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THE TRANSPORT CHALLENGE FOR FUSION POWER PLANTS AT HIGH BETA POLOIDAL

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OVERVIEW

THE STEP PLASMA CHALLENGE

ELECTROMAGNETIC TURBULENCE AT HIGH BETA

GETTING TO HIGH CONFINEMENT

PROSPECTS FOR TESTING THESE IDEAS IN EXPERIMENTS

CONCLUSIONS

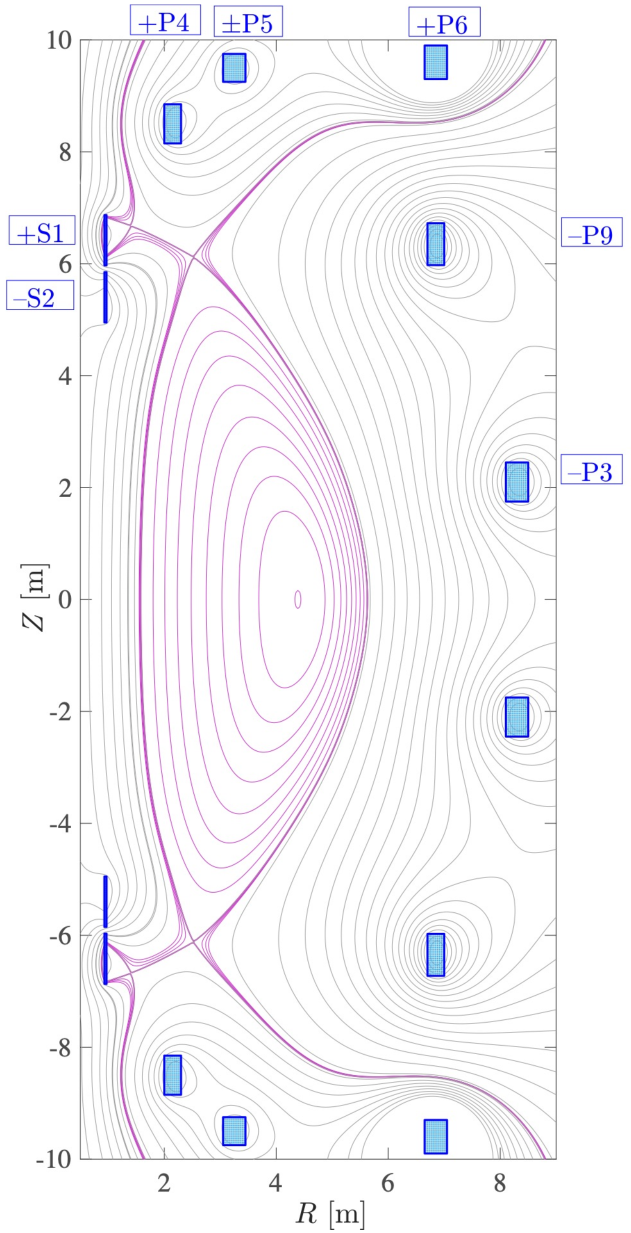
INTRODUCTION

(The) **Spherical Tokamak for Energy Production** is a UK programme, aiming to develop a compact Tritium self-sufficient **prototype reactor** that aims to deliver **net electric power**.

- Conceptual design for candidate flat tops **(FTOP)** published in 2024 [1,2].

Fusion performance needs **large core pressure** (or β) and **low turbulent transport**:

- Aiming to achieve high core pressure.
- Spherical tokamak: small radius means steep gradients are required.
- Pressure and profiles depend crucially on transport and confinement.
- Turbulence increasingly electromagnetic.
- Unstable kinetic ballooning (KBM)-like modes with subdominant microtearing modes.
- Drive large transport in the absence of equilibrium flow shear.



Adequate core performance is one of the biggest physics challenges enroute to STEP or any viable reactor.

REFERENCES
[1] Meyer (2024)
[2] Tholerus *et al.* (2024)

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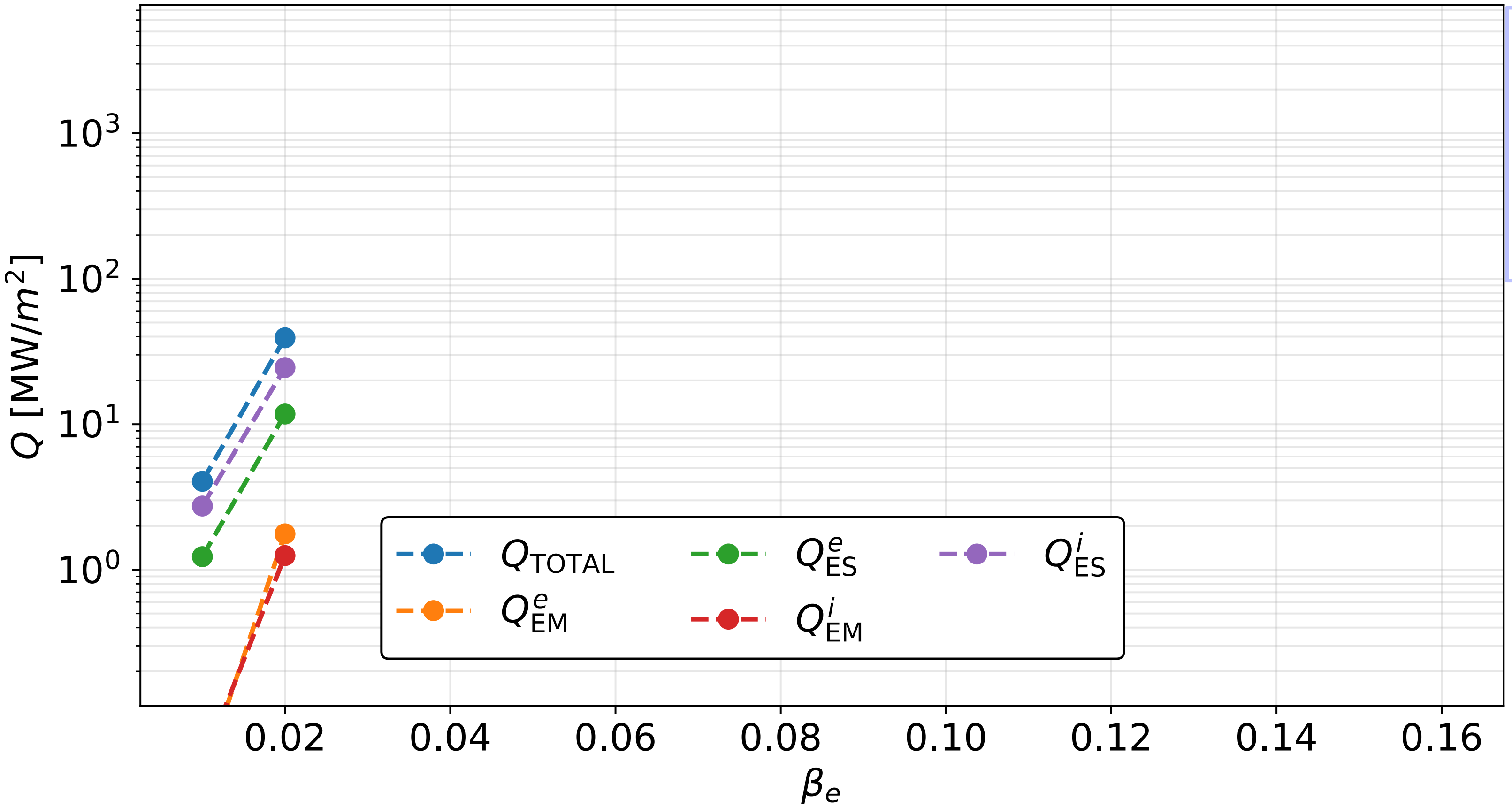
PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** [3,4,5,6,7,8].
- β_e $[\equiv n_e T_e \,/\, (B^2 \,/\, 2\mu_0)]$ scan on reference surface with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).



REFERENCES

[3] Kennedy *et al.* (2023)
[4] Giacomin *et al.* (2024)
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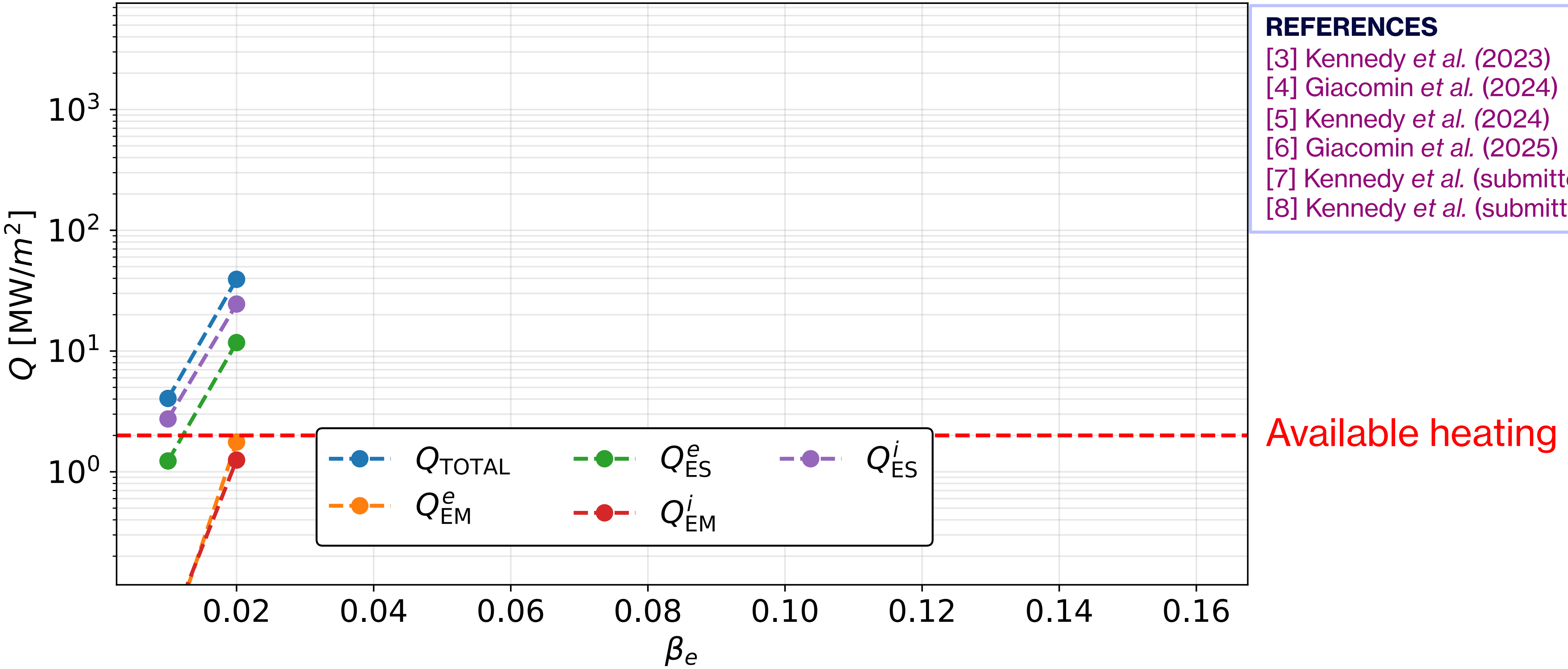

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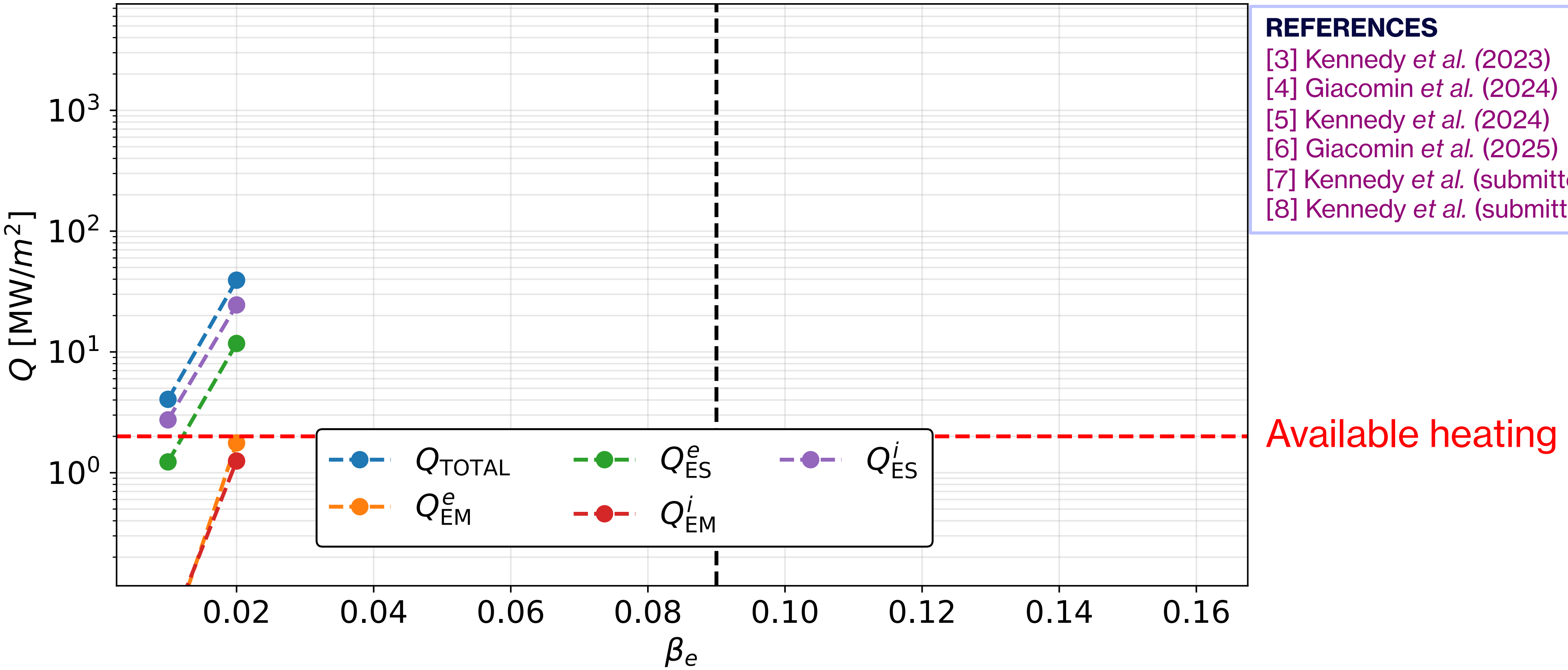

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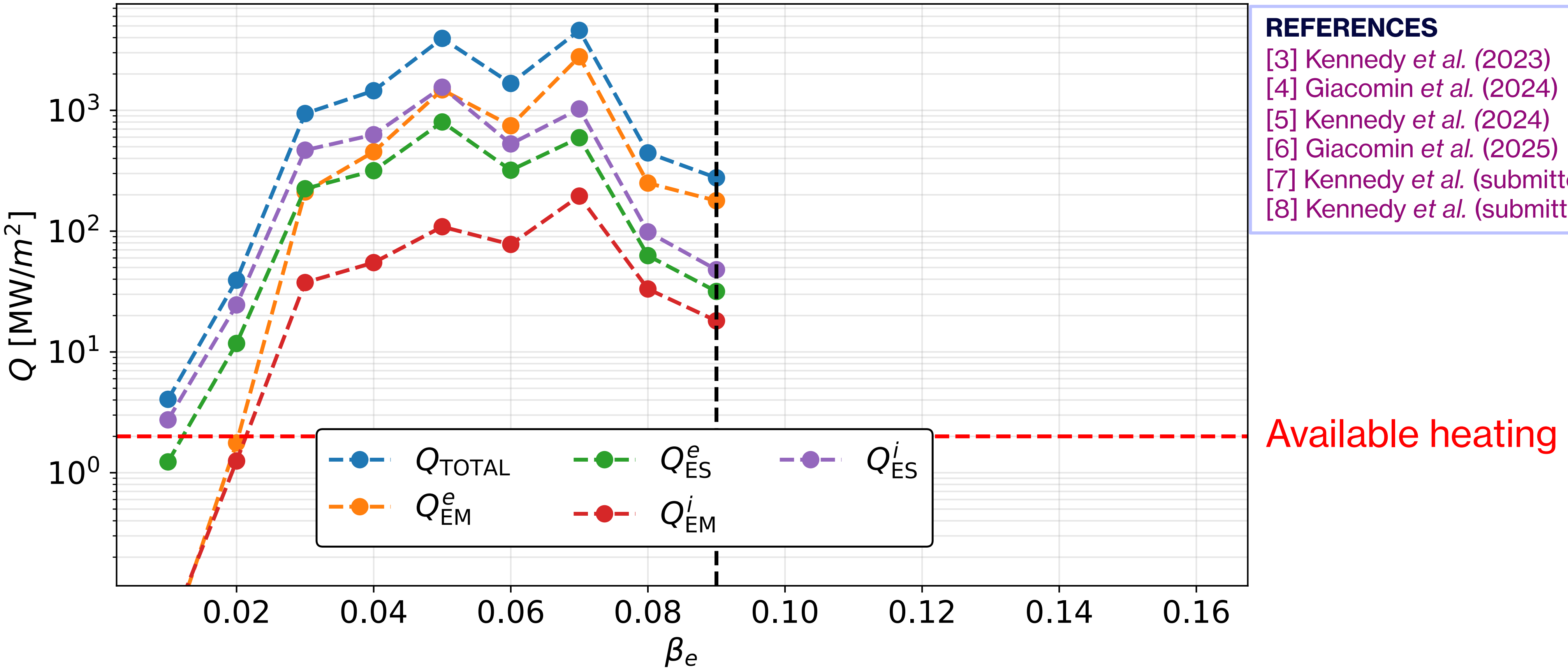

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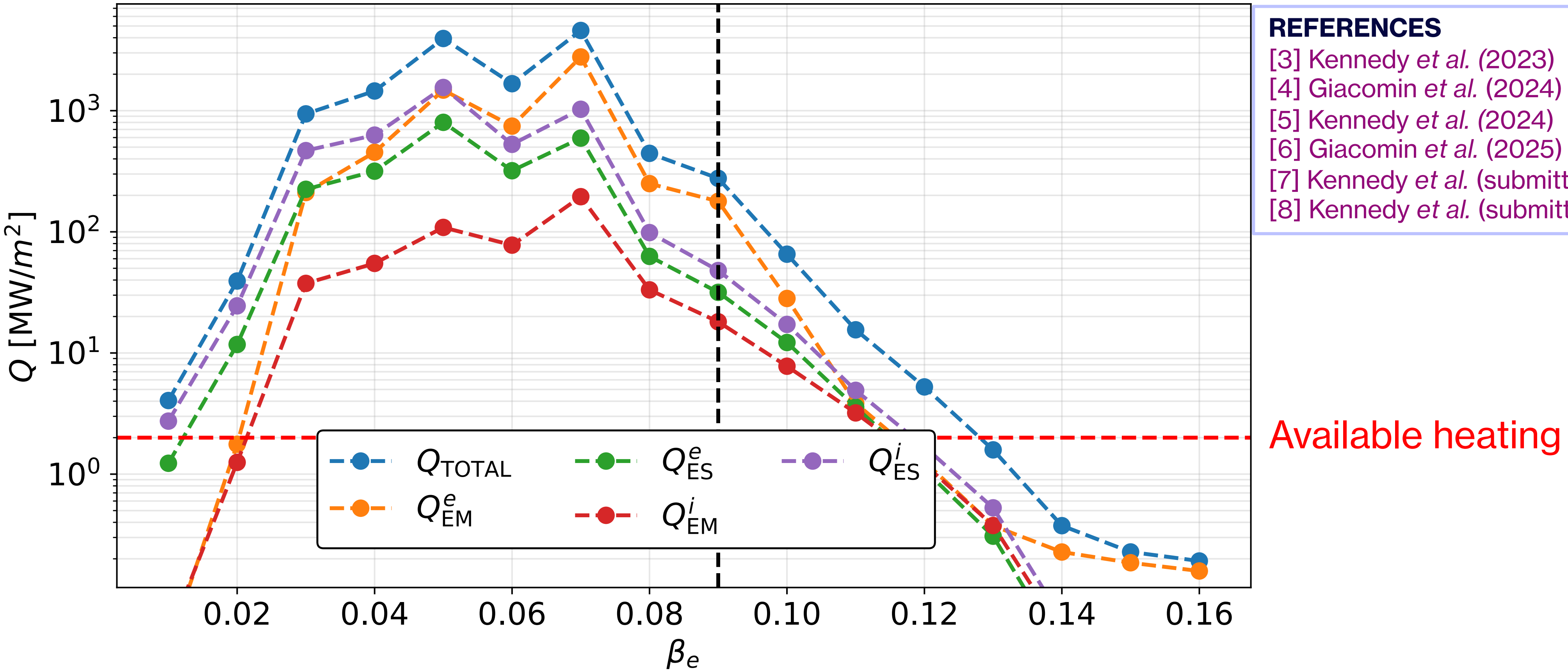

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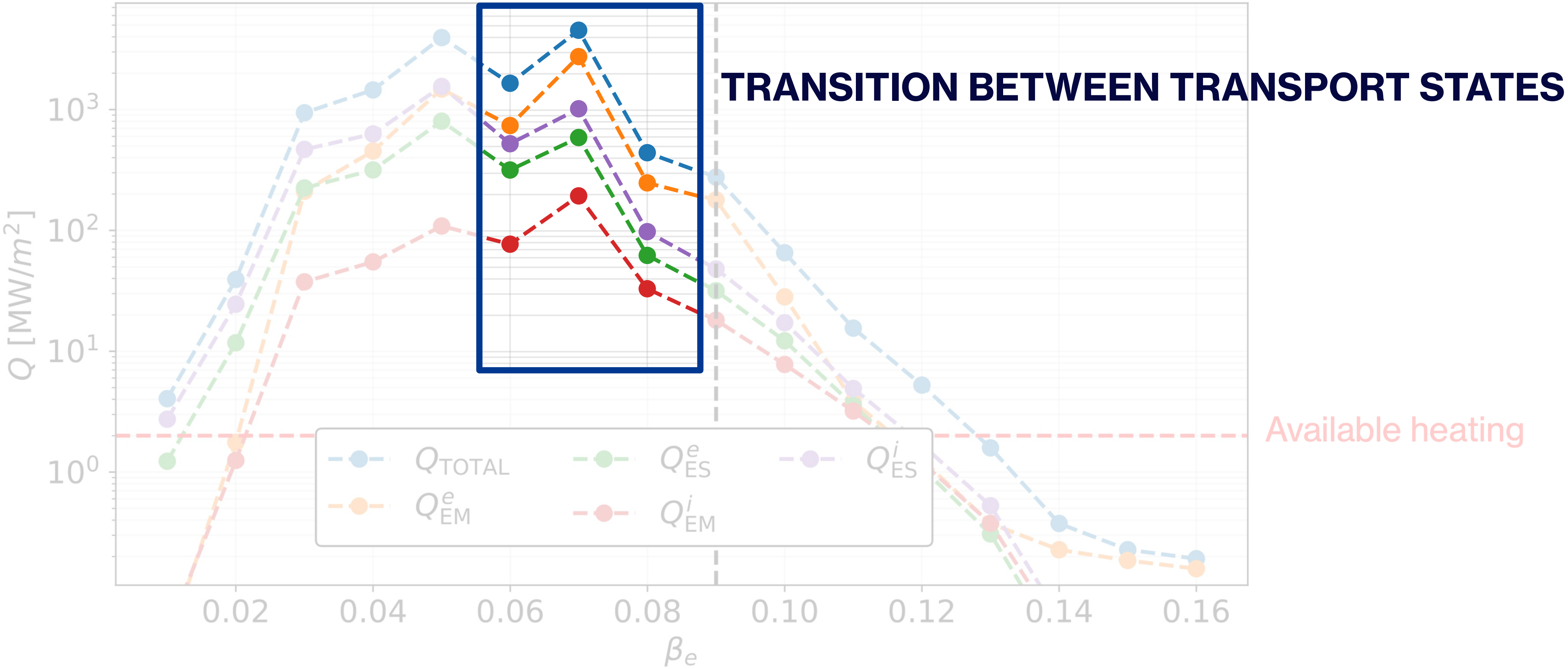

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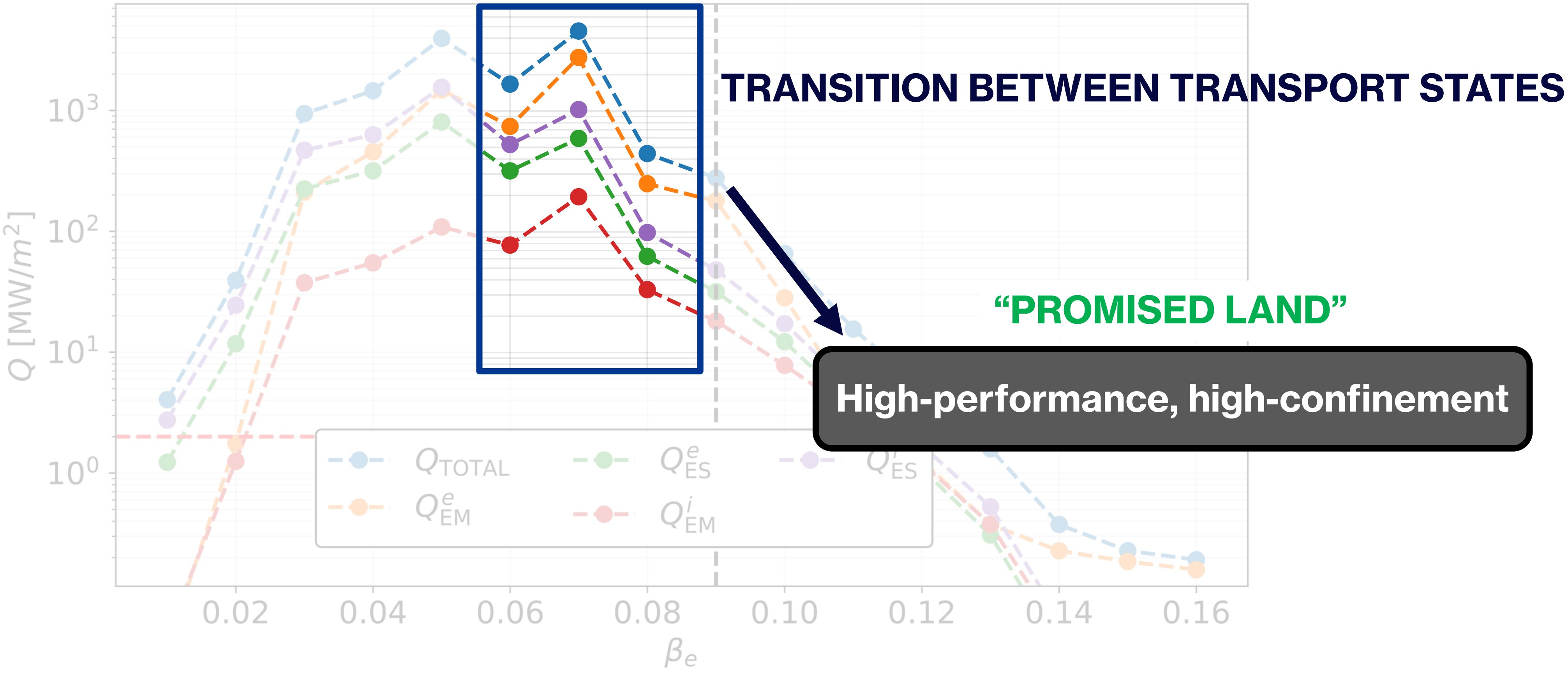

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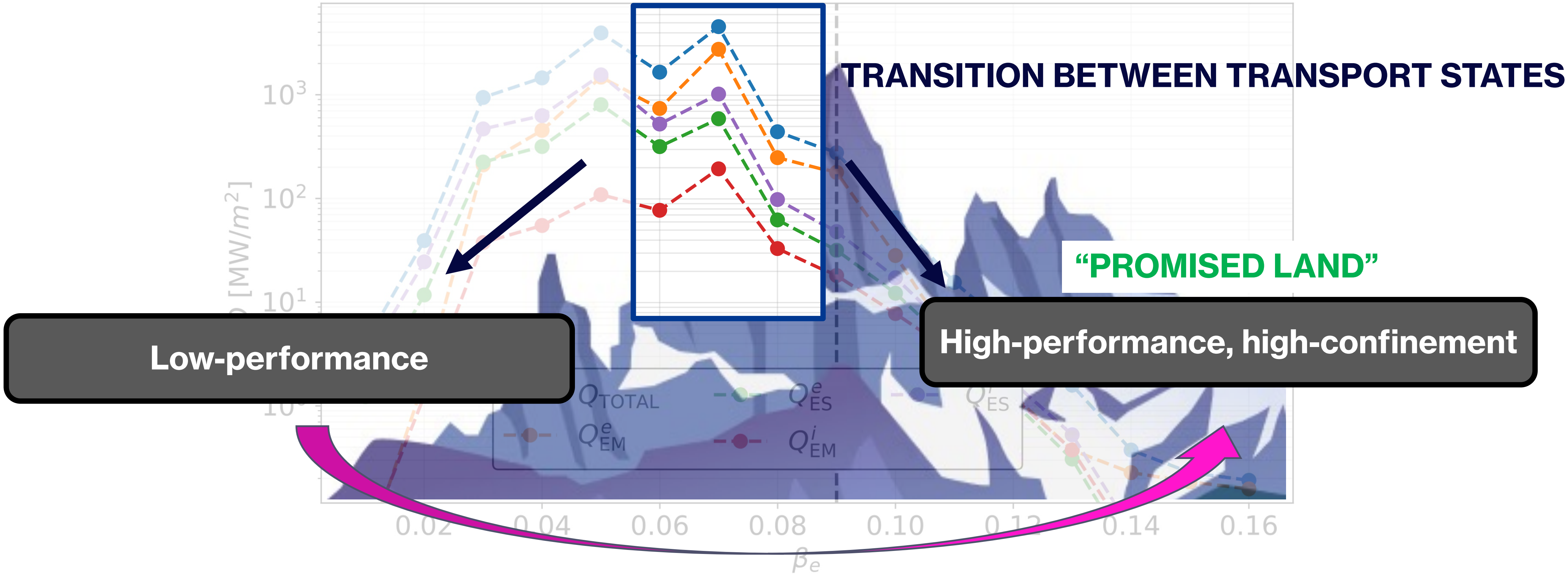

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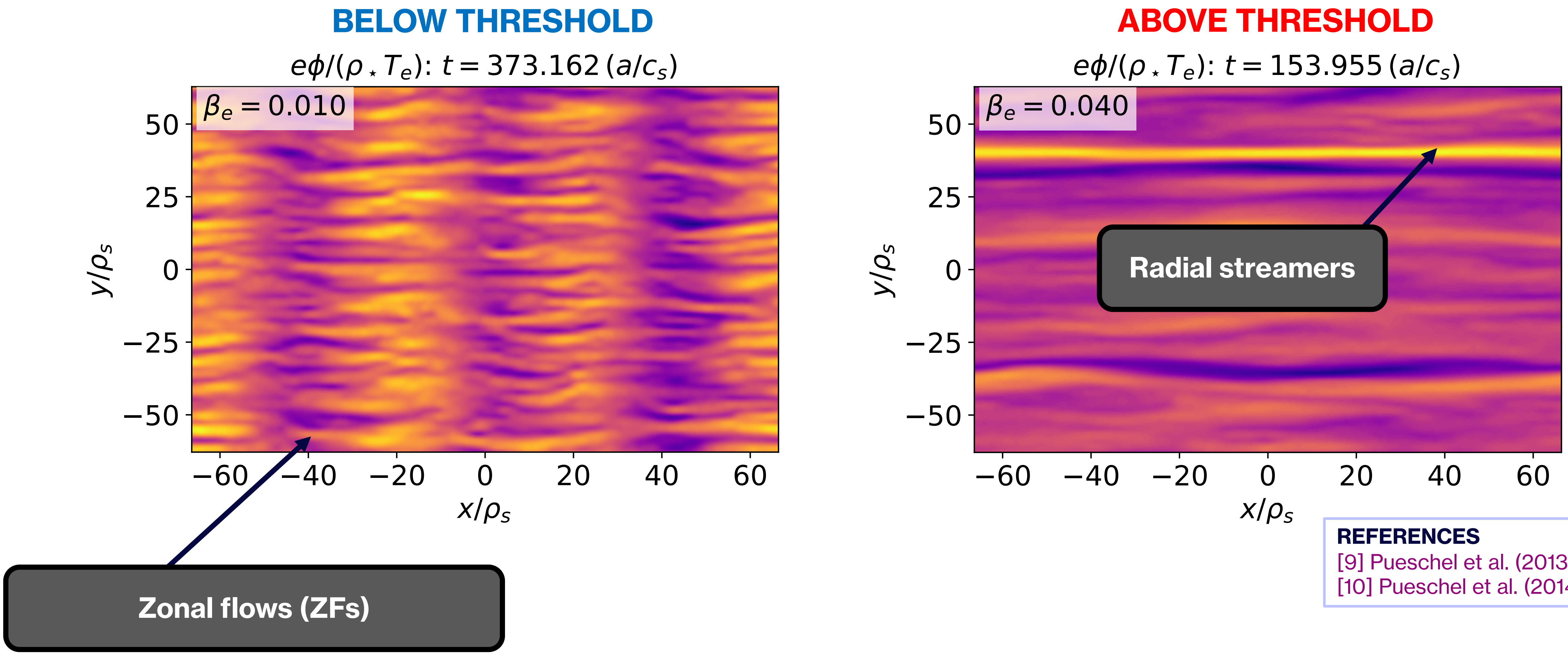
ELECTROMAGNETIC THRESHOLD (STEEP CLIFF)

- How does the turbulence change as we cross the threshold? Transition from a state of **strong zonal flows** to a state dominated by **streamers** **(NON-ZONAL TRANSITION)** [9,10].



REFERENCES
[9] Pueschel et al. (2013)
[10] Pueschel et al. (2014)

ELECTROMAGNETIC THRESHOLD (STEEP CLIFF)

- **Conjecture** that saturation may be governed by the system's ability to generate zonal flows (ZFs) strong enough to shear apart streamers driven by linear instabilities.
- **ZF** generated by **STRESSES**; driven when stresses correlated with total shear.

$$\partial_t E_{\mathrm{ZF}} = \int \mathrm{d}x\, S\, \Pi_{\mathrm{turb}} - \mathrm{dissipation} \longrightarrow \partial_t E_{\mathrm{ZF}} = \int \mathrm{d}x\, S\, \Pi_{\phi} + \int \mathrm{d}x\, S\, \Pi_{A_{\|}} - \mathrm{dissipation}$$

"Game of Stresses"

REFERENCES
[7] Kennedy *et al.* (submitted)
[11] Zhang *et al.* (in prep)
[12] Zhang *et al.* (in prep)

"Reynolds stress" (Π_{ϕ}) tends to reinforce ZFs

"Maxwell stress" ($\Pi_{A_{\|}}$) tends to act in the **opposite direction** to the zonal shear, thereby weakening ZFs.

- ZF viscosities:

$$\nu_R \equiv -\int \mathrm{d}x\, S\, \Pi_{\phi}, \quad \nu_M \equiv -\int \mathrm{d}x\, S\, \Pi_{A_{\|}}$$

SATURATION CONDITIONS

- **ROBUST ZONAL SATURATION** when $E_{ZF} \Uparrow$: i.e. $\nu < 0$
- **FEEBLE ZONAL SATURATION** when $E_{ZF} \Downarrow$: i.e. $\nu > 0$

INTUITION FOR THRESHOLD SCALING

- **Expensive diagnostic** to a **predictive tool**. Predicting the threshold?

$$R \equiv \left| \frac{\overline{\nu_M}}{\overline{\nu_R}} \right| \simeq 1$$

- **Competition** between Reynolds stress and Maxwell stress controlled by **critical-beta**.

- At **low-beta** the large Alfvén speed rapidly smooths magnetic perturbations.

- As **beta is increased**, the **Alfvén speed decreases** until the Alfvén frequency matches the MHD interchange growth rate, defining a critical β where **electromagnetic effects become important.**

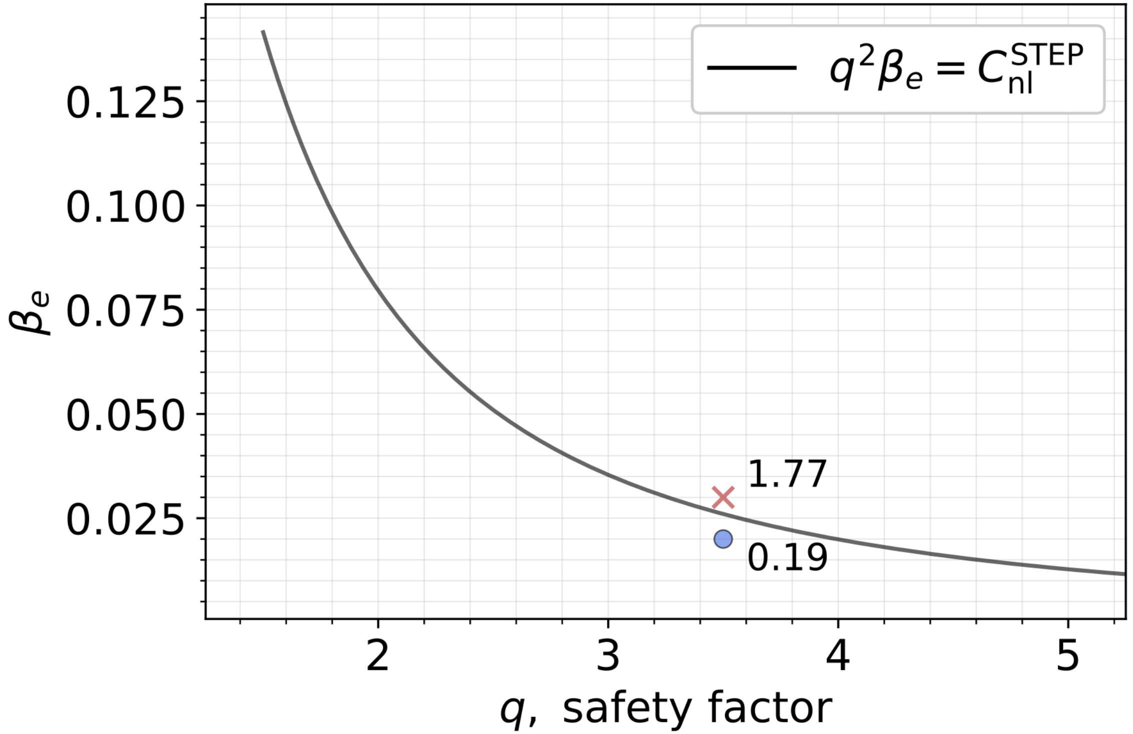
$$q^2 \beta_e^{\text{crit}} = C_{\text{nl}}(\text{geometry})$$

REFERENCES
[12] Zhang *et al.* (in prep)

- Zhang *et al* [12] find $\mathrm{R} > 1$ when $\mathrm{q}^2 \beta_\mathrm{e} > \mathrm{C_{nl}}$ from QL scaling of R.

DOES THIS WORK NUMERICALLY IN STEP?

- Does the theory work numerically? Can the electromagnetic runaway be understood?



KEY

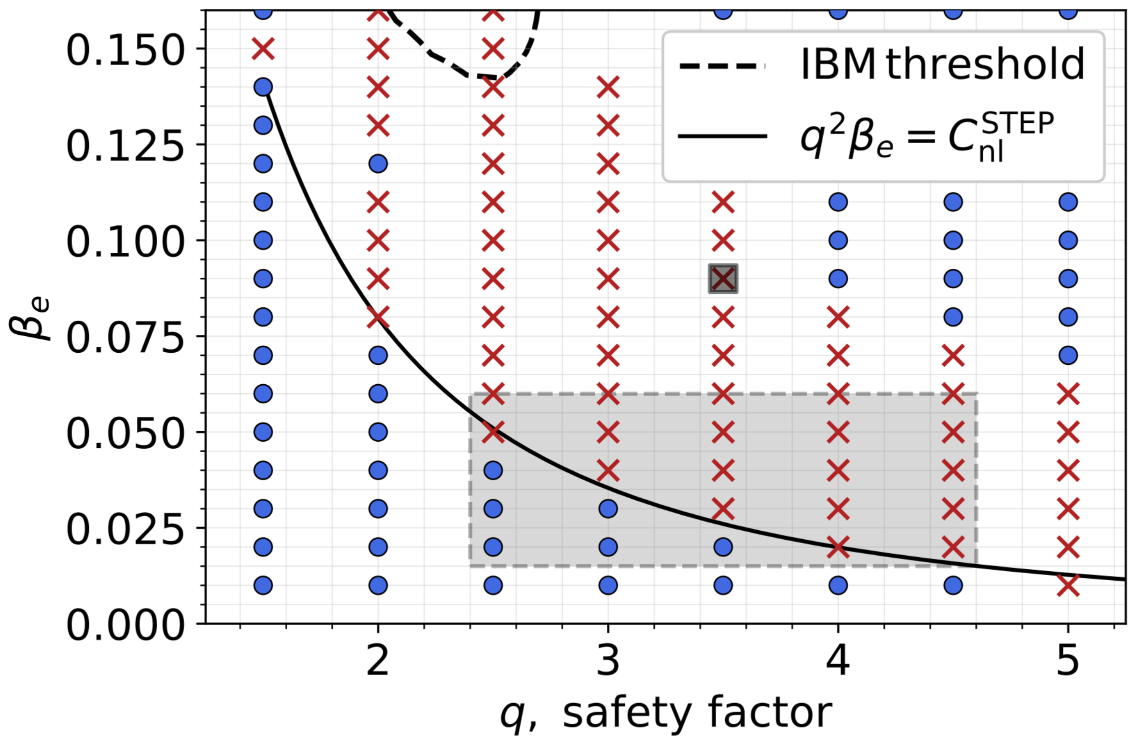
●	Simulation saturates below threshold
×	Simulation **does not** saturate below threshold
1.77	$R \equiv \lvert \nu_M / \nu_R \rvert$

Theory predictions (Kennedy *et al.*, Zhang *et al.*)

- Transition occurs when $\lvert \nu_M / \nu_R \rvert \simeq 1$
- For fixed geometry: $q^2 \beta_e^{\mathrm{crit}} = \mathrm{const.}$

DOES THIS WORK NUMERICALLY IN STEP?

- Theory holds across a large range of q and β_e in STEP.



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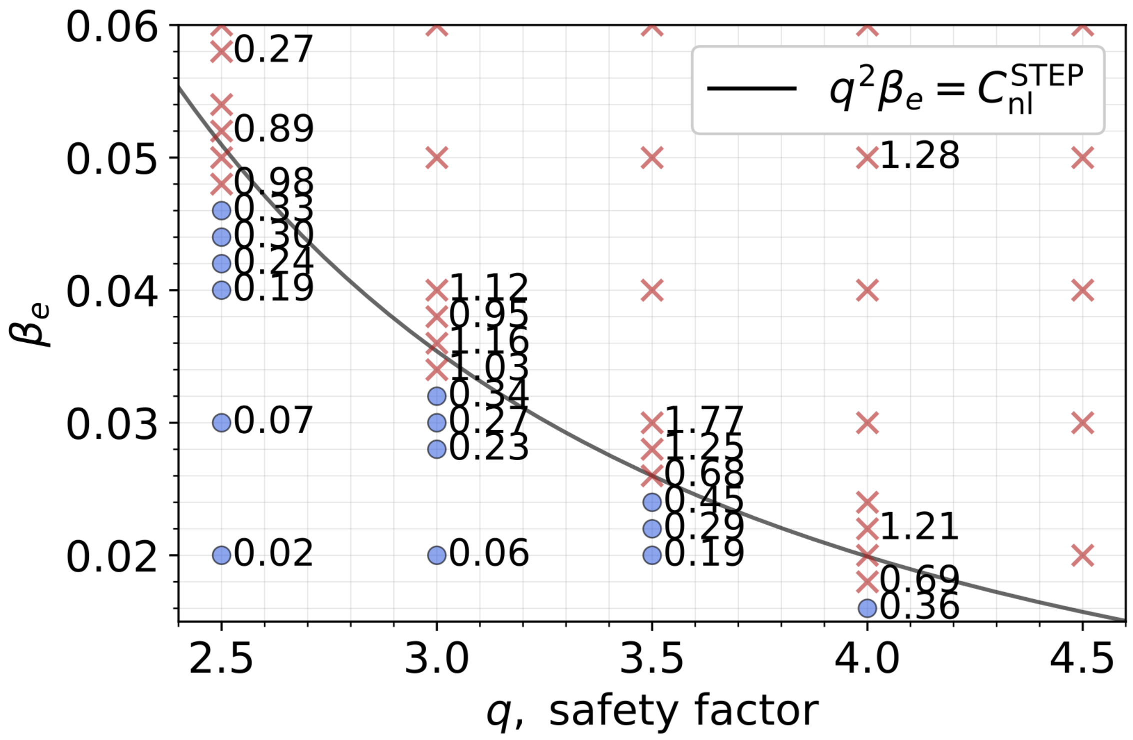

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A LIMIT ON BETA POLOIDAL?

- Criteria in Zhang *et al.* [12] is a statement **about local gyrokinetics** in **fixed geometry.**

$$q^2 \beta_e^{\mathrm{crit}} = C_{\mathrm{nl}}$$

- Con **poloidal beta**; characterises the pressure-induced distortion of poloidal magnetic field lines [7] .

$$q^2 \beta_e \sim \beta_{\mathrm{pol}} \left(\frac{a}{R}\right)^2$$

- Related to current continuity; dynamical role of Alfvén waves.

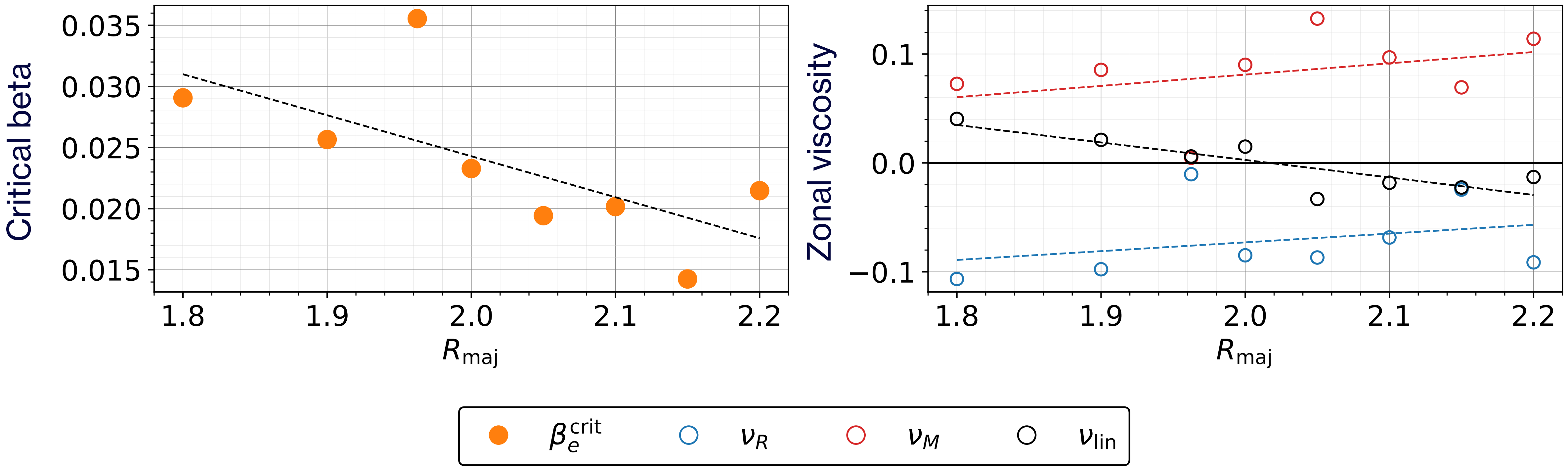
$$\nabla \cdot \mathbf{J} = \nabla \cdot \mathbf{J}_{||} + \nabla \cdot \mathbf{J}_{\perp} = 0$$

$$\frac{\nabla \cdot \mathbf{J}_{\perp}}{\nabla \cdot \mathbf{J}_{||}} \propto q^2 \beta_e \left(\frac{R}{a}\right)^2$$

REFERENCES
[7] Kennedy *et al.* (submitted)
[12] Zhang *et al.* (in prep)

A LIMIT ON BETA POLOIDAL?

- Changes to β_e, the shaping parameter $(R/a)^2$, or q^2, all have equivalent physical impact.
- Critical beta scales with major radius at fixed q.



- Not specific to spherical tokamaks.
- Scaling suggests that this physics is easier to access in conventional-aspect-ratio tokamaks.

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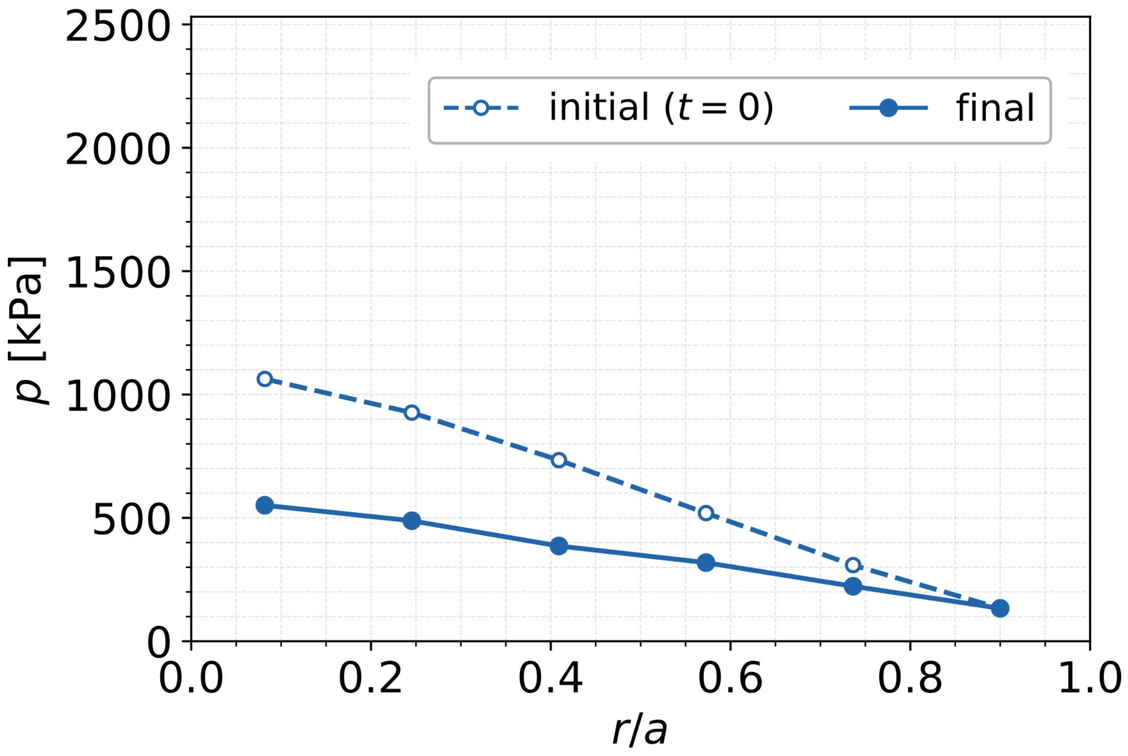
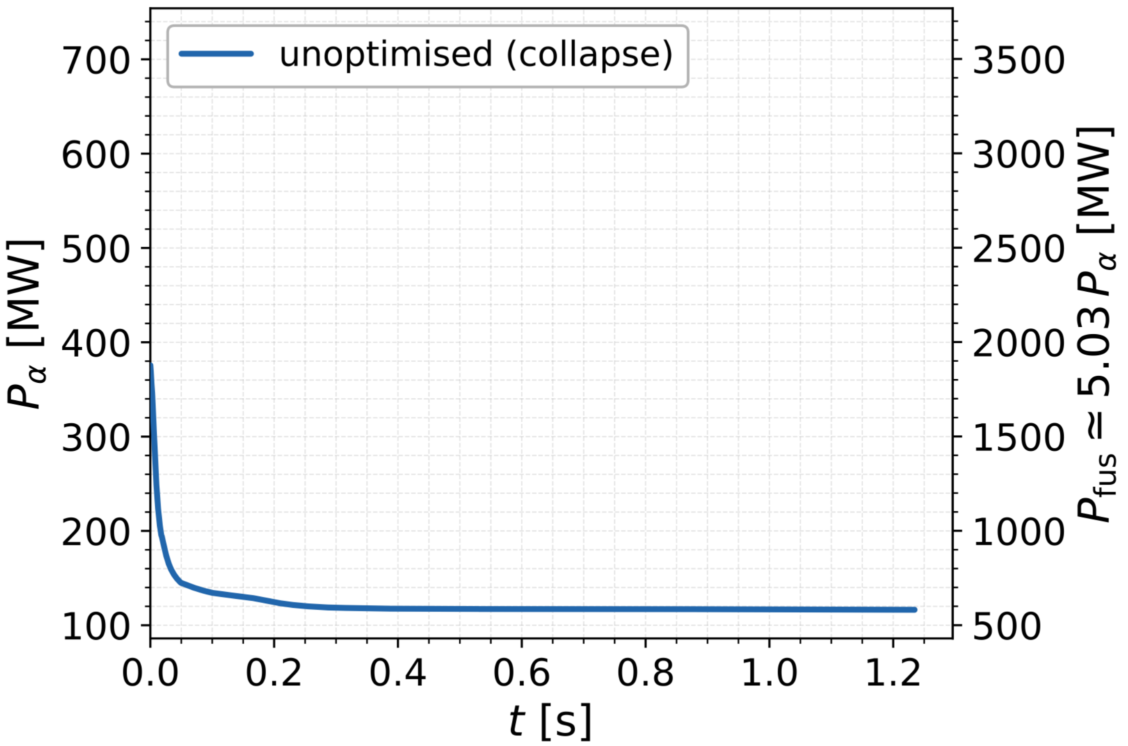
FLUX–DRIVEN TRANSPORT IN SPP1

- Given available sources and sinks, what profiles emerge?
- Giacomin *et al* [6] quasilinear model enables flux-driven simulations using the T3D code.

REFERENCES
[6] Giacomin *et al.* (2025)





- In the absence of equilibrium flows, large electromagnetic transport causes the profiles to collapse!

PROMISED LAND AND SECOND STABILITY

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** [3,4,5,6,7,8].
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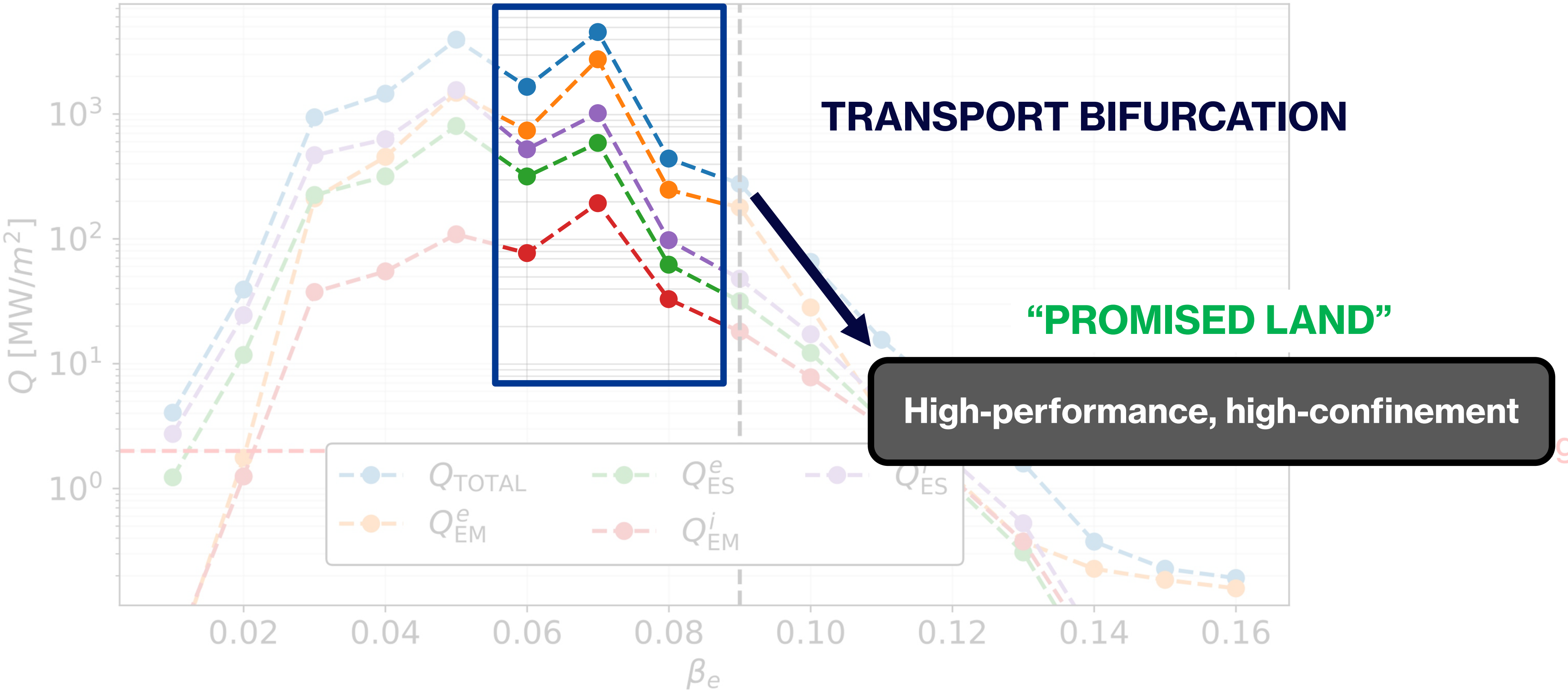
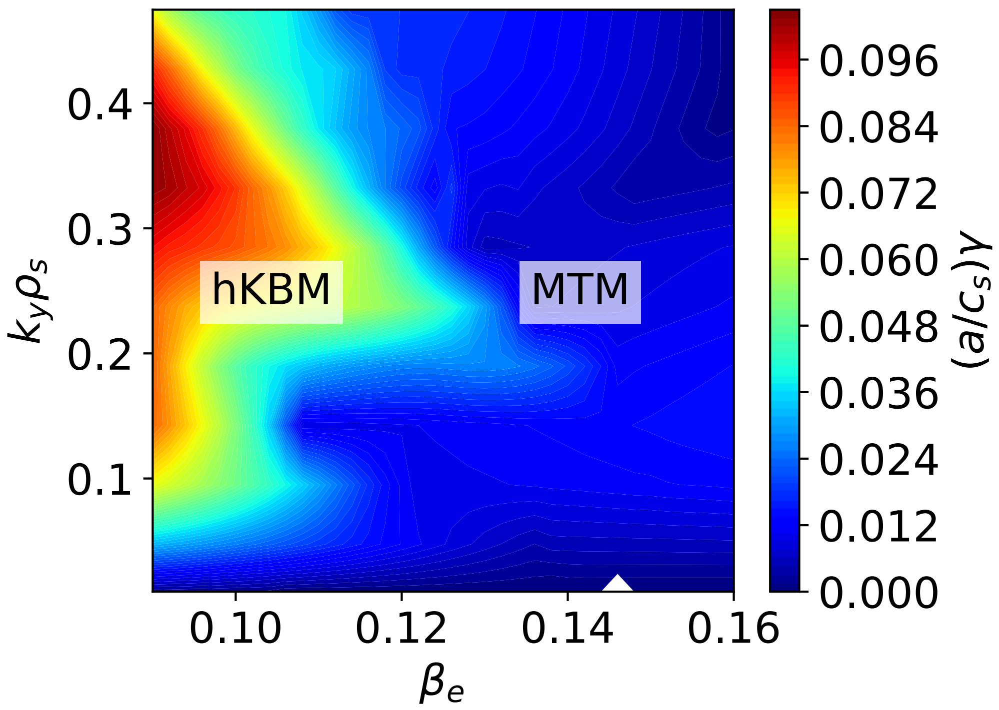
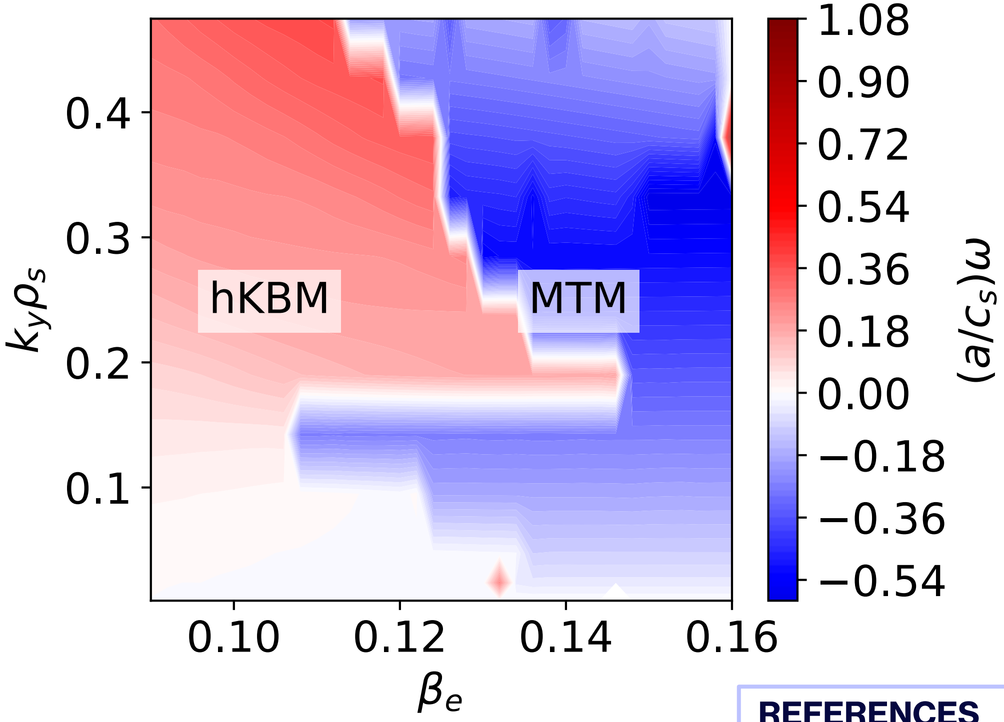


- **No** (equilibrium) **flow shear.** No external momentum sources (only small intrinsic flows) in STEP.

SECOND TRANSITION IS LINEAR PHYSICS

- **Second transition** is **linear physics**; stabilisation of KBM-like modes.
- β' stabilisation; gyrokinetic **second stability**.



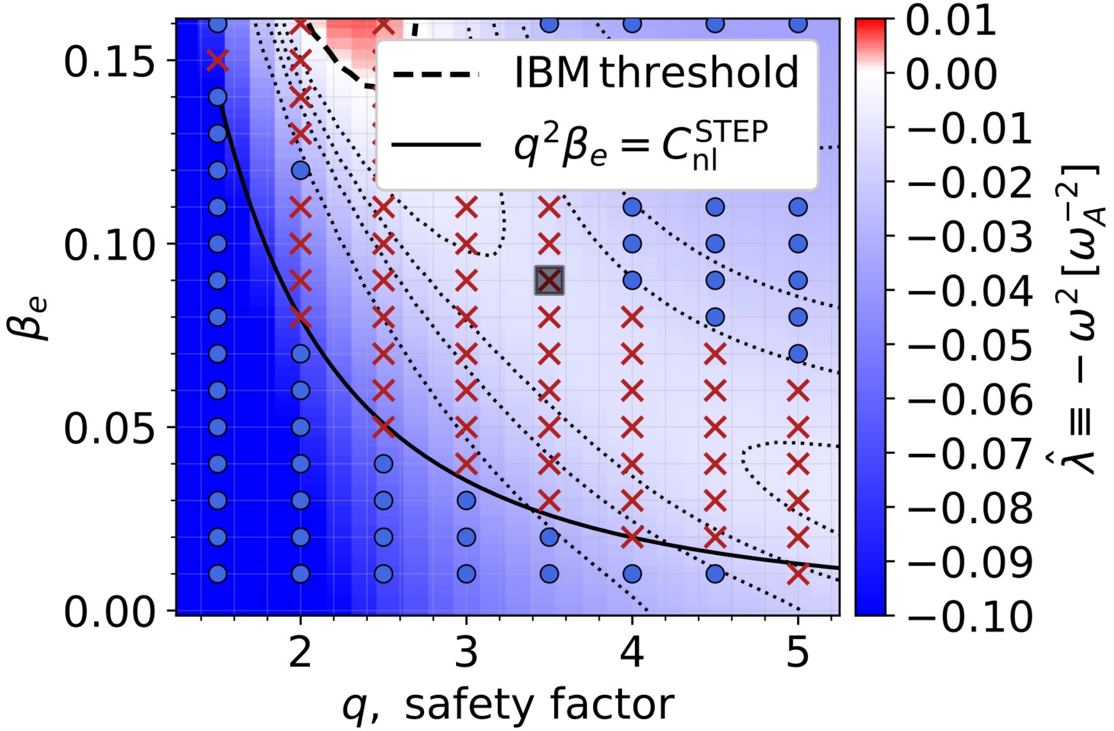


REFERENCES
[13] Bourdelle *et al.* (2003)

- Local shear decreases. Reduced parallel drive in bad curvature region.
- Field line tension increases and stabilises KBM-like modes.

RELATIONSHIP TO IDEAL BALLOONING

- Linear stability of KBM-like modes **and** non-zonal transition both track **Ideal Ballooning Mode stability**.



KEY

■ (red)	$\hat{\lambda} > 0 \longrightarrow$ IBM unstable $\longrightarrow$ growth rate of unstable IBM
■ (blue)	$\hat{\lambda} < 0 \longrightarrow$ IBM stable $\longrightarrow$ real frequency of shear Alfvén wave

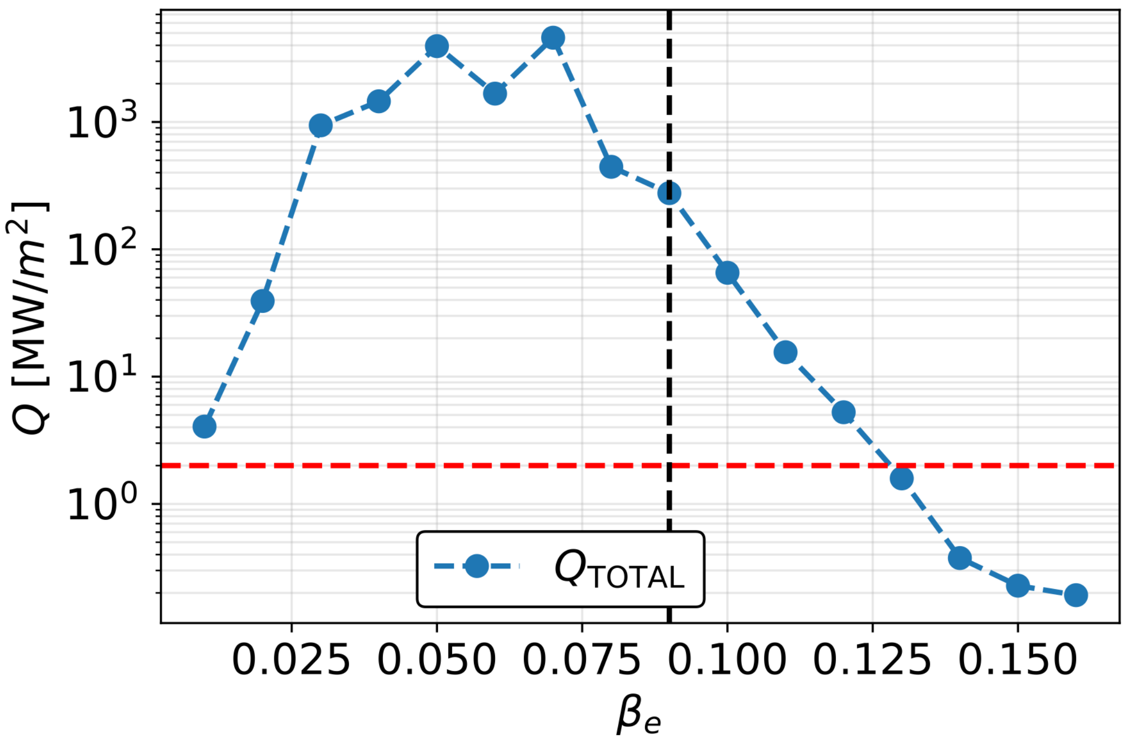
FLUX–DRIVEN TRANSPORT IN SECOND STABILITY

- **Heat flux is a nonlinear function of the driving gradients.**
- For a given flux there is more than one possible gradient in in steady state.
- Evolution of the temperature profile is diffusive.

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x} Q_{\mathrm{turb}}, \quad Q_{\mathrm{turb}} = Q_{\mathrm{turb}}(\nabla T)$$

- In second stability the flux **decreases** with **increasing** pressure gradient.
- This will **steepen** profiles rather than flatten them.

Idea to try moving as much of the plasma into this second-stable region as possible.

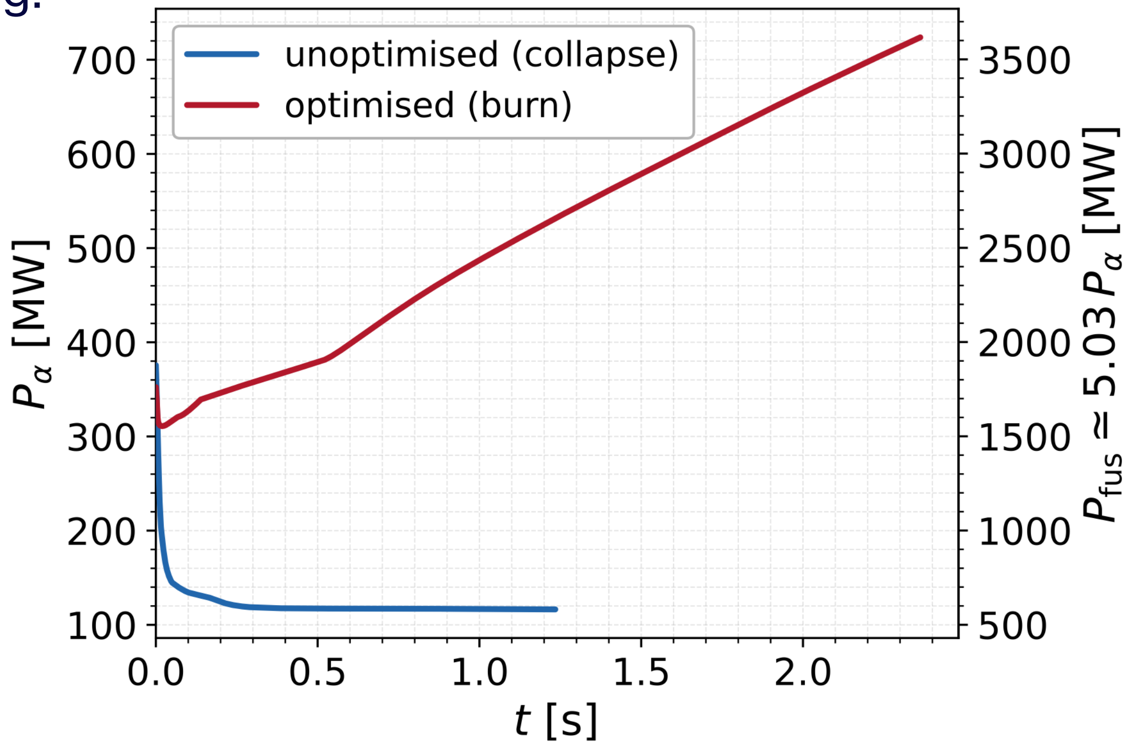


- **Ideal Ballooning Mode as proxy for onset of large fluxes**
- **Optimisation of $q, \hat{s}$ profile to access second stable region.**

FLUX-DRIVEN TRANSPORT IN SECOND STABILITY

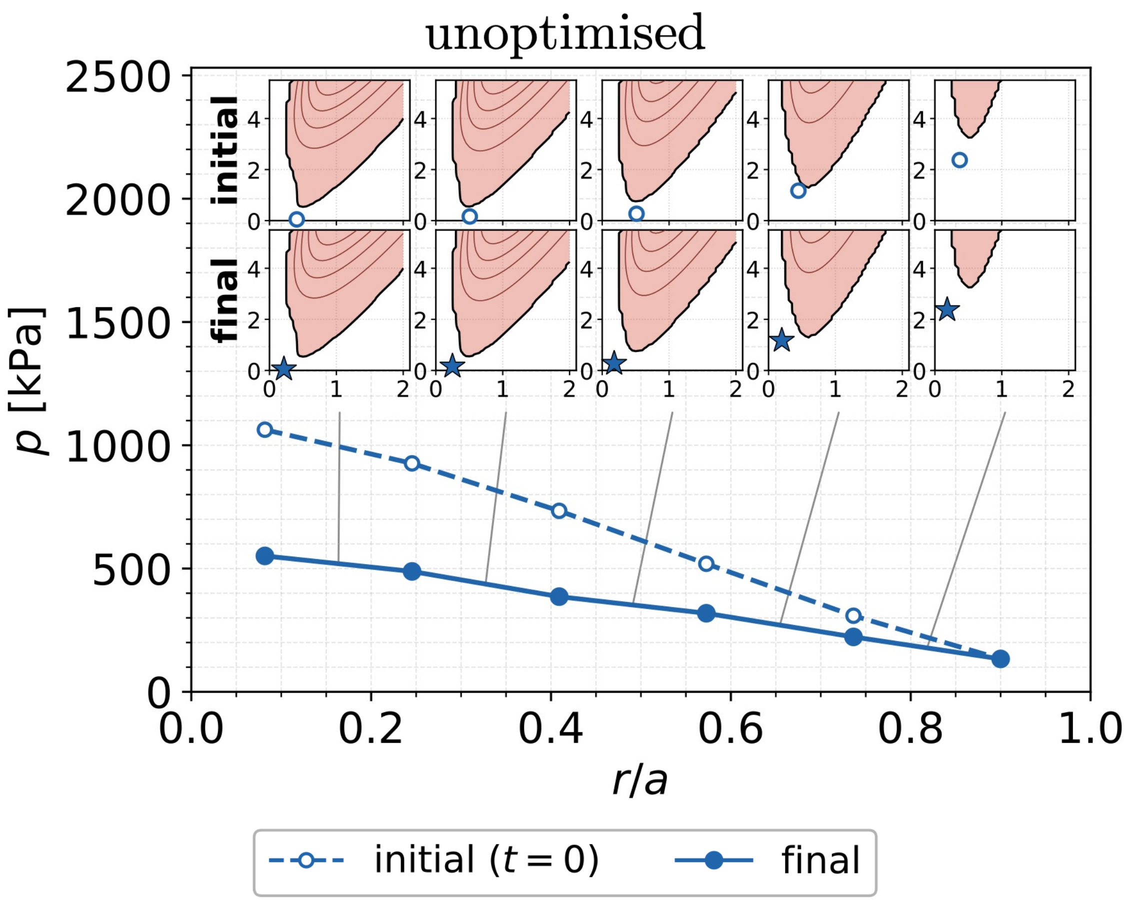
- We can use these ideas to optimise the STEP design. Optimising the q profile to move as much of the plasma as possible into second stability.

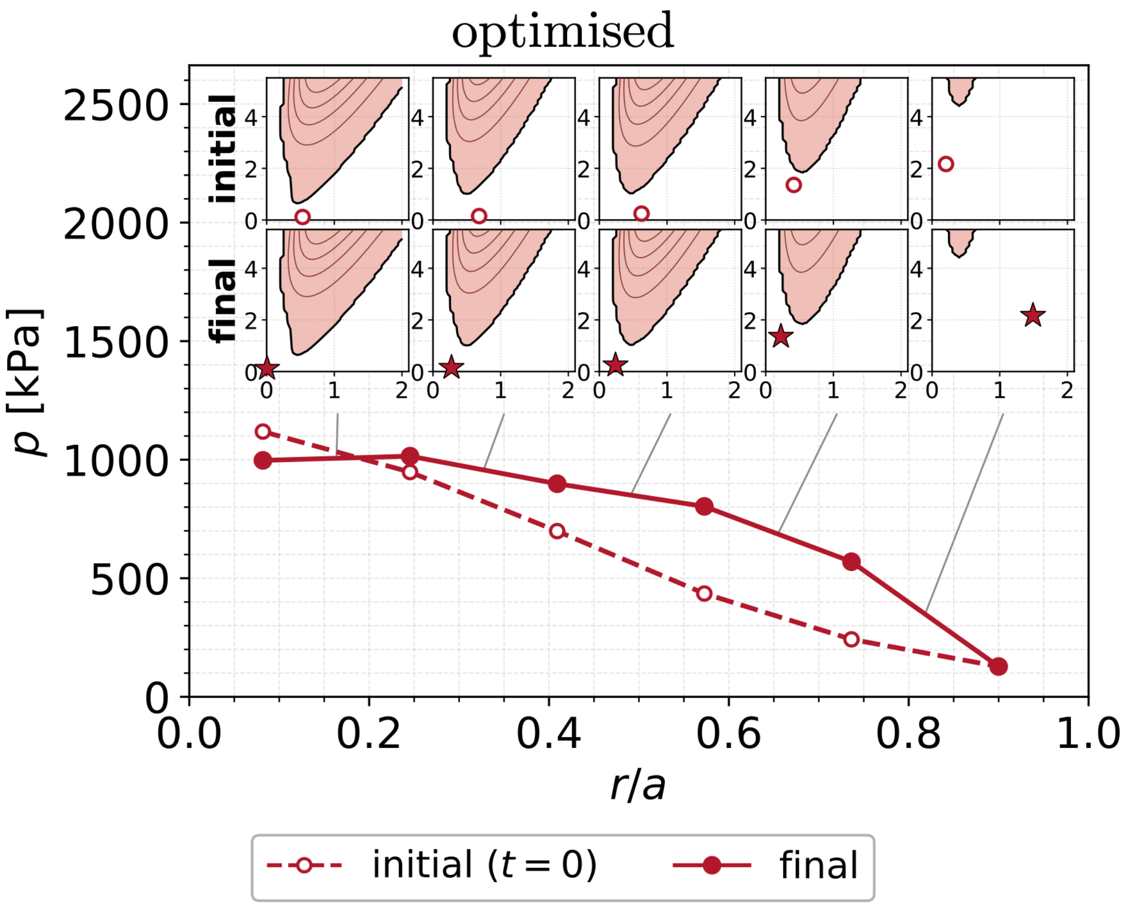
- Initial results are promising!



FLUX–DRIVEN TRANSPORT IN SECOND STABILITY

- Access to second stability and formation of steep gradient regions is crucial!





- Access to these initial conditions remains a challenge

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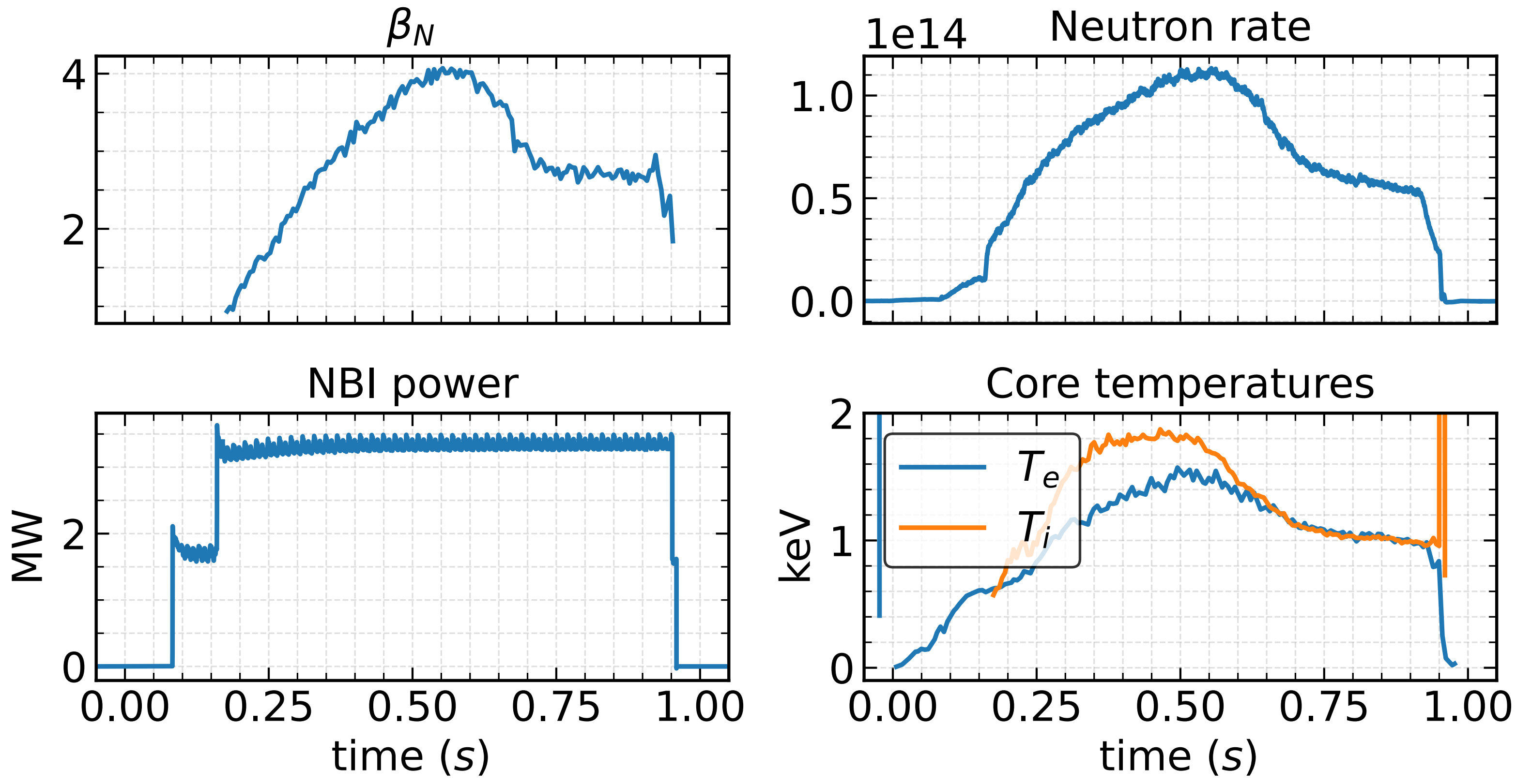
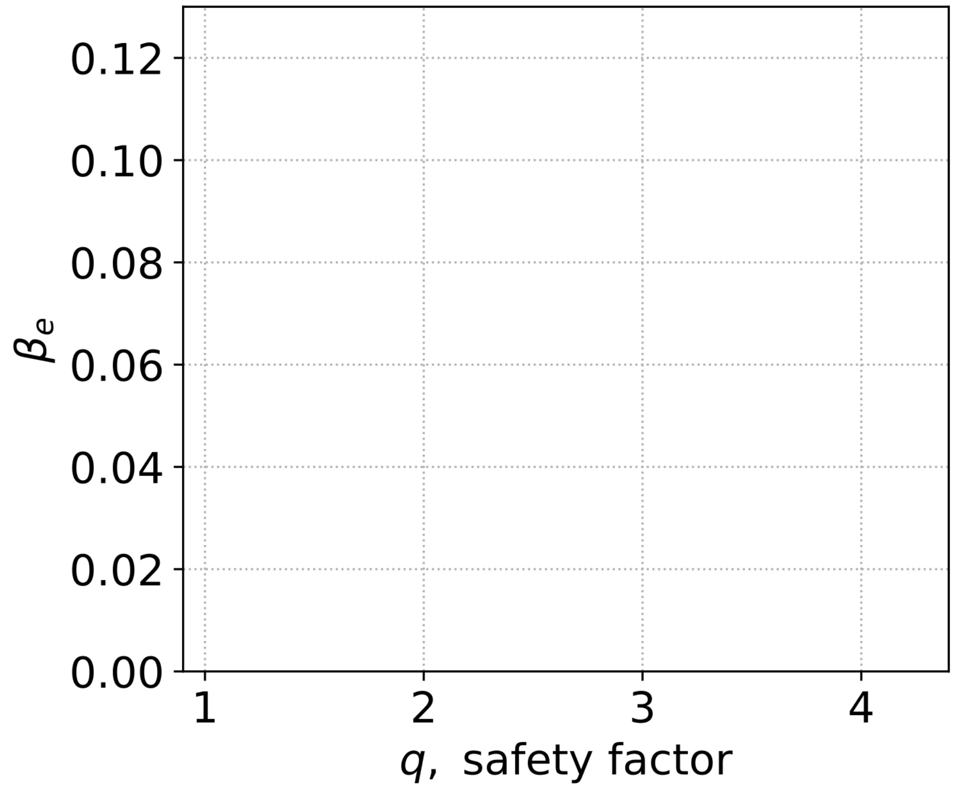
MAST–U #48657

- MAST (Mega Ampere Spherical Tokamak) upgrade is the UK flagship facility for studying fusion plasmas.
- **Discharge #48657** two-beam, high-powered H-mode scenario.
- Achieved peak $\beta_{\mathrm{N}} \sim 4$ (one of the highest achieved on MAST-U)



WHERE HAS MAST-U BEEN?

- Some MAST-U anomalous transport in L-mode explained by electron-scale turbulence [14].
- Ion scale transport needed for consistency with TRANSP modelling of high-performance H-mode.
- Range of q and β_e values accessed during a single MAST-U high-performance discharge **(#48657).**



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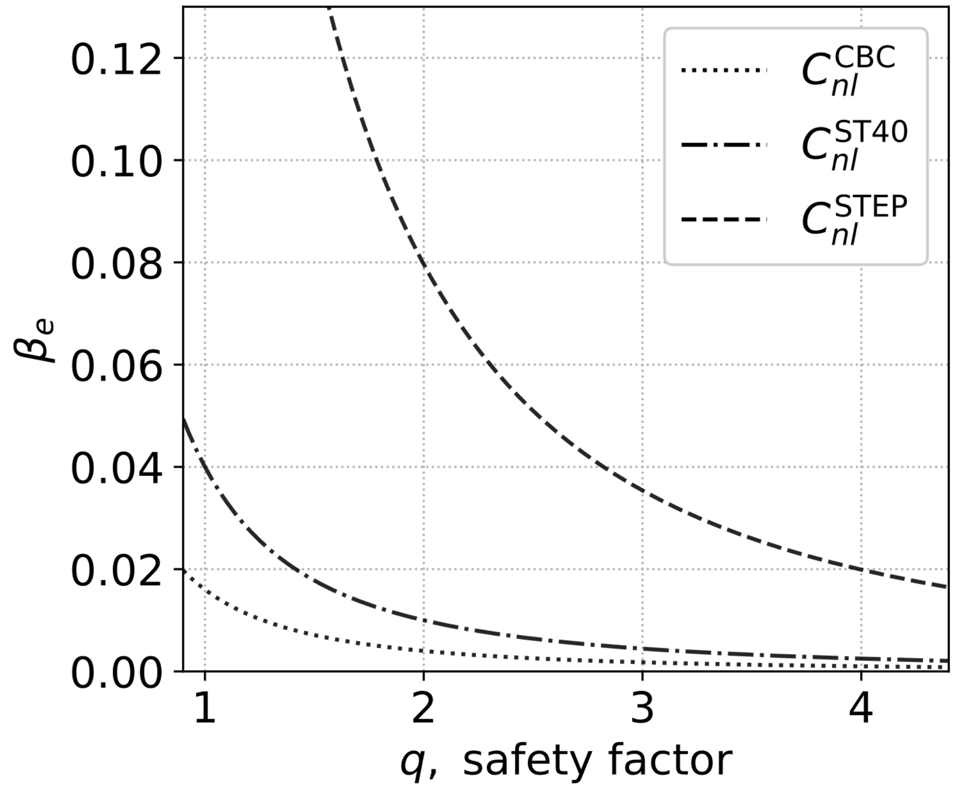

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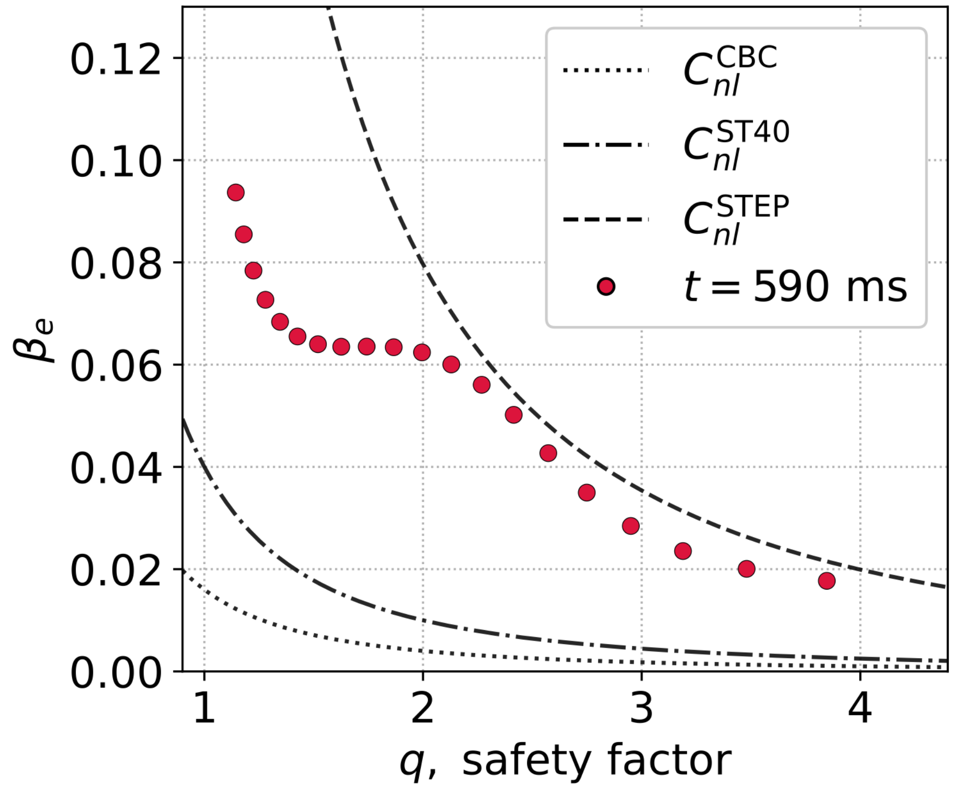

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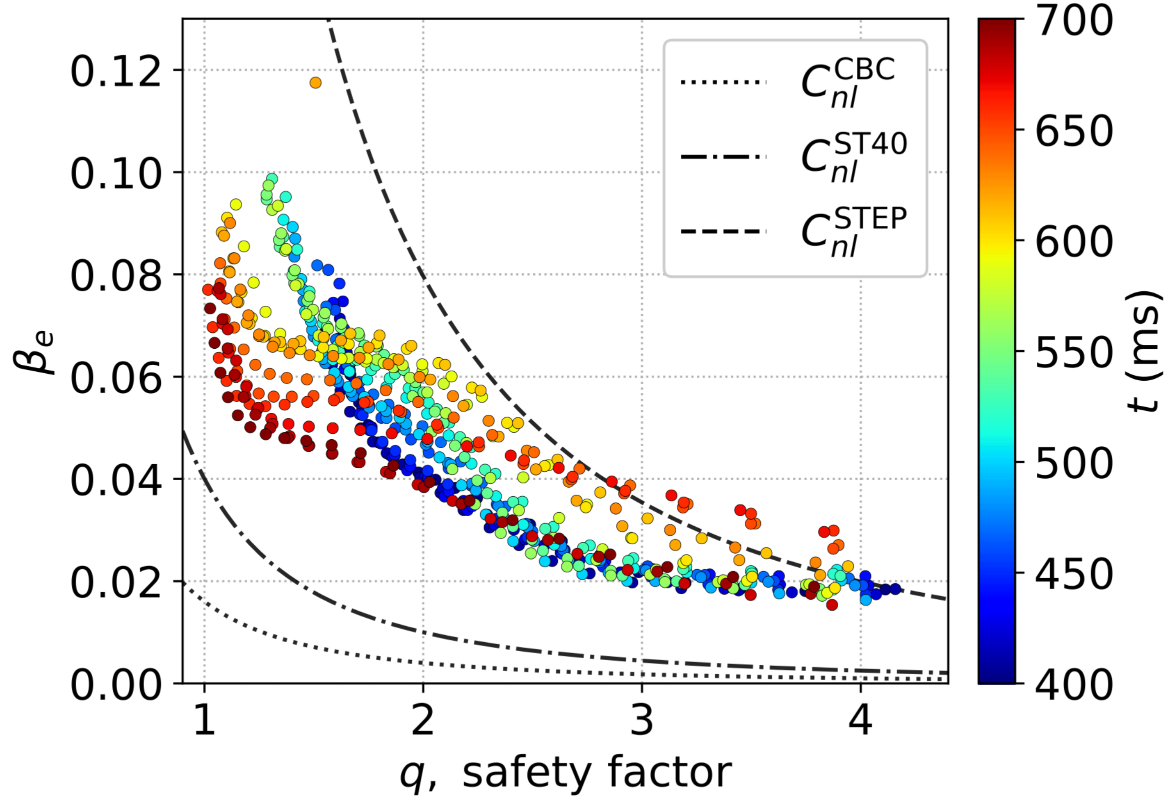
- Ion scale transport needed for consistency with TRANSP modelling of high-performance H-mode.
- Range of q and β_e values accessed during a single MAST-U high-performance discharge **(#48657).**

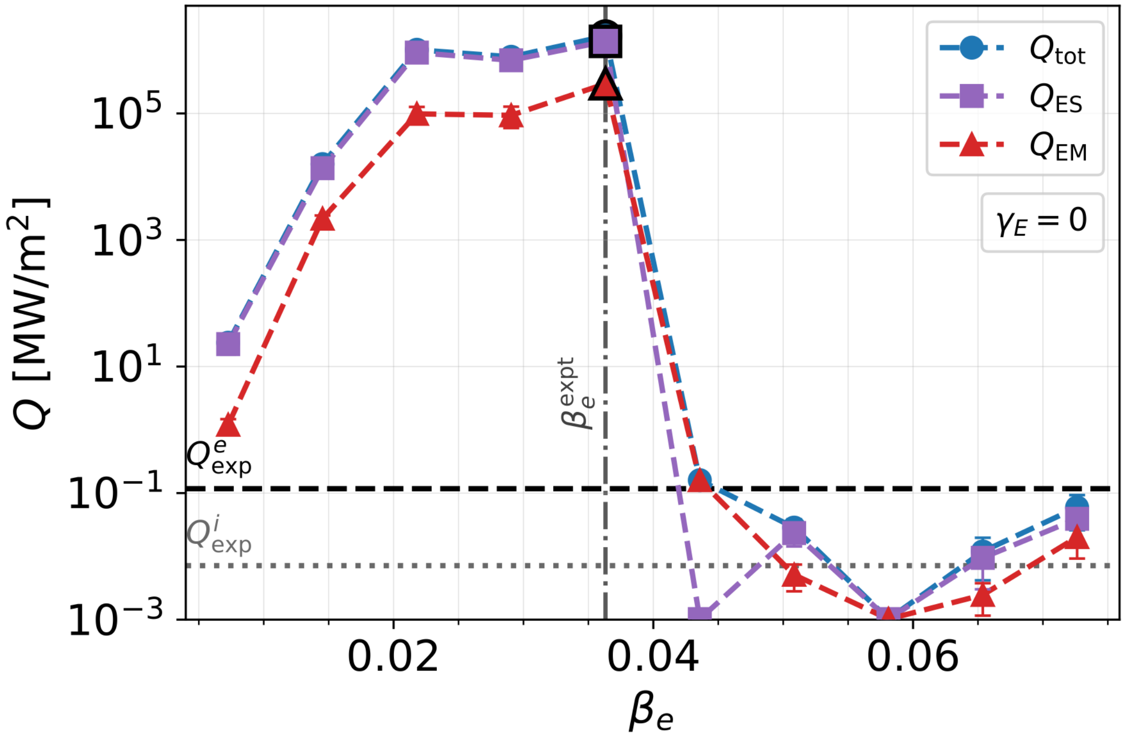


REFERENCES

[18] Patel *et al.* (in prep)

EM TURBULENCE IN MAST–U

- Preliminary gyrokinetic analysis of turbulence close to peak performance in MAST-U.
- Initial results suggest MAST-U is operating close to the onset of large EM turbulence.



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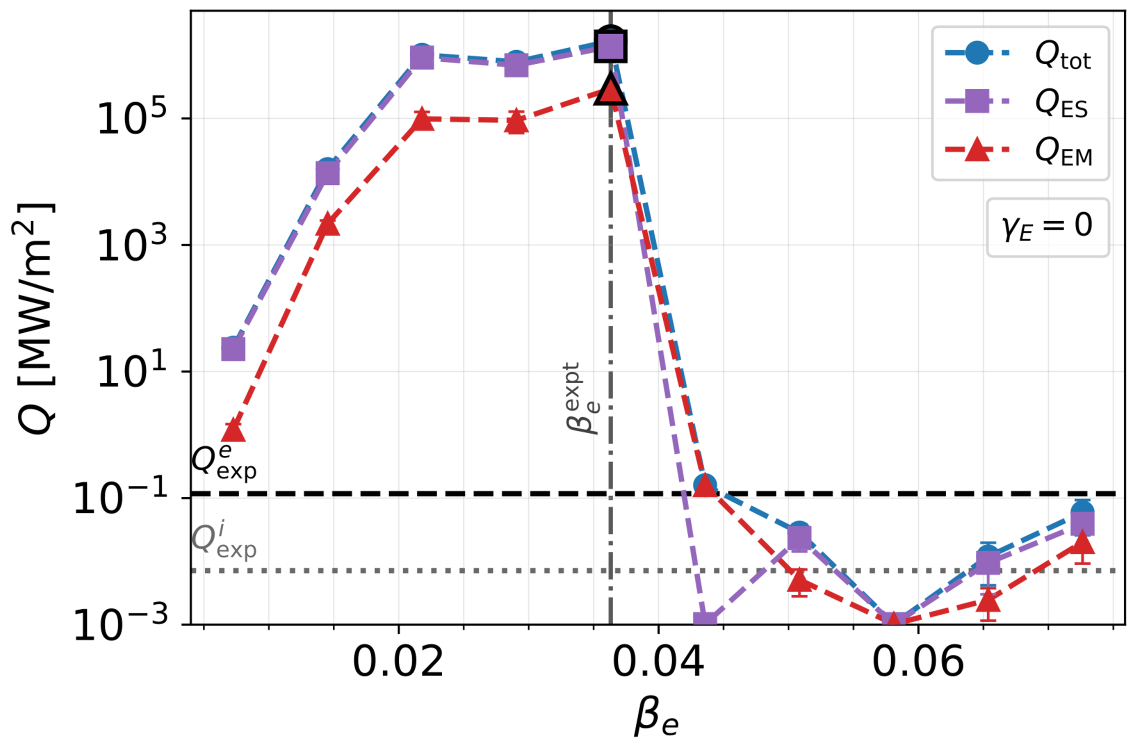

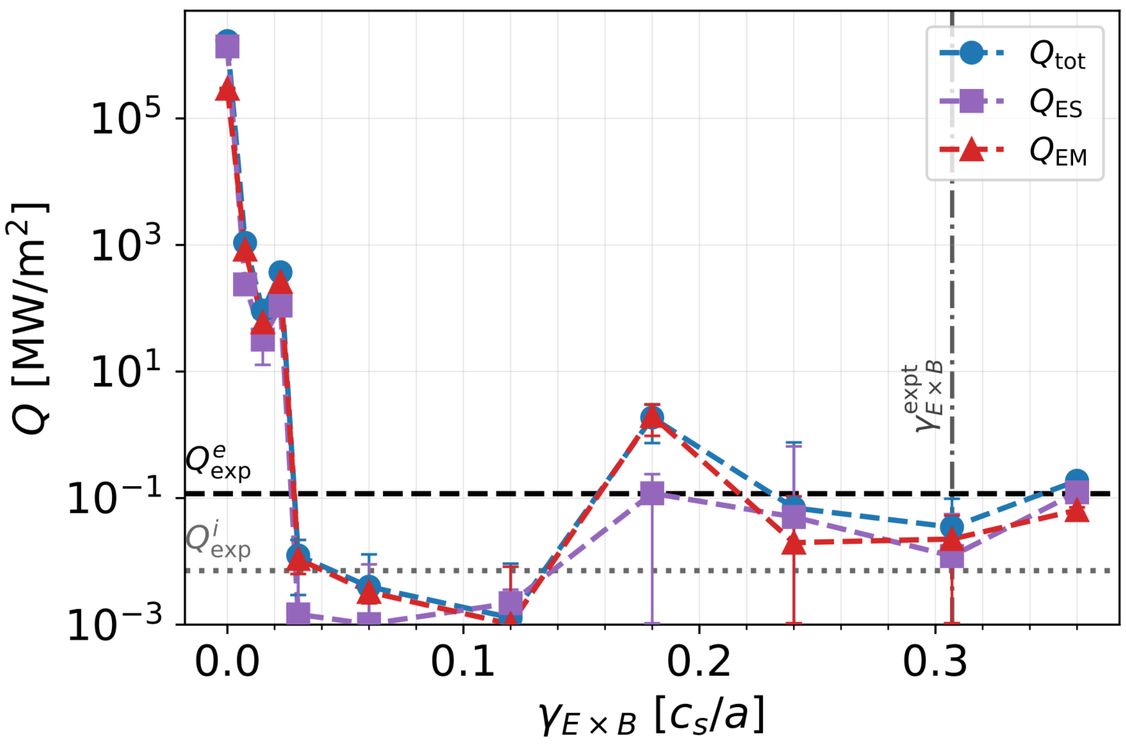

- Very strongly regulated by equilibrium flow shear (external torque from neutral beams).

OVERVIEW

THE STEP PLASMA CHALLENGE

ELECTROMAGNETIC TURBULENCE AT HIGH BETA

GETTING TO HIGH CONFINEMENT

PROSPECTS FOR TESTING THESE IDEAS IN EXPERIMENTS

CONCLUSIONS

CONCLUSIONS

- Local gyrokinetic simulations of STEP-like plasmas show a transition from low- to high-flux states when β_{pol} exceeds a threshold governed by the interplay of Reynolds and Maxwell stresses.

- Can we test whether experiments are indeed constrained by this threshold condition on β_{pol}. Impact of momentum injection on any threshold?

- At sufficiently high betaprime, the system can re-saturate and access a second-stable confinement state, with the ideal ballooning threshold serving as a useful proxy.

- Transport in plasma scenarios highly sensitive to initial conditions, and must find robust routes to access high performance

- Present-day experiments can already access STEP-relevant $(\mathrm{q}, \beta_{\mathrm{e}})$ regimes, but seemingly only in the presence of γ_{E}. Loss of sufficient shear is generally followed be a severe loss of performance in high $\mathrm{q}^2\beta_{\mathrm{e}}$.

- STEP's weak external torque may mean its operational space is limited in β_{pol} unless sufficient shear – via zonal flows, intrinsic rotation, or external generation – decorrelates streamer-like structures and restores confinement.