Physics of ITG transport reduction in negative triangularity plasmas

Rameswar Singh and P H Diamond
UCSD

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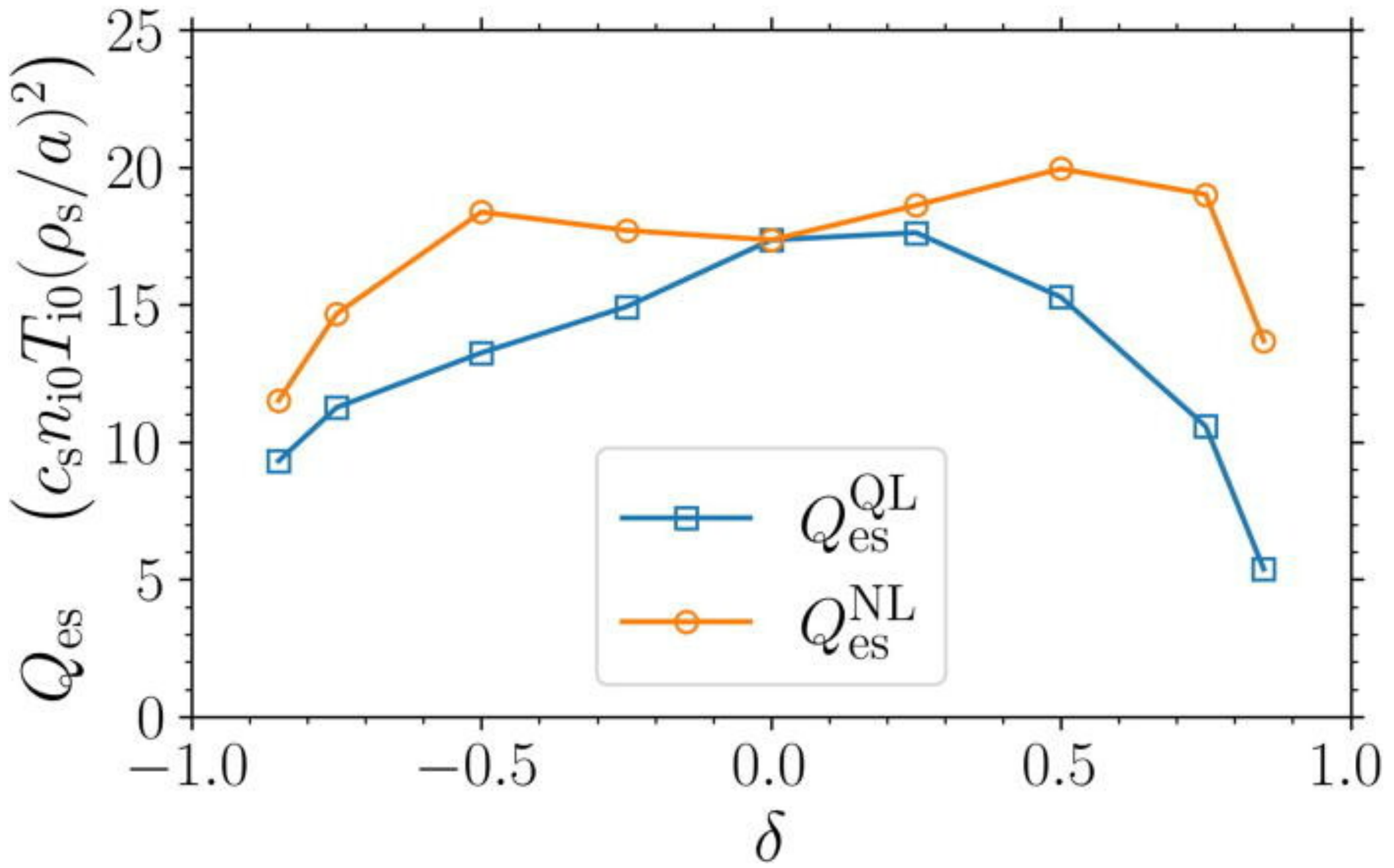
Motivation

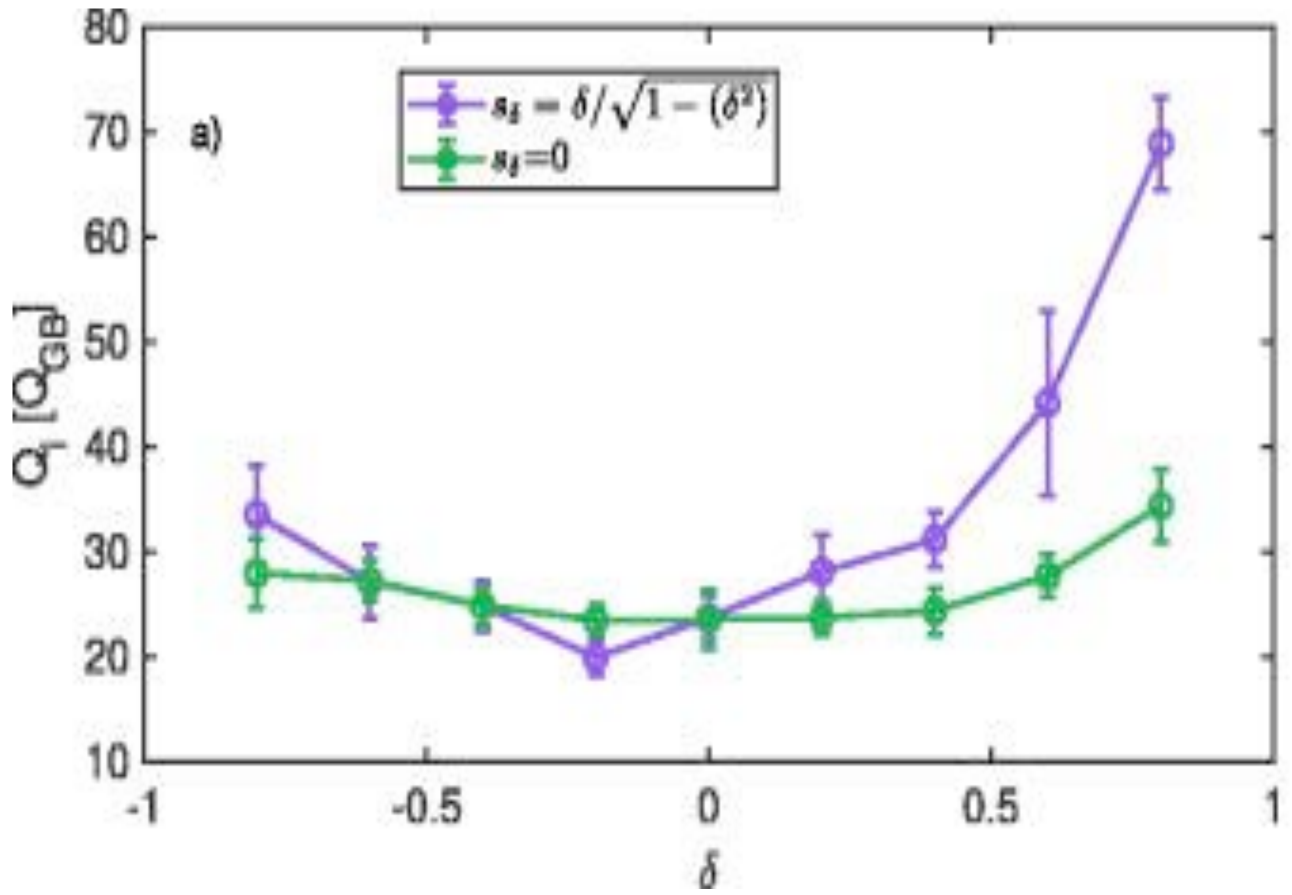
- Improved confinement in NT over PT tokamak experiments is now well established. [Y Camenen+ 2007, M Fontana+2018, M Austin+ 2019, A Marinoni+ 2019, S Coda+2022,…]

- Theoretical understanding lacking! TEM/ITG stabilization often invoked to explain improved confinement in NT.
  - TEM stabilization by precession drift reduction. [A Marinoni+ 2009]
  - ITG turbulence and transport for NT remains poorly understood.

- Previous simulations lacked insights on physical mechanism behind the beneficial effects of NT on ITG . Sometimes, not even general agreement on basic trends with δ!



[J M Duff+ 2022]



[G Merlo+ 2023]

Questions remain…

- What causes the reduced linear growth rate for NT?
- What explains the δ-trend of heat flux?
  - Relative role of fluctuations amplitude and cross-phase in determining the heat flux for NT?
  - Saturation by zonal flows well known in GK simulations [Z Lin+ 1998,1999,…others].
    - What happens to self-generated zonal flow shear for NT?
    - What sets the strength and coherence of zonal shear ? → Gyrokinetic entropy transfer analysis?

Simulation set up

- **Disclaimer:** This is a physics study, not an experimental validation exercise.

- GENE flux tube simulations of collisionless ITG turbulence with adiabatic electrons.

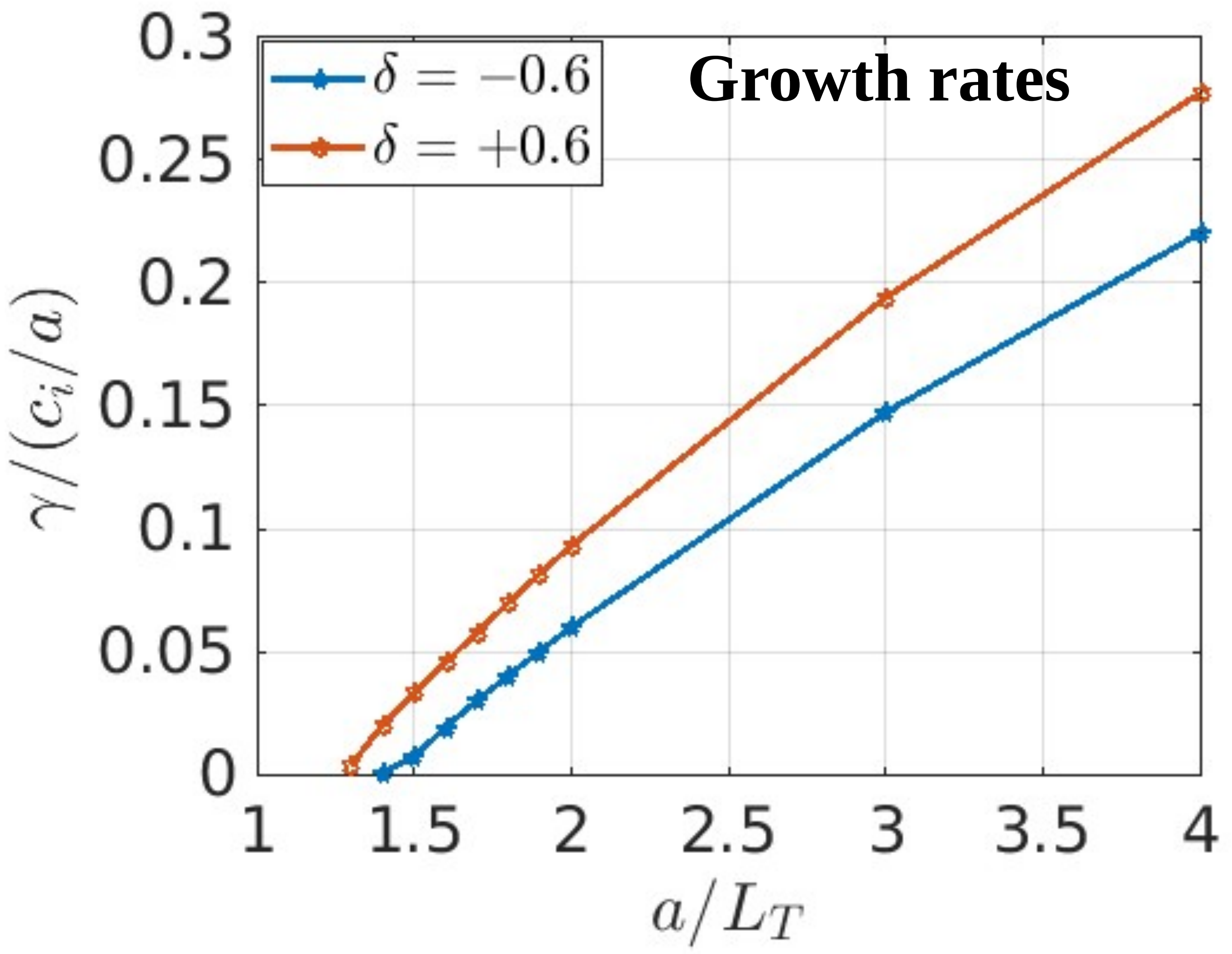
- **Shaping parameters:** aspect ratio $a/R = 1/3$, safety factor $q = 2$, magnetic shear $\hat{s}$=1, triangularity $\delta = [varied]$, triangularity gradient $S_\delta = \frac{r\frac{\partial\delta}{\partial r}}{\sqrt{(1-\delta^2)}} = \frac{\delta}{\sqrt{(1-\delta^2)}}$, elongation $\kappa = 1$, elongation gradient $S_\kappa = \frac{r}{\kappa}\frac{\partial\kappa}{\partial r} = 0$, squareness ζ =0, squareness gradient $S_\zeta = r\frac{\partial\zeta}{\partial r} = 0$, MHD alpha parameter $\alpha_{MHD} = -q^2R\frac{d\beta}{dr} = 0$, Shafranov shift gradient $R_0' = 0$. (Standard GA + shaping)

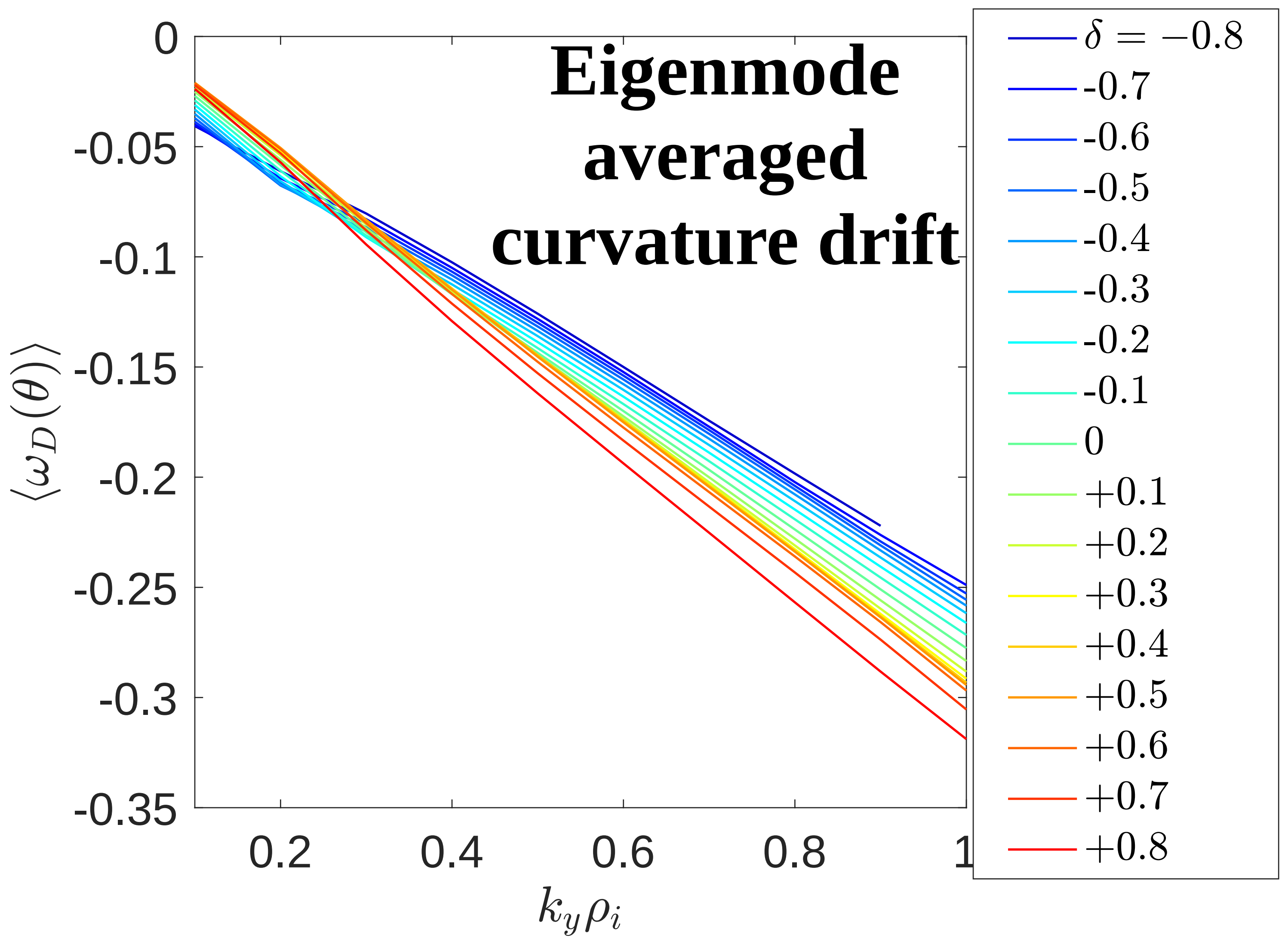
- **Resolutions:** $n_x = 257$, $n_{k_y} = 48$, $n_z = 64$, $n_{v_\parallel} = 48$, $n_\mu = 8$, $L_{v_\parallel} = 3$, $L_\mu = 9$, $L_x = [120-140]\rho_i$, $k_{y,min}\rho_i = 0.05$, hyp_z=2, hyp_v=0.2

- **Gradients:** $a/L_n = 1$, $a/L_T = 4$ [fixed]
- **Collisionless:=> no frictional damping of ZF.**
- **No neoclassical transport.**

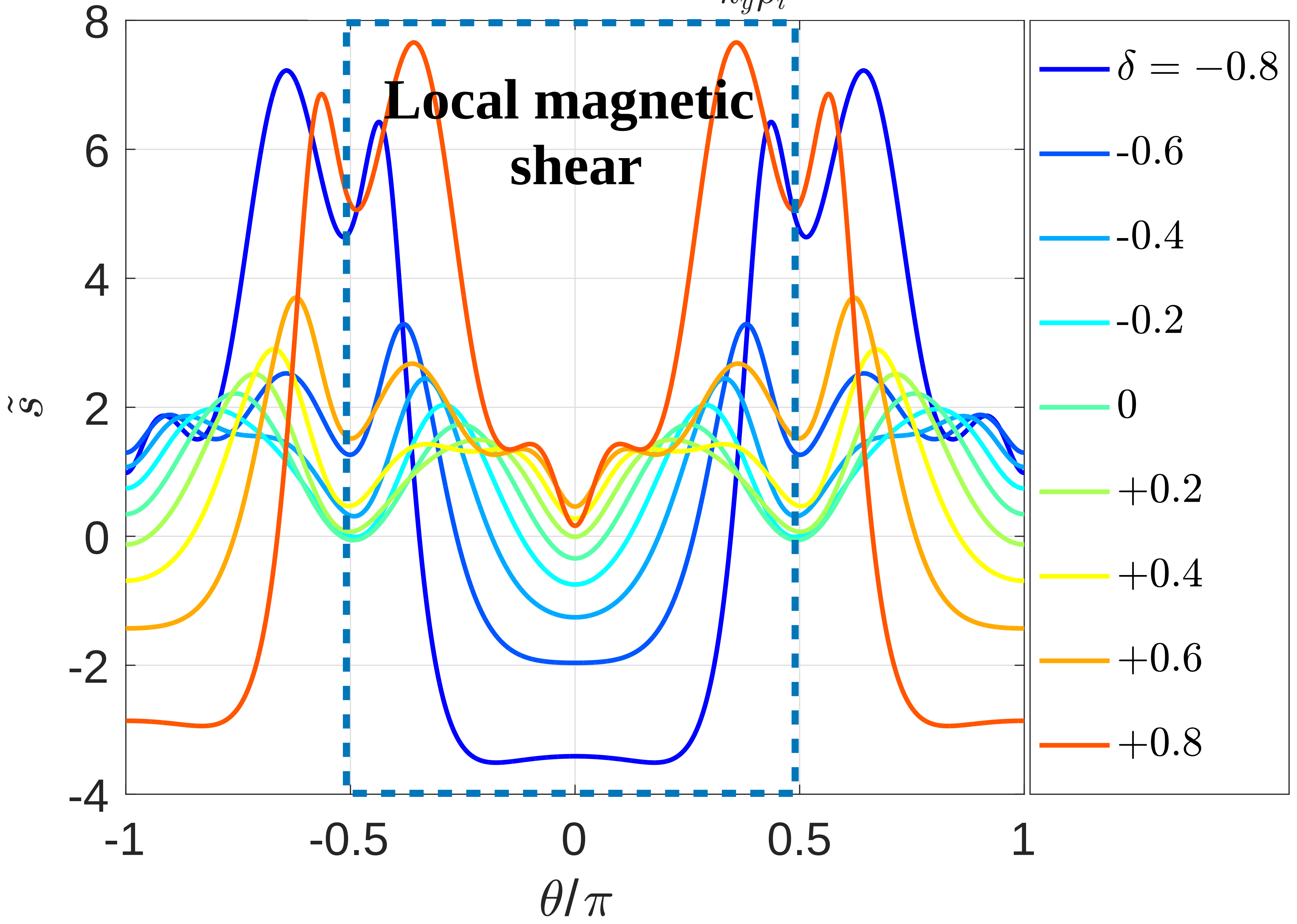
Linear growth rates reduced and critical gradient increased for NT

- Why? [Singh, Diamond, Marinoni NF 2024]
- **Weaker "effective curvature drive" for NT, due to reduced sampling of the bad curvature regions resulting from a narrow eigenmode structure in NT.**

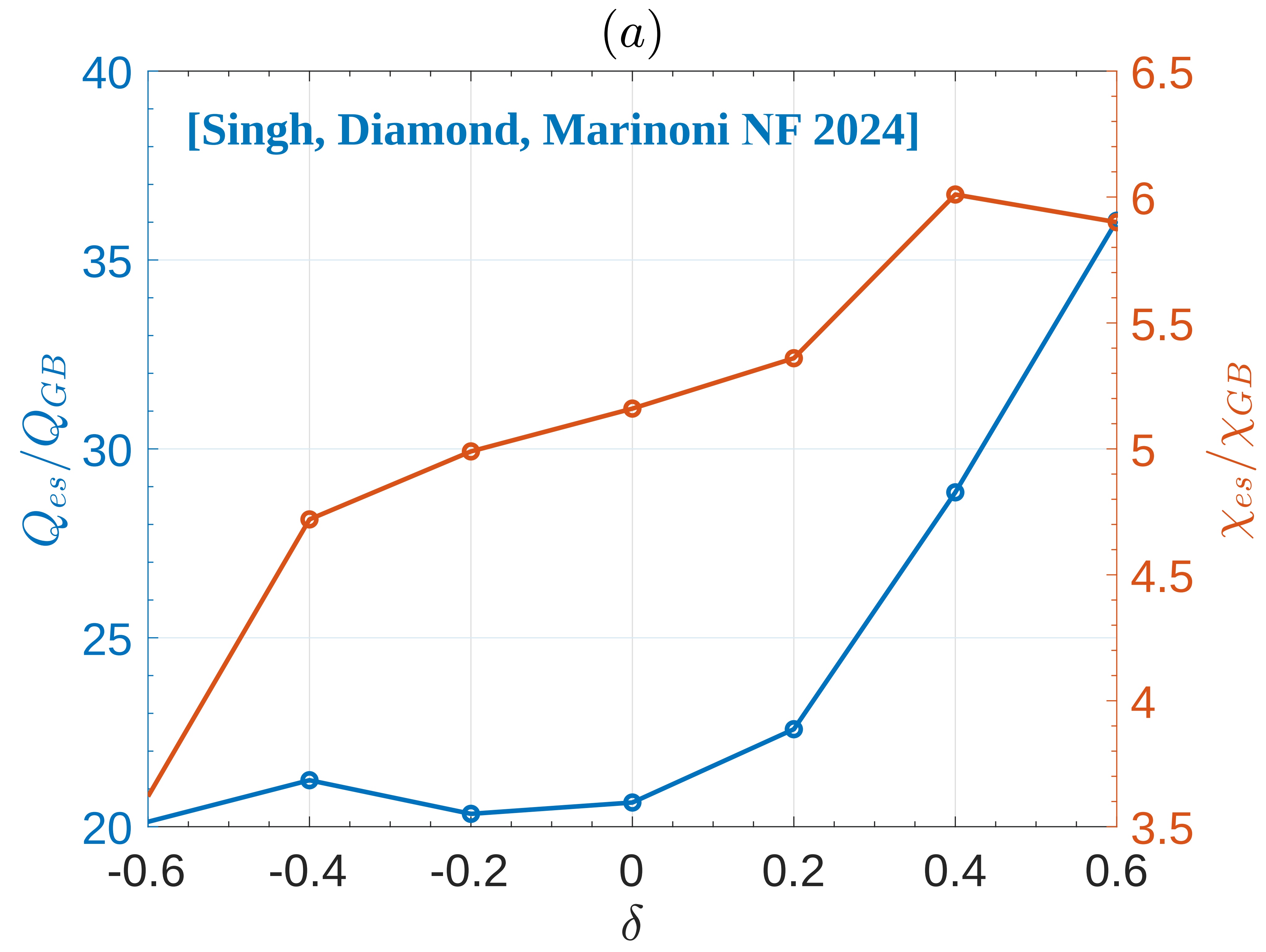




- Depth and width of the negative local-magnetic-shear-well in the bad curvature region increases for stronger NT shapes.
    - **→easier to twist eddies towards the good curvature side as you move along the field line →better stability for NT!**

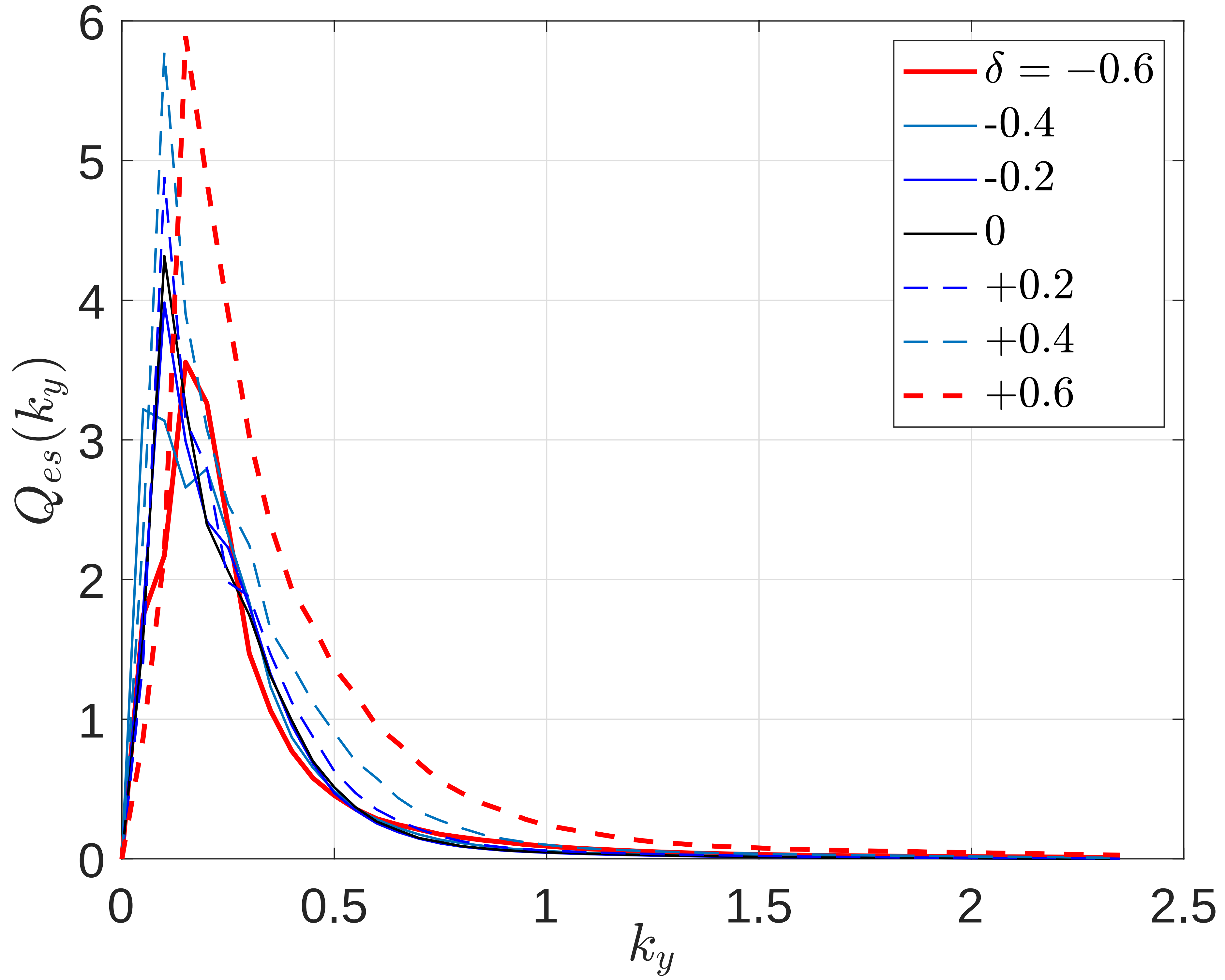


Nonlinear Heat flux vs Triangularity



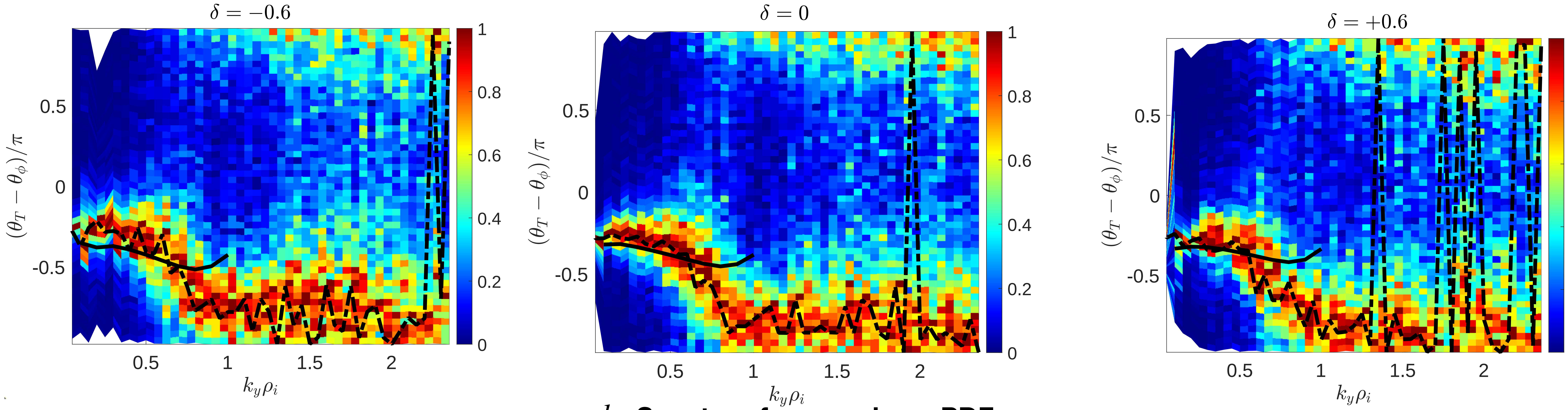
- Turbulent heat diffusivity lower for NT than for PT.

- High k_y contributions (RHS of the spectral peak) depleted more for NT.



- Heat flux $Q_i = \left\langle \sum_{\vec{k}} -k_y \underbrace{\left|T_k\right| \left|\phi_k\right|}_{\text{Amplitudes}} \underbrace{\sin(\theta_T - \theta_\phi)}_{\text{Cross-phase}} \right\rangle$
- Relative role of fluctuations amplitude and cross-phase?

Saturated fluctuation intensity and transport cross-phase vs Triangularity

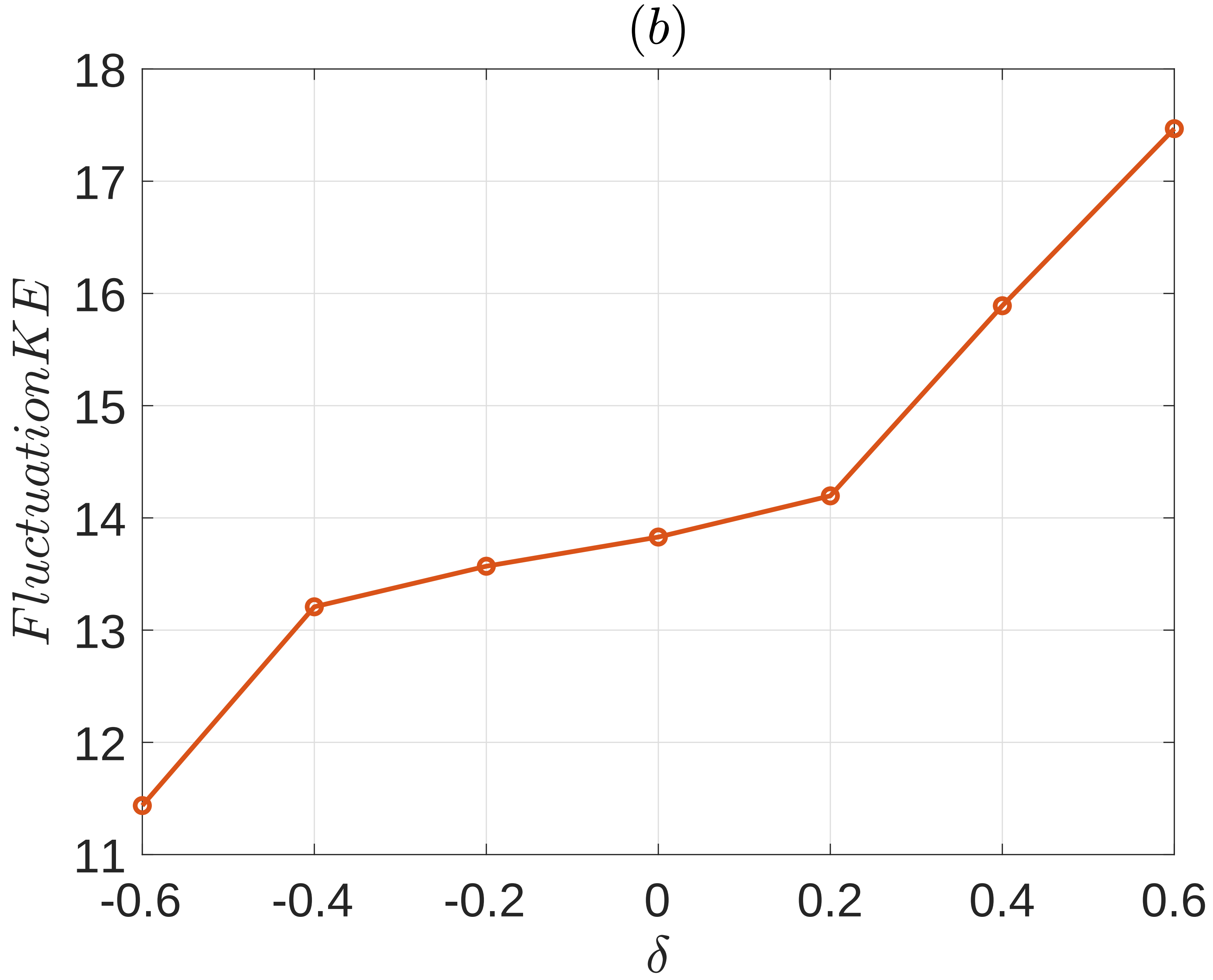


k_y-Spectra of cross-phase PDF

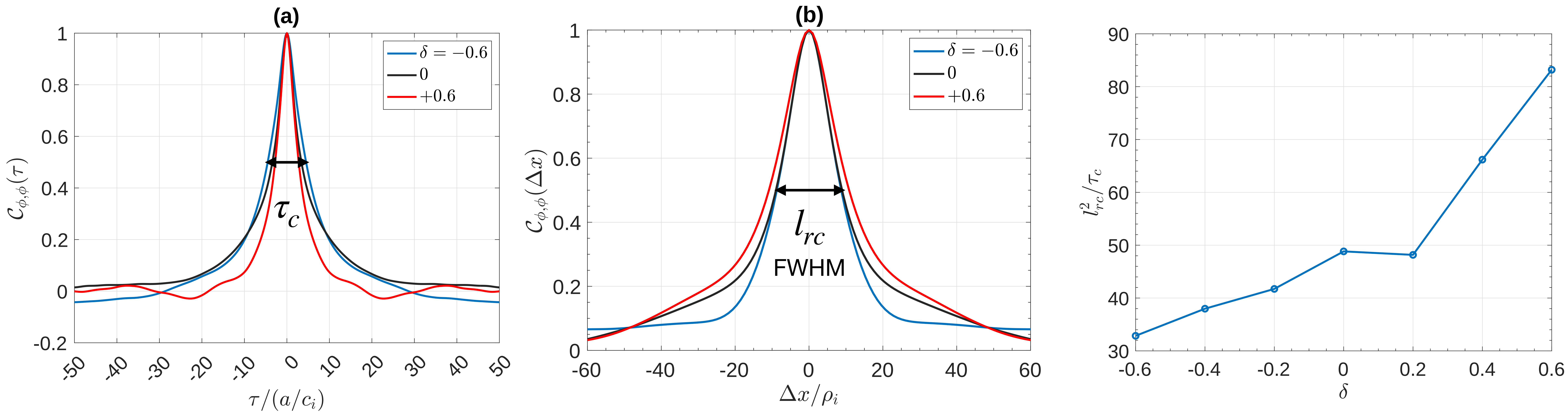
- Fluctuation kinetic energy: $$FKE = \left\langle \sum_{k_x, k_y} \left[1 - \Gamma_{0i}(k_\perp^2 \rho_i^2)\right] \left| \frac{e\delta\phi_k}{T_i \rho^\star} \right|^2 \right\rangle$$ is lower for NT!
- Cross phases between temperature and potential fluctuations $(\theta_T - \theta_\phi)$ are weakly sensitive to δ.

➡**Transport reduction for NT is pre-dominantly due to reduction of fluctuation amplitudes.**

[Singh, Diamond, Marinoni NF 2024]



Fluctuations auto-correlation and random walk diffusivity



[Singh, Diamond, Marinoni NF 2024]

- Auto-correlation time higher for NT: $\tau_c(NT) > \tau_c(PT)$
- Radial auto-correlation length lower for NT: $l_{rc}(NT) < l_{rc}(PT)$ [Consistent with TCV experiment: M Fontana+ 2018]

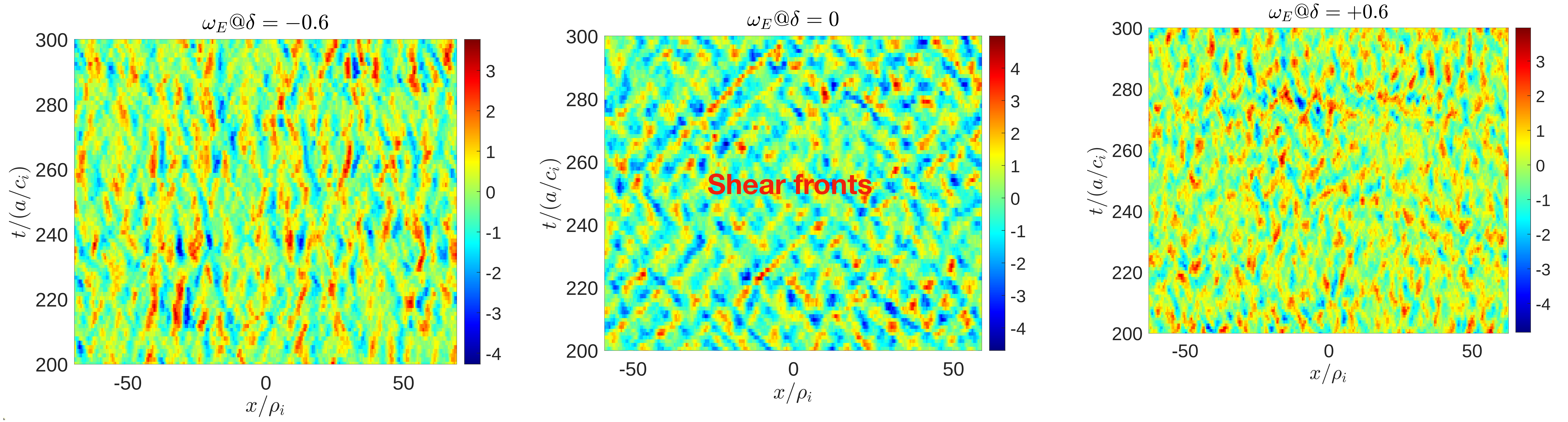
➡ Random walk diffusivity $\dfrac{l_{rc}^2}{\tau_c}$ lower for NT.

Zonal ExB shearing rates: $\omega - k$ spectra

[Singh, Diamond, Marinoni NF 2024]

- Shearing spectra are highly sensitive to δ.
    - No dispersive effect for $\delta = -0.6$
    - Clear dispersive effects for $\delta = 0 \rightarrow$ propagating zonal flows (New branch)
    - Weak dispersion for $\delta = +0.6$
- The spectra roll over at ~GAM frequency

Zonal ExB shearing rates: spatiotemporal features



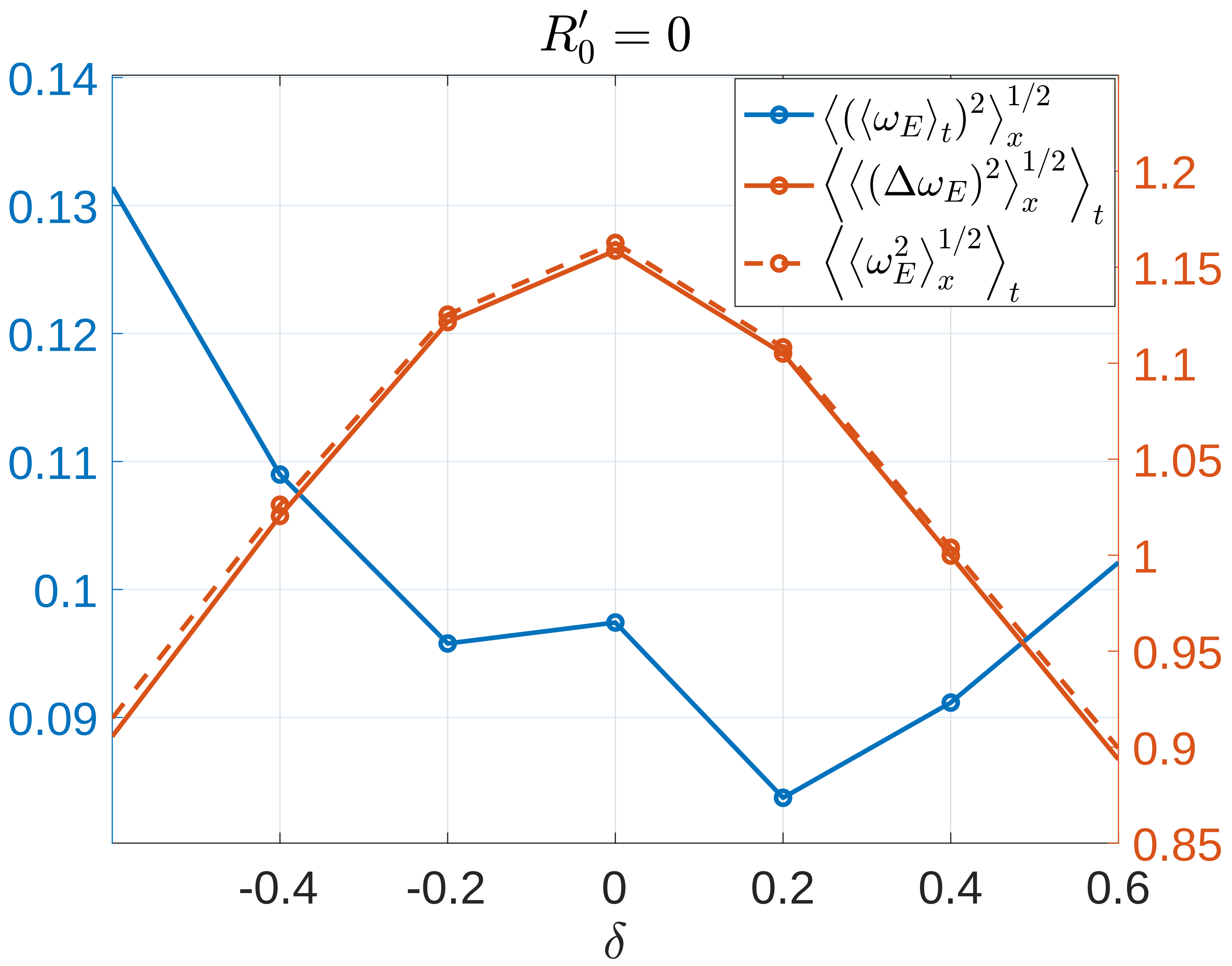
[Singh, Diamond, Marinoni NF 2024]

- Spatiotemporal patterns are highly sensitive to δ.
  - **Spatiotemporal shearing pattern more coherent for NT than for PT. (Why?)**
  - Propagating shearing fronts → dispersive feature for $\delta = 0$! Front speed $\sim 2.25\rho_\star v_{th}$.
- **More coherent spatiotemporal shearing pattern for NT → Stronger mean shearing effect for NT.**

RMS Zonal ExB shearing rates at saturated state

[Singh, Diamond, Marinoni NF 2024]

- **Zero-frequency RMS shearing rate higher for NT than for PT.**
- Total RMS shearing rate and finite frequency RMS shearing rate decreases with increasing $|\delta|$.



✳ Time averaged or zero-frequency RMS shearing rate: $\left\langle \left\langle \omega_E \right\rangle_t^2 \right\rangle_x^{1/2} = \left[\frac{1}{L_x} \int dx \left\langle \omega_E(x,t) \right\rangle_t^2 \right]^{1/2}$, where $\left\langle \omega_E(x,t) \right\rangle_t = \frac{1}{T} \int dt \omega_E(x,t)$

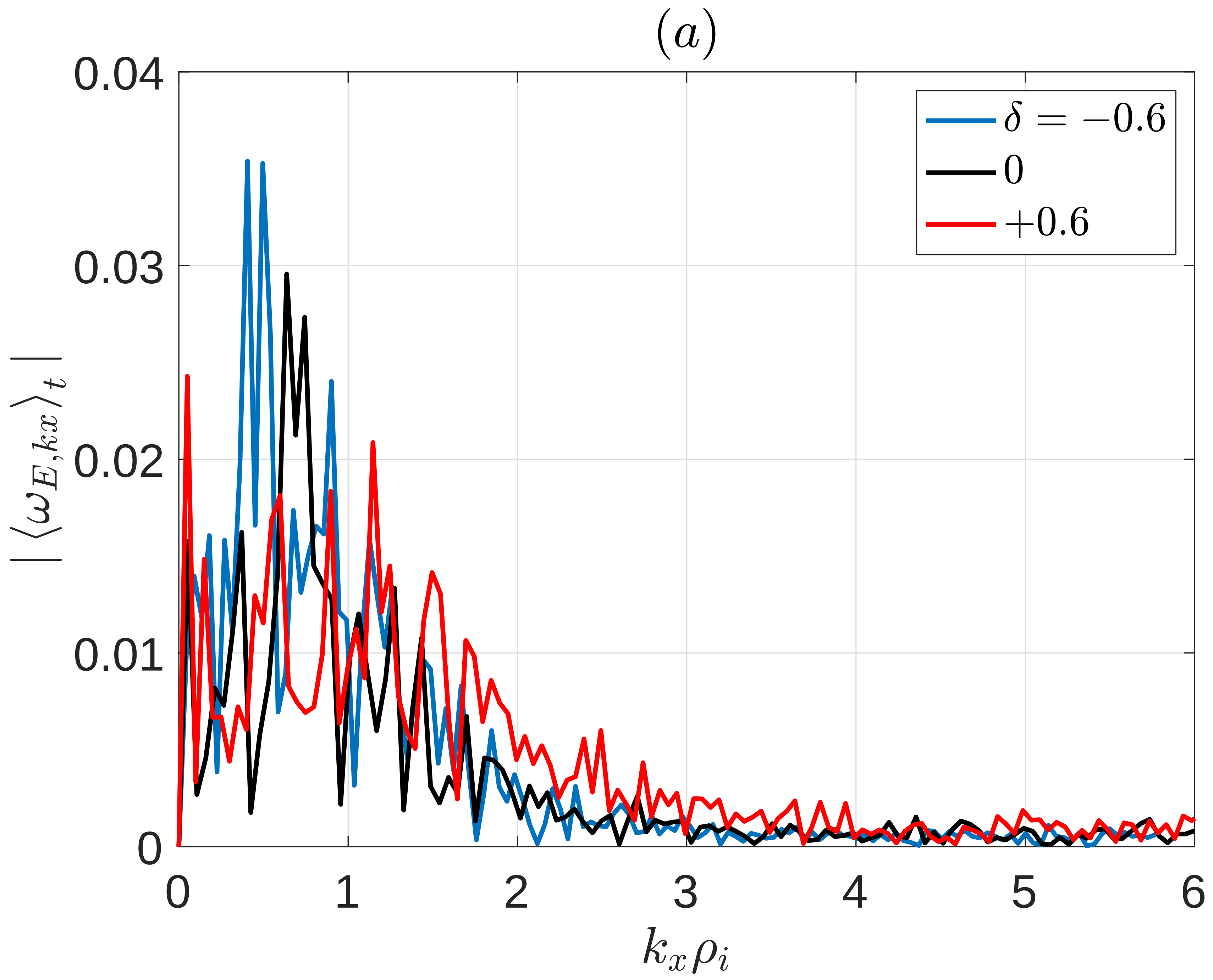
✳ Total RMS shearing rate : $\left\langle \left\langle \omega_E^2(x,t) \right\rangle_x^{1/2} \right\rangle_t = \left[\frac{1}{T} \int dt \frac{1}{L_x} \int dx \omega_E^2(x,t) \right]^{1/2}$

✳ Standard deviation of shearing rate: $\left\langle \left\langle \left(\Delta\omega_E \right)^2 \right\rangle_x^{1/2} \right\rangle_t = \left\langle \left\langle \left(\omega_E(x,t) - \left\langle \omega_E(x,t) \right\rangle_t \right)^2 \right\rangle_x^{1/2} \right\rangle_t$

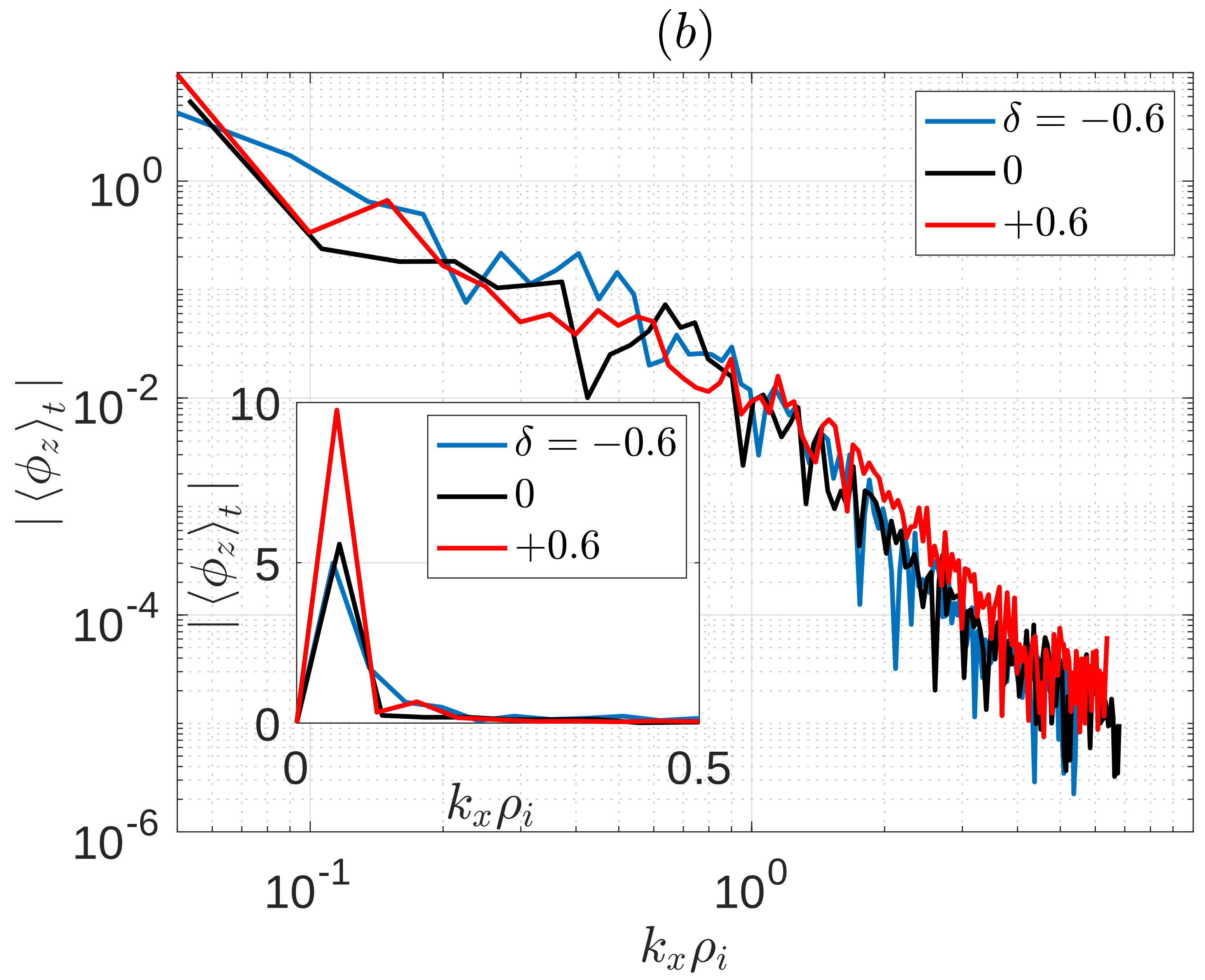
RMS shearing rate depends on the detail of the shearing spectra at saturated state

[Singh, Diamond, Marinoni NF 2024]

- **Different δ-trend of zero-frequency shearing rate and zonal potential spectra.**
- Zonal shear peak at $k_x\rho_i \sim 0.5$ whereas zonal potential peak at $k_x\rho_i \sim 0.05$.
- **Shearing peak stronger while potential peak weaker for NT.**



Shearing peaks stronger for NT than for PT.



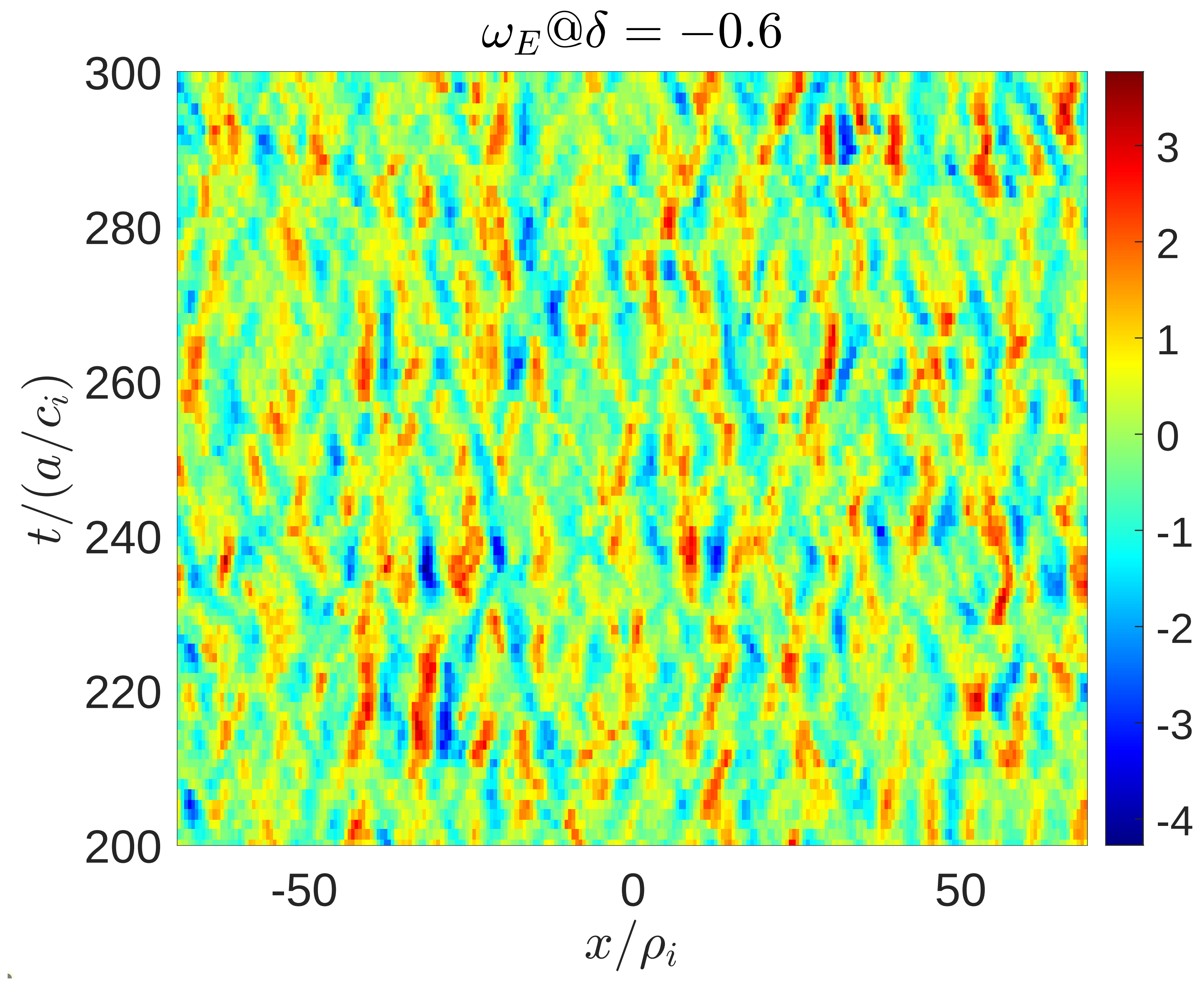
Zonal potential peaks weaker for NT for PT. But zonal potential isn't the point.

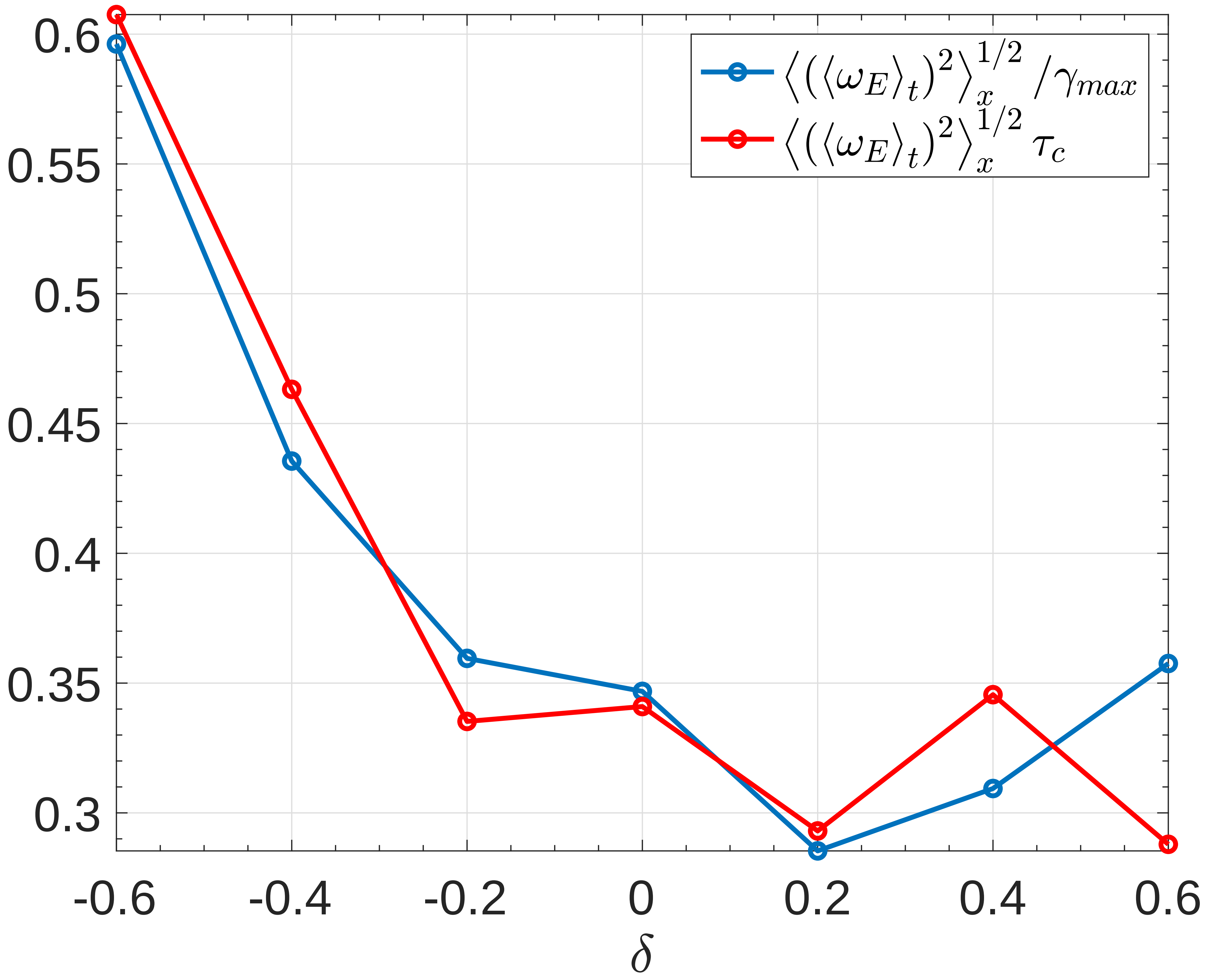
Figure of Merit

[Singh, Diamond, Marinoni NF 2024]

- All analyses point at the dimensionless parameter $\omega_E\tau_c$ or ω_E/γ_{max} as *figure of merit.*

- $\omega_E\tau_c$ higher for NT than for PT. Nicely correlates with the δ-trend of heat diffusivity.



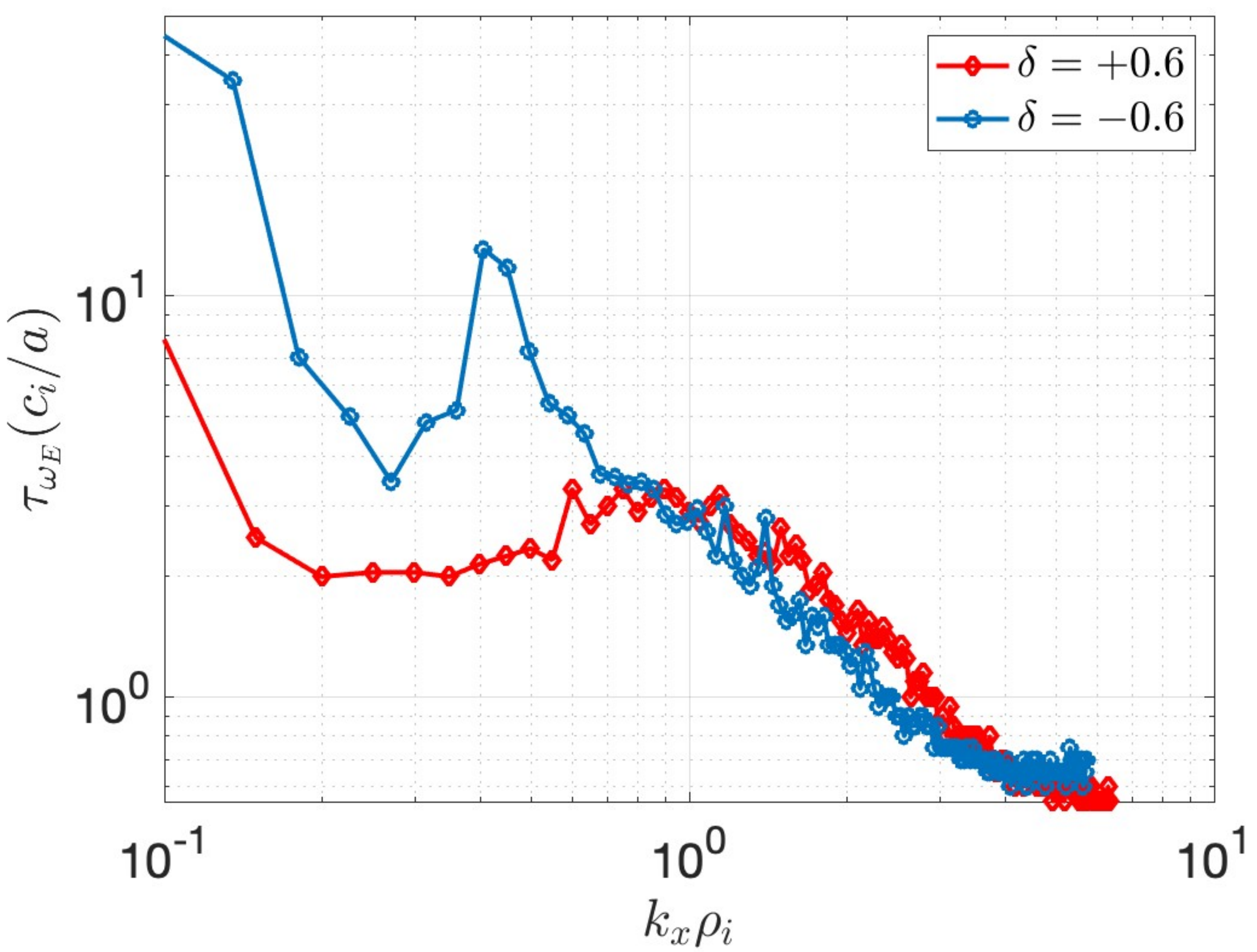


- **So increased zonal ExB shear resulting from the enhanced spatio-temporal coherence is the key.**

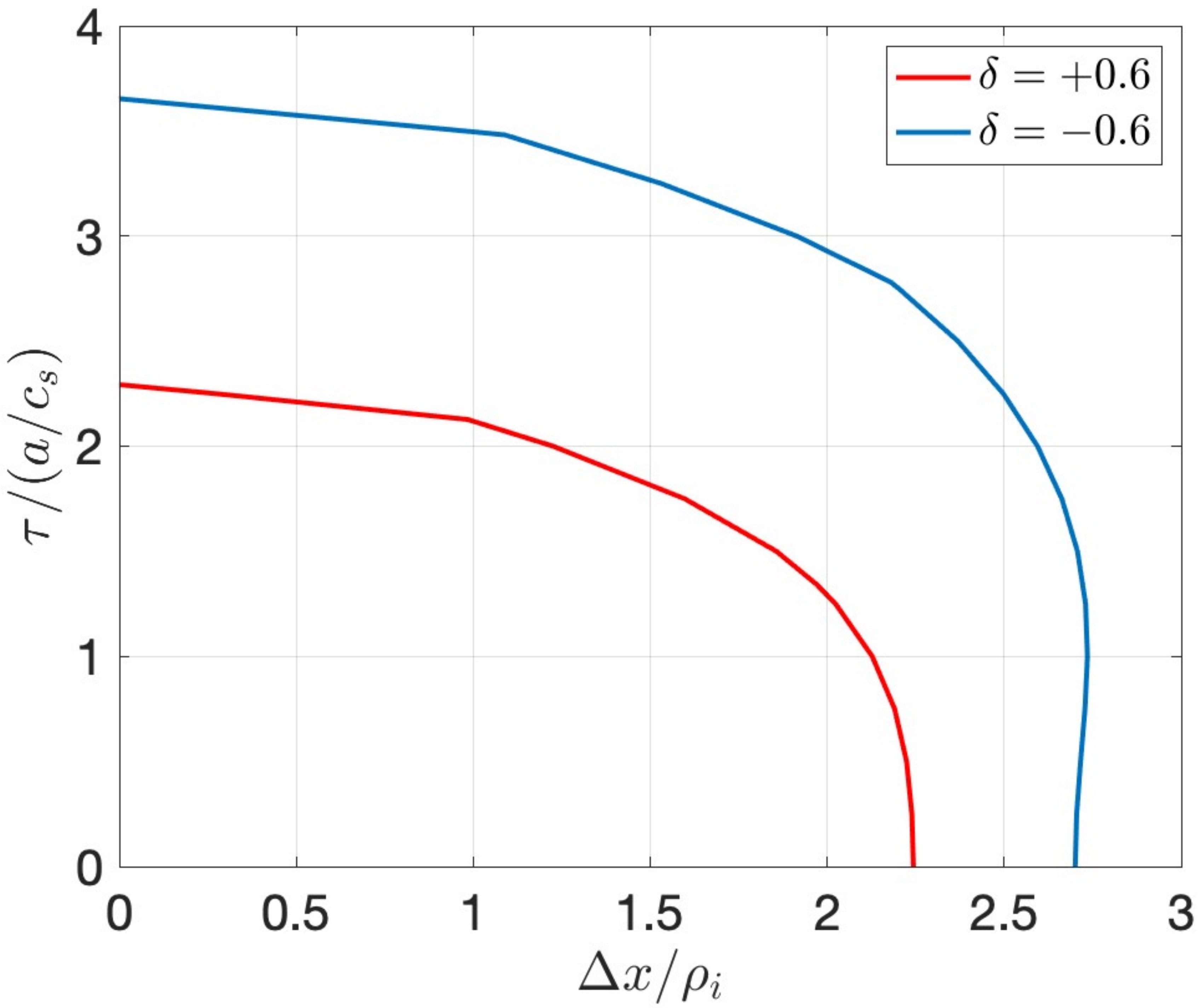
Quantifying zonal shear coherence

- Zonal shear life time is higher for NT.
- Radial size of zonal shear higher for NT.

➡More spatio-temporal coherence of zonal shear for NT.



k_x-spectra of zonal shear life-time obtained from 1/e level of the 1d-autocorrelation function



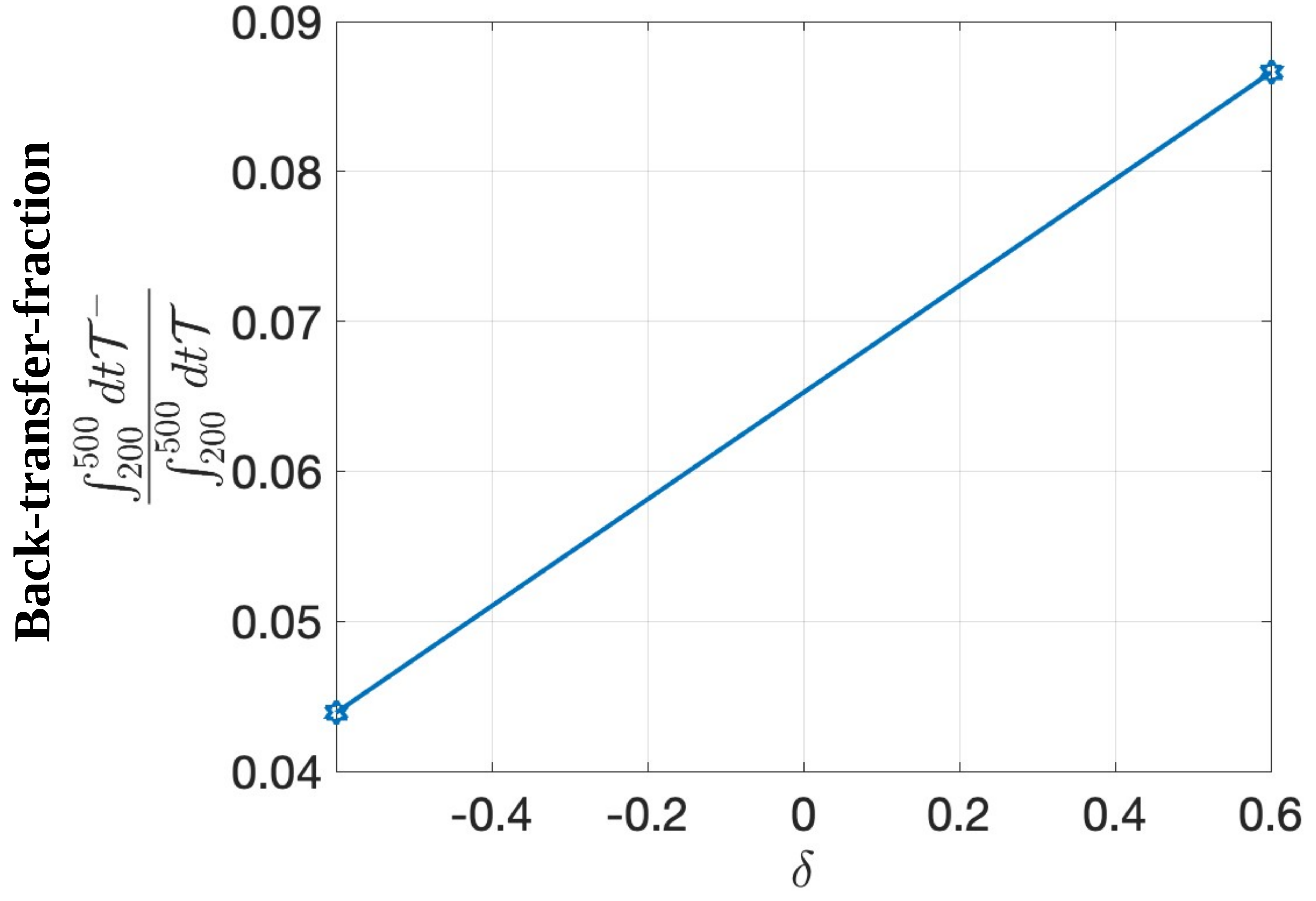
Radial size distribution of zonal shear life-time obtained from 1/e level of the 2d-autocorrelation function

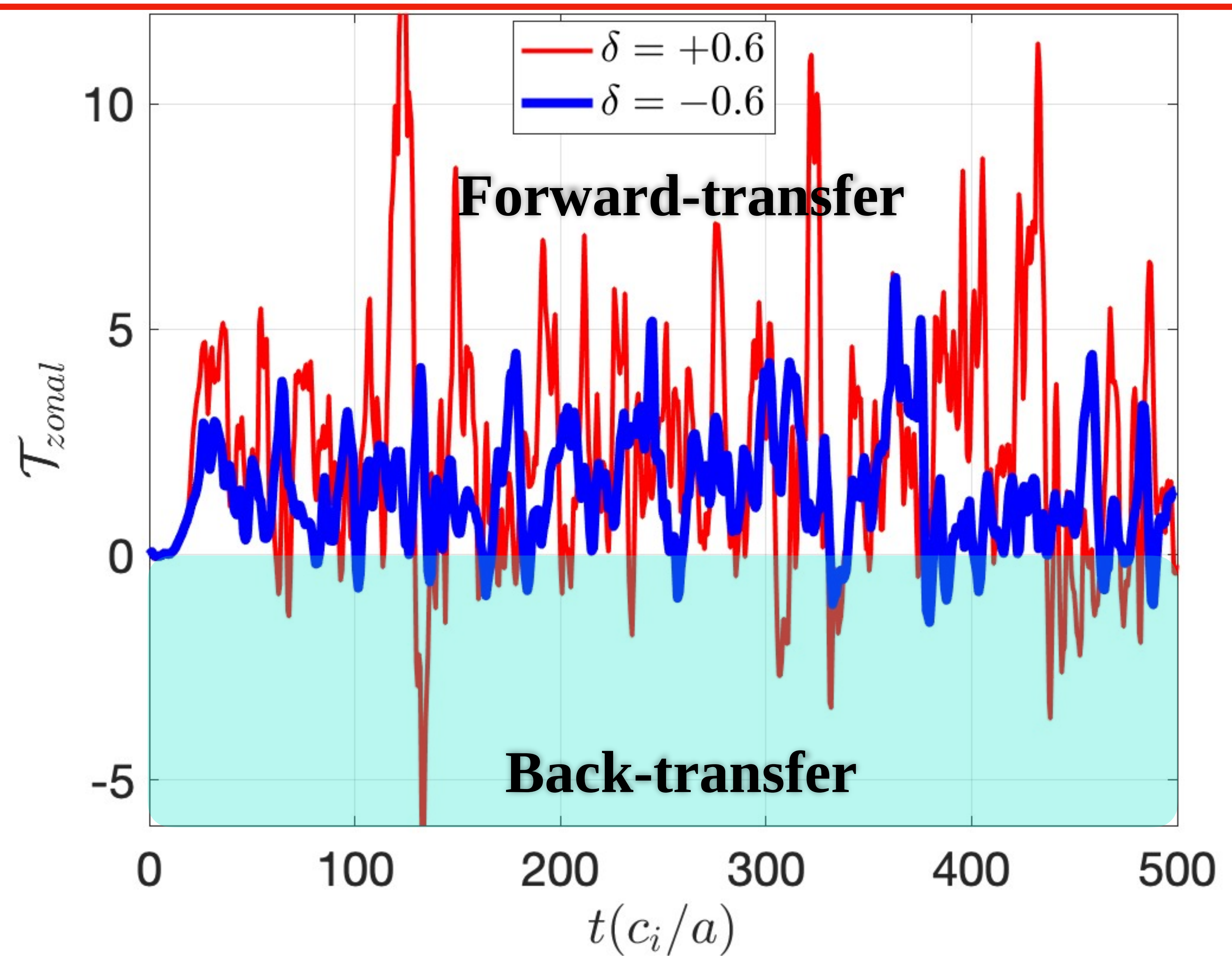
- **But…, why is the zonal shear more coherent for NT?**

Why is the zonal shear more coherent for NT?

- Gyrokinetic zonal entropy transfer analysis:
$$T = 2\Re\left\{\vec{b}\cdot(\vec{k}\times\vec{k'})\int\frac{n_0T_0}{F_0}(g_k+\frac{qF_0}{T_0}\psi_k)\psi(k')g(k-k')dzdv\right\}$$
- $T>0 \rightarrow$ energy transfer from turbulence to zonal mode
- $T<0 \rightarrow$ back-transfer of energy from zonal mode to turbulence.

Reduced Back-transfer fraction for NT.
$\Longrightarrow$ Enhanced zonal shear coherence!





- **Back-transfer events limit the zonal flow stability and coherence!** [P.H.Diamond and Runlai Xu AAPPS-DPP 2024]

- **Animal hunt(tertiary, K H instability…) is pointless in turbulent setting.**

Summary

- Novel insights into how NT mitigates ITG turbulence and transport → $\omega_E \tau_c$ or ω_E/γ_{max} as *figure of merit*.
- Reduced linear growth rate for NT ↔ Reduced eigenmode averaged magnetic drift frequency.
- δ-trend of diffusivity → Predominantly determined by δ-trend of fluctuation amplitude. Cross-phase effect weak.
- Reduced heat flux for NT ↔ Reduced radial correlation length and increased correlation time due to increased zero-frequency zonal ExB shearing rate.
- Enhanced coherence of zonal shear for NT ↔ reduced back-transfer of energy from zonal mode to turbulence. $\Longrightarrow$ more resilient shear layer for NT.

[Singh, Diamond, Marinoni NF 2024]

Future work

- Better understand the role of zonal back-transfer on collisionless zonal flow saturation dynamics.

- Analysis using experimental equilibria and profiles and using non-adiabatic electrons and finite collisionality exploiting both local and flux driven global simulations.

For experiments

- **Measure $\omega - k$ spectra of the zonal flow shear**. Identify finite frequency components? Spatio-temporal features of zonal shear, signatures of propagating zonal fronts→BES velocimetry

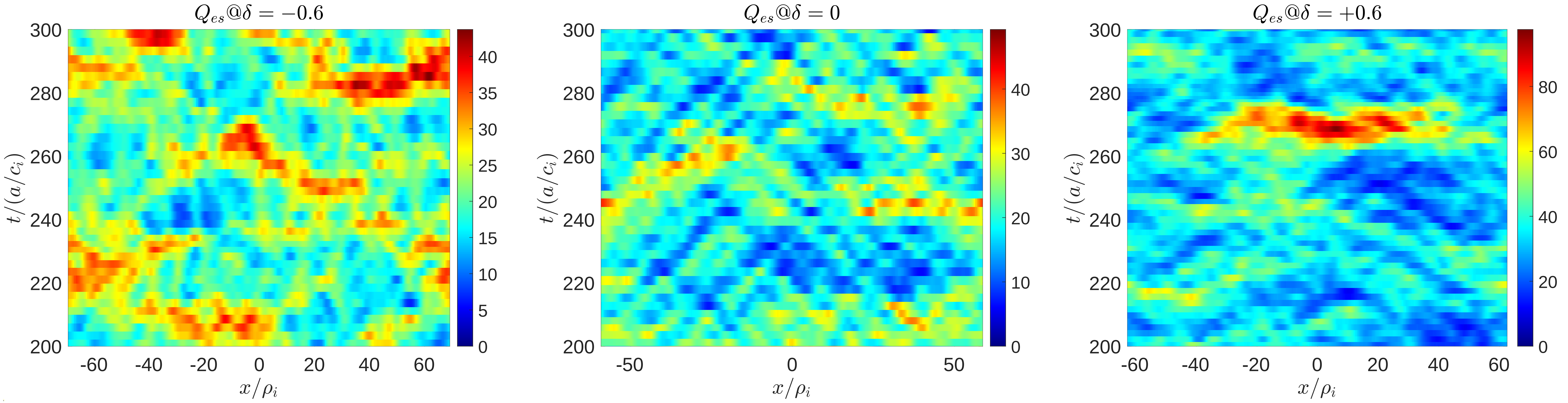
- **Back-transfe**r **events**: Time series of Reynolds power $\frac{\partial \langle v_\theta \rangle}{\partial r} \langle \tilde{v}_r \tilde{v}_\theta \rangle$ vs triangularity to elucidate turbulence → zonal flow energy coupling? →BES velocimetry.

- **Calculate FOM $\omega_E \tau_c$ vs δ.** Radial correlation length and auto-correlation time of fluctuations and zonal flows.

Back-up slides

Heat flux avalanches

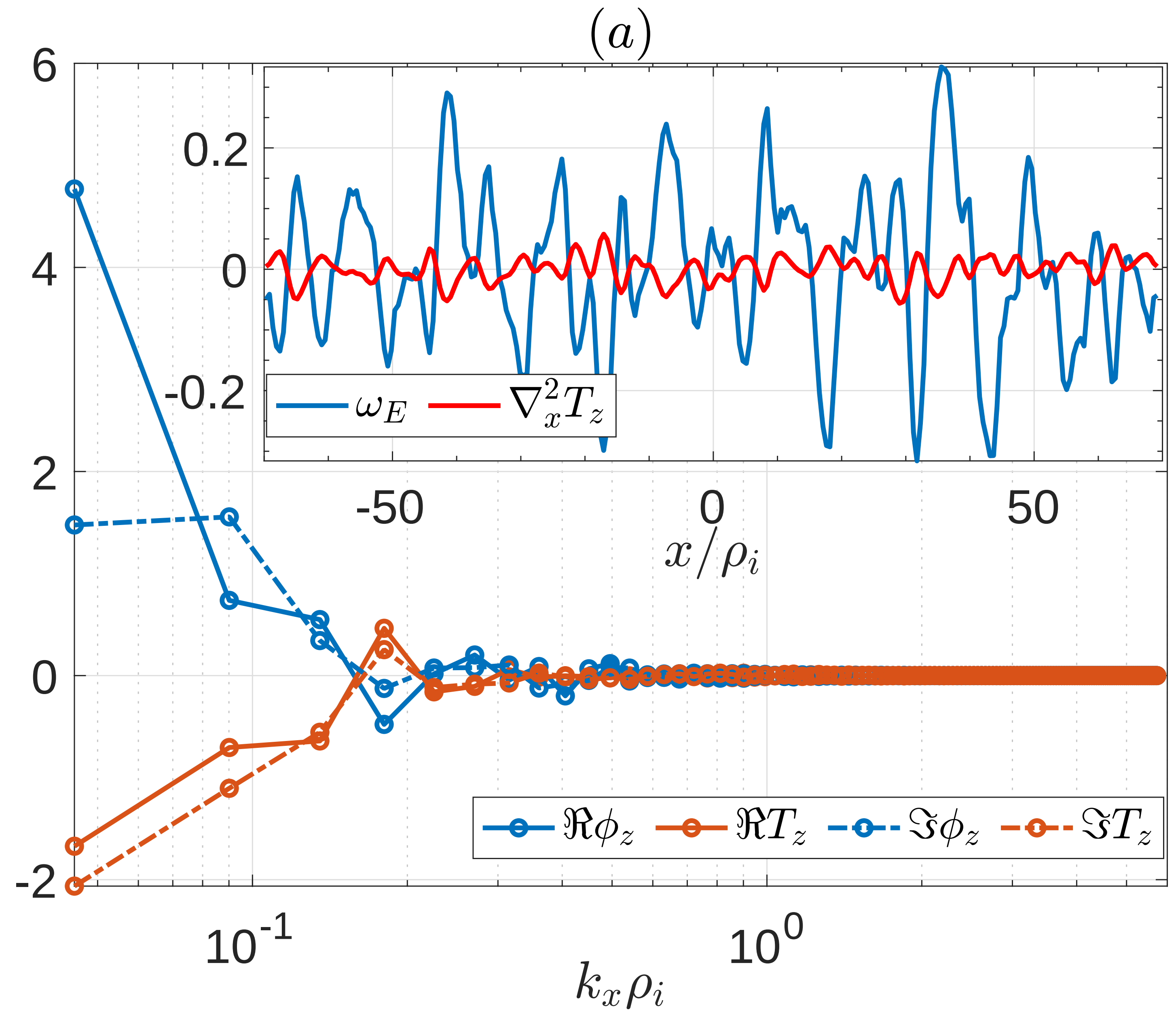
- Avalanches also seen in heat flux space time evolutions. **[Singh, Diamond, Marinoni NF 2024]**

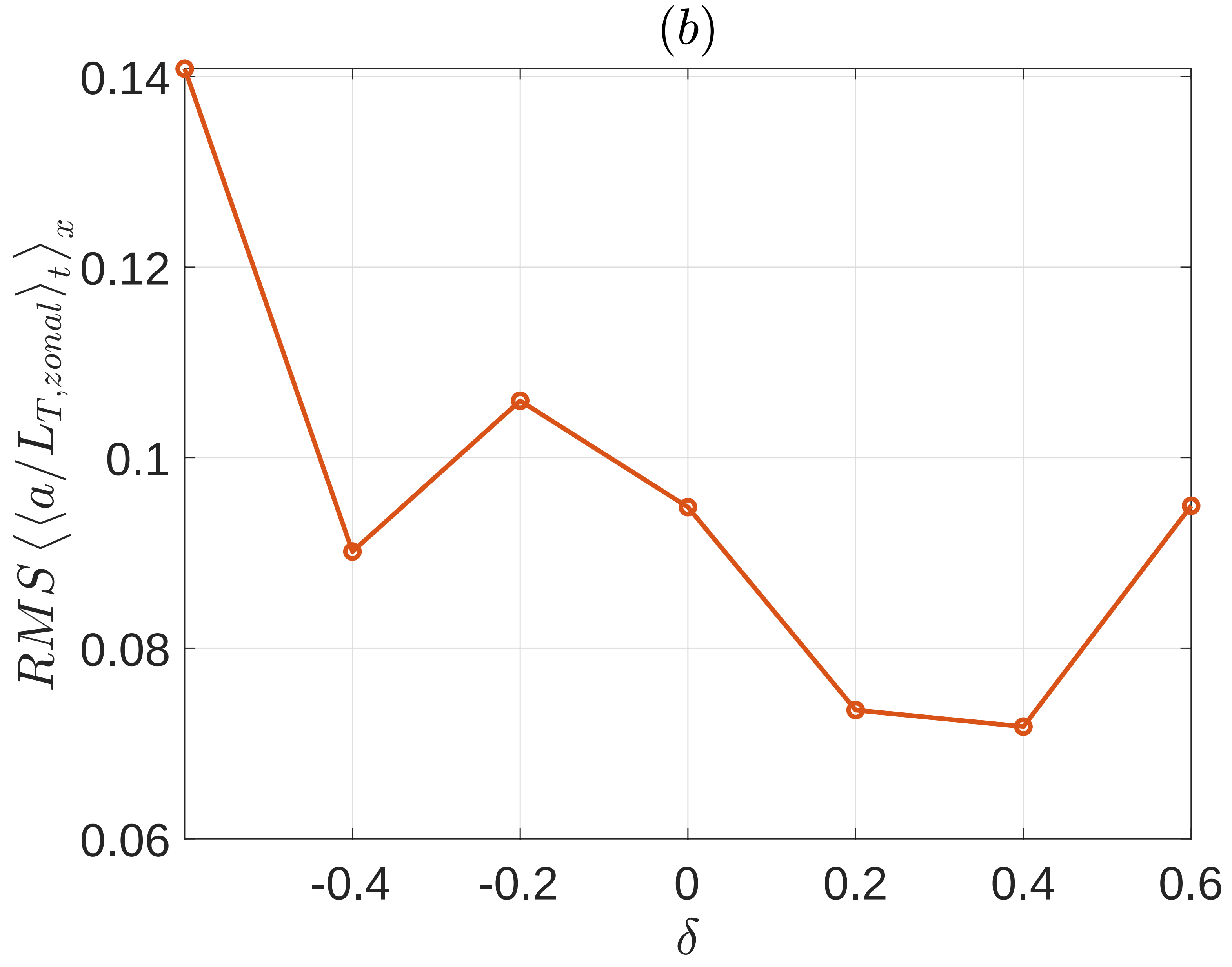


Temperature corrugations dynamics

(a) Zonal temperature spectrally anti-correlated with zonal potential $T_{z,k_x} \propto -\phi_{z,k_x}$. Consequently, zonal ExB shear ω_E is spatially anti-correlated with zonal temperature curvature $\nabla^2 T_z$.

(b) Zonal temperature corrugations are stronger for NT than for PT.





[Singh, Diamond, Marinoni NF 2024]