Efficient steady-state predictions of core plasma profiles with δf nonlinear gyrokinetics using the PORTALS framework

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Predictive transport modeling is critical for effective FPP design

- Given a device design and operational parameters, fusion power production depends on <u>transport processes</u>.

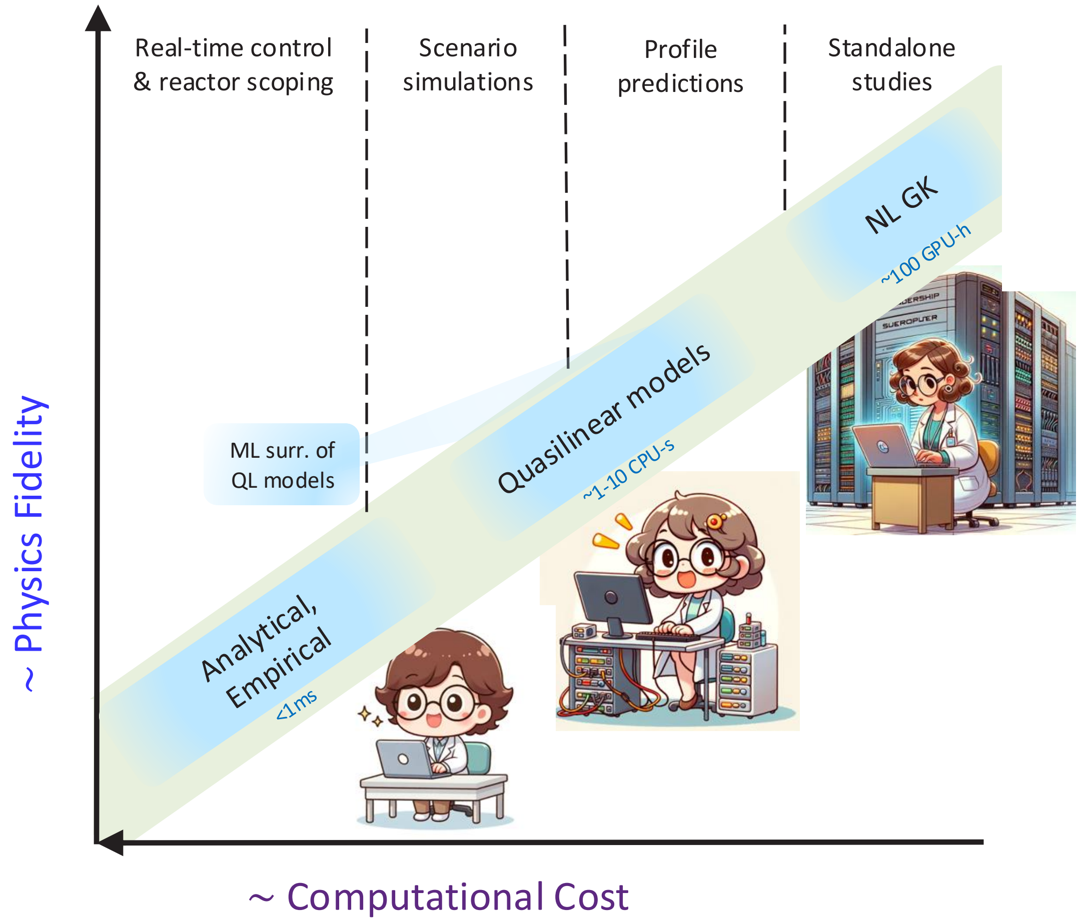
$R_0, a, B_T, I_p, \kappa, \delta$ ...

Some version of power balance
$P_{in} = P_{out}$

Performance (P_{fus}, Q)

P_{ICH}, S_{DT}, S_Z ...

- The characterization of the effect of transport phenomena is a clear trade-off between fidelity and cost:
  - Global energy confinement time (**+ H factor**) in **empirical workflows**.
  - Critical gradient models (**+ parameters**) in **analytical workflows**.
  - Quasilinear transport models (**+ saturation rule**) in **physics-based workflows**.
    - ML Surrogates (+ surrogate quality) in fast workflows.
  - Gyrokinetic codes in **first-principles workflows**.

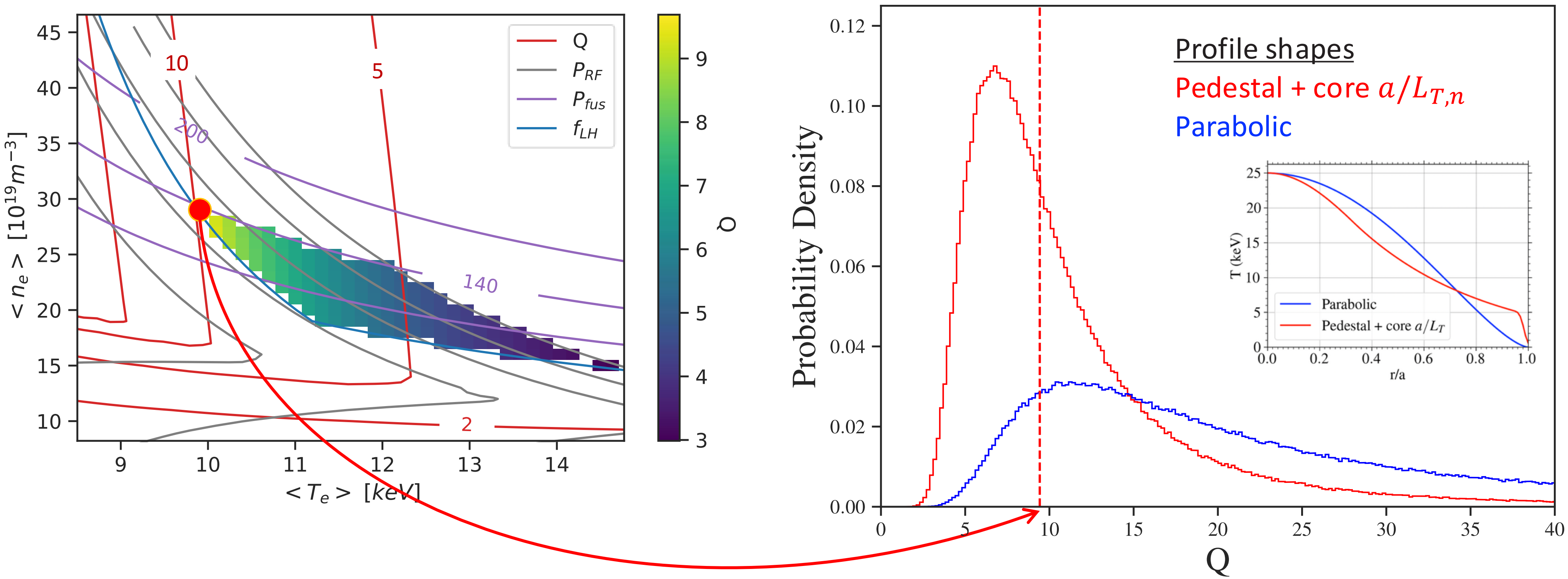


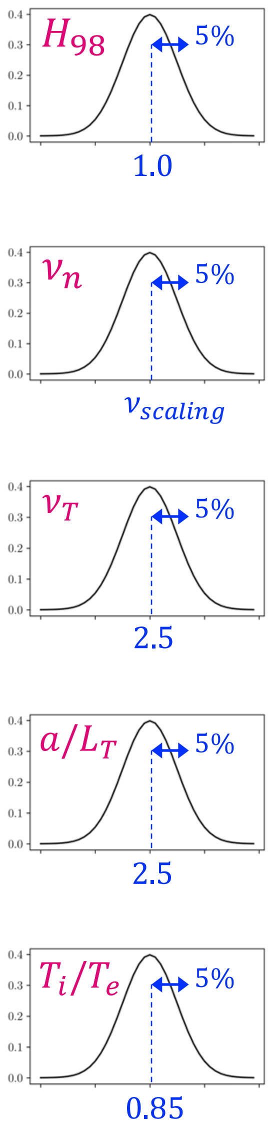
*Cartoon illustrations from chatGPT-4

0D power balance codes can arbitrarily choose performance

- Using energy confinement time from scaling laws is insufficient to predict tokamak performance.
- Uncertainties in transport-related input parameters to POPCONs or system codes result in **high variability** in predicted fusion power and fusion gain.

P. Rodriguez-Fernandez NF 2024





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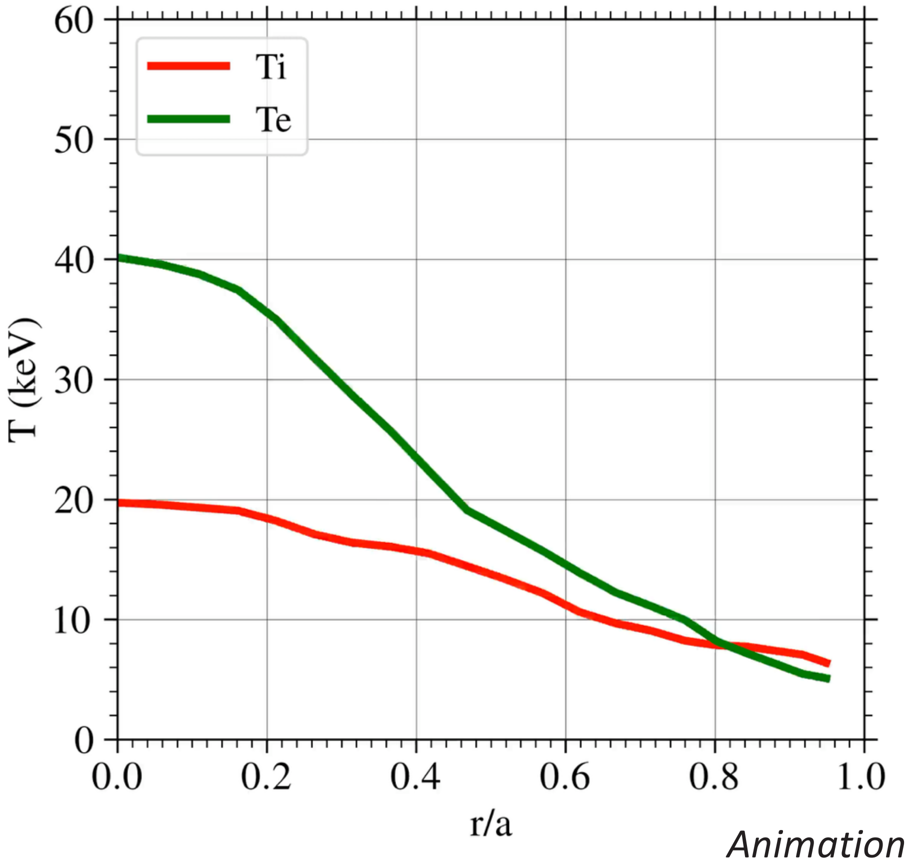
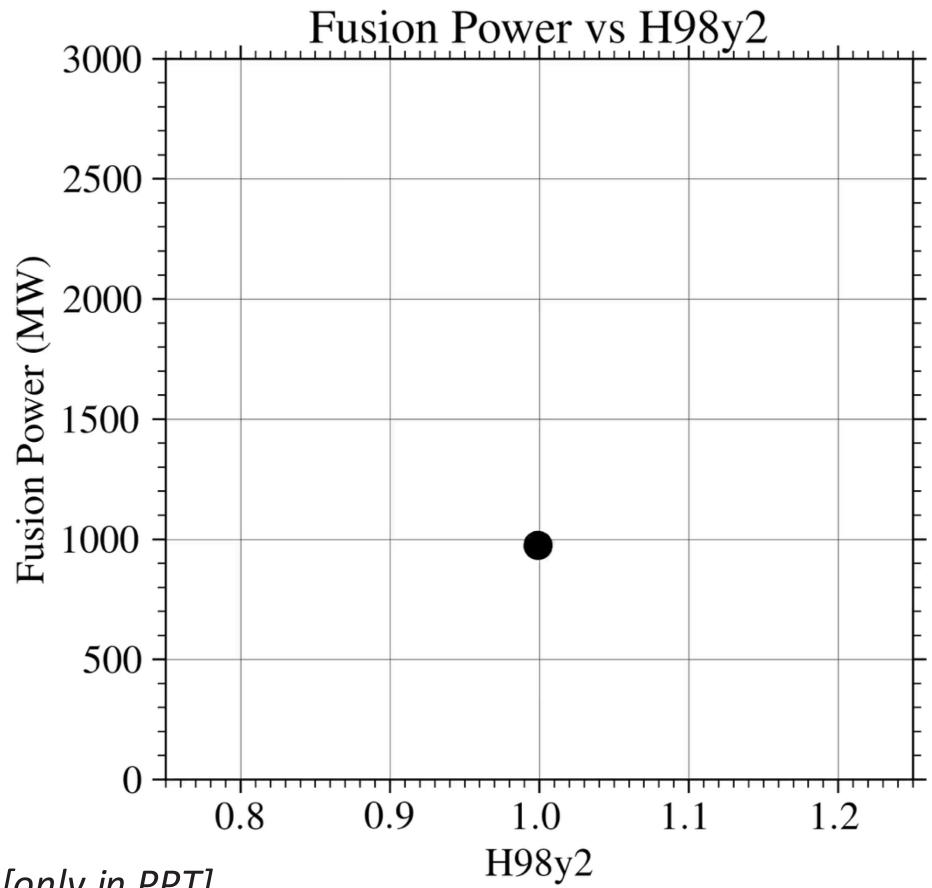
ARC-class





Animation [only in PPT]

Exploratory study (random)

- $H_{98y2} \in [\, 0.999, 1.001 \,]$
- Fixed density

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MIT PSFC

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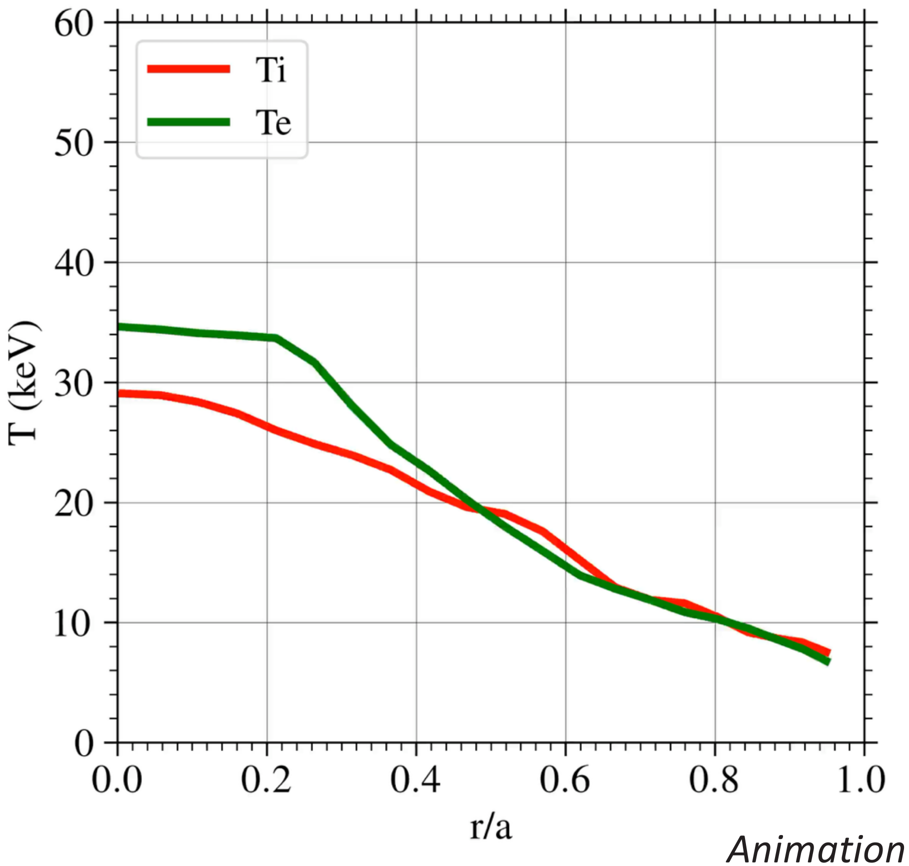

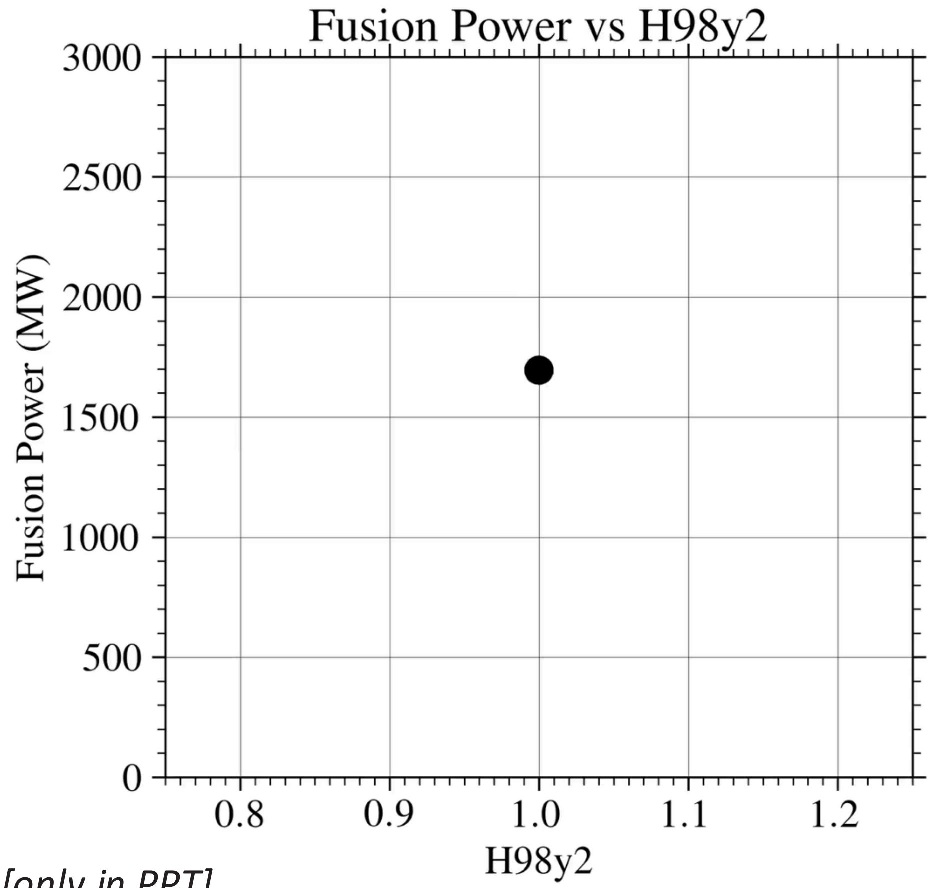

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Exploratory study (random)

- $H_{98y2} \in [\,0.999, 1.001\,]$
- Fixed density
- $\langle T_i \rangle / \langle T_e \rangle \in [\,0.8, 1.2\,]$
- $T_{i0} / \langle T_i \rangle \in [\,1.8, 2.5\,]$

Tokamak performance predictions are subject to numerous uncertainties

MIT PSFC

- In the scoping process of tokamak core performance, open questions still remain that add uncertainty in the modeling:
  - Impurity content
    (sources, penetration, ash accumulation…)
  - Operational regime
    (H-mode flavor, access, sustainment, ELMs…)
  - Boundary conditions
    (edge pressure, temperature ratio, density gradients…)
  - Fast ion effects
    (instabilities, interaction with turbulence…)
  - …

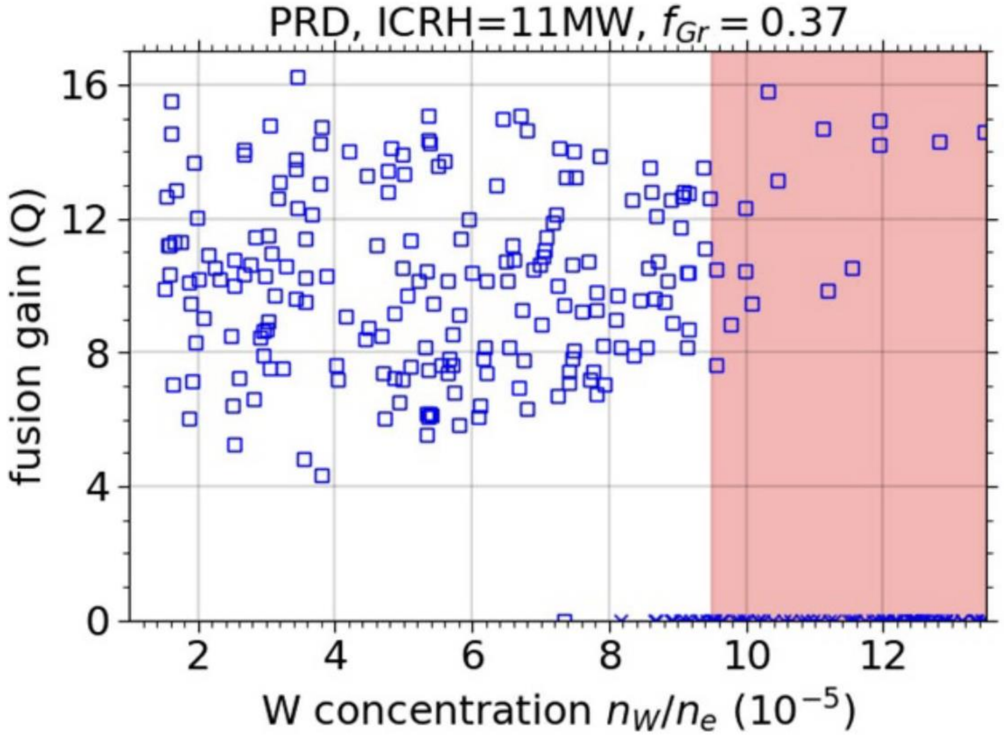
Assumption variations

$f_W \in [1.5 - 13.5] \cdot 10^{-5}$

$f_{DT} \in [0.8 - 0.875]$

$T_i/T_e|_{ped} \in [0.8 - 1.2]$

$p_{top}/p_{EPED} \in [0.8 - 1.2]$



M. Muraca NF 2025

M. Muraca EU TTF 2025 [Poster session 1]

Transport model selection is a big lever for performance

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  - Impurity content (sources, penetration, ash accumulation…)
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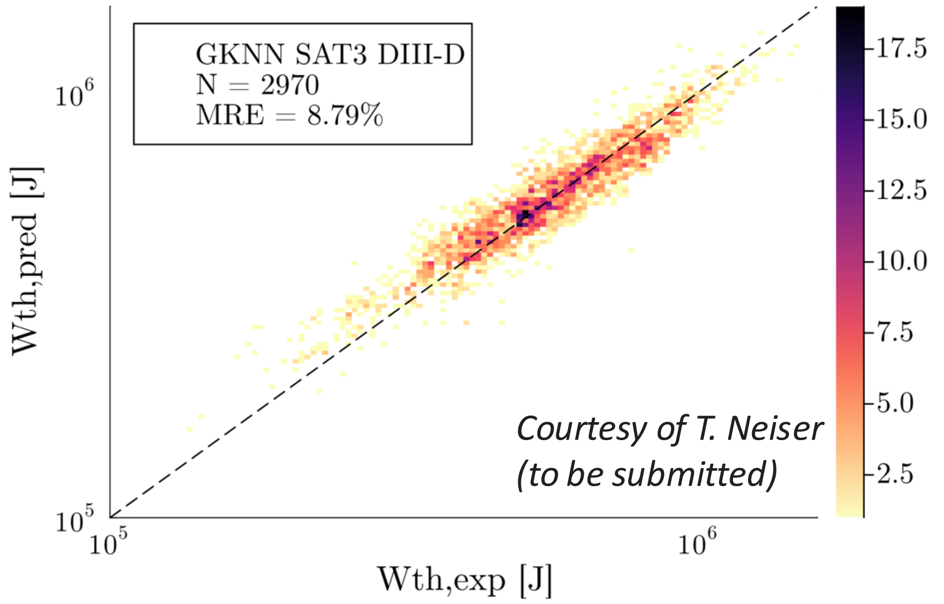


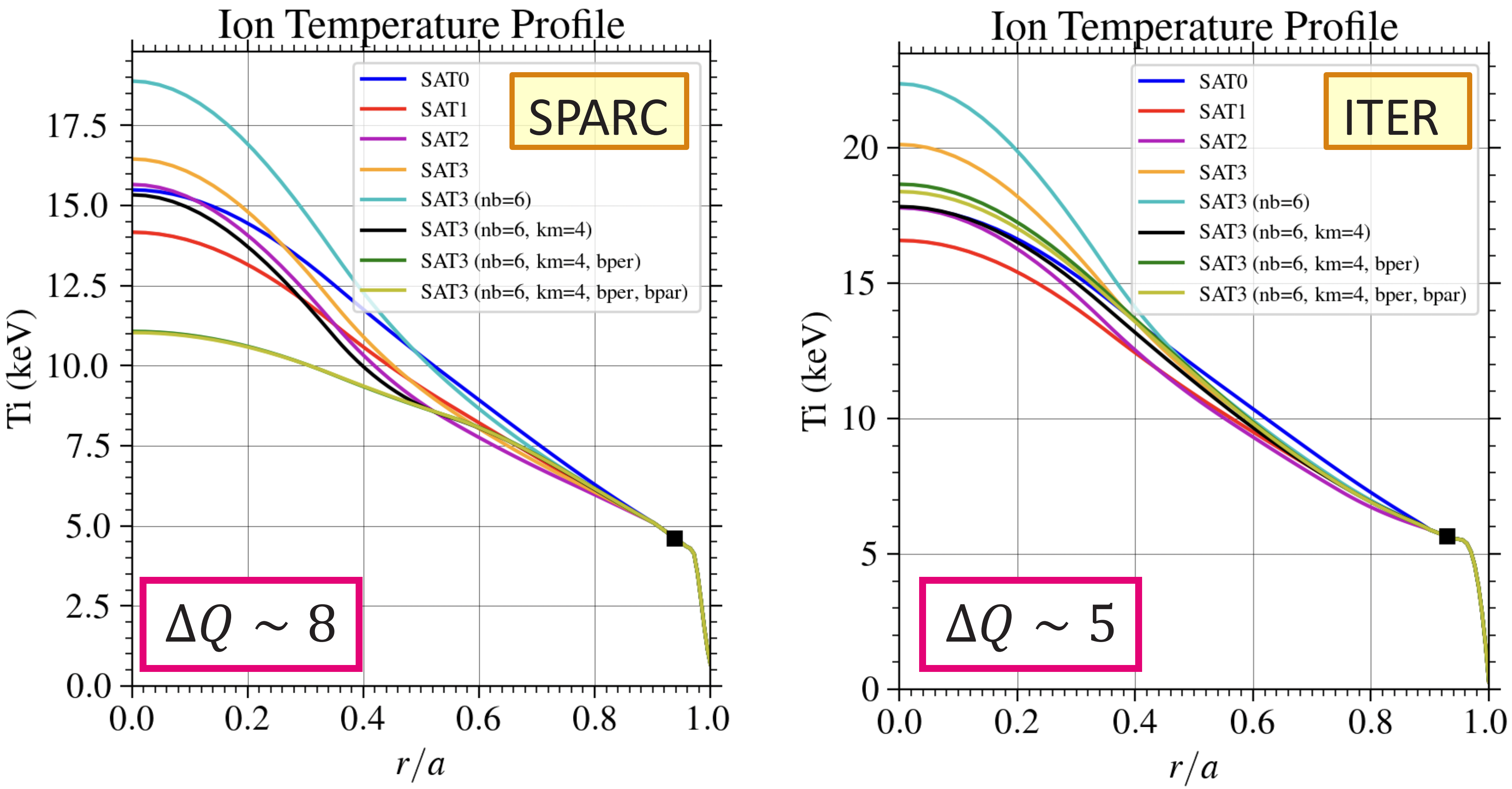
Courtesy of T. Neiser (to be submitted)

Device	H-mode	L-mode	negD
DIII-D	SAT0Q EM → GKNN SAT3 EM	SAT1 EM → GKNN SAT3 EM	SAT1 EM → GKNN SAT3 EM
MAST-U	SAT0Q EM → GKNN SAT3 EM	SAT3 EM → GKNN SAT3 EM	N/A
NSTX	SAT3 EM → GKNN SAT3 EM	SAT3 EM → GKNN SAT3 EM	N/A

- While it is widely assumed that the nonlinear gyrokinetic model captures core transport with enough fidelity, the assumptions in integrated modeling with **quasilinear models introduce a large additional uncertainty**.

Burning plasma & power plant projections sensitive to turbulence saturation

- Predictions of SPARC and ITER, even at fixed BC, can differ substantially depending on what model to use.

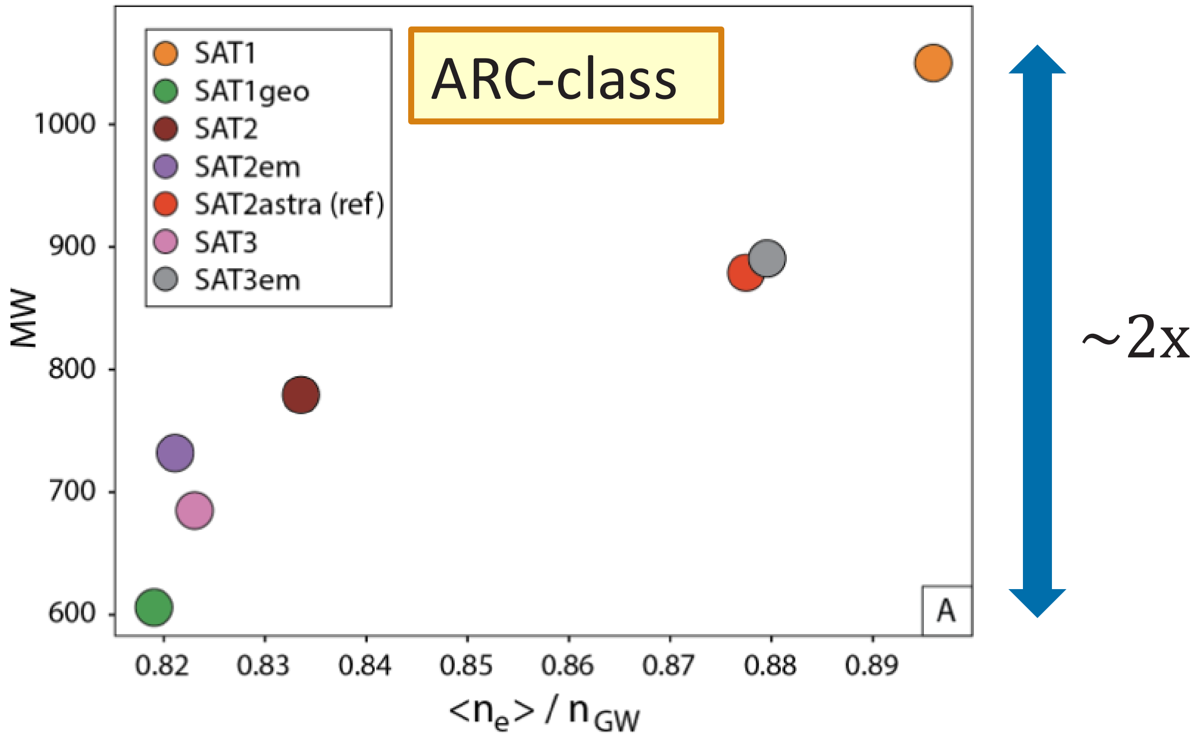


Parameters and assumptions for SPARC PRD plasma as in *P. Rodriguez-Fernandez NF 2024*
ITER Baseline plasma (Be) as in *N. Howard NF 2025*

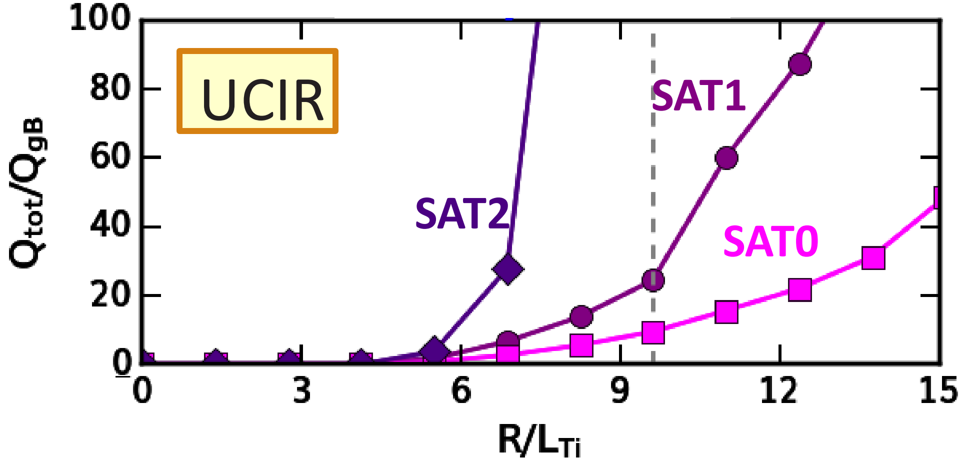
Burning plasma & power plant projections sensitive to turbulence saturation

- Predictions of SPARC and ITER, even at fixed BC, can differ substantially depending on what model to use.
- FPP predictions (plasmas strongly on burning regime) are particularly affected by model selection.

N. Howard (to be submitted)



C. Holland APS-DPP 2021

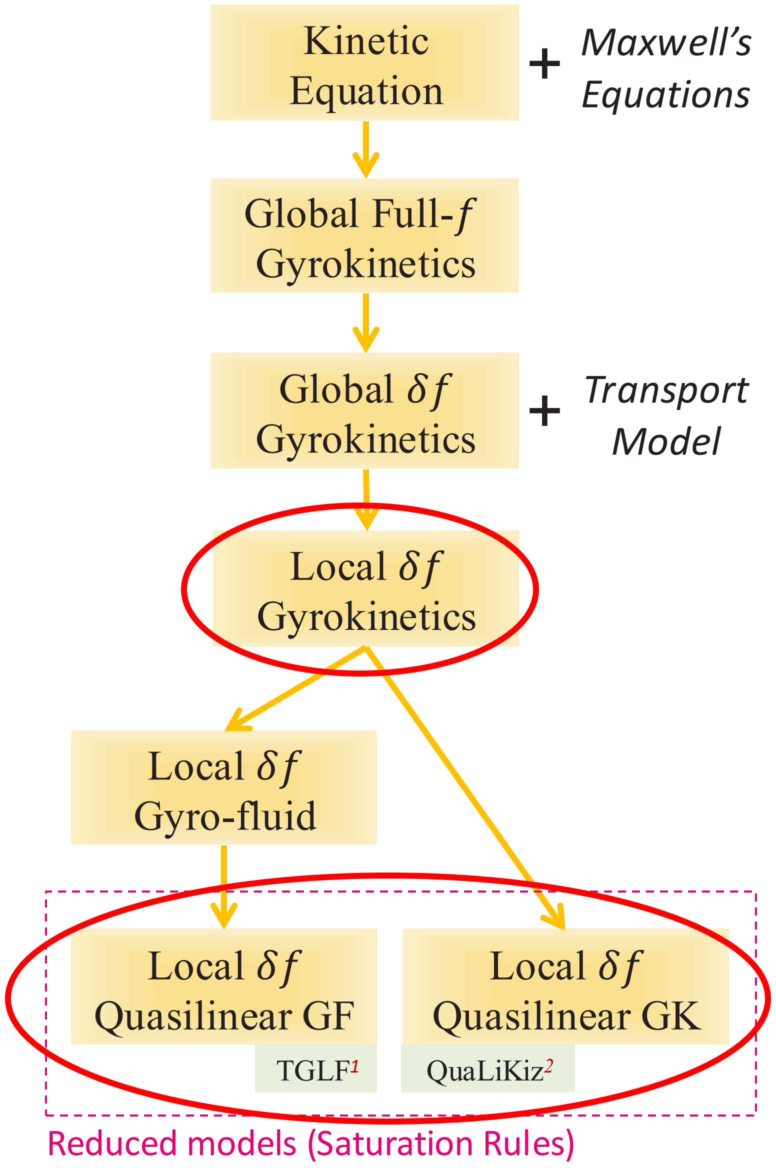


Core model selection hierarchy represents a cost vs. fidelity trade-off

- A **hierarchy of assumptions** has been developed to reduce computational cost from the full-f, 6D + time, kinetic description.
- The jump from nonlinear to reliable **quasilinear models** has made integrated modeling possible ($\sim 10^6$ cost savings with reasonable results).
- In predicting burning plasmas and selecting robust FPP designs, we require **validation** and spot checks with higher fidelity turbulence simulations.
- **New era in core transport research**: the direct use of NL GK to predict kinetic profiles and performance and aid in the design of fusion devices.

Demonstration of high-fidelity solvers in 2022:

- ❑ **PORTALS-CGYRO (MIT) – Rodriguez-Fernandez, Howard & Candy**
- ❑ TANGO-GENE (IPP) – Di Siena, Jenko, et al.
- ❑ TRINITY-GX (PPPL) – Dorland, Mandell, et al.



[1] G.M. Staebler PoP 2007

[2] C. Bourdelle PPCF 2015

Practical predictions require an inverse solver for δf turbulence codes

MIT PSFC

- Solving for the steady-state plasma using local, δf transport models requires solving an inverse problem.

$$\frac{1}{V'}\left[\frac{\partial}{\partial t}\left(\frac{3}{2}n_iT_iV'\right)+n_iT_i\frac{\partial V'}{\partial t}\right]=-\frac{1}{V'}\frac{\partial}{\partial r}\left(\langle q_i\cdot\nabla r\rangle V'\right)+\langle S_i\rangle \longrightarrow \langle q_i\cdot\nabla r\rangle=\frac{1}{V'}\int_0^r\langle S_i\rangle V' dr$$

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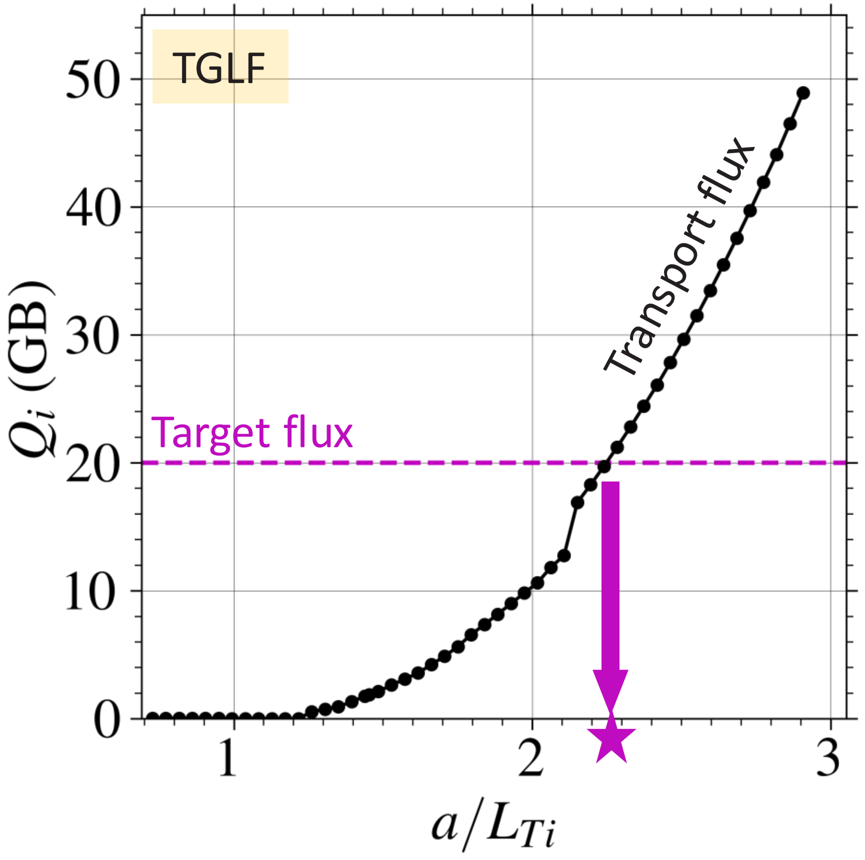

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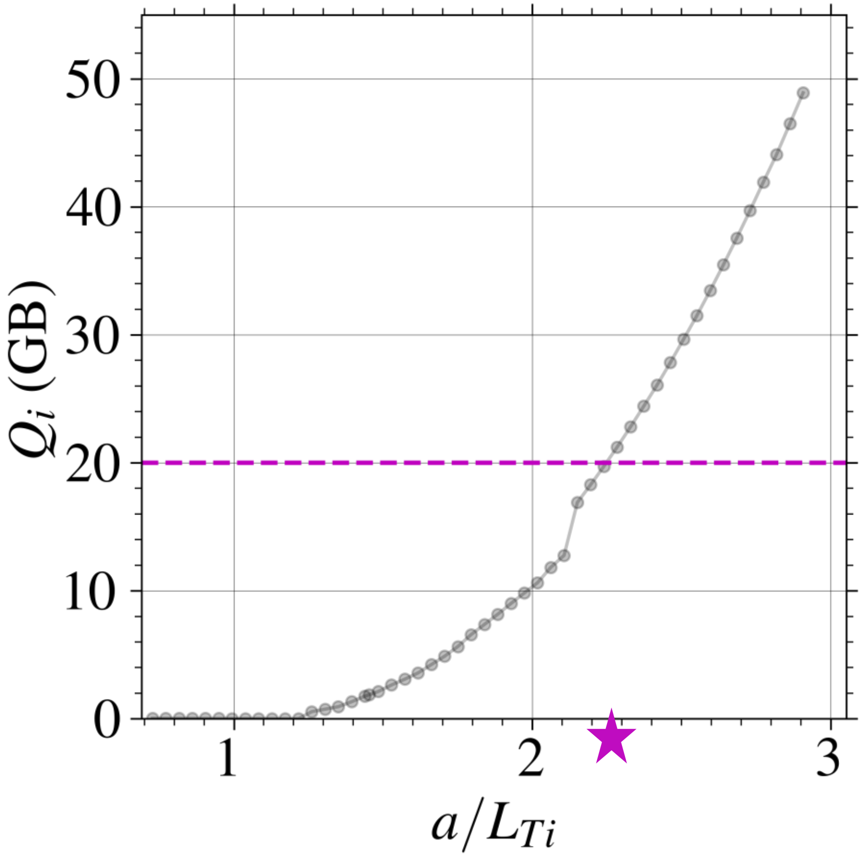

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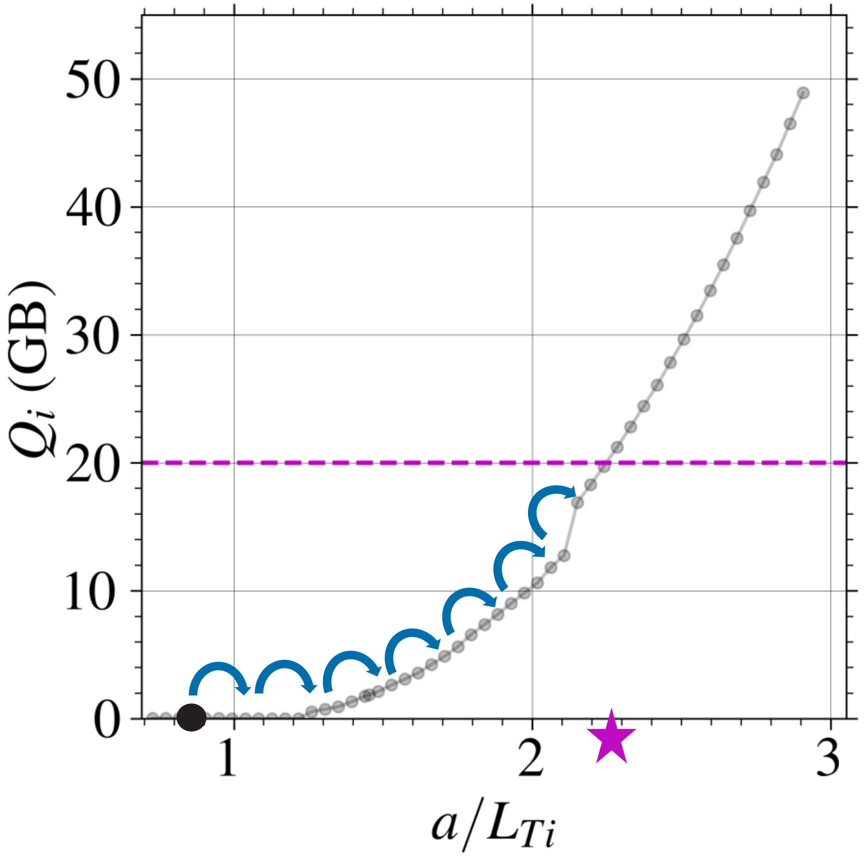

- Standard transport solvers find the steady-state solution via small, stable "steps" towards reducing a residual (time-indep.) or dW/dt (time-dep.).
- Jacobian calculation, use of small steps or ad-hoc modifications of flux response (numerical diffusivity) to achieve convergence is often too costly* to use with **nonlinear gyrokinetics**.
- This work was pioneered by:

  J. Candy et al., Phys. Plasmas (2009) [TGYRO + GYRO]

  M. Barnes et al., Phys. Plasmas (2010) [TRINITY + GENE/GS2]

*Usually 10^2-10^3 evaluations required in standard transport solvers

PORTALS: using surrogates for smarter sampling of the parameter space

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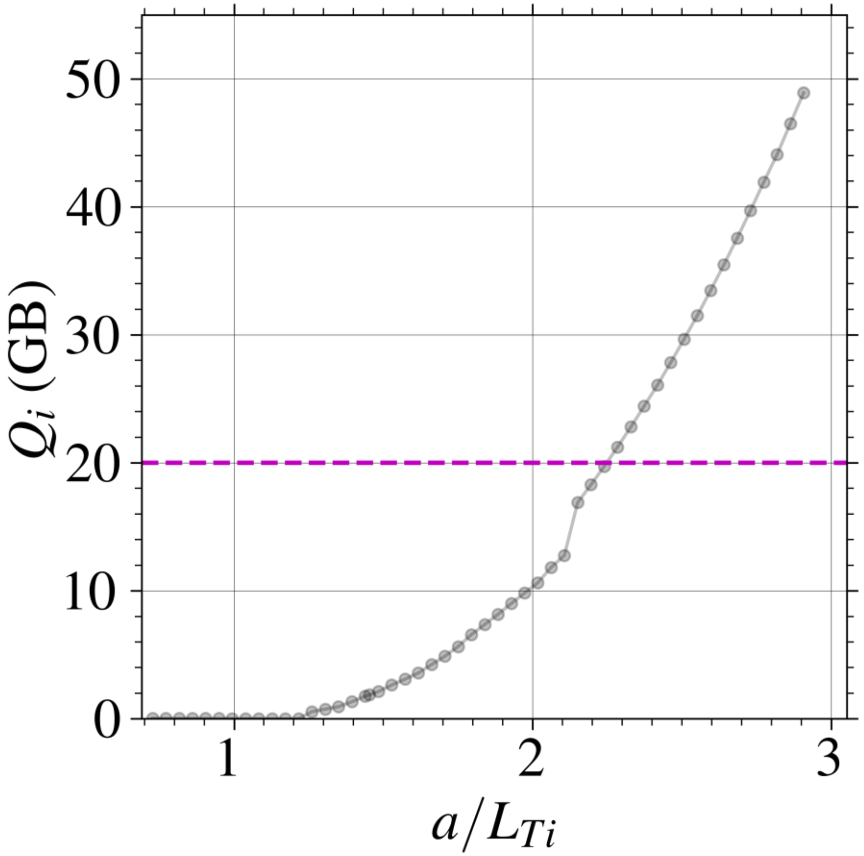

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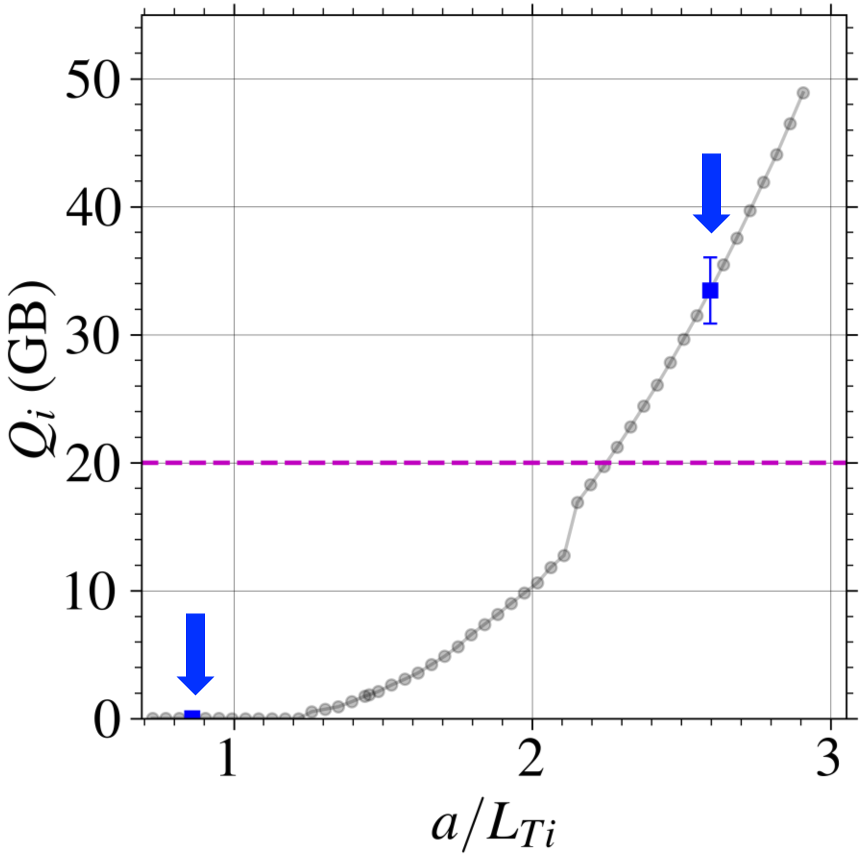

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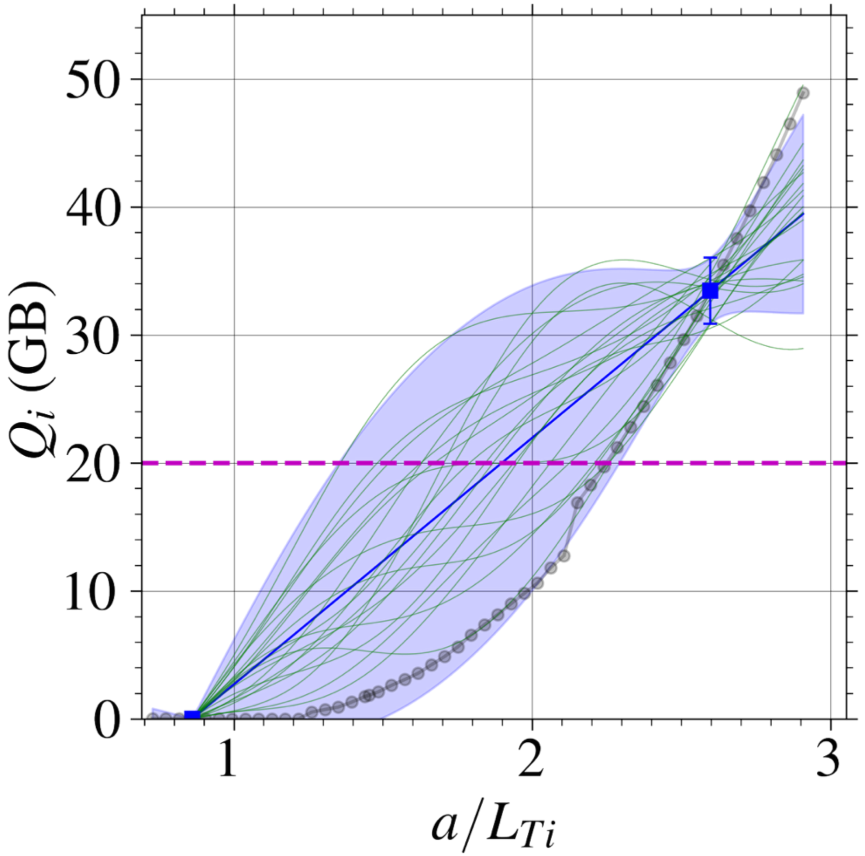

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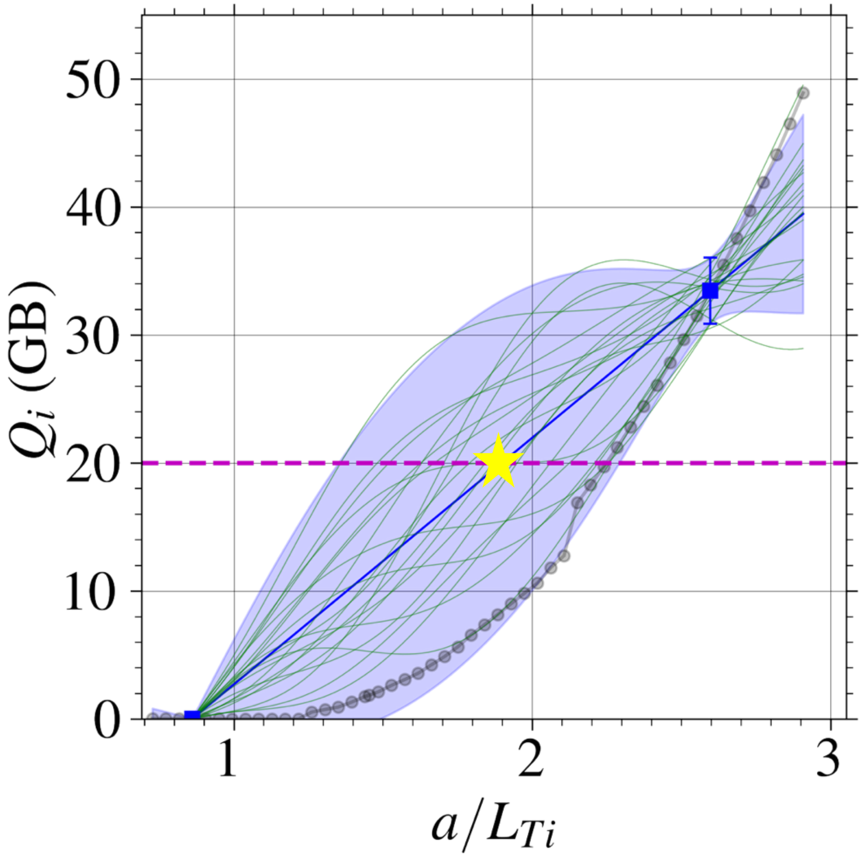

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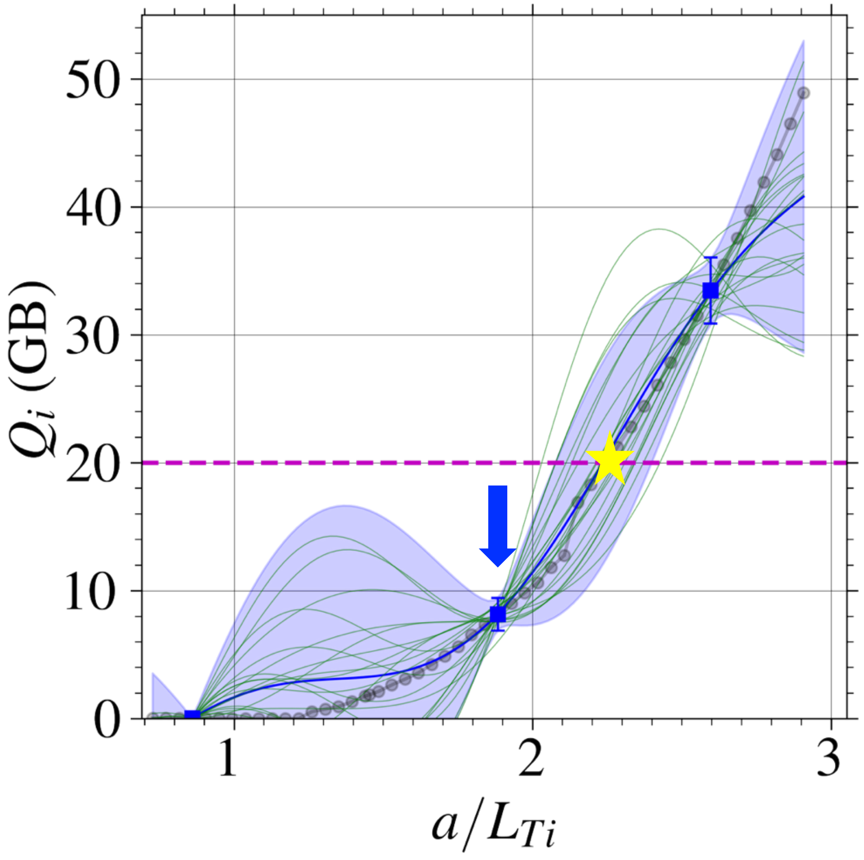

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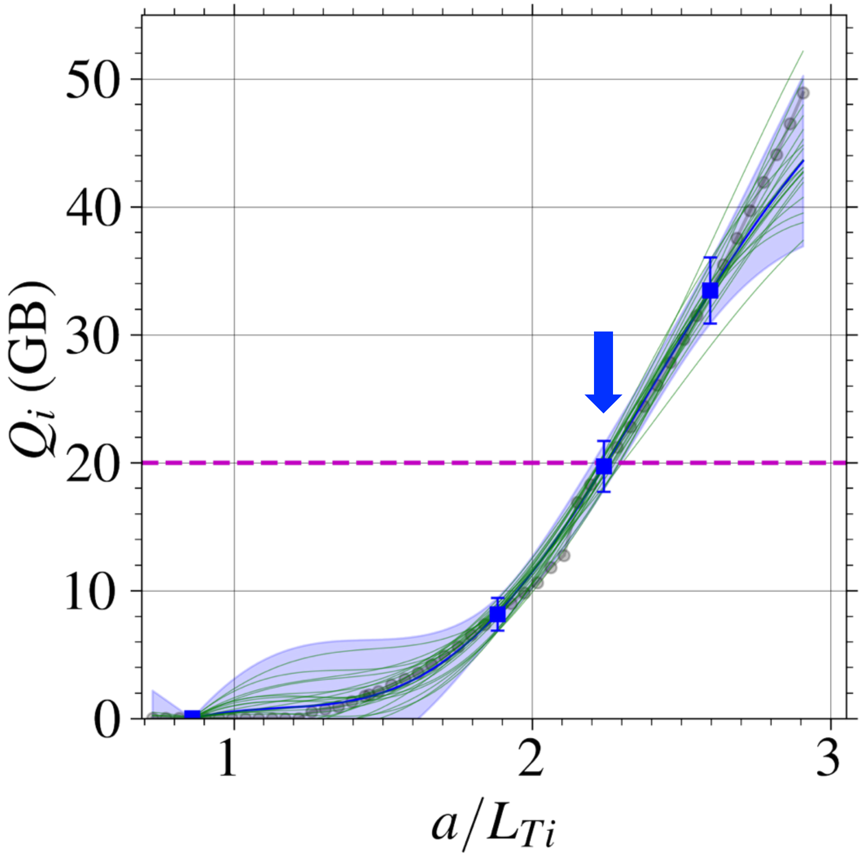

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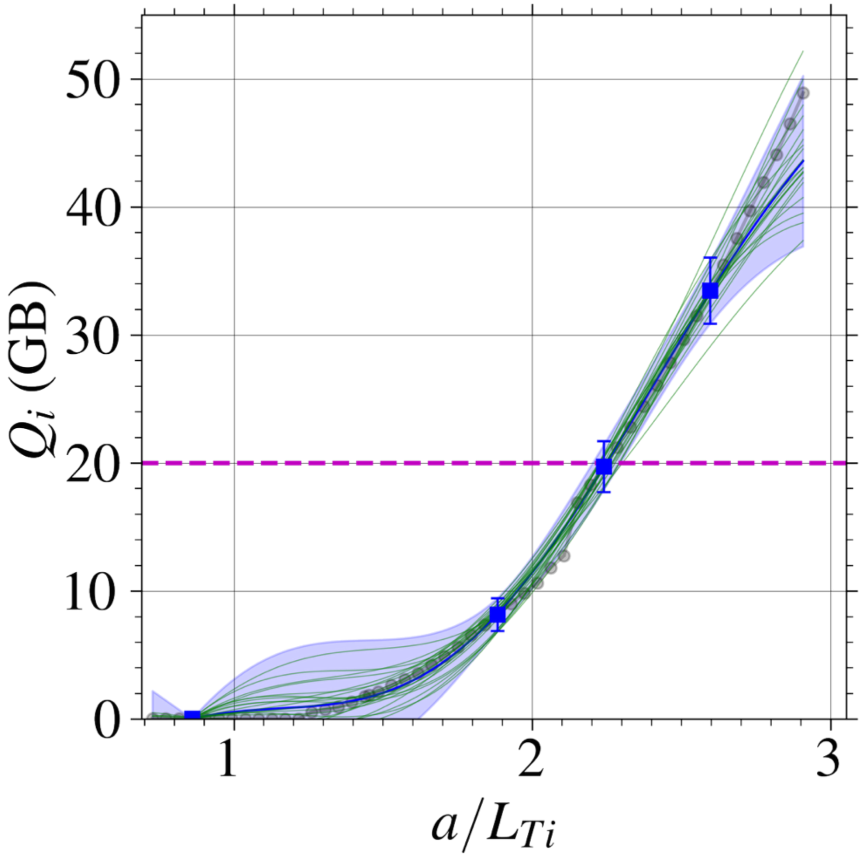

This is the basis of what PORTALS does but… *a bit more complex…*

- ✚ Multi-radius (radial coupling) } multi-objective, multi-variable
- ✚ Multi-channel (channel coupling) } multi-objective, multi-variable
- ✚ Multi-model (neoclassical + turbulence) → surrogate separation
- ✚ Moving-targets (volumetric flows) → targets as surrogates too
- ✚ GB-normalized transport → nonlinear transformations, MC surrogate
- ✚ Discontinuous, critical gradient or turbulence saturation → UQ

Because we evaluate the flux with the actual transport model (surrogates are just used to inform where to evaluate), PORTALS predictions are **NOT surrogate predictions** but actual transport model predictions.

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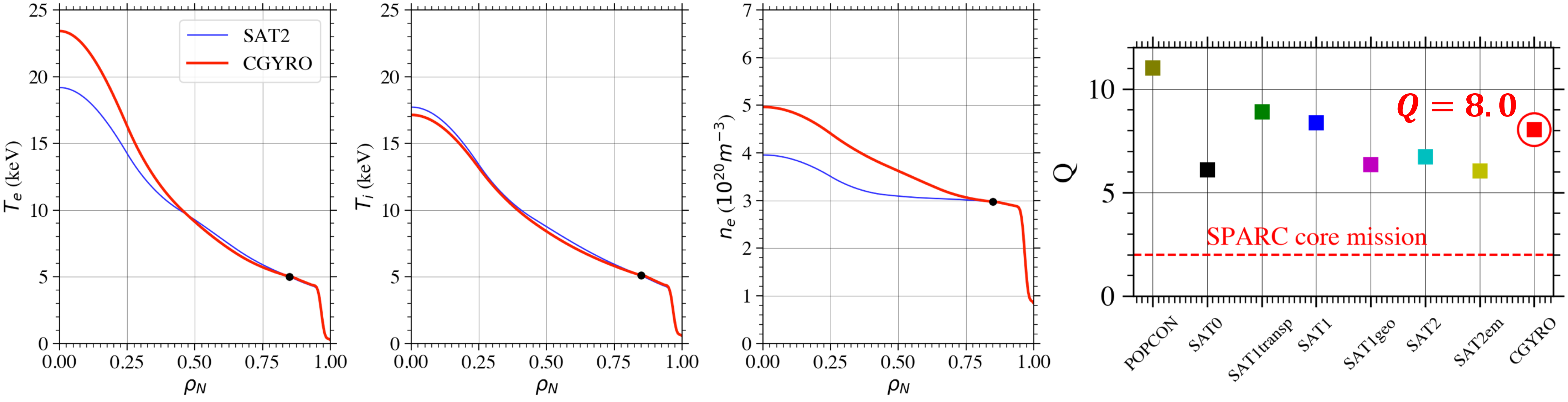
SPARC PRD scenario was the first one to be simulated with PORTALS

MIT PSFC

- SPARC's PRD core simulations with PORTALS-CGYRO made SPARC the **first burning plasma predicted with core nonlinear gyrokinetics**.
- Only 16 profile evaluations $\rightarrow Q \approx 8.0$ prediction at ELMy H-mode pedestal levels.

Physics included

- Multi-channel (T_e, T_i, n_e).
- Evolving alpha heating, energy exchange, radiation (Bremss, line, sync).
- NL CGYRO[1]: EM, 6 GK species, Miller geometry, Sugama collisions, $k_\theta \rho_s \leq 1.2$.



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[1] J. Candy JPC 2016

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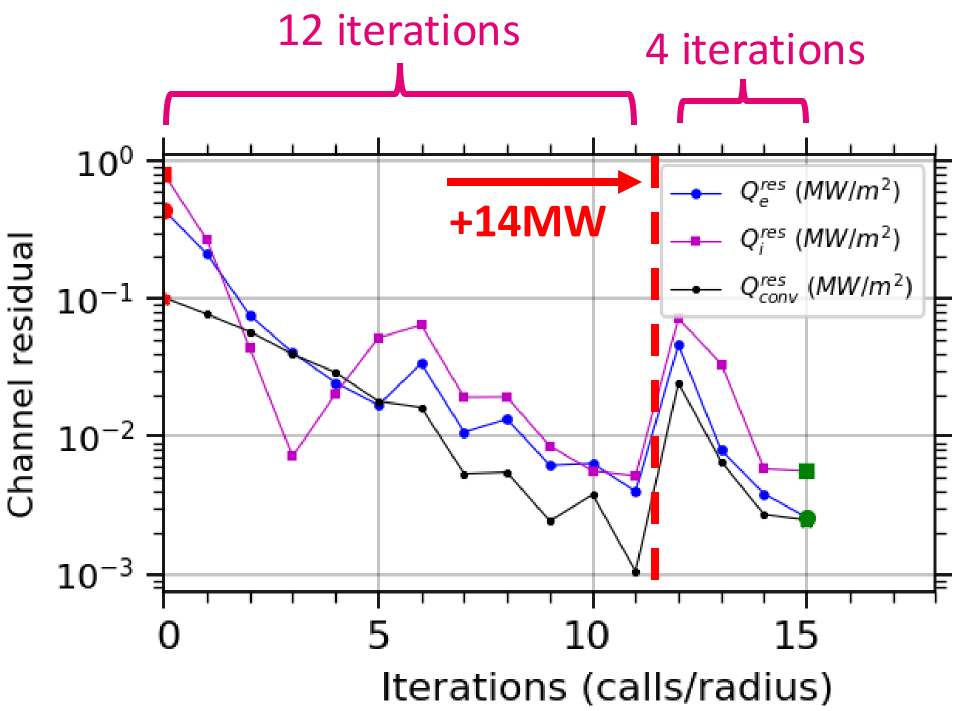
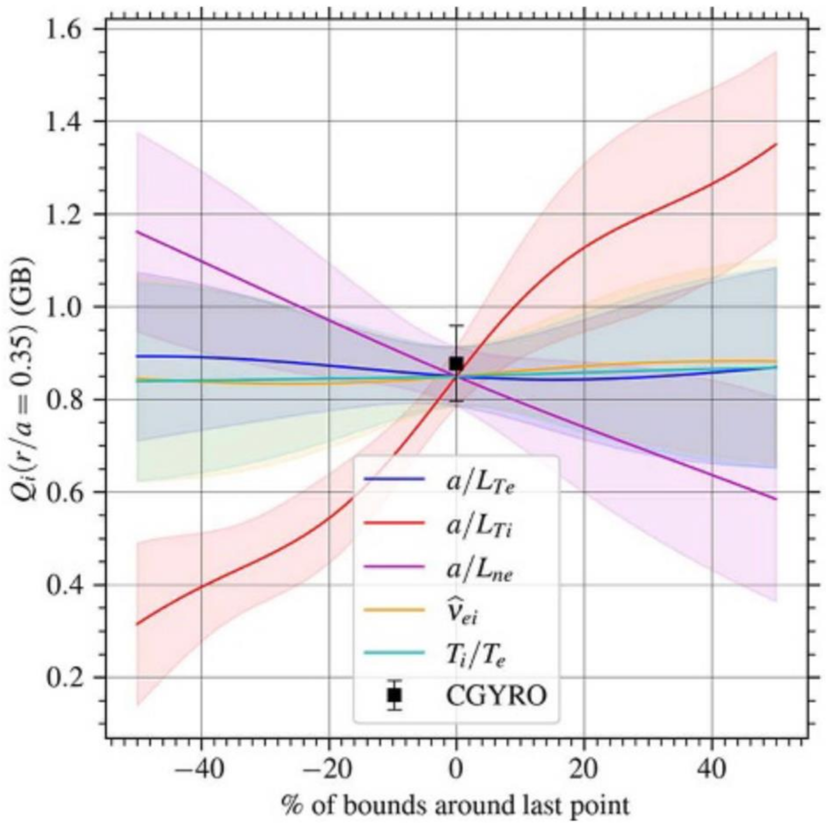


Example Surrogate:



Since surrogates are fitted to local parameters, targets (e.g. P_{ICH}) can be varied to obtain new flux-matched solution at reduced cost.

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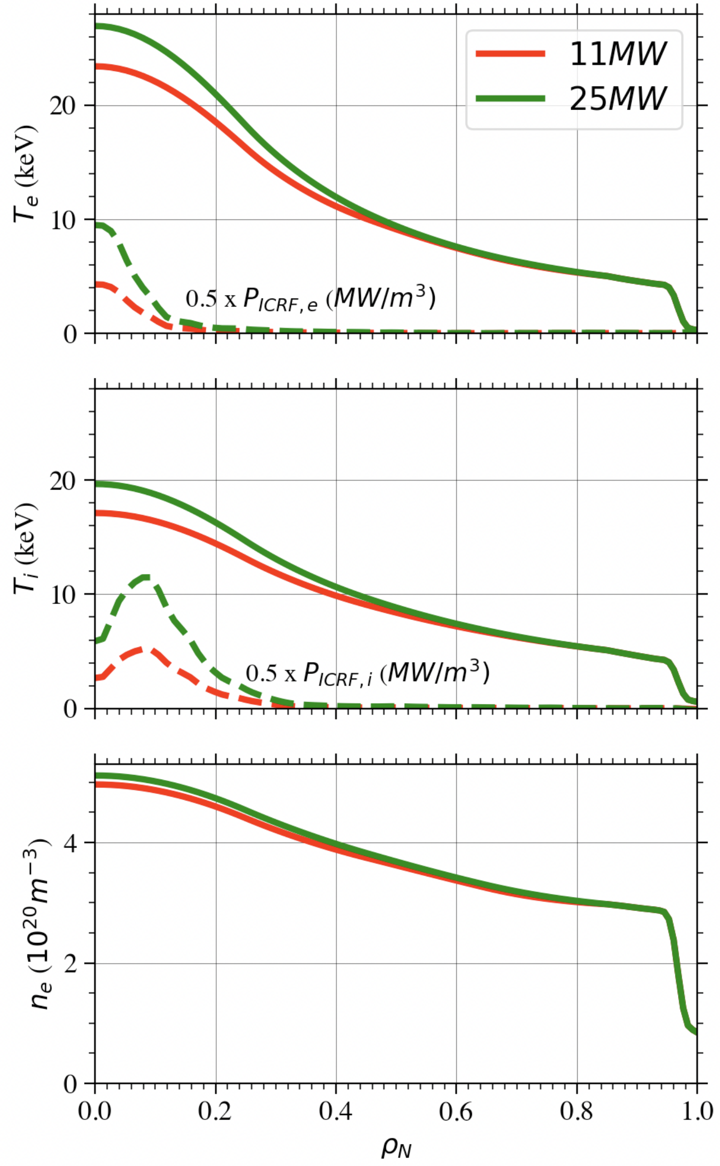
- Predictions of SPARC 25MW-PRD scenario reveal that core plasma is **very stiff**, as expected from ITG dominance.



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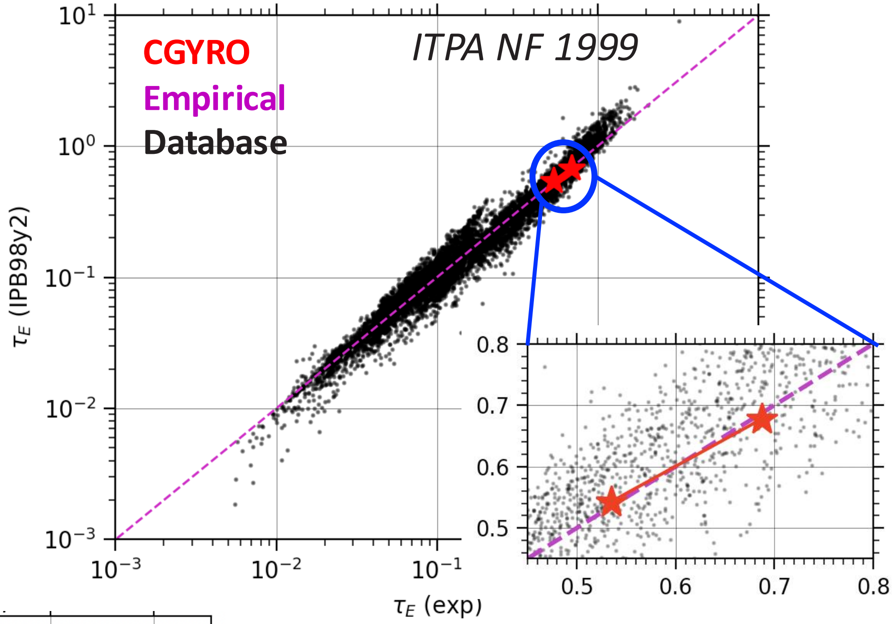
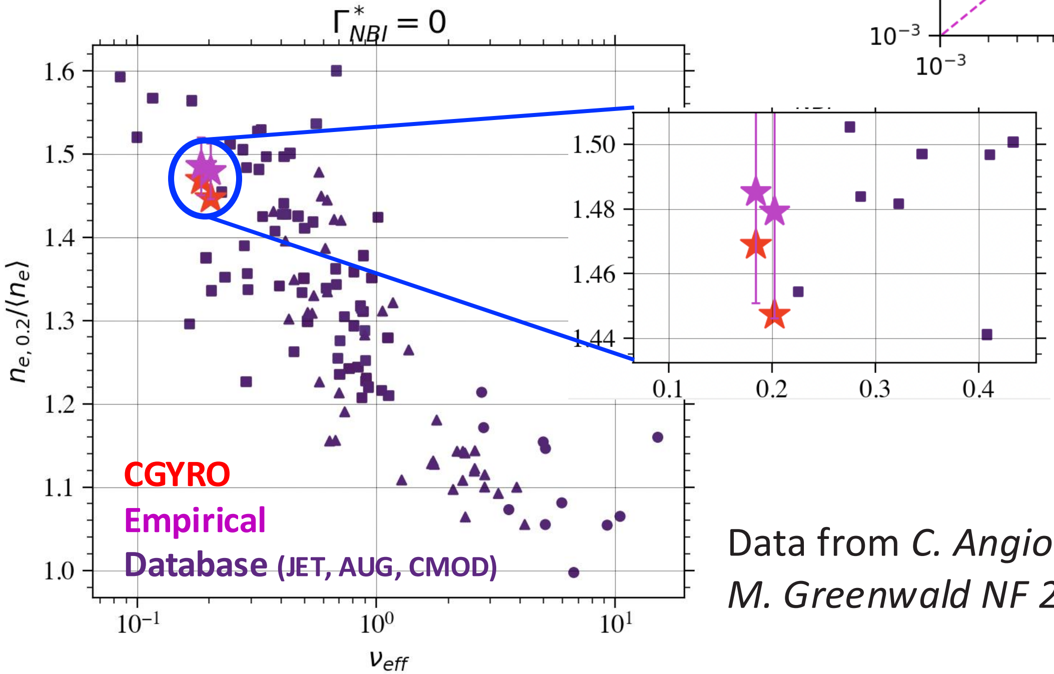
- Predictions of SPARC 25MW-PRD scenario reveal that core plasma is **very stiff**, as expected from ITG dominance.
- In agreement with empirical scaling laws of global quantities.



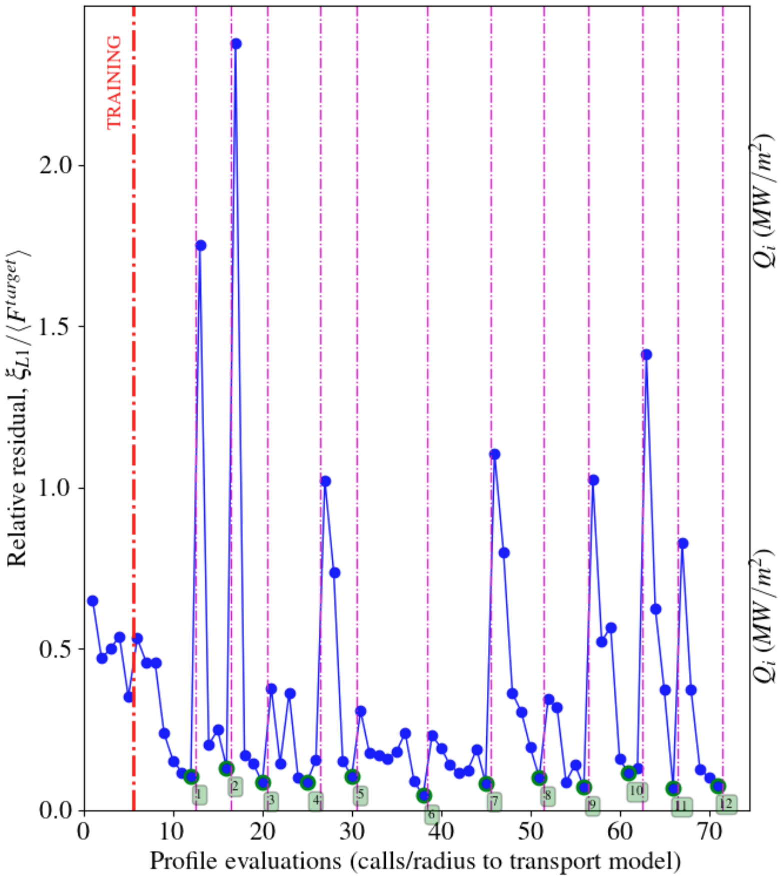


Data from *C. Angioni PoP 2007, M. Greenwald NF 2007*

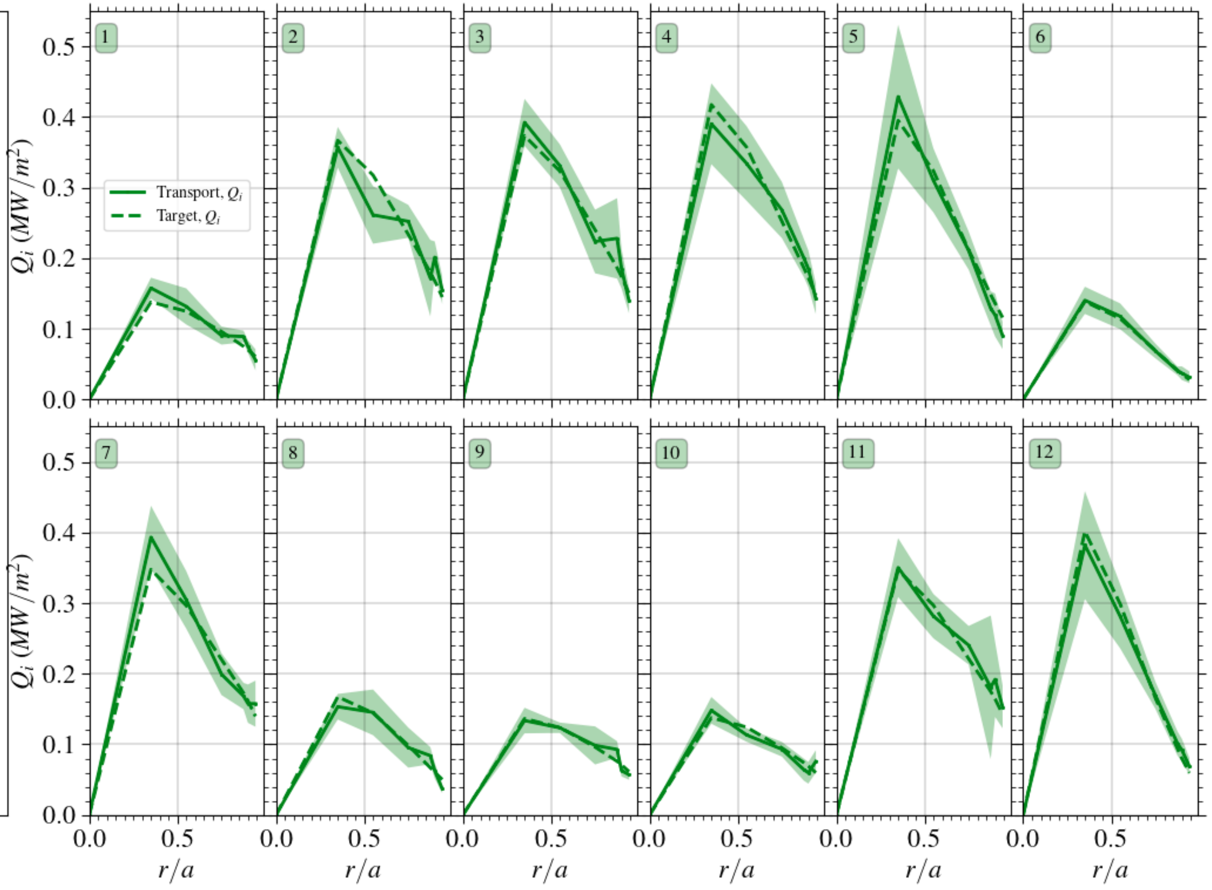
Re-utilization of surrogates very advantageous for space exploration

- Increased interest in $Q > 1$ in early campaigns required scoping of lower edge pressure and heating scenarios.
- **12 scenarios** (varying $T_{0.94}$, $n_{0.94}$, P_{ICH}) were predicted with 71 profile evaluations*.

Residual vs CGYRO evaluation



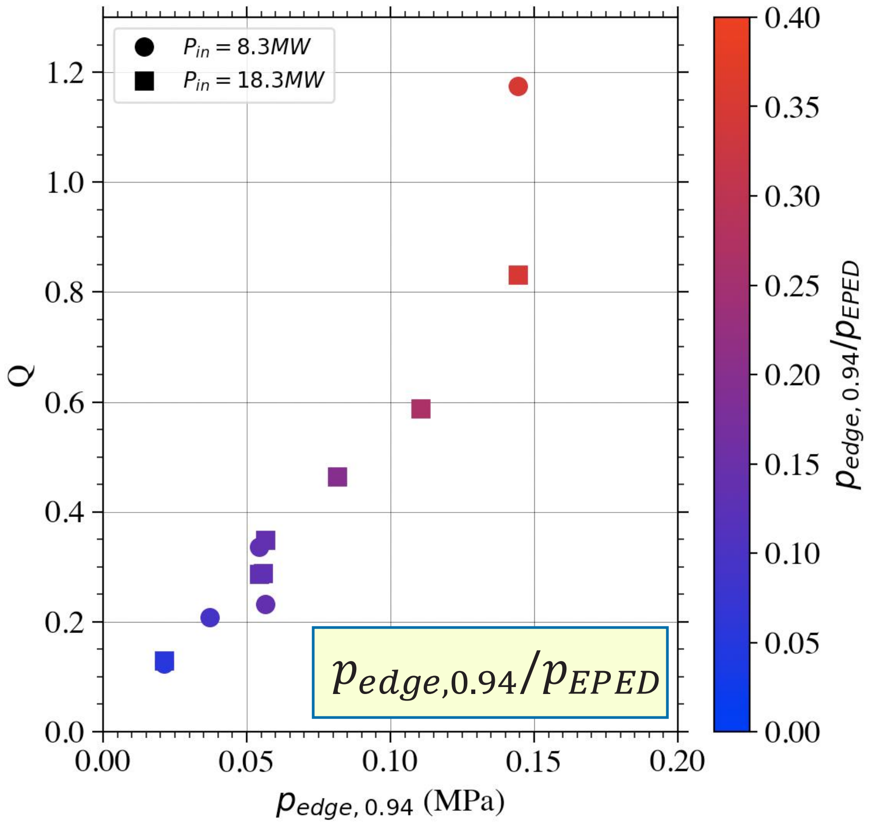
Ion heat flux matching

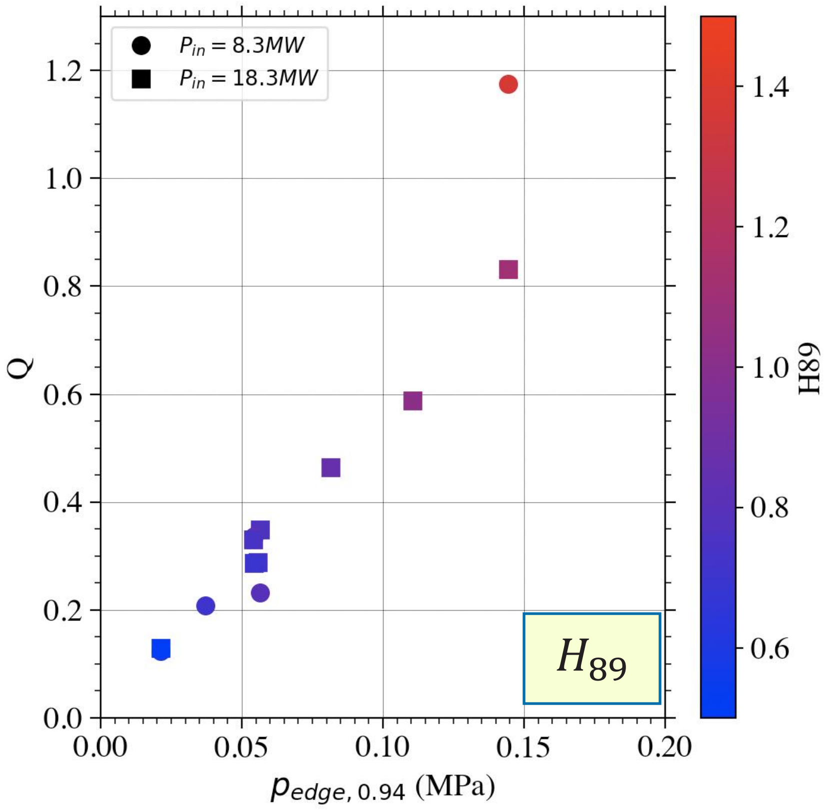


*426 local CGYRO
80k GPU hours
Perlmutter (NERSC)

Pressure pedestal identified as key for breakeven

- Moderate (~35% of PRD H-mode) edge (@ 0.94) pressure needed for breakeven with nominal assumptions.





P. Rodriguez-Fernandez PoP 2024

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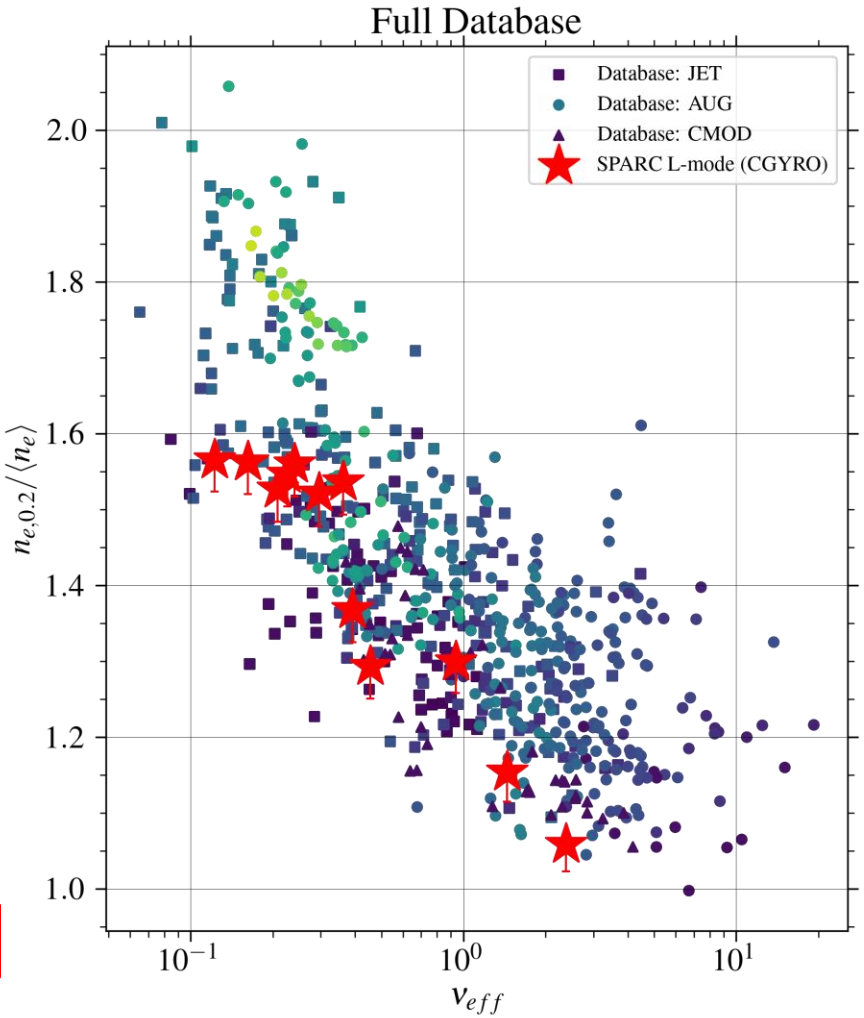

C. Angioni NF 2007, M. Greenwald NF 2007

$$n_{e,0.2}/\langle n_e \rangle = 1.347–0.117\log(\nu_{\mathrm{EFF}}) + 1.33\Gamma^*_{\mathrm{NBI}} - 4.03\beta.$$

P. Rodriguez-Fernandez PoP 2024

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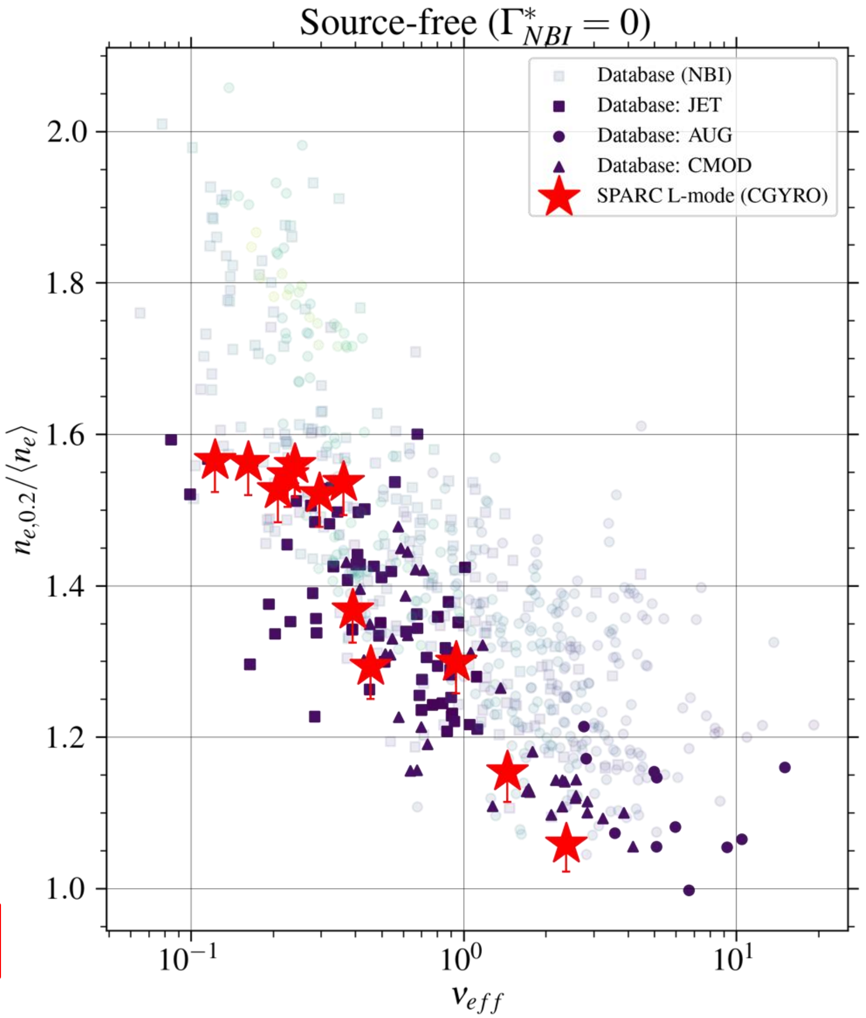

C. Angioni NF 2007, M. Greenwald NF 2007

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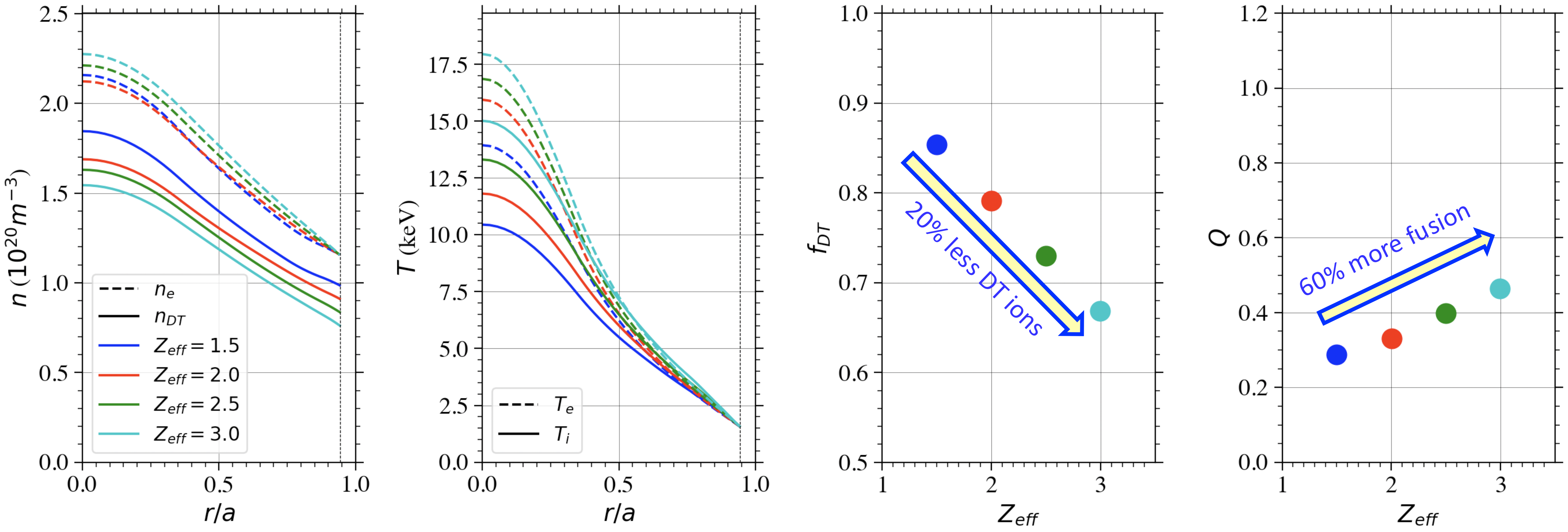

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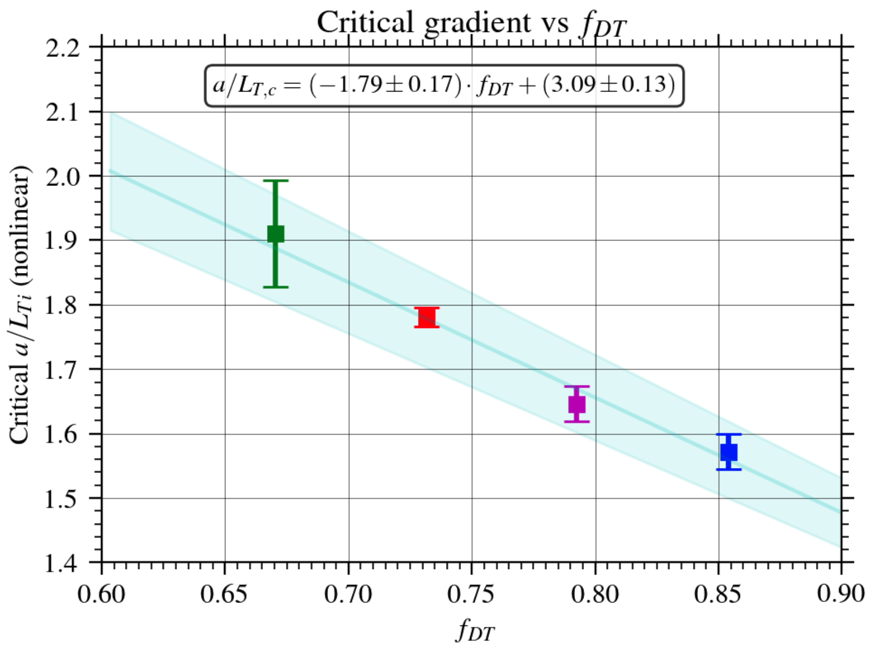
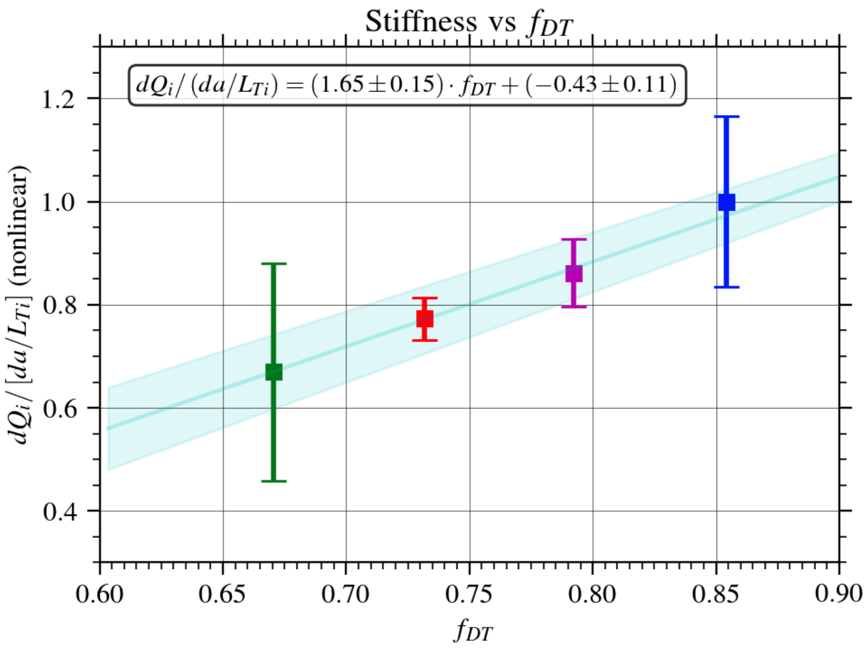


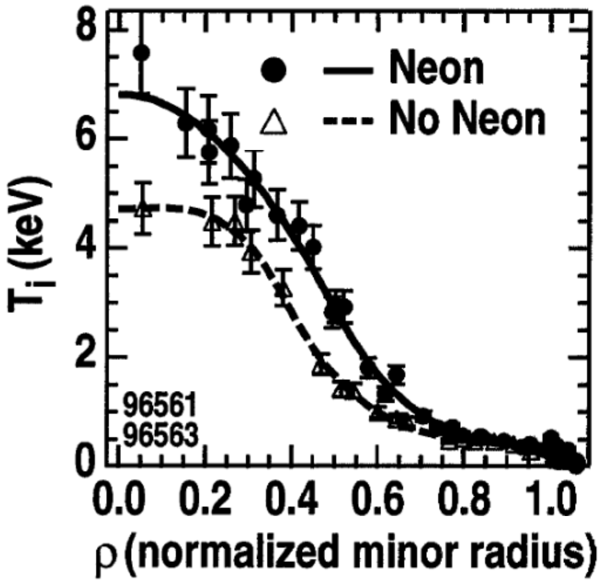
ITG **critical gradient** increases with more diluted DT ✔



Transport stiffness decreases with more diluted DT ✔

Consistent with experiment (e.g. G. McKee PRL 2000)

G. McKee PRL 2000 [DIII-D]



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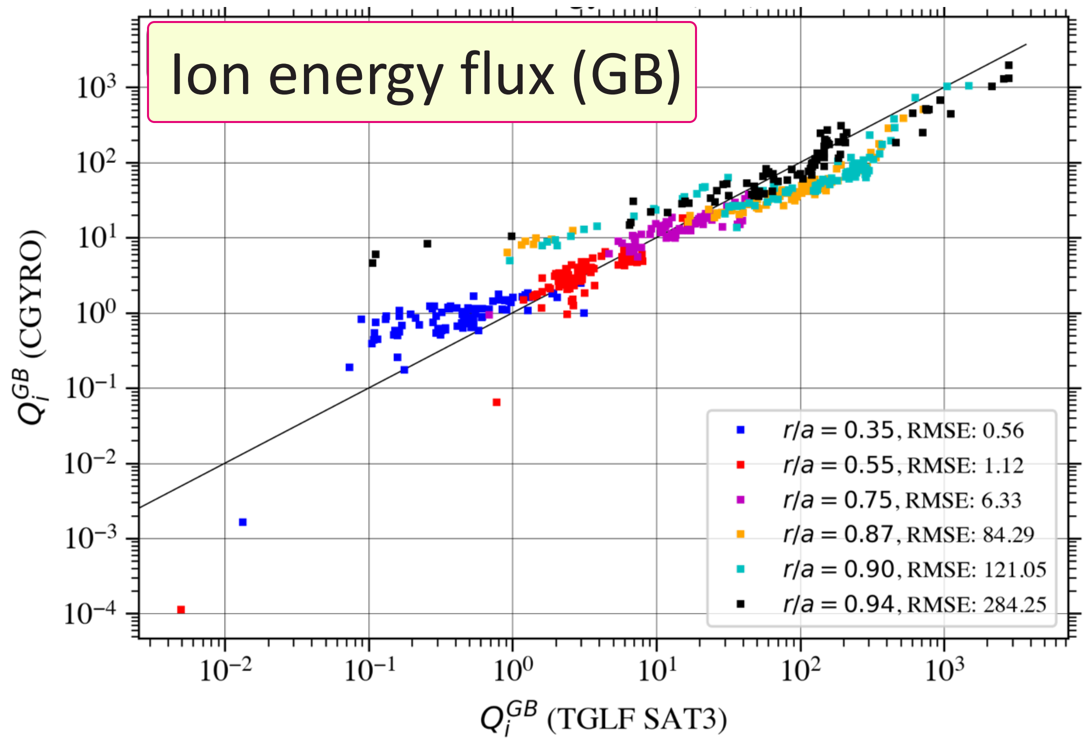
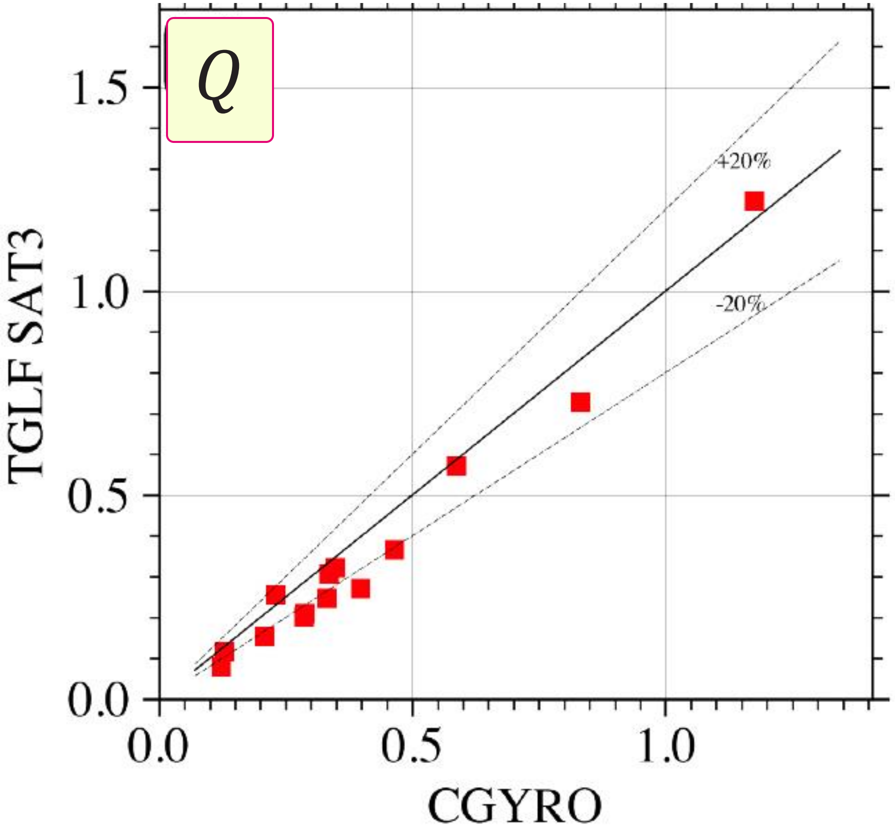
- Exciting result: predicted density peaking consistent with source-free plasmas database.
- Exciting result: stabilization of ITG via DT fuel dilution leads to more fusion when we have less DT!
- Exciting result: TGLF-SAT3 provides a reasonable proxy for core turbulence in these regimes.





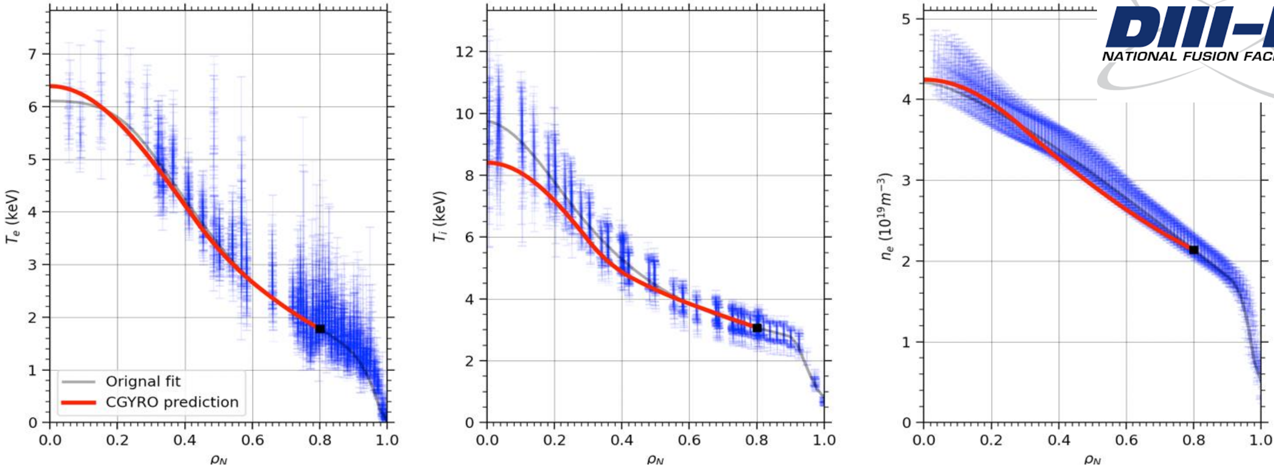
P. Rodriguez-Fernandez PoP 2024

SAT3: H. Dudding NF 2022

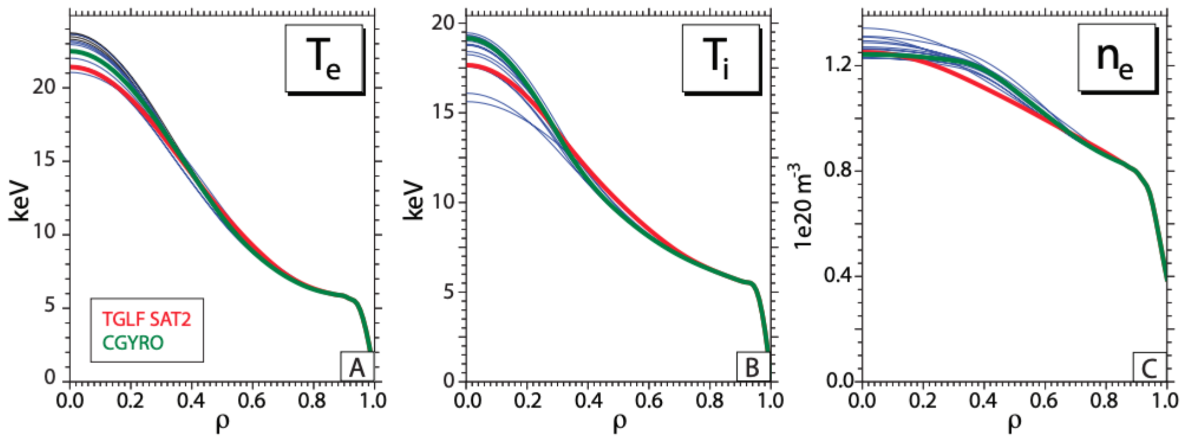
PORTALS-CGYRO is being used to study DIII-D, AUG, JET, ITER, ARC

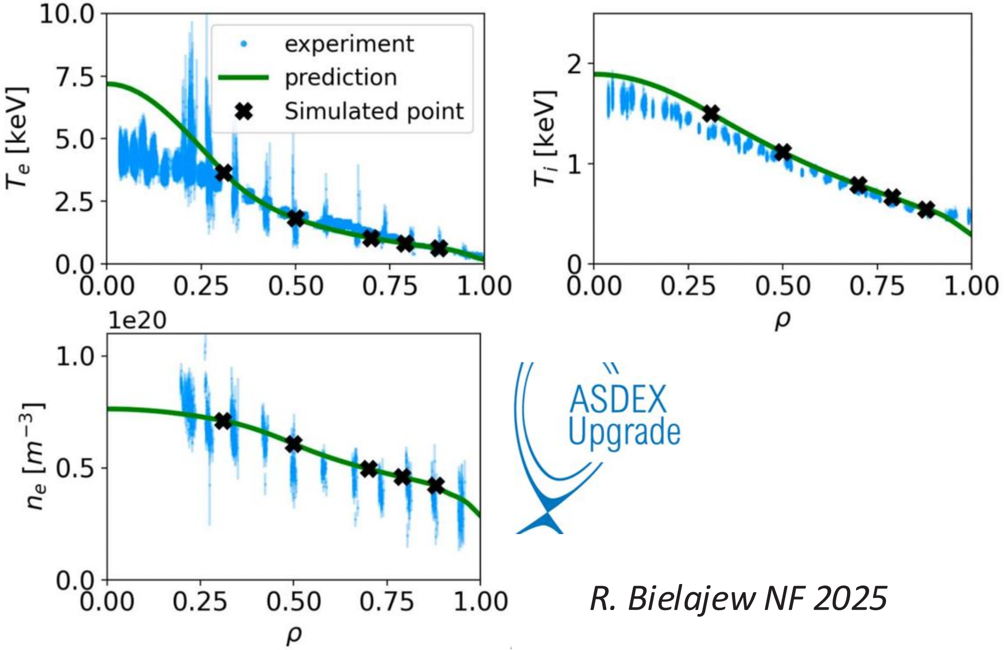
Over **50 PORTALS-CGYRO** profile predictions so far

N.T. Howard PoP 2024, P. Rodriguez-Fernandez NF 2024



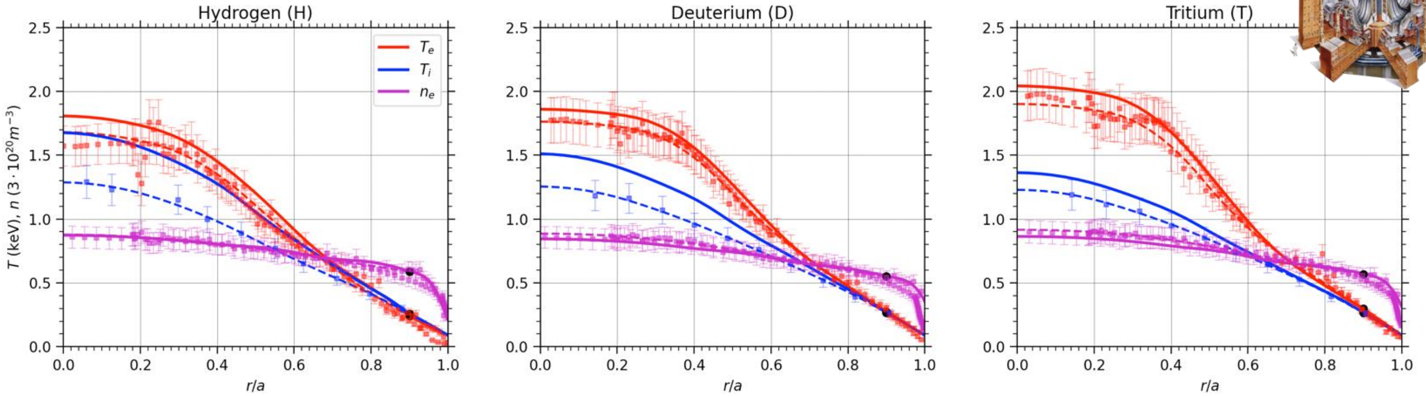
N.T. Howard NF 2025

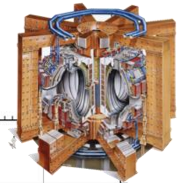




R. Bielajew NF 2025

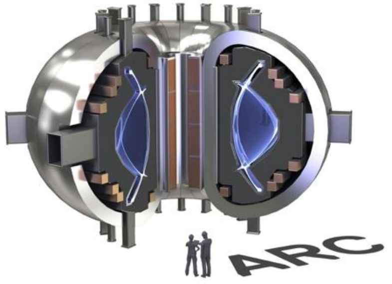
P. Rodriguez-Fernandez EPS 2023



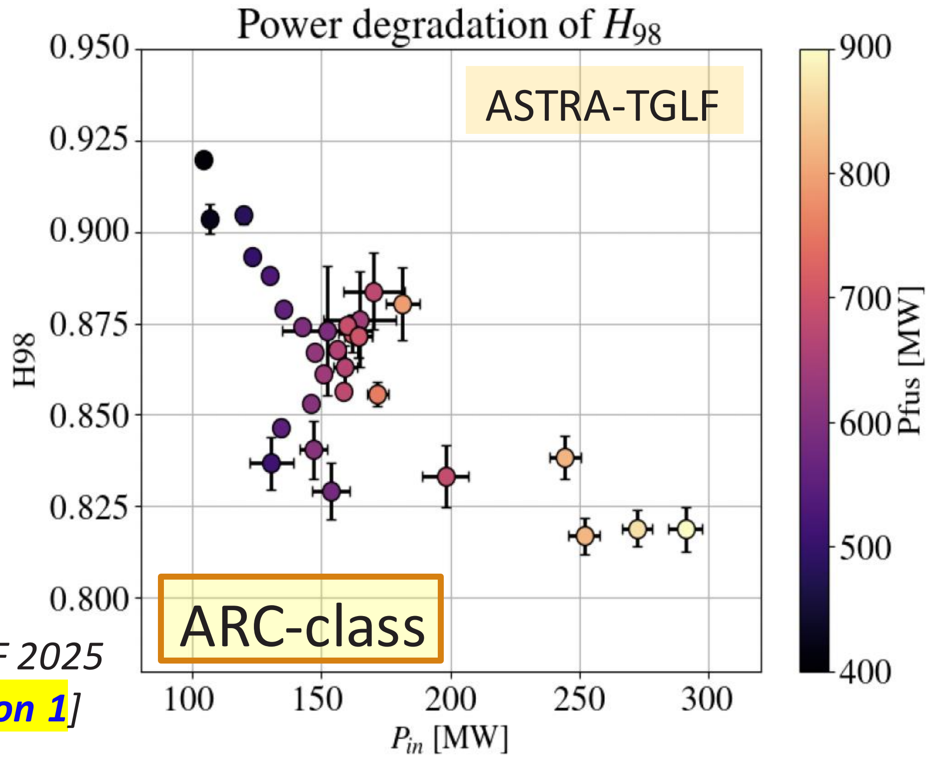


Physics-based modeling is becoming a key element to design ARC's core

MIT PSFC

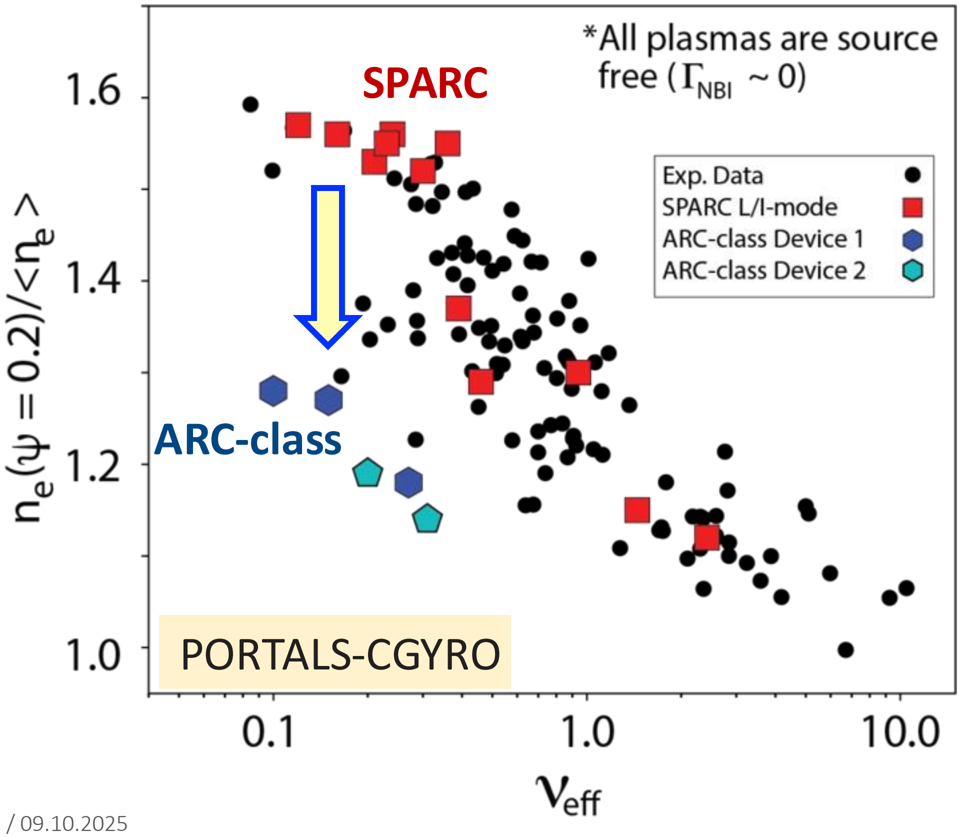


- Turbulence and integrated modeling currently being used, in iteration with engineering teams and edge modelers, to design **ARC power plant's core**.
- Simulations point towards lower **density peaking** than expected from empirical scaling laws, and **stiff transport conditions** limit ability to raise volume-average temperature arbitrarily
- Key to account for physics-based modeling early on!



J. Hall EU TTF 2025 [Poster session 1]

N. Howard EU TTF 2025 [Poster session 1]

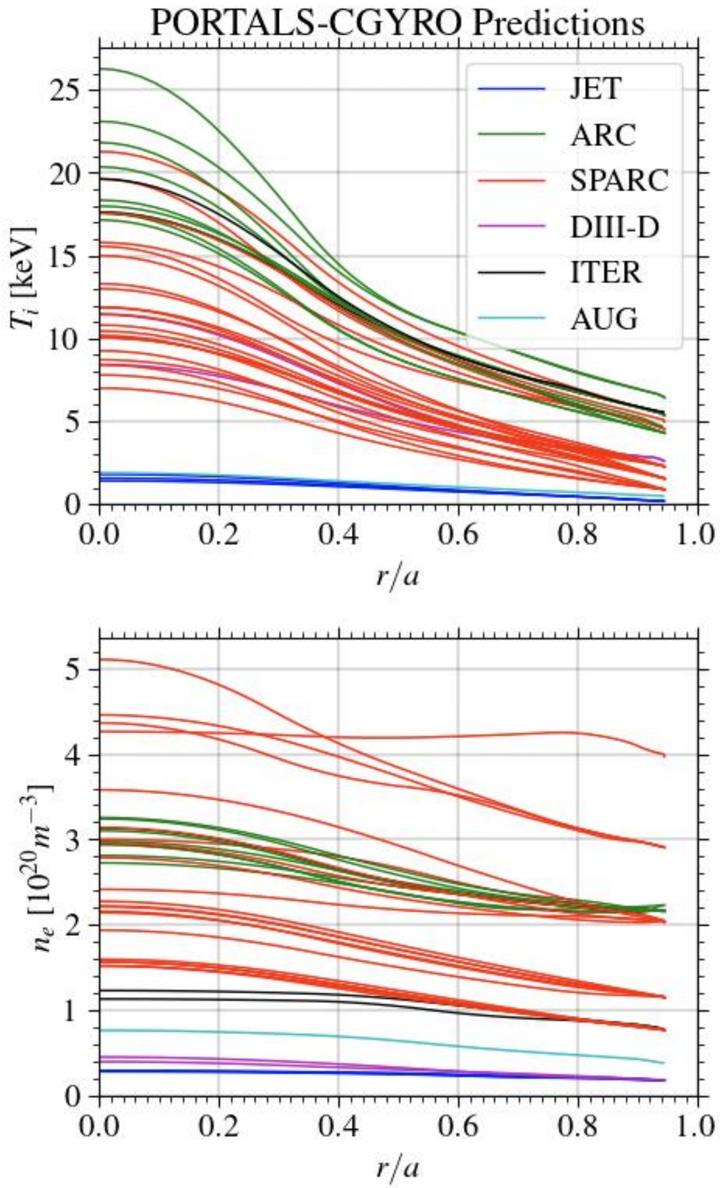


Conclusions

P. Rodriguez-Fernandez et al 2022 Nucl. Fusion 62 076036
P. Rodriguez-Fernandez et al 2024 Nucl. Fusion 64 076034

- **Surrogate-optimization** in flux-matching problem of δf codes as embedded in PORTALS opens new pathways to:
  1) allow predictions of performance in future reactors, and
  2) study turbulence and validation in current experiments

  with first-principles simulations.
- **Physics-based integrated modeling** and **NL GK** are being used to plan SPARC campaigns and inform fusion power plant design to reduce risk of extrapolating from limited empirical databases.
- Profile predictions with NL GK especially useful when **quasilinear models not fully developed or validated** (e.g. *spherical*, *stellarators*, *fast ions*) and when they encounter difficulties (e.g. *source-free particle transport*).



PORTALS developments currently occurring under SciDAC-5 partnership

SMARTS: "Surrogate Models for Accurate and Rapid Transport Solutions"

GK databases, multi-fidelity, multi-channel, modularization and packaging