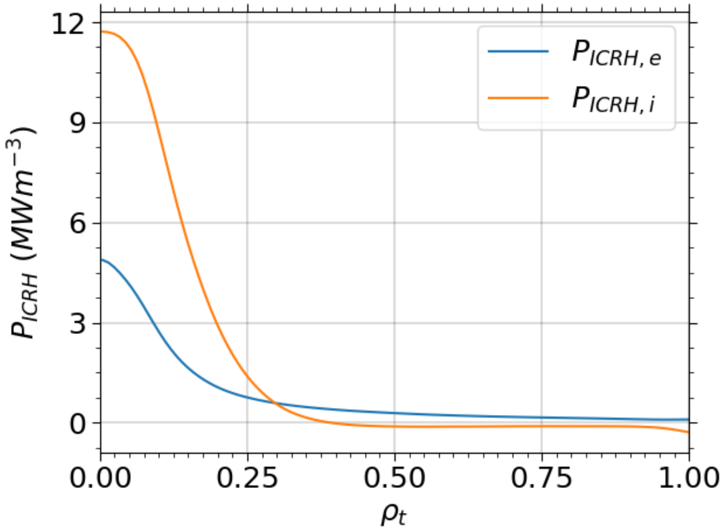

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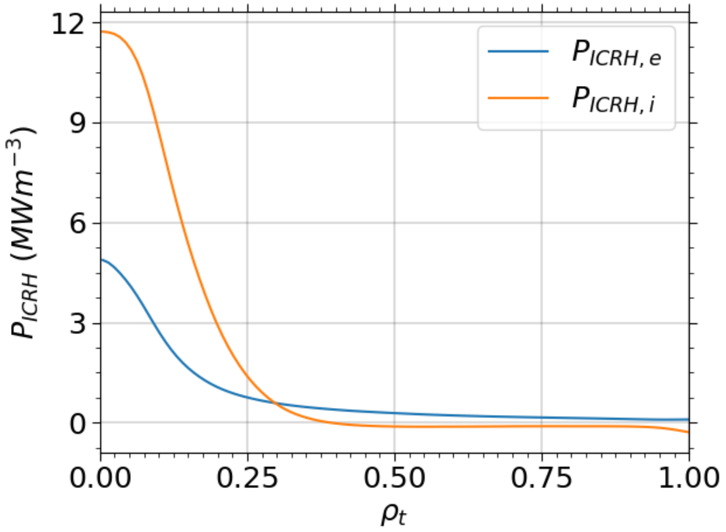

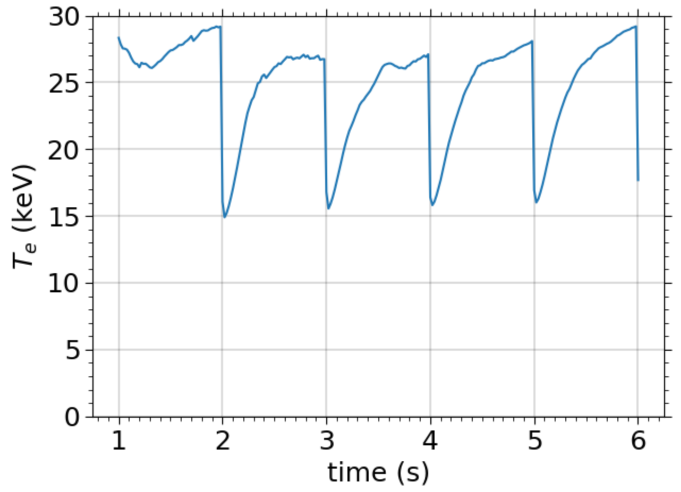

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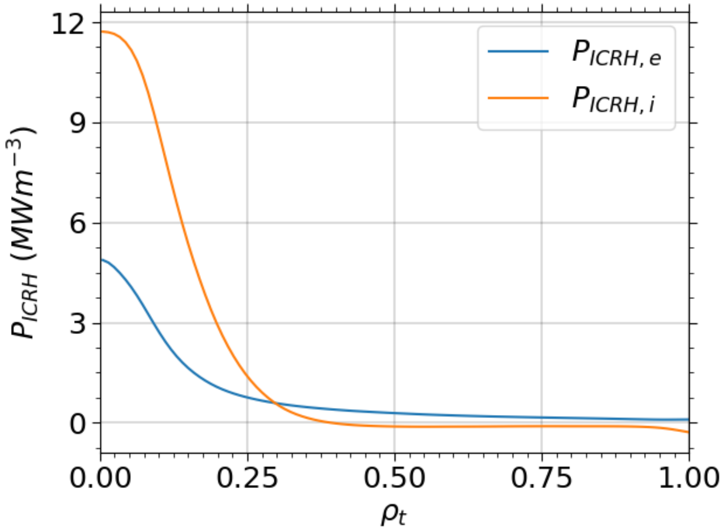

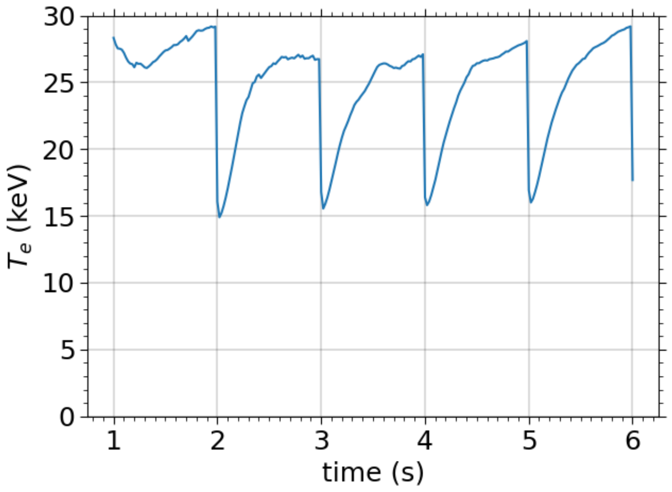

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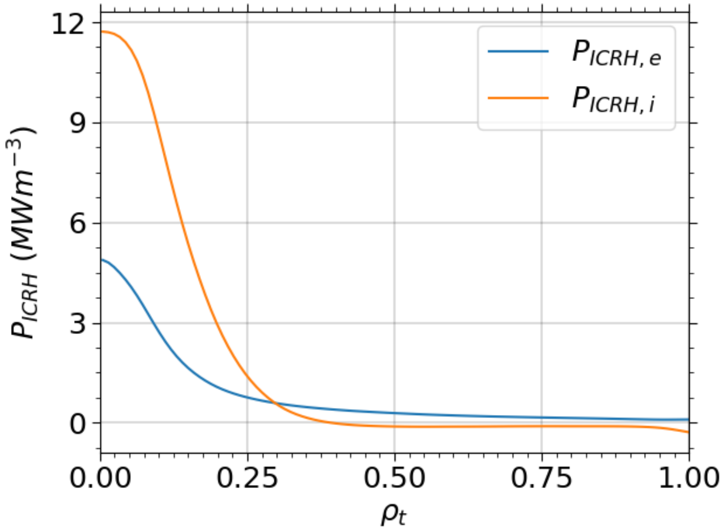

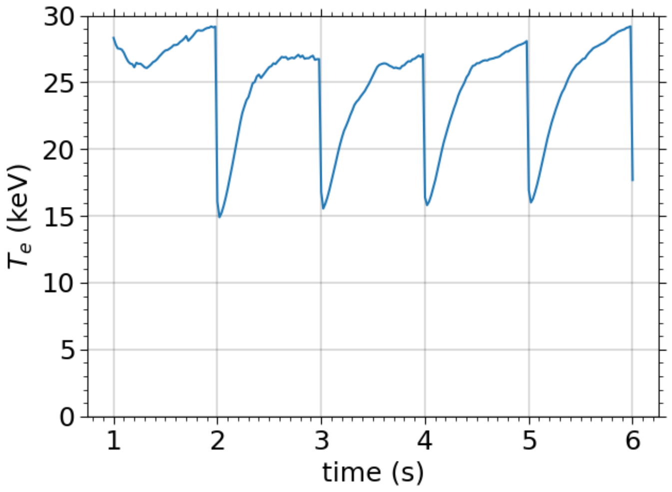

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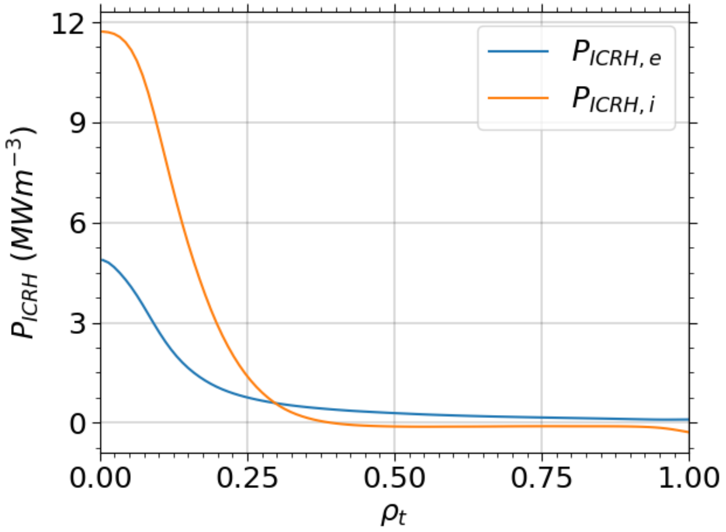

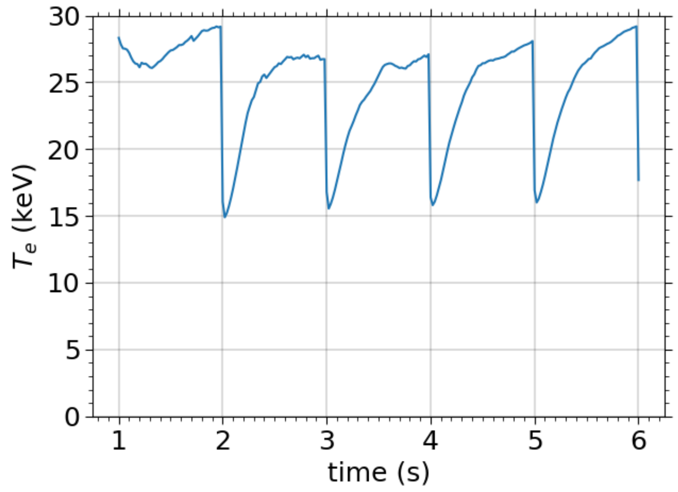

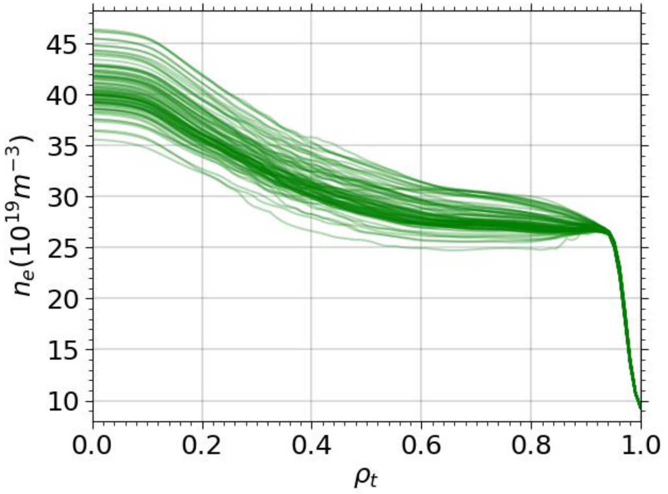

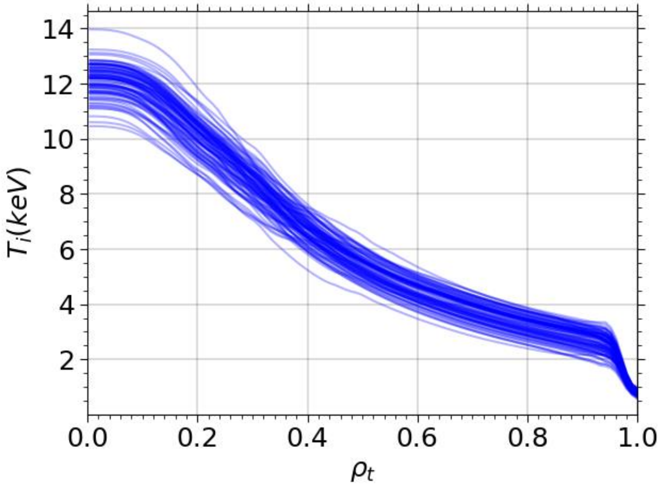

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PRD: scalings predict Q=11. Sensitivity study to input parameters

- SPARC PRD (primary reference discharge) → H-mode

Parameter	Value
R_0	1.85 m
a	0.57 m
B_t	12.2 T
I_p	8.7 MA
q_{95}	3.5
q^*_{Uckan}	3
f_{GW}	0.37
$P_{ICRF,abs}$	11 MW
$\langle n_e \rangle$	3x$10^{20}\ m^{-3}$

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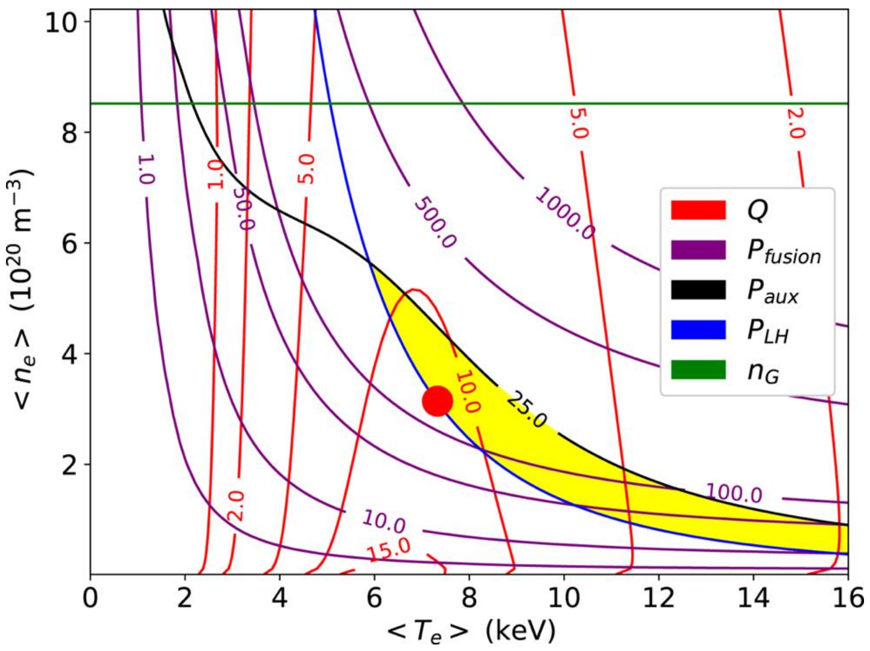
- Extensive study on PRD with low and high-fidelity models [4], [5]
- Q=11 and $P_{fus} = 140MW$ from experimental scalings [4]



[4] A. Creely et al., J. Plasma Phys. (2020), vol. 86
[5] P. Rodriguez-Fernandez *et al* (2022) *Nucl. Fusion* 62

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range	[1.5e-5, 3.5e-4]	[0.8, 0.875]	[0.8, 1.2]	[0.8, 1.2]

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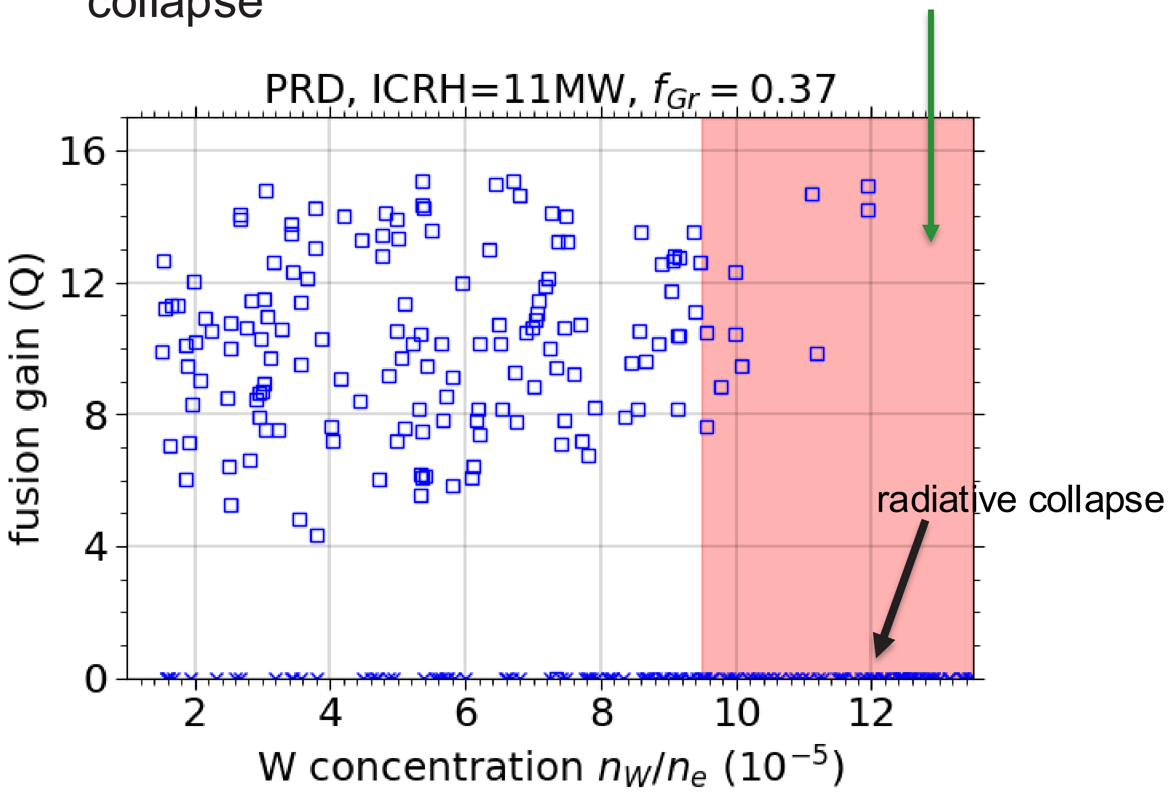

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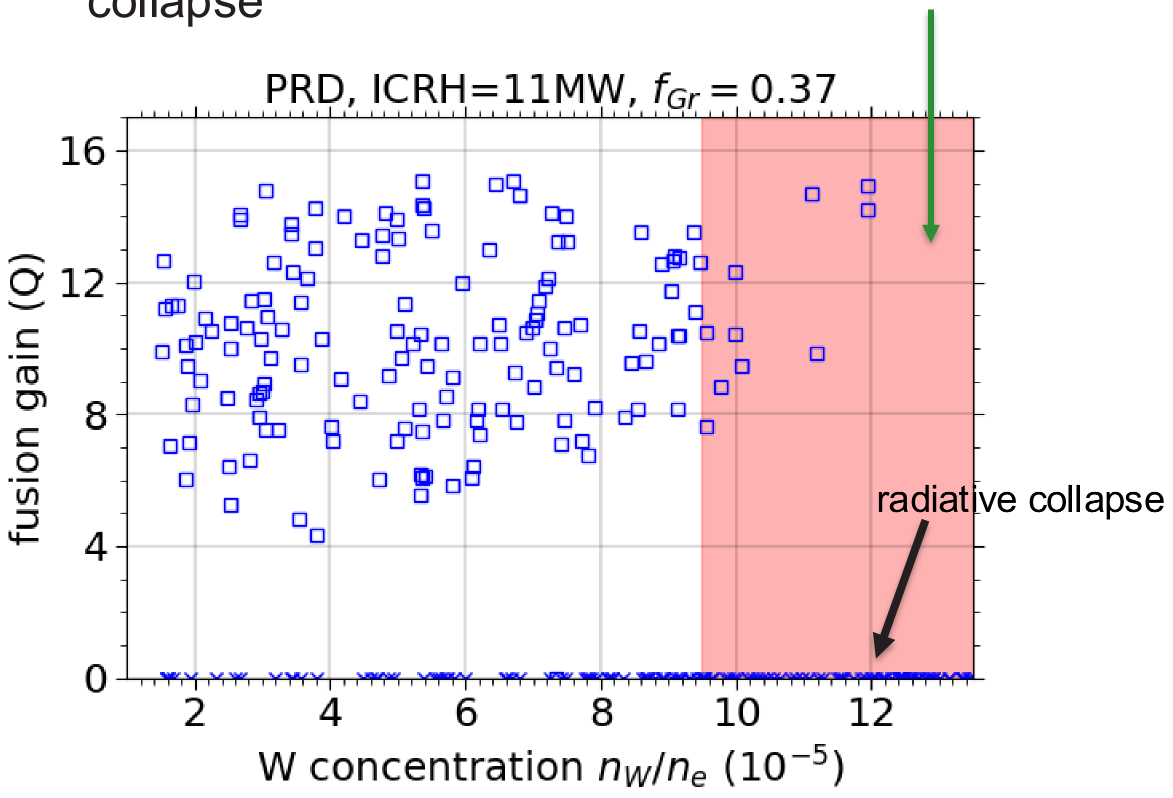
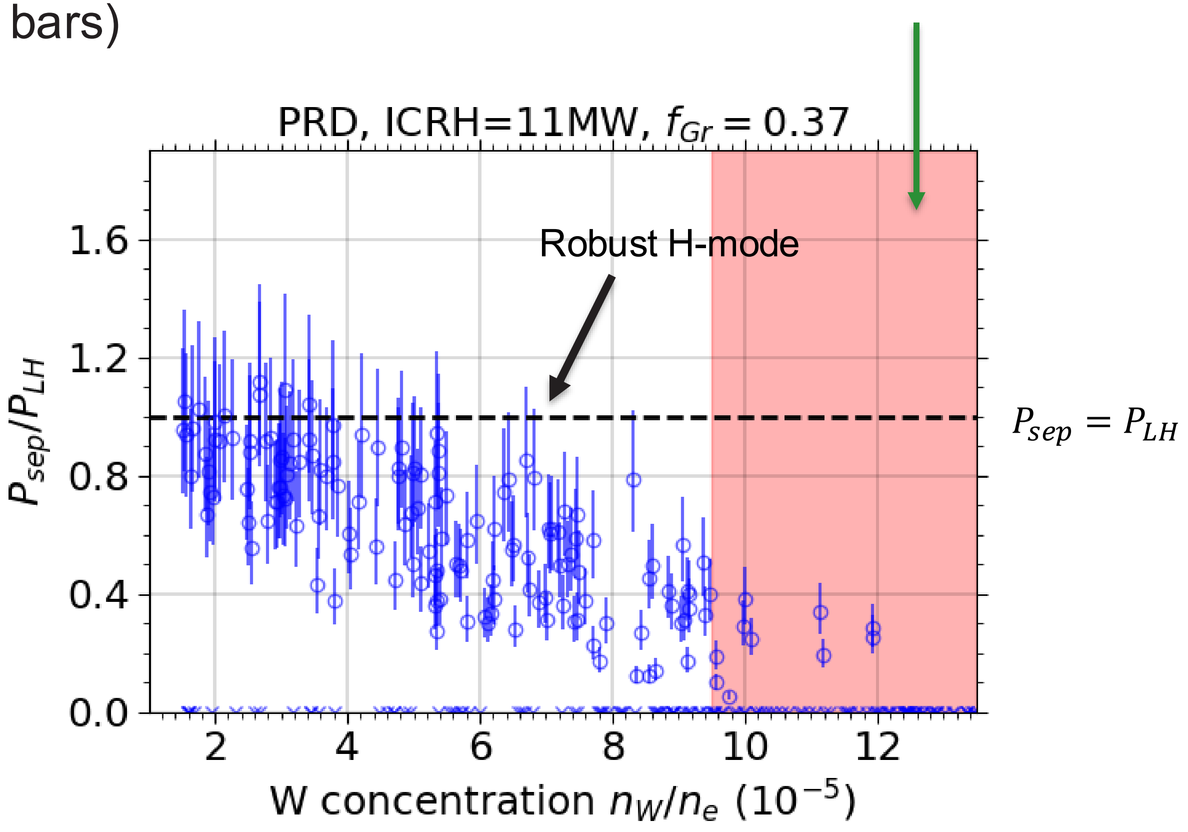
❖ W increases radiation → lower P_{sep} → lower P_{sep}/P_{LH}, where P_{LH} is predicted by Martin scaling [6] (30% error bars)





[6] Y R Martin et al 2008 J. Phys.: Conf. Ser. 123

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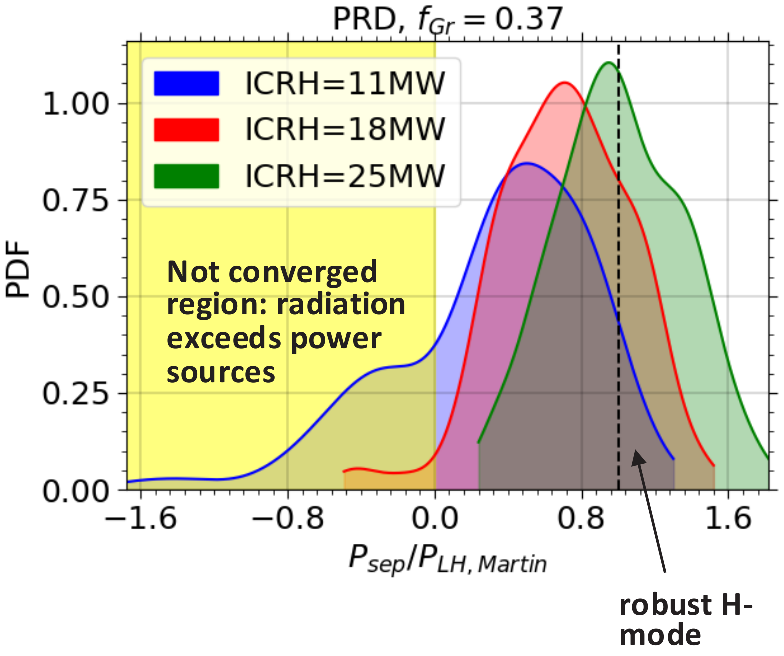

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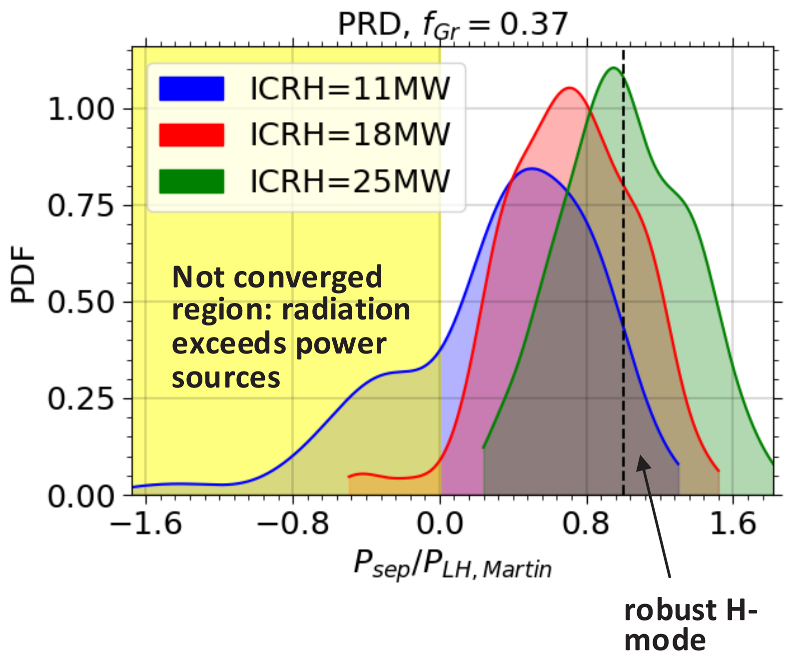
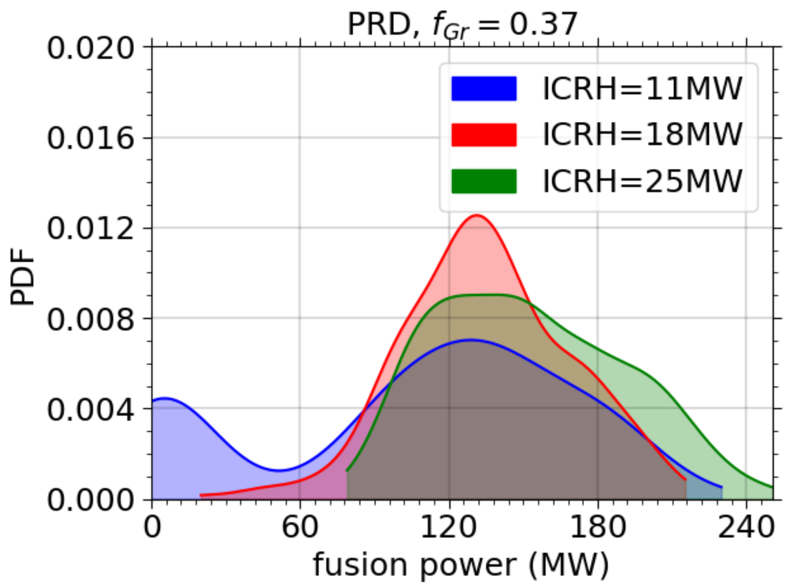
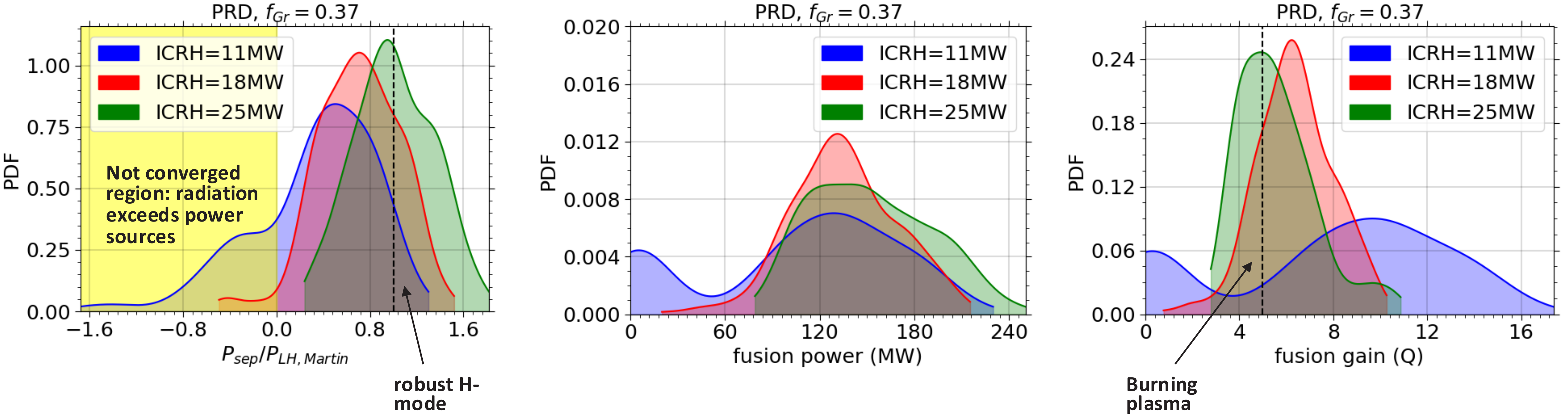




PRD: scan of P_{ICRH}. High power → Q~5 and robust H-mode

- Scan of ICRH power → **851 simulations**
- Increased power:
  - more robust H-mode
  - Same fusion power (profiles stiffness)
  - Lower Q, but still ~5



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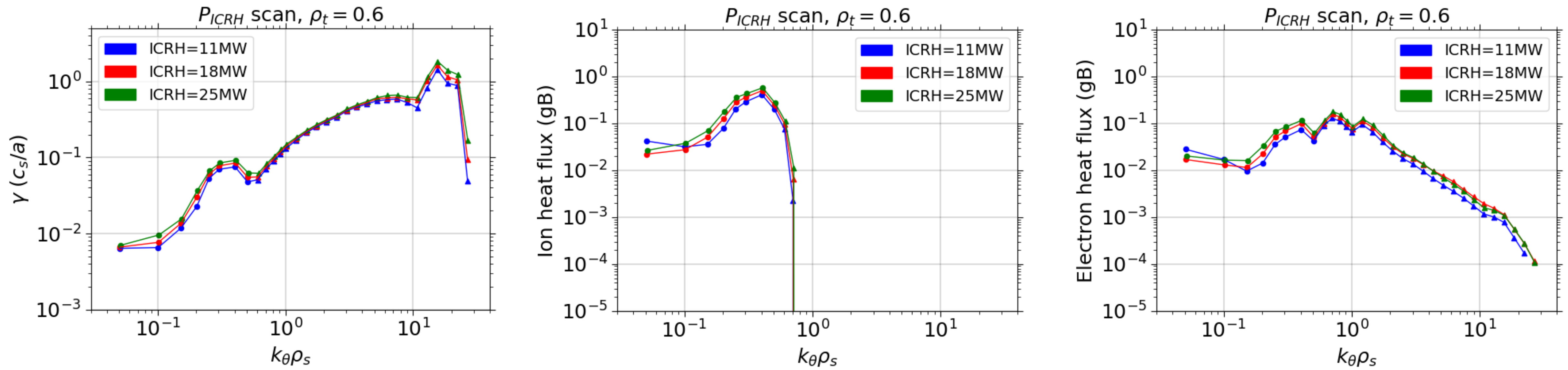

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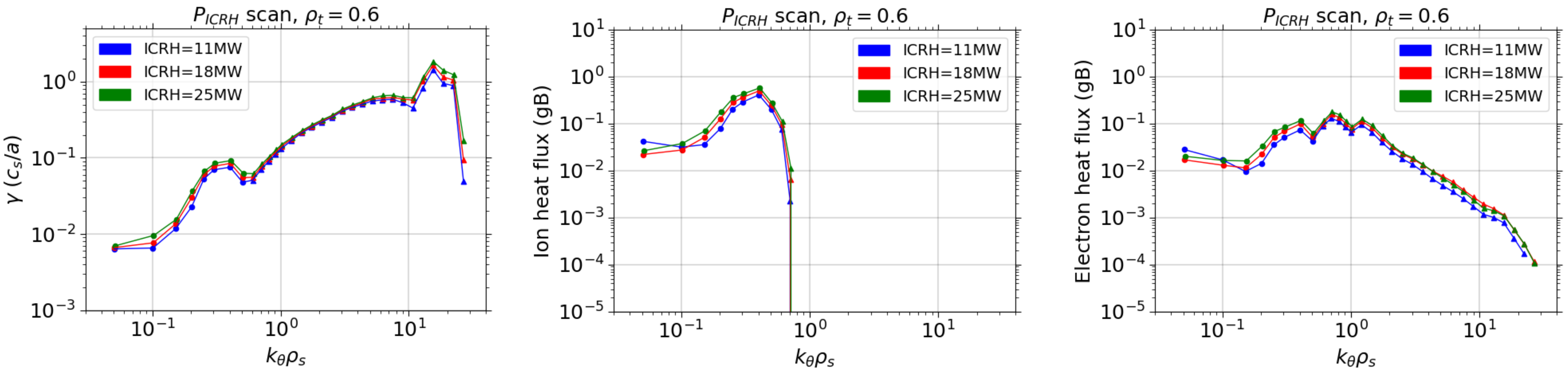
- ITG and ion-scale ($k_y \rho_t < 2$) dominant [7] ⟶ $Q_{e,k\rho<2} / Q_{e,tot} \sim 0.92$



[7] C Holland et al JPP 2023

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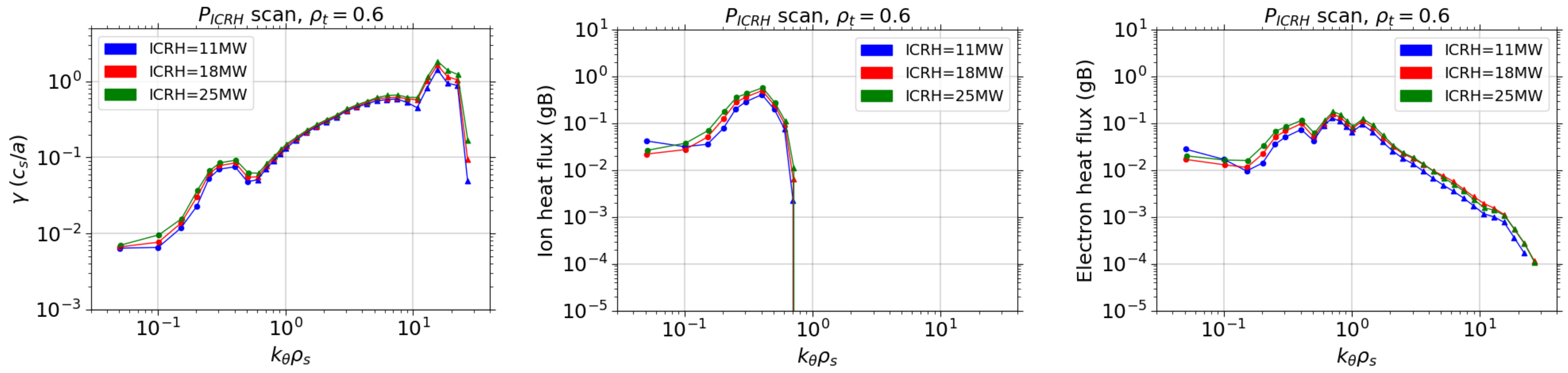
- Almost only electrostatic modes ⟶ $Q_{es} / Q_{tot} > 0.95$



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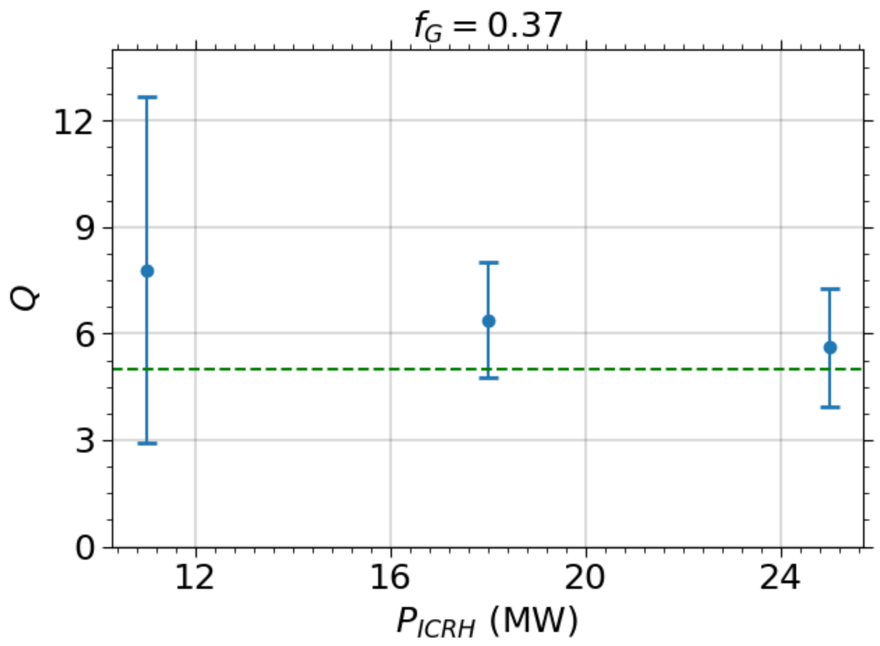
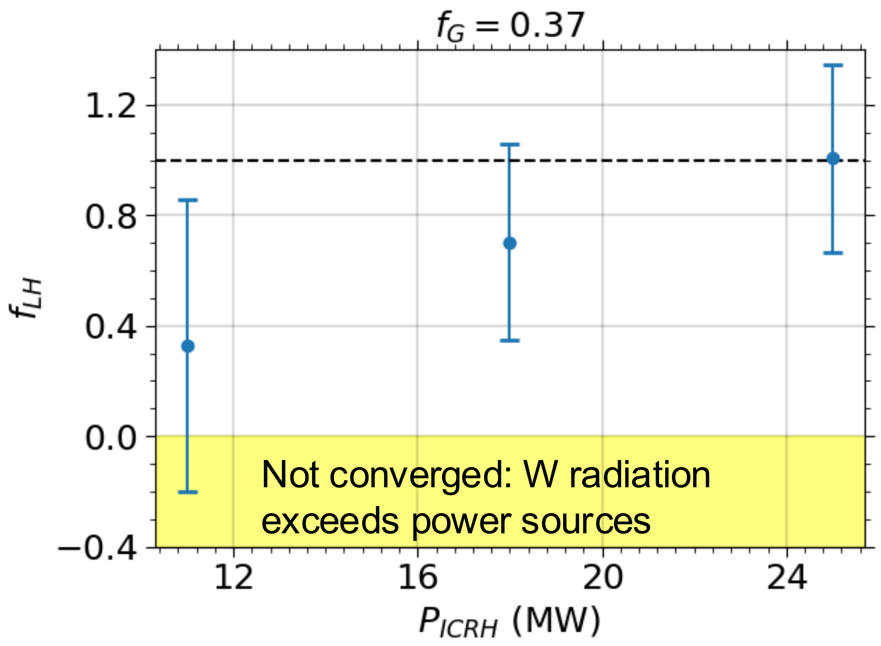
PRD: TAKEAWAYS

- Good fusion performance → Q>2 (SPARC goal), often Q>5





PRD: TAKEAWAYS

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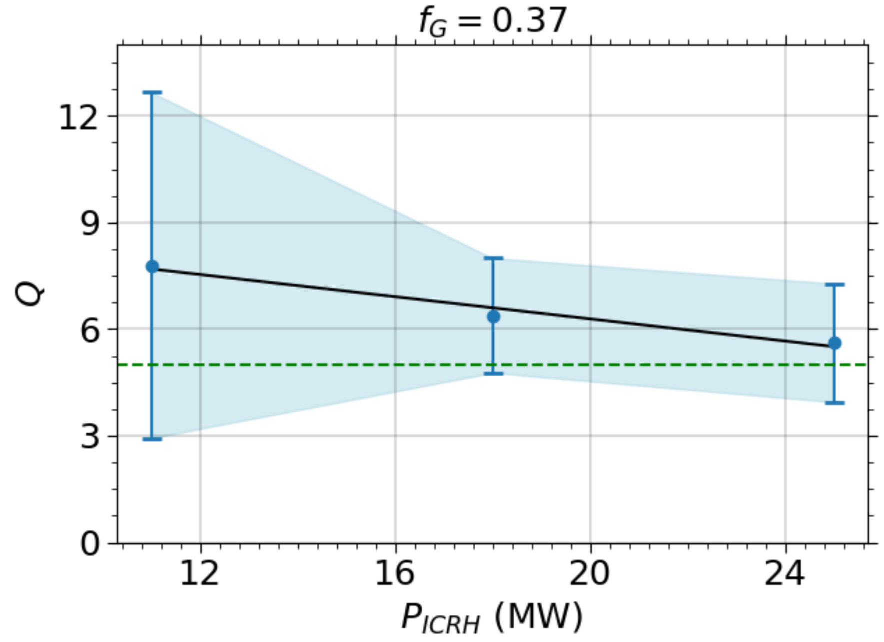
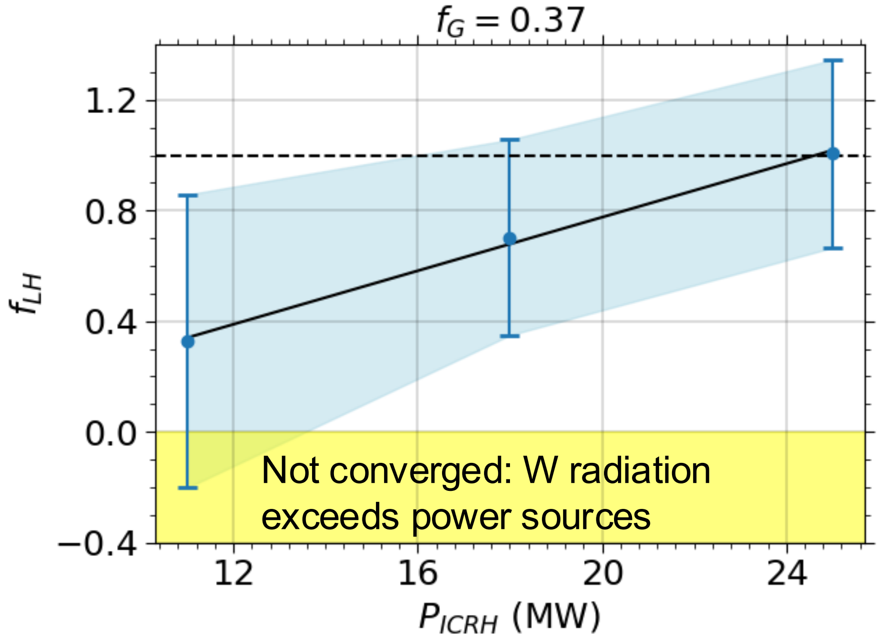
- At high ICRH power → Q~5, robust H-mode and reduced uncertainty





Outline of the talk

- Description of the simulations framework
- Plasma Reference Discharge (PRD) [12T, 8.7MA]
- Reduced field H-mode (H8) [8T, 5.7MA]
- Reduced current H-mode (H12) [12T, 6.5MA]

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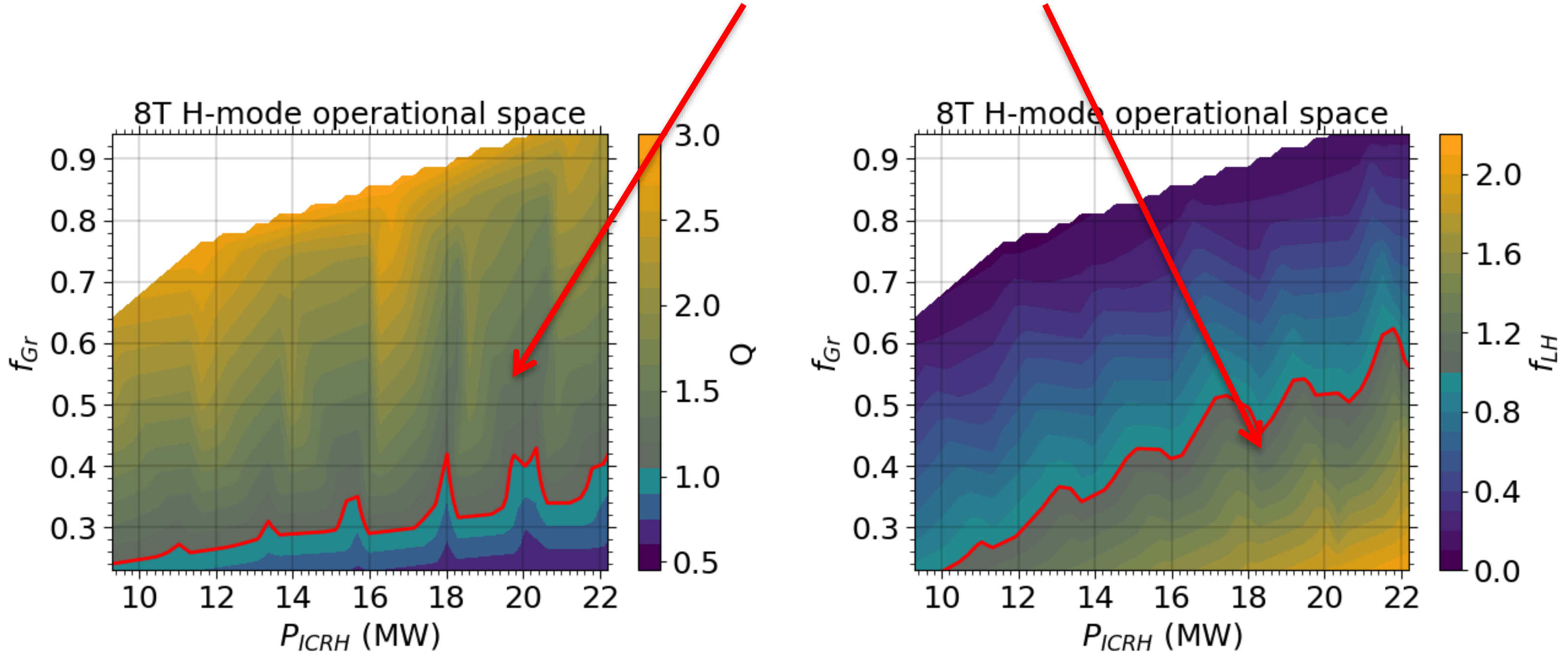

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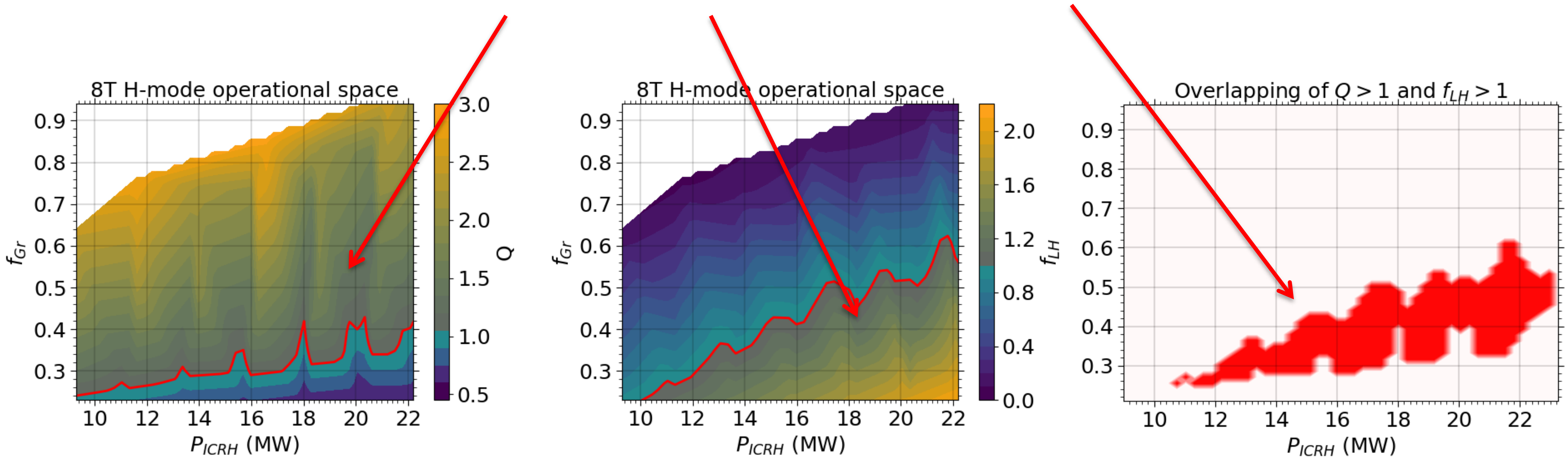

Reduced field H-mode: candidate scenario for Q>1

Parameter	Value
B_t	8 T
I_p	5.7 MA
q_{95}	3.5
q^*_{Uckan}	3
f_{GW}	0.48
$P_{ICRF,max}$	25MW

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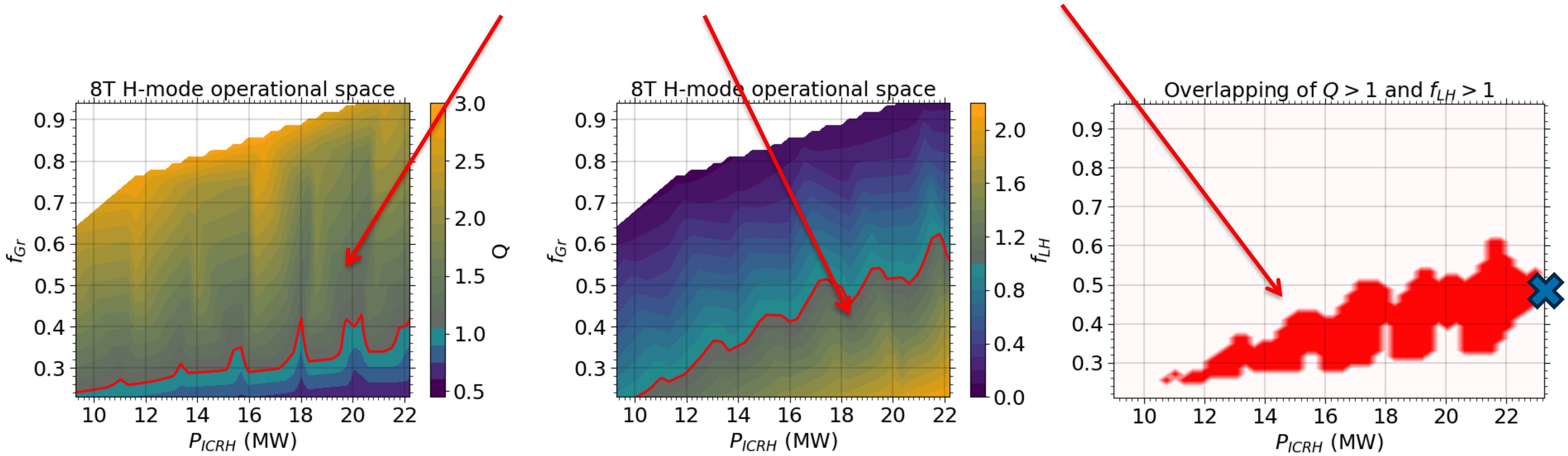

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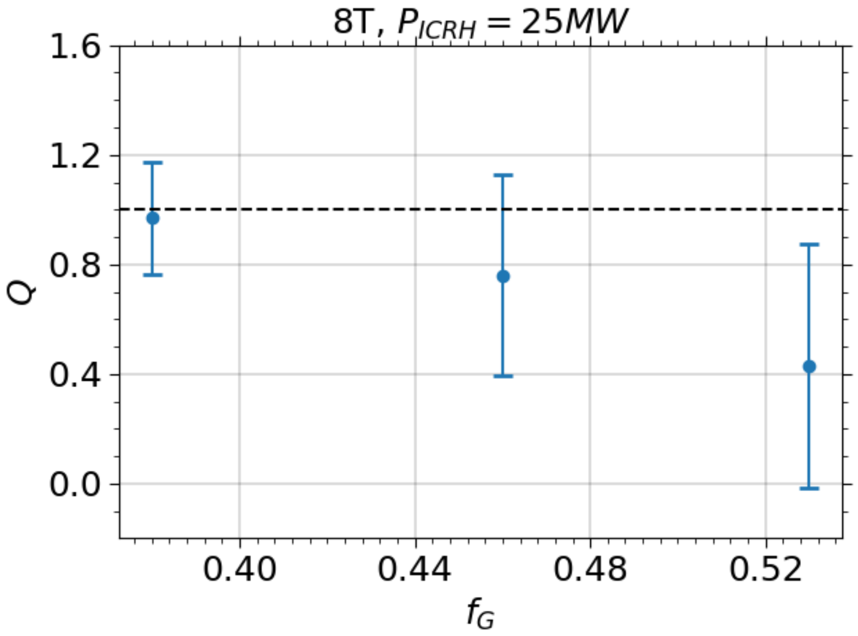

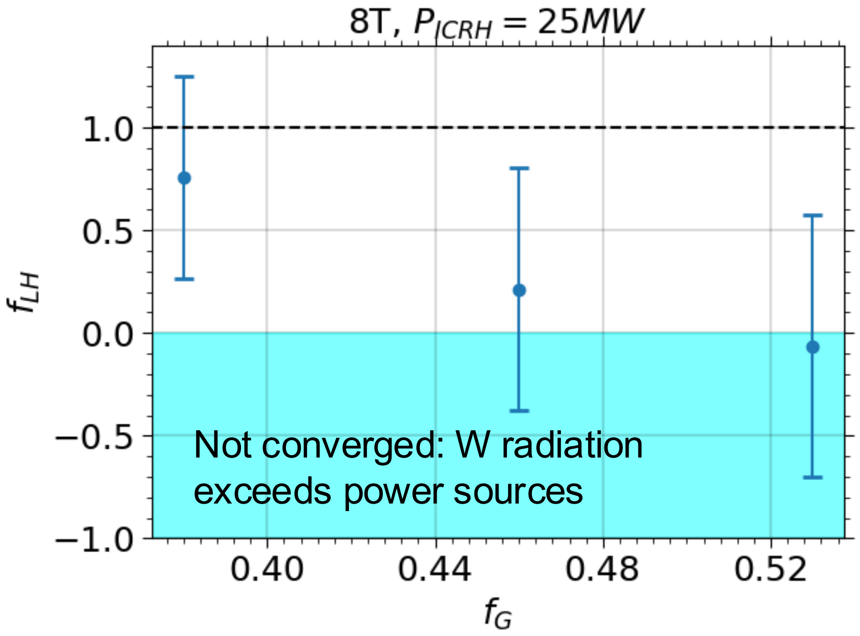

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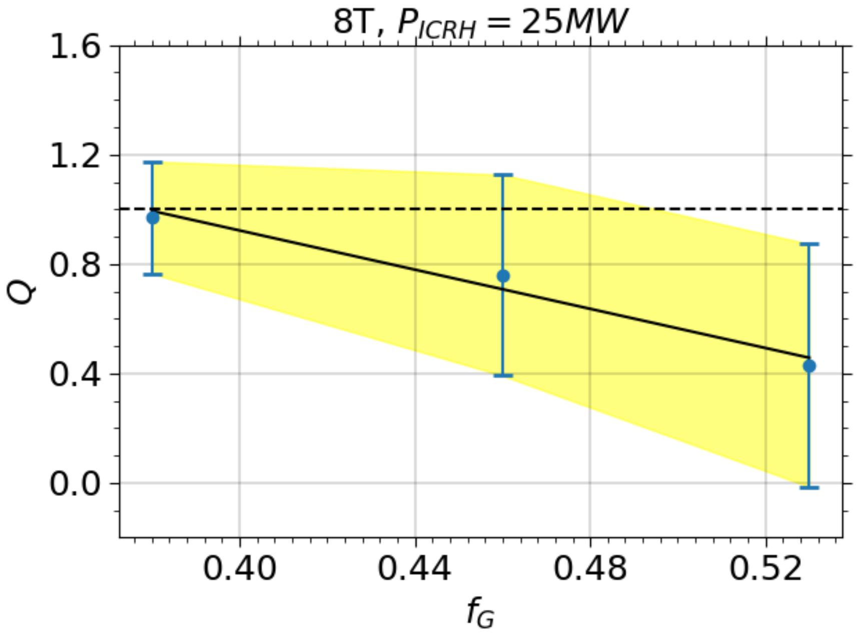

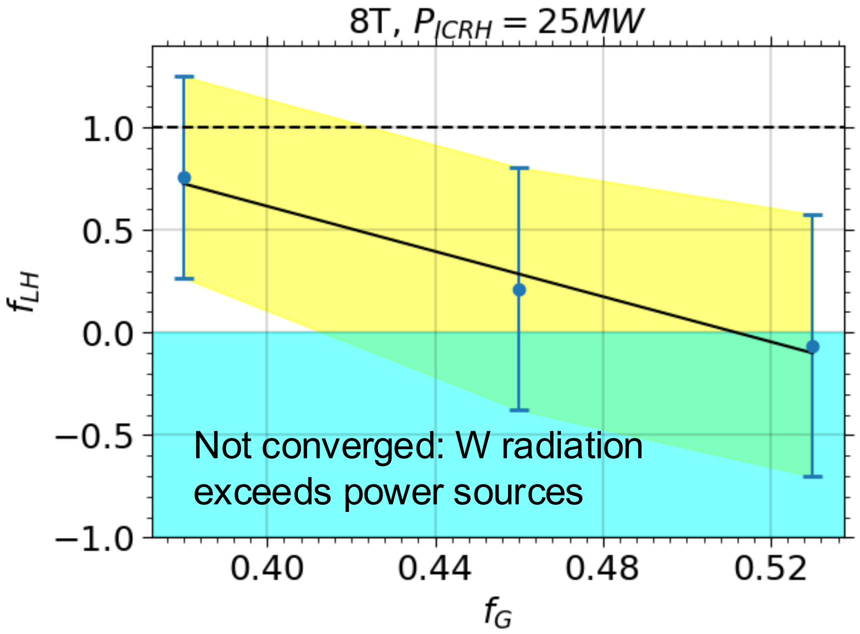

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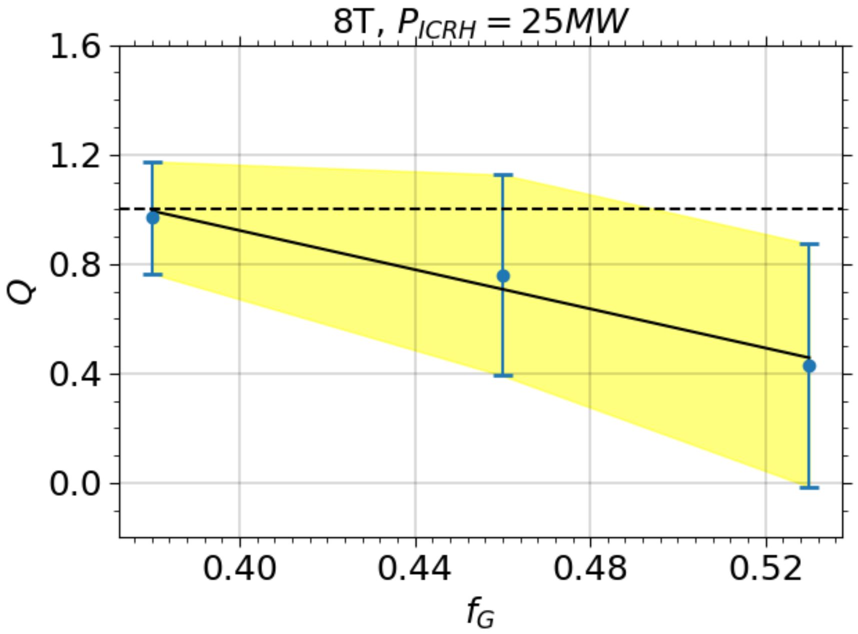
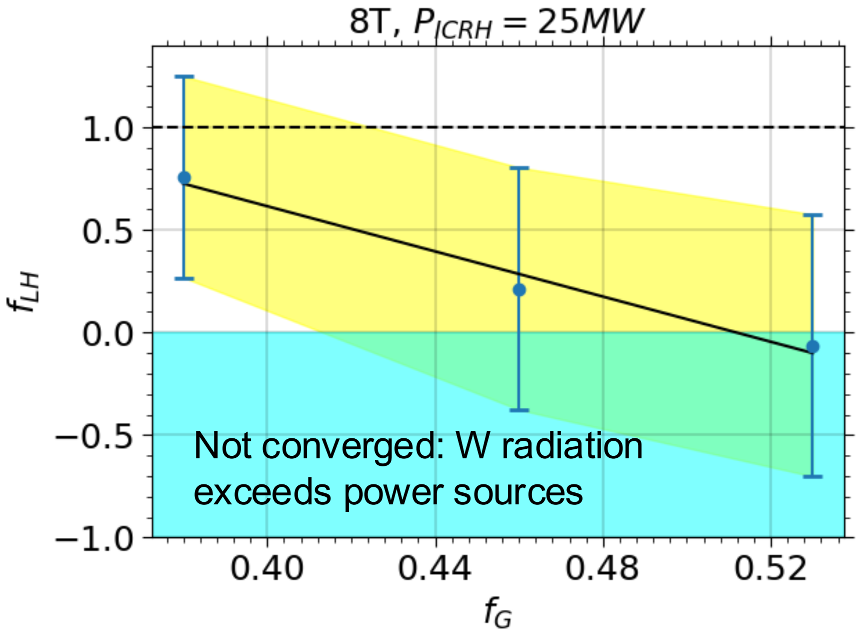
- **Lower fusion than PRD → W radiation plays a big role for H-mode robustness**





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- Span the operational space (current, field, density, power) → additional scenario with robust:
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- Span the operational space (current, field, density, power) → additional scenario with robust:
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- Low current H-mode with:
  - $B_T = 12.2T$ (fixed for ICRH coupling)
  - $I_P = 6.5MA$

Parameter	Value
B_t	12.2 T
I_p	6.5 MA
q_{95}	4.8
q^*_{Uckan}	3.6
f_{Gr}	0.28
$P_{ICRF,max}$	25 MW

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  - ➢ $n_{e,top}$
  - ➢ f_W
  - ➢ P_{ICRH}

→ Effect on:

- **Performance**
- **H-mode robustness**

	Scan ranges
I_p	[5.5 - 6.5] MA
$n_{e,top}$	[1.8 - 3.3] $10^{20} m^{-3}$
f_W	[1.5 - 13.5] 10^{-5}
P_{ICRH}	[15 - 25] MW

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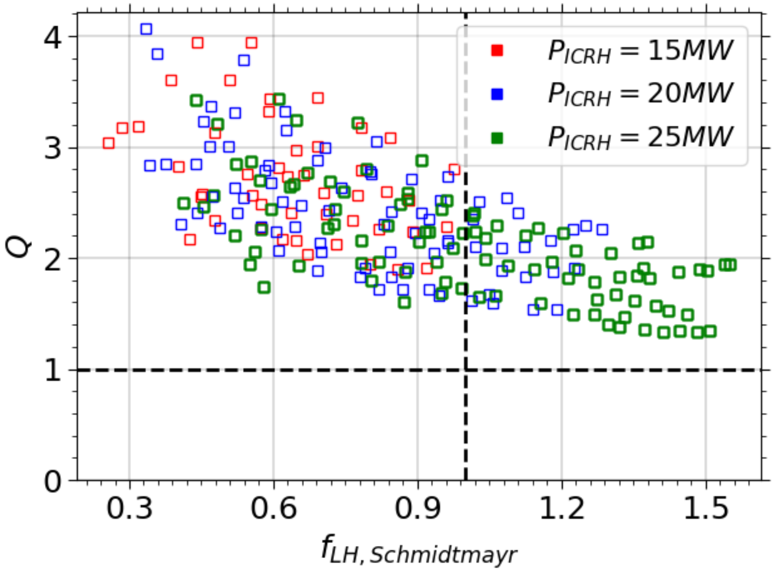
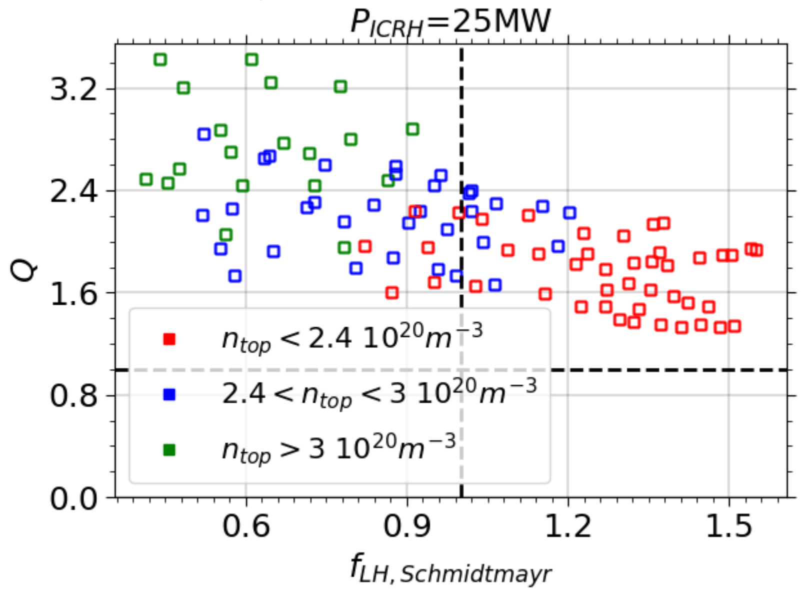
- 567 simulations, ~40k CPUh
- ~40% of total simulations converged
- Optimal operation → High P_{ICRH} and low density

Converged cases: 25% 42% 51%



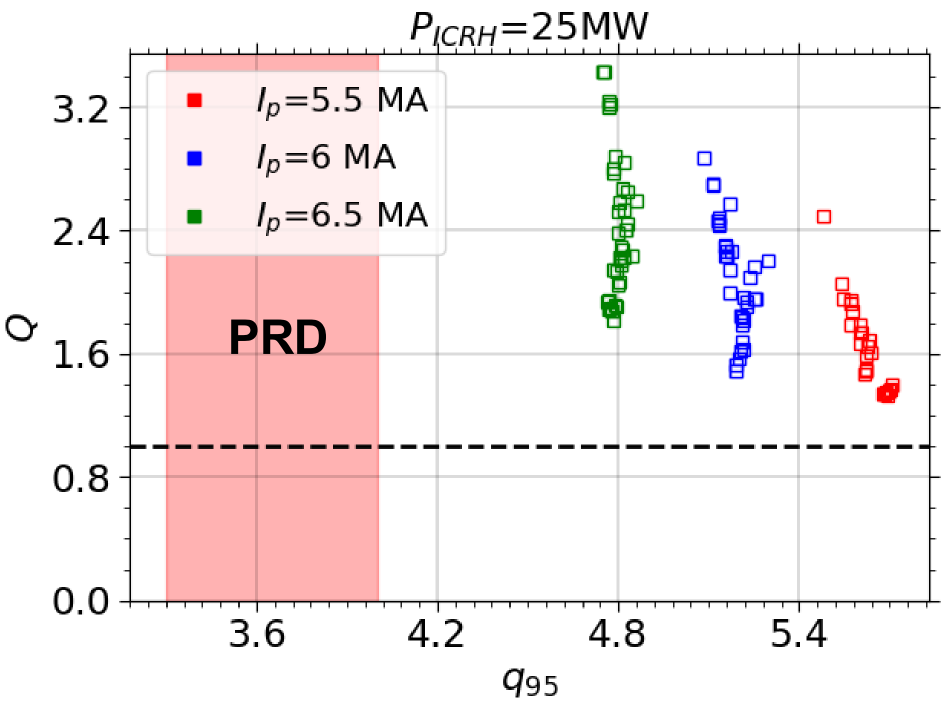
Converged cases: 82% 61% 28%



Reduced current H-mode: possible safer q_{95} operating regime

- Q shows a linear trend with I_p

Converged cases: 40% 54% 59%



Reduced current H-mode: possible safer q_{95} operating regime

- Q shows a linear trend with I_p
- Different I_p → other possible scenarios at different q_{95}

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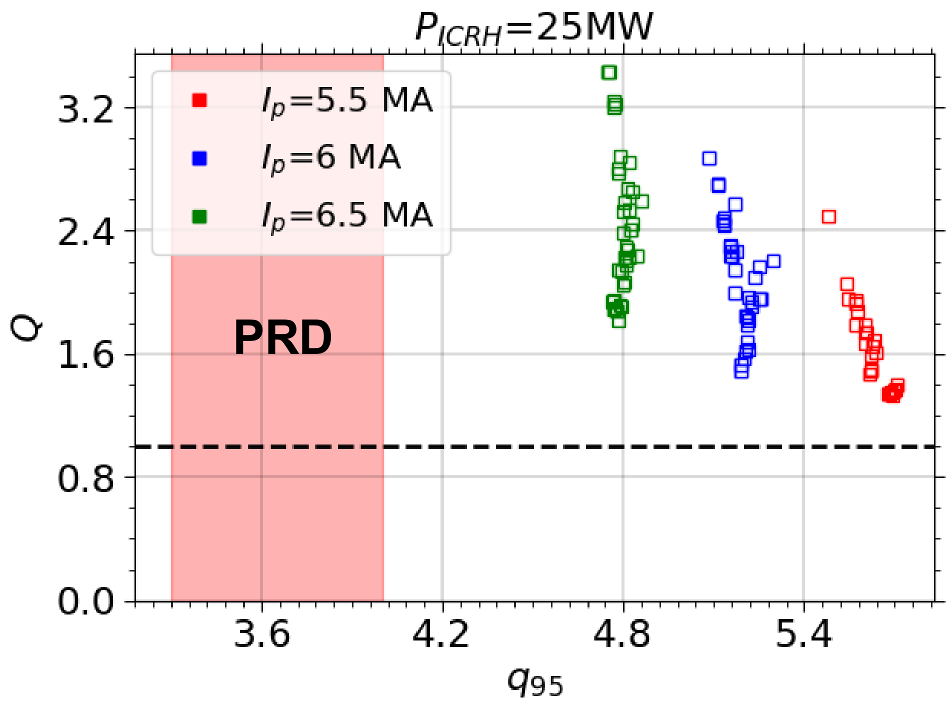

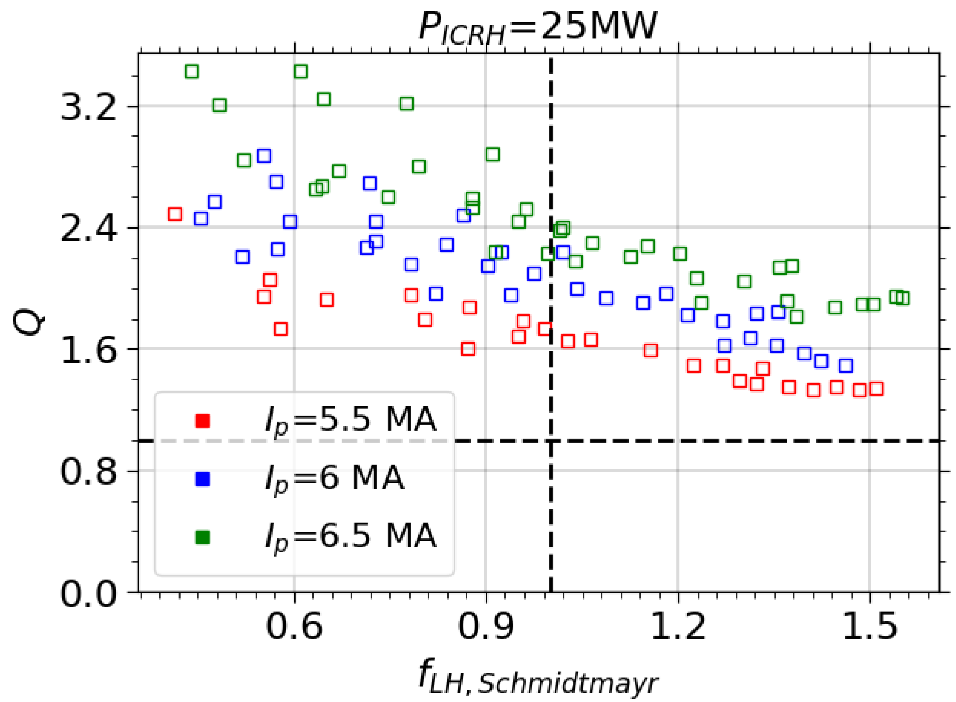

Summary and outlook

- Summary:
  - Database of H-mode simulations → **Q depends strongly on input parameters**
  - density, P_{ICRH} and P_{rad} affect H-mode → **Biggest uncertainty is on H-mode access and sustainment**
  - PRD H-mode → **overall high performance (Q>2 and P_{fus}>50MW)**
  - Low field H-mode → **candidate for breakeven at low density / W concentration**
  - Low current H-mode → **resilient to radiation, best H-mode for Q>1, multiple q_{95} solutions**

- Outlook:
  - Improve pedestal model (SOL reduced model)
  - Increase fidelity of simulations (Impurity transport, radiation modeling, rotation)

- Other results (not shown):
  - Most impactful parameters on Q → $T_{e,top}/T_{i,top}$ and p_{top}/p_{EPED}