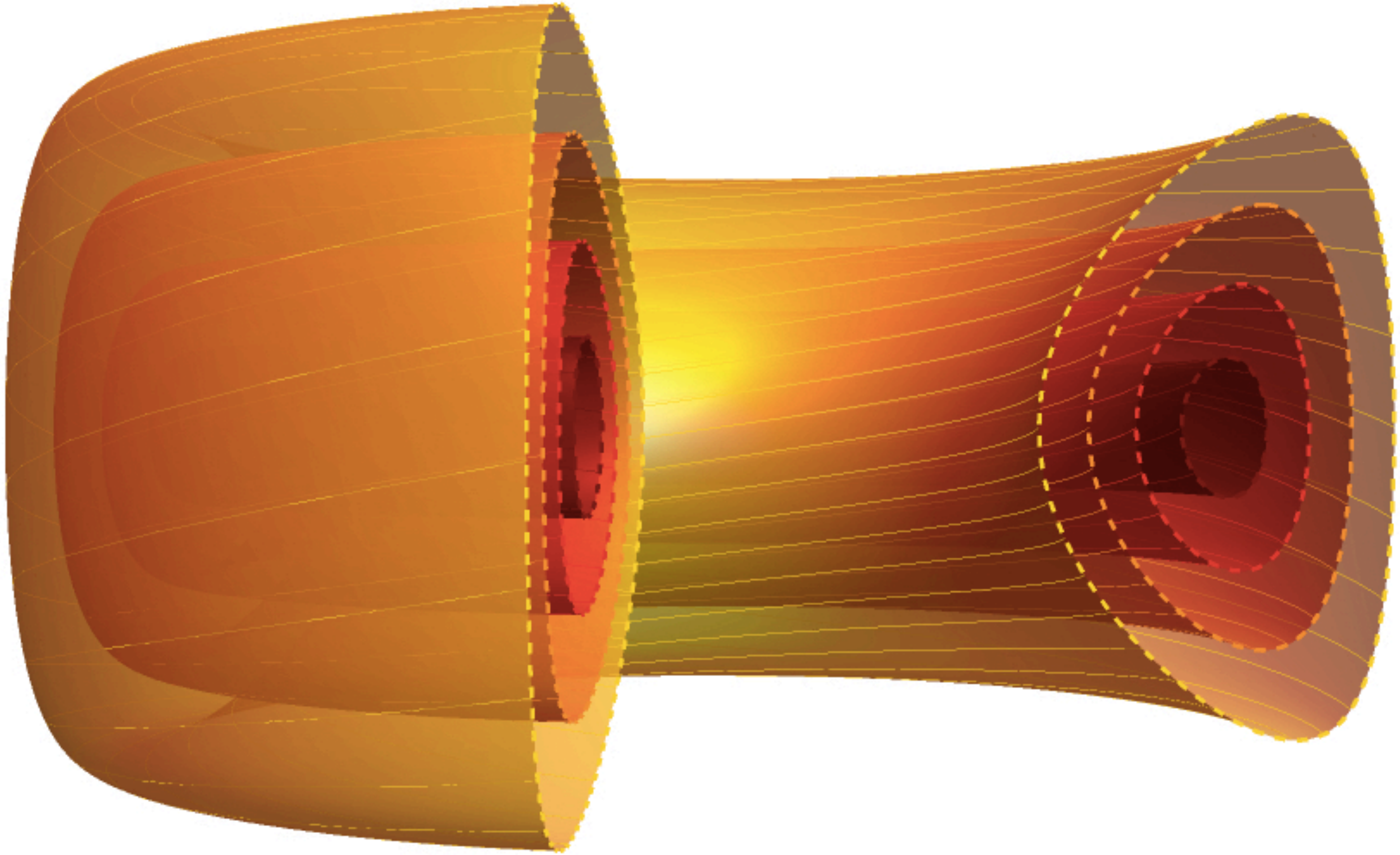
Update on TSVV 2 and future plans



Justin Ball on behalf of the TSVV 2 team

CEA	H. Luetjens
DIFFER	M. Pueschel, J. Citrin
ENEA	G. Fogaccia, P. Muscente, P. Mantica, A. Mariani, G. Vlad, P. Innocente
EPFL	J. Ball, G. Di Giannatale, K. Lim, A. Merle, O. Sauter, M. Vallar, A. Balestri, P. Ricci

2023 Thrust #5 Meeting
7 June 2023

Summary

- TSVV 2 is on schedule, we anticipate all deliverables will be achieved for the gate review, and the scheduling for 2023/2024 looks good

Scientific deliverable	Status	Evidence for achievement
D1.1 Core and pedestal turbulence and physical understanding	Done	See pinboard ID 32978, conference proceeding, conference contribution; additionally a paper is in preparation
D1.2 Power exhaust in current experiments	Done	See pinboard ID 34453 and conference contribution
D2.1 Properties of tearing modes	Partial	Delayed by 6 months; XTOR-K is now ready for PT/NT tearing simulations with and without fast particles; report will be provided mid-2023
D6.1 TGLF/GENE verification for reduced modelling	Done	See pinboard ID 32646 and a paper is in preparation
D6.2 Study of saturation physics	Done	See pinboard IDs 30201, 32701, 32327, and 31543; additionally a paper is in preparation

- No recent personnel changes; only ACH collaboration just began

Highlights on extrapolating to reactor scales

- Confinement in Negative Triangularity (NT) versus Positive Triangularity (PT):
    1. Physical understanding (and behavior in spherical tokamaks)
    2. Global effects (non-uniform magnetic shear and preliminary global ORB5 results)
    3. Finite β effects and electromagnetic turbulence
- Scrape-Off Layer (SOL) width in NT:
    4. Interpretative TCV edge transport modeling with SOLEDGE-EIRENE
    5. Predictive TCV edge transport modeling using GBS

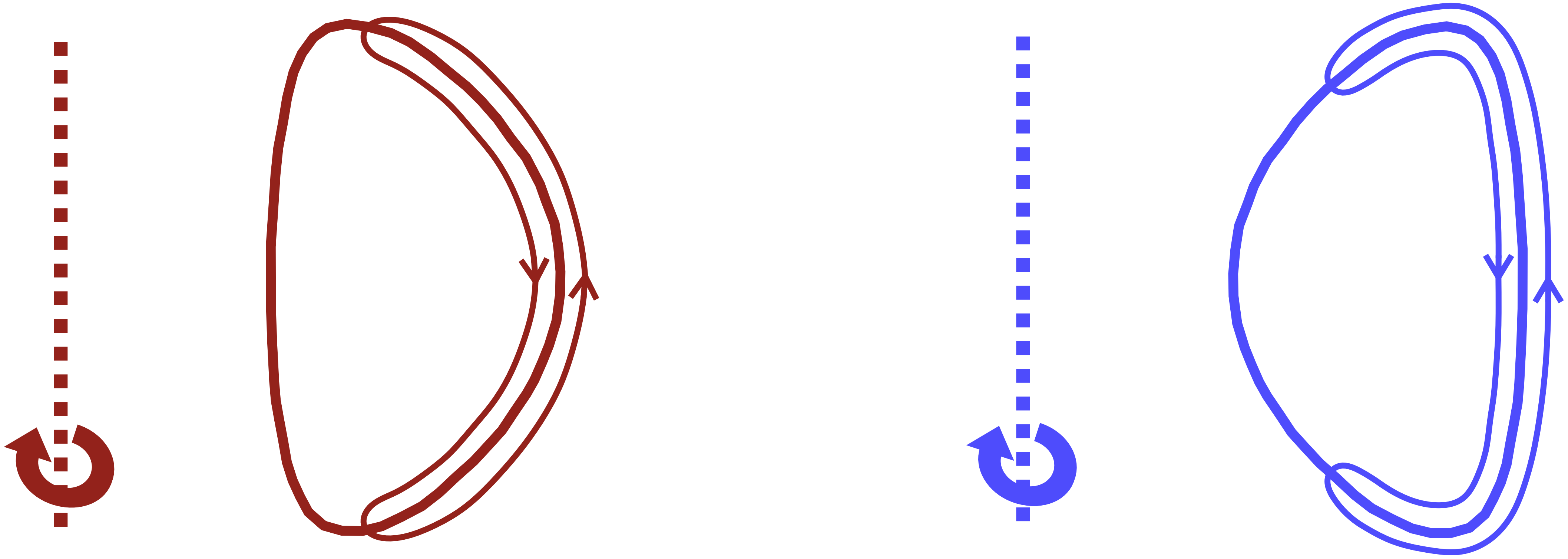
Physical understanding of NT confinement (and behavior in spherical tokamaks)

A. Balestri, et al., *EPS* (2023).

Traditional theoretical argument

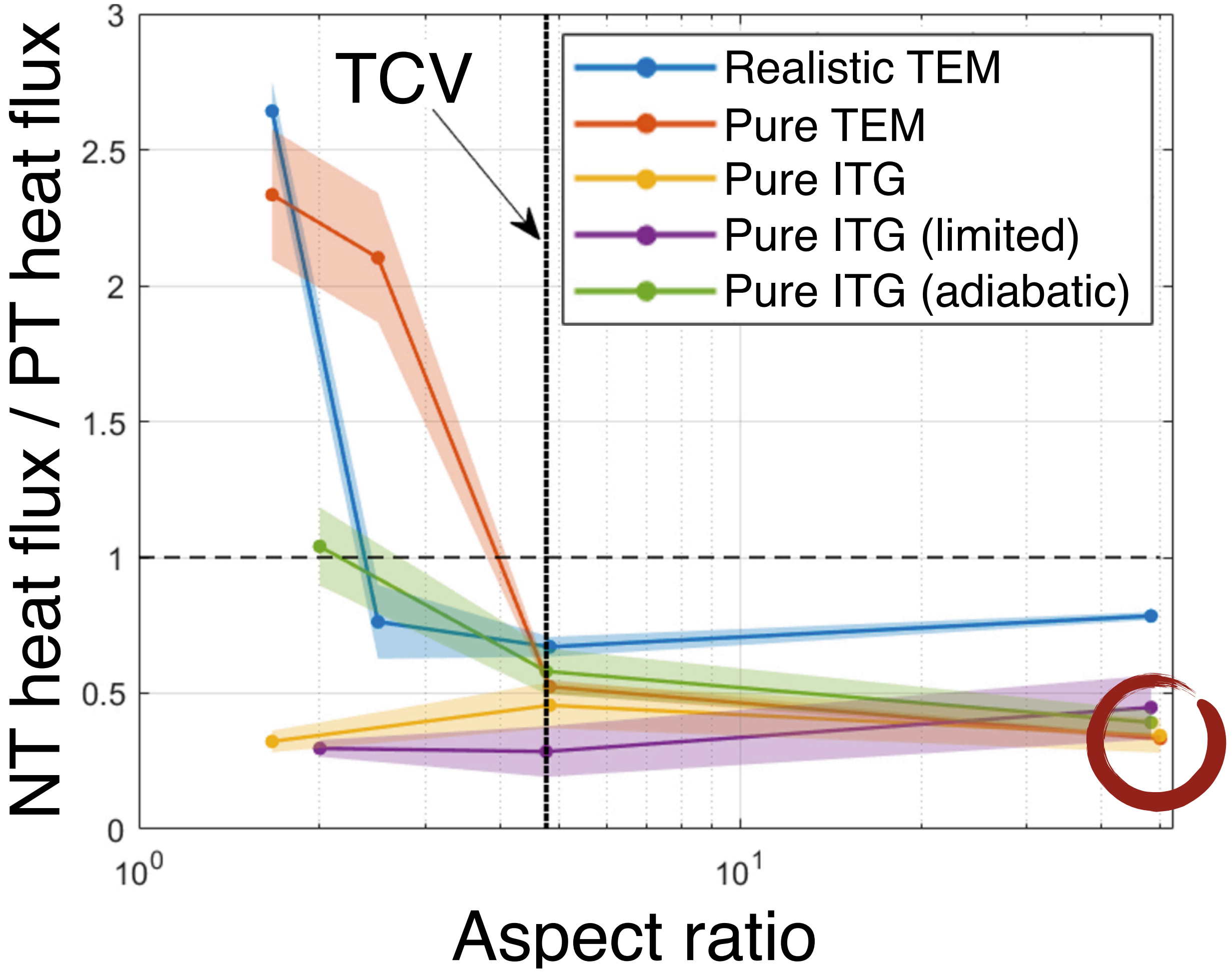
G. Rewoldt, et al. *Phys. Fluids* **25** (1982).
Ohkawa. GA-A19184 (1988).
A. Marinoni, et al., *PPCF* **51** (2009).
G. Merlo, et al., *PPCF* **57** (2015).
G. Merlo, et al., *Phys. Plasmas* **26** (2019).
A. Marinoni, et al., *Rev. Mod. Phys.* **5** (2021).

- Traditional theoretical argument is based on trapped particle stability:
  - NT improves trapped particles' access to the good curvature region



- Intuitively, NT should be most beneficial for Trapped Electron Mode (TEM) turbulence and in spherical tokamaks (which have more trapped particles)

We find the exact opposite!?



- For spherical tokamaks, NT can harm confinement (at least when the turbulence is dominated by the Trapped Electron Mode)

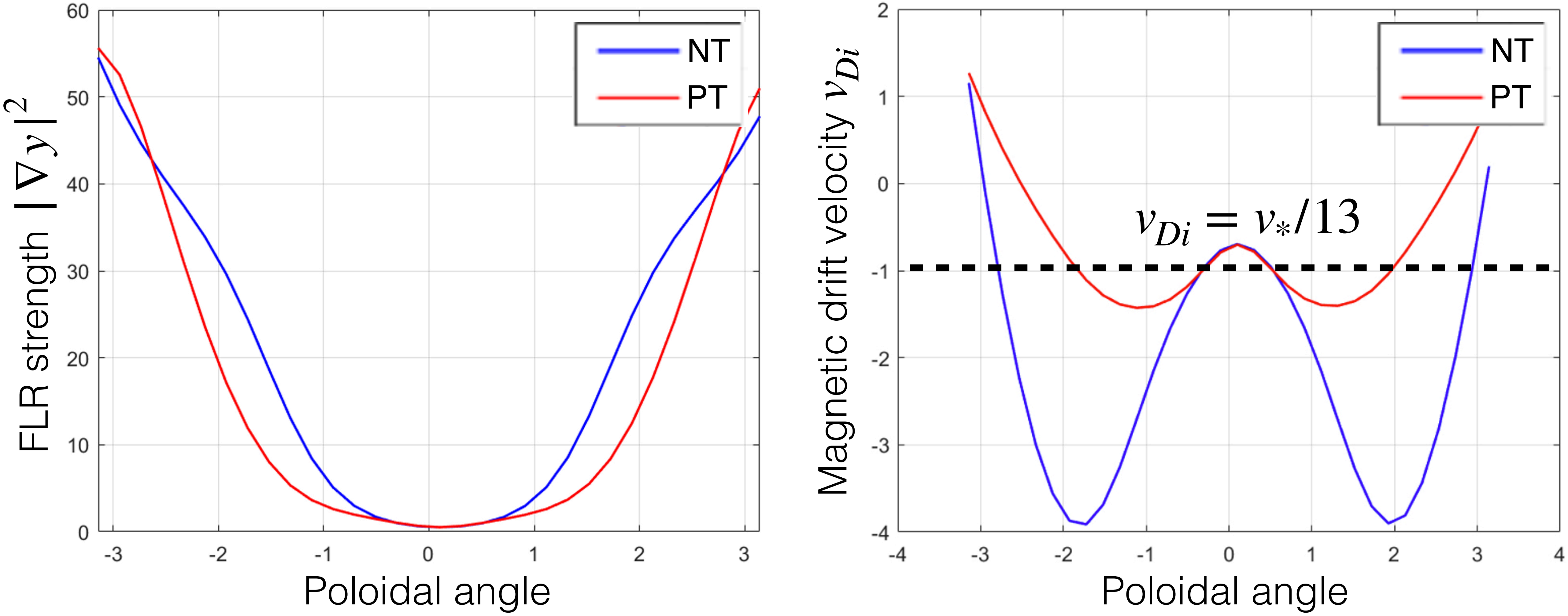
- Restarted from the basics and focused the simplest case:

large aspect ratio, pure Ion Temperature Gradient (ITG)

ITG turbulence in large aspect ratio limit

Biglari et al. *Phys. Fluids B* **1** (1989).
M. Beer *PhD Thesis* (1995).

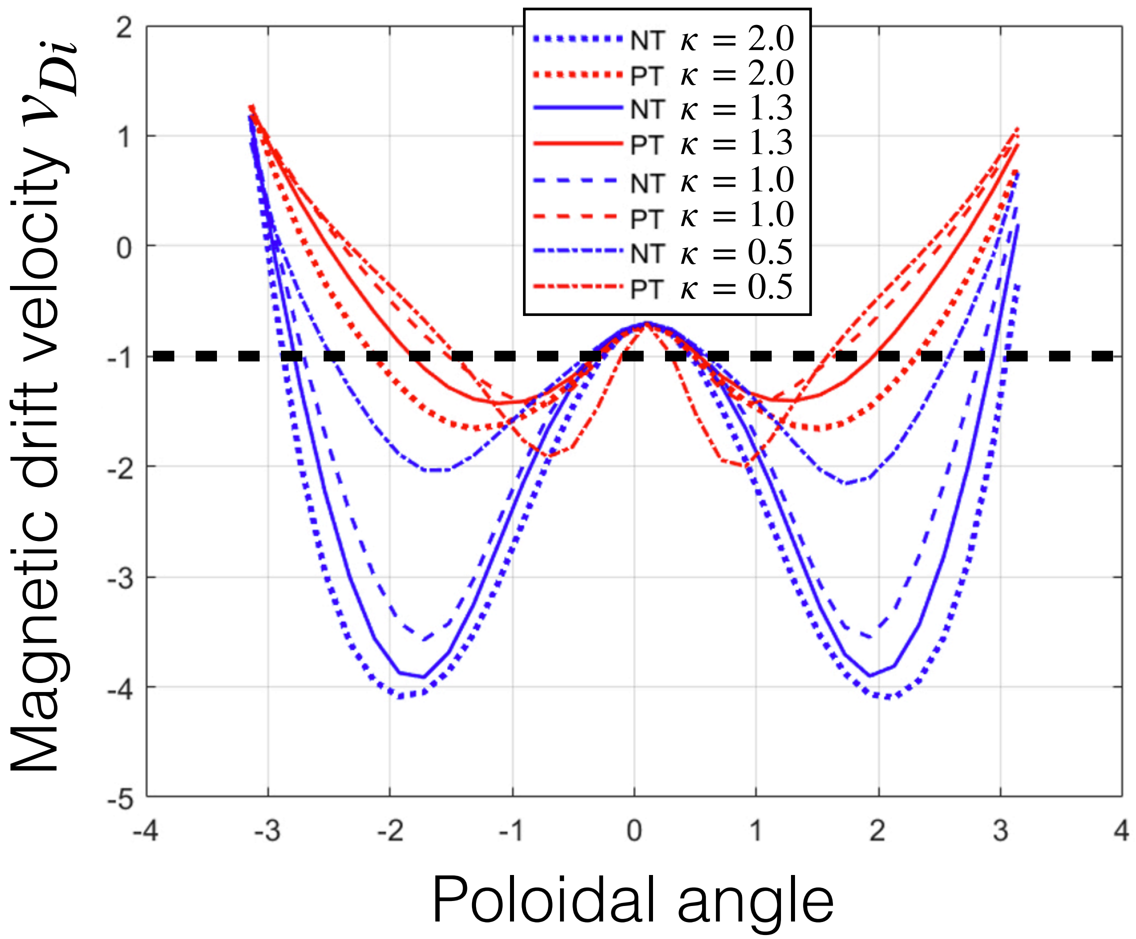
- The plasma shape usually enters into the gyrokinetic model in many places
- In the large aspect ratio limit, only FLR effects and magnetic drifts v_{Di} distinguish different shapes and both are stabilizing in NT

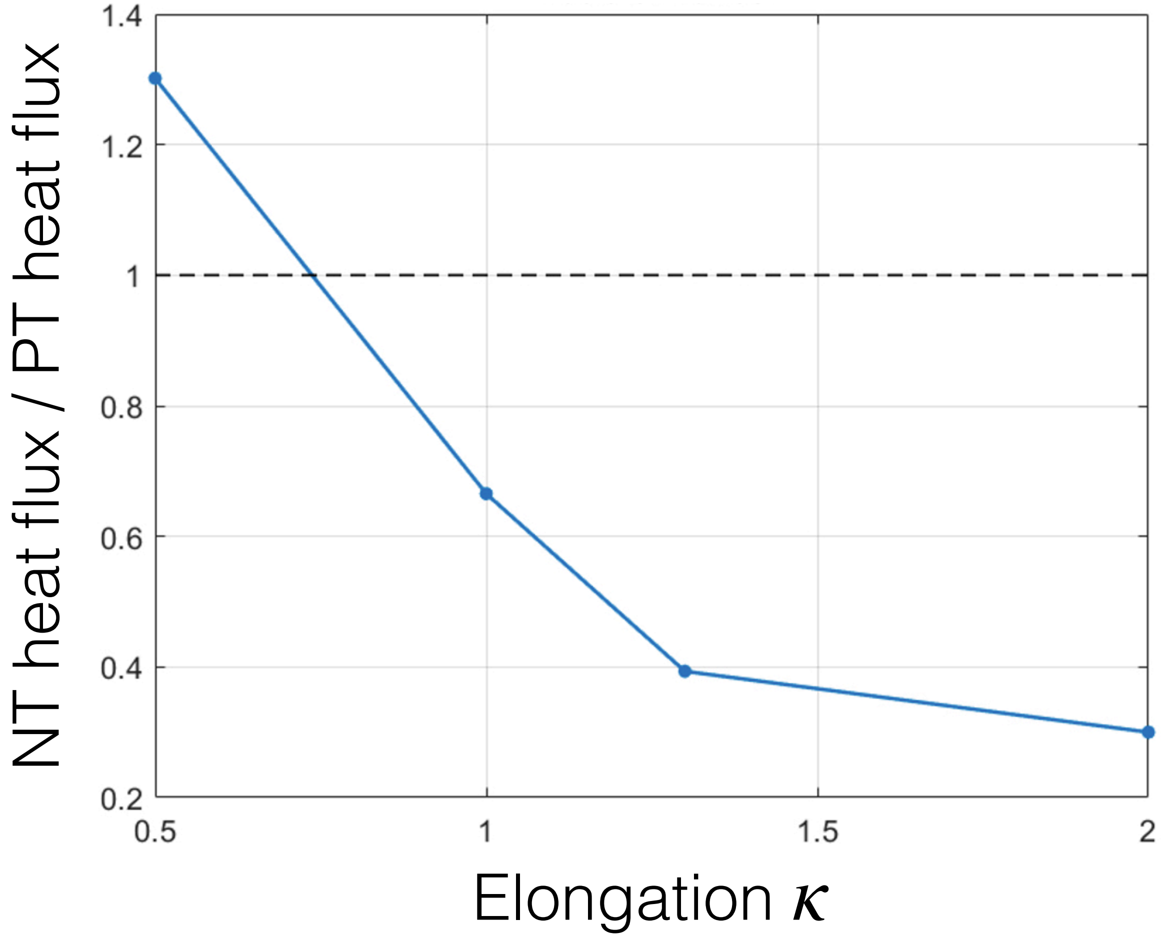


Applying physical picture to elongation scan

- Can also be used to explain the dependence on other geometrical parameters at large aspect ratio (e.g. elongation and magnetic shear)

- Distinction between PT and NT in FLR coefficients doesn't change much



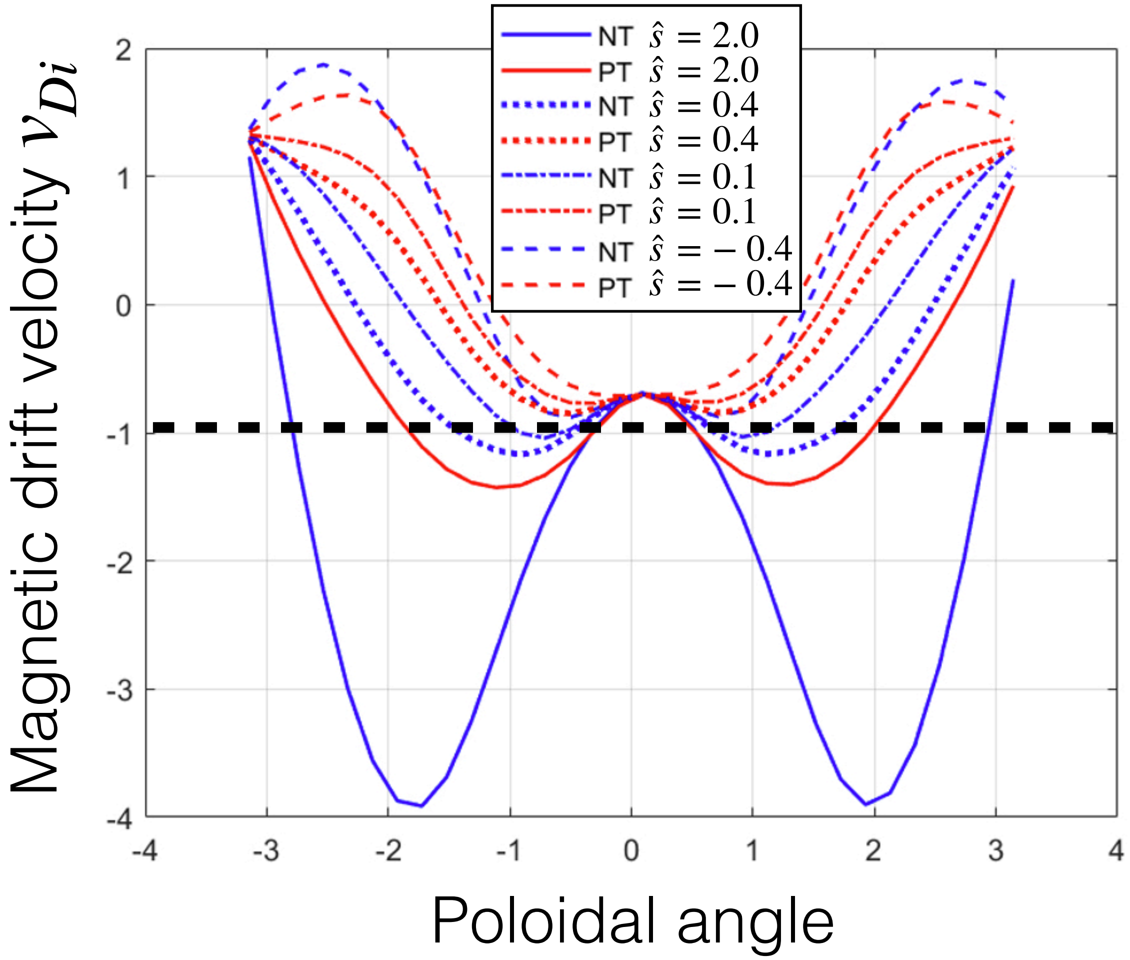


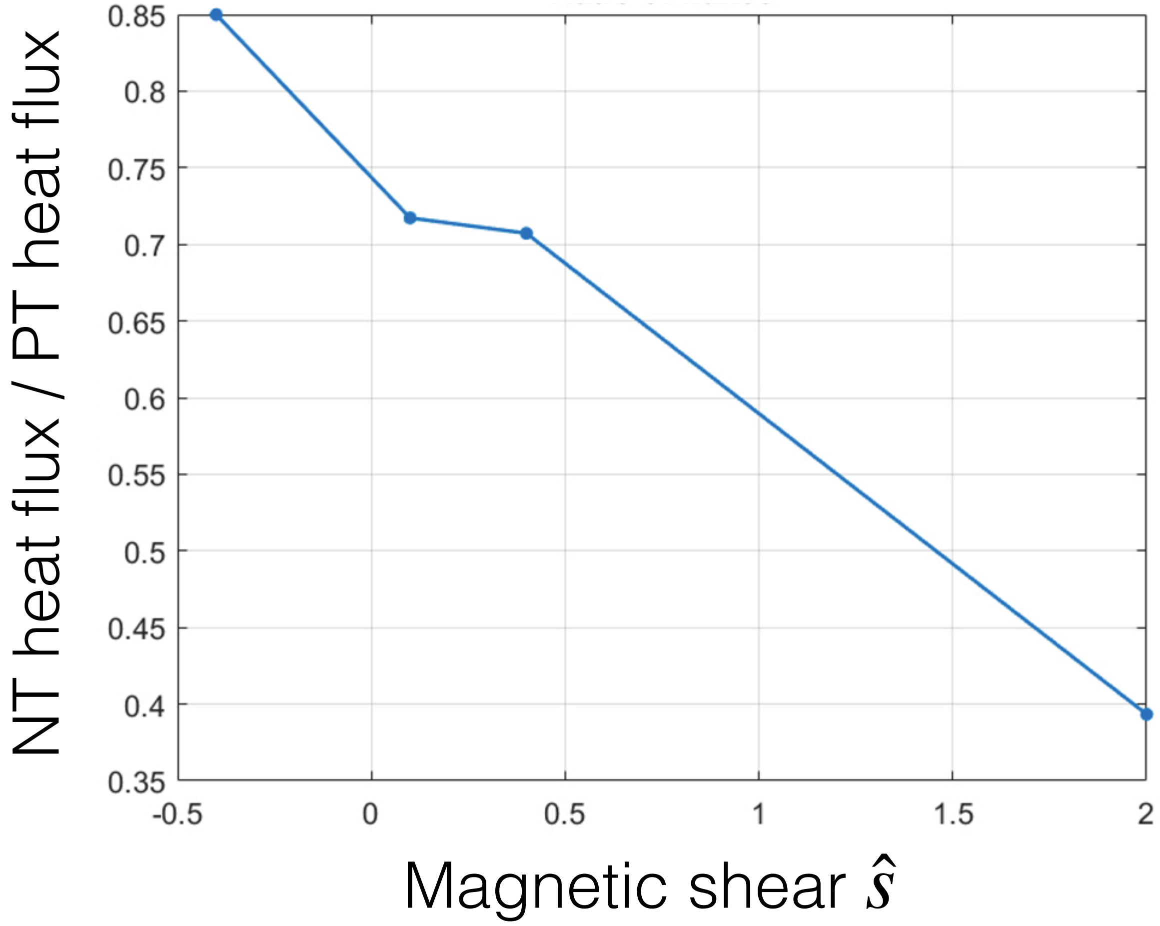
Applying physical picture to magnetic shear scan

Merlo et al. *JPP* ***89*** (2023).

- Can also be used to explain the dependence on other geometrical parameters at large aspect ratio (e.g. elongation and magnetic shear)

- Distinction between PT and NT in FLR coefficients doesn't change much





Strength of global effects

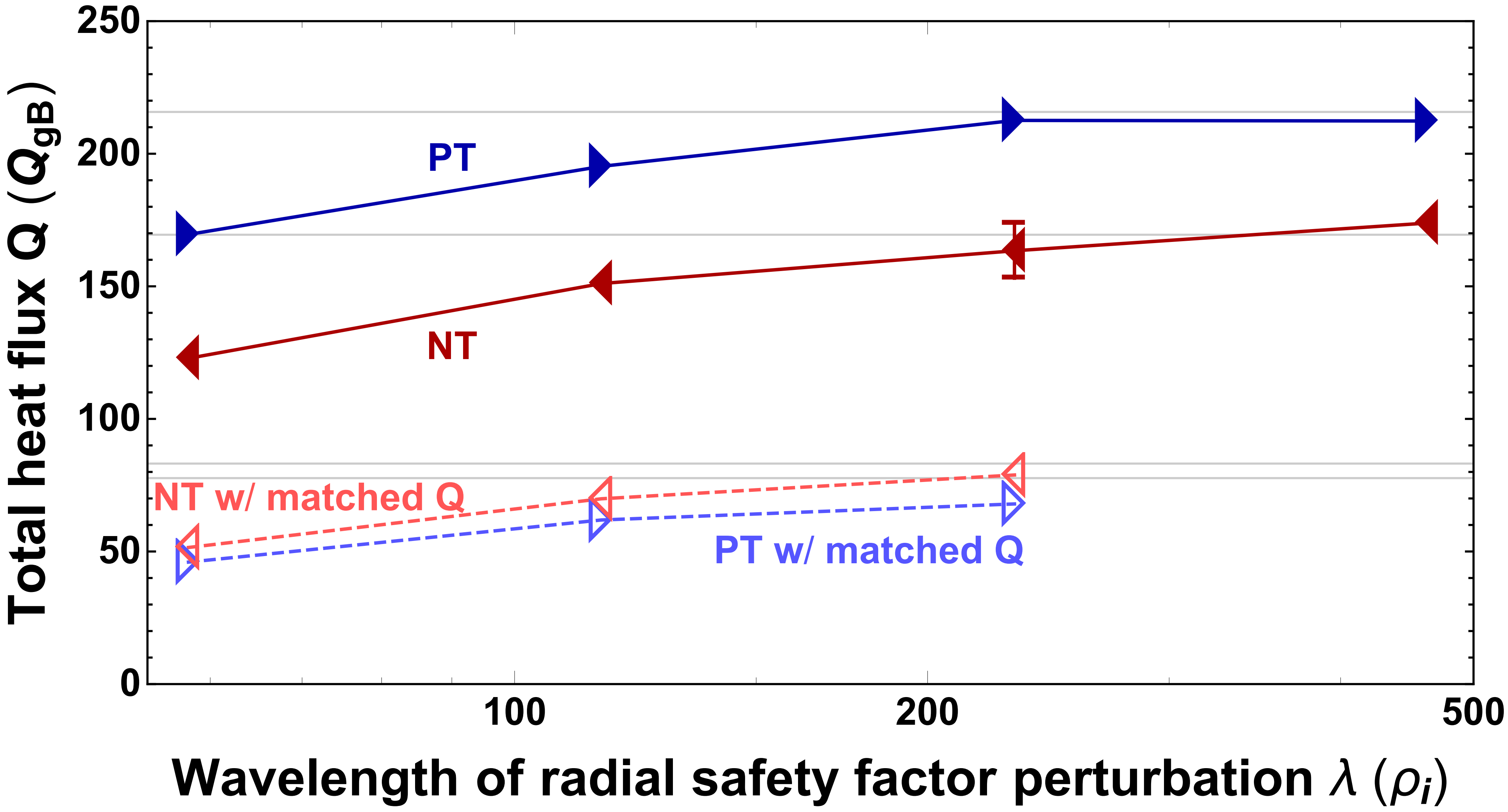
J. Ball et al, *Plasma Phys. Control. Fusion* **65** 014004 (2023).
Di Giannatale et al, J. Phys.: Conf. Ser. ***2397*** *012002 (2022).*

Nonlinear GENE simulations

J. Ball, et al. *PPCF* **65** (2023).

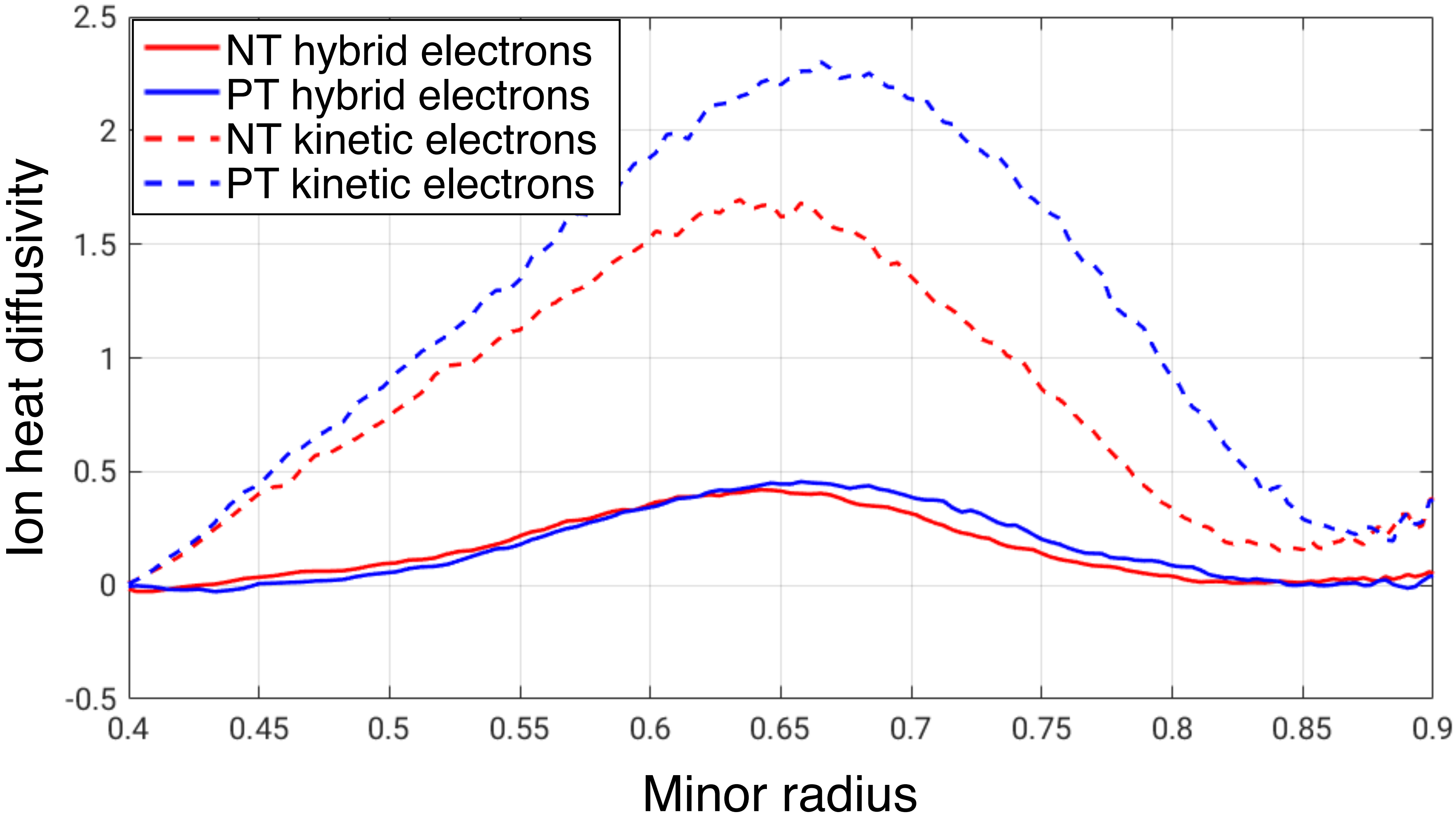
- Using novel flux tube incorporating profile shearing in safety factor profile, we investigated impact of machine size

- NT and PT scale similarly to larger devices



Global ORB5 simulations

- Using fully kinetic (yet still artificially heavy) electrons reveals distinction
- Numerical scan in ρ_* is in-progress

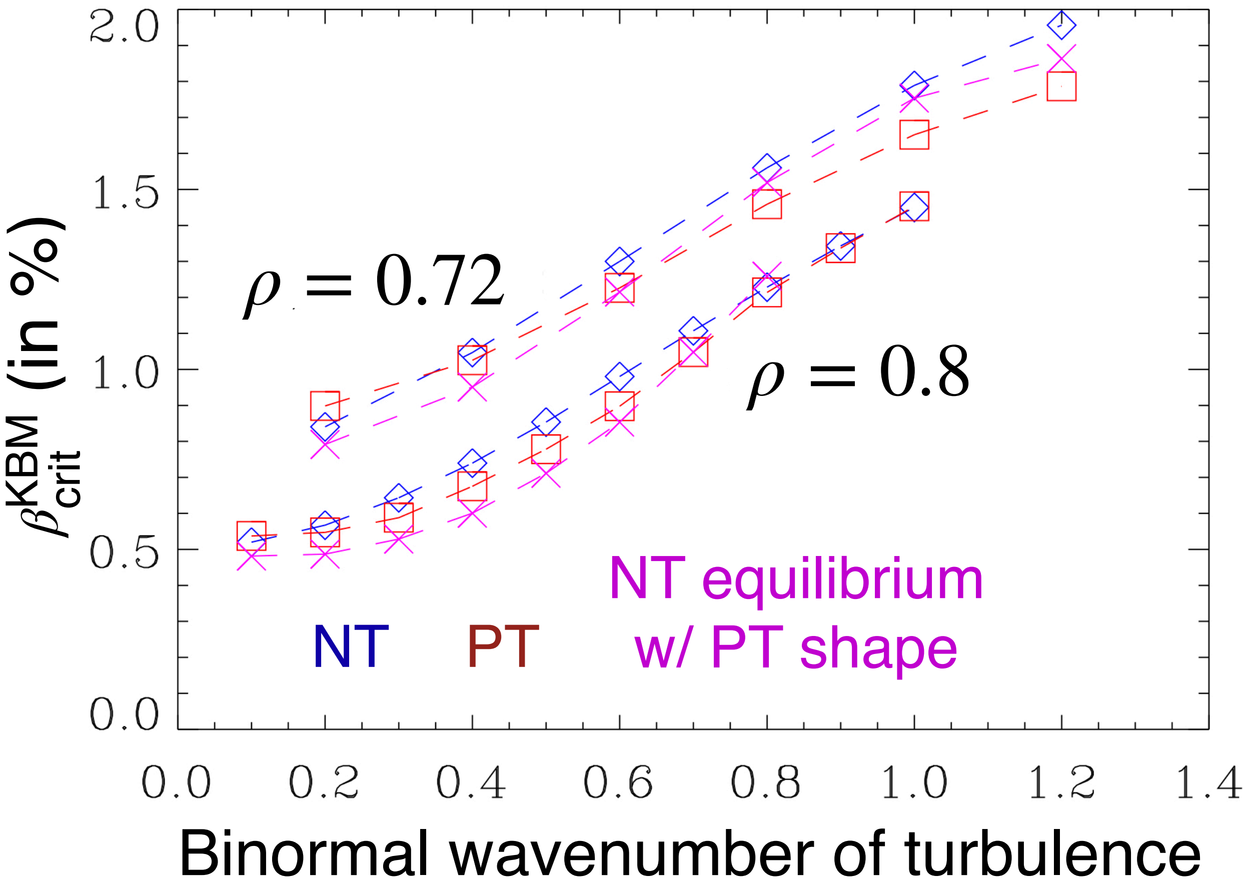


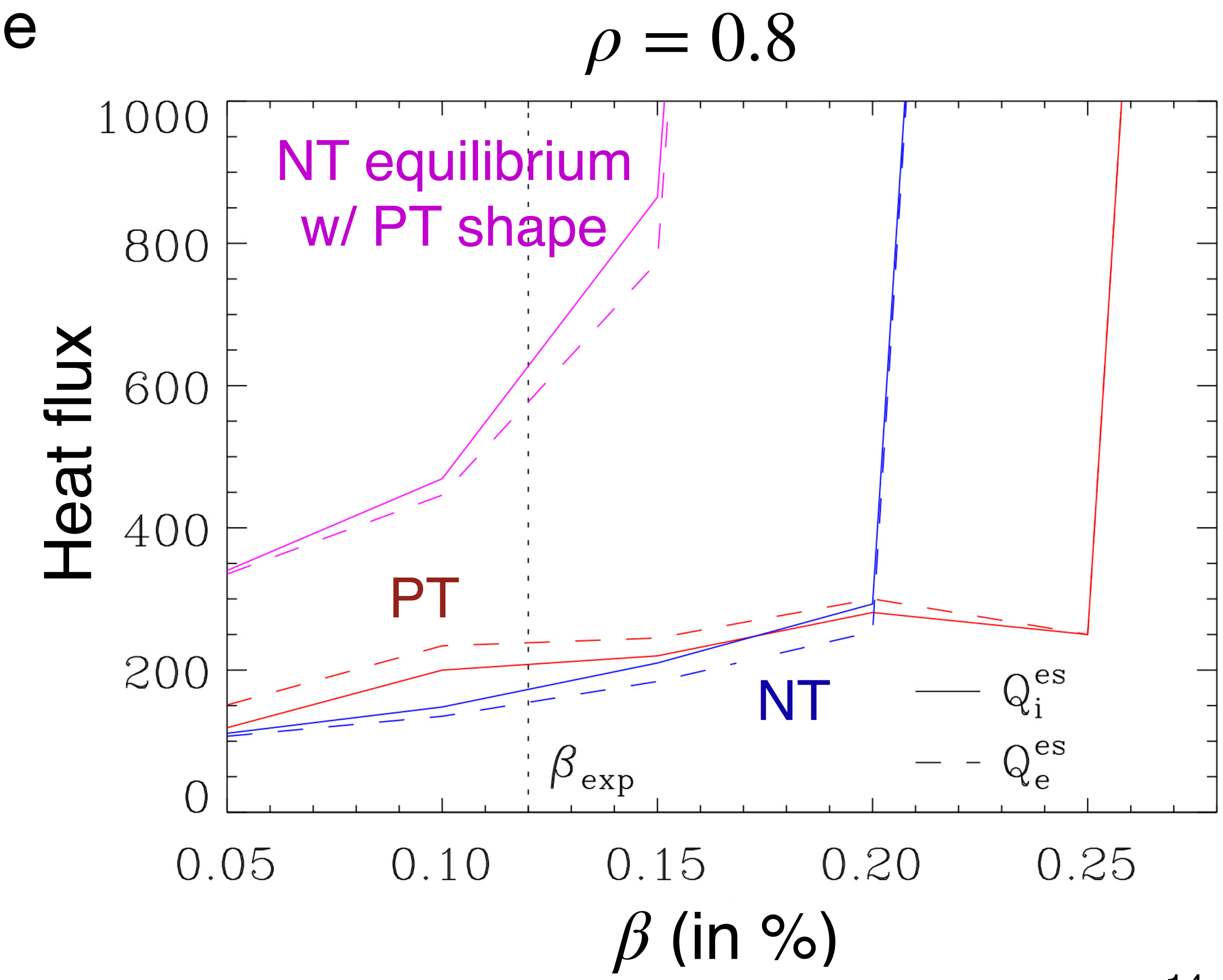
Impact of finite β and electromagnetic turbulence

M.J. Pueschel et al., APS (2022).
M.J. Pueschel et al., US-EU TTF (2022).

Finite β simulations with GENE

- Modeling of NT and PT TCV discharges show little distinction in how they scale with β
- Critical β for the linear onset of KBM turbulence is similar as is the nonlinear effect of β on electrostatic turbulence





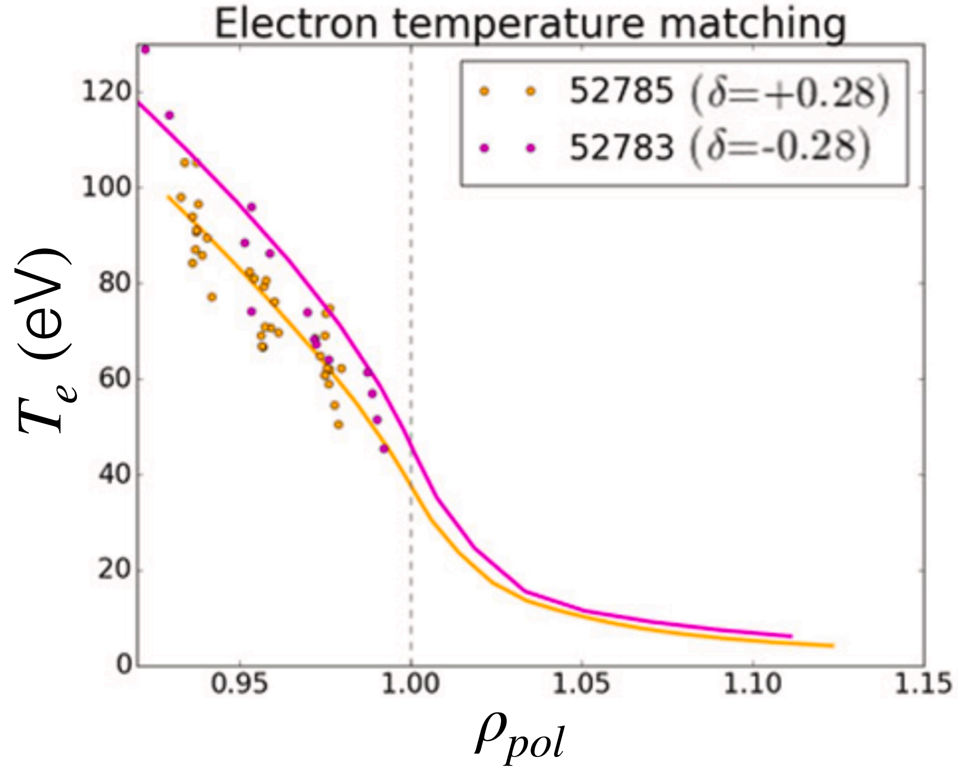
Interpretative TCV edge transport modeling with SOLEDGE-EIRENE

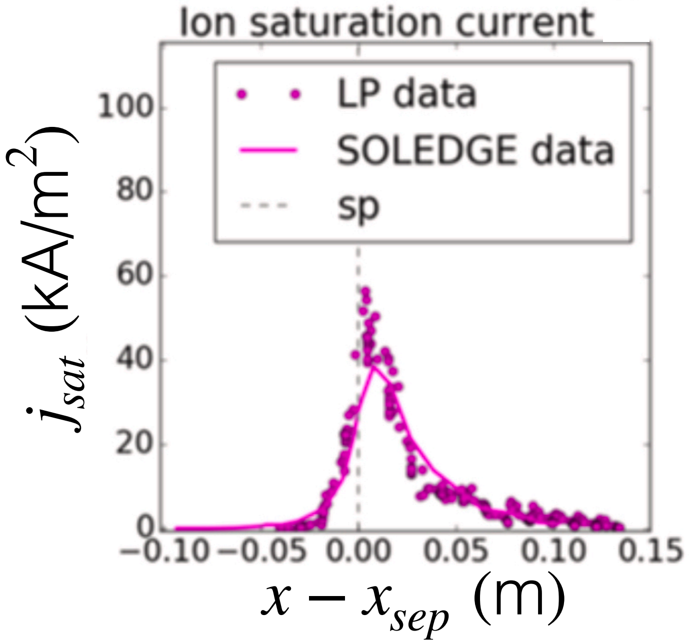
P. Muscente, P. Innocente, et al., *J. Nucl. Mater*. **34** 101386 (2023).

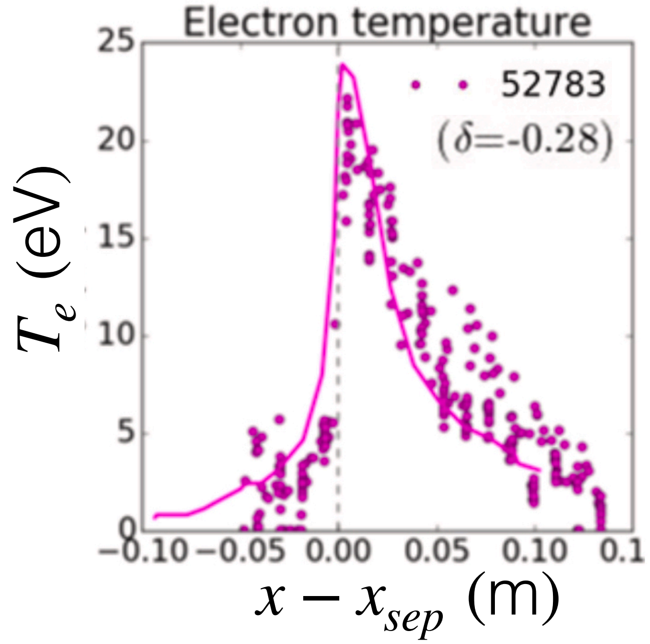
Interpretative analysis of single null TCV discharges

P. Muscente, et al. *J. Nucl. Mater.* (2023).

- A set of single null TCV discharges with triangularity δ^{NXP} were considered
- SOLEDGE, a 2D fluid code for the plasma, was coupled to EIRENE, a kinetic code for the neutrals
- Radial profiles of diffusivities were tuned within SOLEDGE to match experimental observables





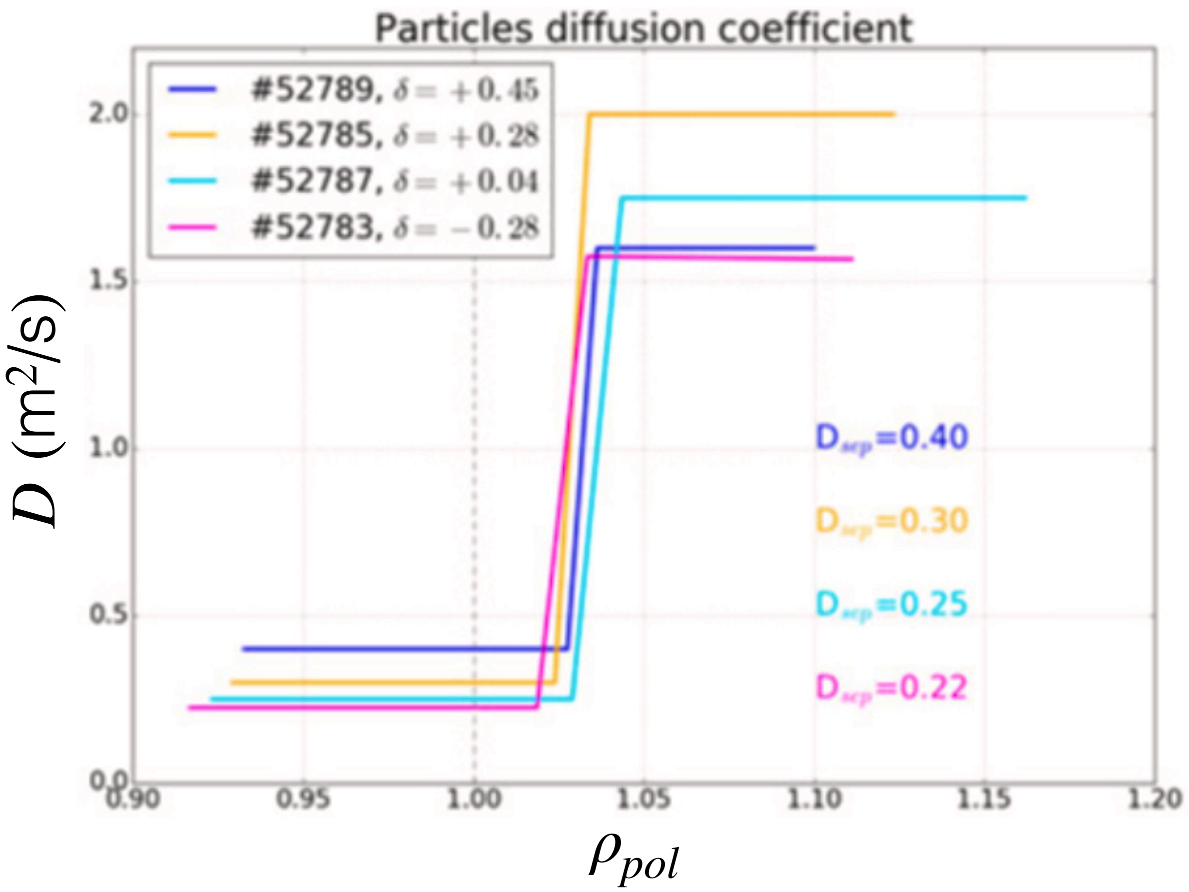


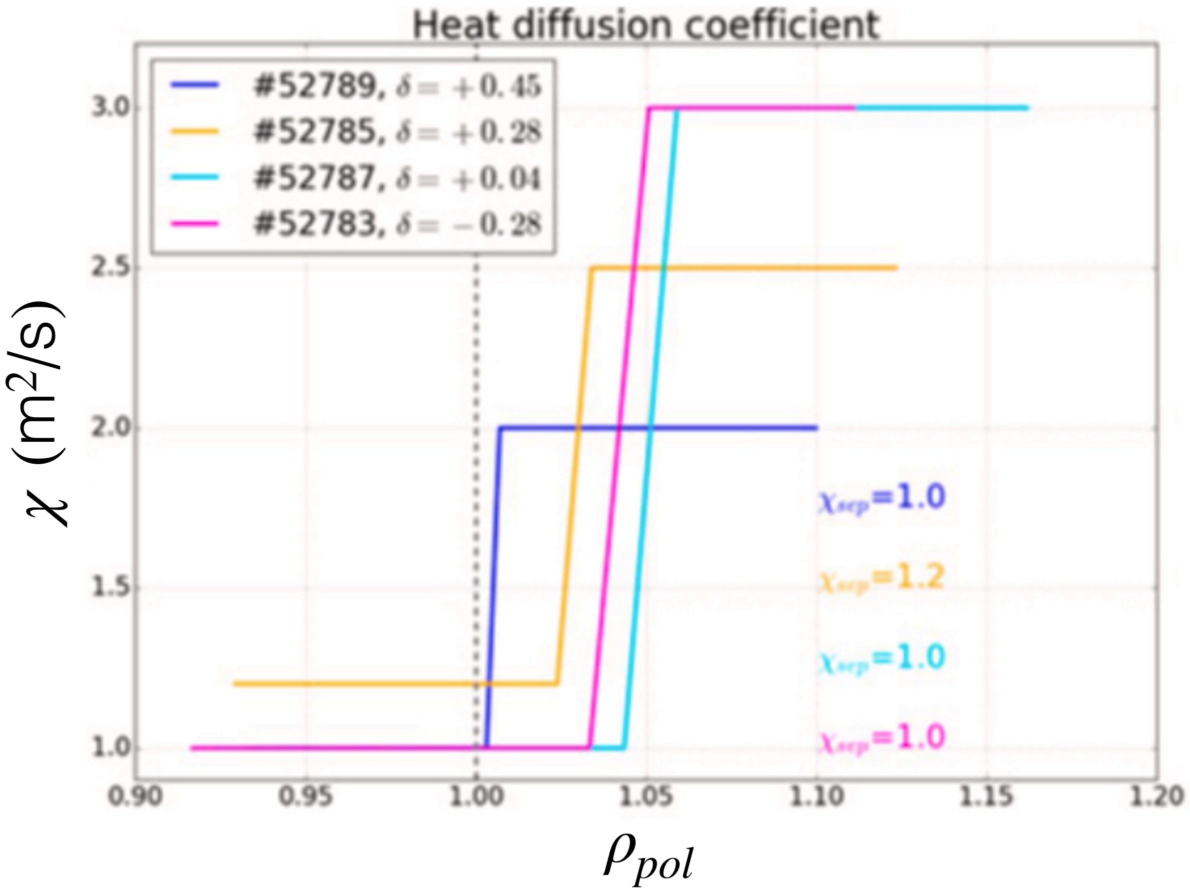
NT reduces the particle diffusivity

P. Muscente, et al. *J. Nucl. Mater.* (2023).

- Matching experiment required a reduced particle diffusivity at the separatrix for NT

- Trend for heat diffusivity was less clear

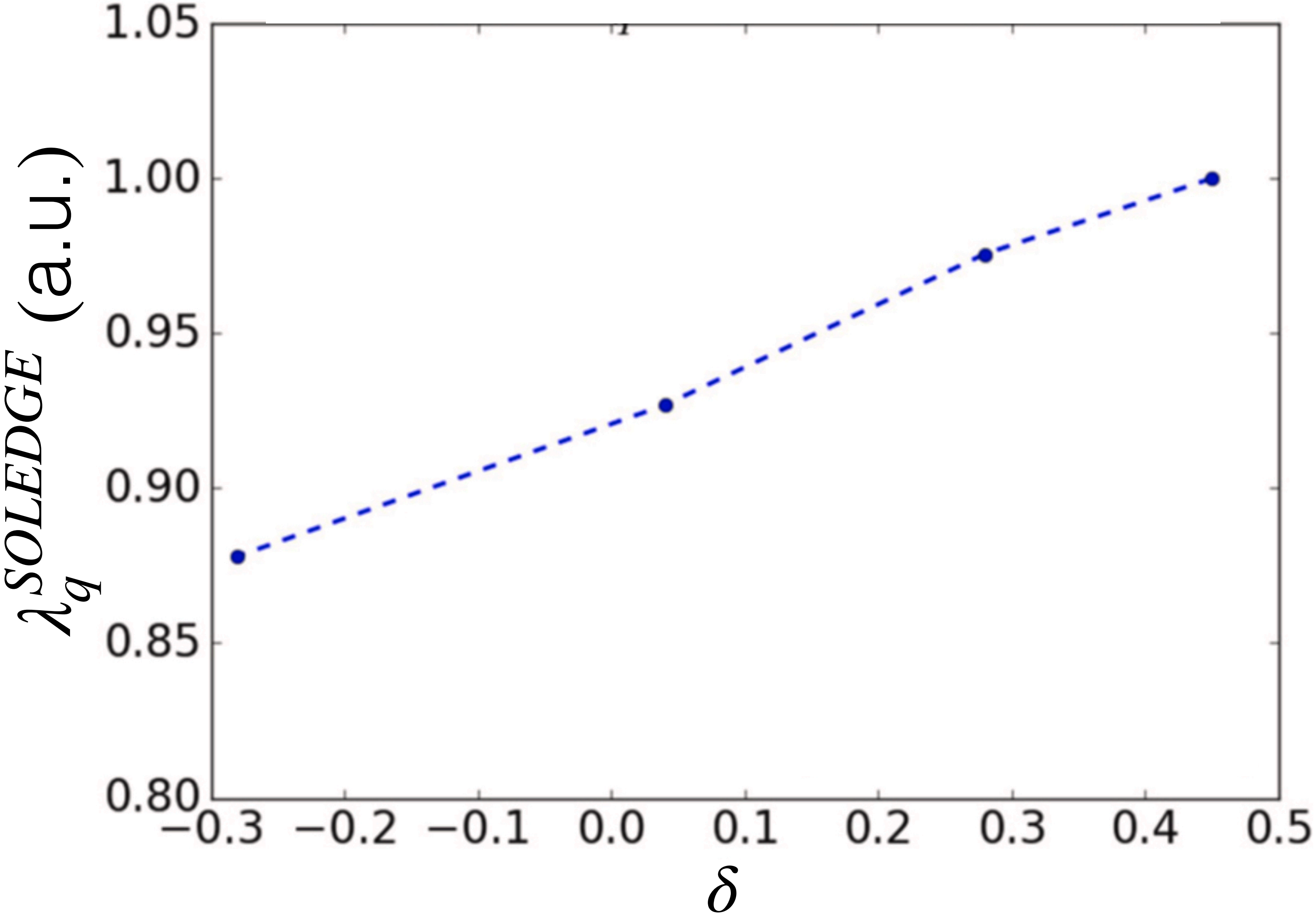




SOLEDGE: NT reduces $\lambda_q^{SOLEDGE}$ somewhat

P. Muscente, et al. *J. Nucl. Mater.* (2023).

- Regardless, heat flux decay length at outer midplane measured in these simulations was lowered by NT



Predictive TCV edge transport modeling using GBS

K. Lim, M. Giacomin, et al., *PPCF* (submitted).

Predictive analysis of single null equilibria

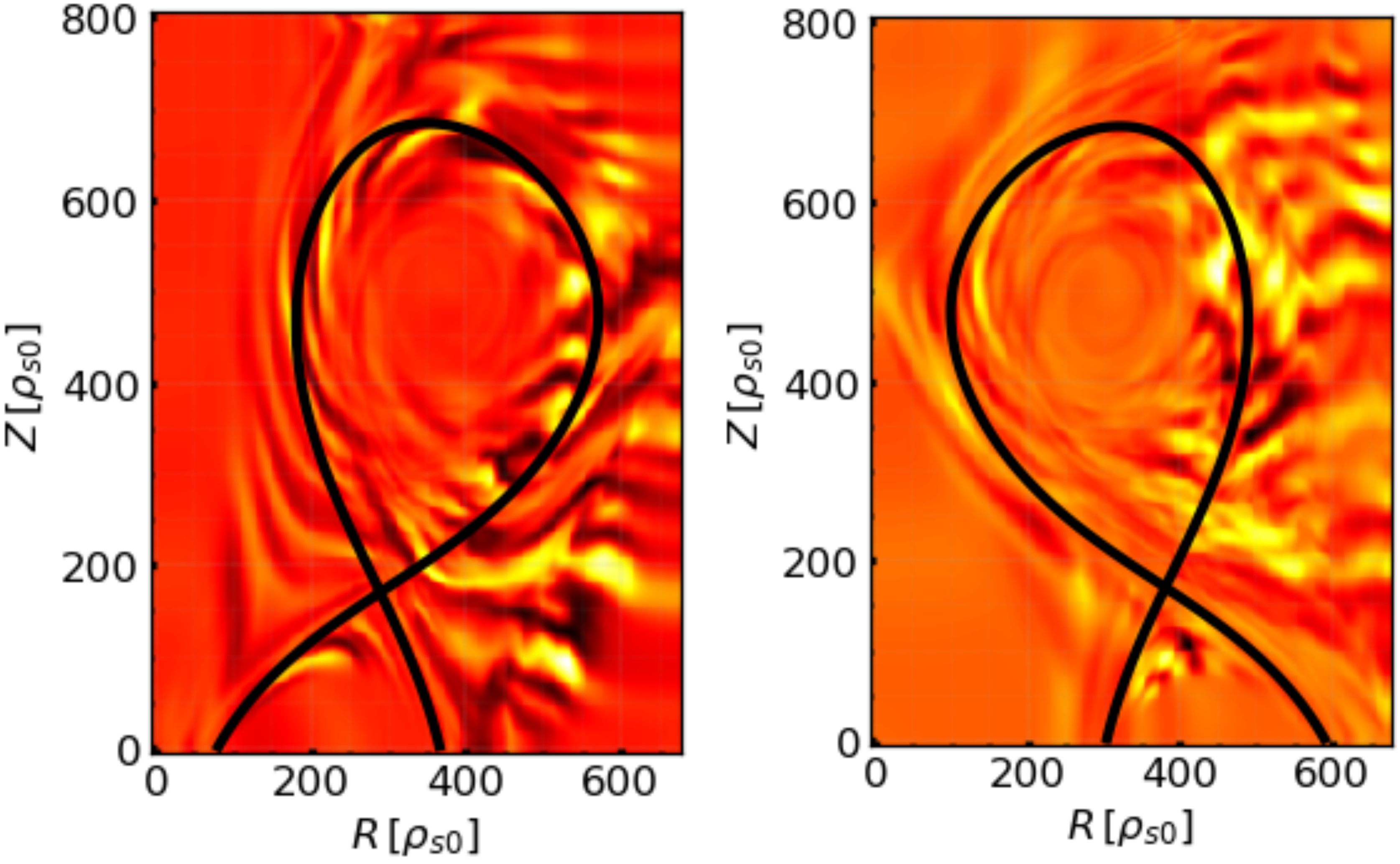
K. Lim, et al. *PPCF* (submitted).

M. Giacomin, et al. *Nucl. Fusion* (2021).

- Two single null equilibria, modeled after TCV discharges with varying triangularity $\delta = \pm 0.3$, were considered

- GBS, solving a drift reduced Braginskii model, predicts edge plasma turbulence

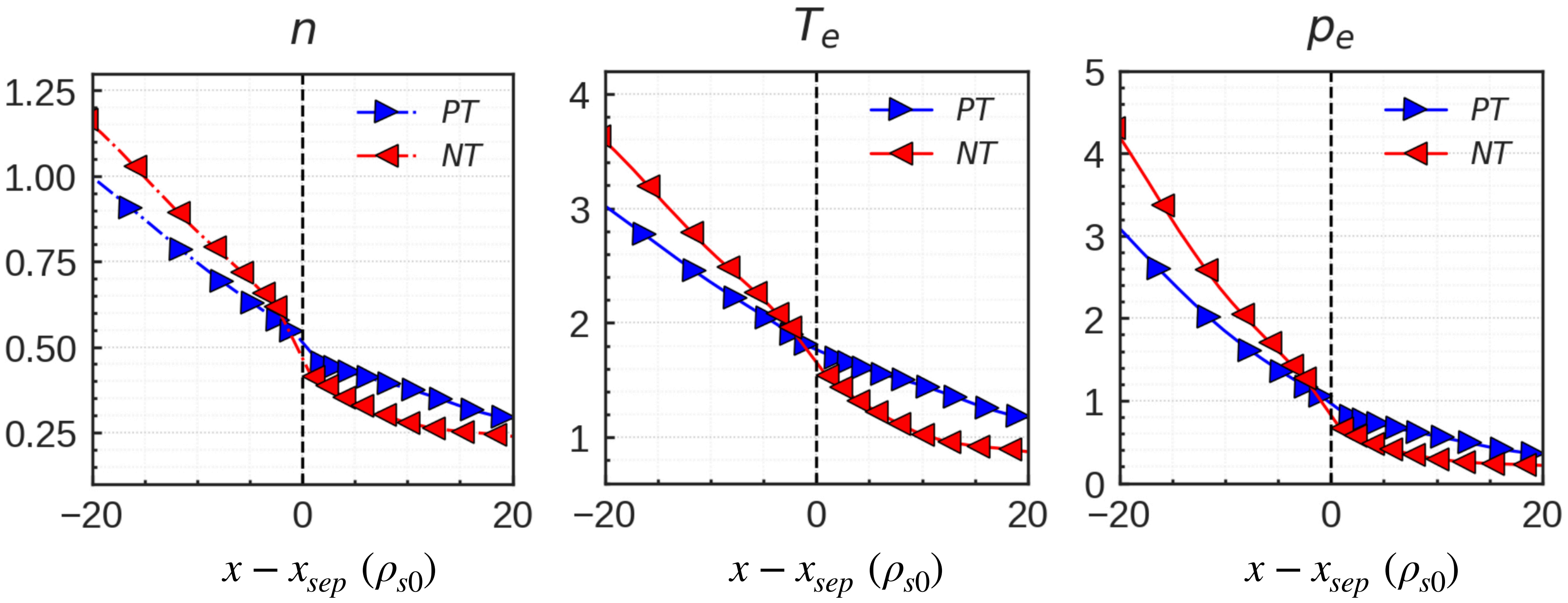
- Also, used to extend a theory-based scaling law for λ_q to include triangularity, which has been validated on a multi-machine database



GBS: NT reduces λ_q somewhat

K. Lim, et al. *PPCF* (submitted).

- GBS finds that NT improves the energy confinement time τ_E, but steepens the profile gradients at the separatrix, thereby reducing λ_q by ~30%



- Similarly, the theory-based scaling law predicts 40% lower λ_q for NT

Summary and synthesis

- GENE and ORB5 simulations find better confinement in NT and we believe we understand why
- NT may degrade confinement in spherical tokamaks
- Profile shearing and electromagnetic effects appear similar in PT and NT, suggesting confinement improvement will scale to a reactor
- Interpretative SOLEDGE-EIRENE and predictive GBS simulations indicate a somewhat reduced λ_q in NT, compared to PT **L-mode**
- NT λ_q should still be wider than in PT **H-mode**
- If cross-field transport is significantly correlated across the separatrix, it is to be expected that λ_q in NT will be between PT L-mode and PT H-mode

All done.

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.

Physical mechanism behind NT at large aspect ratio

Biglari et al. *Phys. Fluids B* **1** (1989).
M. Beer *PhD Thesis* (1995).

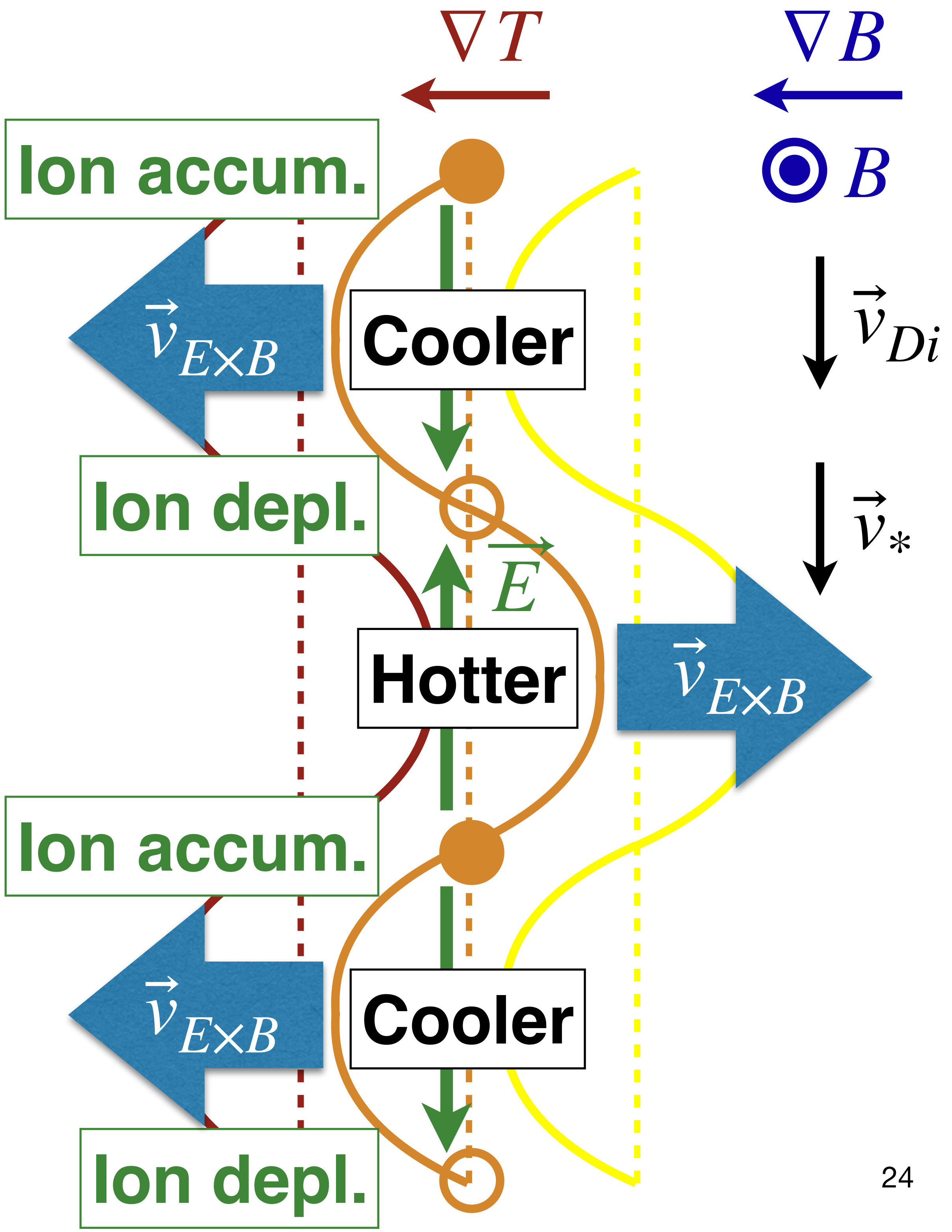
- Turbulence in tokamaks arises from a destabilization of drift waves
- Drift waves travel with a velocity:

$$\vec{v}_* \propto \overrightarrow{B} \times \nabla T$$

- Adding ∇B and curvature can destabilize the drift waves, through the ion magnetic drift velocity:

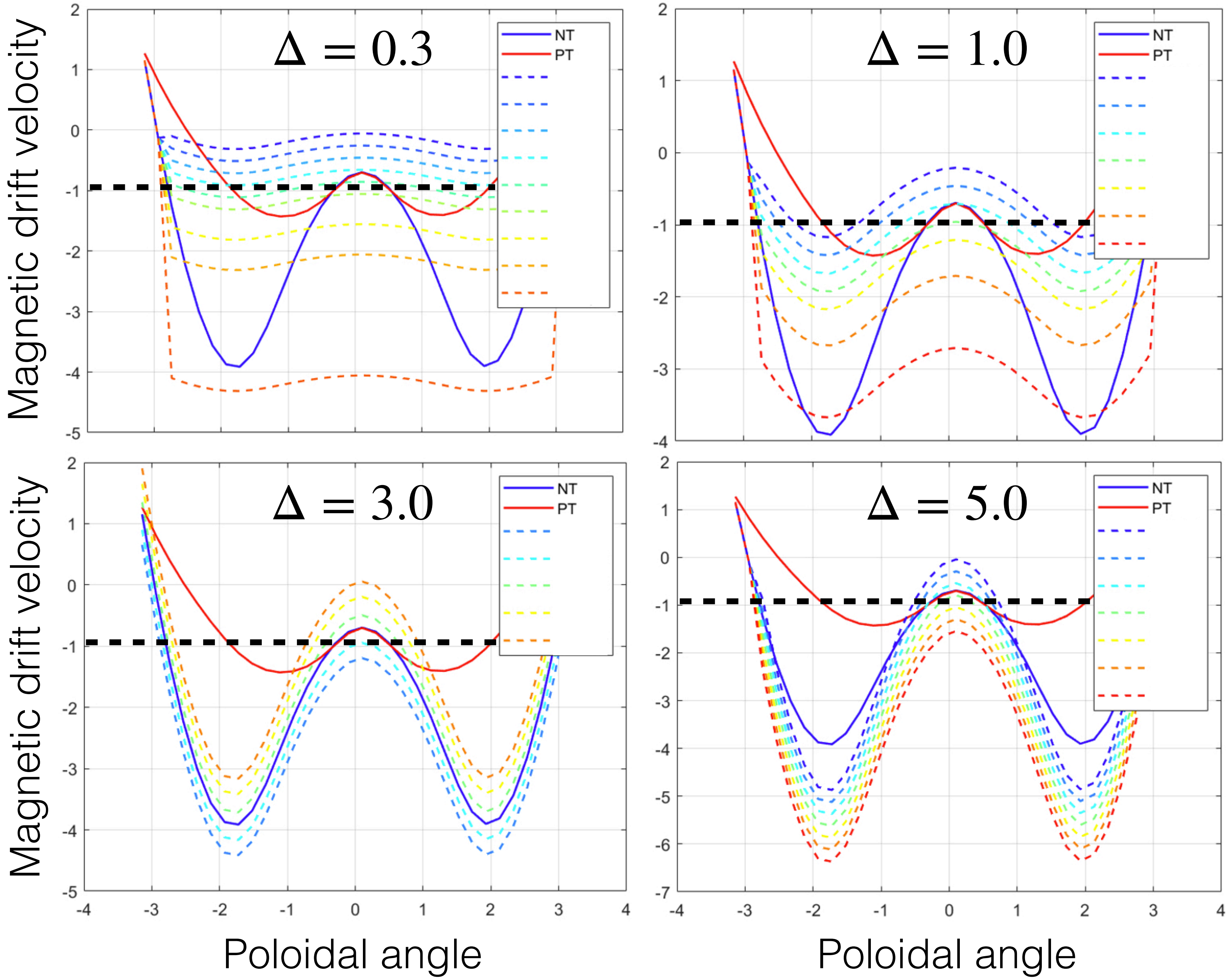
$$\vec{v}_{Di} \propto T_i \overrightarrow{B} \times \nabla B$$

- **For growth these velocities must be similar $\vec{v}_{Di} \approx \vec{v}_*/4$**



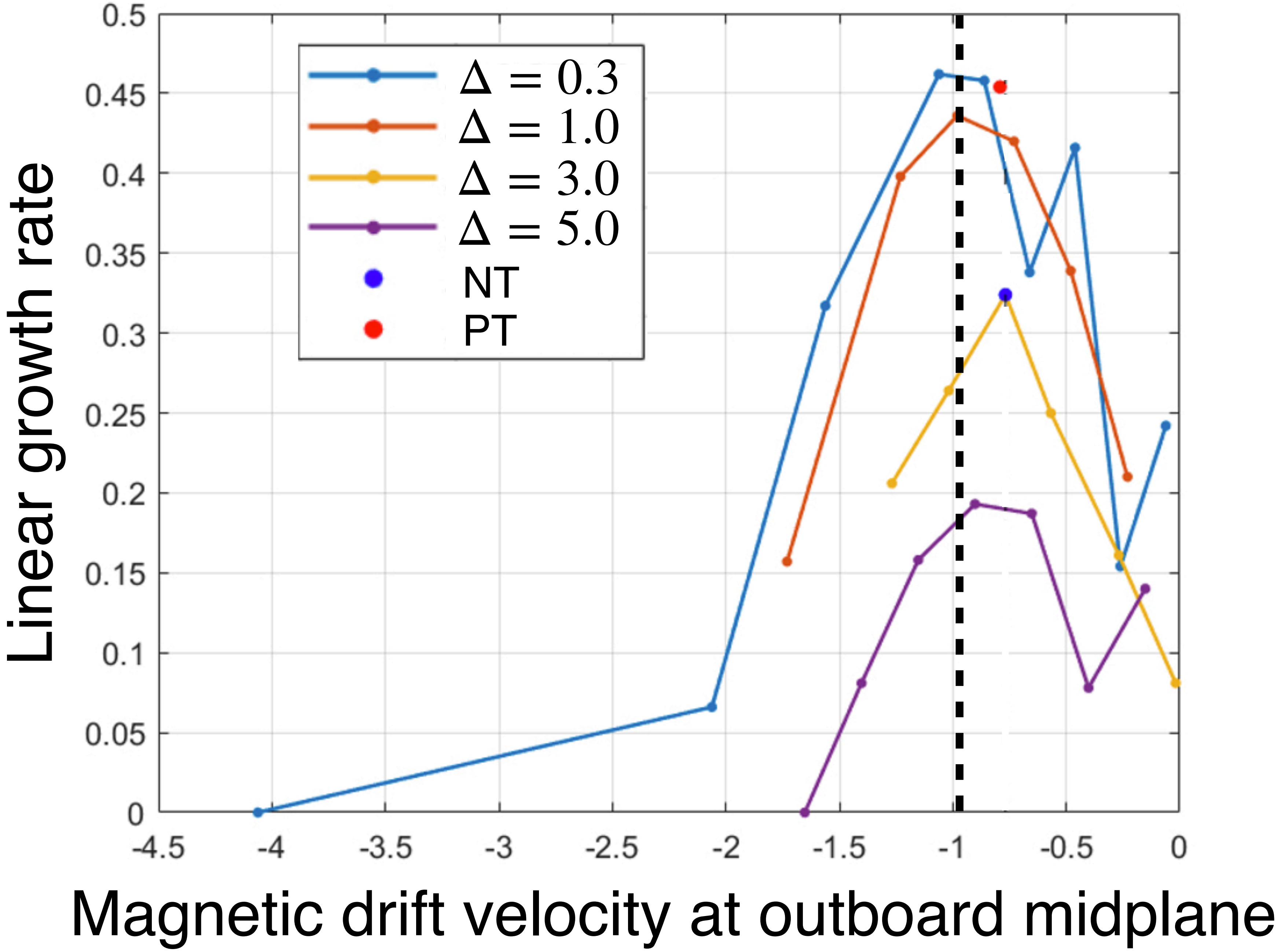
Artificially modifying the magnetic drift velocity

- Modify poloidal variation of the magnetic drift velocity and its value at the outboard midplane



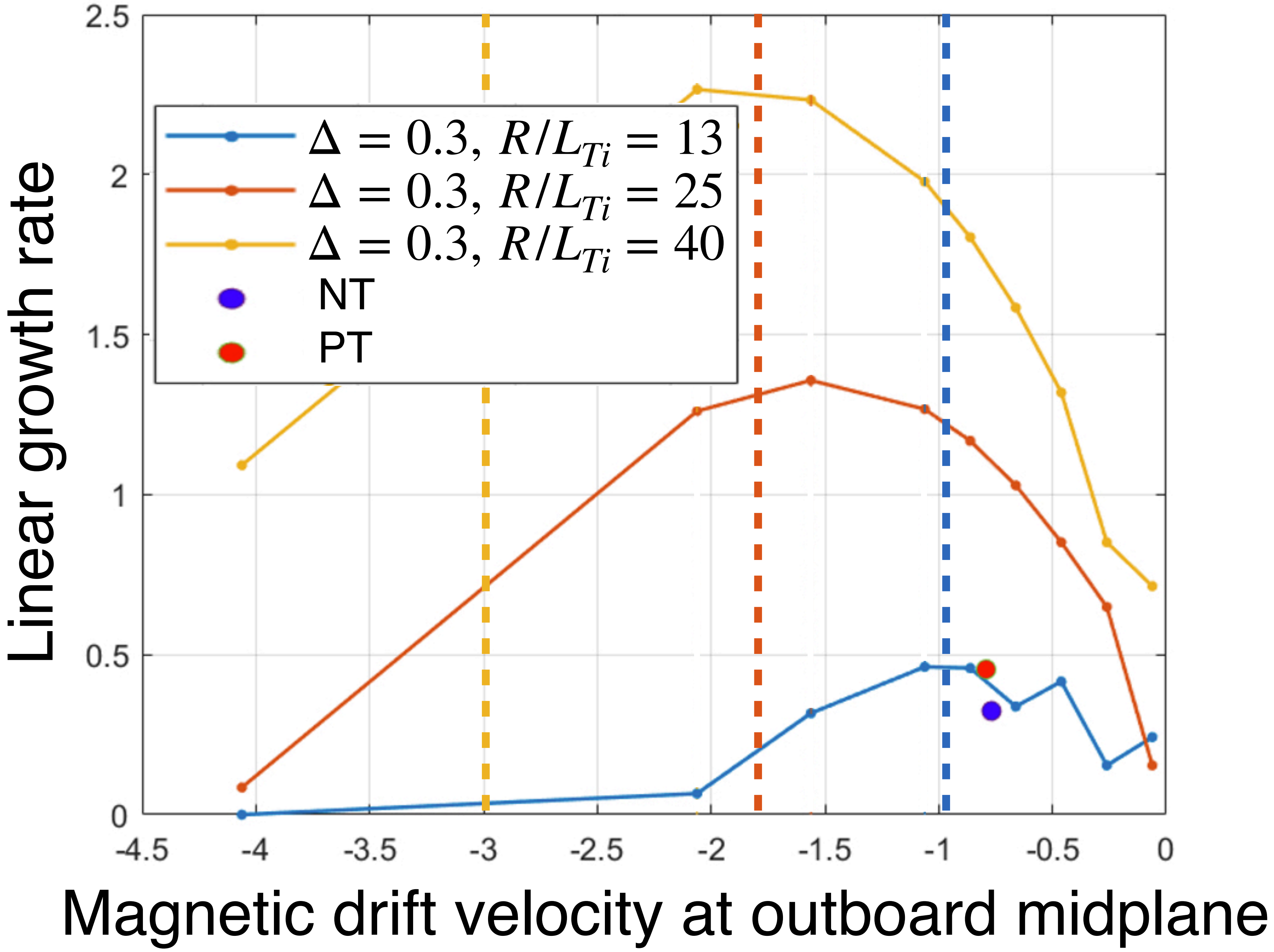
Artificially modifying the magnetic drift velocity

- Fastest growth occurs when $v_{Di} = v_*/13$ with minimal poloidal variation



Changing temperature gradient

- Changing the temperature gradient alters the drift wave velocity v_*, thereby changing the ideal magnetic drift velocity



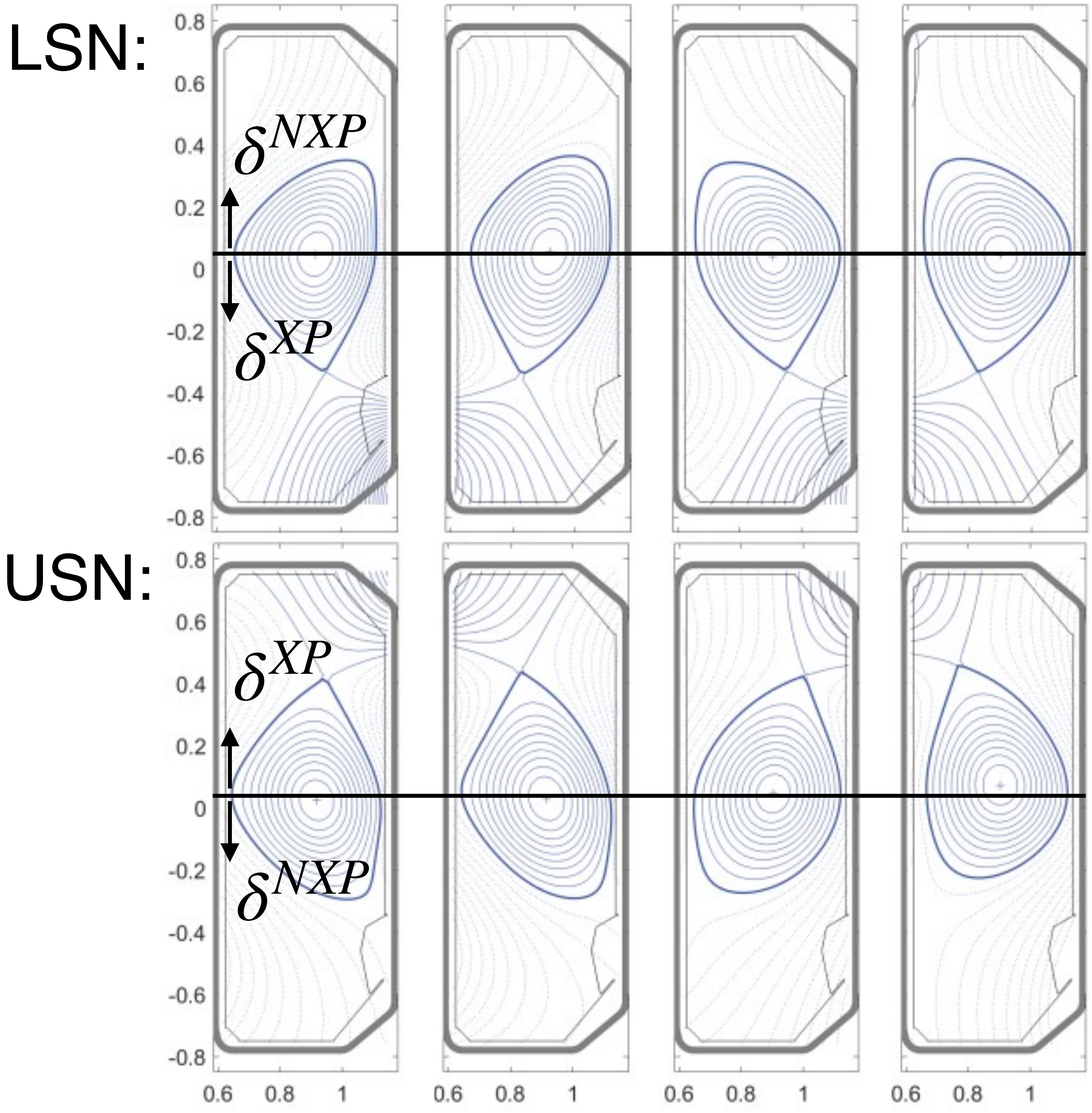
Feasibility of a double null NT reactor

S. Coda, et al., *EPS* (2023).

Top and bottom δ scan in single null TCV plasmas

S. Coda. *EPS* I5.103 (2021).

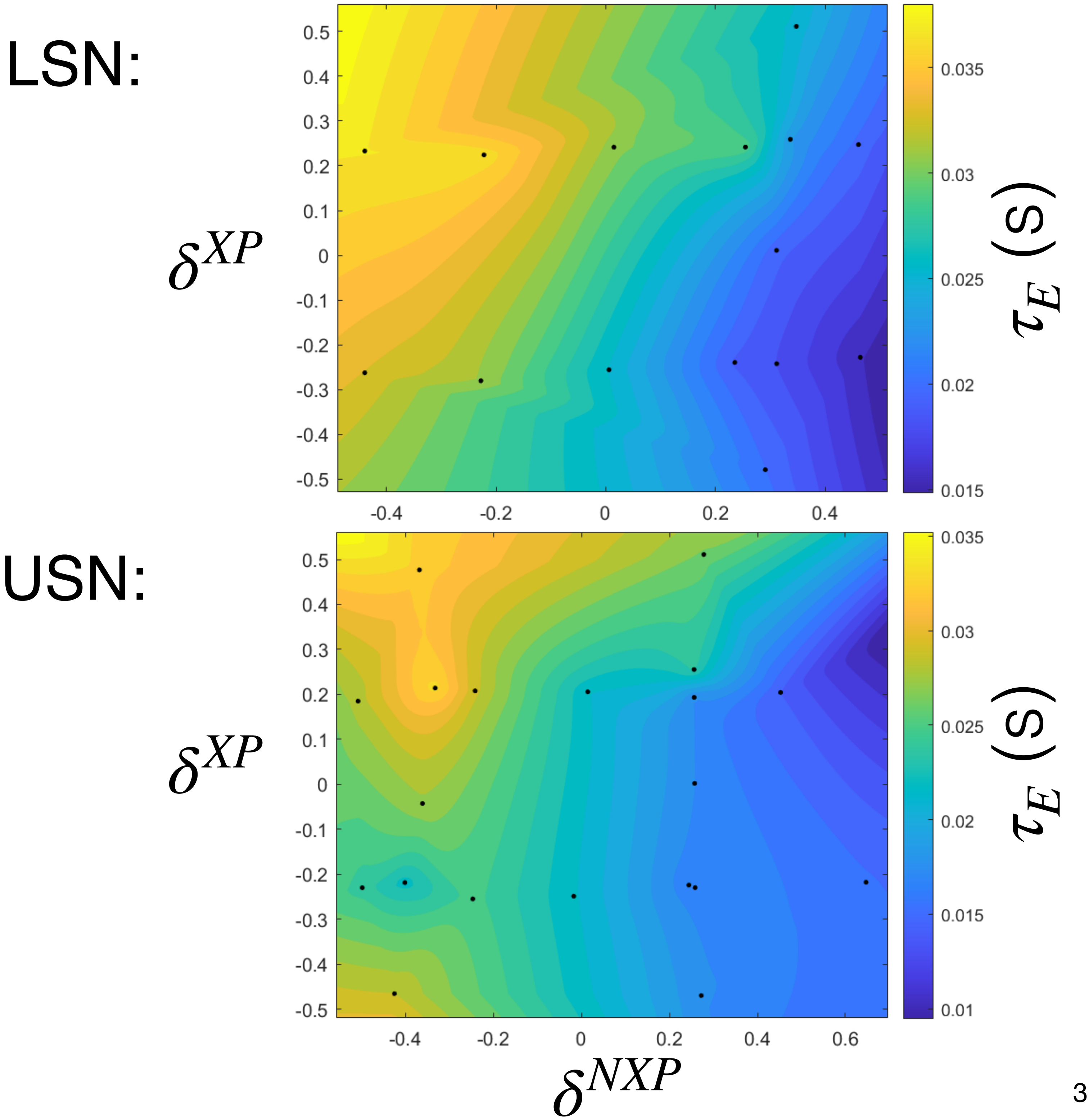
- X-point and non-X-point triangularity were independently varied for both upper (USN) and lower (LSN) single null discharges



Top and bottom δ scan in single null TCV plasmas

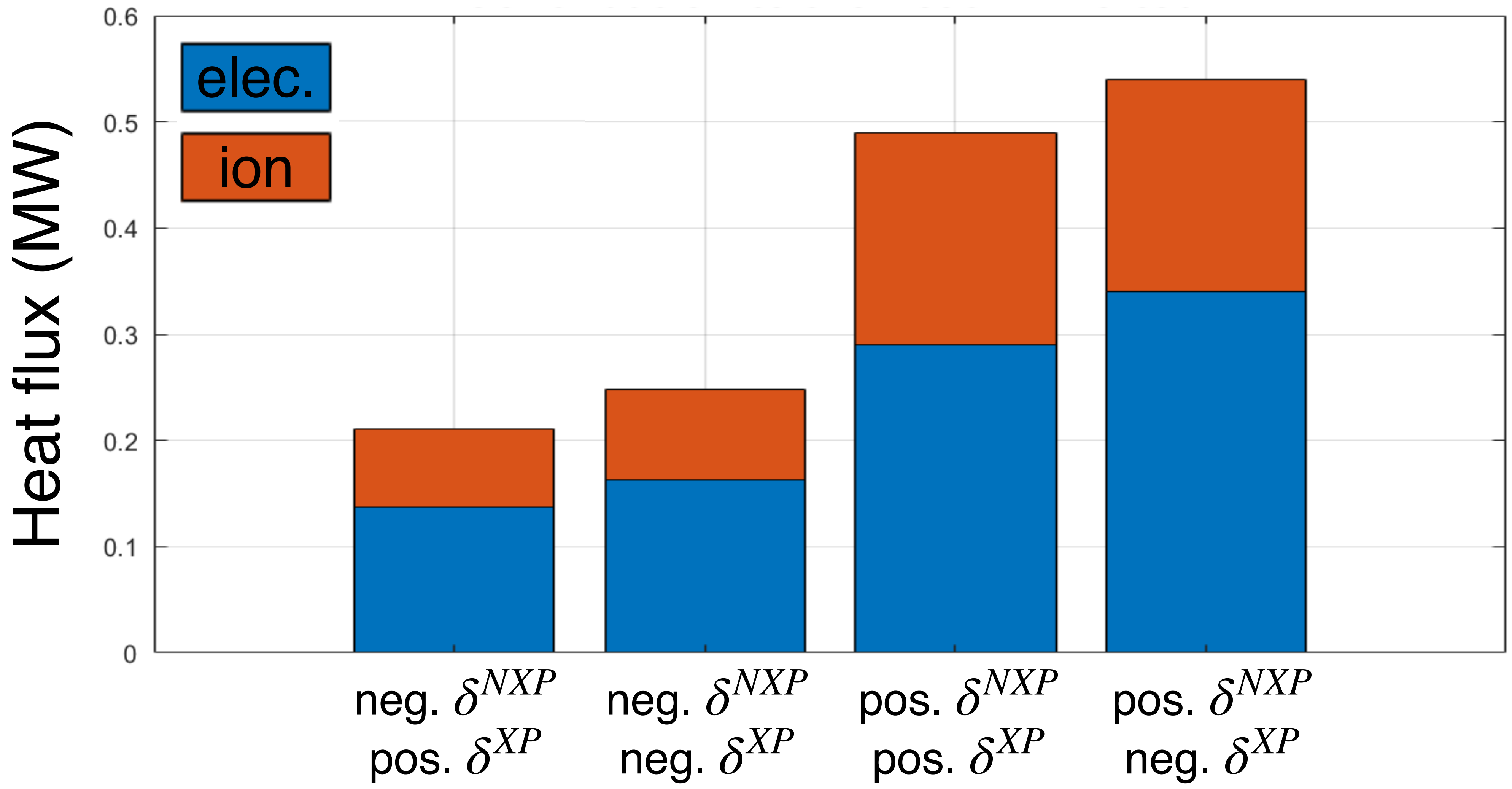
S. Coda. *EPS* I5.103 (2021).

- X-point and non-X-point triangularity were independently varied for both upper (USN) and lower (LSN) single null discharges
- As expected, negative values of δ_{NXP} were very beneficial for confinement
- Surprisingly, positive values of δ^{XP} were slightly beneficial



Investigate with realistic gyrokinetic modeling

- Local GENE simulations using the experimental geometry at $\rho_{tor} = 0.9$

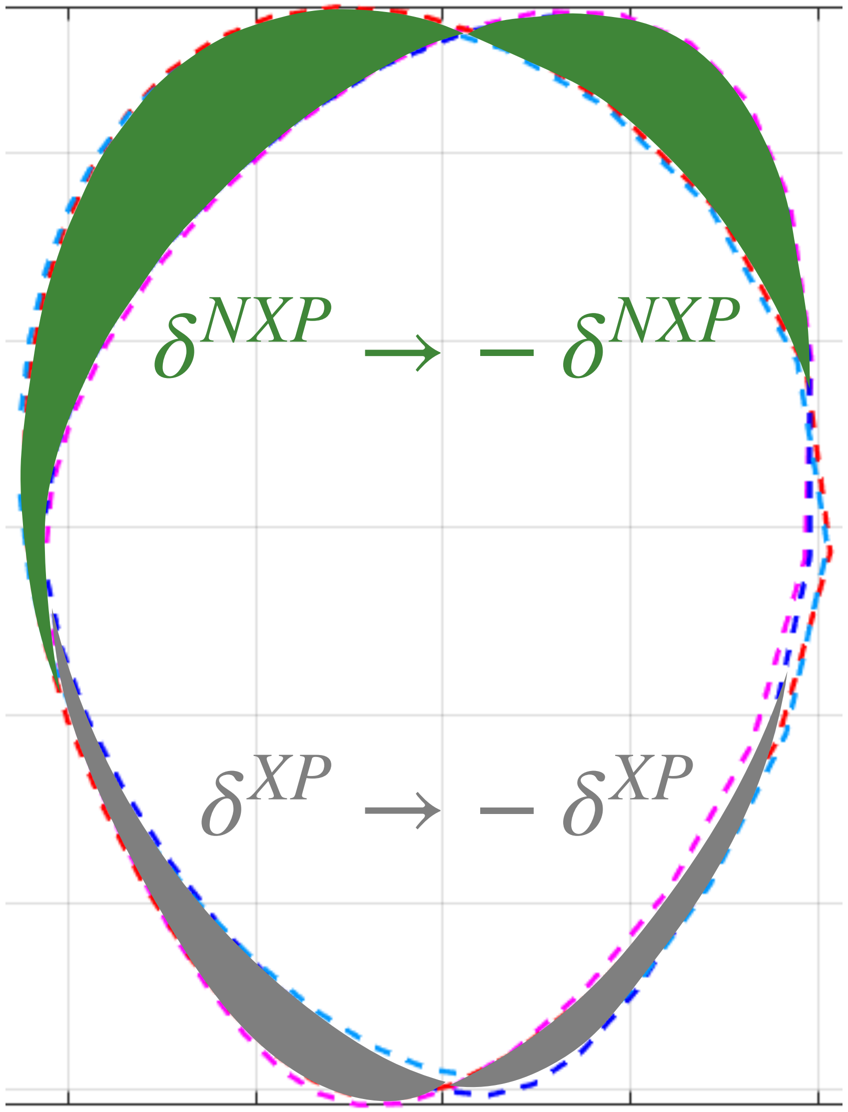


- Reproduces the experimental trends well and are quantitively consistent

Why doesn't δ^{XP} have much effect?

J. Ball, F. Parra. *PPCF* (2015).

- It doesn't actually change the flux surface shape much!
- X-point is created by high poloidal shaping harmonics above squareness
- The effect of these high harmonics is very poloidally localized
- High harmonics don't penetrate well, meaning the effect is very radially localized at the edge



δ^{NXP} penetrates more effectively than δ^{XP}