Recent progress towards a physics-based understanding of the H-mode transition

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L. Schmitz, G. McKee, Z. Yan, M. Xu, G.S. Xu

Motivation:

- The physics of the L-H transition has been a key open issue
- Empirical P_{th} scalings have large uncertainties
  - Can we do better w/ a physics-based model?
- Can we learn how to control access to other improved confinement regimes w/o problems of H-mode
  - E.g. I-mode in AUG, C-Mod

A picture of origin of L-H Transition is Emerging

- Equilibrium shear flows at boundary exist in L-mode
- Results in finite reynolds stress that reinforces shear flow
- Flow drive from turbulence increases with L-mode heating power
- When flow drive rate exceeds turbulence drive rate **(R_T>1)** turbulence collapses
- This then allows grad-P buildup (H-Mode pedestal)

Modeling & experiment suggest turbulent-driven ExB flow plays key role

- 0-d Predator-prey models predicts limit cycle regime (Kim & Diamond PRL'03)
  - *Prey*: turbulence,
  - *Predators*: zonal flow, mean flow
- Evidence for limit-cycle between L-mode & H-mode:
  - ASDEX (Zohm'94), TJ-II (Estrada'09,'15), AUG (Conway PRL'11), DIII-D (Schmitz PRL'13), …
- 1-d Predator-prey model (Miki & Diamond, '12, '13)
  - key role of ZF-triggered turbulence collapse leading to grad-P buildup
  - Interplay between ZF and mean (ion diamag) flows
  - 1-d front propagation effects (Schmitz'12, Estrada'15)

ExB flow drive leads to turbulence collapse in simplified model

Turbulent Kinetic Energy:

$$\frac{\partial \tilde{K}}{\partial t} = \left(\gamma_{in} - \gamma^{pl}_{corr}\right)\tilde{K} - \boxed{P} - \boxed{\partial_r \tilde{T}}$$

Large-scale Shear Flow Kinetic Energy:

$$\frac{\partial \bar{K}}{\partial t} = \boxed{P} - \boxed{\partial_r \bar{T}} - \nu_{LF}\bar{K}$$

Turbulence Collapse Condition:

$$R_T \equiv \frac{P - \partial_r \tilde{T}}{\left(\gamma_{in} - \gamma^{pl}_{corr}\right)\tilde{K}} > 1$$

Manz, PoP’12, Cziegler’15

See also Vianello, PPCF 2005 & 2006
Hidalgo, Sanchez, JNM & PPCF 05,06

Definitions:

$$\tilde{K} = \frac{1}{2}\left\langle \tilde{v}^2 \right\rangle \qquad \bar{K} = \frac{1}{2}\left\langle V^{LF} \right\rangle^2$$

$$\boxed{P = \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle \frac{\partial \left\langle V^{LF} \right\rangle}{\partial r}}$$

$$\boxed{\tilde{T} = \left\langle \tilde{v}_r \tilde{v}_\theta^2 \right\rangle \qquad \bar{T} = \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle \left\langle V^{LF} \right\rangle}$$

$$\gamma_{in} = \gamma_{in}(\nabla n, \nabla T, V_E')$$

$$\left\langle V^{LF} \right\rangle = \left\langle V_{ExB} \right\rangle + \left\langle V_i^{dia} \right\rangle$$

Ion Diamagnetic Flow ***Survives*** Turbulence Collapse & *Locks In H-mode State*

Leads to closed form reduced predator-prey model

- Model closed with few key assumptions (Kim&Diamond PRL'03)
  - $q \propto -\left\langle \tilde{v}_{\perp}^{2} \right\rangle \tau_{corr} \nabla p_i$
  - $\bar{V}_{i,dia} \propto \nabla p_i$
  - $\left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle \propto \dfrac{\left\langle \tilde{v}_{\perp}^{2} \right\rangle \bar{V}'^{LF}_{ExB}}{1+\alpha \bar{V}'^{2}_{E}}$

Recent work on C-Mod validates key assumption in predator-prey model

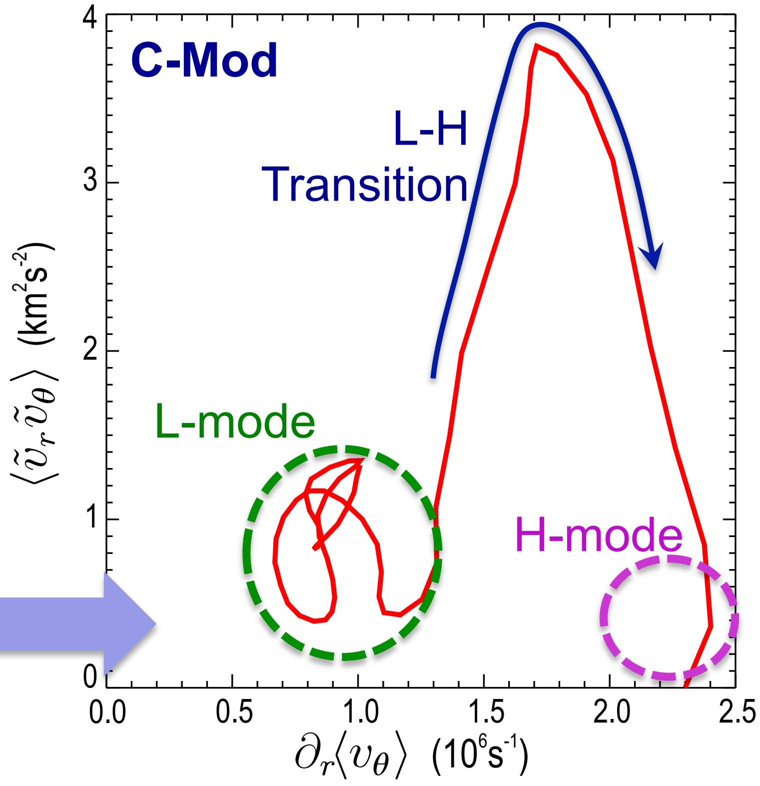
- Model (Kim&Diamond PRL'03) was closed with few key assumptions

- $q \propto -\langle \tilde{v}_\perp^2 \rangle \tau_{corr} \nabla p_i$

- $\bar{V}_{i,dia} \propto \nabla p_i$

- $\langle \tilde{v}_r \tilde{v}_\theta \rangle \propto \dfrac{\langle \tilde{v}_\perp^2 \rangle \bar{V}'^{LF}_{ExB}}{1+\alpha \bar{V}'^2_E}$

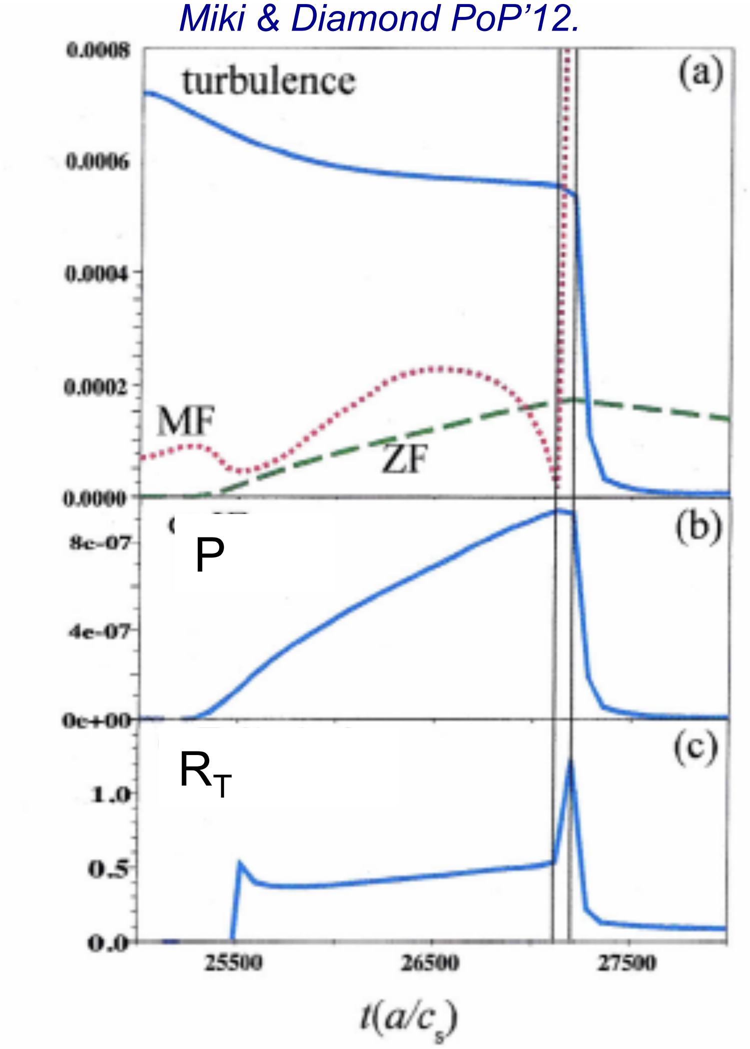
Experiments support this *ansatz*



1-D Reduced Model Shows L-H Transition Dynamics

- Turbulent-driven m,n=0,0 ExB flow builds up & regulates turbulence
- ZF production, P, grows with heat flux
- Turbulence collapse when flow drive exceeds growth rate (R_T>1)
- grad-P_{ion} ExB flow then builds; turbulent-driven m,n=0 ExB decays
- Strong grad-P_{ion} Mean Flow (MF) locks-in H-mode

Miki & Diamond PoP'12.



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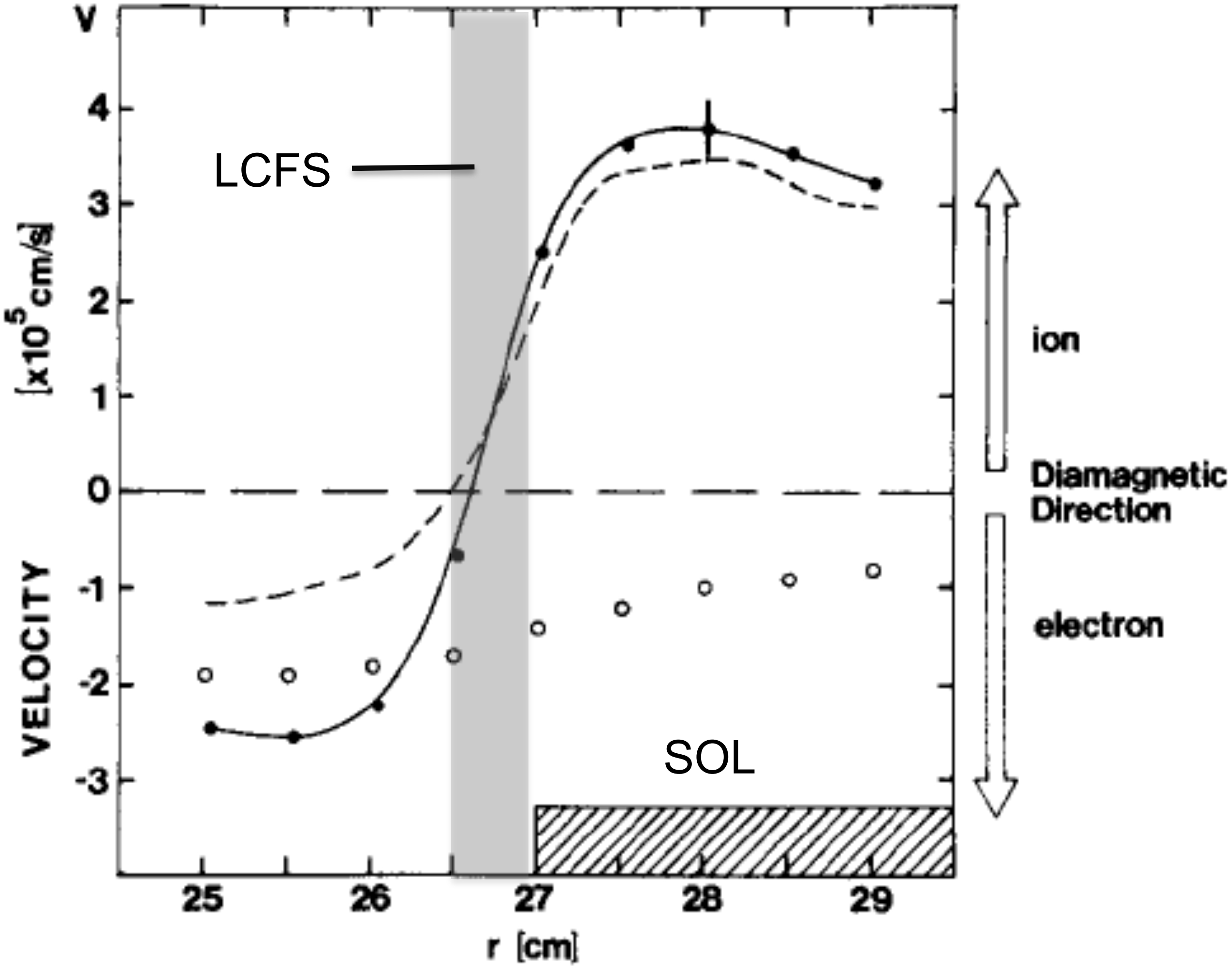
A Shear Layer Sustained by Equilibrium Exists at LCFS

TEXT   Ritz PF’84



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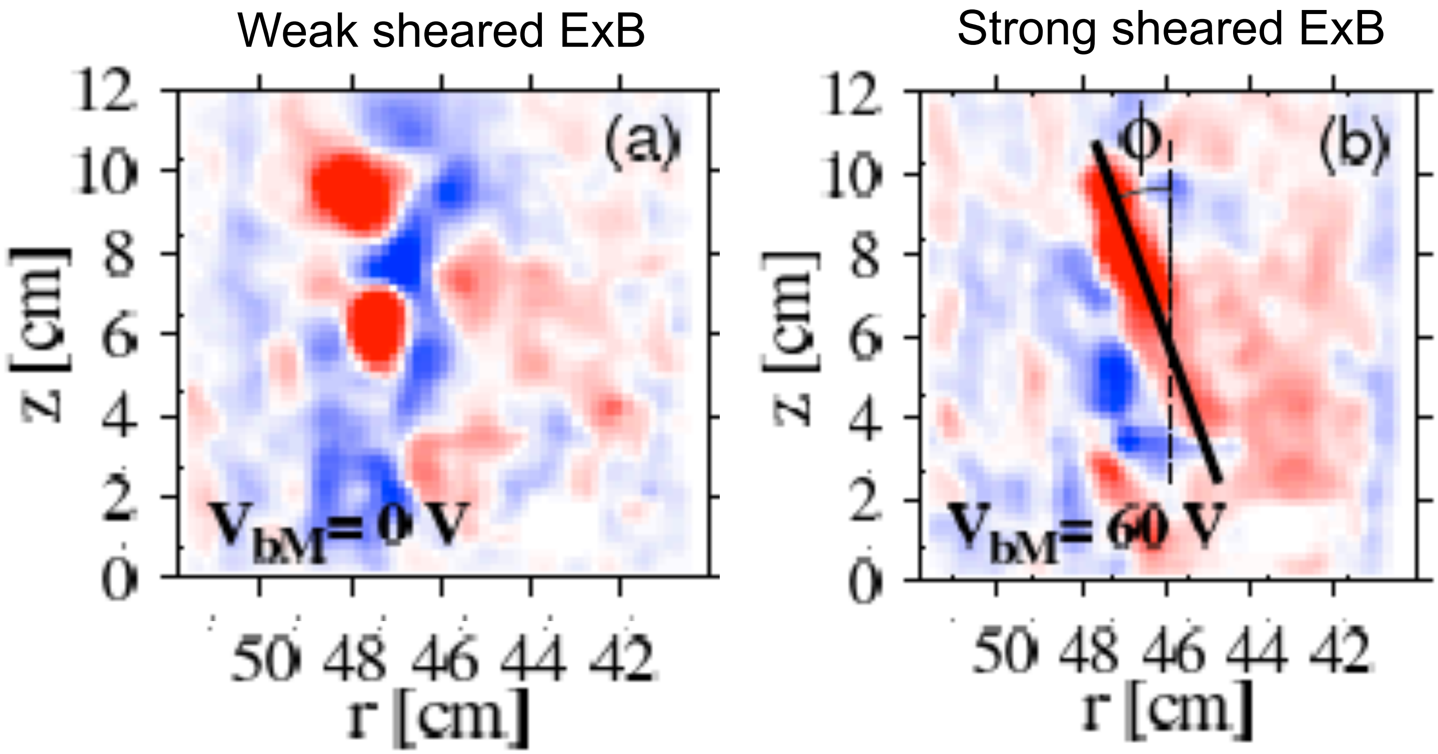
Sheared ExB flow tilts & stretches eddies

TEXTOR Shesterikov, Xu et al PRL 2013

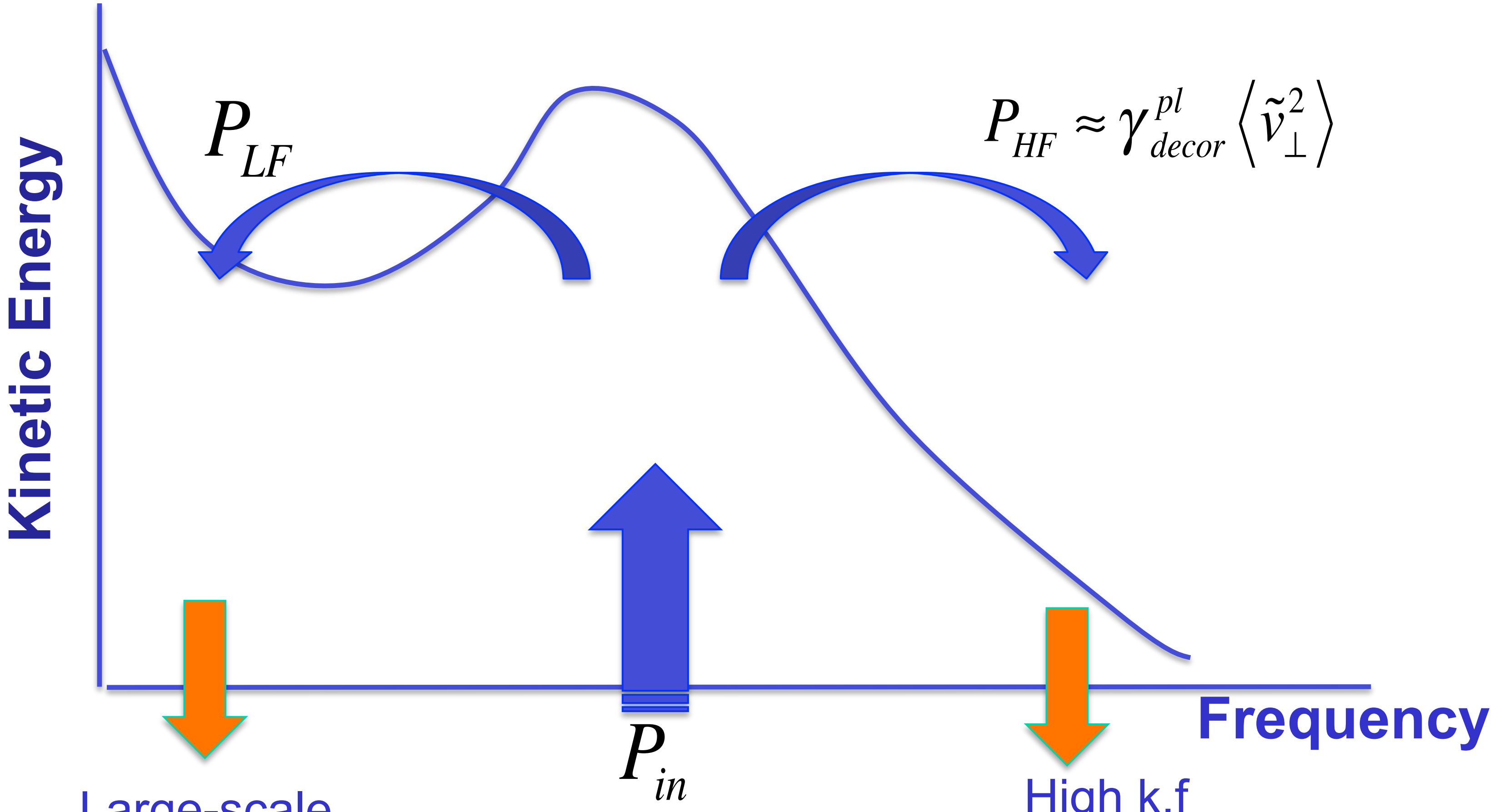


Eddy tilting correlates V_r and V_θ

➔Non-zero Reynolds Stress

➔ Turbulence can drive sheared flow

Spectral representation: L-mode turbulence established from energy input, nonlinear transfer & dissipation



Kinetic Energy

Frequency

P_{LF}

$P_{HF} \approx \gamma_{decor}^{pl} \left\langle \tilde{v}_{\perp}^{2} \right\rangle$

P_{in}

Large-scale dissipation

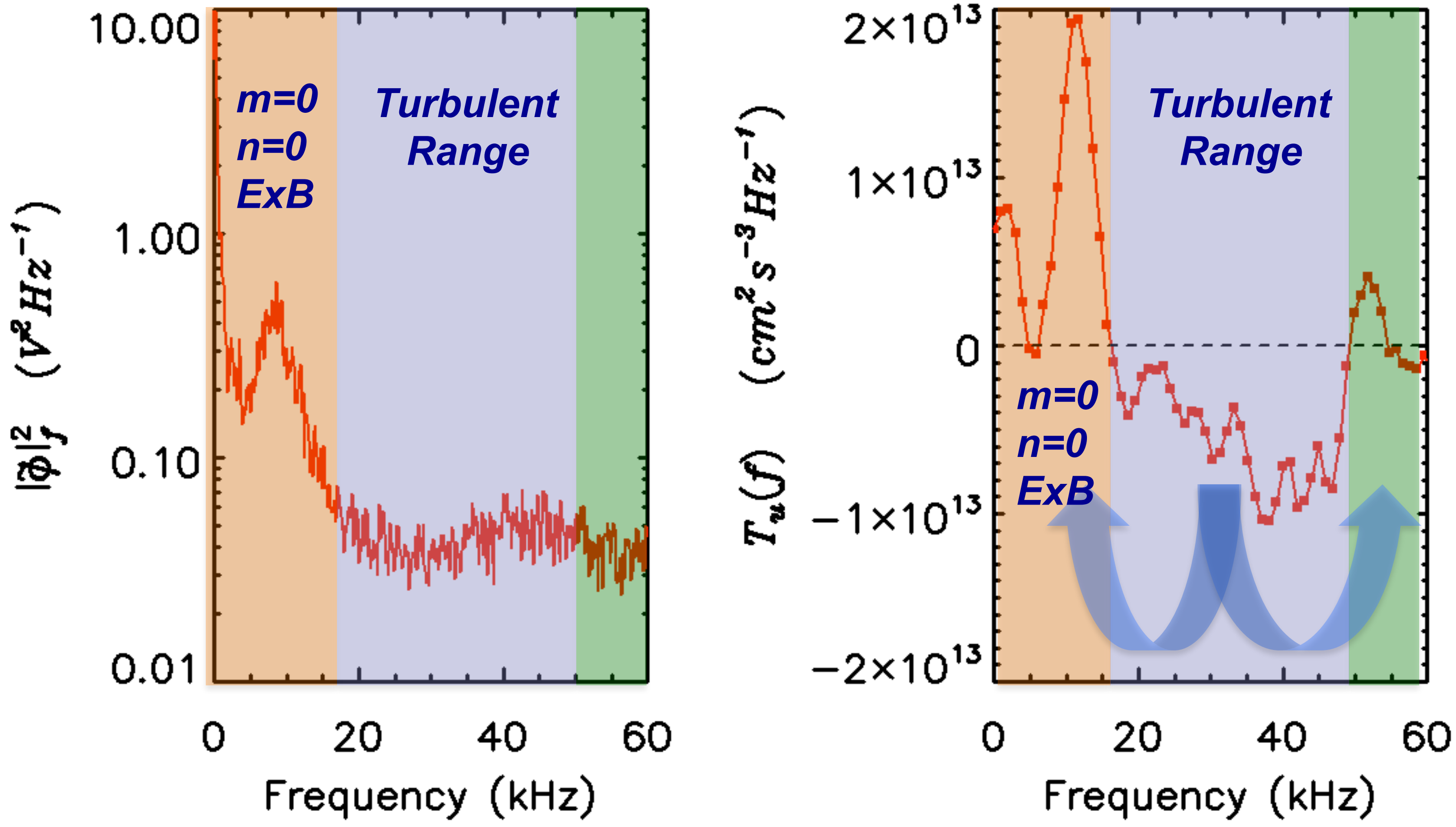
Gradient Drive Regulated by $\nabla n, \nabla T_{i,e}$

High k,f dissipation

Weakly heated L-mode experiments confirm this picture

See M. Xu PRL ’12 for flow drive physics & M. Xu PoP’10 for technique
See K. Zhao, PRL’06, PPCF’11 for identification of m/n=0/0 structure

HL-2A



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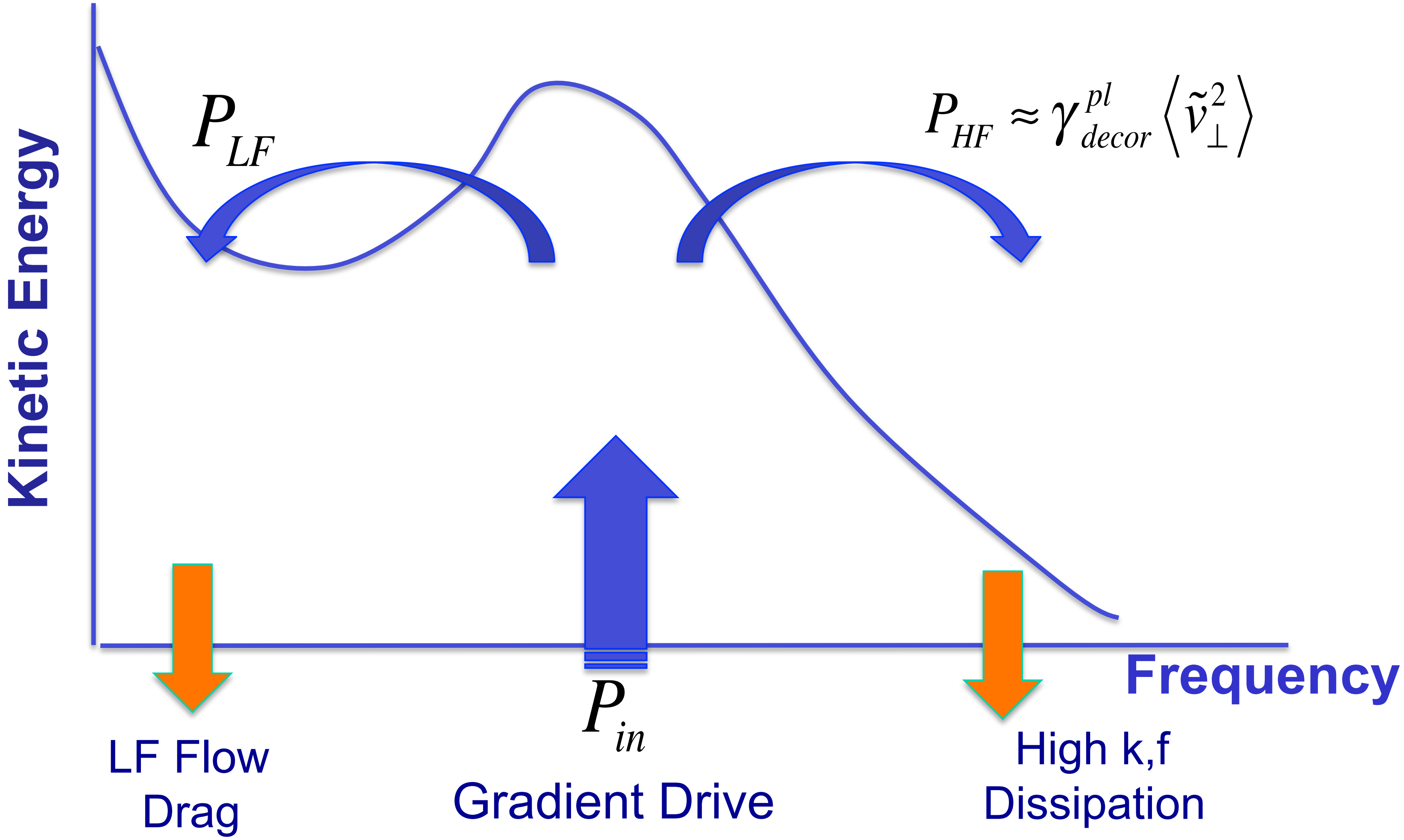


Kinetic Energy

Frequency

P_{LF}

$P_{HF} \approx \gamma_{decor}^{pl} \left\langle \tilde{v}_\perp^2 \right\rangle$

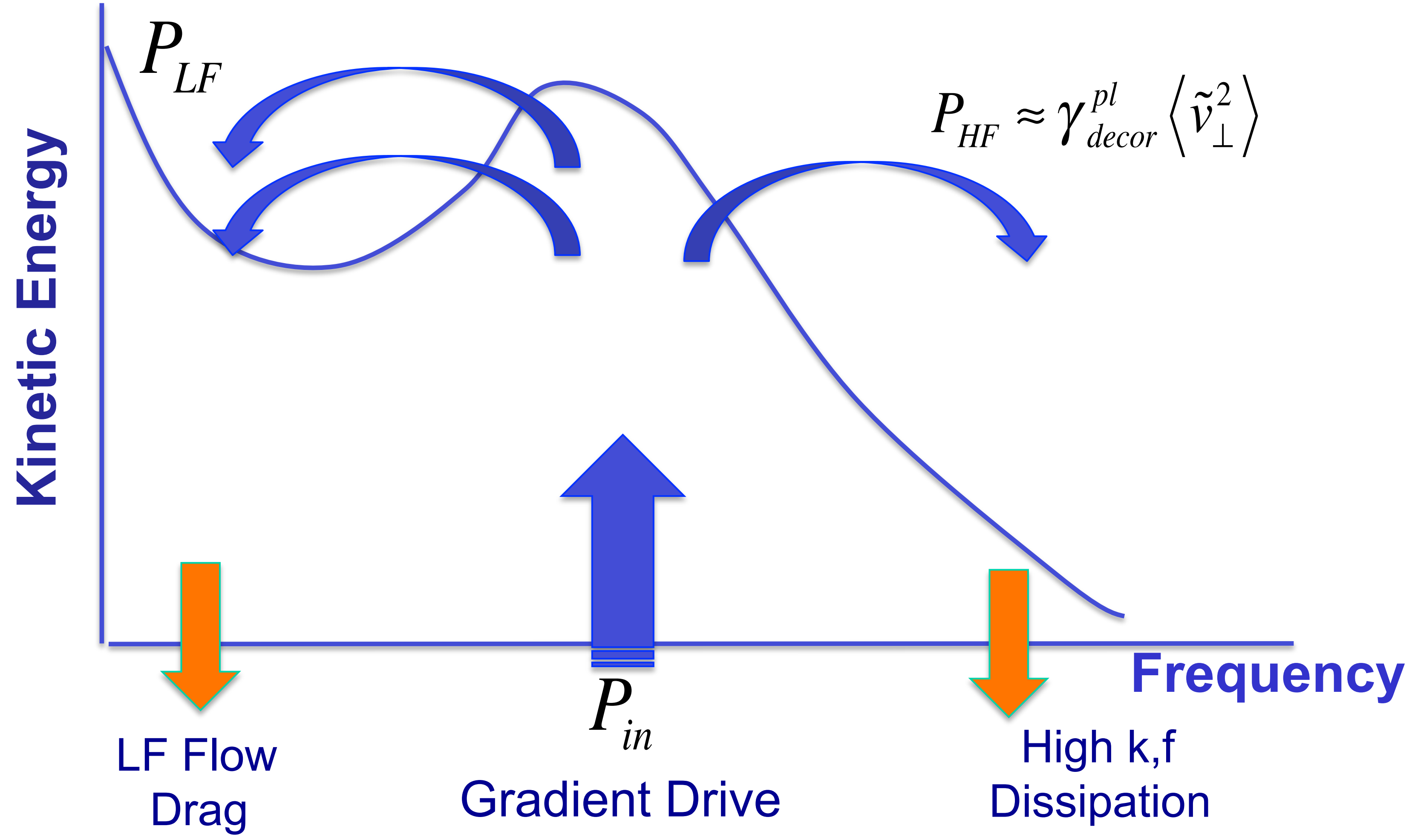
P_{in}

LF Flow Drag

Gradient Drive

High k,f Dissipation

Power transfer to shear flow increases with plasma heating

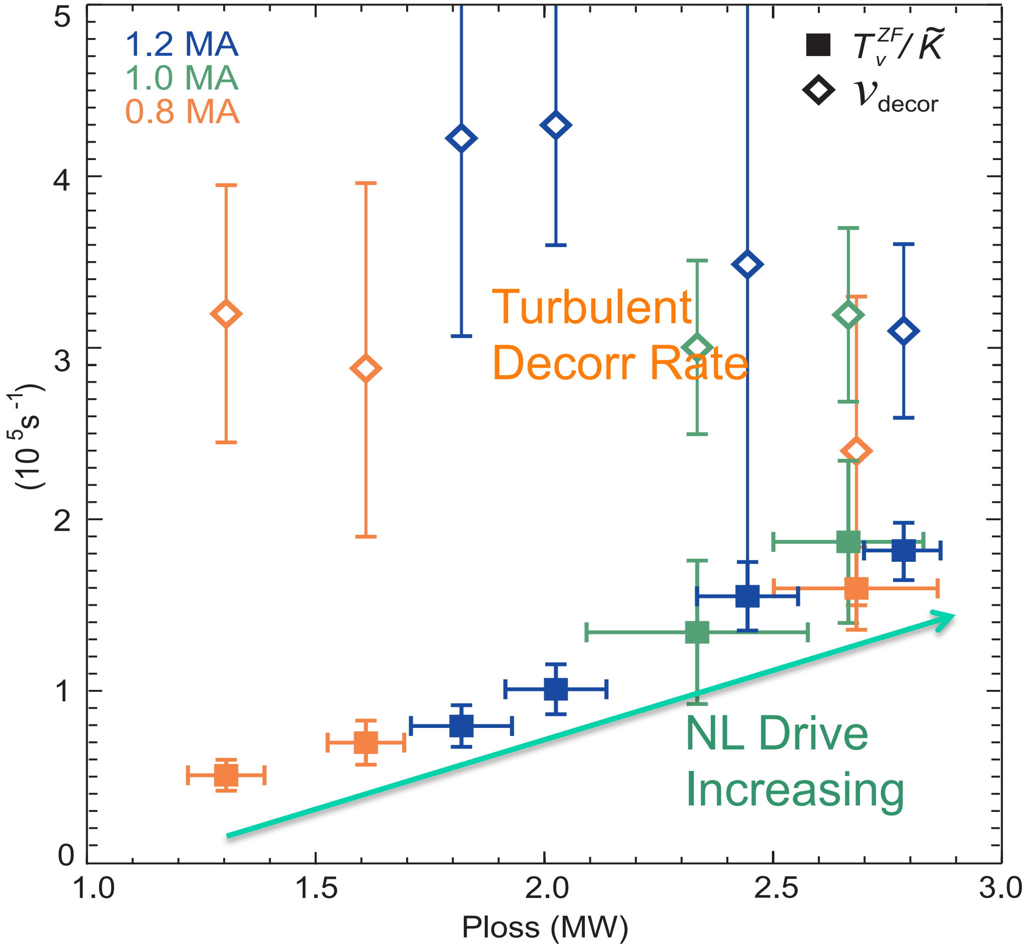


Nonlinear shear flow drive becomes important at higher heat flux

Cziegler, et al, NF 2015 (accepted),

$$T_v^{ZF} = -\mathrm{Re}\left[\sum_{f_1;\, f=f_{ZF}} \left\langle \tilde{v}_\theta(f)\tilde{v}_r(f-f_1)\partial_r \tilde{v}_\theta(f_1) \right\rangle \right]$$

C-Mod



G.R. Tynan, EFTSOMP WORKSHOP 2015, Lisbon, June 2015

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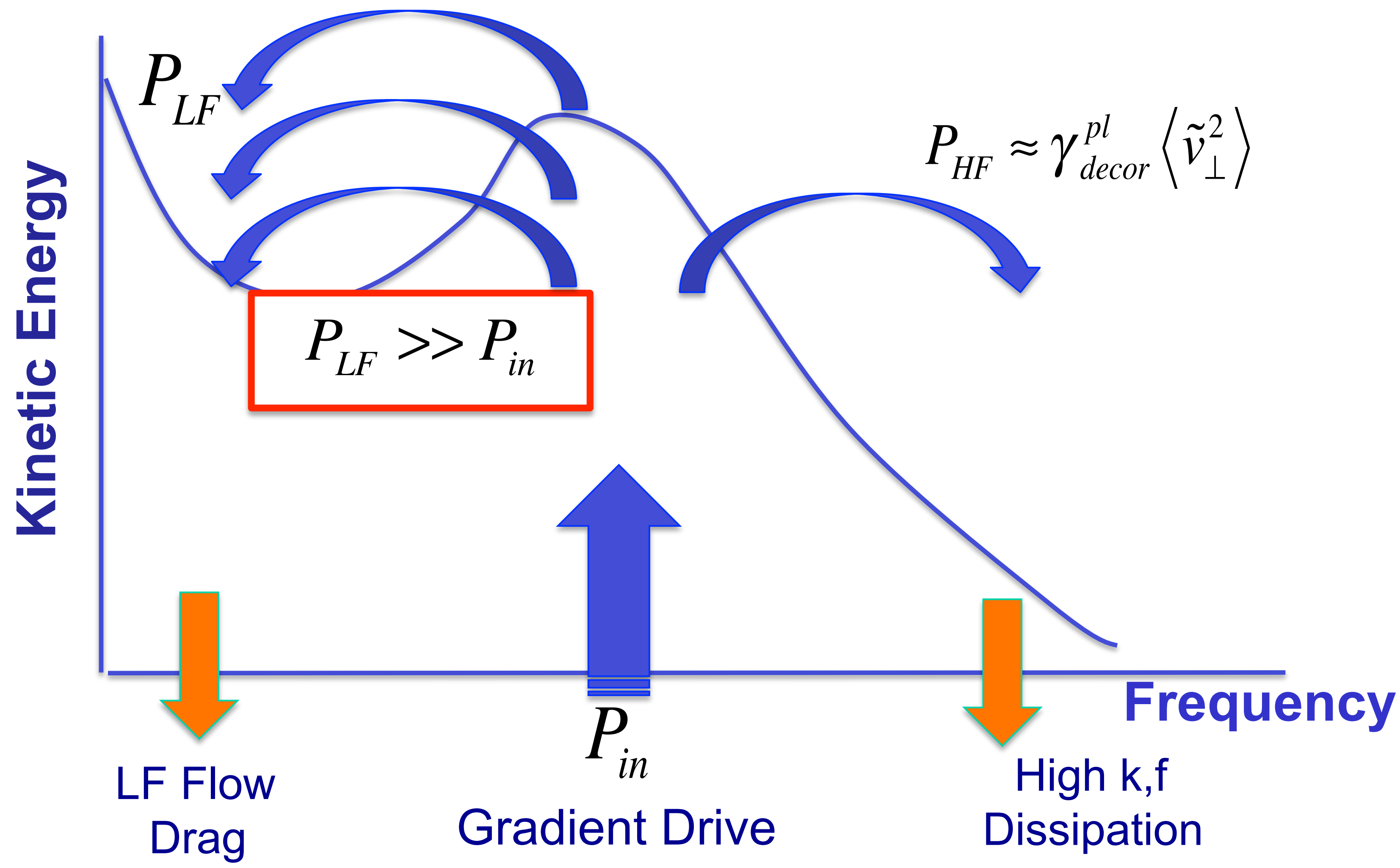
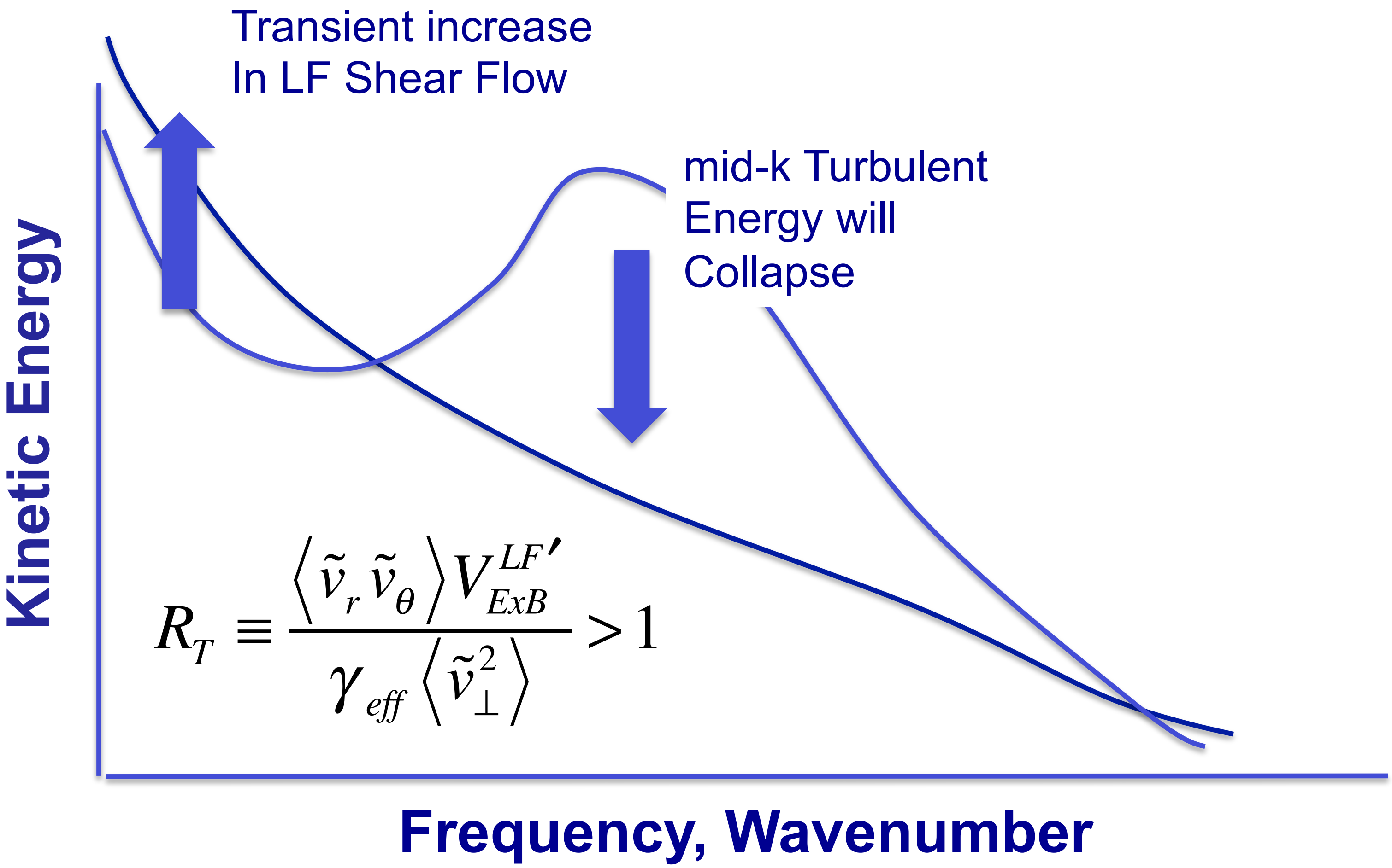
- This then allows grad-P buildup (H-Mode pedestal)

Further heating leads rate of flow drive exceeding rate of energy input into turbulence



At this point, turbulence cannot be sustained…and thus turbulence amplitude collapses



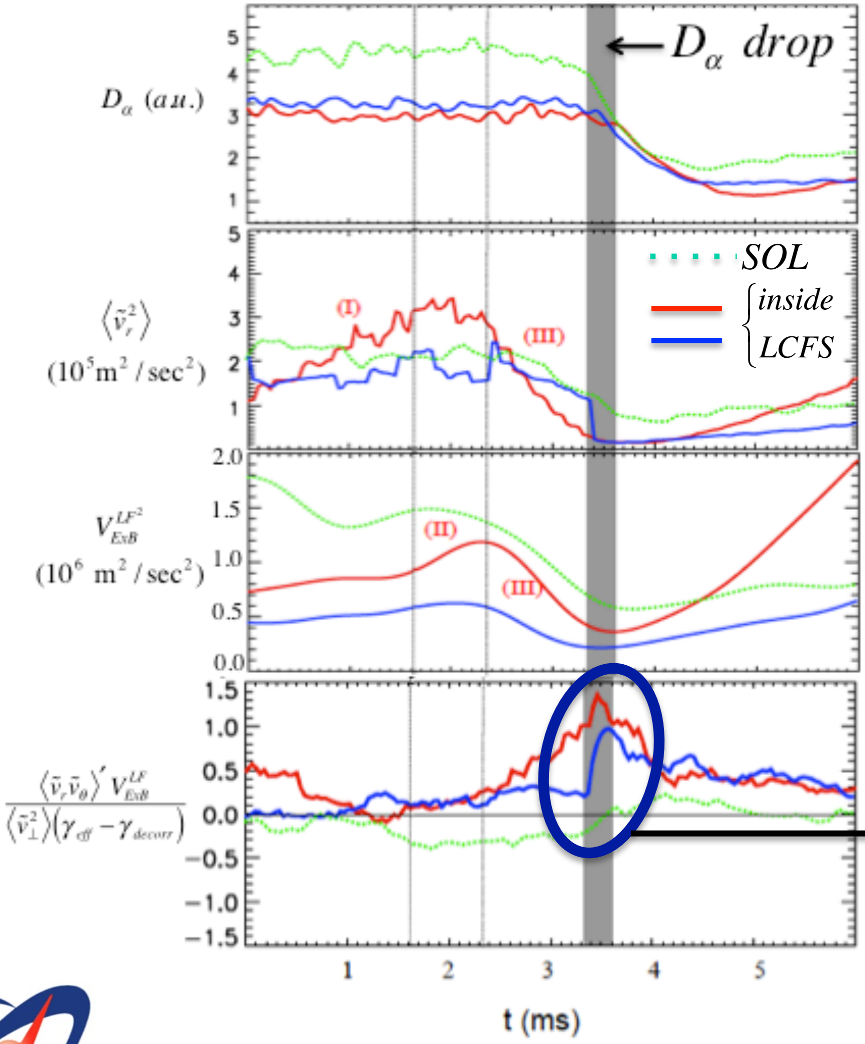
$$R_T \equiv \frac{\left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle V_{ExB}^{LF\prime}}{\gamma_{eff} \left\langle \tilde{v}_\perp^2 \right\rangle} > 1$$

RECENT EXPERIMENTS SHOW THIS BEHAVIOR

- EAST (Manz et al PoP'12, GS Xu et al NF'14)
- TEXTOR (Shesterikov et al PRL'13)
- DIII-D (Yan et al PRL'14)
- ALCATOR C-Mod (Cziegler, PPCF'14, NF'15)

L-H Transition When m,n=0 LF ExB Drive Exceeds Energy Input Rate into Turbulence

Manz et al, PoP Aug 2012



- Turbulence Energy & LF ExB Energy Increase
- Power Transfer Increases
- Power Transfer Grows to ~Equal Turbulent Energy Input Rate
- L-H Transition Occurs

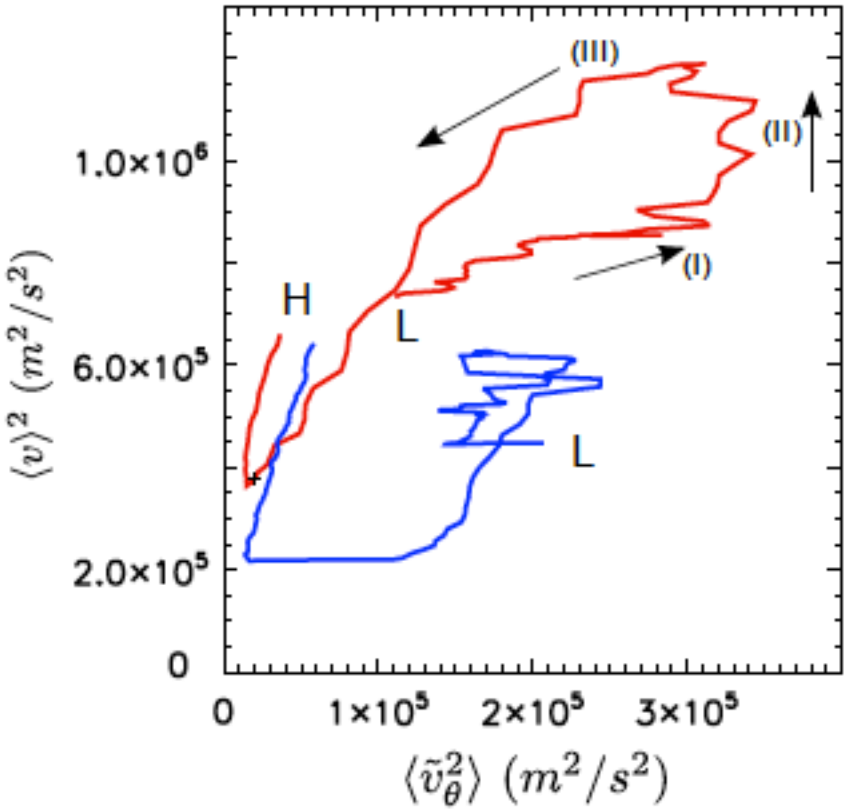
$$\langle \tilde{v}_r \tilde{v}_\theta \rangle V'_{ZF} \approx \left(\gamma_{eff} - \gamma_{decorr} \right) \tilde{v}_\perp^2$$

Turbulence & LF m,n=0 ExB Energy Exhibit **One Orbit of Phase Space** Before the L-H Transition

- Turbulence Increases in L-mode (I)
- Power Transfer Increases the LF Shear Flow (I-II)
- Flow Saturates Turbulence (II-III)
- Transition to H-mode State Locks in LF Shear Flow
- Strong radial dependence

Manz et al, PoP Aug 2012

EAST

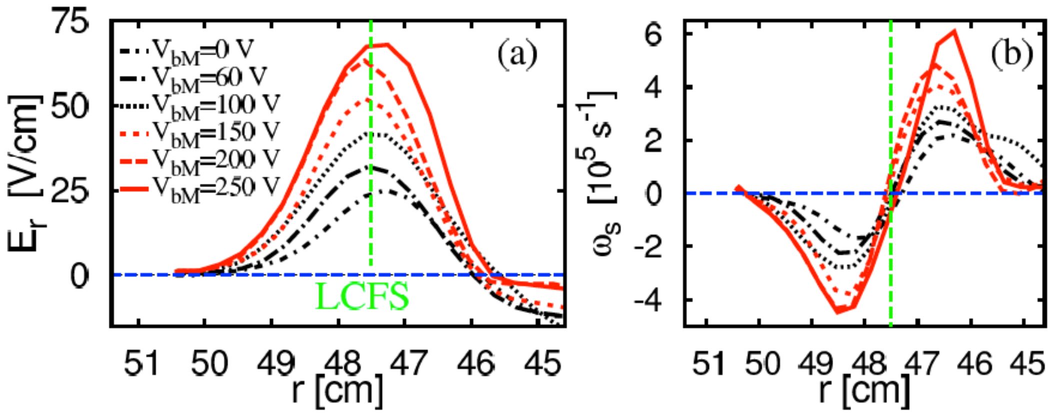


L-H Transition Appears to be Degenerate Case of Multi-orbit LCO Regime

TEXTOR: Energy Transfer During Biased L-H Transition

Turbulent-driven ExB Flow Plays Roll in Biased H-mode Transition

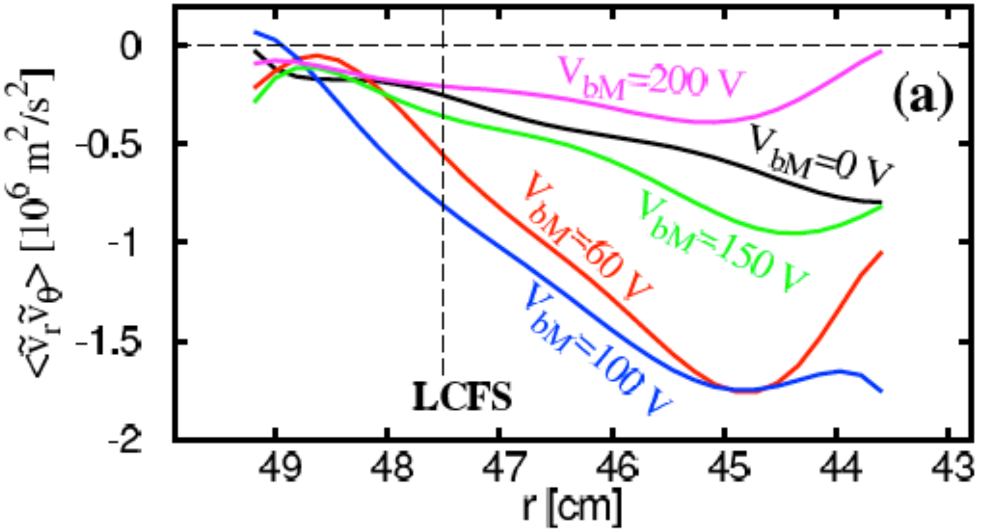
TEXTOR Shesterikov, Xu et al, PRL 2013



For lower values of shearing

$$\left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle \propto \bar{V}_E'$$

$\rightarrow$ Negative Viscosity

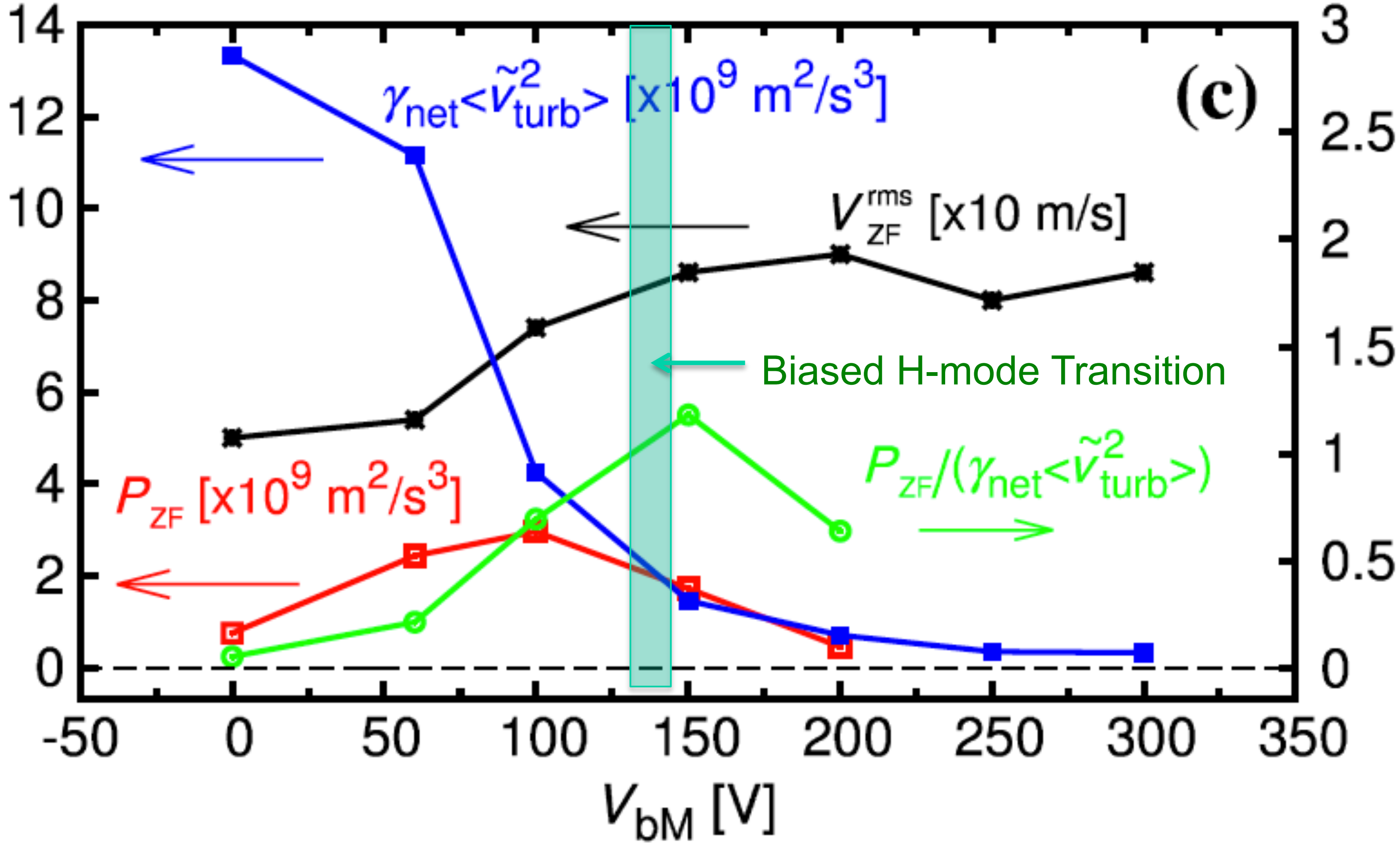


Stress reinforces ExB flow

Stress saturates and decreases for larger values of stress

Biased H-mode Onset Occurs When Power Transfer to LF ExB Shear Flow Exceeds Threshold

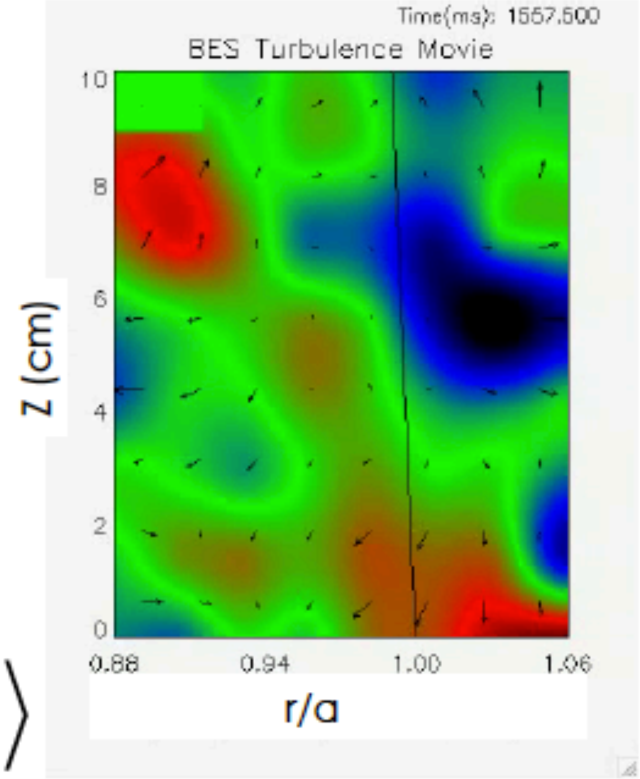
TEXTOR Shesterikov, Xu et al, PRL 2013



DIII-D: L-H Transition Studies via BES velocimetry

Turbulent Velocity Fluctuation Measured from Image-based Velocimetry

- **Vector-matching frame by frame to infer short time scale velocity fluctuation [1]**
  - Orthogonal Dynamic Programming
- **With measured $\tilde{V}_\theta$ and $\tilde{V}_r$**
  - Analyze velocity fluctuation spectrum
  - Infer Reynolds stress, in principal proportional to the electrostatic Reynolds stress: $\left\langle \tilde{V}_r \tilde{V}_\theta \right\rangle$
    (Requires further validation)

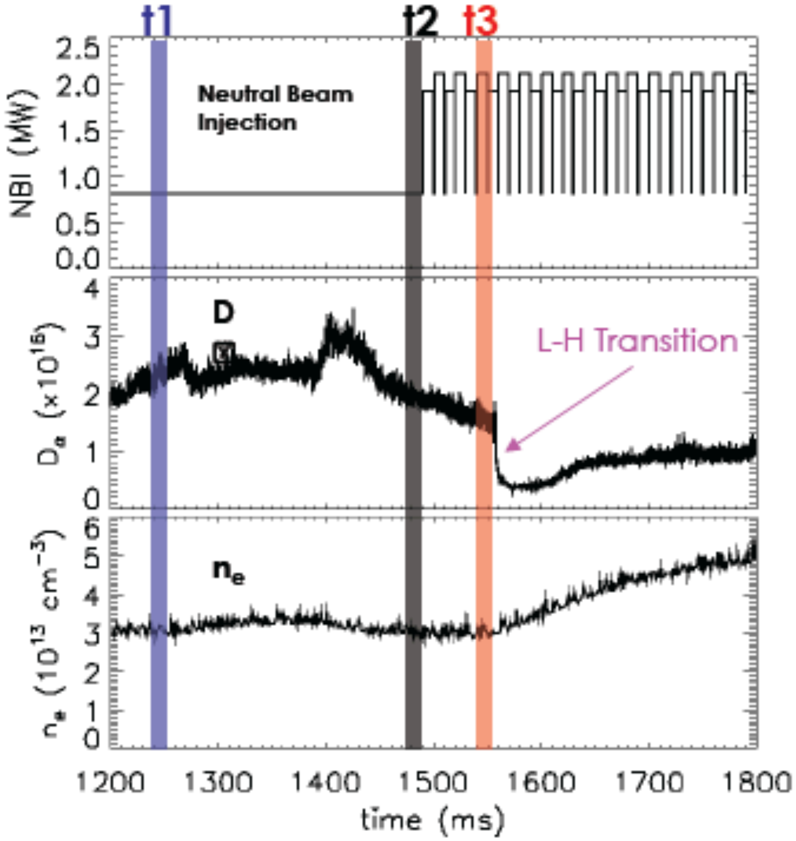


Z. Yan et al, PRL 2014

[1] G. McKee, et al., RSI, 75, 3490, 2004

Turbulence Increases with Time and Power Approaching L-H Transition

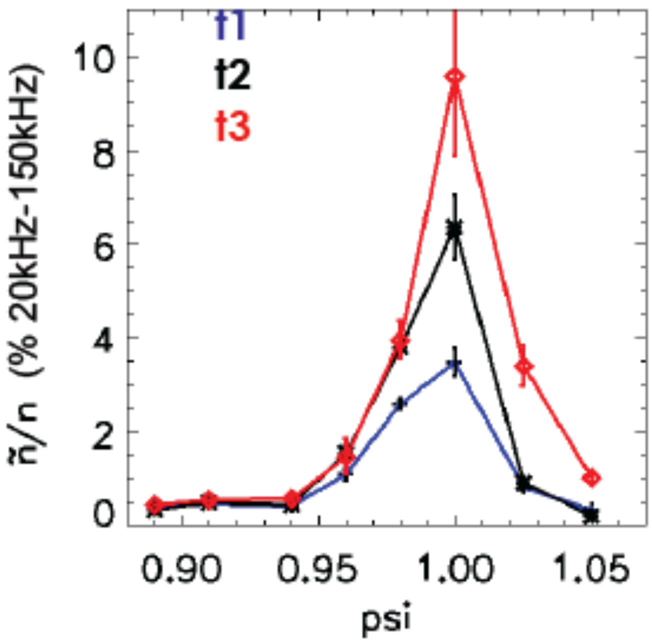
Z. Yan et al, PRL 2014



t1, t2: $P_{INPUT} < P_{L\text{-}H}$

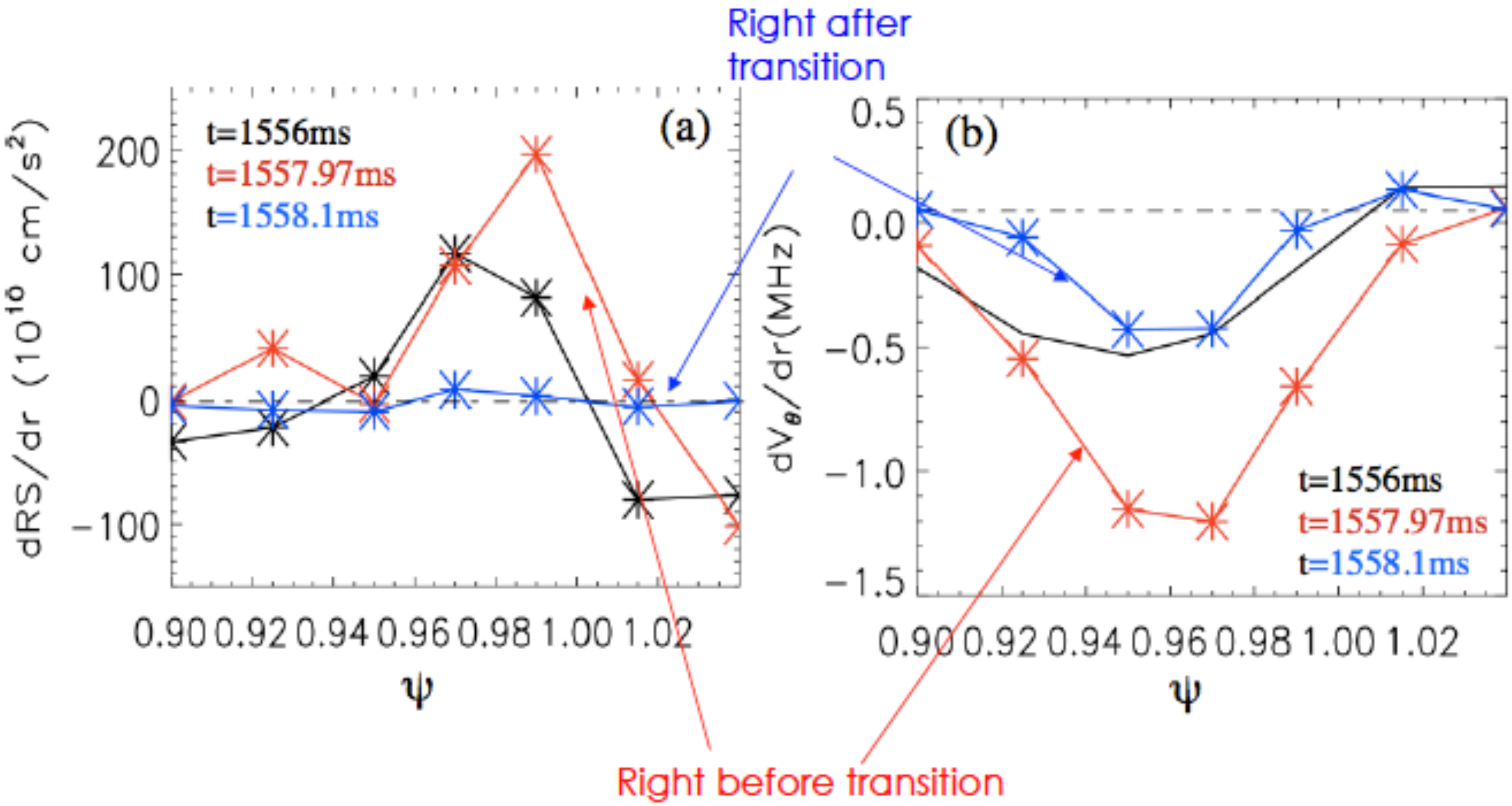
t3: $P_{INPUT} \geq P_{L\text{-}H}$

Frequency Integrated over 20khz-150kHz $\tilde{n}/n$



Increased turbulence provides increased drive for zonal flow

The Final Increases Are Localized in The Pedestal Region


Radial profile of Reynolds stress gradient

Radial profile of velocity shear

Right after transition

Right before transition

Z. Yan et al, PRL 2014

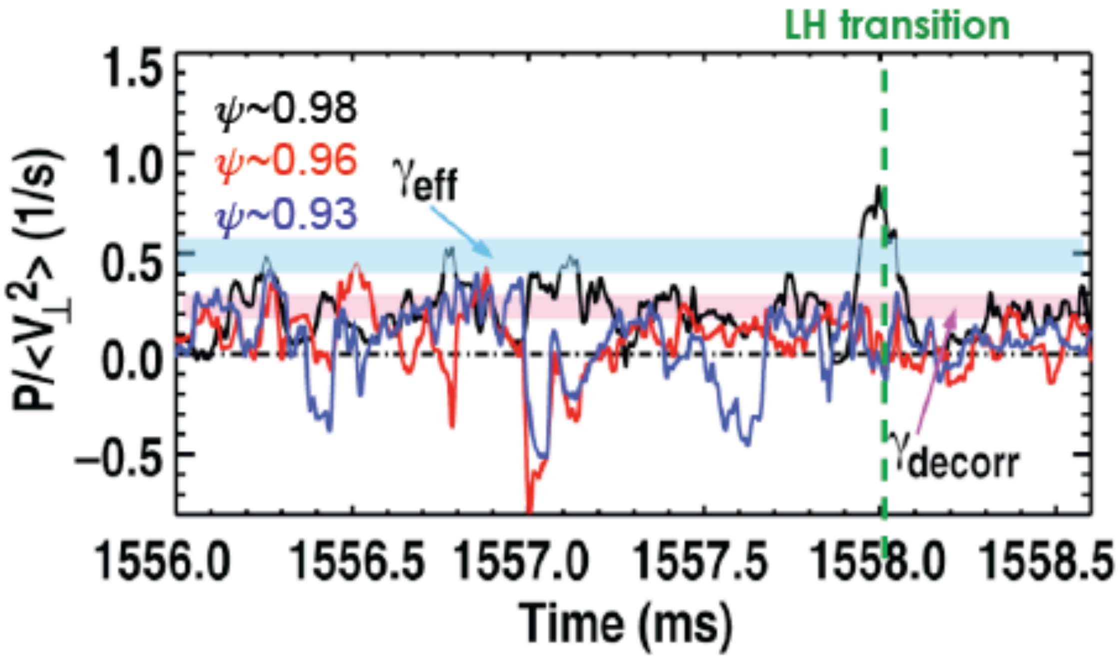
Energy Transfer Jumps Up Right Before the Transition and Localized at the Plasma Edge Region

Evolution of zonal flow and turbulence [2]

Z. Yan et al, PRL 2014

$$\frac{1}{2}\frac{\partial\langle\tilde{v}^2\rangle}{\partial t}=\gamma_{eff}\langle\tilde{v}^2\rangle\boxed{-\langle\tilde{v}_r\tilde{v}_\theta\rangle\frac{\partial V_E^{LF}}{\partial r}}$$

$$\frac{1}{2}\frac{\partial}{\partial t}\langle V_E^{LF^2}\rangle=+\langle\tilde{v}_r\tilde{v}_\theta\rangle\frac{\partial V_E^{LF}}{\partial r}-\gamma_{LF}\langle V_E^{LF^2}\rangle$$

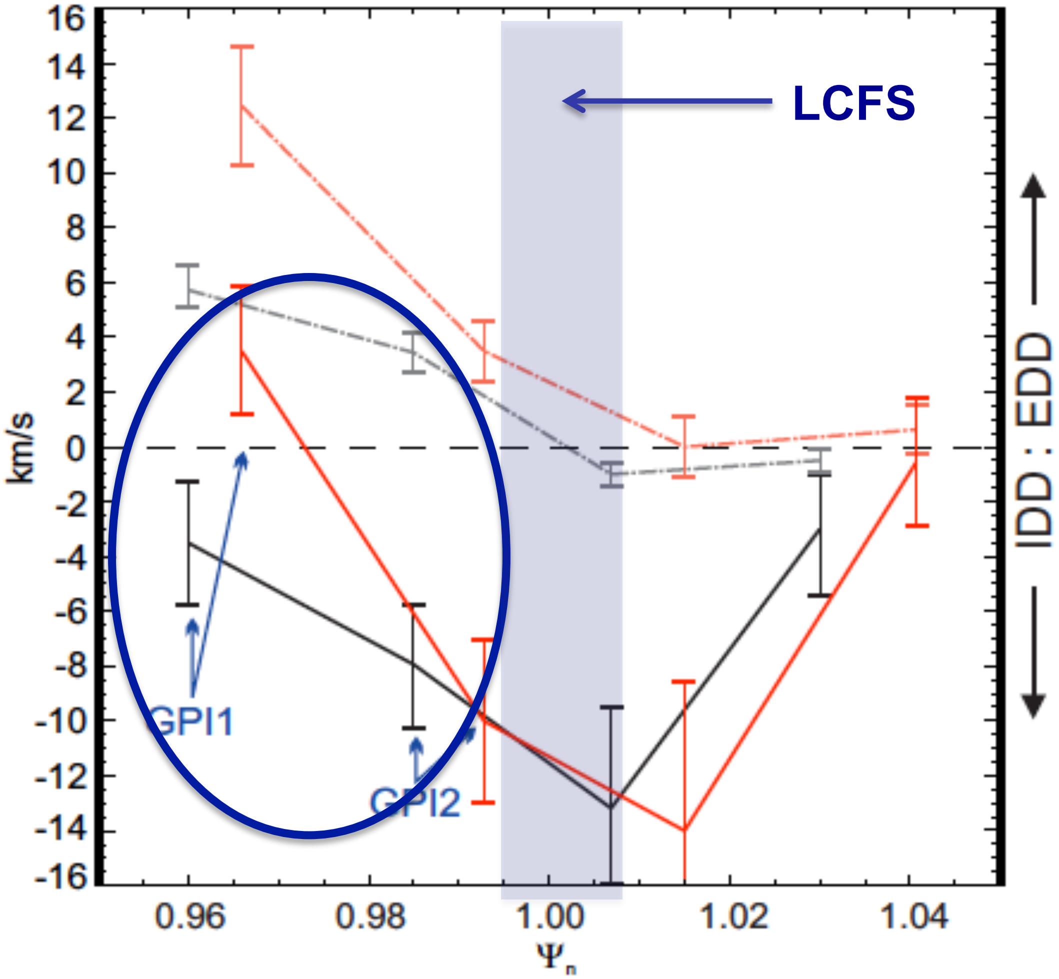


[2] P. Manz, et al., PoP, 19, 012309,2012

C-Mod: L-H Transition Studies via He-GPI velocimetry

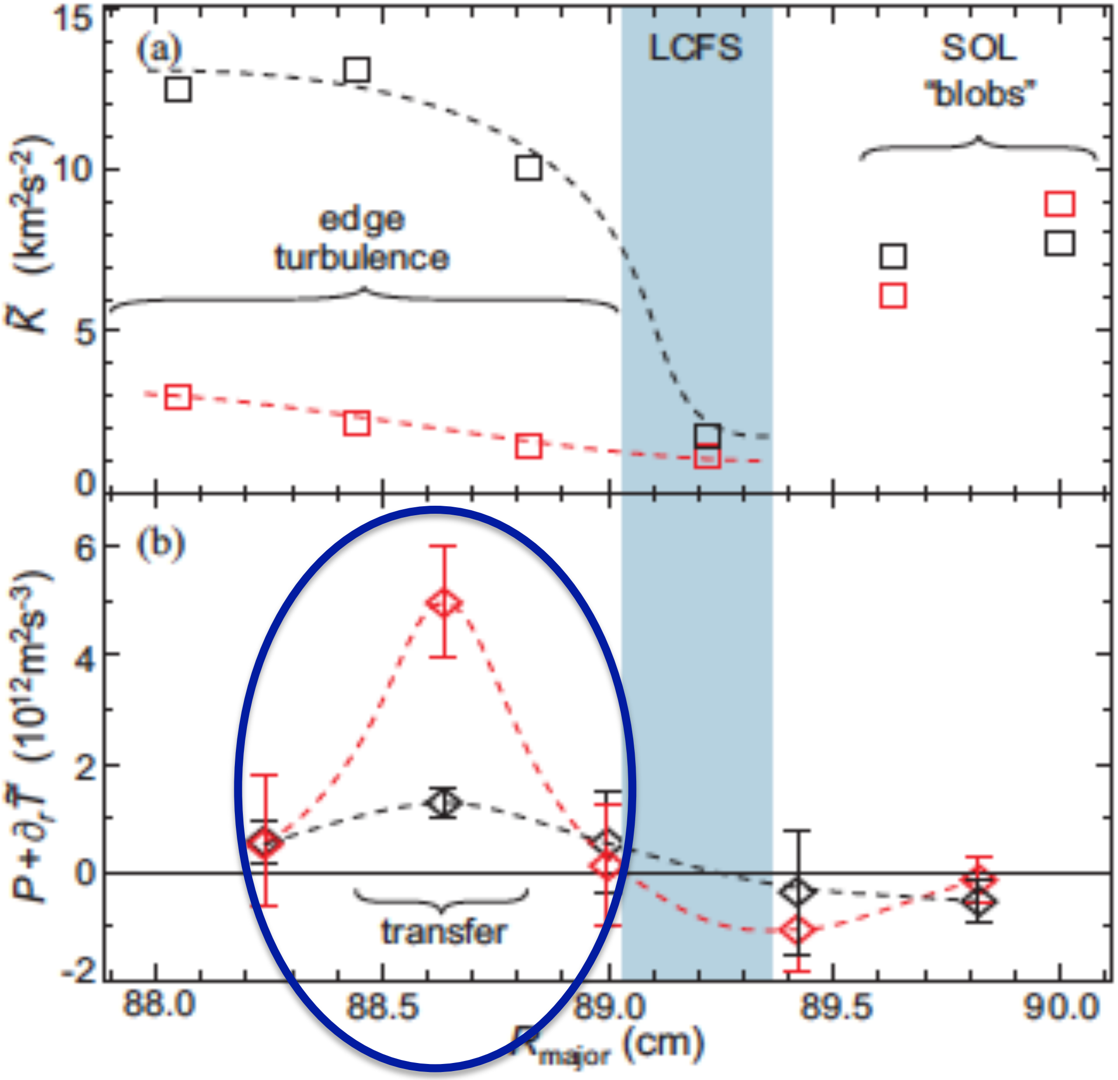
Observe a “kick” in V_{pol} at L-H transition

Cziegler et al PPCF’14



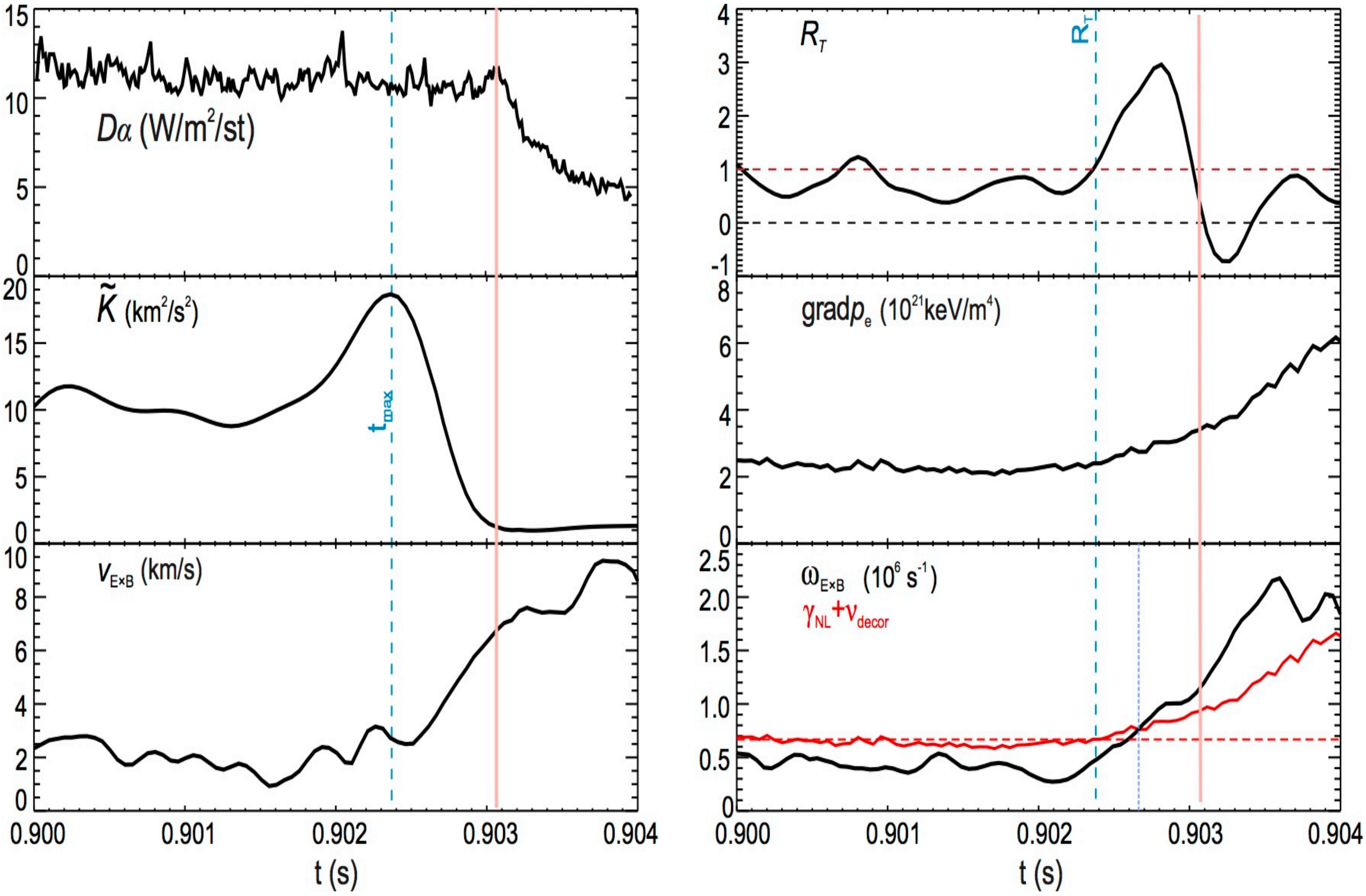
Spatial localization of flow drive & turbulence quenching

Cziegler, NF'15



Time sequence of transition

Tynan, Cziegler et al, submitted



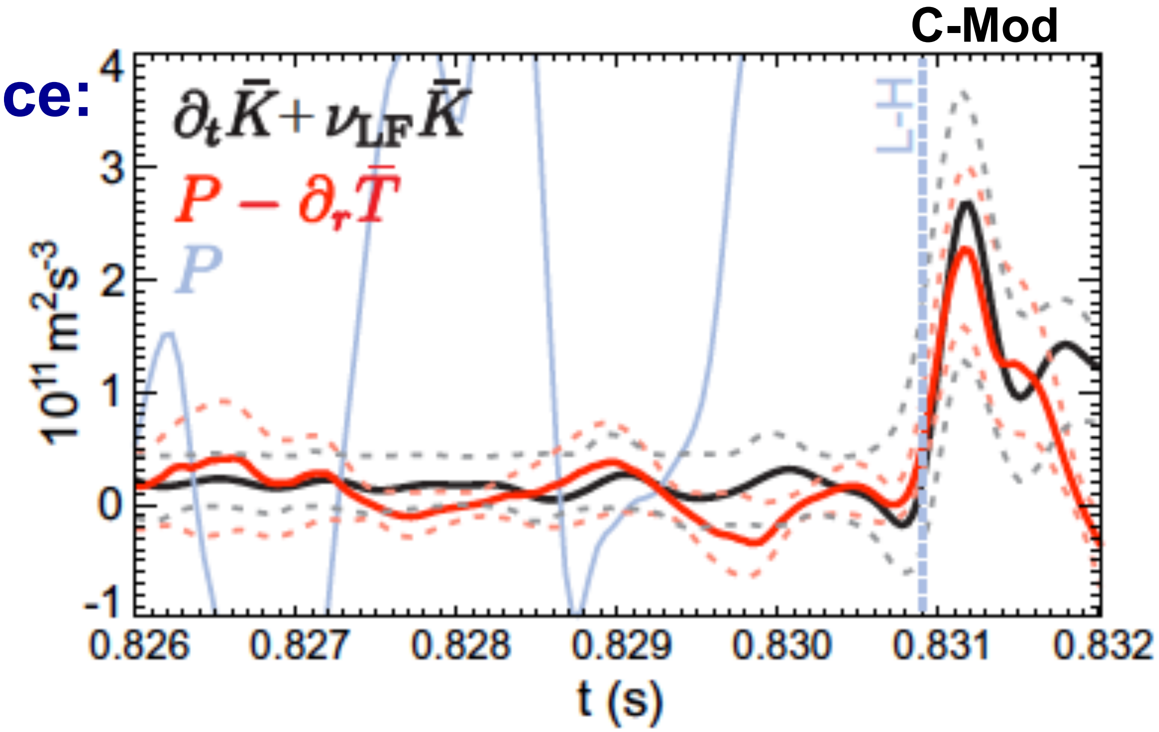
Flow drive is consistent with observed flow

Cziegler, PPCF ’14

ExB Flow Power Balance:

$$\frac{\partial}{\partial t}\bar{K} + \nu_{ZF}\bar{K} = P - \partial_r \bar{T}$$

Flow Damping
Determined
From Steady-state
L-mode Experimental
Value



Flow drive also consistent with estimated damping (including toroidal effects) in EAST (GS Xu NF ‘14)

Turbulence simulations now available…

- Chone’ et al PoP’14
- Park et al PoP’15
- Nielsen et al, ArchivX, submitted ‘15

Turbulence simulations now available…

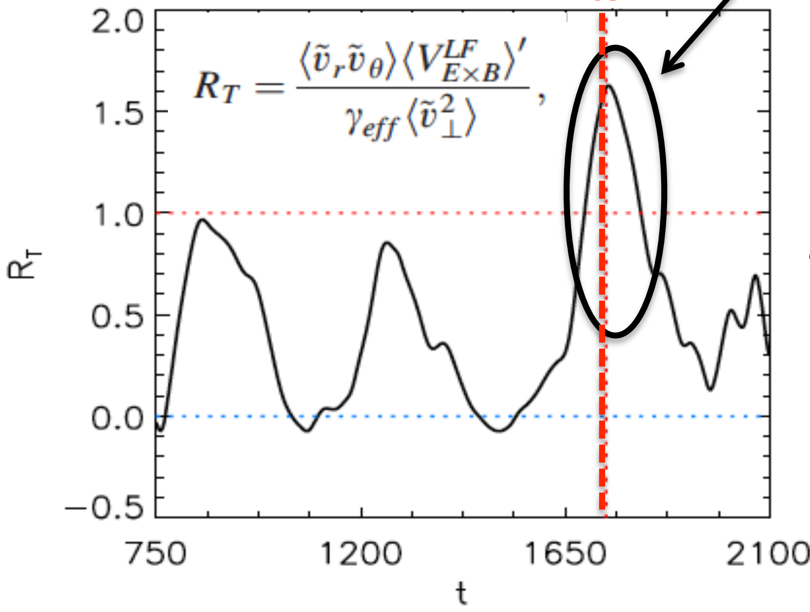
- Chone' et al PoP'14
  - "The transition scenario from one regime to another is the following: increasing the input power leads to more violent avalanches, triggering strong stabilising ZF. The resulting steepening of the pressure gradient further generates a sheared mean flow via the neoclassical friction. If the shear becomes strong enough to prevent a new burst, the barrier locks on because of this positive feed-back loop between pressure gradient and poloidal flow, mediated by neoclassical terms."

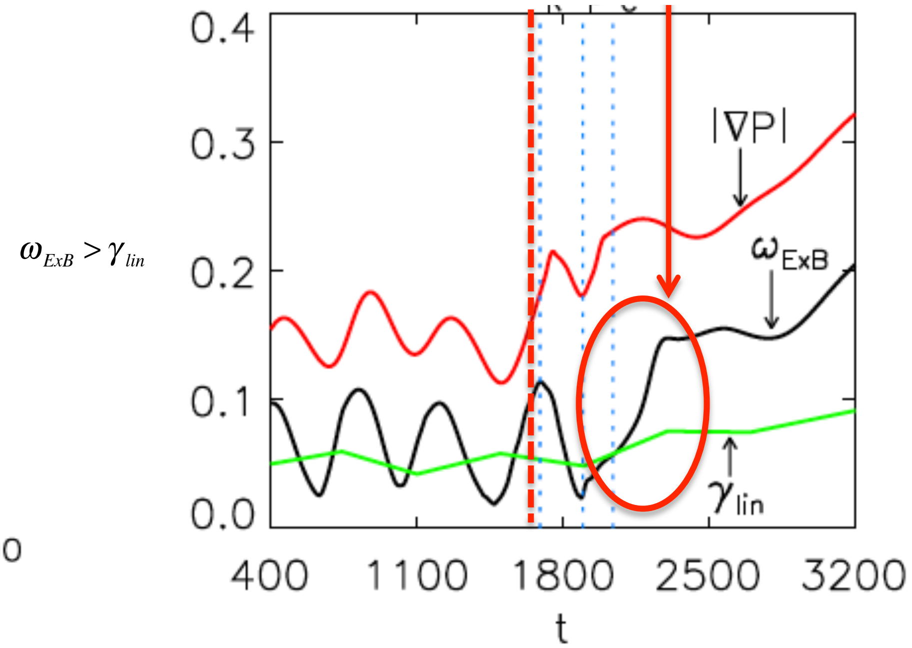
Turbulence simulations show same sequence

Park et al, PoP 2015, RBM Model (Improvement Needed!)

R_T>1 Yields Turbulence Collapse

$\omega_{ExB} > \gamma_{lin}$ ***AFTER*** **Turbulence Quench**





- **Chone' et al PoP'14** state that turbulent-driven ExB flow, together with mean flow, plays key role in edge barrier formation

A picture of L-H Transition is Emerging

SAME PICTURE IN

MULTIPLE EXPERIMENT

REDUCED MODELS, AND

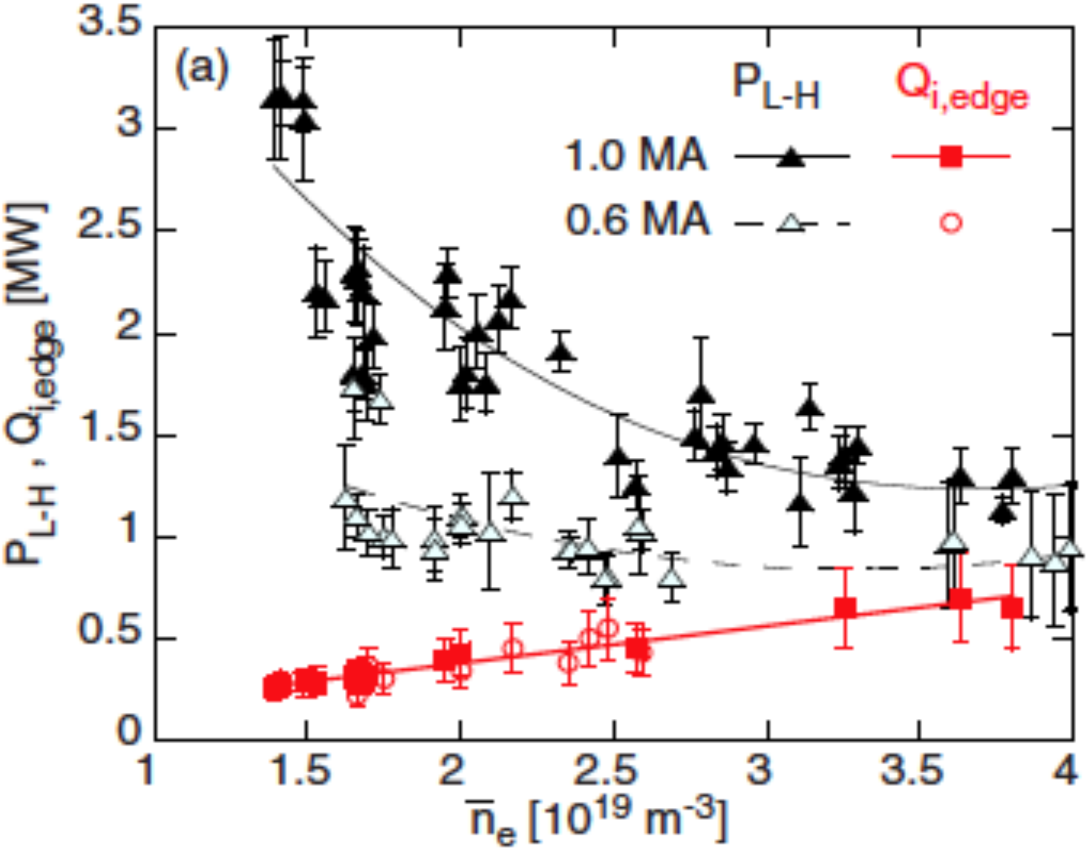
TURBULENT SIMULATIONS

Linking Microscopic Turbulence Physics to Macroscopic System Behavior

- AUG Results Show Ion Heat Flux is Key
- Motivates Modified 1-D Predator-Prey Model (Malkov et al '15)

L-H transition appears related ion heat flux at LCFS

AUG, Ryter, NF'14



Extend Predator-prey to Separate e-ion Channels

Malkov, PoP'15

- Based on 1-D numerical 5-field model (Miki & Diamond 2012,13+)
- Currently operates on 6 fields $(+P_e)$ with self-consistenly evolved transport coefficients
- Heat transport, + Two species with coupling, i,e:

$$\frac{\partial P_i}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}r\Gamma_i=\frac{2m}{M\tau}(P_e-P_i)+Q_i+\mathit{Anom\ coupl.\ to}\ T_e+\mathit{ZF\ dissip}$$

$$\frac{\partial P_e}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}r\Gamma_e=-\frac{2m}{M\tau}(P_e-P_i)+Q_e+\mathit{An\ cpl\ to}\ T_i\ \text{(both thru turb)}$$

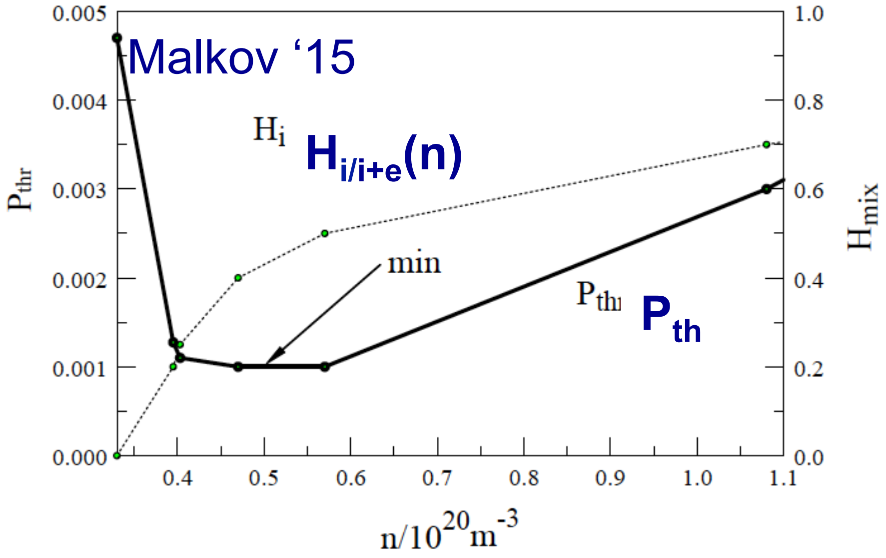
$$\Gamma=-(\chi_{neo}+\chi_t)\frac{\partial P}{\partial r}$$

- Density and the mean flow, as before

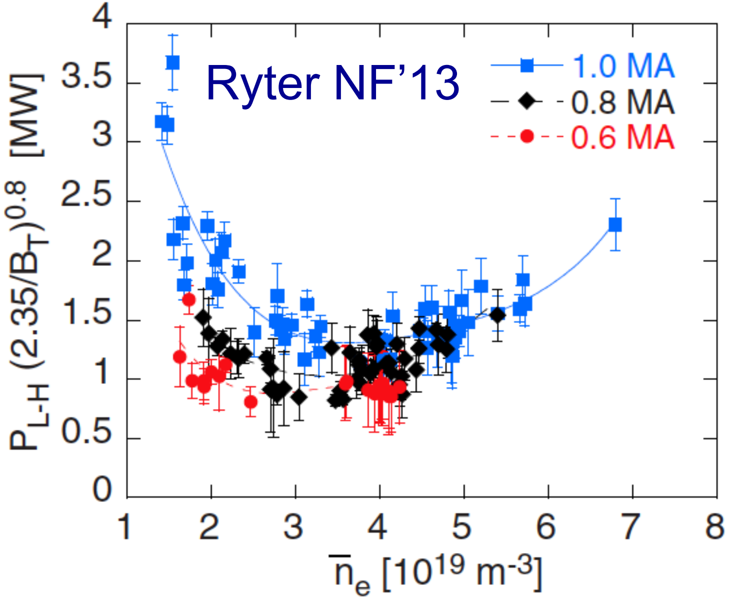
Model with $H_{i/i+e}$ (n)~n gives minimum in P_{th}(n)

Key Parameter:
e-i heating mix

$$H_{i/(i+e)} = \frac{Q_i}{Q_i + Q_e}$$



AUG

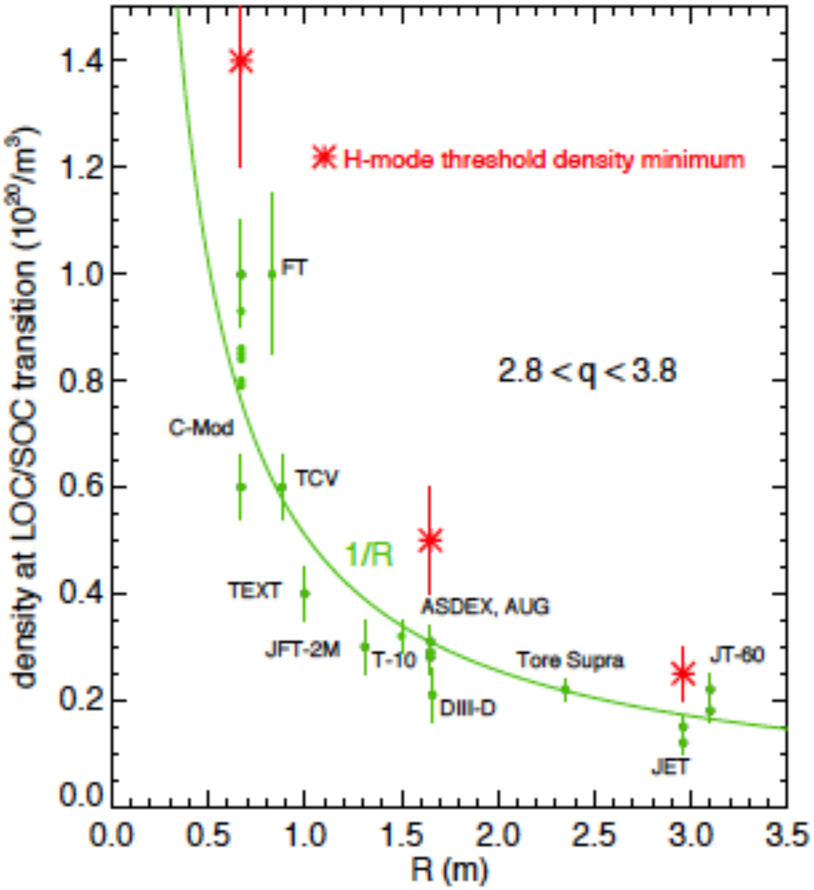


- **Result requires $H_{i/i+e}$ (n) ~n to yield minimum in P_{th}(n)**
- **Normalized e-i equilibration time $\tau_{e-i}^{coll} / \tau_{E_e}$ important**
- **Ion heat flux at LCFS is key; linked to transport across plasma column**

(*n.b.* see also X. Wu et al, NF '15 for very recent similar work)

Link between e-i equilibration and minimum in P_{th} ?

Malkov’15



- P_{th} minimum correlated with LOC-SOC transition
- LOC-SOC due to increased e-i collisional coupling
- Suggests P_{th} minimum related to e-i coupling

Summary of collisionally coupled model results

Malkov PoP15

- P_{thr}(n) grows monotonically in both pure ion ($H_{i/i+e}$=1) and pure electron ($H_{i/i+e}$=0) heating regimes with *collisional* coupling
- The descending low-density branch with distinct minimum, results from combined increased electron-to-ion collisional heat transfer *and* growing fraction $H_{i/i+e}$ of heat deposited directly to ions
- Upturn in P_{thr} due to increase of shear flow damping (trapped-passing ions, neutrals,…)
- Finite heating mix, $H_{i/i+e}$, essential for core heat transport to build edge grad-P_{ion}
- Many mechanisms to give $H_{i/i+e}$>0

Open Questions

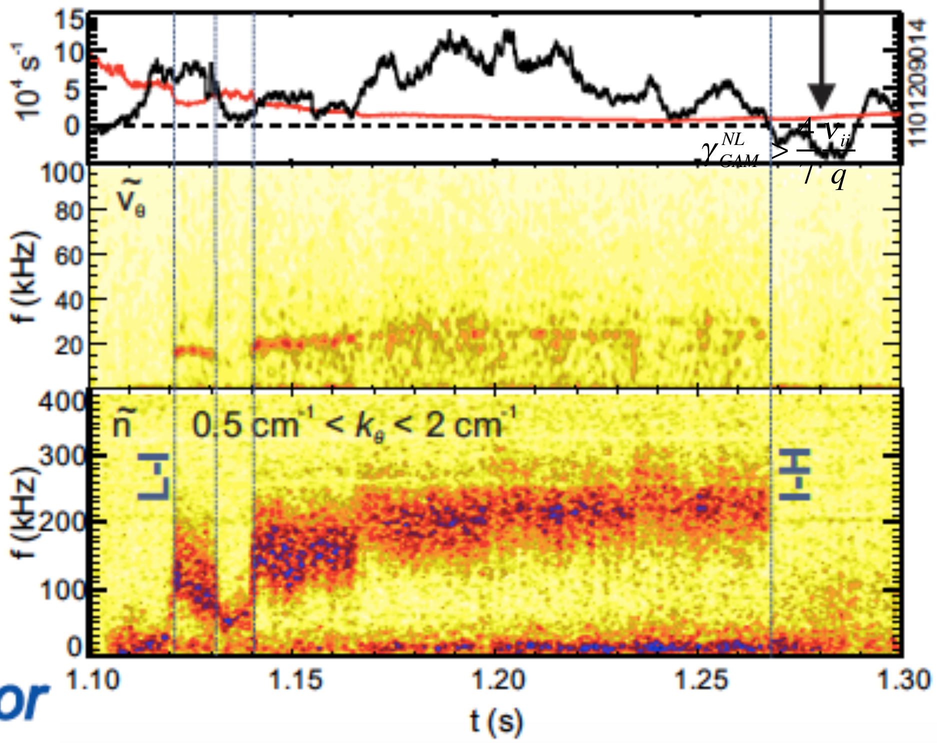
- How to Reconcile w/ lack of ZF in AUG (Ryter, EPS'15)?
- Access to more attractive improved confinement regimes (e.g. I-mode) (Cmod, AUG)
- Significance (or lack thereof) of GAMs in turbulent-driven L-H transition model (Scott'04, Hallatschek'07, Kobayashi PRL'13, Itoh'14)
- H-mode Access in Collisionless (ITER) regime
- Origin of grad-B x B favorable power threshold (Fedorczak & Diamond'12)
- Effect of divertor configuration on access (Hughes TTF'15)
- Isotope effect (e.g. Ryter'13)
- Origin of co/cntr rotation effect on P_{th} (McKee'09)

Access to I-mode related to nonlinear GAM drive

Cziegler et al, PoP'13

Drive term compared to collisional damping rate from neoclassical theory:

$$\gamma = 4/7(\nu_{ii}/q)$$



$$\gamma^{GAM}_{\mathrm{NL}} = \frac{\sum_{f_1} T_v(f_1^{GAM}, f)}{|v_\perp|^2(f)}$$

L-mode – I_mode transition related to GAM drive exceeding GAM damping rate, i.e.

$$\gamma^{NL}_{GAM} > \frac{4}{7}\frac{\nu_{ii}}{q}$$

Reminiscent of L-H Transition!

What about GAM damping effects on V_θ ?

Neoclassical Damping Rate given by: $\nu_{ZF} \sim (1+2q^2)\nu_{ii}$

Results in a Reynolds Force That is too Small
To explain Observed V_θ Transient; Kobayashi PRL’13, Itoh’14

RESPONSE:

- ZFs grow/GAMs die as L-H is Approached (McKee’, M.Xu PRL’12)
- EAST, HT-6M Show That Reynolds Stress **IS** Consistent w/ ExB Shear Flow & neoclassical Damping (GS Xu, IAEA’04, GS Xu, PRL’11)
- C-Mod shows that flow transient consistent with stress & empirically derived flow damping (Cziegler PPCF’14)

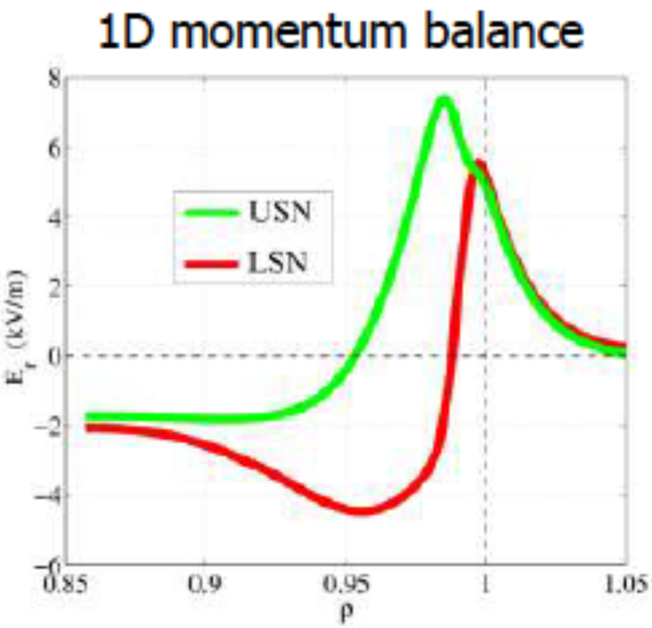
Further Quantitative Experiment Study, Models/ Simulations with Toroidal Flow Needed to Resolve

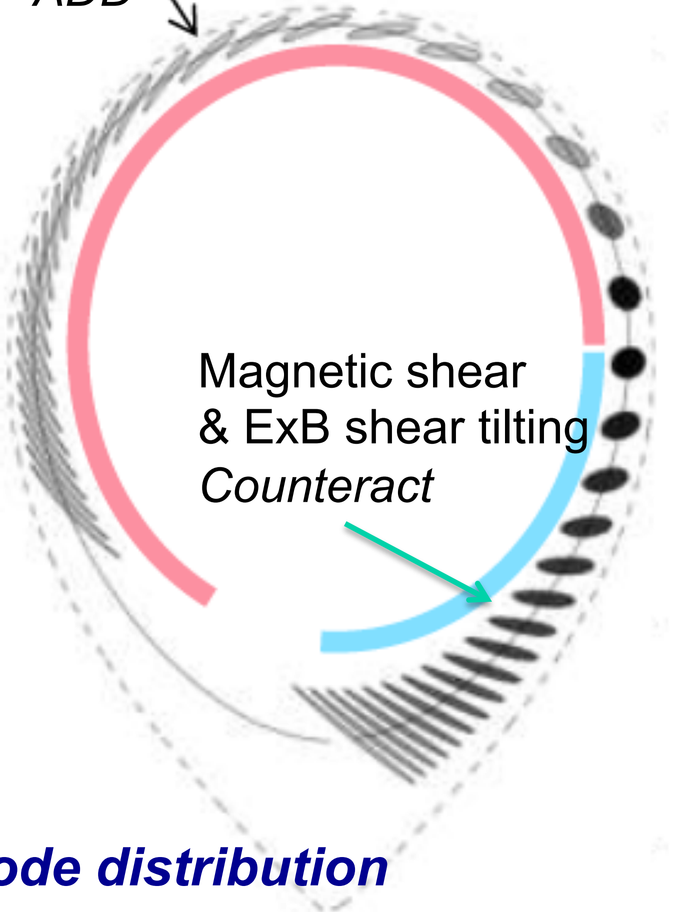
Extending reduced model to collisionless regime (ITER relevant)

- Predator-prey model: ZF damping is collisional
  - Need ZF instability ➔ turbulence ➔ ion heating?
- Anomalous heat exchange important (Zhao&Diamond'13)
  - Heat exchange linked to fluctuation intensity-dependent coupling
  - Multiple pathways possible
    - CTEM ➔ <J.E> dissipation ➔ ion heating
    - ITG-driven turbulent dissipation ➔ ion heating
    - ZF dissipation ➔ ion heating

Possible Origin of grad-BxB Effect

- Magnetic-shear induced tilting competes/ complements ExB shearing
- Up-down asymmetry determines dominant effect
- RESULT: Stronger sheared ExB in favorable configuration


1D momentum balance


Magnetic shear
& ExB shear tilting
ADD

Magnetic shear
& ExB shear tilting
Counteract

…But result depends on detailed poloidal mode distribution

Fedorczak, Diamond et al ‘13

Conclusions

- Microturbulence and reduced model studies point to origin of H-mode:
  - Increased heating leads to enhanced turbulent Reynolds stress driven sheared ExB flows
  - Transition initiated when rate of turbulent-ExB shear flow drive exceeds turbulent energy input rate
  - Results in turbulence collapse that allows edge pedestal to grow, locking in H-mode
- Turbulence simulations capture same picture
- Macroscale studies suggest ion heat flux at LCFS key
- Motivated modified predator-prey model that captures $P_{thr}(n)$ dependence
- Many Open Issues: ITER Collisionless regime,grad-BxB effect, Isotope effect, role of GAMs, I-mode vs H-mode, ….