



Understanding TEMs in negative triangularity plasmas

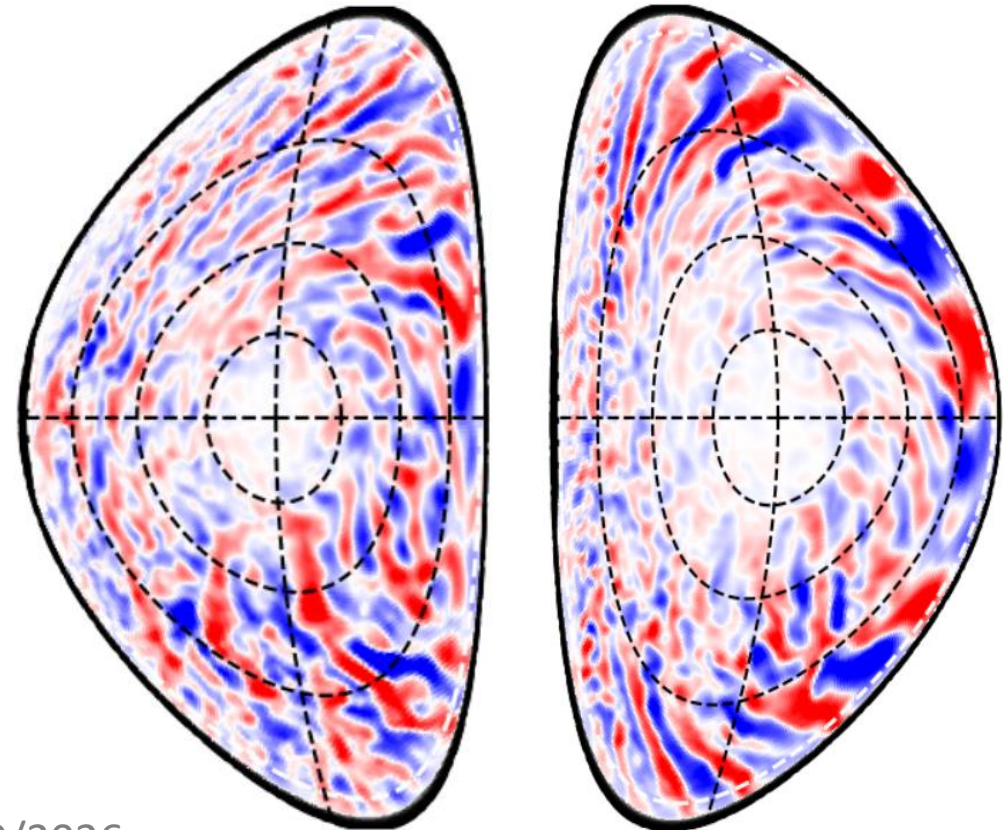
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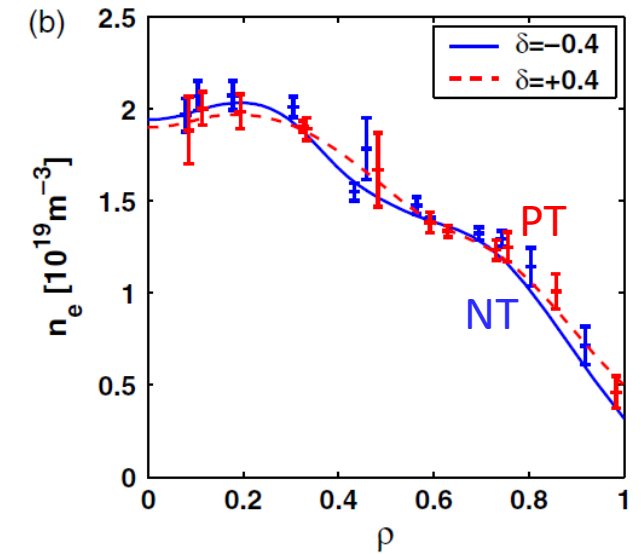
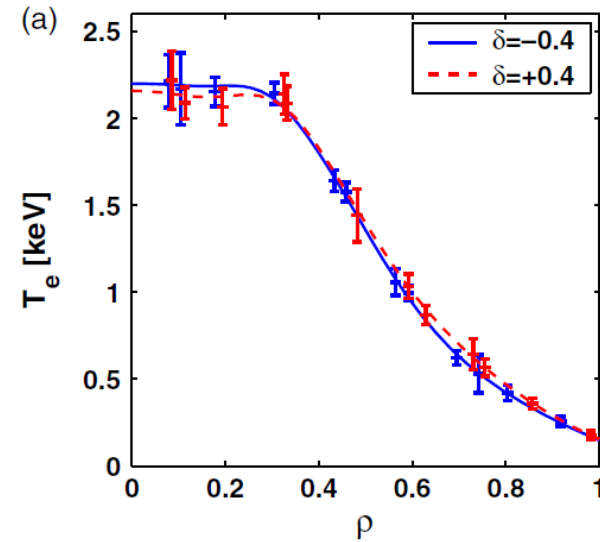
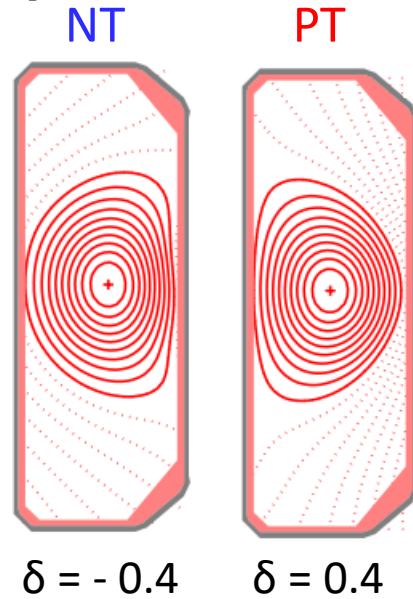


OUTLINE

- Introduction and motivations
- **Study of trapped electron modes in NT:**
 - Linear stability analysis using a reduced model
 - Non linear analysis using the GK code GYSELA
- Conclusions and perspectives

CONFINEMENT IMPROVEMENT IN NEGATIVE TRIANGULARITY

[Camenen 07]



NT configuration requests **half the power** (ECRH) to get to the same plasma conditions of PT



Improved confinement
(confirmed with NBI heating)

H-MODE CONFINEMENT WITHOUT L -> H TRANSITION

ITER will operate in high confinement mode configuration (H-mode)

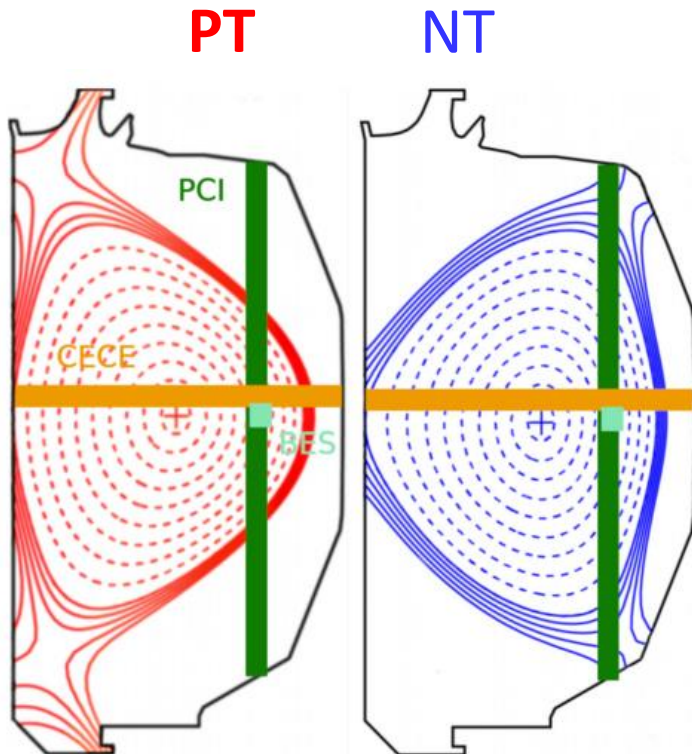


Prone to edge plasma instabilities (ELMs) and other issues (small width of the Scrape-Off-Layer)

Negative triangularity plasmas get to H-mode confinement level even being in **L-mode**



No edge instabilities

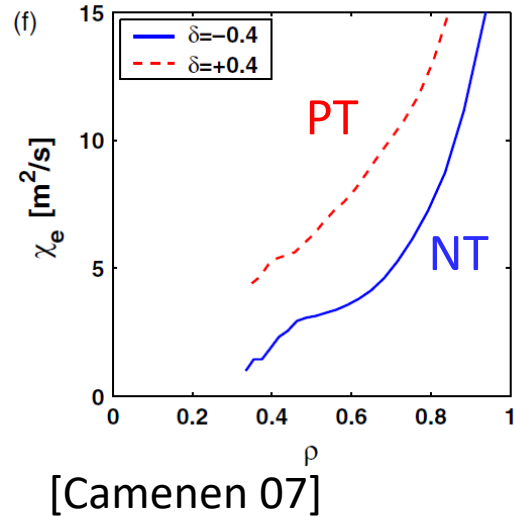


Transition not achieved or power threshold for H-mode higher

[Marinoni 19]

REDUCED TRANSPORT

$$Q_T = -N \chi_T \nabla T$$



NT heat fluxes and diffusion coefficients are **half** than PT ones

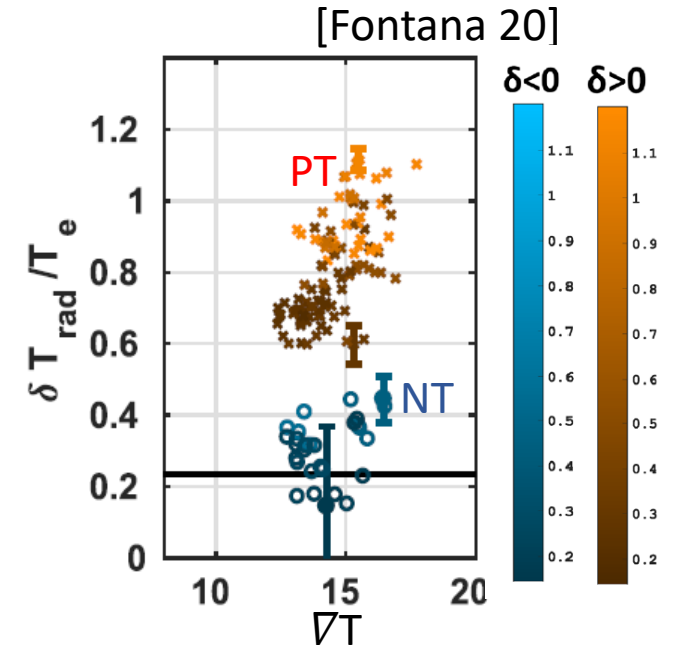
Transport is lower in NT than in PT plasmas

Dominated by **microinstabilities**, driven unstable by strong density or temperature gradients

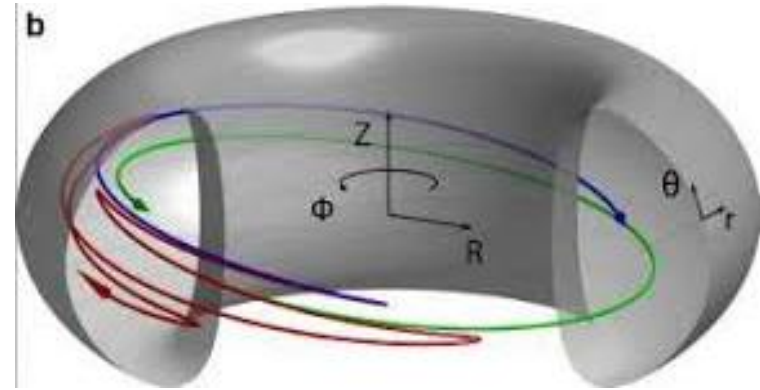
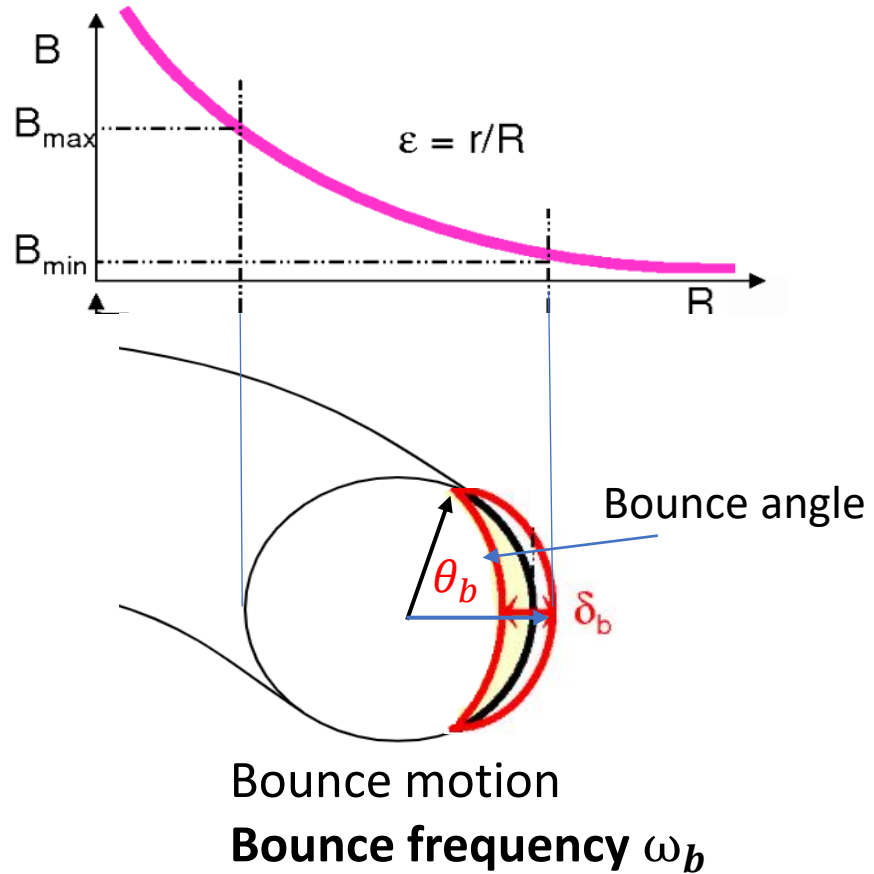
INTERPRETATION

stabilizing role of negative triangularity in the **electron channel**

Trapped electrons drive instability

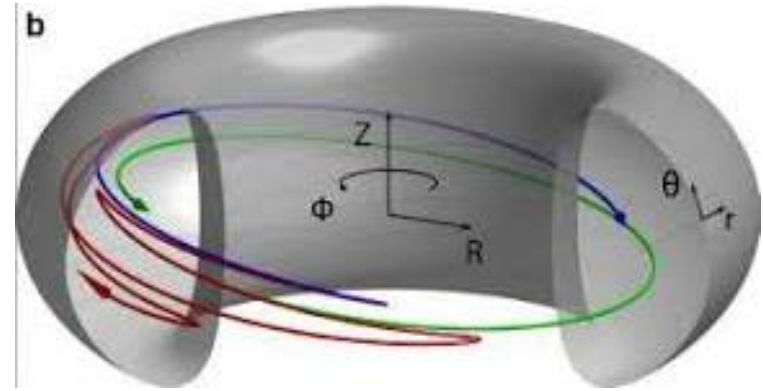
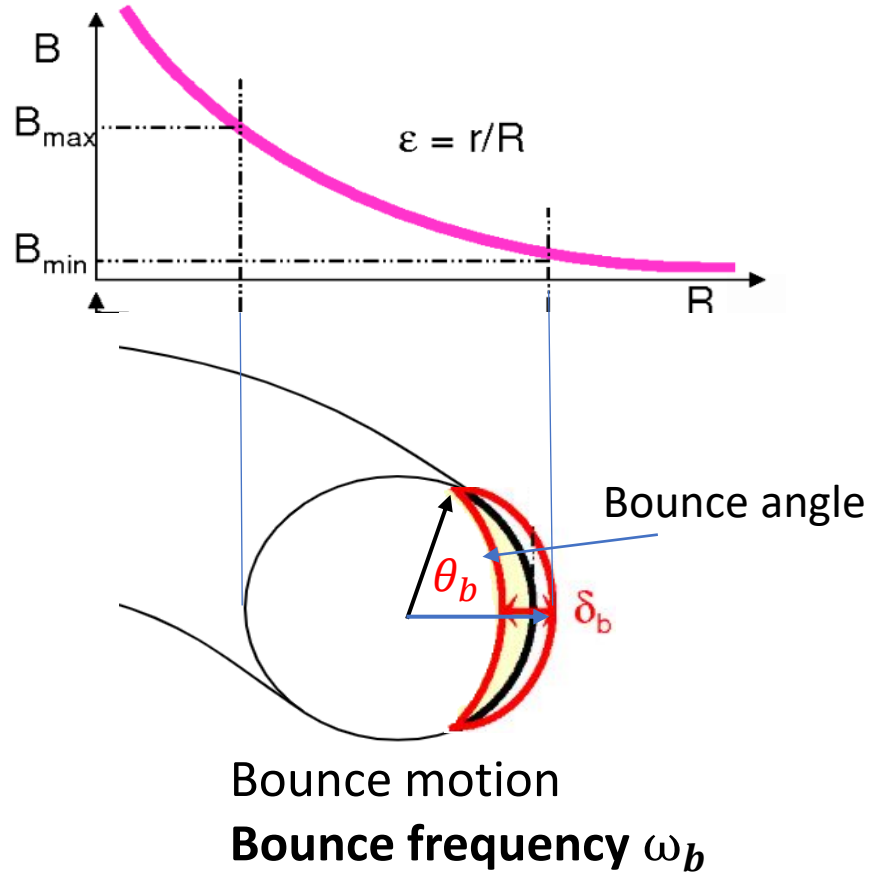


TRAPPED ELECTRONS



Trapped electrons **drift in the toroidal direction**
Precession frequency $\omega_d < \omega_b$

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TRAPPED ELECTRON MODES

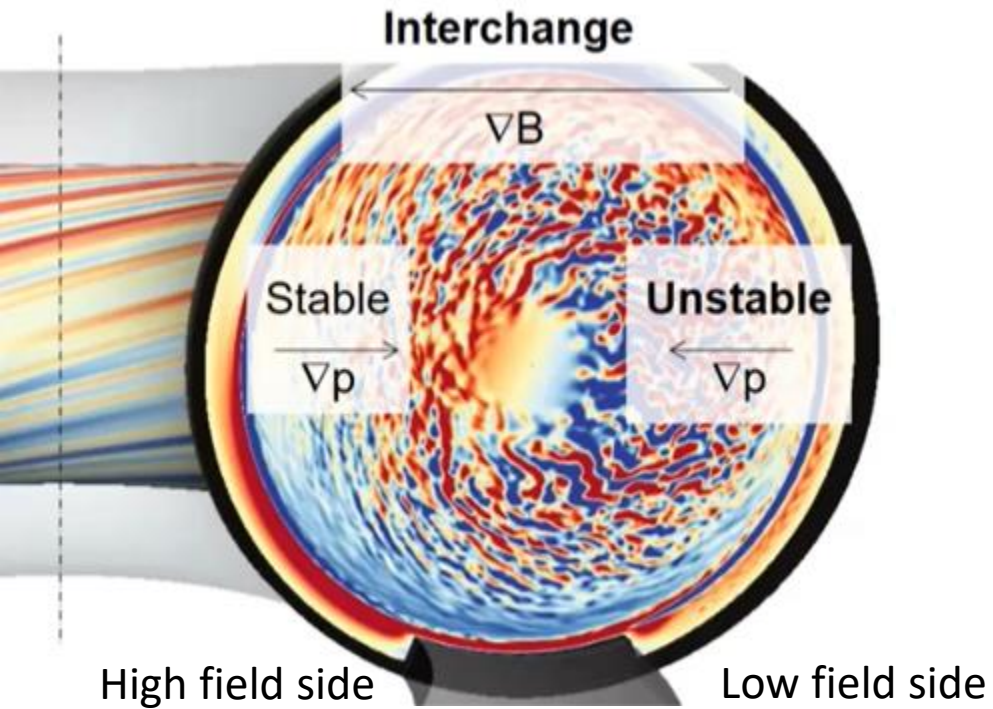
IMPORTANCE IN FUSION

- Electron heating commonly used : control
- Energetic ions heat electrons
- $T_e \geq T_i$ in a fusion reactor

TRAPPED ELECTRON MODES

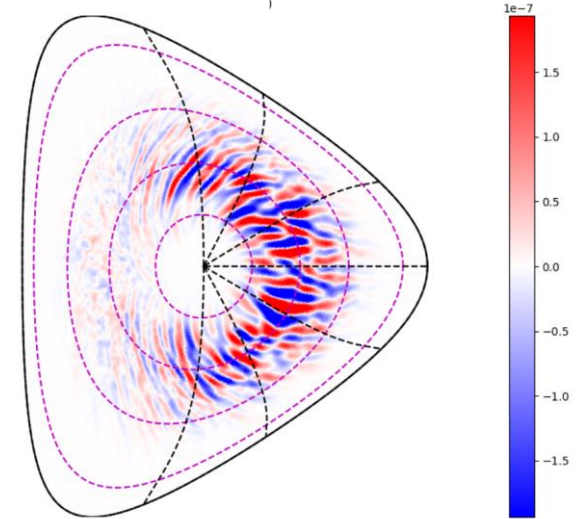
pressure gradients in an inhomogeneous B $\longrightarrow$ charge separation $\longrightarrow$ perturbation of the electrostatic potential

Rayleigh-Bénard $\nabla p \cdot \nabla B > 0$



BALLOONING

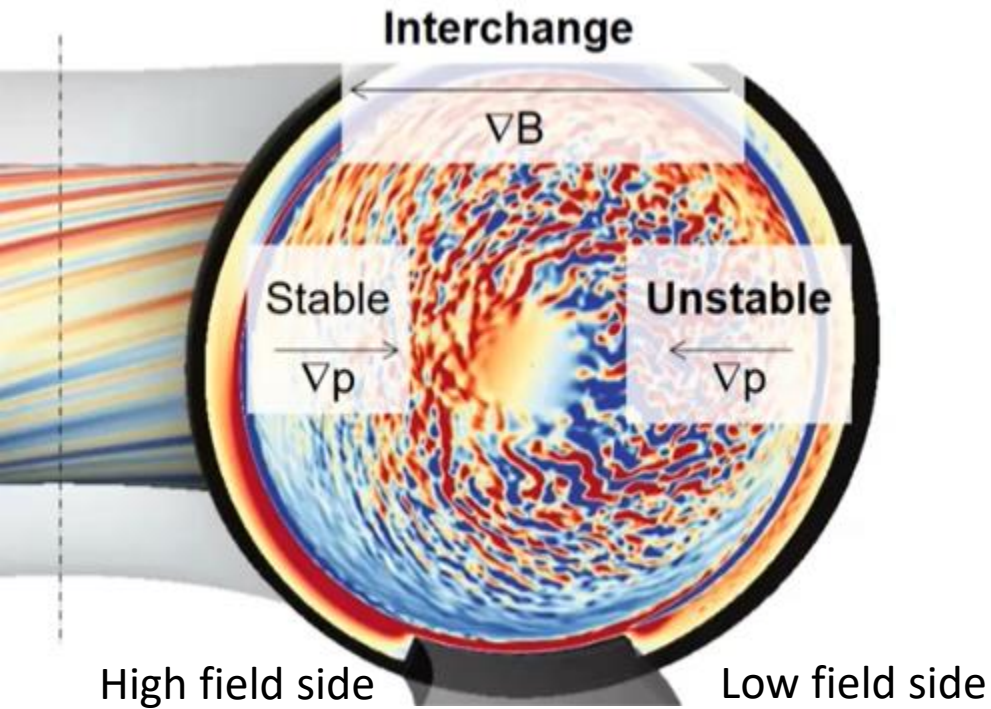
$\delta\Phi_{n \neq 0}$



TRAPPED ELECTRON MODES

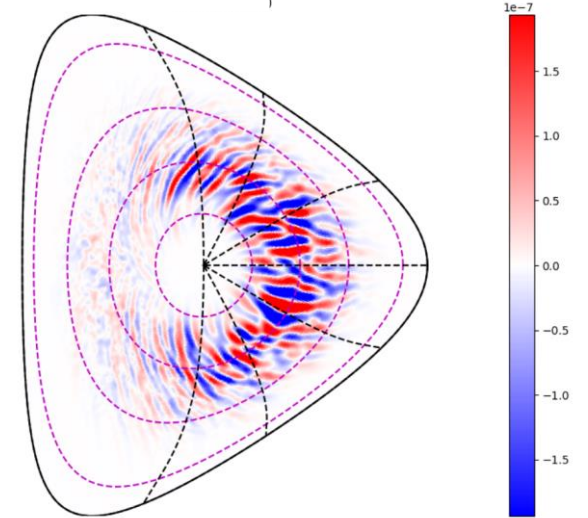
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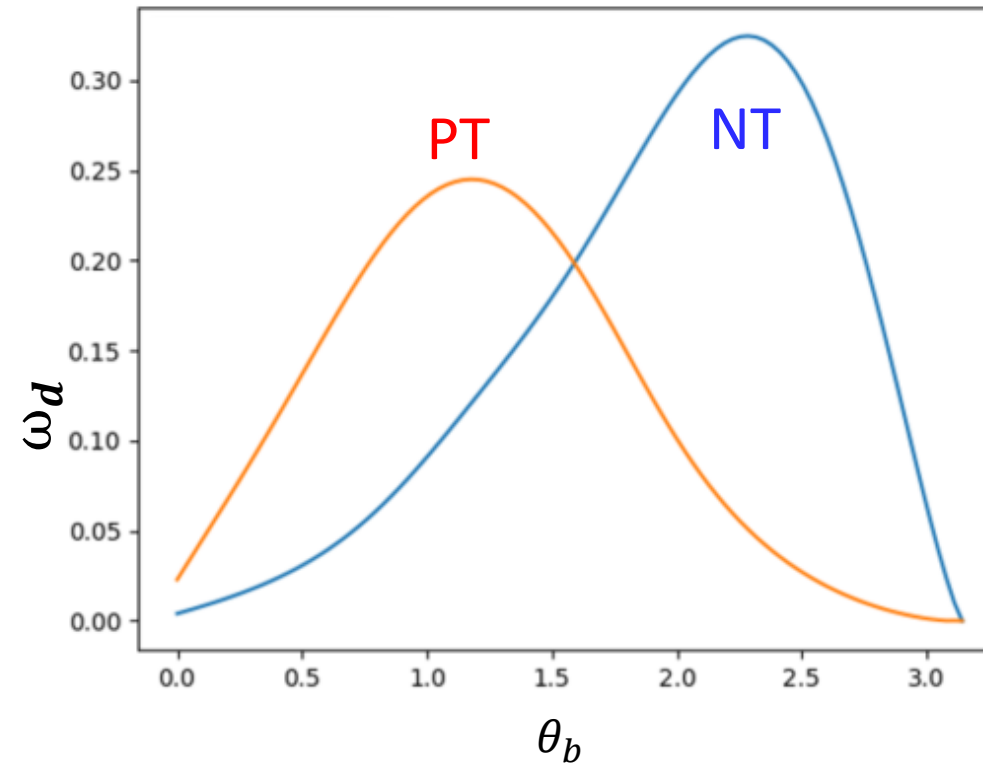
TEM instability: resonant interaction between the electrostatic perturbation and the toroidal precessional drift of trapped electrons

Dependent on geometry

PRECESSION FREQUENCY DEPENDS ON TRIANGULARITY

[Marinoni 09]

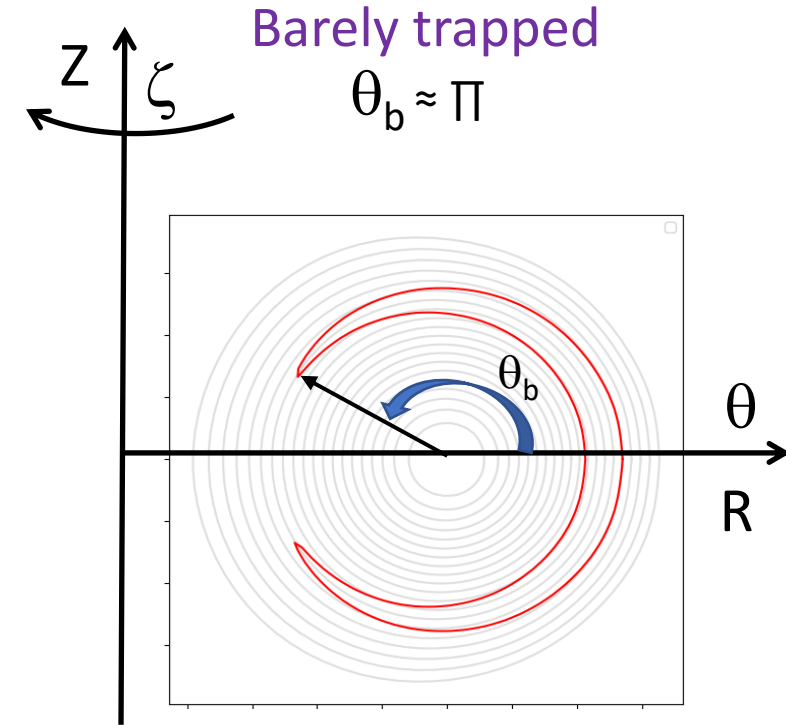
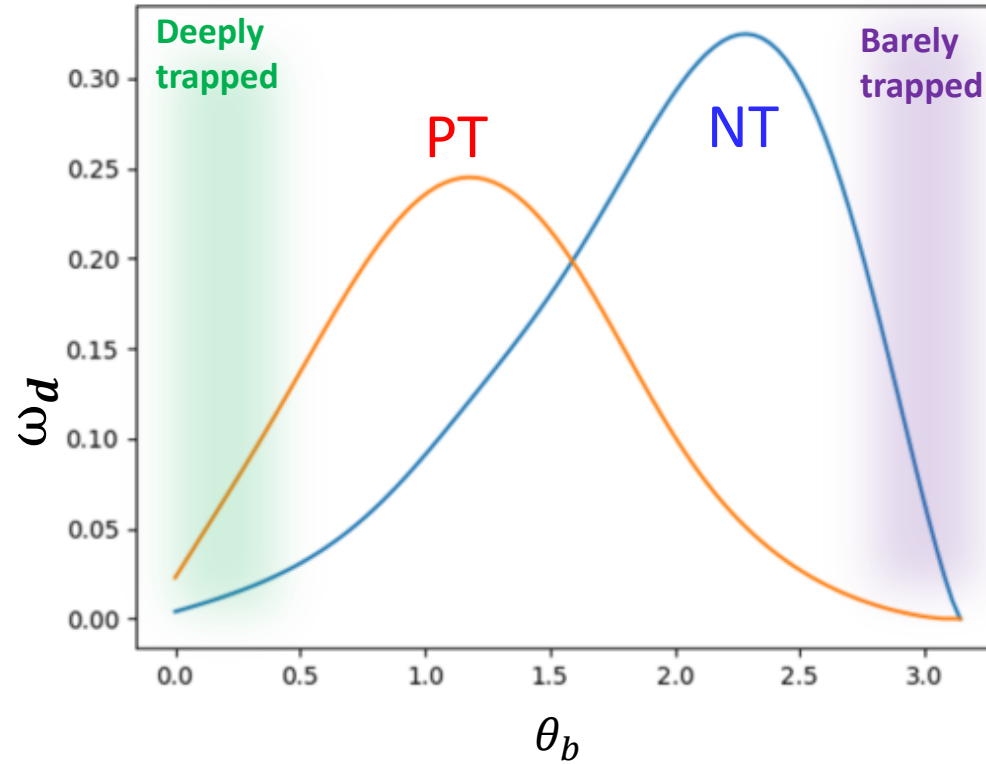
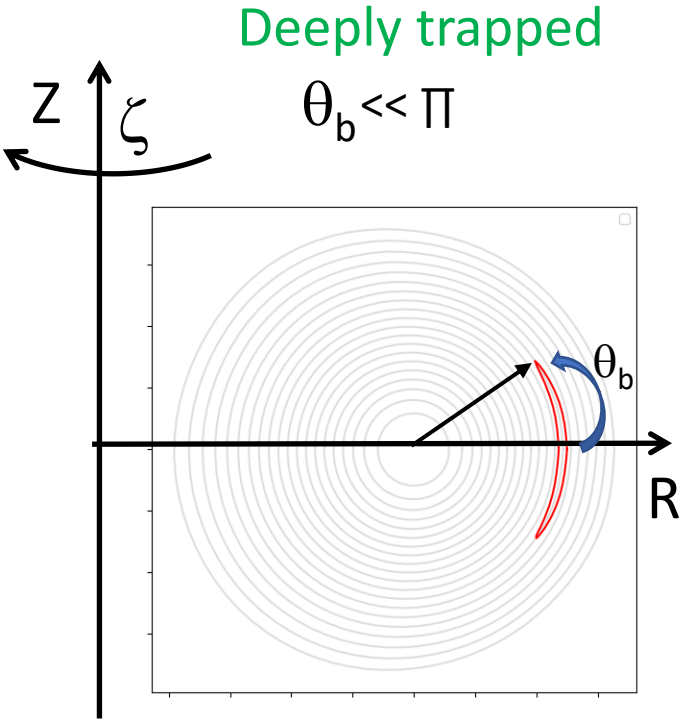
[Graves 13]



PRECESSION FREQUENCY DEPENDS ON TRIANGULARITY

[Marinoni 09]

[Graves 13]

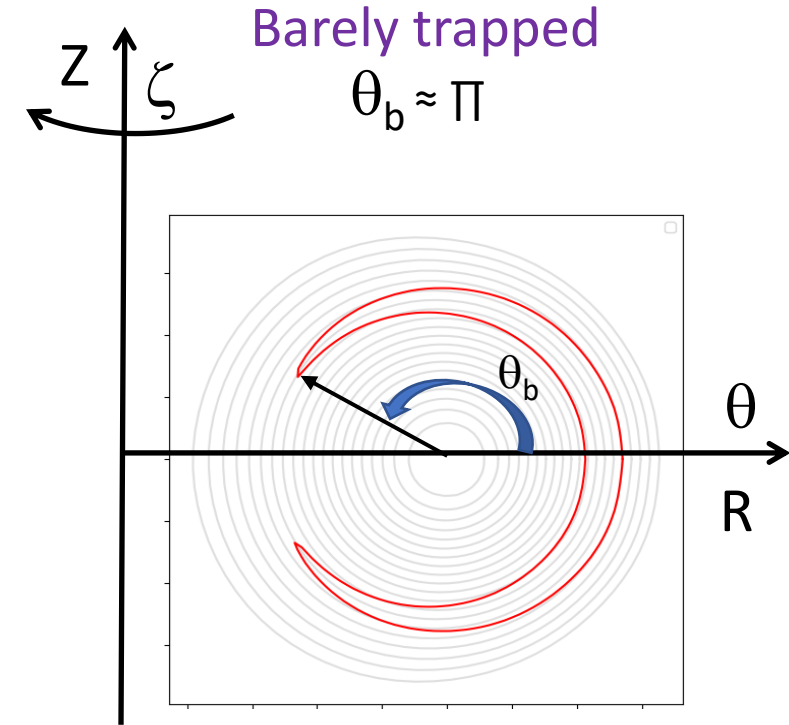
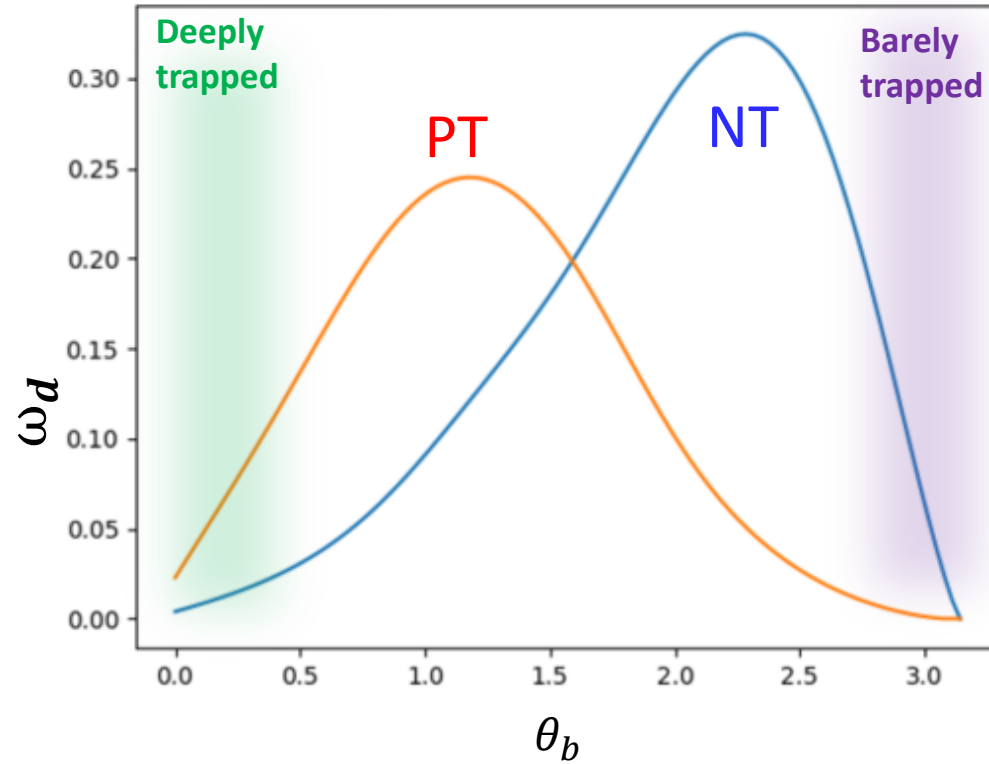
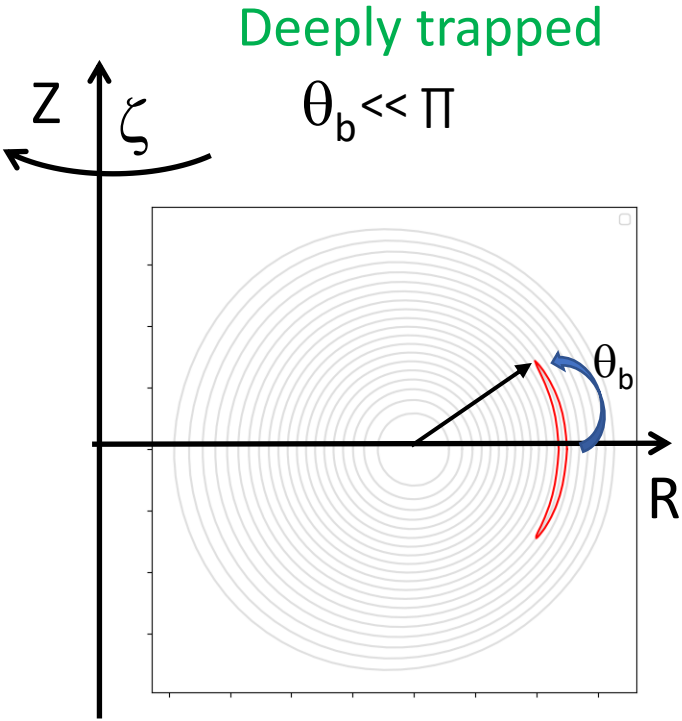


ω_d for negative triangularity plasmas is lower than for positive triangularity for deeply trapped electrons

PRECESSION FREQUENCY DEPENDS ON TRIANGULARITY

[Marinoni 09]

[Graves 13]



ω_d for negative triangularity plasmas is lower than for positive triangularity for deeply trapped electrons

Reduced linear model for understanding of the physics
behind stabilization of TEMs by NT [Garbet 24, De Gianni 26]

LINEAR STABILITY ANALYSIS: A REDUCED MODEL

REDUCED MODEL: LINEAR STABILITY ANALYSIS

Vlasov equation

Evolution of the distribution function

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \dot{\alpha} \cdot \frac{\partial f}{\partial \alpha} + \dot{J} \cdot \frac{\partial f}{\partial J} = 0.$$

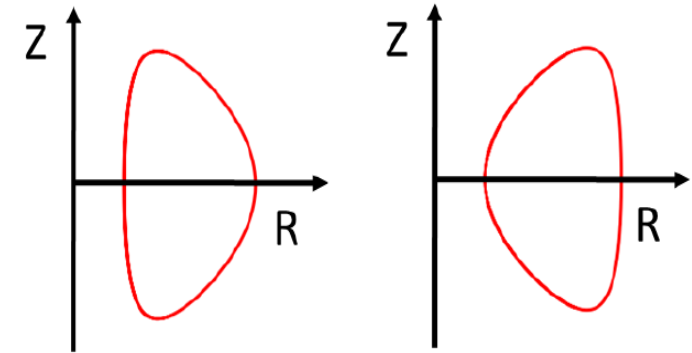
Quasi-neutrality

Evolution of the electrostatic field

$$\sum_s \int d^3r d^3v e_s \phi^* \delta f_s = 0.$$

[C.D. Stephens 21]
[Garbet 24]

Analytical equilibrium



DISPERSION RELATION

$$\Xi_{adia} + \Xi_e + \frac{T_e}{T_i} \Xi_i = 0$$

adiabatic contribution

trapped electrons contribution

- RESONANCE WITH PRECESSION FREQUENCY
- NO PARALLEL DYNAMICS

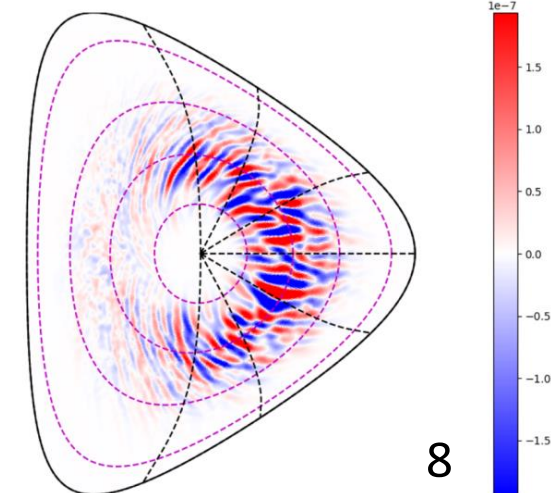
ions contribution

- FINITE LARMOR RADIUS EFFECTS
- NO RESONANCES

The mode structure accounts for ballooning

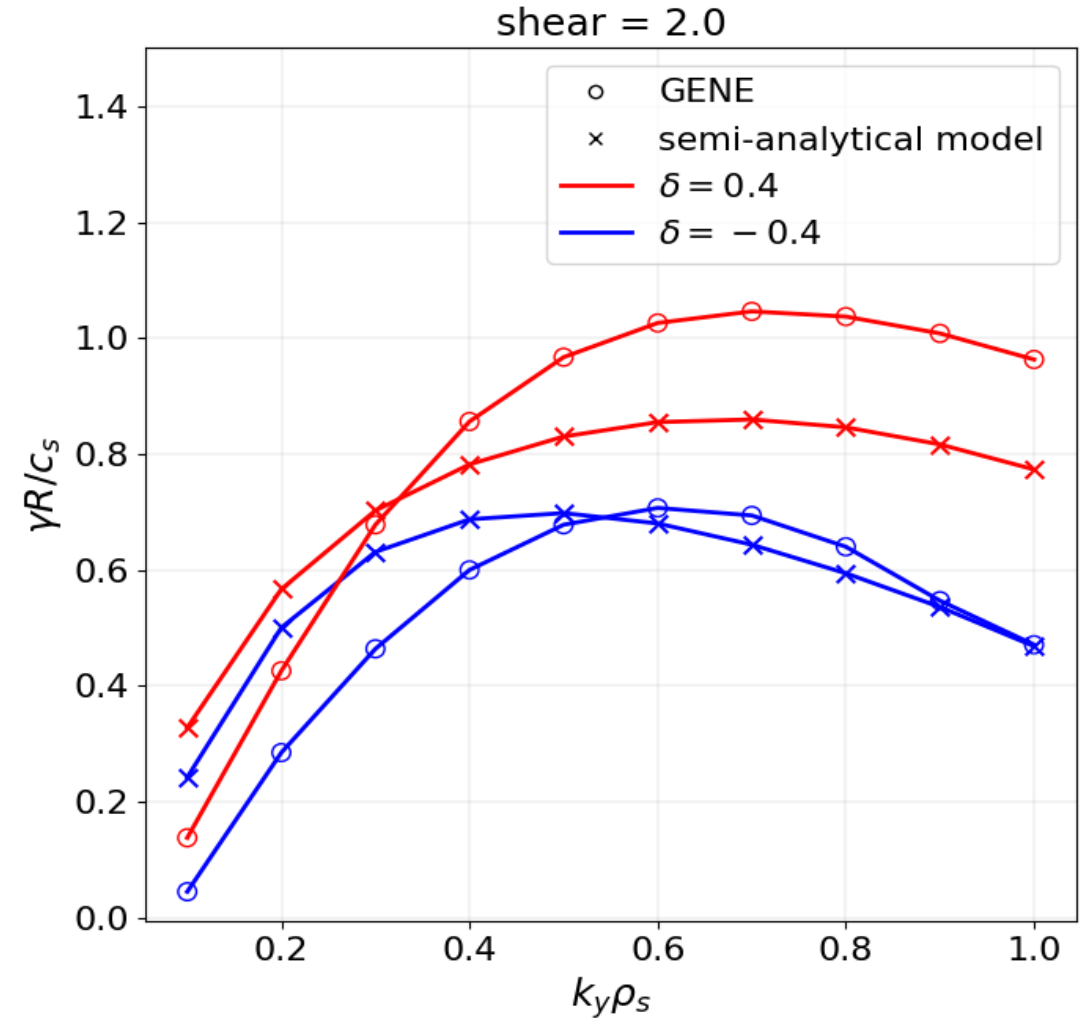
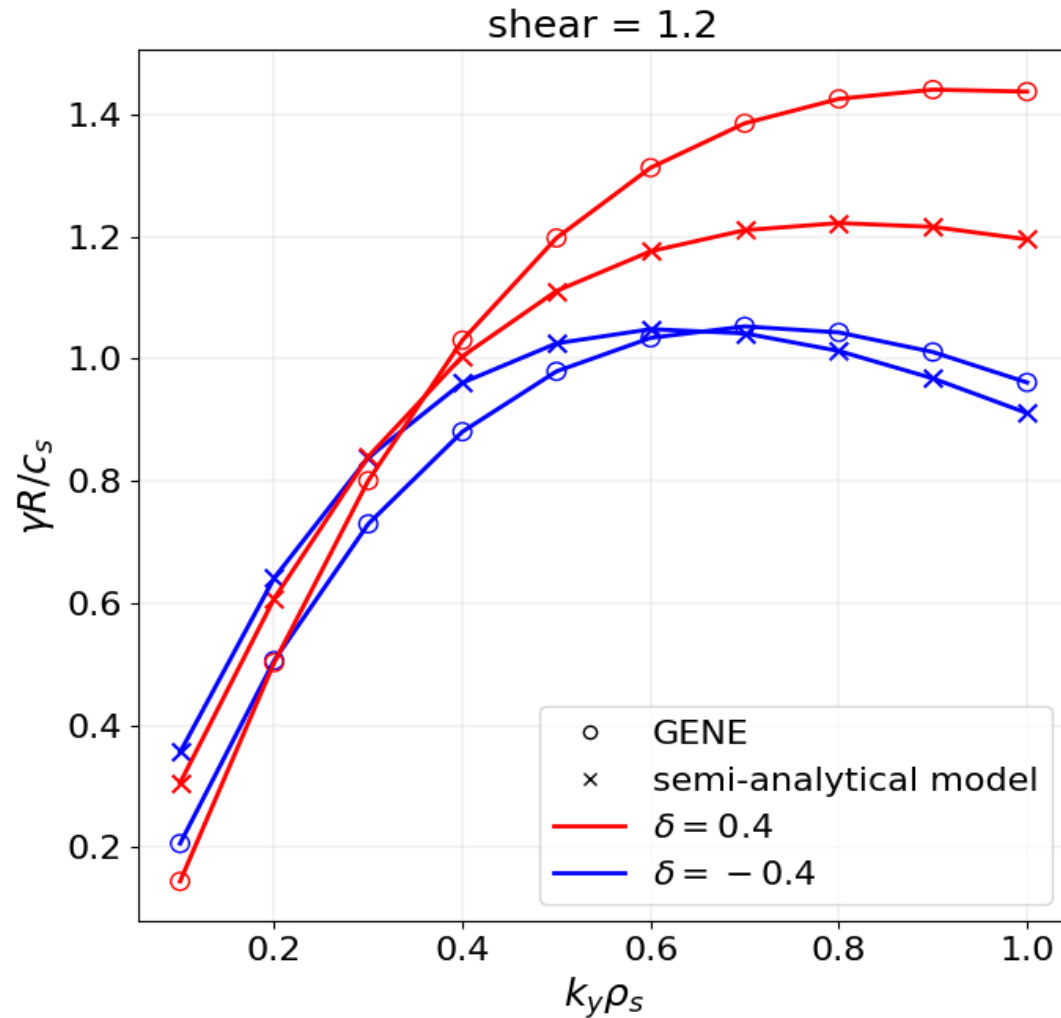
$$\hat{\phi}(\theta) = \hat{\phi}_0 \exp(-D\theta^2)$$

$\delta\Phi_{n \neq 0}$



BENCHMARK AGAINST GENE LOCAL SIMULATIONS [Merlo 23]

Mode structures fitted on GENE mode structures

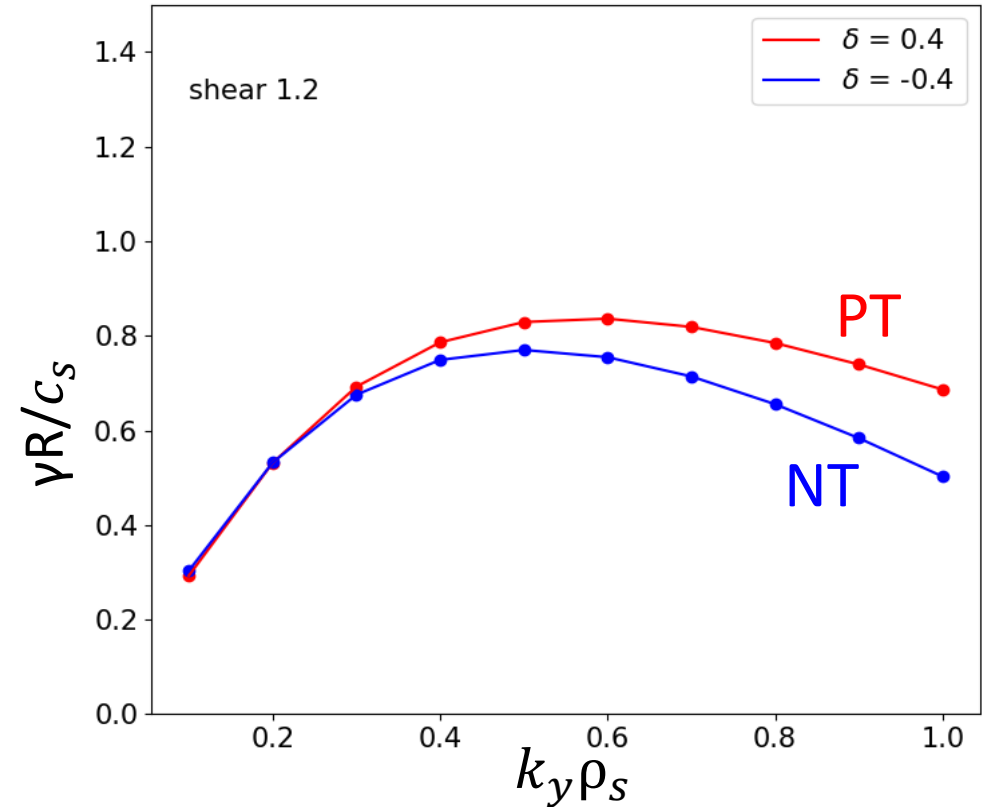
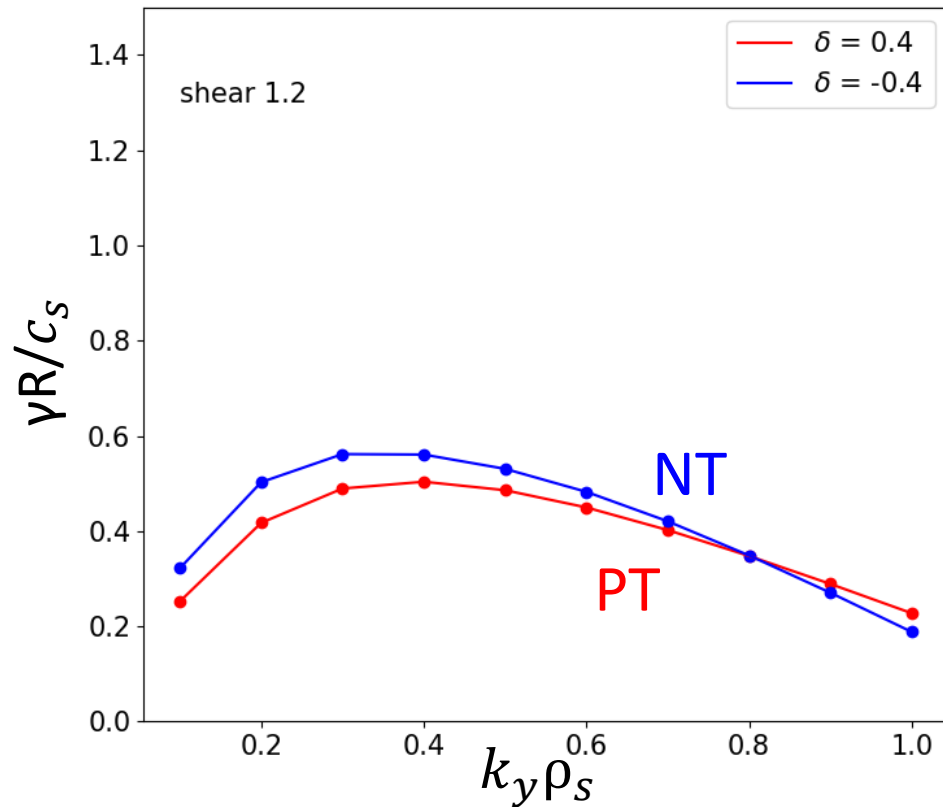


Semi-quantitative agreement at medium-high magnetic shear values

TURBULENCE BALLOONING IS CRUCIAL FOR NT STABILIZATION

Without ballooning : $\hat{\phi}(\theta) = \hat{\phi}_0$

With ballooning: $\hat{\phi}(\theta) = \hat{\phi}_0 \exp(-D\theta^2)$



Without accounting for ballooning

NT more unstable than PT

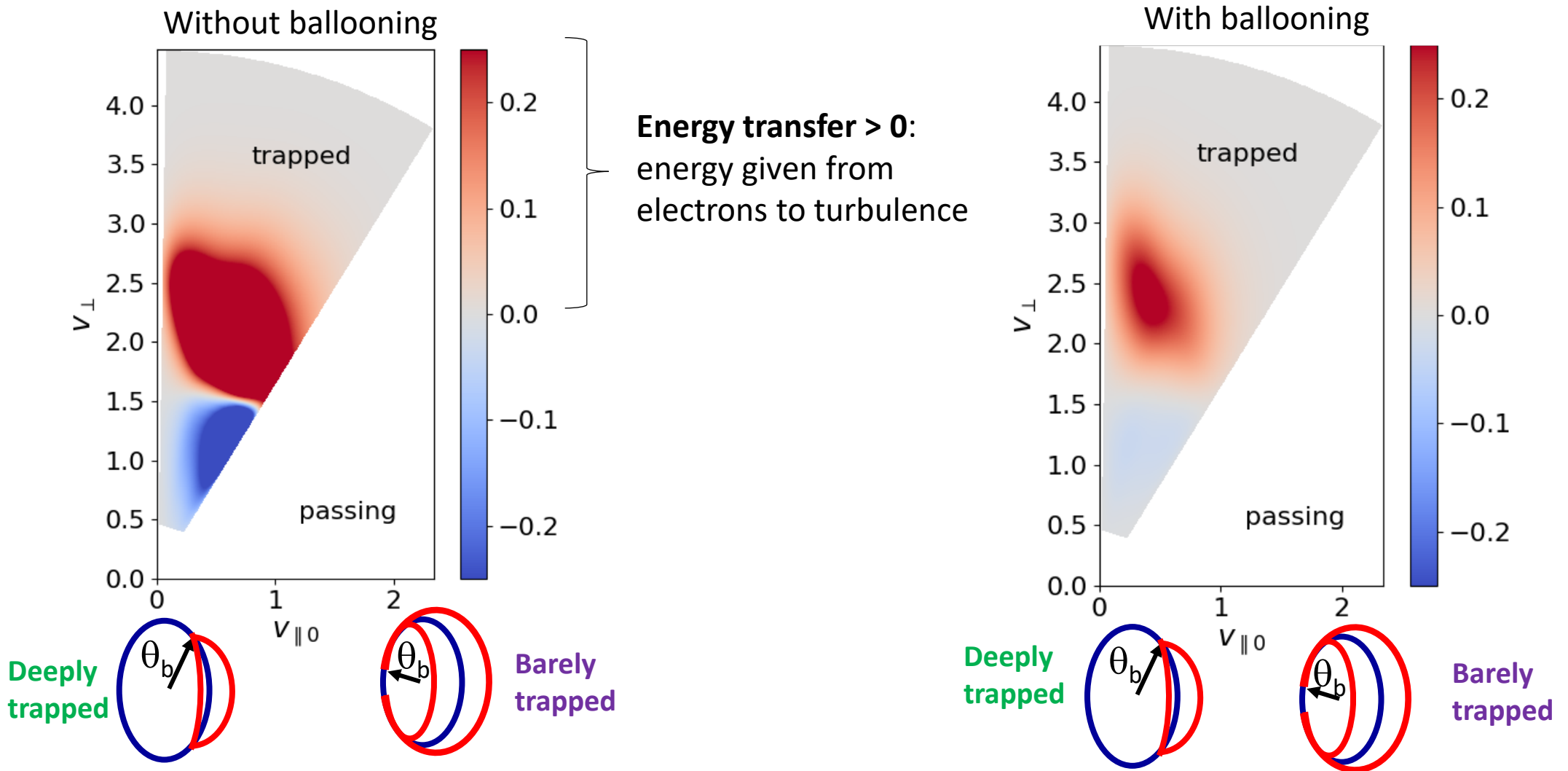
When accounting for ballooning

NT more stable than PT

Analysis of the dynamics for physical interpretation

DEEPLY TRAPPED ELECTRONS RULE THE DYNAMICS [De Gianni 26]

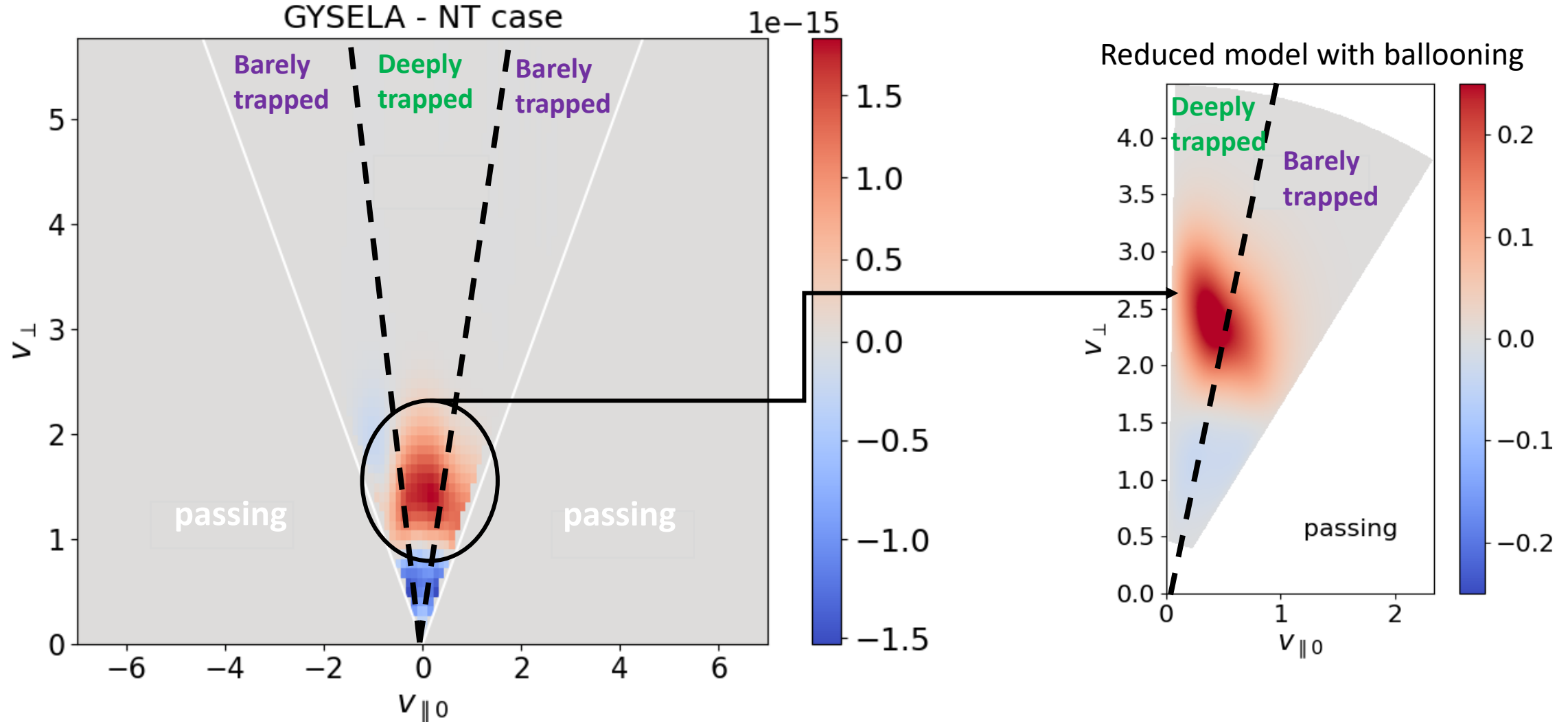
*From the dispersion relation to the **energy transfer**: understanding the dynamics of the instability*



Ballooning $\rightarrow$ deeply trapped electrons rule the dynamics of TEMs $\rightarrow$ Is it what happens in real life?

GYSELA SIMULATIONS CONFIRM THE RESULTS OF REDUCED MODEL

Energy transfer (v_D component) in GYSELA

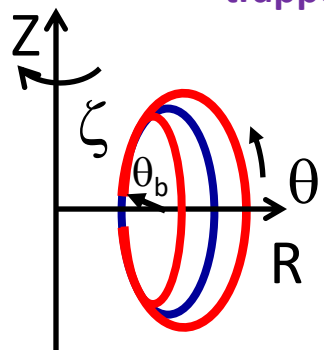
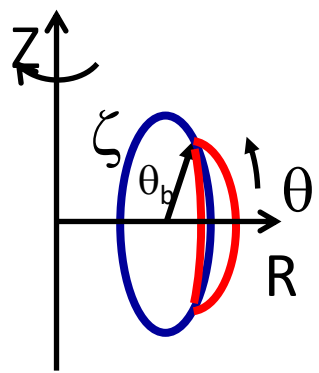
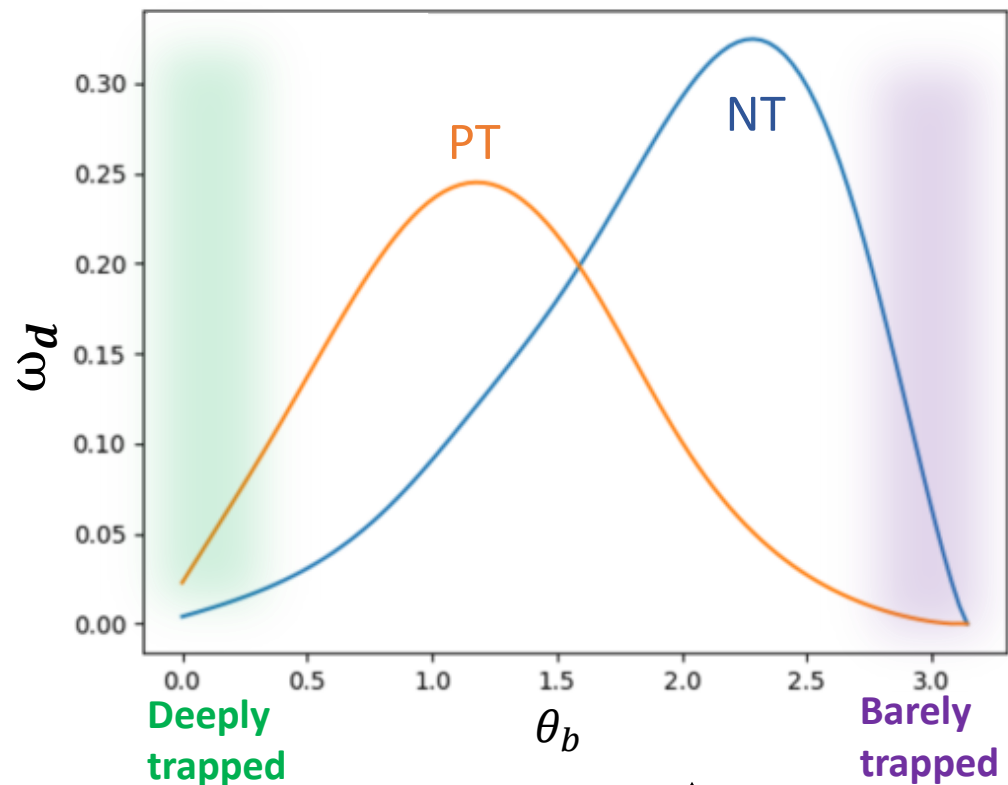


Deeply trapped electrons rule the dynamics of TEMs! → Why deeply trapped electrons are advantageous for NT?

PHYSICAL INTERPRETATION

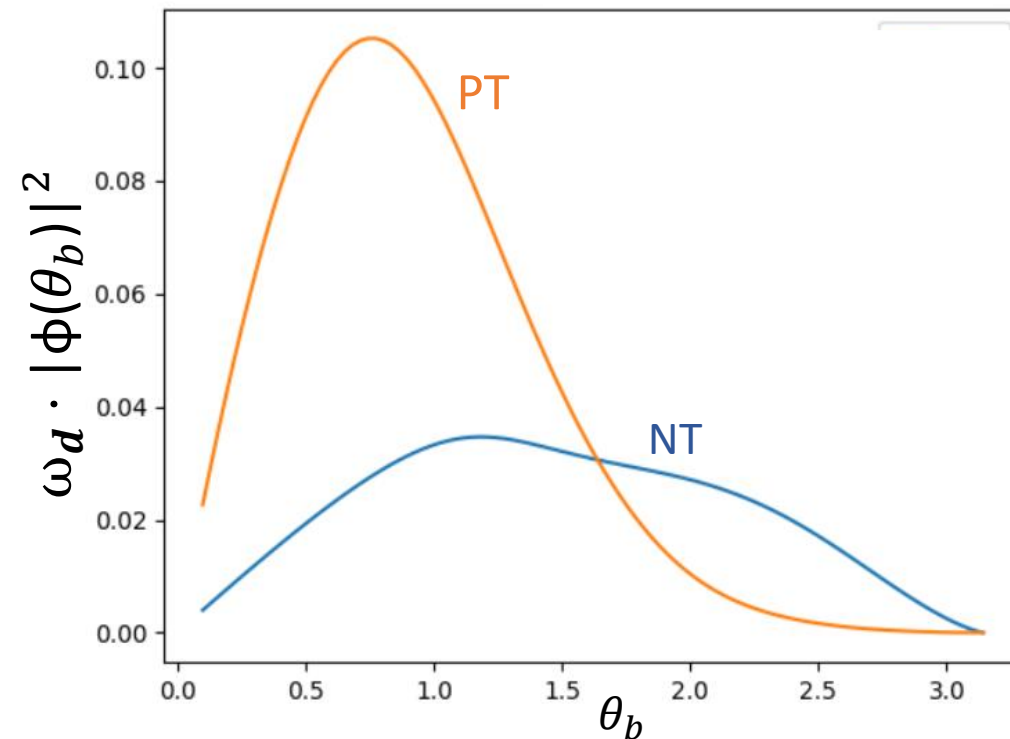
far from threshold : INTERCHANGE

Without ballooning: $\hat{\phi}(\theta) = \hat{\phi}_0$



$$\gamma \propto \sqrt{\langle \omega_d \rangle_{\theta_b}}$$

With ballooning: $\hat{\phi}(\theta) = \hat{\phi}_0 \exp(-D\theta^2)$



BALLOONING enhances response of **deeply trapped electrons**

Responsible of NT stabilization wrt PT

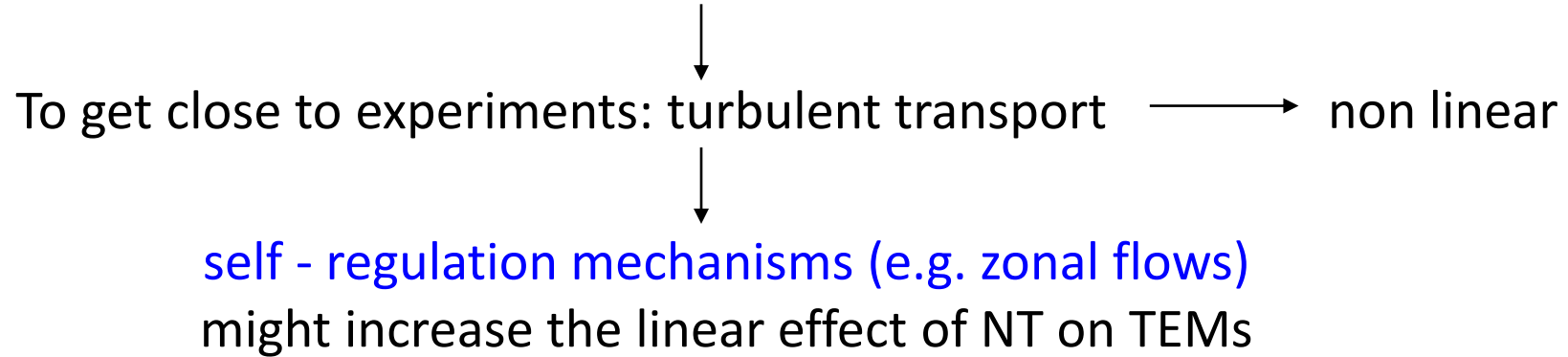
LINEAR ANALYSIS: CONCLUSIONS

- Deeply trapped electrons are participating more to the instability due to ballooning
- Interchange analysis: deeply trapped electrons dynamics is favorable to NT
- Even if $\gamma_{NT} < \gamma_{PT}$, differences are small

NON LINEAR ANALYSIS USING GYSELA

NON LINEAR PHYSICS

Linear γ give trends, but quantitatively differences are small



Gradient driven: profiles not free to evolve

- Able to reproduce experimental heat fluxes
[Merlo 21] [Marinoni 09] [Marinoni 24]
- NT not advantageous at small aspect ratio
[Balestri 24]
- NT stabilization dependent on the shear
[Merlo 23]
- Global effect coming from the edge
[Di Giannatale 24]

Flux driven: self-consistent evolution of background profiles

- Higher Reynolds-stresses in NT [Becoulet 26]
- PT stronger non locality and avalanches
[Di Giannatale 22]

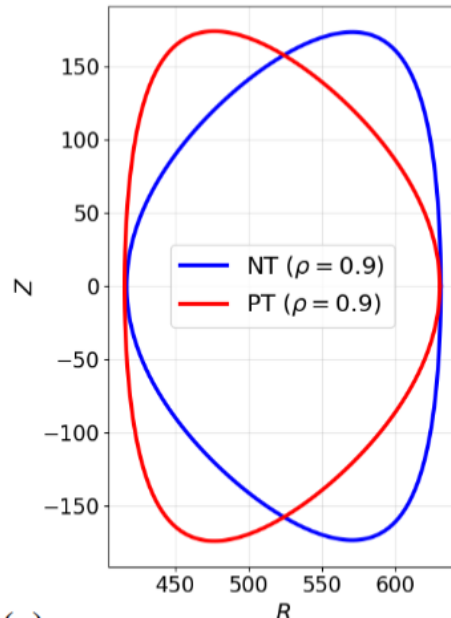
PT vs NT GYSELA SIMULATIONS

GYSELA:

- Vlasov-Poisson system + hyperdiffusion with trapped kinetic electrons
- **Flux - driven**: profiles free to evolve
- Equilibria from Grad-Shafranov solver GVEC

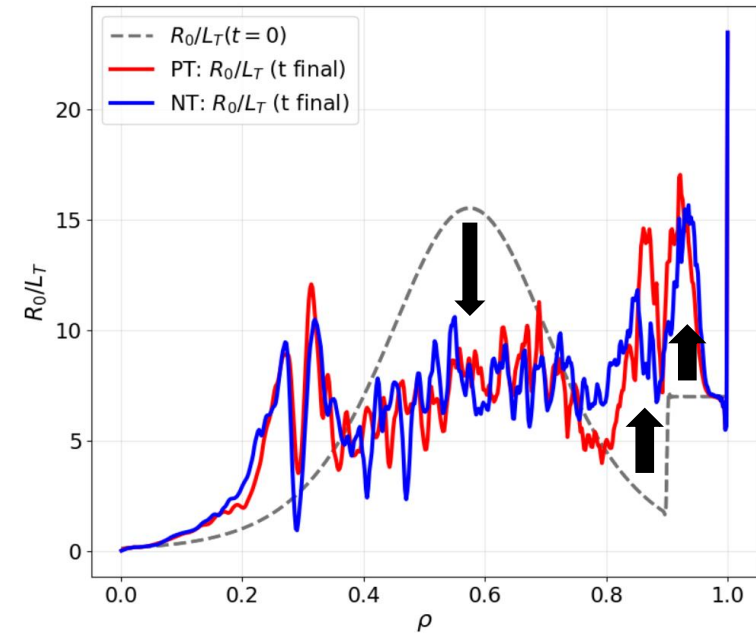
SET-UP:

- TCV – like inspired by [Camenen 07]
- TEMs dominant configuration



First analysis: no heating source

Gradients change significantly wrt initial configuration:
getting closer to marginality



$$\tau_c < t_{\text{sim}} < \tau_E$$

- Profiles do not vary much in the time-window analysed
- NT vs PT profiles do not differ drastically

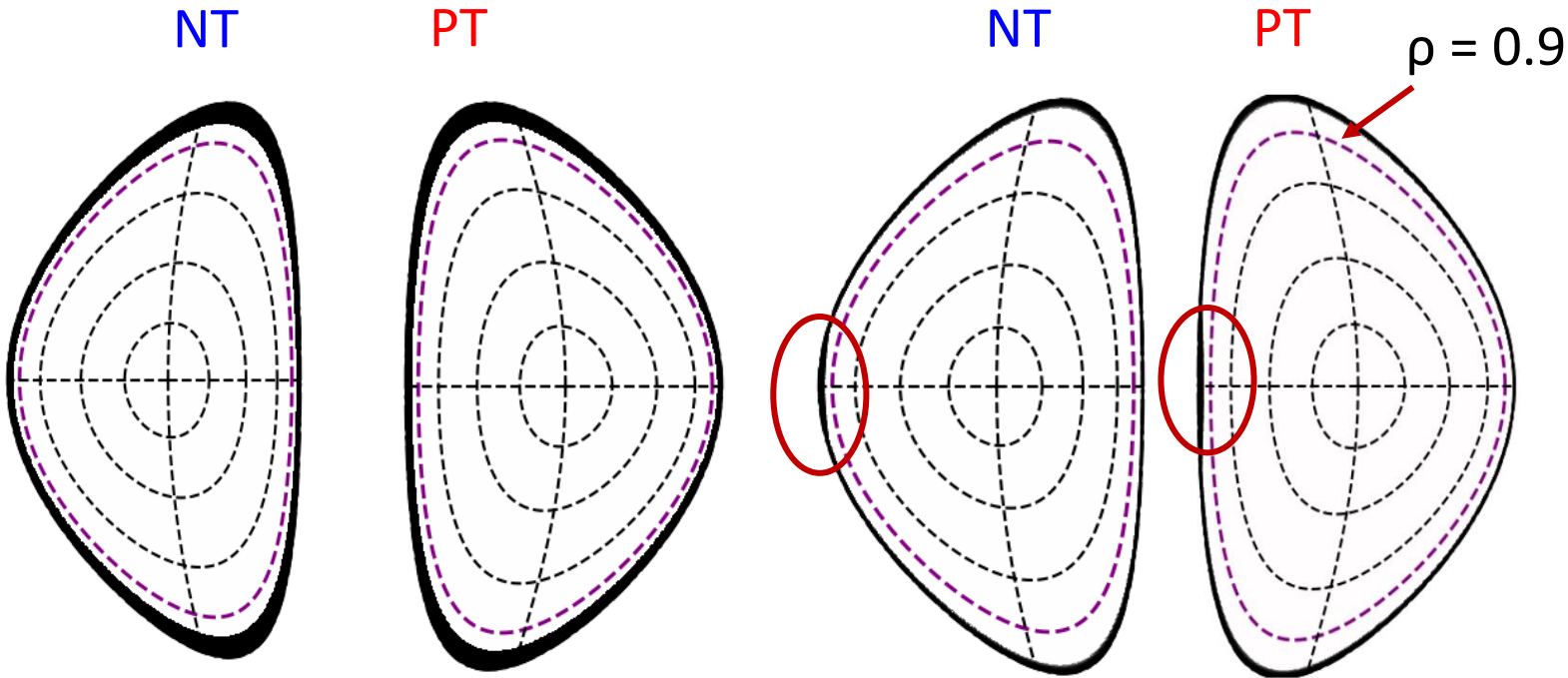
BOUNDARY CONDITIONS

$$\frac{d\overline{F}}{dt} = -\mathcal{M} \nu (\overline{F} - \overline{F}_{\text{init}})$$

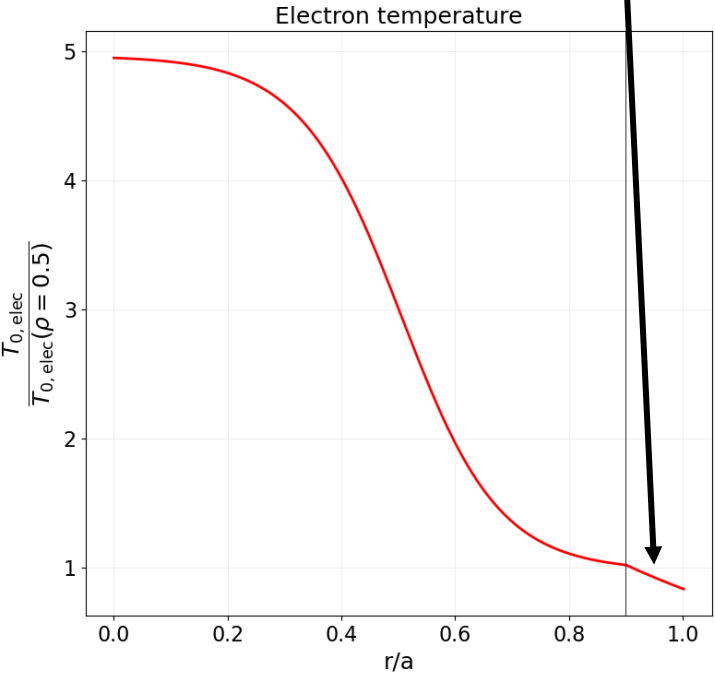
Immersed boundary conditions with mask:

Poloidally uniform

Poloidally non-uniform:
Thicker on the High Field Side



In all cases:
decaying profile after $\rho = 0.9$



Not a limiter: no sheath physics here! → Poloidally asymmetries & thinner mask on the rest of the poloidal cross-section

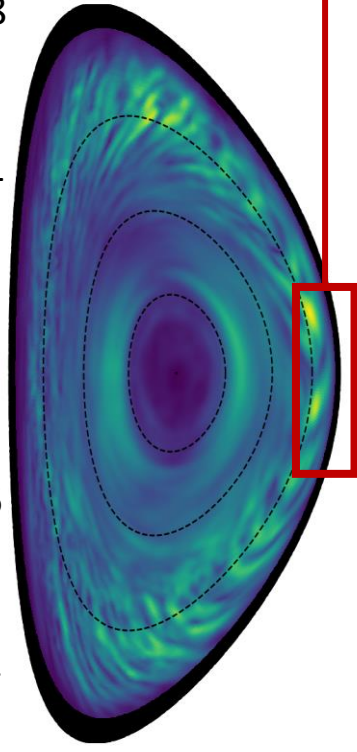
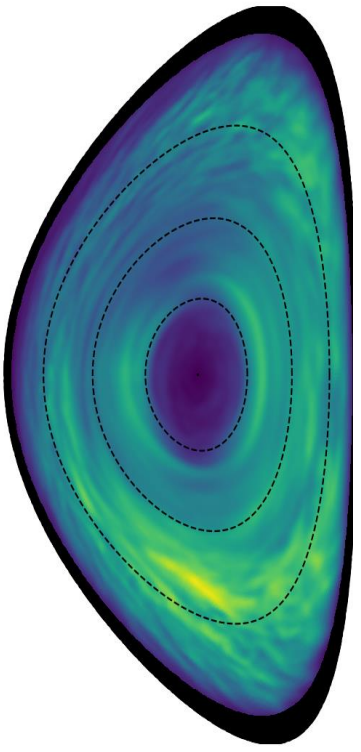
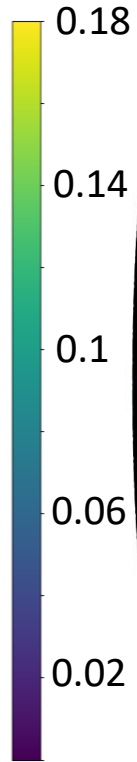
TURBULENCE CHARACTERIZATION

$$\langle \delta\phi \rangle_{t,rms}$$

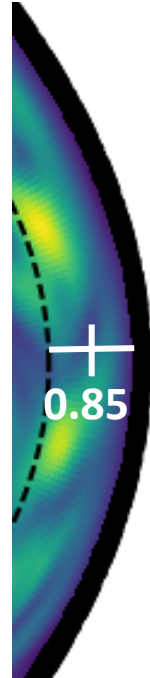
Poloidally uniform boundary

NT

PT



↓
strong up-down asymmetry



TURBULENCE CHARACTERIZATION

$$\langle \delta\phi \rangle_{t,rms}$$

Poloidally uniform boundary

Poloidally non - uniform boundary

NT

PT

NT

PT

0.18

0.14

0.1

0.06

0.02

0.20

0.15

0.10

0.05

0.

0.85

0.85

strong up-down asymmetry

Turbulence spreads to a outer region
when non - uniform boundary is used

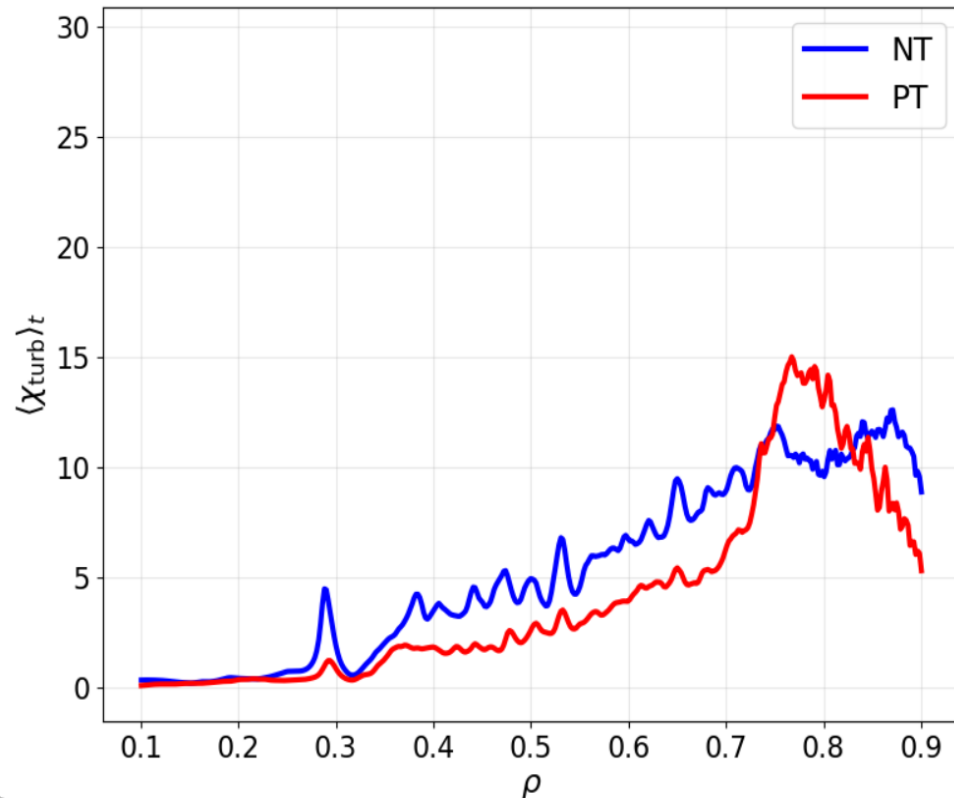
strong turbulence at $\rho > 0.85$

Turbulence propagates outwards
Not originated in the edge

TRANSPORT DEPENDS STRONGLY ON BOUNDARY CONDITIONS

Effective diffusion coefficient: $\chi_{\text{turb}} = - \frac{Q_{e,\text{turb}}}{n \frac{dT_e}{dr}}$

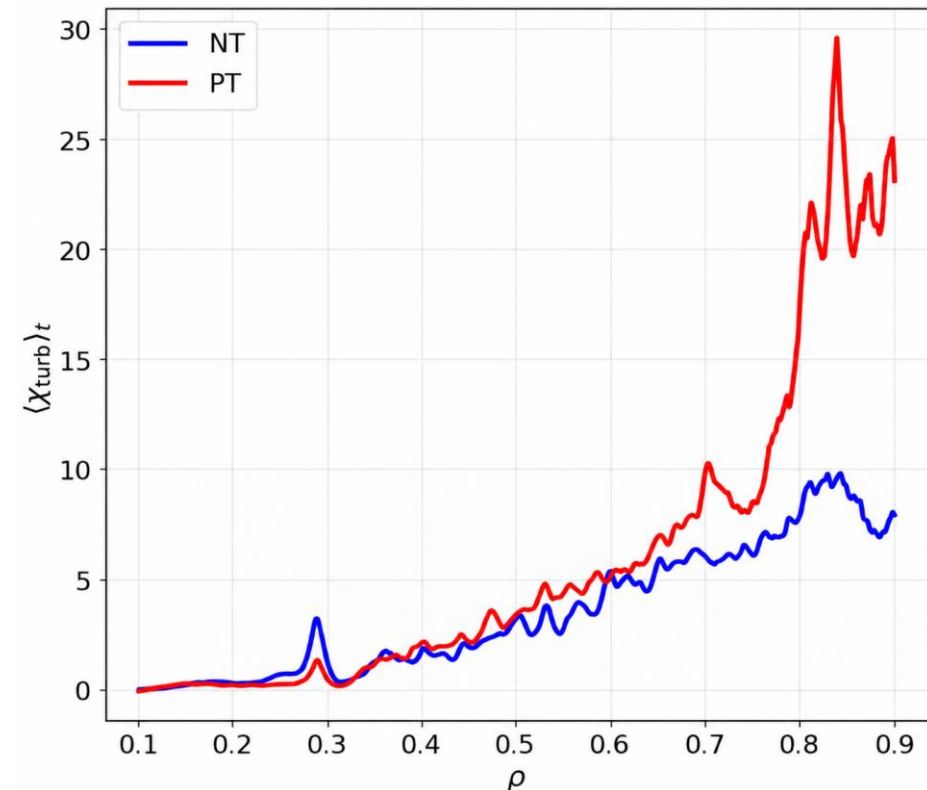
Poloidally uniform boundary



NT has a stronger transport than PT

$$\tau_{E,\text{NT}} \approx \tau_{E,\text{PT}}$$

Poloidally non – uniform boundary



More transport for PT in the edge

The effect propagates towards the centre

$$\tau_{E,\text{NT}} \approx 2 \tau_{E,\text{PT}}$$

~20% improvement (resp. ~30% reduction) of confinement in NT (resp. PT)
with poloidally non – uniform boundary compared with uniform boundary

No clear difference of power transfer to zonal flow via Reynolds stresses

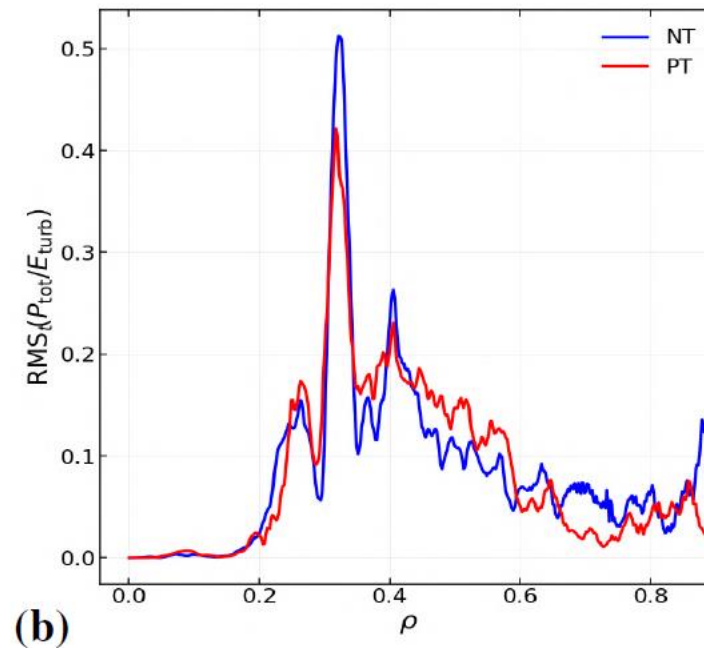
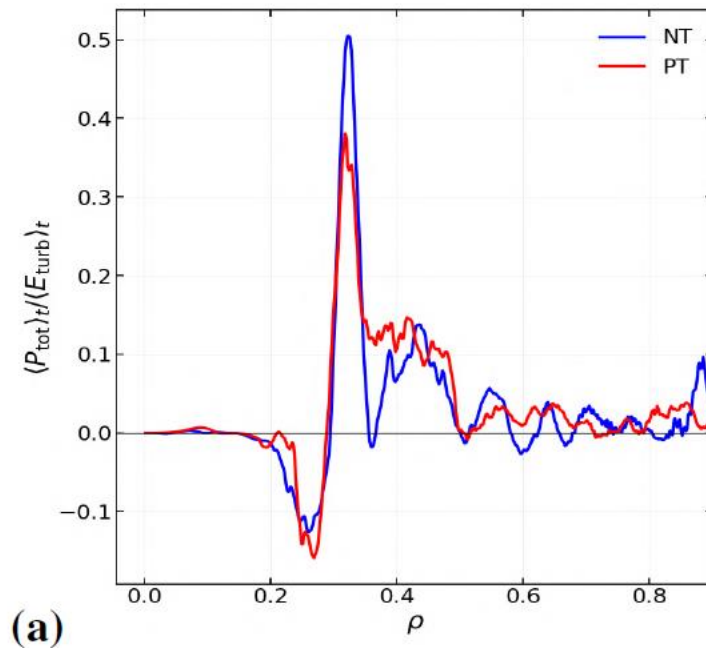
Reynolds-stress contribution to the zonal-flow

$$\frac{1}{2} \frac{\partial \langle u_{E\theta} \rangle^2}{\partial t} = P_{\text{tot}} = P_E + P^* \quad P_E = -\langle u_{E\theta} \rangle \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \pi) \quad P^* = -\langle u_{E\theta} \rangle \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \pi^*)$$

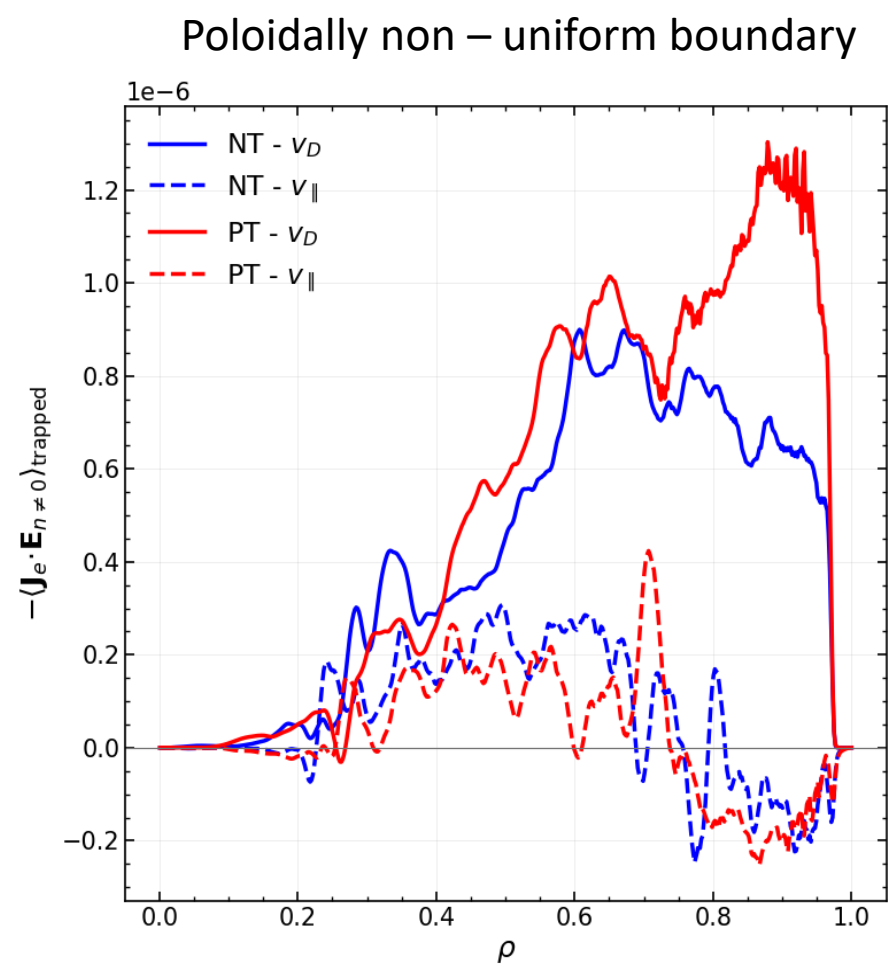
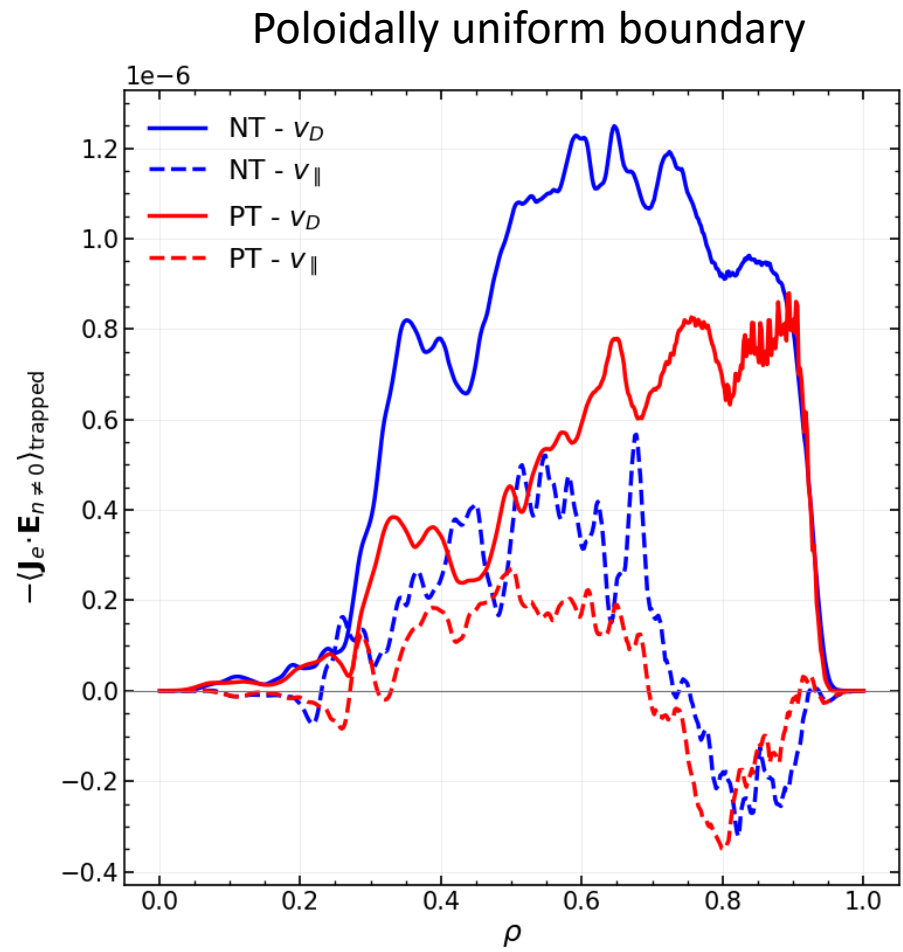
Normalised by the turbulent energy

$$E_{\text{turb}}(r, t) = \left\langle \left| \frac{\partial \delta \phi}{\partial r} \right|^2 + \left| \frac{1}{r} \frac{\partial \delta \phi}{\partial \theta} \right|^2 \right\rangle$$

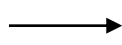
Poloidally non-uniform boundary



LOCAL TRANSFER OF ENERGY STRONGLY IMPACTED BY BOUNDARY CONDITIONS



Big differences in the power exchange between trapped electrons and electric field
Especially v_d component

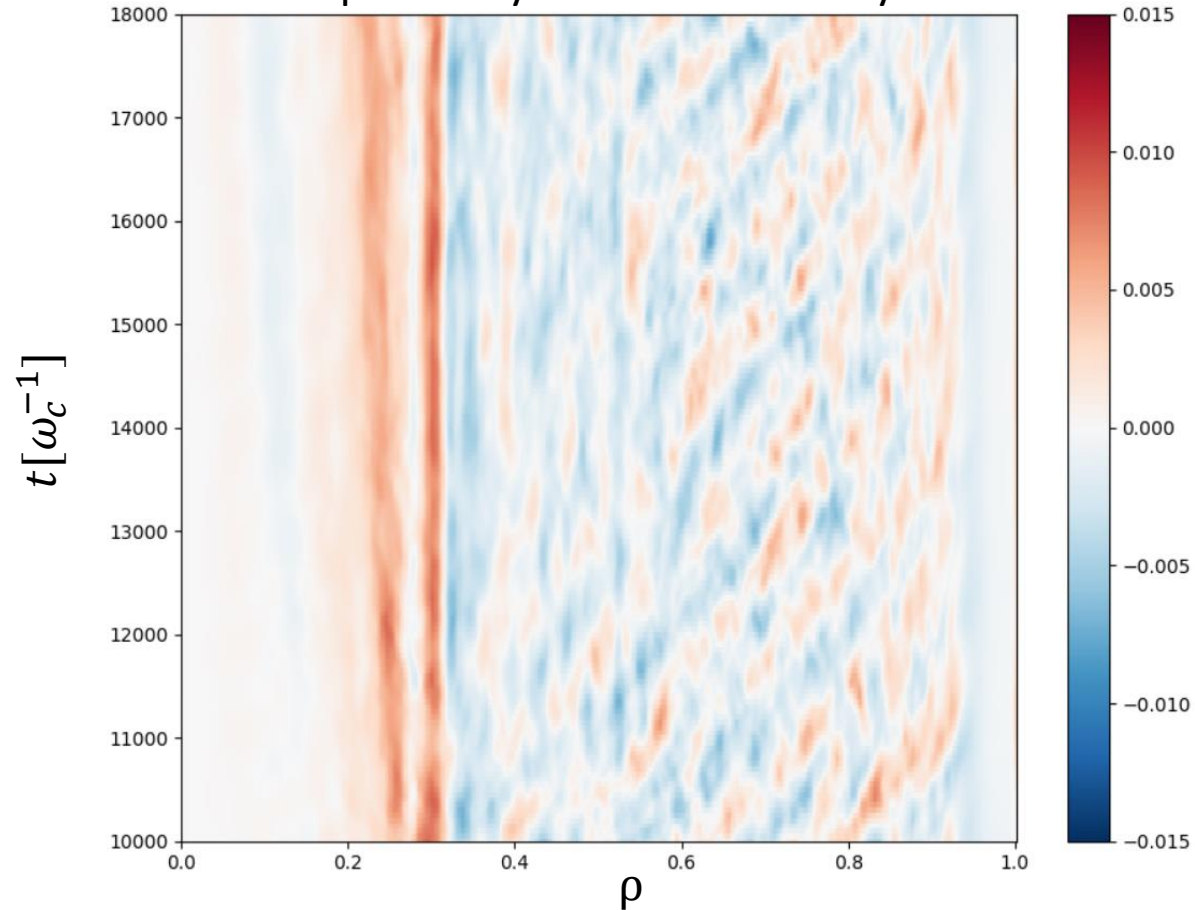


Same as linear mechanism, amplified by non local transport

DIFFERENT STRUCTURES IN PT AND NT: POLOIDALLY UNIFORM BOUNDARY

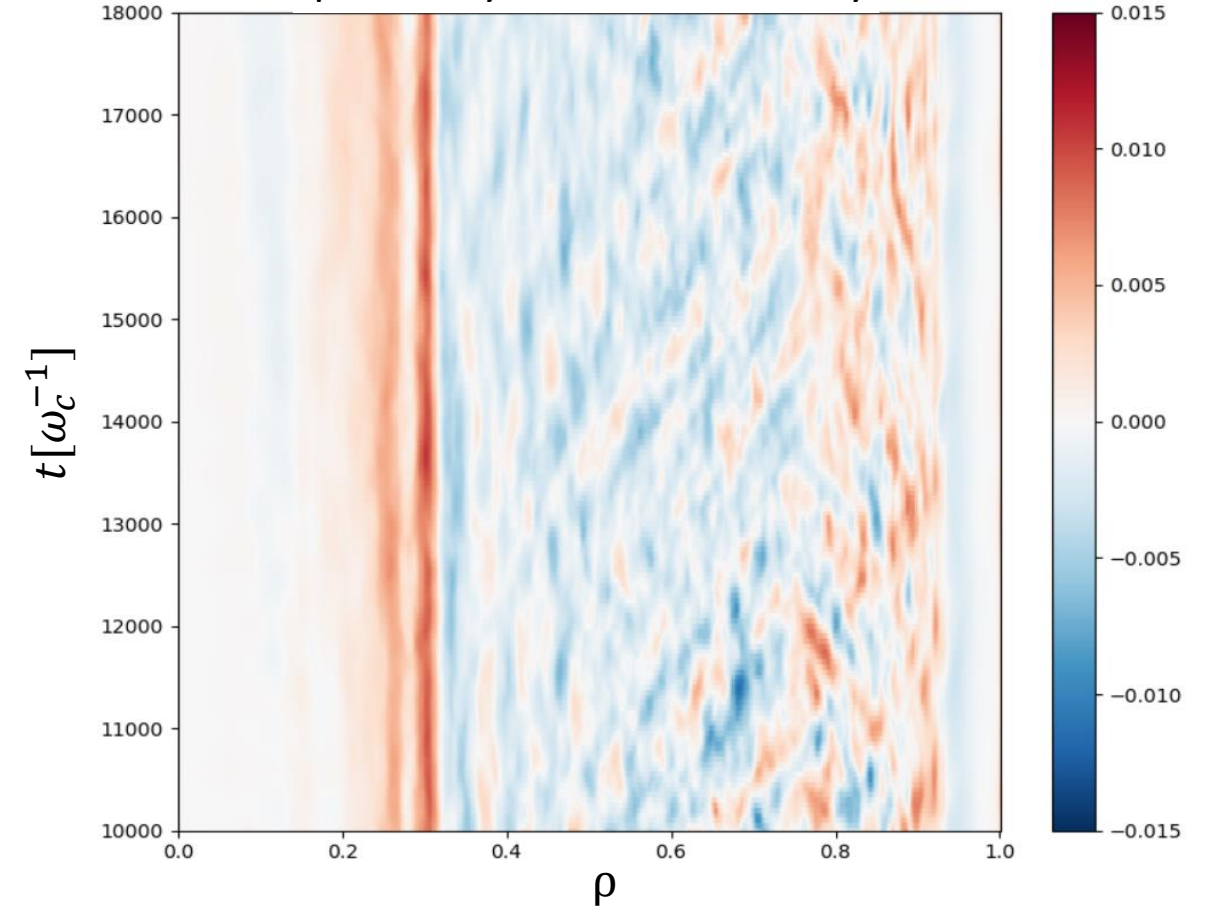
$$\omega_{ExB} = \frac{1}{rB} \frac{d^2 \phi_{00}}{dr^2}$$

NT: poloidally uniform boundary



ρ
↓
~ coherent structures

PT: poloidally uniform boundary

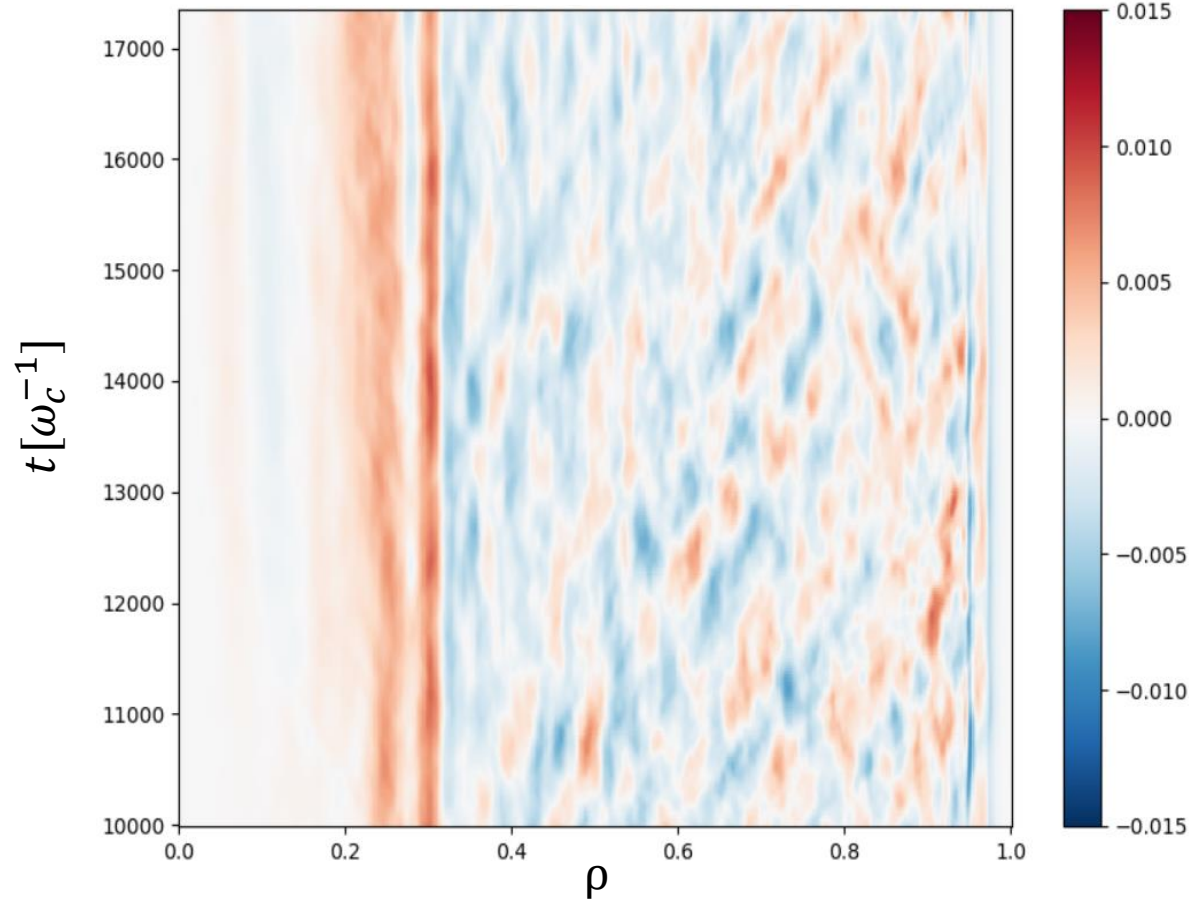


Fragmentated structures with
inversion of the slope around $\rho = 0.75$

DIFFERENT STRUCTURES IN PT AND NT: POLOIDALLY NON-UNIFORM BOUNDARY

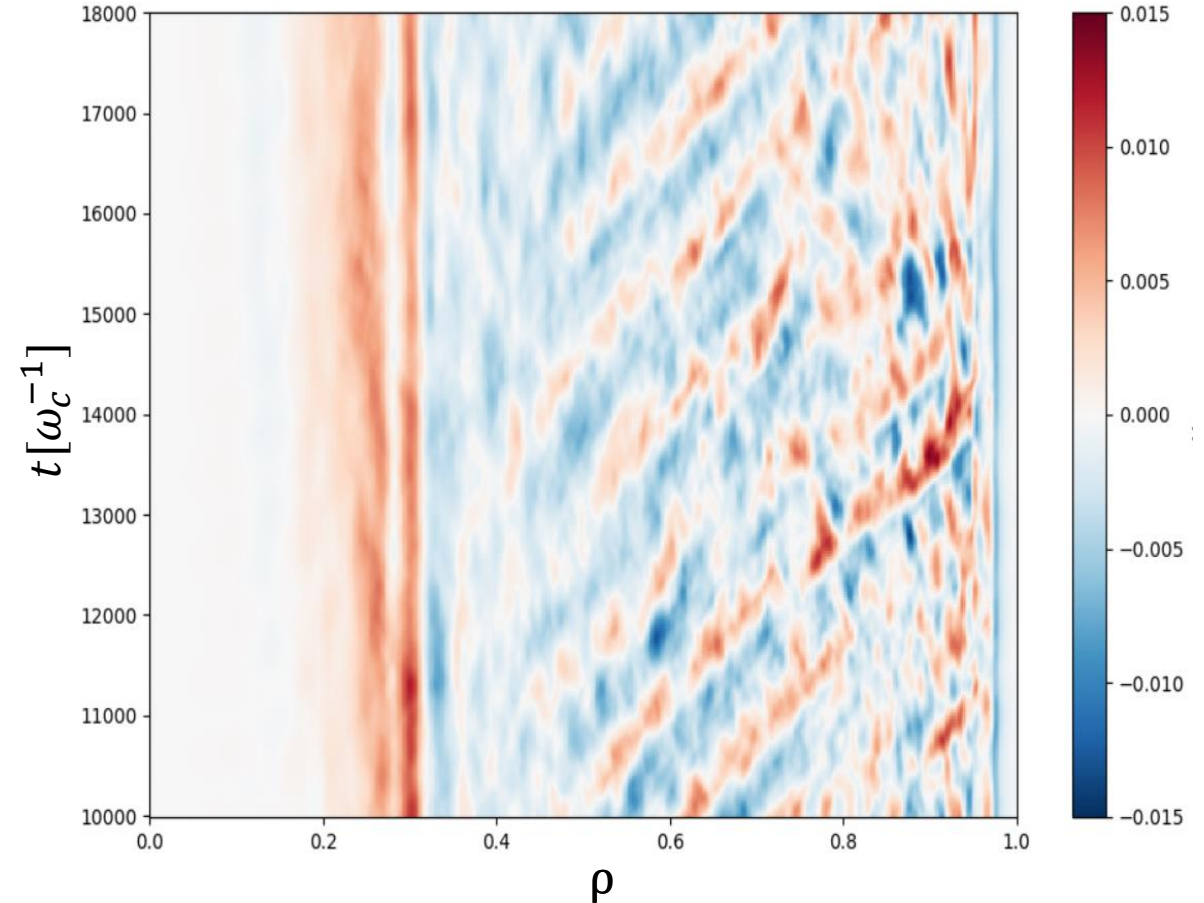
$$\omega_{ExB} = \frac{1}{rB} \frac{d^2 \phi_{00}}{dr^2}$$

NT: poloidally non – uniform boundary



More fragmentated structures

PT: poloidally non – uniform boundary



Avalanche - like structures: higher non local transport efficiency [cf. Di Giannatale 22]

NON LINEAR ANALYSIS: CONCLUSIONS

TEMs flux driven simulations with experimental profiles are challenging and expensive

TEMs TCV-like configurations without heating sources:

- State closer to marginality wrt experimental one
- Poloidally uniform boundary conditions : $\tau_{E,NT} \approx \tau_{E,PT}$
- Poloidally non – uniform boundary conditions: $\tau_{E,NT} \approx 2 \tau_{E,PT}$
- Non local transport in PT and NT highly influenced by boundary conditions

PERSPECTIVES:

- More analysis on the impact of poloidal asymmetry on transport
- More analysis on zonal flows
- Simulation with heat source

BACK-UP SLIDES

Culham equilibrium

$$R_s(\theta) = R_0 + \Delta_s + (\rho_s - E_s - P_s) \cos \theta + T_s \cos 2\theta$$

$$Z_s(\theta) = (\rho_s + E_s - P_s) \sin \theta - T_s \sin 2\theta$$

Magnetic drift velocity

$$\mathbf{v}_D = \frac{m_a v_{\parallel}^2}{e_a B} \mathbf{b} \times \boldsymbol{\kappa} + \frac{\mu}{e_a} \mathbf{b} \times \frac{\nabla B}{B}$$

$$\begin{aligned} \mathbf{v}_D \cdot \nabla \alpha &= \frac{q_s}{r_s} \frac{1}{e_a B_s R_s} \left(m_a v_{\parallel}^2 + \mu B_s \right) \\ &\quad \left(\frac{r_s^2}{a_s^2} \frac{1}{r_s} \frac{\partial Z_s}{\partial \theta} - \left(s_s \theta - \alpha_m \tilde{D} \right) \frac{1}{r_s} \frac{\partial R_s}{\partial \theta} \right) \\ &\quad - \frac{\alpha_m q_s}{2 q_s^2} \frac{q_s}{r_s} \frac{\mu B_s}{e_a B_s R_s} \end{aligned}$$

$$\mathbf{v}_D \cdot \nabla \psi = \frac{1}{q_s e_a R_s} \left(m_a v_{\parallel}^2 + \mu B_s \right) \frac{\partial R_s}{\partial \theta}$$

$$\Omega_d=\frac{\int_{-\theta_b}^{\theta_b}\frac{d\ell}{v_{\parallel}}\mathbf{v}_D\cdot\nabla\alpha}{\int_{-\theta_b}^{\theta_b}\frac{d\ell}{v_{\parallel}}}$$

$$\frac{1}{\Omega_b}=\left.\frac{\partial \mathcal{J}}{\partial H}\right|_{\mu,\psi}=\frac{1}{\pi}\int_{-\theta_b}^{\theta_b}d\theta\sqrt{g_s}\frac{B_s}{v_{\parallel}}$$

$$\frac{1}{\bar{\Omega}_b(\lambda)}=\frac{1}{2\pi}\int_{-\theta_b}^{\theta_b}d\theta\frac{R_s^{3/2}(\theta)}{R_{max}}\frac{1}{\sqrt{2\left(R_s(\theta)-R_s(\theta_b)\right)}}$$

$$f_t=\int_{\lambda_-}^{\lambda_+}\frac{d\lambda}{\sqrt{2}\bar{\Omega}_b(\lambda)}$$

Perpendicular wave number

+

$$\mathbf{k}_\perp = n \nabla \alpha + n \frac{dq}{d\psi} \theta_k \nabla \psi$$

and therefore its modulus on the resonant surface

$$k_\perp^2 = n^2 \left(|\nabla \alpha_s|^2 + \frac{dq_s}{d\psi} \theta_k (\nabla \psi_s \cdot \nabla \alpha_s) + \left(\frac{dq_s}{d\psi} \right)^2 \theta_k^2 |\nabla \psi_s|^2 \right)$$

Using Eq.(32) and the definition $\Lambda = \frac{\nabla \alpha_s \cdot \nabla \psi_s}{B_s}$, one gets

$$k_\perp^2 = n^2 \left(\frac{B_s^2}{|\nabla \psi_s|^2} (1 + \Lambda^2) + \frac{dq_s}{d\psi} \theta_k B_s \Lambda + \left(\frac{dq_s}{d\psi} \right)^2 \theta_k^2 |\nabla \psi_s|^2 \right)$$

Moreover an explicit expression of Λ was already derived (see Eq.(33))

$$\Lambda = -\frac{a_s^2}{r_s^2} \left(s_s \theta - \alpha_m \tilde{D} \right)$$

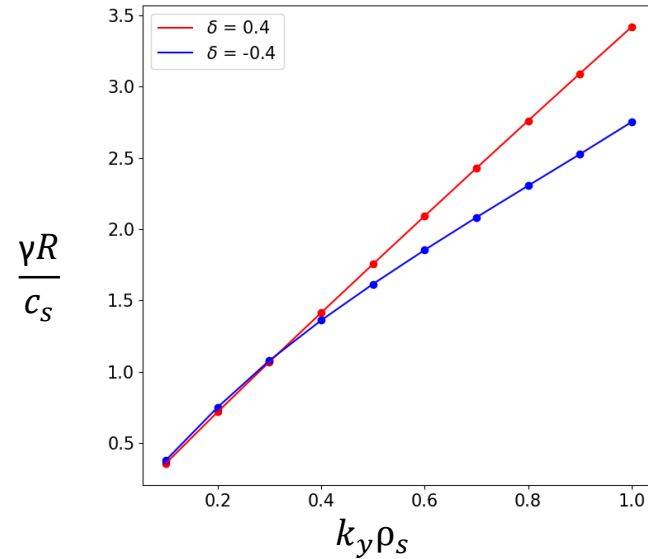
In the large aspect ratio limit, a tractable expression is obtained

$$k_\perp^2 = k_\theta^2 \left(\frac{r_s^2}{a_s^2} (1 + \Lambda^2) + 2s_s \Lambda \theta_k + \frac{r_s^2}{a_s^2} s_s^2 \theta_k^2 \right)$$

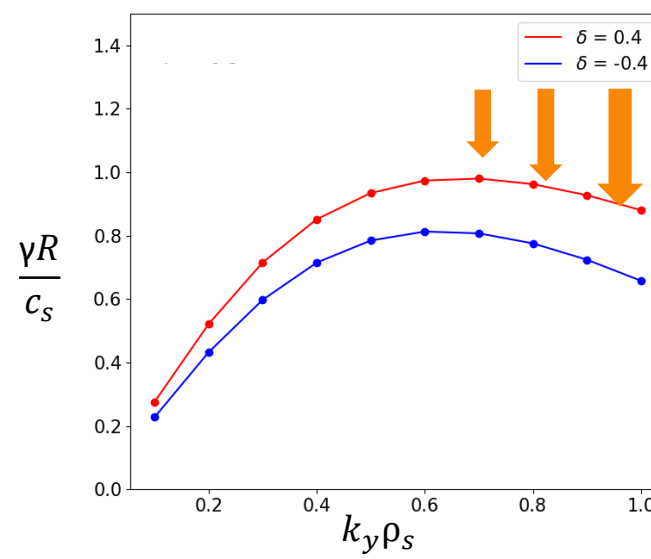
FLR STABILISATION IS KEY FOR SMALL STRUCTURES & LARGE SHEAR

$s=1.2$

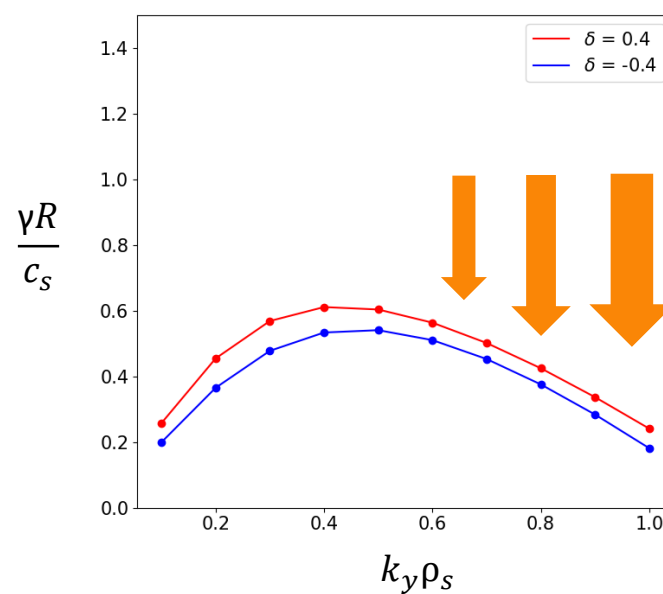
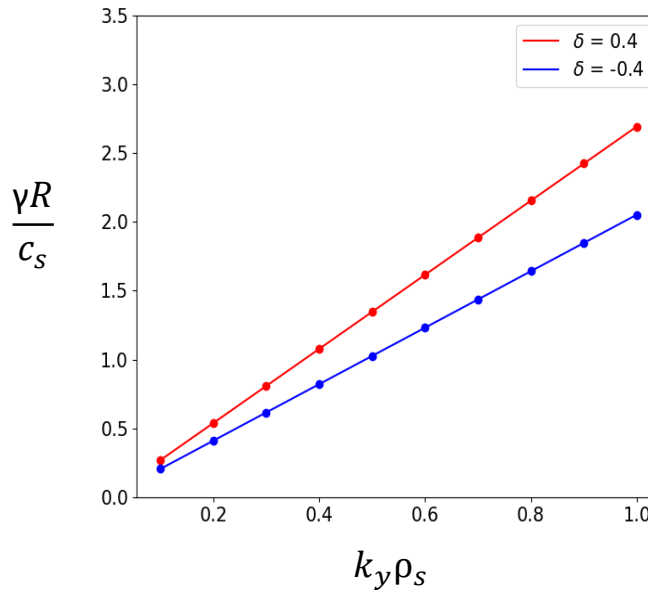
NO FLR effects, $D=1$



FLR effects, $D=1$



$s=2.0$



Reminder, FLR effects:

- are stabilising for the TEM instability
- increase with $k_\perp$
- increase with the magnetic shear s

Energy exchange

$$\begin{aligned}
 \mathcal{P}_{EM} &\equiv - \int_V dV \mathbf{E} \cdot \mathbf{j} \\
 &= \int_V dV (\phi \partial_t \rho + \mathbf{j} \cdot \partial_t \mathbf{A})
 \end{aligned}
 \longrightarrow
 \begin{aligned}
 p_{EM} &= \phi \partial_t \tilde{\rho} \\
 &= -i\omega (\phi e^{-i\omega t} + \phi^* e^{i\omega t}) (\rho e^{-i\omega t} - \rho^* e^{i\omega t}) \\
 &= 2\omega \operatorname{Im} (\rho \phi e^{-2i\omega t} + \rho \phi^*)
 \end{aligned}$$

$$P_{EM} \propto 2 \int d^3x [\omega_r \operatorname{Im} (\rho \phi^*) + \gamma \operatorname{Re} (\rho \phi^*)]$$

$$\begin{aligned}
 P_{EM} &\propto -2e_a^2 \omega_r \operatorname{Im} \left[\sqrt{\frac{2}{\pi}} \int_{\lambda_-}^{\lambda_+} \frac{d\lambda}{\overline{\Omega}_b} \int_0^{+\infty} d\mathcal{E} \sqrt{\mathcal{E}} e^{-\mathcal{E}} \left[1 - \frac{\hat{\omega}_{*T} \left(\mathcal{E} - \frac{3}{2} + \frac{1}{\eta} \right) - \hat{\omega}}{\overline{\Omega}_d \mathcal{E} - \hat{\omega} - i\hat{\nu}_0 \mathcal{E}^{-3/2}} \right] W^2(\mathcal{E}, \theta_b) \right] \\
 &\quad - 2e_a^2 \gamma \operatorname{Re} \left[\sqrt{\frac{2}{\pi}} \int_{\lambda_-}^{\lambda_+} \frac{d\lambda}{\overline{\Omega}_b} \int_0^{+\infty} d\mathcal{E} \sqrt{\mathcal{E}} e^{-\mathcal{E}} \left[1 - \frac{\hat{\omega}_{*T} \left(\mathcal{E} - \frac{3}{2} + \frac{1}{\eta} \right) - \hat{\omega}}{\overline{\Omega}_d \mathcal{E} - \hat{\omega} - i\hat{\nu}_0 \mathcal{E}^{-3/2}} \right] W^2(\mathcal{E}, \theta_b) \right]
 \end{aligned}$$

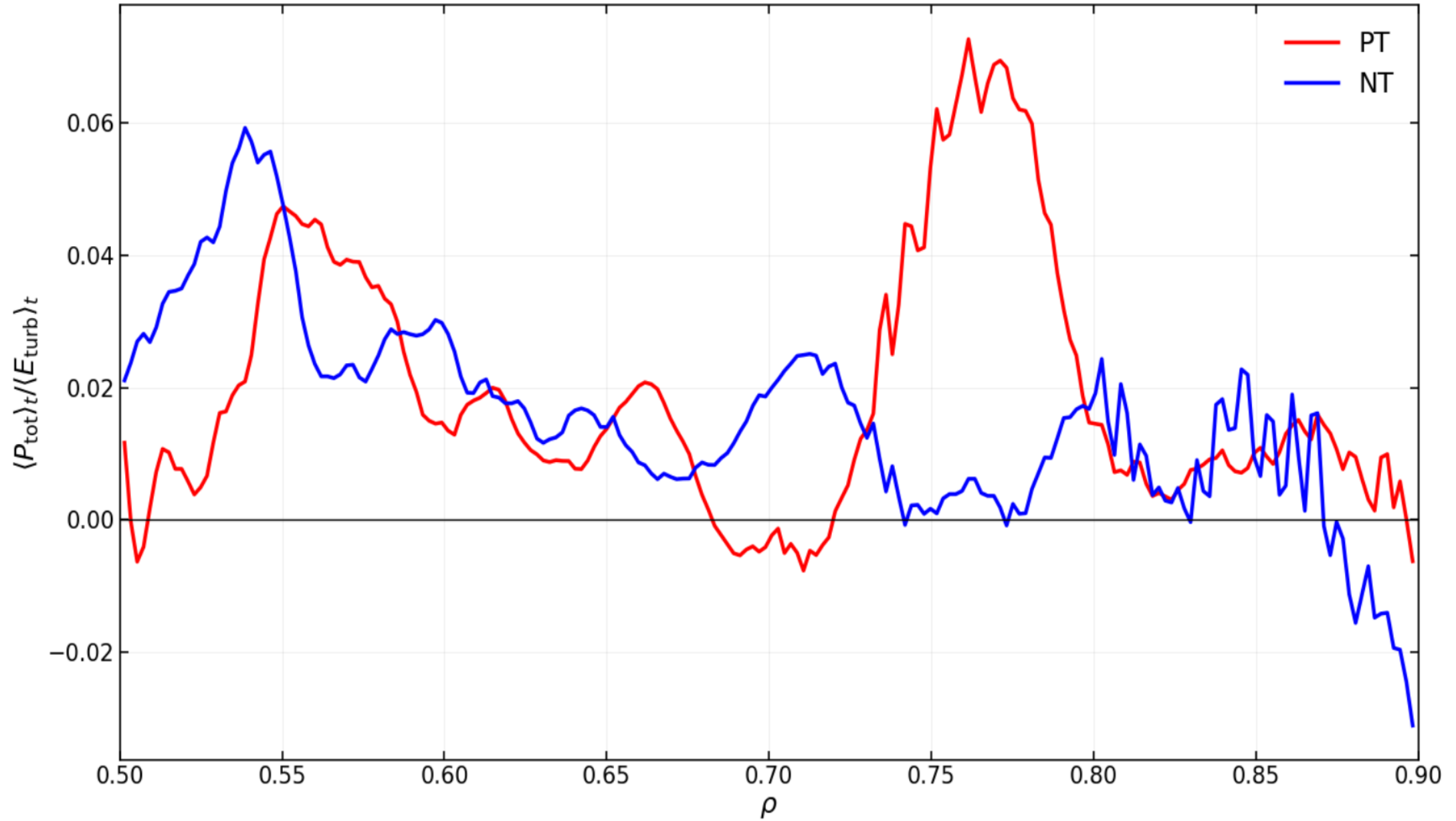
W function

$$\langle \tilde{\phi}_\omega \rangle_b = \int_0^{2\pi} \frac{d\alpha_b}{2\pi} \hat{\phi}(\hat{\theta}) \exp\left(-i \frac{\delta_b}{d} \sqrt{\mathcal{E}} \hat{\delta} \hat{\theta}\right)$$

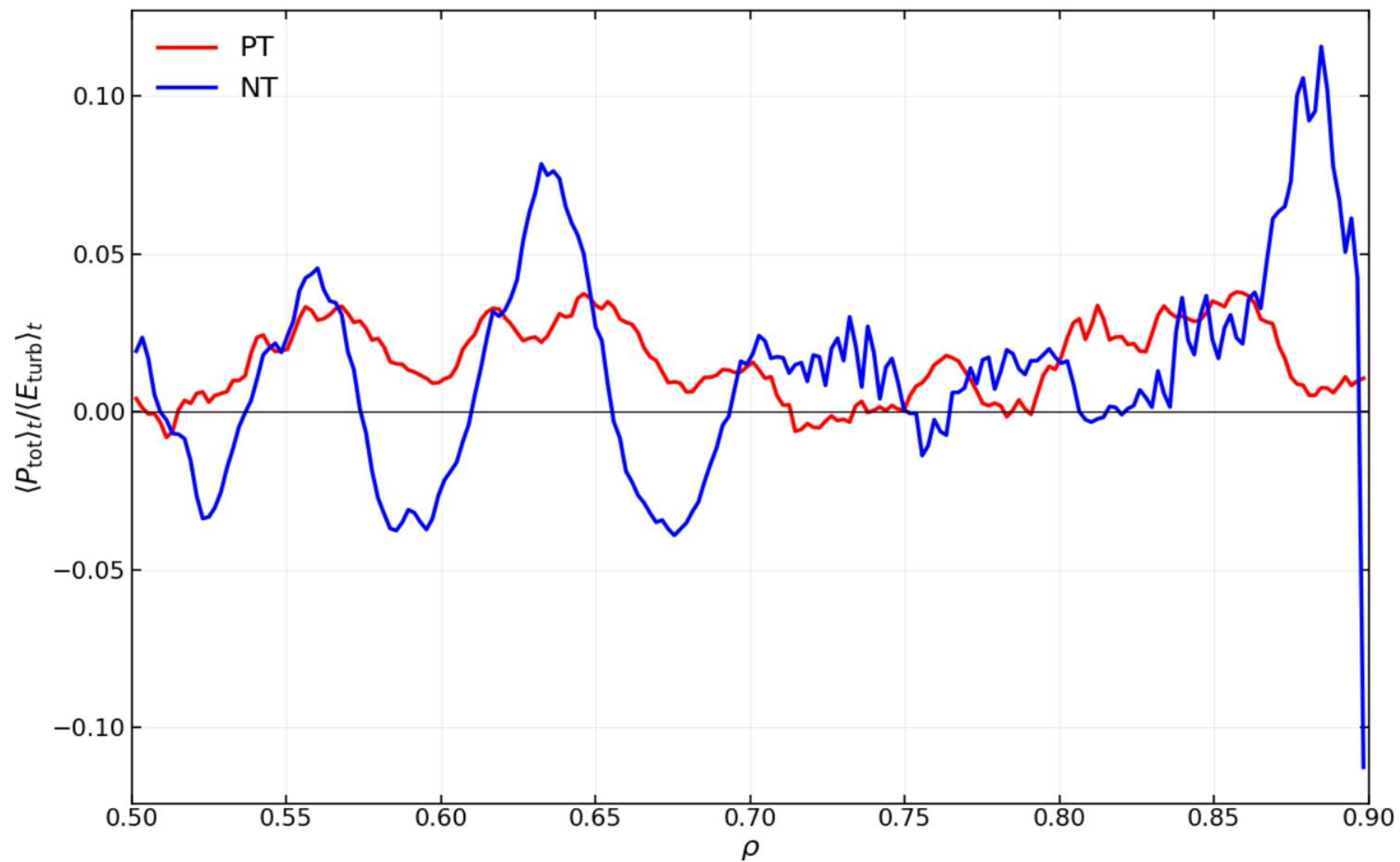


$$\begin{aligned} W(\mathcal{E}, \theta_b) &= \exp\left(-\frac{D}{2} \theta_b^2\right) \\ &\quad \int_0^{2\pi} \frac{d\alpha_b}{2\pi} \exp\left[\left(-i \frac{\delta_b}{d} \sqrt{\mathcal{E}} \sin(2\alpha_b) + D \cos(2\alpha_b)\right) \frac{\theta_b^2}{2}\right] \\ &= \exp\left(-\frac{D}{2} \theta_b^2\right) I_0\left[\left(D^2 - \frac{\delta_b^2}{d^2} \mathcal{E}\right)^{1/2} \frac{\theta_b^2}{2}\right] \end{aligned}$$

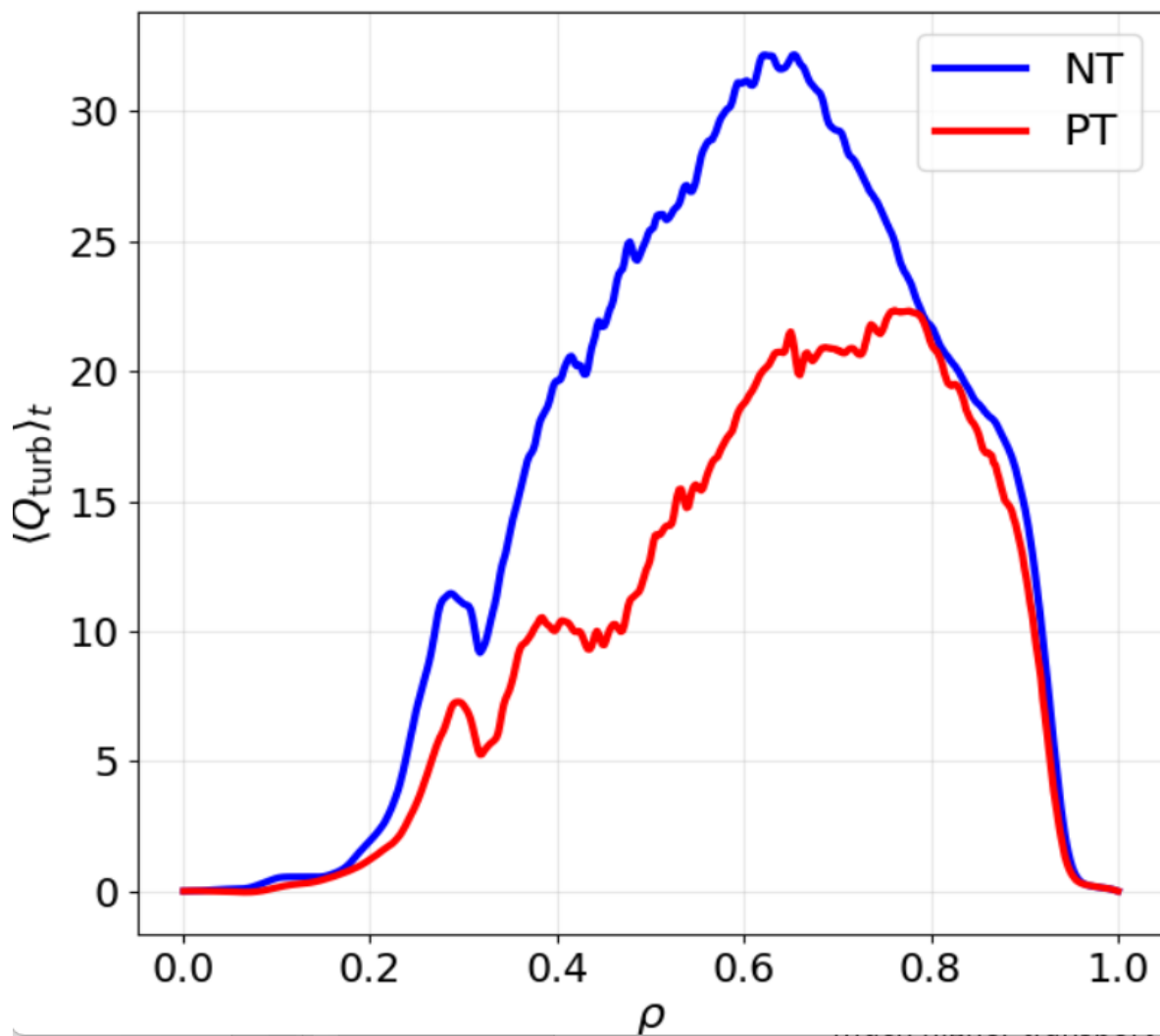
Uniform boundary



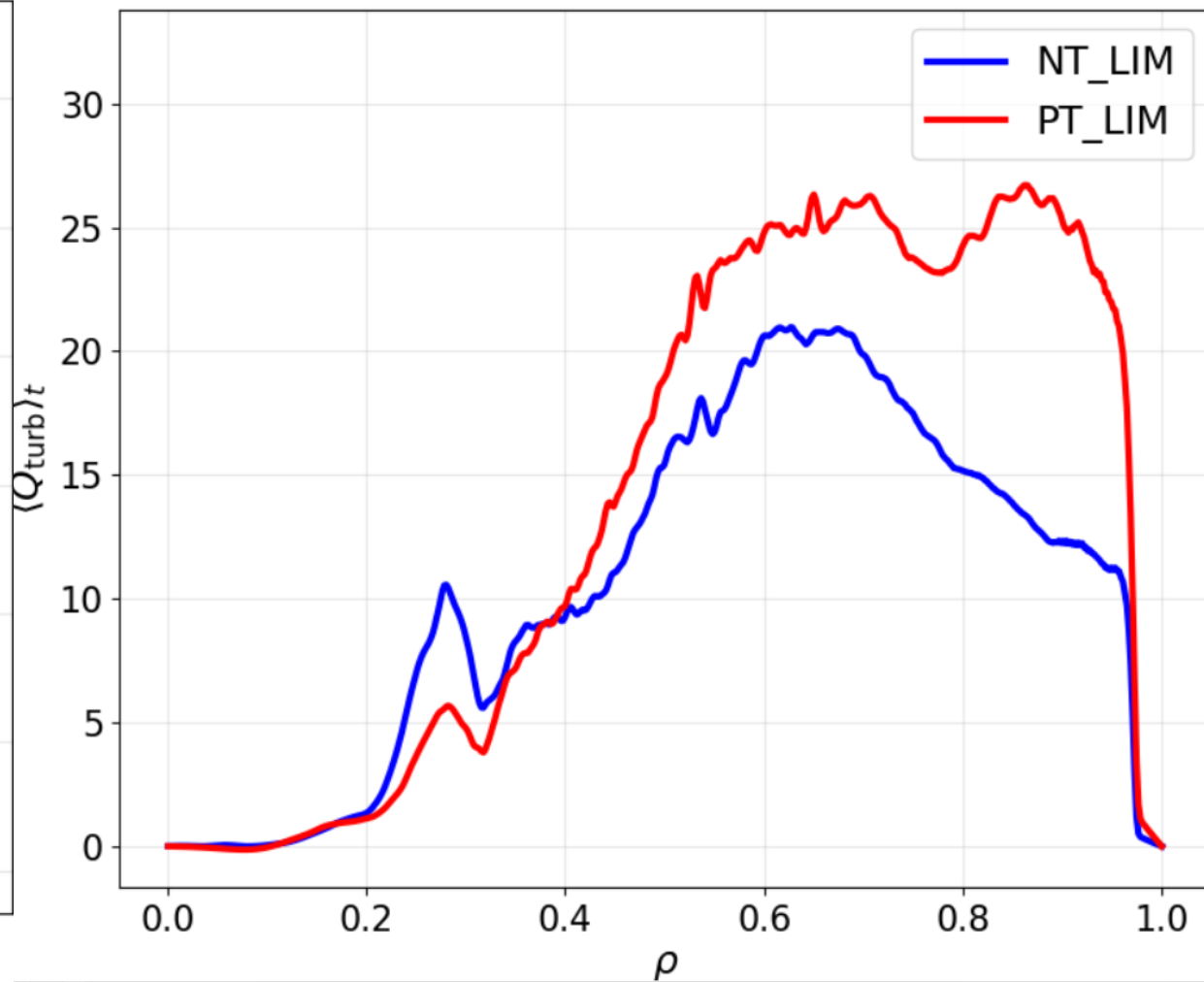
Non-uniform boundary



UNIFORM MASK

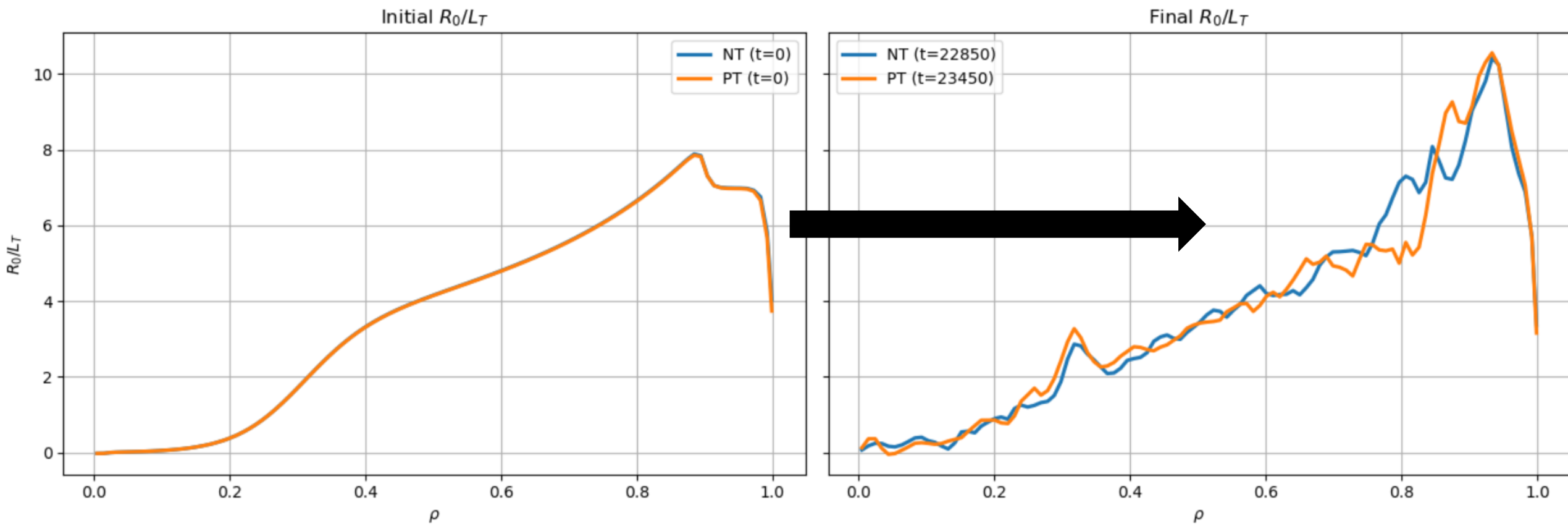


LIMITER-LIKE MASK

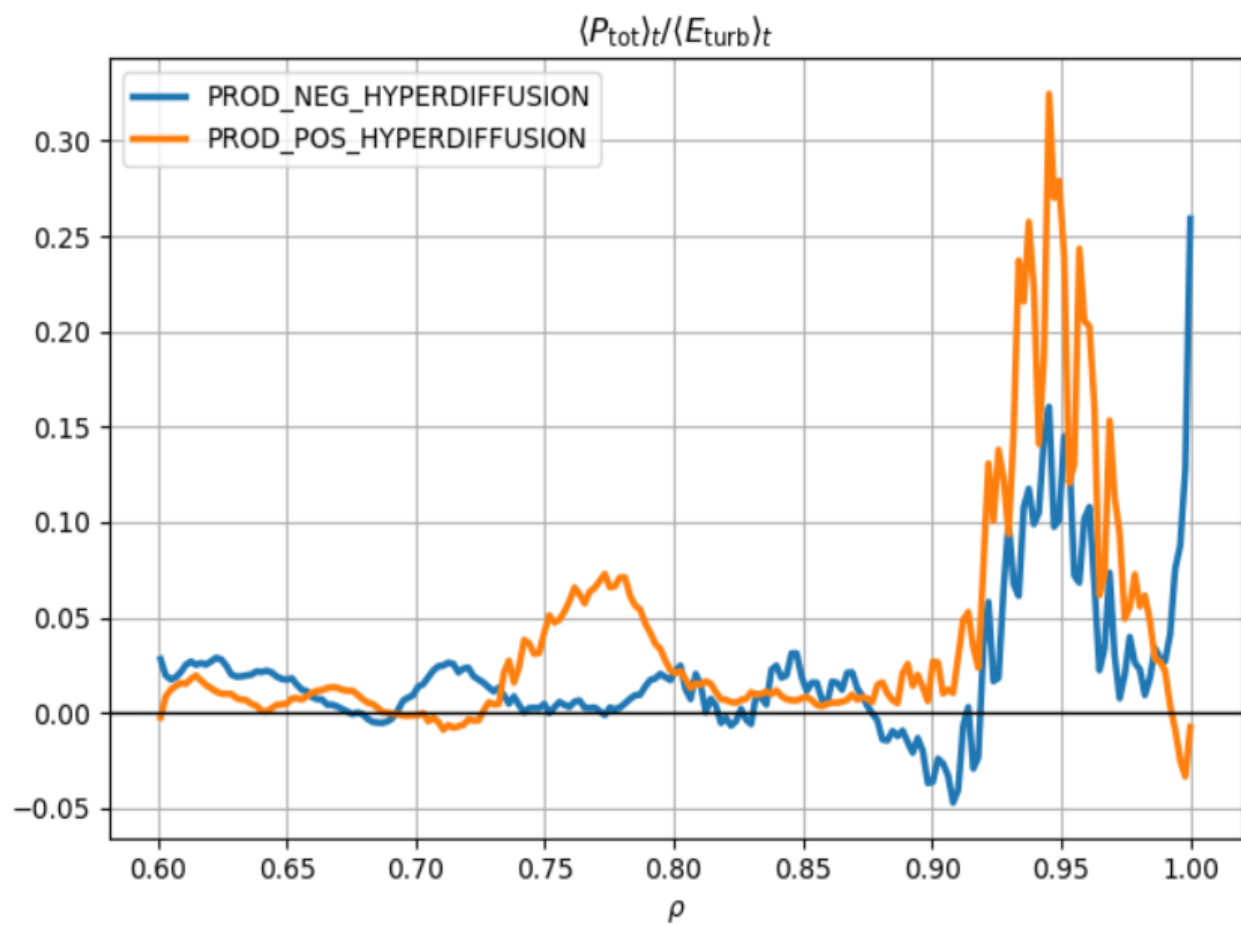


Much higher transport in PT with limiter
A bit lower in NT with limiter

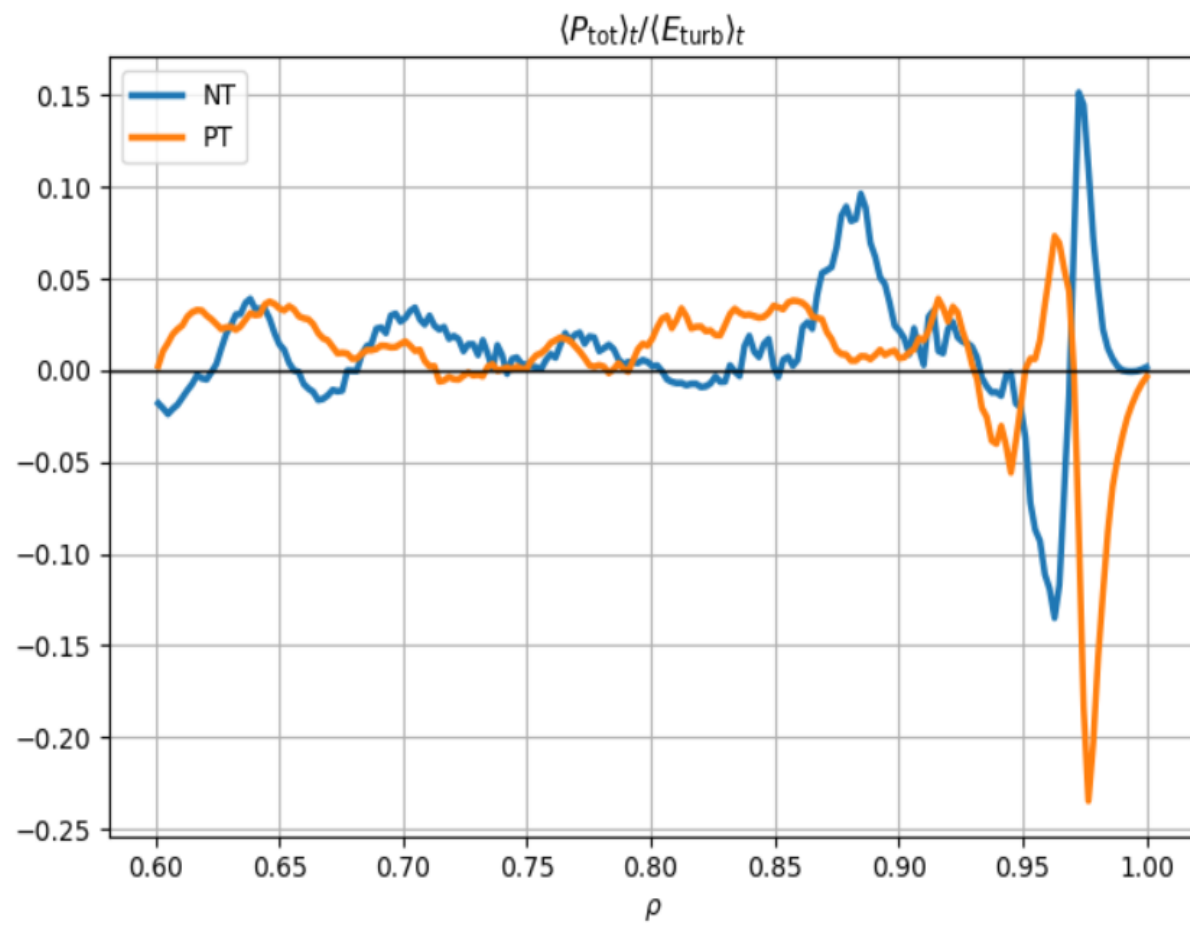
Ions



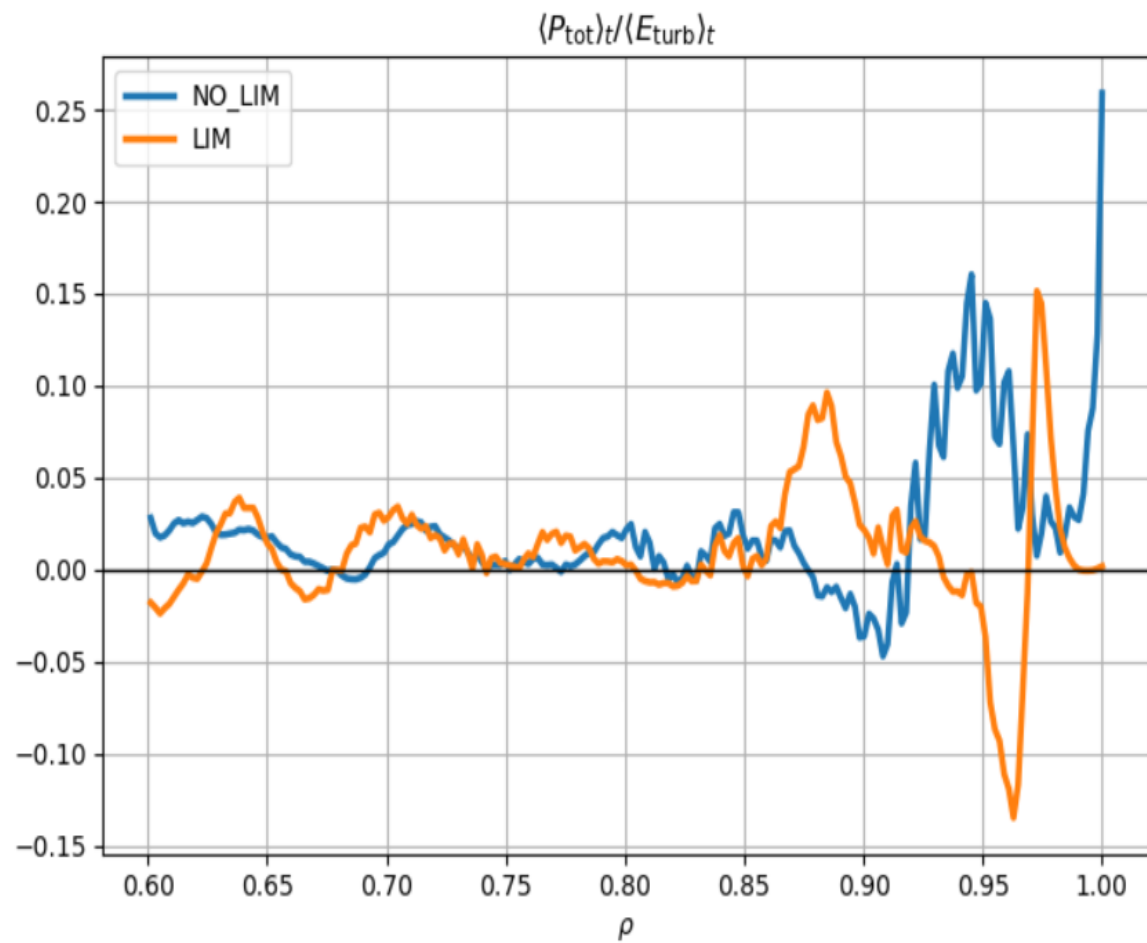
UNIFORM



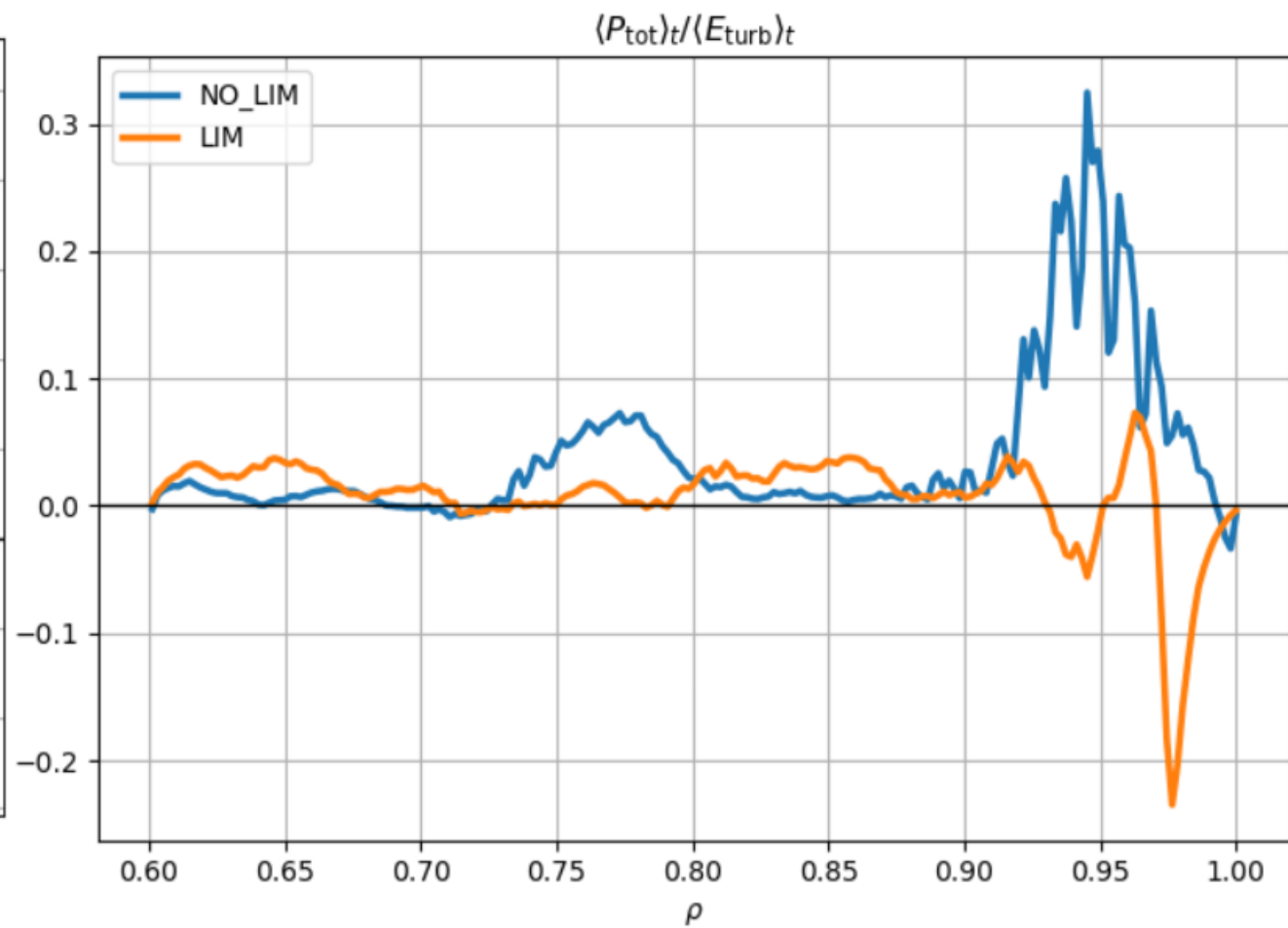
LIMITER-LIKE



NEG



POS

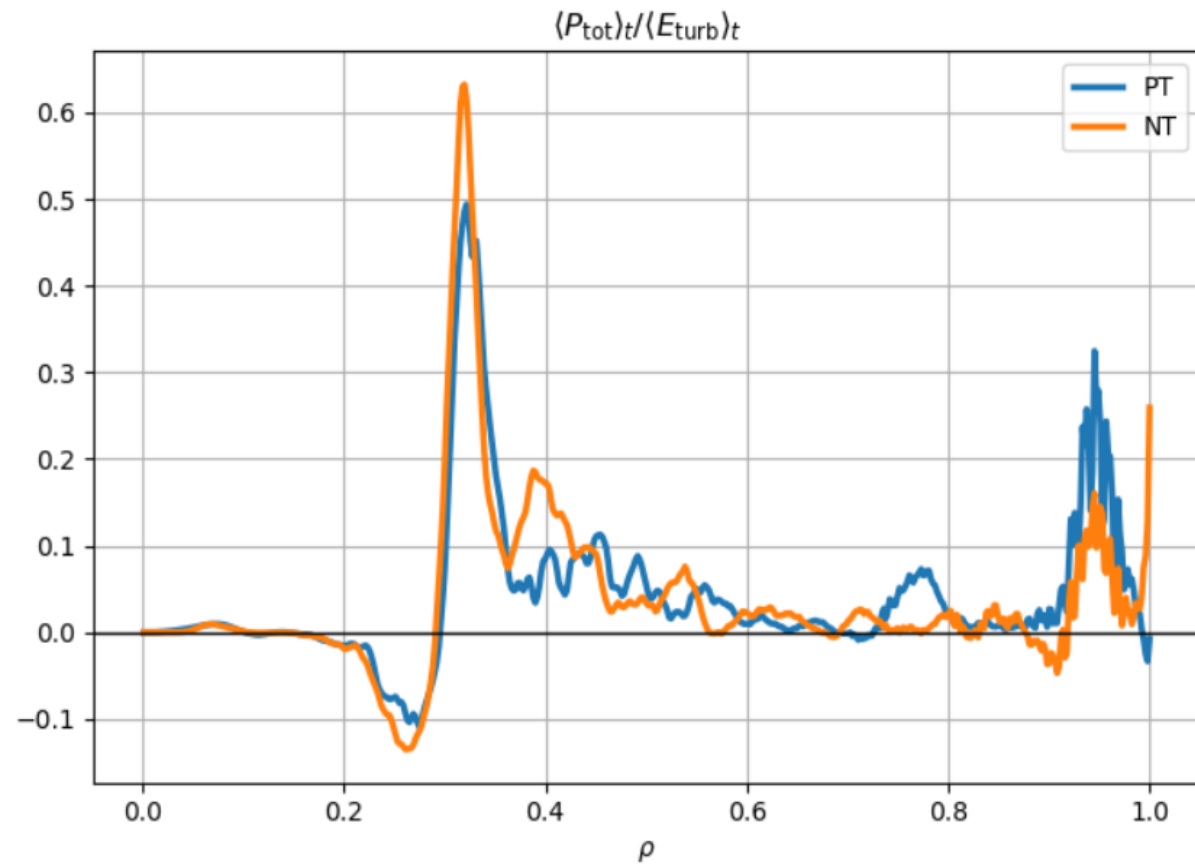


$$P_{\text{tot}} = \frac{1}{2} \frac{\partial \langle u_{E\theta} \rangle^2}{\partial t} = -\langle u_{E\theta} \rangle \frac{1}{r^2} \frac{\partial}{\partial r} [r^2 (\pi + \pi^*)]$$

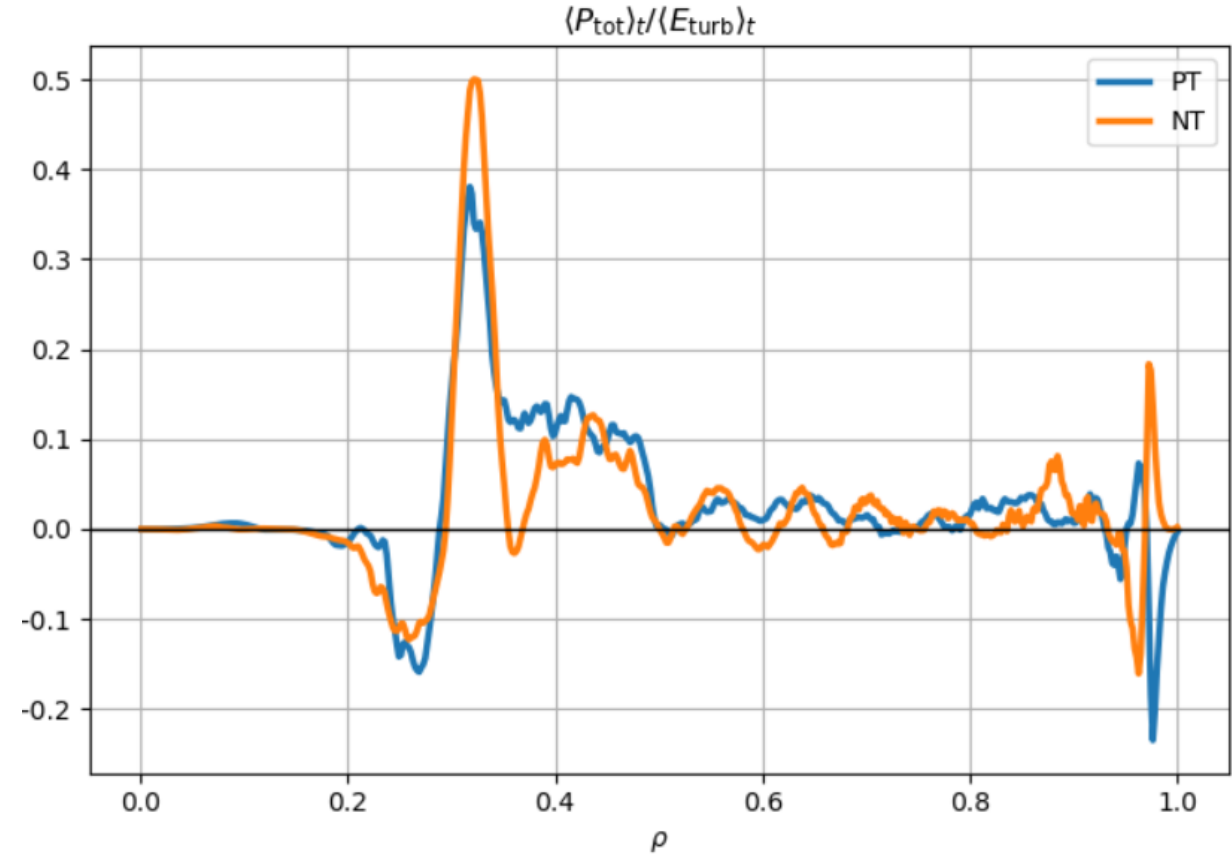
$$\mathcal{E}_{\text{turb}}^{\phi} = \langle \tilde{v}_E^2 \rangle_{\theta} = \left\langle \left(\partial_r \delta \phi^{(\vartheta)} \right)^2 \right\rangle_{\theta} + \left\langle \left(\frac{1}{r} \partial_{\theta} \delta \phi^{(\vartheta)} \right)^2 \right\rangle_{\theta}$$

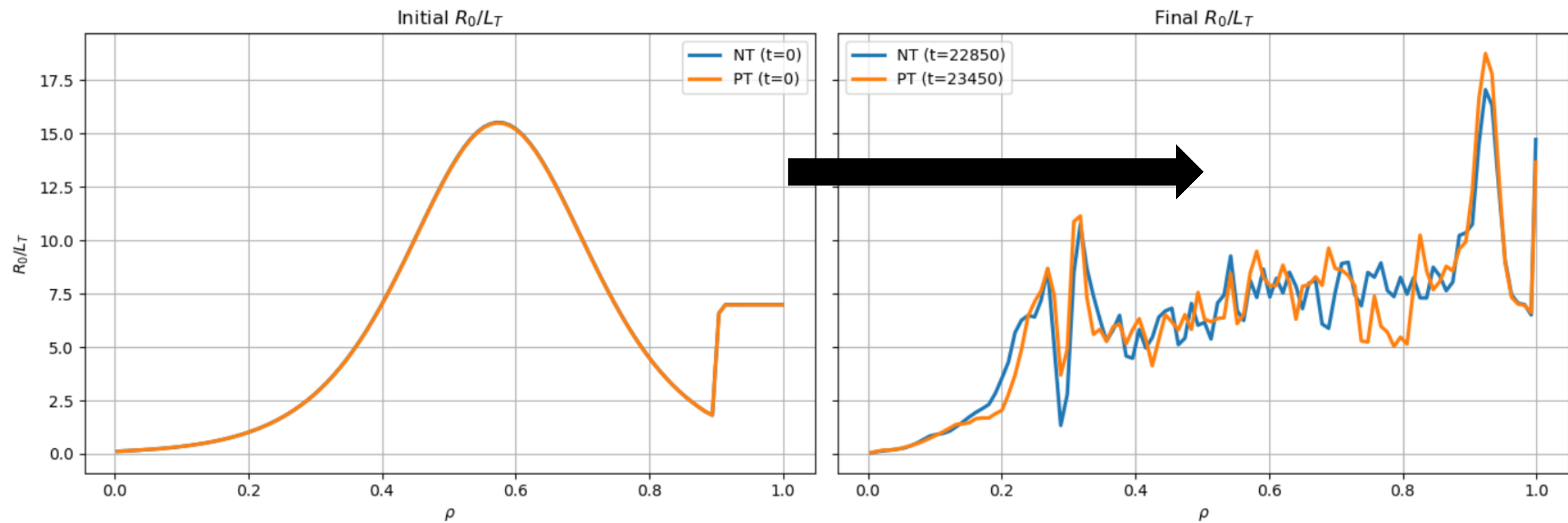
$$\text{delta phi} = \text{phi3D} - \text{phi3D}_{(n=0)}$$

Without limiter



With limiter



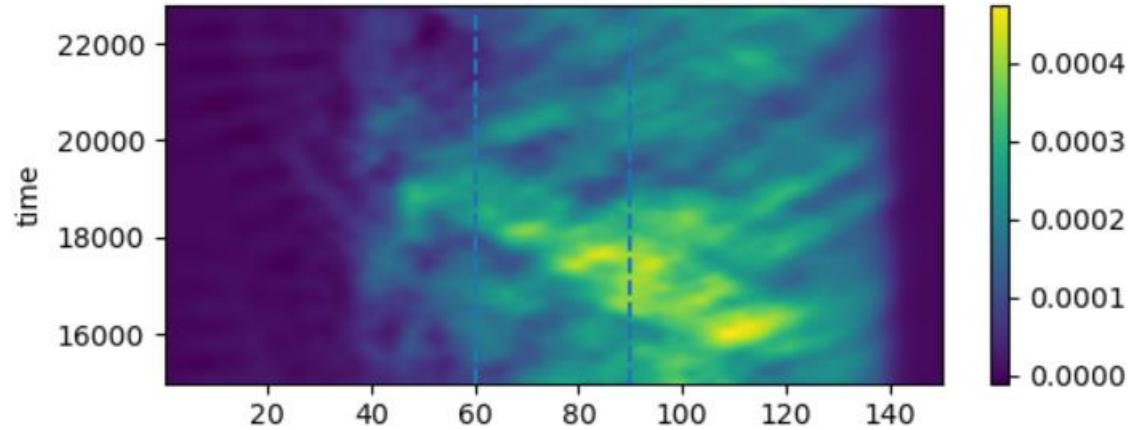


Electronic profiles decrease a lot → getting close to marginality for TEMs

Fluxes

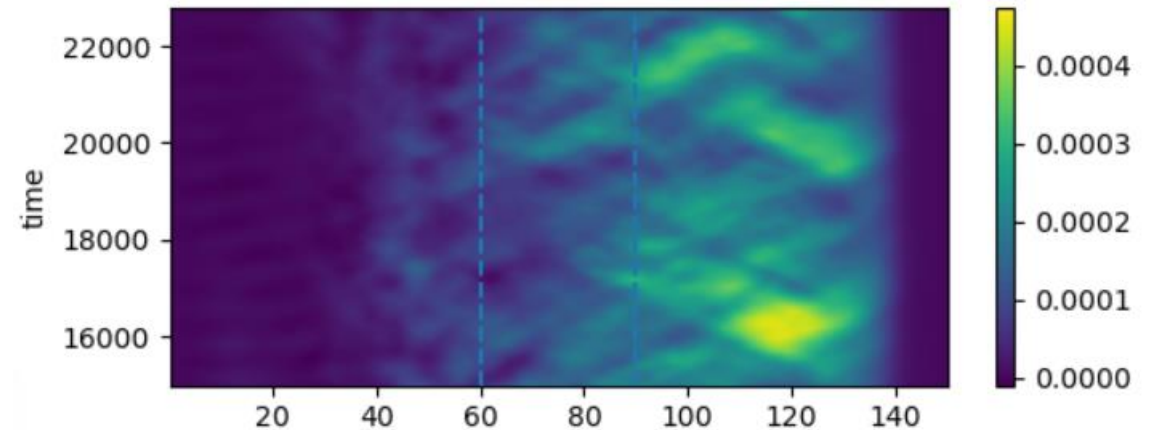
NEGATIVE

Turbulent heat flux



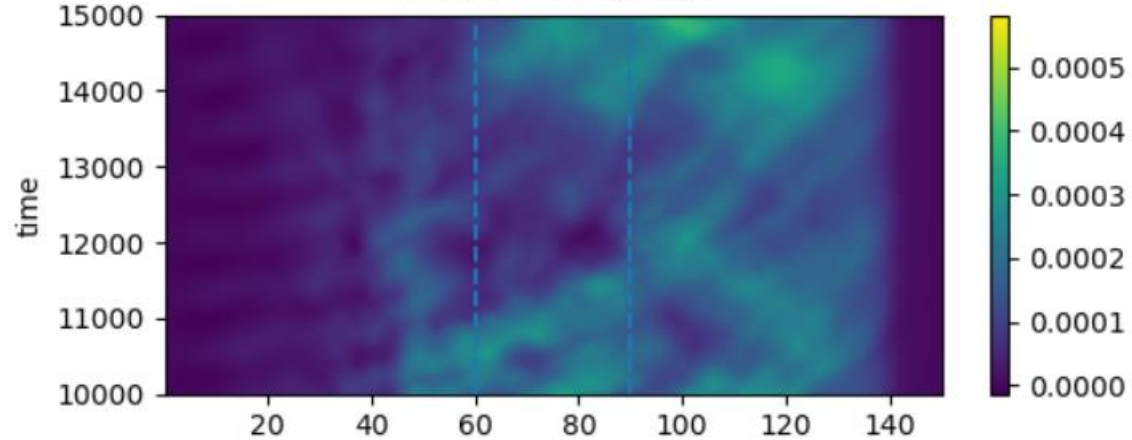
POSITIVE

Turbulent heat flux



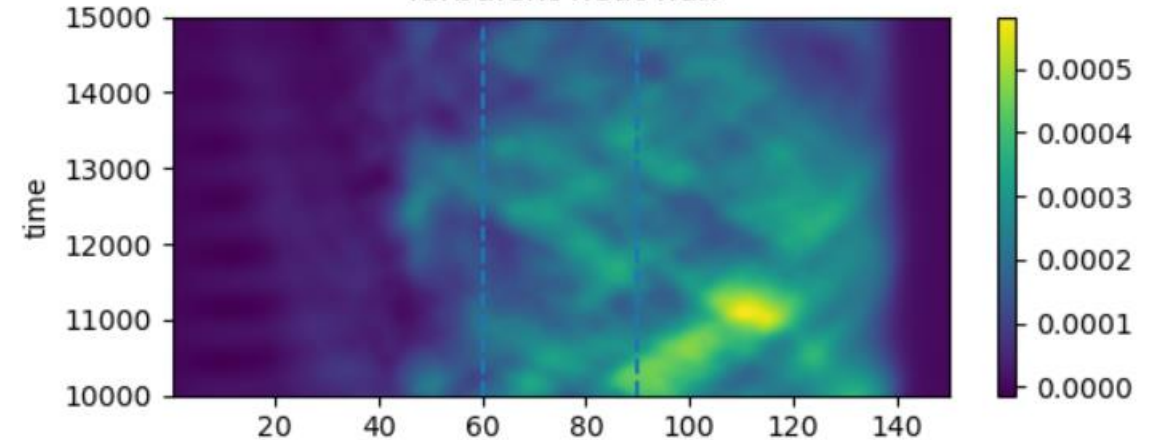
NEGATIVE

Turbulent heat flux



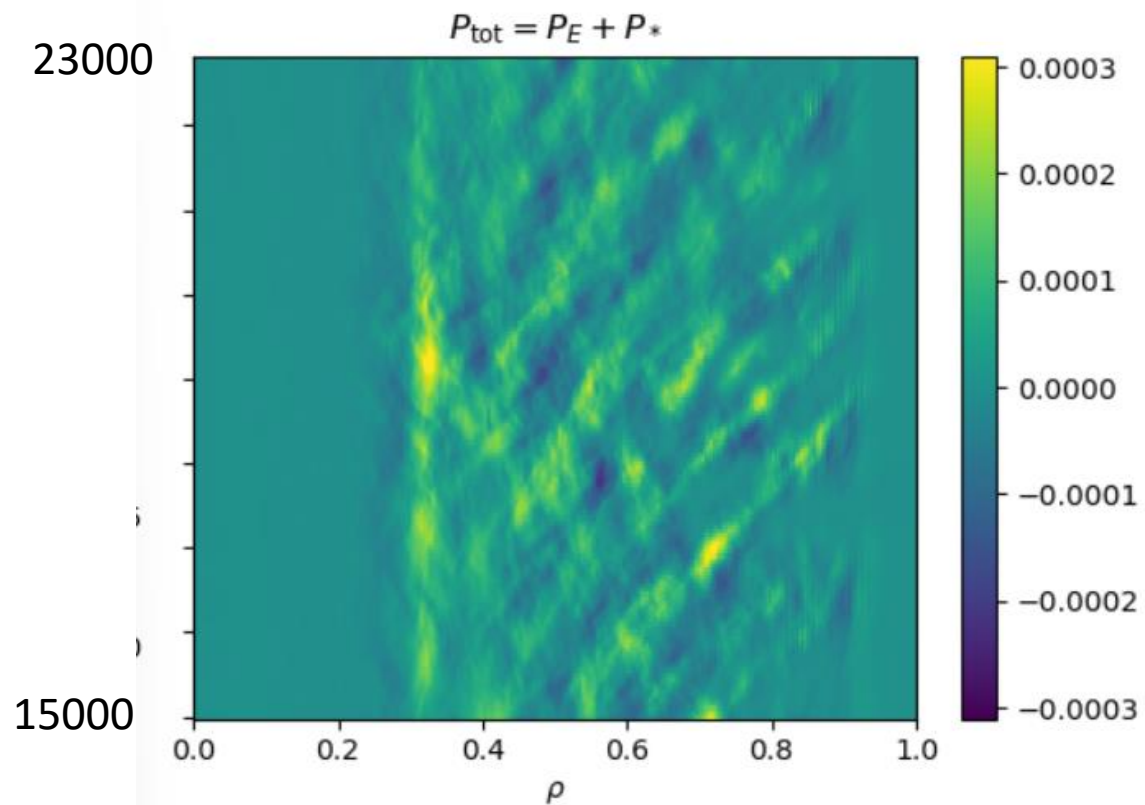
POSITIVE

Turbulent heat flux

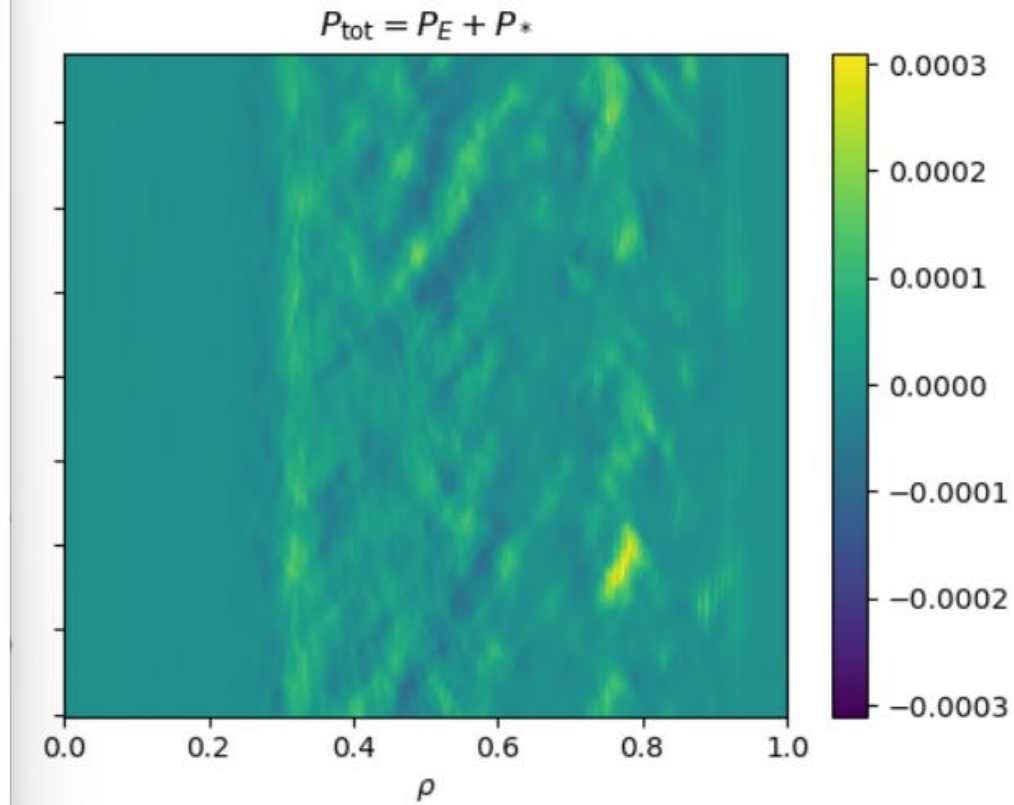


Since they are flux surface averaged, isn't the fact that surfaces are different already taken into account?
If multiplying by S , Q_{NT} will increase even more wrt Q_{PT}

negative

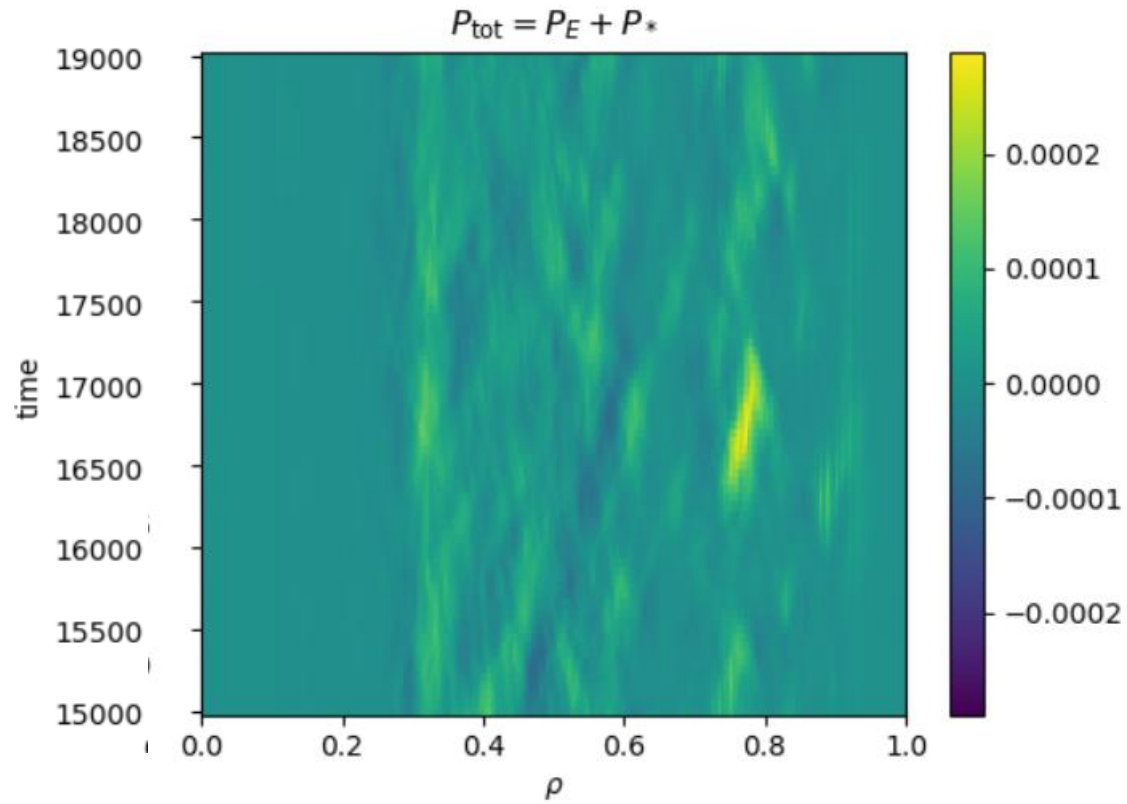


positive

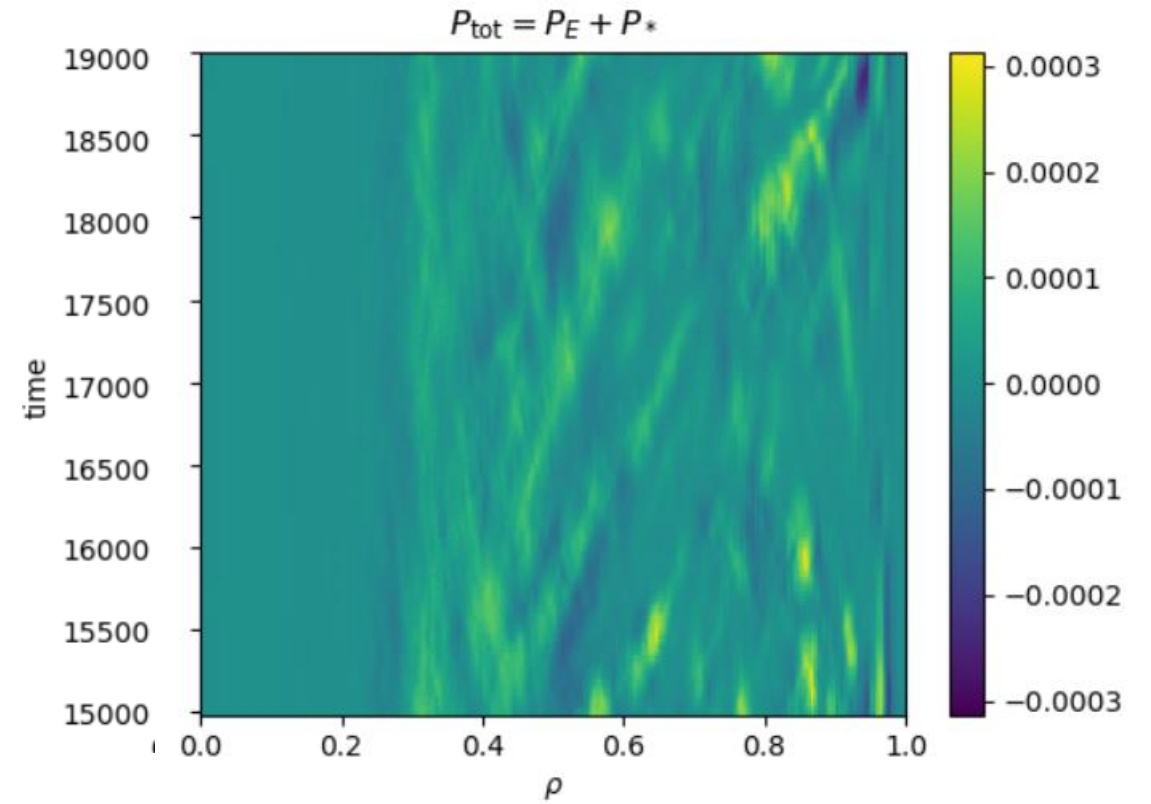


$$P_{\text{tot}} = \frac{1}{2} \frac{\partial \langle u_{E\theta} \rangle^2}{\partial t} = -\langle u_{E\theta} \rangle \frac{1}{r^2} \frac{\partial}{\partial r} [r^2 (\pi + \pi^*)]$$

Without limiter

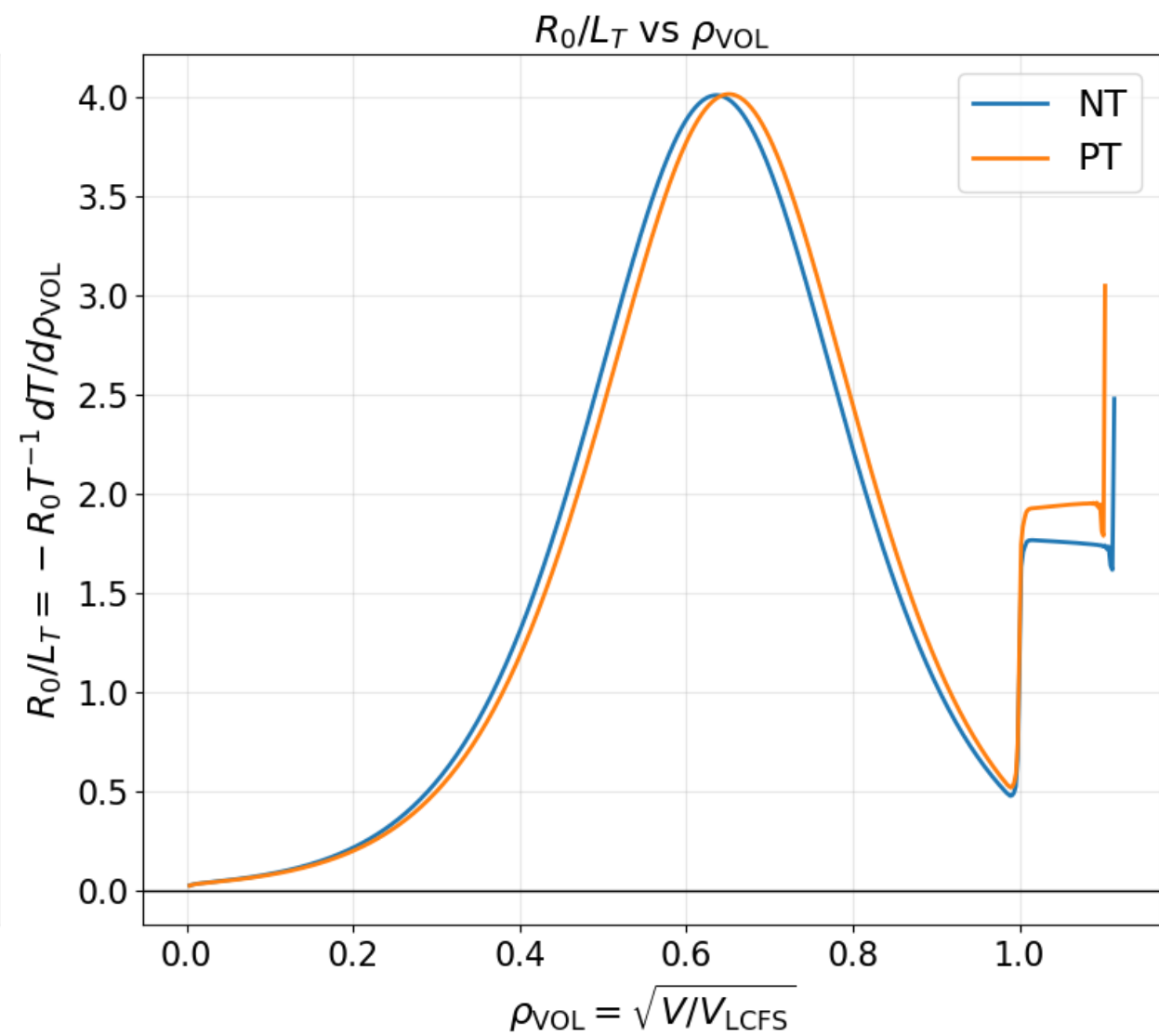
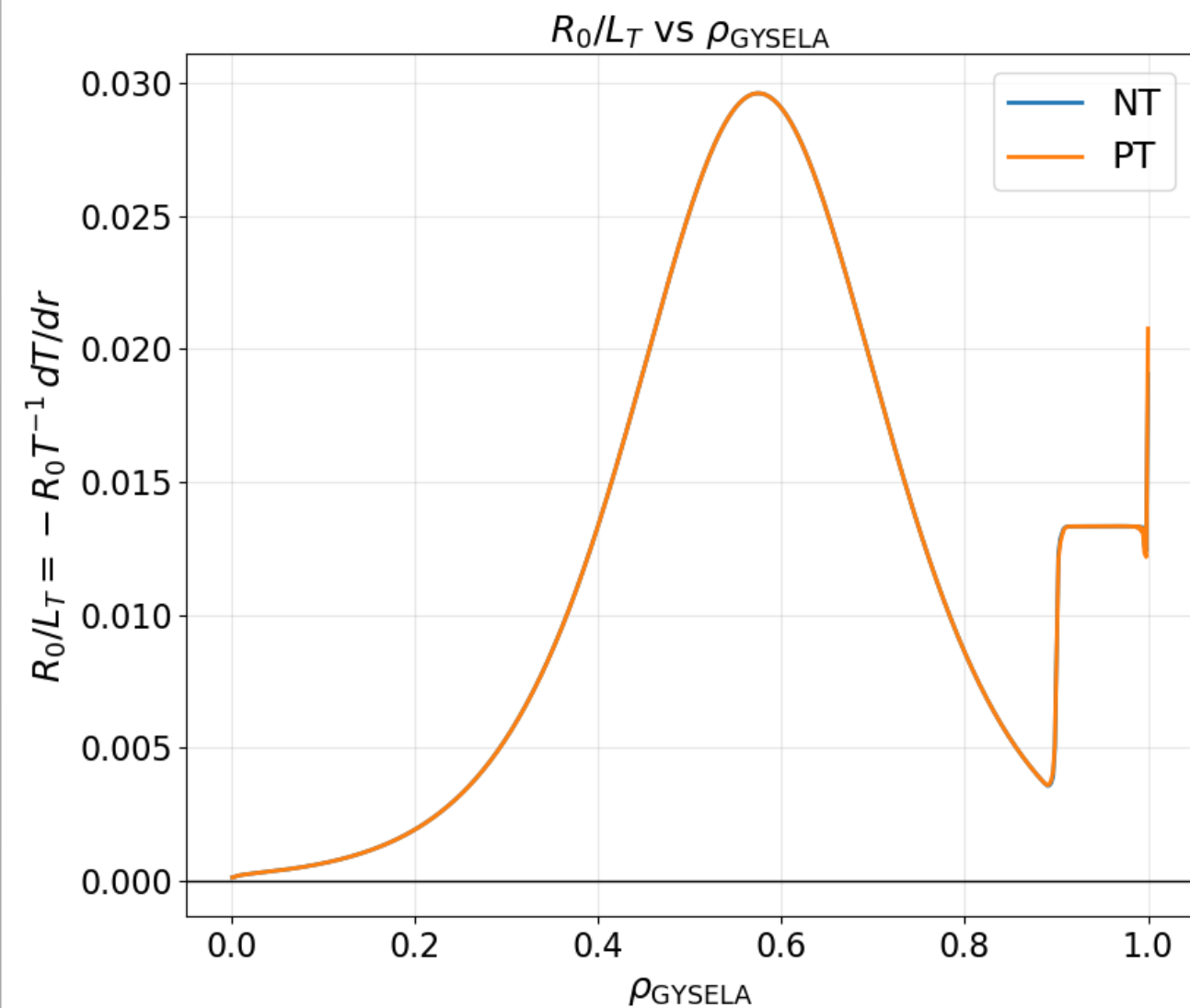


With limiter

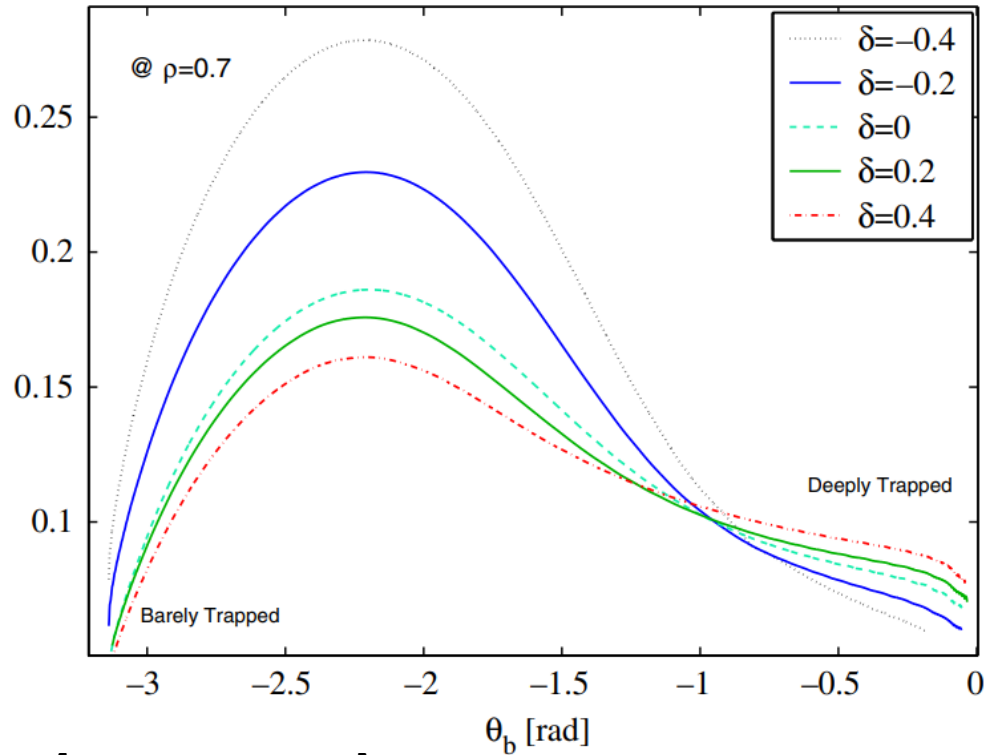


Higher turbulence $\rightarrow$ higher production of zonal flows, but the point is more than transport is more avalanche-like (no change in the slope)

Time-averaged temperature-gradient comparison

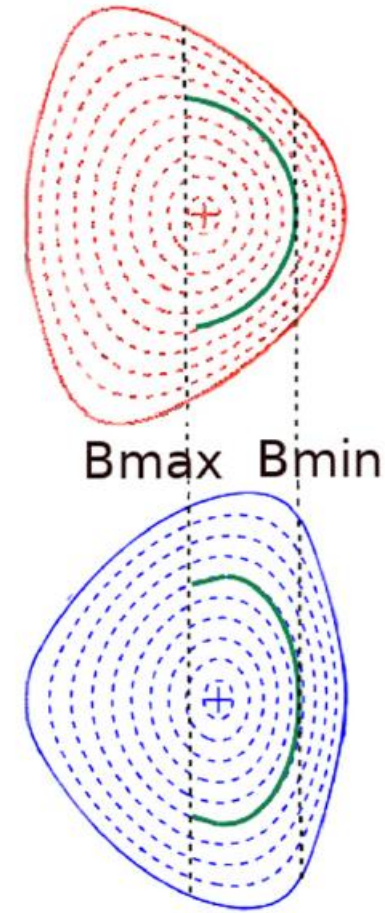


TRIANGULARITY MODIFIES THE PRECESSION FREQUENCY

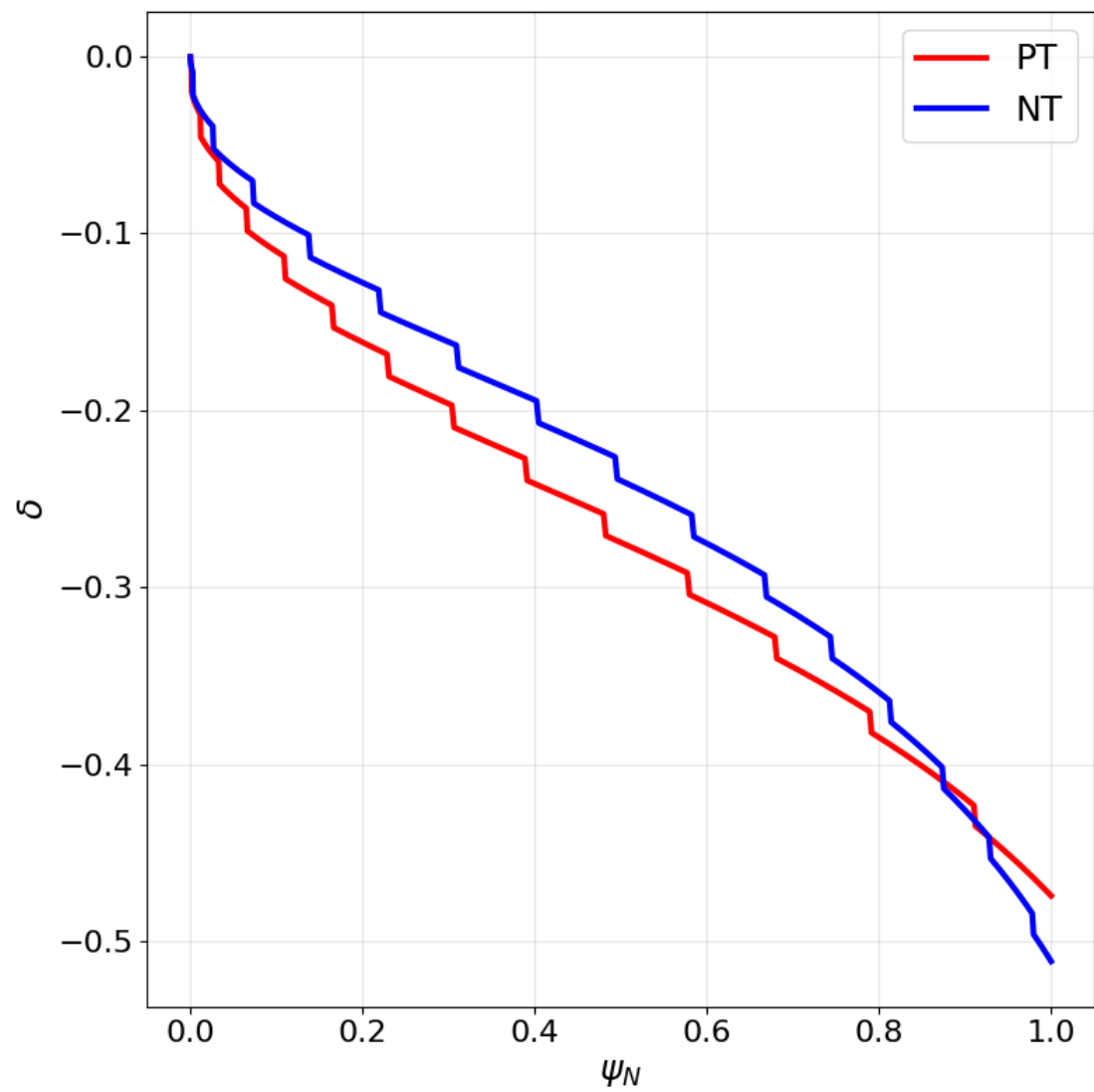


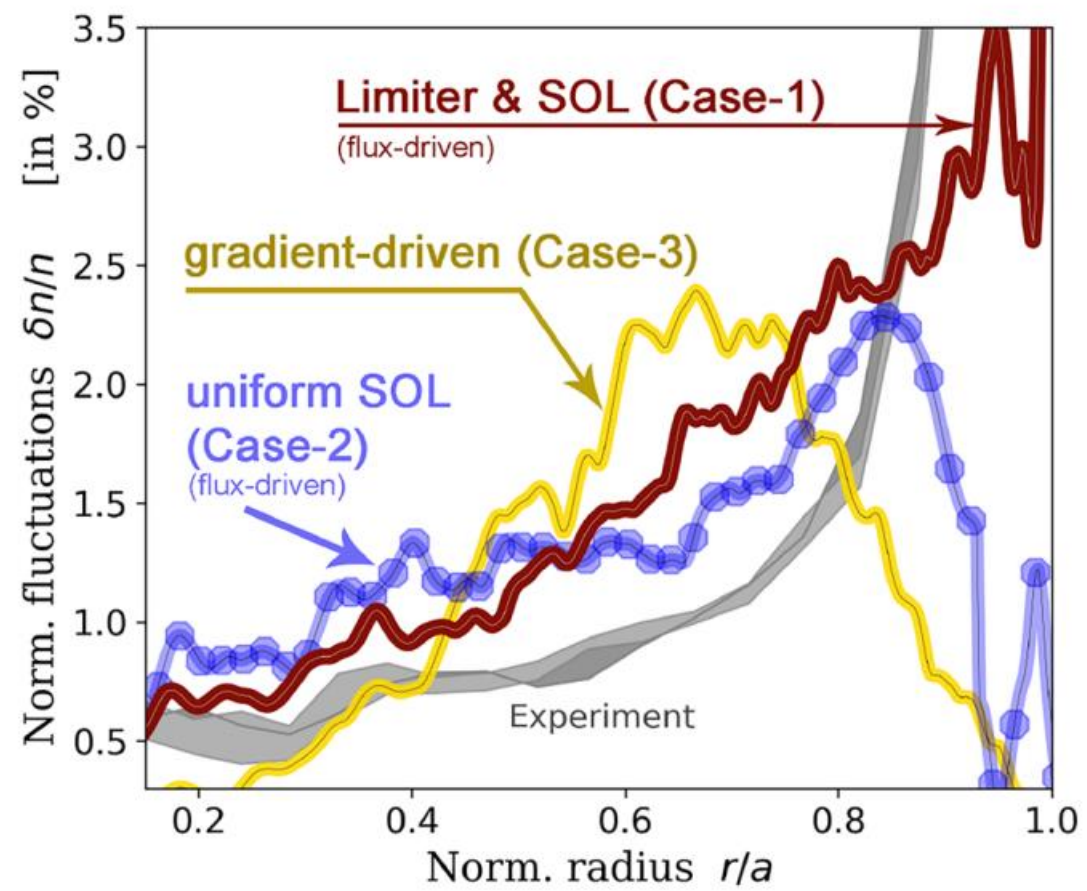
[Marinoni 2009]

[Graves 2013]



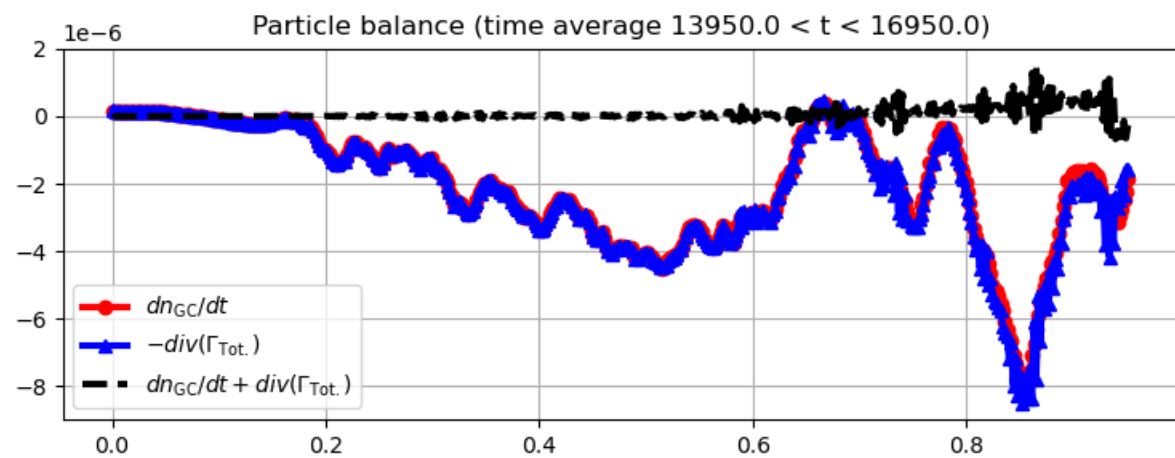
Different triangularity means different exploration of the space for the same trapped electron: the same trapped electron has a different drive





Conservation errors

POS LIMITER



NEG LIMITER

