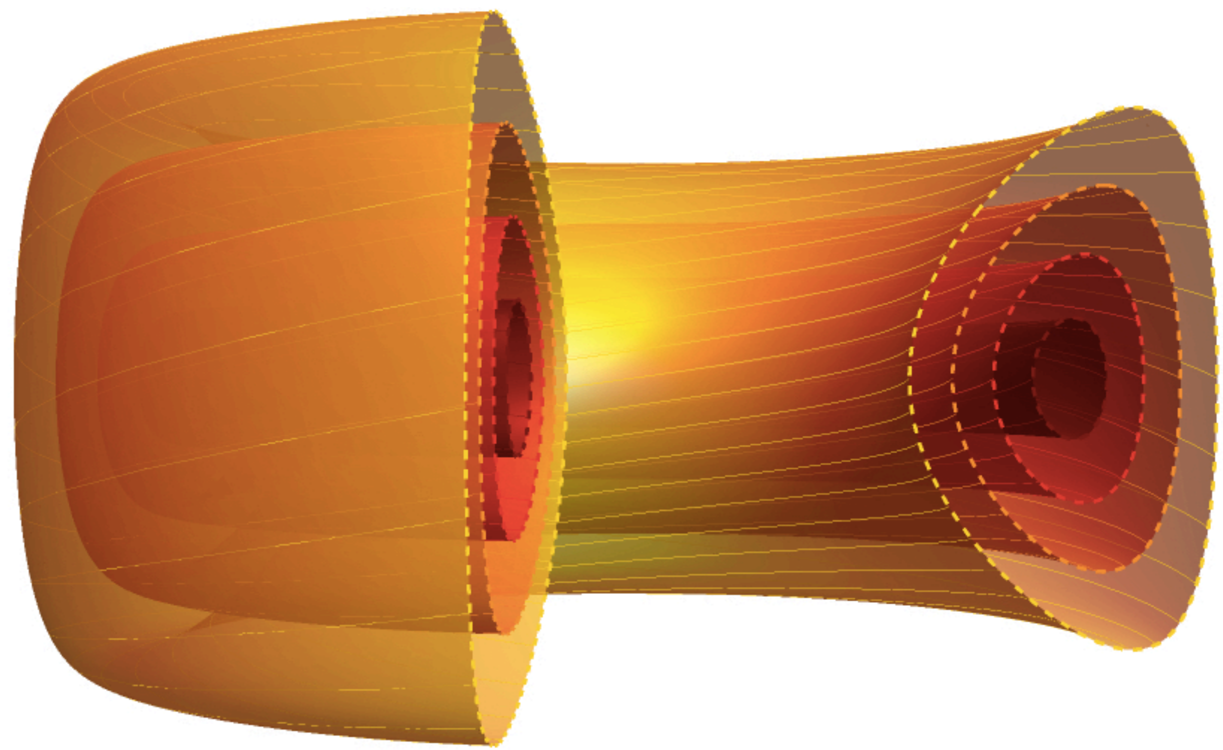
Turbulence in negative triangularity tokamaks



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Motivation for Negative Triangularity (NT)

Camenen et al. *PPCF* ***47*** (2005).
Austin et al. *PRL* ***122*** (2019).

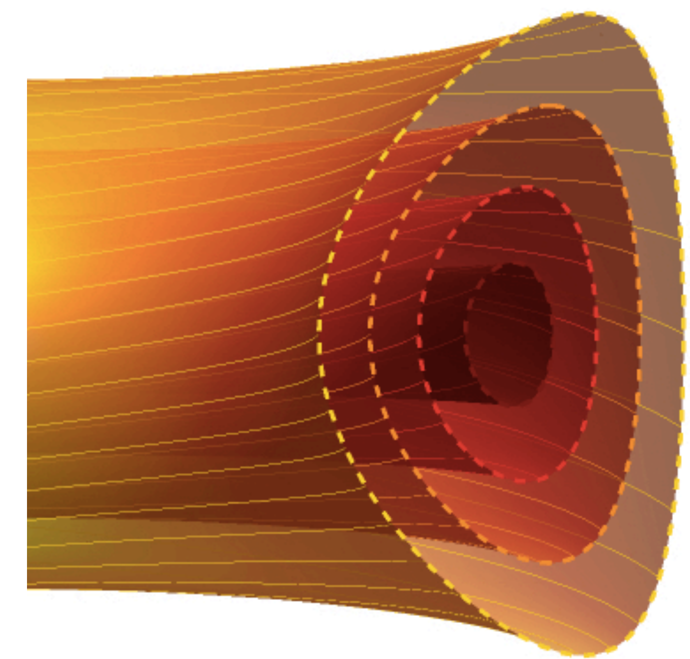
"H-mode like confinement in L-mode"

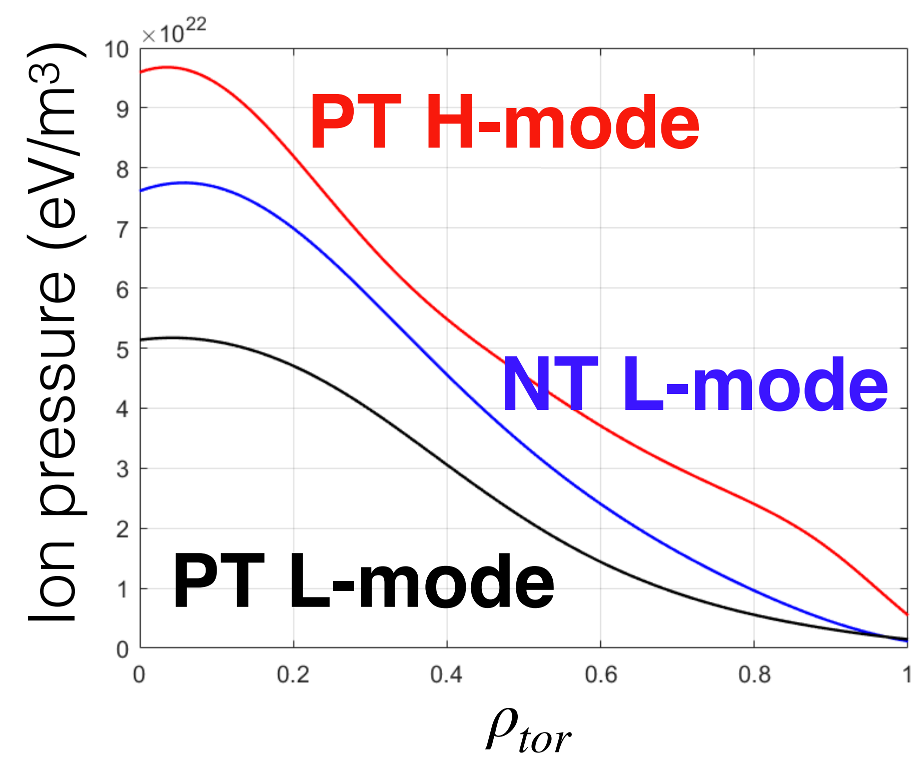
- NT DEMO could have the following benefits:

1. **Improves energy confinement**

2. Increases the L-H power threshold, thereby keeping the plasma in L-mode and avoiding ELMs

3. Improves divertor power handling (i.e. L-mode-like SOL width, larger major radial location)





Outline

J. Ball, et al., *PPCF* **65** 014004 (2023).

Using JFRS-1 resources, we performed gyrokinetic simulations using GENE to study the following topics:

1. **Understanding why NT is beneficial, via its dependence on aspect ratio**

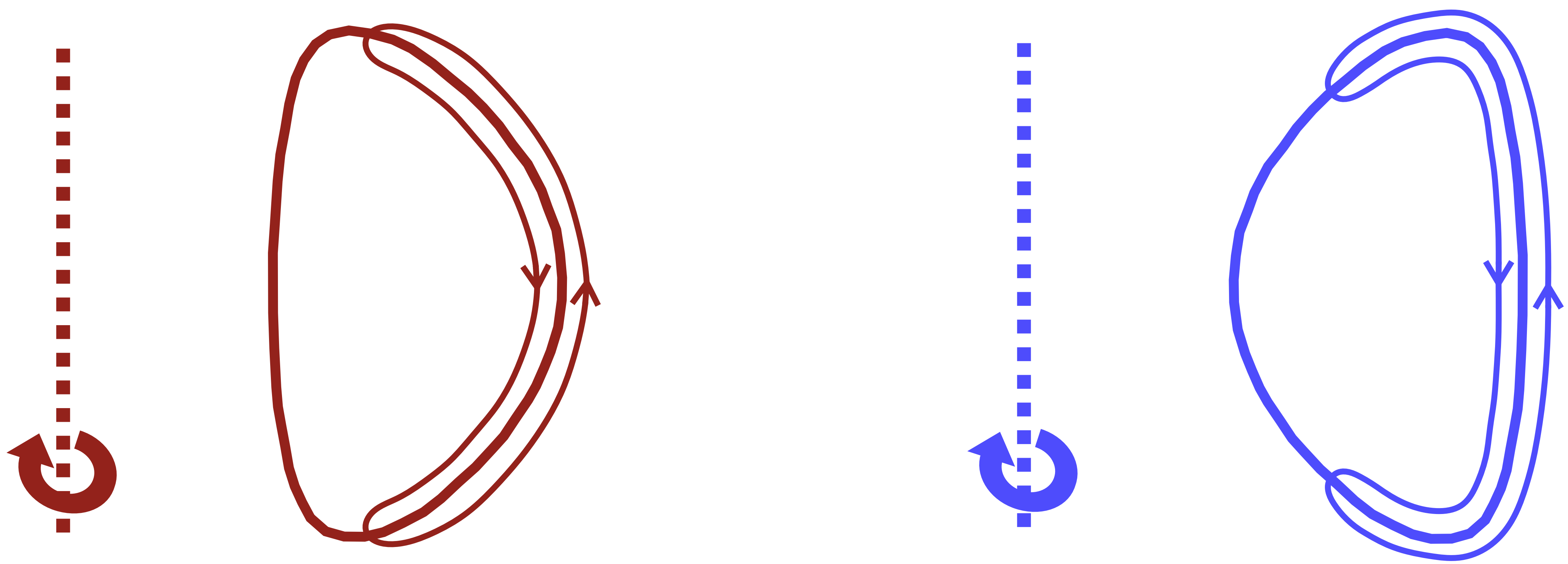
2. Extrapolating behavior to a NT DEMO power plant, using a novel flux tube domain with non-uniform magnetic shear to include profile shearing

Physical understanding of NT, via its aspect ratio dependence

Traditional theoretical argument

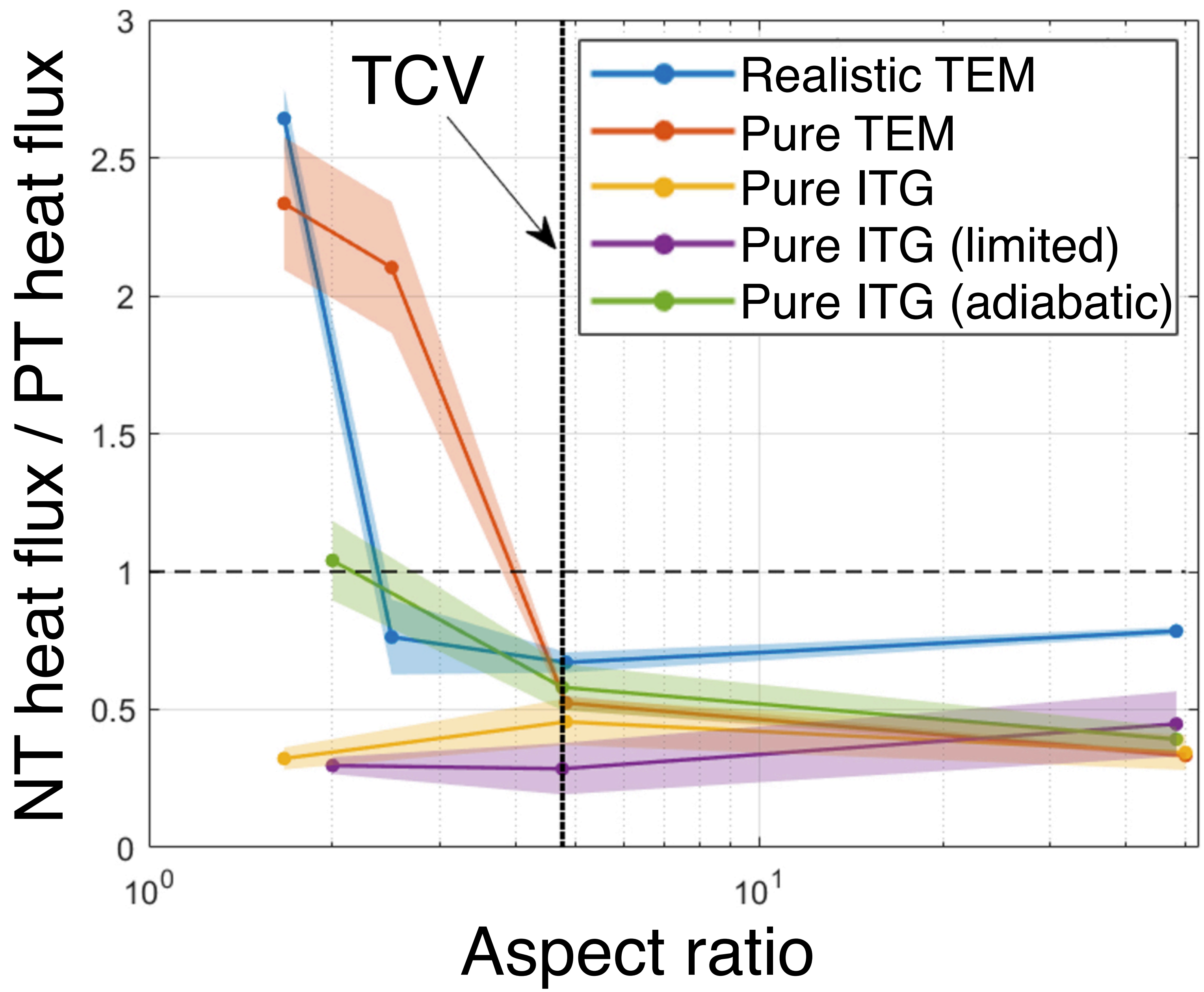
G. Rewoldt, et al. *Phys. Fluids* **25** (1982).
Ohkawa. GA-A19184 (1988).
A. Marinoni, et al., *PPCF* **51** (2009).
G. Merlo, et al., *PPCF* **57** (2015).
G. Merlo, et al., *Phys. Plasmas* **26** (2019).
A. Marinoni, et al., *Rev. Mod. Phys.* **5** (2021).

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



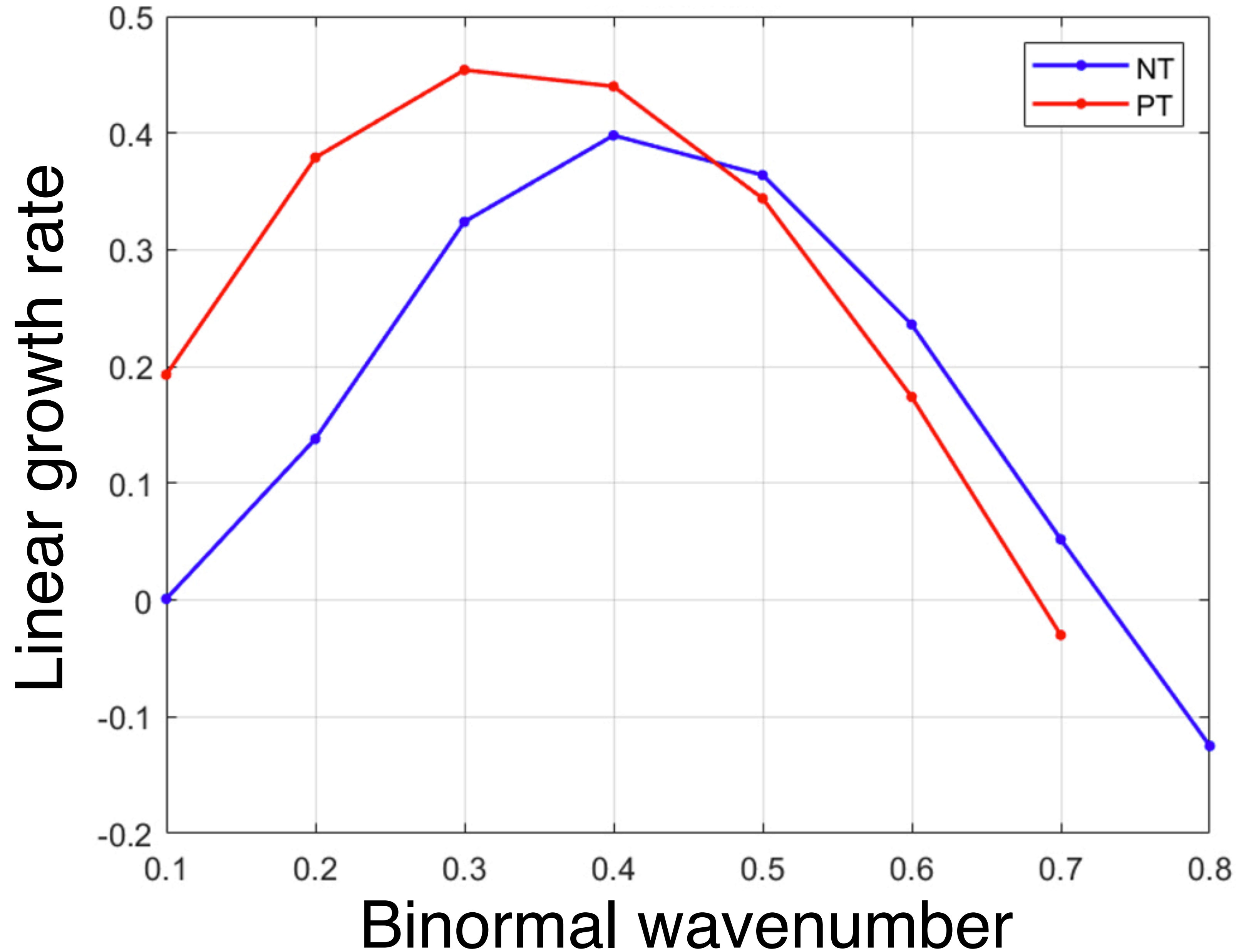
- Intuitively, NT should be most beneficial for Trapped Electron Mode (TEM) turbulence and in spherical tokamaks (which have more trapped particles)

We find the exact opposite!?



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

Establishing the physical mechanism behind NT



- Restarted from the basics and focused the simplest case:

large aspect ratio, pure Ion Temperature Gradient (ITG)

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

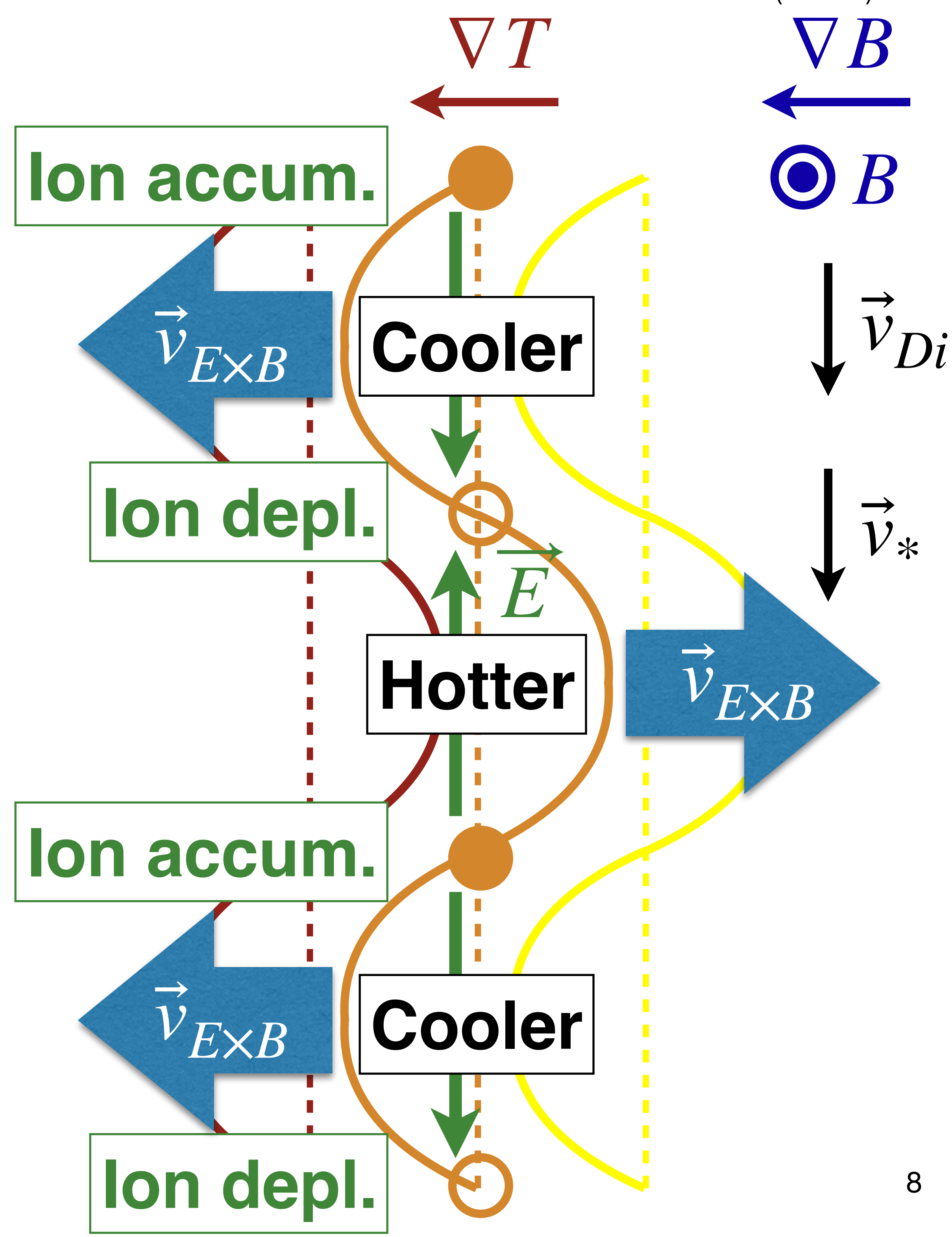
- Drift waves travel with a velocity:

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

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

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

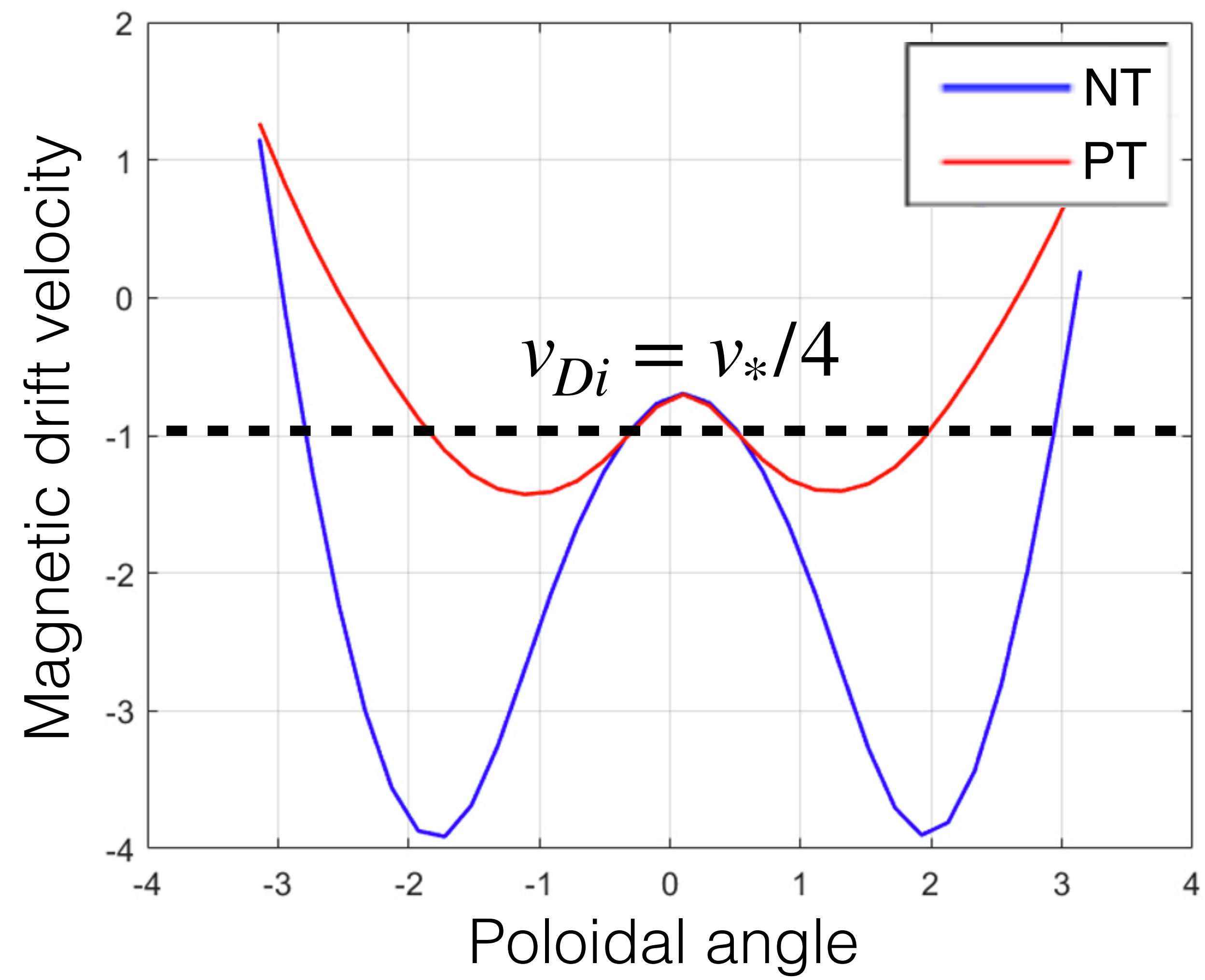
- **For growth these velocities must be similar** $\vec{v}_{Di} \approx \vec{v}_*/4$



Testing our hypothesis

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

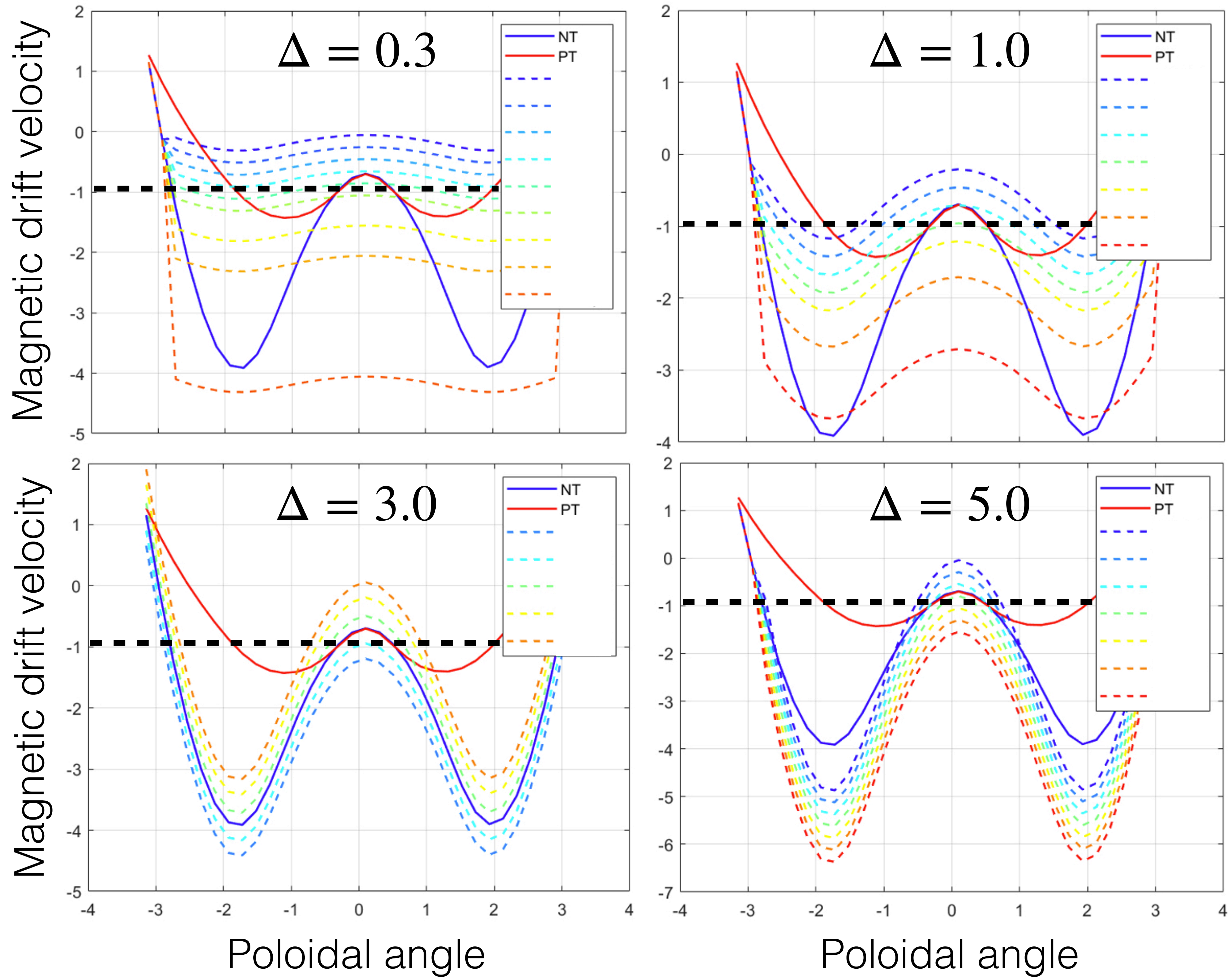
- The plasma shape usually enters into the gyrokinetic model in many places
- In the large aspect ratio limit, only FLR effects and magnetic drifts distinguish different shapes
- Artificially swapping FLR effects between PT and NT simulations reveals that they have little impact on the linear growth rate



- Thus, the magnetic drifts appear most important, but is our physical picture correct?

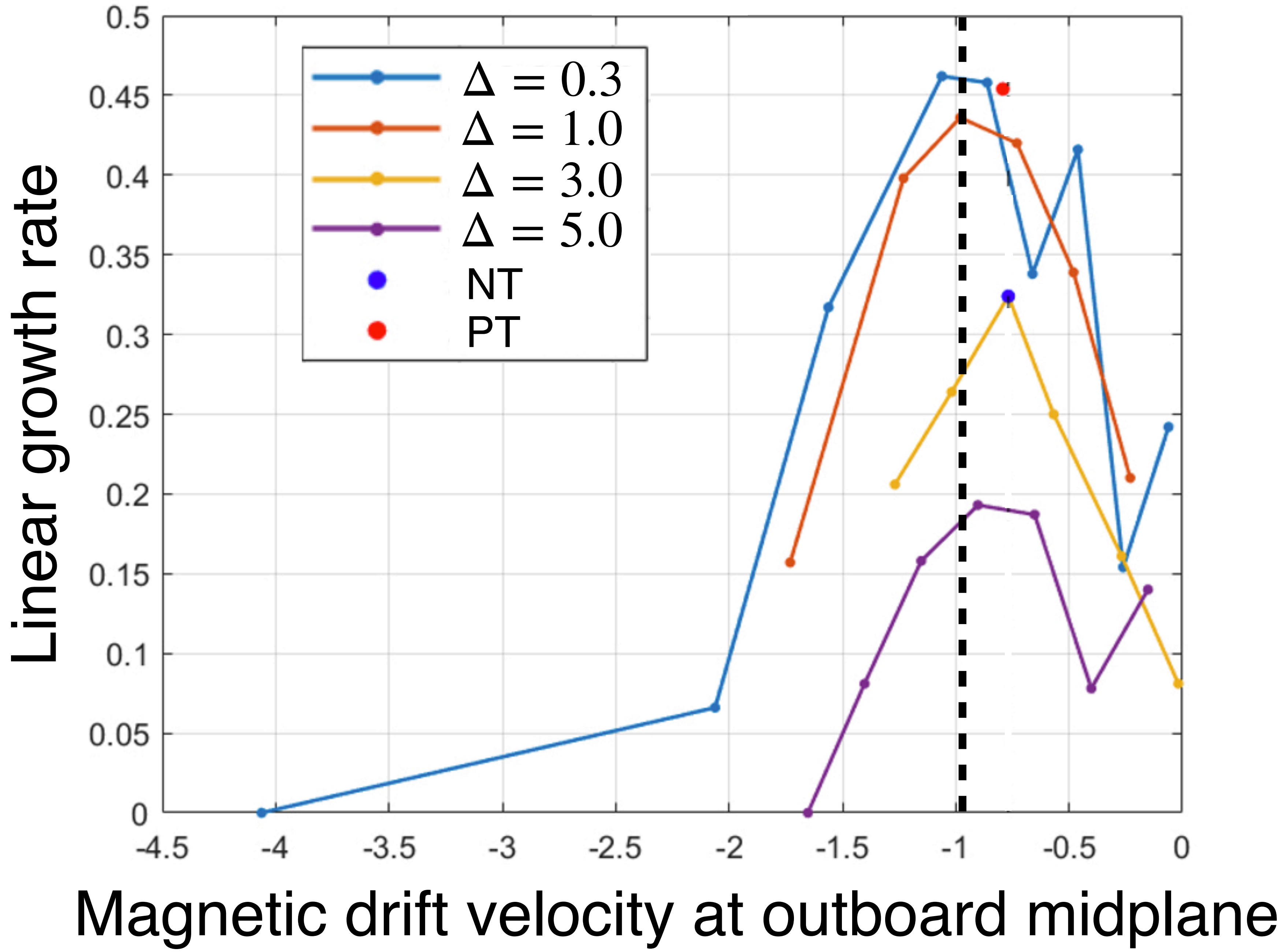
Artificially modifying the magnetic drift velocity

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



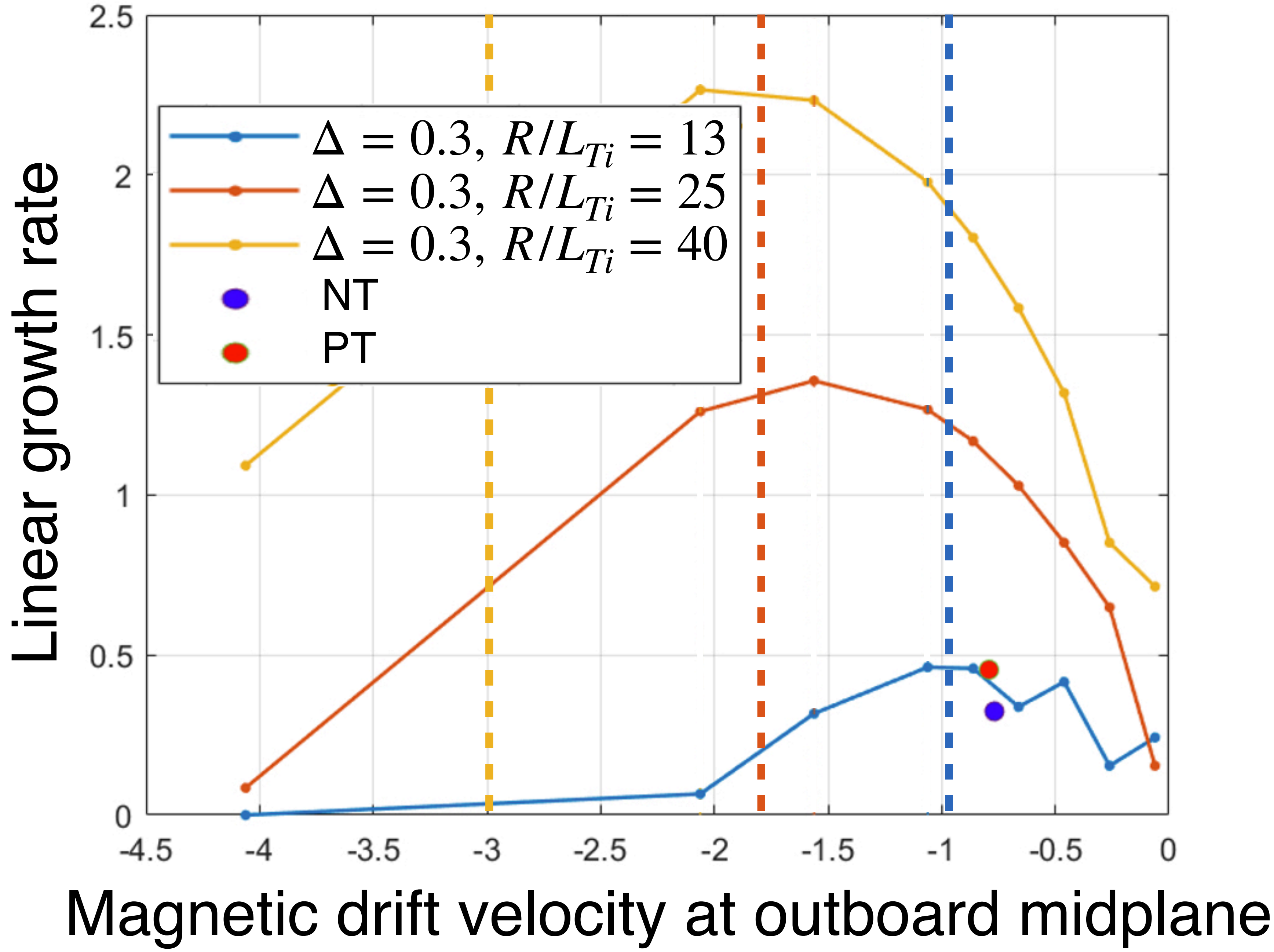
Artificially modifying the magnetic drift velocity

- Fastest growth occurs when $v_{Di} = v_*/4$ with minimal poloidal variation



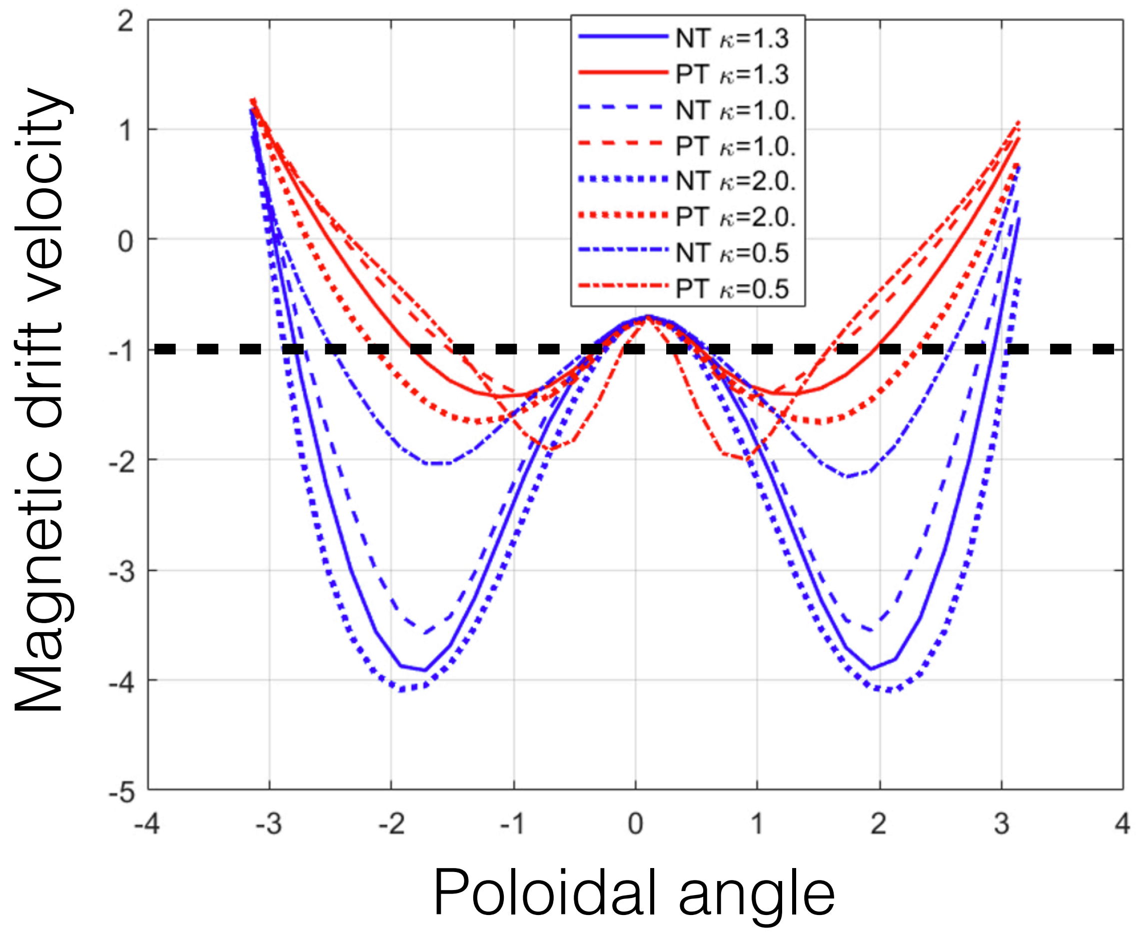
Change temperature gradient

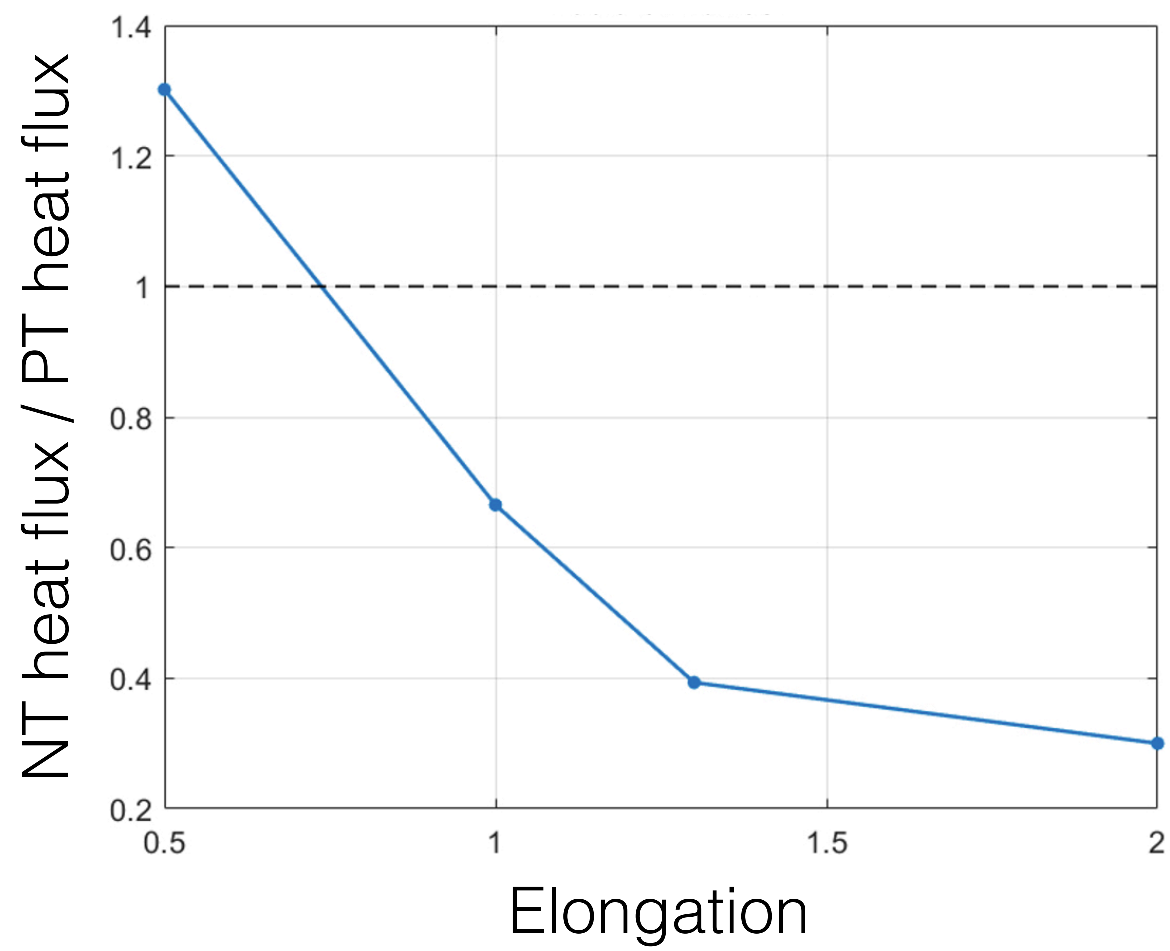
- Changing the temperature gradient alters the drift wave velocity, thereby changing the ideal magnetic drift velocity



Applying physical picture to other geometries

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





Conclusions and future work

- At standard and large aspect ratio, NT generally improves confinement (which is consistent with experiment)
- In spherical tokamaks, NT may have worse confinement (in certain turbulence regimes), which can be studied in the new SMART tokamak
- The confinement improvement from NT for ITG turbulence at large aspect ratio can be explained by a better matching between the drift wave velocity and magnetic drift velocity
- We expect this physical interpretation still holds for ITG in conventional aspect ratio and even spherical tokamaks
- We plan to develop an analogous interpretation for TEM turbulence and see how it applies in spherical tokamaks

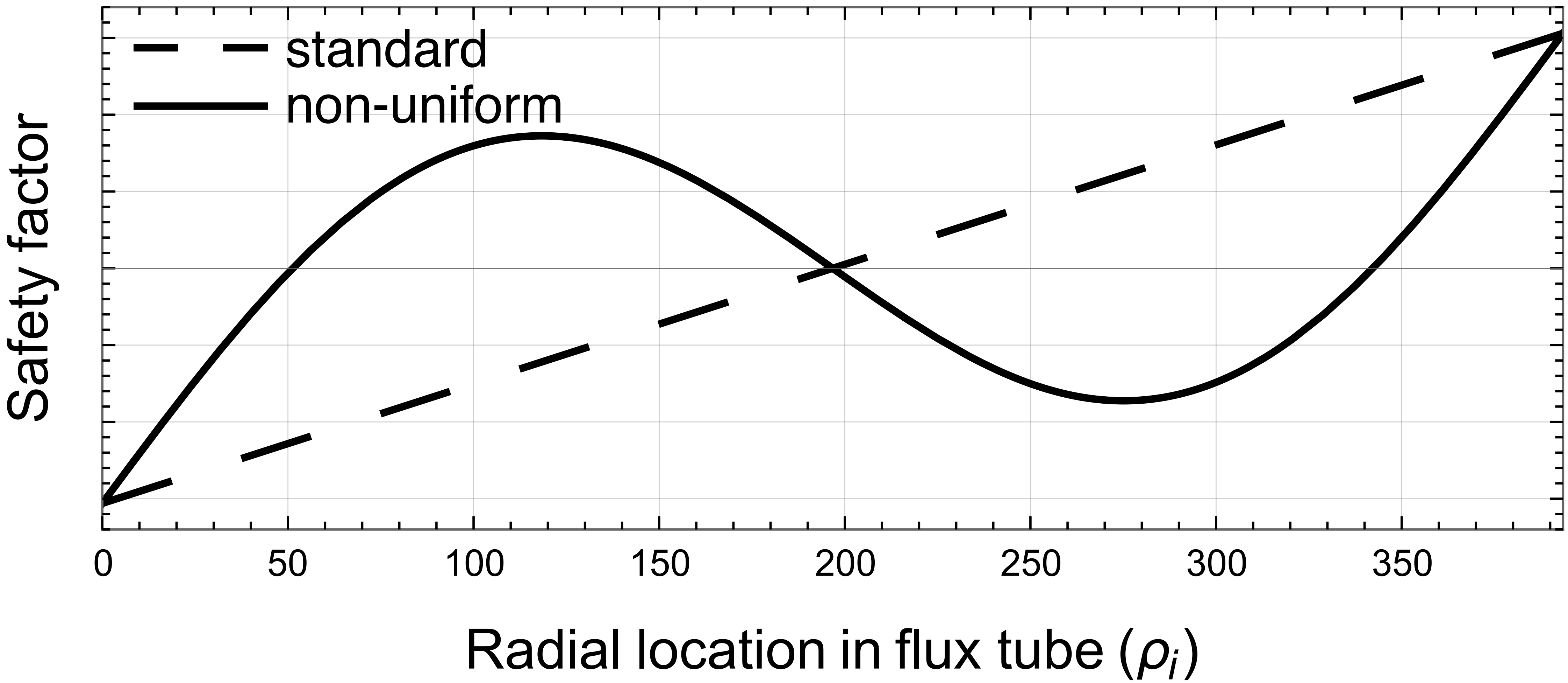
All done.

Extrapolating to a NT power plant

J. Ball, et al., *PPCF* **65** 014004 (2023).

Flux tube with non-uniform magnetic shear

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



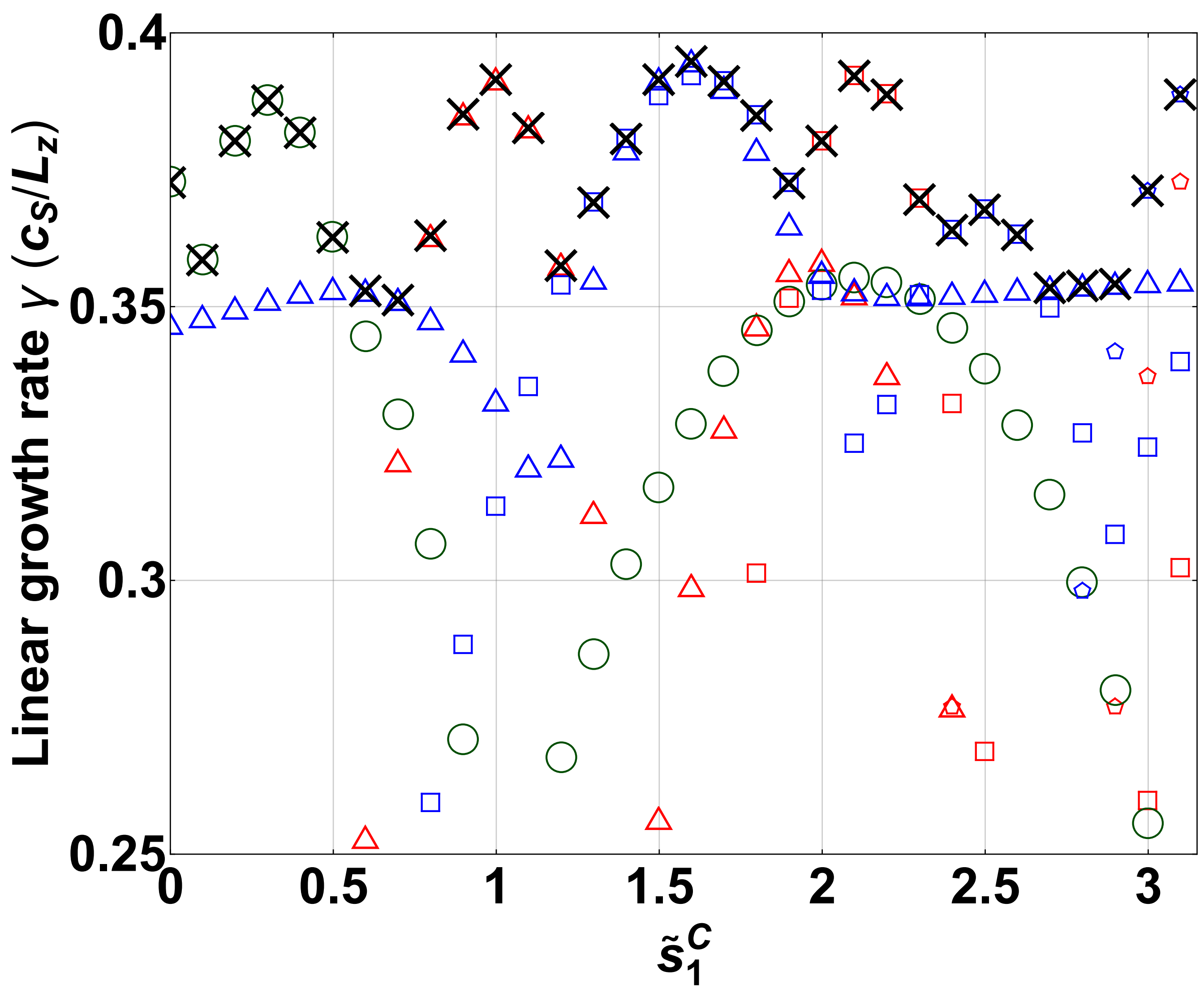
- Standard flux tube simulation domain in GENE generalized to include arbitrary gyroradius-scale variation in the radial profile of the safety factor
- Required changes were systematically derived from the Fokker-Planck equation in a realistic asymptotic limit

Linear benchmark shows perfect agreement

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

- Compared modified GENE code to analytic results in the cold ion limit

- GENE always finds the fastest growing mode and the correct growth rate



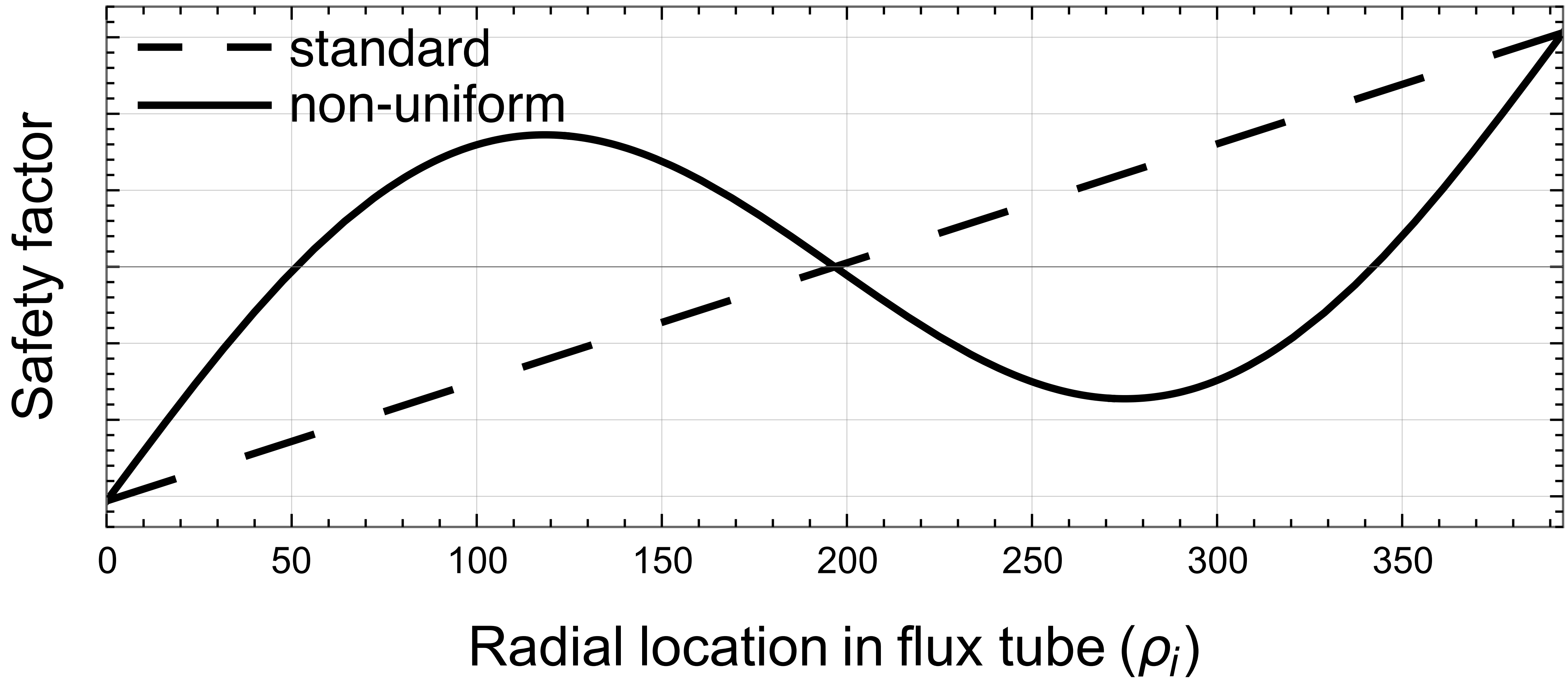
× — GENE

Colored points — analytic (various parallel wavelengths)

Machine size scan

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

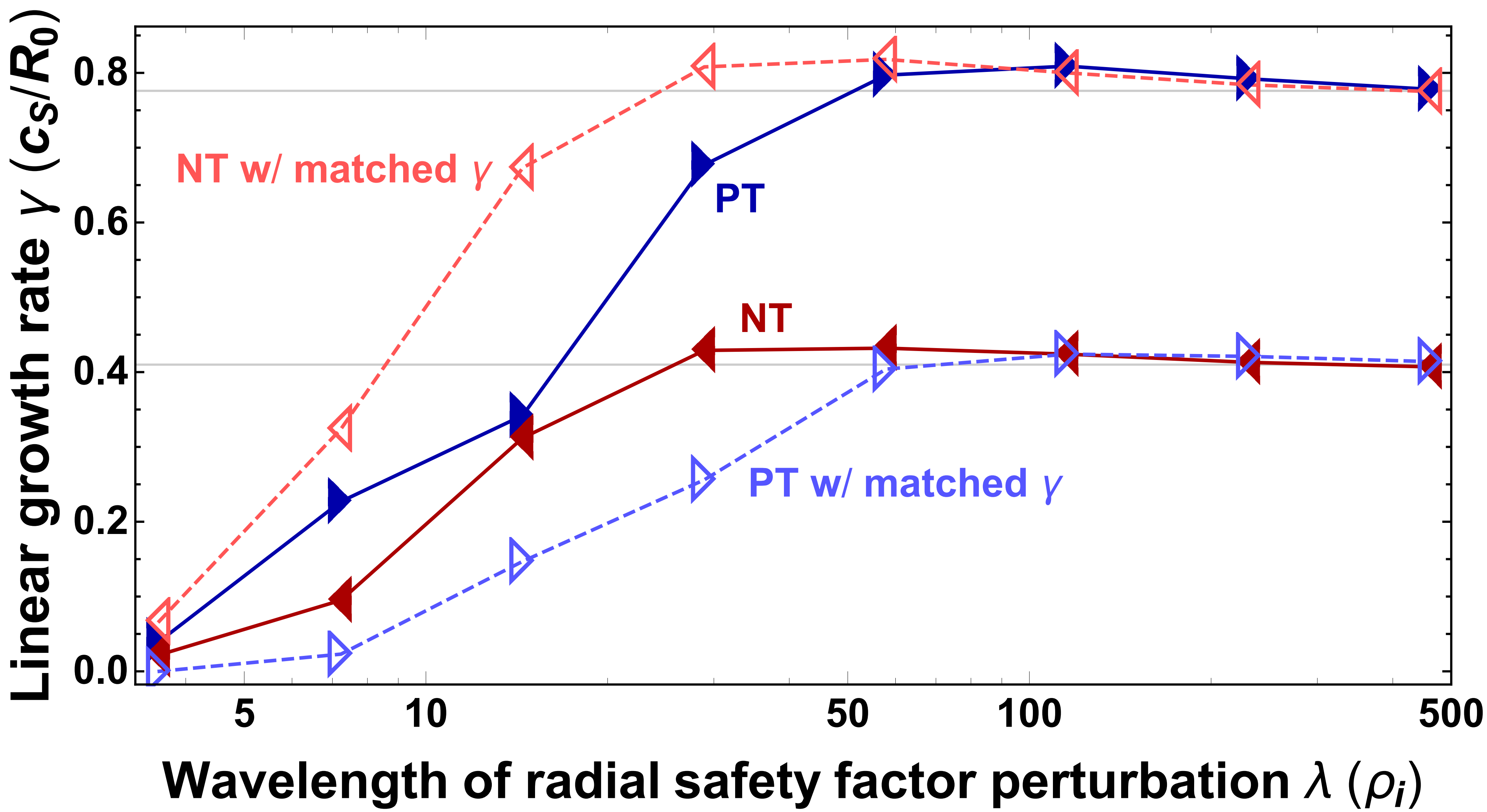
- Increasing the wavelength of the safety factor modulation (at constant amplitude) can be thought of as a scan in machine size



- Thus, this can give useful information to extrapolate from existing devices up to a NT power plant

Linear machine size scan for NT versus PT

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



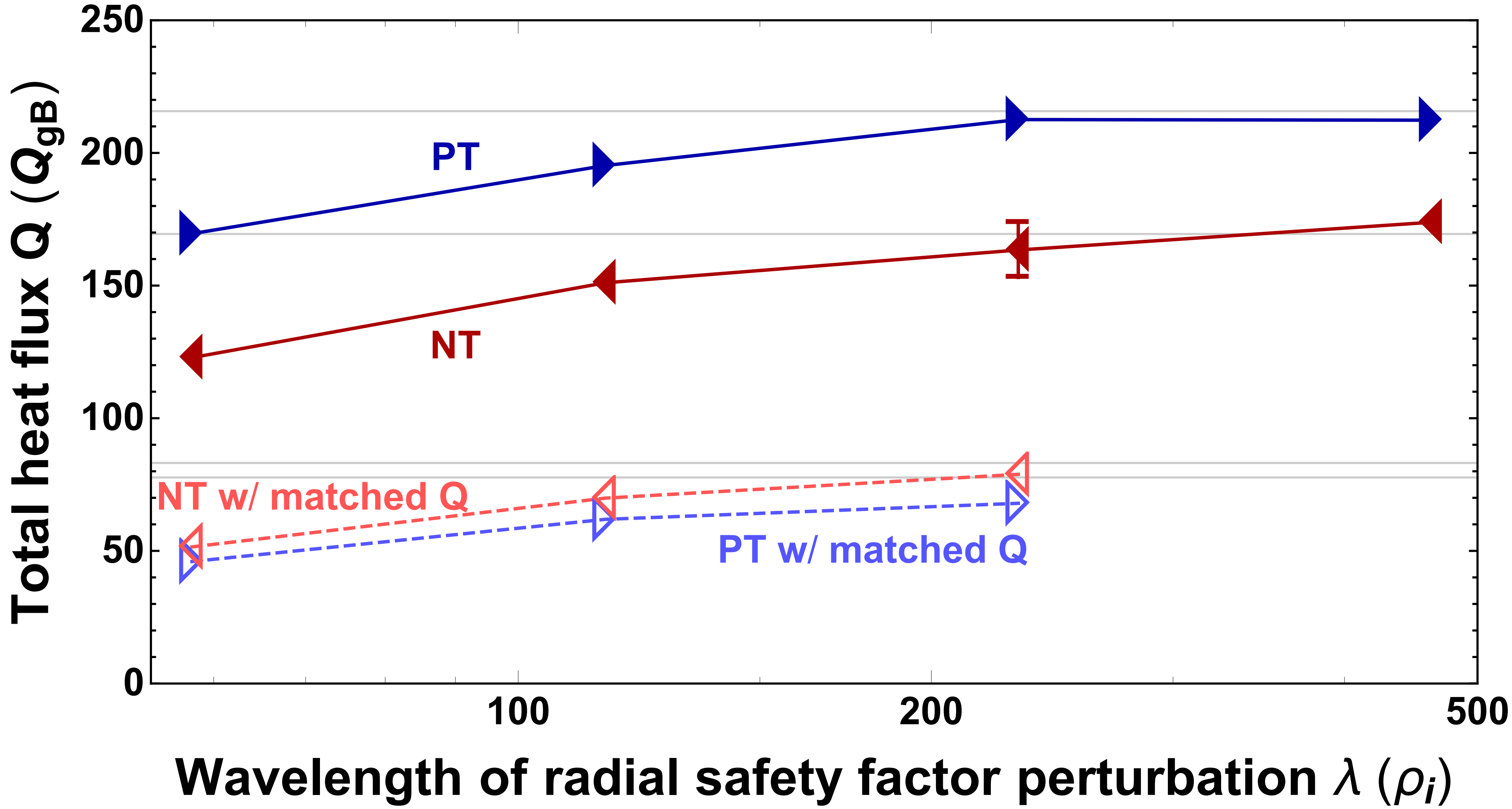
- Used idealized equilibria holding the background gradients constant
- Linearly, NT scales to a power plant better than PT

EPFL

Swiss Plasma Center

Nonlinear machine size scan for NT versus PT

J. Ball, et al. *PPCF* **65** (2023).
G. Merlo, et al. *PPCF* **63** (2021).

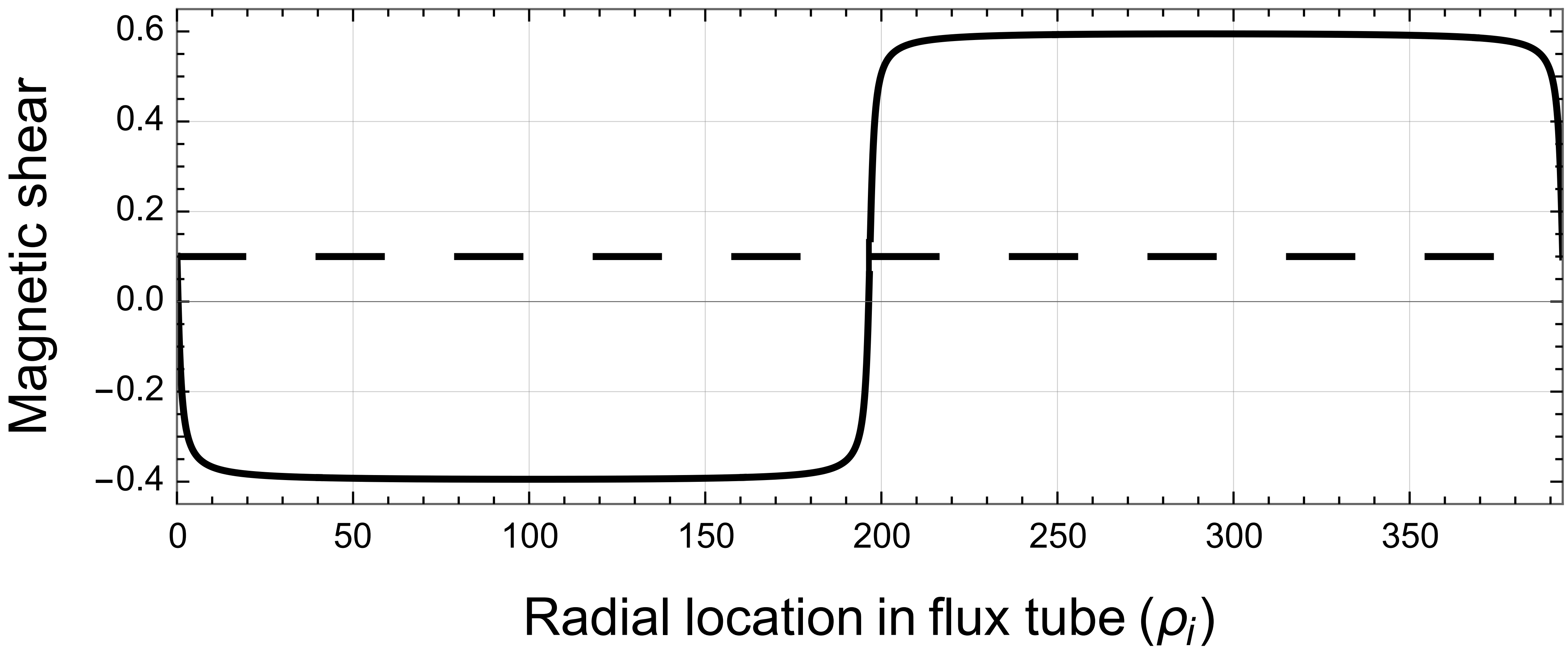


- NT and PT scale similarly to larger devices
- More trustworthy/realistic than linear results

Nonlinear benchmark

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

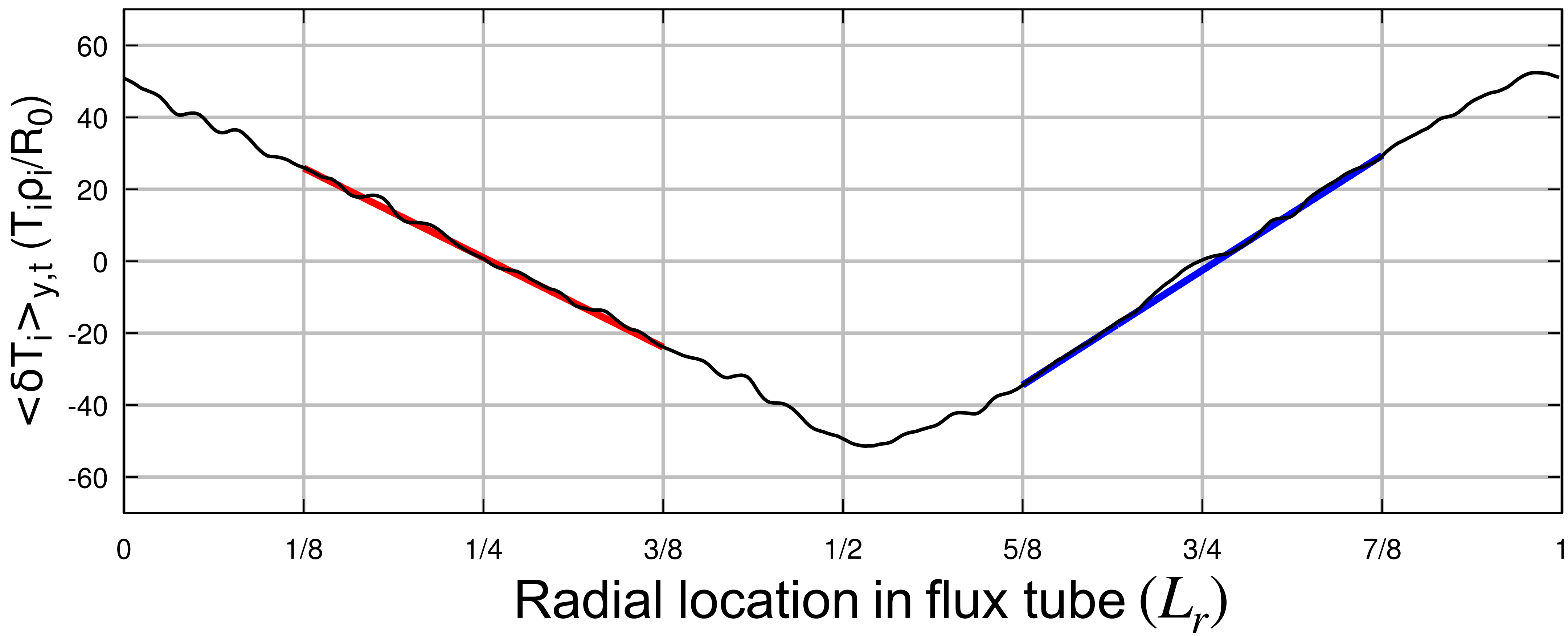
- Use non-uniform shear to make two uniform shear regions in one simulation



Nonlinear benchmark

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

- Use non-uniform shear to make two uniform shear regions in one simulation
- Since there are no energy sources/sinks, the temperature profile adapts to ensure the heat flux is the same at all radial locations



Nonlinear benchmark shows excellent agreement

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

- Use non-uniform shear to make two uniform shear regions in one simulation
- Since there are no energy sources/sinks, the temperature profile adapts to ensure the heat flux is the same at all radial locations
- Compare flux-gradient relationship with two standard simulations