On the Physics of Non-Diffusive Momentum Transport and the Origins of Intrinsic Rotation in Tokamaks.

P. H. Diamond; U.C.S.D.

March, 2009

see: P.D., et. al.; Nuclear Fusion 49 045002 2009.
for summary and numerous references.

Many others in talk.

Collaborators/Contributors

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$W \to \langle V_\phi(r) \rangle$

i. Summary of Phenomenology

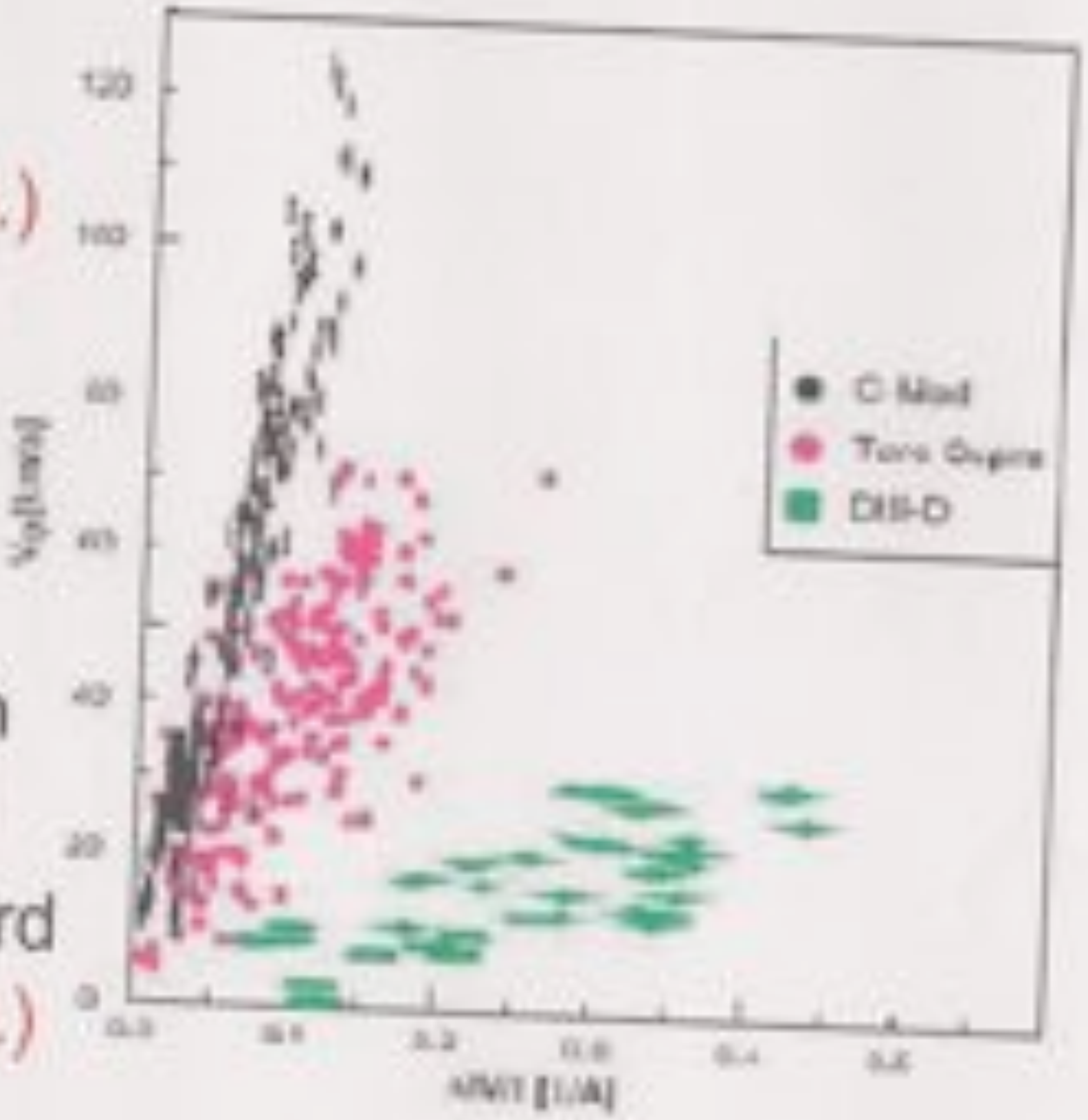
$Q \to V_\phi$ conversion

a) Intrinsic Rotation Basics – Tokamak Plasma as Engine!?

- Intrinsic (spontaneous) toroidal rotation observed in nearly all tokamaks
- H-mode phenomenology demonstrates clear empirical trends, L-mode phenomenology remains complex and unclear → SOL interaction?
- In H-mode:
  - rotation typically co-current
  - $\Delta v_\phi \sim \Delta W / I_p$, $M_A \sim \beta_N$ (Rice et al.)
  - no apparent scalings with ρ^*, ν^*
  - offset in torque scan matches intrinsic rotation (Solomon et al.)

"Intrinsic rotation ~ 1 beam"

- Observations appear consistent with rotation originating at the edge with transition (L→H)
  - Observed co-current velocity builds inward from periphery (Ince-Cushman, Rice et al.)
  - rotation direction inverts at L→H mode transition (certain cases)



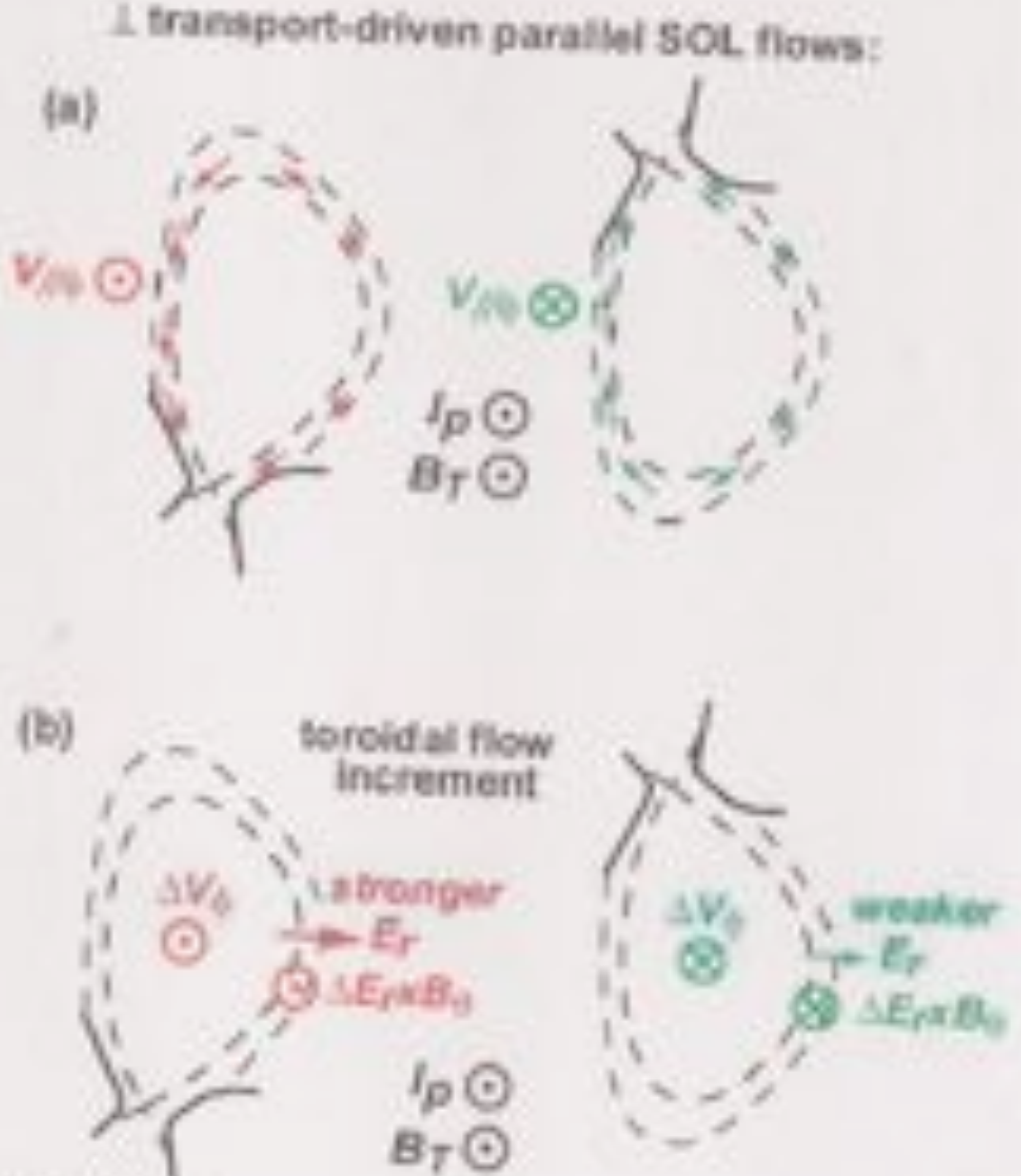
What of $\langle \frac{1}{2} \rho \overline{V}_\phi^2 \rangle / W$?

→ Efficiency Factor ?!

I_p unfavorable ?!

b) Boundary Condition Effects – SOL → Core Coupling in L-mode

"Tail wags the dog…"



- Strong SOL flows observed with
  - "strong ballooning" particle flux↔outboard mid-plane source
  - SOL symmetry breaking (LSN, USN)

- SOL flow correlated with Δv_ϕ increment in L-mode i.e. C-Mod (LaBombard et al. '04)

LSN → $V_{\nabla B}$ toward X-point → Δv_ϕ co
USN → $V_{\nabla B}$ away from X-point → Δv_ϕ counter

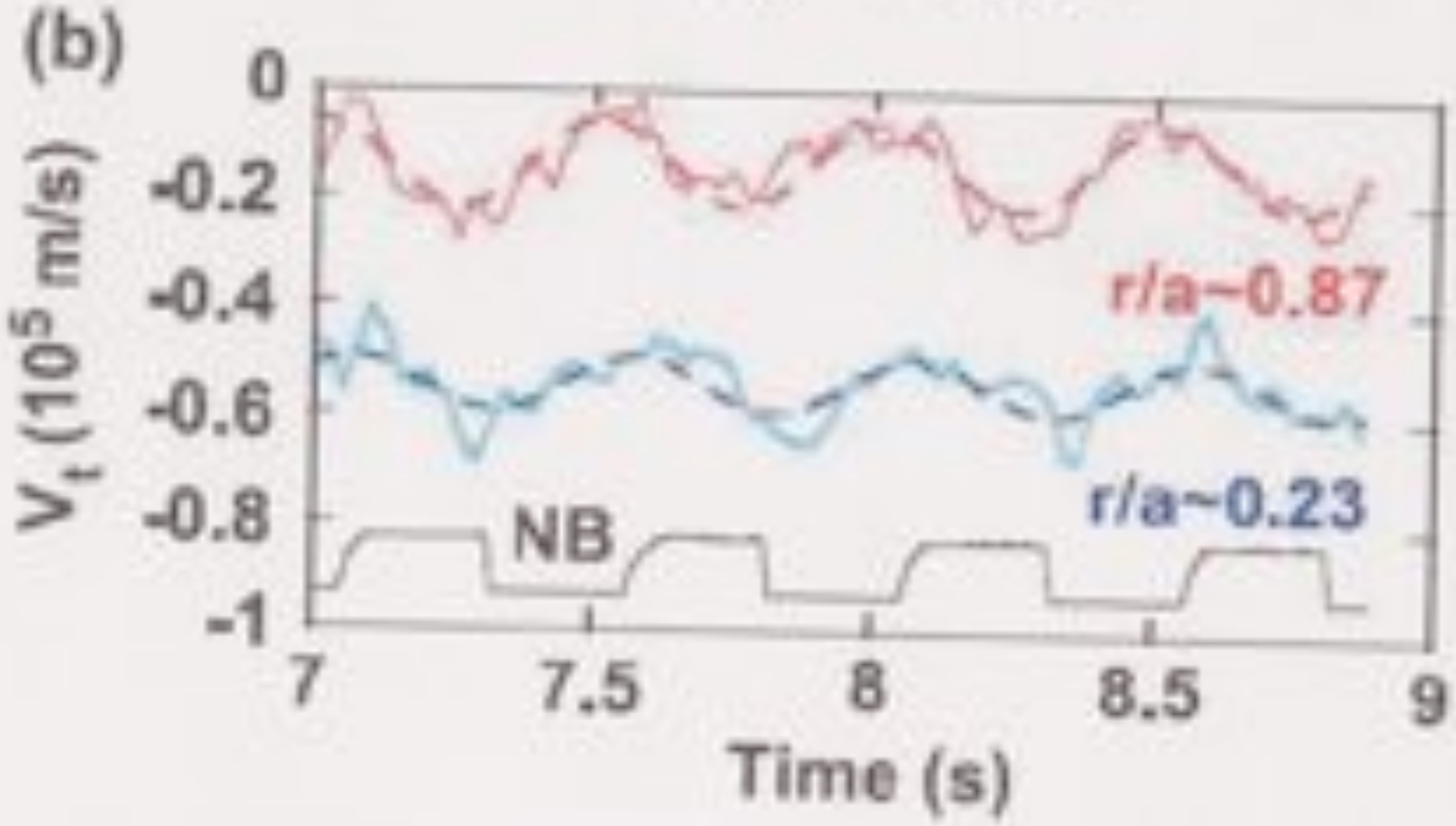
But:

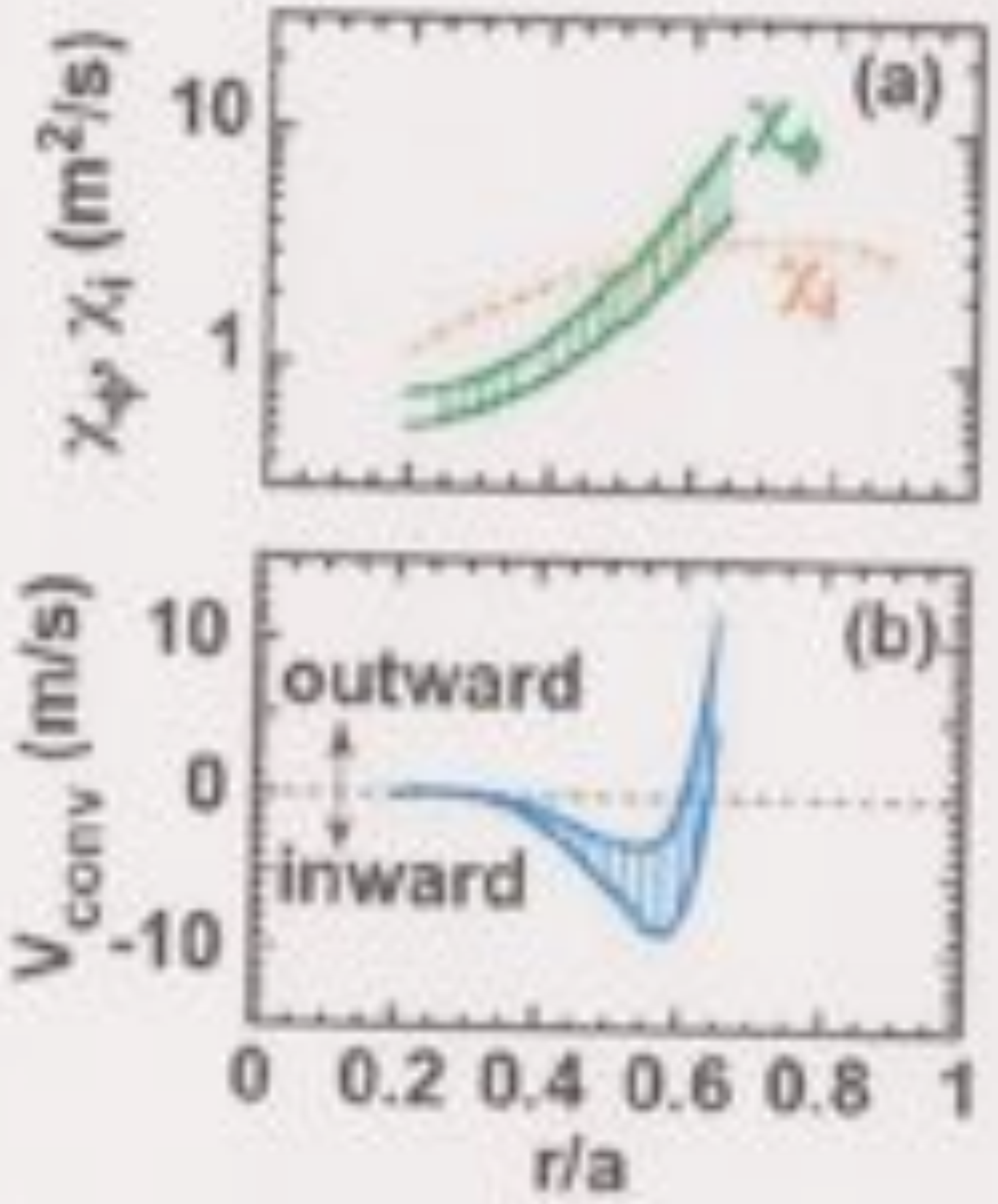
- in H-mode, Δv_ϕ is always co

"Tail cut off…" $\Rightarrow \begin{cases} \text{ETB forms} \\ \Gamma_n(\theta) \text{ symmetrized by } V_E' \end{cases}$

c.) Indications of Off-Diagonal Momentum Flux (Internal)

- Historically, $\chi_\phi \sim \chi_i$ (S. Scott et al. '90; Mattor, P.D. '88), yet many deviations from $Pr \sim 1$ observed . $Pr < 1$ (raw) ⇒ off diagonal component?!.
- ∇P_i–driven momentum pinch suggested by inductive analysis (Ida et al. 2001, extending 1995 paper)
- Perturbation Experiments From JT-60U (Yoshida et al. 2006)
  - ripple loss + pulsed beams => pulsed torque
  - inward V clearly indicated



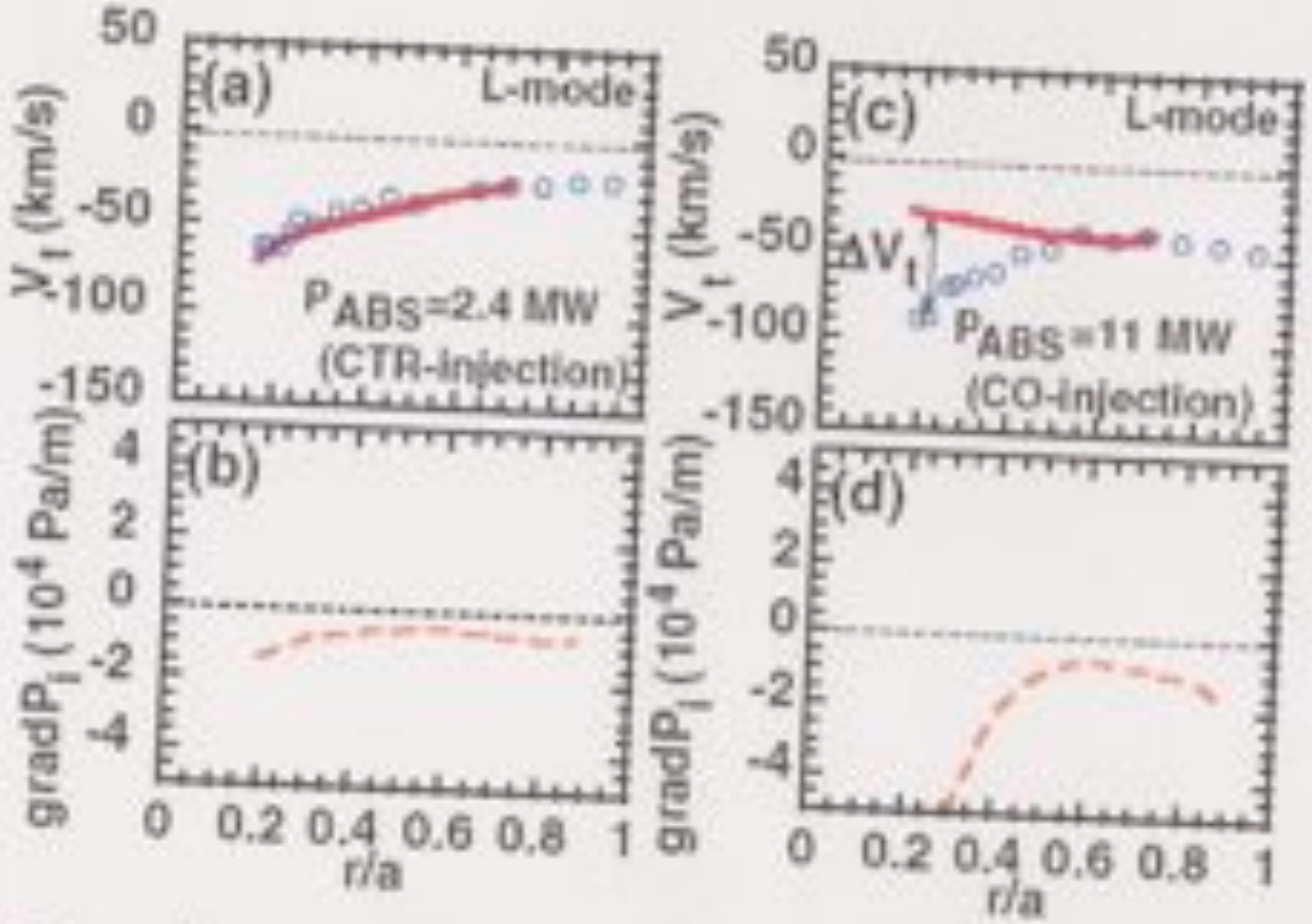


$\chi_\phi > \chi_i$!?

χ_ϕ, V fit

c.) Indications of Off-Diagonal Momentum Flux
contd

- $V_{residual} = V_{measured} - V_{perturbation}$ observed in β-scan on JT-60U (Yoshida et al. 2008)
  $V_{residual}$ coincident with region of steep ∇P_i



→ Interestingly: χ_ϕ, V appear insufficient to account for profiles, at high β.
→ Departure ↔ ∇P_i.

II.) Confronting the Phenomenology, 3

$Q \to V_\phi$ conversion

(i.) "Intrinsic" character:

→ seeming irrelevance of fast particles (C-Mod):
 i.e. OH H-mode recovers trend

→ Solomon off-set experiment:
 · 1 beam cntr ⇒ V_ϕ, $V_\phi' \to 0$ → idling the engine

(ii.) Beyond "Edge source" + pinch:

→ perturbative χ_ϕ, V fails to recover JT60U profiles, high β. (Yoshida)

→ $\left.\begin{matrix}\text{TCV}\\ \text{C-Mod}\end{matrix}\right\}$ internal momentum profile bifurcations at rising n ($\nu_{*e} \to \nu_{*i}$)

(iii.) Role of $\langle V_E \rangle'$: → symmetry breaking

→ correlation with, flow reversals at H-mode

→ $\underset{\text{peak}}{\langle \tilde{V}_r \tilde{V}_\parallel \rangle}$ correlation with $\langle V_E \rangle' \to$ TJ II (Hidalgo)

II. Addressing the Phenomenology, $\underline{\underline{b}}$

→ $\boxed{\text{Structure of Momentum Flux}}$ → the key point!

i. Focus: Off-Diagonal Momentum Flux in Electrostatic Drift Wave Turbulence – INWARD COMPONENT?!, – anything else?

→ ii. Beyond "Diffusion and Convection"

- particle number conserved → $\Gamma_n = -D\frac{d\langle n\rangle}{dr} + V\langle n\rangle$
  - pinch is only "off-diagonal" for particles
- but: wave-particle momentum exchange possible!

$\Pi = \langle n\rangle(\text{Reyn. Str.}) + \langle v_\phi\rangle\Gamma_n$

→ $\Pi_{r,\phi} \cong \langle n\rangle\langle\tilde{v}_r\tilde{v}_\phi\rangle + \langle v_\phi\rangle\langle\tilde{v}_r\tilde{n}\rangle$

$$\langle\tilde{v}_r\tilde{v}_\phi\rangle = -\chi_\phi\frac{\partial\langle v_\phi\rangle}{\partial r} + \underset{\text{pinch}}{V}\langle v_\phi\rangle + \Pi^{resid}_{r,\phi}$$

"residual stress"

→ residual stress/flux possible and distinct from pinch, indep V.

→ residual stress acts with boundary condition to generate intrinsic rotation → can accelerate plasma from rest.

What of V, Π^{resid} ? → Foundations
→ General Features
→ Specifics

→ symmetry breaking is crucial.

→ For $\underset{\approx}{\text{net}}$ intrinsic rotation:

(volume integrated)

$$\partial_t \langle P_\phi \rangle = - \underline{\nabla} \cdot \underline{\underline{\Pi}}_{r\phi}$$

$$\Pi_{r\phi} = nm \left[- \chi_\phi \frac{\partial \langle v_\phi \rangle}{\partial r} + V \langle v_\phi \rangle + \Pi_{r\phi}^{resid} \right]$$

$$\partial_t \int_0^a dr \, \langle P_\phi \rangle = - \Pi_{r\phi} \Big|_0^a$$

{ Intrinsic rotation is $\Pi_{r\phi} = 0$ state with non-trivial $\nabla \langle v_\phi \rangle$

$$\Rightarrow \quad \frac{\partial \langle v_\phi \rangle}{\partial r}\Big|_a = \left[\left(\Pi_{r\phi}^{resid} + V \langle v_\phi \rangle \right) / \chi_\phi \right] \Big|_a .$$

∴ to maintain intrinsic rotation, need:

* → $V\big|_a < 0$, $\langle v_\phi \rangle\big|_a \neq 0$ → inward velocity pinch

↔ SOL flow?

and/or → $\langle v_\phi \rangle\big|_a \neq 0$

→ edge pinch is critical.

* → $\Pi_{r\phi}^{resid}\big|_a \neq 0$ → residual stress

→ can accelerate flow from rest, no slip b.c.'s.

What ?

ii.) **Why ?** a Residual Stress ? $\underline{\underline{I}}$ → Significance

→ $\Pi^{resid.}_{r,\phi}$ is only way to spin-up from rest, in principle

i.e. $\langle V_\phi \rangle , \langle V_\phi \rangle' \to 0$

$$\partial_t \int_0^a \langle P_\phi \rangle dr = -\langle n \rangle \Pi^{resid}_{r,\phi} \Big|_0^a$$

$\rightsquigarrow \nabla P/_{edge}$

⇒ ties acceleration to $\Pi^{resid}_{r,\phi}(a)$ → (edge gradients)!

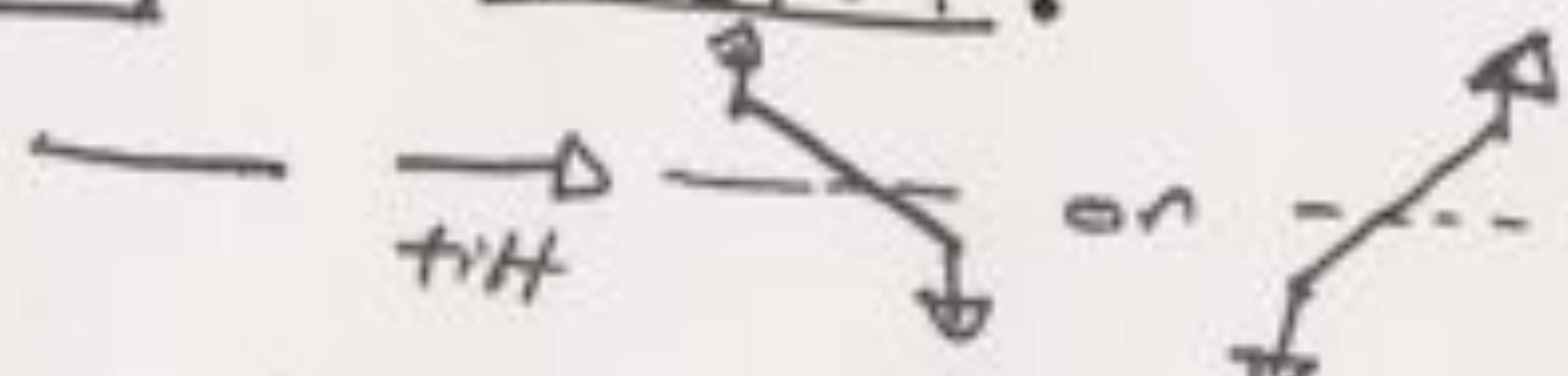
→ N.B. → $\Pi^{resid}_{r,\phi} = F(\nabla T_i, \nabla P_i, \nabla n, \text{etc.})$ { converts Q_i → momentum ↓ converter in engine

→ $\overset{\text{pinch}}{V}$ alone cannot spin-up, absent $V_\phi(a) \neq 0$.

→ Boundary Condition is Critical → Reynolds stress is transport.

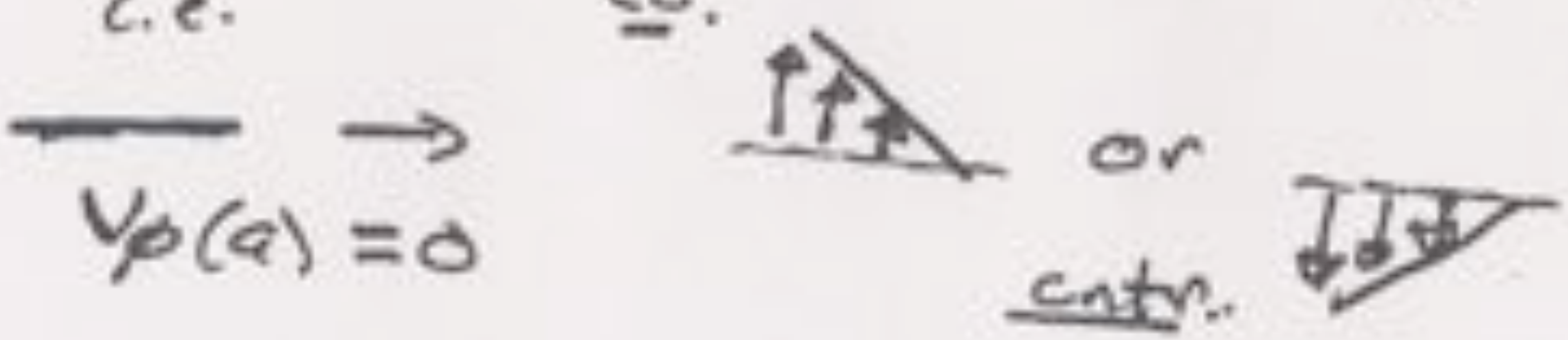
Flux ⇒ dipole shear no net momentum

i.e.



Flux + BC ⇒ net momentum

i.e.



i.e. $V_\phi(a) = 0$

iii.) Properties of $S^{resid}_{r\phi}$

→ sign of S^r matters → co vs counter, but

→ either sign S^r generates rotation.

i.e. consider $V_\phi(a) = 0$, $V = 0$ (simplicity)

$\Pi_{r,\phi} = 0$ → intrinsic rotation solution

$$\Pi_{r,\phi} = -\chi_\phi \frac{\partial \langle v_\phi \rangle}{\partial r} + S^{res}$$

⇒ $V_\phi(r) = -\int_r^a \frac{S^{res}}{\chi_\phi} \, dr'$ ⇒ $S^{res} < 0$ ⇒ co-rotation

$S^{res} > 0$ ⇒ counter-rotation

i.e. $S^{res} < 0$  co

$S^{res} > 0$  cntr.

contrast Convection:

$\begin{cases} V > 0 \rightarrow \text{unfavorable} \\ V < 0 \rightarrow \text{favorable} \end{cases}$

of course, $S^{res}(r)$ can change sign in radius ...

⇒ localized reversals.

Properties, cont'd

→ $S_{r,\phi}^{resid}$ converts $\begin{matrix}\nabla P \\ \nabla T\end{matrix} \rightarrow \nabla V_\phi$ via $\begin{cases}\text{flux} \\ \text{B.C}\end{cases}$ *

→ Contrast with pinch:

- balance with $\chi_\phi \Rightarrow L_{V_\phi}$ for pinch

$\Rightarrow \partial V_\phi/\partial r$ for S^{resid}

- each can play in different regions of profile

- only one sign of V ($<0 \rightarrow$ inward) is good for rotation.

- pinch cannot accelerate rotation from rest

∴ Residual stress is conceptually distinct from a pinch.

N.B. Likely that pinch and residual stress work <u>together</u> to form rotation profiles.

but where does Π^{resid} really come from? → Physics

iii. Key Theoretical Issues → Foundations of Mean Field / Q.-L. Theory for Momentum.

→ { – flux of wave momentum?
– origins of symmetry breaking? }

< Where do O.D.'s come from?
→ waves

a) Wave Momentum (P.D. et al. 2008) → often simpler to account for

→ Momentum Budget: {Resonant + Non-Resonant* / Particles + Fields} > classic QL conservation structure.

"Non-Resonant" = "Waves"

→ Wave momentum flux crucial for fluid-like DWT, and for conservation

a) Calculating $\Pi_{r,\parallel}^{wave}$

- Necessary to compute radial flux of parallel mom. ↔ $\Pi_{\parallel}^{W} \equiv \sum_k v_{grx} k_{\parallel} N_k$
- In simplest scenario, finite momentum flux requires:
  - radial wave flux ↔ $\langle v_{grx} \rangle \neq 0$
  - symmetry breaking ↔ $\langle k_{\parallel} \rangle \neq 0$

* i.e. transport of momentum often more transparent via looking at waves.

Foundations

Wave Momentum Flux I.

- Proceed via Chapman-Enskog expansion (radiation hydrodynamics in large optical depth limit) in Wave Kinetics
  - in short mean free path limit, expansion parameter given by: $\tau_{c,\mathbf{k}}\left(v_{gr}/L_I\right), \tau_{c,\mathbf{k}}\langle v_E\rangle' \sim \varepsilon$

some similarity to modulational instability

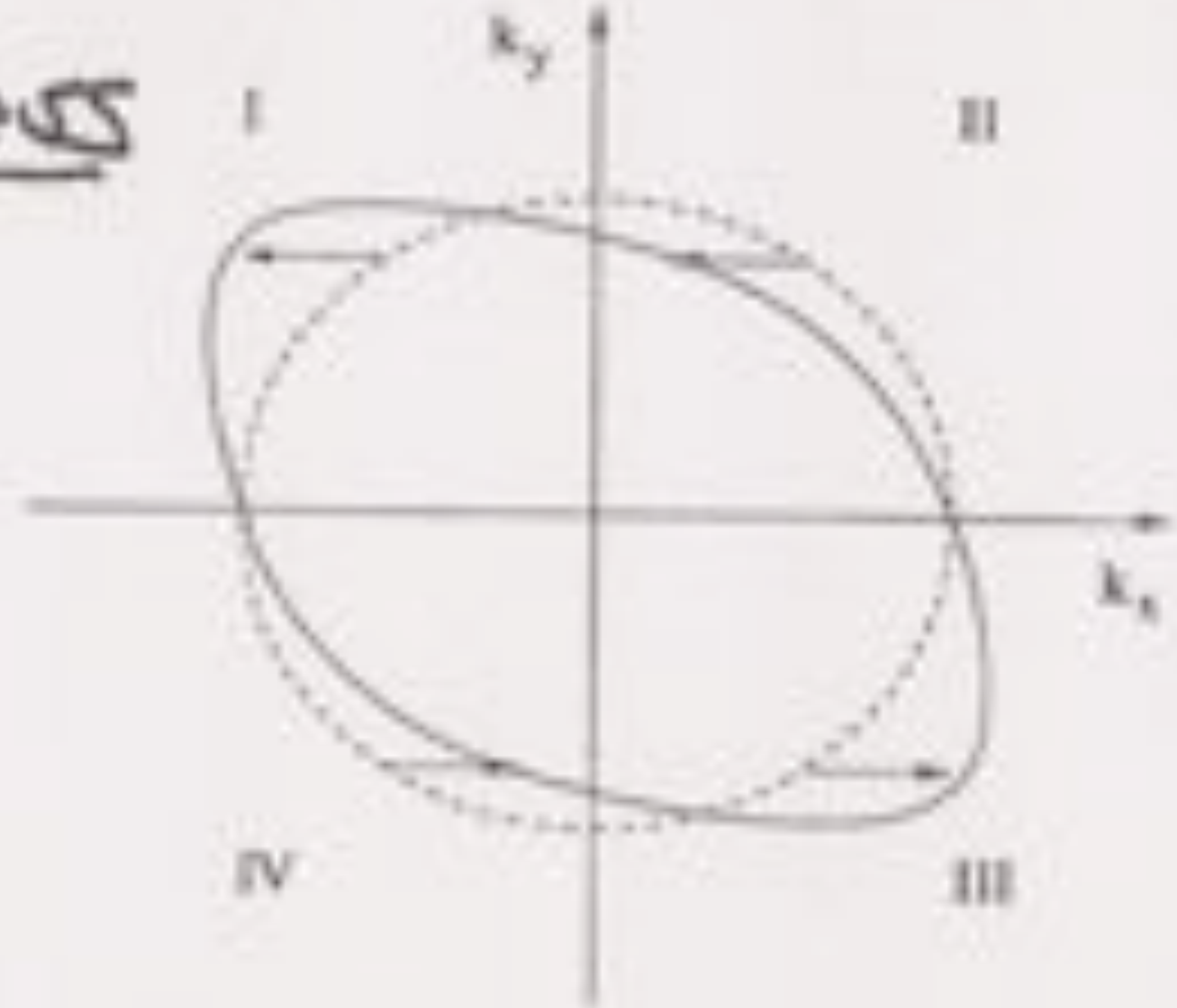
- Lowest order: $C_w\left(N_k\right)=0$ => saturated spectrum due to wave interactions

spatial k-space

- Next order, yields: $\delta N_{\mathbf{k}}=-\tau_{c,\mathbf{k}} v_{gr} \frac{\partial\left\langle N_{\mathbf{k}}\right\rangle}{\partial r}+\tau_{c,\mathbf{k}} k_\theta\left\langle v_E\right\rangle' \frac{\partial\left\langle N_{\mathbf{k}}\right\rangle}{\partial k_r}$

modulation of wave field ⇒ induces stress

- 1st term ~ $\tau_{c,\mathbf{k}}/\tau_{\ln N}$
- 2nd term ~ $\tau_{c,\mathbf{k}}\left\langle v_E\right\rangle'$



Wave Momentum Flux (cont'd)

- Wave momentum flux:

flux in space

shearing / wind-up ⇒ flux in k_r

$$\Pi^{w}_{r,\|} = \int d\mathbf{k} k_{\|} \left\{ \langle v_{0r} \rangle \langle N_{\mathbf{k}} \rangle - \underbrace{\tau_{c,\mathbf{k}} v_{gr}^{2}}_{\sim D_{GB}\,!} \frac{\partial \langle N_{\mathbf{k}} \rangle}{\partial r} + \tau_{c,\mathbf{k}} v_{gr} k_{\theta} \langle v_E \rangle' \frac{\partial \langle N_{\mathbf{k}} \rangle}{\partial k_r} \right\}$$

mode dependent

$\langle N(r) \rangle$

- Second term ↔ radiative diffusion of quanta
  - requires gradient in turbulence intensity profile (universally increasing)
  - related to momentum flux from edge? ! ⇒ inward ⇒ $\langle k_{\|} \rangle \rightarrow$ co vs cntr.

→ related spreading --- (quanta flux)

- Third term ↔ refraction induced wave population imbalance
  - crucial for regimes of strong shear flow
    - →most active near edge, or ITB
    - →sensitive to L→H mode transition, local steepening in ∇P
  - mode dependence, via v^{*} → possible TCV relevance (electron → ITG DW ⇒ flow reversal)

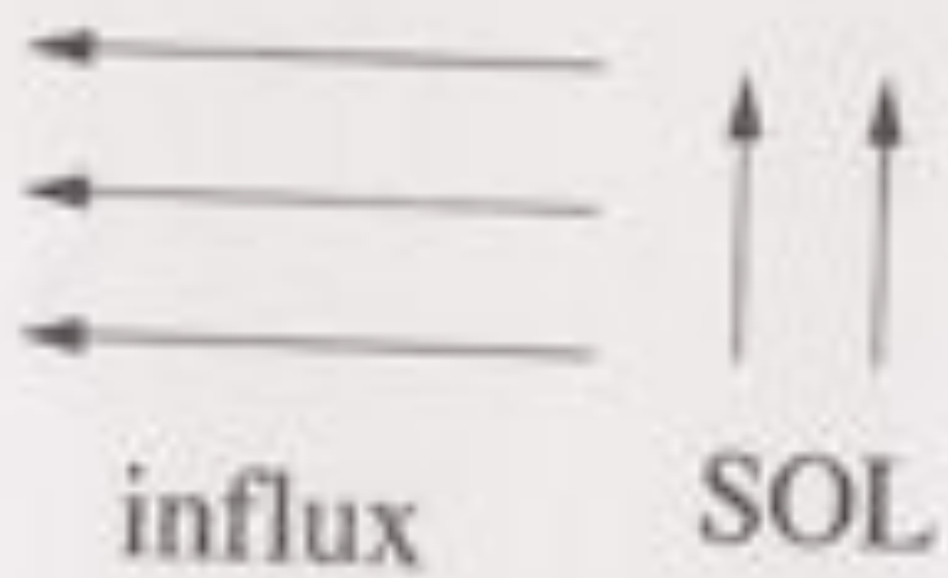
$\langle V_E \rangle'$-driven wave momentum flux ⇒ Π^{resid}.

6.

Momentum Flux (cont'd)

* • Mechanisms of symmetry breaking: → Moments of W.K.E.

1. Influx: radial inflow of wave momentum
   - potentially critical in edge region
   - captures possible influx of momentum from SOL



→ $\boxed{2.}$ Wind-up: mode sheared by poloidal velocity → ala' spiral arm

most intensively studied

   - requires magnetic shear, i.e. $\partial k_{\parallel}/\partial k_r \neq 0$
   - critical in barrier regions, either pedestal or ITB, but not limited to these

3. Growth asymmetry
   - enters due to parallel velocity shear - unlikely
4. Refraction due to GAMs → refractive force
   - largely unexplored
   - likely to be most important near edge

$$\langle k_{\parallel} \rangle = -\int d\underline{k}_r \frac{\partial k_{\parallel}}{\partial k_r} k_\theta \langle V_E \rangle' \frac{\langle N \rangle}{\gamma_{k}}$$

$$\sim \langle V_E \rangle'$$

Conclusion → Residual stress conceptually viable.

v.) Analogues of Residual Stress – it should not be a surprise....

① → Some similarity to turbulent heating

i.e. $\frac{dT_i}{dt} = C_{i,e}^{colln} + C_i^{turbulent}$

anomalous heating

$\frac{dT_e}{dt} = C_{e,i}^{colln} + C_e^{turbulent}$

turbulent flctns. heating

but $\int dx \left[C_i^t + C_e^t \right] = \int dx \, \langle \tilde{\underline{E}} \cdot \tilde{\underline{J}} \rangle$

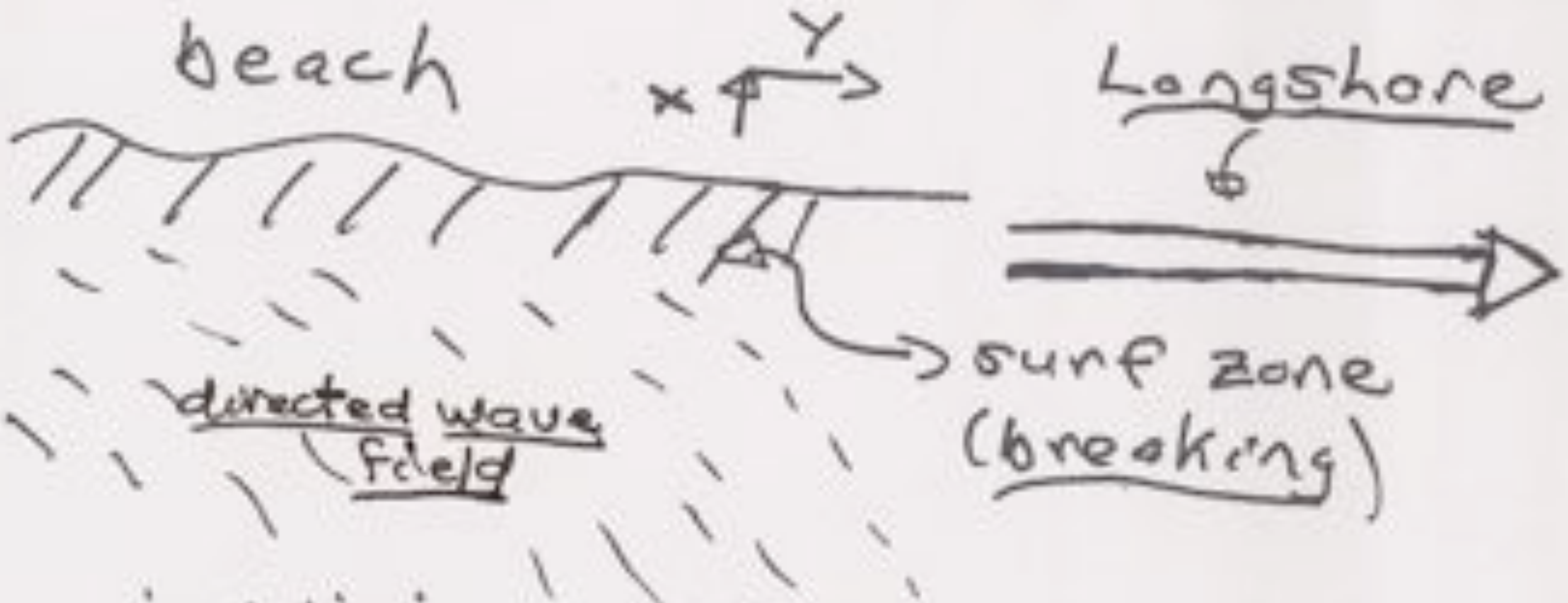
$= - \tilde{\phi} \tilde{J}_r \Big|_{bndry}$ c.f. { Tang, Manheimer '77

→ turbulent heating:

- local, fluctuation driven heat source/sink
- globally constrained to integrate to s.t.

→ residual stress may be viewed as globally constrained turbulent torque density.

② → Longshore Current (why DIII-D is second best flow generator in S.D.)



Longshore current
↳ mean flow generated parallel to beach.

impinging wave field
→ wind driven
→ incident stress field $\langle \tilde{v}_i \tilde{v}_j \rangle$
→ ultimately ν_T is $\nu_T[S]$
→ close analogy with rotation obvious
→ b.c. important here, too.

⟺ description boils down to:

$$-\partial_x \Big(\underbrace{-\nu_T \frac{\partial \langle V_y \rangle}{\partial x}}_{\text{eddy viscosity due breaking}} + \underbrace{S_{x,y}}_{\text{wave stress}} \Big) = 0$$

eddy viscosity due breaking ⟷ χ_ϕ

wave stress ⟷ residual stress (wave energy)

The Calculation

VI.) Physics of Residual Stress due $\langle V_E \rangle'$

- Key Point: → $\langle V_E \rangle'$ converts poloidal flow shear into toroidal flow shear via: asymmetry in wave to particle momentum deposition } outgoing b.c.'s
- finite $\langle V_E \rangle'$ + generic drift-acoustic coupling
  - → shifted spectral envelope (persists in torus)

$\langle k_{\parallel} \rangle \neq 0$

Most studied but not unique

$\langle k_{\parallel} \rangle \neq 0 \rightarrow$ shear

[S. Itoh, PF '92, Dominguez et al., PFB '93, Diamond et al., IAEA '94]

  - → special case of refraction-induced "winding" asymmetry (see previous)

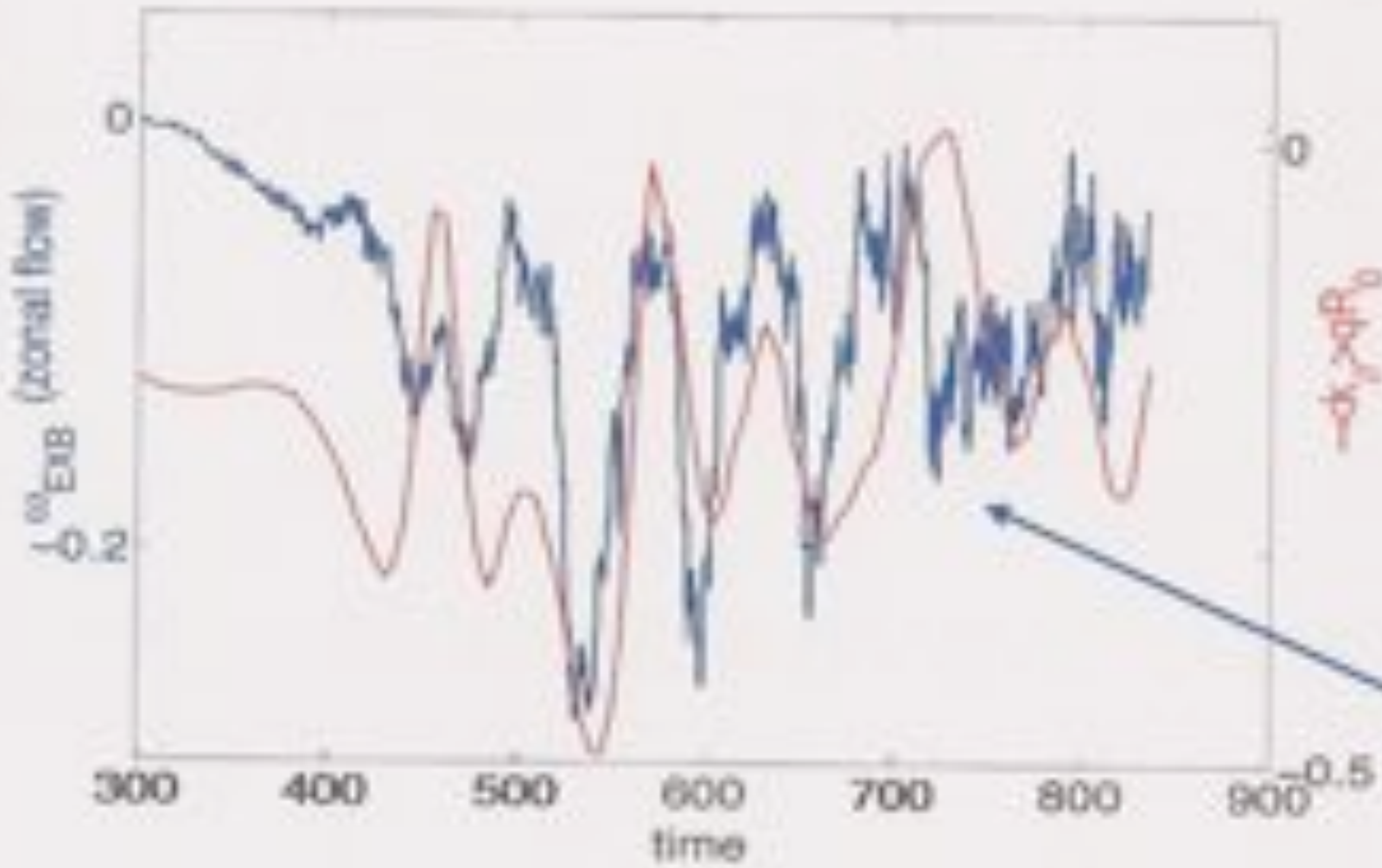
* • directional imbalance in
  - → acoustic wave populations
  - → profile of momentum deposition by ion Landau damping

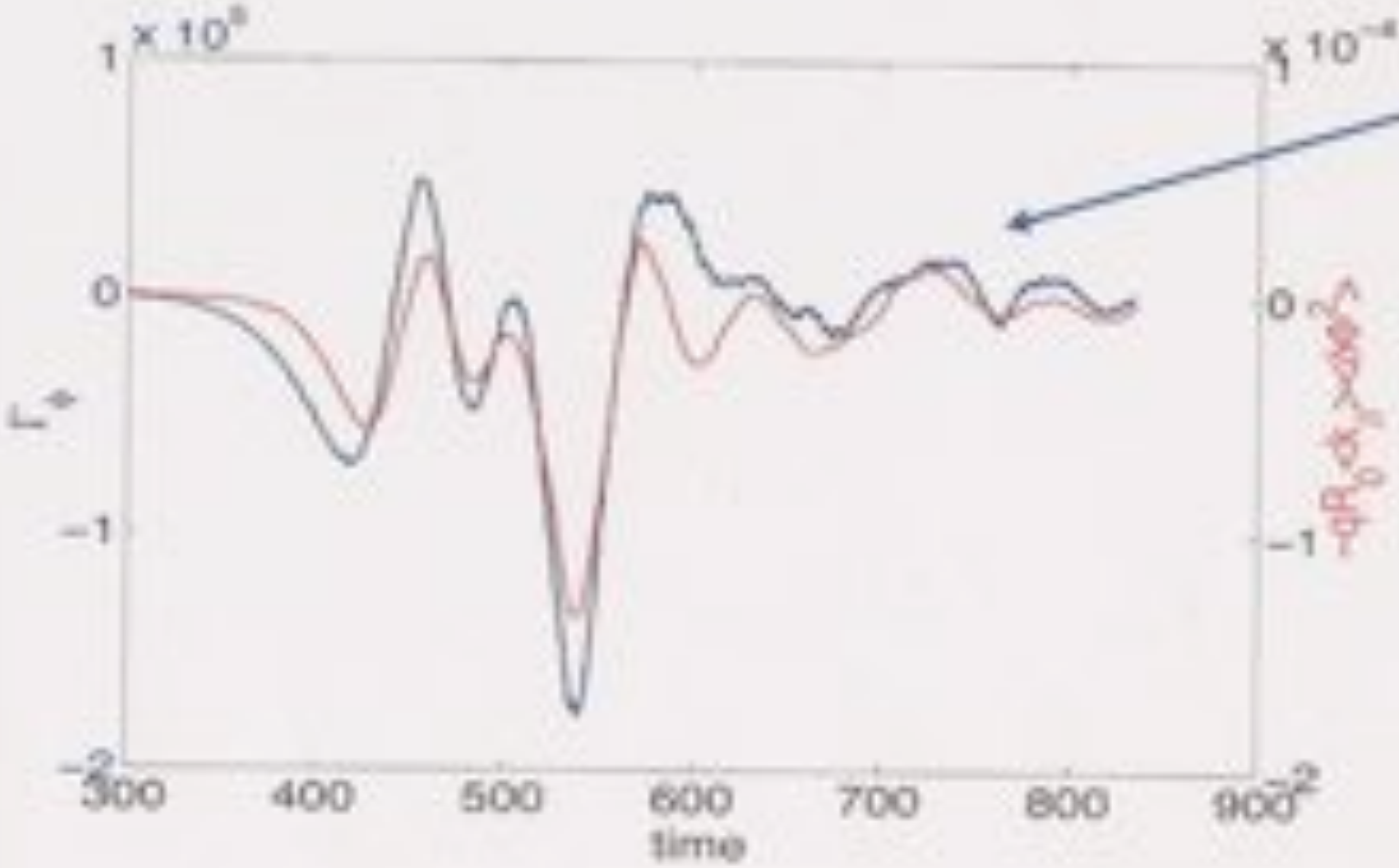
$\langle k_{\parallel} \rangle = 0$ $\langle k_{\parallel} \rangle \neq 0$

broken symmetry in turbulence → akin α-effect in dynamo theory.

Toroidal Momentum Flux strongly correlated with Zonal Flow Shear in GTS ITG Simulations

[W.Wang et al., Paper TH/P8-44, IAEA '08]
P.R.L. 2009





Self-generated zonal flow is quasi-stationary in global ITG simulations

Conversion: (no input V_ϕ)

Poloidal → Toroidal Zonal Flow

Strong correlation among Zonal flow shear, $k_\parallel$ spectra, Inward Momentum Flux

Mechanism:

Generation of Residual Stress due to $k_\parallel$ symmetry breaking induced by ZF shear:

(extending the mechanism due to mean ExB shear)

[Gurcan et al., PoP '07]

{Zonal structures only → need global solution for intr. rot.

→ Closer Look at Theory → Solomon Experiment

- observe $\langle V_E\rangle'$ drives $\langle V_\phi\rangle'$, yet $\langle V_E\rangle'$ given by

$$(E_r/B_\theta)' = V_\phi' + \partial\left(\frac{1}{nq_iB_\theta}\frac{\partial p}{\partial r}\right)' - \frac{\partial}{\partial r}(u_\theta B_\phi)$$

⇒ feedback loop for $\langle V_\phi\rangle'$!

⇒ renormalization of χ_ϕ ?!

⇒ is intrinsic rotation modulationally driven ?!

- if consider $\langle \tilde{v}_r\tilde{v}_\phi\rangle_{NR} \to \Pi_{r,\phi}$ (i.e. anisotropic wave pressure)

diffusion of momentum (resonant)

$$\partial_t\langle V_\phi\rangle - \partial_r \chi_\phi \partial_r\langle V_\phi\rangle = -\partial_r \Pi^{wave}_{r\phi} + T_{ext}$$

wave stress; external torque density

$$\begin{cases} \delta\Pi^{wave}_{r,\phi} = \int d\underline{k}\, v_{gr} k_\parallel \delta N \\ \delta N = \tau_{c,\,\text{mode}} \left[k_\theta\langle V_E'\rangle\frac{\partial\langle N\rangle}{\partial k_r} - v_{gr}\frac{\partial\langle N\rangle}{\partial r}\right]\end{cases}$$

↳ broken symmetry via $\langle V_E\rangle'$

response to test $\begin{cases}\text{shear} \\ \text{inhomogeneity}\end{cases}$

$\therefore$ <u>stationarity:</u>

$$\underset{\substack{\uparrow \\ \text{net external torque}}}{T^{ext}} = \int dk_1\, k_\parallel V_{gr} \tau_c \Big[\underset{\substack{\text{wave stress} \\ \downarrow}}{k_\theta \frac{\partial \langle N \rangle}{\partial k_r} \langle V_E \rangle'} - V_{gr} \frac{\partial \langle N \rangle}{\partial r} \Big] \Big|_a$$

$$- n m \chi_\phi \frac{\partial \langle V_\phi(a) \rangle}{\partial r} \leftarrow \text{momentum diffusion}$$

relates external torque T^{ext} to $\langle V_\phi(a) \rangle'$ and wave turbulence spectrum.

$\Rightarrow$

$$\frac{\partial \langle V_\phi(a) \rangle}{\partial r} = \Big[T_{ext} - \Big\{ \Big(\int dk_1\, k_\parallel V_{gr} \tau_c k_\theta \frac{\partial \langle N \rangle}{\partial k_r} \Big) \langle V_E \rangle_0' + D_{rad} \frac{\partial \langle P_\parallel \rangle}{\partial r} \Big\} \Big] \Big/ n m \chi_{\phi,R}(a)$$

$$\chi_{\phi,R}(a) = \chi_\phi(a) - \Big\{ \frac{1}{nm} \int dk_1\, k_\parallel V_{gr} \tau_c k_\theta \frac{\partial \langle N \rangle}{\partial k_r} \Big)_a$$

$\rightarrow$ {hint of modulational instability of toroidal flow.

$\rightarrow$ renormalized χ_ϕ via feedback　sgn $\delta\chi_\phi \rightarrow$ sgn $k_\parallel$

$\rightarrow$ sgn $\langle V_E \rangle_0'$

$\rightarrow \langle V_E \rangle_0' = V_{dia}' - (V_\theta B_\phi)' / B_\phi$

In particular:

off-set → determines the "cancelling" torque

$$\langle V_\phi \rangle' \Big|_a = \frac{1}{n m \chi_{\phi,R}(a)} \left[T_{ext} - T^{(0)} \right]$$

→ off-set linear plot for edge shear

↑ proportionality is renormalized χ_ϕ

$$T^{(0)} = D_{rad} \frac{\partial \langle P_\parallel \rangle}{\partial r} + \left(\int d\underline{k}\, k_\parallel V_{gr} \tau_c k_\theta \frac{\partial \langle N \rangle}{\partial k_r} \right) \langle V_E \rangle_0'$$

$V_d' + V_\theta'$

↓ wave momentum profile

↓ parallel zonal growth (compare Z.F. modulation)

$T_{ext} = T^{(0)}$ zeroes intrinsic rotation

$$\chi_{\phi,R}(a) = \chi_\phi(a) - \frac{1}{nm} \int d\underline{k}\, k_\parallel V_{gr} \tau_c k_\theta \frac{\partial \langle N \rangle}{\partial k_r}$$

↓

$\mathrm{sgn}\, k_\parallel \Rightarrow \delta\chi_\phi > 0 \rightarrow \chi_\phi \gtrsim \chi_i$ possible

$\delta\chi_\phi < 0 \rightarrow$ enhanced flow.

n.b. unlikely:
$\chi_{\phi,R} < 0$, as
$k_\parallel \ll k_\perp$.

Some Observations → Feedback loops a/d' zonal flows.

→ intrinsic rotation shear driven by:
- wave momentum population gradient, V_q', V_θ'
- parallel modulational growth ↔ resembles ⊥ ZF modulational instability

→ a) "negative viscosity phenomena" at work in intrinsic rotation ($\delta\chi_\phi < 0$)

b) perturbative $\chi_\phi > \chi_i$ plausible, as includes $\delta\chi_\phi$. (c.f. Yoshida)

→ since $\langle k_\parallel \rangle \sim \langle V_E \rangle'$, modulational growth could be substantial at L → H transition

→ expect toroidal Z.F.'s (c.f. WXW simulation) "choppy" toroidal flow profiles.

→ alternative mechanism: Polarization (McDevitt, P.D., TSH; 2008)

VII) Physics of the Momentum Pinch

→ the other part of the story ....

① → TEP Pinch → robust, universal effect

key: $\underline{\nabla} \cdot \underline{V}_{E\times B} \neq 0$, in torus

⇒ relaxation/mixing to 'canonical profiles'.

$$\nabla(L_\phi/B^2) \rightarrow 0$$

② → Thermoelectric Pinch

key: ∇T_i drives inward $\Pi_{r,\phi}$

③ → Recoil Pinch of Velocity

key: Interplay of Particle and Momentum Transport

* Role of Pinch: → synergistic with Residual Stress.

→ build profile, once Π^{resid} triggers rotation

→ couple to SOL flow at LCFS; as trigger/initiator mechanism.

① Turbulent Equipartition of Magnetically Weighted Quantities

- Turbulence Equipartition Pinch (TEP) of density has been demonstrated via simple model with nonuniform B [Yankov '94, Naulin '98] i.e. [Freezing-in Law effect.

$$\partial_t n + \nabla \cdot (n\mathbf{v}_E) = 0 \qquad \nabla \cdot \mathbf{v}_E \neq 0 \qquad (\partial_t + \mathbf{v}_E \cdot \nabla)\underbrace{\left(\frac{n}{B}\right)}_{\text{"Frozen in" quantity}} = 0$$

a la' $\nabla(P/B)$ drive for interchange.

- Extended to trapped electrons in tokamaks [Isichenko *et al.* '97, Baker-MNR '98]
- Turbulence Mixing ➡ Relaxation towards canonical profiles i.e. $\nabla(n/B) \to 0$, above [Garbet '05]
  'appears' as pinch
- Inward Pinch in the observed field *n* as a consequence of a tendency towards homogenization of the locally conserved field *n/B*
- For angular momentum density [Hahm *et al.*, PoP 2007]

$$\partial_t \left(nU_\parallel R\right) + \nabla \cdot \left(nU_\parallel R\mathbf{v}_E\right) \approx 0 \qquad \nabla \cdot \mathbf{v}_E \neq 0 \qquad (\partial_t + \mathbf{v}_E \cdot \nabla)\left(\frac{nU_\parallel R}{B^2}\right) \approx 0$$

compressibility of $\underline{E}\times\underline{B}$ velocity is key, again.

- Inward Pinch in observed quantity $nU_\parallel R$ is a consequence of a tendency towards Homogenization of the locally conserved quantity $nU_\parallel R/B^2$

⇒ produces 'TEP pinch'

→ n, $V_\parallel$ frozen to B, each

→ $1/B^\alpha$ → volume weighting factor.

② Turbulent Equipartition Pinch of Angular Momentum

[Hahm, Diamond, Gurcan, Rewoldt, PoP 2007, 2008, Gurcan et al., PRL 2008]

From angular momentum conservation and compressible ExB flow

$$\partial_t\left(nU_\parallel R\right)+\nabla\cdot\left(nU_\parallel R\mathbf{v}_E\right)\approx 0 \qquad \nabla\cdot\mathbf{v}_E\neq 0 \qquad (\partial_t+\mathbf{v}_E\cdot\nabla)\left(\frac{nU_\parallel R}{B^2}\right)\approx 0$$

Mixing/Diffusion of Magnetically weighted angular momentum $nU_\parallel R/B^2$

---> Inward Pinch in observed quantity $nU_\parallel$

$$\Pi_{MWA}=\left\langle\delta v_r\delta(nU_\parallel R/B^2)\right\rangle=\ldots \text{ quasilinear calculation } \ldots= -\chi_{MWA}\frac{d}{dr}\left(nU_\parallel R/B^2\right)$$
$$=\left[-\chi_\phi\frac{d}{dr}(nU_\parallel)+V_{TEP}(nU_\parallel)\right]\frac{R}{B^2}$$

with $\quad \dfrac{V_{TEP}}{\chi_\phi}=-\dfrac{B^2 d}{Rdr}\dfrac{R}{B^2}\cong-\dfrac{3}{R}$ $\Rightarrow$ TEP pinch robust, inward, but tied to R.

(with definitions w.r.t. angular rotation freq: $\omega_\phi\equiv U_\parallel/R$, $\dfrac{V_{TEP}}{\chi_\phi}\cong-\dfrac{4}{R}$)

also from derivation based on conservative gyrokinetic equation [Hahm, PF 1988]

Symmetry Breaking from Ballooning Fluctuations

→ Density and Momentum TEP strongly correlated

Alternative Perspective → Angular Momentum Homogenization (Gurcan, P.D., TSH '08)

→ turbulence will tend to mix or "homogenize" L_ϕ, absent external torque ⇒ General trend

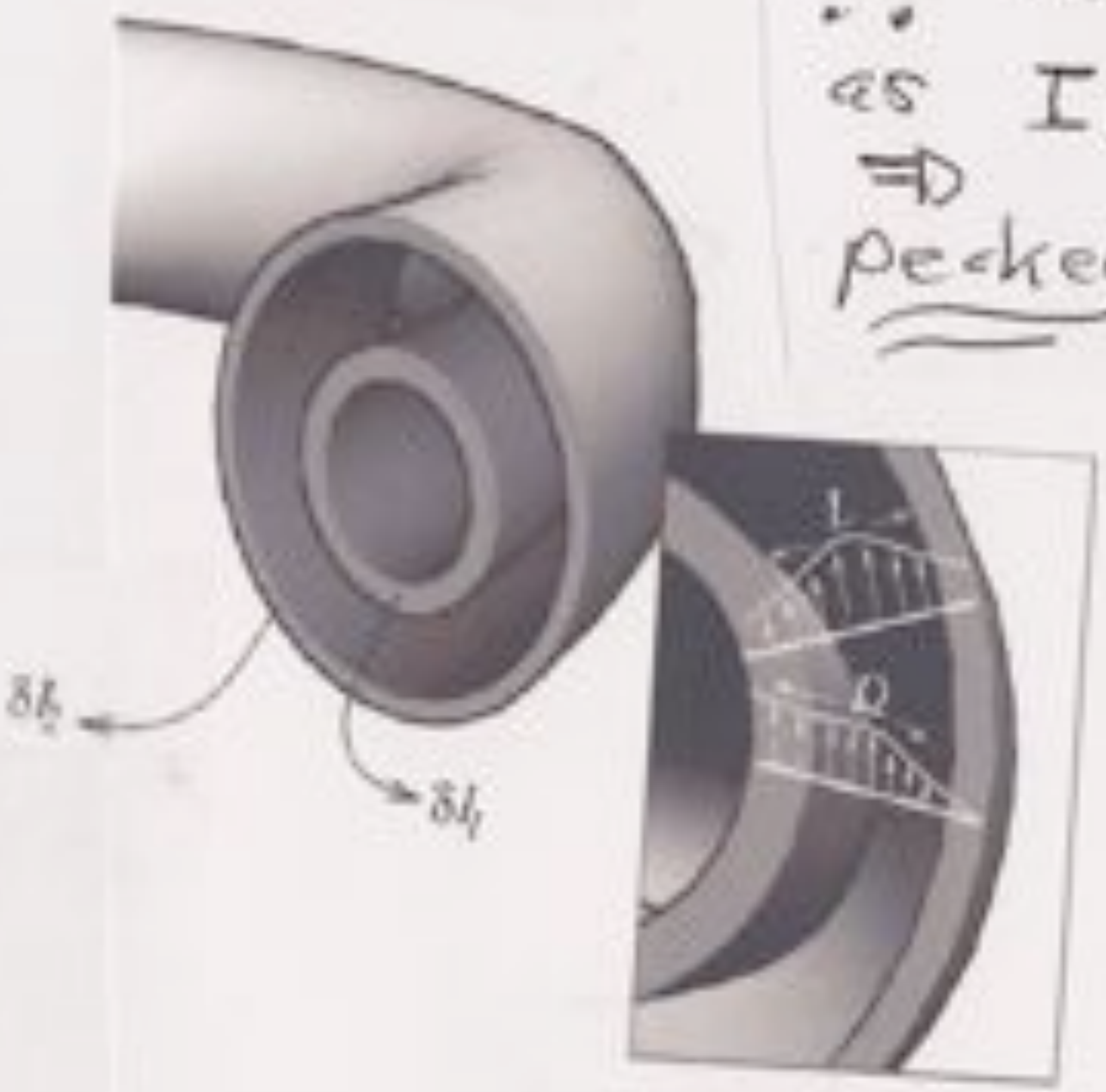
→ first proposed by R. Hide, '69; in planetary context.

→ Basic Idea: $L_\phi \to$ homogeneous

$\therefore$ $L_\phi(r) \sim I(r)\,\Omega_\phi(r)$

as $I(r)$ increasing with $r \Rightarrow \Omega_\phi(r)$ decreases.

⇒ peaked rotation profiles



⇒ advection $n U_{\parallel} R / B^2$ emerges from moment of inertia volume factors

→ promising for simplicity.

Thermo-electric Pinch

V_{TH} : Thermo-dynamic, piece of Reynolds stress related to δT_i

$$V_{TH} = 4\left\langle \frac{c}{B} \Sigma_k k_\theta \operatorname{Re}\left(\tau_c \omega_{di} \delta\phi^* \left(\delta T_i / T_i\right)\right)\right\rangle$$

dependent on mode-characteristics (e.g., phase angle between δT_i and $\delta\phi$)
sensitive to gyrofluid approximation, dispersion relation,
and frequency broadening/shift etc.

$V_{TH} < 0$ always (inward) for V_{*e} direction mode (TEM)
$V_{TH} > 0$ typically (outward) for V_{*i} direction mode (ITG)

c.f. ITG-specific calculation by *[Peeters et.al., PRL '07]*

Convective Momentum Pinch also exists

$$\Pi_{r,\phi} \cong \langle n \rangle \langle \tilde{v}_r \tilde{v}_\phi \rangle + \langle v_\phi \rangle \langle \tilde{v}_r \tilde{n} \rangle$$

originates from particle

flux

VIII.) Towards a simple illustrative model of Intrinsic Rotation in H-mode

Key Elements:

→ $\langle v_\phi \rangle$ profile

$\Pi^R_{r,\phi}$ (Residual Stress) due $\langle V_E \rangle'$ and B.C.

(up) ⟶ increment in rotation at L-H transition

$\Delta(\nabla P) \leftrightarrow \Delta W_p$

$\langle V_E \rangle$ evolution

V_{TEP} due $\nabla \cdot \mathbf{v}_E \neq 0$ ⟶ peaking on axis

(in)

→ couple to simple ExB shear-based L-H transition model

N.B. $\Pi^R_{r,\phi}$ decays with $\langle V_E \rangle'$ slower than $\chi_\phi, \chi_i, D \ldots$

residual stress ~ $\langle V_E \rangle'$ asymmetry

→ fix $\langle v_\phi \rangle$ at boundary → simplicity

Simple Illustrative Model → { Spin-up ↔ Transport Bifurcation Coupling

the Engine

Conservation Laws:

$$\frac{\partial n}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_n) = S_n$$

$$\frac{\partial P}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(rQ) = H$$

Power

$$\frac{\partial L_\phi}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\Pi_\phi) = \tau_\phi$$

Angular Momentum

extract V_ϕ using n

Fluxes:

where

$$\Gamma_n = -D_0\frac{\partial n}{\partial r} - D_1\varepsilon\left(\frac{\partial n}{\partial r} + V_r n\right)$$

$$\Pi_\phi = -\nu_0\frac{\partial L_\phi}{\partial r} - \nu_1\varepsilon\left[\frac{\partial L_\phi}{\partial r} + V_r L_\phi\right] + S$$

$$S = -\varepsilon\alpha(r)\left(1 - \frac{\sigma}{P_0}\frac{\partial P}{\partial r}\right)\frac{\partial v_{Ey}}{\partial r}$$

$$Q = -\chi_0\frac{\partial P}{\partial r} - \chi_1\varepsilon\frac{\partial P}{\partial r}$$

TEP Pinch for Momentum and Density

Residual Stress due to ExB Shear (converter)

Radial Force Balance:

$$E_r \cong \frac{1}{ne}\frac{\partial P}{\partial r} - u_{\theta,Neo}B_\phi + u_\phi B_\theta$$

(converter)

$$\varepsilon = \frac{\mathcal{E}_0}{1 + \beta\left(\frac{\partial u_{Ey}}{\partial r}\right)^2}$$

ExB Shear Reduction
[Hinton, PF-B '91]

L-mode Turbulence Intensity $\mathcal{E}_0$ only adjustable parameter

B.C.'s: $L_\phi(a), V_\phi(a), n(a)$: given

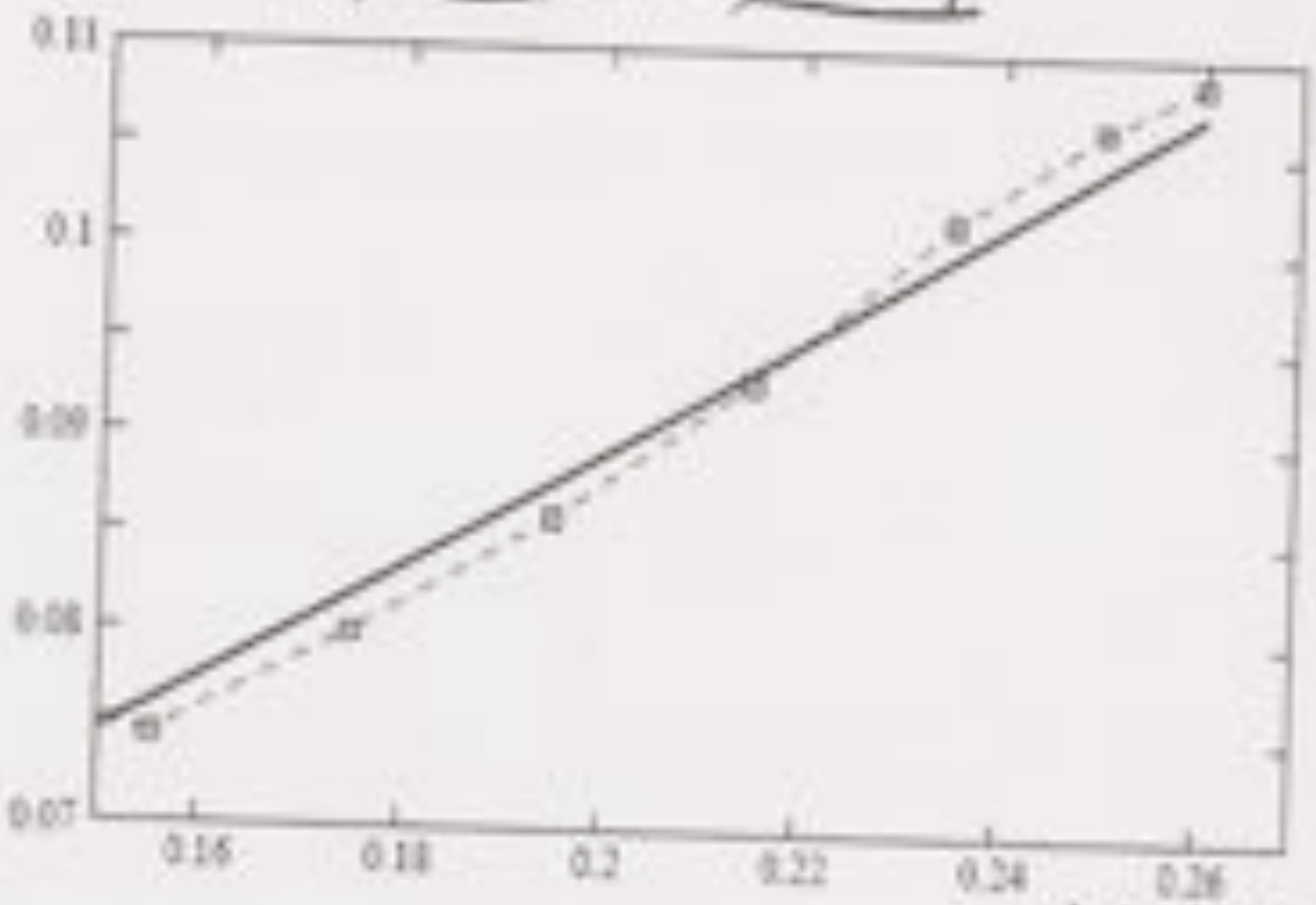
$S \sim \langle V_E\rangle' \mathcal{E}$

$\chi_\phi \sim \mathcal{E}$.

etc

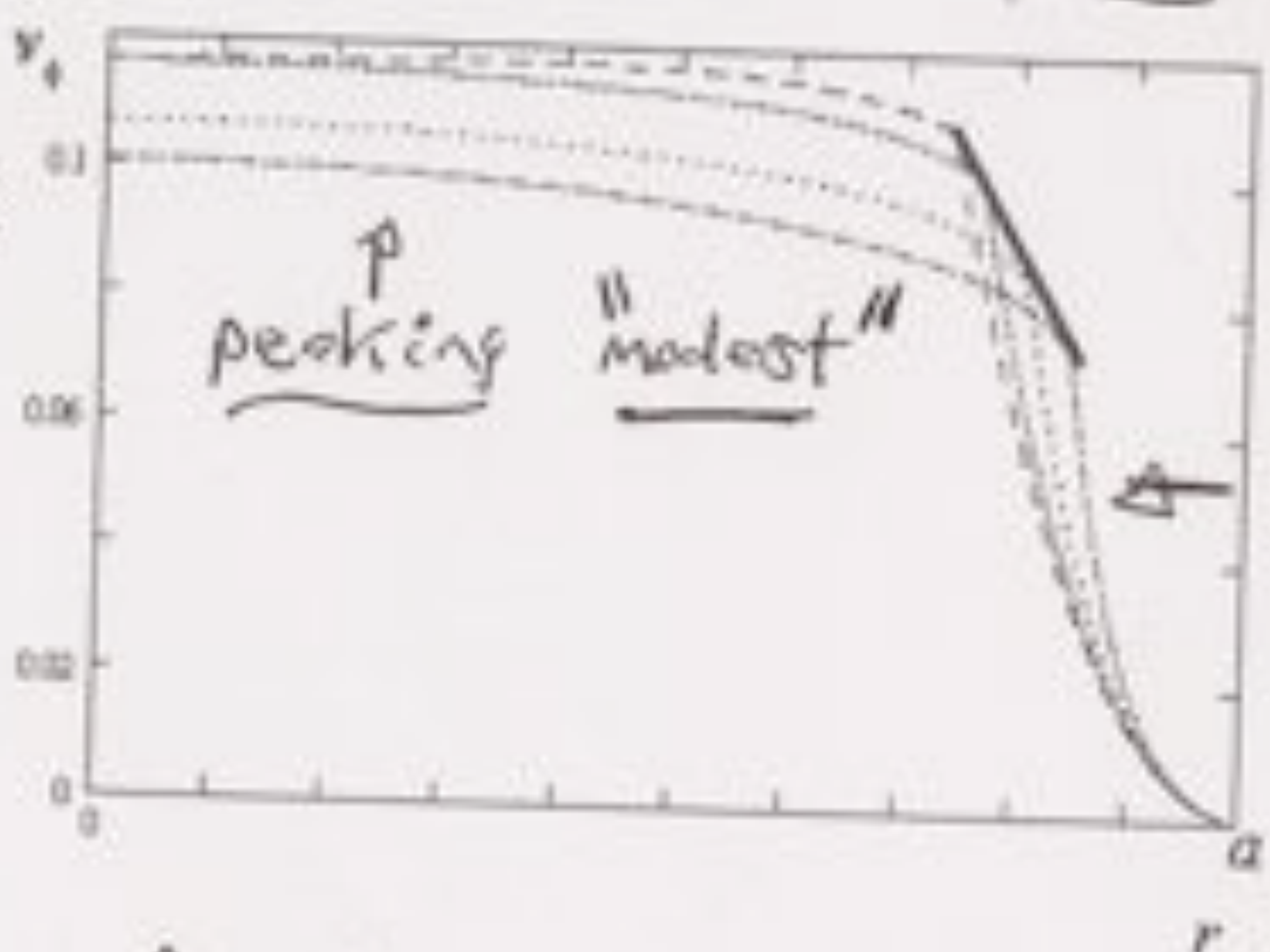
Scaling Trends manifested by Model

v_{ped} → pedestal velocity



width w_{ped}

V_ϕ profile



- Dimensional analysis for pedestal flow velocity suggests scaling with width:

Scaling with ρ from turbulence characteristics

$$v_\phi/v_{Ti} \propto \left(\Delta r_{Turb}/a\right)\left(\Delta_{ped}/a\right) \propto \left(\rho^*\right)^\alpha \left(\Delta_{ped}/a\right)$$

- With the simple model linking width to height,

$$\Delta_{ped} \propto P_{pea} \longrightarrow \Delta v_\phi / v_{Ti} \propto \left(\rho^*\right)^\alpha \Delta W_p$$

where ΔW_p : Incremental Stored Energy

- I_p scaling not recovered for GB model→ pedestal/edge turbulence issues?
  → try Snyder model !
- Model is not quantitatively accurate,
  - predicts a scaling of the pedestal toroidal velocity with the pedestal width.

    $$V_{\phi,ped} \propto \Delta_{ped} \propto P_{ped}$$

  - but recovers qualitative behavior

Punch Line: Model ties H-mode intrinsic rotation to pedestal structure.

Some Observations → Rather speculative

→ though model simple, it gives testable qualitative predictions

- strong correlation between pedestal quantities and and intrinsic rotation (c.f. C-Mod results)

  i.e. $V_\phi > V_{\phi,\text{ped}} \sim W_{\text{ped}}$

$$V_\phi / v_{Ti} \sim \left(\frac{\Delta n}{a}_{\text{Turb}}\right)\left(\Delta_{\text{ped}}/a\right) \sim \rho_*^{\alpha}\left(\Delta_{\text{ped}}/a\right)$$

- $\boxed{\text{Engine Efficiency} \sim \rho_*^{2\alpha}\left(\Delta_{\text{ped}}/a\right)^2}$ → could be augmented by more active pinch

  if $\alpha = 0$ (pedestal) ⇒ En. Eff. $\sim (\Delta_{\text{ped}}/a)^2$ (low)

  as usual, edge turbulence critical .....

→ if take $\alpha \sim 0$ and $\Delta_{\text{ped}}/a \sim (\beta_p)^{1/2}$ (Snyder – semi-empirical)

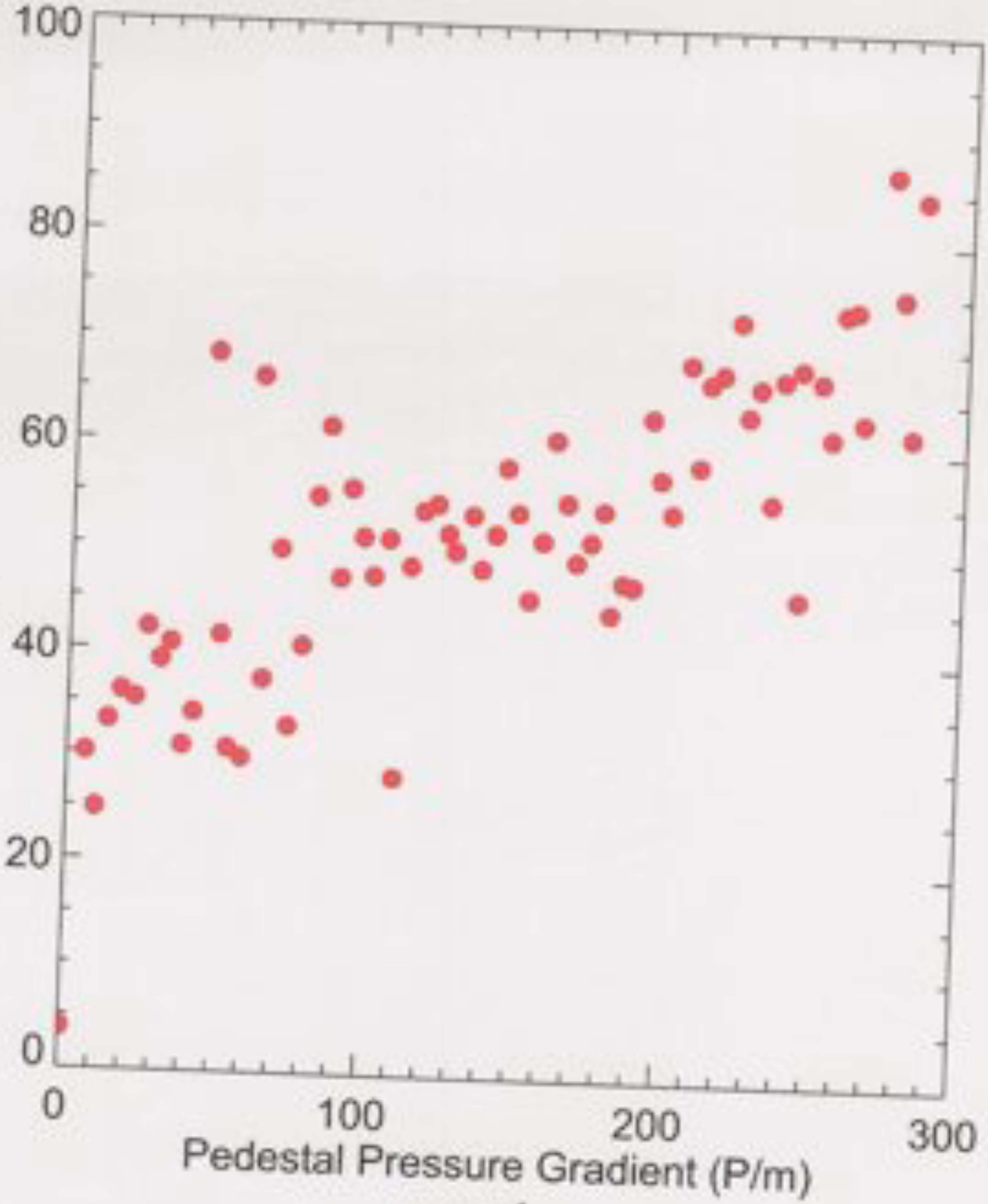
⇒ $V_\phi / v_{Ti} \sim \sqrt{\beta_p}$ ⇒ Ⓒ Rice scaling → unfavorable I_p via pedestal physics

Engine Eff. : $\sim (\Delta_{\text{ped}}/a)^2 \sim \beta_p$

→ Low efficiency, low loss engine ....

Tokamak - as - Engine

courtesy: J. Rice → C-Mod Scans



V_T

$\nabla P|_{pedestal}$

Key Issue ! $\Leftrightarrow$ also important in L-H threshold

IX.) Physics of "Boundary Condition" Effects

- SOL Flows: [LaBombard et al., NF '04]

"ballooning" particle flux produced by outboard source and SOL symmetry breaking (LSN vs USN)
Influence core Δv_ϕ in L-mode

LSN → $V_{\nabla B}$ toward X-point → Δv_ϕ co
USN → $V_{\nabla B}$ from X-point → Δv_ϕ counter
DN → little SOL flow
But, in H-mode, Δv_ϕ is always CO

⊥ transport-driven parallel SOL flows:

(a)

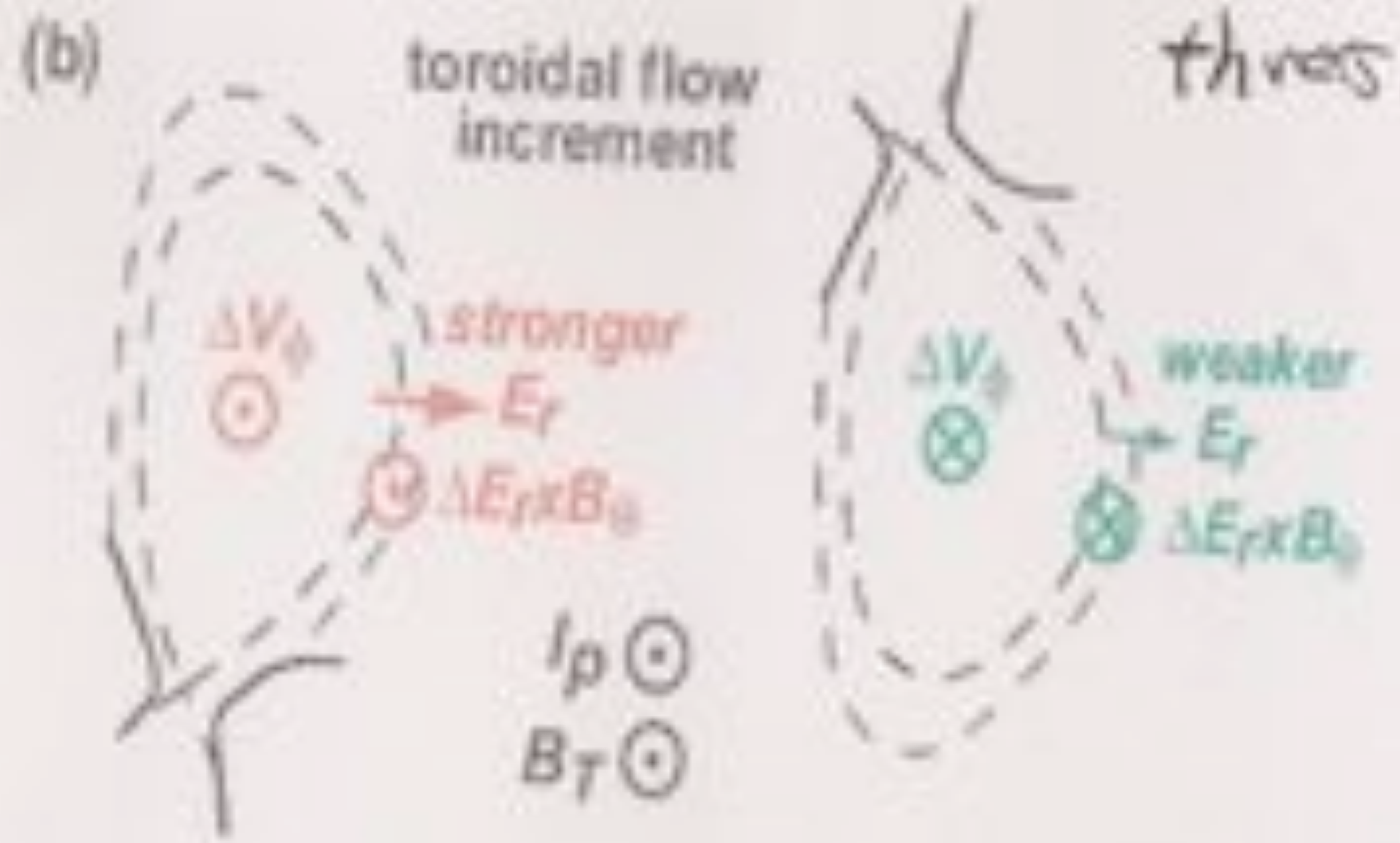
I_S spin-up threshold = L-H threshold?

- Key question: How can SOL flow influence core plasma ? $\Rightarrow \nabla \langle V_\phi \rangle \big|_a$ $\boxed{\text{Pinch + sep. flow}}$
- For $S_\parallel(r)$ = speed profile of SOL flow

$\frac{dS_\parallel(r)}{dr} > 0$ in SOL —> Inward viscous stress of SOL flow on core $\Rightarrow \langle V_\phi \rangle \big|_b \neq 0$

Key: SOL symmetry breaking sets Δv_ϕ direction
Strong for parallel shear flow instability for $\nabla V_\parallel > \nabla n$
Alternative: Recoil from Blob Ejection (Myra), Pinch

(b)



But: Core plasma also influences SOL flow. $\Rightarrow$ synergy

→ Furthur Thoughts on Boundary Condition

- B.C. is dynamic — evolves with core turbulence at transition
  - can't treat as fixed
- SOL Flow produced by:
  - poloidal asymmetry of particle flux
  - SOL symmetry breaking (USN vs LSN vs DN)

but

- increasing $E \times B$ shear may tend to reduce poloidal asymmetry of particle flux

i.e. $\Gamma_n(\theta)$ + shear $\uparrow$ → Γ_n more symmetric source ⇒ reduced SOL flow ⇒ reduced $V_\phi(a)$?!

- Difficult coupled dynamics of edge/pedestal and SOL flow may be central to intrinsic rotation.

X.) Speculations on Stiffness

→ Y. Kamada (JAEA) asks the simple yet interesting question:

" Why are T_i profiles generally stiffer than V_ϕ profiles, yet $\chi_\phi \sim \chi_i$?"

→ There may be a simple answer!

Contents

- Q_i, Π_ϕ physics essentials, for ion transport regimes
- $\begin{cases} \text{Origin of } T_i \text{ stiffness} \\ \text{Formation of } 1/L_{V_\phi} \text{ for } \begin{cases} \text{intrinsic rotation} \\ \tau_\phi \neq 0 \end{cases} \end{cases}$
- Lessons
- What of Electron Regimes?

c.) Transport Essentials - Ion Regime

$\rightarrow \quad Q_i = -\chi_i \nabla T_i \quad - \chi_i^{neo} \nabla T_i$

+ convection

$$\Pi_{r,\phi} = \underset{ⓐ}{-\chi_\phi \frac{\partial \langle v_\phi \rangle}{\partial r}} + \underset{ⓑ}{V \langle v_\phi \rangle} + \underset{ⓒ}{\Pi_{r,\phi}^{resid}}$$

ⓐ

$$\rightarrow \chi_{i,\phi} = \underbrace{f\left(L_{Tc}/L_{Ti} - 1\right)}_{\text{thresh}} \langle \tilde{V}_r^2 \rangle \tau_{c,\phi} / \left[1 + \sigma \langle V_E \rangle'^2\right]$$

distinct from threshold

① threshold function - ITG physics (includes ZF, etc)

② correlation times $\Rightarrow$ {resonant fraction ratio}

③ $\langle V_E \rangle'$ shear supression — $\langle V_E \rangle' \rightarrow$ radial force balance ∇P, V_θ, V_ϕ

①, ②, ③ $\rightarrow$ transport knobs

ⓑ

$$V \cong \chi_\phi \left(\underbrace{\frac{a}{R}}_{\text{TEP}} + \underbrace{\frac{b}{L_{Ti}}}_{\text{thermoelectric}} + \frac{c}{L_n} \right) \qquad \begin{cases} a < 0 \\ b \gtrless 0 \\ c \gtrless 0 \end{cases}$$

$\frac{c}{L_n} \rightarrow$ convective (non-ad. electrons)

ⓒ

$$\Pi^{resid} \cong \chi_\phi \sigma \frac{a}{L_p} \langle V_E \rangle' \rightarrow \text{simplified model}$$

Comments

→ f_{thresh} not purely linear ⇒ can contain physics of Dimits shift, Z. F. damping, etc

→ form of shear quench is approximate. $\langle V_\theta \rangle$ is major unknown.

→ should distinguish:

"raw" Prandtl # $\sim \left(\Pi / \langle V_\phi \rangle'\right) / \left(Q / \langle T_i \rangle'\right)$ from:

"intrinsic" Prandtl # $\sim \chi_\phi / \chi_i$

$\Rightarrow L_T \sim L_{T_c} \Leftrightarrow \underbrace{\chi_\phi / \chi_i}_{\text{set by resonance physics} \to \tau_\phi / \tau_i} \sim (V_{ph}/v_T)^2 \Big/ \left[1 + \left(\frac{V_{ph}}{v_T}\right)^2 + \left(\frac{V_{ph}}{v_T}\right)^4\right] \sim .2 \to .7$

n.b. $\chi_i^{neo} \gg \chi_\phi^{neo}$

→ Momentum O.O.'s

$V \to$ TEP, thermoelectric, convective → { mode dependent; signs can flip }

$\Pi_{r,\phi}^{resid}$ → understanding still developing... (cf IAEA Th 1-1; Gurcan, et al. '07) Primarily active in pedestal (ii.) Relative Stiffness $\leftrightarrow$ T_i, V_ϕ

Compare: $\to$ heat balance $\Rightarrow$ $\langle T_i \rangle'$
vs
$\to$ momentum balance $\Rightarrow$ $\langle V_\phi \rangle'$ for intrinsic rotation
$\to$ momentum balance with torque

} illustrates relative stiffness

a.) Heat Balance

$$Q_{in} = -\left\{ \frac{f\left(\frac{L_{T_c}}{L_T} - 1\right) \langle \tilde{v}_r^2 \rangle \tau_c^0}{(1 + \alpha \langle V_E' \rangle^2)} \right\} \frac{\partial \langle T_i \rangle}{\partial r} + Q_{neo}$$

- strongly nonlinear diffusion, via $\left\{ \begin{array}{l} \text{threshold fctn.} \\ \text{E-field shear} \end{array} \right.$
- implies $\underbrace{\Delta(\partial T_i / \partial r)}_{\text{increment from marginal}} \sim P_{in}^{\alpha}$, $\boxed{\alpha < 1 \quad \rightsquigarrow \text{"stiffness exponent"}}$

  typically $\alpha \sim 1/2$
- $E \times B$ shear (including V_ϕ') can reduce "stiffness coefficient" i.e. magnitude χ_i, via quenching

★ - as transport is strongly nonlinear, stiffness exponent seems more useful than stiffness coefficient b.) Momentum Balance – Intrinsic Rotation

→ $T_{ext} = 0$ ⇒ $\Pi_{r,\phi} = 0$

→ π^{resid} primarily active in pedestal (cf. Hahm, this mtg.)
in core, balance χ_ϕ and V, i.e

$\chi_\phi \lesssim \chi_i$

$$\frac{1}{L_{v_\phi}} = \frac{1}{v_\phi}\frac{\partial v_\phi}{\partial r} \cong \frac{V}{\chi_\phi} \cong \Big(\underset{\substack{\delta \\ TEP}}{\frac{a}{R}} + \underset{\substack{\delta \\ TH}}{\frac{b}{L_{T_i}}} + \underset{\substack{\delta \\ conv.}}{\frac{c}{L_n}}\Big) \qquad \begin{matrix} a<0 \\ b \gtrless 0 \\ c \gtrless 0 \end{matrix}$$

→ no leading dependence on $L_{T_e}/L_T - 1$ ⟺ some weak dependence in a, b, c.

→ profile is not "stiff" vis-a-vis pinning to marginality ⟺ L_v not enter χ, except via $\langle V_E \rangle'$
⇒ $\alpha \cong 0$

→ yet, v_ϕ "self-organizes", and is controlled by R, L_{T_i}, L_n, dynamically ⇒ "preferred" L_v should appear.

→ for strong, inward thermoelectric momentum pinch, L_{T_i} stiffness ⇒ L_{v_ϕ} stiffness possible outcome (probably a rarity) c.) Momentum Balance – Torque

→ for $\tau_{ext} \neq 0$, have $\Pi_{r\phi} \neq 0$

→ simplest
$$\tau_{ext} = -\chi_\phi \frac{\partial \langle v_\phi \rangle}{\partial r} + \Pi_{neo}$$
$$\cong -\left\{ \frac{f\left(\frac{L_n}{L_T}-1\right)\langle \tilde{v}_r^2 \rangle \tau_\phi}{\left(1+\alpha \langle v_E \rangle'^2\right)} \right\} \frac{\partial \langle v_\phi \rangle}{\partial r}$$

$\left\{ \begin{array}{l} v_\phi \text{ enters} \\ \chi_\phi \text{ only} \\ \text{via } \langle v_E \rangle' \end{array} \right.$

→ if subcritical to ITB,
- linear diffusion; $\chi_\phi \lesssim \chi_i$
- $\alpha \sim 1$ → stiffness exponent ~ 1.

⇒ momentum profile not stiff

→ for ITB, $\langle v_E \rangle'$ loosens both T_i, V_ϕ

→ suggests a cross-over when τ_{ext} drives V_ϕ sufficient to exceed intrinsic V_ϕ!
i.e. τ_{ext} vs $\partial_r \Pi^{resid}$. → Solomon experiment.

→ Answer

- rotation stiffness "different" and usually "weaker" than T_i stiffness a consequence of ITG threshold insensitivity to V_ϕ, except via $\langle V_E \rangle$
- heat transport → nonlinear diffusion, $\alpha \ll 1$

  momentum transport → "self-organization", $\alpha \sim 0$ (intrinsic)
  or
  → linear diffusion, $\alpha \sim 1$ (driven)
- from torque balance;

$$\gamma^{ext} - \pi^{resid} = -\chi_\phi \frac{\partial \langle V_\phi \rangle}{\partial r} + V \langle V_\phi \rangle$$

$\exists$ critical γ^{ext} for $\alpha \sim 0 \to \alpha \sim 1$ transition
Theory should predict this → HW for ITPA.

- T_i stiffness may leave footprint on V_ϕ → avalanches!

Lessons

→ more than 1 type of "profile resiliency" or "stiffness" is possible:

i.e. contrast: – threshold nonlinearity ⇒ ∇T_i

– pinch vs ν_ϕ self organization ⇒ ∇V_ϕ

→ $\langle V_E \rangle'$ may release both stiffness!

→ stiffness "exponent" may be useful, in addition to "coefficient"

→ Intrinsic rotation studies should replace global scalings with:

– rotation profile structure studies → resilience, scaling in core ?

– T_{crit} for $\alpha = 0 \rightarrow \alpha = 1$ ⇒ quantify Π_{resid}?

– dual perturbation experiments

→ What of Electron Regimes ?

- for CTEM, threshold function is 'softer'
- $T_e \to T_i$ coupling critical for $V'_{E\,\text{or}}$ feedback

⇒ expect less disparity between resilience of electron temperature, V_ϕ profiles

⇒ $P_{r_e} = \chi_\phi / \chi_e$ becomes true FOM.

Likely < 1, as ions non-resonant in CTEM.

⇒ Theory should predict these, as HW for next meeting.

Conclusions: what have we learned?

- Momentum Transport ---> Off-diagonal Flux : $\left\{\begin{array}{l}\text{Residual Stress}\\ \text{Pinch}\end{array}\right\}$ two components

Π^{resid} requires $\langle k_\parallel \rangle \neq 0$ symmetry breaking which can come from $\langle V_E \rangle'$

with B.C., can accelerate $\langle v_\phi \rangle$ → "converter" for intrinsic rotation engine

V_{pinch} $\left\{\begin{array}{ll} V_{TEP} & \text{robust, universal, related to particle pinch, albeit modest} \\ V_{TH} & \text{mode-dependent} \rightarrow \text{a mess...} \\ V_{recoil} & \text{— very important for boundary interaction} \end{array}\right.$

- Intrinsic Prandtl Number in Stiff Profiles $\chi_\phi/\chi_i < 1$
- Off-diagonal Π^{resid} + B.C. ---> Intrinsic Rotation → tokamak as "engine"
  - –Model recovers essentials

$V_{\phi,ped} \propto \Delta_{ped} \propto P_{ped} \propto \Delta W_p$; $E_{ff} \sim (\Delta_{ped}/a)^2$ Δ snyder → Rice.

- Physics of B.C. is a major unknown.

- Relative Stiffness of Momentum, Temperature ?! May be explained simply..

Ongoing and Future Theoretical Work

- Electromagnetics:
  - saturation of intrinsic rotation with β *[McDevitt, Diamond, PoP '08]*
  - Alfvenic waves in burning plasmas --> field momentum
- Alternative symmetry breaking mechanism
  - Polarization effects → McDevitt, et al. submitted ⇒ Polarization stress
  - GAMs and refractive force
  - SOL effects → couple via ∇ at $r=a$.
- Poloidal Rotation ↔ coupled to toroidal via $\langle V_E \rangle_0'$
  - correct neoclassical theory for ITB, ETB regimes
  - anomaly: off-diagonal elements
  - Charney-Drazin theorem constrainsts → Z.F. analogue for toroidal rotation
- SOL-Core coupling Dynamics {Need expand scope of SOL flow - particle transport coupling
  - SOL Stress on Core → stress +/or ∇.
  - symmetrization at L-H transition ---> source for SOL? → fate in H-mode
  - blobs and wave breaking
- Detailed Modelling Work ---> Specific Phenomenology

FSP will solve all ....

Challenges to Experimentalists

- Boundary Condition ↔ SOL Flow-Core interaction ?
  - dynamics/evolution during slow transitions
  - Low vs high neutral opacity regime comparisons
  - SN vs DN comparisons
  - Poloidal Rotation: is it neoclassical ? → D.F- Pradalier, et al, suggest subtleties . . . .
- Core Transport Dynamics
  - $\Pi^{R}_{r,\phi}$ in Core (c.f. JT-60U) --- Residual Rotation ?
  - Compare momentum pinch and particle pinch
  - ITB regime intrinsic rotation --- $\langle V_E \rangle'$, magnetic shear sensitivity — RF driven ITB.
  - Intrinsic Prandtl Number in Stiff Profiles ?
  - Corrugated $\langle v_\phi \rangle$ Profile due Zonal Flows?
- Intrinsic Rotation in Electron-dominated Plasmas (ITER relevant!)
  - CTEM as transport agent
- Relative Stiffness of $\left\{ \begin{array}{c} \text{ion} \\ \text{electron} \\ \text{toroidal momentum} \end{array} \right\}$ channels ?

Big Picture

"General Circulation in the Tokamak" as a fascinating and critical problem?! → Can we sell it as real science ?

- Ocean/Atmosphere
  - rotation (earth)
  - continents
  - solar heating
  - eddys
  - jets
  - Hadley cells
  - annular modes
  - western boundary layer
- Tokamak
  - ***B***-geometry
  - boundary
  - heat flux
  - drift-ITG
  - zonal flows
  - poloidal flows
  - KH of zonal flows
  - pedestal

hierarchical structure of "global" flow pattern?