Characterization of Predicted Confinement and Transport in an ARC-class Tokamak Power Plant

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MIT PSFC Plasma Science and Fusion Center
Commonwealth Fusion Systems
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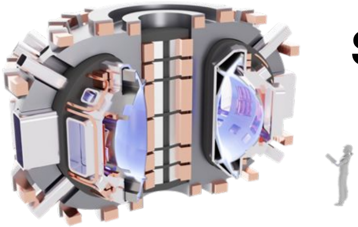
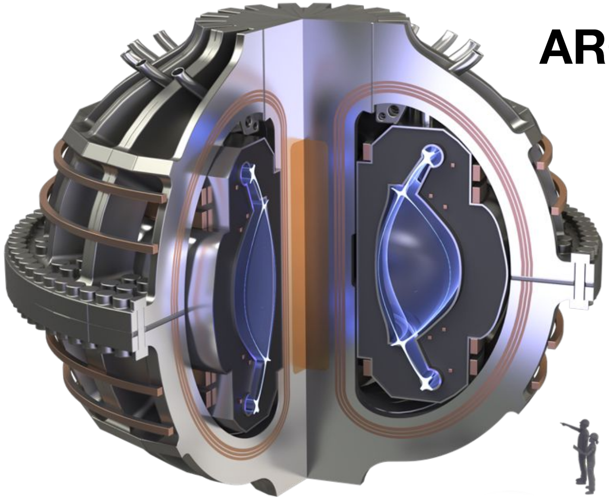
Analysis of an ARC-class device predicts a plasma with very similar core transport physics as analogous SPARC and ITER scenarios

- Beyond demonstration of Q > 2, operation of the SPARC tokamak intended to retire physics risks for ARC

- In support of this mission, a INFUSE-funded collaboration was initiated to
  - Characterize core transport and turbulence physics in the ARC V1C scenario, and
  - Assess to what extent this physics will be analogous to expectations for SPARC
  - Inform ARC design refinements and SPARC operational planning



SPARC



ARC

Talk Outline- address three questions

1. Why did we pursue this specific project?

2. What did we do?

3. What did we learn?

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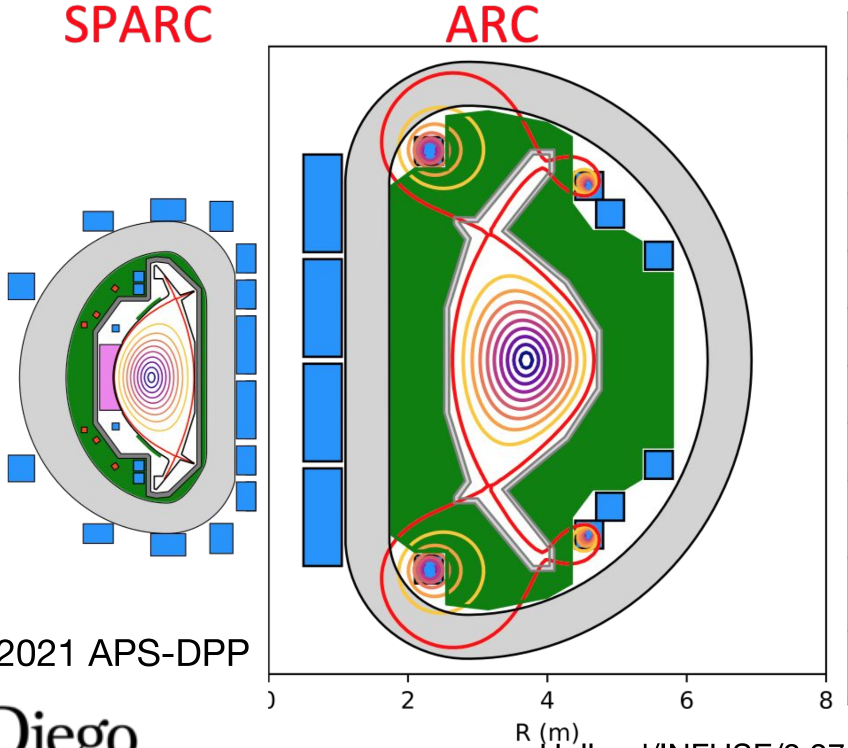
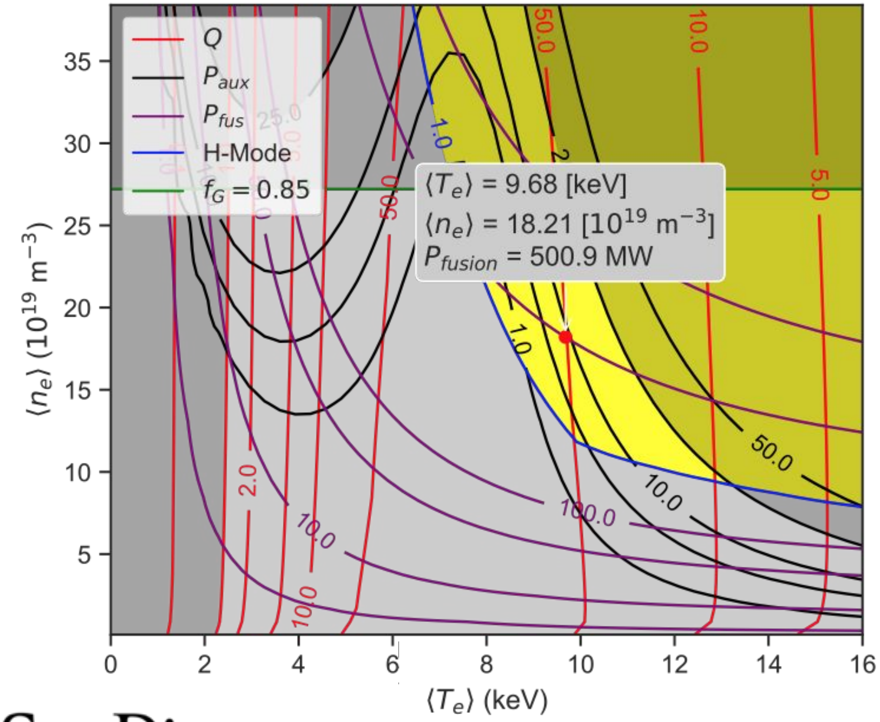
Nominal ARC V1C [1] scenario: P_{fus} = 500 MW via pulsed operation in a R_0 = 3.65 m, B_0 = 11.6 T tokamak



	SPARC Range	ARC_{500}	
P_{fusion}	0 - 141	501	MW
Q	0 - 11	50	
$\langle T_e \rangle$	5 - 13	9.7	keV
$\langle n_e \rangle$	1.4 – 5.5	1.8	$10^{20}m^{-3}$
$H_{98,y2}$	1.0	1.0	
f_g	0.17-0.65	0.6	
β_N	0.8 – 1.5	1.2	m·T/MA
ρ^*	0.0013 - 0.0040	0.0018	
$P_{sep}B_0/R_0$	125 - 184	263	MW·T/m
$P_{sep}B_0/R_0n_{e,20}^2$	41 - 109	79.4	$MW·T·m^5$

[1] A. Creely, 2021 APS-DPP

Initial 0-D parameters for the ARC V1C scenario determined via POPCON analysis



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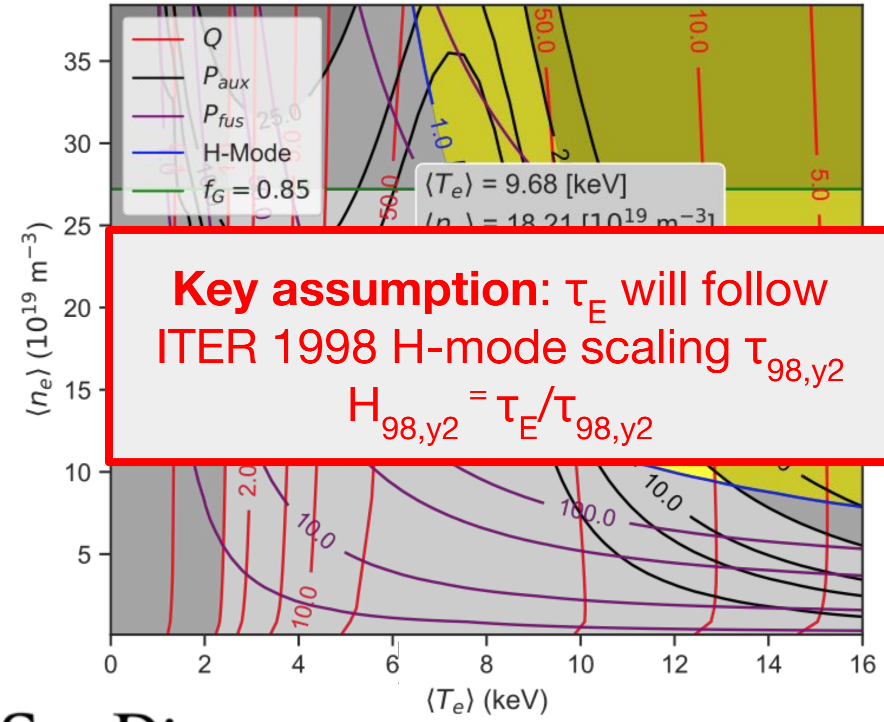

Key assumption: τ_E will follow ITER 1998 H-mode scaling $\tau_{98,y2}$

$H_{98,y2} = \tau_E/\tau_{98,y2}$

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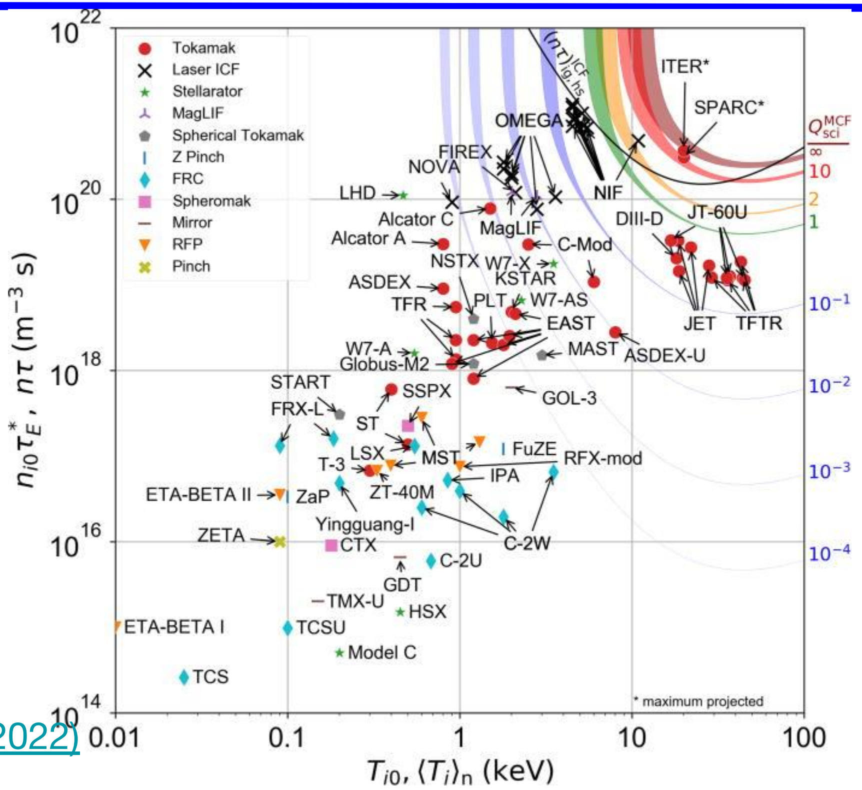
Why this project? To have more confidence in expected performance than scaling laws can provide

- Well-known that increasing energy confinement time τ_E improves power plant efficiency and attractiveness

- Hierarchy of models for predicting τ_E that trade-off between computational cost and accuracy
  - Empirical scaling laws
  - Reduced transport models
  - Direct numerical simulation



S. E Wurtzel and S. C. Hsu, Phys. Plasmas **29** 062103 (2022)

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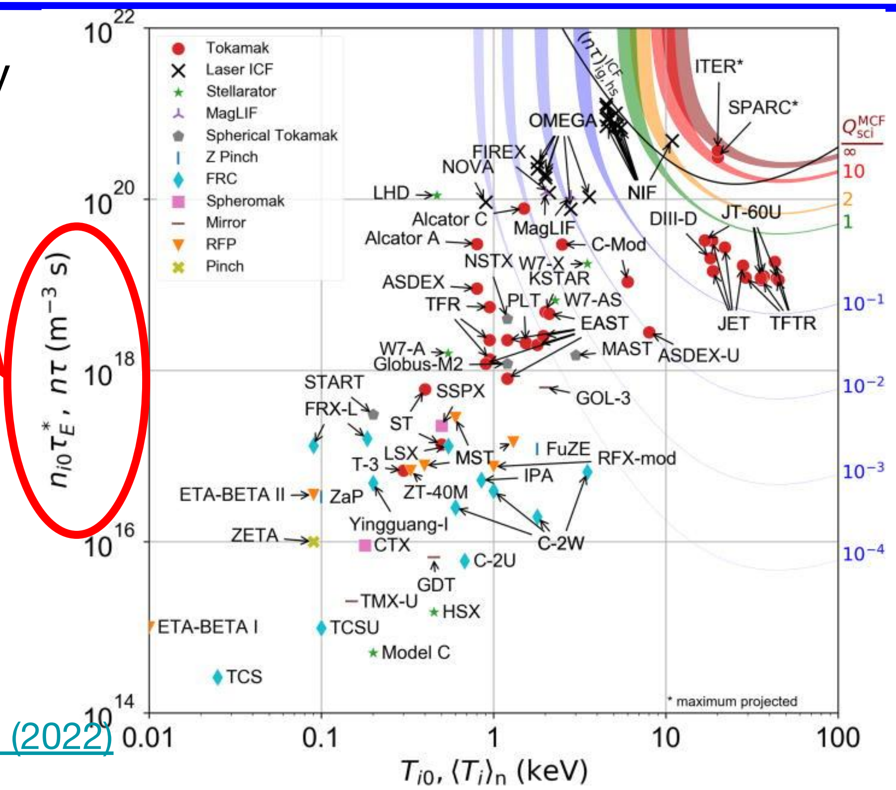
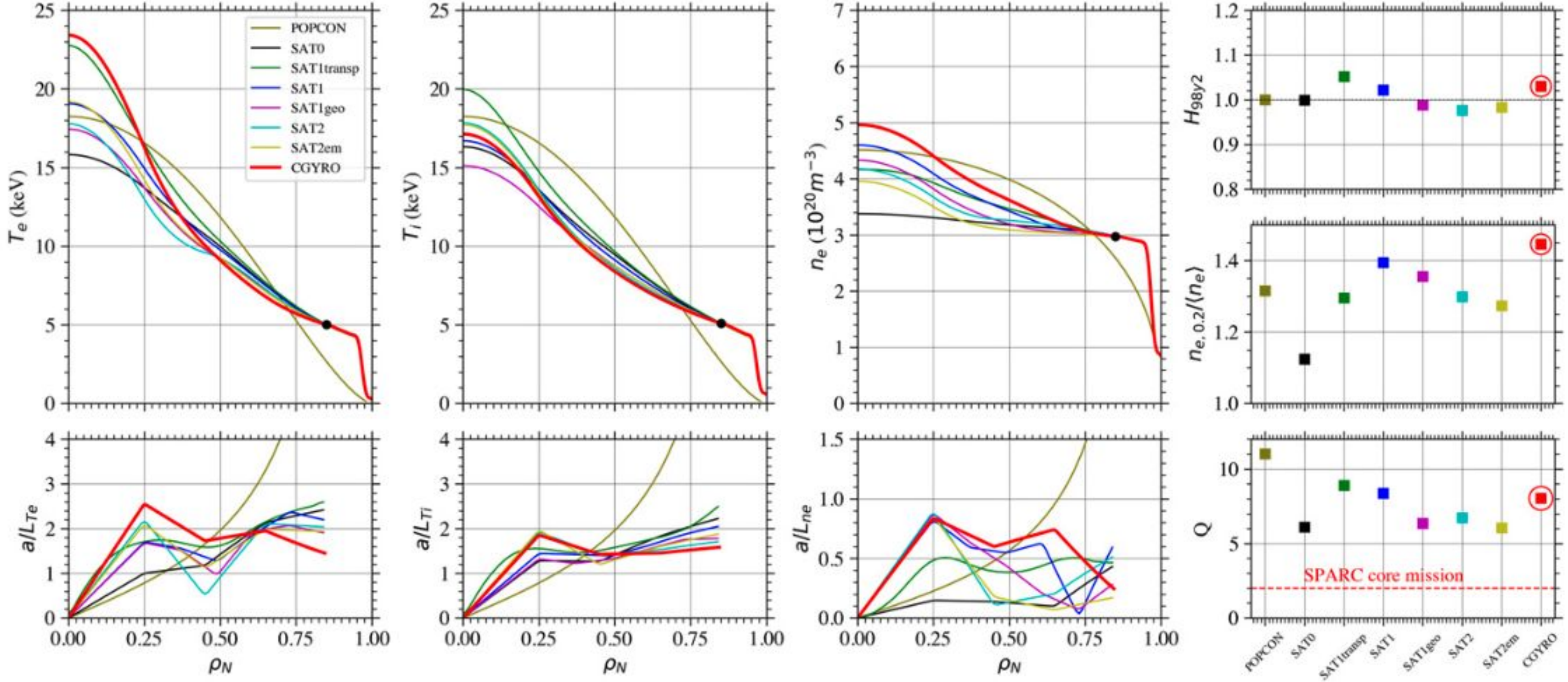


S. E Wurtzel and S. C. Hsu, Phys. Plasmas **29** 062103 (2022)

Different transport models predict a factor of 2 variation in SPARC Q_{fusion} but same values of $H_{98,y2}$



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P. Rodriguez-Fernandez *et al*, Nucl. Fusion **62** 0760306 (2022)

Why this problem? Because it was a great fit for INFUSE structure

- Clear questions of direct relevance to CFS mission
  - Will SPARC provide a good proxy for ARC core physics? Why or why not?
- The questions could be answered in a timely fashion
  - New surrogate-model based workflow enables us to make high-fidelity predictions with 10x fewer simulations than before
- Urgency of project matches well with INFUSE timescales
  - Don’t need ASAP, but also don’t want to wait too long
- Good match of expertise, interests, and availability of personnel
  - Need all three to be successful
- Addresses non-proprietary publishable research
  - Can (and have) openly share the work

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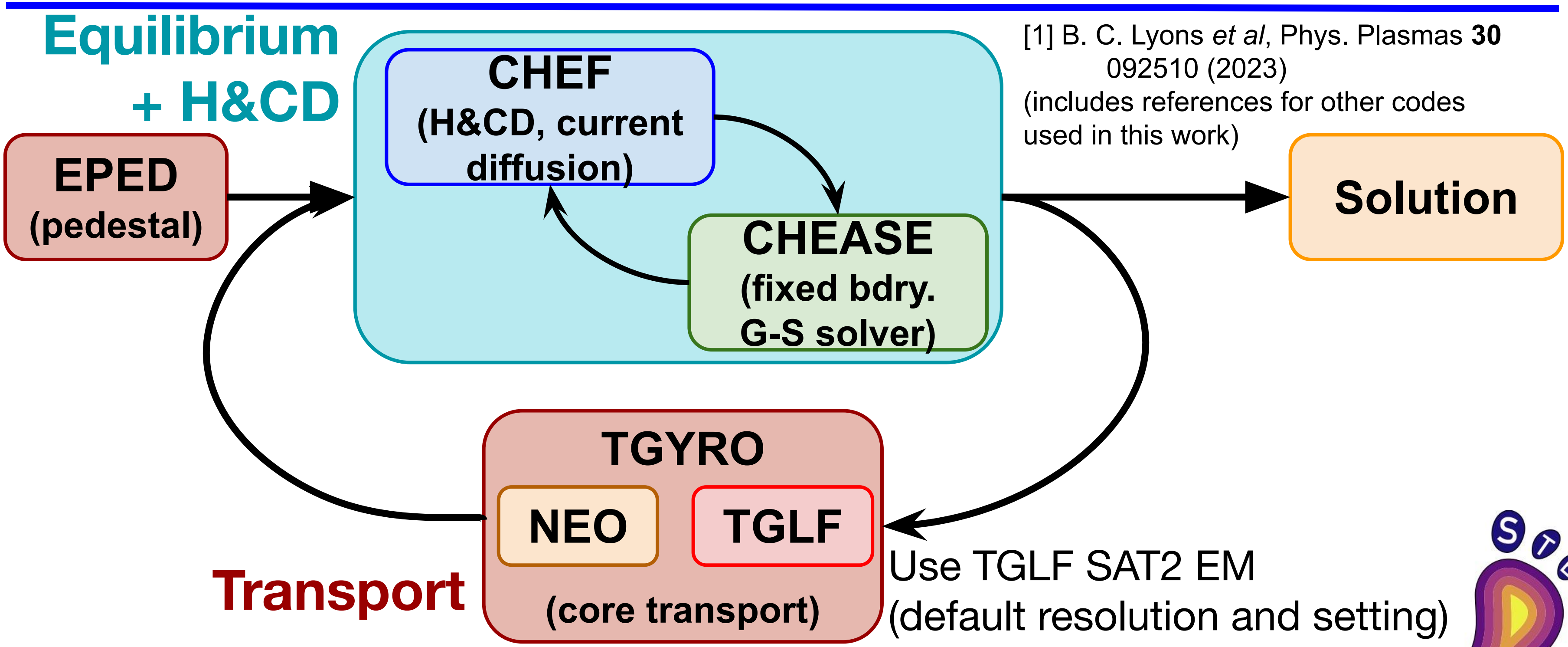
Starting from the POPCON parameters, the OMFIT STEP [1] tool was used to develop self-consistent 1.5D transport solutions

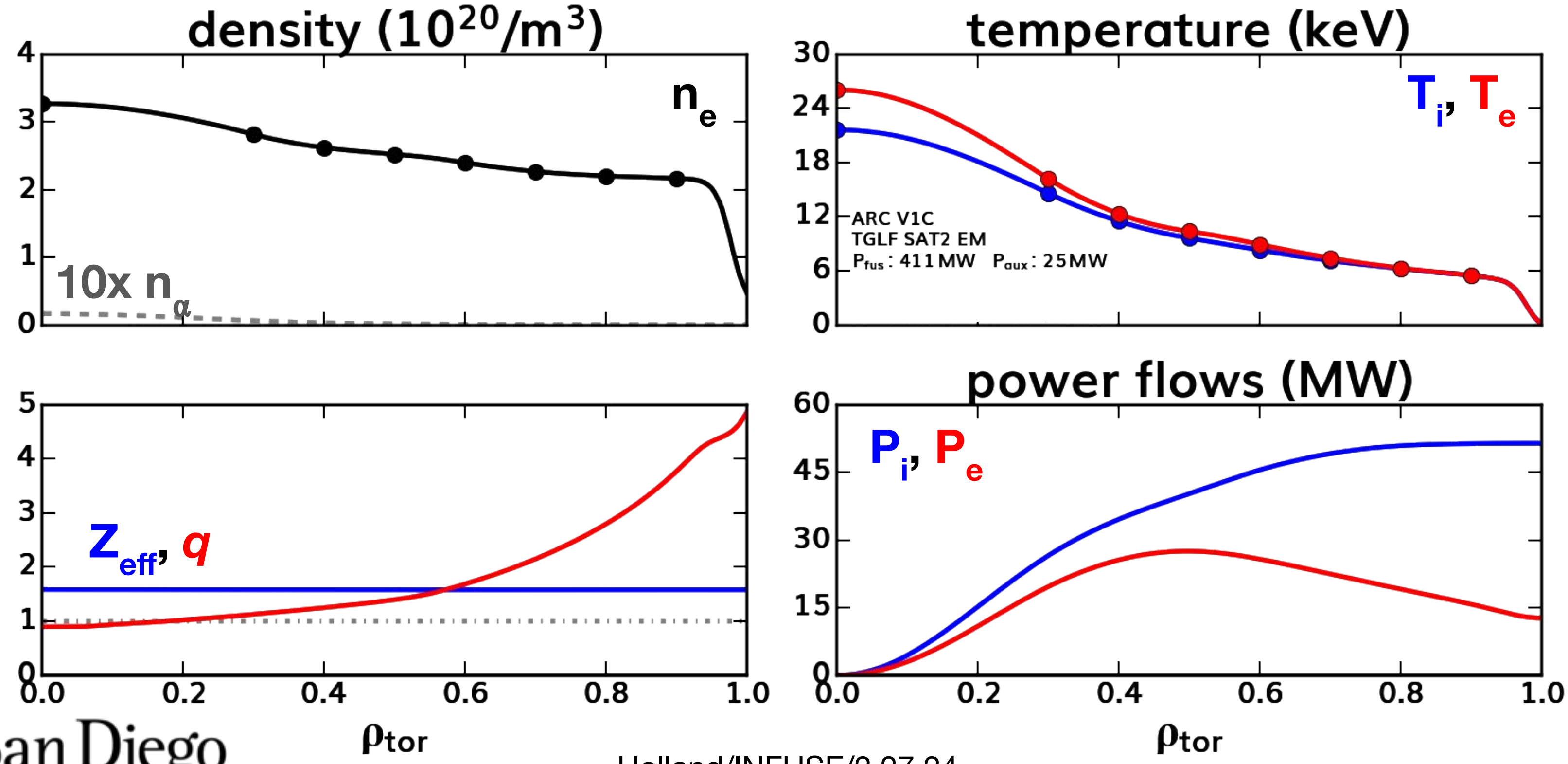


[1] B. C. Lyons *et al*, Phys. Plasmas **30** 092510 (2023)
(includes references for other codes used in this work)

Use TGLF SAT2 EM
(default resolution and setting)

https://omfit.io/modules/mod_STEP.html

Typical ARC V1C solution predicted by reduced models: modest n_e peaking, $T_e > T_i$, ion power flow $P_i > P_e$



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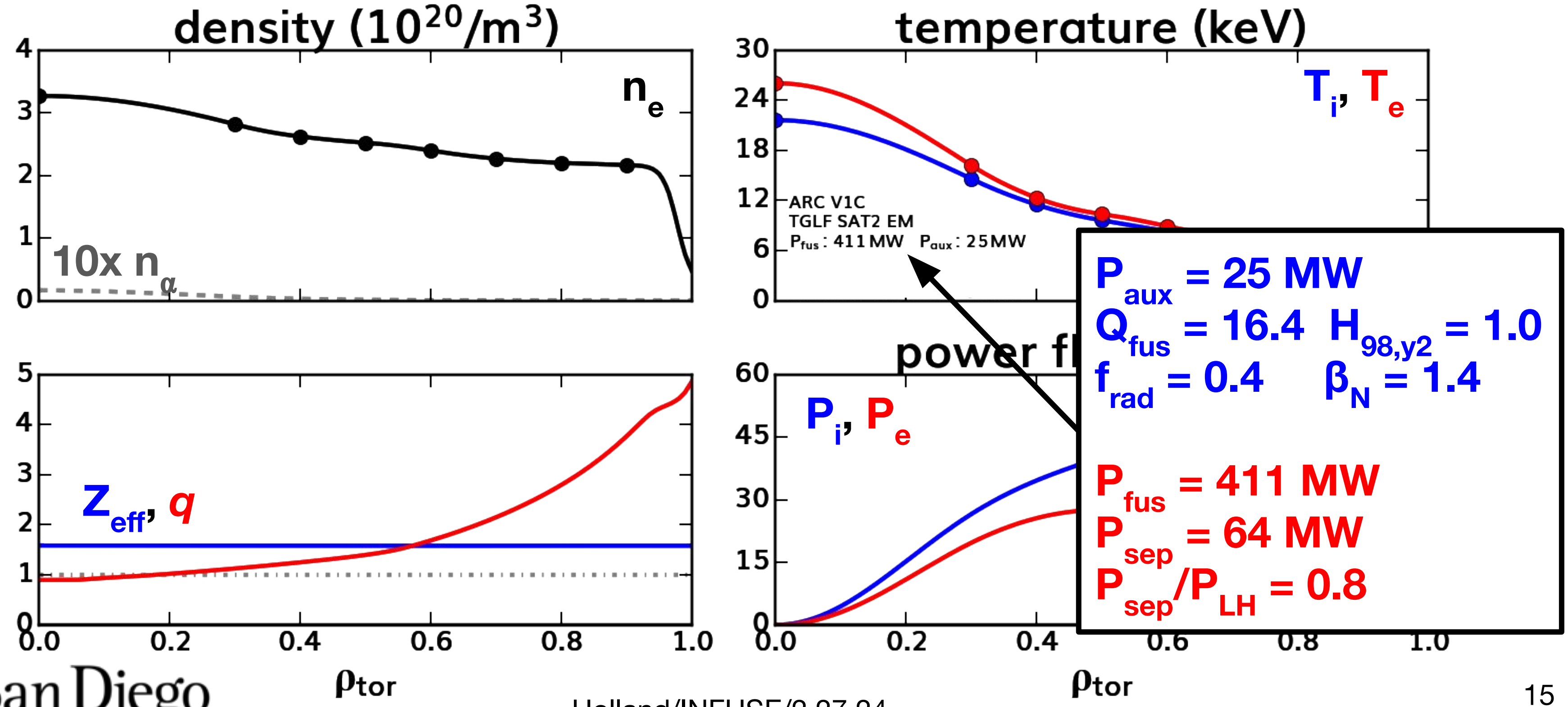
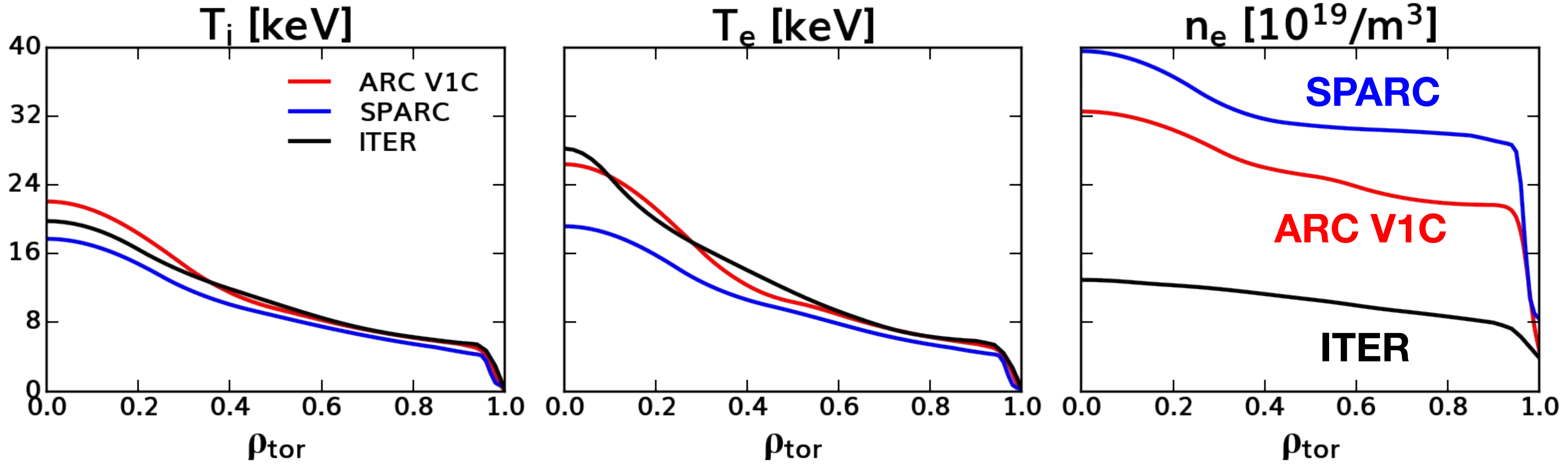
Results close to POPCON predictions but about 20% lower P_{fusion} than targeted (even with $H_{98,y2}$ = 1.0)



ARC V1C, SPARC, and ITER predicted to have very similar profile shapes with this workflow



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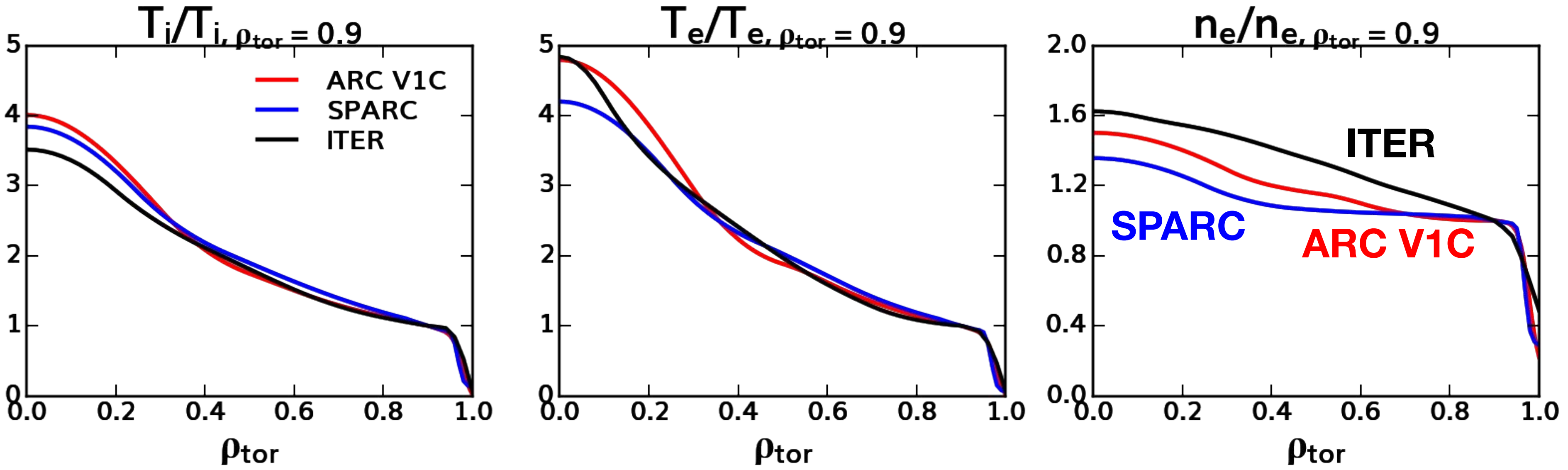

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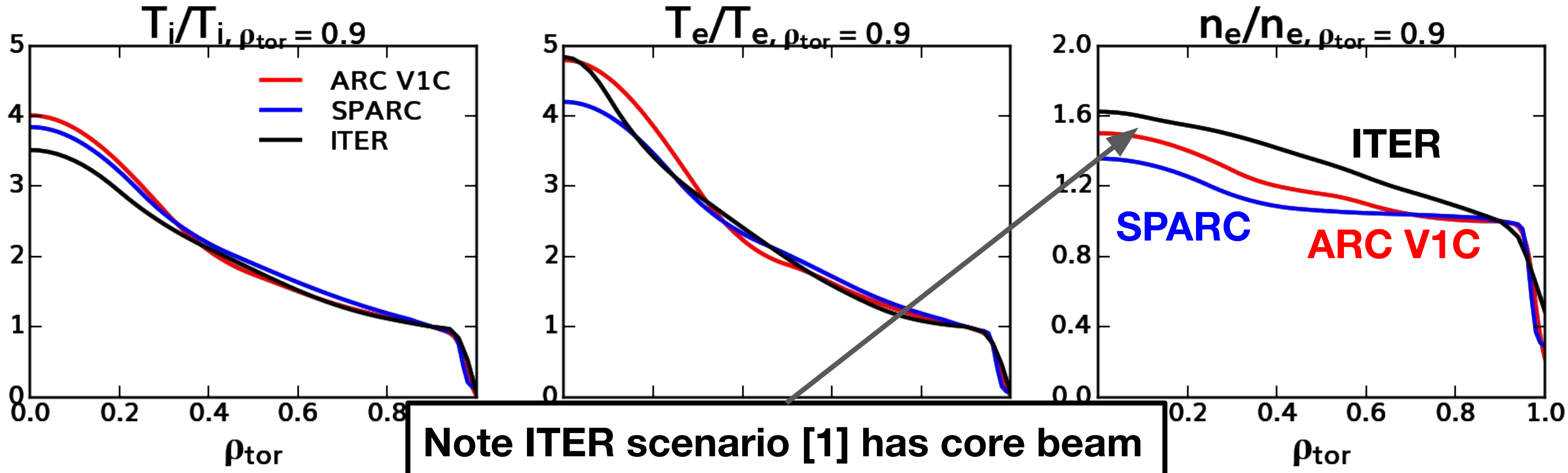

Note ITER scenario [1] has core beam & pellet fueling, SPARC & ARC do not
[1] P. Mantica *et al.*, PPCF 2019

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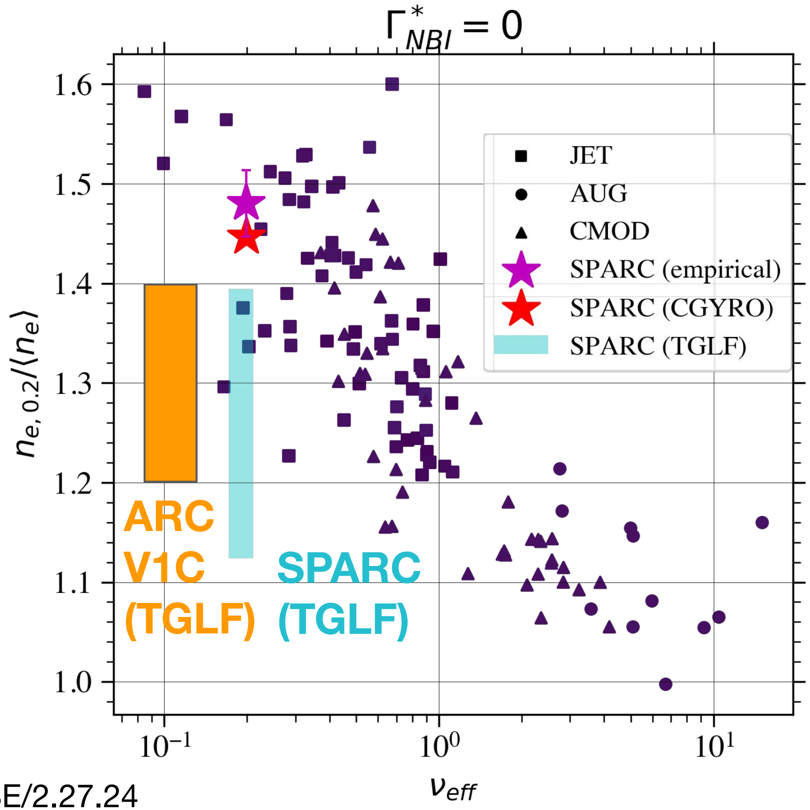
Reduced model-based predictions of density peaking in SPARC and ARC V1C both below Angioni 2007 scaling

- Plot adapted from
  P. Rodriguez-Fernandez *et al*,
  Nucl. Fusion **62** 0760306 (2022)

- Peaking data and analysis from
  - C. Angioni *et al*,
    Phys. Plasmas **14** 055905 (2007)
  - M. Greenwald *et al*,
    Nucl. Fusion **47** L26 (20007)



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But high-fidelity modeling of SPARC predicts peaking in line with scaling- what about ARC?

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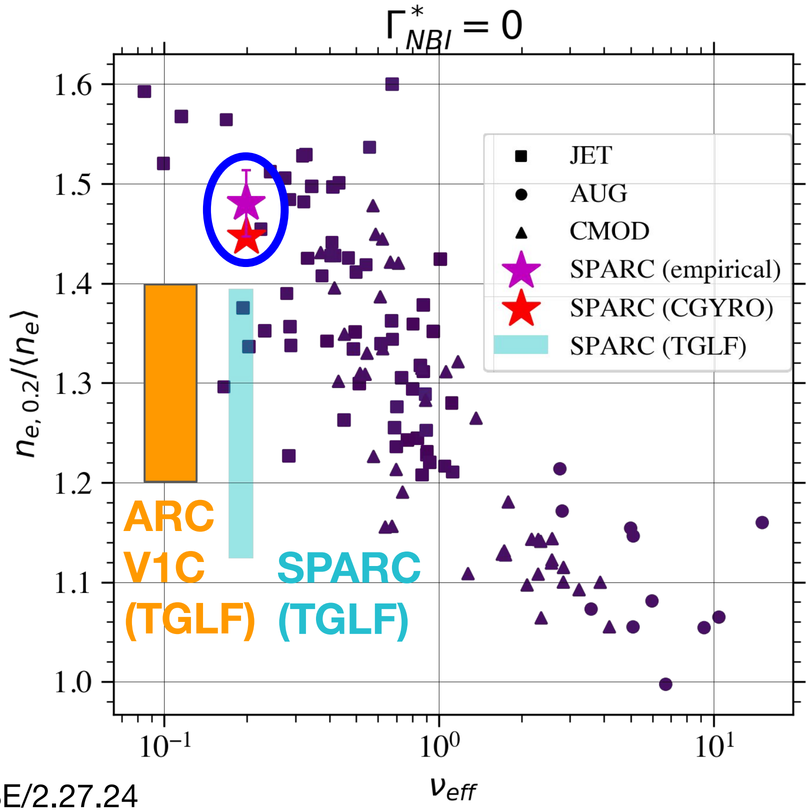

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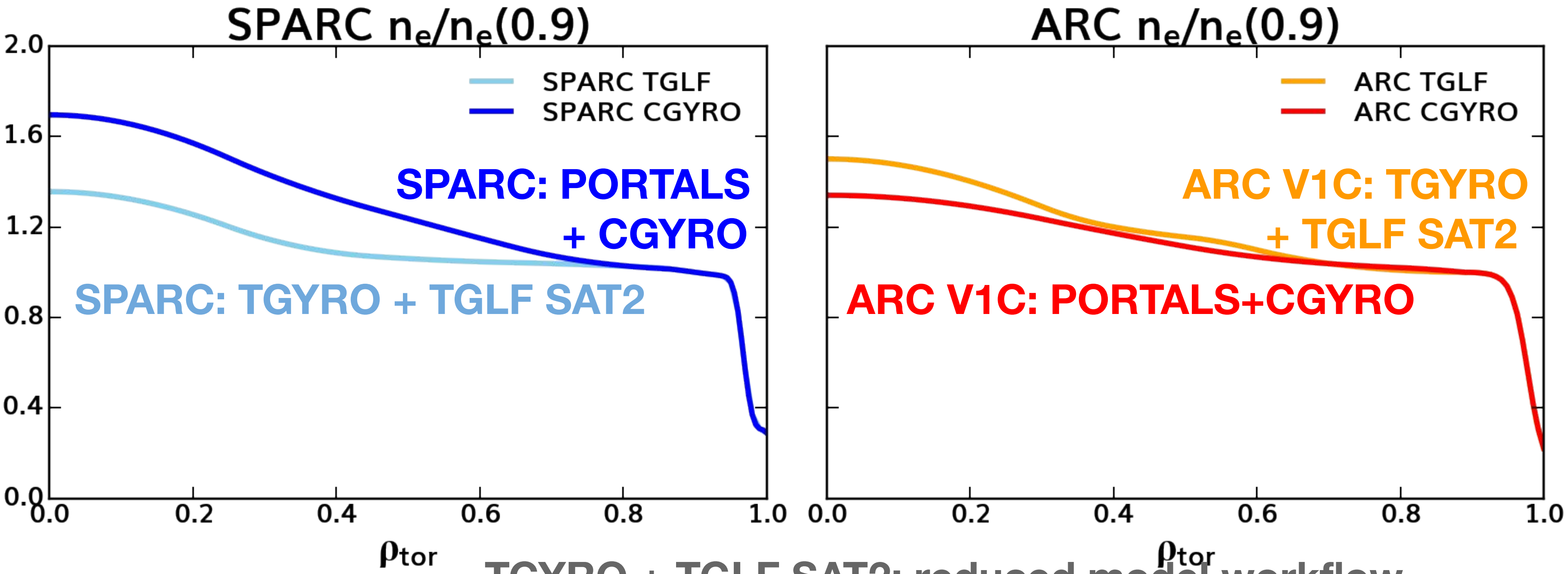
Surprise- unlike SPARC, high-fidelity modeling did not predict an increase in n_e peaking for ARC V1C



TGYRO + TGLF SAT2: reduced model workflow

PORTALS + CGYRO: high fidelity model workflow

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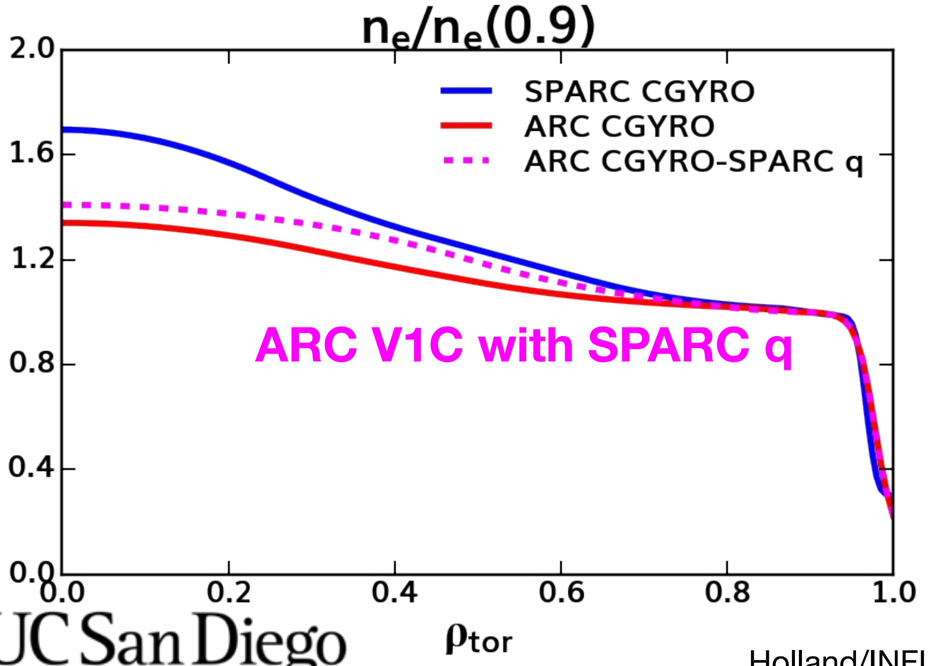
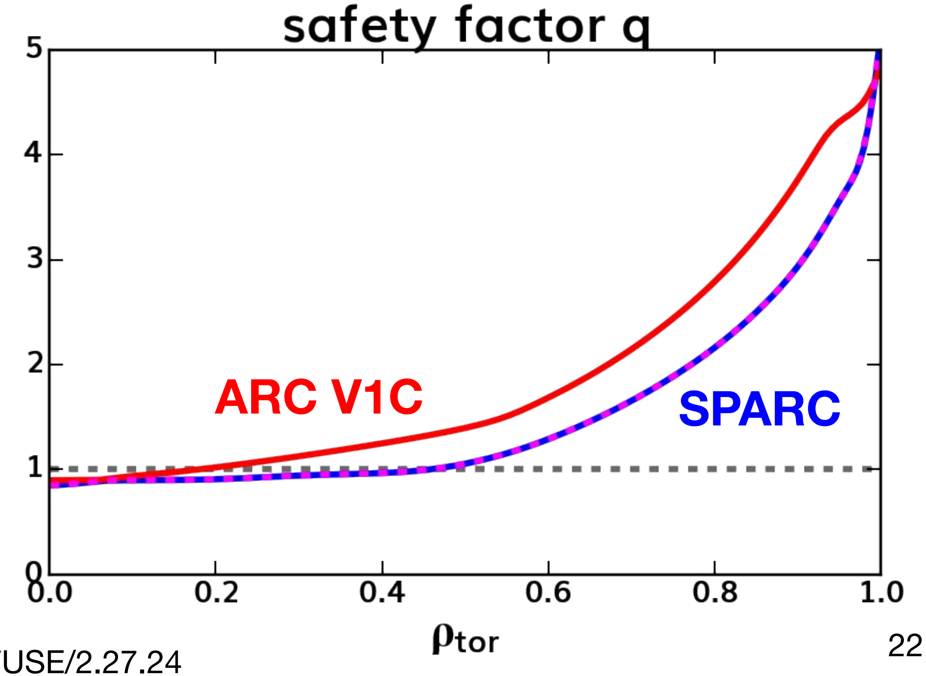
Using a more diffused current profile for ARC leads to increased peaking at mid-radius, closer profiles

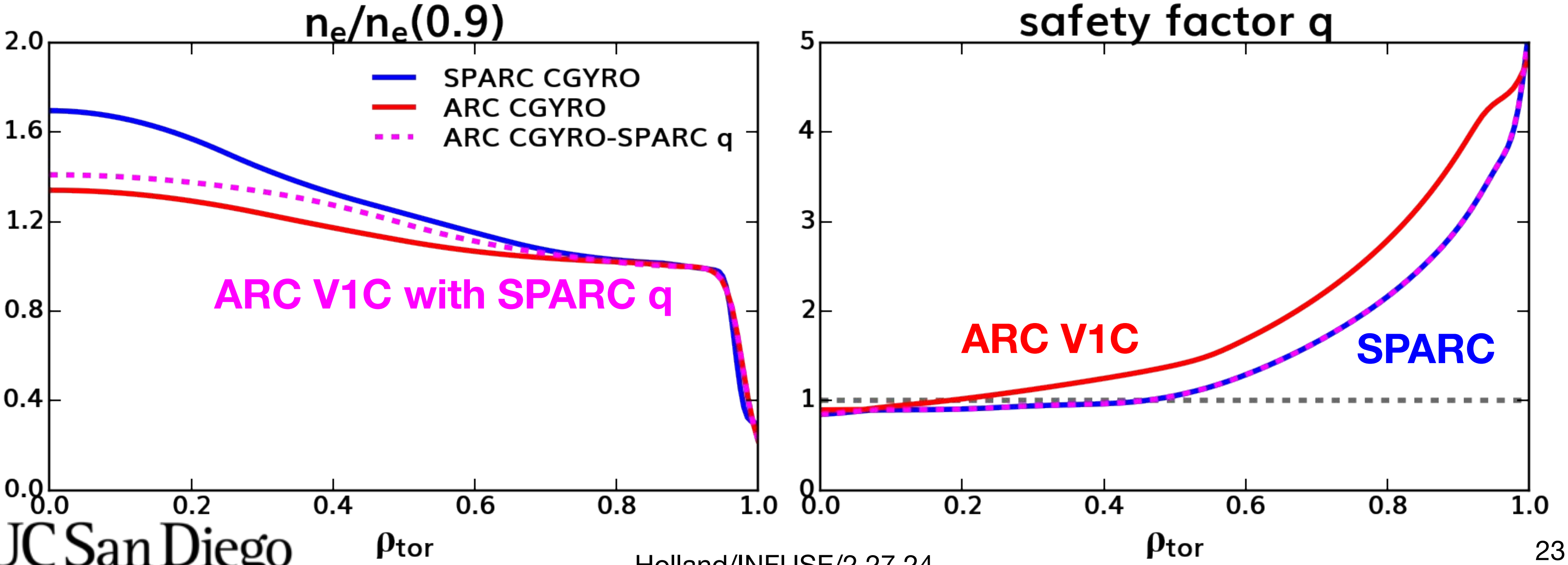
- Difference in *q* profiles from different descriptions of sawtooth-driven current evolution; can also be seen as different times in sawtooth cycle





Source of remaining differences in deep core still under investigation

- Perhaps differences in collisionality, β, inclusion of $\delta B_{\|}$ fluctuations, or just uncertainties in representing near-marginal turbulence?



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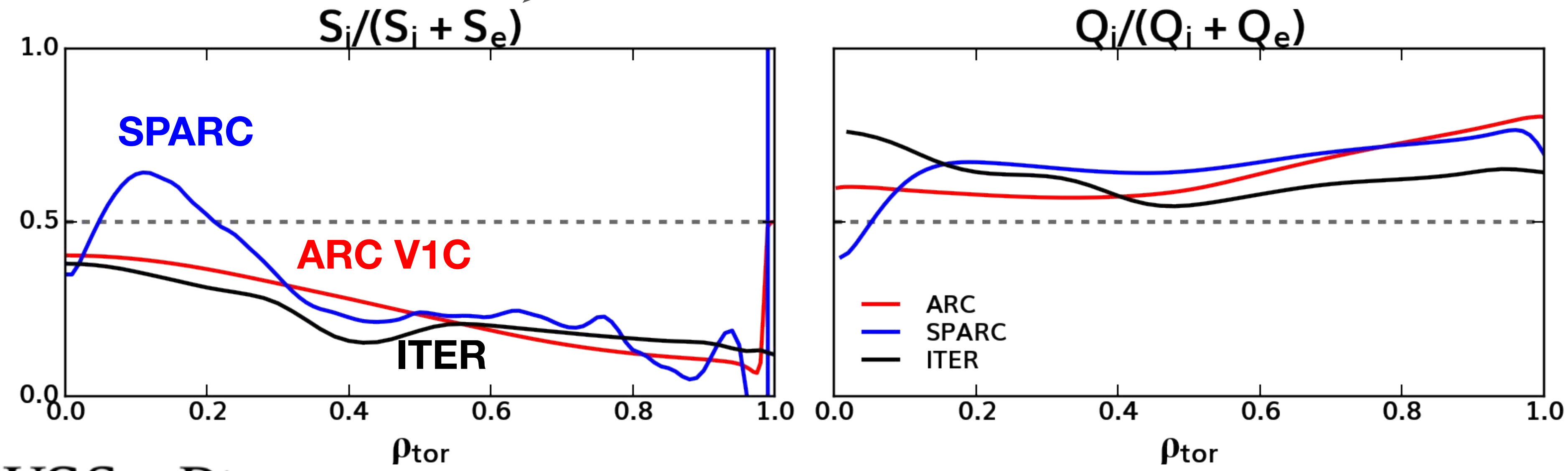
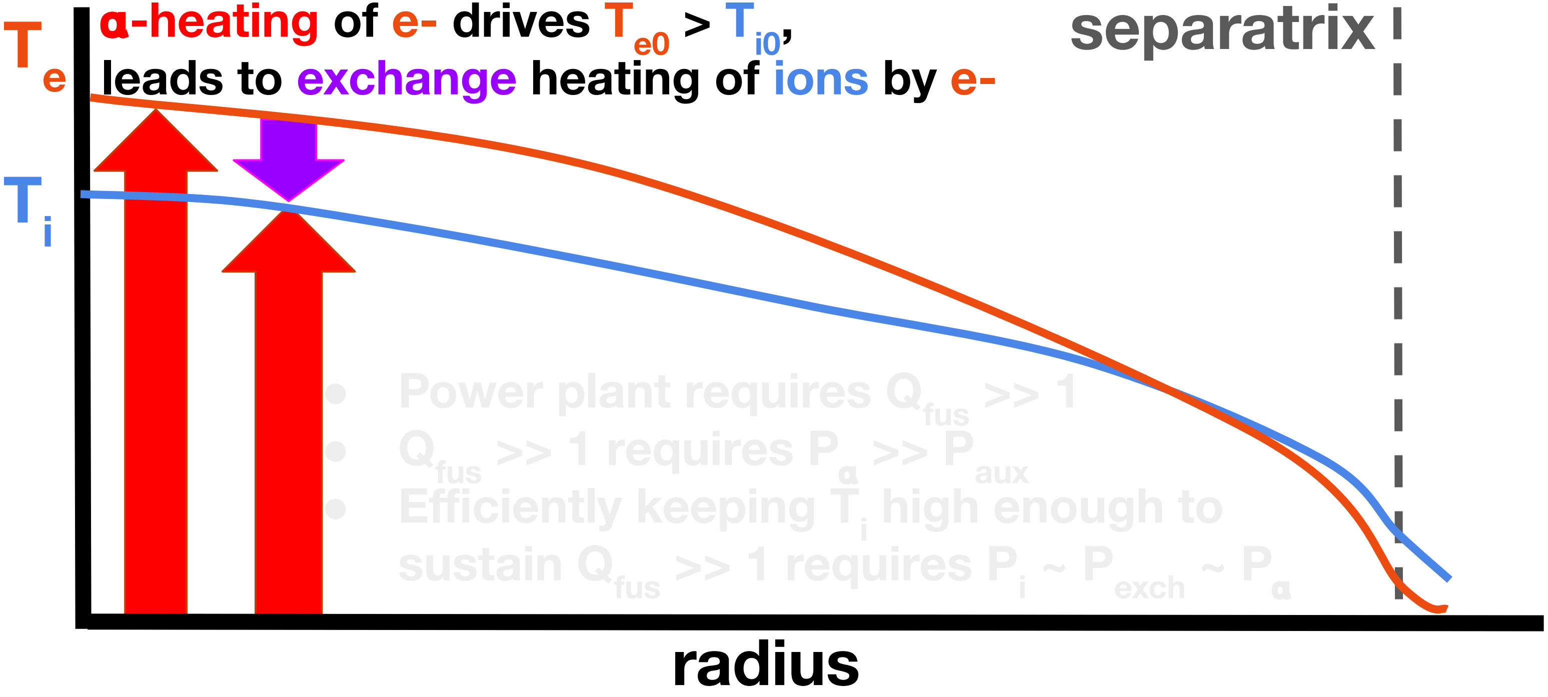
Key result of modeling: although all three plasmas (ARC, SPARC, ITER) have dominant electron heating, strong radiation and collisional coupling make ion thermal transport the dominant energy loss channel

$$\frac{3}{2}\frac{\partial p_{i,e}}{\partial t} + \frac{\partial Q_{i,e}}{\partial r} \simeq \boxed{S_{i,e}^{aux} + S_{i,e}^{\alpha}} - S_{rad} \pm \frac{3}{2}\nu_{exch} n_e (T_e - T_i)$$



Required dominance of ion transport for tokamak power plants can be understood via a simple model [1]



[1] C. Holland *et al*, J. Plasma Phys **89** 05890418 (2023)

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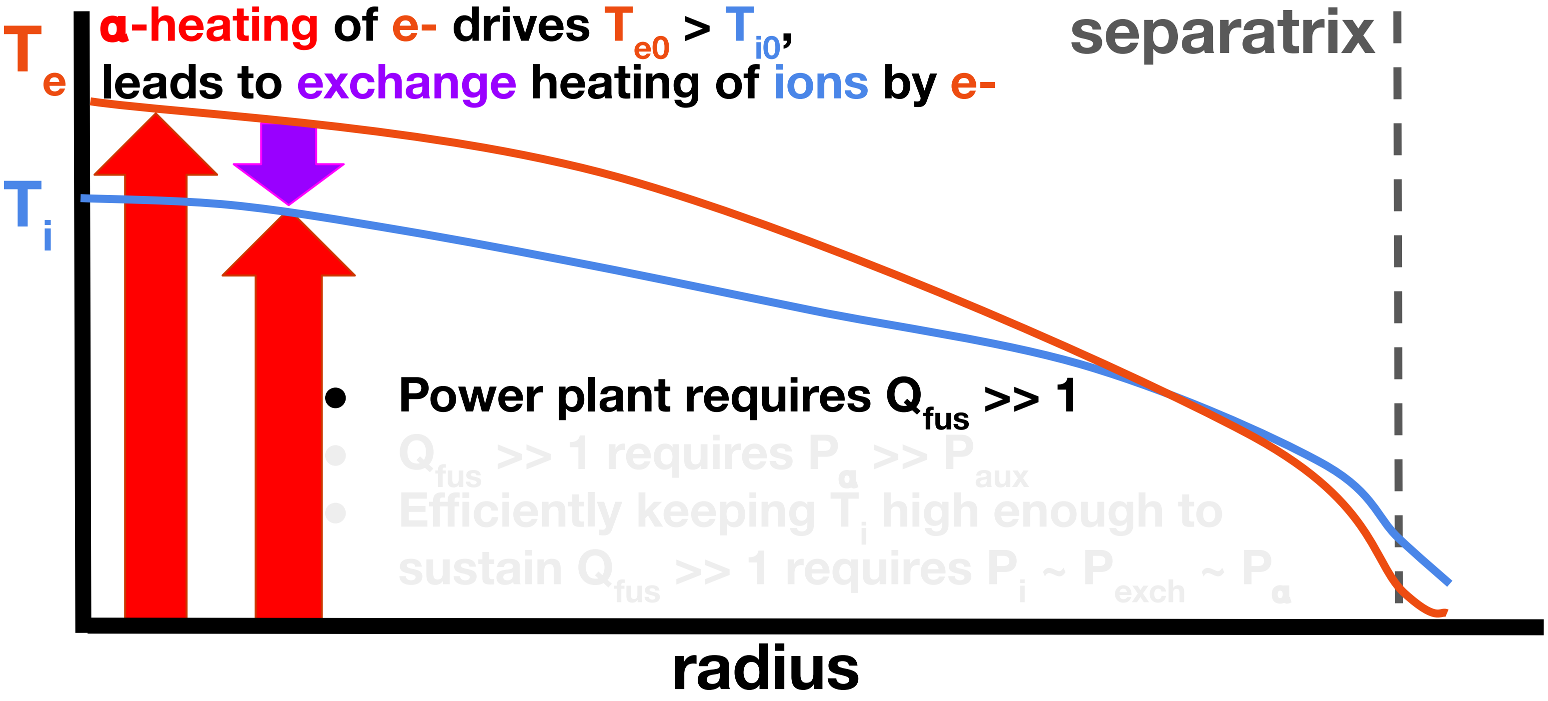

- **Power plant requires Q_{fus} >> 1**
- **Q_{fus} >> 1 requires P_α >> P_{aux}**
- **Efficiently keeping T_i high enough to sustain Q_{fus} >> 1 requires $P_i \sim P_{exch} \sim P_\alpha$**

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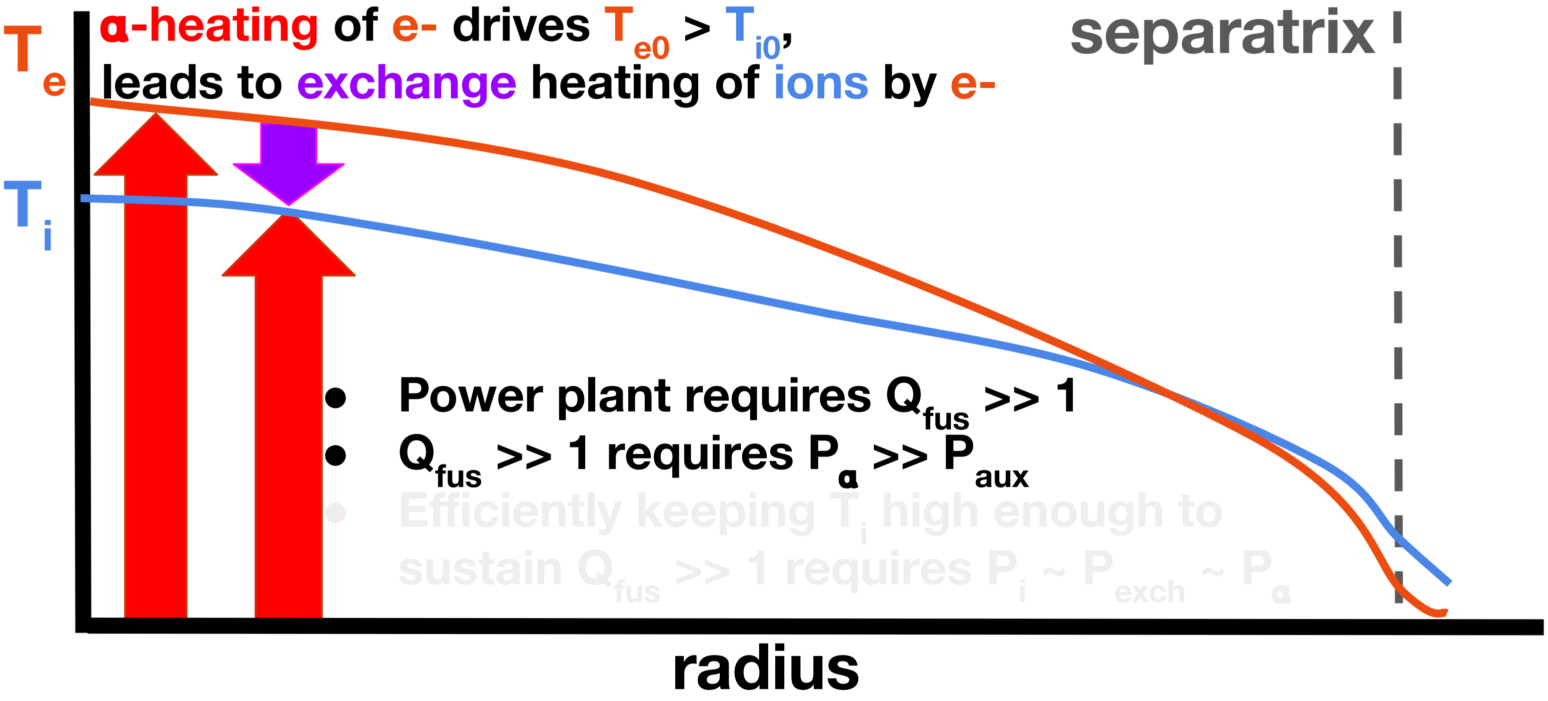

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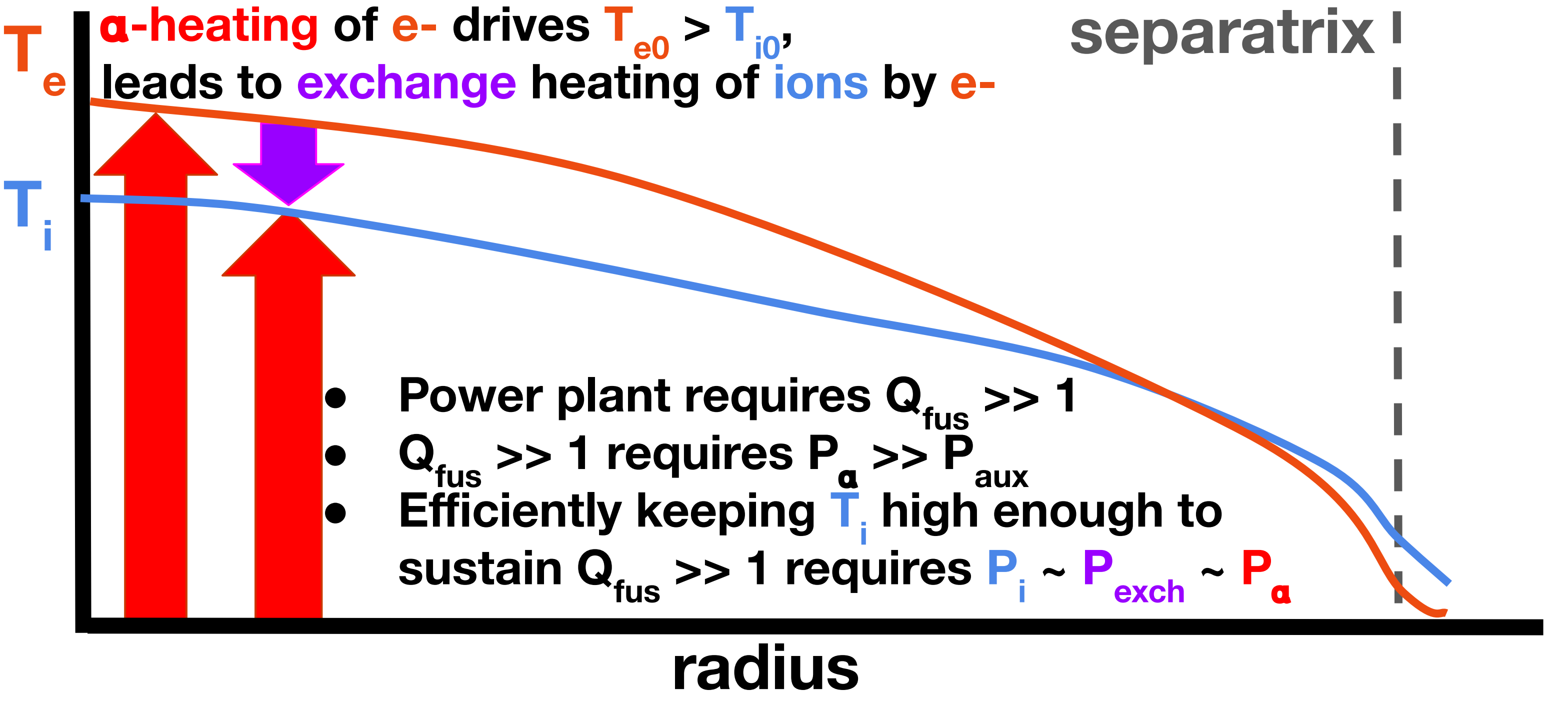

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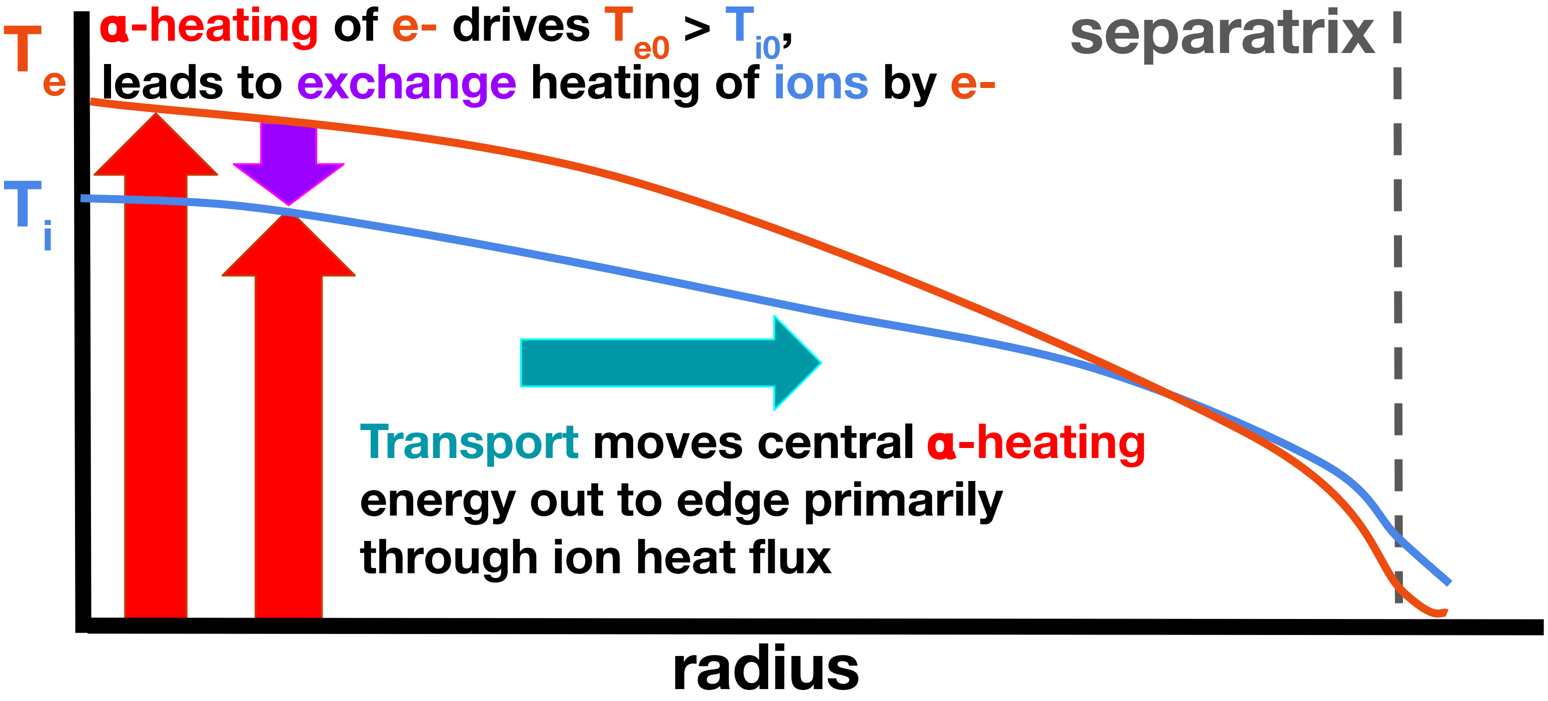

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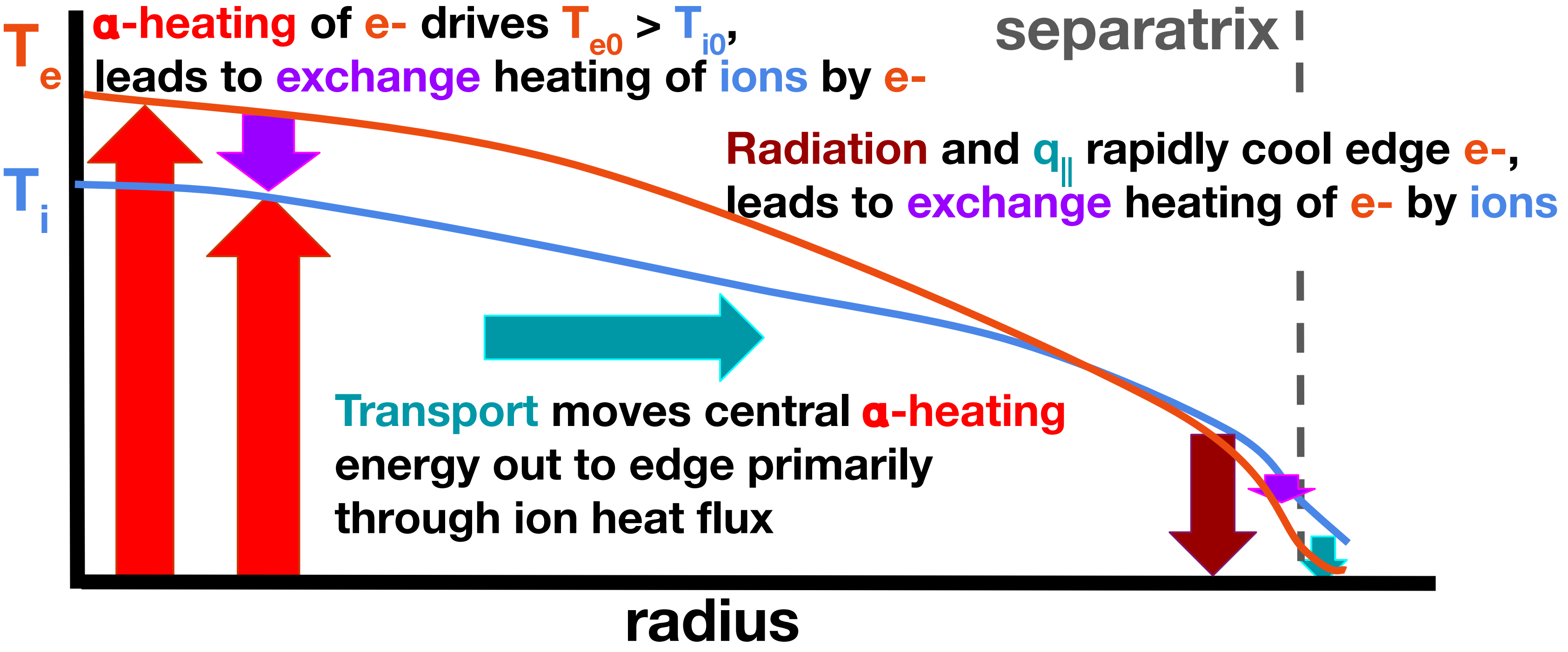

[1] C. Holland *et al*, J. Plasma Phys **89** 05890418 (2023)

Viable power plant must have significant turbulent core ion heat flux; "fingerprint" paradigm [1] requires ITG/TEM

- **Neoclassical**: too small
  - Required by power plant ν_i^*
- **MTM**, **ETG**:
  - can be present, but can't provide needed χ_i/χ_e
- **KBM/MHD-like modes**: only drive particle outflow, power plants likely require core thermal particle pinch
  - Also want to avoid EP-driven modes: alpha redistribution, wall damage
- **Leaves ITG (+TEM) as only viable process**

(A) [1] M. Kotschenreuther *et al*, Nucl. Fusion **59** 096001 2019

Mode type	χ_i/χ_e	D_e/χ_e	D_Z/χ_e
MHD-like	1	2/3	2/3
MTM	~1/10	~1/10	~1/10
ETG	~1/10	~1/20	~1/20

(B)

Mode type	χ_i/χ_e	$D_e/(\chi_i + \chi_e)$	$D_Z/(\chi_i + \chi_e)$
ITG/TEM	1-4	$-1/10 \pm 1/3$	~1

What did we learn?

- **Good stuff**: higher-fidelity models supported the POPCON analysis to within 20-30%
- **Not-so-good stuff**: performance lower than expected from POPCON analysis, in particular below L-H threshold
- **Interesting stuff**: less density peaking predicted in ARC than SPARC, still working to understand why
- **Most important stuff**: core transport and turbulence characteristics should be same in ARC, SPARC, and ITER
    - **SPARC can serve as a good proxy for ARC and ITER core confinement**

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