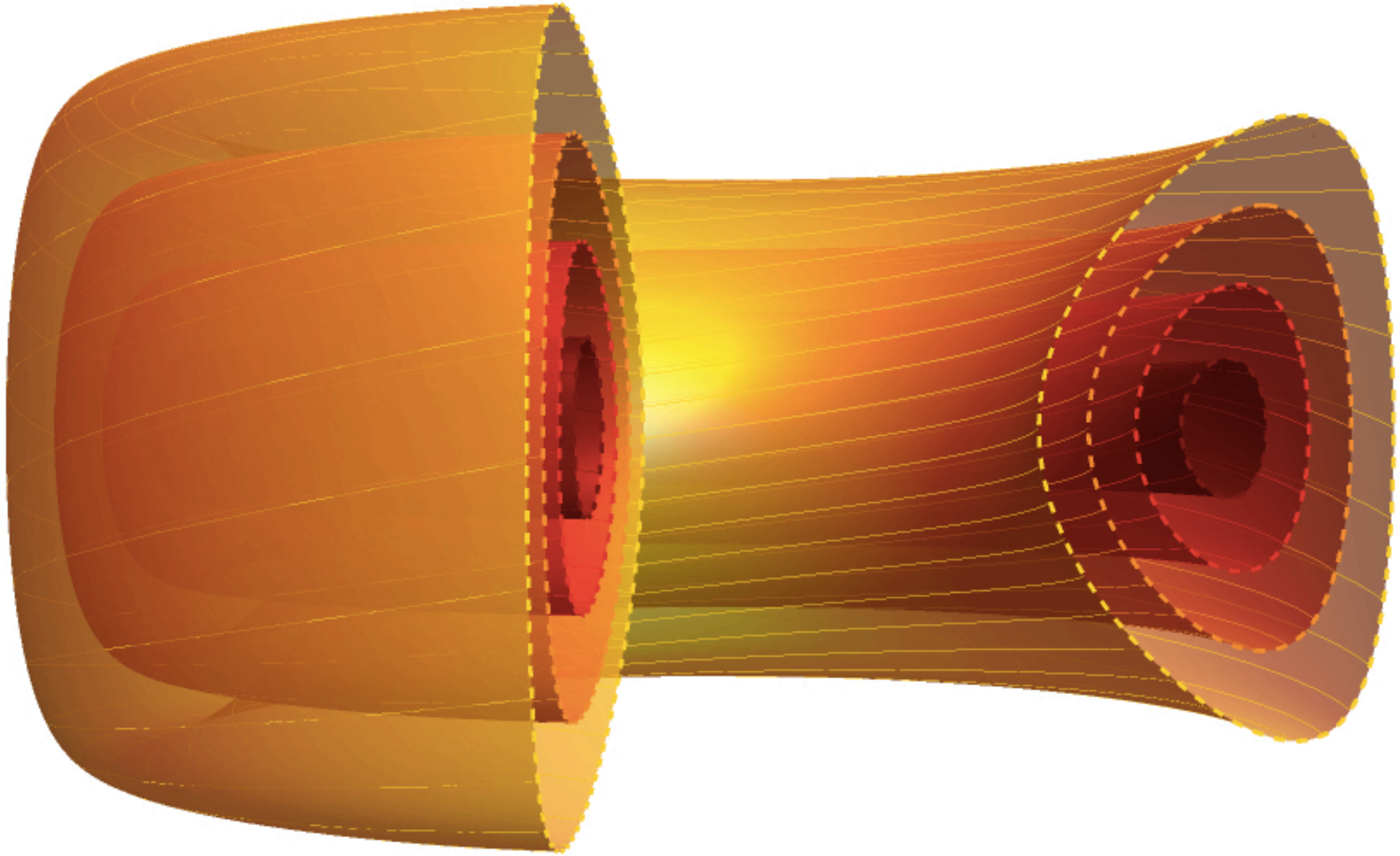
TSVV-02: Negative triangularity and plasma shaping



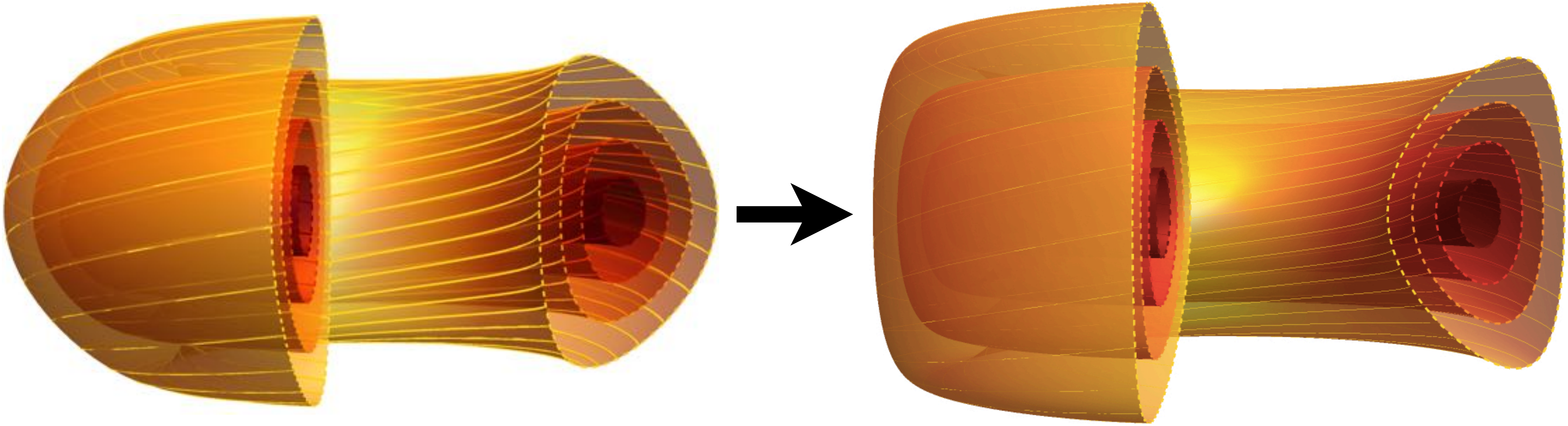
Justin Ball on behalf of the TSVV-02 team

CEA	L. De Gianni, P. Donnel, H. Luetjens
DIFFER	M. Pueschel
ENEA	M. Falessi, V. Fusco, P. Innocente, P. Muscente, P. Mantica, A. Mariani, G. Vlad
EPFL	A. Balestri, G. Di Giannatale, K. Lim, J. Poley, O. Sauter, H. Sun, A.J. Van Vuuren

EUROfusion Science Meeting - TSVV Final Reports
14 January 2026

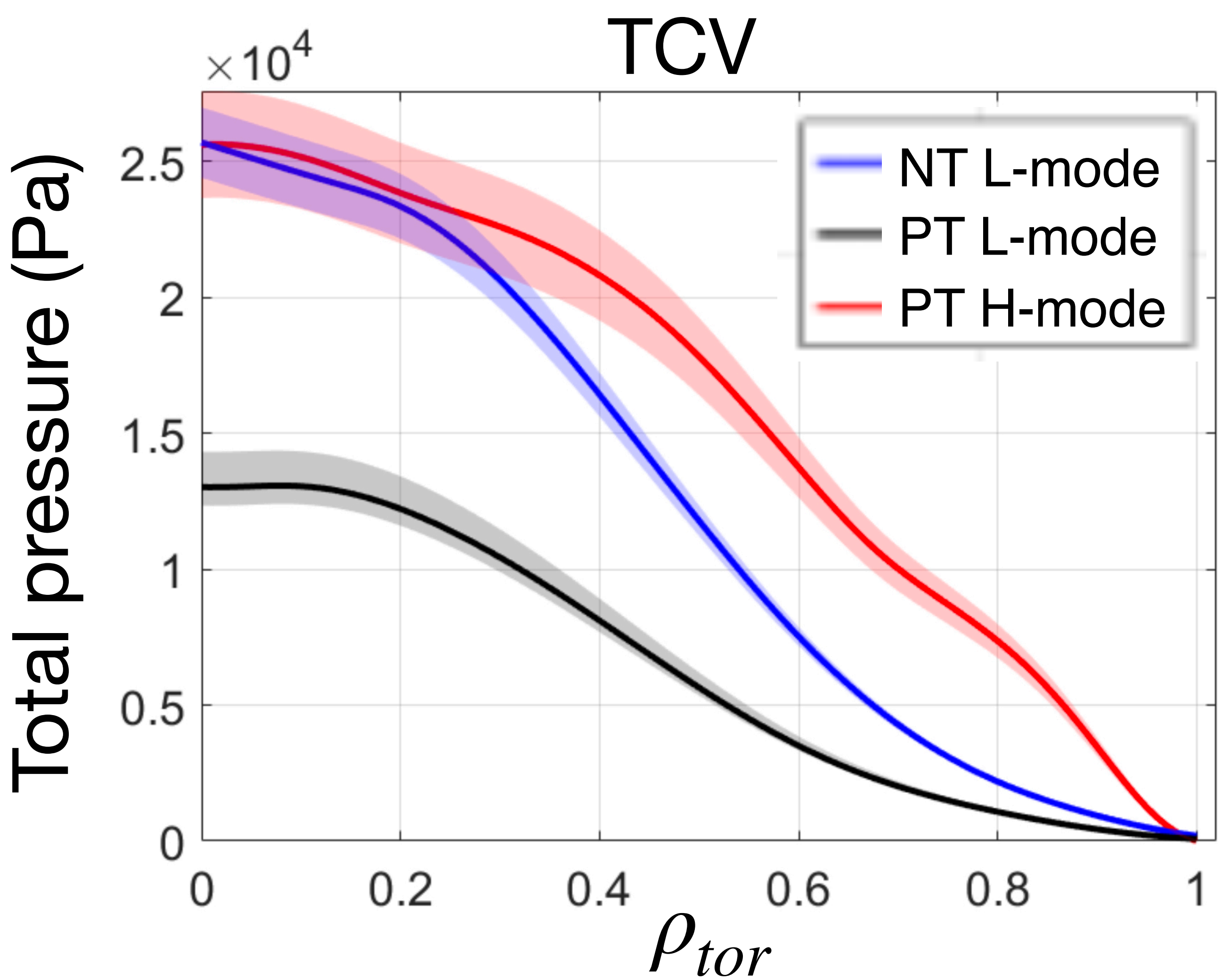
Assess a new operating regime for power plants

<u>Positive Triangularity (PT) in H-mode</u>	**<u>Negative Triangularity (NT) in L-mode</u>**

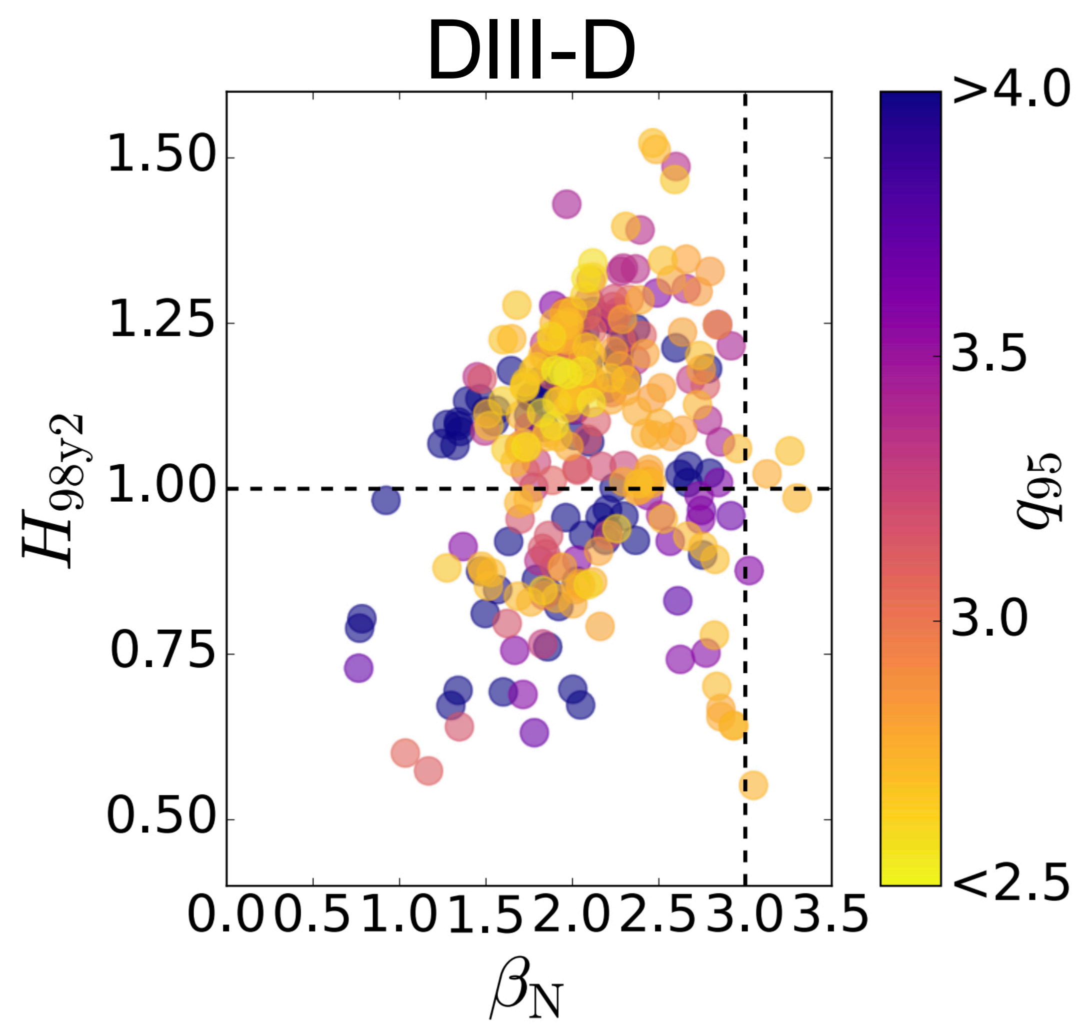


1) H-mode performance	1) H-mode-**like** performance
2) ELMs	2) **No** ELMs
3) Standard H-mode SOL	3) **L-mode-like** SOL
4) Everything else is fairly similar	4) Everything else is fairly similar

1) Core confinement



[A. Balestri PPCF (2024)]

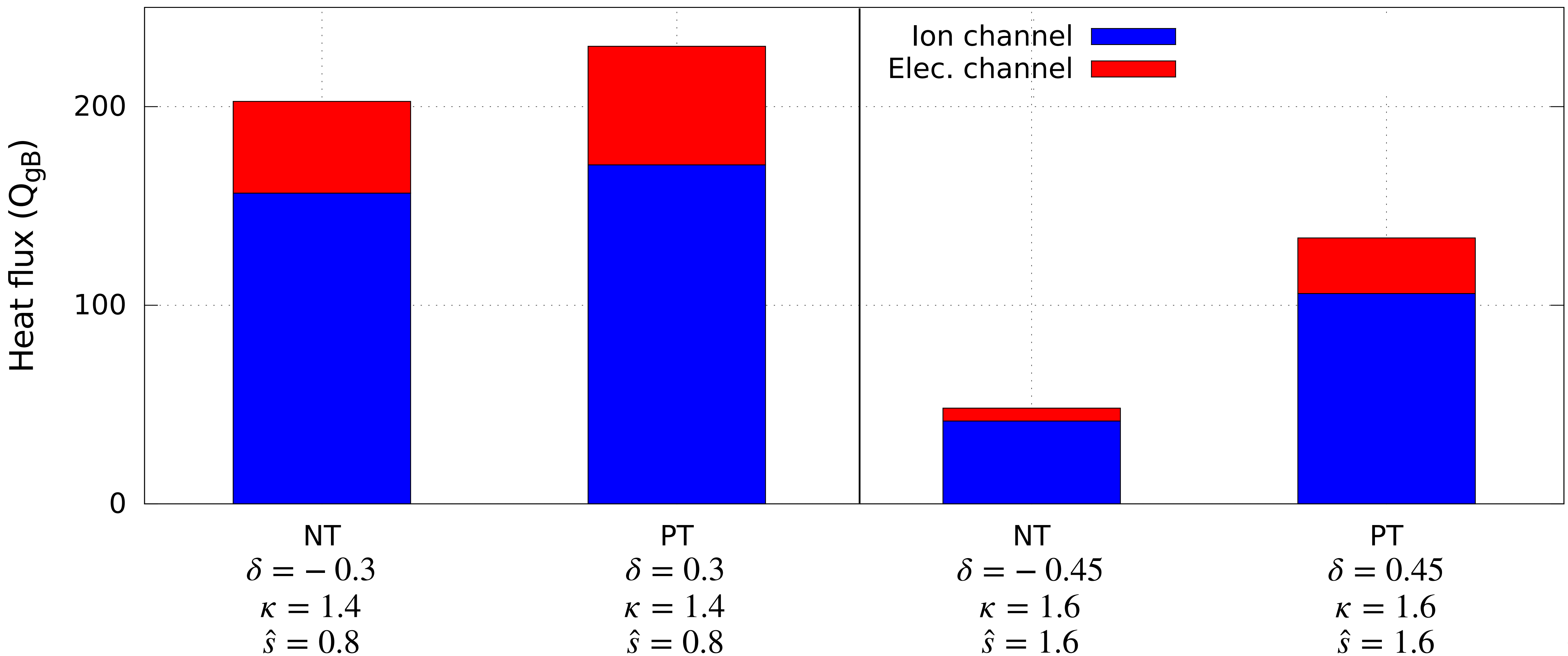


[C. Paz-Soldan Nucl. Fusion (2024)]

Basic gyrokinetic (GK) studies

[1] G. Merlo Phys. Plasmas (2019).
[2] A. Balestri PPCF (2024).
[3] J. Ball PPCF (2022).
[4] A. Mariani Nucl. Fusion (2024).
[5] J. Duff Phys. Plasmas (2021)., M.J. Pueschel Nucl. Fusion (2024).
[6] J. Ball PMI-5.2.1-T050 (2020). G. Merlo PPCF (2015).
[7] H. Sun Nucl. Fusion (2025). [8] X. Garbet Nucl. Fusion (2024). L. De Gianni PPCF (submitted).

- GK simulations generally display a transport reduction when flipping PT→NT (holding background profiles constant)[1-4]
- Effect larger at high $|\delta|$, large aspect ratio, high $\hat{s}$, and high κ



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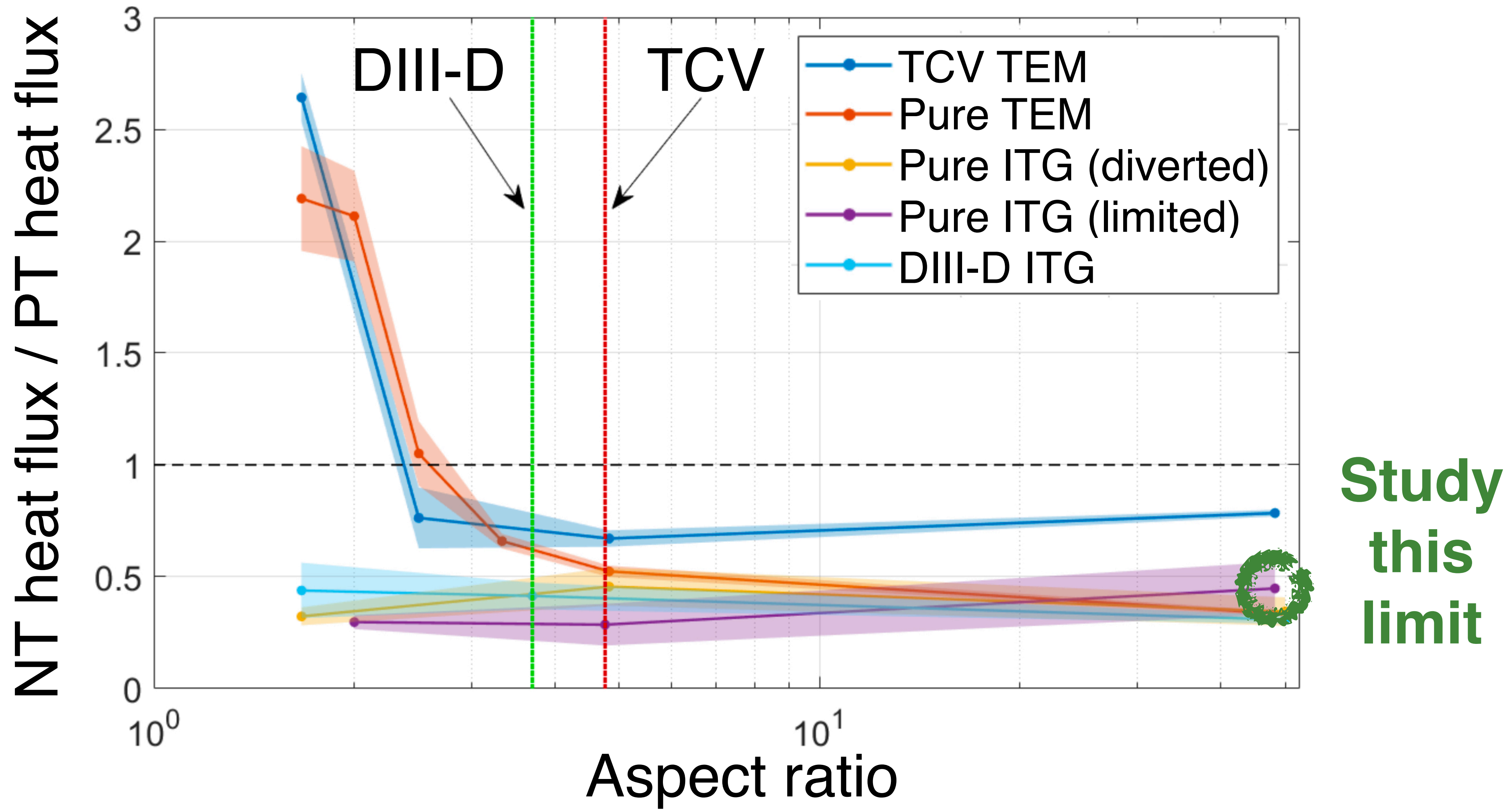
Basic gyrokinetic (GK) studies

- GK simulations generally display a transport reduction when flipping PT→NT (holding background profiles constant)[1-4]
- Effect larger at high $|\delta|$, large aspect ratio, high $\hat{s}$, and high κ
- Usually need kinetic treatment of electrons to observe this[3]
- Nonlinear saturation physics can be considerably different[5]
- Triangularity primarily affects the critical gradient, but not the stiffness[4,6]
- Explored exotic shapes beyond NT[7] and developed analytic frameworks to understand effect of shaping on ITG[2] and TEM[8] turbulence

Physical picture for ITG

[1] G. Rewoldt Phys. Fluids (1982).
[2] T. Ohkawa GA-A19184 (1988).
[3] A. Marinoni PPCF (2009).
[4] G. Merlo Phys. Plasmas (2019).
[5] A. Balestri PPCF (2024).
[6] X. Garbet Nucl. Fusion (2024). L. De Gianni PPCF (submitted).

- Aspect ratio scan shows traditional theoretical argument for stabilization by NT[1-4] (based on trapped particle stability) is incomplete[5]

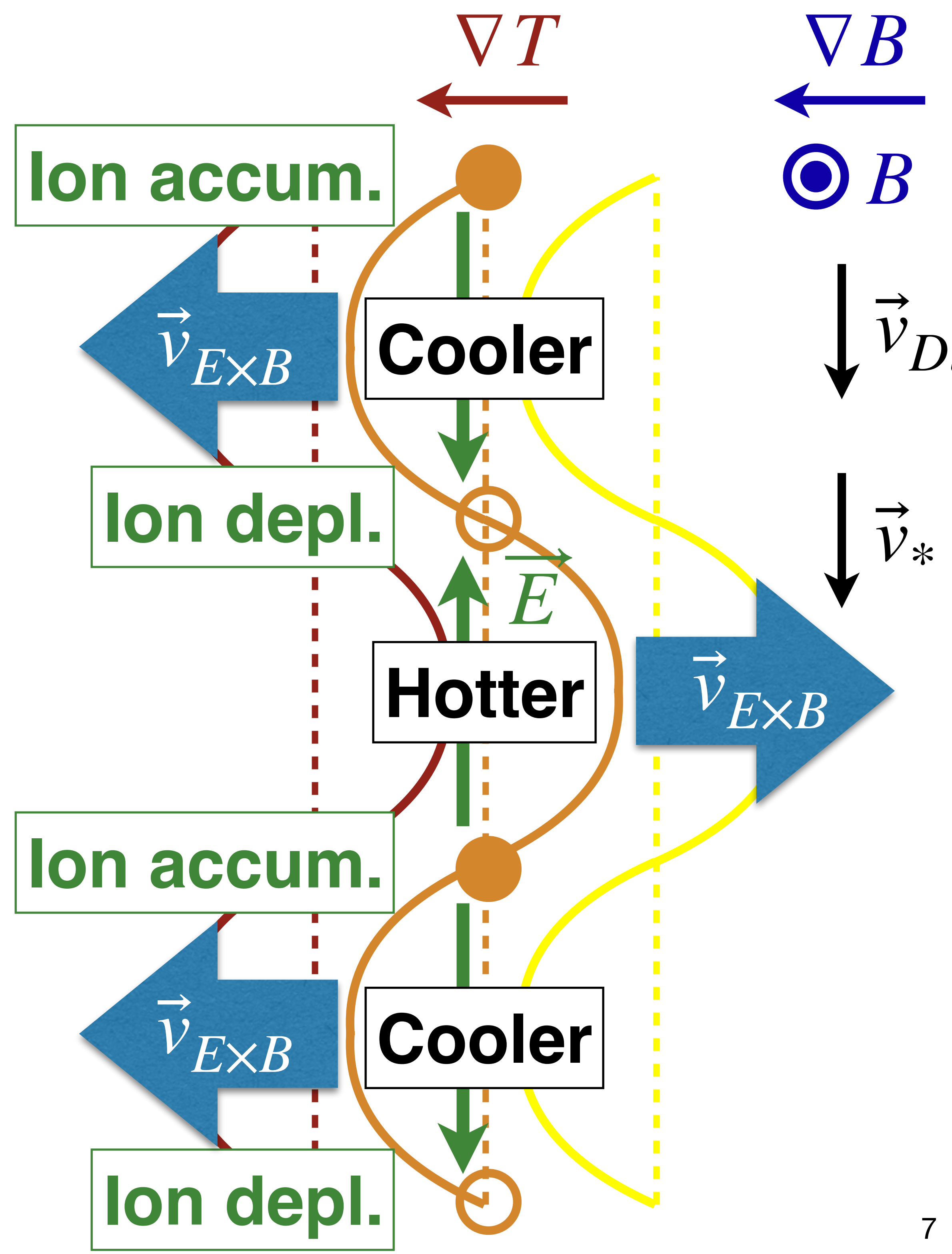


- A separate in-depth study has been performed for TEM[6]

Physical picture for ITG

[1] M. Beer PhD Thesis (1995).
[2] H. Biglari Phys. Fluids B (1989).
[3] A. Balestri PPCF (2024).

- Turbulence in tokamaks arises from a destabilization of drift waves
- Drift waves travel with a velocity
$$\vec{v}_* \propto \overrightarrow{B} \times \nabla T$$
- Destabilized by ion magnetic drift velocity
$$\vec{v}_{Di} \propto T_i \overrightarrow{B} \times \nabla B$$
- These velocities must be similar $\vec{v}_{Di} \approx \vec{v}_*$ to enable instability[1,2]
- PT enables this resonance, but not NT[3]
- Can explain dependence of NT confinement on $\hat{s}$, κ, and aspect ratio[3]

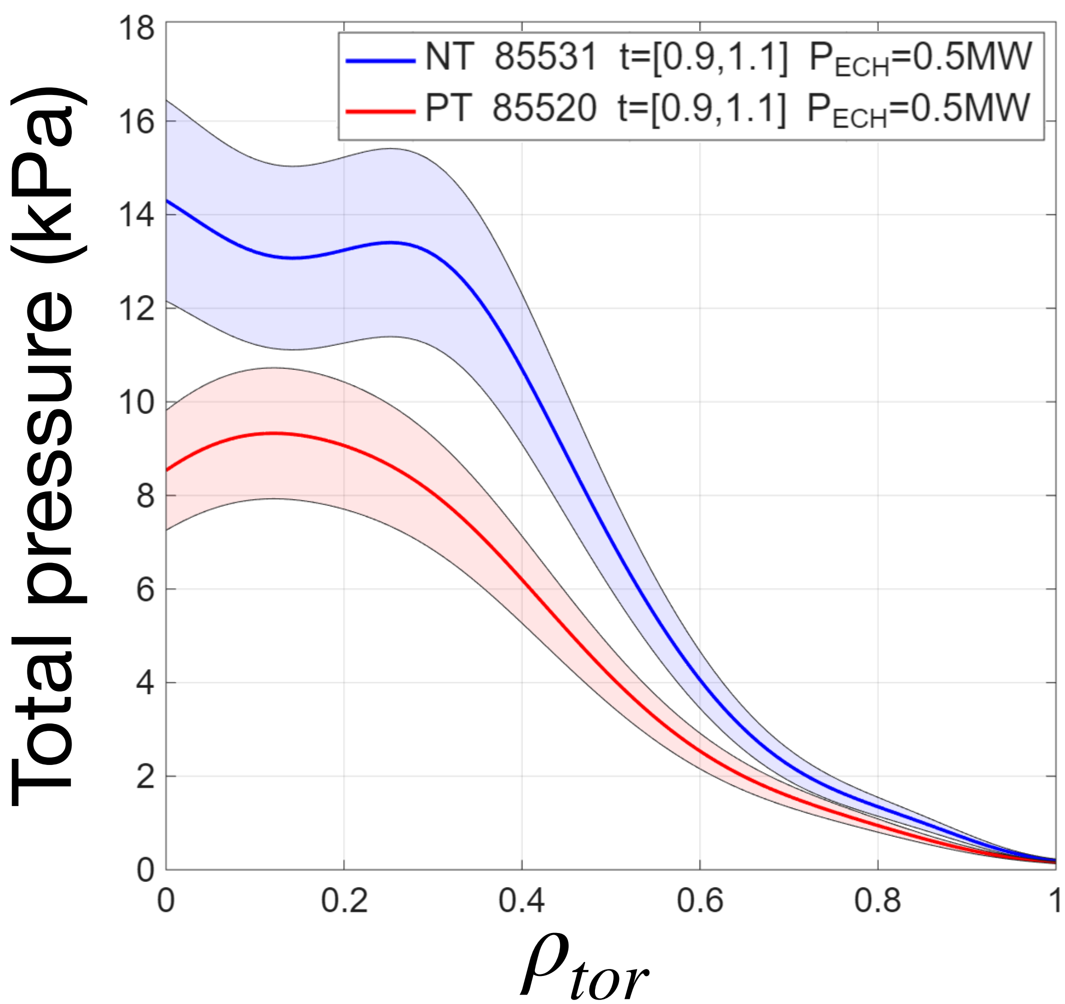


Validation with experiment

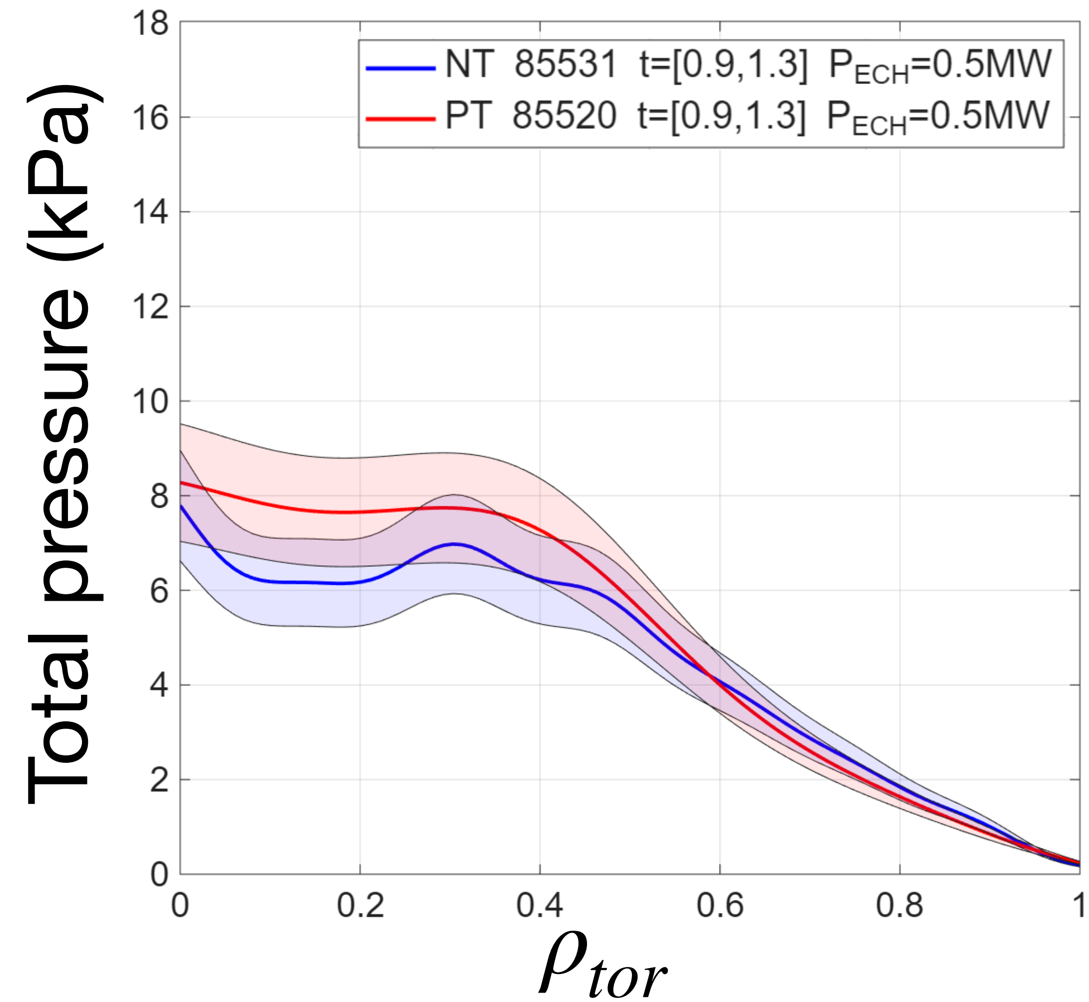
[1] A. Marinoni PPCF (2009).
[2] G. Merlo JPP (2023).
[3] A. Balestri PPCF (2024).
[4] M.J. Pueschel Nucl. Fusion (2024).
[5] A. Balestri (in prep.).

- Validated prediction that NT harms confinement when $\kappa < 1$ on TCV[5]

$\kappa = 1.5$



$\kappa = 1.0$

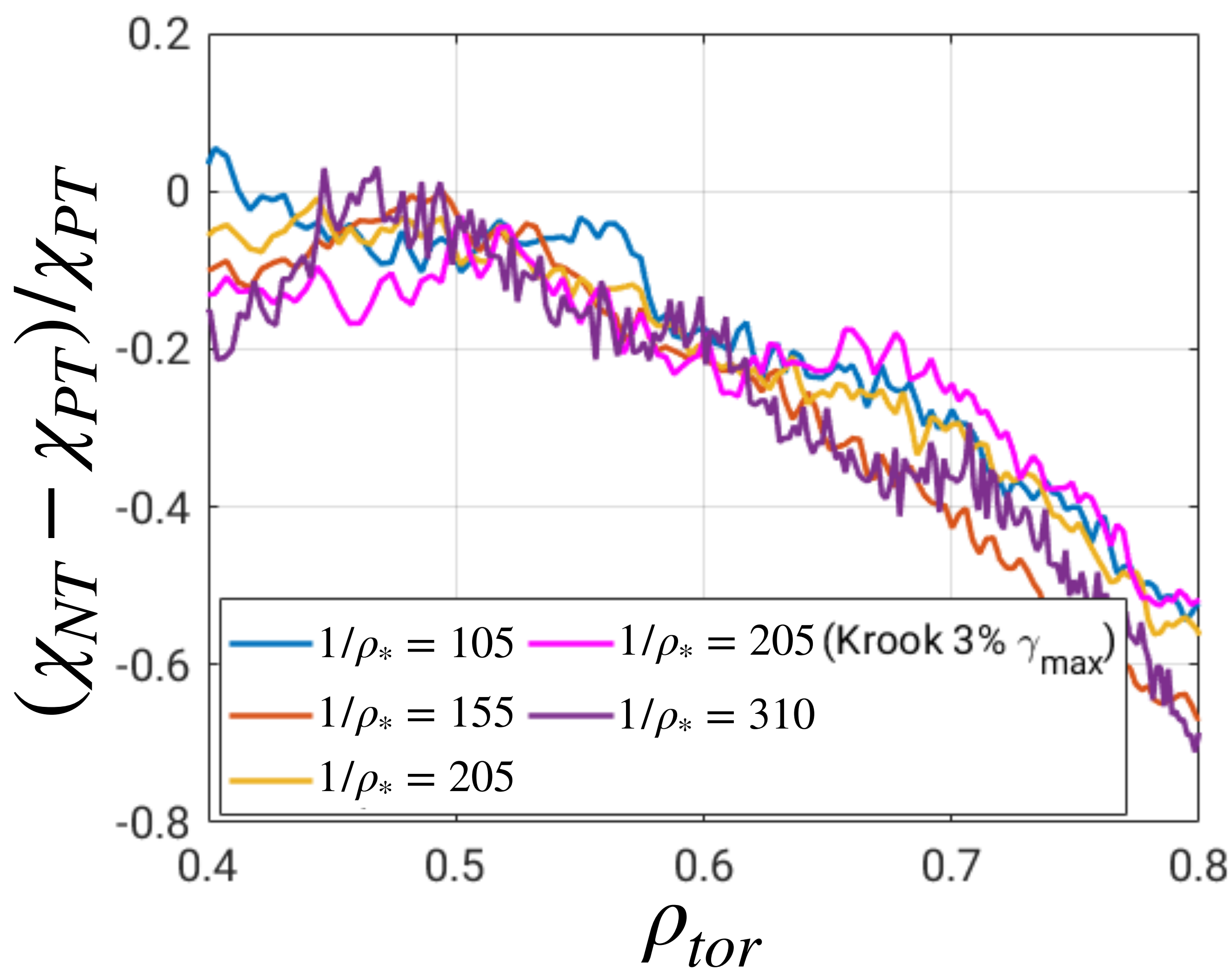


- GK simulations agree, both qualitatively and quantitatively, with TCV[1-5], DIII-D[5], AUG[5], and JET[5] experiments

Extrapolating to a power plant: size

[1] G. Di Giannatale PPCF (2024).
[2] J. Ball PPCF (2022).

- Global ORB5 simulations indicate confinement improvement from NT is independent of machine size[1]

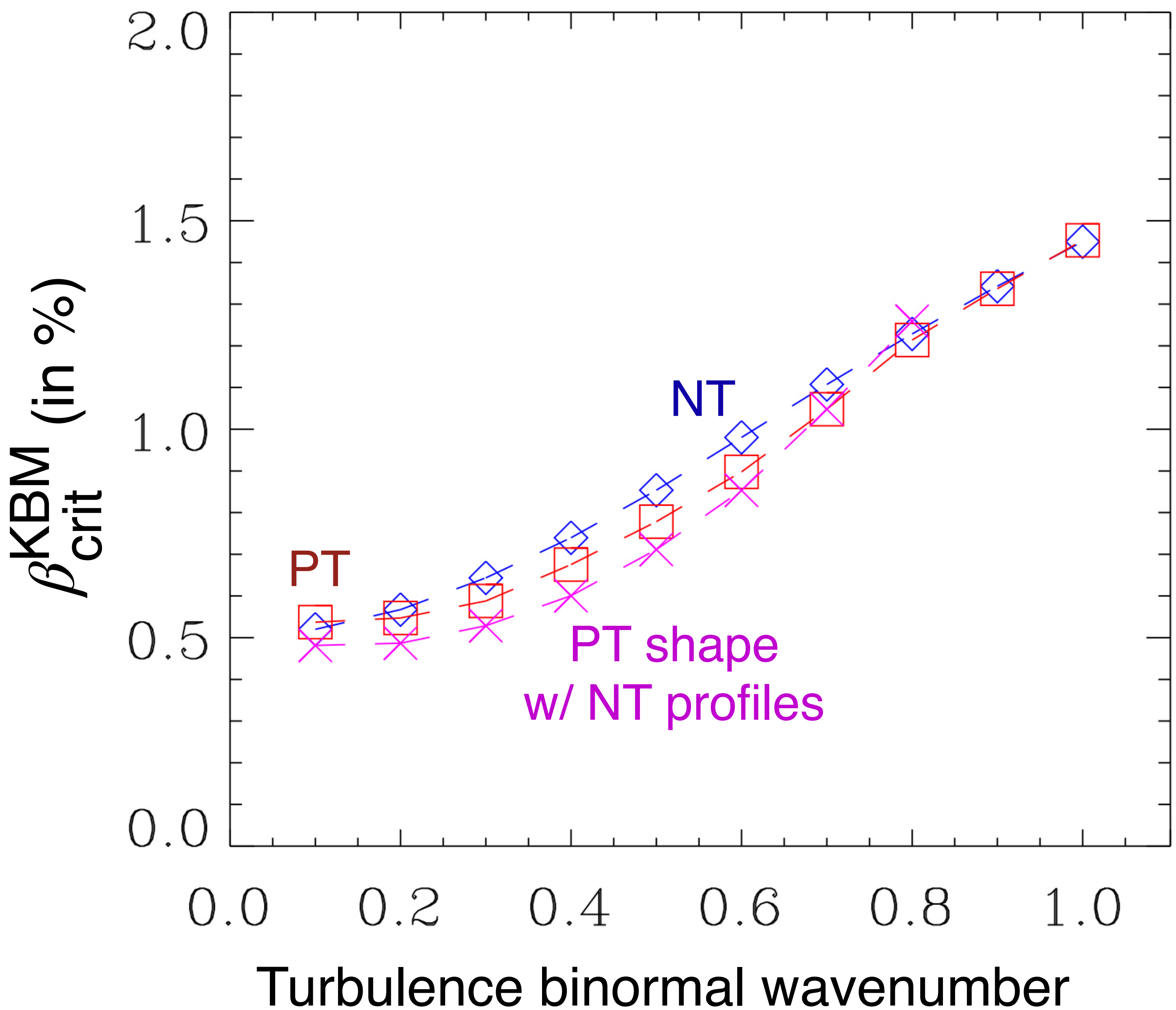


- Novel GENE flux tube simulations with profile shearing show the same[2]

Extrapolating to a power plant: β

[1] M.J. Pueschel PoP (2025).
[2] A. Mariani Nucl. Fusion (2024).
[3] R. Davies PPCF (2022).
[4] A. Balestri PPCF (2025).

- Local GK simulations indicate KBM turbulence is similar in NT and PT for conventional tokamaks[1,2], but worse for spherical tokamaks[3]



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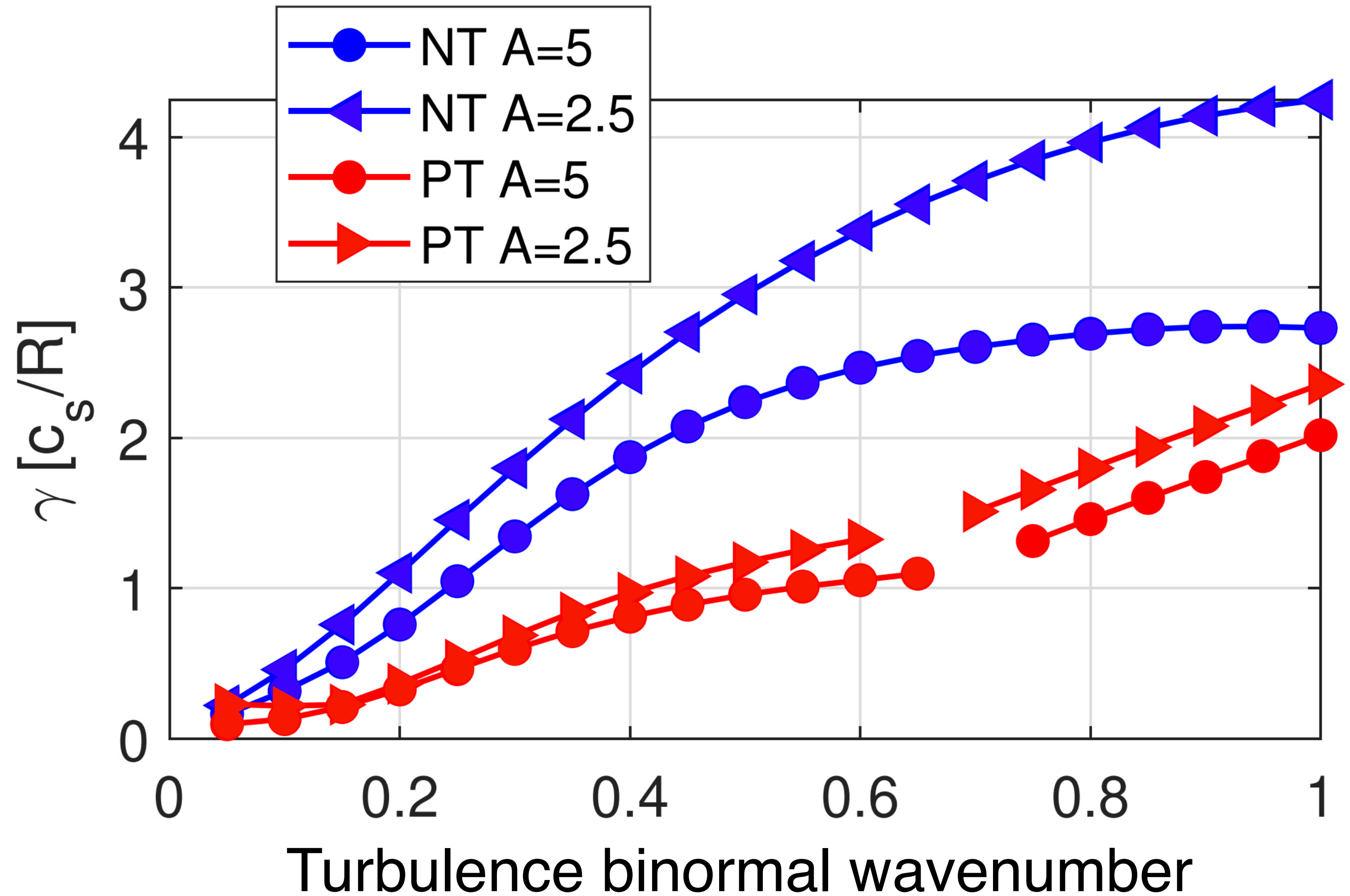
- MTM are often worse in NT <u>regardless of aspect ratio</u>[1,4]



Extrapolating to a power plant: β

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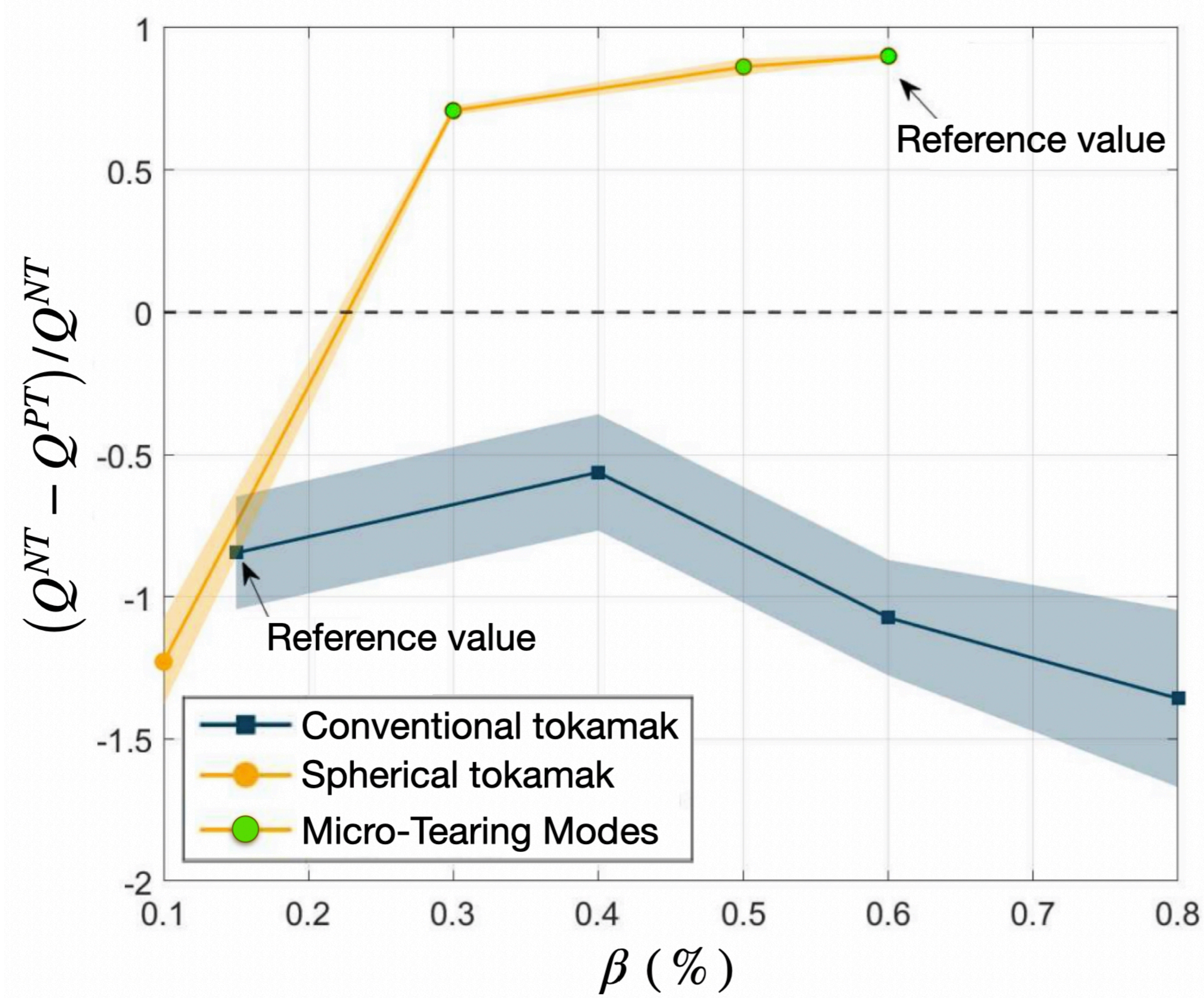
- Local GK simulations indicate KBM turbulence is similar in NT and PT for conventional tokamaks[1,2], but worse for spherical tokamaks[3]

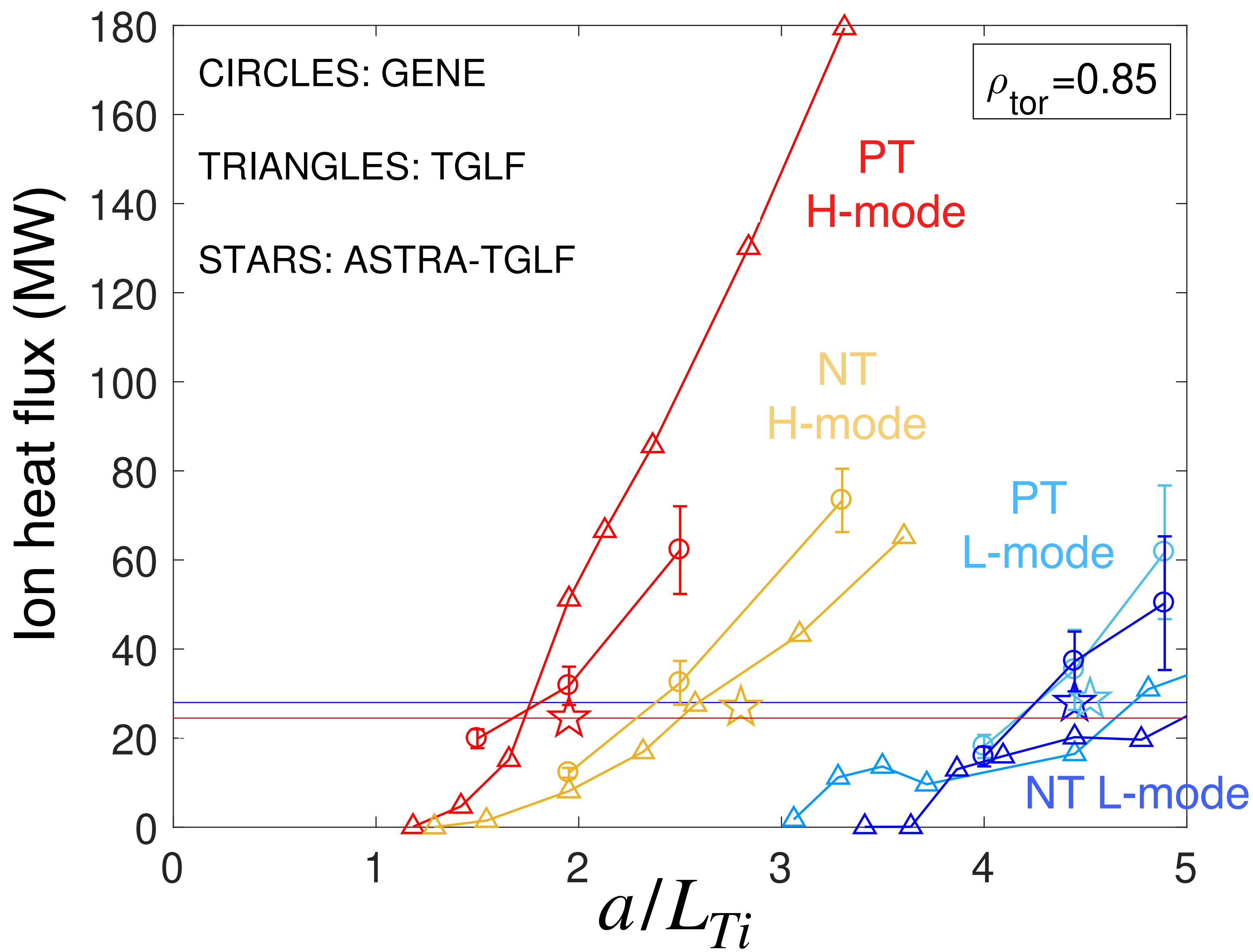
- MTM are often worse in NT <u>regardless of aspect ratio</u>[1,4]
  - Not expected to be present for conventional aspect ratio parameters[4]
  - Could be a problem for NT spherical tokamaks[4]
  - Can be entirely explained by faster magnetic drifts in NT[4]



Integrated modeling of NT

[1] A. Mariani Nucl. Fusion (2024).
[2] A. Mariani Nucl. Fusion (2024).
[3] A. Balestri PPCF (2024).

- ASTRA-TGLF (SAT2) modeling verified against local GENE in the outer core[1]



Integrated modeling of NT

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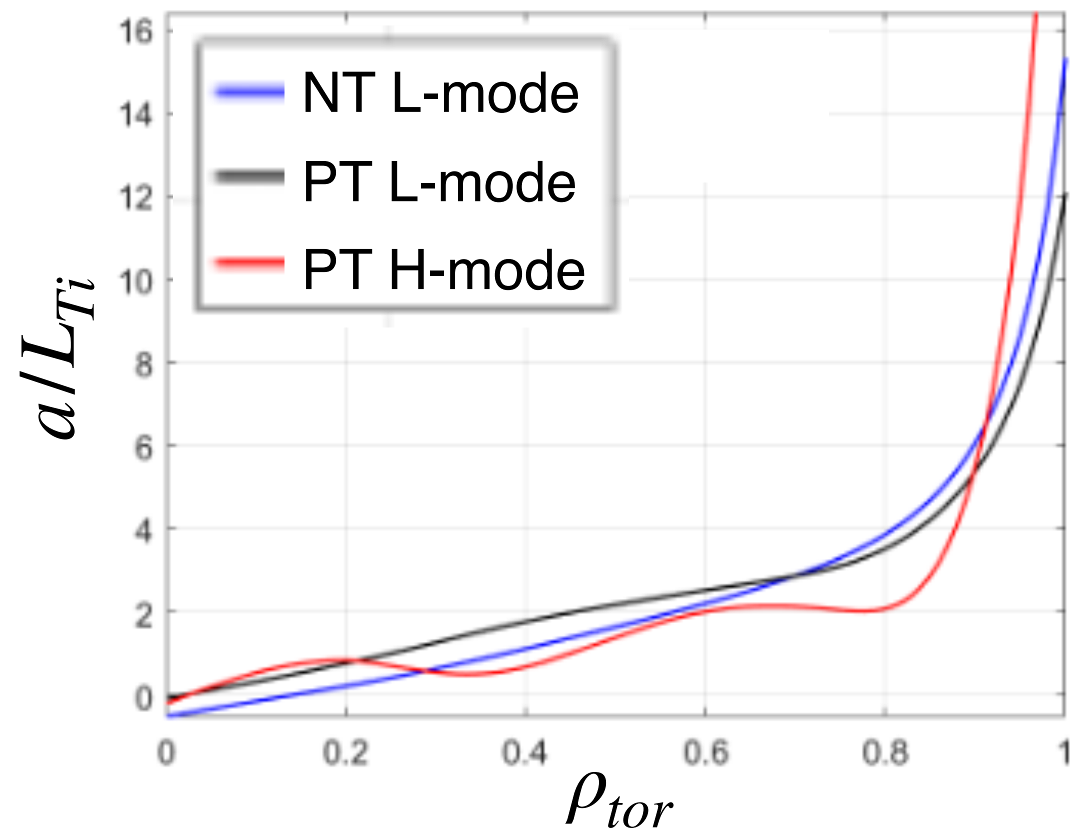
- ASTRA-TGLF (SAT2) modeling verified against local GENE in the outer core[1]

- For AUG NT experiments, finds good agreement in profiles (but improvement is modest relative to equivalent PT shape)

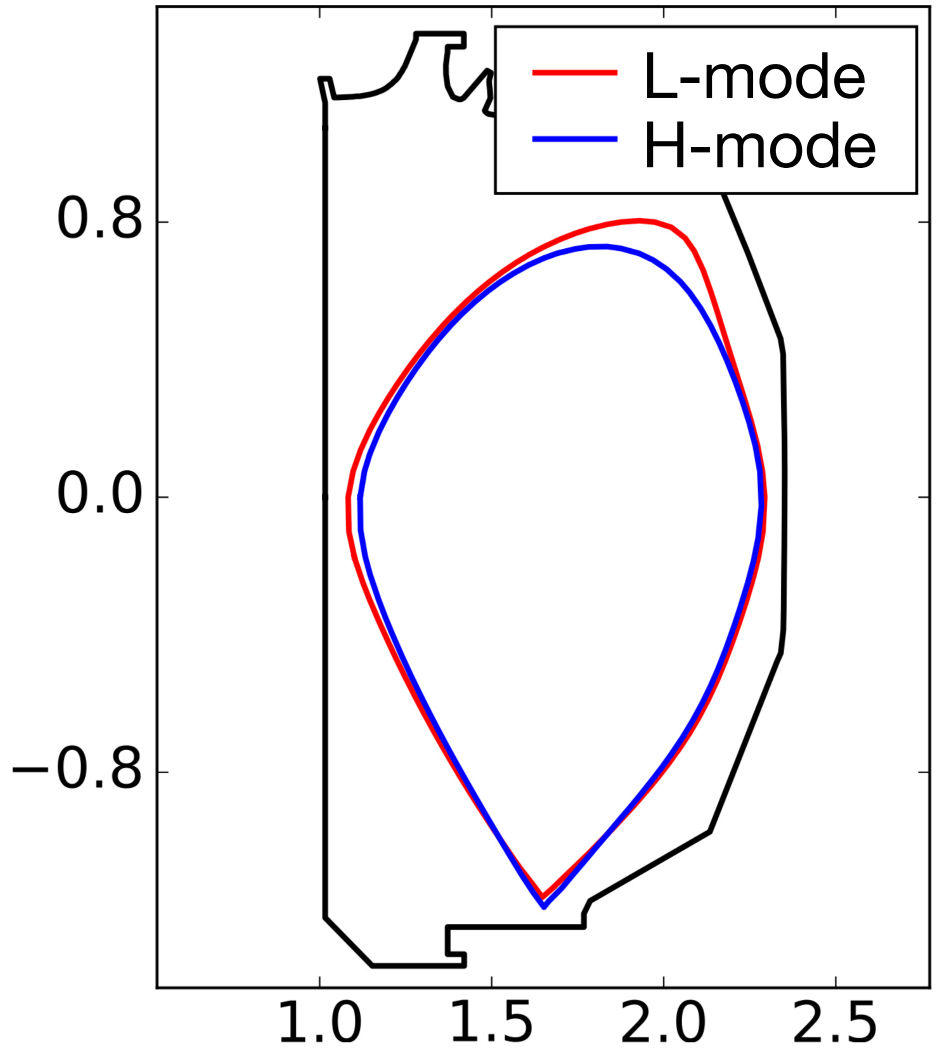
- For TCV NT experiments, under-predicts the T_i profile (which exhibits a strong improvement relative to PT)

- Modeling is challenging as the quantitative improvement often arises from $\rho_{tor} > 0.9$[1,2,3]



  - There are indications that TGLF may differ from GENE in this region

2) No L-H transition

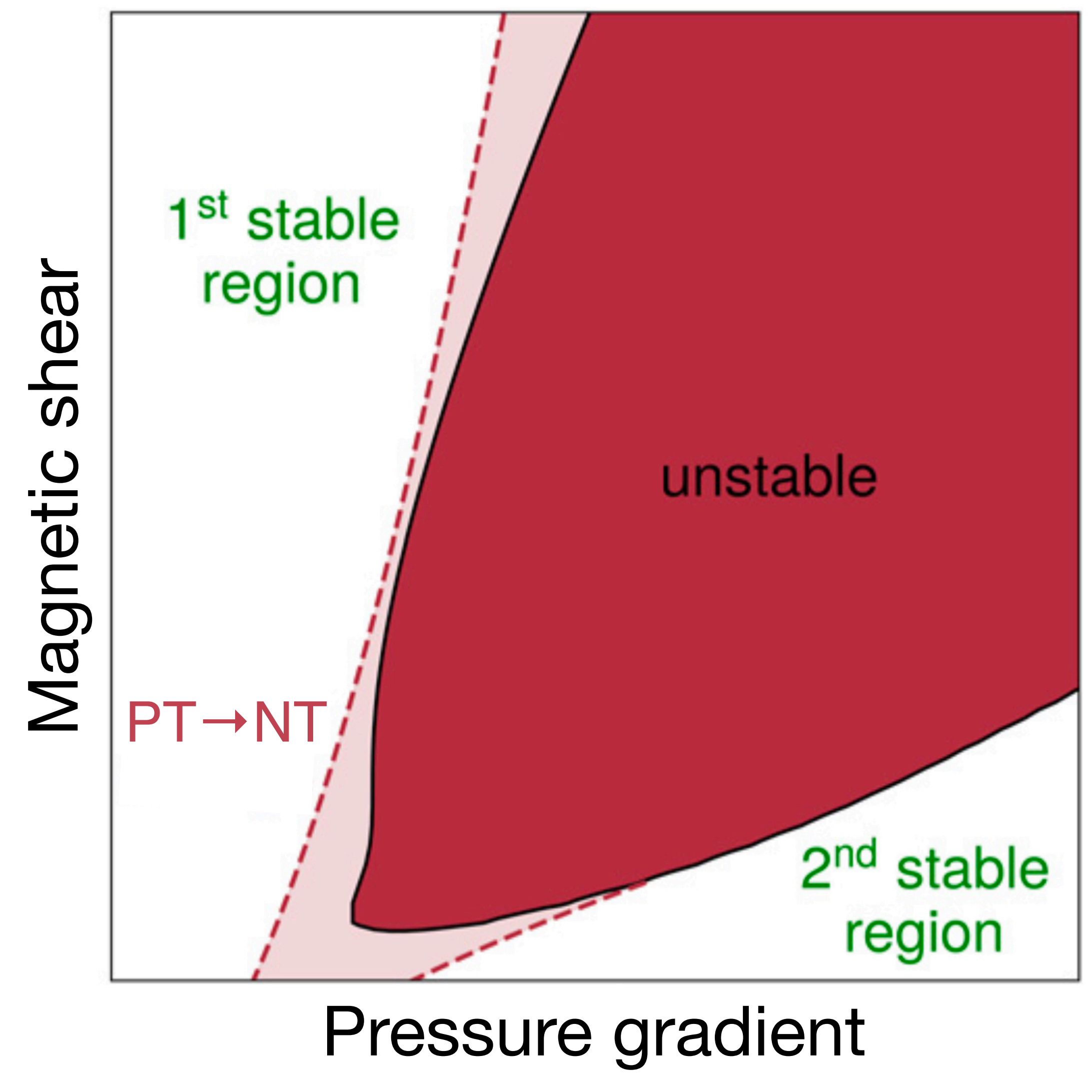


[S. Saarelma PPCF (2021)]

Transition to H-mode

[1] A. Merle. PPCF (2017).
[2] A. Marinoni. Rev. Mod. Phys. (2021).
[3] S. Saarelma. PPCF (2021).
[4] O. Nelson. Nucl. Fusion (2022).
[5] O. Sauter IAEA (2023).
[6] T. Happel Nucl. Fusion (2023).

- Sufficiently negative δ closes access to the 2nd stability region for infinite-n ballooning modes, which is associated with the transition to H-mode[1-4]



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- Sufficiently negative δ closes access to the 2nd stability region for infinite-n ballooning modes, which is associated with the transition to H-mode[1-4]

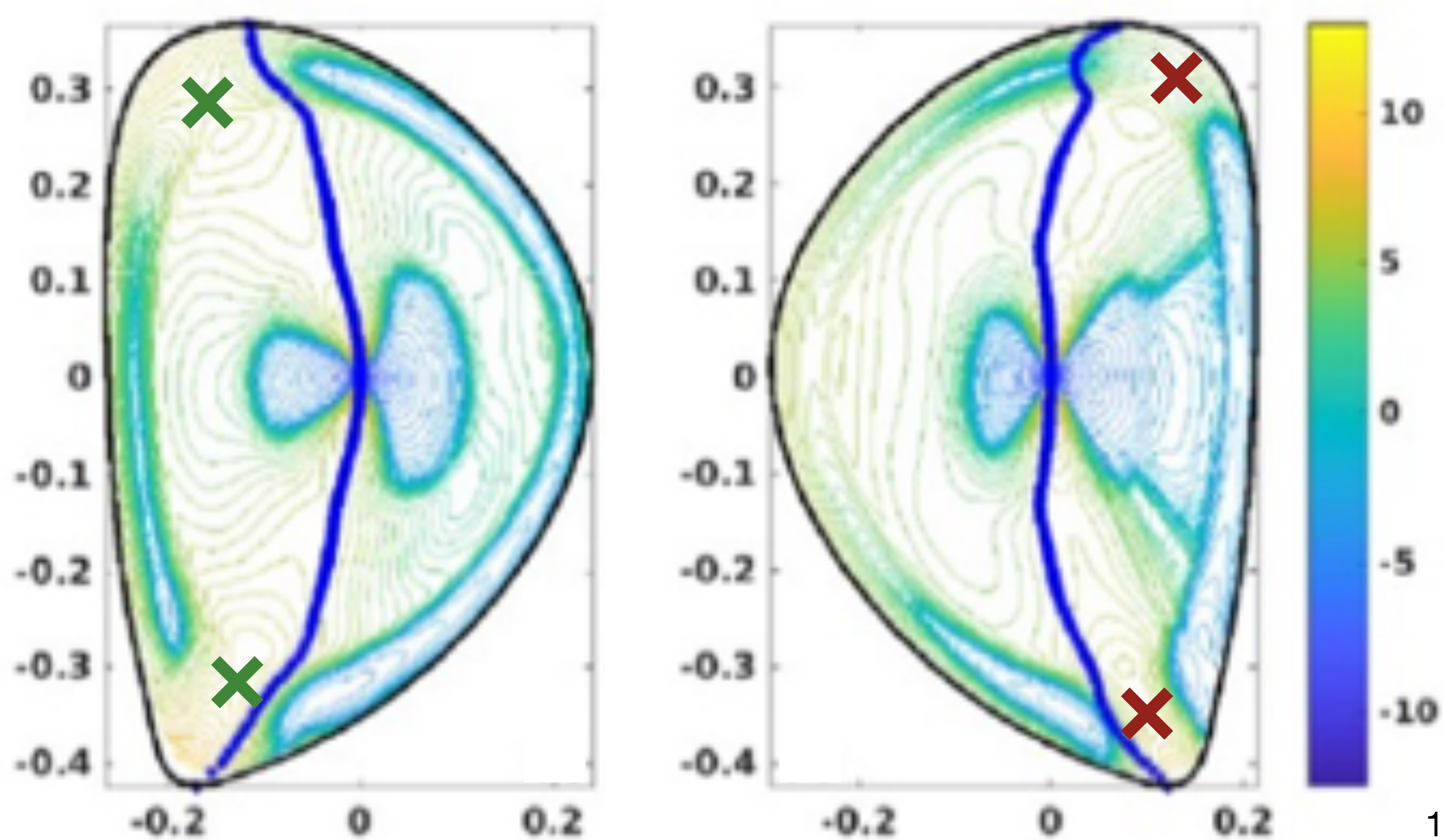
- Developed proxy for blocking the H-mode transition — when the maximum in the edge local magnetic shear crosses into the bad curvature region[5]

- Can be used to explain ASDEX Upgrade results[6]

- Argument appears independent of machine size

- NT JET used 30MW of heating

Local $\hat{s}$

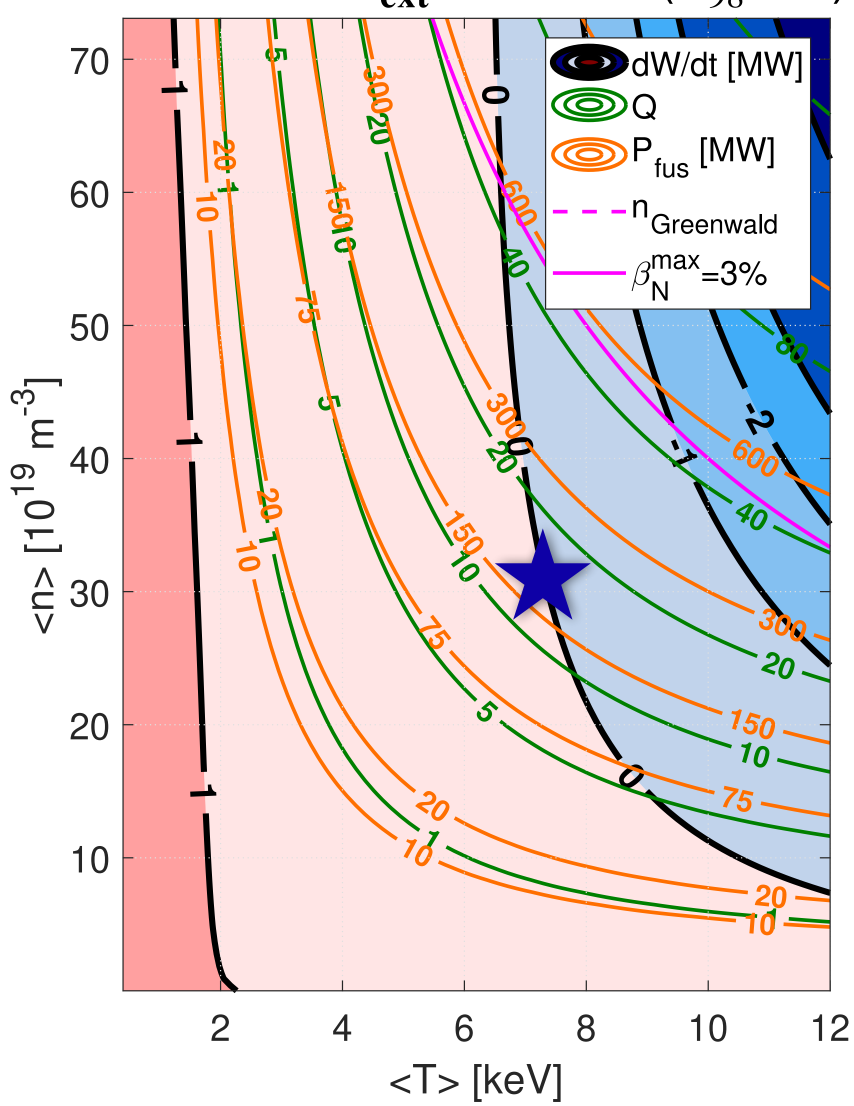


No need to exceed L-H power threshold

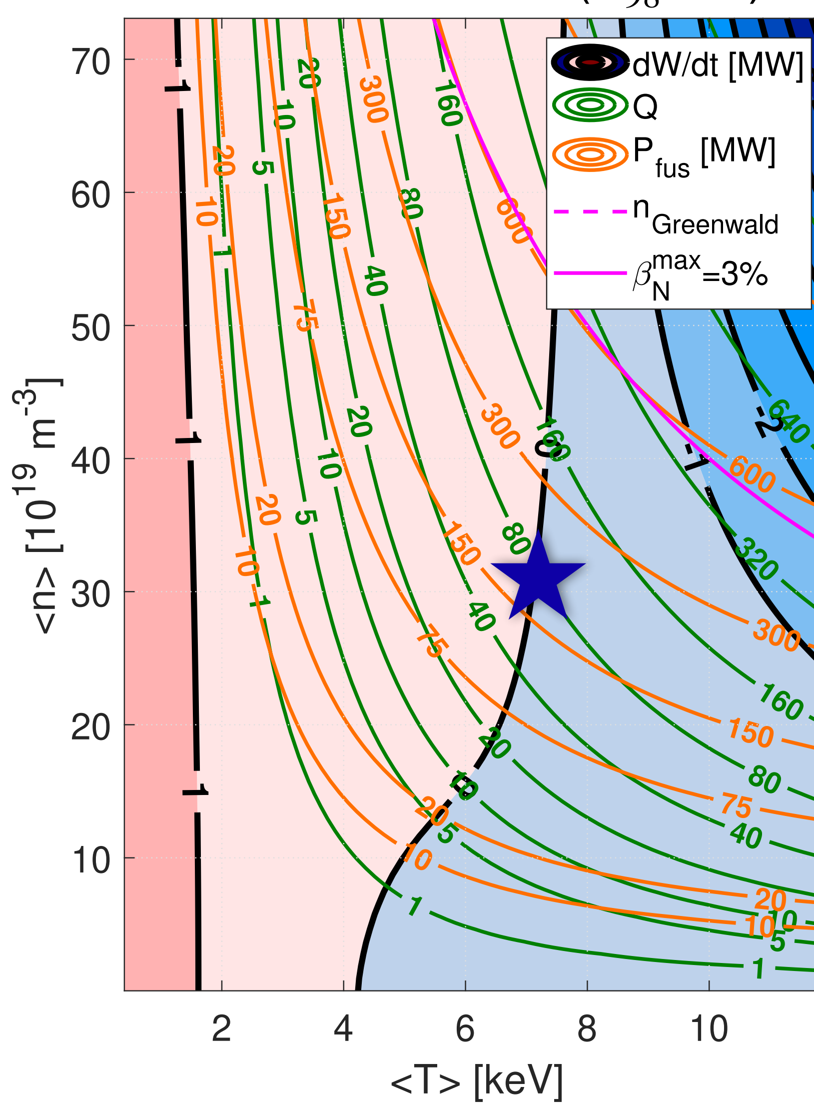
[1] A. Balestri Nucl. Fusion (2025).

- Confinement strongly degrades with external heating power ($\tau_E \propto P_{ext}^{-0.67}$)
- Tradeoffs were analyzed using simple 0-D POPCON analysis[1]
- Reveals low power, high Q NT scenarios that are inaccessible to PT
- Particularly attractive for a burning plasma experiment

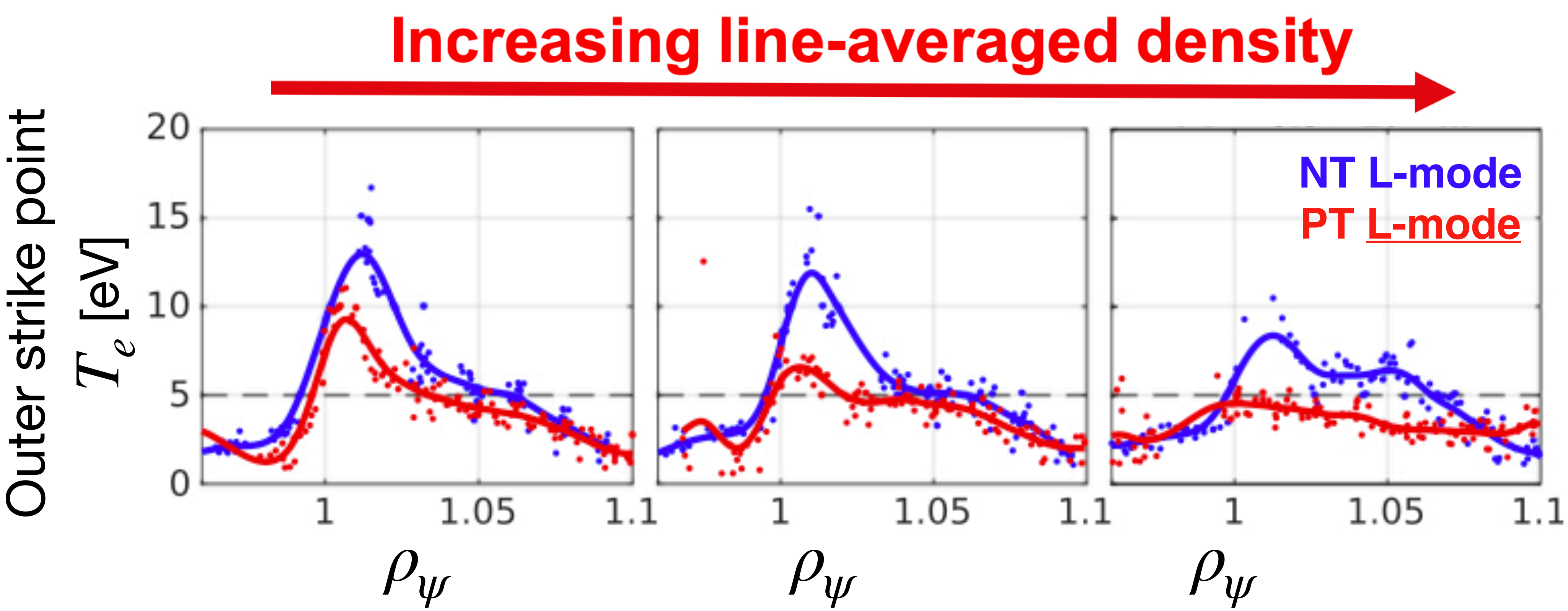
SPARC **PT** $\mathbf{P_{ext} = 11}$ **MW** ($H_{98} = 1$)



SPARC **NT Ohmic** ($H_{98} = 1$)



3) SOL dynamics



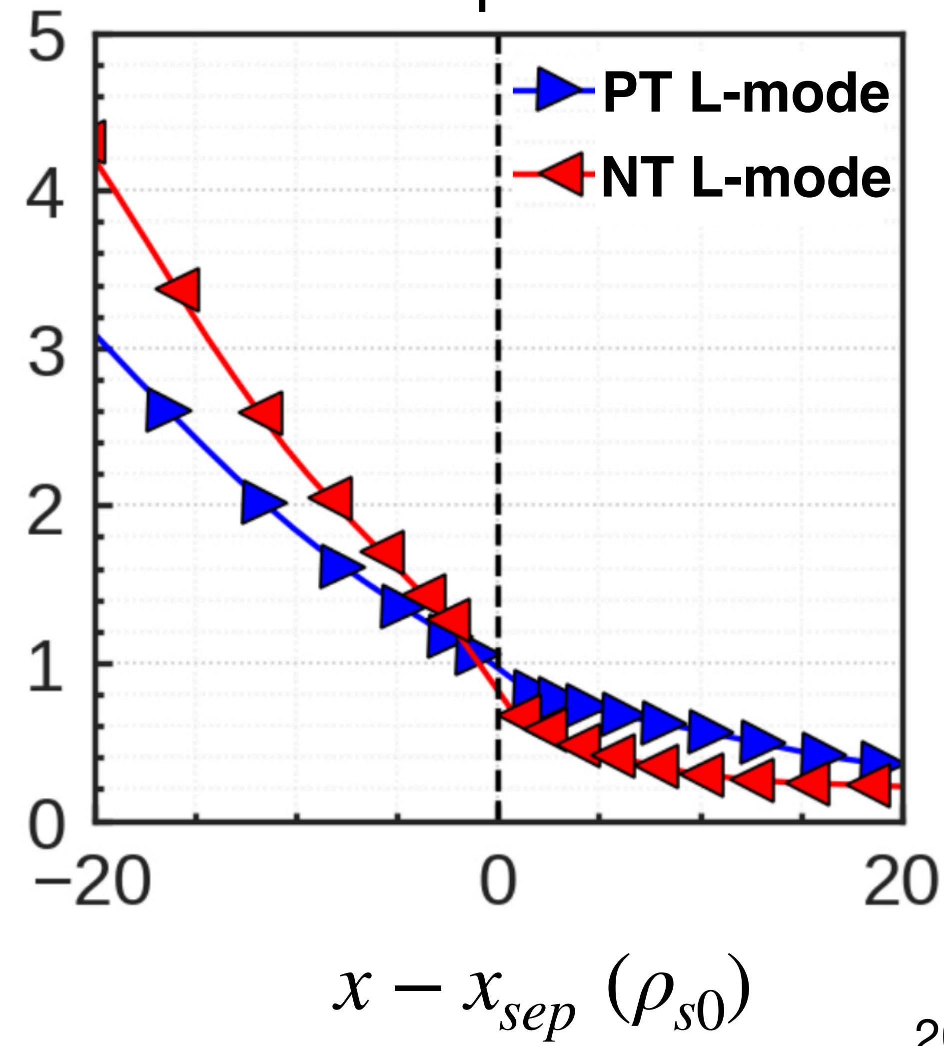
[O. Fevrier PPCF (2023)]

SOL width in TCV discharges

[1] P. Muscente J. Nucl. Mater. (2023).
[2] K. Lim PPCF (2023).
[3] K. Lim arXiv:2412.20780.
[4] E. Laribi Nucl. Mater. Energy (2021).
[5] F. Riva PPCF (2017). M. Faitsch PPCF (2018).
[6] D. Silvagni PPCF (2020). R. Morgan Nucl. Fusion (2025).

- Predictive GBS and interpretive SOLEDGE-EIRENE simulations of $\delta = \pm 0.3$
- NT steepens profile gradients at the separatrix, reducing λ_q by ~30%[1,2,3]
- Agrees with GBS, TOKAM3X, and TCV work[4,5]
- For double null plasmas, GBS finds more power is transferred to inner targets[3]
- Appears that λ_q in NT will be intermediate between PT L-mode and PT H-mode[6]
- Intuitive based on confinement just inside the separatrix

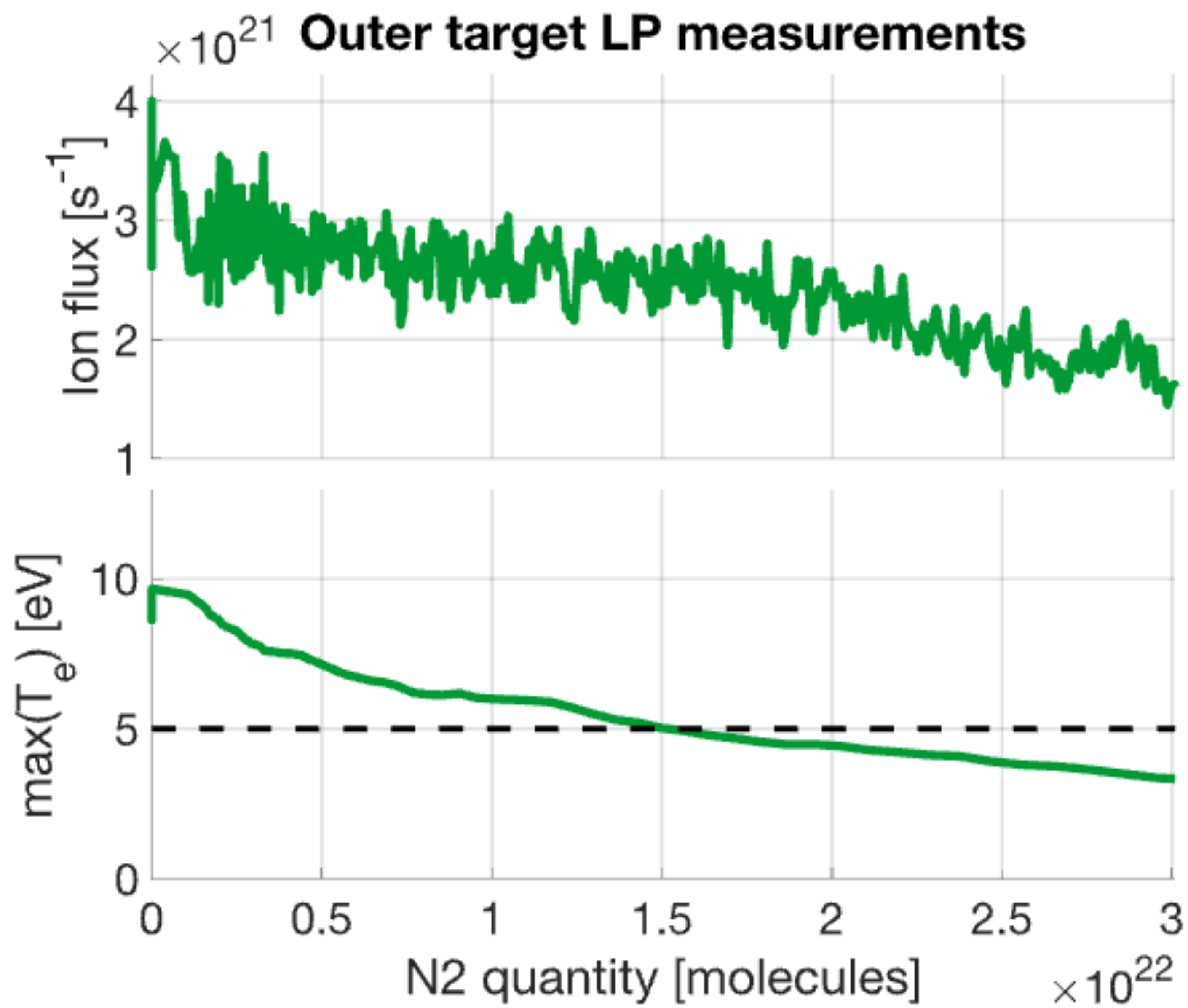
Electron pressure[2]



Divertor detachment

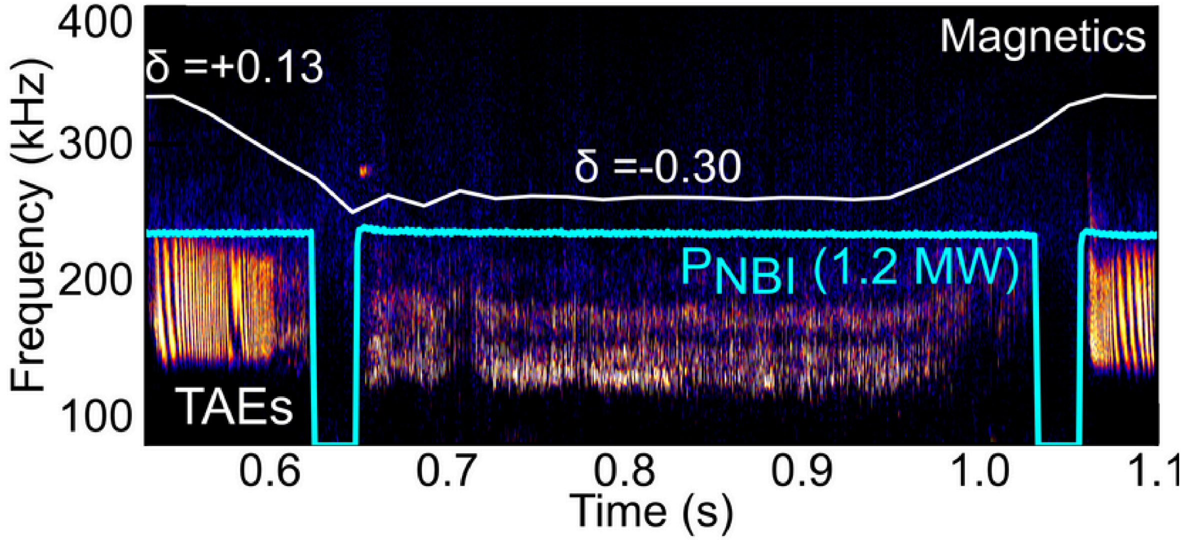
[1] G. Durr-Legoupil-Nicoud EPS (2024).
[2] O. Fevrier PPCF (2024).
[3] F. Mombelli arXiv:2506.03966.

- Detachment of NT plasmas achieved in TCV with N_2 seeding[1]
  - Lowers τ_E by ~20%
  - Increased divertor closure using baffles lowers the density threshold
  - More difficult to detach than in PT L-mode[2]
- SOLPS-ITER indicates caused by cross-field transport, rather than the shape directly[3]

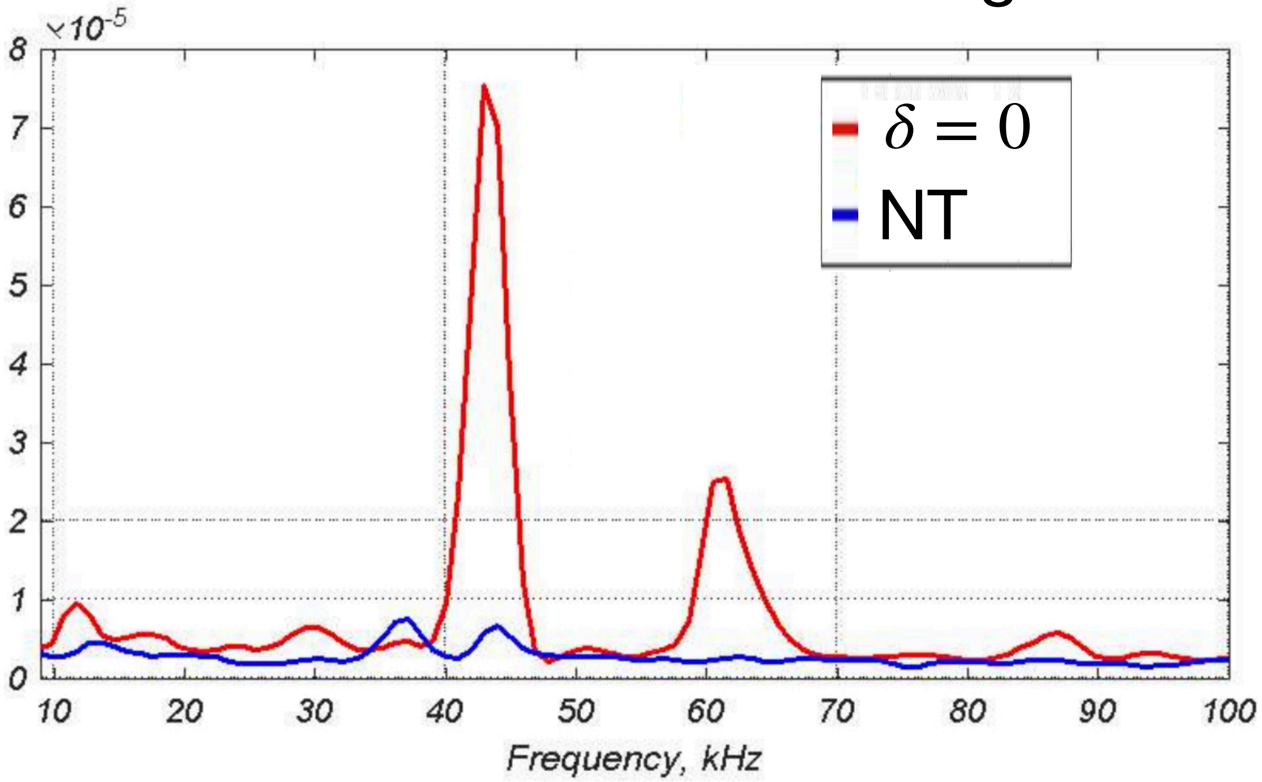


4) Other considerations

TAE Amplitude



Fast Ion Loss Detector Signal



[A. Karpushov EPS (2023)]

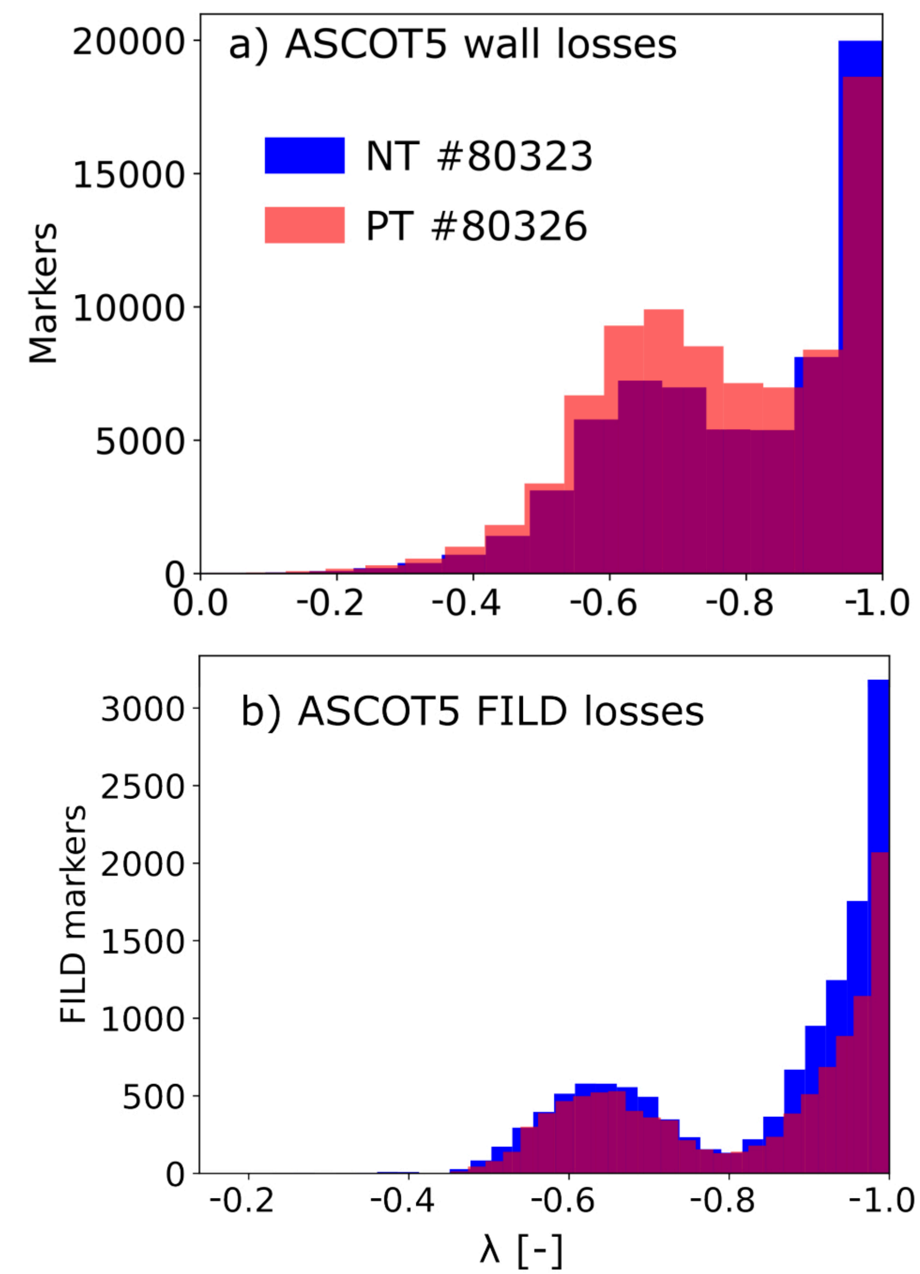
Fast ions and MHD stability

[1] P. Oyola IAEA (2023). A. Karpushov EPS (2023).
[2] G. Wei Nucl. Fusion (2025).
[3] M. Vallar Nucl. Fusion (2022).
[4] J. Poley Nucl. Fusion (submitted).
[5] S. Marchioni EPFL PhD Thesis (2025).
[6] S. Guizzo PPCF (2024).

- Interpretative model of TCV experiments indicates that NT reduces the amplitude of TAEs and their transport of fast ions[1]

- Theory indicates triangularity has little impact on TAE stability in the fluid limit, but kinetic effects reveals that NT results in somewhat higher growth rates than PT[2]

- Relative to PT, fast ions in NT experience increased transport by sawteeth[3] and similar transport in MHD-quiescent plasmas[4]



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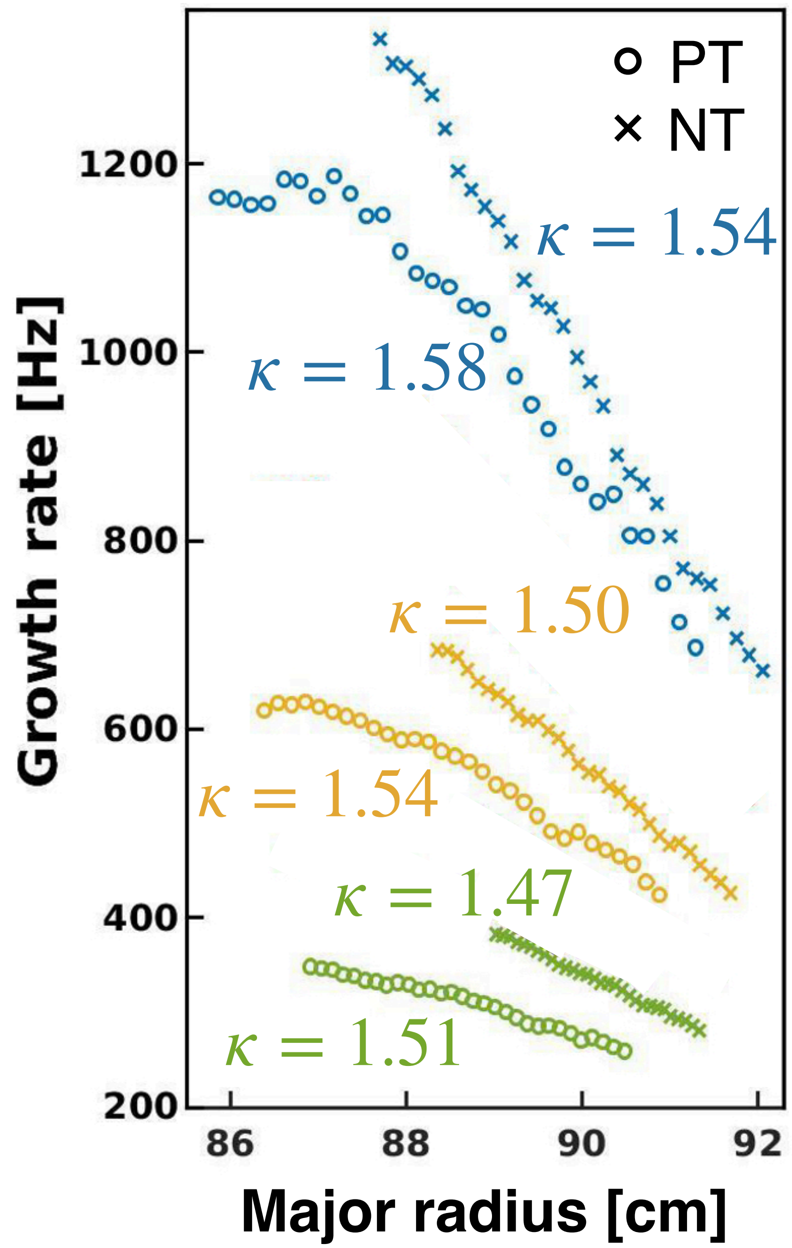
- Relative to PT, fast ions in NT experience increased transport by sawteeth[3] and similar transport in MHD-quiescent plasmas[4]
- Vertical stability worse in NT, but may be addressed by stabilizing plates[5,6]



Takeaways

[1] S. Doyle FED (2021).

- GK finds better confinement in NT and now we better understand why
- Confinement improvement should scale to a reactor (if MTMs are avoided)
  - May not be true in spherical tokamaks (testable on SMART[1])
- ASTRA-TGLF agrees with GENE, but puzzles remain in profile predictions
- Lack of H-mode transition appears robust and enables attractive scenarios
- SOL width in NT should be intermediate between PT L-mode and PT H-mode (as should detachment physics)
- NT and PT similar for fast ion physics, Alfven eigenmodes, and tearing modes, while stronger vertical instability should be kept in mind

Thank you!

This presentation (including hyperlinks to all citations) can be downloaded at this event's Indico site: https://indico.euro-fusion.org/event/3700/

This work has been carried out within the framework of the EUROfusion Consortium, partially funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). The Swiss contribution to this work has been funded by the Swiss State Secretariat for Education, Research and Innovation (SERI). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, the European Commission or SERI. Neither the European Union nor the European Commission nor SERI can be held responsible for them.