STEP

A TALE OF TWO (VISCO)CITIES

ELECTROMAGNETIC TURBULENCE AND TRANSPORT BIFURCATIONS: IMPLICATIONS FOR NEXT-GENERATION FUSION POWER PLANTS

DANIEL KENNEDY

Senior Turbulence and Transport Physicist

UK Atomic Energy Authority

STEP TURBULENCE COLLABORATORS

D. Kennedy, C.M. Roach, A. Bokshi, F.J. Casson, H.G. Dudding, P.G. Ivanov, B.S. Patel, E. Tholerus, H. Wilson

UK Atomic Energy Authority, Culham Campus, Abingdon, OX14 3DB, United Kingdom

D. Dickinson

York Plasma Institute, University of York, York, YO10 5DD, United Kingdom

Y. Zhang, A.A. Schekochihin, M. Barnes, R. Dutta

Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, OX1 3PU, United Kingdom

T. Adkins

Department of Physics, University of Otago, Dunedin, 9016, New Zealand

G. Merlo, F. Sheffield, T. Görler

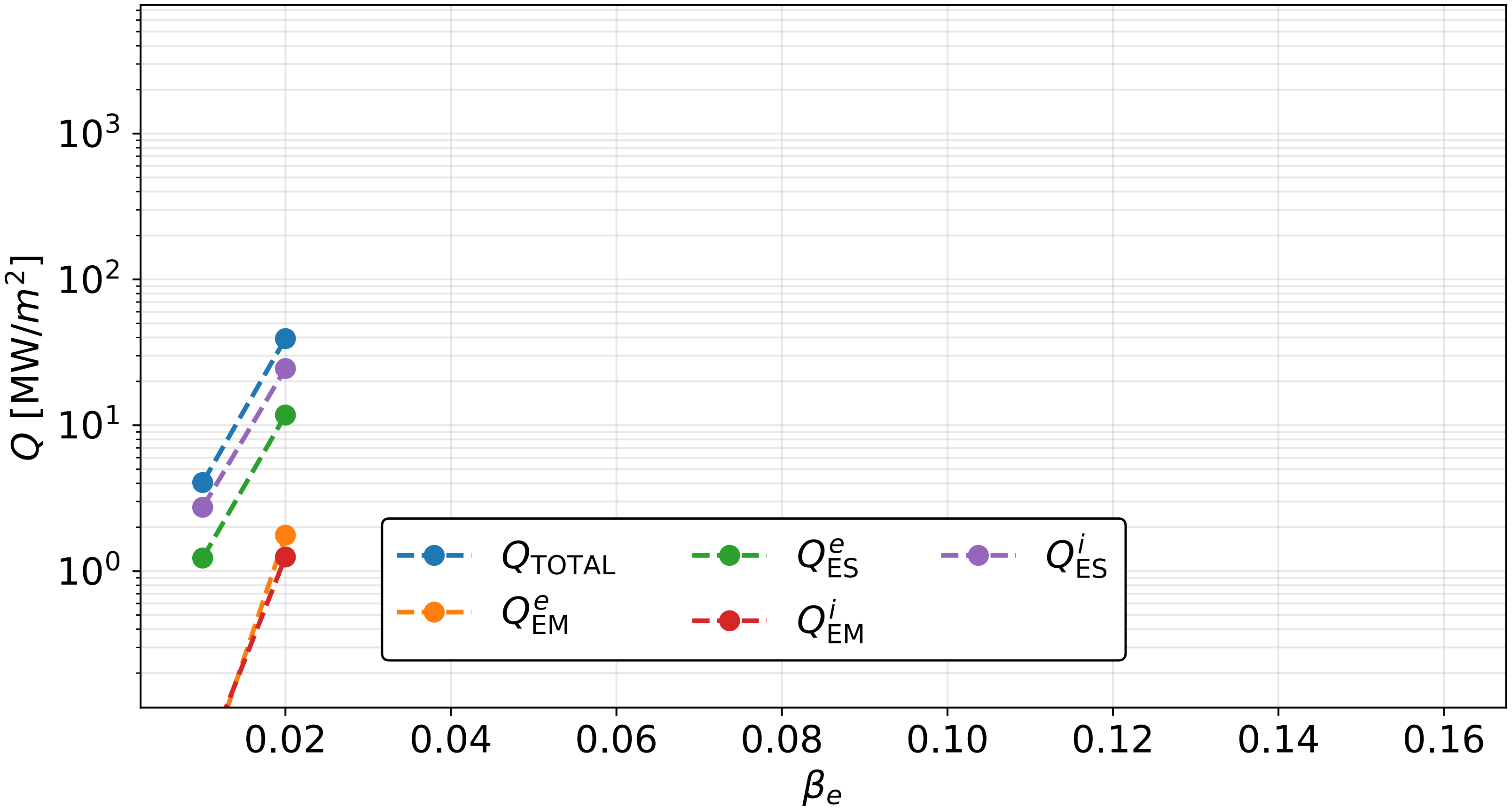
Max Planck Institute for Plasma Physics, Boltzmannstr. 2, Garching 85748, Germany

KEY REFERENCES

[1] Kennedy *et al.* [in prep]
[2] Zhang *et al.* [in prep]

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT \,/\, (B^2 \,/\, 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).

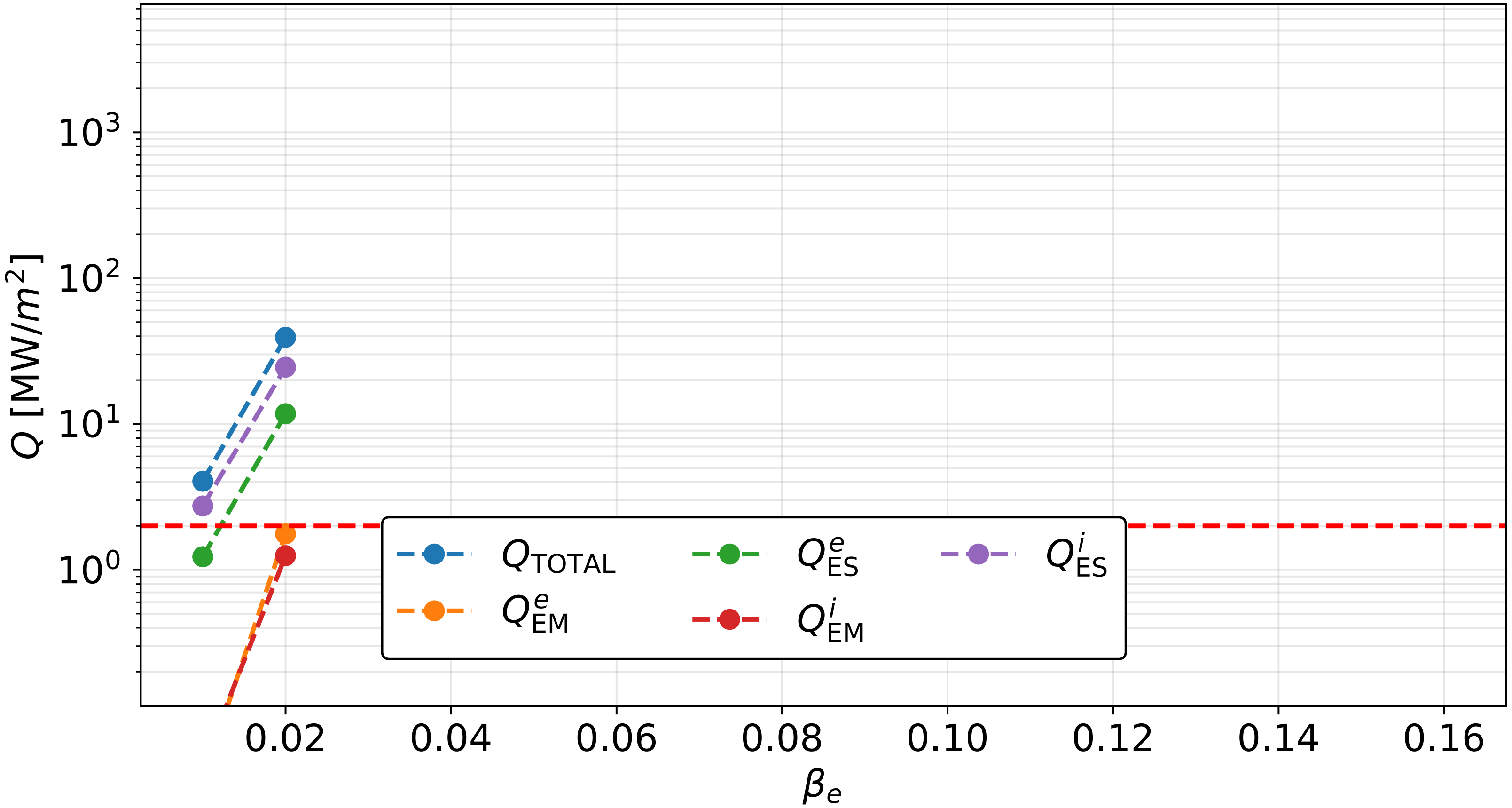


REFERENCES
[3] Kennedy *et al.* (2023)
[4] Kennedy *et al.* (2024)
[5] Giacomin *et al.* (2024)
[6] Tholerus *et al.* (2024)
[7] Giacomin *et al.* (2025)
[8] Pueschel *et al.* (2013)

- **No** (equilibrium) **flow shear.** Reasonable given no external momentum sources (only small intrinsic flows) in STEP.
- **Representative** of a more general trend [2,8].

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT\ /\ (B^2\ /\ 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).

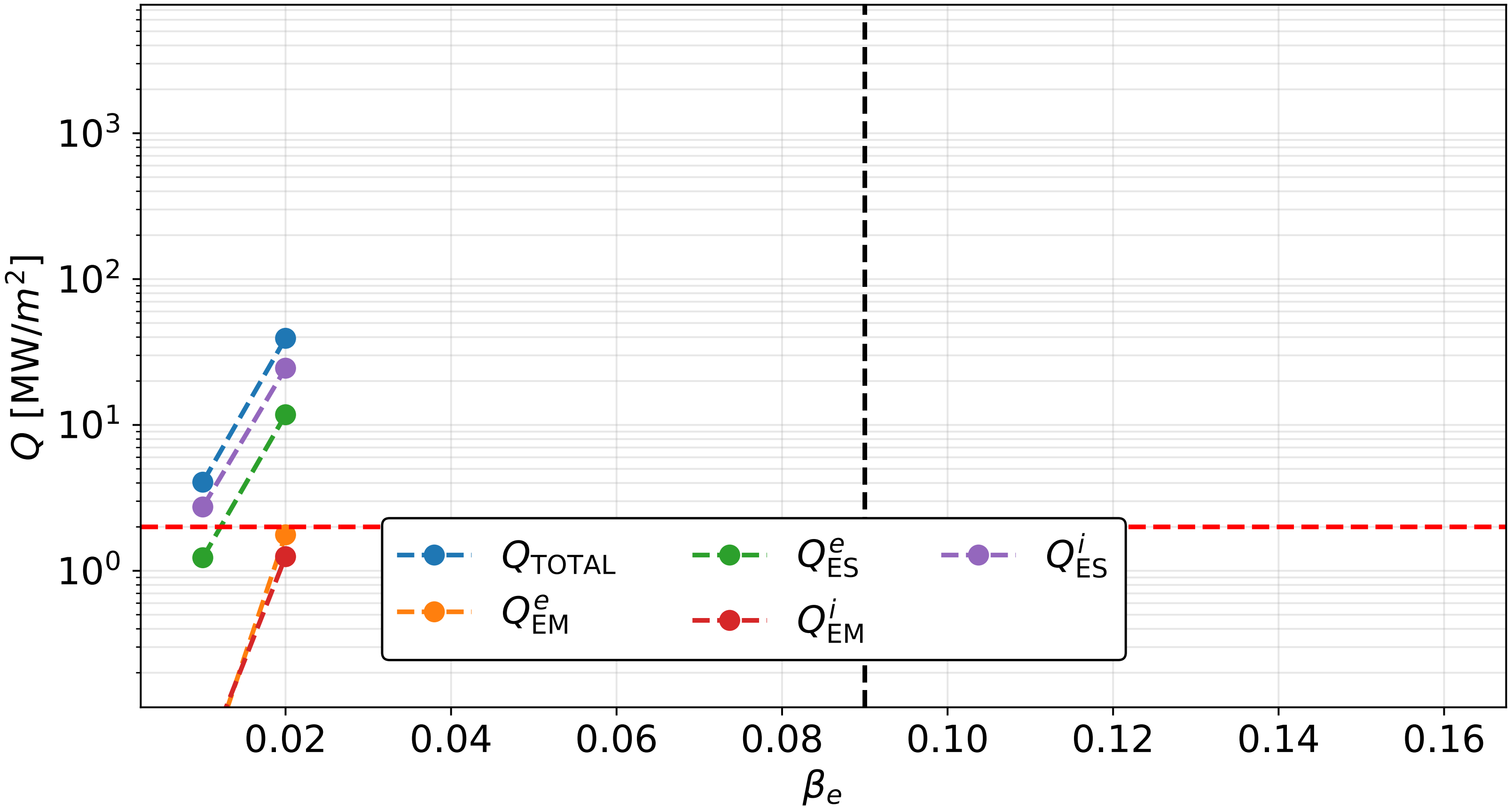


REFERENCES
[3] Kennedy *et al.* (2023)
[4] Kennedy *et al.* (2024)
[5] Giacomin *et al.* (2024)
[6] Tholerus *et al.* (2024)
[7] Giacomin *et al.* (2025)
[8] Pueschel *et al.* (2013)

- **No** (equilibrium) **flow shear.** Reasonable given no external momentum sources (only small intrinsic flows) in STEP.
- **Representative** of a more general trend [2,8].

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT\ /\ (B^2\ /\ 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).

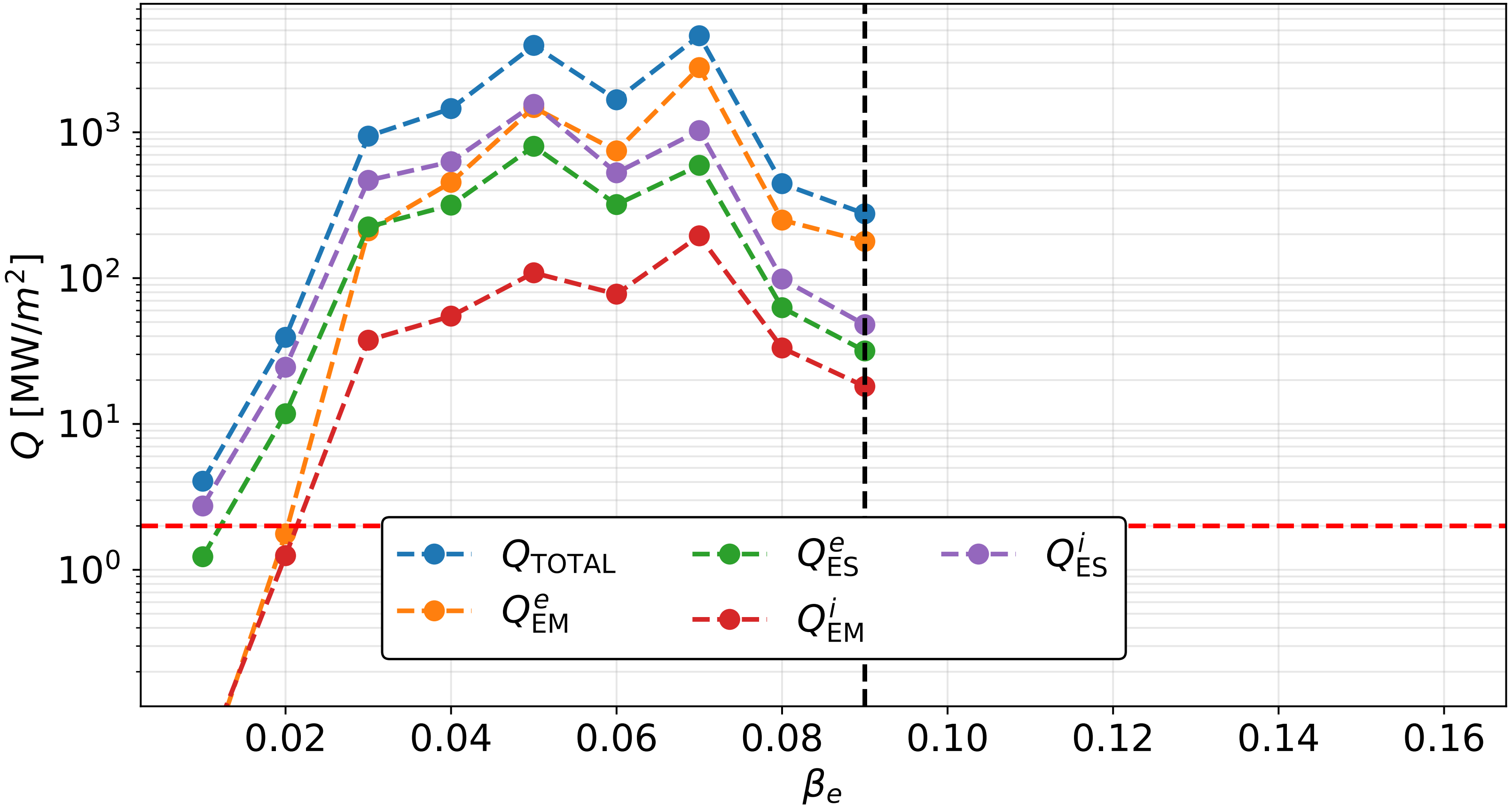


REFERENCES
[3] Kennedy *et al.* (2023)
[4] Kennedy *et al.* (2024)
[5] Giacomin *et al.* (2024)
[6] Tholerus *et al.* (2024)
[7] Giacomin *et al.* (2025)
[8] Pueschel *et al.* (2013)

- **No** (equilibrium) **flow shear**. Reasonable given no external momentum sources (only small intrinsic flows) in STEP.
- **Representative** of a more general trend [2,8].

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT\ /\ (B^2\ /\ 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).

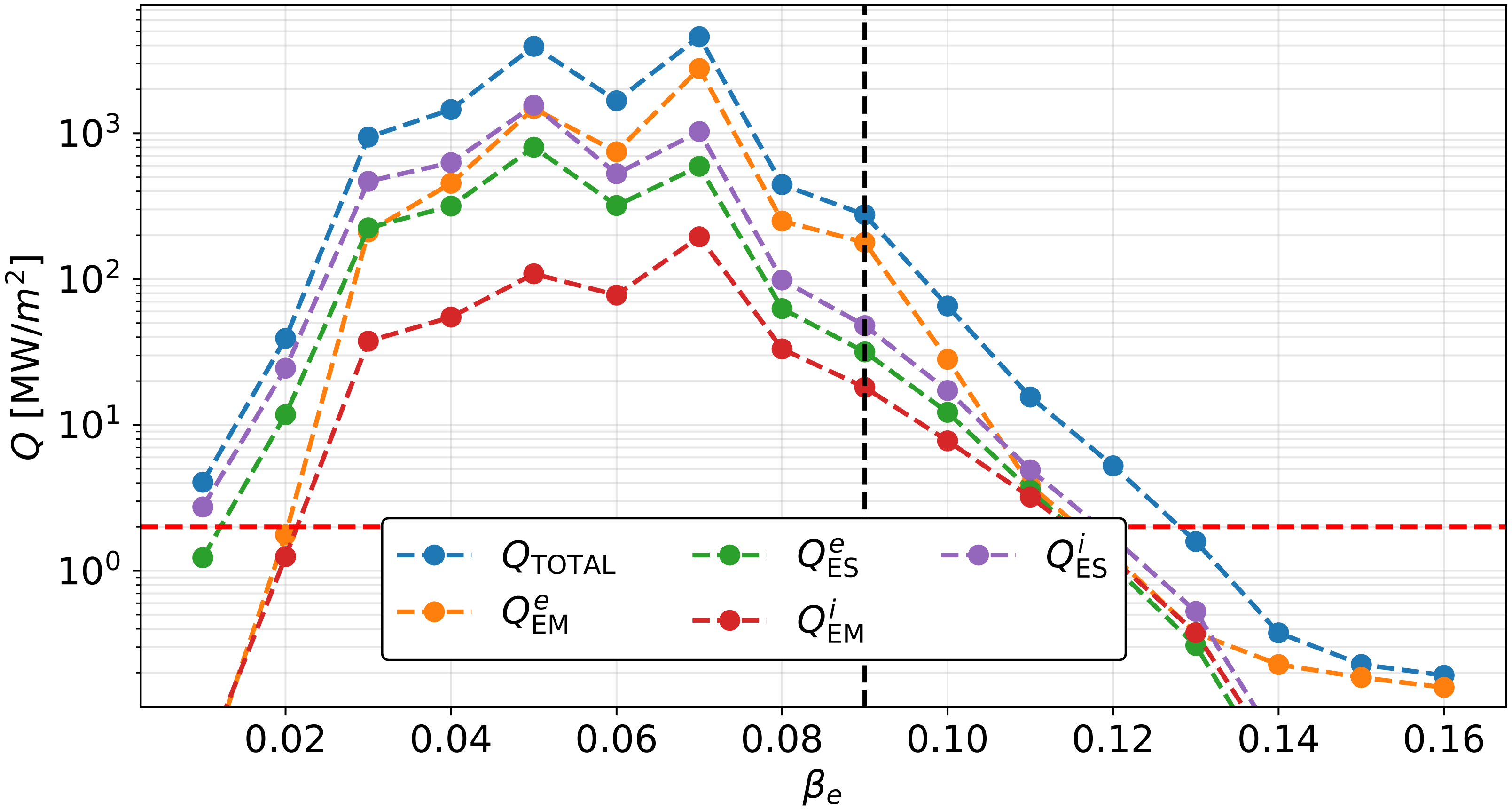


- **No** (equilibrium) **flow shear.** Reasonable given no external momentum sources (only small intrinsic flows) in STEP.
- **Representative** of a more general trend [2,8].

REFERENCES
[3] Kennedy *et al.* (2023)
[4] Kennedy *et al.* (2024)
[5] Giacomin *et al.* (2024)
[6] Tholerus *et al.* (2024)
[7] Giacomin *et al.* (2025)
[8] Pueschel *et al.* (2013)

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT\ /\ (B^2\ /\ 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).



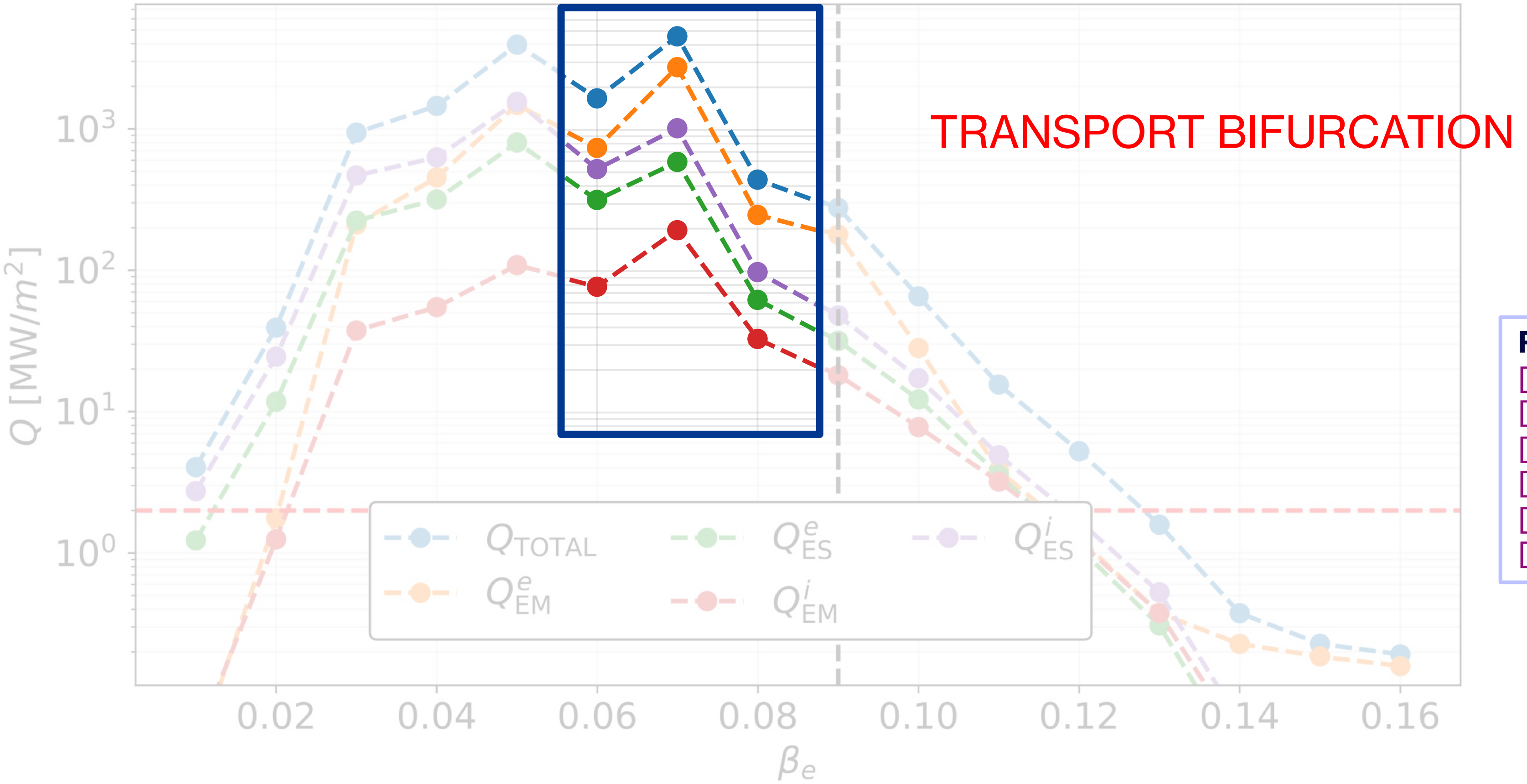
REFERENCES

[3] Kennedy *et al.* (2023)
[4] Kennedy *et al.* (2024)
[5] Giacomin *et al.* (2024)
[6] Tholerus *et al.* (2024)
[7] Giacomin *et al.* (2025)
[8] Pueschel *et al.* (2013)

- **No** (equilibrium) **flow shear**. Reasonable given no external momentum sources (only small intrinsic flows) in STEP.
- **Representative** of a more general trend [2,8].

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT\ /\ (B^2\ /\ 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).

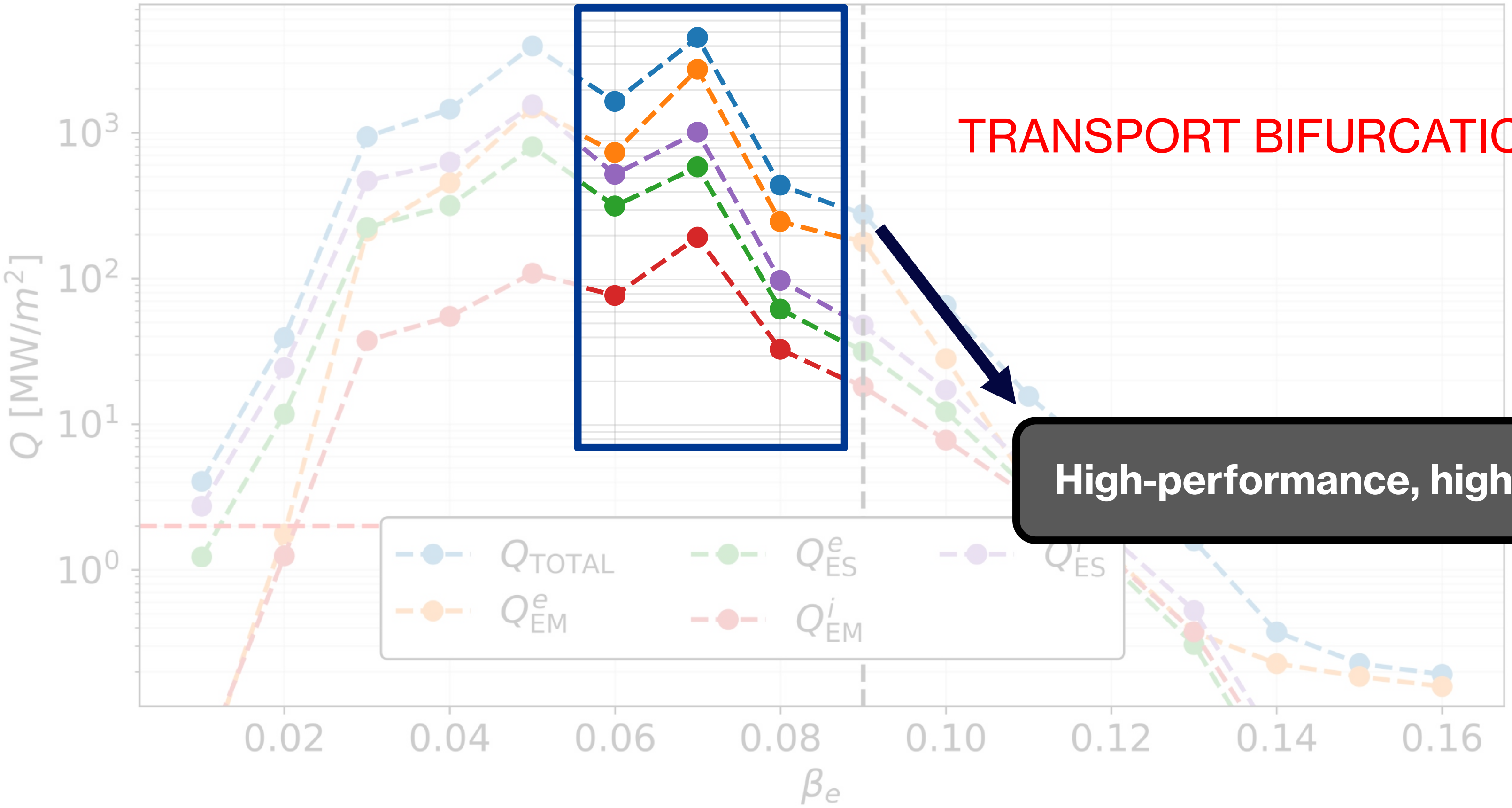


REFERENCES
[3] Kennedy *et al.* (2023)
[4] Kennedy *et al.* (2024)
[5] Giacomin *et al.* (2024)
[6] Tholerus *et al.* (2024)
[7] Giacomin *et al.* (2025)
[8] Pueschel *et al.* (2013)

- **No** (equilibrium) **flow shear**. Reasonable given no external momentum sources (only small intrinsic flows) in STEP.
- **Representative** of a more general trend [2,8].

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT \ / \ (B^2 \ / \ 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \ \propto \ \beta'$ (i.e., consistent with scaling p profile).



TRANSPORT BIFURCATION

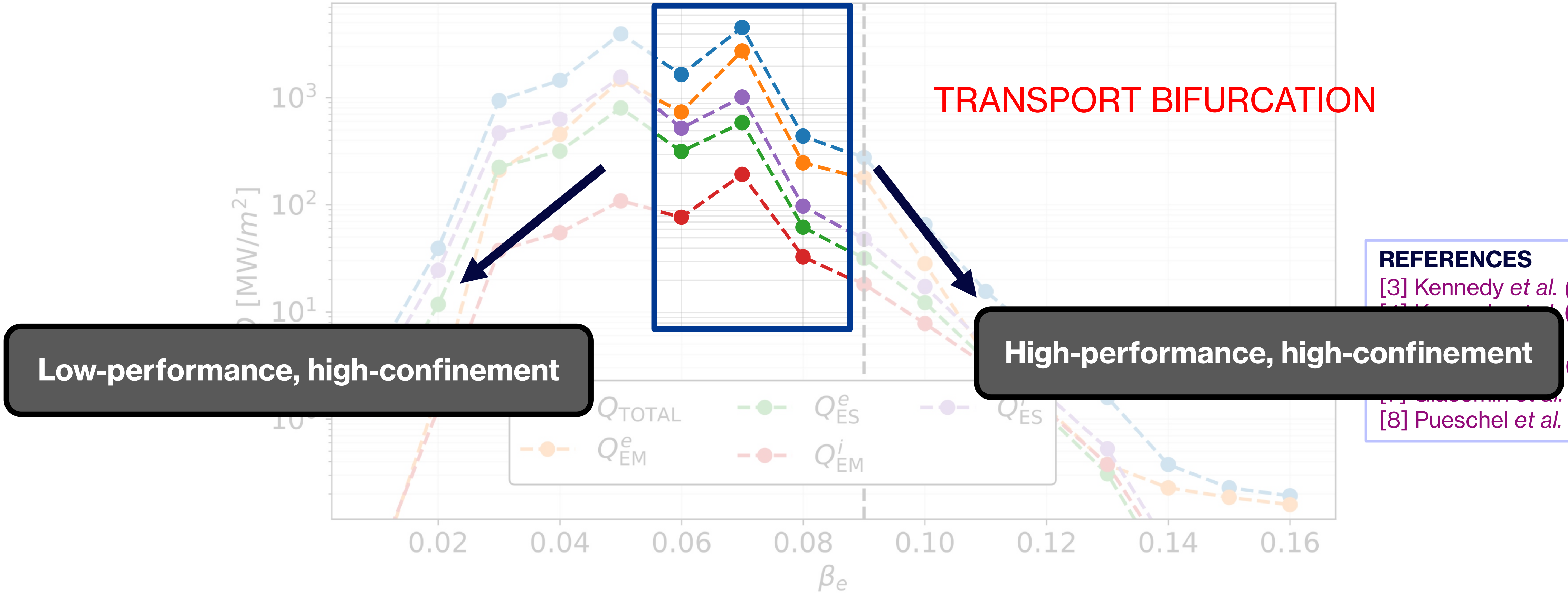
High-performance, high-confinement

REFERENCES
[3] Kennedy *et al.* (2023)
(2024)
(2024)
(2024)
(2025)
[8] Pueschel *et al.* (2013)

- **No** (equilibrium) **flow shear.** Reasonable given no external momentum sources (only small intrinsic flows) in STEP.
- **Representative** of a more general trend [2,8].

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT\ /\ (B^2\ /\ 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).

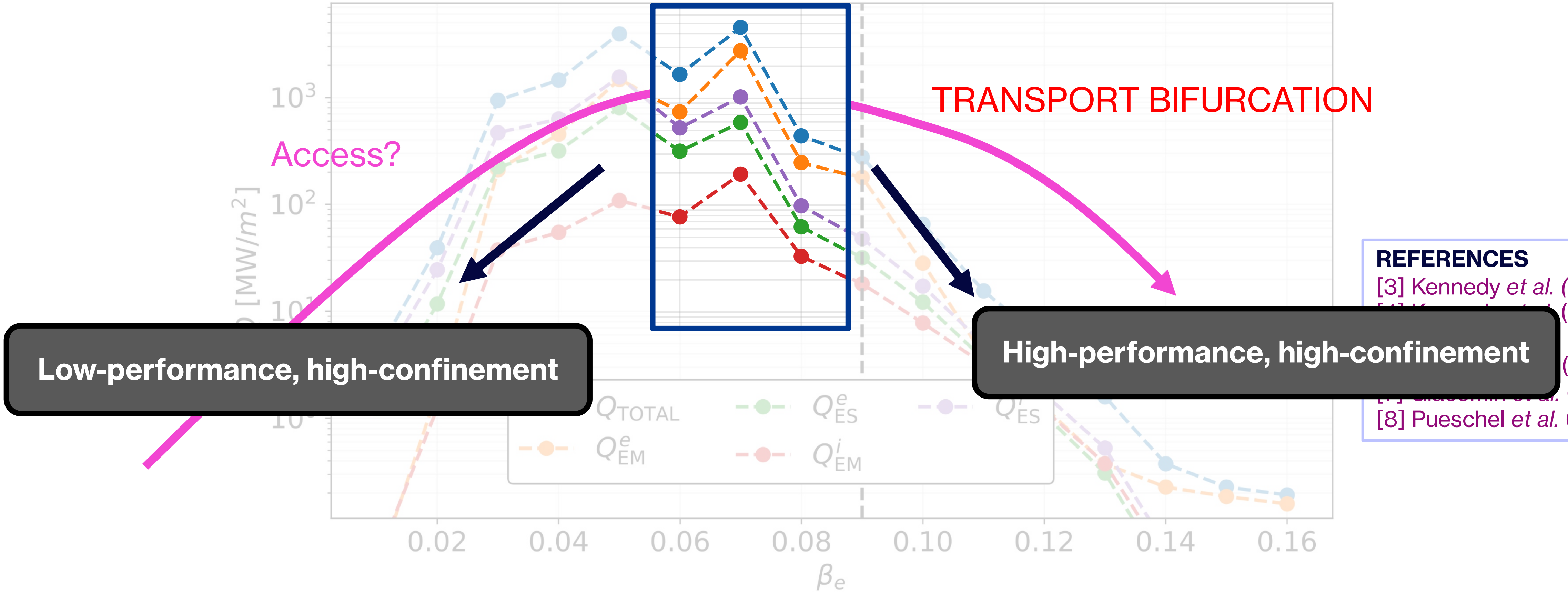


REFERENCES
[3] Kennedy *et al.* (2023)
(2024)
(2024)
(2024)
(2025)
[8] Pueschel *et al.* (2013)

- **No** (equilibrium) **flow shear**. Reasonable given no external momentum sources (only small intrinsic flows) in STEP.
- **Representative** of a more general trend [2,8].

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,7].
- $\beta[\equiv nT\ /\ (B^2\ /\ 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).

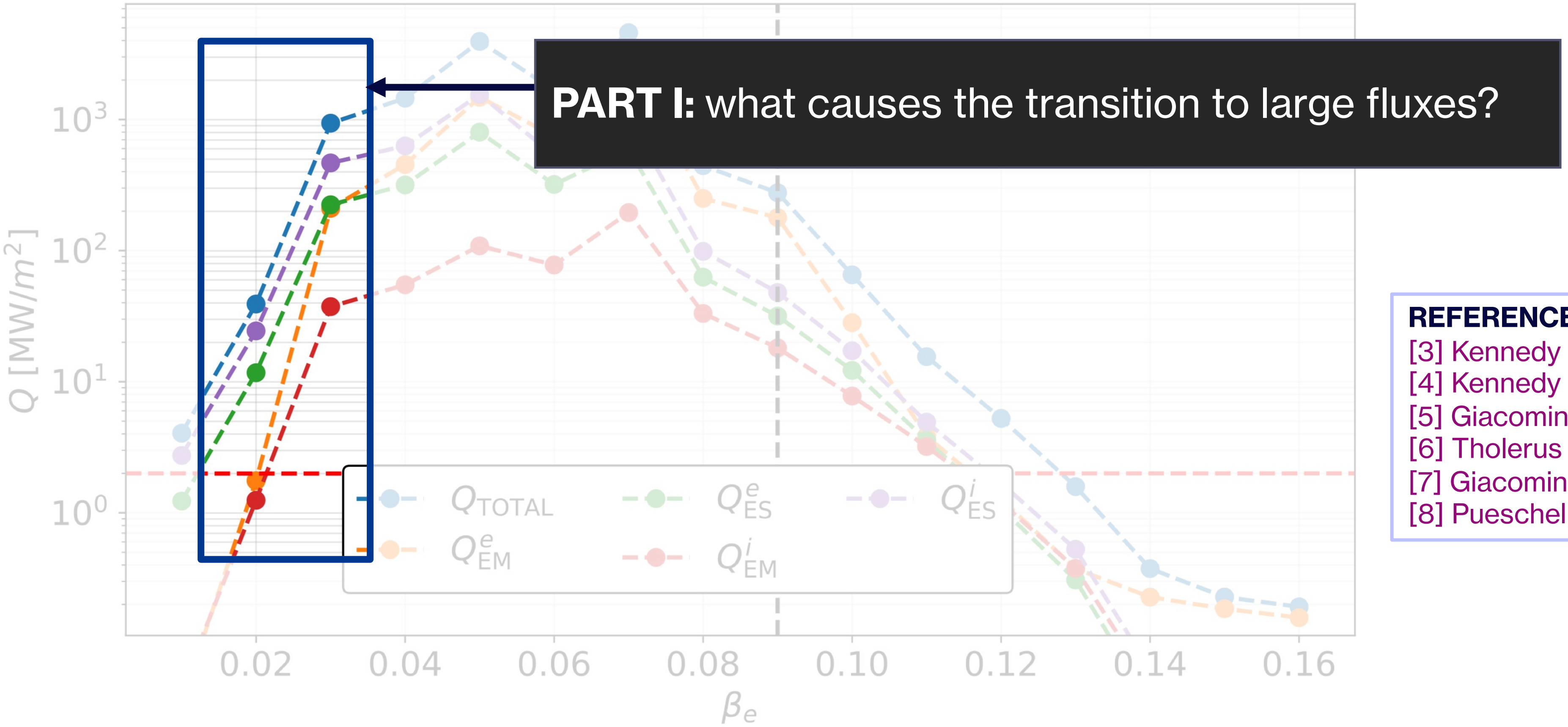


REFERENCES
[3] Kennedy *et al.* (2023)
(2024)
(2024)
(2024)
(2025)
[8] Pueschel *et al.* (2013)

- **No** (equilibrium) **flow shear**. Reasonable given no external momentum sources (only small intrinsic flows) in STEP.
- **Representative** of a more general trend [2,8].

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT \,/\, (B^2 \,/\, 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).



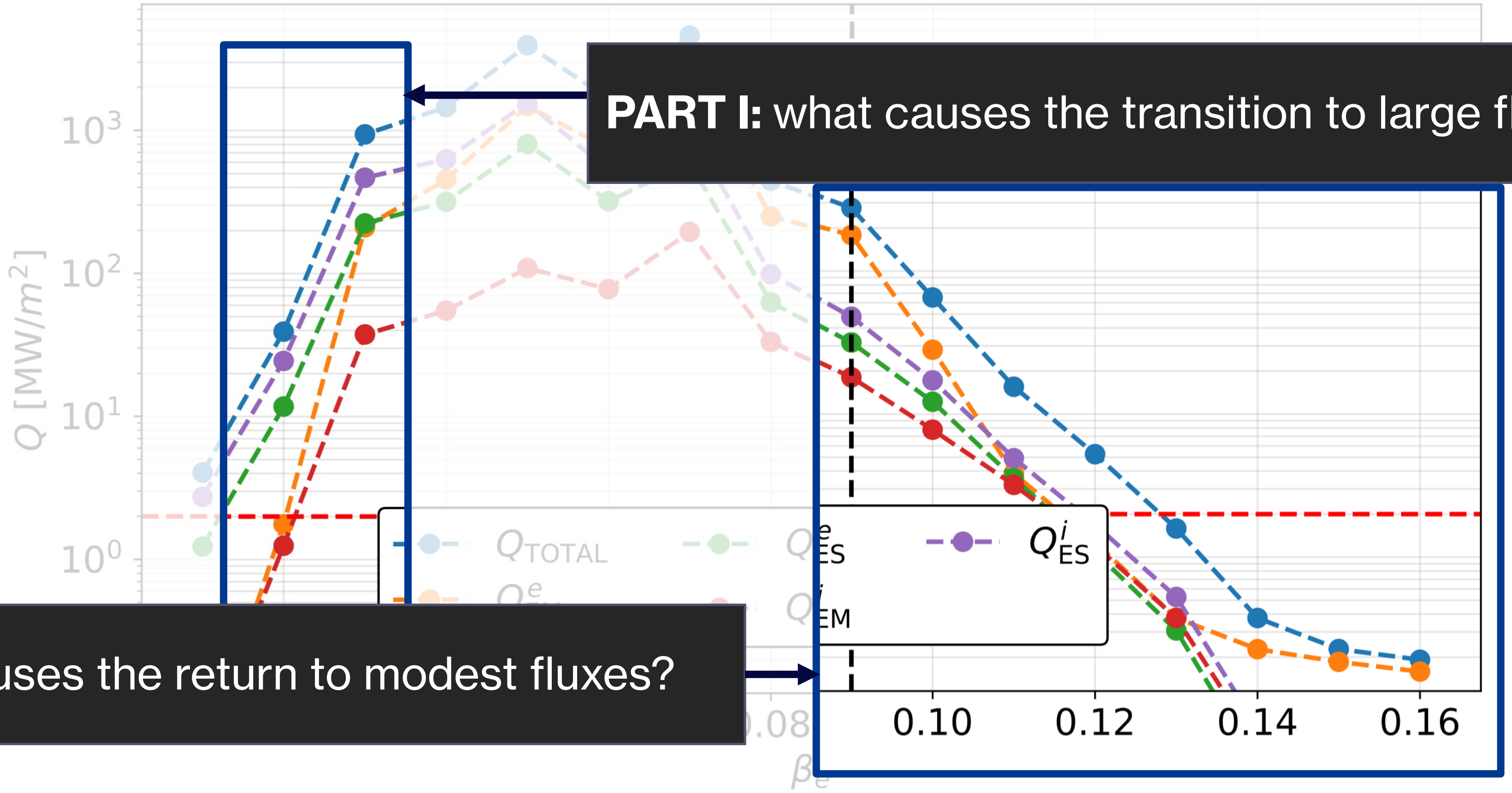
REFERENCES

[3] Kennedy *et al.* (2023)
[4] Kennedy *et al.* (2024)
[5] Giacomin *et al.* (2024)
[6] Tholerus *et al.* (2024)
[7] Giacomin *et al.* (2025)
[8] Pueschel *et al.* (2013)

- **No** (equilibrium) **flow shear.** Reasonable given no external momentum sources (only small intrinsic flows) in STEP.
- **Representative** of a more general trend [2,8].

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT\ /\ (B^2\ /\ 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).



PART I: what causes the transition to large fluxes?

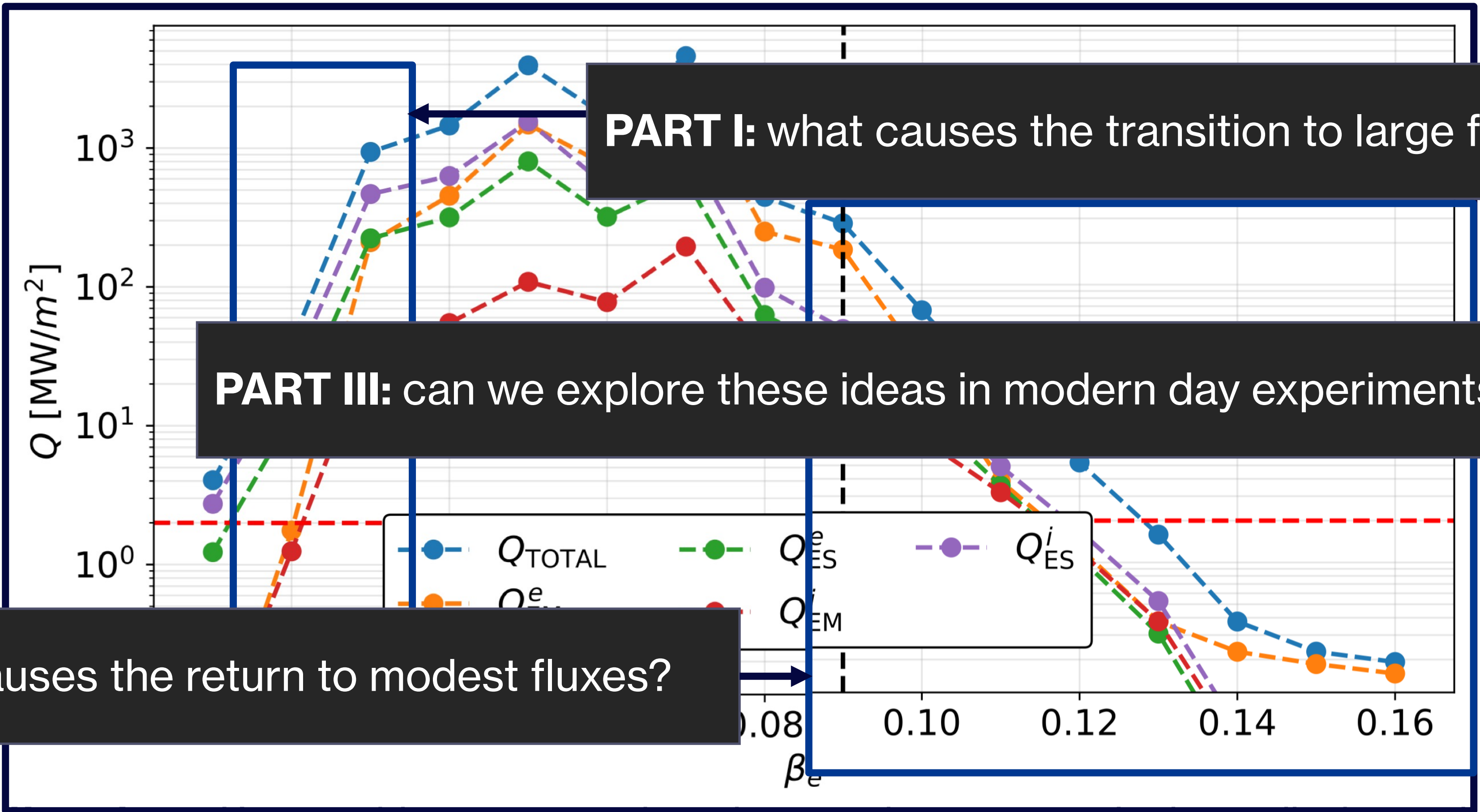
PART II: what causes the return to modest fluxes?

REFERENCES
[3] Kennedy *et al.* (2023)
[4] Kennedy *et al.* (2024)
[5] Giacomin *et al.* (2024)
[6] Tholerus *et al.* (2024)
[7] Giacomin *et al.* (2025)
[8] Pueschel *et al.* (2013)

- **No** (equilibrium) **flow shear**. Reasonable given no external momentum sources (only small intrinsic flows) in STEP.
- **Representative** of a more general trend [2,8].

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT\ /\ (B^2\ /\ 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).



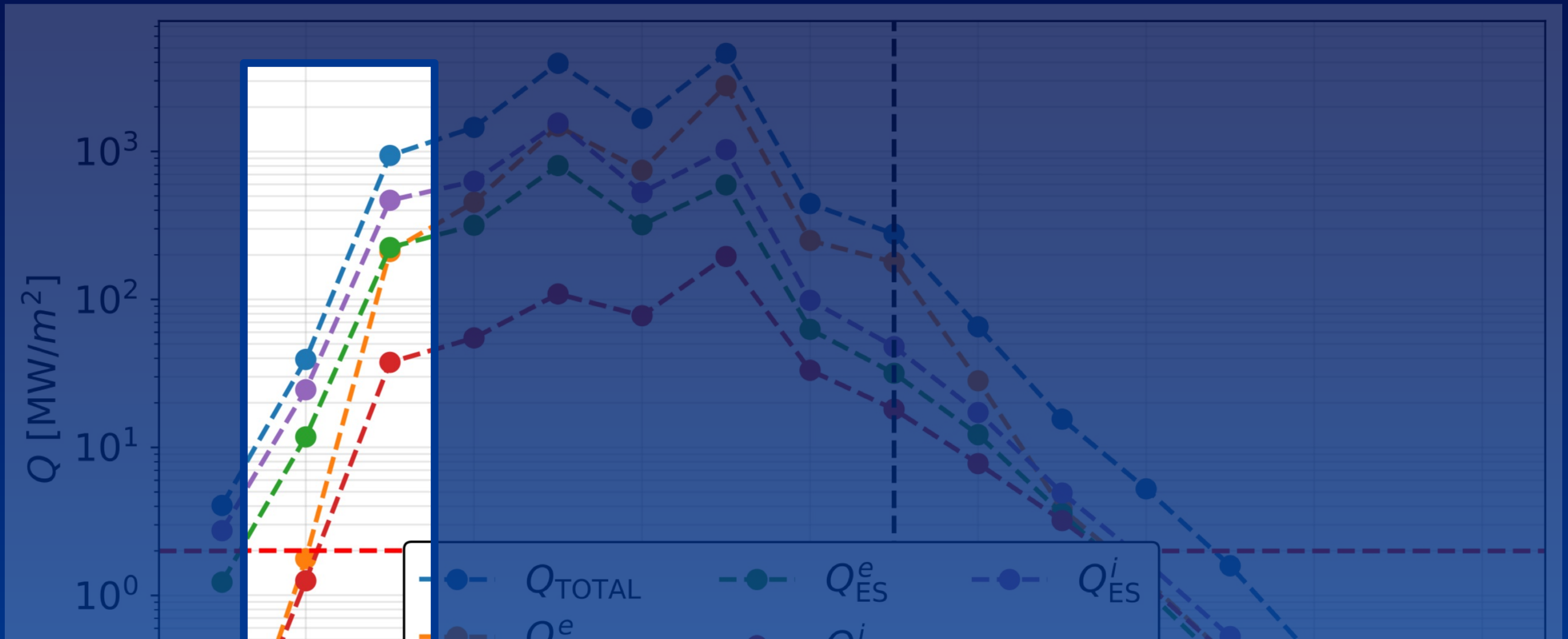
FERENCES
Kennedy *et al.* (2023)
Kennedy *et al.* (2024)
[5] Giacomin *et al.* (2024)
[6] Tholerus *et al.* (2024)
[7] Giacomin *et al.* (2025)
[8] Pueschel *et al.* (2013)

- **No** (equilibrium) flow shear. Reasonable given no external momentum sources (only small intrinsic flows) in STEP.
- **Representative** of a more general trend [2,8].

STEP

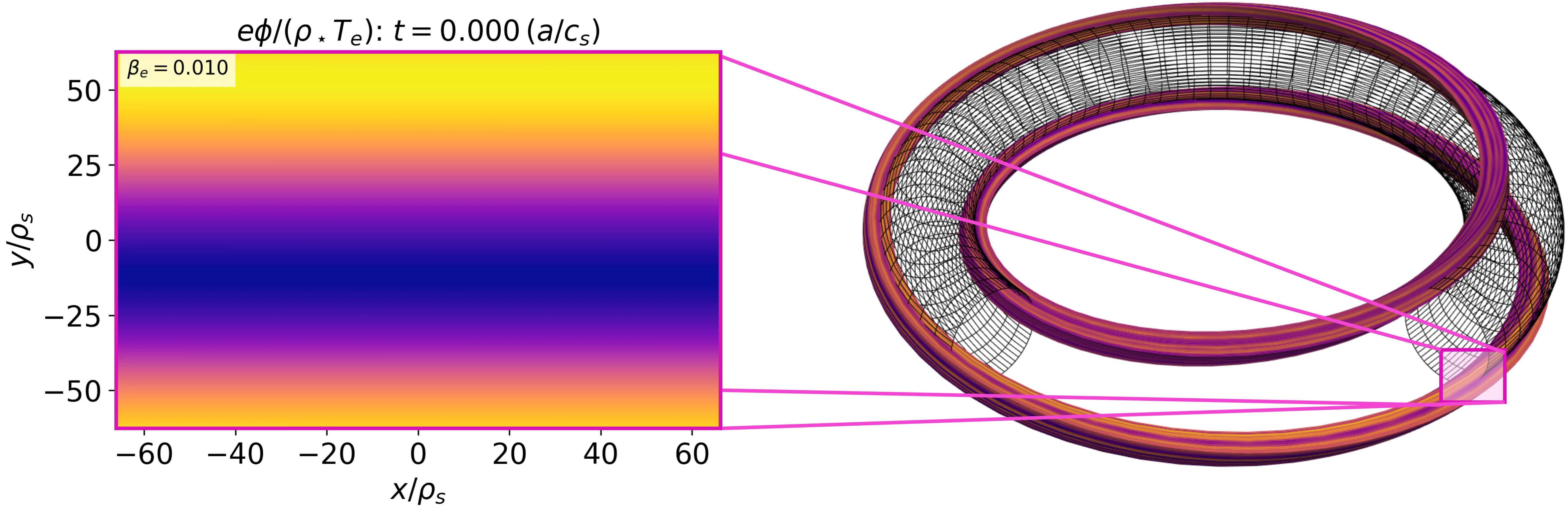
PART I

What causes the transition to large fluxes?



ELECTROMAGNETIC THRESHOLD

- How does the turbulence change as we cross the threshold?

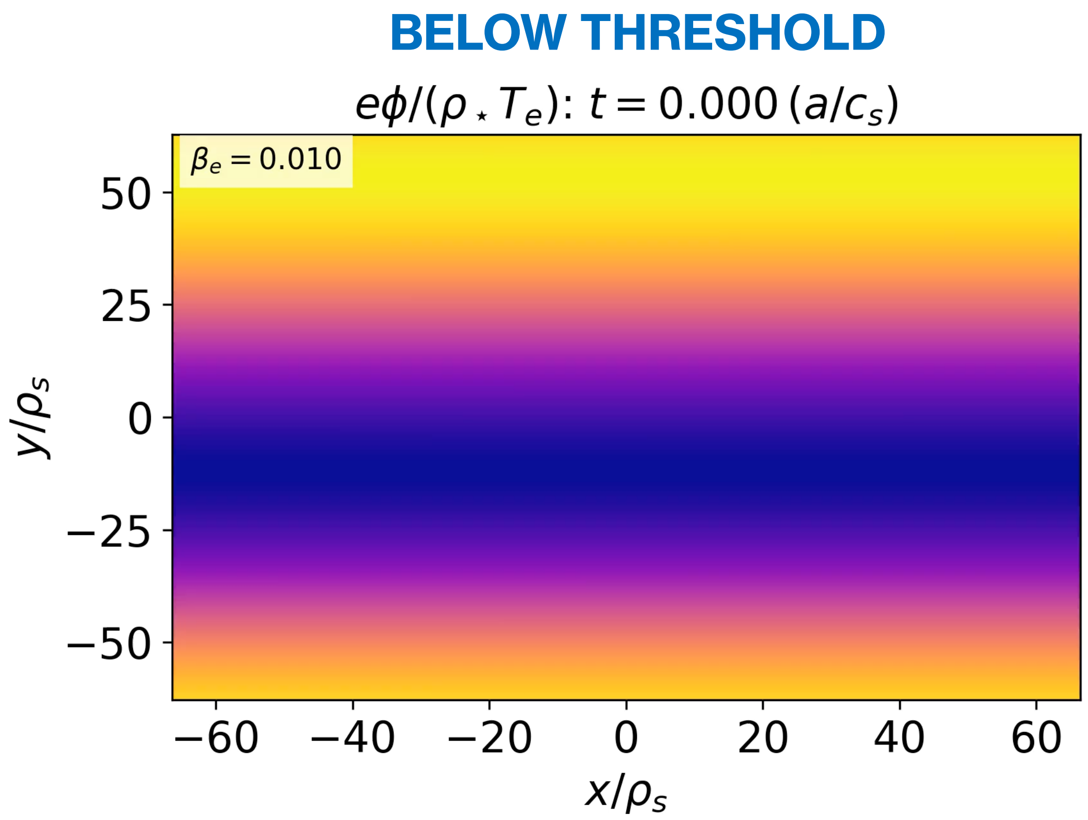


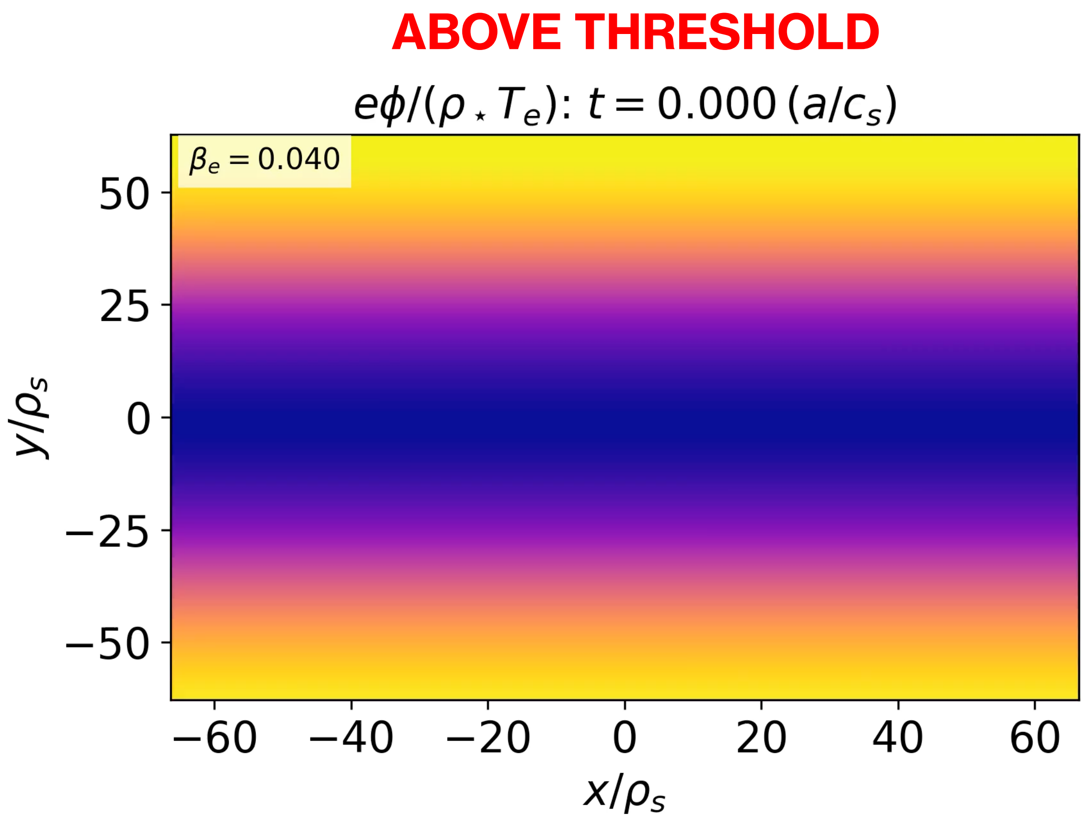
Visualisation via **PYROKINETICS** a python library for standarising gyrokinetic analysis [9].

REFERENCES
[9] Patel *et al.* (2024)

ELECTROMAGNETIC THRESHOLD

- How does the turbulence change as we cross the threshold?





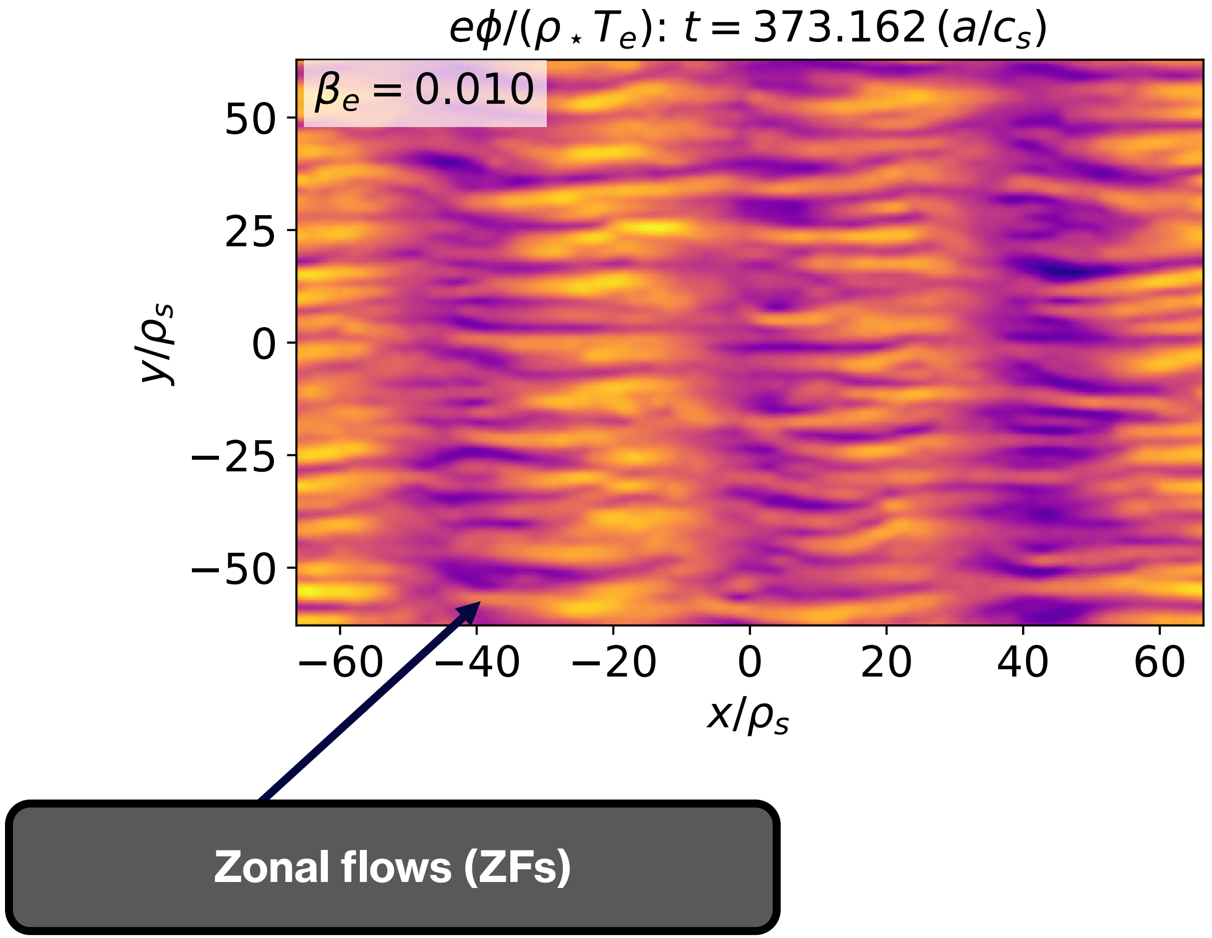
Visualisation via **PYROKINETICS** a python library for standarising gyrokinetic analysis [9].

REFERENCES
[9] Patel *et al.* (2024)

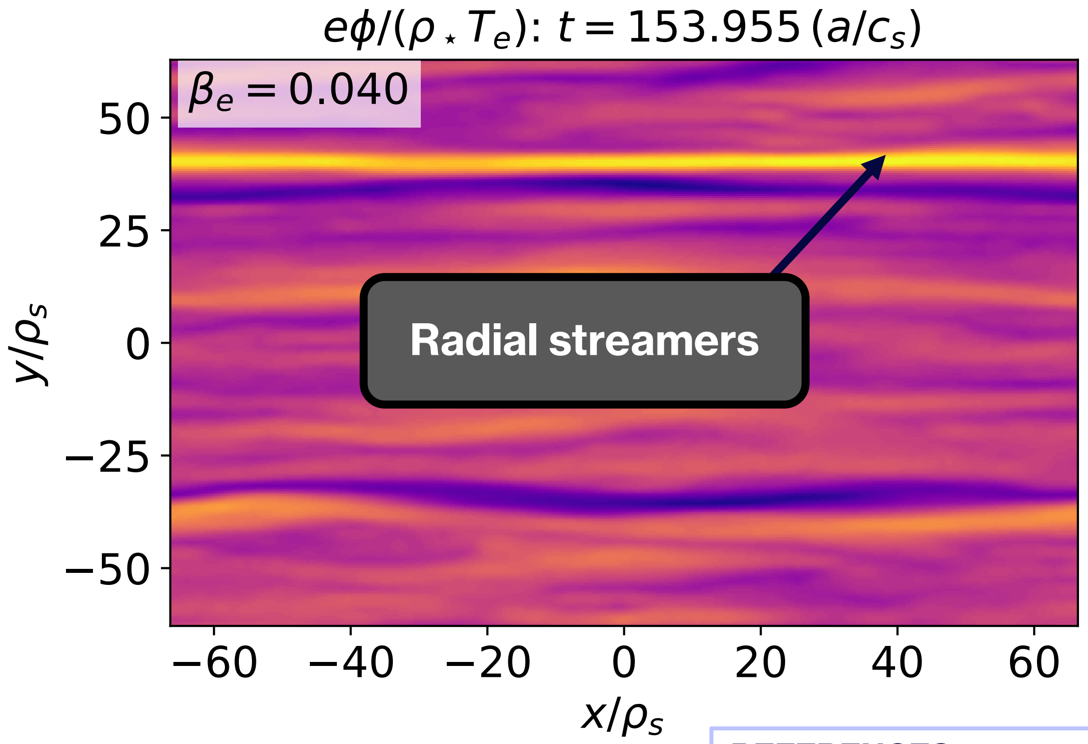
ELECTROMAGNETIC THRESHOLD

- 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)** [8,10,11].

BELOW THRESHOLD



ABOVE THRESHOLD



REFERENCES

[8] Pueschel et al. (2013a)
[10] Pueschel et al. (2013b)
[11] Pueschel et al. (2014)

ELECTROMAGNETIC THRESHOLD

Conjecture [1,2] that the saturation, or otherwise, of electromagnetic δf-gyrokinetic turbulence is determined by the ability of the system (or lack thereof) to form sufficiently strong zonal perturbations to shear apart any streamer structures that attempt to be established by the linear instabilities present.

$$\frac{\partial}{\partial t}\left\langle \sum_{\boldsymbol{k}_\perp} \mathrm{e}^{\mathrm{i}\boldsymbol{k}_\perp\cdot\boldsymbol{r}}\left[\sum_s \frac{q_s^2 n_s}{T_s}(1-\Gamma_{0s})\phi_{\boldsymbol{k}_\perp} - \sum_s q_s n_s \Gamma_{1s}\frac{\delta B_{\parallel \boldsymbol{k}_\perp}}{B}\right]\right\rangle_\psi = \Pi_{\mathrm{lin}} + \Pi_{\mathrm{turb}}$$

LINEAR MOMENTUM FLUX = **LINEAR TERM** (inhomogeneity of the magnetic field) + **COLLISIONS**

$$\Pi_{\mathrm{lin}} \equiv -\left\langle \sum_s q_s \int \mathrm{d}^3\boldsymbol{v}\left[(\boldsymbol{v}_{ds}\cdot\nabla x)\left\langle\frac{\partial h_s}{\partial x}\right\rangle_{\boldsymbol{r}}\right] + \sum_{s'}\left\langle\left\langle C_{ss'}^{(l)}[h_s]\right\rangle_{\boldsymbol{R}_s}\right\rangle_{\boldsymbol{r}}\right\rangle_\psi$$

NONLINEAR MOMENTUM FLUX = **nonlinear advection due to effects in the drift velocity**

$$\Pi_{\mathrm{turb}} \equiv -\left\langle \sum_s q_s \int \mathrm{d}^3\boldsymbol{v}\,\langle \boldsymbol{v}_\chi\cdot\nabla h_s\rangle_r\right\rangle_\psi$$

$$\boldsymbol{v}_\chi \equiv \frac{c}{B}\boldsymbol{b}\times\frac{\partial\langle\chi\rangle_{\boldsymbol{R}_s}}{\partial \boldsymbol{R}_s}, \quad \chi \equiv \phi - \frac{\mathbf{v}\cdot\mathbf{A}}{c}$$

REFERENCES
[1] Kennedy *et al.* [in prep]
[2] Zhang *et al.* [in prep]

ELECTROMAGNETIC THRESHOLD

- Useful to partition the nonlinear momentum flux into the different field contributions

$$\Pi_\phi \equiv -\left\langle q_s \int \mathrm{d}^3\boldsymbol{v} \left\langle \left(\frac{c}{B}\boldsymbol{b} \times \frac{\partial}{\partial \boldsymbol{R}_s} \langle \phi \rangle_{\boldsymbol{R}_s} \right) \cdot \nabla h_s \right\rangle_{\boldsymbol{r}} \right\rangle_\psi$$

$$\Pi_{A_\parallel} \equiv -\left\langle q_s \int \mathrm{d}^3\boldsymbol{v} \left\langle \left(\frac{c}{B}\boldsymbol{b} \times \frac{\partial}{\partial \boldsymbol{R}_s} \left\langle -\frac{v_\parallel A_\parallel}{c} \right\rangle_{\boldsymbol{R}_s} \right) \cdot \nabla h_s \right\rangle_{\boldsymbol{r}} \right\rangle_\psi,$$

$$\Pi_{\delta B_\parallel} \equiv -\left\langle q_s \int \mathrm{d}^3\boldsymbol{v} \left\langle \left(\frac{c}{B}\boldsymbol{b} \times \frac{\partial}{\partial \boldsymbol{R}_s} \left\langle -\frac{\boldsymbol{v}_\perp \cdot \boldsymbol{A}_\perp}{c} \right\rangle_{\boldsymbol{R}_s} \right) \cdot \nabla h_s \right\rangle_{\boldsymbol{r}} \right\rangle_\psi.$$

Following [12,13]; consider placing our turbulence into a patch of constant zonal shear.

The “**Reynolds stress**” (Π_ϕ) tends to reinforce ZFs (shear zones).

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

A large enough Maxwell stress can overwhelm the ZF enhancing Reynolds stress; triggering non-zonal transition.

REFERENCES
[12] Ivanov *et al.* (2020)
[13] Ivanov *et al.* (2022)

NUMERICAL DIAGNOSTICS

- Instructive to reformulate these equations as an **evolution equation** for the **zonal flow energy** at long-wavelength.

$$\partial_t E_{\mathrm{ZF}} = -\nu_{\mathrm{lin}} - \nu_R - \nu_M$$

- Introduce the **turbulent zonal-flow viscosity**; how the “stresses” are correlated with zonal shear.

$$\nu_{\mathrm{lin}} \equiv -\int \mathrm{d}x\, S\, \Pi_{\mathrm{lin}}, \quad \nu_R \equiv -\int \mathrm{d}x\, S\, \Pi_{\phi}, \quad \nu_M \equiv -\int \mathrm{d}x\, S\, \Pi_{A_\parallel}, \quad S \equiv \partial_x^2 \phi_{\mathrm{Z}}$$

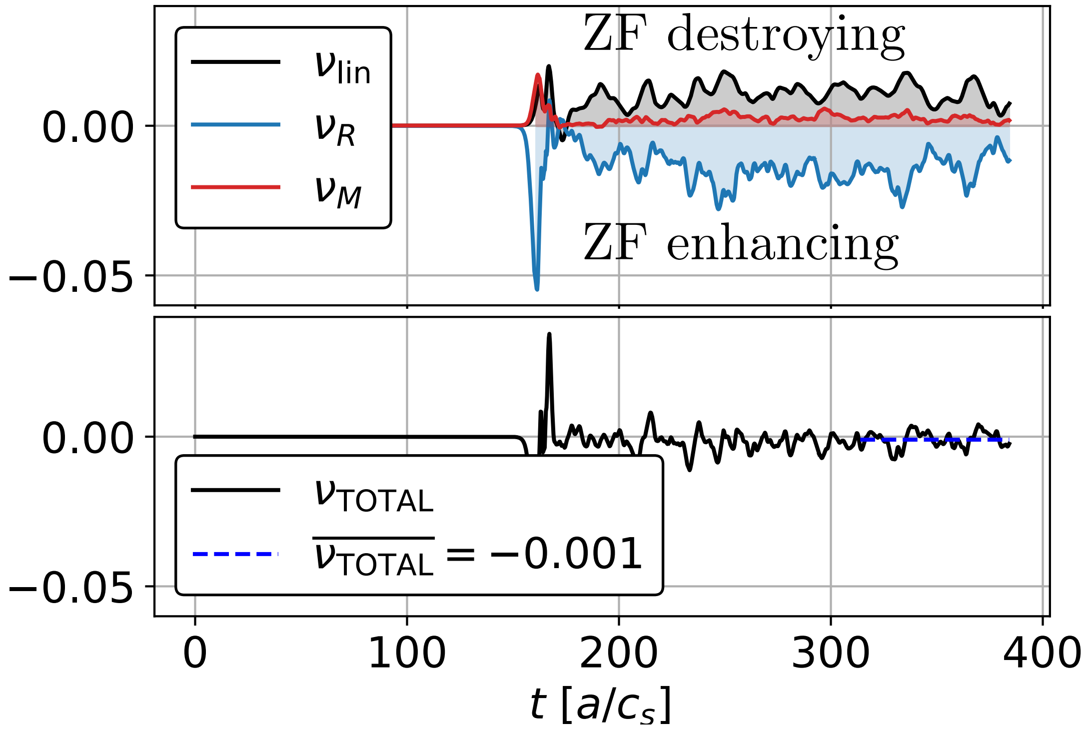
SATURATION CONDITIONS

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

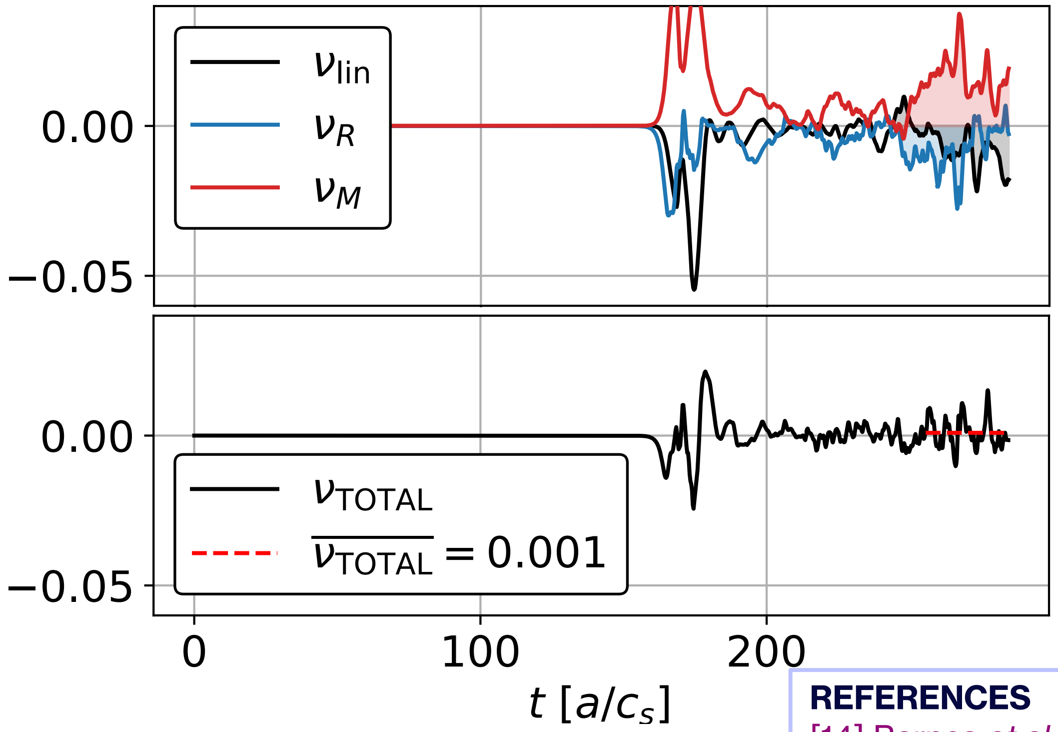
DOES THIS WORK NUMERICALLY IN STEP?

- Time-traces of the **turbulent zonal-flow viscosities** calculated by the gyrokinetic code STELLA [14].

BELOW THRESHOLD



ABOVE THRESHOLD



REFERENCES
[14] Barnes *et al.* (2019)

- Non-zonal transition accompanied by **change in sign** of the total turbulent zonal-flow viscosity. Reynolds stress (ZF enhancing) can no longer balance the Maxwell stress (ZF destroying).

INTUITION FOR THRESHOLD SCALING

- We want to turn an **expensive diagnostic** into a **predictive tool**. Can we predict the threshold where the transition happens?

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

- Intuitively expect **competition** between Reynolds stress and Maxwell stress to be controlled by a **critical-beta**.

- At **low-beta** the large Alfvén speed rapidly smooths magnetic perturbations, so magnetic-flutter stress is negligible, and saturation is set by electrostatic physics.

- 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.**

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

- Zhang *et al* [2] find same result from QL scaling of R.

REFERENCES

[2] Zhang *et al.* [in prep]

RECIPE FOR PREDICTING THRESHOLD

- Zhang *et al* [2] also provides a recipe for **predicting** where the transition will happen.

- On given flux surface, run one low-β_{e} GK simulation.

- Compute the viscosity ratio

$$R_0 \equiv R(\beta_e^{\mathrm{low}})$$

- Estimate threshold via a simple rescaling

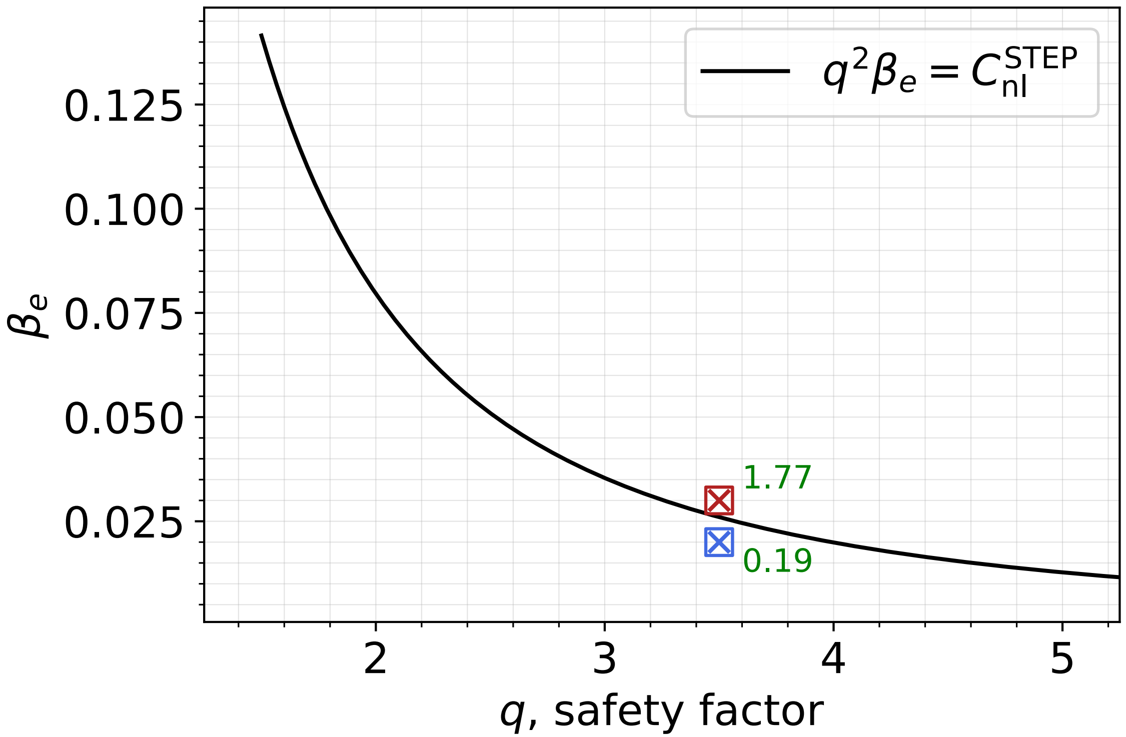
$$\beta_e^{\mathrm{crit}} \simeq \frac{\beta_e^{\mathrm{low}}}{R_0}$$

REFERENCES

[2] Zhang *et al.* [in prep]

DOES THIS WORK NUMERICALLY IN STEP?

- Look at two points close to where the transition happens.



KEY

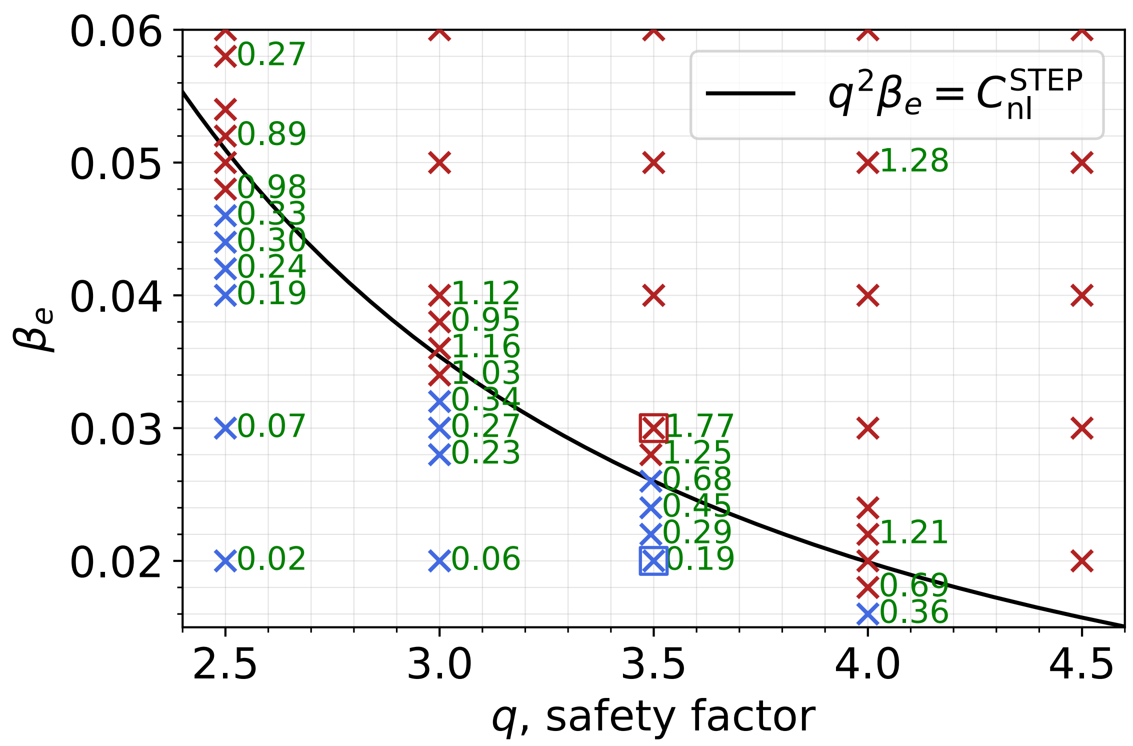
× (red)	Simulation does *not* saturate at $Q_{\mathrm{tot}} < 100\ \mathrm{MWm}^{-2}$
× (blue)	Simulation *saturates* at $Q_{\mathrm{tot}} < 100\ \mathrm{MWm}^{-2}$
1.77	$R \equiv \lvert \nu_M/\nu_R \rvert$ (Maxwell/Reynolds viscosity ratio)

Hypotheses (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?

- For **fixed geometry** this holds across a large range of q and β_e.



KEY

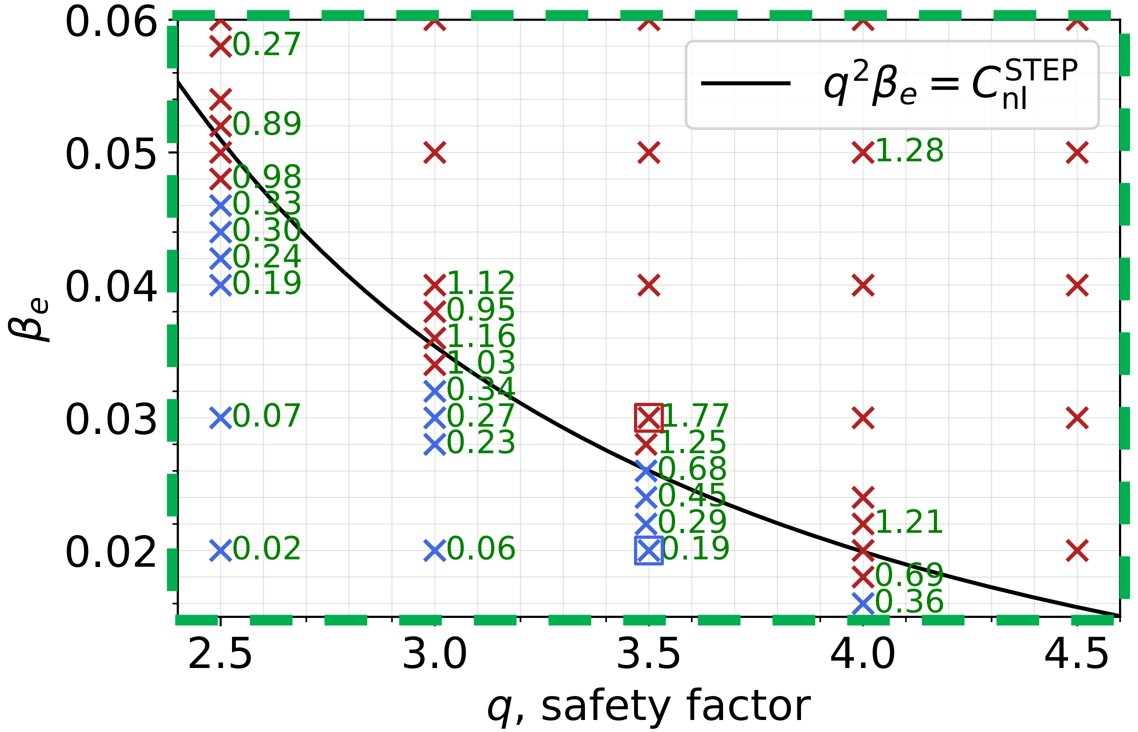
× (red)	Simulation does *not* saturate at $Q_{\rm tot} < 100$ MWm^{-2}
× (blue)	Simulation *saturates* at $Q_{\rm tot} < 100$ MWm^{-2}
1.77	$R \equiv \lvert\nu_M/\nu_R\rvert$ (Maxwell/Reynolds viscosity ratio)

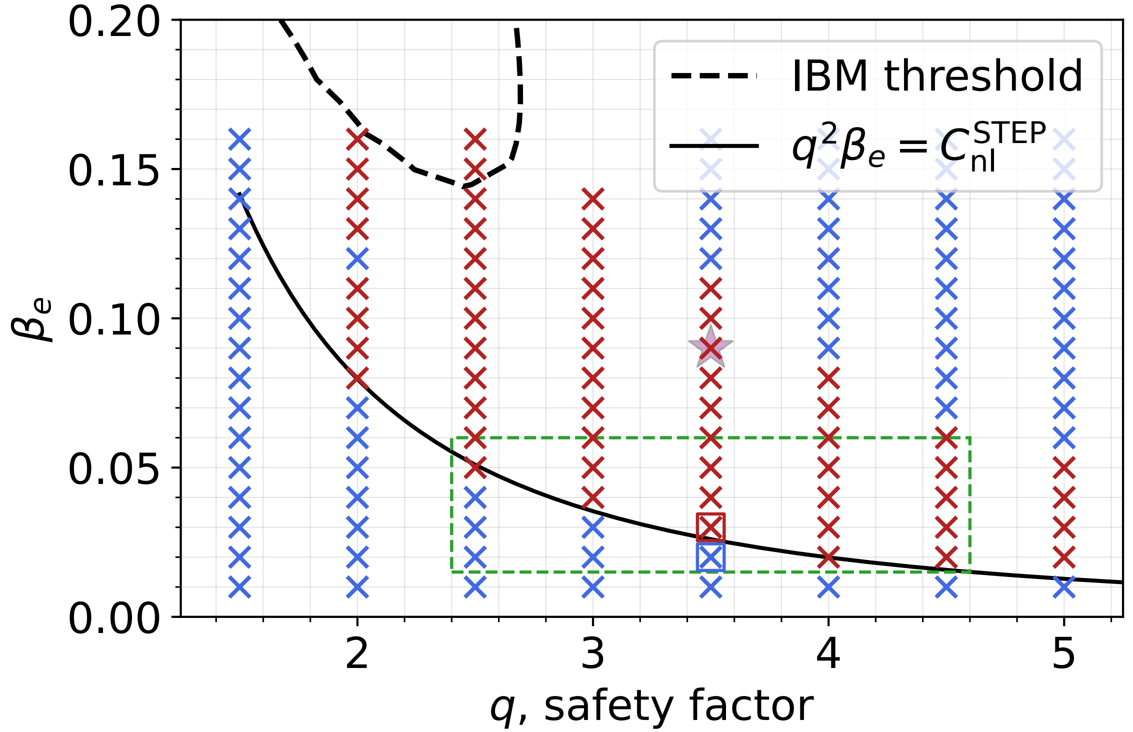
Hypotheses (Zhang *et al.*)

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

DOES THIS WORK NUMERICALLY?

- For **fixed geometry** this holds across a large range of q and β_e.





KEY

×	Simulation does *not* saturate at $Q_{\mathrm{tot}} < 100\ \mathrm{MWm}^{-2}$
×	Simulation *saturates* at $Q_{\mathrm{tot}} < 100\ \mathrm{MWm}^{-2}$
1.77	$R \equiv \lvert\nu_M/\nu_R\rvert$ (Maxwell/Reynolds viscosity ratio)

Hypotheses (Zhang *et al.*)

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

A LIMIT ON BETA POLOIDAL?

- Criteria in Zhang *et al.* [2] is a statement **about local gyrokinetics** in **fixed geometry.**

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

- A useful way of reformulating this is as a condition on **poloidal beta**; a more **geometric quantity** that characterises the pressure-induced distortion of poloidal magnetic field lines [1] .

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

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

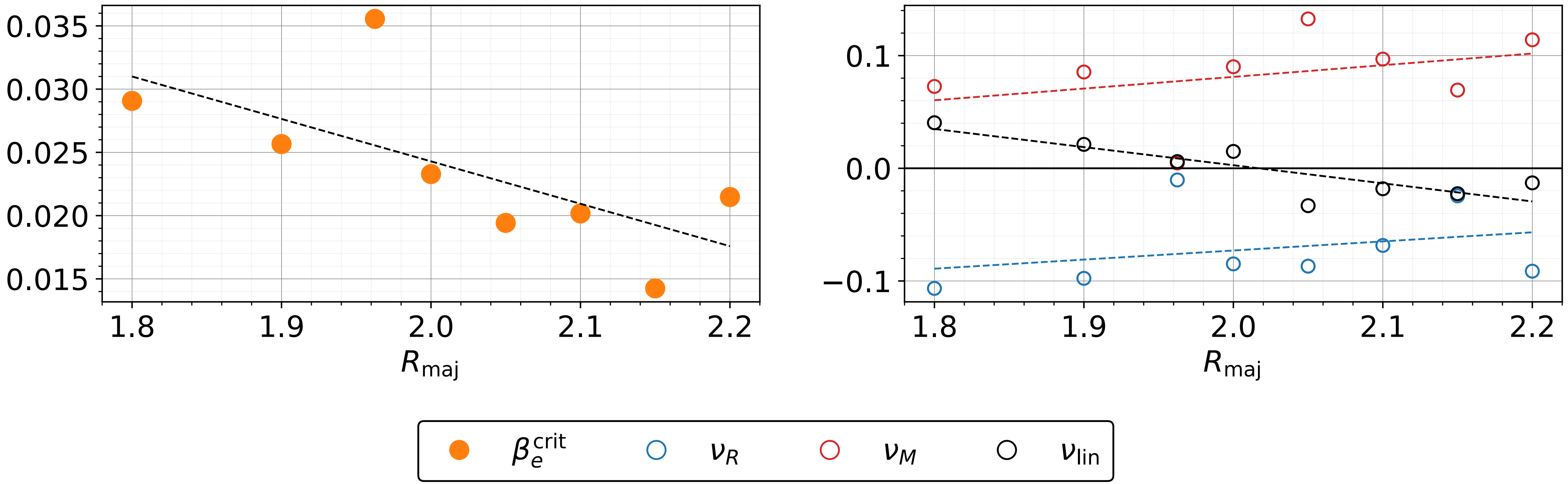
$$\nabla \cdot \mathbf{J} = \nabla \cdot \mathbf{J}_{||} + \nabla \cdot \mathbf{J}_{\perp} = 0$$

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

REFERENCES
[1] Kennedy *et al.* [in prep]
[2] Zhang *et al.* [in prep]

A LIMIT ON BETA POLOIDAL?

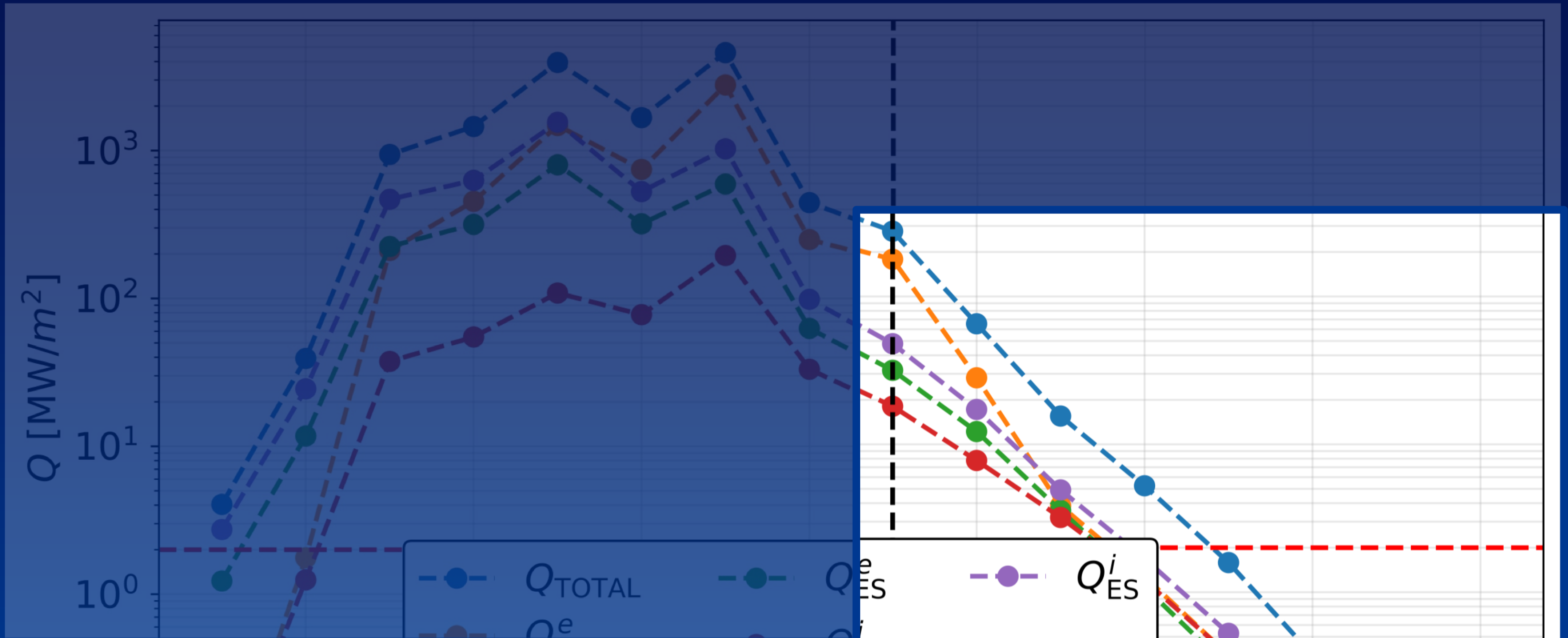
- In the large-aspect-ratio limit, changes to β_e, the shaping parameter $(R/a)^2$, or q^2, all have equivalent physical impact in pushing the system towards the non-zonal regime.



- Nothing here is specific to spherical tokamaks.
- Scaling suggests that this physics is easier to access in conventional-aspect-ratio tokamaks.
- Explains why threshold is much lower in cyclone-base-case (large-aspect-ratio tokamak).

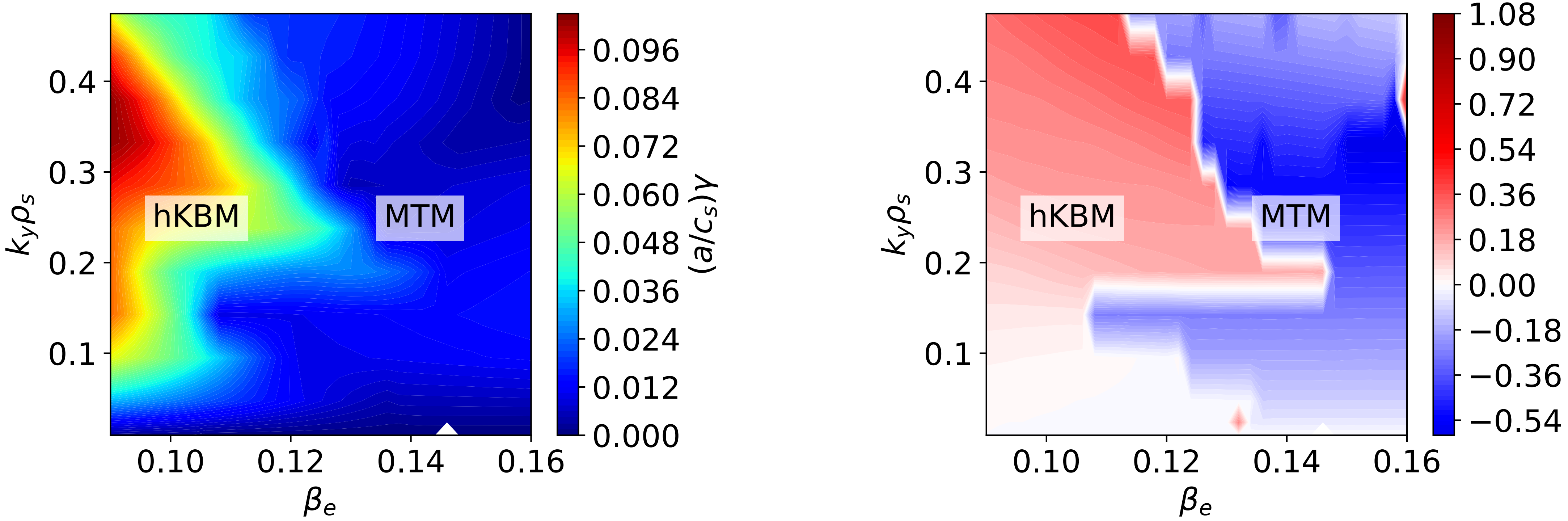
PART II

What causes the return to modest fluxes?



SECOND TRANSITION IS LINEAR PHYSICS

- **First transition** (to large fluxes) is a **nonlinear phenomenon.**
- **Second transition** (return to modest fluxes) is **linear physics**; stabilisation of KBM-like modes.

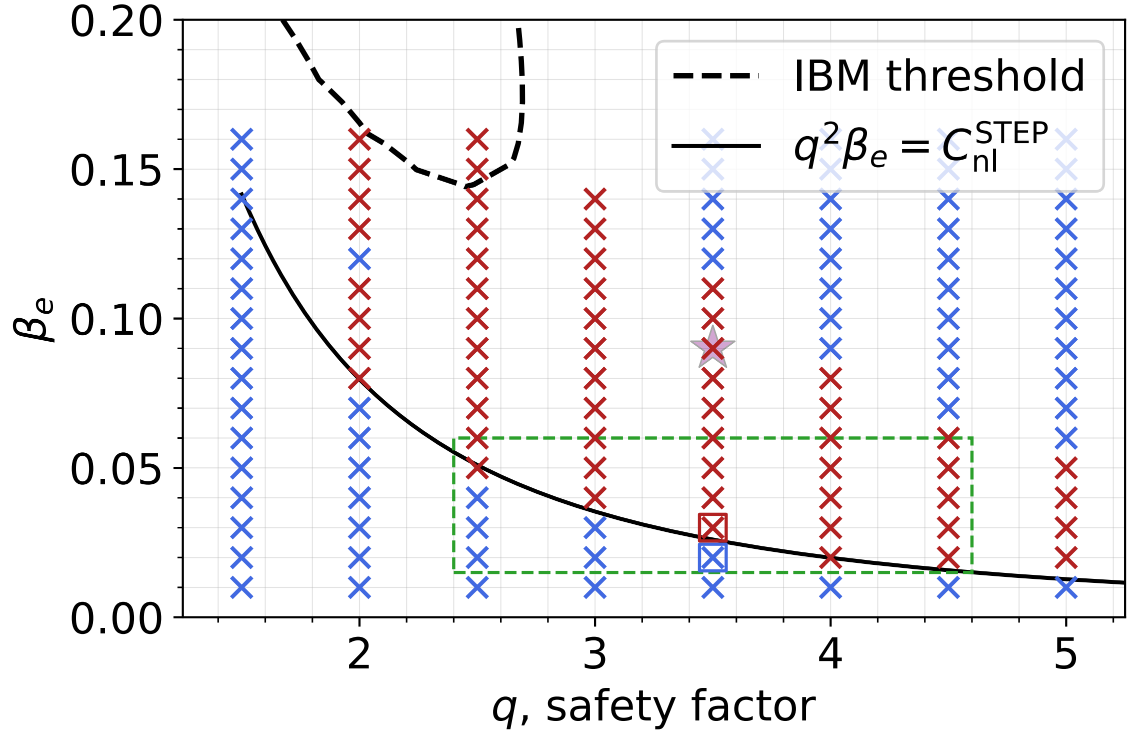


- β' stabilisation [15]. Pressure gradient now **decreases effective local shear** and **field-line bending** on outboard midplane.
- Deep connection to the ideal ballooning mode.

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

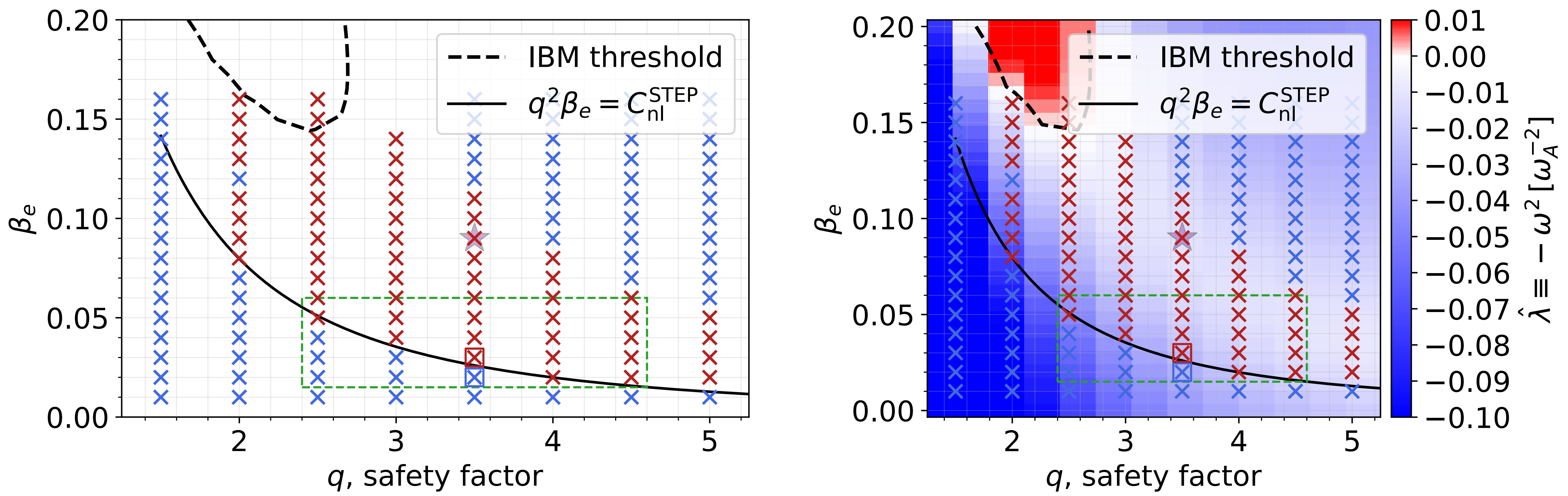
RELATIONSHIP TO IDEAL BALLOONING

- The **ideal ballooning mode** is a pressure-gradient–driven instability that "balloons" on the outboard (bad-curvature) side when magnetic field lines can't bend enough to oppose the outward push from the pressure gradient.



RELATIONSHIP TO IDEAL BALLOONING

- The **ideal ballooning mode** is a pressure-gradient–driven instability that "balloons" on the outboard (bad-curvature) side when magnetic field lines can't bend enough to oppose the outward push from the pressure gradient.



KEY

■ $\hat{\lambda} > 0 \longrightarrow$ IBM unstable $\longrightarrow$ growth rate of unstable IBM

■ $\hat{\lambda} < 0 \longrightarrow$ IBM stable $\longrightarrow$ real frequency of shear Alfvén wave

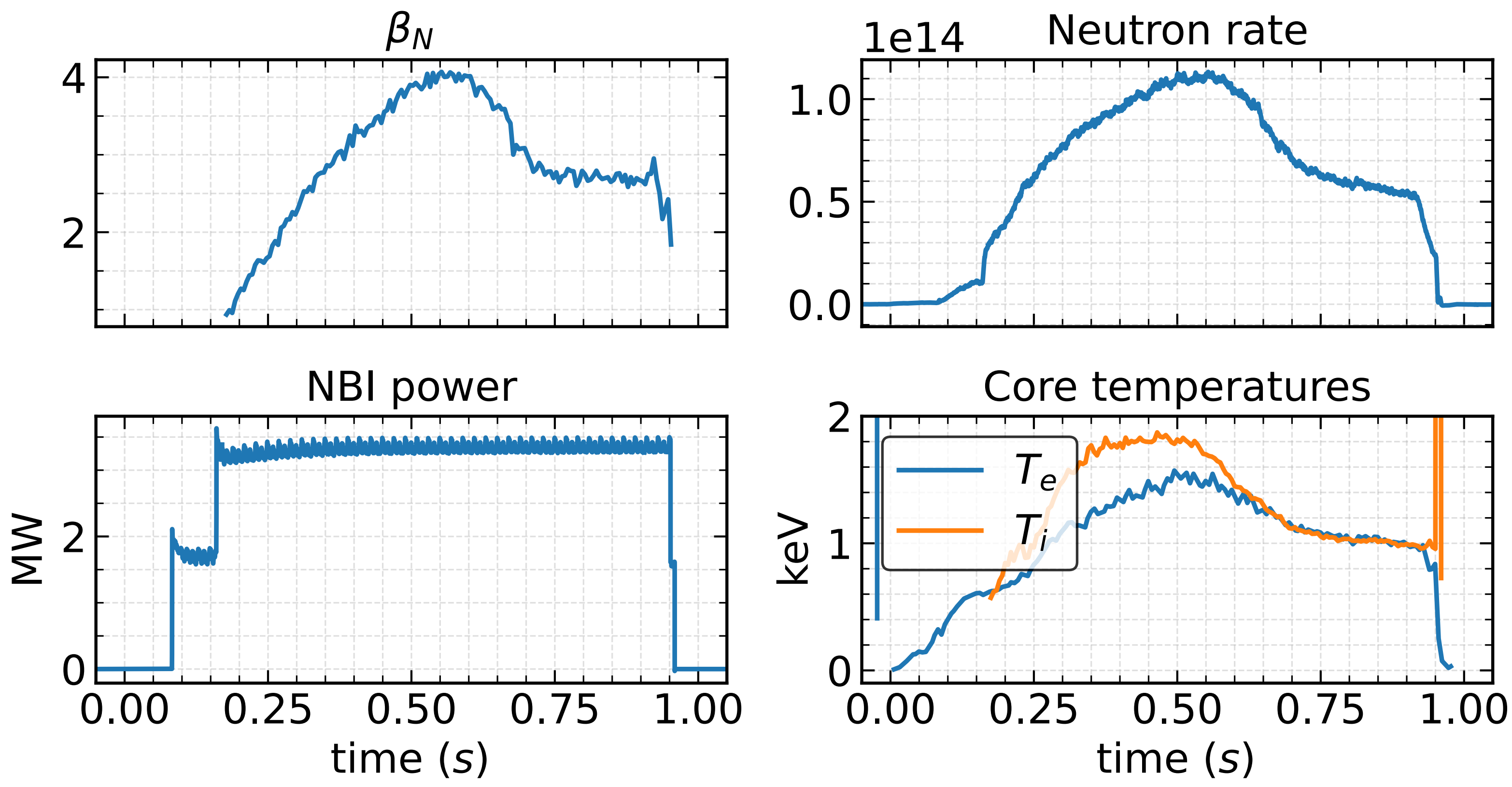
STEP

PART III

Can we explore these ideas in modern day experiments?

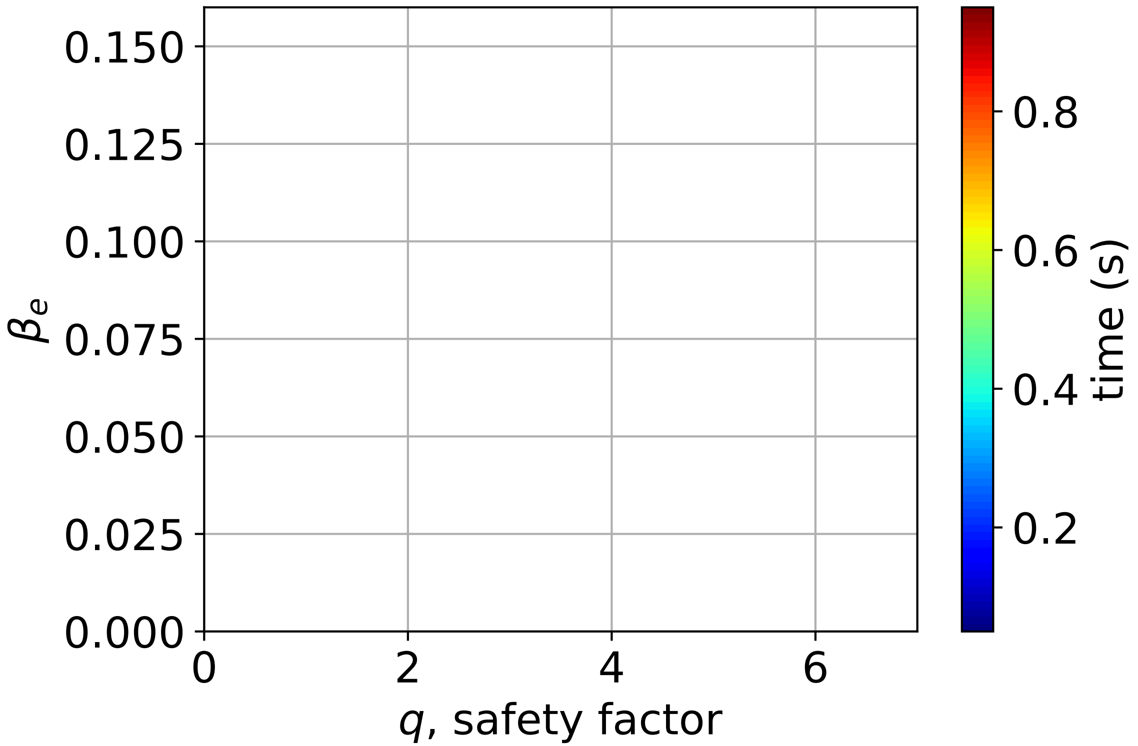
MAST–U #48657

- 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 $\boldsymbol{\beta_N \sim 4}$ (one of the highest achieved on MAST-U).



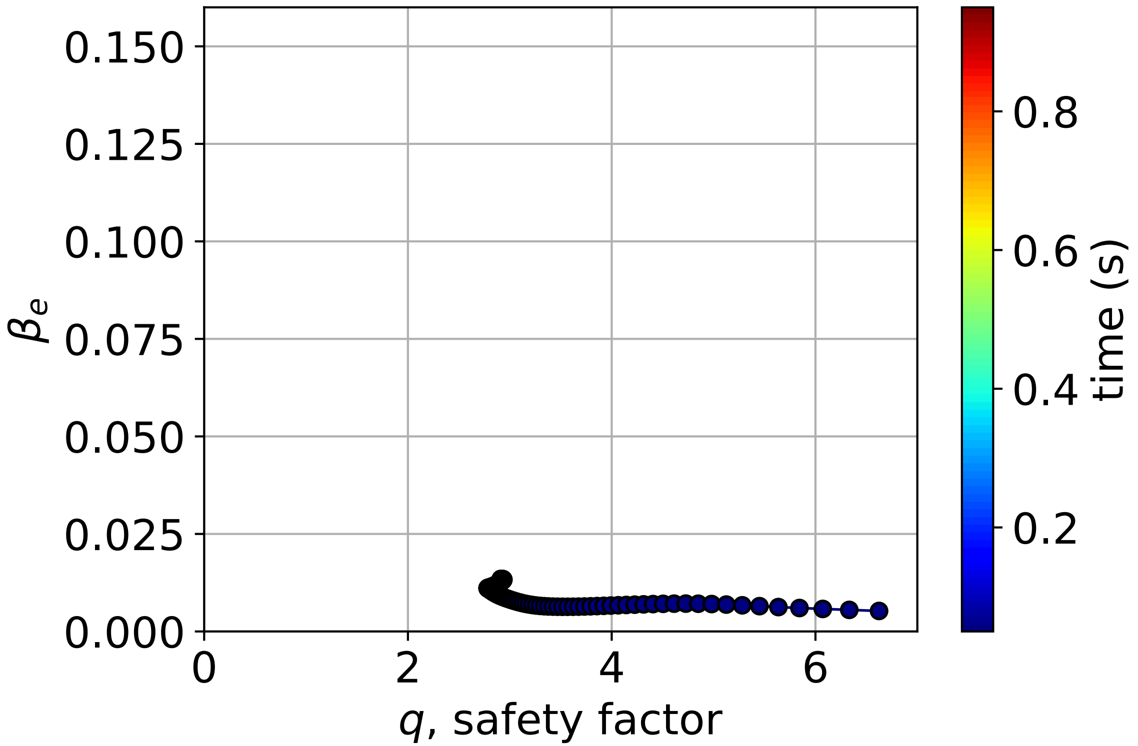
WHERE HAS MAST–U BEEN?

- Range of q and β_e values accessed during a single MAST-U high-performance discharge **(#48657).**



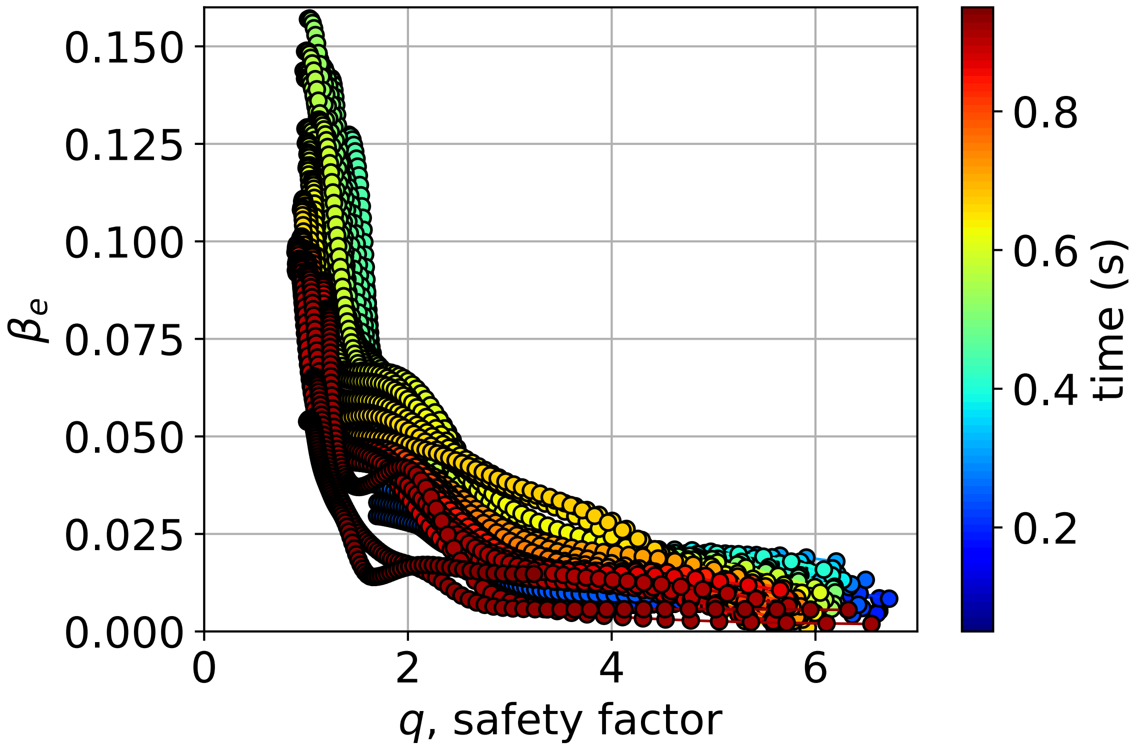
WHERE HAS MAST–U BEEN?

- Range of q and β_e values accessed during a single MAST-U high-performance discharge **(#48657).**



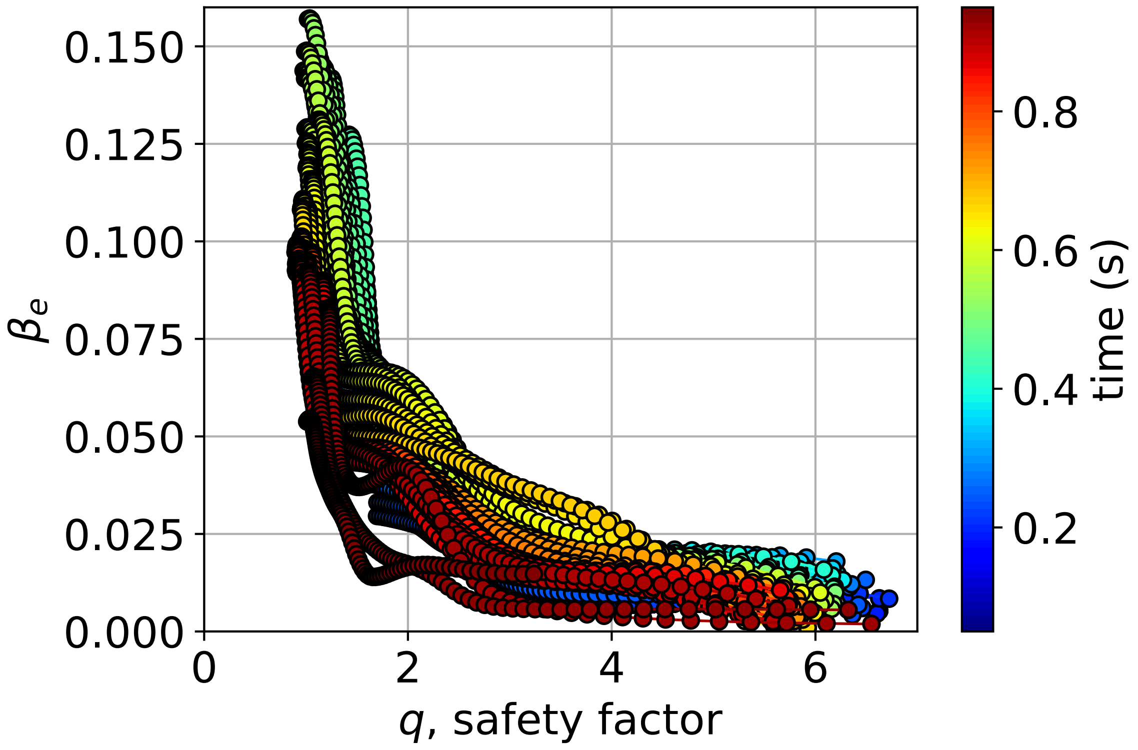
WHERE HAS MAST–U BEEN?

- Range of q and β_e values accessed during a single MAST-U high-performance discharge **(#48657).**



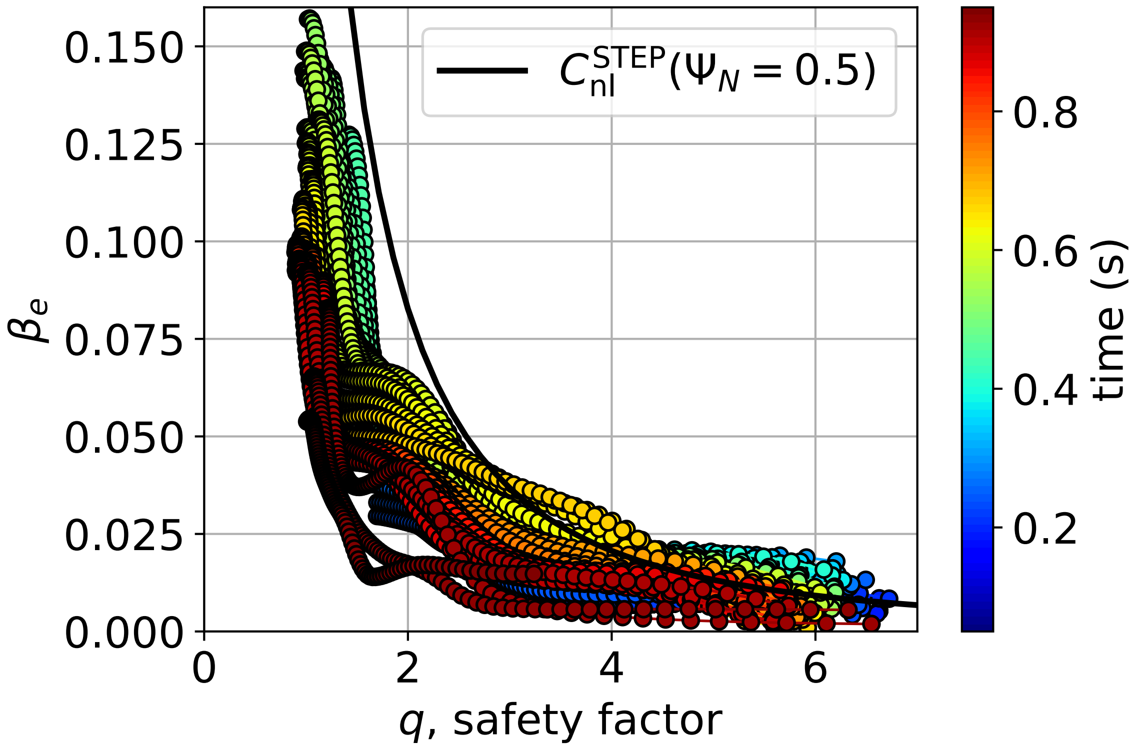
WHERE HAS MAST-U BEEN?

- Range of q and β_e values accessed during a single MAST-U high-performance discharge **(#48657).**
- How does this compare to our STEP gyrokinetic threshold?



WHERE HAS MAST-U BEEN?

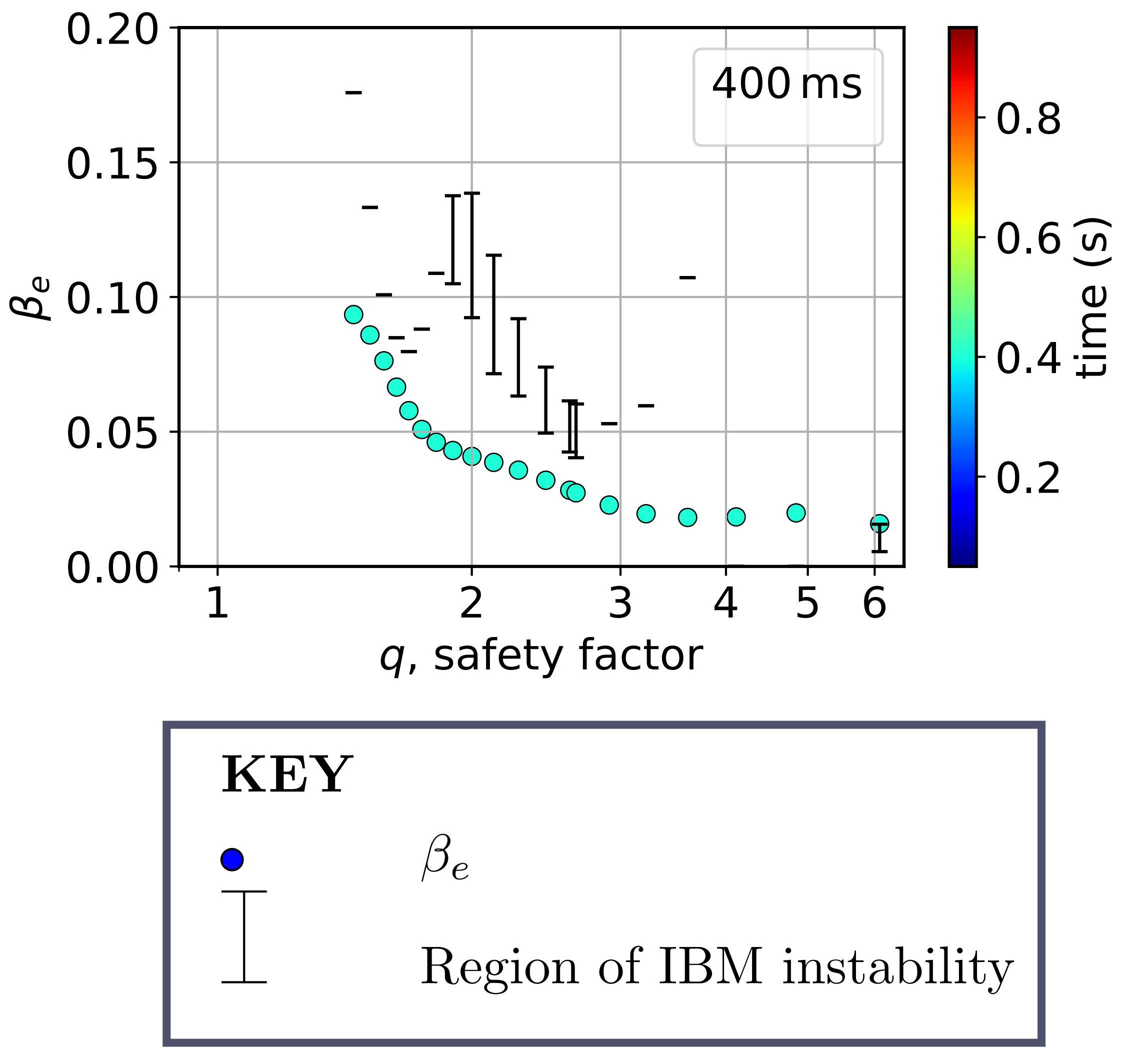
- Range of q and β_e values accessed during a single MAST-U high-performance discharge **(#48657).**
- How does this compare to our STEP gyrokinetic threshold?



- MAST-U has seemingly come close to regions of parameter space where local GK returns large fluxes.
- Must be taken cum-grano-salis since we are now talking about a global plasma vs a local threshold.

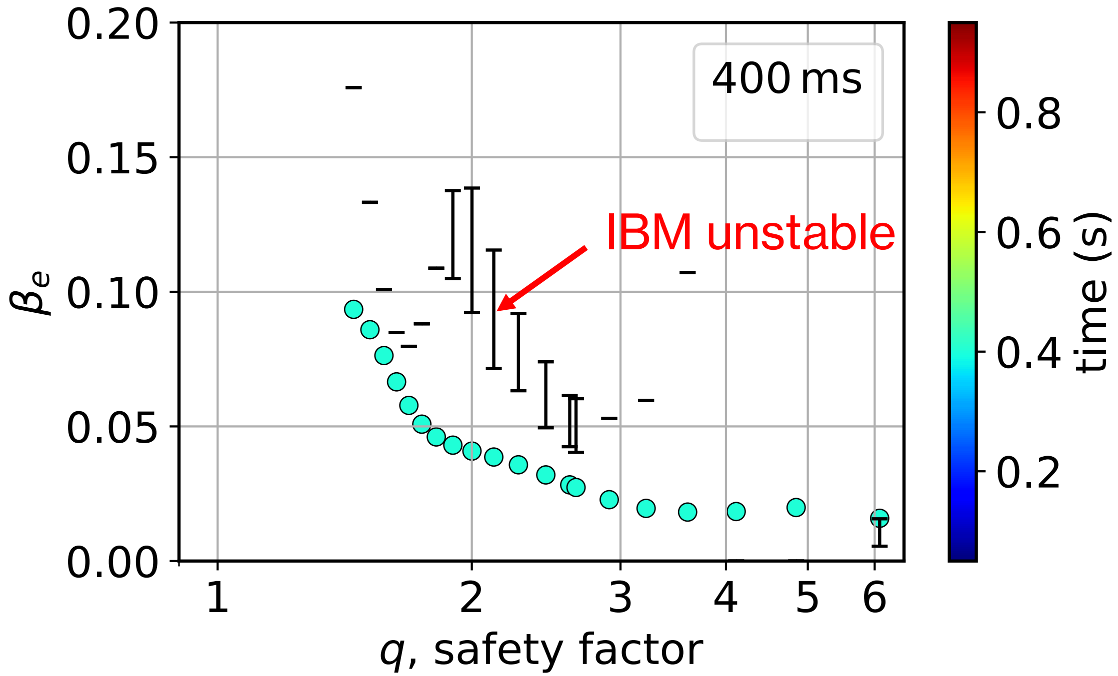
CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



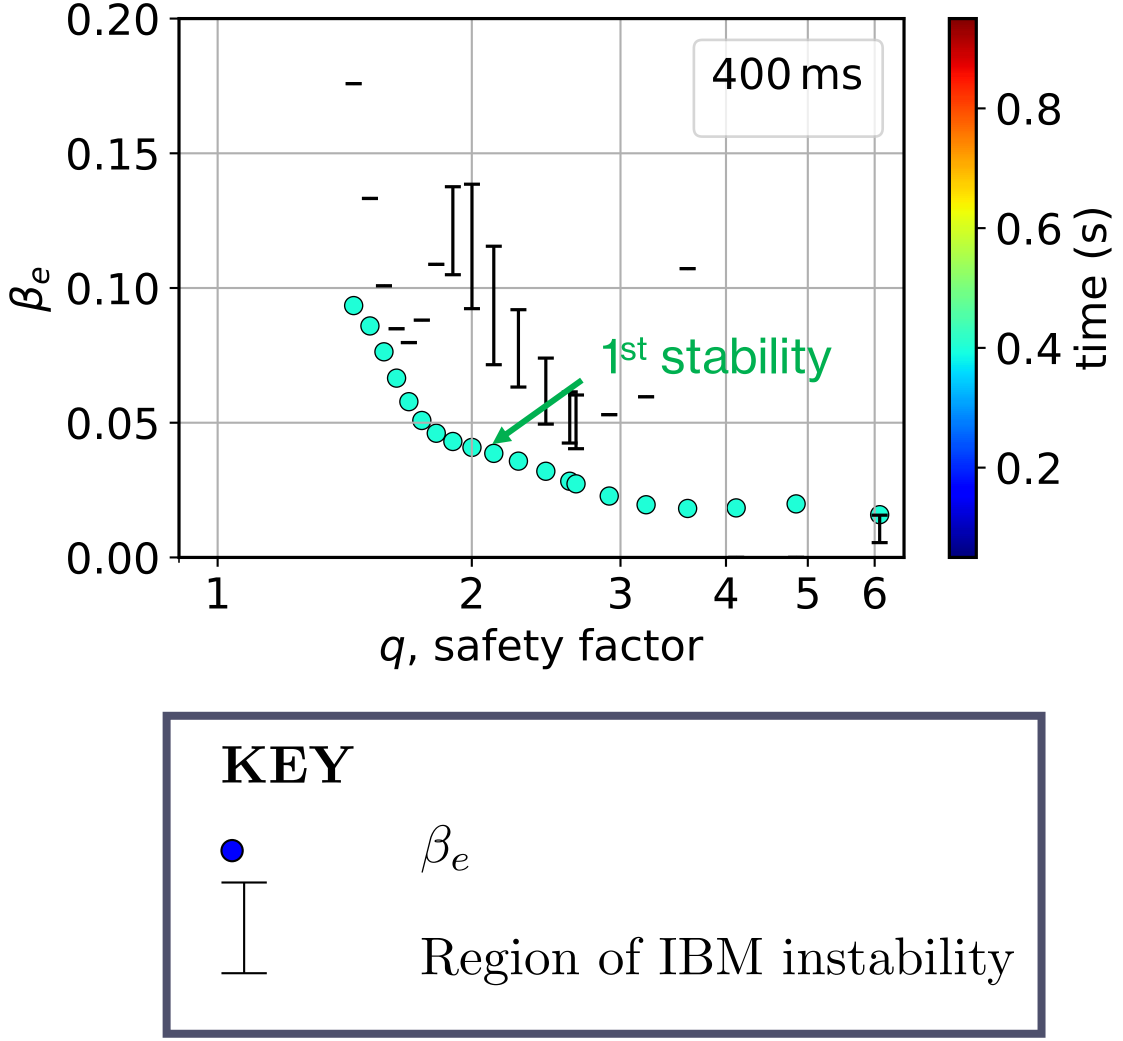
KEY

● β_e

⌶ Region of IBM instability

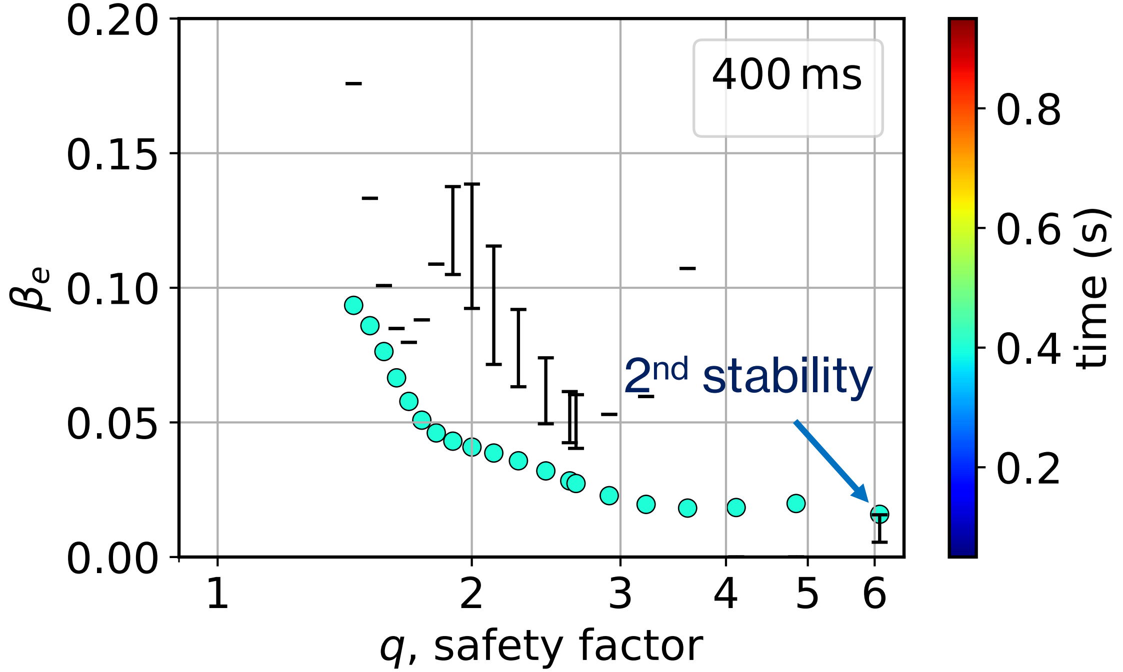
CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



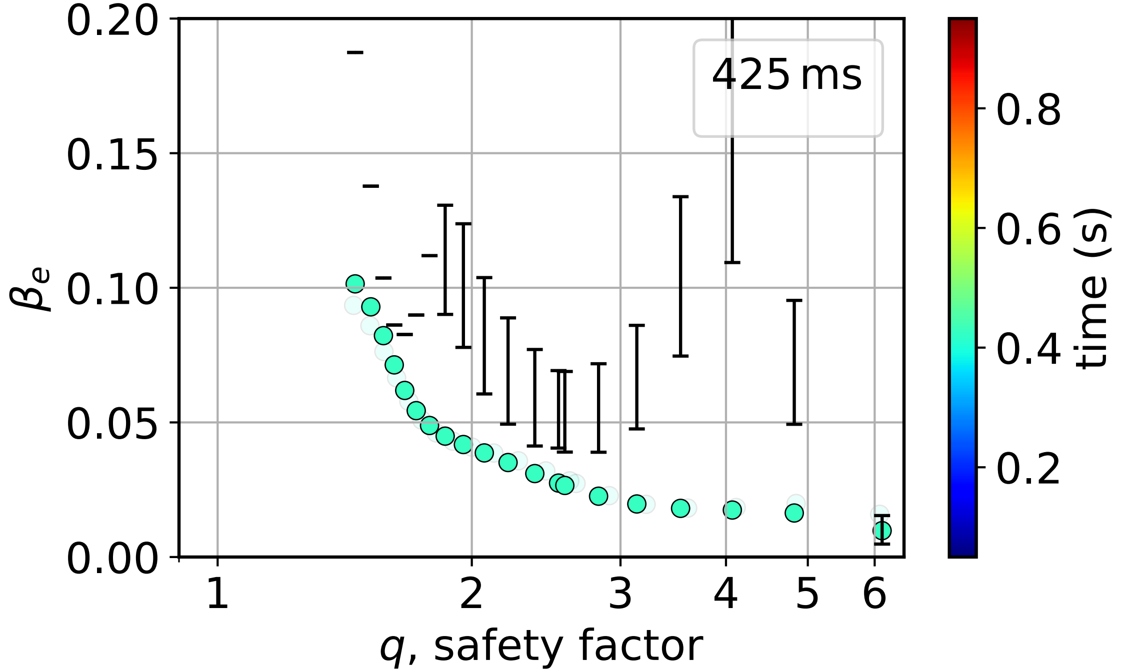
CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



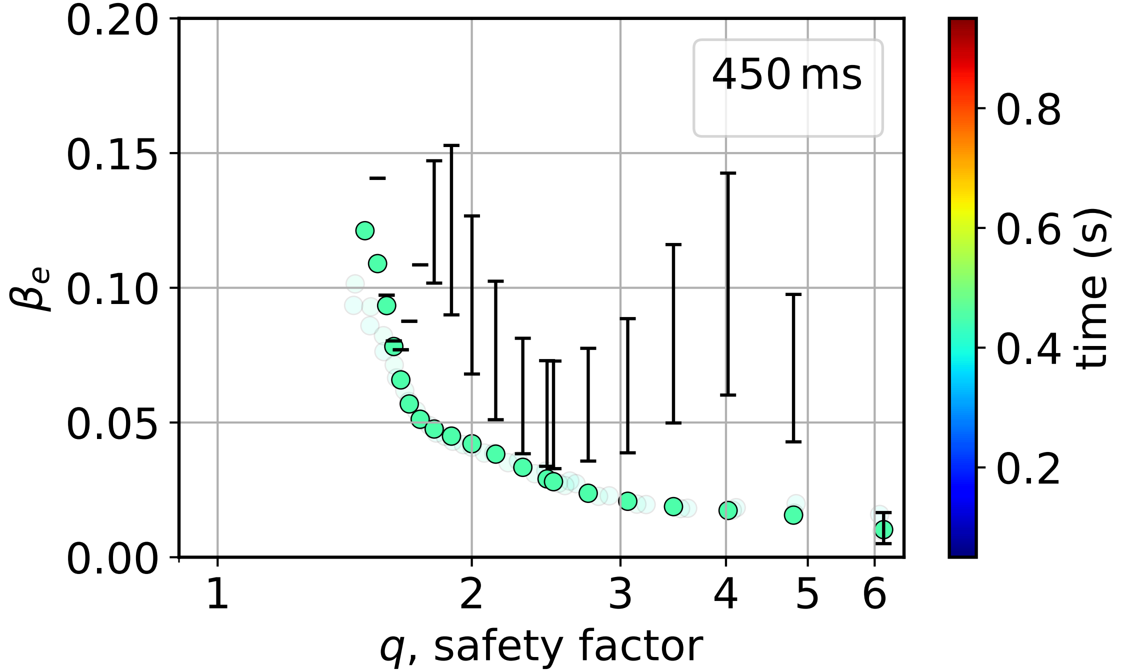
KEY

● β_e

⌶ Region of IBM instability

CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**

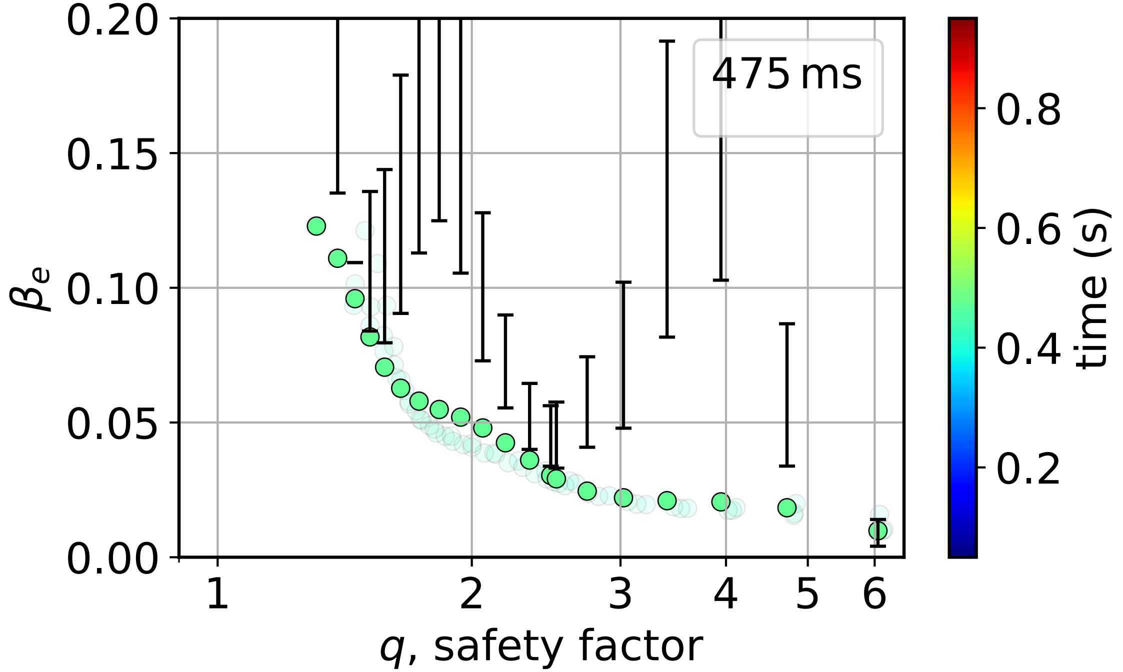


KEY

- ● β_e
- ⊥ Region of IBM instability

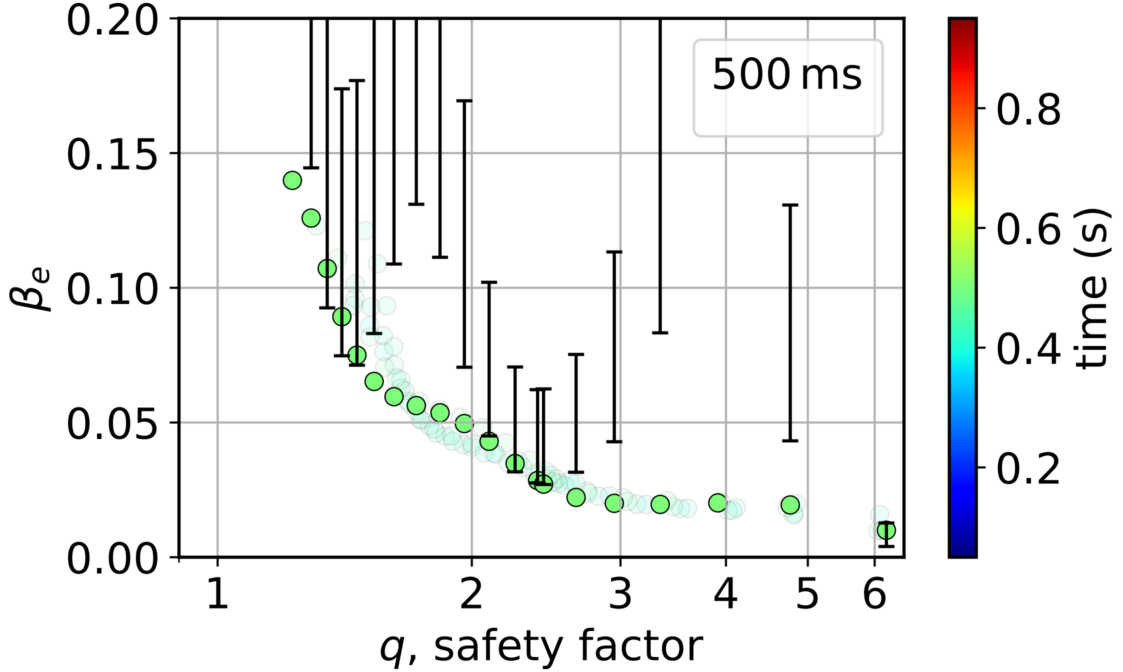
CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



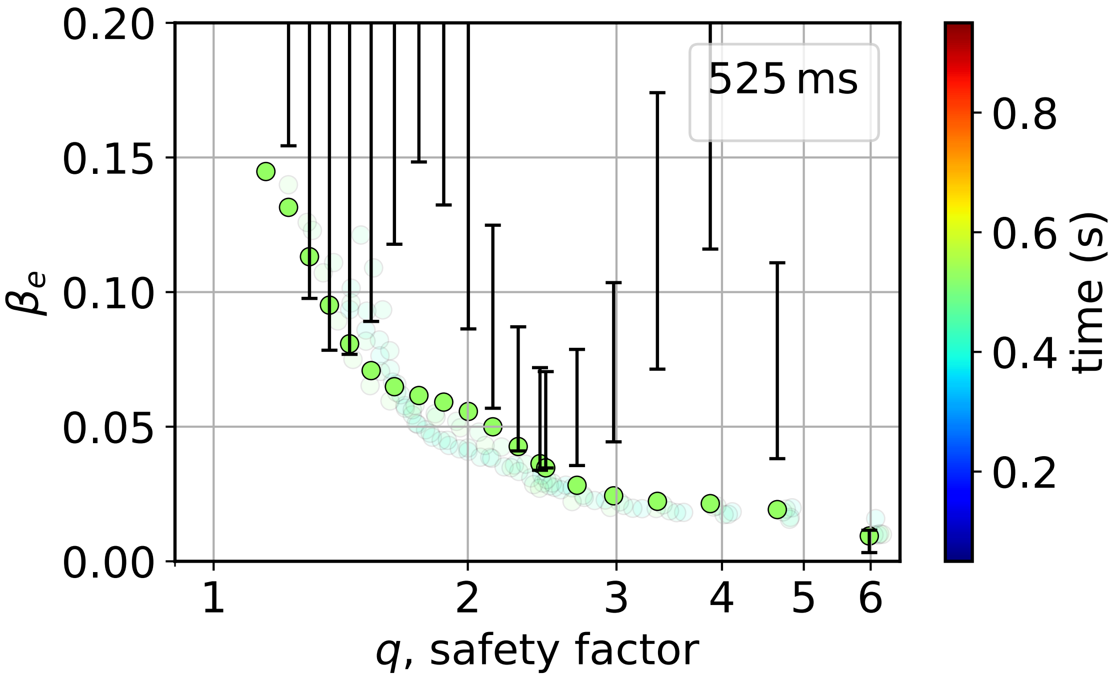
CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



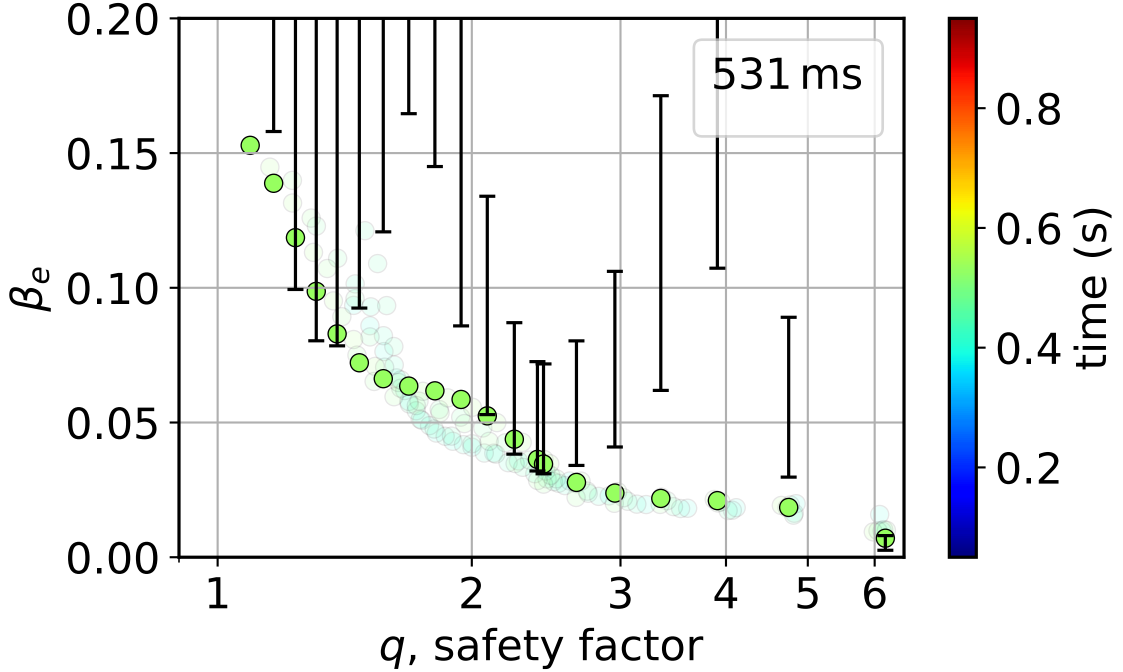
KEY

β_e

Region of IBM instability

CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



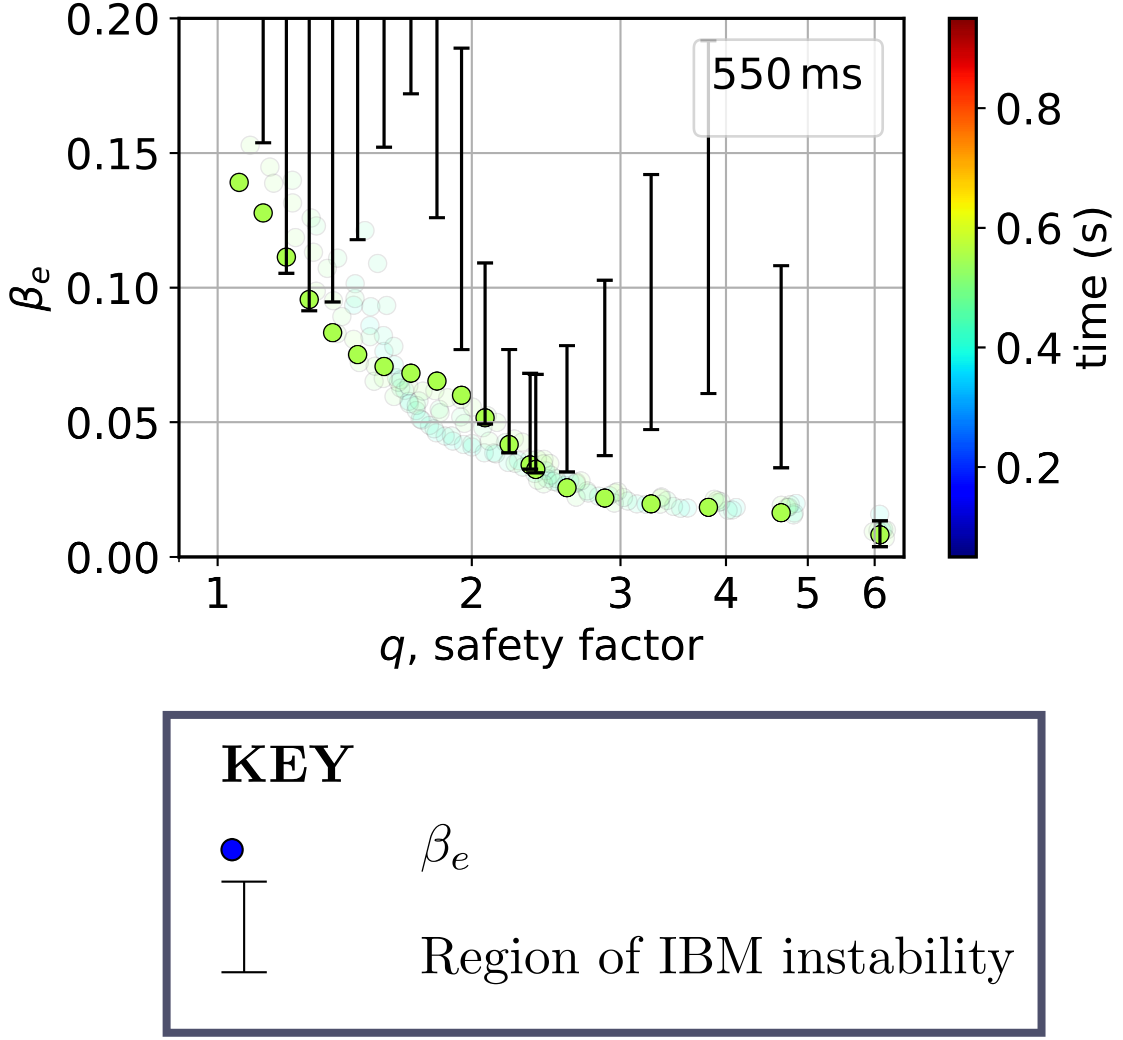
KEY

β_e

Region of IBM instability

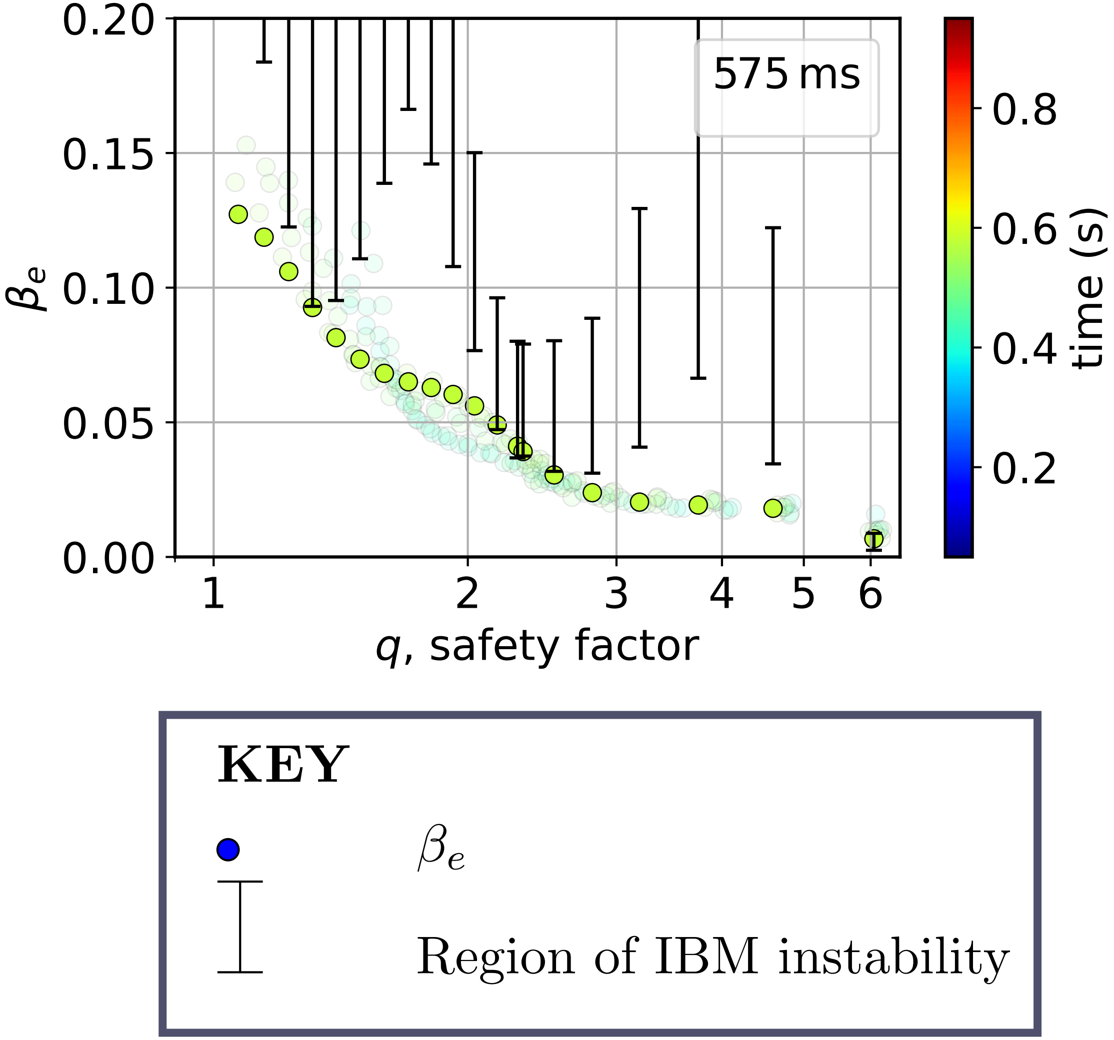
CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



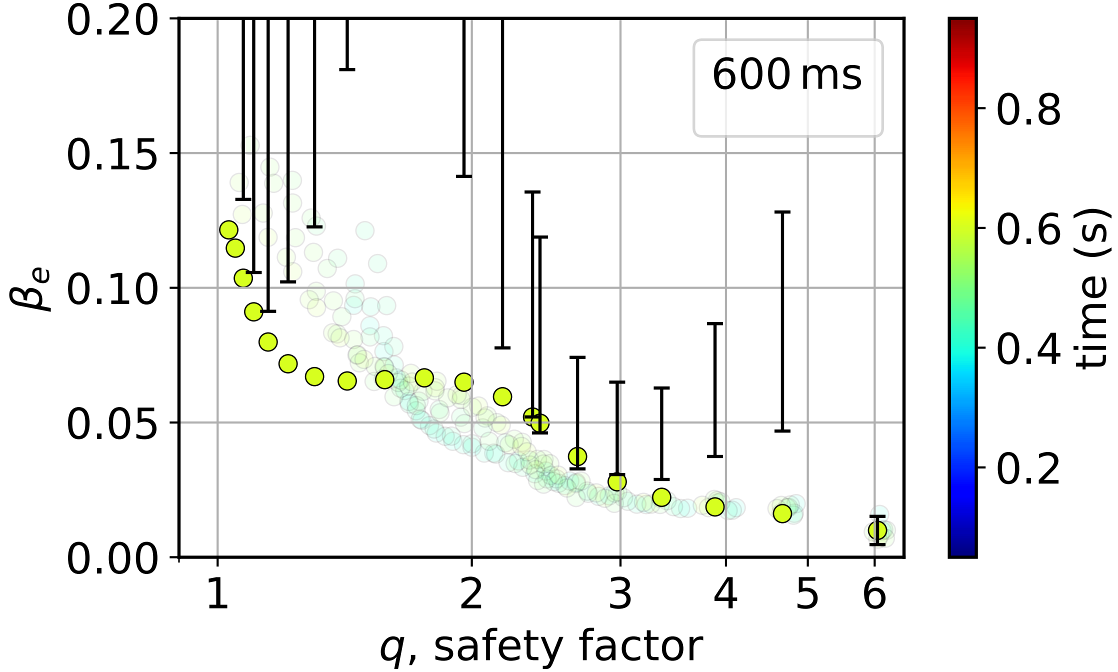
CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



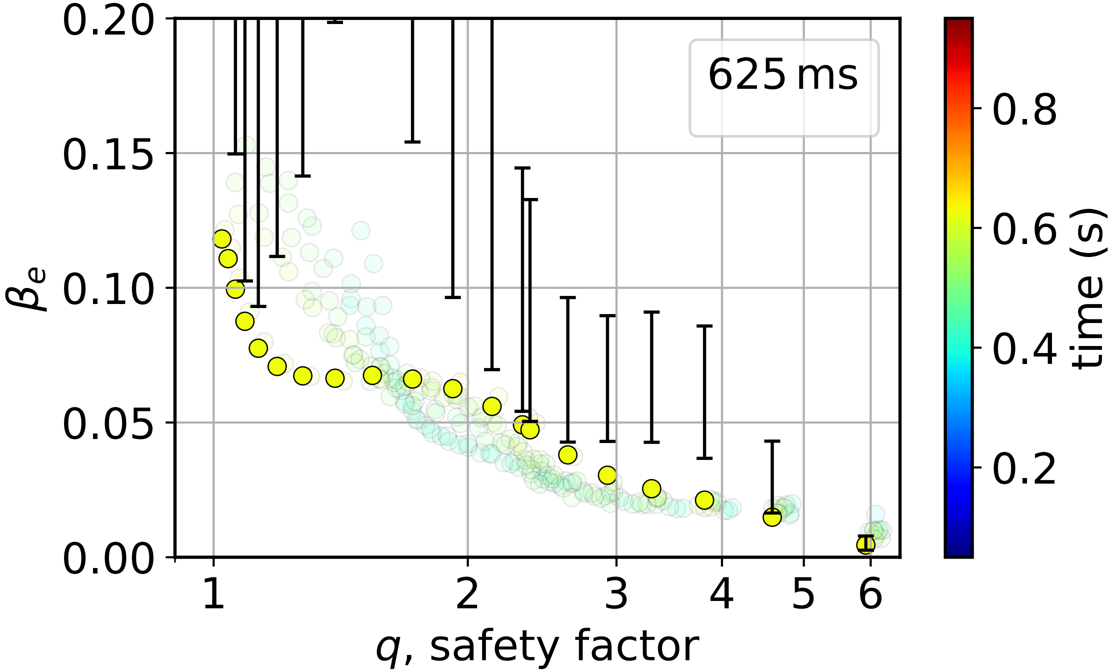
CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



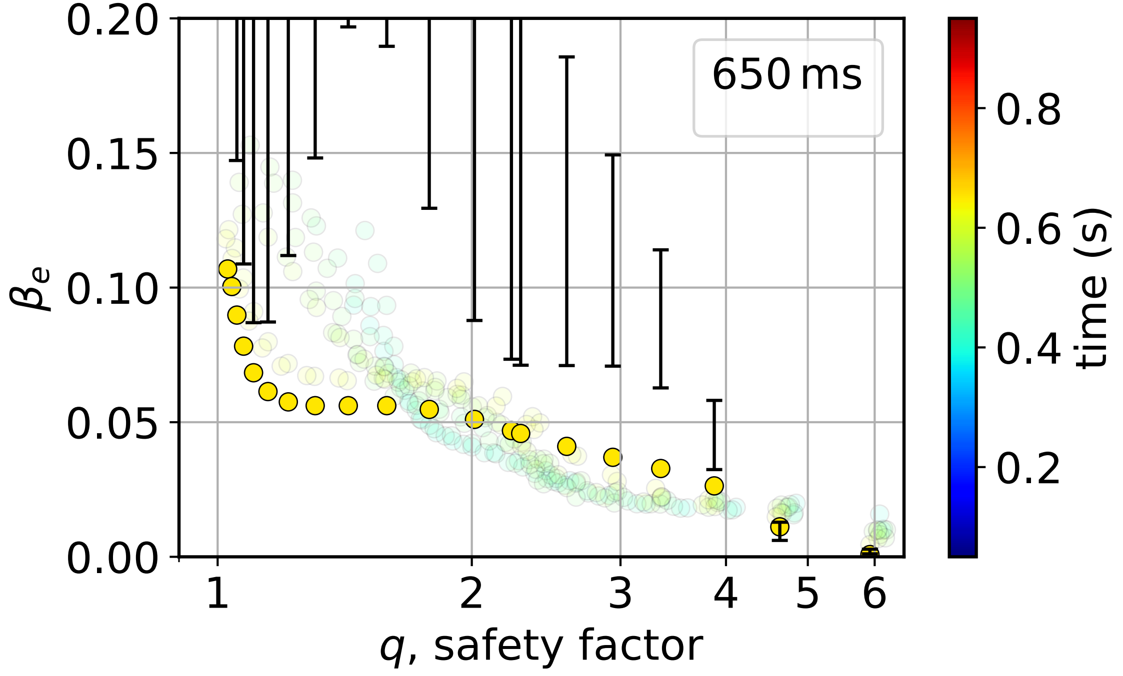
KEY

β_e

Region of IBM instability

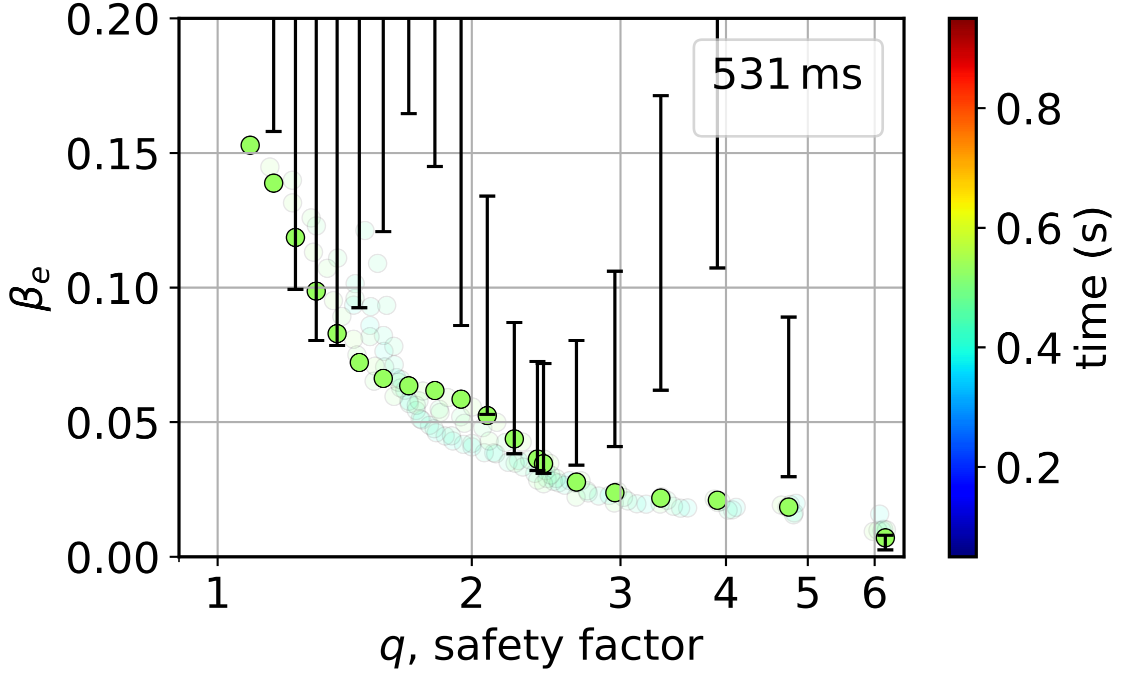
CONNECTION TO IDEAL BALLOONING

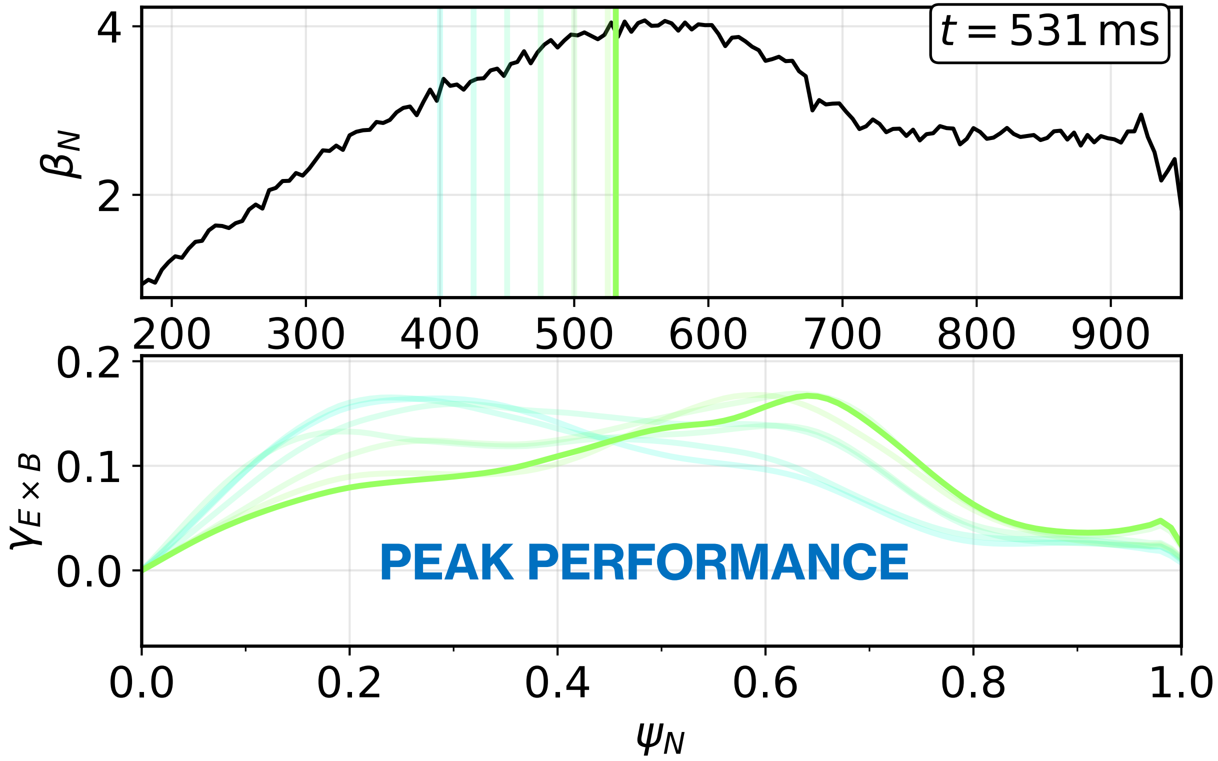
- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**



CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**

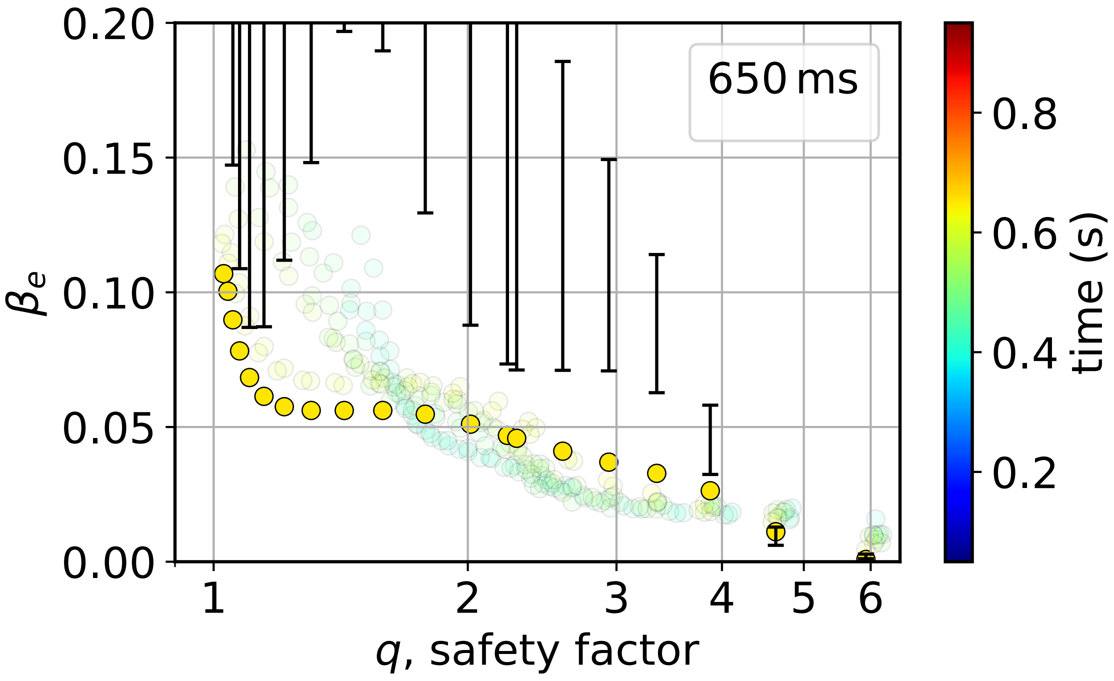


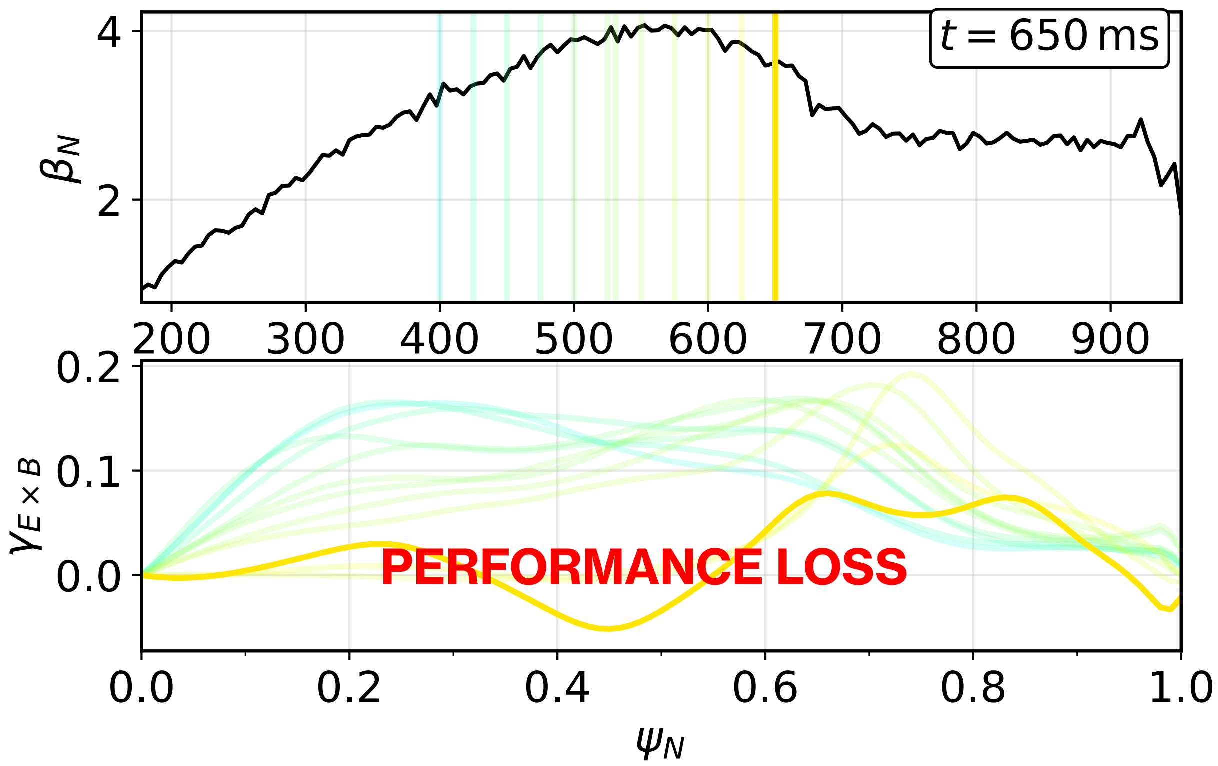


- **MAST-U accesses STEP relevant** (q, β_e) **in the presence of strong flow shear.**
- Spot checked with GK simulations.

CONNECTION TO IDEAL BALLOONING

- A fair comparison requires at least one GK simulation **for each flux surface at each time step**.
- As a fast proxy, **evaluate ideal ballooning stability for each flux surface at each time step.**





- **Experimental performance degrades when the flow shear is lost.**
- MHD activity complicates analysis and interpretation.

PART IV

Conclusions and Outlook

CONCLUSIONS

Critical transitions and transport bifurcations:

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

CALL TO ACTION: 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 β_e, the system can re-saturate and access a second-stable confinement state, with the ideal ballooning threshold serving as a useful proxy.

- Bifurcation behaviour implies strong sensitivity to initial conditions in self-consistent transport simulations. we need to understand and model what happens at bifurcations to improved flux states.

Experimental validation:

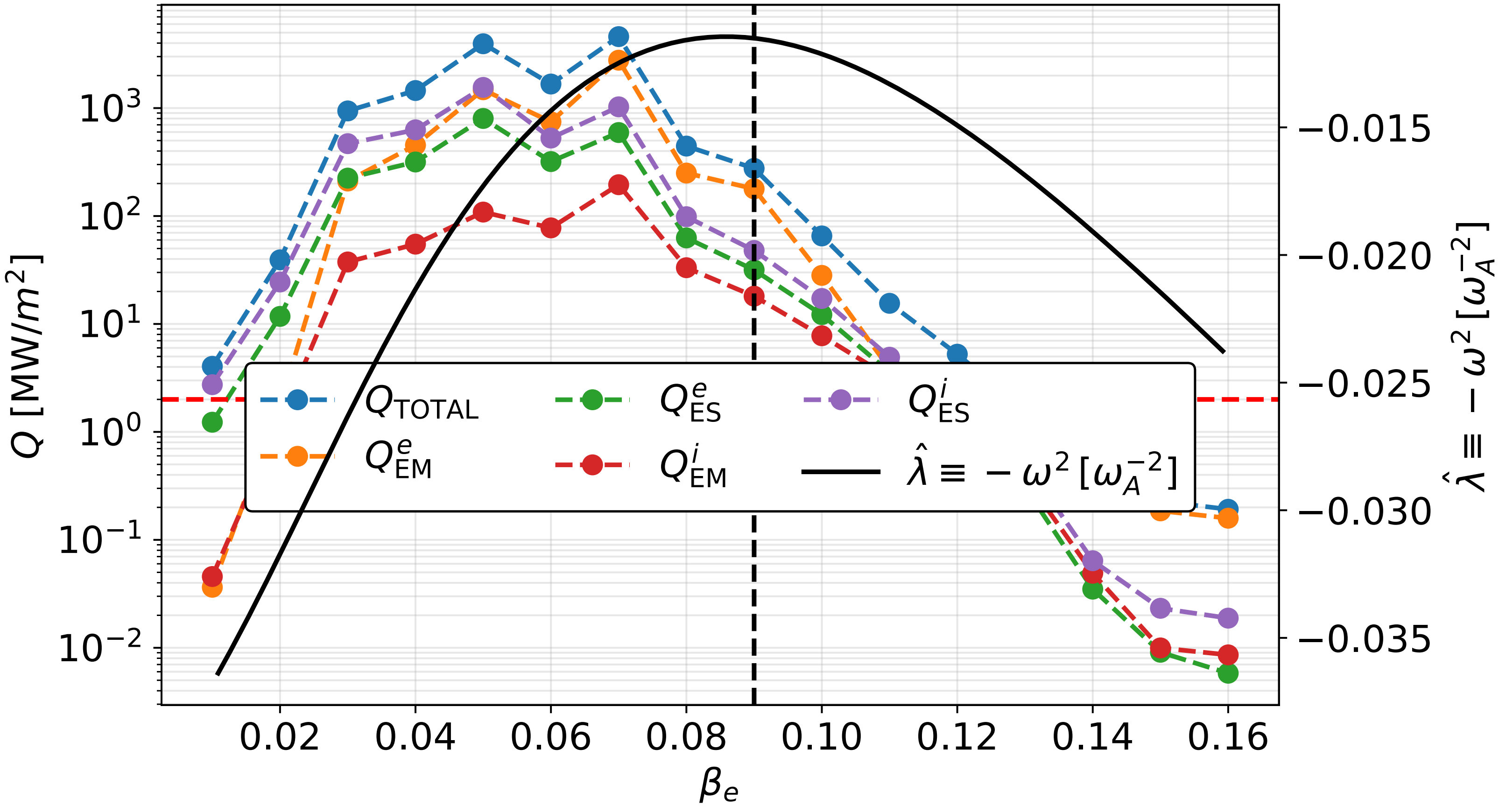
- Present-day experiments can already access STEP-relevant $(\mathrm{q}, \beta_{\mathrm{e}})$ regimes, but seemingly only in the presence of γ_{E}. Loss of sufficient shear is typically followed be a severe loss of performance in high $\mathrm{q}^2\beta_{\mathrm{e}}$.

Flow shear sensitivity:

- 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.

MOVING STEP AWAY FROM IBM BOUNDARY

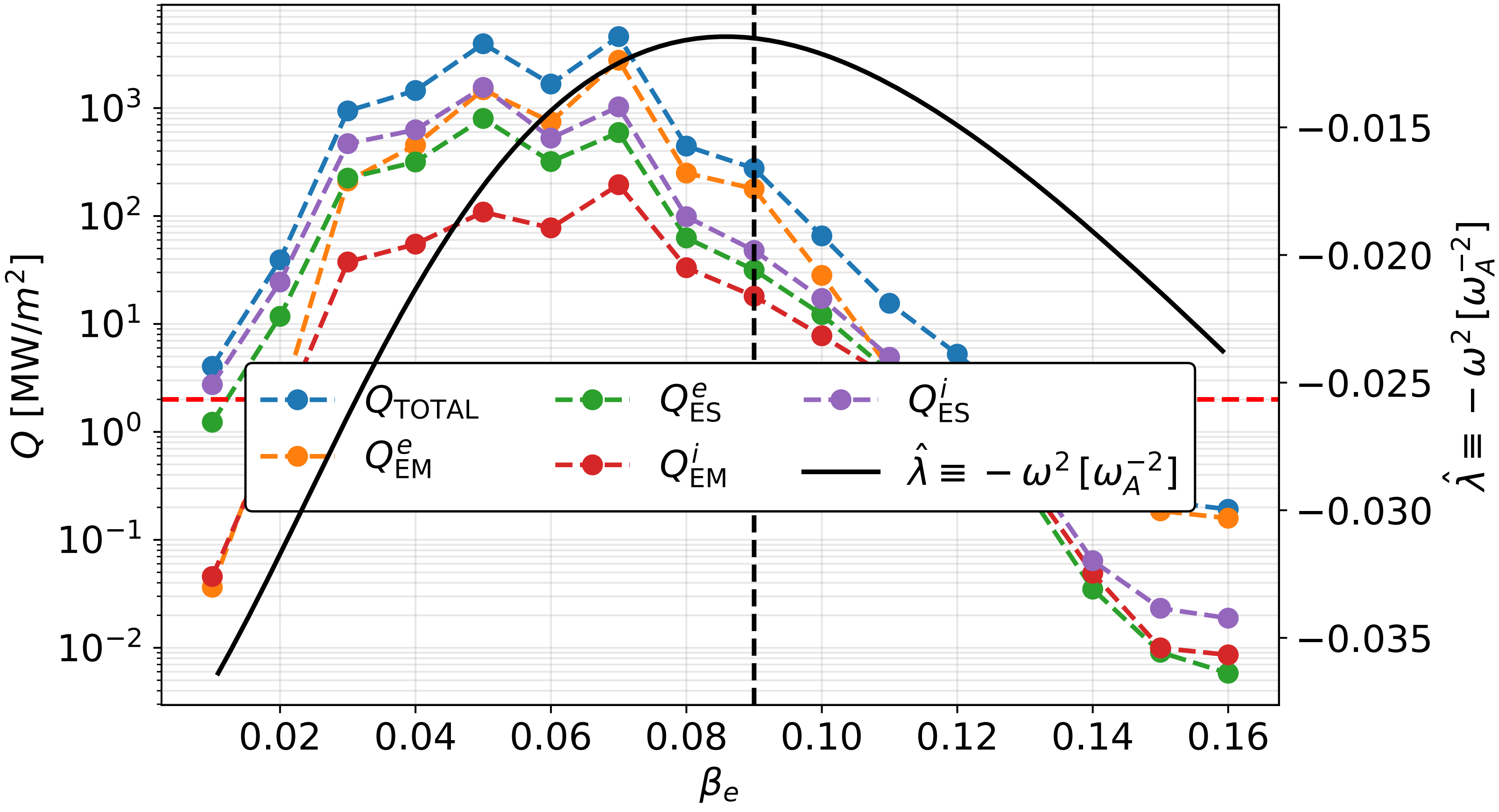
- The **ideal ballooning mode eigenvalue** is a reasonable proxy for the heat flux. In particular, it captures access to second-stability.



- Use IBM-driven insights to optimise the STEP scenario development.

MOVING STEP AWAY FROM IBM BOUNDARY

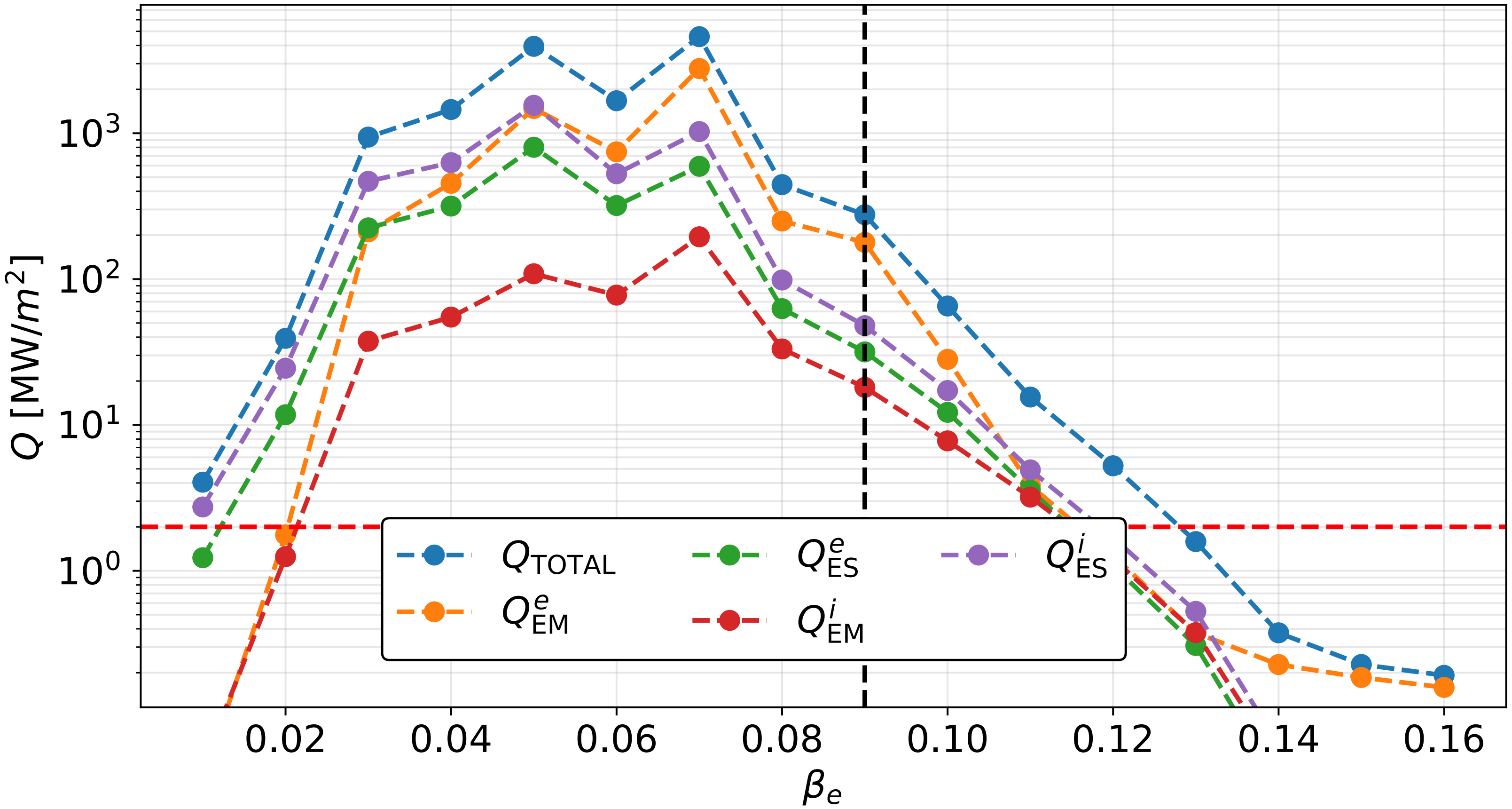
- The **ideal ballooning mode eigenvalue** is a reasonable proxy for the heat flux. In particular, it captures access to second-stability.



- Use IBM-driven insights to optimise the STEP scenario development.

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT\ /\ (B^2\ /\ 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).

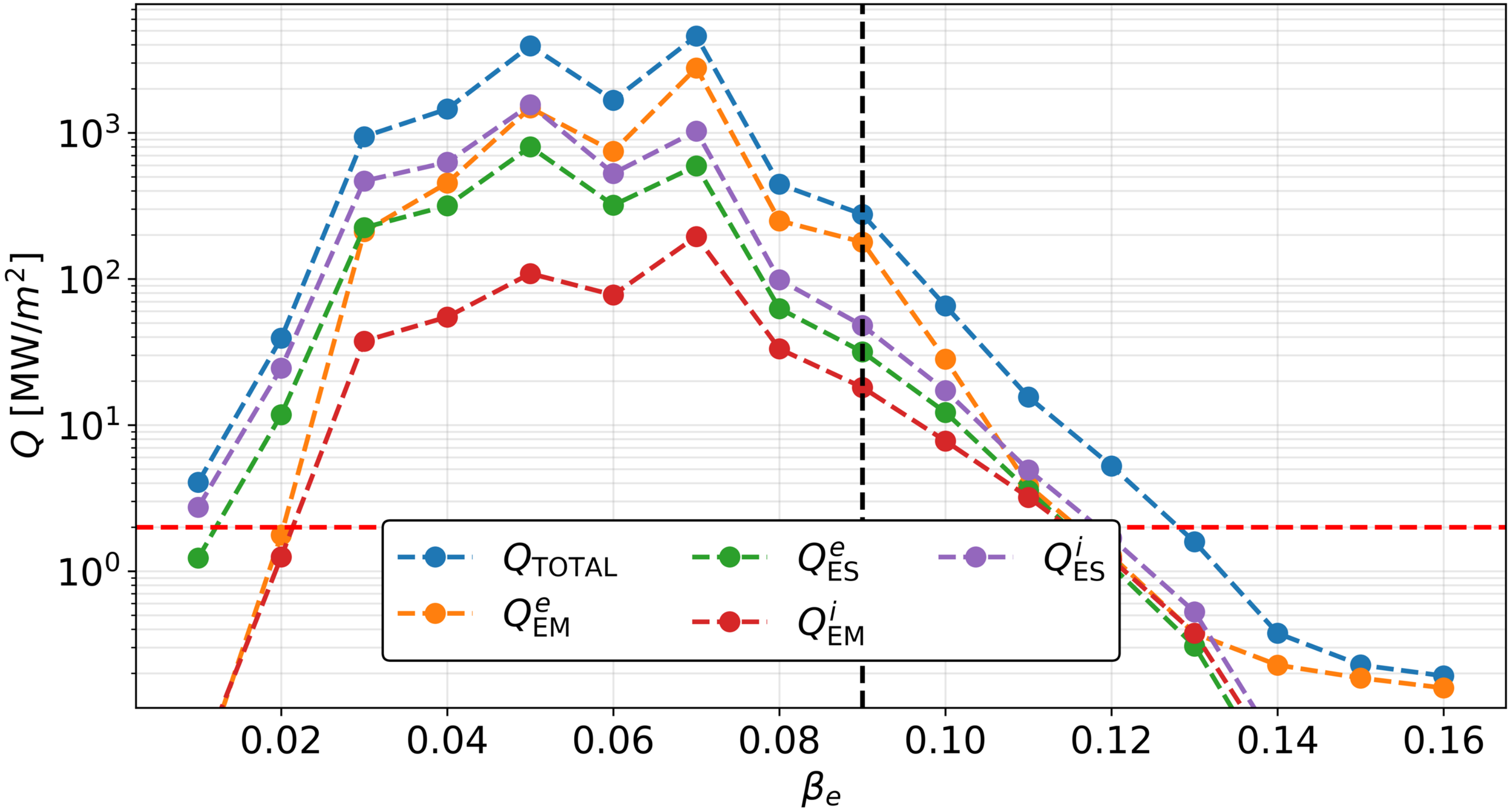


- **No** (equilibrium) **flow shear**. Reasonable given no external momentum sources in STEP.
- **Representative** of a more general trend [2,8].

REFERENCES
[3] Kennedy *et al.* (2023)
[4] Kennedy *et al.* (2024)
[5] Giacomin *et al.* (2024)
[6] Tholerus *et al.* (2024)
[7] Giacomin *et al.* (2025)
[8] Pueschel *et al.* (2013)

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT \,/\, (B^2 \,/\, 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).

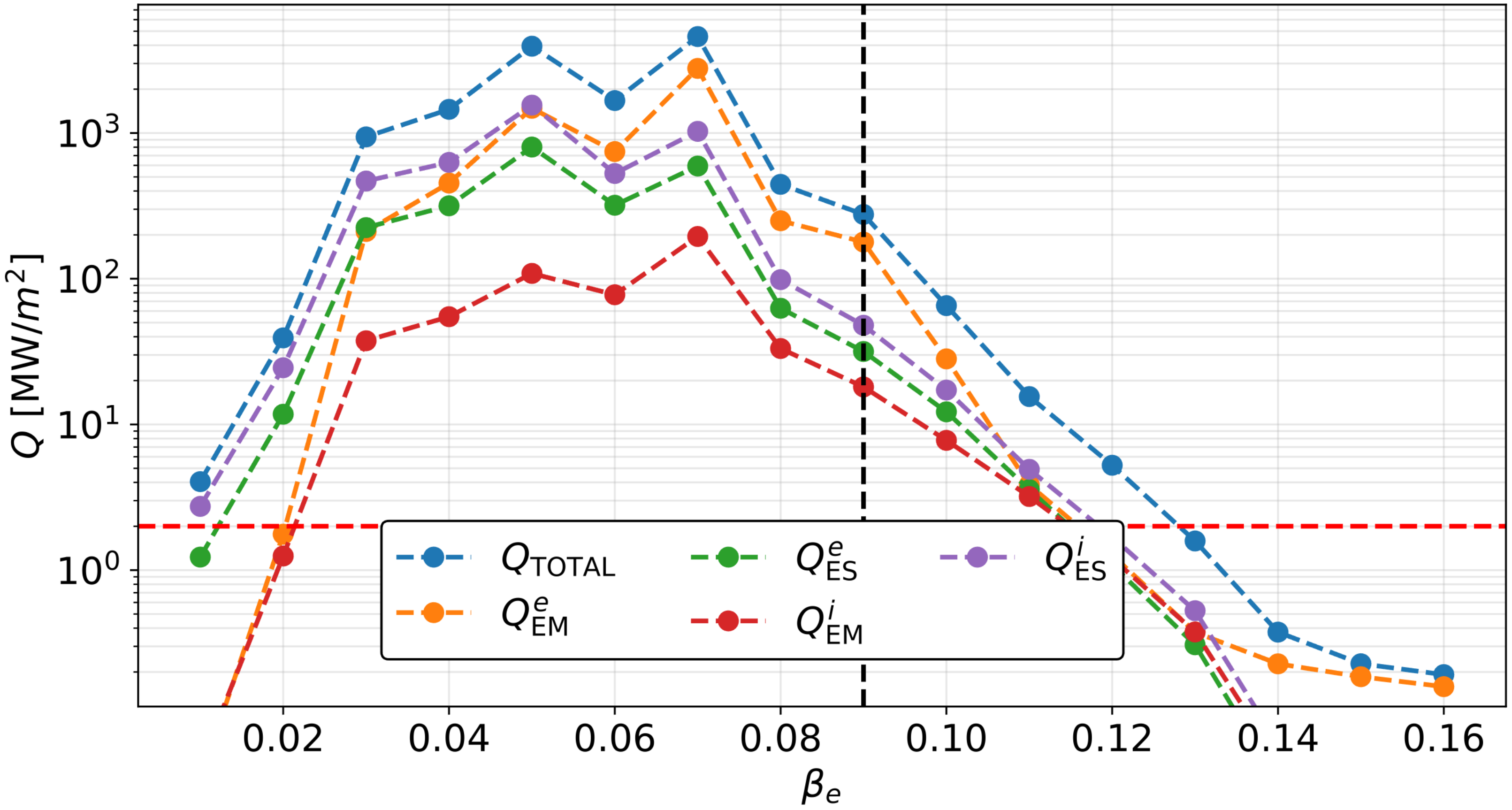


- **No** (equilibrium) **flow shear**. Reasonable given no external momentum sources in STEP.
- **Representative** of a more general trend [2,8].

REFERENCES
[3] Kennedy *et al.* (2023)
[4] Kennedy *et al.* (2024)
[5] Giacomin *et al.* (2024)
[6] Tholerus *et al.* (2024)
[7] Giacomin *et al.* (2025)
[8] Pueschel *et al.* (2013)

PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** returned by **local gyrokinetic simulations** of an early **STEP-FTOP** (STEP-HD-EC) [3,4,5,6,7].
- $\beta[\equiv nT\ /\ (B^2\ /\ 2\mu_0)]$ scan on reference surface ($\gamma_E = 0$) with $\beta \propto \beta'$ (i.e., consistent with scaling p profile).



- **No** (equilibrium) **flow shear**. Reasonable given no external momentum sources in STEP.
- **Representative** of a more general trend [2,8].

REFERENCES
[3] Kennedy *et al.* (2023)
[4] Kennedy *et al.* (2024)
[5] Giacomin *et al.* (2024)
[6] Tholerus *et al.* (2024)
[7] Giacomin *et al.* (2025)
[8] Pueschel *et al.* (2013)