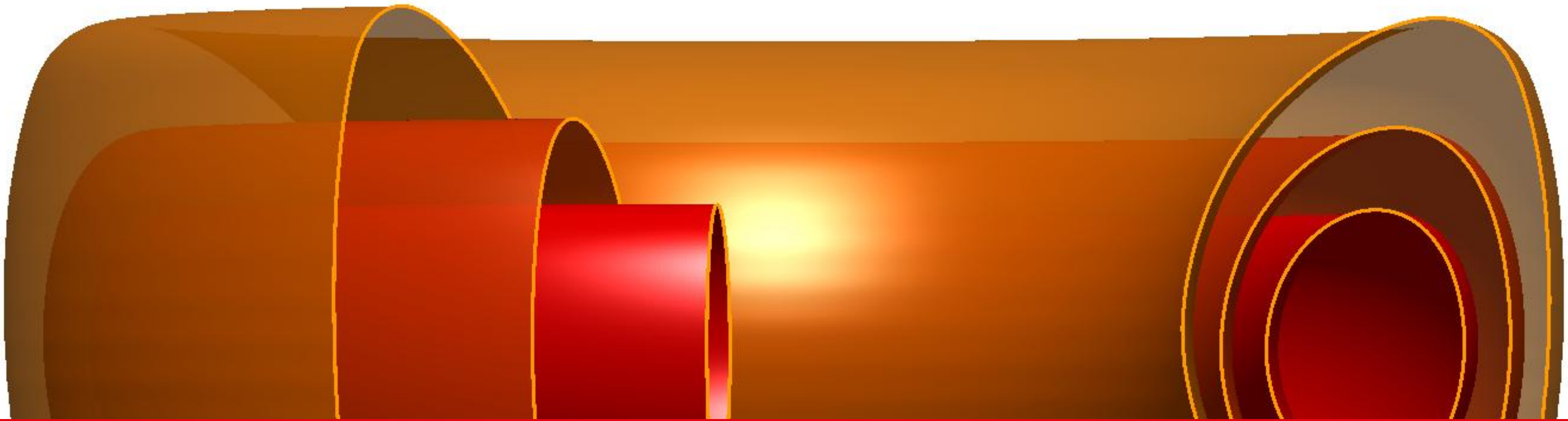


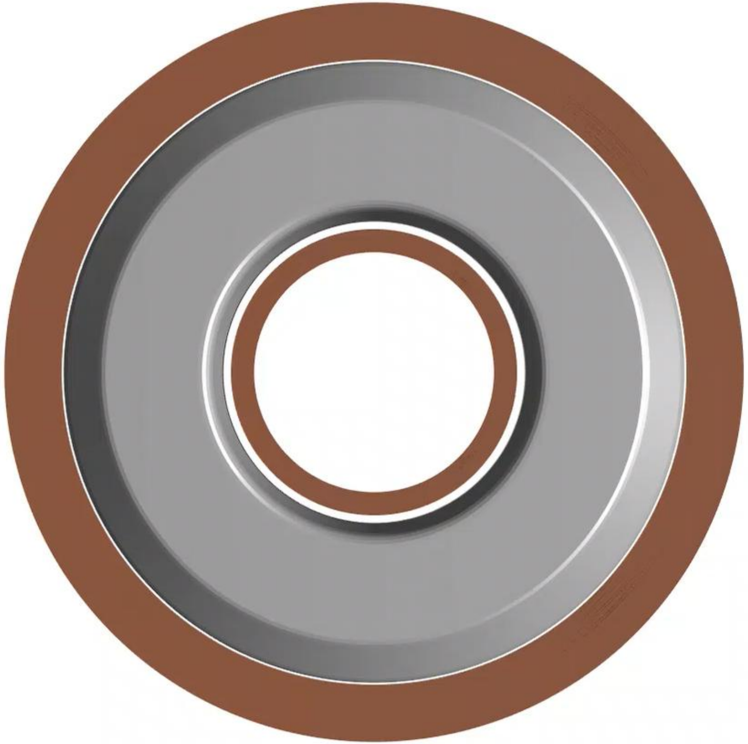
On the interplay between negative triangularity, aspect ratio and micro-tearing turbulence

A. Balestri[1], J. Ball[1], S. Coda[1]

[1]Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), 1015 Lausanne, Switzerland,

Swiss Plasma Center

Changing the shape of plasma flux surfaces drastically affects the stability and confinement



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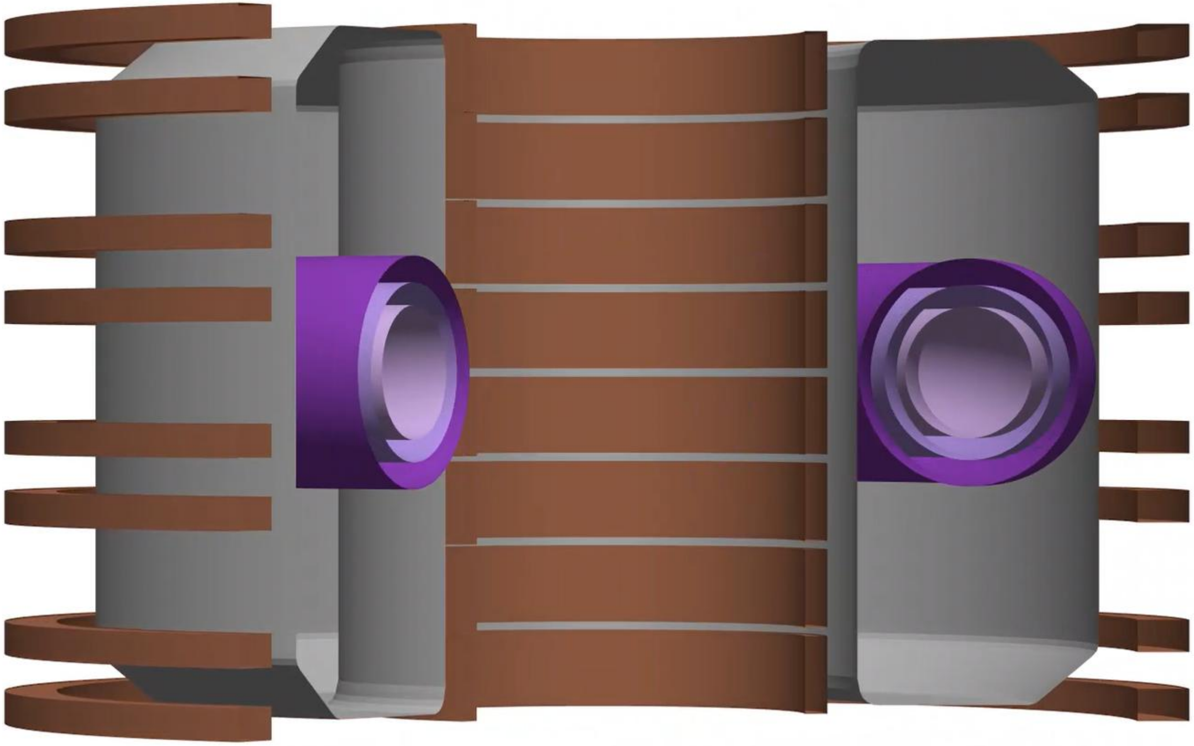

Elongation

$$\kappa = \frac{Z_{max} - Z_{min}}{2a}$$

Triangularity

$$\delta^{up} = \frac{R_0 - R_{up}}{a}$$

$$\delta^{low} = \frac{R_0 - R_{low}}{a}$$

$$\delta = \frac{\delta^{up} + \delta^{low}}{2}$$

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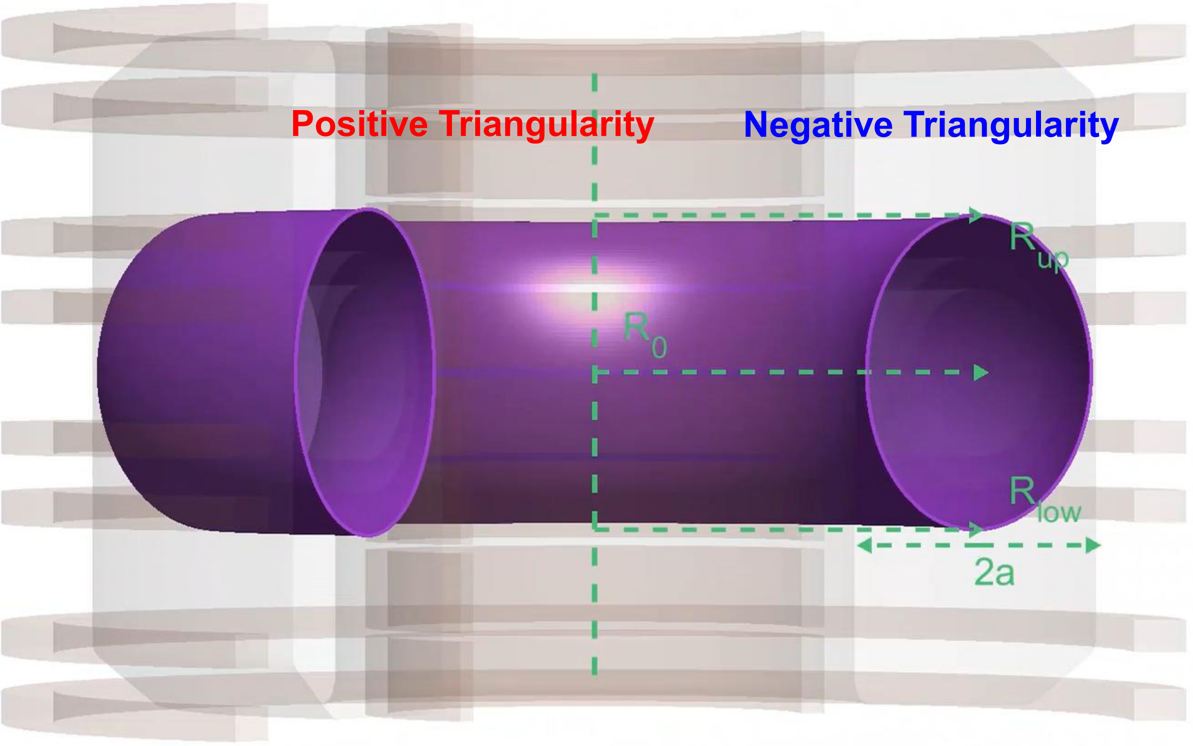

Elongation

$$\kappa = \frac{Z_{max} - Z_{min}}{2a}$$

Triangularity

$$\delta^{up} = \frac{R_{geo} - R_{up}}{a}$$

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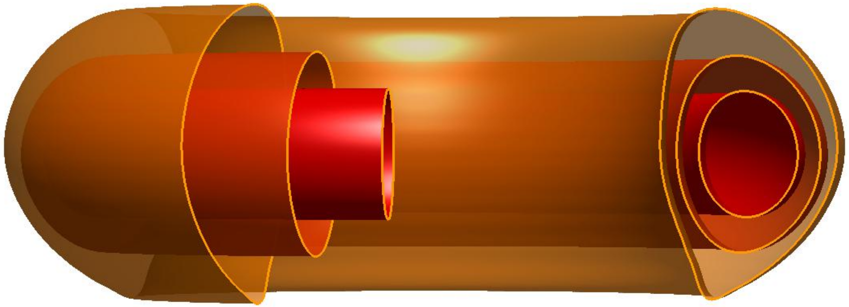
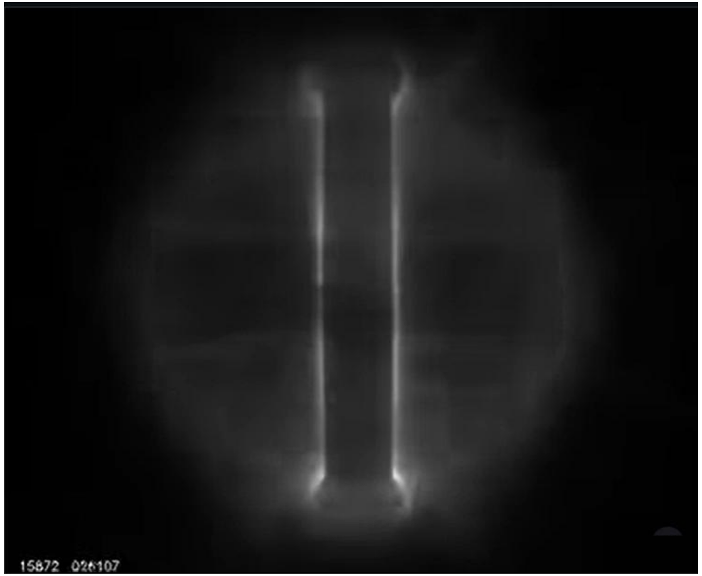
Positive Triangularity plasmas and H-mode

[1] F. Wagner et al., 1982
PRL 49 14081412





Positive Triangularity (PT) plasmas can enter the **H-mode** (High Confinement) regime:

- Discovered in 1980 on ASDEX [1]
- Accessed when heating power exceeds a power threshold
- Turbulence suppression at the edge and formation of External transport barrier (ETB)

EPFL

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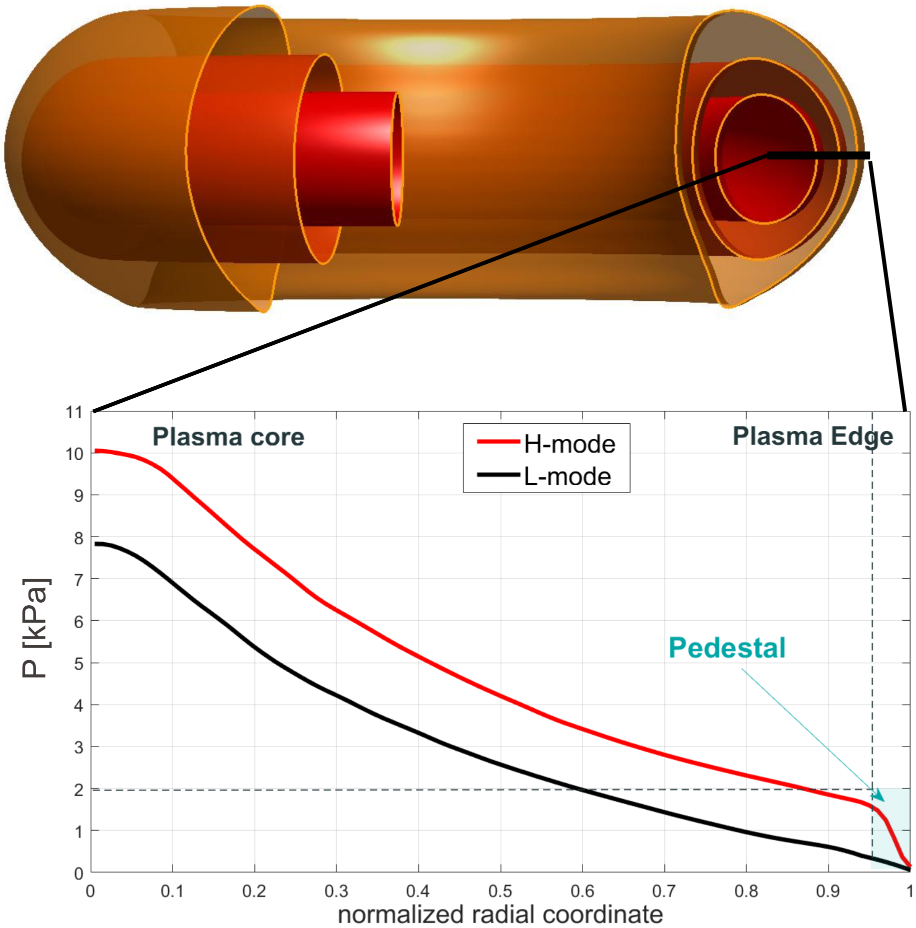

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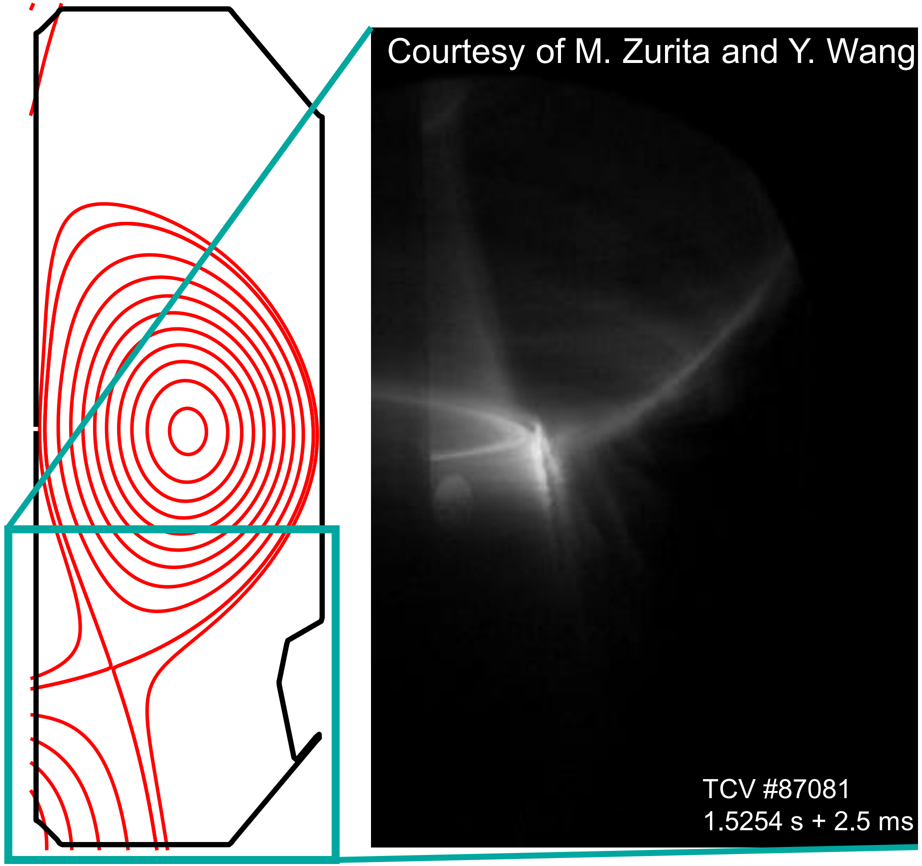
- Turbulence suppression at the edge and formation of External transport barrier (ETB)
- Formation of a steep pressure gradient, i.e. the pedestal

Confinement and performance are doubled!

EPFL

Positive Triangularity plasmas and H-mode: a poisoned challice



H-mode is plagued by severe issues, and the most important being the presence of **Edge Localized Modes (ELMs)**

Periodic relaxations of the pedestal trigger ELMs which flush huge amount of energy and particles against the wall of the machine

In a reactor, a single ELM can potentially destroy part of the wall

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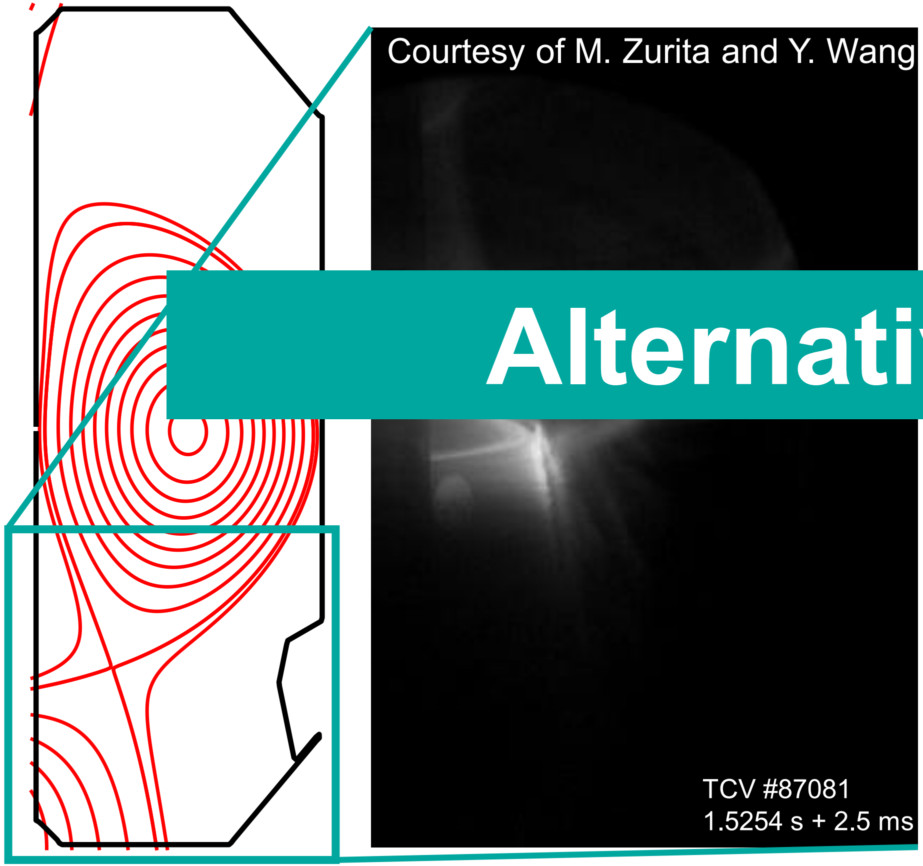
Positive Triangularity plasmas and H-mode: a poisoned challice



H-mode is plagued by severe issues, and the most important being the presence of **Edge Localized Modes (ELMs)**

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…nd
particles against the wall of the machine

Alternatives?

In a reactor, a single ELM can potentially destroy part of the wall

Negative Triangularity plasmas: H-mode performance without H-mode

[1] A. Merle et al., 2017 PPCF 59 104001
[2] A. O. Nelson et al., 2024 PPCF 66 105014
[3] O. Sauter et al., 66th APS 2024
[4] A. Marinoni et al., 2009 PPCF 51 055016
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[8] A. Mariani et al., 2024 NF 64 106024

Experiments (TCV, DIII-D, AUG) and simulations showed that Negative Triangularity (NT):

- Robustly inhibits access to H-mode [1,2,3]

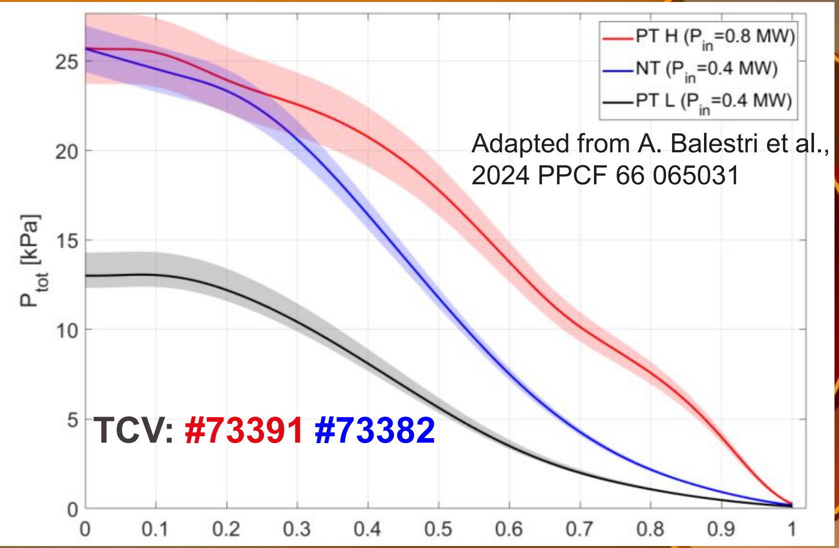
  ⬇

  Intrinsically **ELM-free**

- **Reduction of turbulent transport [4,5,6,7,8]**

  ⬇

  Recover H-mode performance



Adapted from A. Balestri et al., 2024 PPCF 66 065031

Negative Triangularity plasmas: H-mode performance without H-mode

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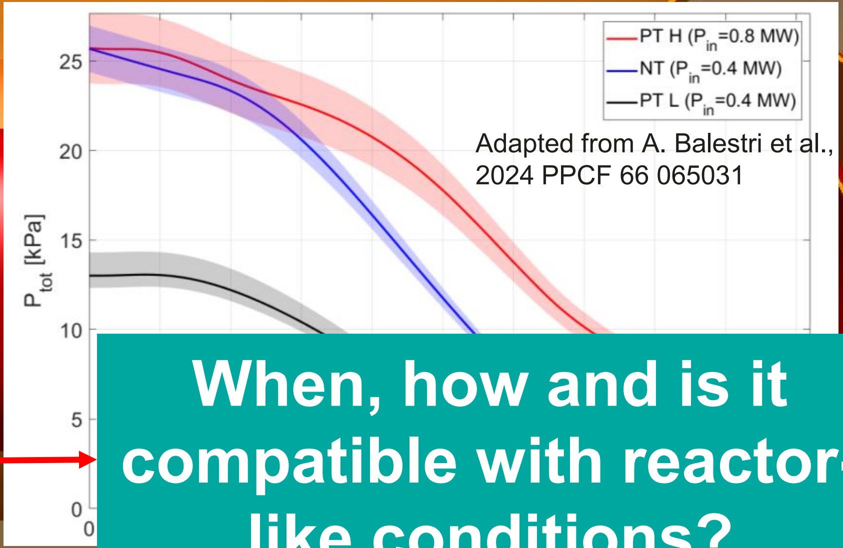

Adapted from A. Balestri et al., 2024 PPCF 66 065031

When, how and is it compatible with reactor-like conditions?

What do we know from simulations? (some highlights)

- NT strongly stabilizes ITG and TEM turbulence in conventional aspect ratio tokamaks [1-11]
- NT stabilizes ITG turbulence at low aspect ratio (spherical tokamaks [8])
- Stabilizing effect of NT on ITG and TEM enhanced by:
  - large magnetic shear [3]
  - large elongation [8]
- No ρ^* effect observed in ITG/TEM dominated regime [5,9]
- No effect of collisions on NT beneficial effect [10]

[1] A. Marinoni et al., 2009 PPCF 51 055016
[2] G. Merlo et al., 2015 PPCF 57 054010
[3] G. Merlo et al, 2023 JPP 89 905890104
[4] G. Merlo et al, 2023 PoP 30 102302
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[6] A. Mariani et al., 2024 NF 64 106024
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[8] A. Balestri et al., 2024 PPCF 66 075012
[9] G. Di Giannatale et al., 2024 PPCF 66 095003
[10] A. C. D. Hoffman et al., 2024 PPCF 67 015031
[11] G. Di Giannatale et al., 2025 PPCF 67 085003
[12] L. De Gianni et al., 2026 NF 68 065008
[13] M. Becoulet et al., 2026 PPCF 68 035031

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Most of the work has focused on the electrostatic regime with low β

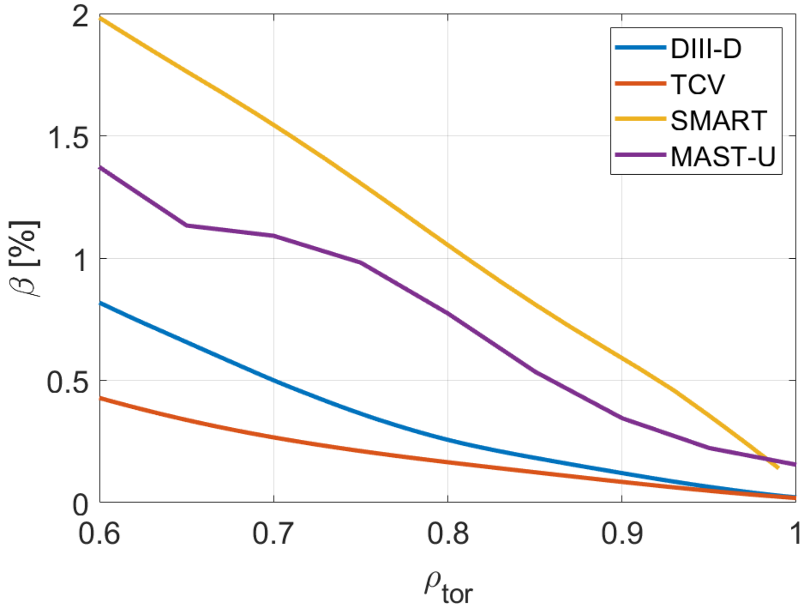
Motivation

Fusion plasmas are supposed to achieve large β regimes, where electromagnetic instabilities can play a dominant role:

- Micro-Tearing Modes (MTMs)
- Kinetic Ballooning Modes (KBMs)

Particularly of interest for Spherical Tokamaks (STs), where large β is achieved

Investigate if and how triangularity affects MTMs stability



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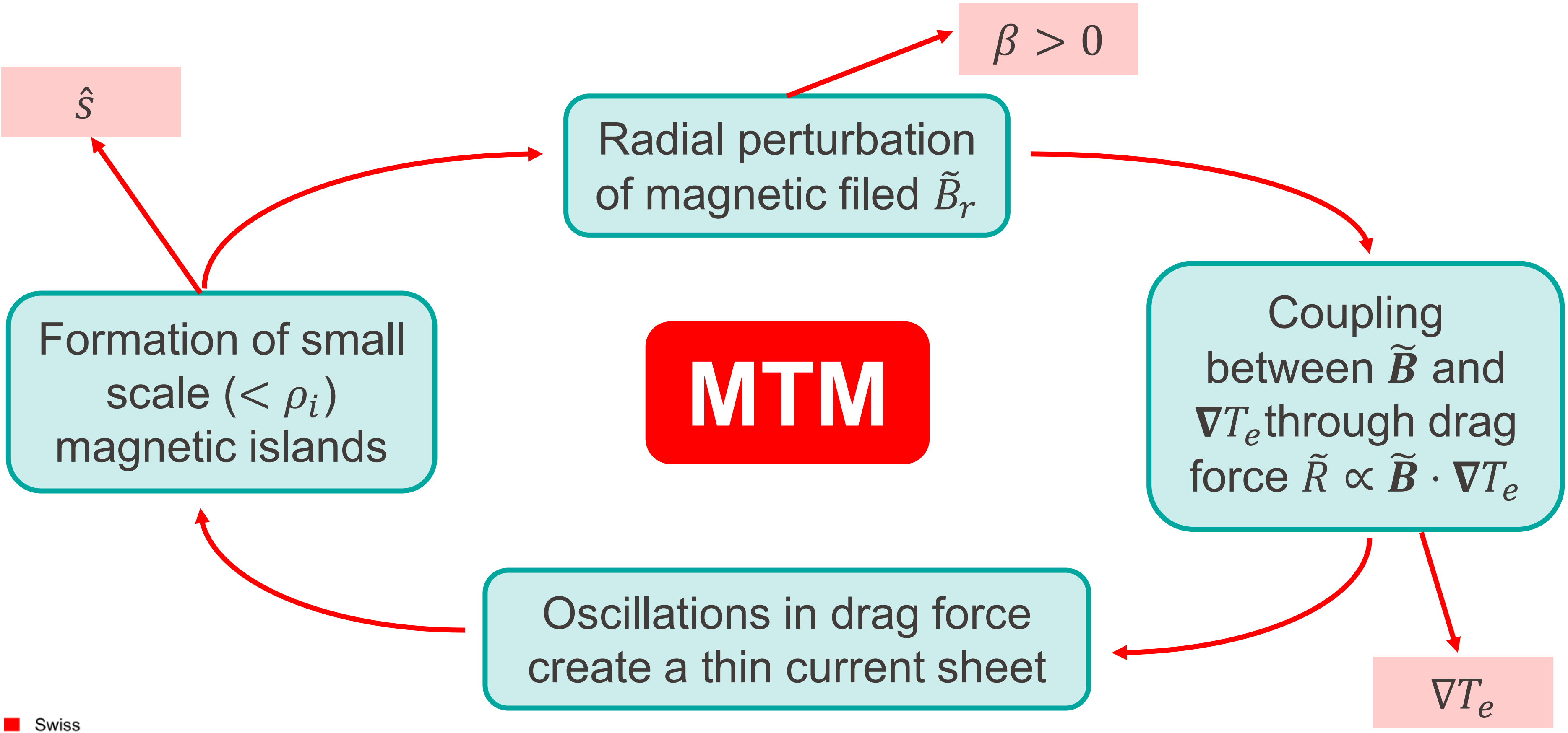
What are the MTMs? (A general and simplified picture)



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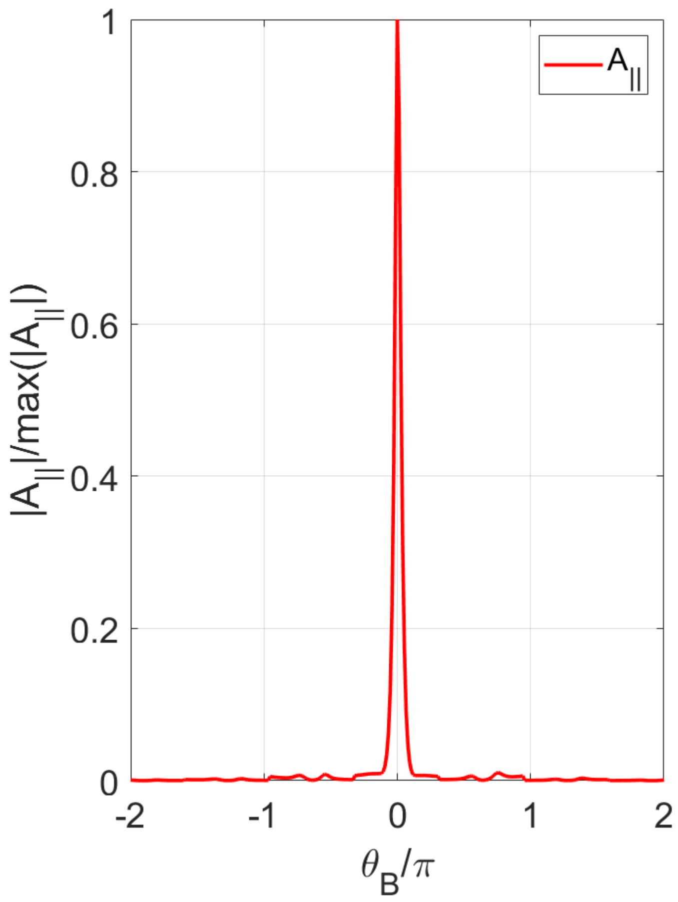
How to identify MTMs?

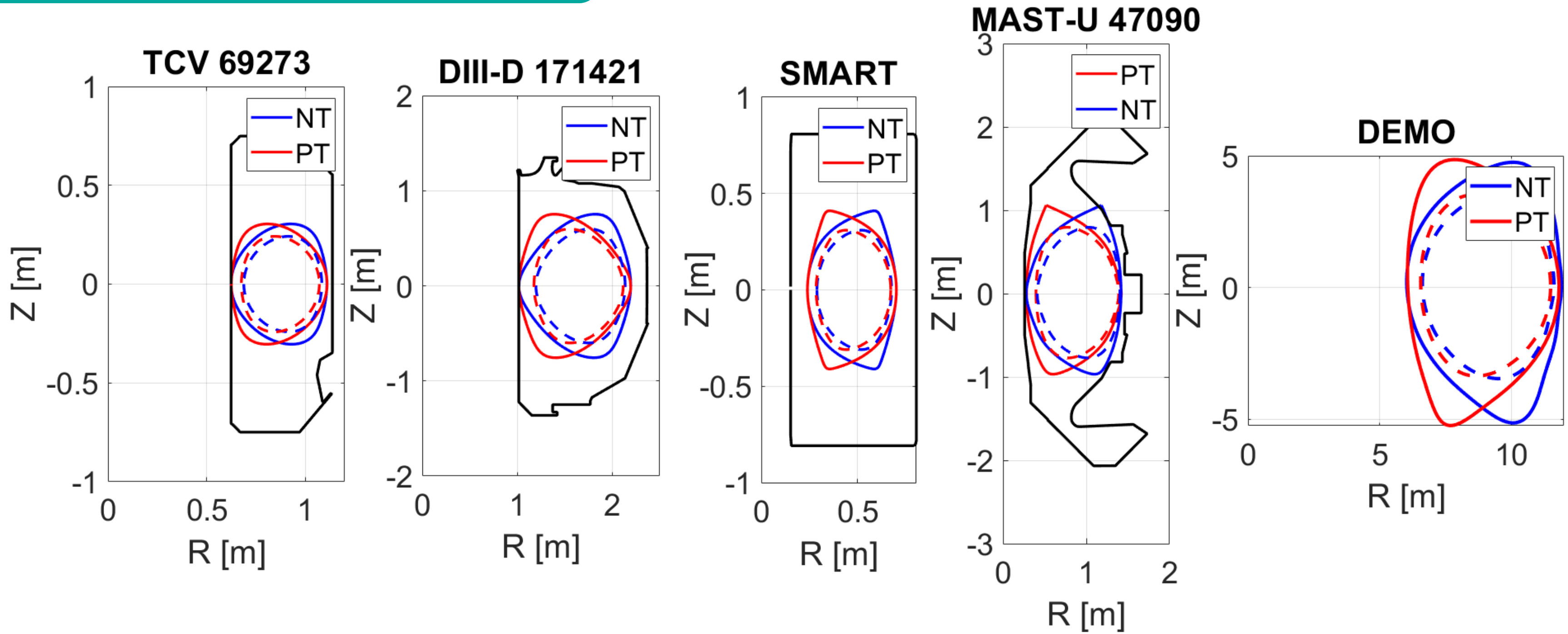
- Mode moving in the electron diamagnetic direction
- Even parity of $A_{||}$ in ballooning space
- Electromagnetic component of electron heat flux dominates over electrostatic one ($Q_{e,em} \gg Q_{e,es}$)
- Negligible particle transport



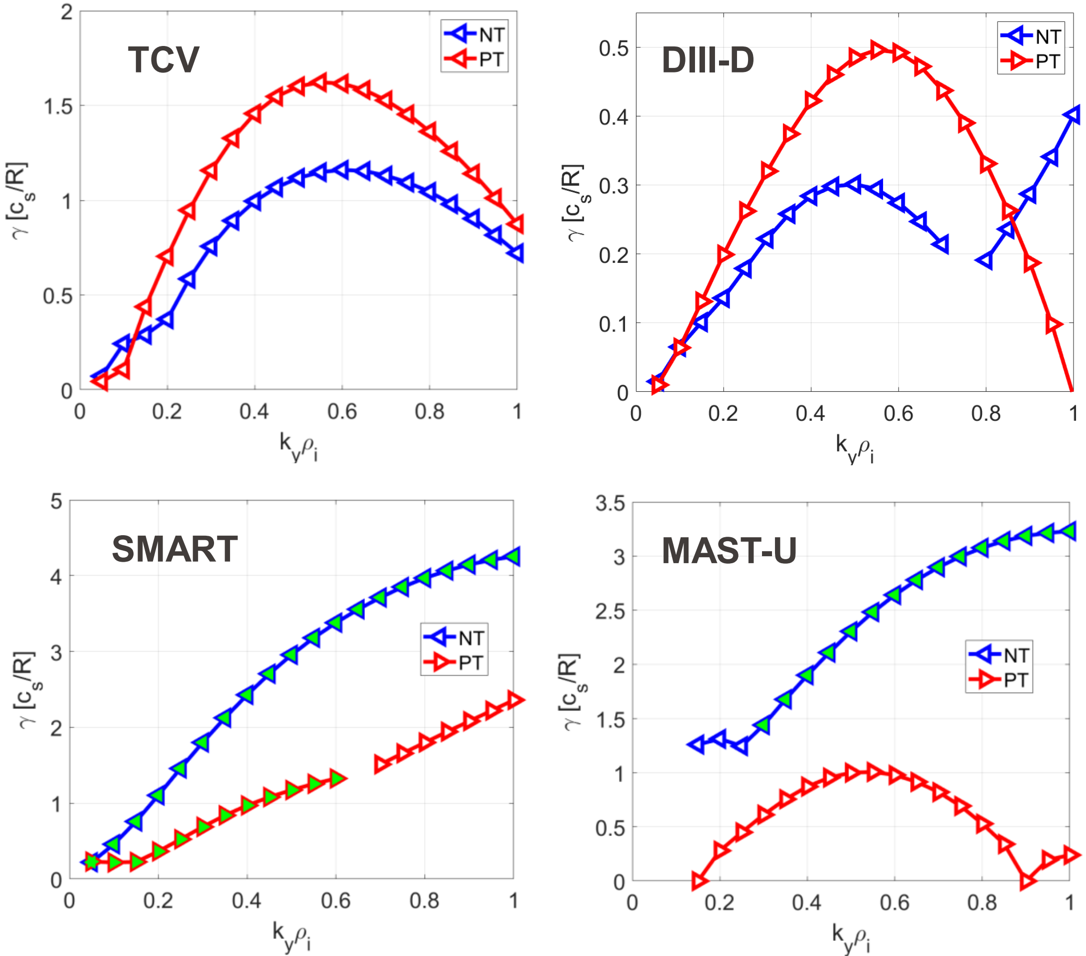
Simulations set-up

GENE local gradient-driven gyrokinetic simulations of several NT and PT scenarios in the outer core $0.75 < \rho_{tor} < 0.9$.

	TCV	DIII-D	DEMO	SMART	MAST-U
ρ_{tor}	0.85	0.8	0.75	0.88	0.8
A	5	4	3.5	2.2	1.8



Linear k_y spectra (ion scale)



- **Conventional A**: NT more stable and ITG/TEM dominate
- **Low A**: NT worse and MTMs dominate

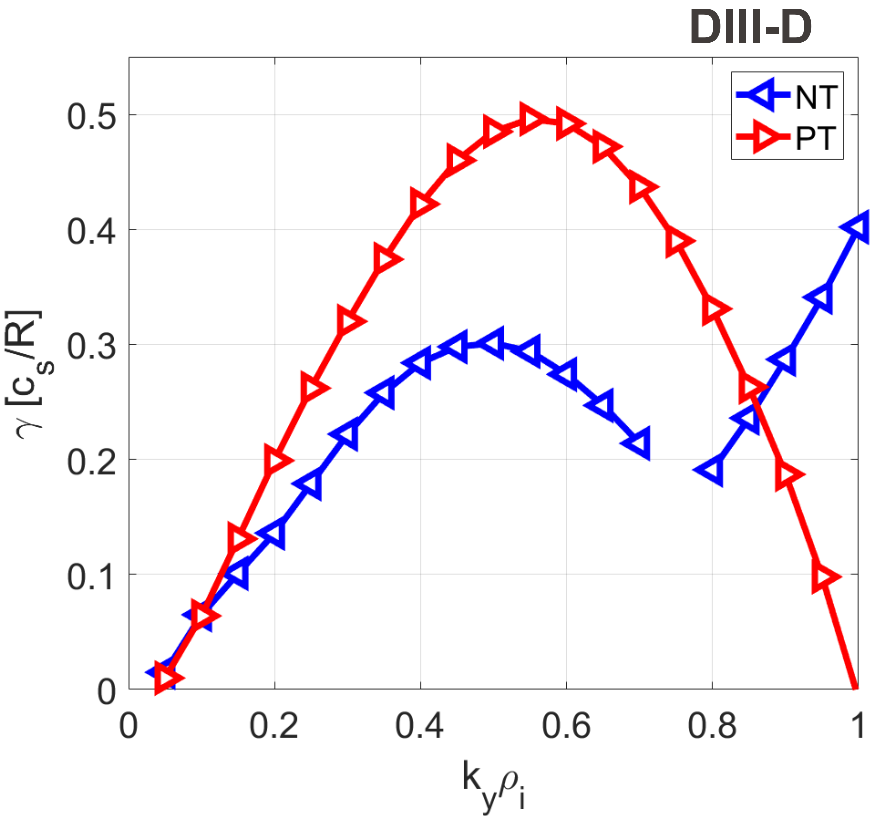
Role of β and $\hat{s}$ in MTM stability

	TCV	DIII-D	DEMO	SMART	MAST-U
ρ_{tor}	0.85	0.8	0.75	0.88	0.8
A	5	4	3.5	2.2	1.8
β [%]	0.16	0.13	0.14	0.6	0.7
$\hat{s}$	2.5	1.8	2.0	3.75	4.9

Conventional A scenarios characterized by low β and small $\hat{s}$

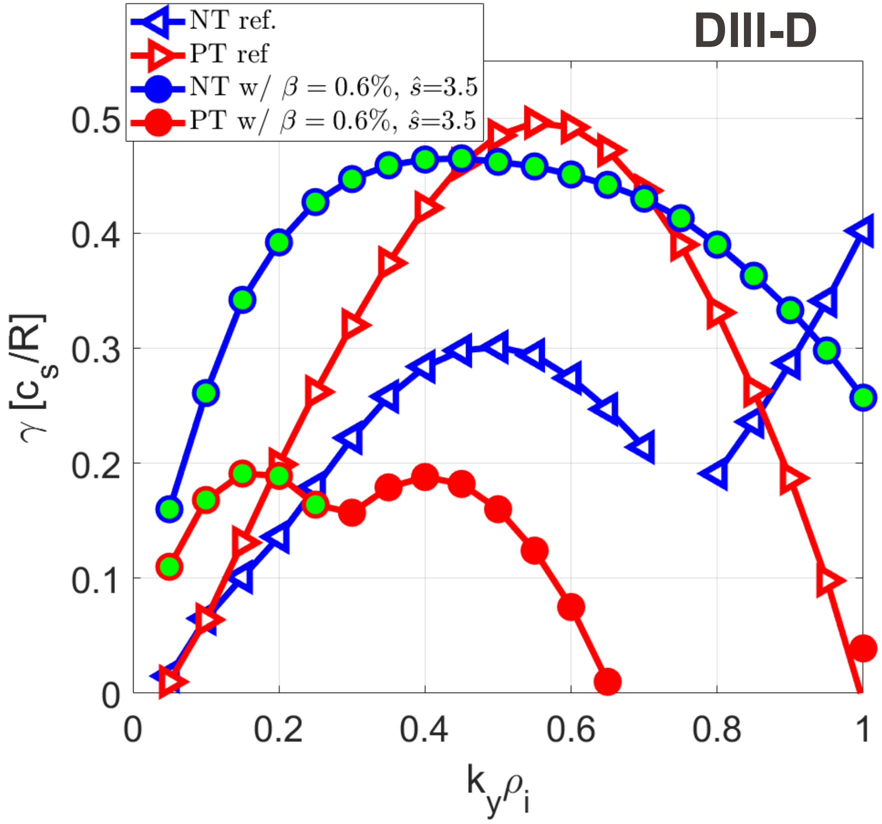
Low A scenarios characterized by large β and large $\hat{s}$

Role of β and $\hat{s}$ in MTM stability



We imposed the nominal value of β and $\hat{s}$ from SMART (low A) in the DIII-D scenarios (conventional A)

Role of β and $\hat{s}$ in MTM stability



We imposed the nominal value of β and $\hat{s}$ from SMART (low A) in the DIII-D scenarios (conventional A)

When β and $\hat{s}$ are sufficiently large:

- MTMs are destabilized across the full ion scale in NT
- NT becomes more unstable than PT

Linear scan of β, $\hat{s}$ and R/L_{Te}

To better understand the role of β, $\hat{s}$ and R/L_{Te} in destabilizing MTMs NT and PT, we performed multiple linear scans for all the previous scenarios:

- Fixed $k_y\rho_i$=0.2
- Scan in β
- Scan in $\hat{s}$
- Scan in R/L_{Te} (keeping fixed R/L_{Ti})

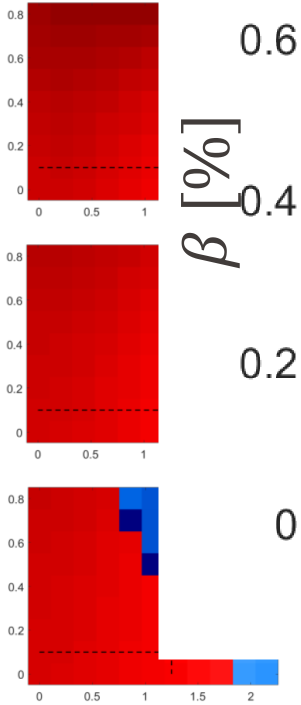
TCV | DIII-D | DEMO | SMART | MAST-U

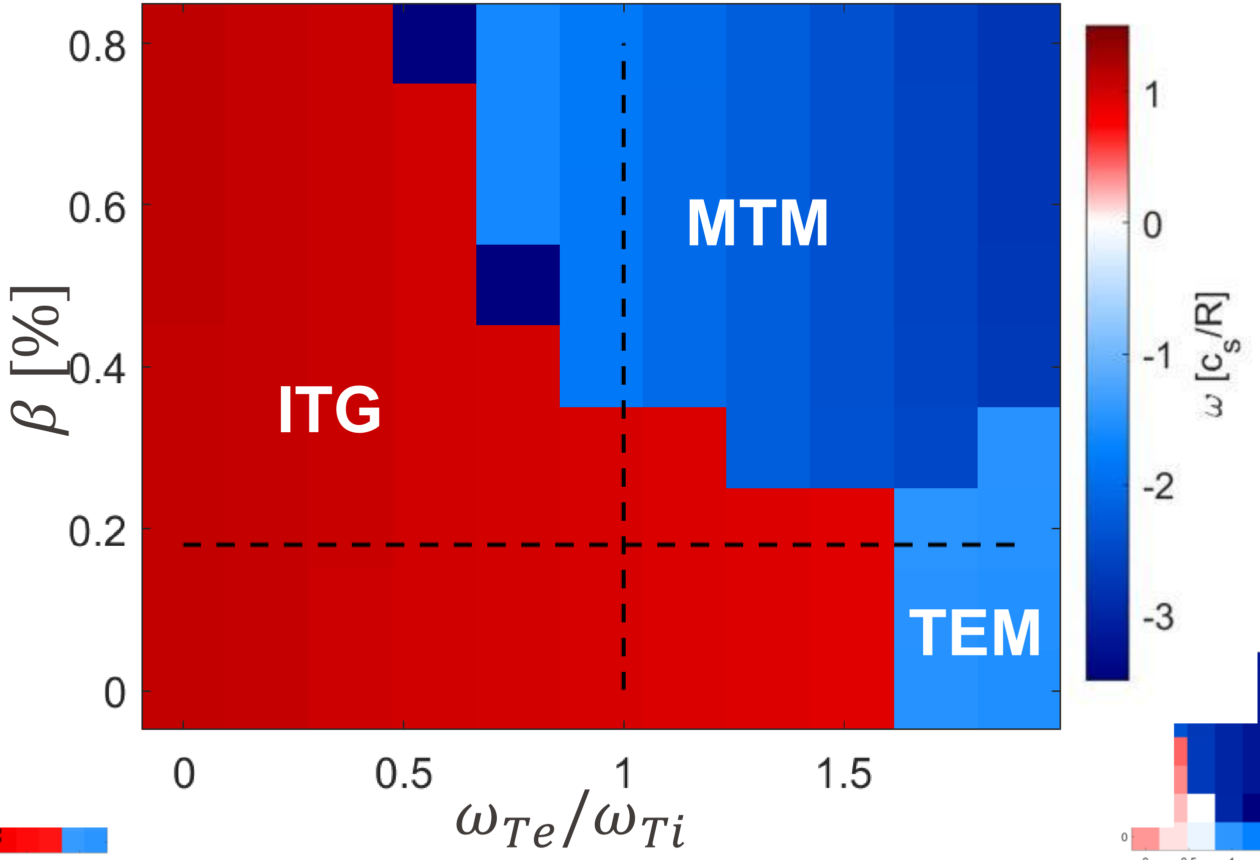
$\hat{s} = 1.5$

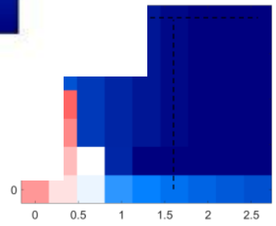
$\hat{s} = 2.5$

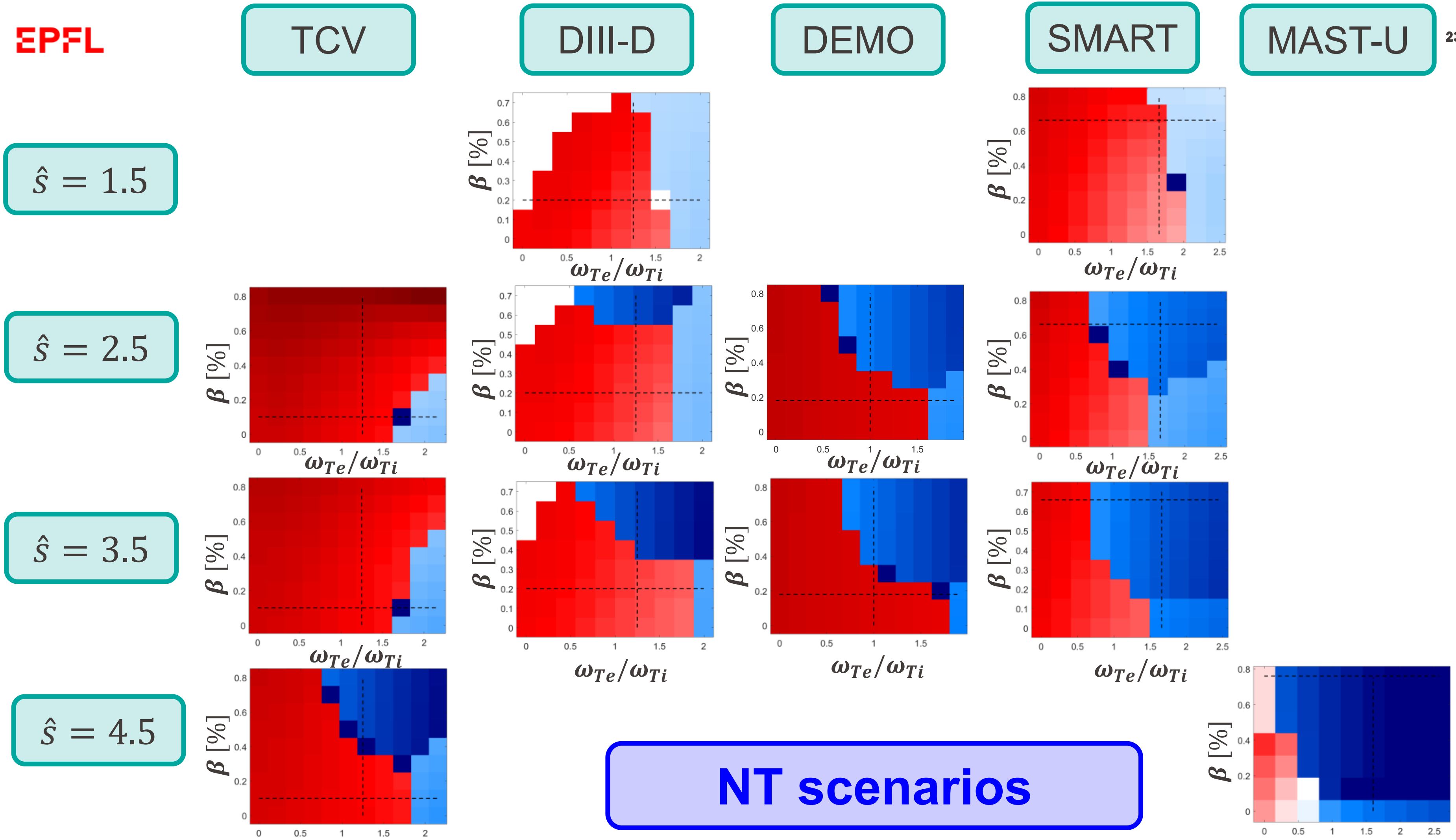
$\hat{s} = 3.5$

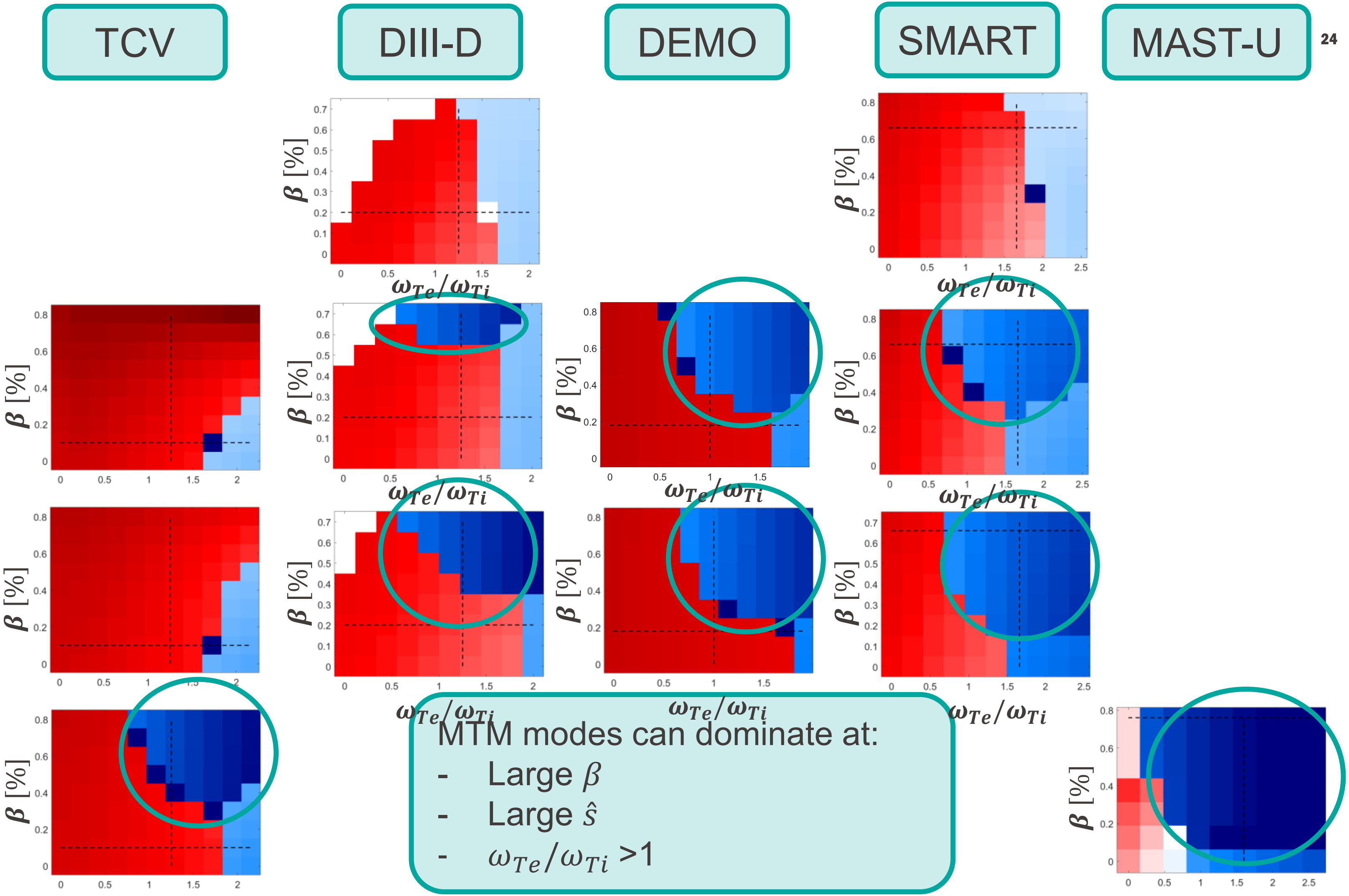
$\hat{s} = 4.5$





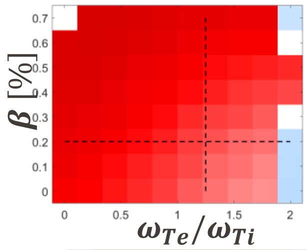


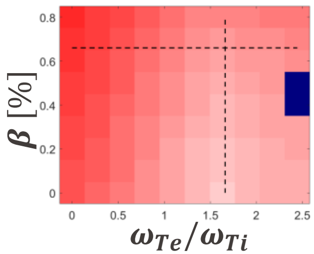

TCV
DIII-D
DEMO
SMART
MAST-U
$\hat{s} = 1.5$
$\hat{s} = 2.5$
$\hat{s} = 3.5$
$\hat{s} = 4.5$
β [%]
ω_{Te}/ω_{Ti}
NT scenarios


TCV
DIII-D
DEMO
SMART
MAST-U
$\hat{s} = 1.5$
$\hat{s} = 2.5$
$\hat{s} = 3.5$
$\hat{s} = 4.5$
β [%]
ω_{Te}/ω_{Ti}
MTM modes can dominate at:
- Large β
- Large $\hat{s}$
- ω_{Te}/ω_{Ti} >1

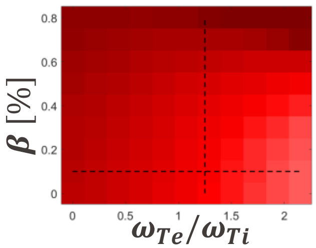
TCV | DIII-D | DEMO | SMART | MAST-U

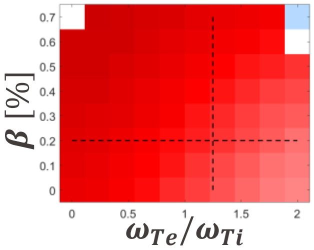
$\hat{s} = 1.5$

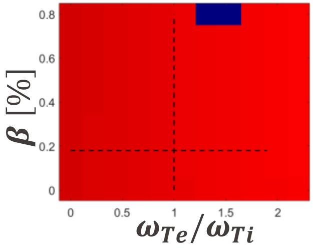


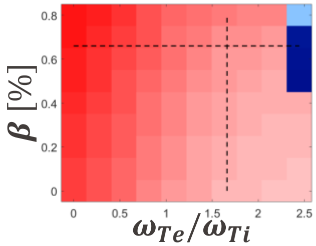


$\hat{s} = 2.5$

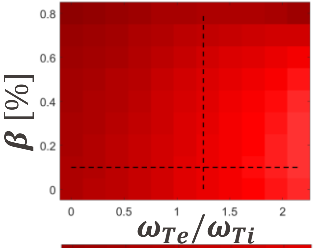


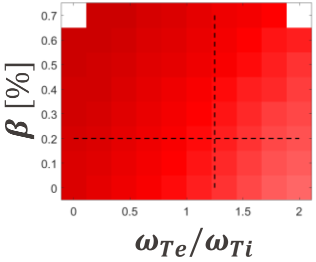


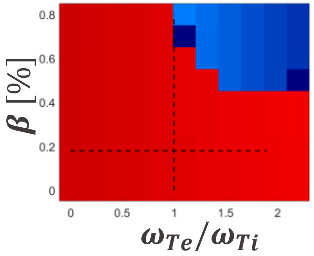


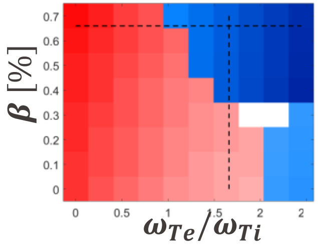


$\hat{s} = 3.5$

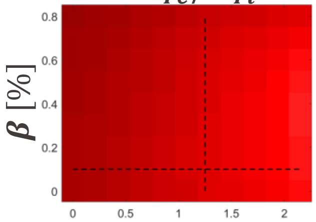


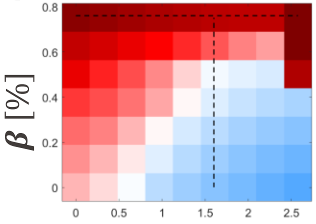






$\hat{s} = 4.5$





PT scenarios

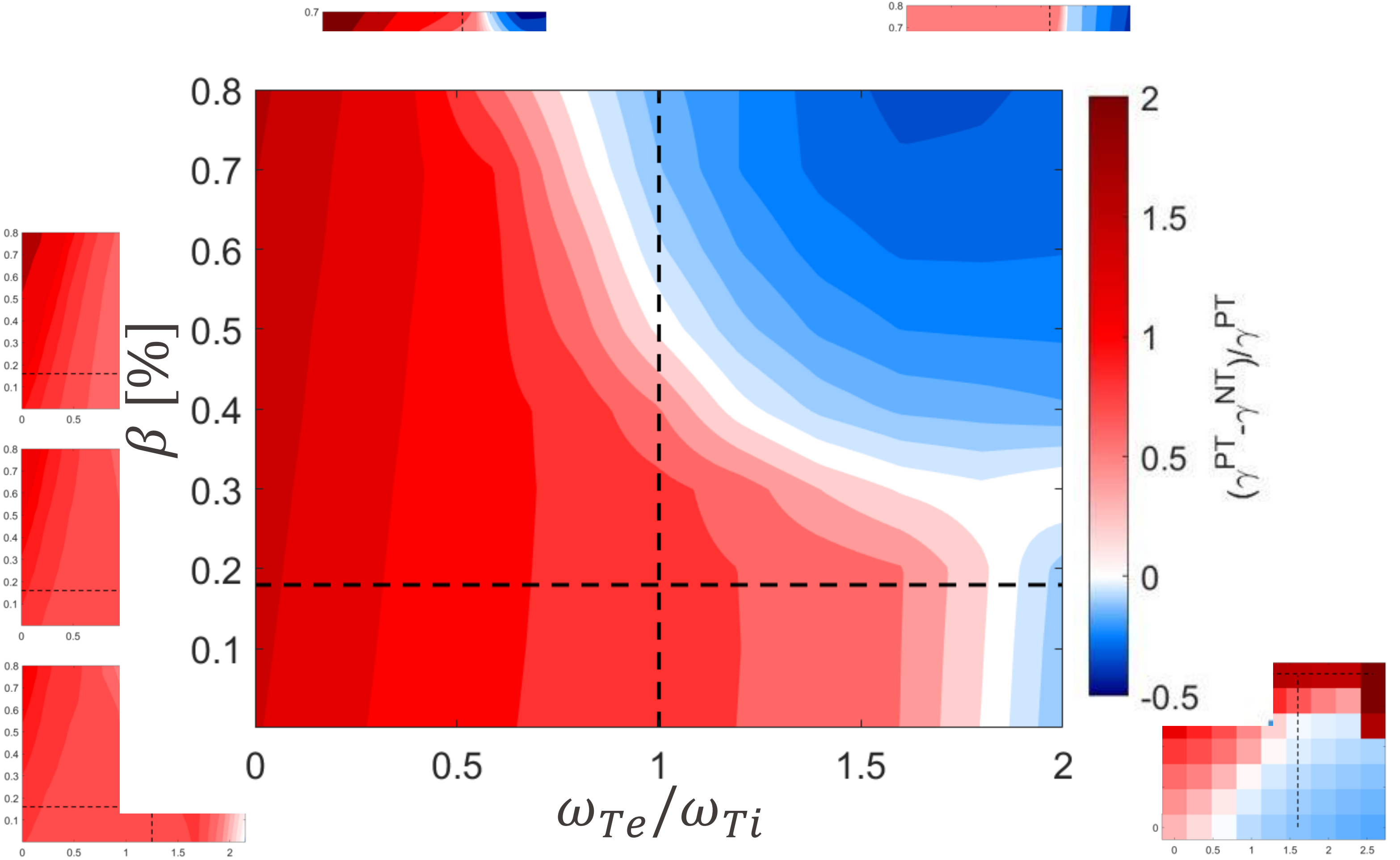
TCV | DIII-D | DEMO | SMART | MAST-U

$\hat{s} = 1.5$

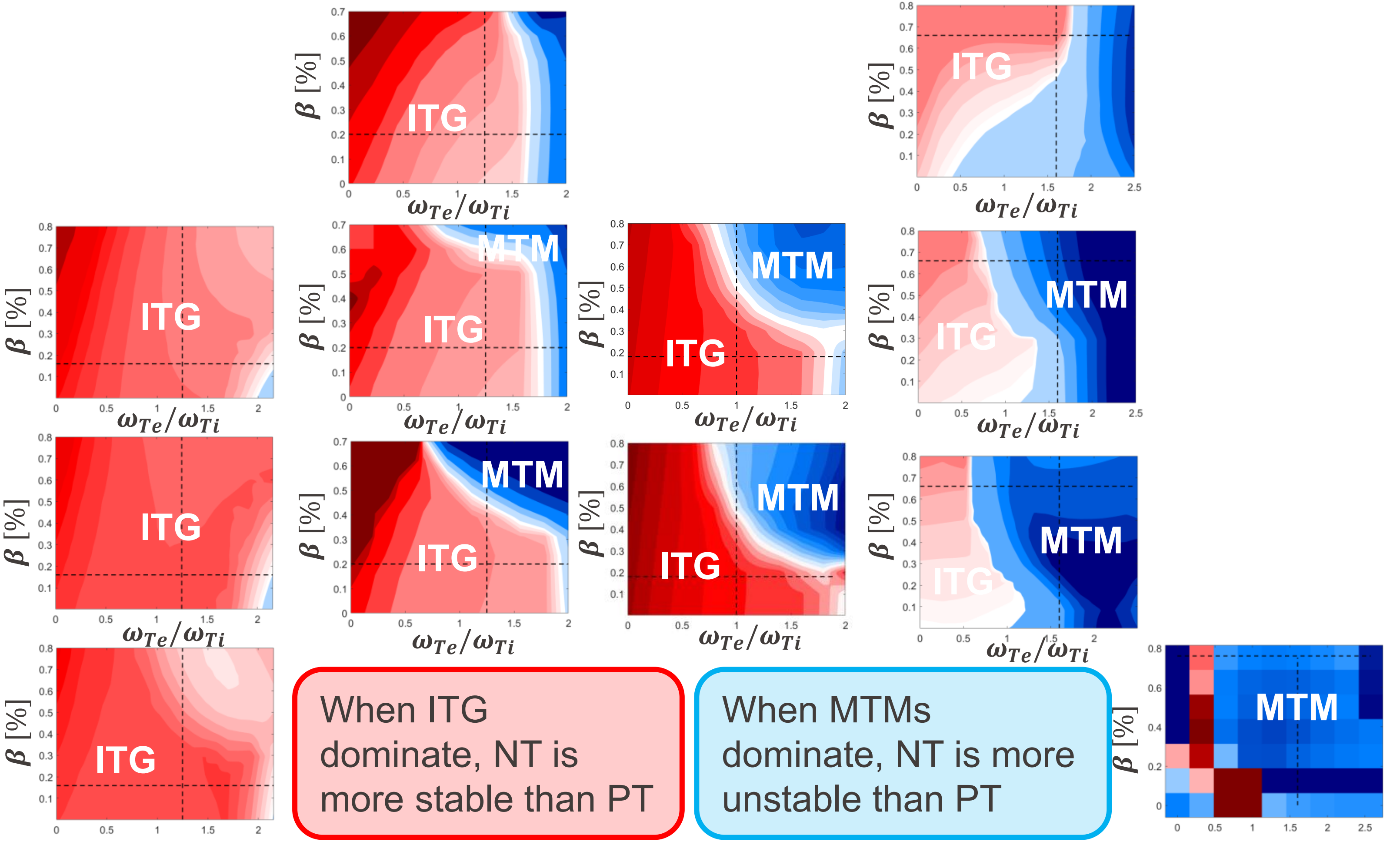
$\hat{s} = 2.5$

$\hat{s} = 3.5$

$\hat{s} = 4.5$

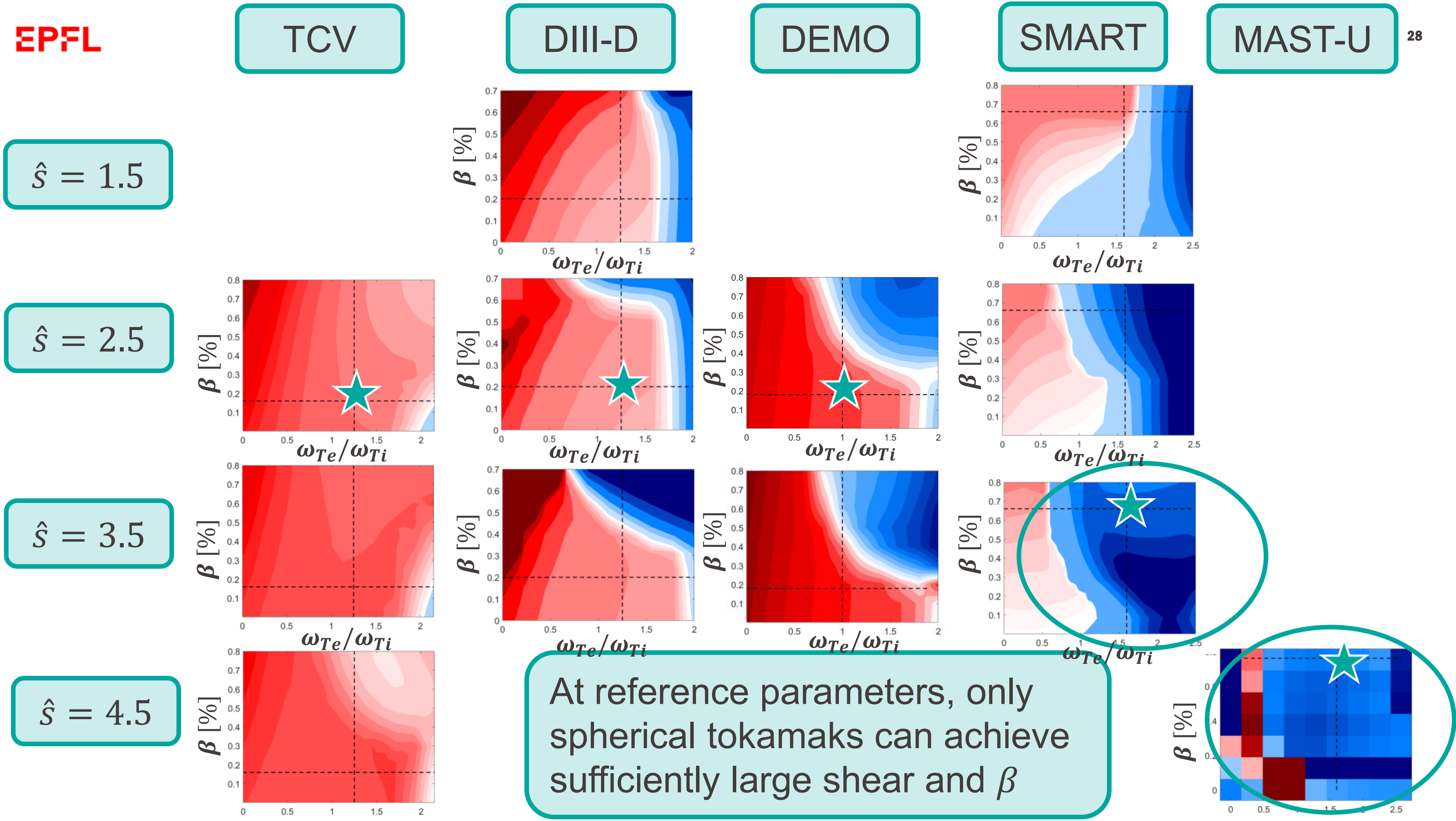


	TCV	DIII-D	DEMO	SMART	MAST-U
$\hat{s} = 1.5$					
$\hat{s} = 2.5$					
$\hat{s} = 3.5$					
$\hat{s} = 4.5$					



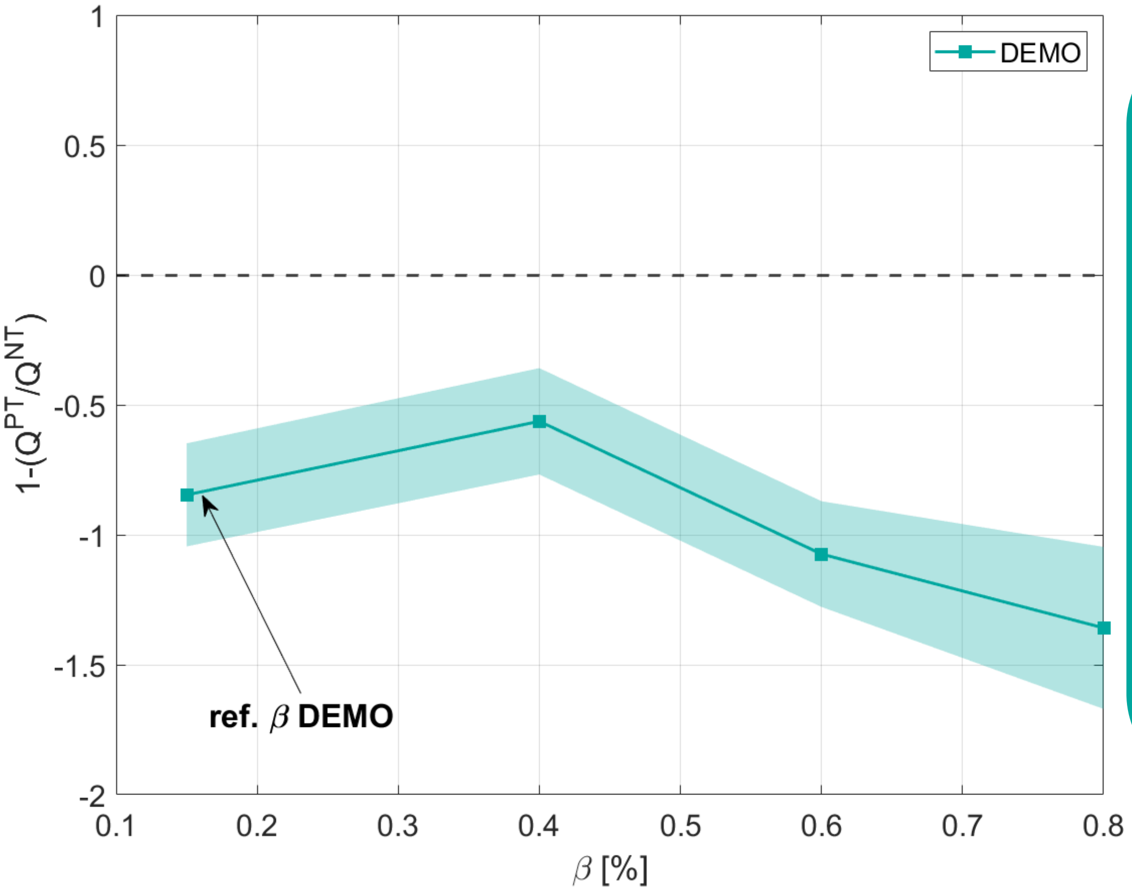
When ITG dominate, NT is more stable than PT

When MTMs dominate, NT is more unstable than PT



At reference parameters, only spherical tokamaks can achieve sufficiently large shear and β

Nonlinear simulations confirm the linear picture



DEMO

↓

Low $\hat{s}$ ($\hat{s} = 2.5$)

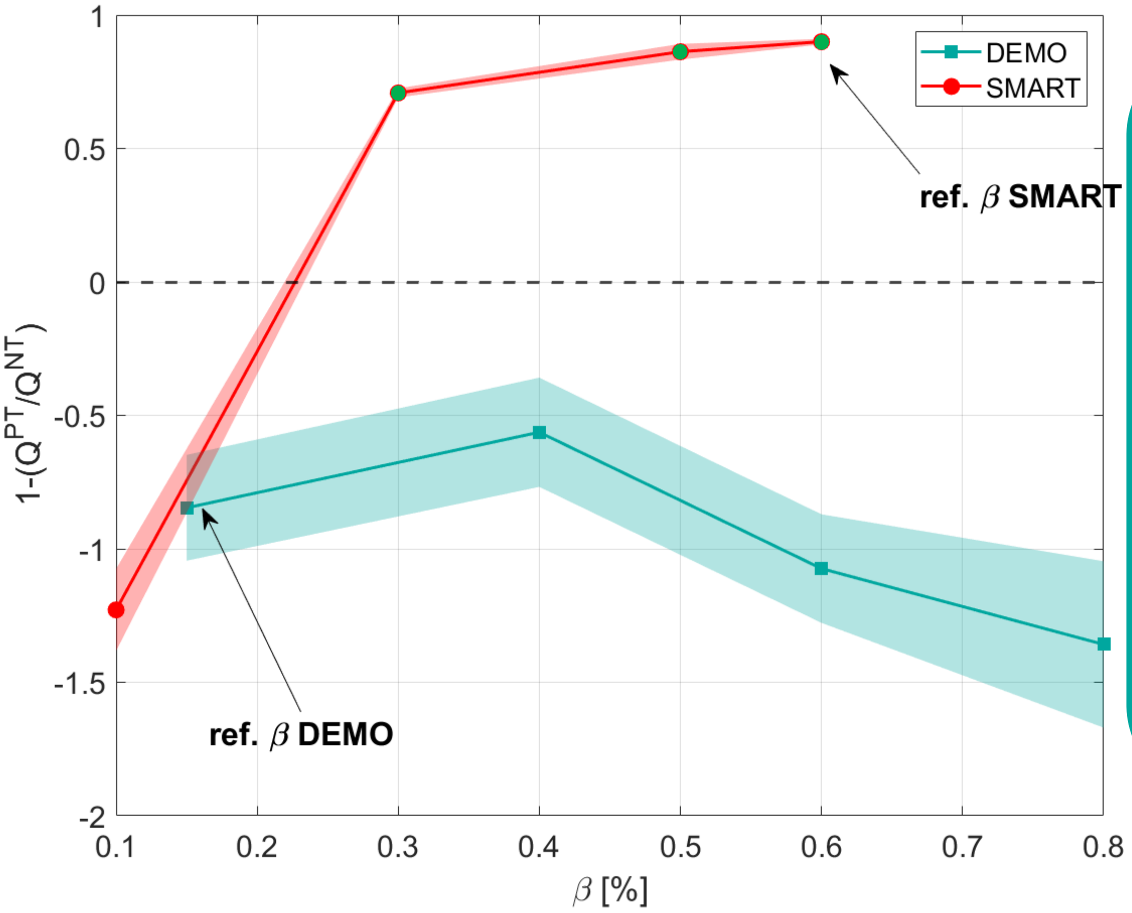
↓

MTM not triggered at any β

↓

ITG dominate turbulence and NT better than PT

Nonlinear simulations confirm the linear picture



SMART

↓

High $\hat{s}$ ($\hat{s} = 3.7$)

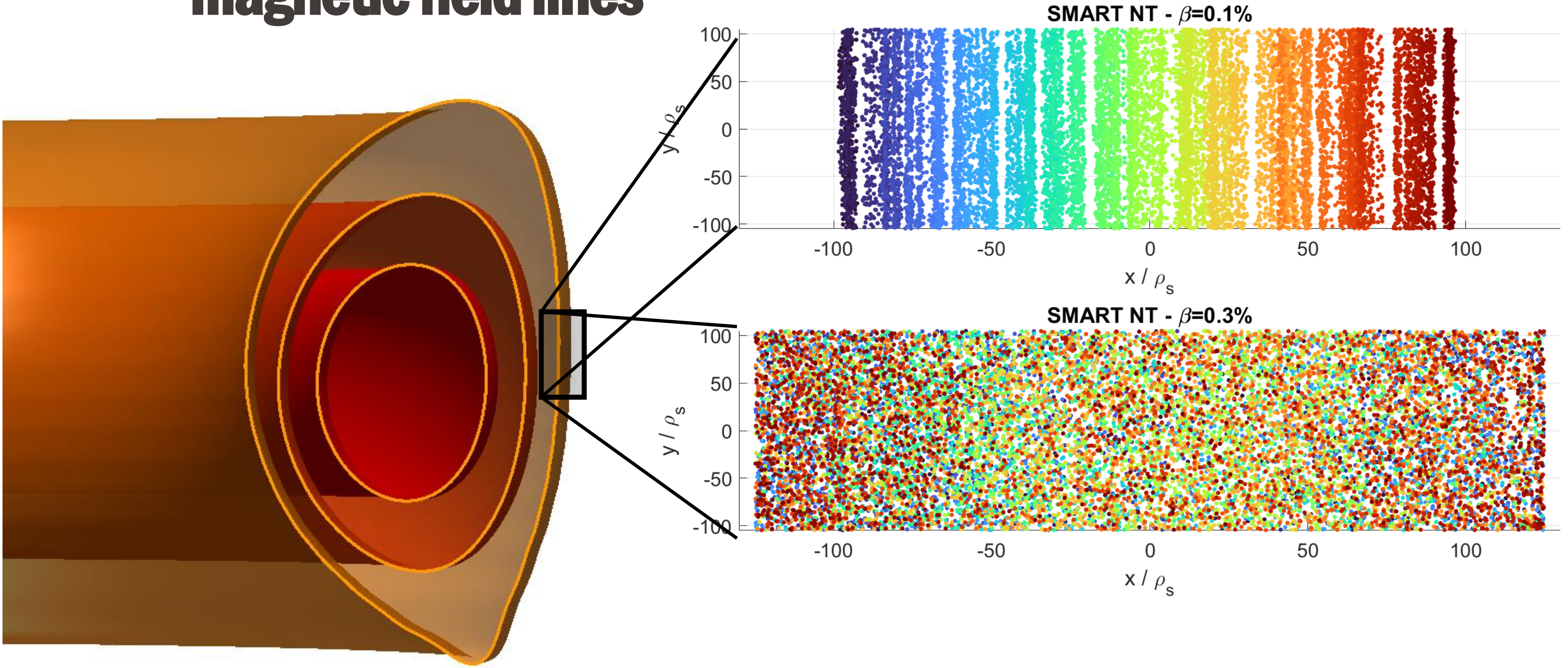
↓

MTMs (green dots) triggered at sufficiently large β in NT

↓

NT worse than PT when MTM dominate

MTM simulations show great stochastization of magnetic field lines



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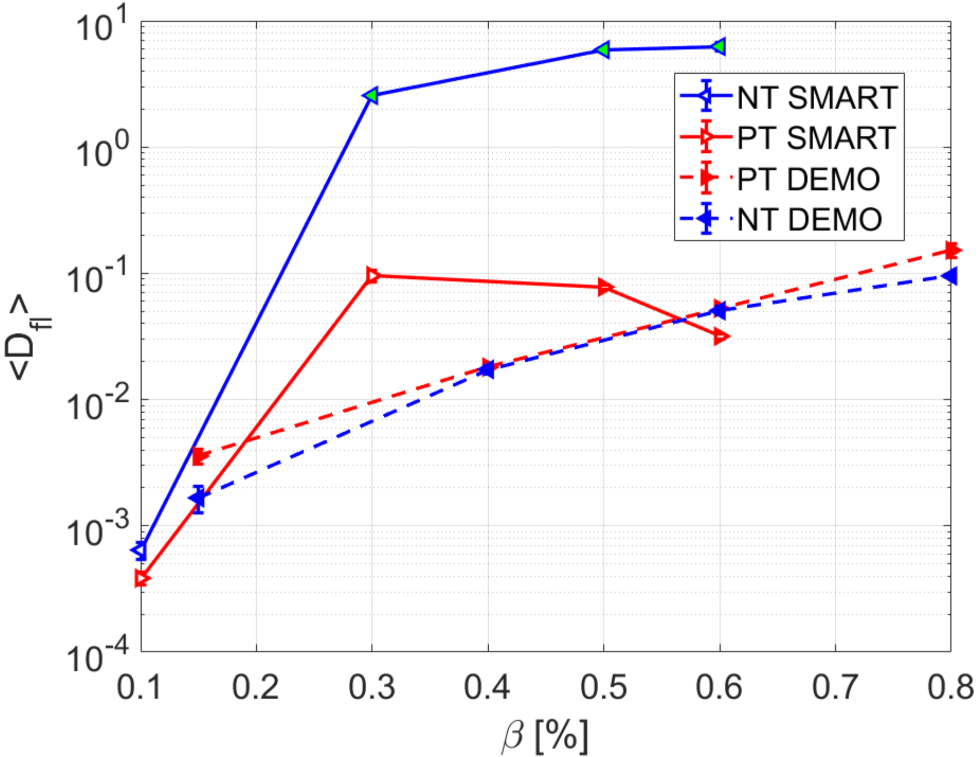


Stochastization in MTM-dominated regimes is reflected in large diffusion of magnetic field lines

$$D_{fl}(l,p) = \frac{[r(l,p) - r(l,0)]^2}{2\pi q_0 R(p+1)}$$

Where l is a magnetic field line, p the number of poloidal turns, $r(l,p)$ the radial position of the line at the outboard midplane

A brief summary

- NT is more sensitive to MTMs than PT. When MTMs dominate, NT is much more unstable than PT
- Aspect ratio **does not** play a direct role in destabilizing MTMs in NT.
- To destabilize MTMs in NT we need large β **AND** large $\hat{s}$ **AND** large electron temperature gradient.
- These conditions can be met only in STs. Should not be an issue in conventional A tokamaks.
- For the same parameter PT stays dominated by electrostatic turbulence.

Why MTMs are stronger in NT?

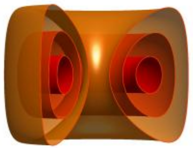
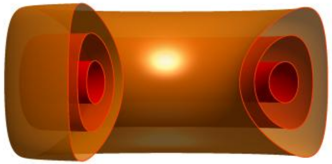
Fundamental study of impact of geometry on MTM turbulence

To study the impact of geometry on MTM turbulence we considered a simplified scenario:

Pure-MTM (pMTM):
- $R/L_{Ti} = 0$
- $R/L_n = 0$
- $\beta = 0.7\%$
- $A = 50$

→ Isolate the impact of magnetic drift and FLR effects

Why the large aspect ratio case?


Aspect Ratio →

← **Complexity**

Finite Larmor Radius (FLR) effects: $J_0(k_\perp \rho_\sigma)$

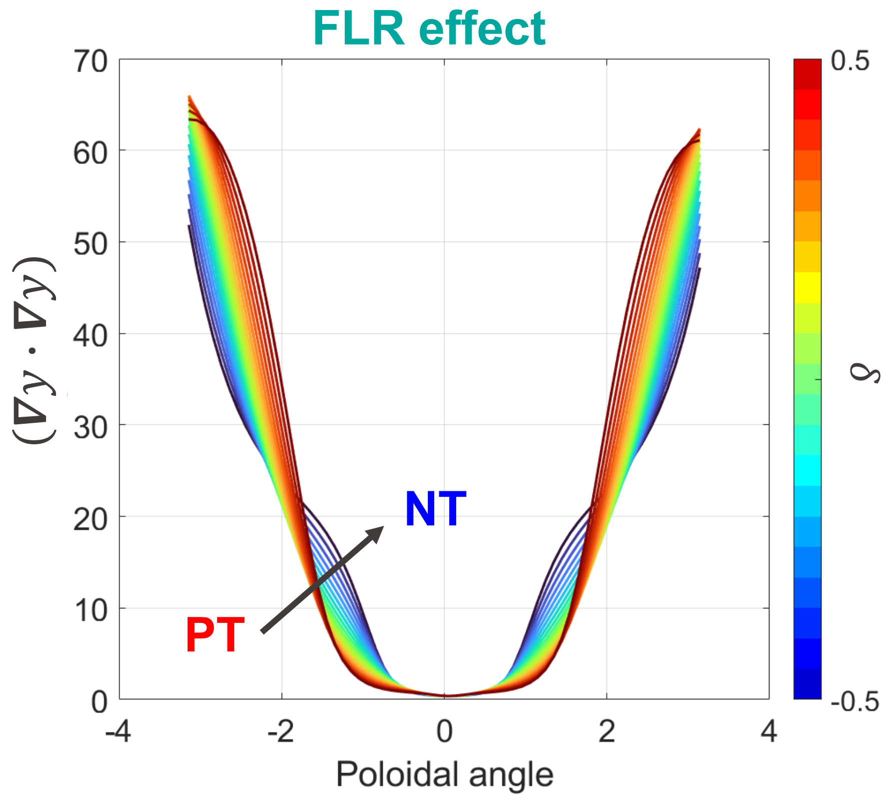
$$k_\perp^2 = \cancel{(\nabla x \cdot \nabla x)k_x^2} + \cancel{2(\nabla x \cdot \nabla y)k_x k_y} + (\nabla y \cdot \nabla y)k_y^2$$

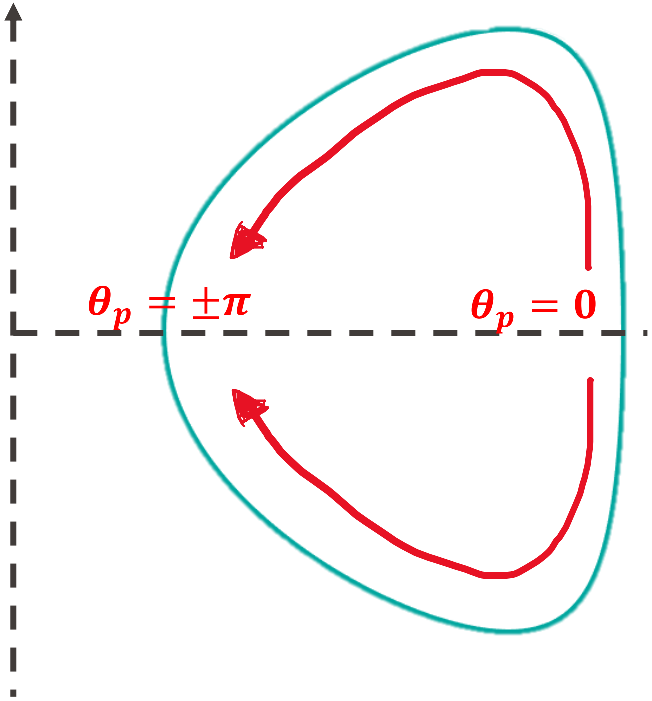
Magnetic drift: ω_D

$$\omega_D = \boldsymbol{v}_D \cdot \boldsymbol{k}_\perp \propto \boldsymbol{k}_\perp \cdot (\boldsymbol{b} \times \nabla B) \propto (\cancel{k_x v_{Dx}} + k_y v_{Dy})$$

At large aspect ratio, geometry enters the GK equation only through two terms

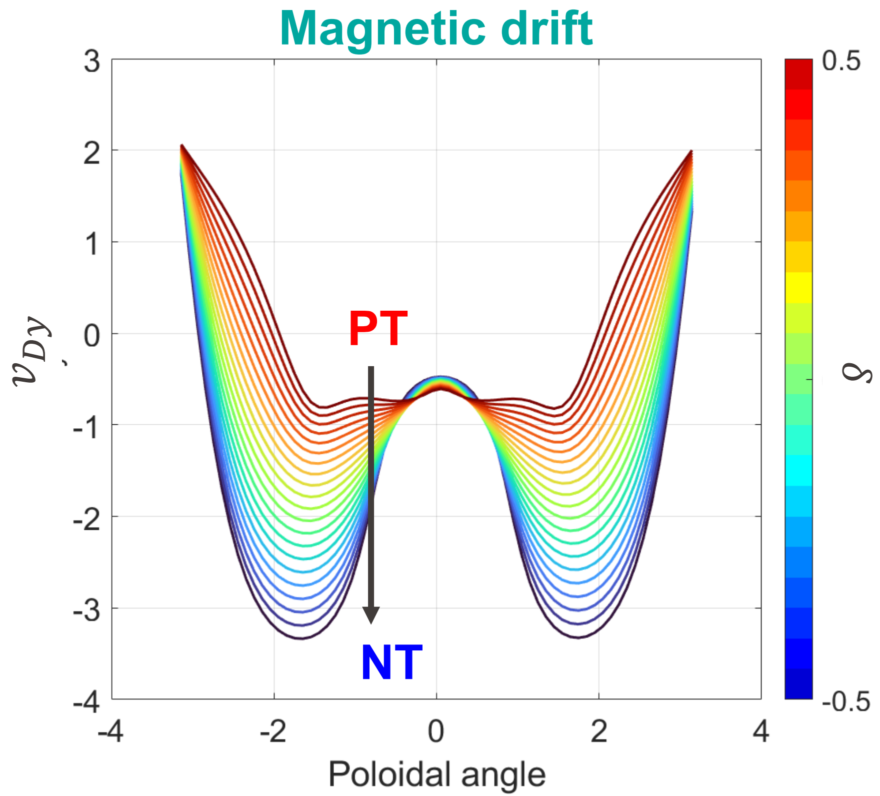
Geometric dependence of FLR effect

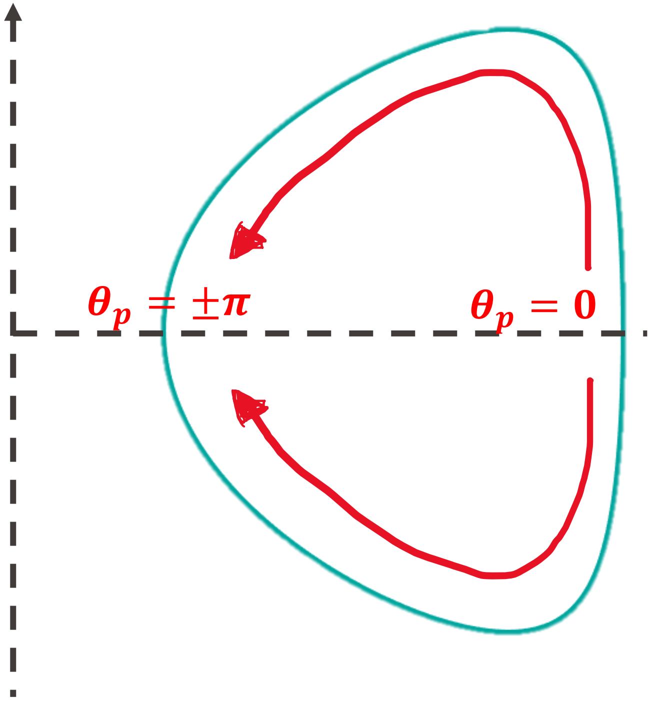




NT makes the FLR effects stronger at the outboard midplane

Geometric dependence of magnetic drifts





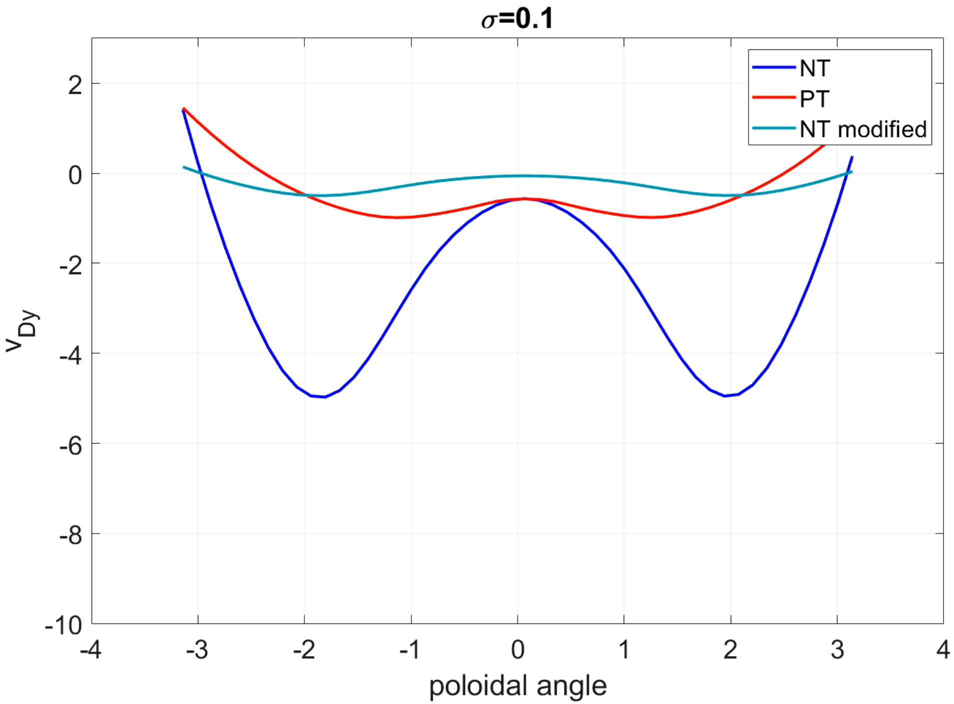
NT increases the magnetic drift of the ions

Magnetic drift scan (methodology)

To understand the impact of magnetic drifts, we have modified artificially the original NT magnetic drift profile:

$$v_{Dy}(z) = \sigma v_{Dy}^{NT}(z) + v_{Dy0}$$

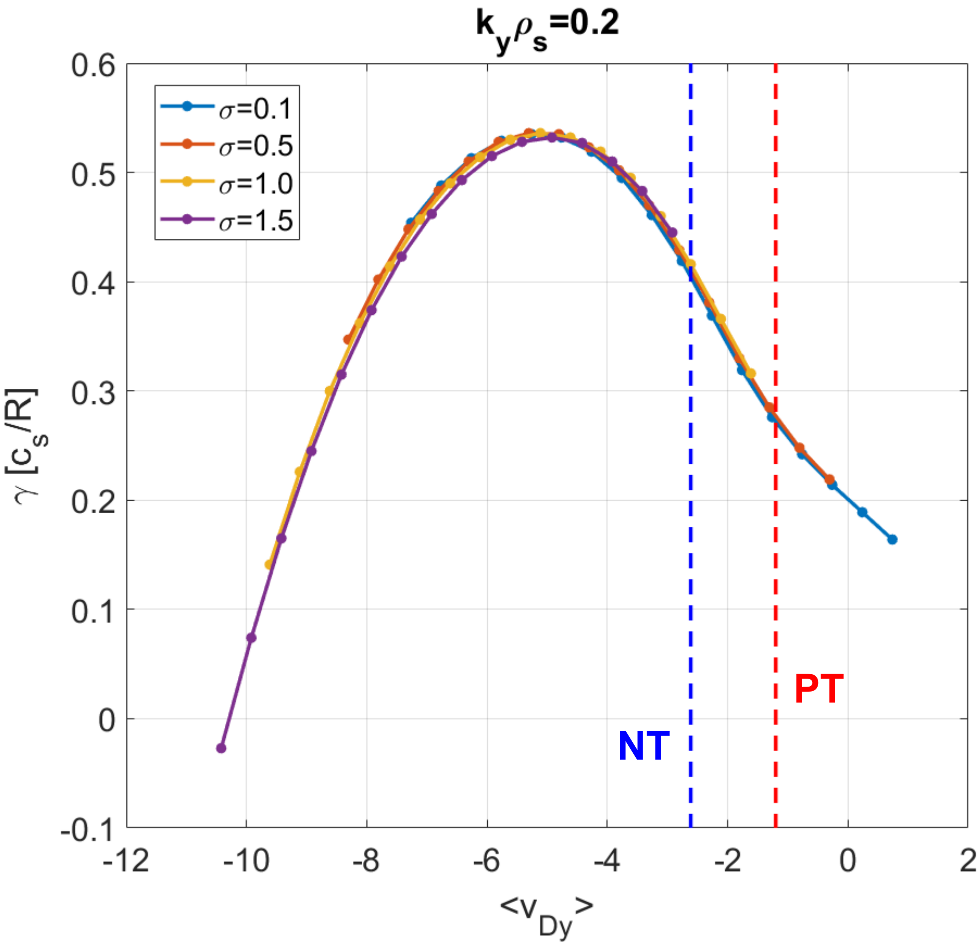
For each modified magnetic drift profile, we run a linear simulation at fixed k_y



Magnetic drift scan in pMTM regime

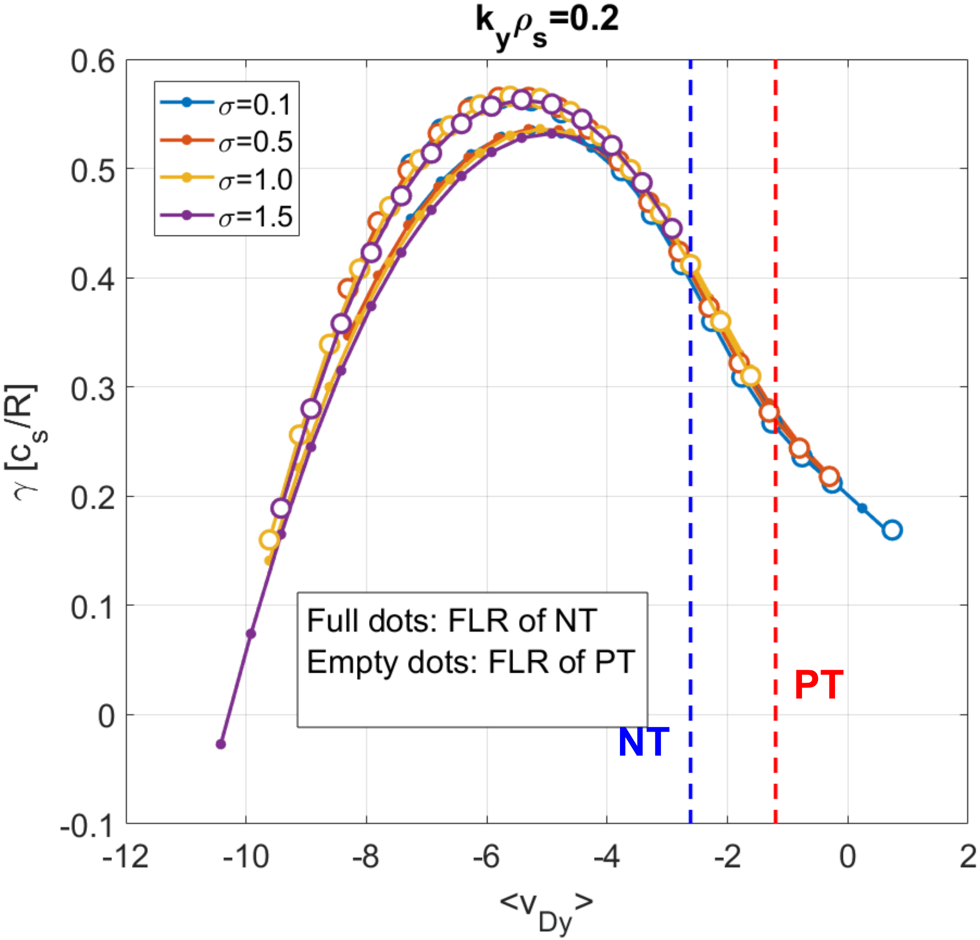
MTMs sensitive only to average magnetic drift velocity.

This penalizes NT against PT.

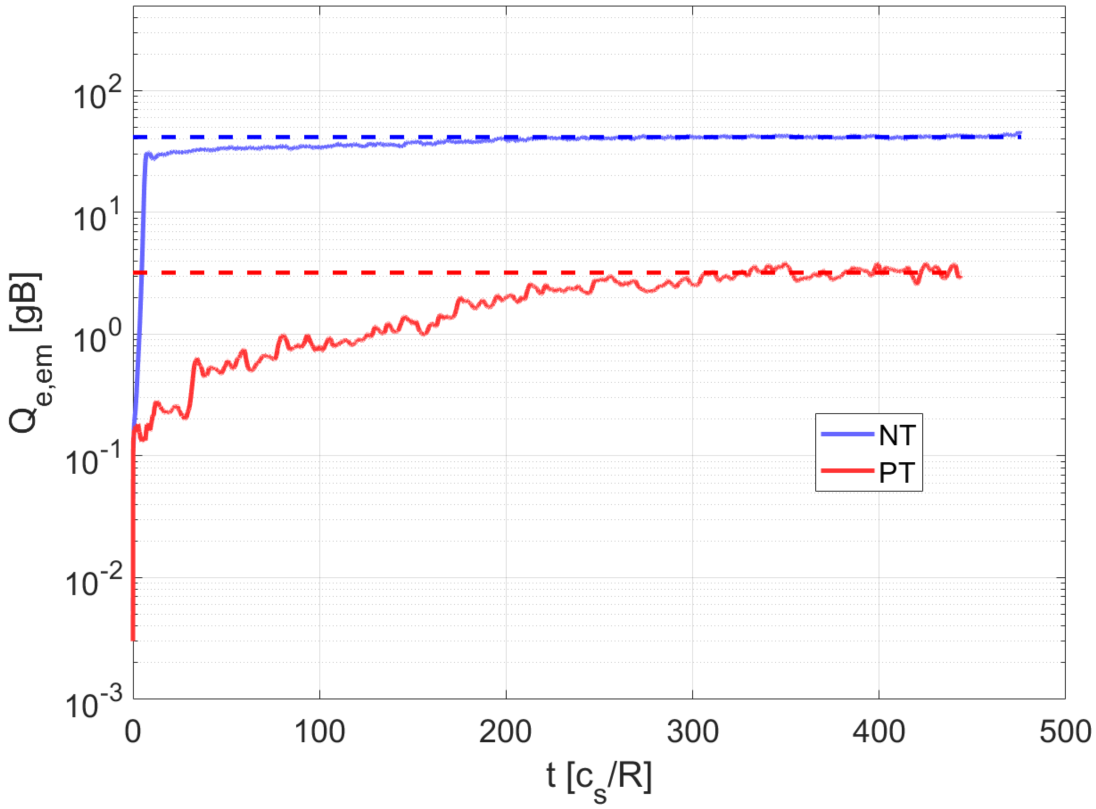


FLR effects in pMTM regime

MTMs almost insensitive to FLR effects

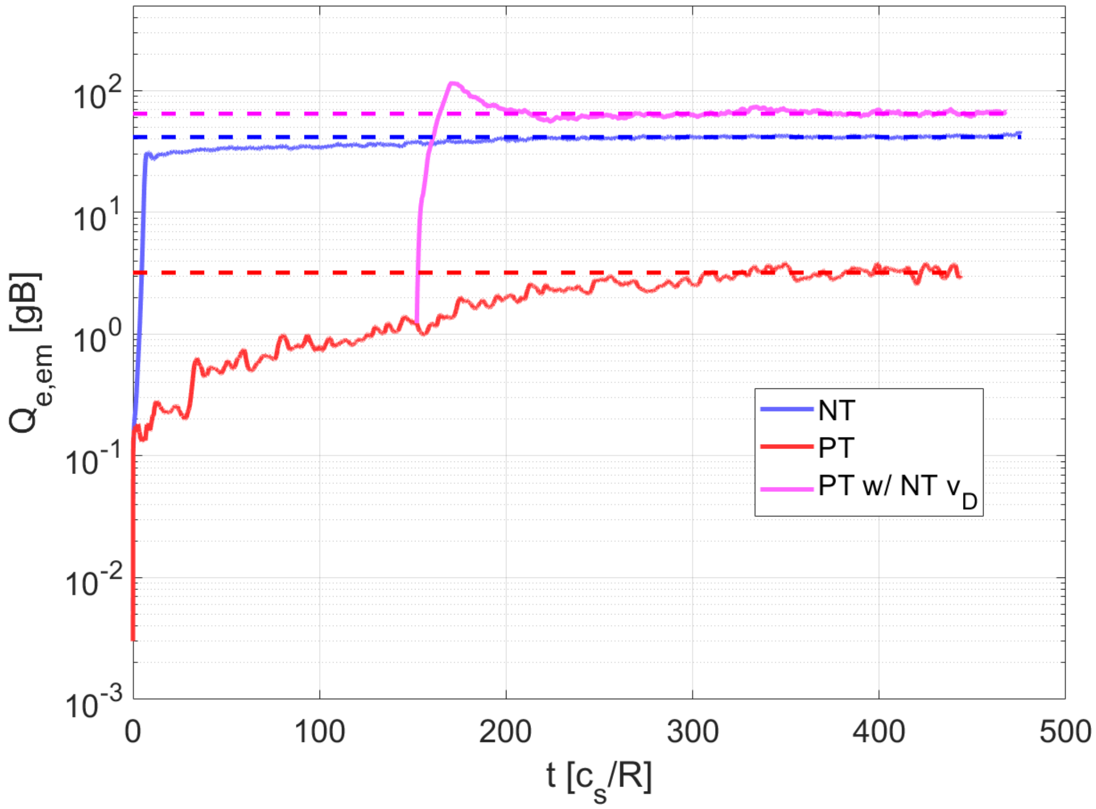


NL simulations confirm the linear picture



- NT much worse than PT with self-consistent equilibria
- When v_D profile from NT is imposed in PT, MTM strongly destabilized
- When FLR effects from NT are imposed, no difference

NL simulations confirm the linear picture



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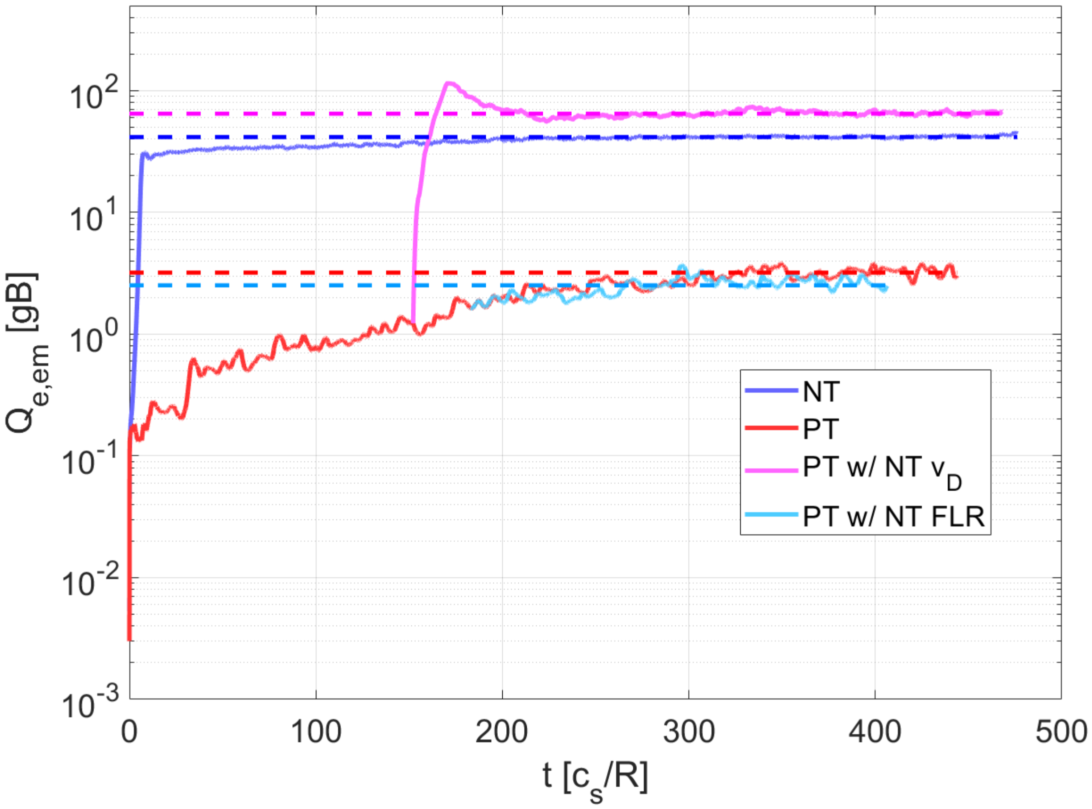

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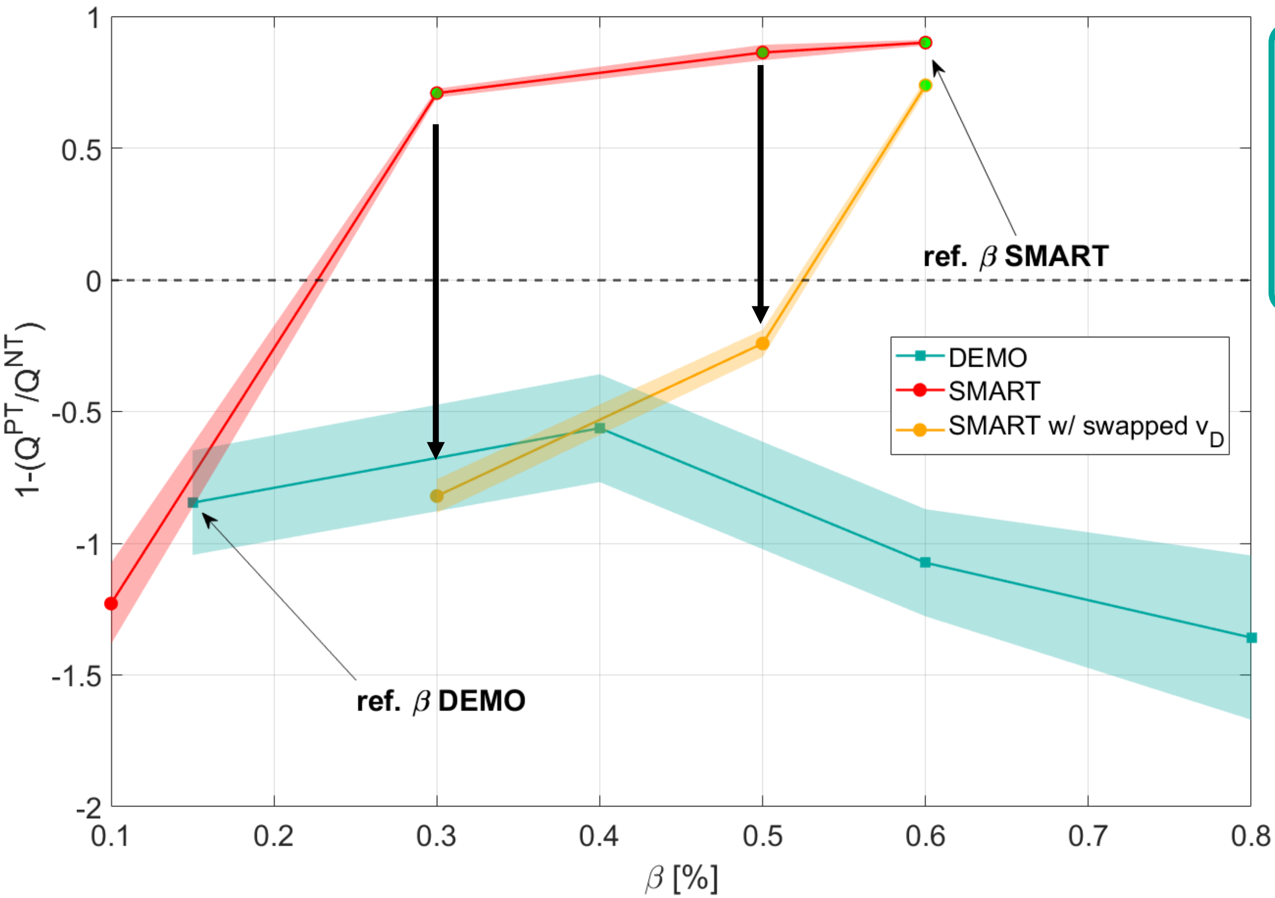
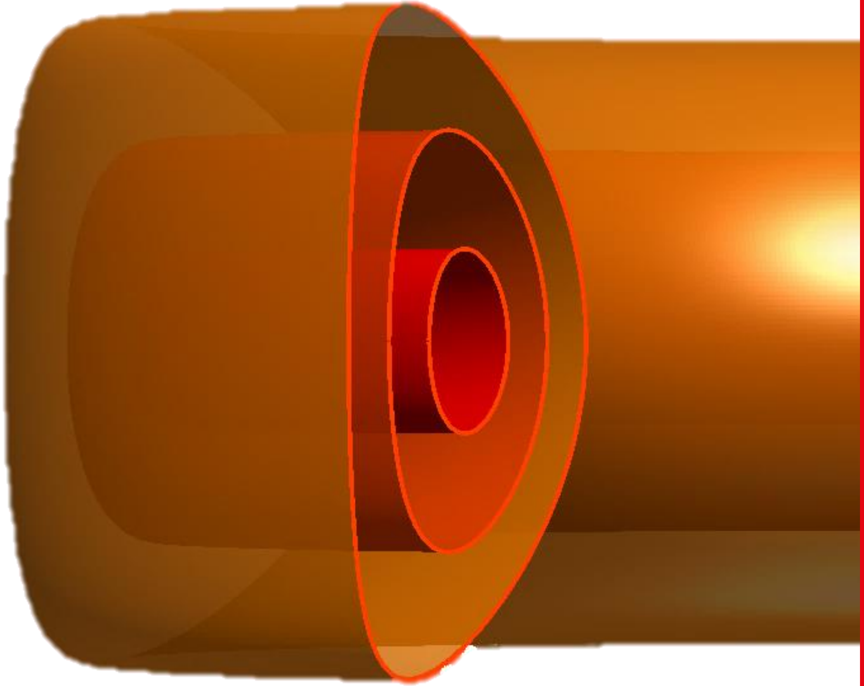
Realistic nonlinear simulations



Magnetic drift profile from PT imposed in NT SMART simulations

MTMs suppressed for $\beta = 0.3\%$ and $\beta = 0.5\%$

Physical model valid even in more realistic scenarios

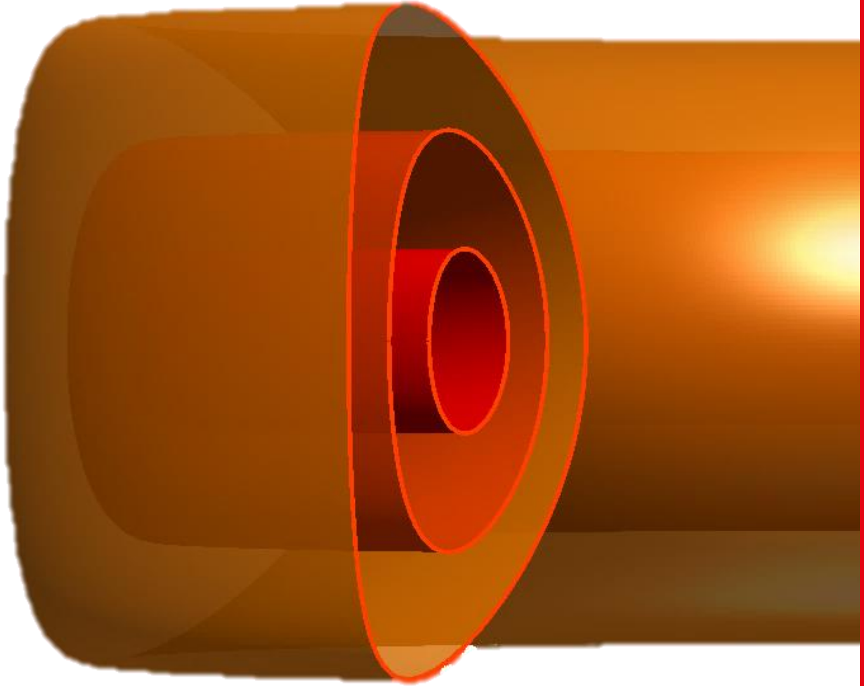


Conclusions

Summary & Conclusions

- NT is more sensitive to MTMs than PT. When MTMs dominate, NT is much more unstable than PT
- Aspect ratio **does not** play a direct role in destabilizing MTMs in NT.
- To destabilize MTMs in NT we need large β **AND** large $\hat{s}$ **AND** large electron temperature gradient.
- These conditions can be met only in STs. Should not be an issue in conventional A tokamaks.
- MTMs are more unstable in NT than in PT because of faster magnetic drift velocities

Thank you!



Backup slides

Where does geometry enter the gyrokinetic equation?

$$\frac{\partial g}{\partial t} = L[g] + N[g] \quad + \text{GK Maxwell's equations}$$

Drive term

Pressure term

Parallel advection term

$$L[g] = \left(\omega_n + \left(v_\parallel^2 + \mu B_0 - \frac{3}{2}\right)\omega_{T\sigma}\right) F_{0\sigma} i k_y \bar{\chi} - \frac{\beta T_{0\sigma}}{q_\sigma B_0^2} v_\parallel^2 \omega_P \Gamma_{\sigma y} - \frac{v_{T\sigma}}{J B_0} v_\parallel \Gamma_{\sigma z}$$

$$+ \frac{T_{0\sigma}(2v_\parallel^2 + \mu B_0)}{q_\sigma B_0}\left(v_{Dy}\Gamma_{\sigma y} + v_{Dx}\Gamma_{\sigma x}\right) + \frac{v_{T\sigma}}{2JB}\partial_z B_0 \mu \frac{\partial f_\sigma}{\partial v_\parallel} + \langle C_\sigma(f)\rangle$$

Curvature terms

Trapping term

Collisions

$$N[g] = -\sum_{\mathbf{k}'_\perp} \left(k'_x k_y - k_x k'_y\right)\bar{\chi}(\mathbf{k}'_\perp)\,(\mathbf{k}_\perp - \mathbf{k}'_\perp)$$

$$\bar{\chi} = J_0(k_\perp \rho_i)\chi$$

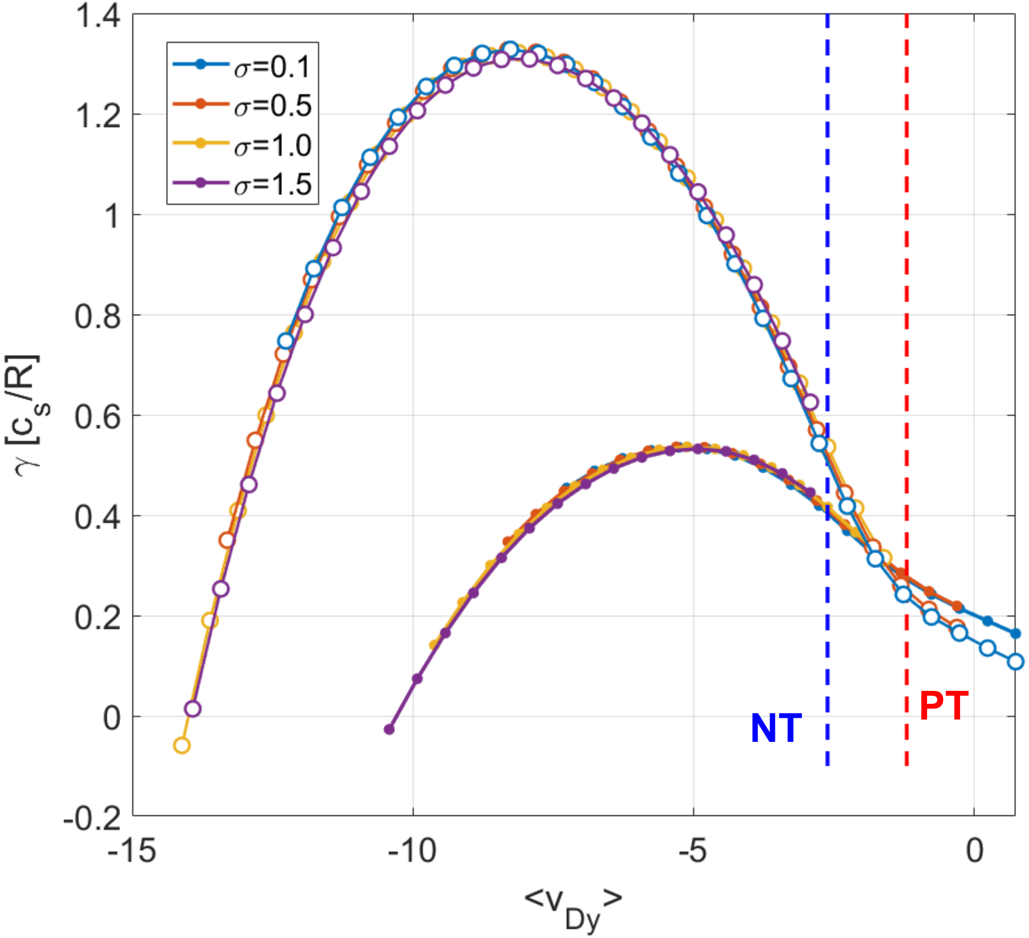
FLR effects from gyroaverage operator

$$k_\perp = (\nabla x \cdot \nabla x)k_x^2 + 2(\nabla x \cdot \nabla y)k_x k_y + (\nabla y \cdot \nabla y)k_y^2$$

Magnetic drift scan in pMTM regime

MTMs sensitive only to average magnetic drift velocity.

This penalizes NT against PT.



Magnetic drift scan in pMTM regime

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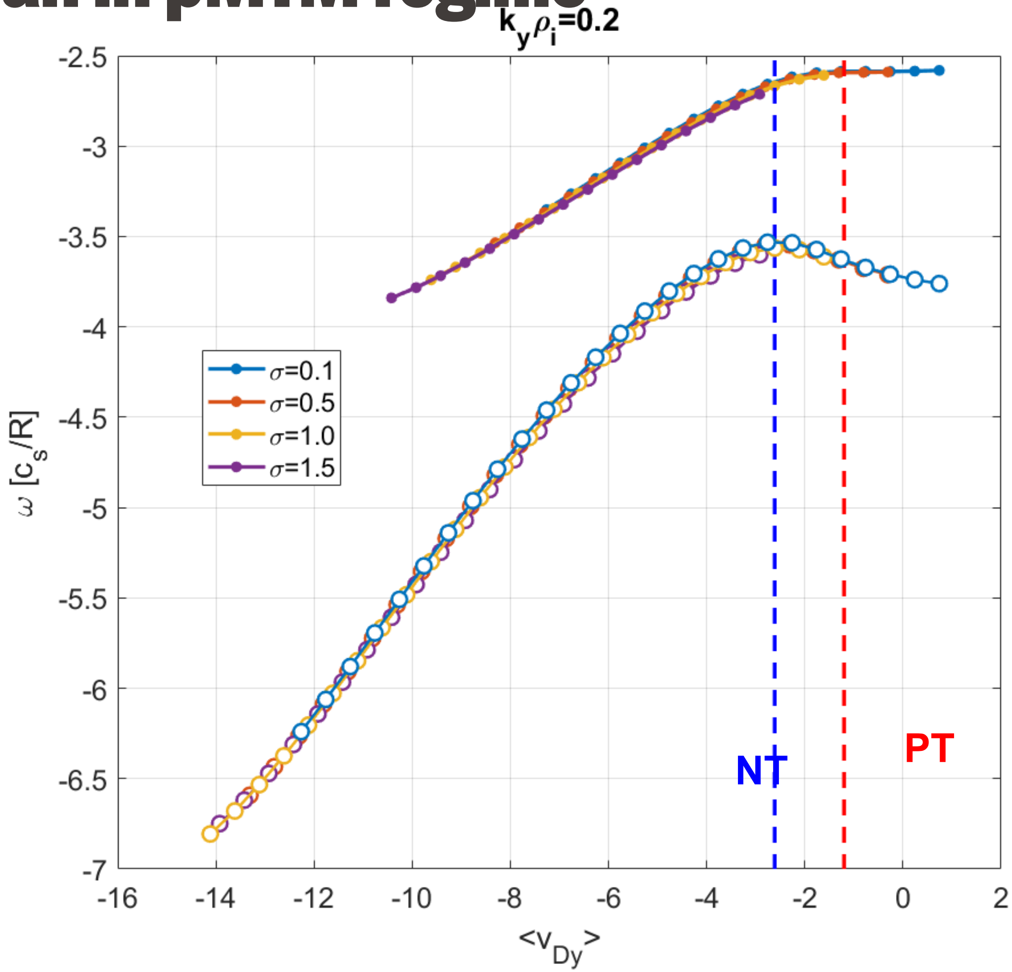
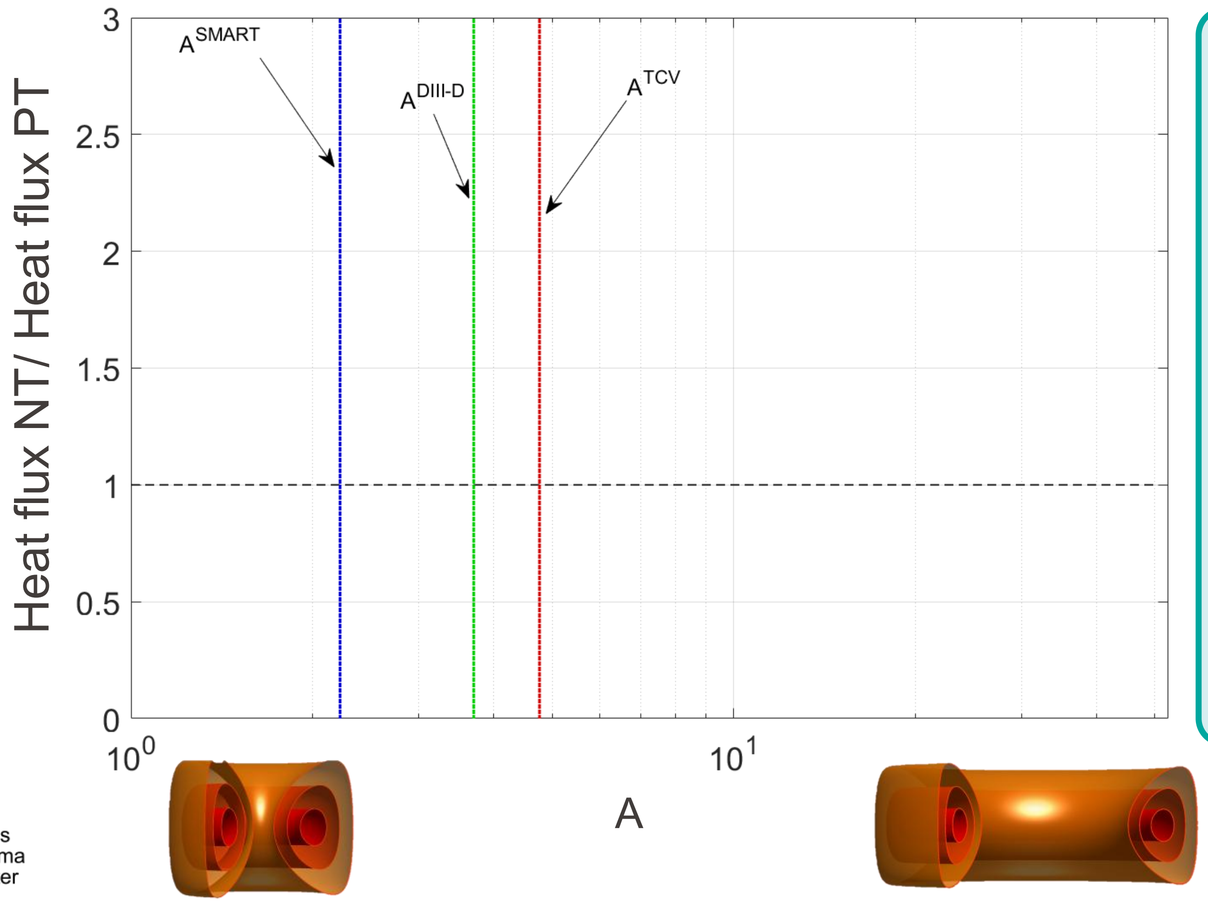


Aspect ratio scan

[1] D. J. Cruz-Zabala et al., 2024 NF 64 126071

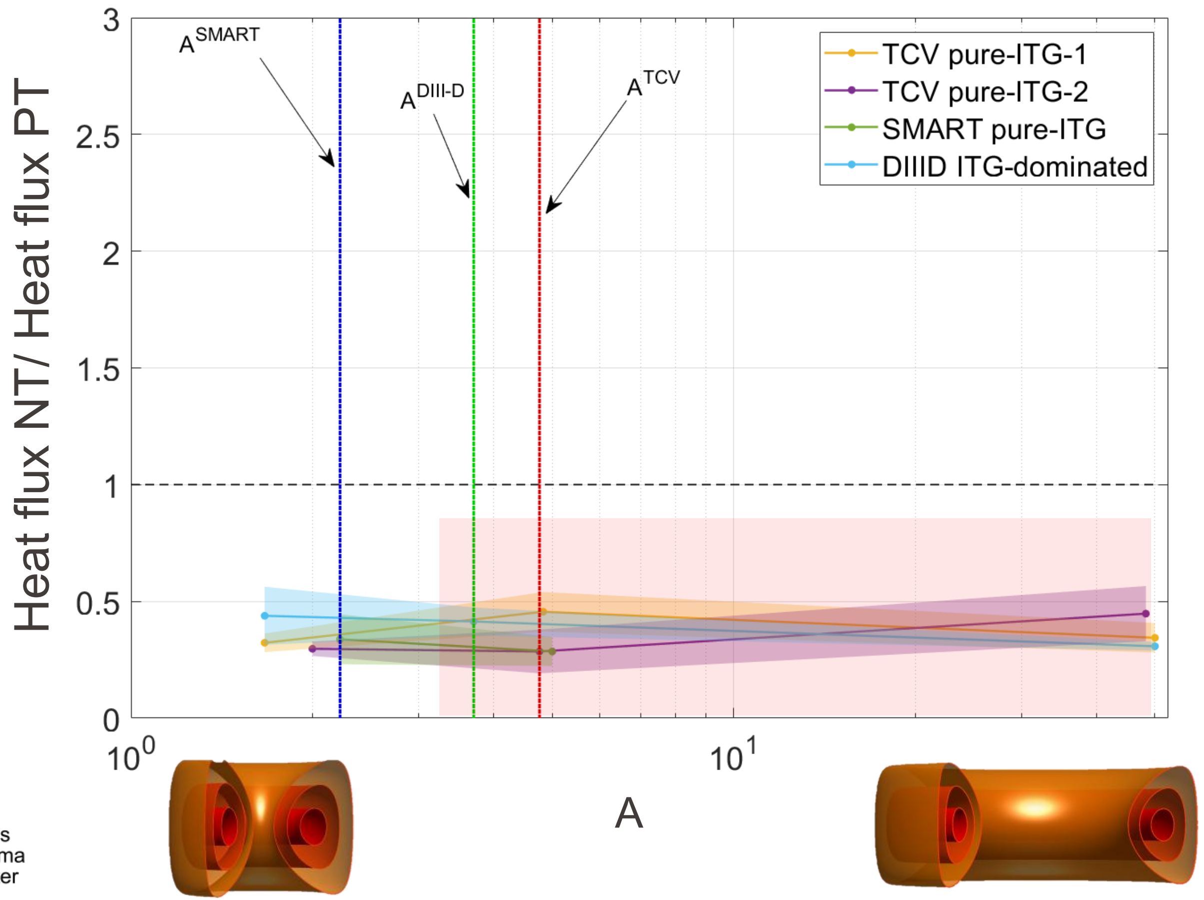


Flux-tube ($\rho_{tor} = 0.85$) nonlinear gradient-driven GENE simulations

Aspect ratio (A) artificially changed from reference TCV, DIII-D and SMART [1] scenarios

Aspect ratio scan

[1] A. Balestri et al., 2024 PPCF 66 075012



ITG regimes

↓

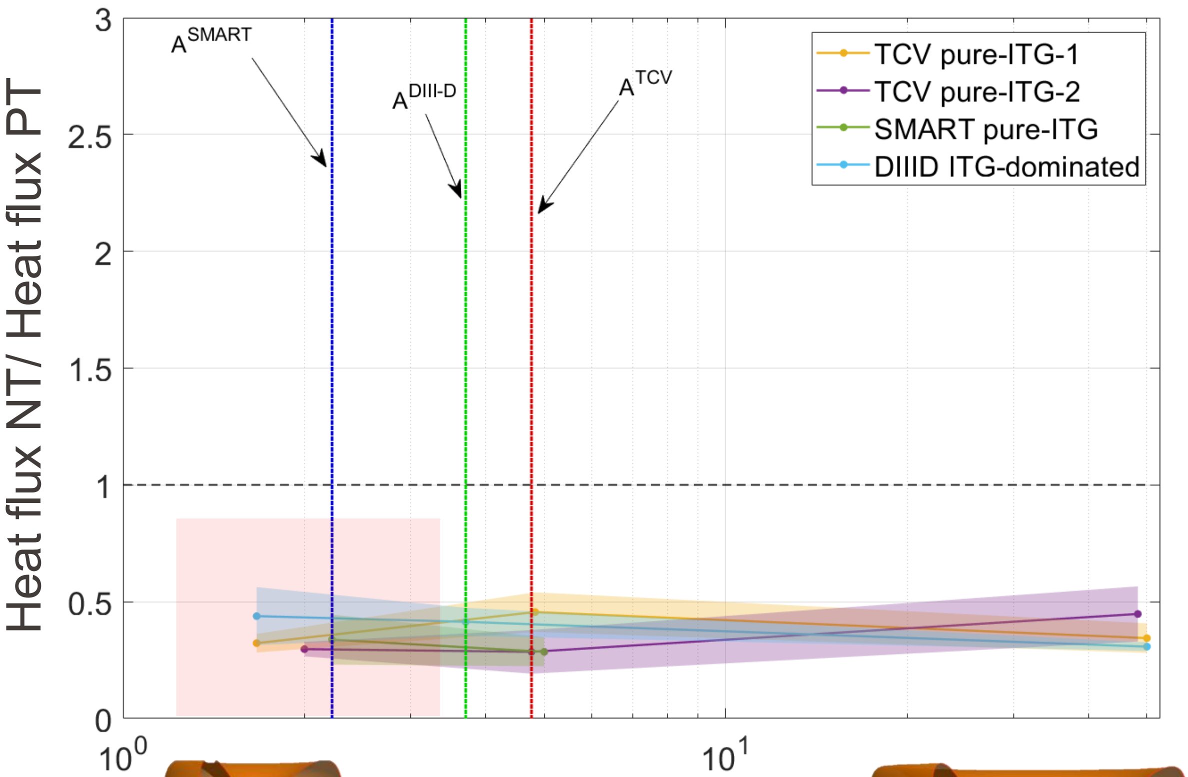
NT has always better confinement than PT

- Stronger FLR effects around the outboard midplane (LFS) [1]
- Faster magnetic drifts around the outboard midplane (LFS) [1]

Swiss Plasma Center

Aspect ratio scan

[1] A. Balestri et al., 2024 PPCF 66 075012



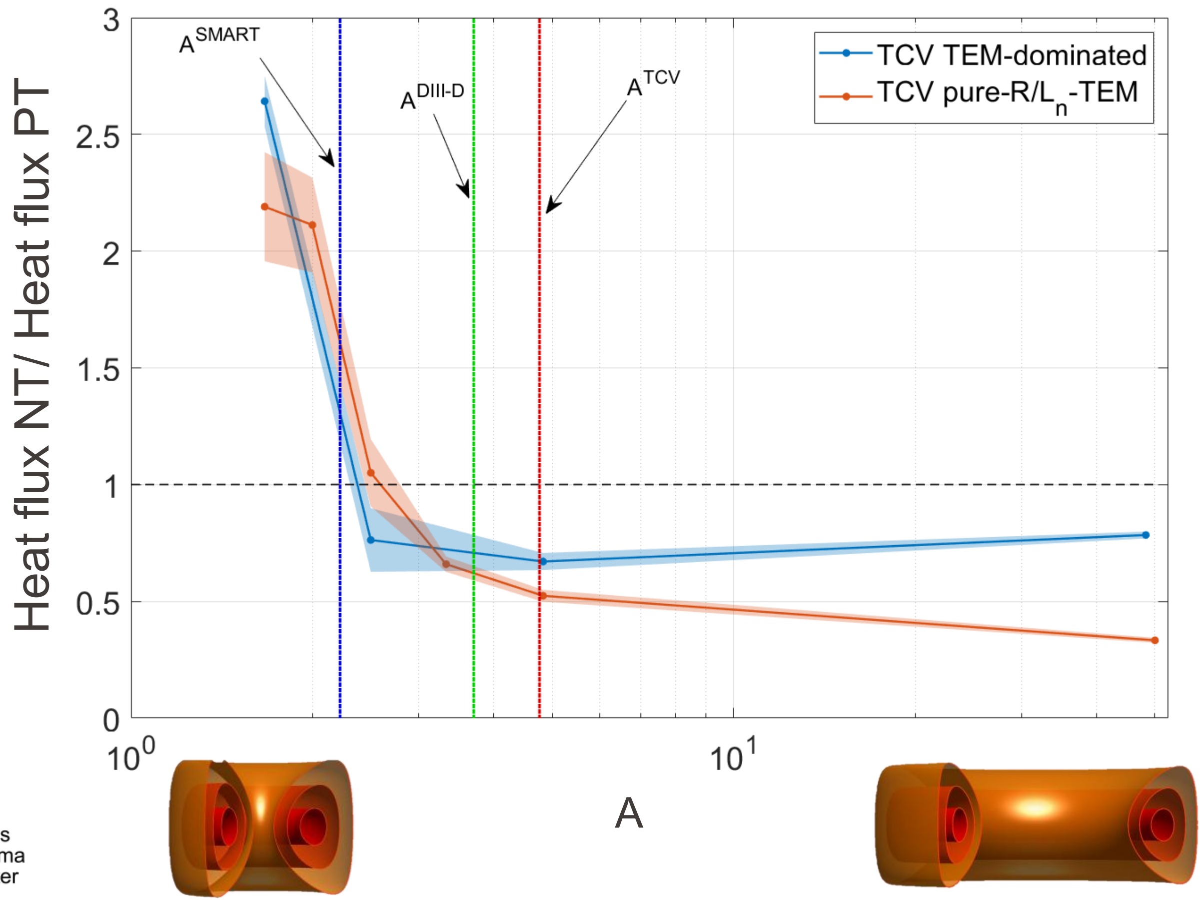
ITG regimes

↓

NT has always better confinement than PT

Still unclear, strong nonlinear interaction between magnetic drifts, FLR effect and parallel dynamics

Aspect ratio scan



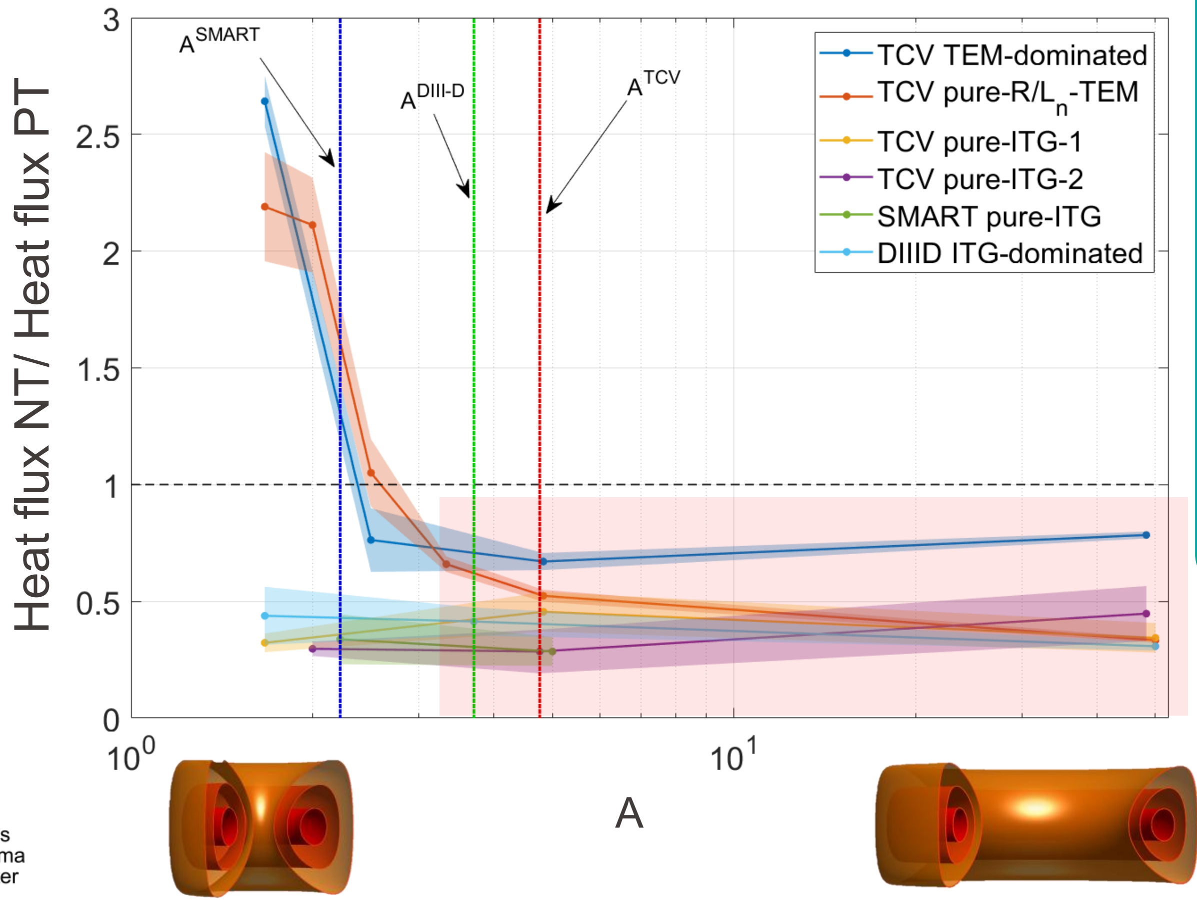
TEM regimes

↓

NT better than PT at large and conventional A.

NT worse at small A.

Aspect ratio scan



Conventional and large A tokamak

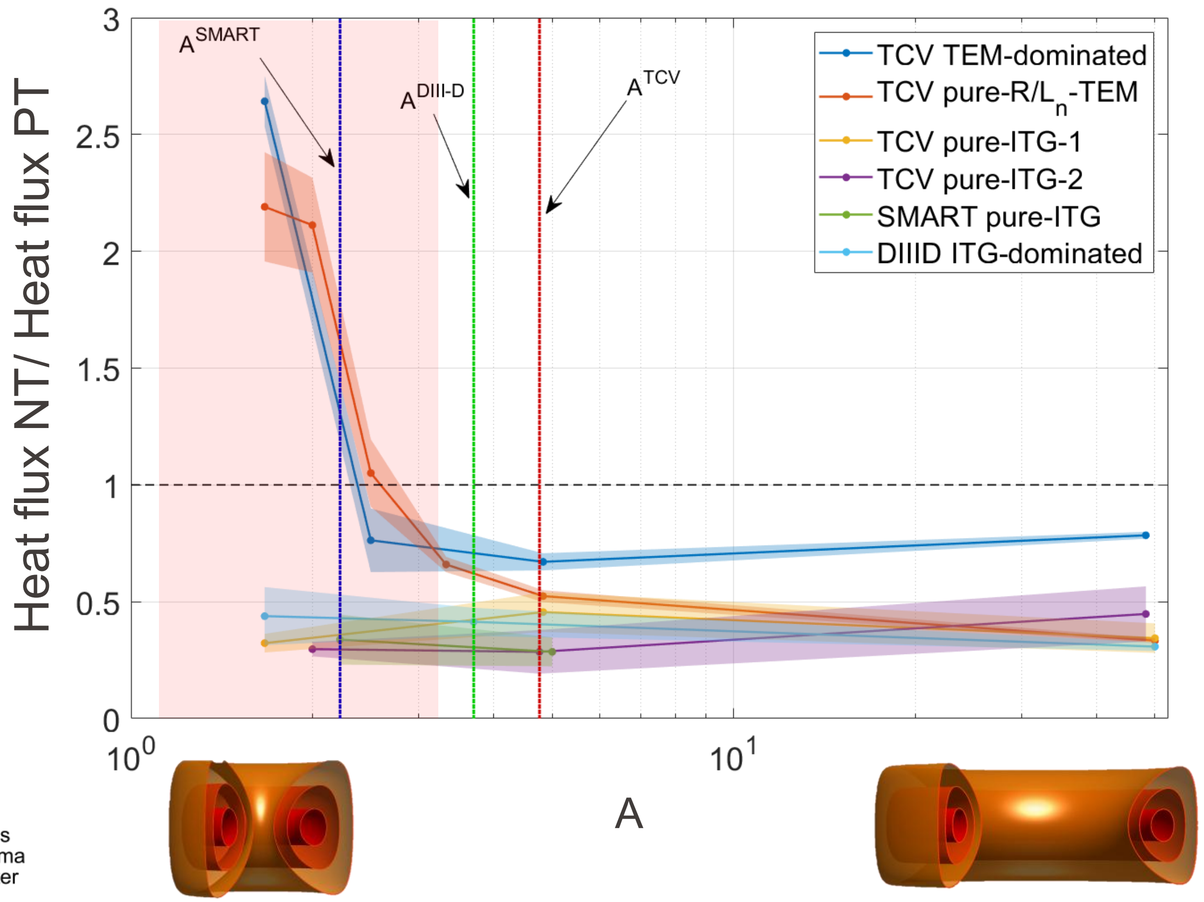
↓

NT has better confinement than PT in ITG and TEM regimes.

Consistent with previous works [1-6] and experimental results on TCV and DIII-D

[1] A. Marinoni et al., 2009 PPCF 51 055016
[2] G. Merlo et al., 2015 PPCF 57 054010
[3] G. Merlo et al, 2023 PoP 30 102302
[4] A. Mariani et al., 2024 NF 64 046018
[5] G. Di Giannatale et al., 2024 PPCF 66 095003
[6] A. Balestri et al., 2024 PPCF 66 065031

Aspect ratio scan



Spherical Tokamak

↓

First observations that NT better than PT in ITG regimes and worse in TEM dominated ones

Experimental activity on SMART fundamental to validate predictions

EPFL

Magnetic drift scan in pITG regime

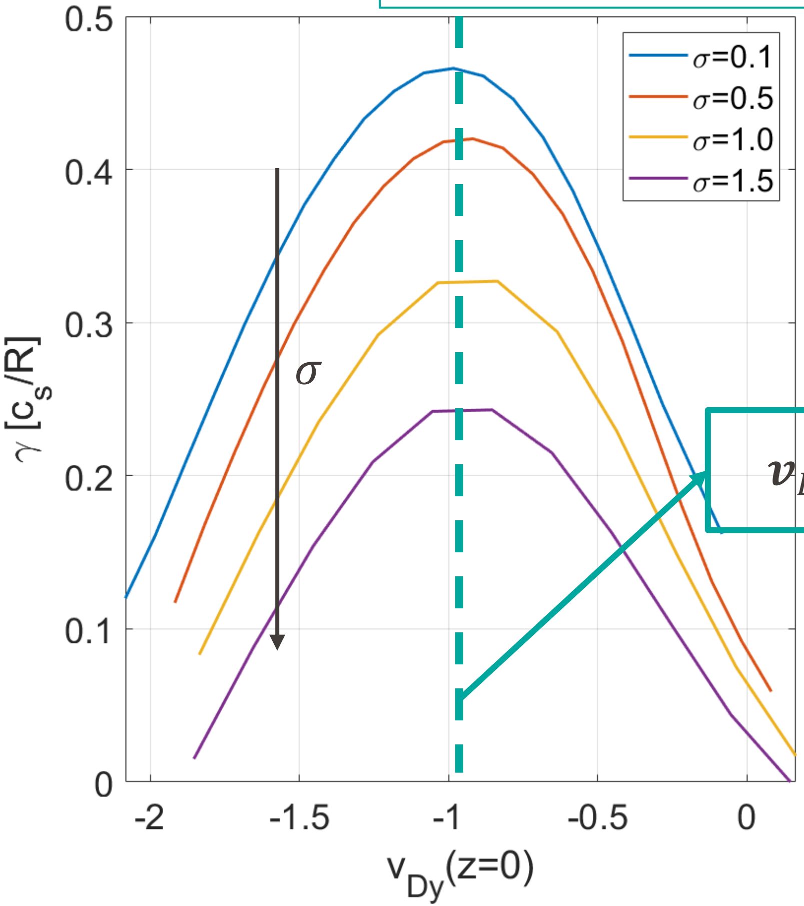
[1] M. Beer, *Gyrofluid models of turbulent transport in tokamaks"*, Ph.D. Thesis (1994)

- Existence of a "rollover" point.
- Growth rates decrease with increasing variation of v_{Dy}.

Faster magnetic drifts wrt. the rollover point imply more stable modes

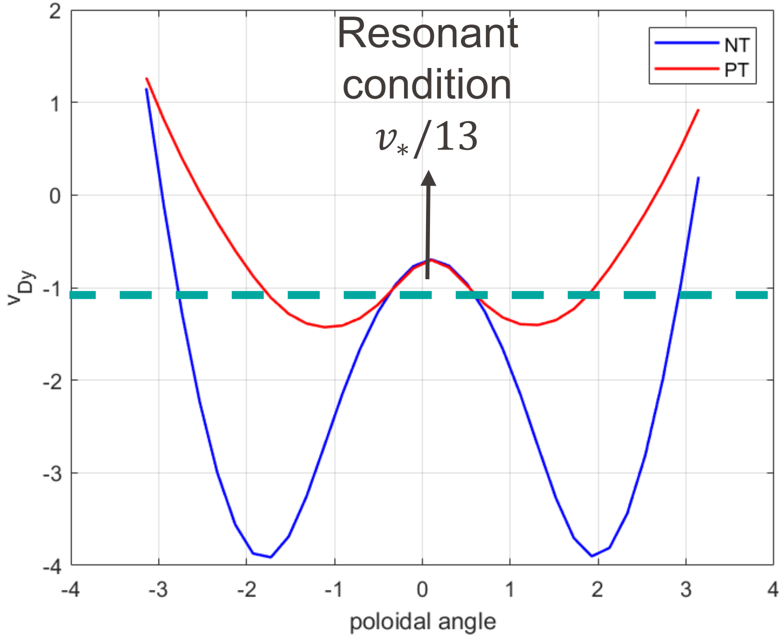
In agreement with [1], where the maximum growth rate can be found when:

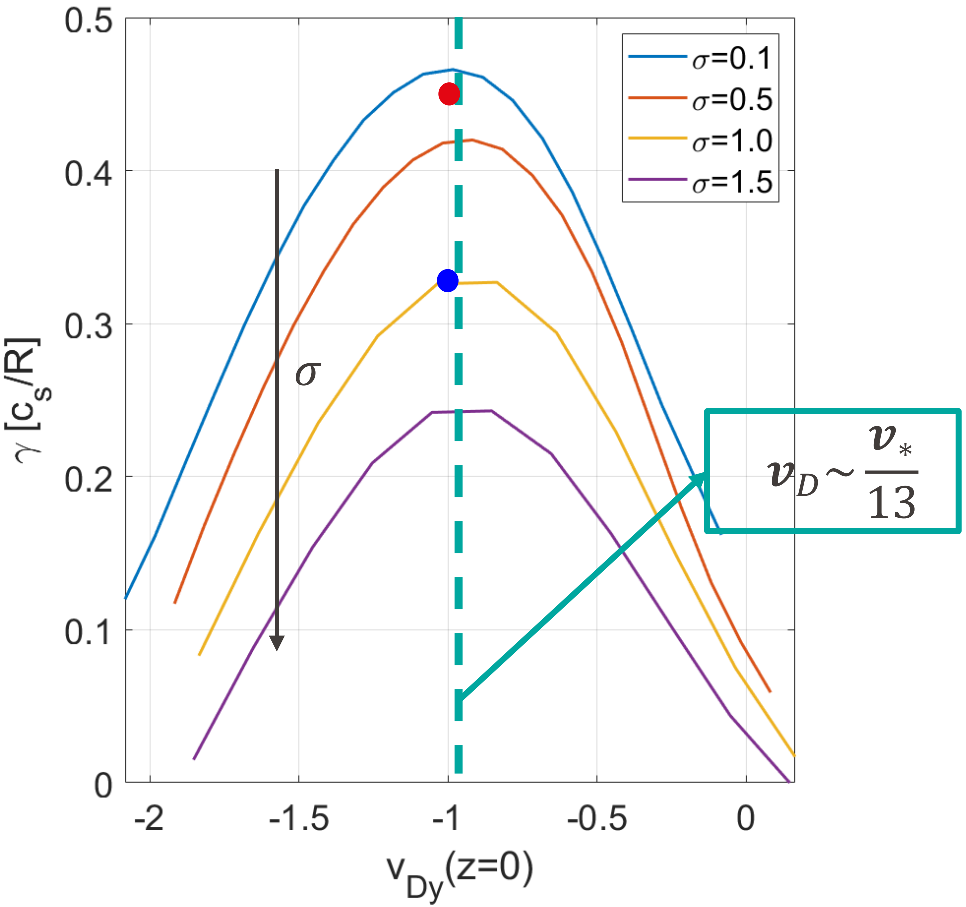
$$\gamma^{MAX} \Leftrightarrow v_D = \frac{v_*}{4}$$



$v_D \sim \frac{v_*}{13}$

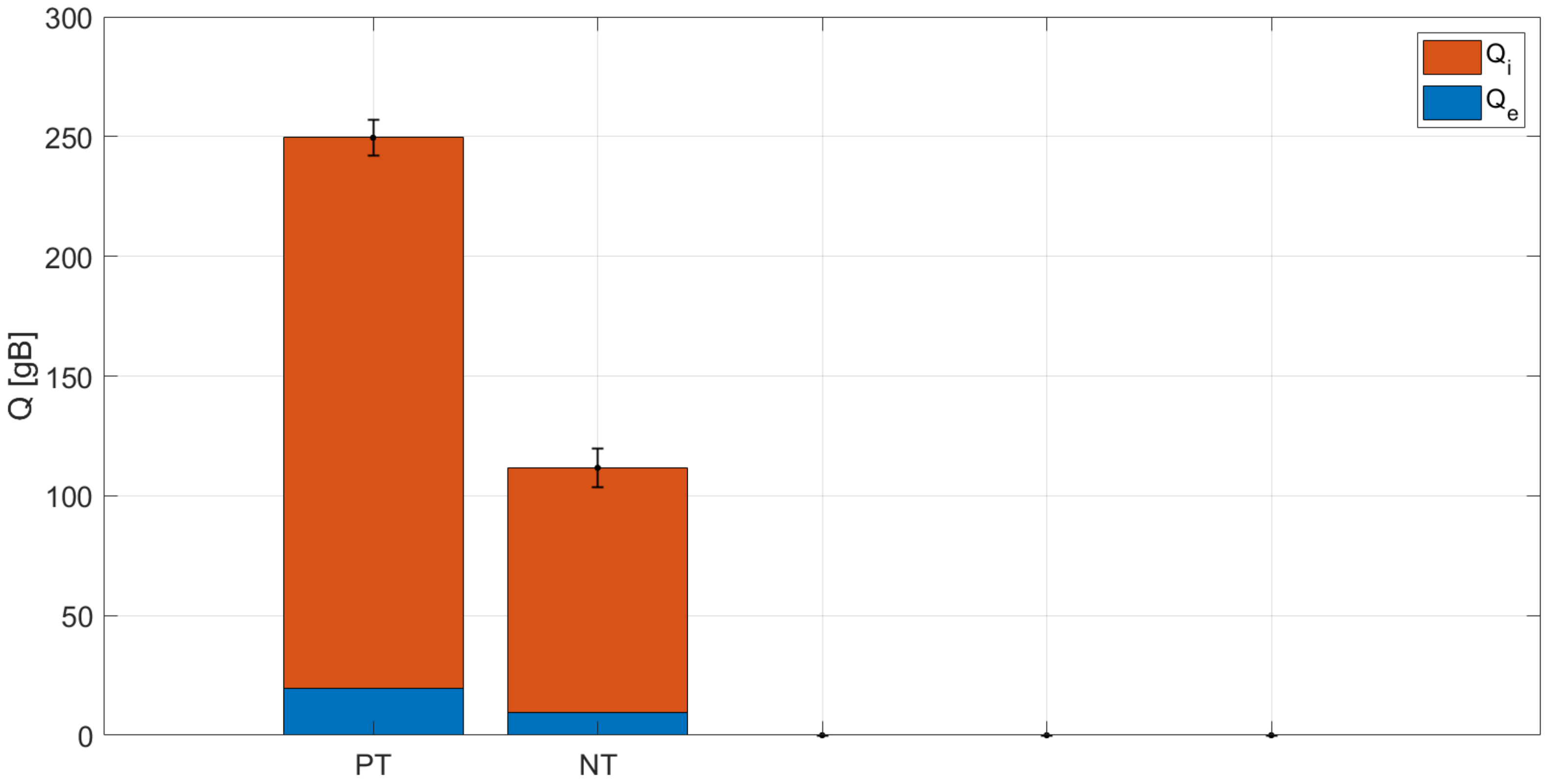
Magnetic drift scan in pITG regime



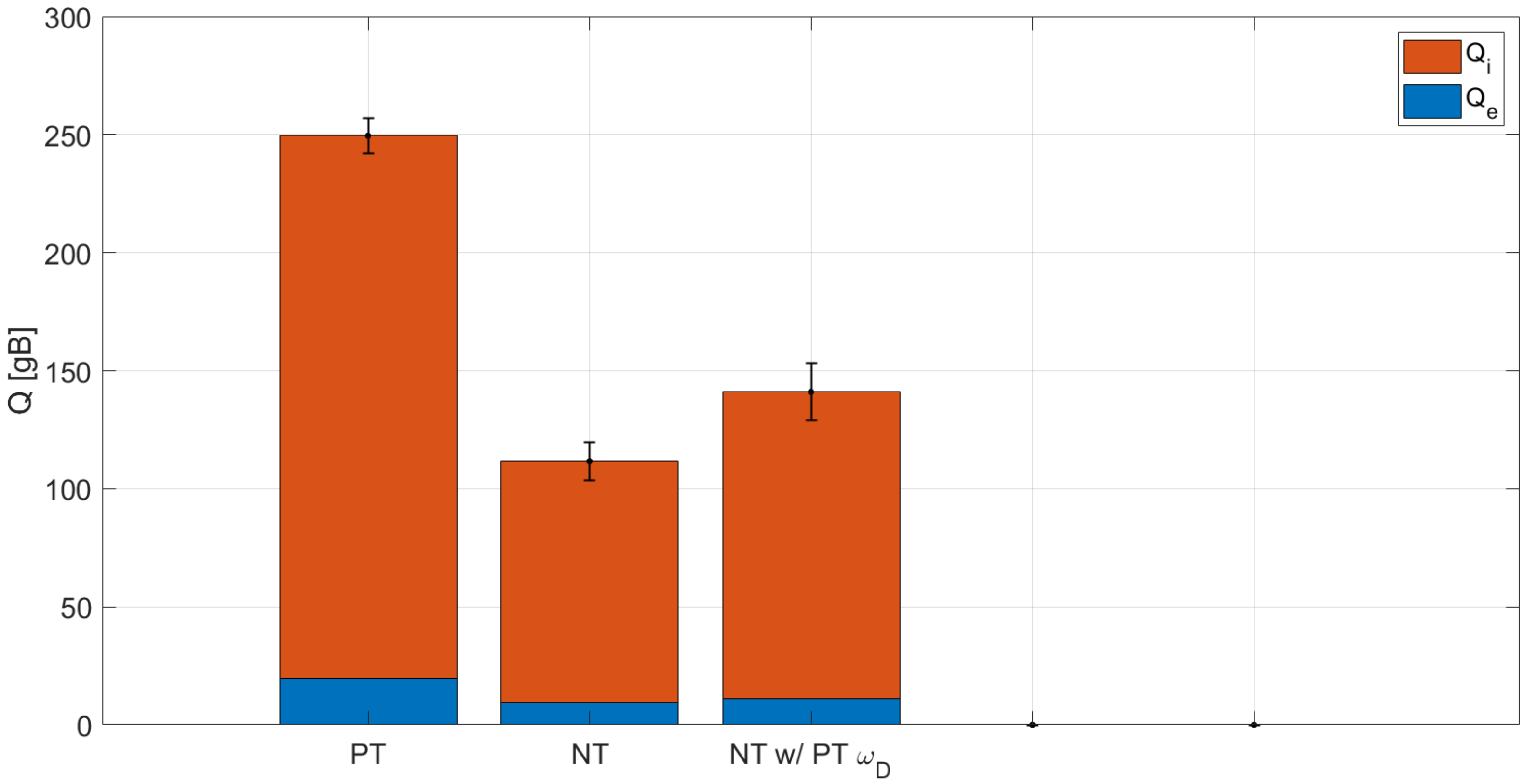


NT makes the ions drift faster, causing a mismatch between v_D and v_*. This pushes the ITG away from the resonant condition

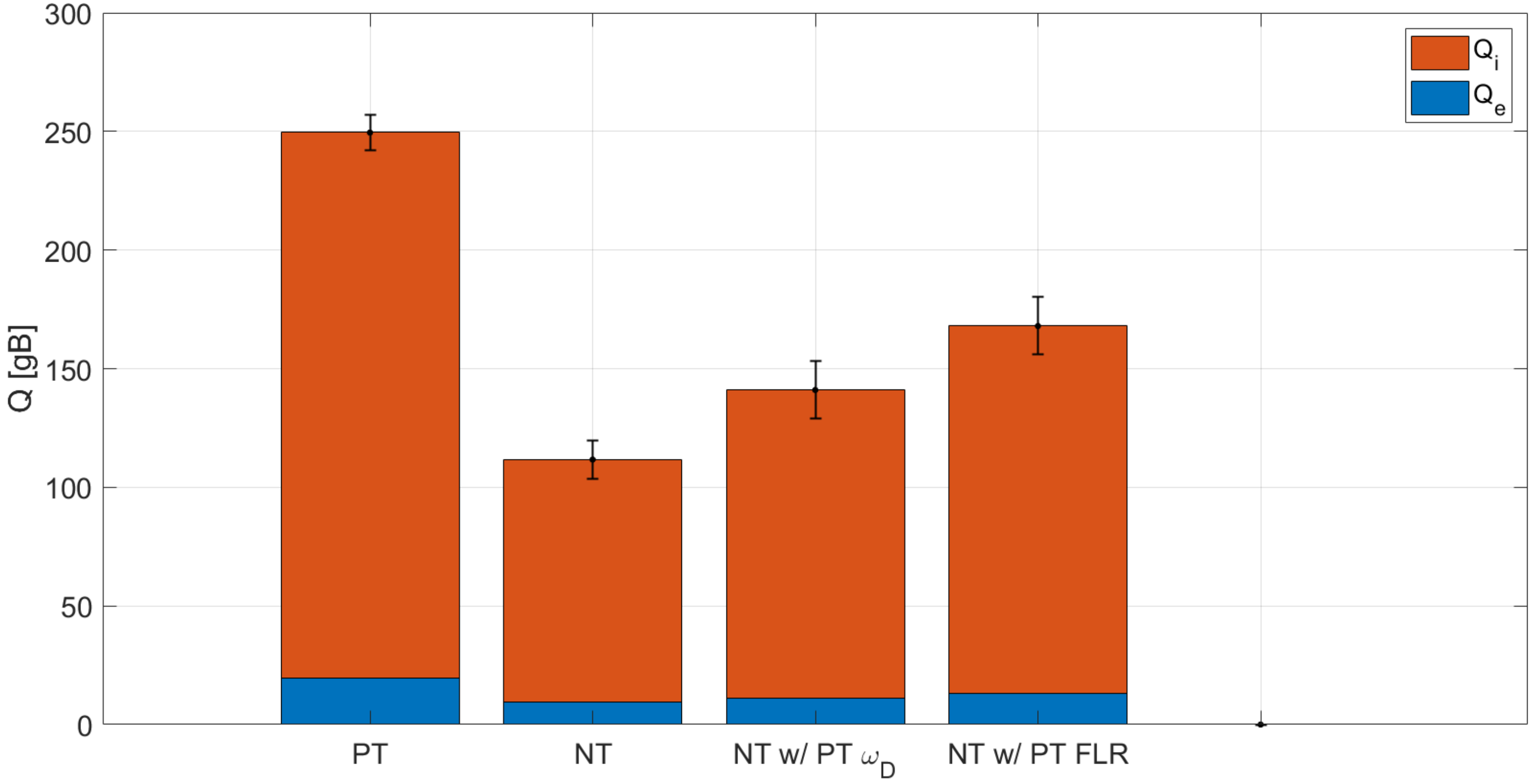
NL simulations – Large A pITG



NL simulations – Large A pITG



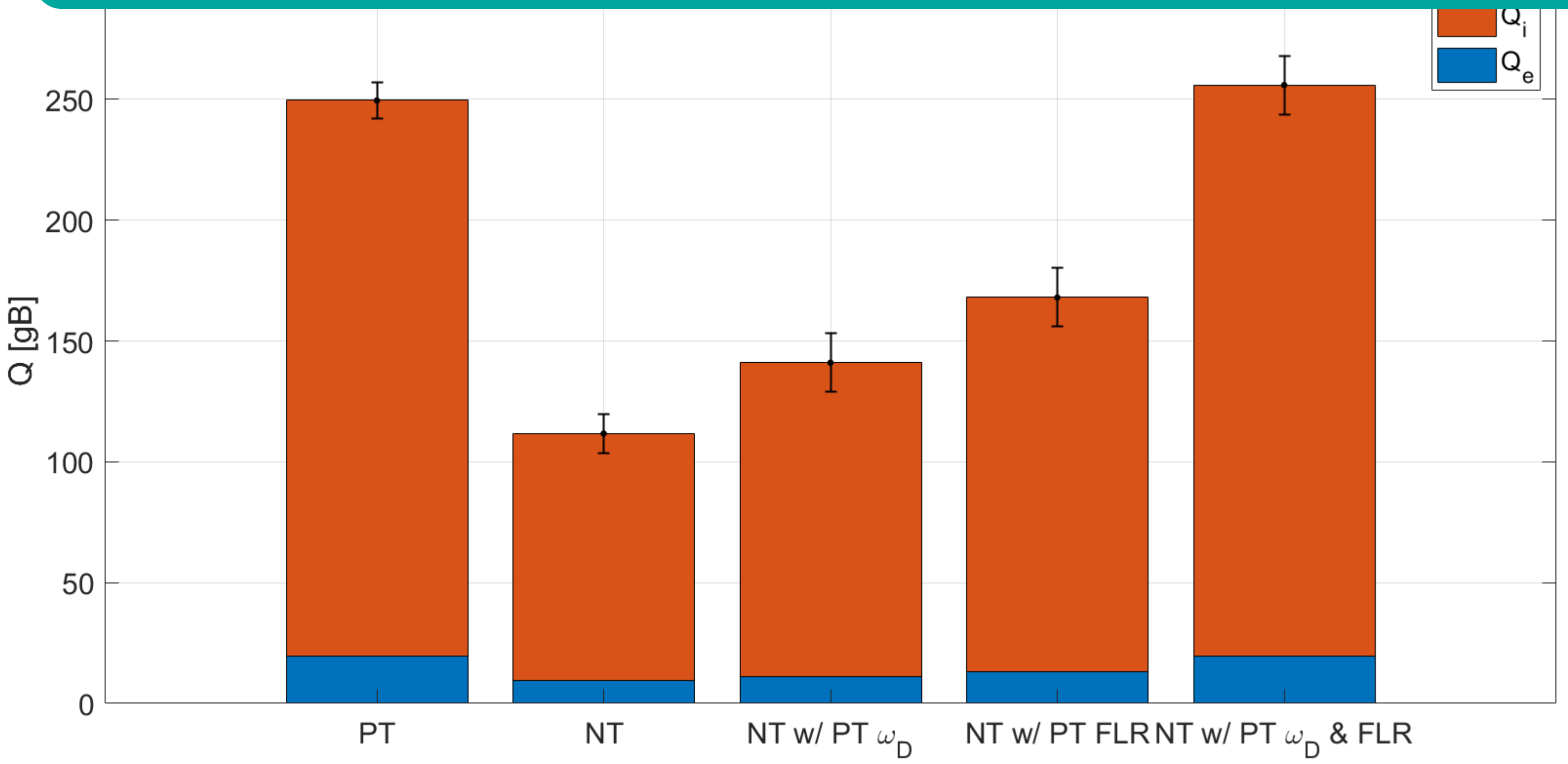
NL simulations – Large A pITG



EPFL

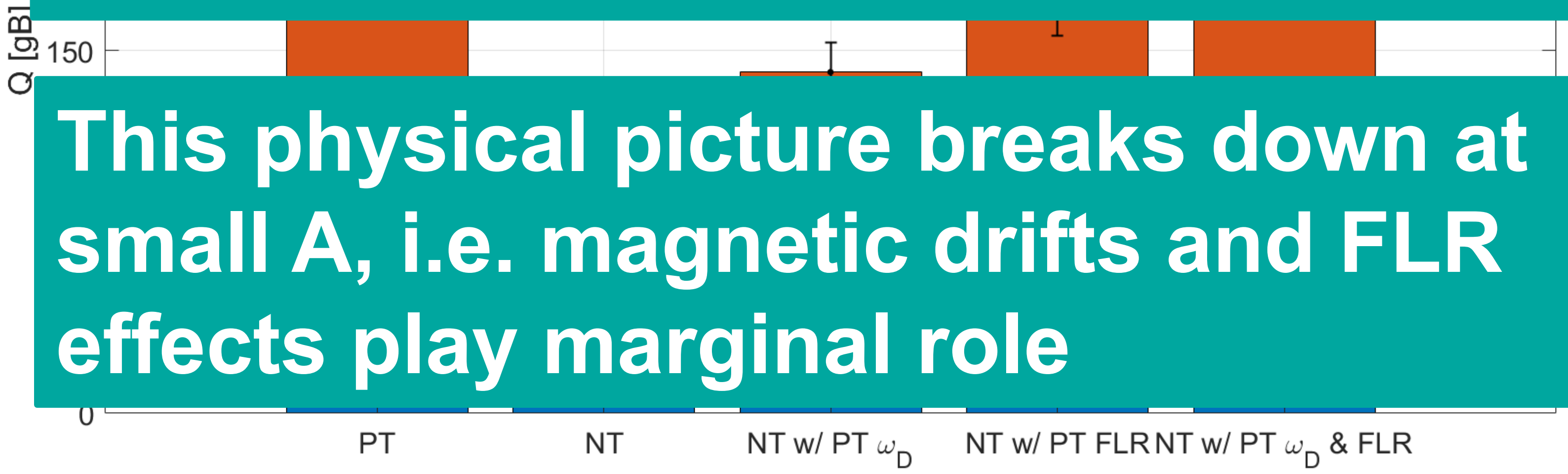
NL simulations – Large A pITG

We can conclude that faster magnetic drifts and stronger FLR effects are the **only** responsible for the reduction of ITG turbulence at large A in NT



NL simulations – Large A pITG

The same observations hold for conventional A, i.e. faster magnetic drifts and stronger FLR effects cause the reduction of ITGs in NT



This physical picture breaks down at small A, i.e. magnetic drifts and FLR effects play marginal role