Zonal Flow Screening in Negative Triangularity Tokamaks

[Singh and Diamond 2022 *Nucl. Fusion* (accepted)]

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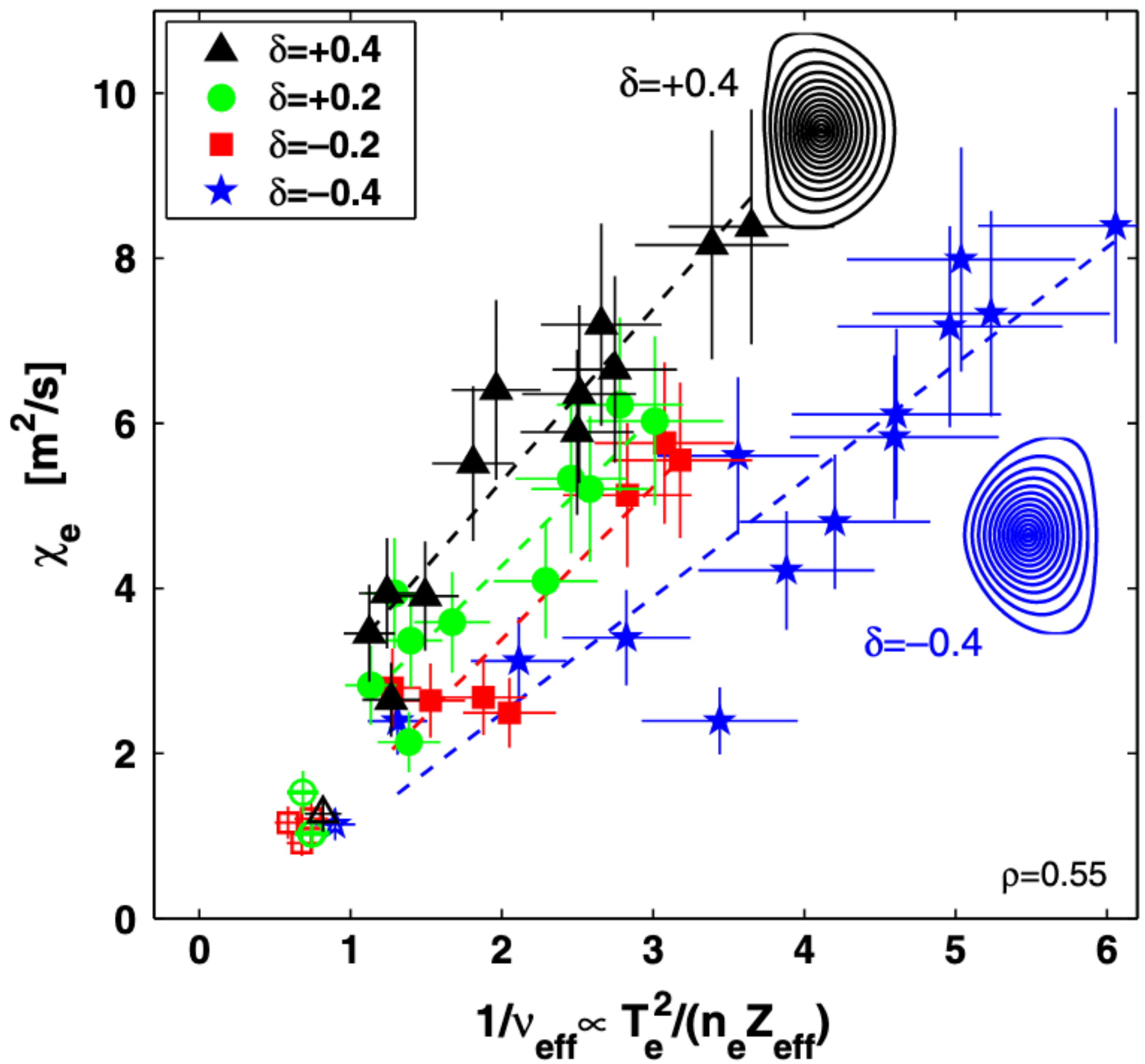
Effect of triangularity on confinement, fluctuations and L-H transition

TCV experiments

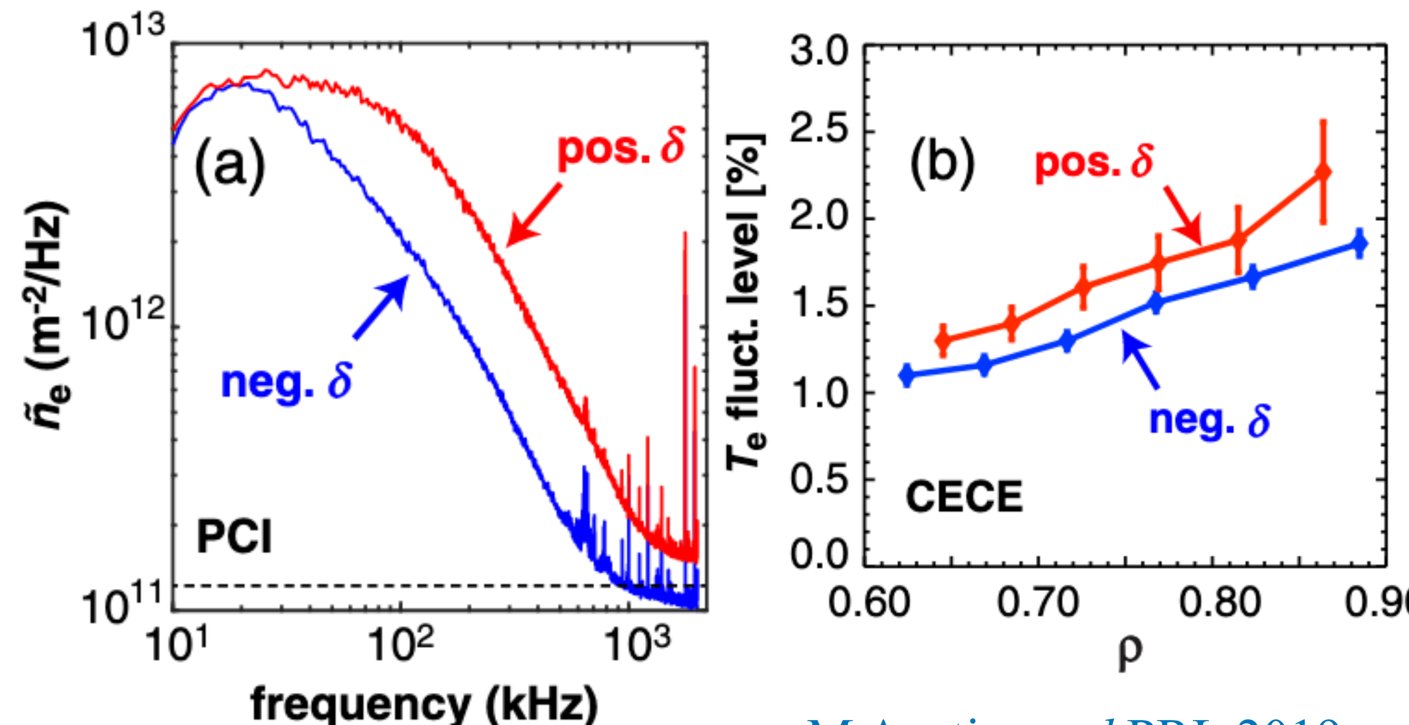
EC Heated L-mode Plasmas

Doubled Energy Confinement Time on TCV when $\delta \rightarrow -\delta$



Y. Camenen *et al* NF 2007

DIII-D experiments



M Austin *et al* PRL 2019

- **High -ve δ shape is robust against L-H transition.**

$P_{LH,th} = 4\text{MW} \rightarrow >13\text{MW}$ when $\delta_u = -0.18 \rightarrow -0.36$

Key Issues

- Improved confinement:
  - Linear TEM stabilization was linked to improved confinement [Marinoni *et al* 2009] — role of zonal flows overlooked.
  - What about ITG and Zonal flows?

- L-H transition:
  - Threshold power for NT>> Threshold power for PT (why?)
    - Linked to loss of access to 2nd stability region of $n = \infty$ ideal MHD ballooning modes. [Saarelma *et al* PPCF 2021, Nelson *et al* NF 2022]
    - Caveat: H mode is NOT always in 2nd stable region.
  - What about role of zonal flows ?
  - Mean ExB shearing in NT ? (In progress)

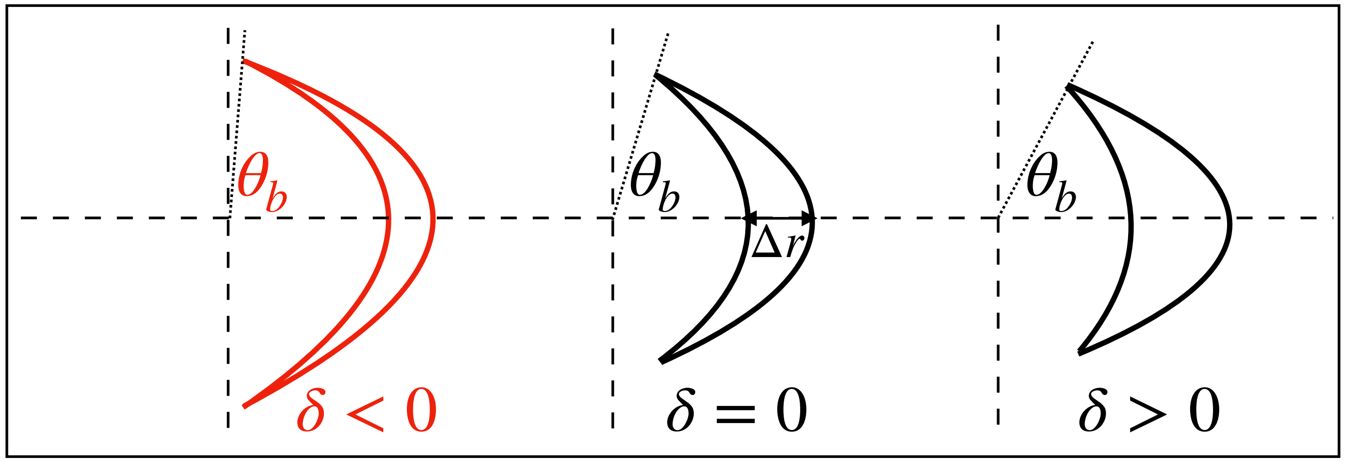
L-H trigger by zonal flows is well established for PT

[Kim and Diamond 2003, L Schmitz *et al* 2012, G D Conway *et al* 2011, G Tynan *et al* 2013, P Manz *et al* 2012, G S Xu *et al* 2011, Z Yan and G R McKee *et al* 2014]

What happens to zonal flows in NT?

Expectations from conventional wisdom

Axisymmetry guarantees omnigenity i.e., $\overline{v_{Dr}} = 0$



Neg. T → reduced banana width
→Zonal flow screening length !?
→Fate of zonal flow in Neg T?

Reduction in banana width

Reduction in Neoclassical polarization

→ Enhanced zonal flow residual !?

Reduced random walk steps size

→ Reduced neoclassical transport

What happens to zonal flows in negative triangularity ?

- Get beyond linear theory → saturated state
- ITG → saturation by zonal flows dominant [Z Lin, …]
- Zonal intensity spectral evolution:

$$\frac{\partial}{\partial t}\chi_k \left\langle \left|\phi_k\right|^2 \right\rangle = \Re \sum_{\vec{k}=\vec{p}+\vec{q}} \hat{z}\cdot\vec{p}\times\vec{q}\,\left(q^2-p^2\right)\left\langle \phi_k^{\star}\phi_p\phi_q \right\rangle$$

Triplet correlation

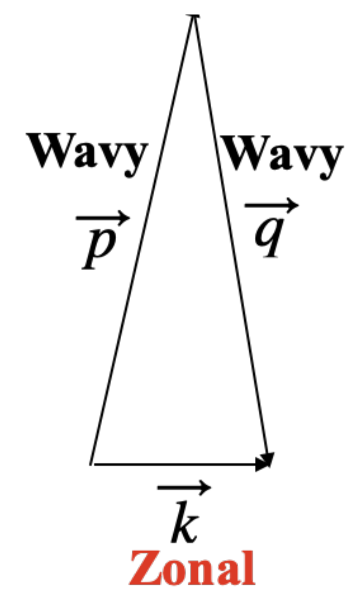
Scale of ZF set by ion susceptibility $\chi_k = k_\perp^2\rho^2\left(1+\frac{q^2}{\epsilon^2}\right) \rightarrow l_z = \sqrt{\rho_i^2+\rho_\theta^2}$

Circular Geometry

$\left\langle \phi_k^{\star}\phi_p\phi_q \right\rangle$

Coherent → $\sim \left\langle \left|\phi_k\right|^2 \right\rangle \left\langle \left|\phi_q\right|^2 \right\rangle$ **Relaxation/ Modulation**

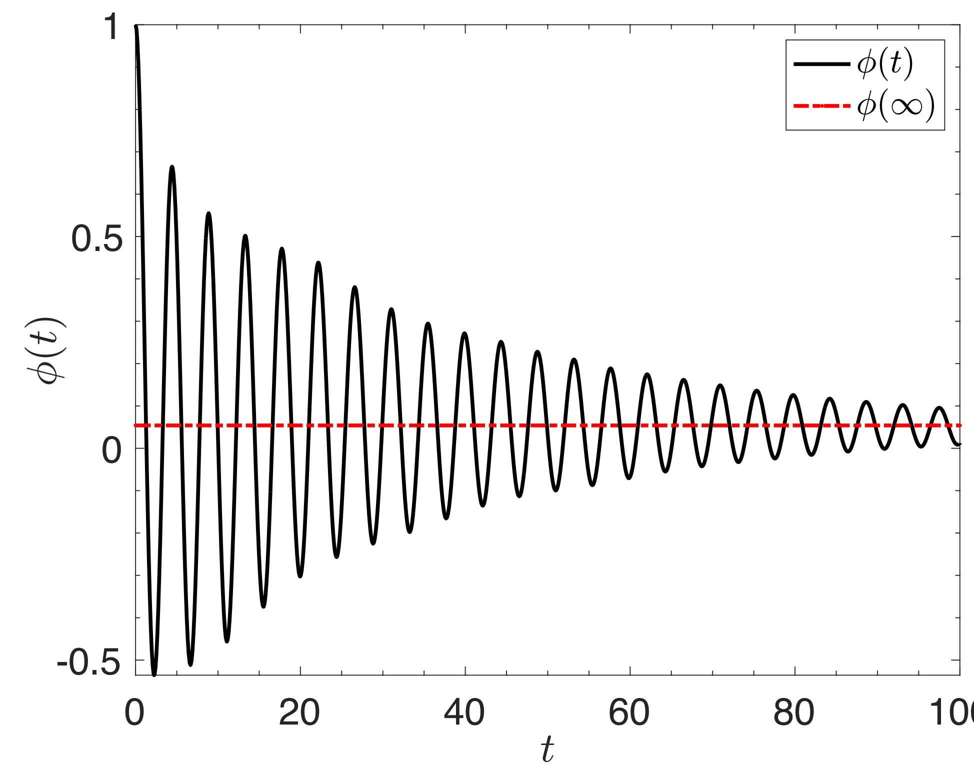
Incoherent → $\sim \frac{1}{\chi_k}\left\langle \left|\phi_p\right|^2 \right\rangle \left\langle \left|\phi_q\right|^2 \right\rangle$ **Noise**



- **ZF drive is screened by χ_k.**
- **What happens to χ_k in NT ?**

Rosenbluth-Hinton residual zonal flow

- The collisionless residual zonal flow level $\phi_k(\infty) = \phi_k(0)\dfrac{\chi_{k,cl}}{\chi_{k,cl} + \chi_{k,neo}}$



Classical susceptibility

$$\chi_{k,cl} = \left\langle k_\perp^2 \rho_i^2 \right\rangle = \frac{m_i T_i}{e^2}\left\langle k_\perp^2 / B^2 \right\rangle$$

Due to departure of particle from flux surface due to gyro motion

Neo-classical susceptibility

$$\chi_{k,neo} = \frac{(m_i I S')^2}{n_0 e^2}\left\langle \int d^3 v F_M \frac{v_\parallel}{B}\left[\frac{v_\parallel}{B} - \overline{\left(\frac{v_\parallel}{B}\right)}\right]\right\rangle = \left\langle k_\perp \rho_i^2 \right\rangle \frac{q^2}{\epsilon^2}\Theta$$

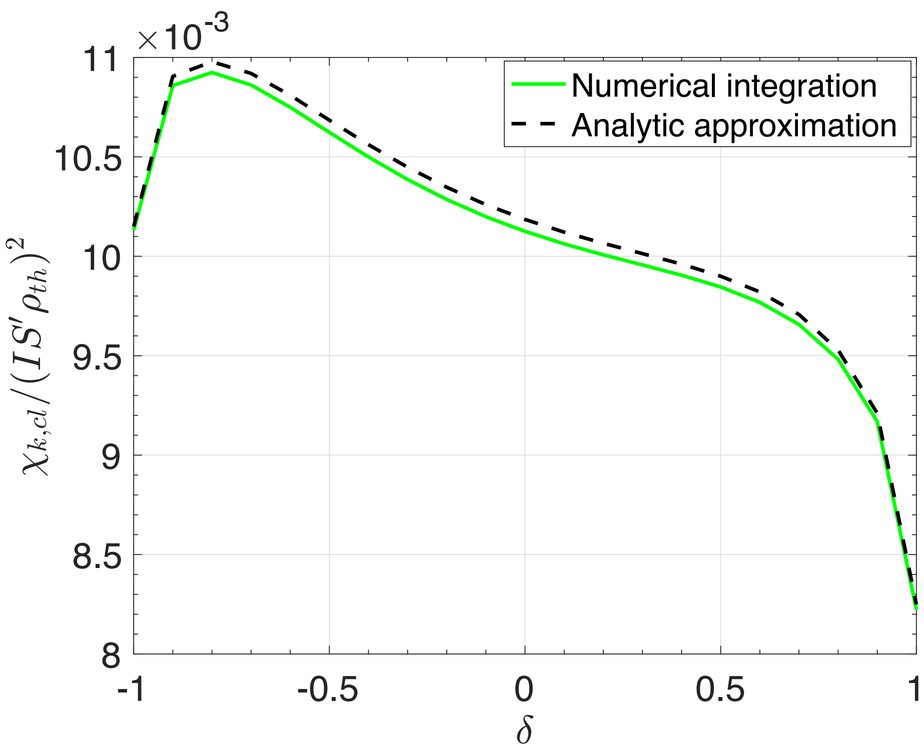
Due to departure of guiding center from flux surface due to magnetic drift

Shaping factor (Θ)

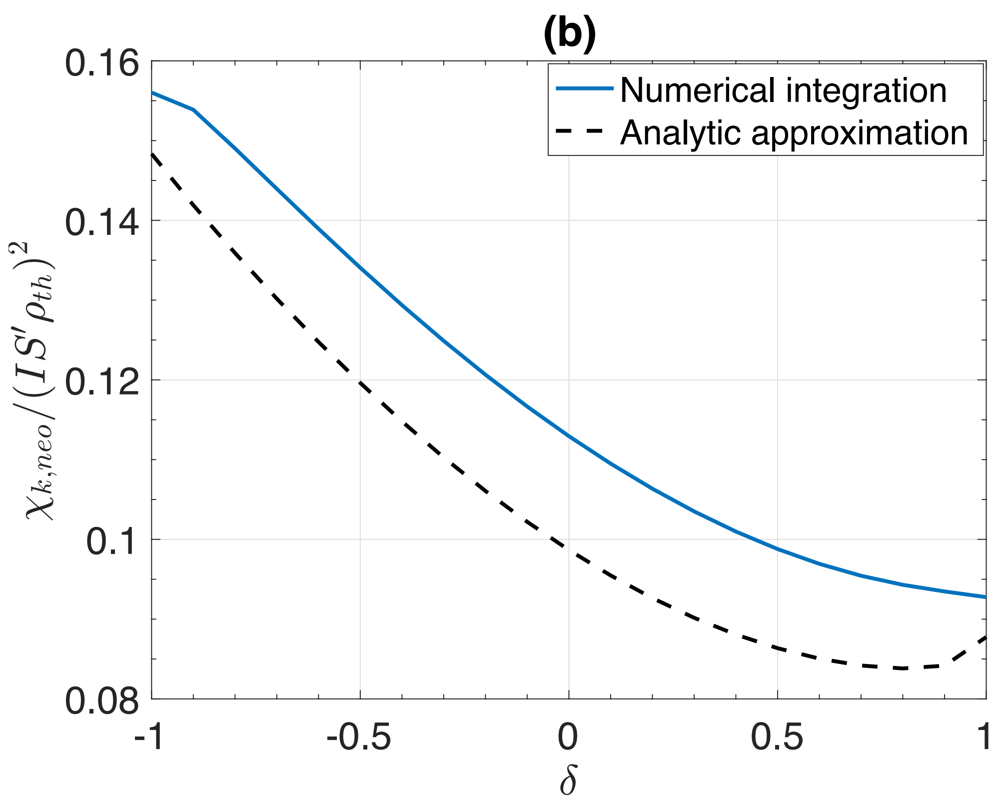
- Calculated for Miller's parametrized up-down symmetric equilibrium.

Classical and Neo-classical susceptibility

- The collisionless residual zonal flow level $\phi_k(\infty) = \phi_k(0)\dfrac{\chi_{k,cl}}{\chi_{k,cl} + \chi_{k,neo}}$
- $\chi_{k,cl}$ increases with decreasing δ. **Notice** $\chi_{k,cl}(\delta^-) > \chi_{k,cl}(\delta^+)$.
- $\chi_{k,neo}$ increases with decreasing δ. **Notice** $\chi_{k,neo}(\delta^-) > \chi_{k,neo}(\delta^+)$.



Classical Susceptibility

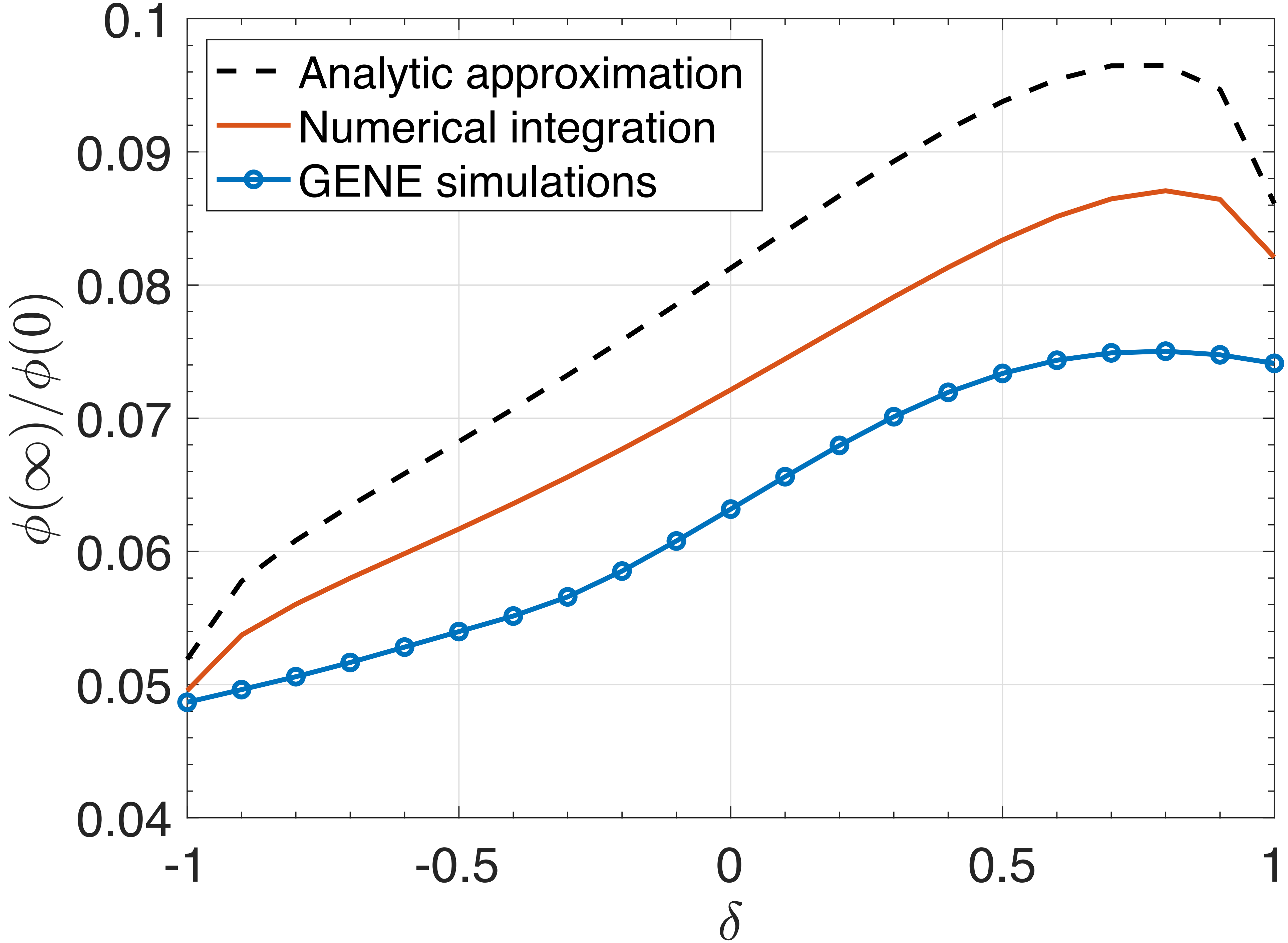


Neo-classical Susceptibility

Zonal flow screening length $l_z = \sqrt{\chi_{tot}/k_r^2}$ is bigger for δ^- than for δ^+!

Zonal flow residual is lower for -ve δ than that for +ve δ

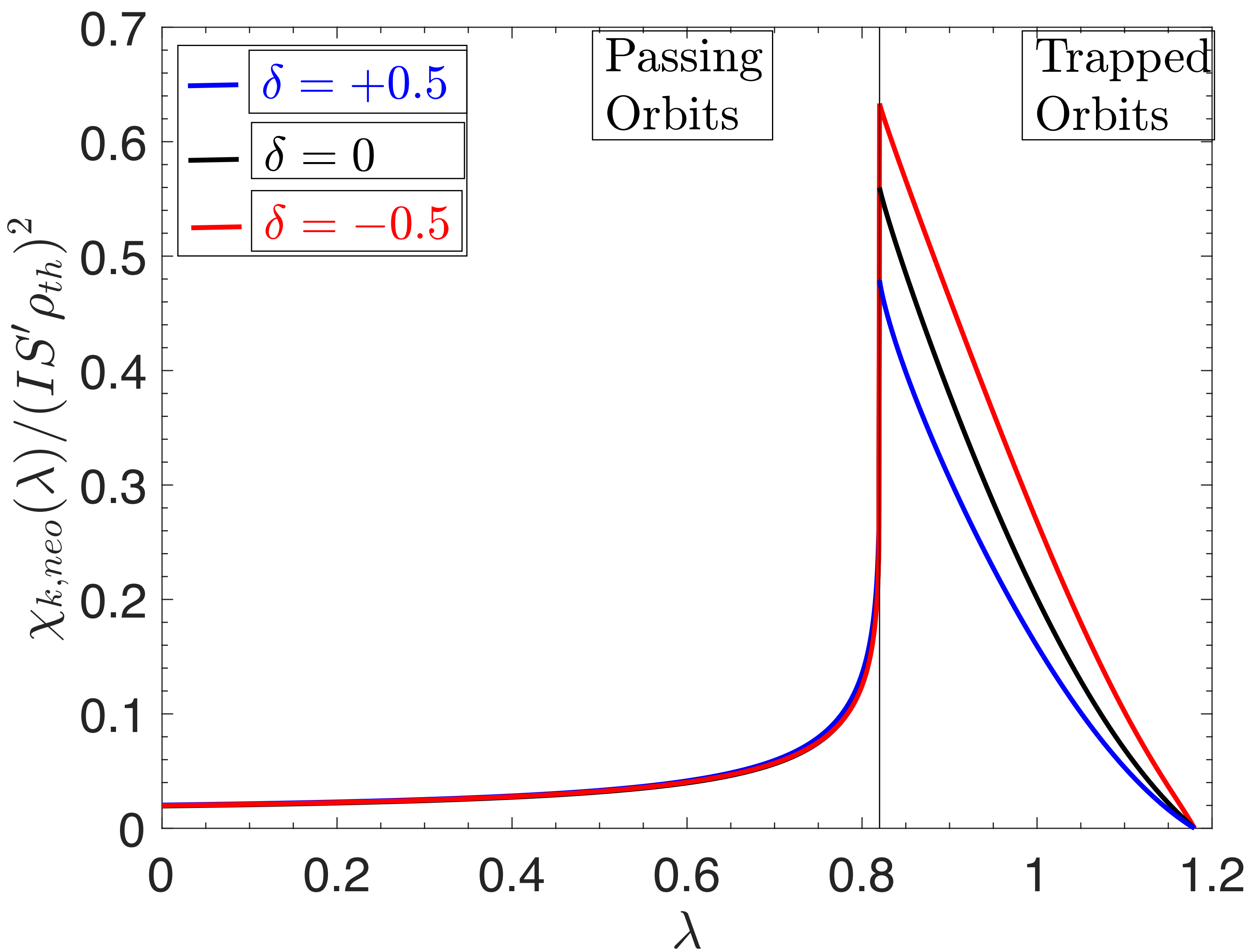
GENE simulations support the theoretical prediction



Surprise! banana width ↓ yet residual ↓

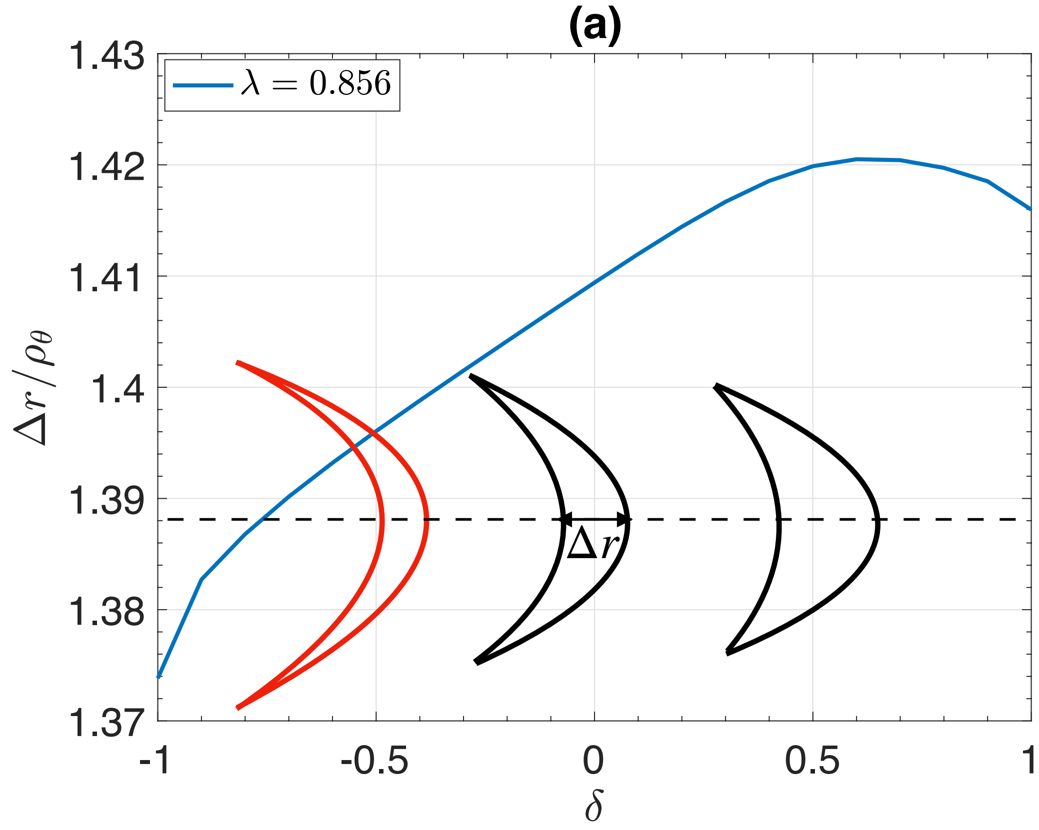
A closer look at Neo-classical susceptibility

- Dominant contribution to $\chi_{k,neo}$ from trapped orbits.
- Trapped part of the spectrum is elevated on decreasing δ.
- Passing part of the spectrum is weakly affected by δ.

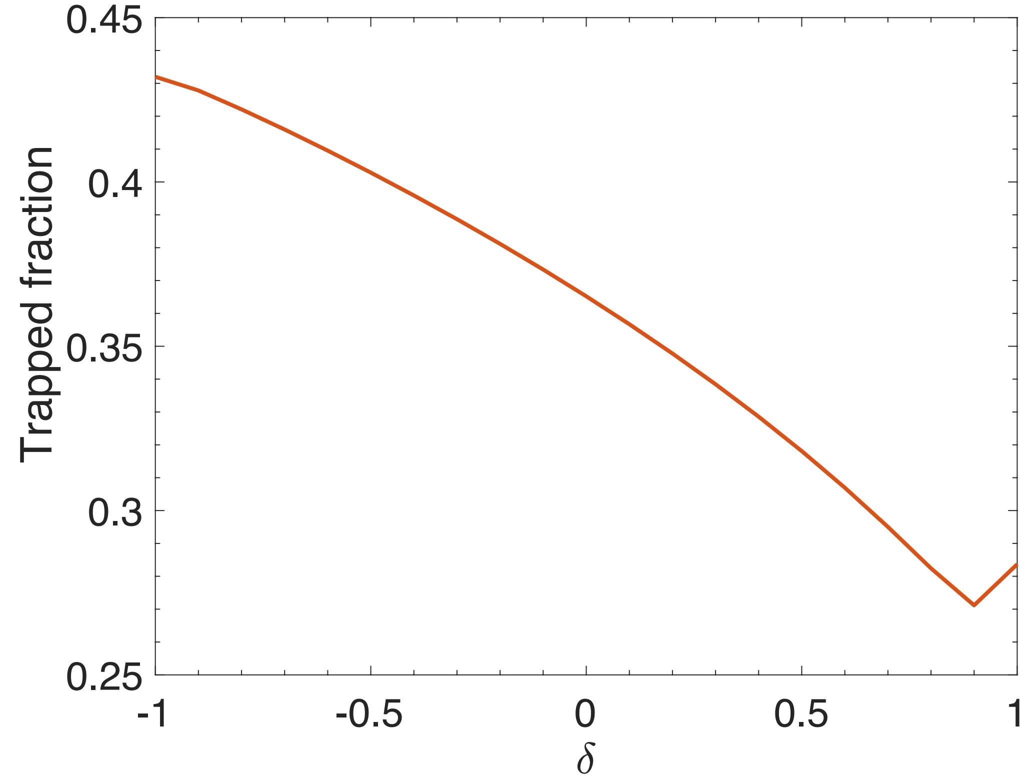


Pitch angle spectrum of Neo-classical susceptibility

Why $\chi_{k,neo} \uparrow$ when banana width $\downarrow$?



Trapped orbits are thinner for $\delta < 0$



Trapped fraction increases with decreasing triangularity

- Smaller banana width →smaller polarization
- Larger trapped fraction → larger polarization
- Polarization reduction by banana width reduction is offset by polarization enhancement by trapped fraction enhancement.
- Hence, bananas are thinner in -ve δ than +ve δ, yet $\chi_{k,neo}(\delta^-) > \chi_{k,neo}(\delta^+)$!

Summary of Theory

[Singh and Diamond 2022 *Nucl. Fusion* (accepted)]

- Neoclassical susceptibility is higher in δ^{-} despite of reduction in banana width. This is due to increase in trapped fraction in δ^{-}.
- This means zonal flow screening length increases in δ^{-}.
- As a result, zonal flow residual is reduced in δ^{-}compared to δ^{+}.
- A bigger screening length, implies weaker zonal flows for fixed drive.
  - ➡ *Weaker regulation of turbulence and transport by zonal flow in* δ^{-}.
  - ➡ Caution: Zonal flow physics is not exclusively determined by screening! Reynolds stress cross-phase vs δ?

Lessons

- Can NOT attribute negative triangularity core transport improvement to simple elements of zonal flow physics.

Implications

- ZF reduction consistent with trend of increased power threshold in NT. Quantitative analysis/prediction of $P_{th,L\rightarrow H}$ needed.
- This also requires knowledge of how mean ExB shearing rate affected when $\delta \rightarrow -\delta$? (In progress)

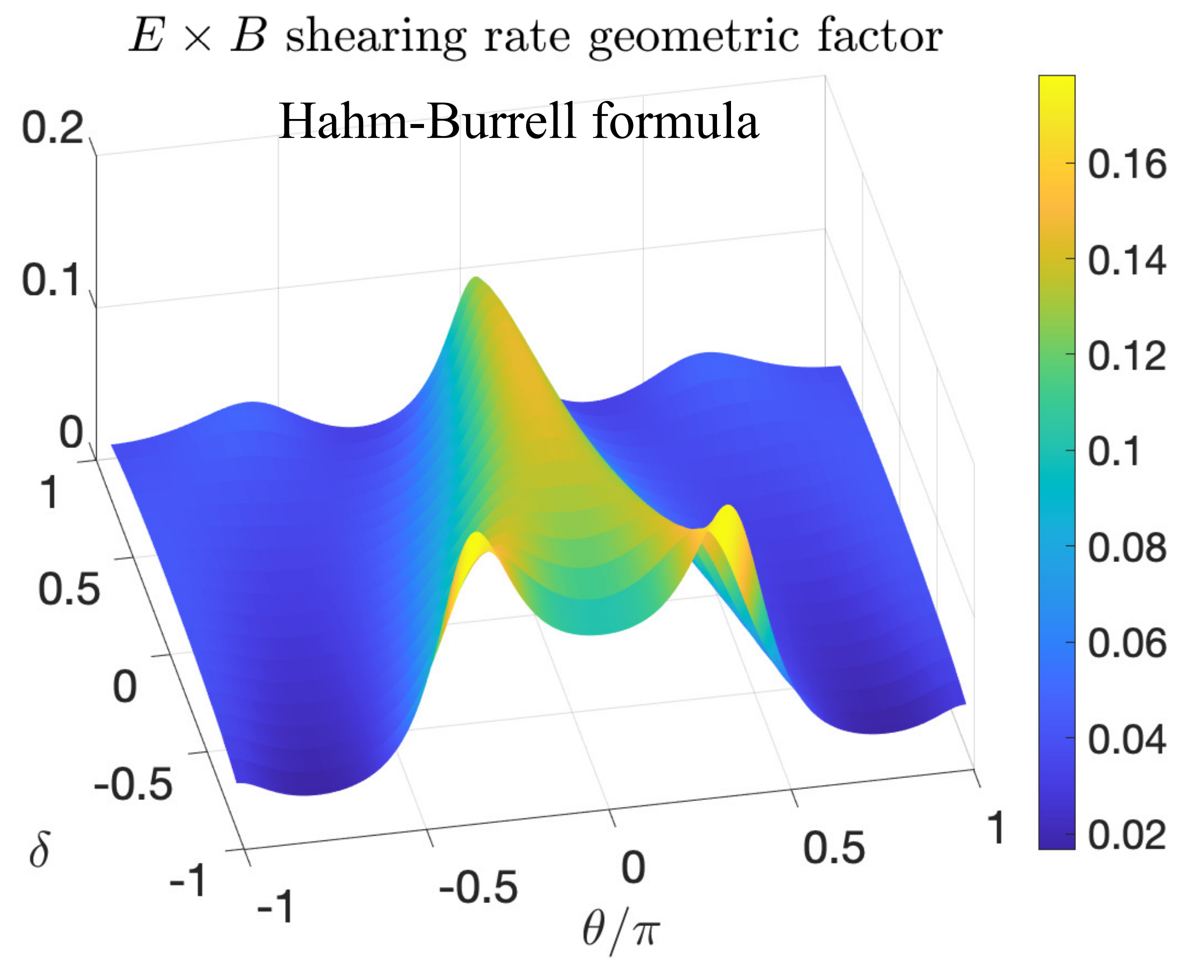
Suggestions

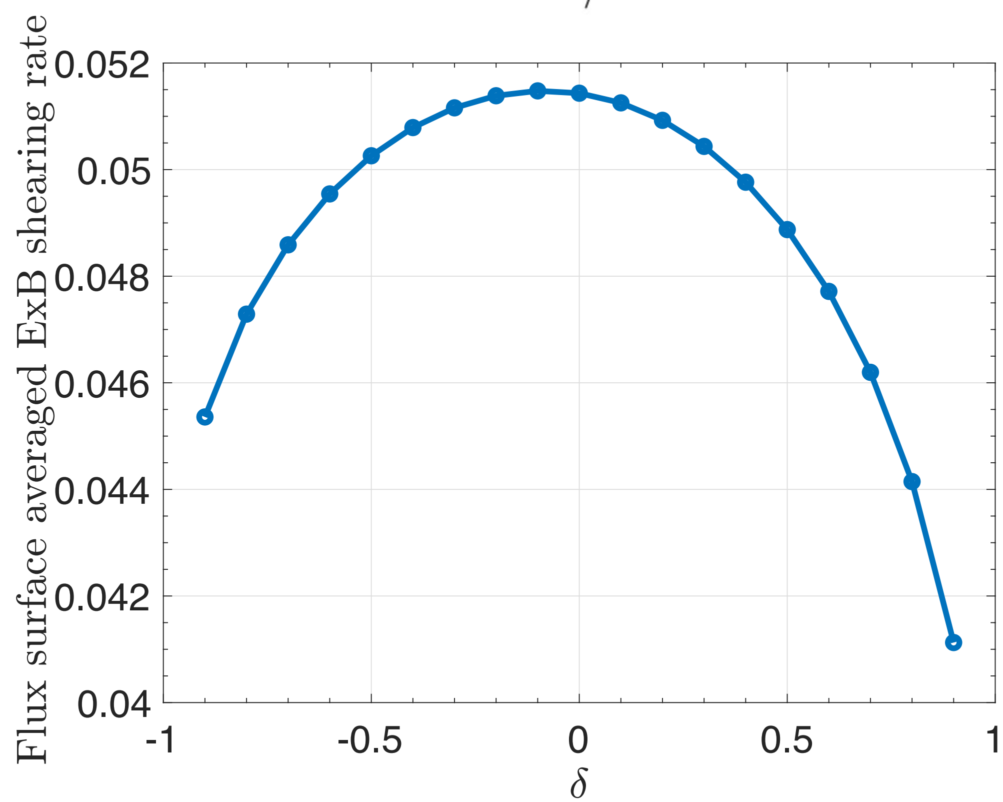
- Compare zonal flow radial correlation length, zonal flow shear strength for $\delta > 0$ and $\delta < 0$. Reynolds power vs δ.

Back up slides

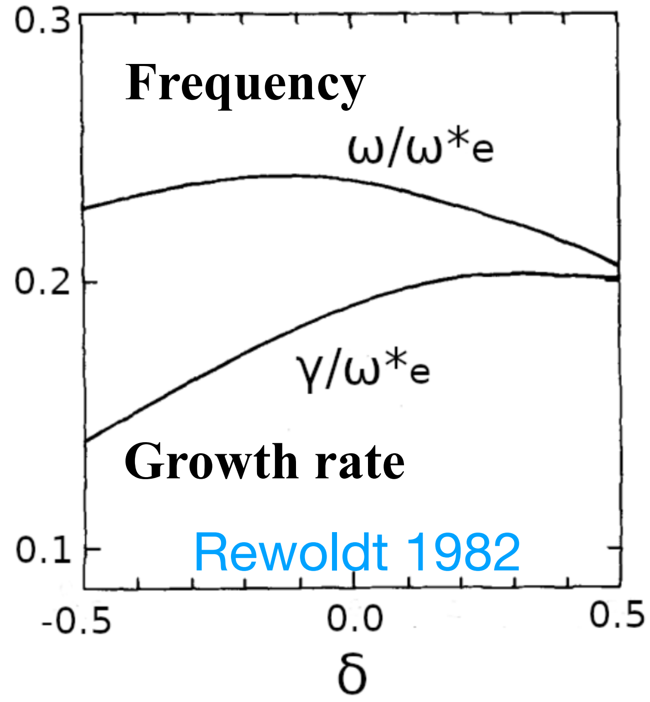
Effect of triangularity on mean ExB shearing rate

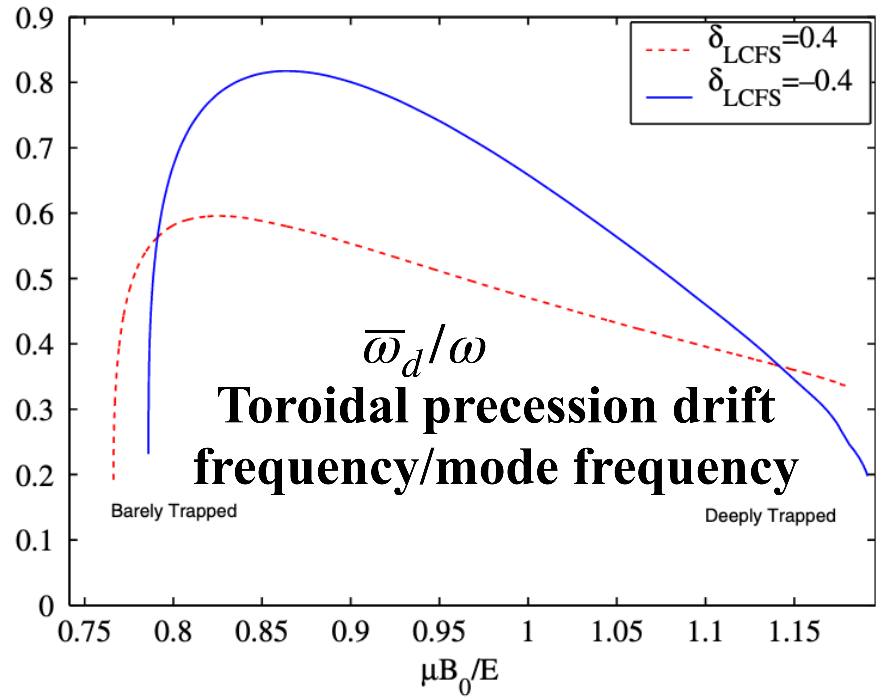
- Peak shearing bifurcates at $\delta = 0$ into 2 peaks for $\delta \to -\delta$.
- Peak shears move toward the good curvature region and shearing rate at $\theta = 0$ decreases with increasing NT.
- Poloidal width of shear increases → FSA ExB shear for NT > PT.
- But shear peaks away from the region where fluctuations are ballooned.
  - ➡ L→H initiated at location away from $\theta = 0$! (Experiments ?)
  - ➡ Shearing efficiency reduced!
  - ➡ Consistent with increased $P_{th,L\to H}$!
  - ➡ 2D L-H transition model needed!

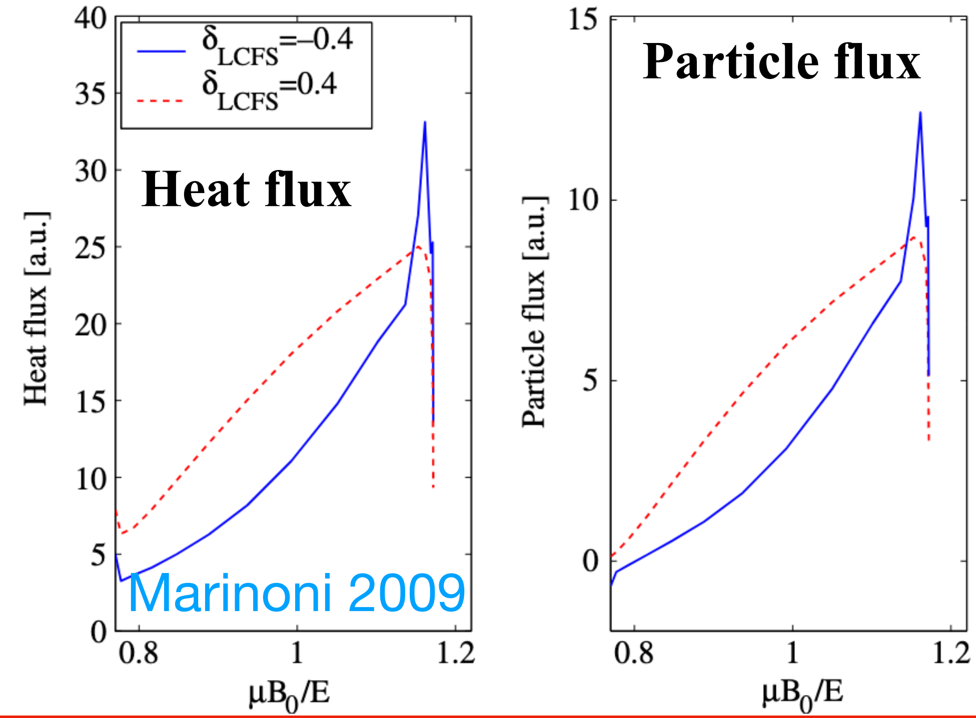




Trapped Electron Mode reduction in negative triangularity by modification of toroidal precession drift frequency







Higher $\overline{\omega}_d/\omega$ linked to growth rate and nonlinear flux reduction for $\delta<0$.

Bounce averaged kinetic equation: $\overline{g} = \dfrac{\omega - \omega_{\star e}(1+\eta_e(E/T_e - 3/2))}{\omega - \overline{\omega}_d(E,\hat{s})}\dfrac{e\overline{\phi}}{T_e}e^{-E/T_e}$

Electron density response: $\dfrac{\delta n_e}{n} = (1 - i\delta)\dfrac{e\phi}{T_e}$

Precession resonance

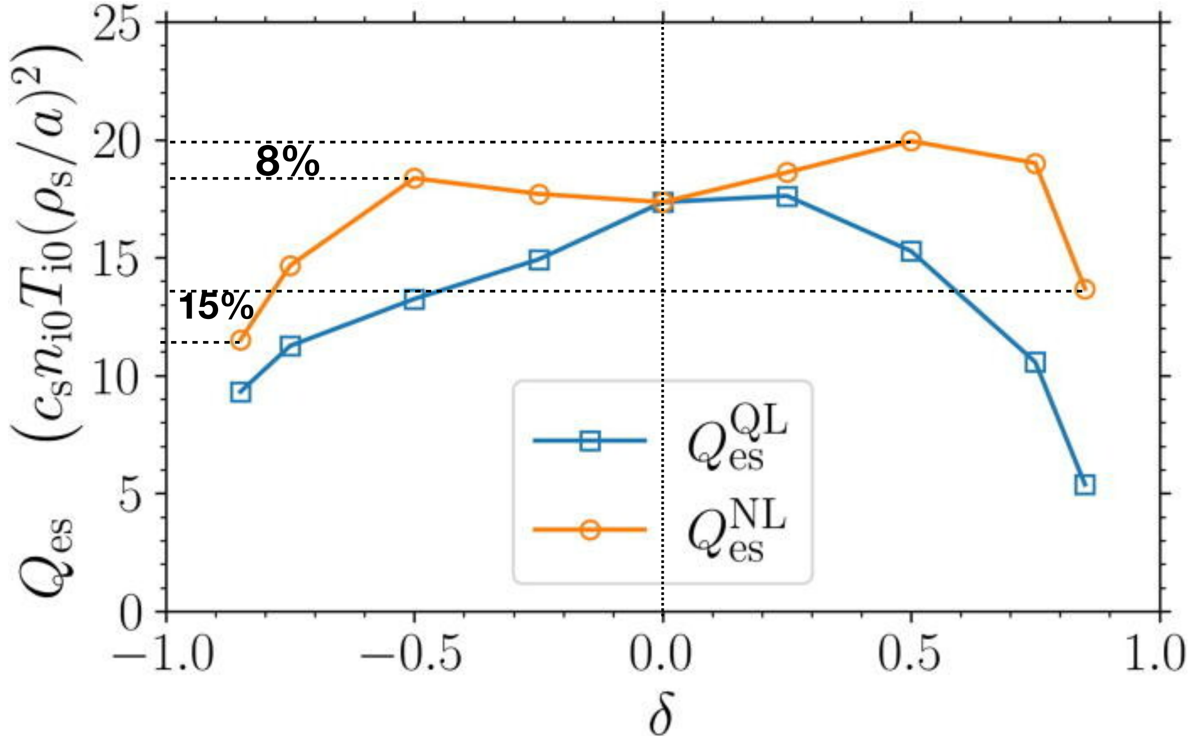
$$\delta = -\Im 2\frac{(2\epsilon)^{1/2}}{\pi^{1/2}}\int d\left(\frac{E}{T}\right)\left(\frac{E}{T}\right)^{1/2}\overline{g} = (2\pi\epsilon)^{1/2}\left(\frac{\omega}{\overline{\omega}_d}\right)^{1/2} e^{-\left(\frac{\omega}{\overline{\omega}_d}\right)}\left[\frac{\omega_{\star e}}{\overline{\omega}_d}\left\{1+\eta_e\left(\frac{\omega}{\overline{\omega}_d}-\frac{3}{2}\right)\right\}-\frac{\omega}{\overline{\omega}_d}\right]$$

Ion density response: $\dfrac{\delta n_i}{n} = \dfrac{\omega_{\star T_i}}{\omega}\left(\dfrac{k_\parallel v_{thi}^2}{\omega^2} - k_\perp^2\rho_i^2 - \dfrac{\omega_{di}}{\omega}\right)\dfrac{e\phi}{T_i}$

Solving perturbatively (for $\delta \ll 1$) the dispersion relation yields the growth rate: $\dfrac{\gamma}{\omega_r} = \dfrac{\delta}{3}$

What about ITG and zonal flows?

ITG driven heat flux is weakly effected by negative triangularity

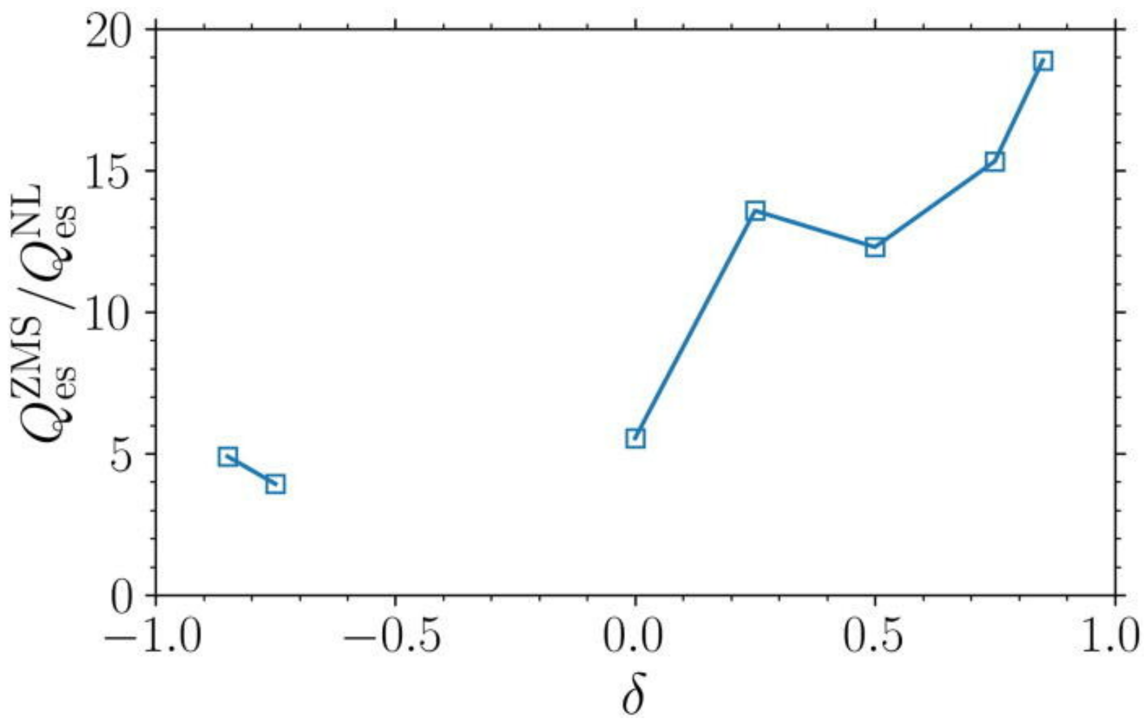


Feeble effect of -ve δ on NL heat flux. Max. $\Delta Q = 15\,\%$, @ $|\delta| = 1$

Duff PoP 2022

Artificially suppressing zonal modes increased nonlinear heat flux by a factor of about four for $\delta < 0$, increasing with $\delta > 0$ by almost a factor of 20.

Weaker regulation of turbulence by zonal flow in $\delta < 0$?



Ratio of heat flux with zonal flows suppressed to heat flux with self-consistent zonal flows.