(Mostly) Mean $E \times B$ shearing rate in negative triangularity tokamaks

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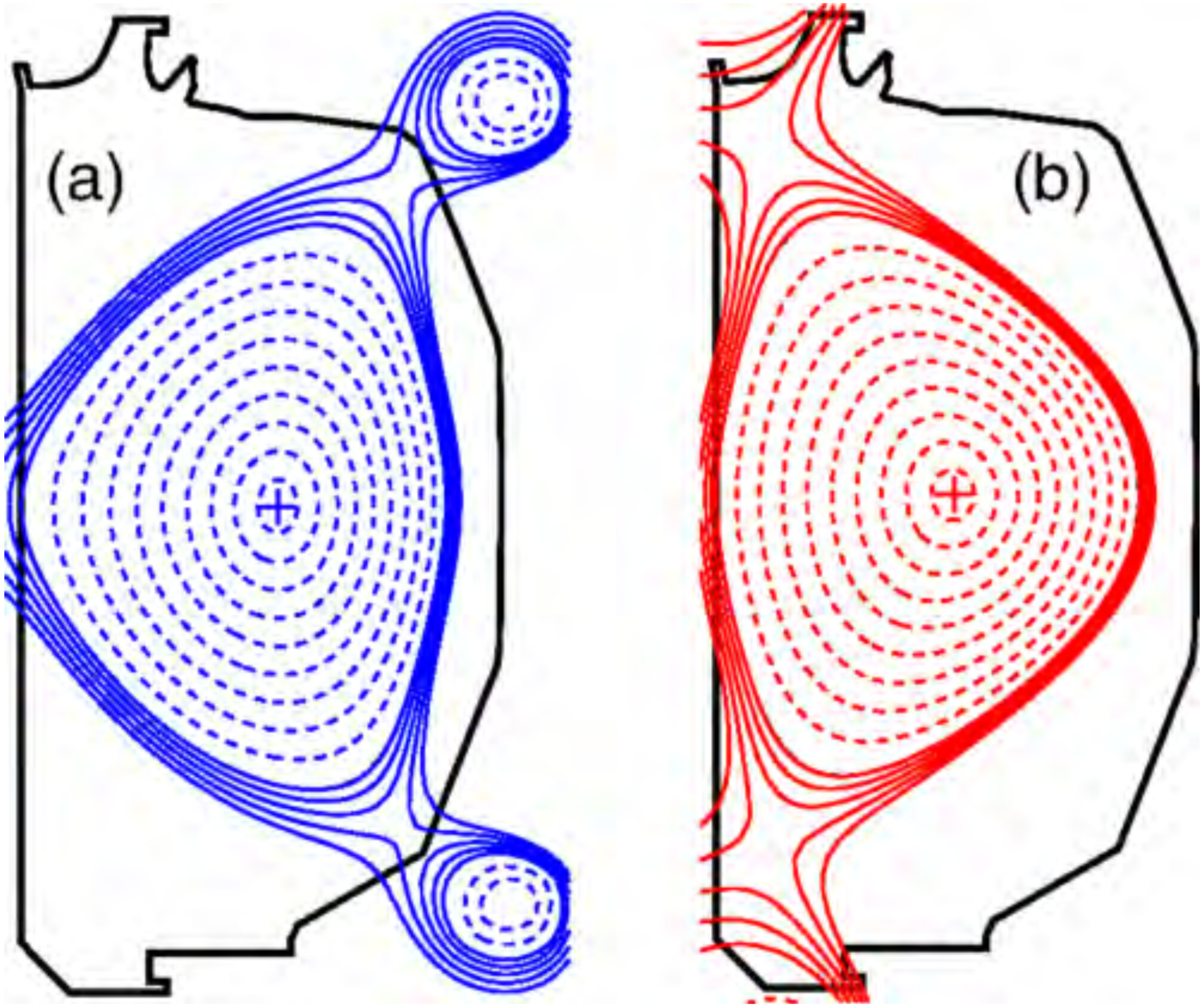
What is negative triangularity?



Austin PRL 2019

NT **PT**

Object of the game in NT

- Get good confinement;
  - “good”= H-mode *like*

- Stay out of H-mode
  - Avoid ELMs, impurity issues, heat load problems . . .

Why?

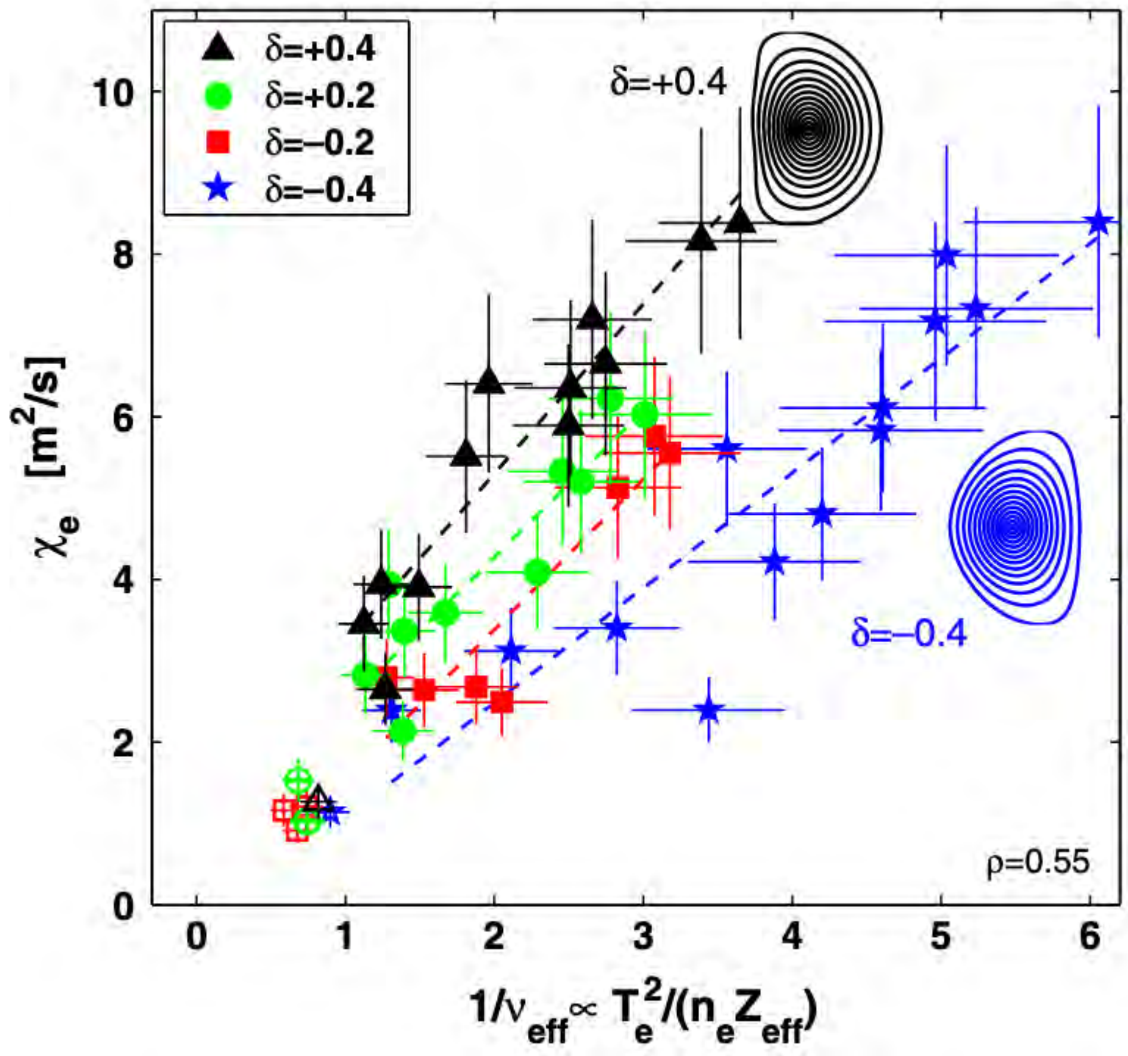
- Rarely asked: ITB + NT edge?!

➡ExB shear . . .

Effect of triangularity on confinement and fluctuations

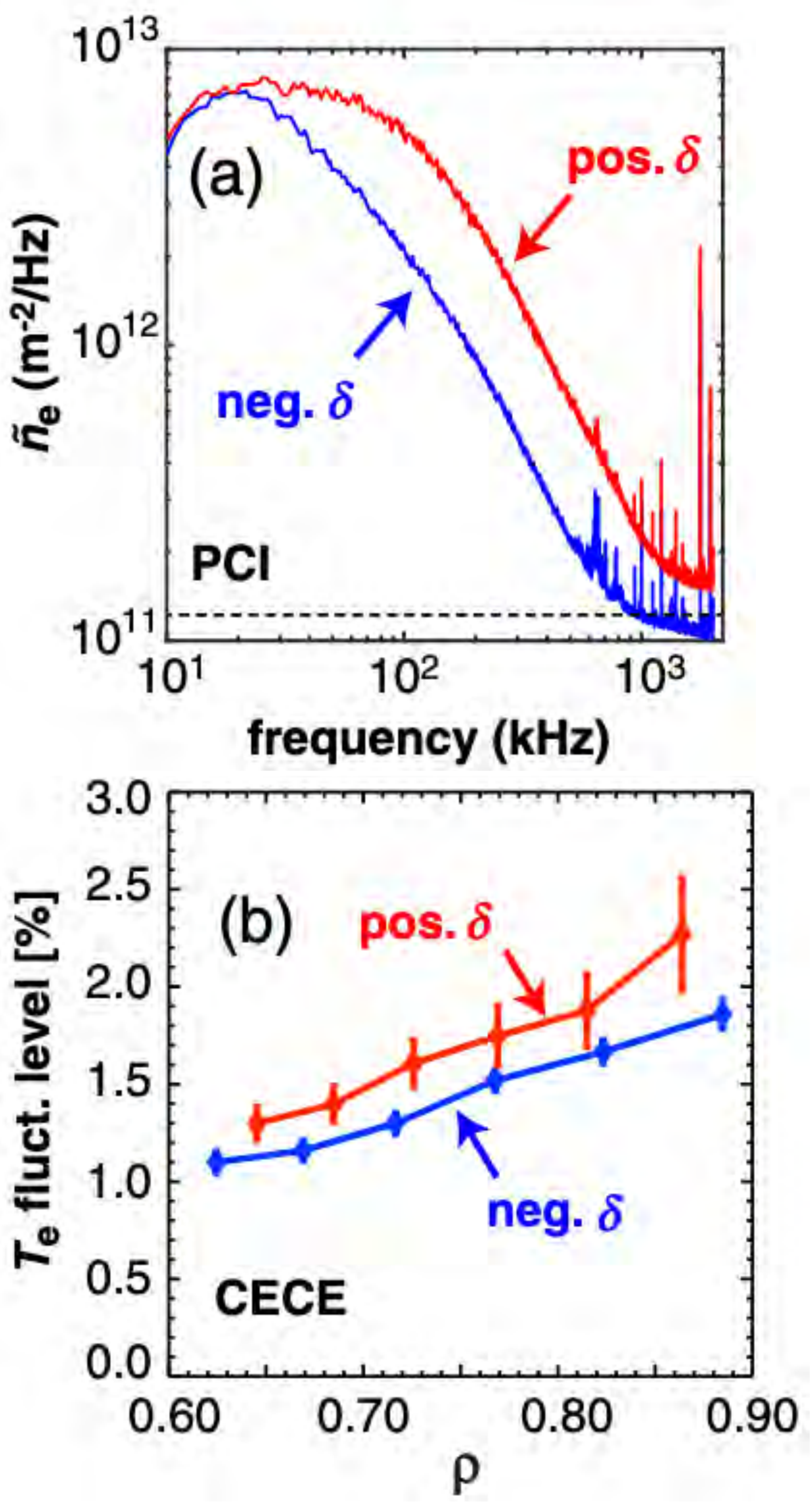
TCV experiments

- EC heated L-mode plasmas
- Energy confinement time doubled when $\delta \rightarrow -\delta$
- More effective in low collisionality regime
- Role of ExB shear ?



Y. Camenen et *al* NF 2007

DIII-D experiments

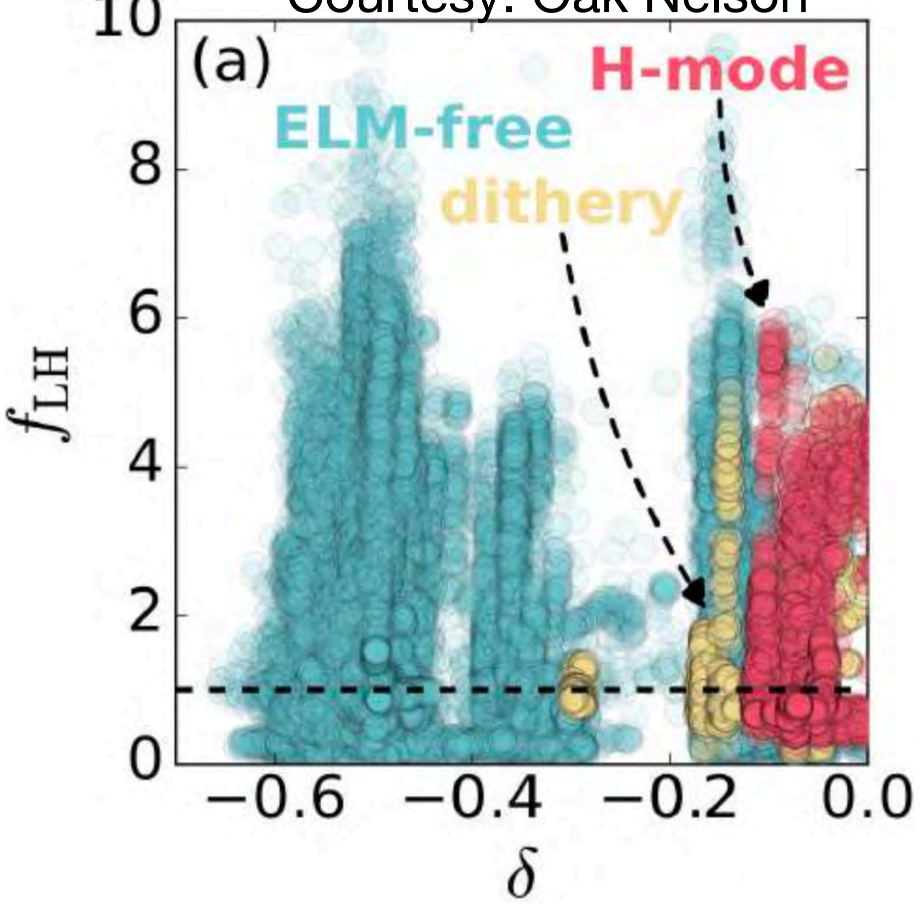


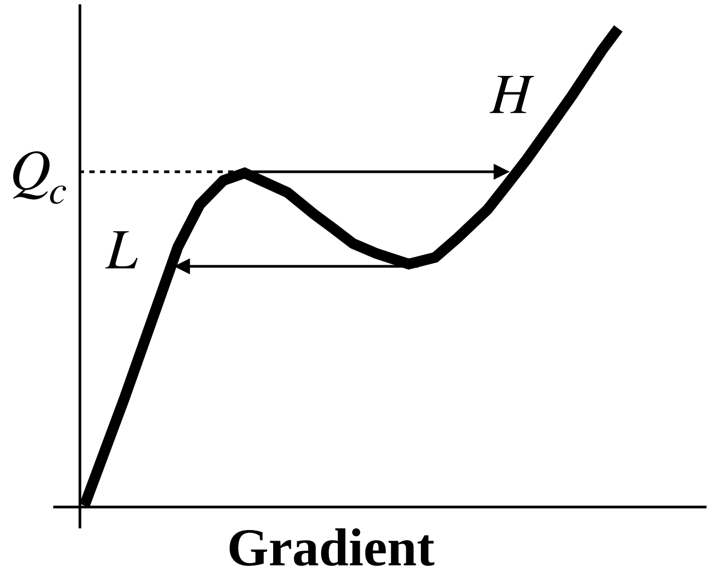
M Austin *et al* PRL 2019

Effect of triangularity on L-H transition

- No H mode transition for $\delta < \delta_{crit} \sim -0.18$
    - $P_{L\to H}$ diverges $\delta < \delta_{crit}$.
    - loss of access to 2nd stability region of $n = \infty$ ideal MHD ballooning modes. [Saarelma *et al* PPCF 2021, Nelson *et al* NF 2022]
    - 2nd stability region is never open for $\delta < \delta_{crit}$.

Courtesy: Oak Nelson





- Is H mode operation always in 2nd stability region?
    - Magnetic separatrix and finite edge current can cause coalescence of 1st and 2nd stable region. [Bishop NF 1986]
    - Many past examples of (PT) H mode operation in the 1st stability region.
- What happens to the E_r' induced transport bifurcation picture of L-H transition in NT?

Role of mean ExB shear in NT pedestal formation?

N.B: Broader view

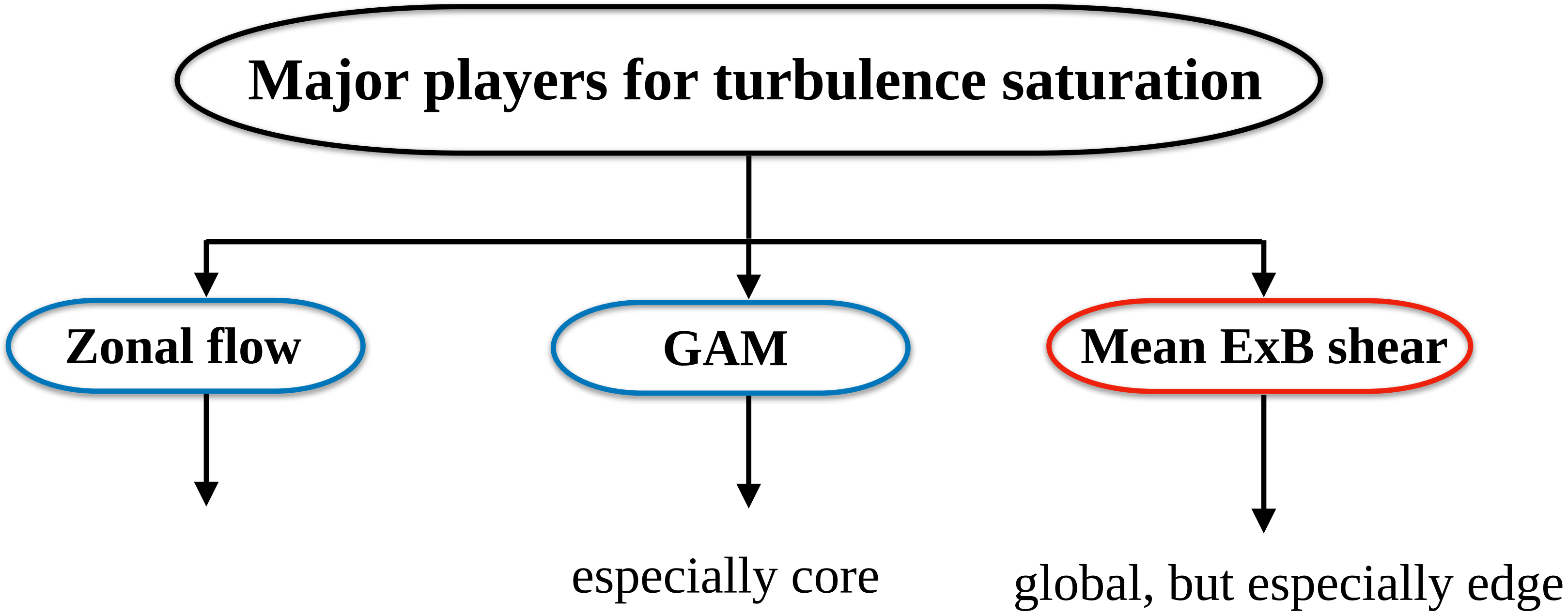
- If we really have a story on L→H, should be able to explain why NT seemingly does *not* transition!

- What can we learn about L→H from NT?

- Is ballooning second stability more important than thought?

How to reconcile confinement improvement in NT L Mode/NT edge with enhanced L-H power threshold?

- Need think beyond linear stabilization of zoo of modes(TEM/ITG,…)!
- Understanding flux surface shaping effects on turbulence saturation mechanism is important.



Major players for turbulence saturation

Zonal flow

GAM

Mean ExB shear

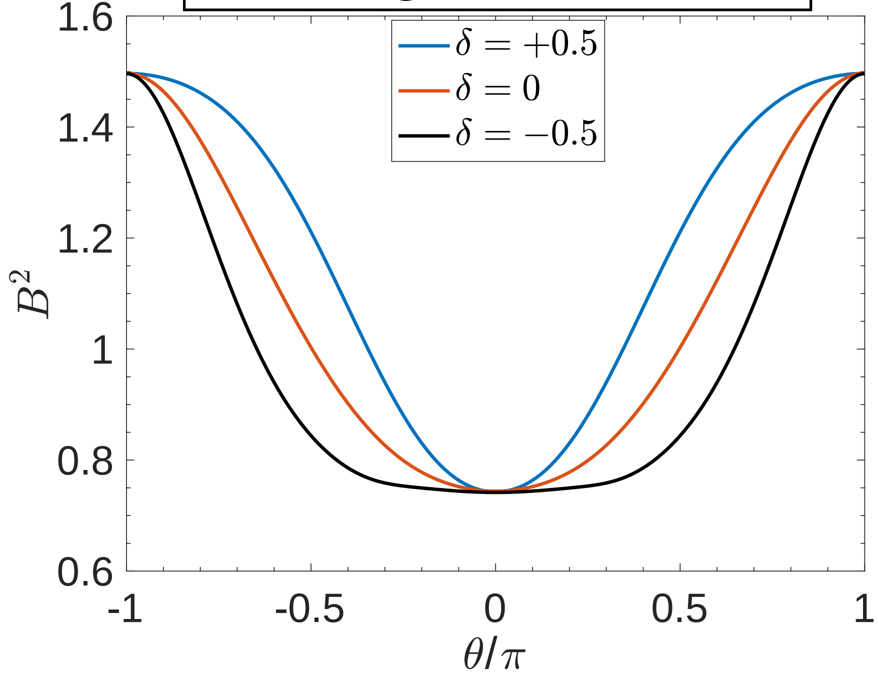
especially core

global, but especially edge

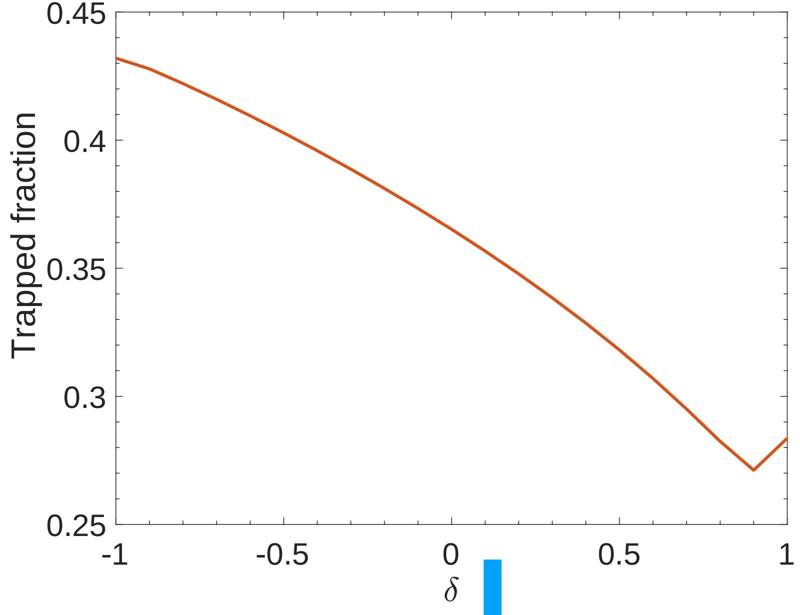
Zonal flows are reduced in NT

[Singh and Diamond NF 2022]

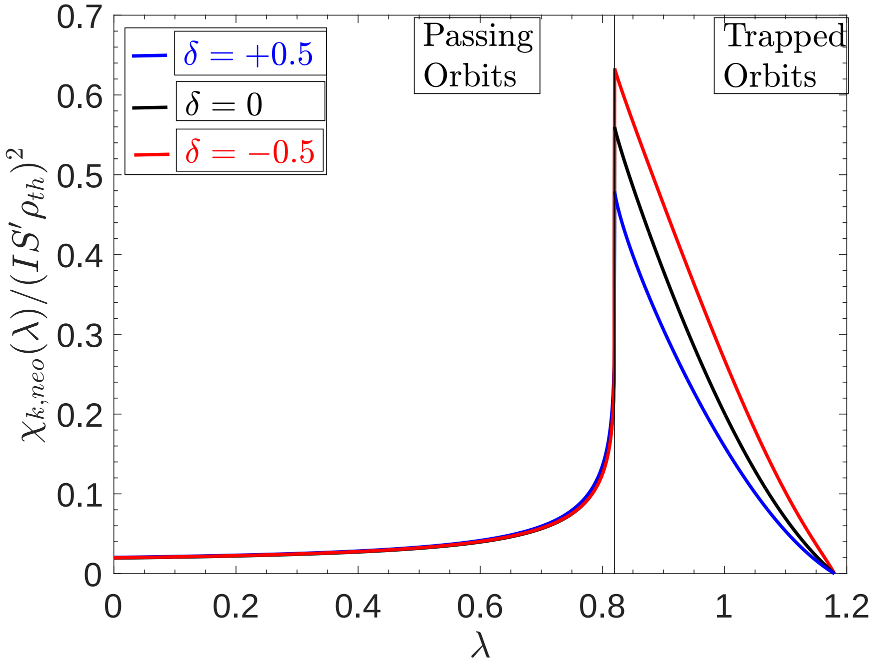
Wider magnetic well for NT.



Increased trapped fraction for NT.

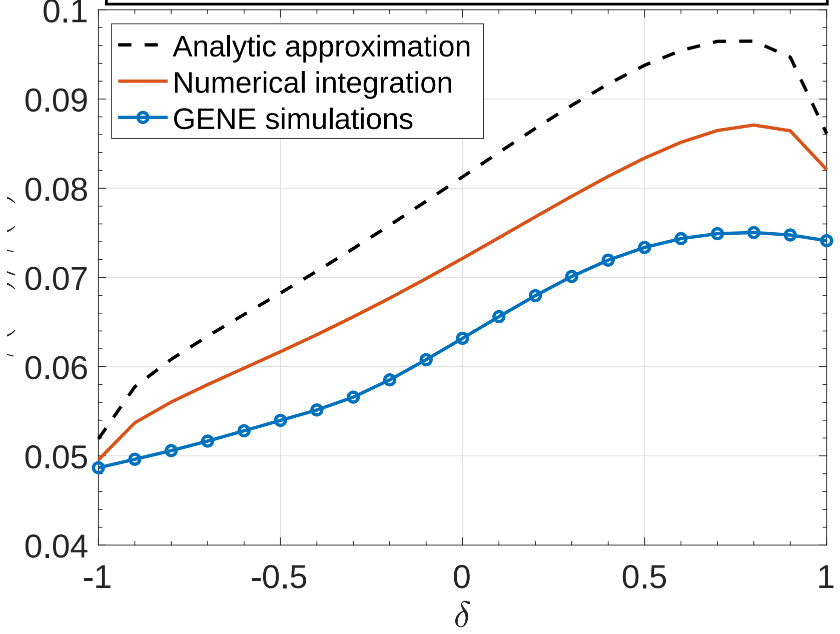


Increased neoclassical susceptibility for NT.



Reduced zonal flows for NT.

Consistent with increased $P_{L\rightarrow H,th}$!



Reduction → Stronger screening ↔ increased trapped fraction

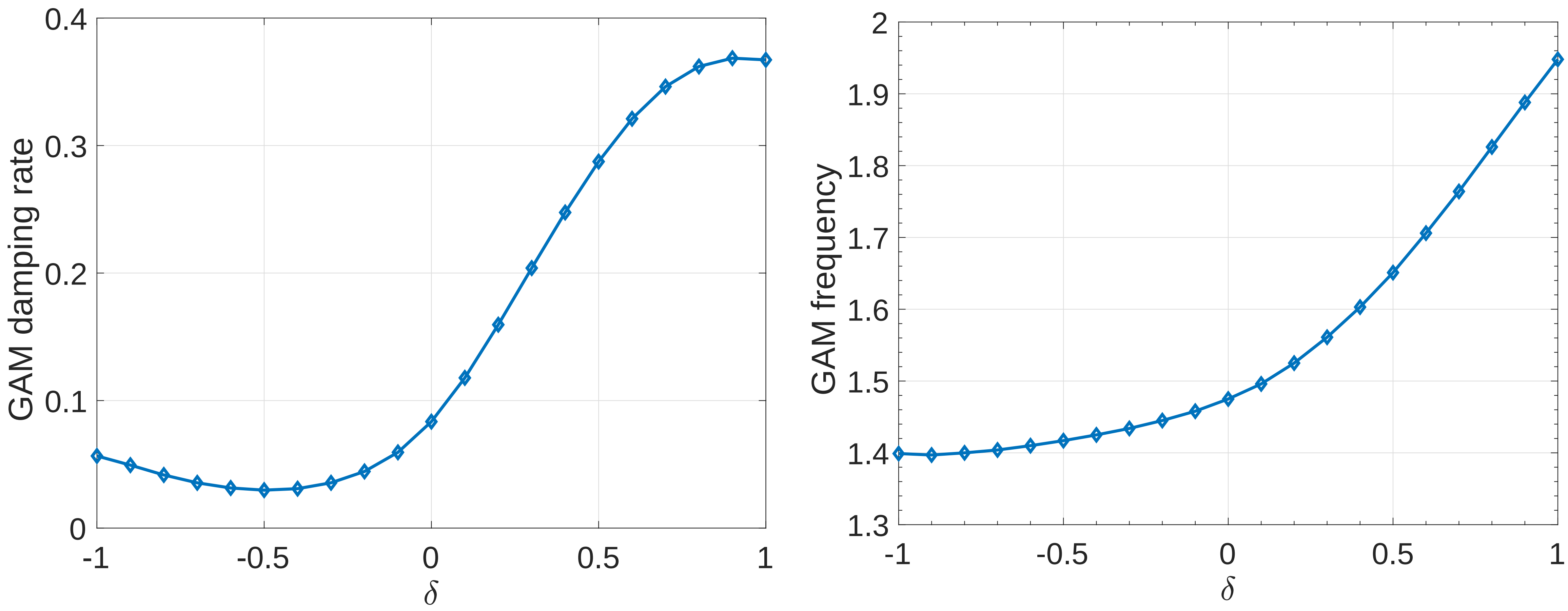
Summary of zonal flow theory in NT

[Singh and Diamond NF 2022]

- Neoclassical susceptibility is higher for δ^- despite of reduction in banana width. This is due to increase in trapped fraction for δ^-.
- This means zonal flow screening length increases for 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?

What about GAM shearing?

GAM frequency and damping rates reduced in NT



- GAM Landau damping is more strongly (~7 times) reduced than the GAM frequency for NT!

  $\Longrightarrow$More coherent and stronger GAM ExB shearing field for NT than for PT !

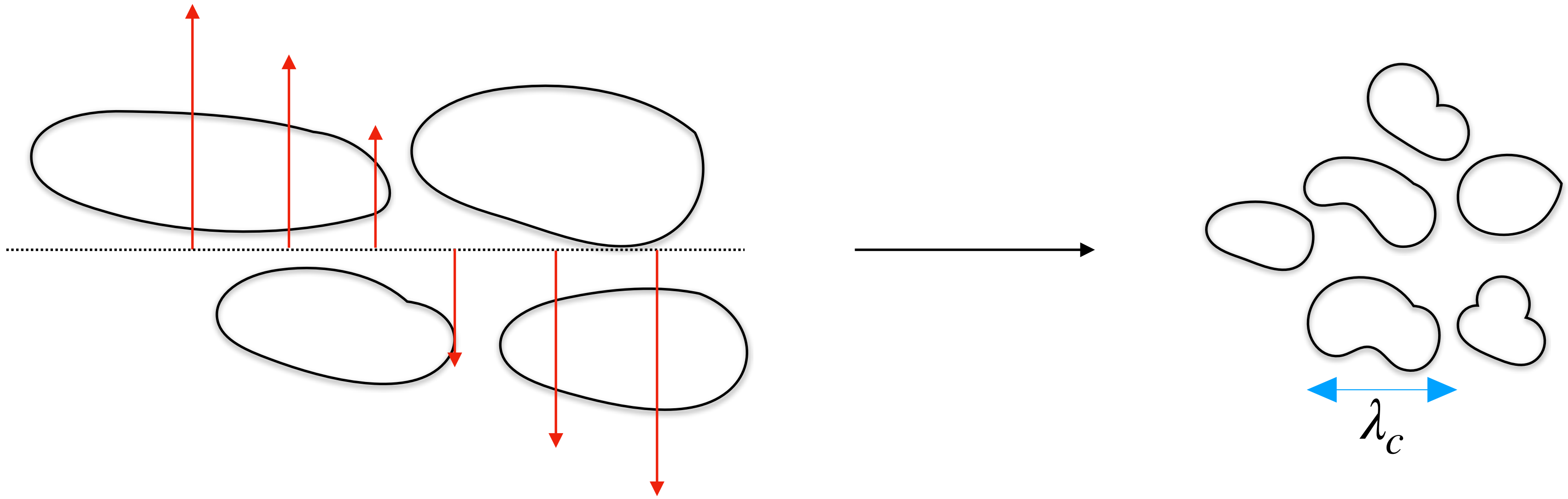
  $\Longrightarrow$NT plasma turbulence is likely saturated by GAMs!

To be continued . . .

What happens to mean ExB shear for NT??

ExB shear suppression of turbulence is the holy grail of physics of transport barriers

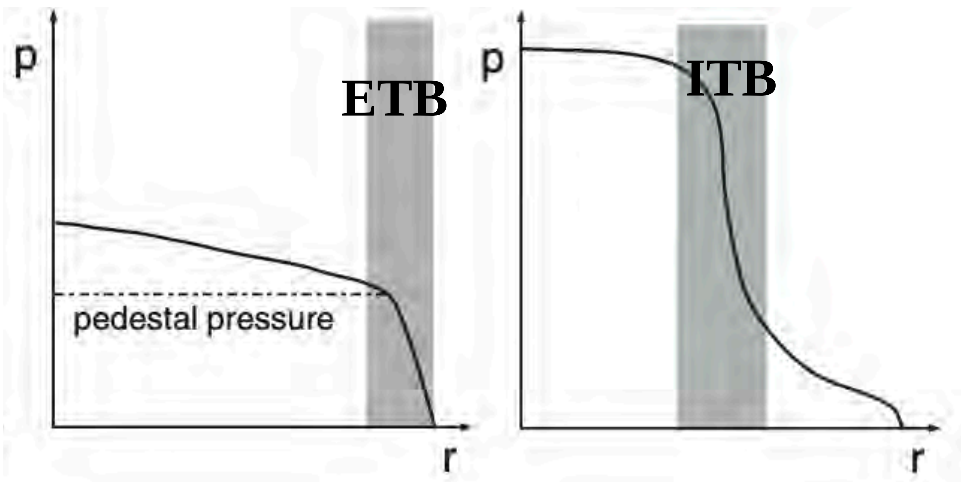
- ExB flow shear reduces radial size of eddies and transport.



$D \sim \lambda_c^2/\tau_c$

- Turbulence quenches when shearing rate $\omega_E > \Delta\omega \sim \gamma_{lin}$ [BDT 90]
- As a result transport is reduced and pressure gradient steepens.

- Transport bifurcation due to mean ExB shearing
    - ETB formation during L-H transition
    - ITB formation in high β_p reversed q discharges



Geometry dependence of mean ExB shearing rate ω_E

ExB shearing rate in general axisymmetric toroidal geometry obtained from a 2-point correlation calculation: [Hahm & Burrell PoP 1995]

$$\omega_E = \left(\frac{\Delta\psi_0}{\Delta\zeta}\right)\frac{\partial^2}{\partial\psi^2}\Phi_0(\psi),$$

ψ:= poloidal flux ζ:= toroidal angle

Φ_0:= Mean electrostatic potential

$\Delta\psi_0$:=Turbulence correlation length in ψ

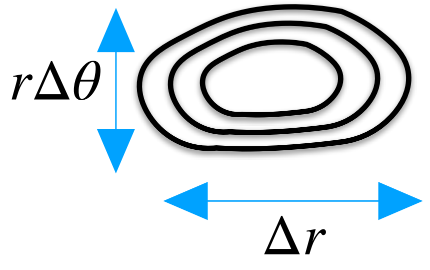
$\Delta\zeta$:=Turbulence correlation in toroidal angle ζ

- $\Delta\psi$ is related to radial turbulence correlation length Δr: $\Delta\psi = \Delta r\dfrac{\partial\psi}{\partial r} = \Delta r\dfrac{RB_\theta}{\left|\vec{\nabla} r\right|}$,

  where ψ' is obtained from the definition of global safety factor q: $\psi' = \dfrac{I(\psi)}{2\pi q(\psi)}\oint d\theta\dfrac{\mathcal{J}}{R^2}$

- $\Delta\zeta$ is related to poloidal correlation angle $\Delta\zeta = \nu\Delta\theta$, where the local safety factor $\nu = \dfrac{I\mathcal{J}}{R^2\psi'}$

- Thus, $\omega_E = \dfrac{\Delta r}{\Delta\theta}\boxed{\dfrac{R^2\psi'^2}{I\mathcal{J}}}\dfrac{\partial^2}{\partial\psi^2}\Phi_0(\psi)$,



Geometry dependent factor

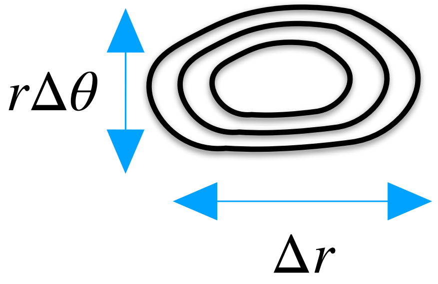
- $\frac{\partial^2}{\partial\psi^2}\Phi_0(\psi)$ is set by the radial force balance of ions - as usual!

Geometry dependence of mean ExB shearing rate ω_E

[Hahm & Burrell PoP 1995]

$$\omega_E = \frac{\Delta r}{\Delta \theta}\boxed{\frac{R^2\psi'^2}{I\mathcal{J}}}\frac{\partial^2}{\partial\psi^2}\Phi_0(\psi),$$

Calculated for Miller's equilibrium for **fixed** $\frac{\Delta r}{\Delta\theta}$ and $\frac{\partial^2}{\partial\psi^2}\Phi_0(\psi)$.



$$R = R_0(r) + r\cos[\theta + (sin^{-1}\delta)sin\theta],\ Z = \kappa(r) r \sin\theta$$

Jacobian:

$$\mathcal{J} = R\kappa r\left[R_0'\cos(\theta) + \cos\left(\sin^{-1}\delta\sin\theta\right) + \sin(\theta + \sin^{-1}\delta\sin\theta)\sin\theta\left\{S_\kappa - S_\delta\cos\theta + \left(1 + S_\kappa\right)\sin^{-1}\delta\cos\theta\right\}\right]$$

Shafranov shift gradient

Triangularity gradient

Elongation gradient

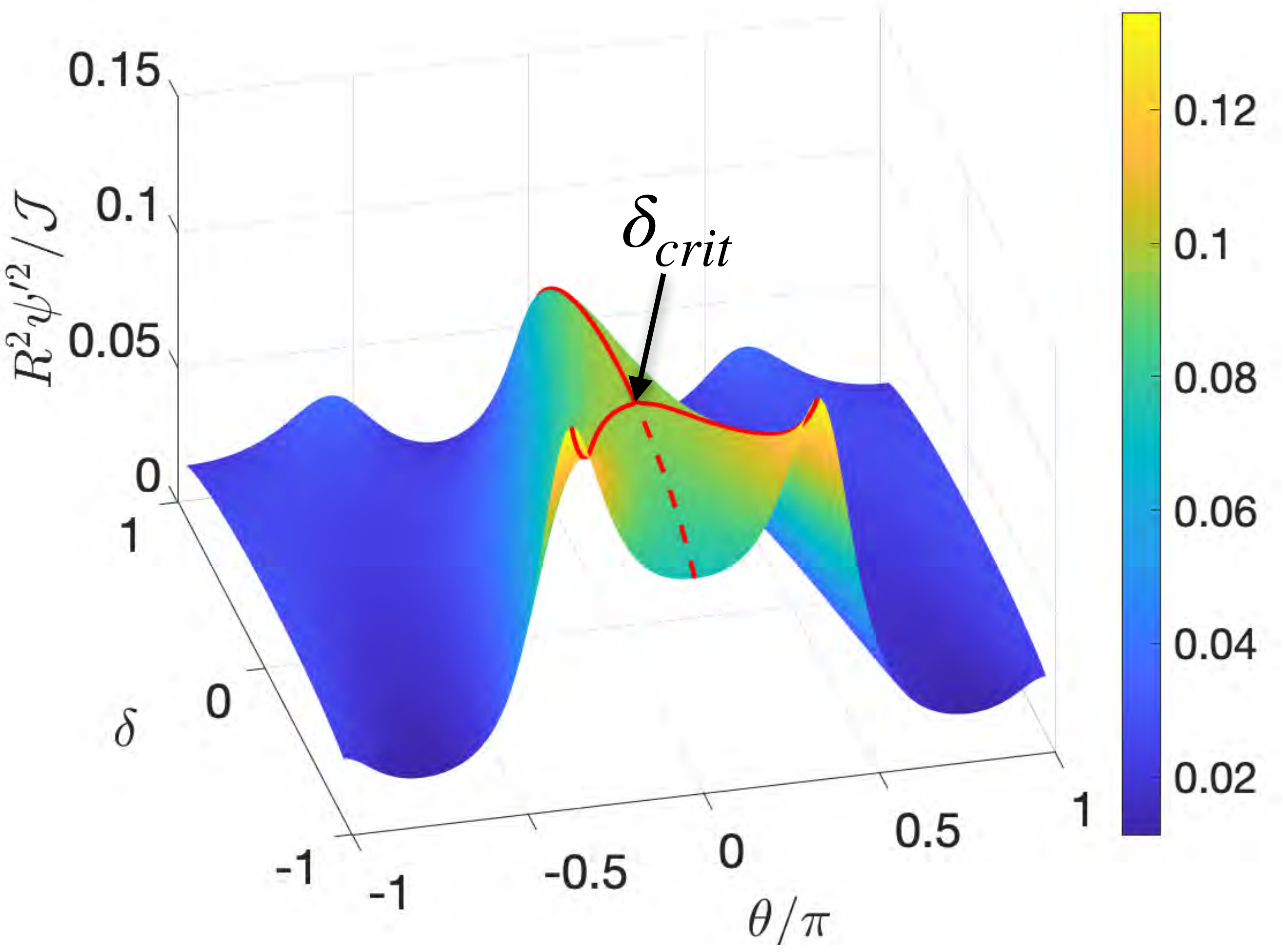
Shape dependence of shearing rate is inferred from shape dependence of $\frac{R^2\psi'^2}{\mathcal{J}}$.

Variation of mean ExB shearing rate with triangularity δ

- **Max shear off the outboard mid-plane for NT→** Shearing is less effective for $k_x = 0$ modes i.e, the modes ballooning at $\theta = 0$.

- **The peak shearing bifurcates at $\delta_{crit} \leq 0$.**
  - Why? The Jacobian is a nonlinear function of δ which exhibits spontaneous symmetry breaking.
  - Peak shears move toward good curvature region.

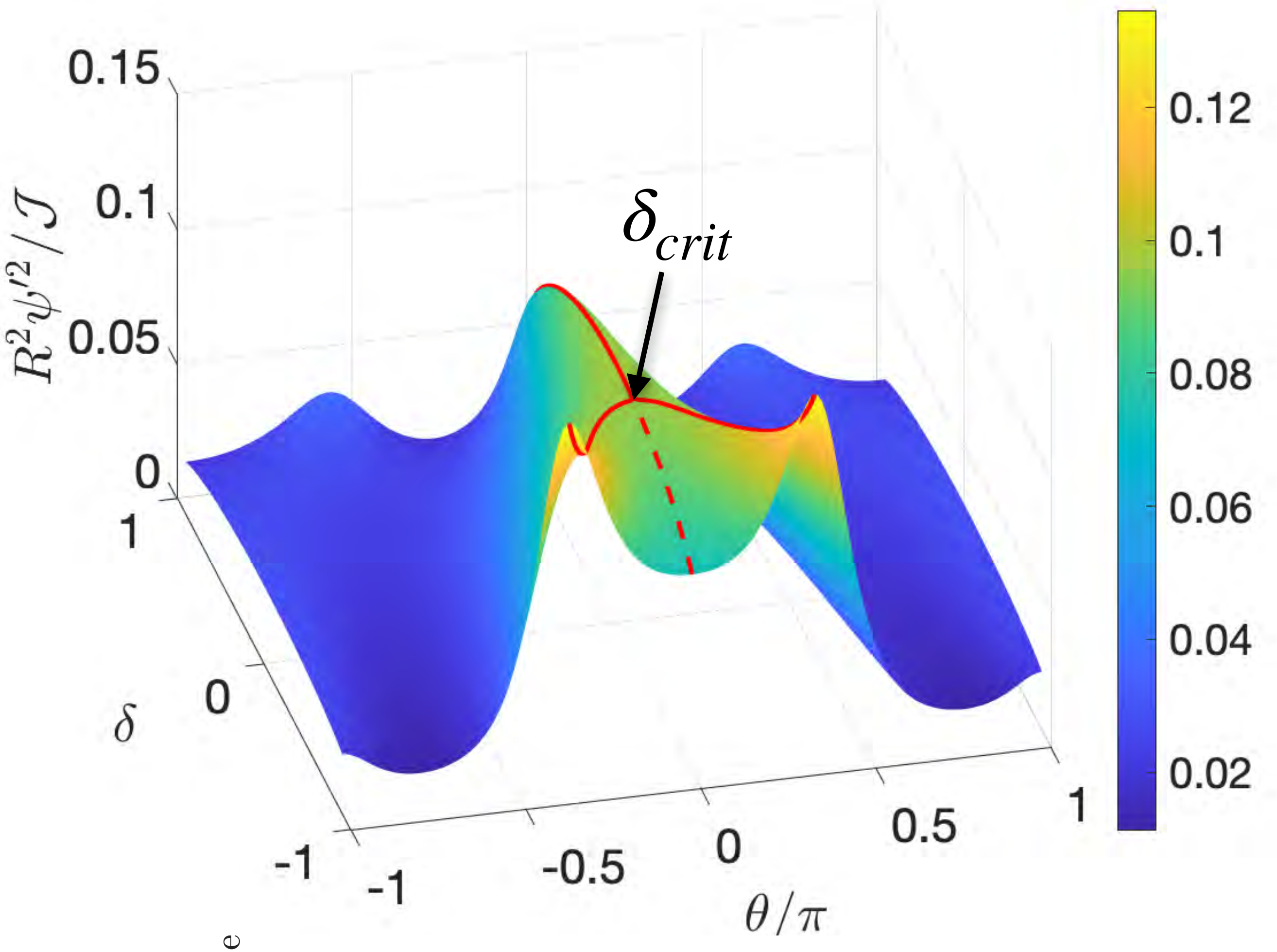
Geometric ‘bifurcation’ of shearing rate



N.B: Calculated at fixed ‘core’ r.

Variation of mean ExB shearing rate with triangularity δ

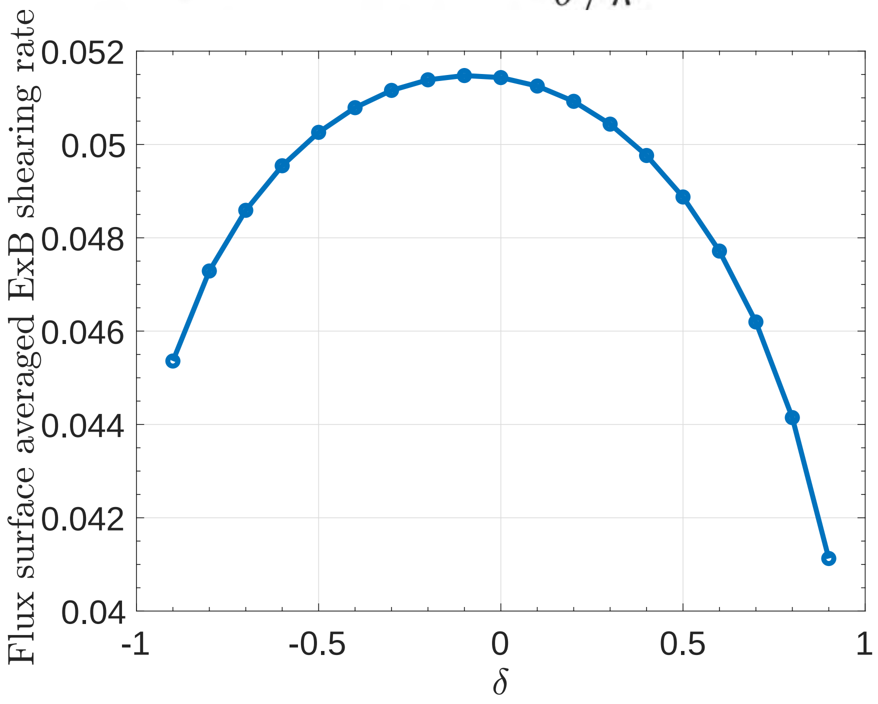
- **Shear at $\theta = 0$:** (for fixed $\Phi_0''(\psi)$)
  - $\downarrow$ with increasing NT.
  - Weaker for NT than for PT. Note that fluctuations balloon at $\theta = 0$. Thus shearing efficiency $\downarrow \implies P_{L \to H,th} \uparrow$ (!?).



Geometric bifurcation of shearing rate

- Flux surface averaged shearing rate is slightly higher for NT than for PT.

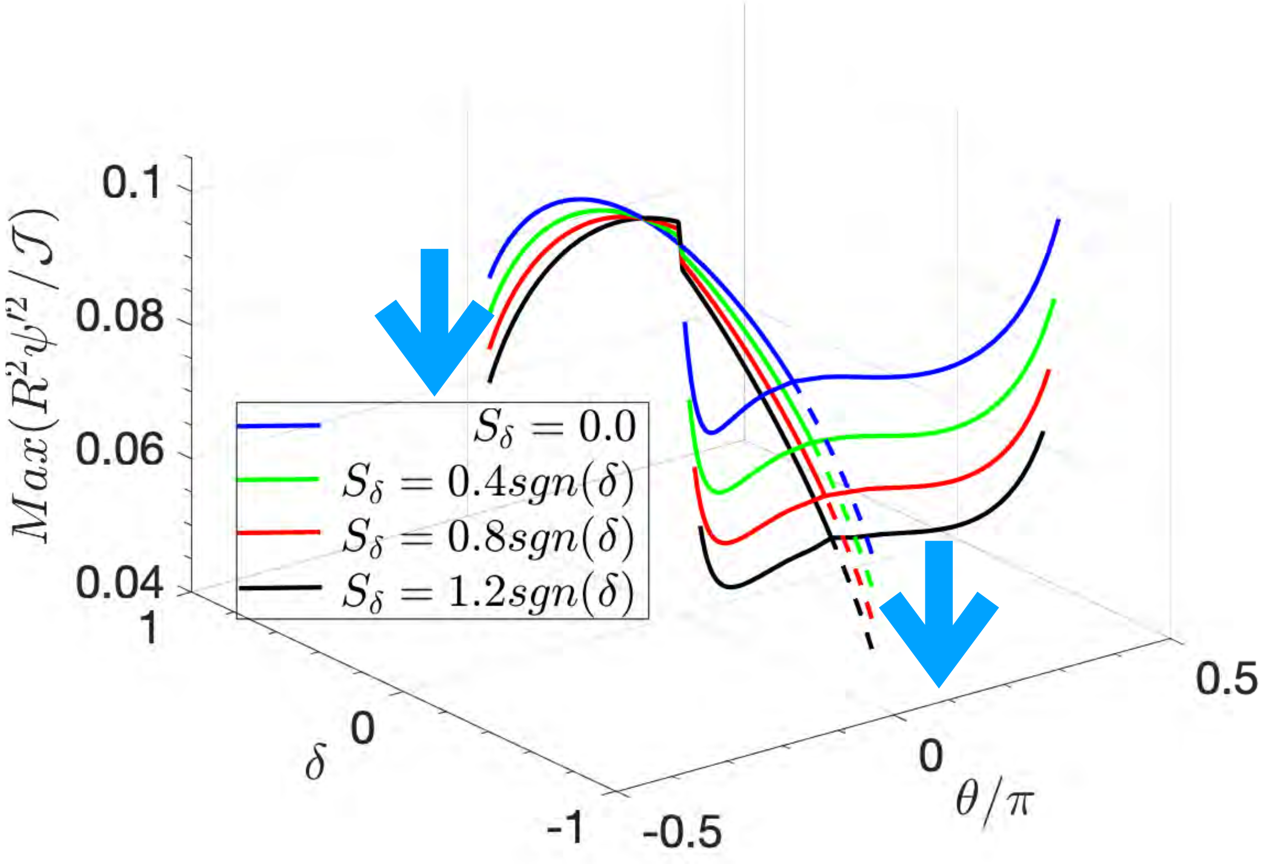
  - Global confinement ?!



Variation of mean ExB shearing rate with triangularity gradient S_δ

On increasing $|S_\delta|$:

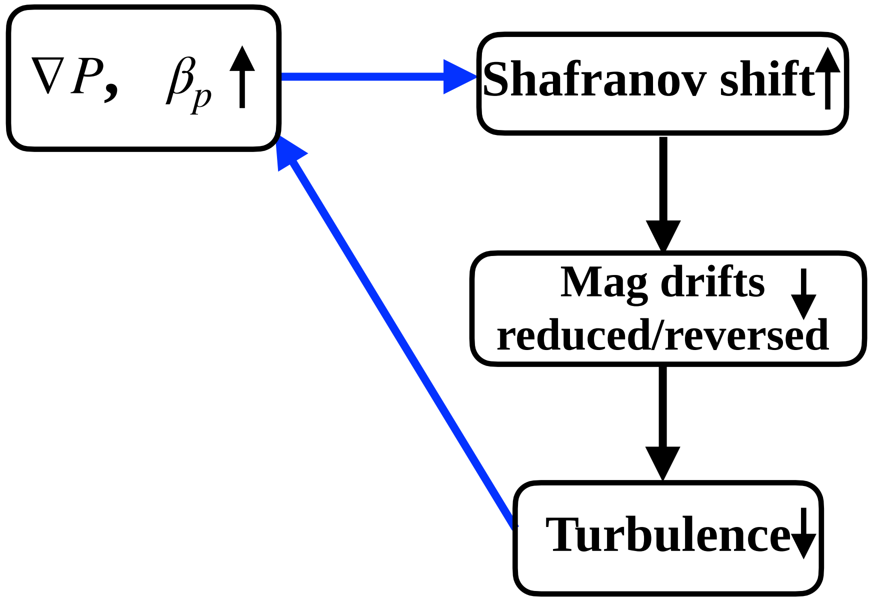
- Shearing rate decreases.
- δ_{crit} moves toward δ^-.



➡Radial profile of triangularity matters!
➡Can triangularity profile can be tailored to boost mean ExB shear?

Shafranov shift induced transport bifurcation

- ITB formation in high-β_p regime is often linked to transport bifurcation due to turbulence stabilization by Shafranov shift due to mag drift reduction/reversal, *ignoring* the mean ExB shear effect. [Mike Beer *et al* PoP 1997, S Ding et *al* PoP 2017, J McClenaghan et *al* PoP 2019, G M Staebler et *al* PoP 2017]



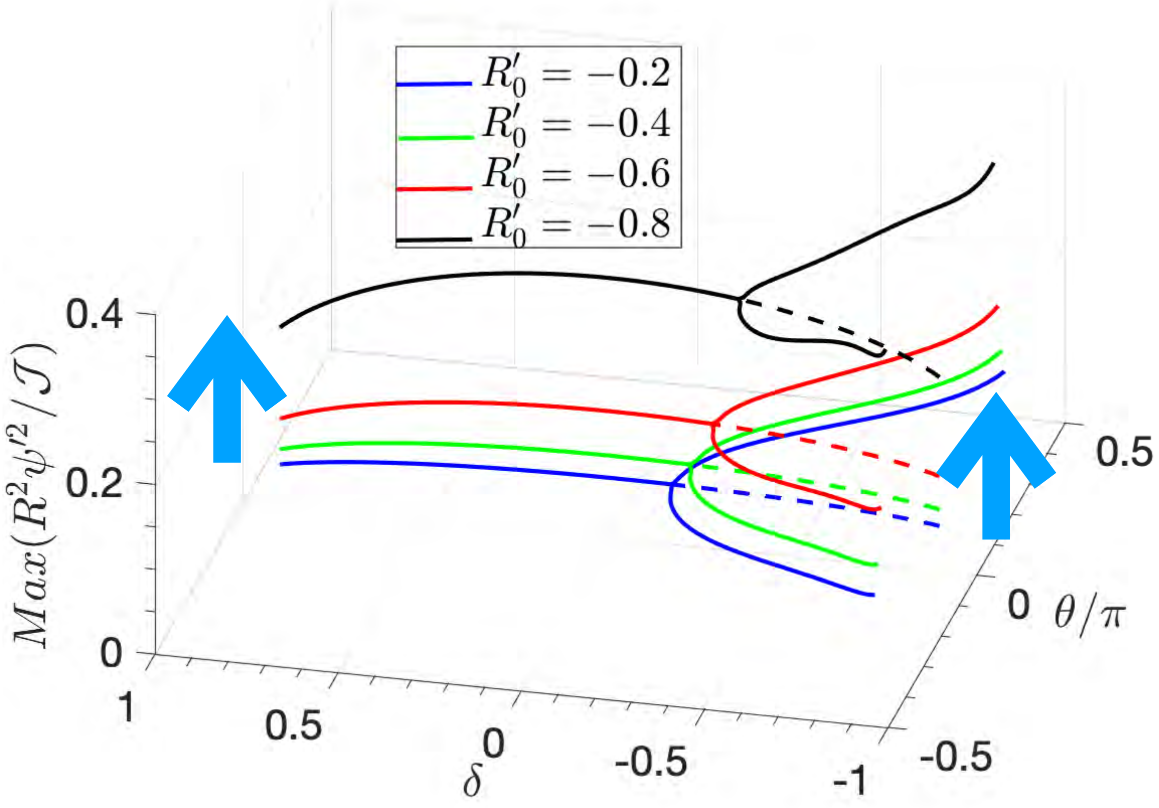
Feedback loop for Shafranov shift induced transport bifurcation

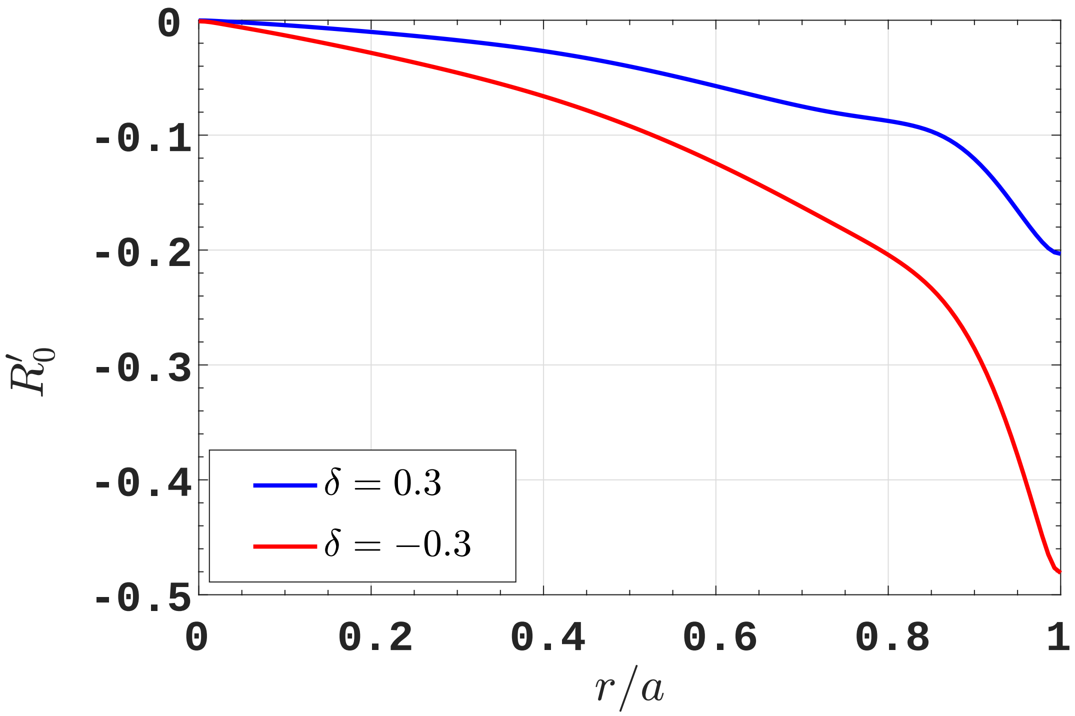
- But… like it or not - mean shear *exist* in high-β_p discharges!
- So how does mean shear and Shafranov shift interact ?
- Interplay of mean ExB shear, Shafranov shift and NT?

Variation of mean ExB shearing rate with Shafranov shift gradient R_0'

On increasing $-R_0'$:

- Shearing rate increases for all δ.
- δ_c moves toward δ^- on increasing $-R_0'$.
- Key reason→flux compression.





Shafranov shift gradient obtained using CHEASE code

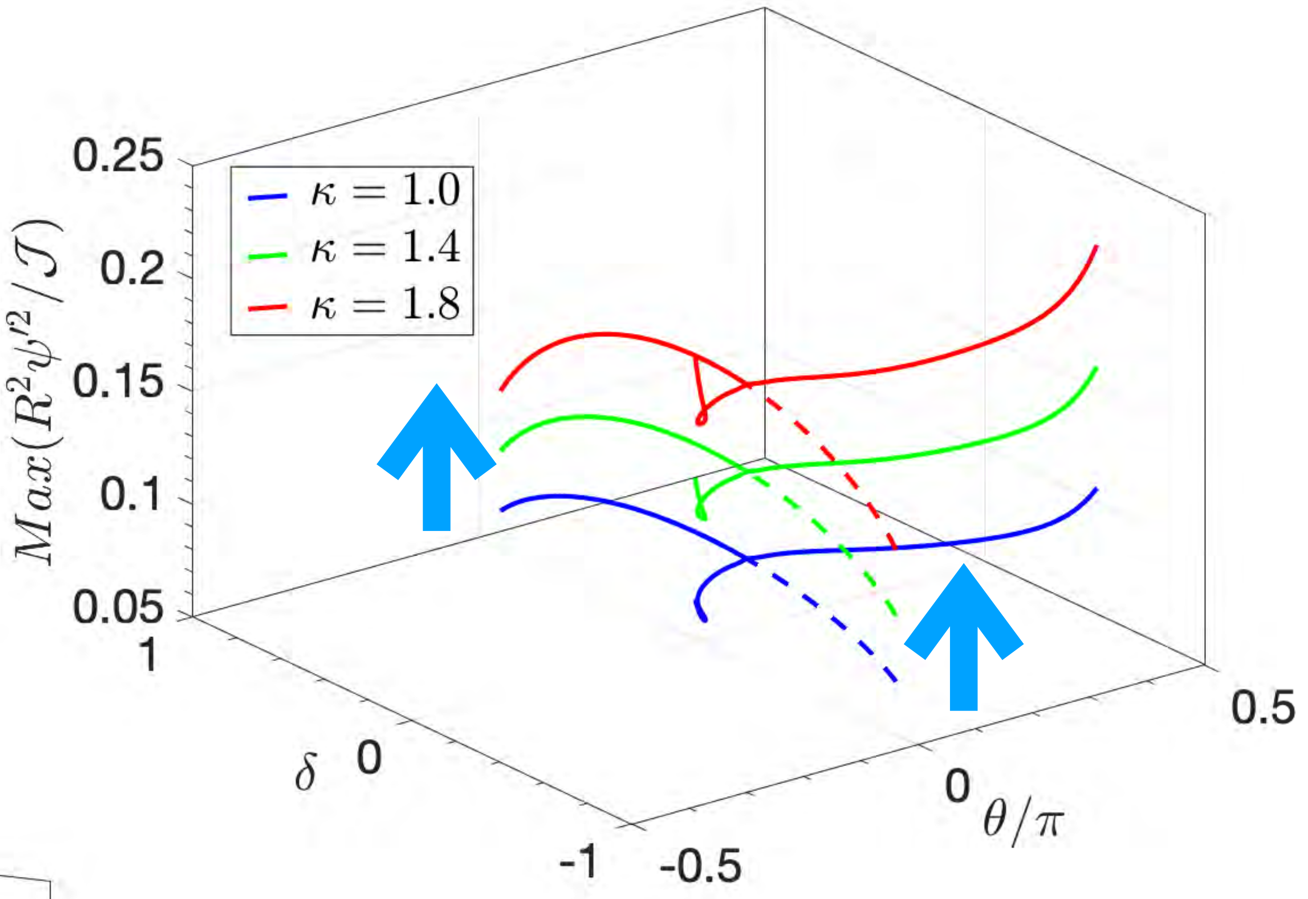
Significant for:

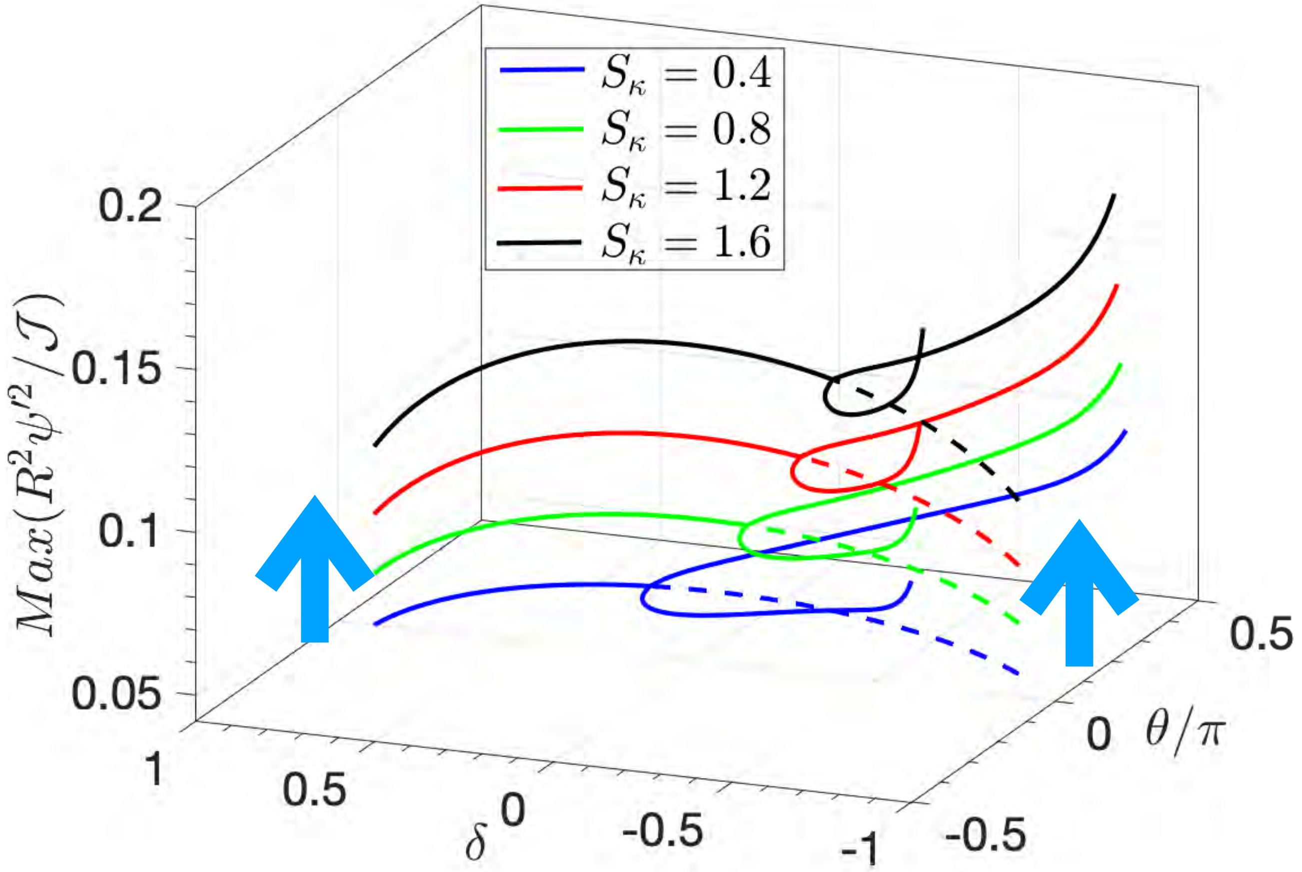
- high β_p regime (i.e, RS ITB) as $R_0' \propto \frac{r}{R_0}\beta_p$
- NT shapes
  - as $\beta_p(\delta^-) > \beta_p(\delta^+)$
  - Numerical MHD equilibrium study shows $R_0'(\delta^-) > R_0'(\delta^+)$ even for fixed β_p.

Mean ExB shearing rate increases with elongation κ and elongation gradient S_κ

On increasing κ:

- Shearing rate increases $\forall\ \theta$ and δ
- δ_{crit} is independent of κ.





On increasing S_κ:

- Shearing rate increases $\forall\ \delta$.
- δ_{crit} moves along δ^-.

Conclusions

Pure geometrical modification of ExB shearing rate as PT → NT shapes

- **Max shear off the outboard mid-plane for NT as →** Shearing is more effective for $k_x \neq 0$ modes for NT. Are these relevant?

- **The peak shearing bifurcates at** $\delta_{crit} \leq 0$. Peak shears move toward good curvature region and the shear at $\theta = 0$ decreases with increasing NT. Note that fluctuations balloon at $\theta = 0$. Thus shearing efficiency $\downarrow \implies P_{L\to H,th} \uparrow$(!?). Is this sufficient ?

- **Shearing rate decreases with increasing triangularity gradient** S_δ **and increases with increasing elongation** κ**, and elongation gradient** S_κ.

- **Direct effect of Shafranov shift gradient** $-R_0'$ **on shearing rate:** Shearing rate increases with increasing $-R_0'$ for all δ. Key reason→flux compression. Significant for high β_p regime and NT shapes.

These results has implications not just for L-H transition for NT but also for ITB discharges in PT and NT(proposed), and NT core and and pedestal.

NT micro stability studies have ignored ExB shear.

Implications I

- Shafranov shift affects turbulence in 2 distinct ways:

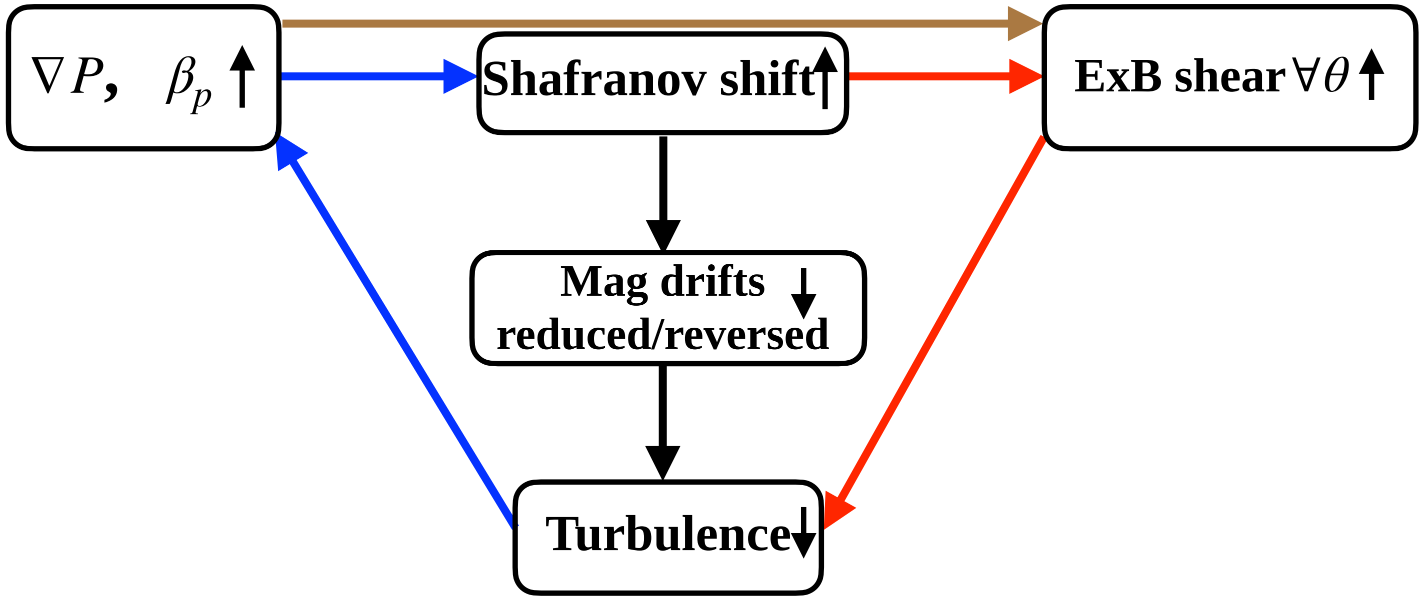
  (I) Stabilizes turbulence by reduction/reversal of magnetic drifts

  (II) Directly enhances the mean shear, → additional turbulence suppression

  Both can cause bifurcation to enhanced confinement state independently. Bifurcation by (I) is often invoked as a mechanism of confinement improvement in high-β_p regime, *ignoring* the mean shear effect.

Enhanced mean ExB shearing by Shafranov shift provides a +ve feedback on the feedback loop of the Shafranov shift induced transport bifurcation.

Shafranov shift also has a +ve effect on the mean ExB shear induced transport bifurcation, not only through a reduction of the linear growth rate but also through the enhanced ExB sharing rate.

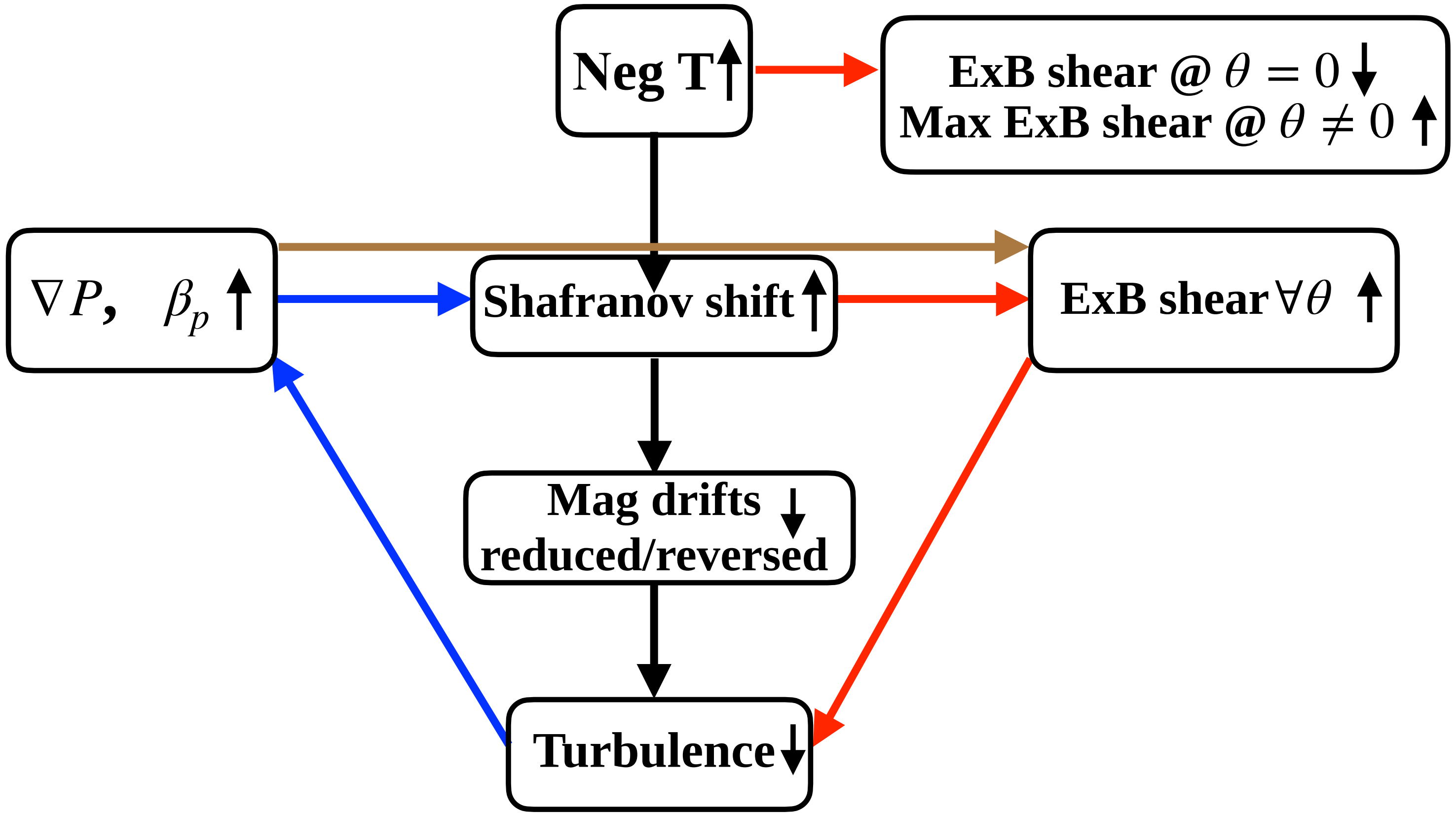


Both (I) and (II) can work in tandem to reduce the ∇P_{crit} for the onset of ITB in reversed shear PT shape

Implications II

- For realistic MHD equilibrium, Shafranov shift ↑ when PT→ NT

➡shear increase by enhanced Shafranov shift competes with shear reduction at $\theta = 0$ when PT $\rightarrow$ NT



Neg T↑

ExB shear @ $\theta = 0$ ↓
Max ExB shear @ $\theta \neq 0$ ↑

∇P**,** β_p ↑

Shafranov shift ↑

ExB shear $\forall \theta$ ↑

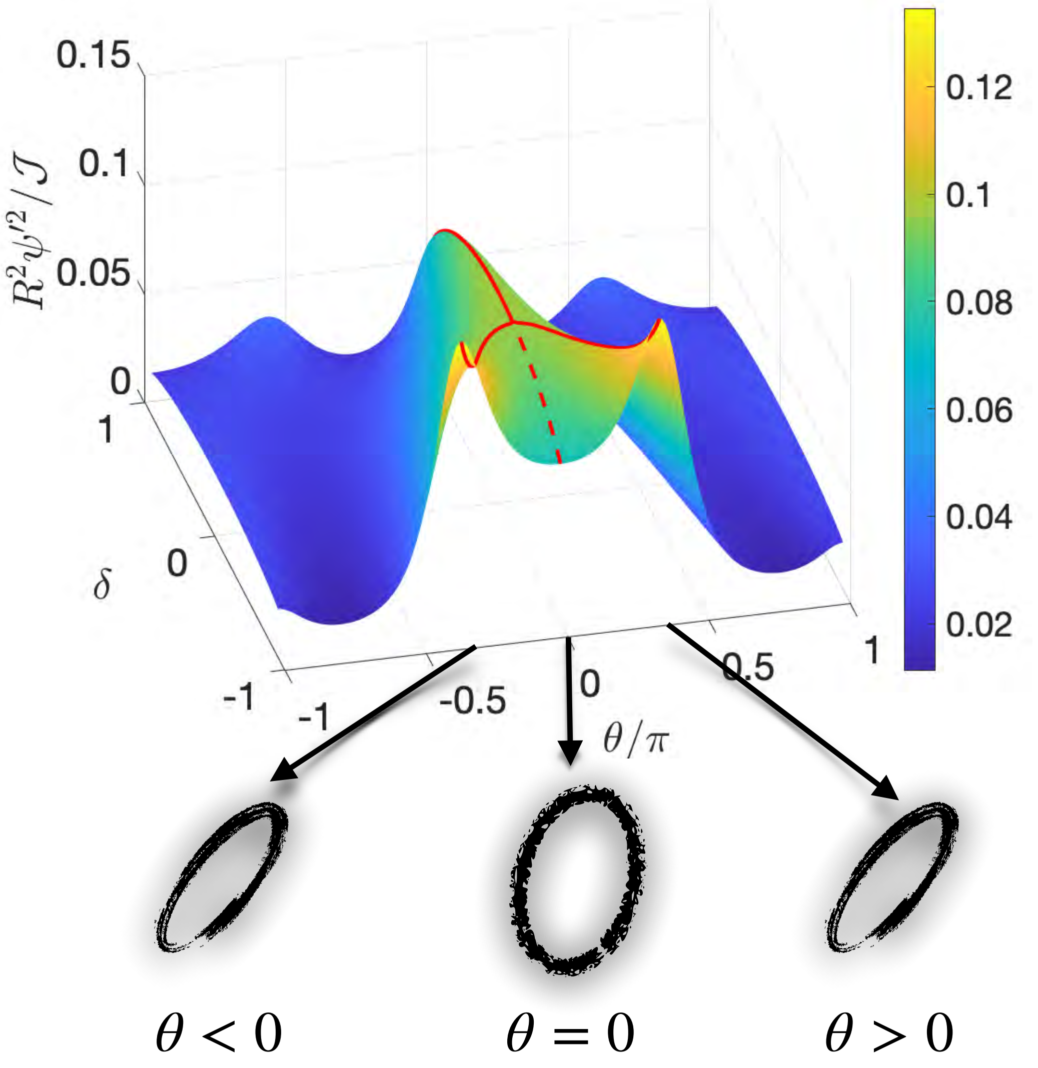
Mag drifts ↓
reduced/reversed

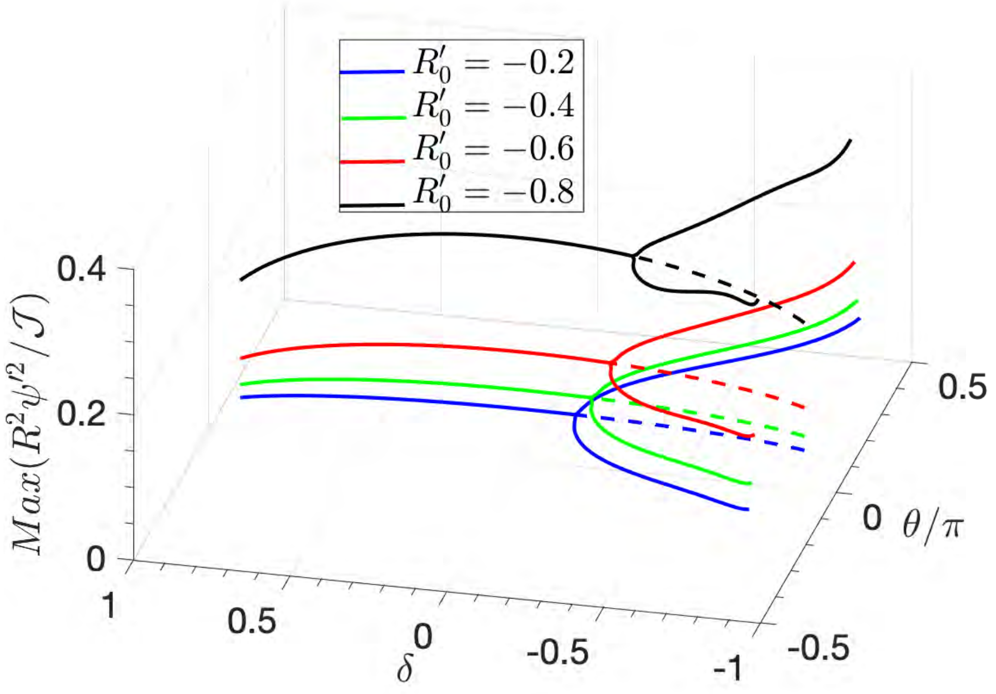
Turbulence↓

- For experimental equilibrium, parametric dependencies $R_0' \equiv R_0'(\delta)$, $\kappa \equiv \kappa(\delta)$, $S_\kappa \equiv S_\kappa(\delta)$, $S_\delta \equiv S_\delta(\delta)$ from numerical codes can help calculate shear accurately, - - -in progress!

For the experimentalists

- **Mean ExB Shearing is maximal off the mid-pane for NT:**
  $\Longrightarrow$Eddy tilting should be strongest off the mid-plane.
  - Direct imaging using gas-puffing?
  - Joint pdf of radial and poloidal velocity fluctuations (i.e., $\tilde{v}_r$ & $\tilde{v}_\theta$) should show max tilting (most-correlated) off the mid-plane for NT.





- **Shafranov shift gradient R_0' directly boosts the mean ExB shear:**
  - Re-assess the role of mean ExB shear in high-β_p reverse shear discharges.

For the experimentalists

- **On turbulence saturation: (GAM vs ZFs)**
  - Study variation of ratio of zonal flow energy to GAM energy $\left(\frac{E_{ZF}}{E_{GAM}}\right)$ when PT→NT. - - - Fluctuation diagnostics
  - Frequency resolved Reynolds stress $\left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle$ and power $\langle v \rangle_\theta^{'} \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle$ vs triangularity- - -BES diagnostics
  - Radial correlation length of zonal flows vs triangularity. - - - BES diagnostics

From the experimentalists

- Explain initial separatrix pressure gradient steepening as $P \uparrow$, yet no propagation inward for $\delta < \delta_{crit}$ (L Schmitz)

- Revisit analysis for asymmetric δ. (K Thome)
  - Synergy between δ asymmetry and ExB shear induced asymmetry?!

- $\langle \omega_E \rangle$ vs radius vs δ plot. (G McKee)

- ExB shear effects on ballooning stability near δ_{crit}? (PD, Nelson)

Once more:

NT is interesting test bed for the “conventional wisdom” of turbulence and transport.

Any good story should explain both $\delta > 0$ and $\delta < 0$.