Energy Exchange Dynamics across L-H Transitions in NSTX

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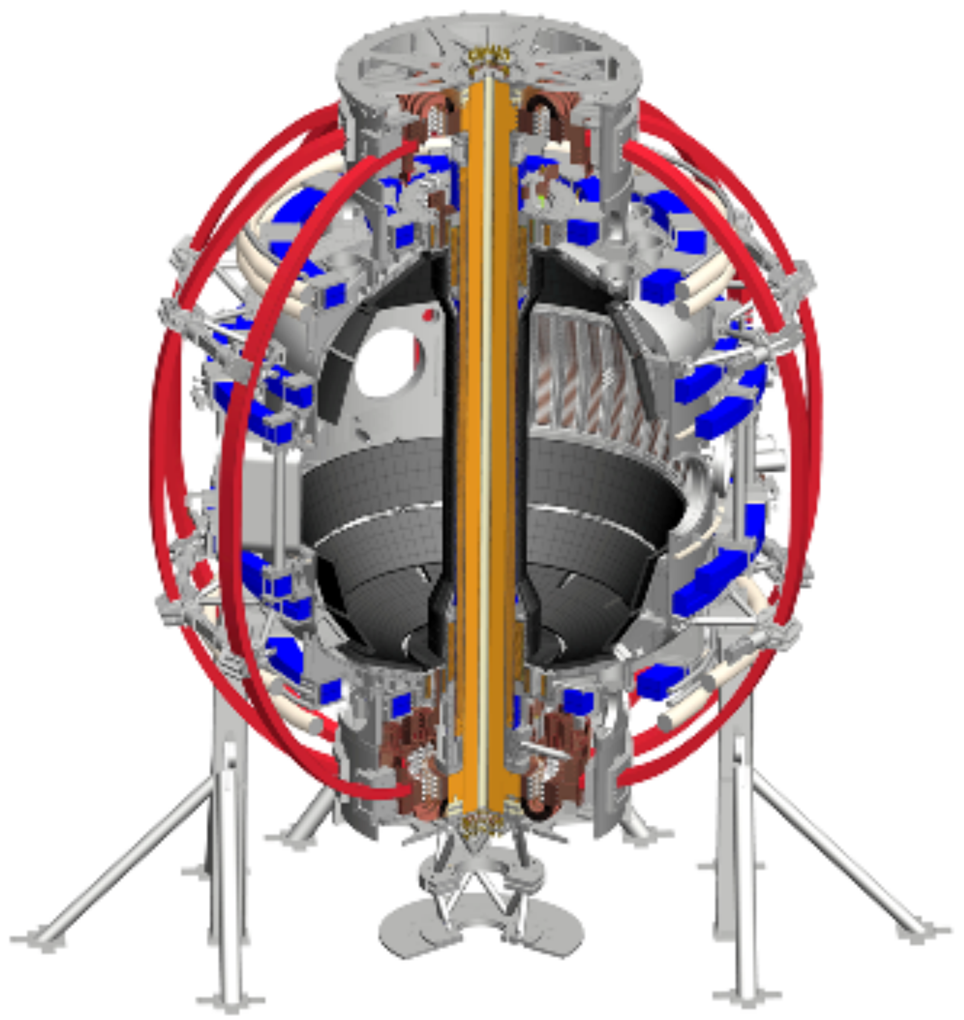

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Most models on L-H transition have two parts

L-H transition theories are summarized
Connor and Wilson PPCF 42 R1 (2000) Review paper.

1. **Generation of sheared flow.**

2. **Suppression of turbulence by flow shear.**

Most models on L-H transition have two parts

L-H transition theories are summarized
Connor and Wilson PPCF 42 R1 (2000) Review paper.

1. **Generation of sheared flow.**

Focus of this Talk

2. **Suppression of turbulence by flow shear.**
   - **Energy transfer to flows *directly* depletes the turbulent fluctuations.**

non-zonal ExB energy

$$\frac{n_0 m_i \left\langle \tilde{v}_\perp^2 \right\rangle}{2}$$

→

Zonal ExB energy

$$\frac{n_o m_i \langle \bar{v}_\theta \rangle^2}{2}$$

Some experimental investigations showed a transfer of energy from turbulence to mean flow

- ☑ Studies using Langmuir probes provided evidence that nonlinear exchange of kinetic energy between small scale turbulence and edge zonal flows.

  Manz et al. PoP 19 072311
  Xu et al. NF 54 (2014)

- ☑ Recent work on C-Mod using gas-puff imaging (GPI) provided a timeline for the L-H transition:

  Cziegler et al. PPCF 2014

  - First peaking of the normalized Reynolds power
  - Then the collapse of the turbulence
  - Finally the rise of the diamagnetic electric field shear

- ☑ On DIII-D, heating power increases the energy transfer from turbulence to the poloidal flow.

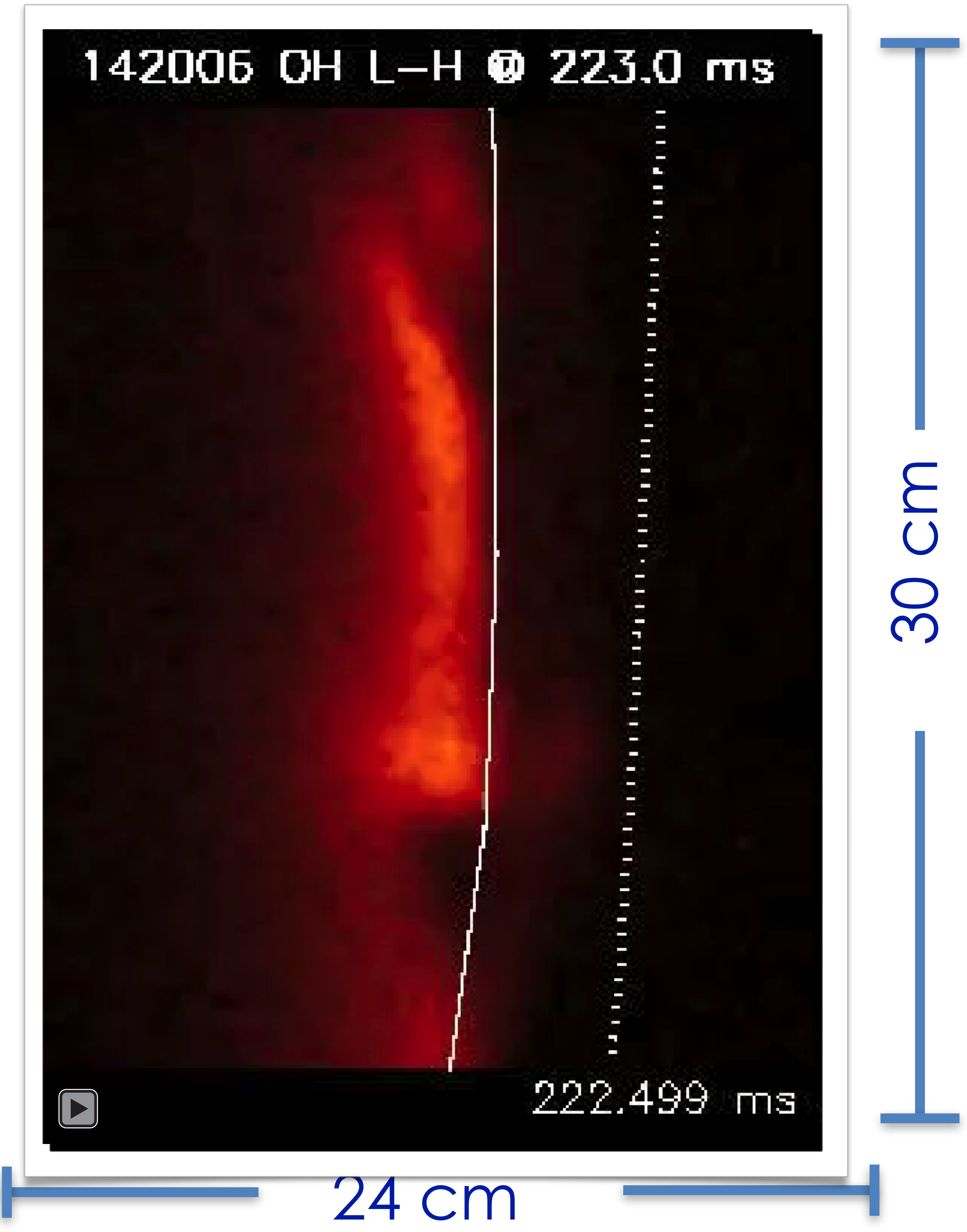
  Yan et al. PRL 2014
  See Review paper Tynan PPCF 2016

- ☐ However, in JET, near the edge shear layer, no evidence of energy transfer from turbulence to flows was found.

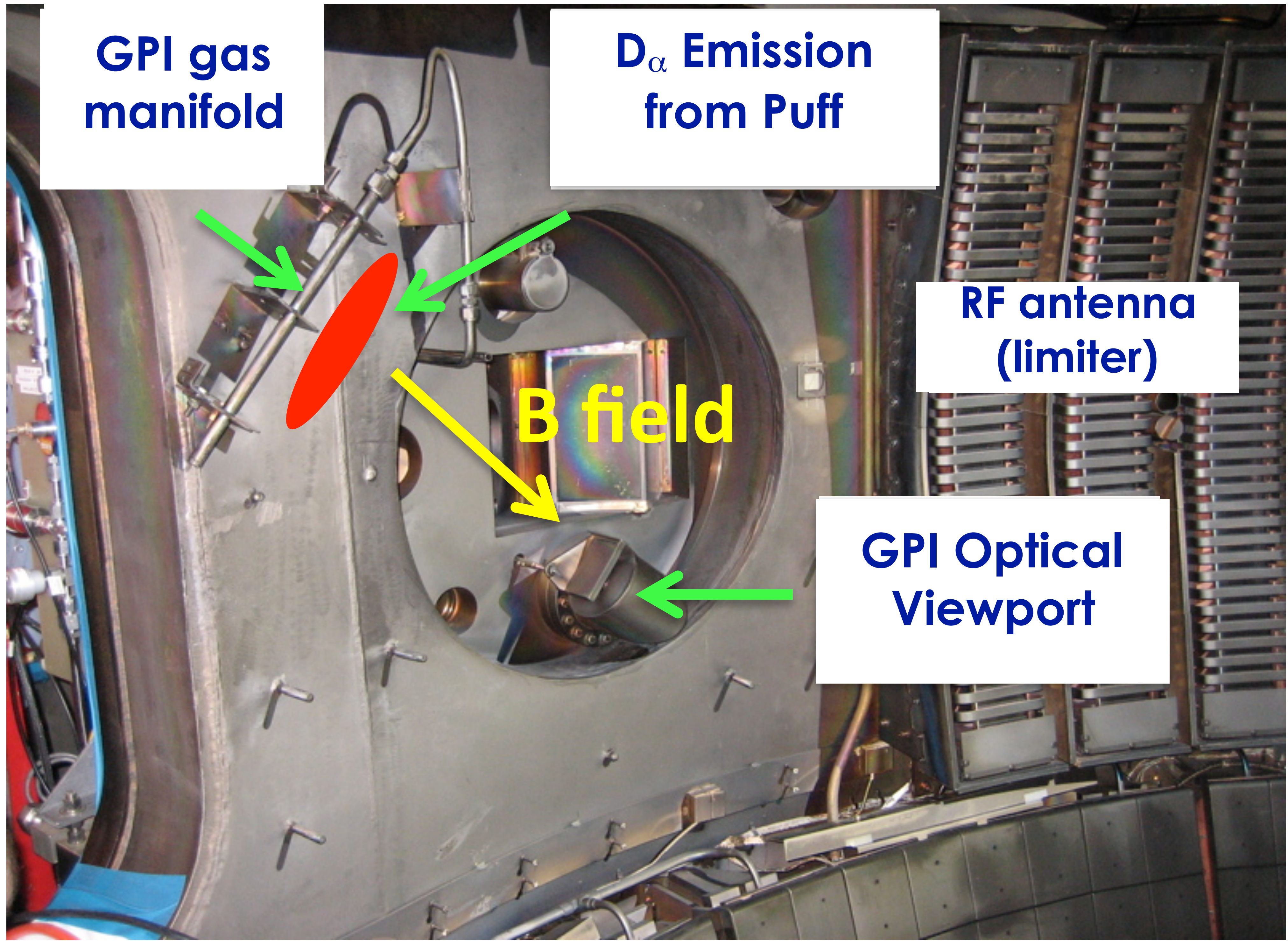
  Sanchez et al. JNM 2005

NSTX results are inconsistent with energy transfer to flows directly depletes the turbulent fluctuations.

Gas-puff imaging diagnostic is central to the NSTX L-H transitions analysis



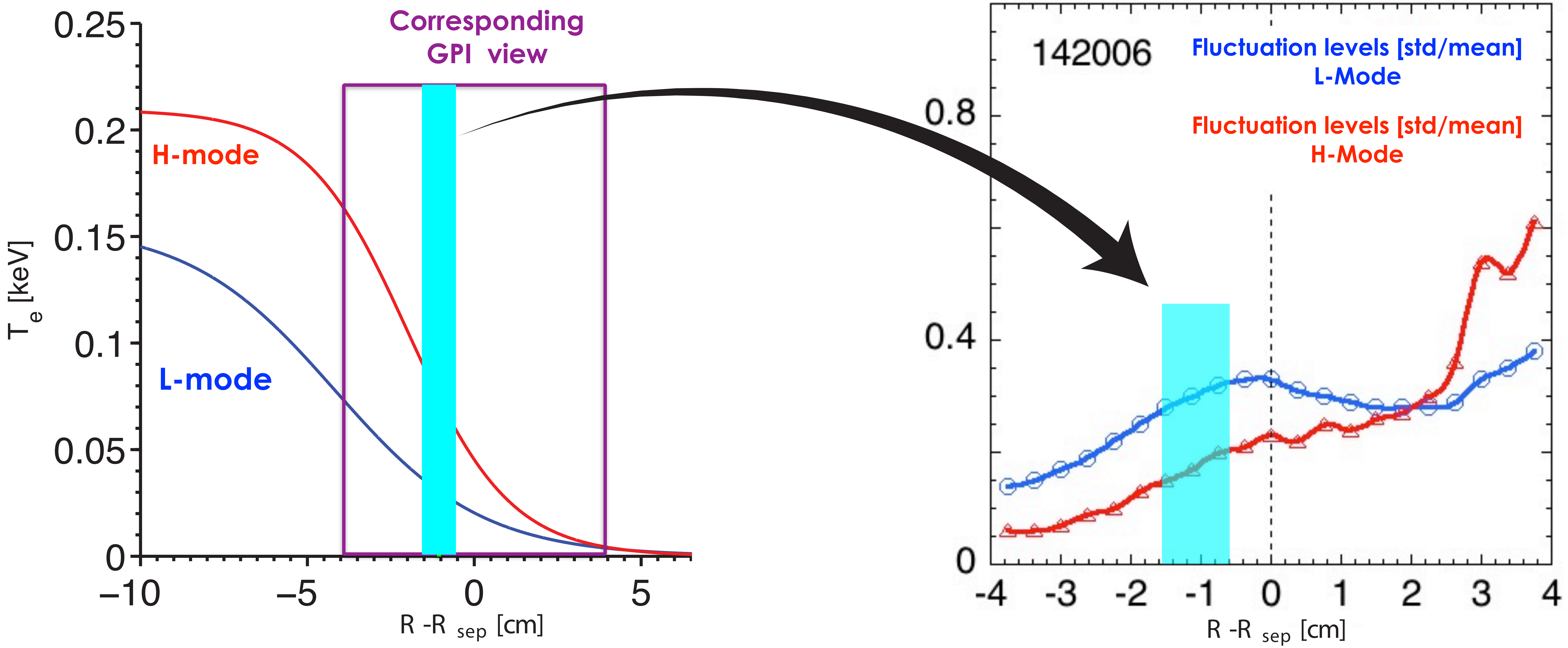
- GPI provides edge turbulence images
  - **Temporal resolution ~ 2.5 μs**
  - **Spatial resolution ~ 1 cm**



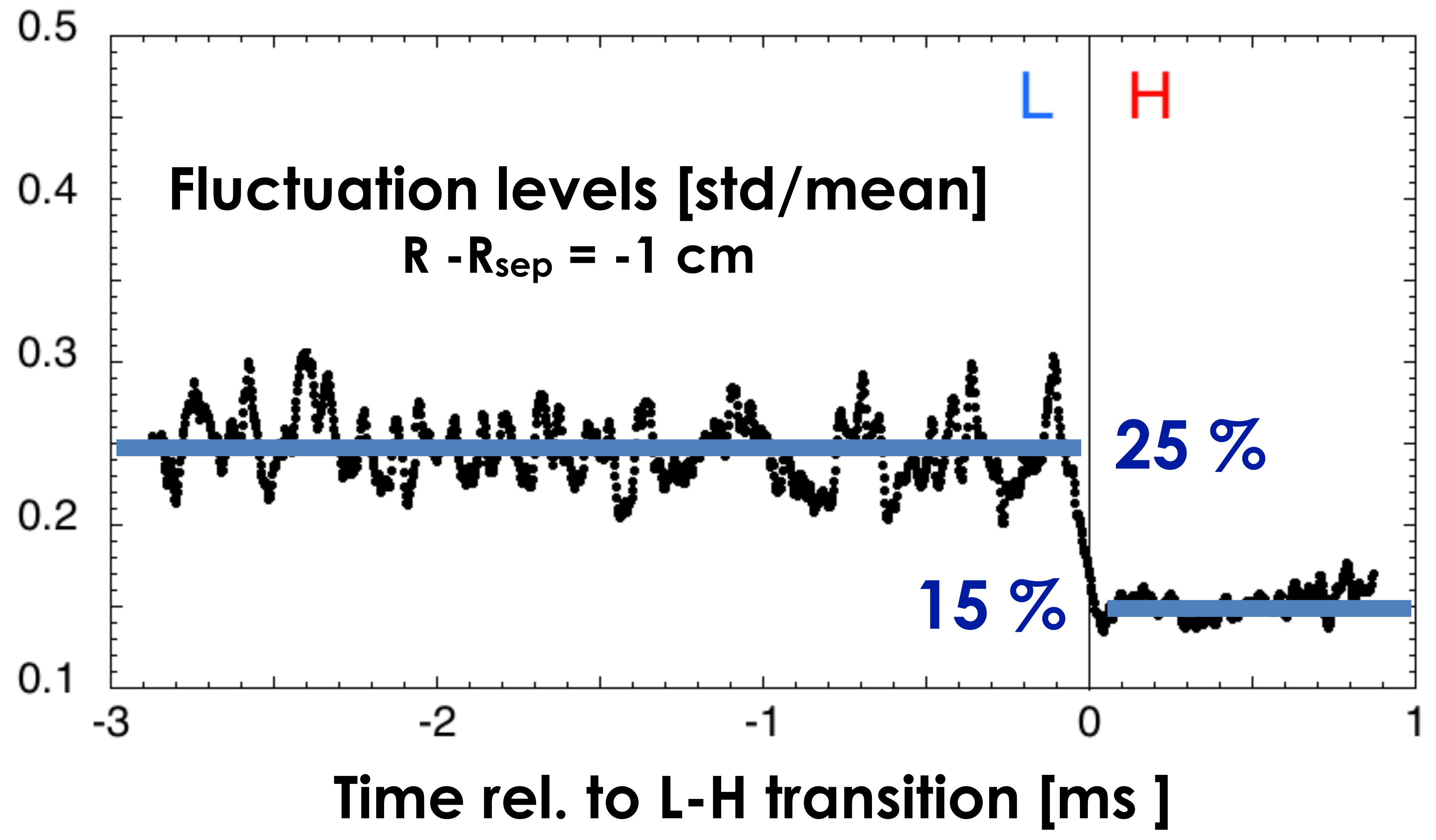
Discharge characteristics (total of 17):

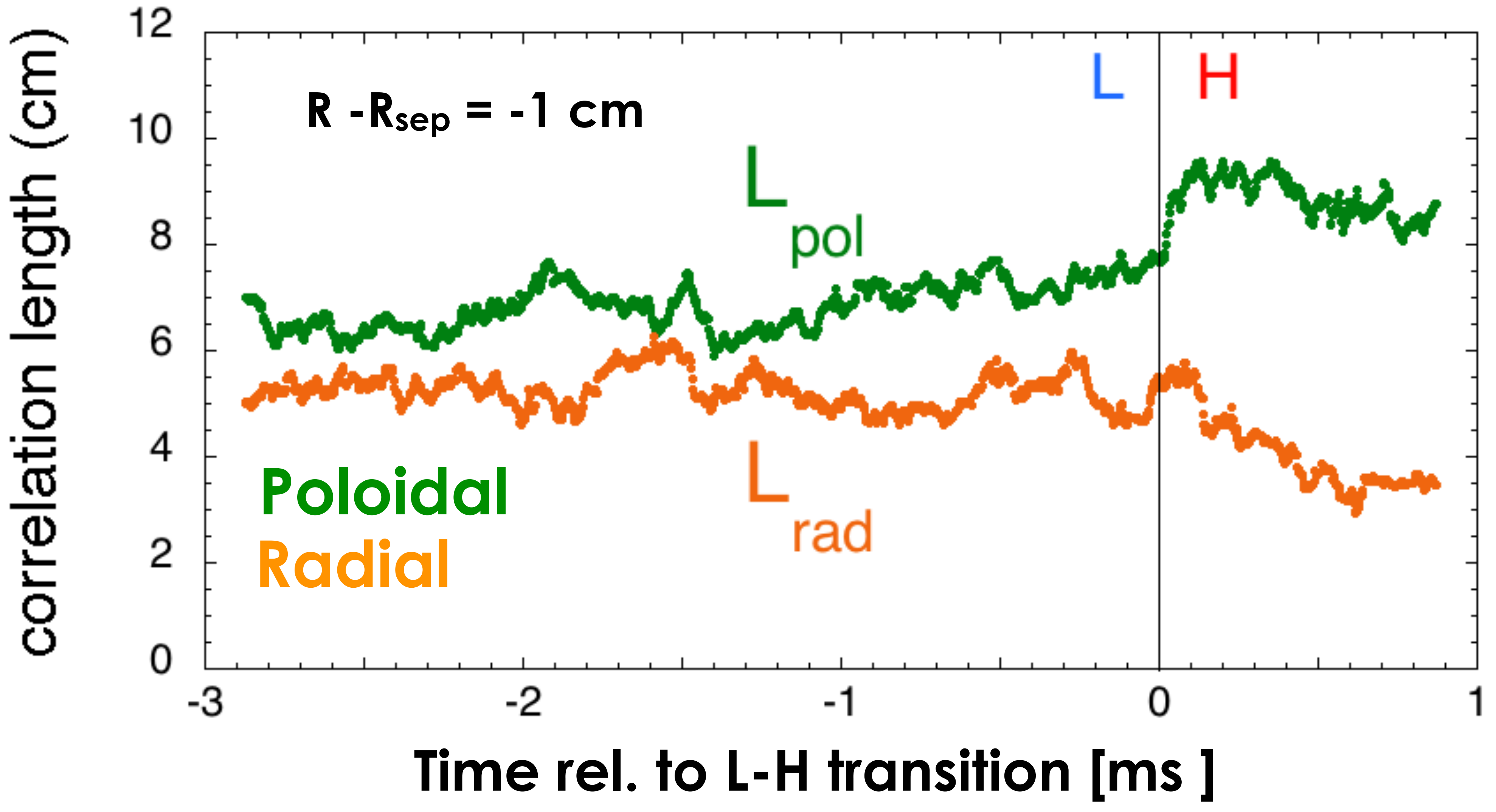
NBI-Heated: 138113:138119
Ohmically-Heated: 141745:141751(not shown here)
RF- Heated: 141919:141922, 142006(not shown here)

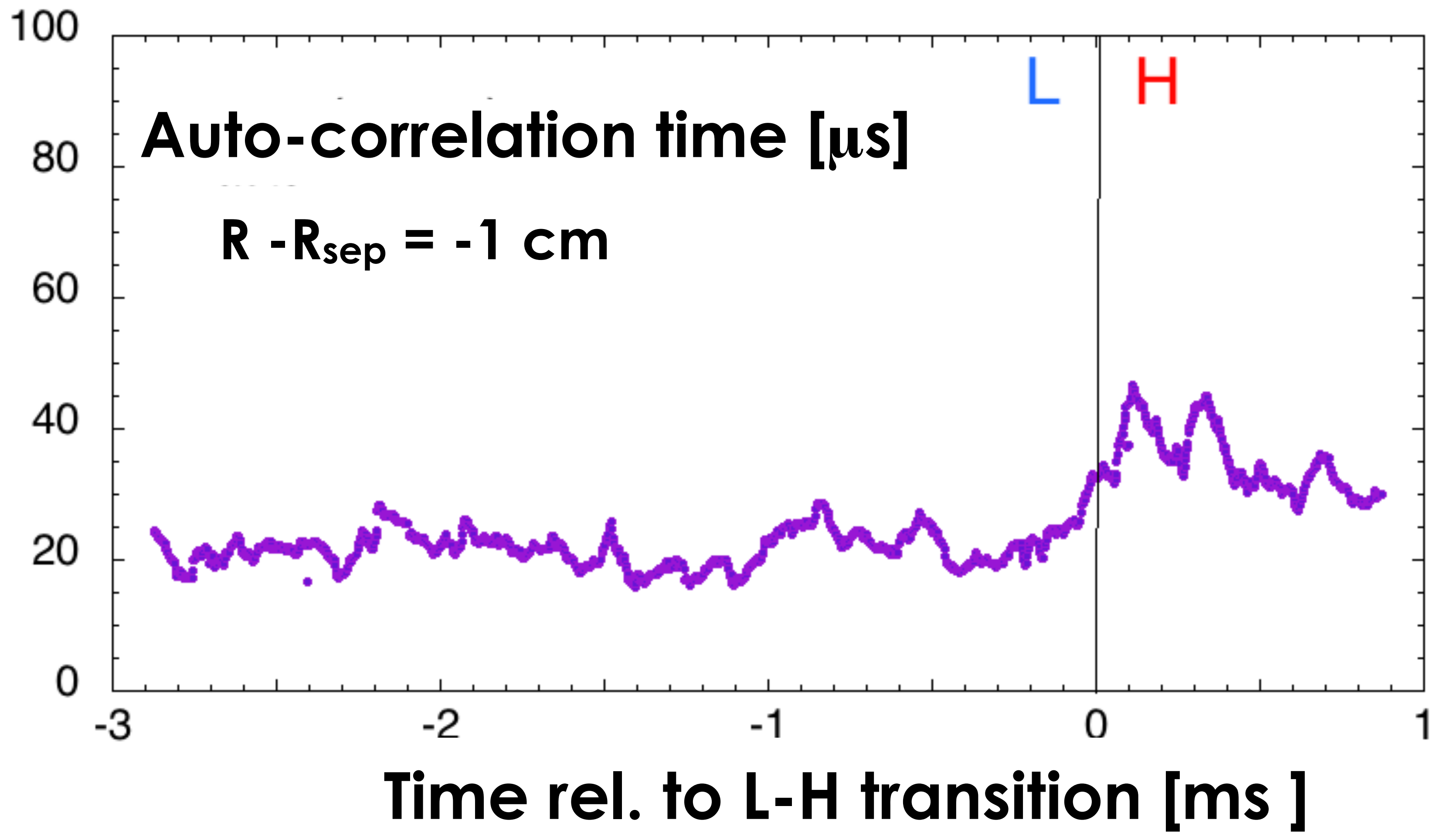
Analysis is radially localized near the GPI maximum level of fluctuations



There is no significant change of turbulence quantities *preceding* the L-H transition but clear drop in fluctuation levels across the transition







- **Turbulence quantities changes are similar to previous observations.**

Can direct energy transfer from turbulence to mean flow explain the drop in fluctuation levels?

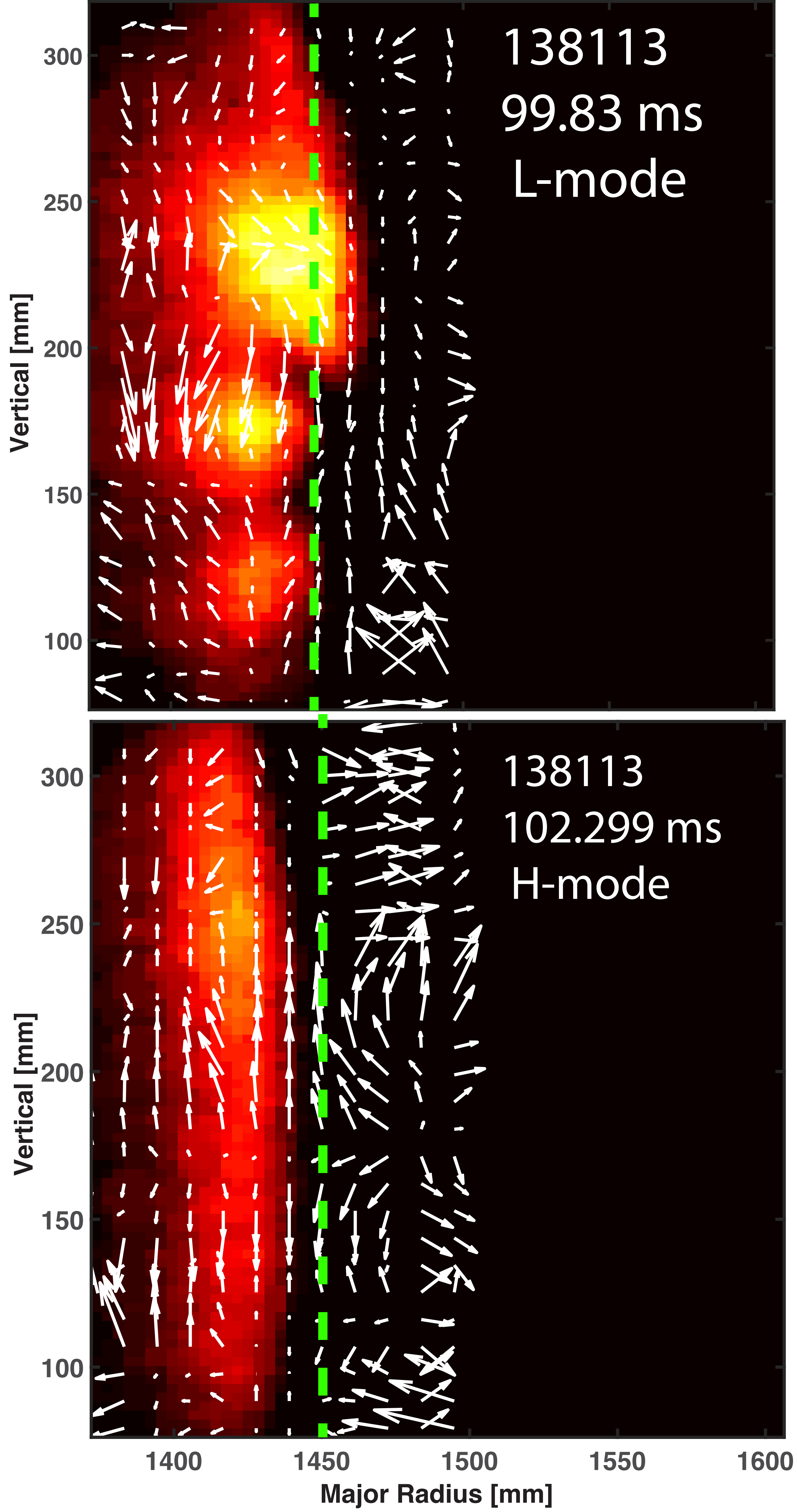
Orthogonal dynamic programming (ODP) applied to GPI data for imaging velocimetry

S Banerjee *et al.*, Rev. Sci. Instum. **86**, 033505 (2015)

- ODP enables to reconstruct a **2D velocity field**.
  - Comparison with TDE & Fourier type velocimetry shows ~80% correlation.

$$v_i = \bar{v}_i + \tilde{v}_i,\ i \in [r, \theta],\ \forall t$$

- Caveat:
  - Velocimetry techniques show only velocities **normal** to the intensity iso-contours.
  - This caveat is shared by **all** velocimetry approaches.



We test the suppression of turbulence via energy transfer from turbulence to mean flow

- **Evaluate the sign of production term: does turbulence drive flows or vice versa?**

- **Is the absolute value of the production term big enough to explain the rate of change of the thermal free energy?**

- ***Does the energy in the mean flow increase as much as the turbulence energy drops? [see backup]***

Energy transfer direction is determined using the production term

Positive Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

non-zonal ExB energy

$$\frac{n_o m_i \langle \tilde{v}_\theta^2 \rangle}{2}$$

P>0 →

← P<0

Zonal ExB energy

$$\frac{n_o m_i \langle \bar{v}_\theta \rangle^2}{2}$$

Negative Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

In order to deplete the turbulence the production term must be positive.

In NSTX, energy is transferred from mean flows to turbulence

non-zonal ExB energy

$$\frac{n_o m_i \langle \tilde{v}_\theta^2 \rangle}{2}$$

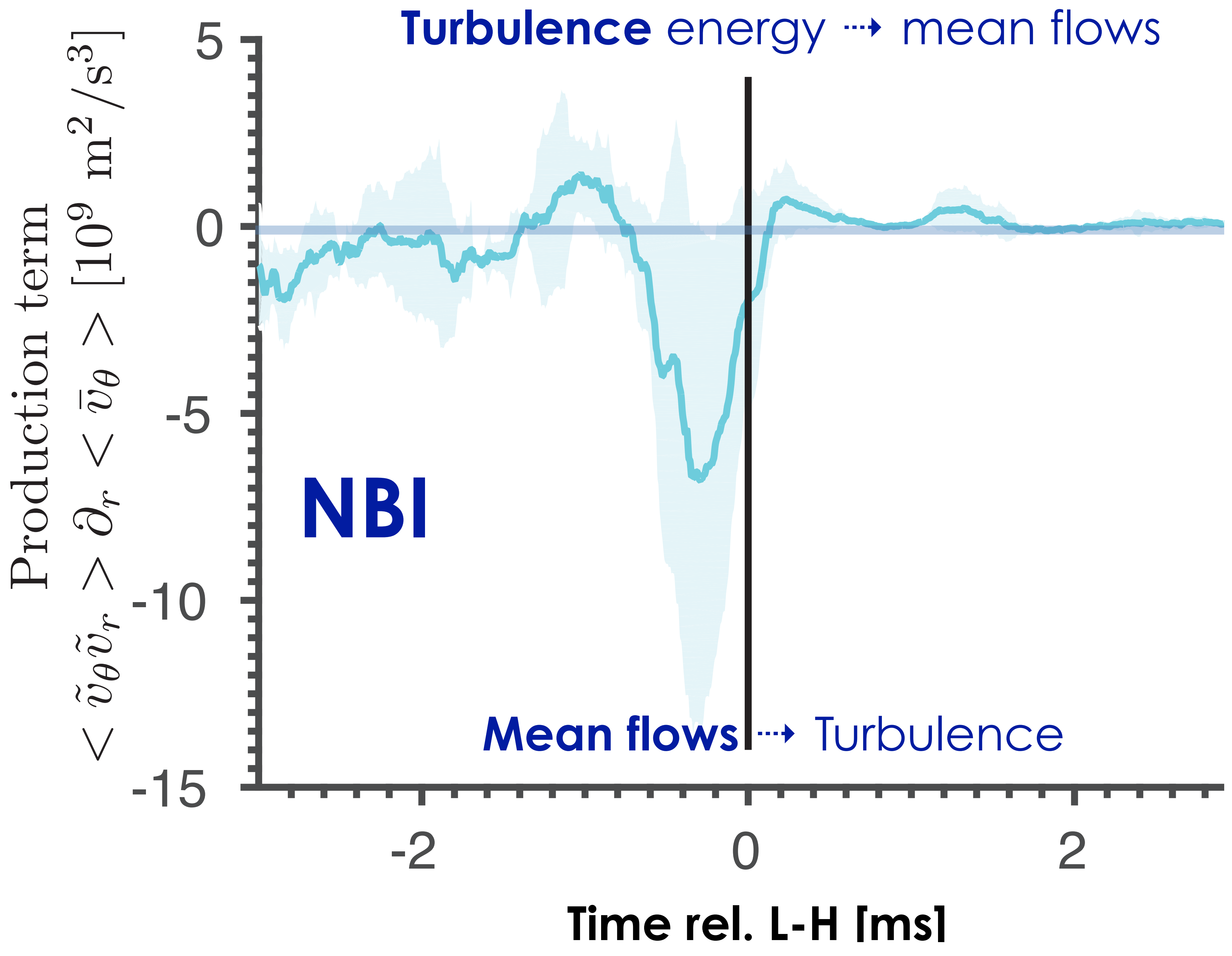
Production term

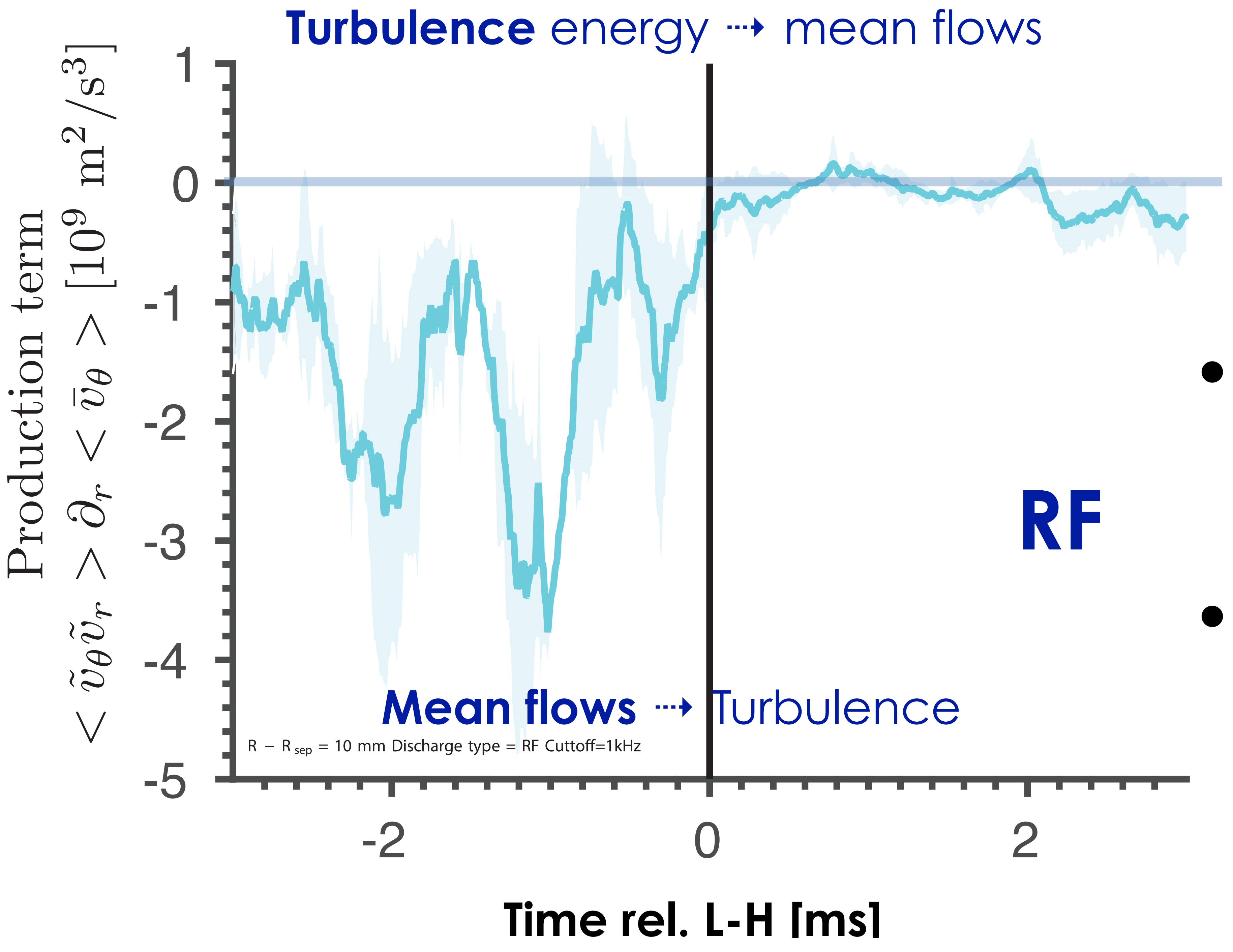
$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

Zonal ExB energy

$$\frac{n_o m_i \langle \bar{v}_\theta \rangle^2}{2}$$

Production term





- **We observe energy transfer from zonal flow to turbulence.**
- **Inconsistent with the turbulence depletion hypothesis prior to the L-H transition.**

We test the suppression of turbulence via energy transfer from turbulence to mean flow

- Evaluate the sign of production term: does turbulence drive flows or vice versa?

In NSTX, energy is transferred from mean flows to turbulence

Given that the sign of the production is of order-unity, we now test the rapid turbulence suppression at the L-H transition using order of magnitude estimates

We test the suppression of turbulence via energy transfer from turbulence to mean flow

- Evaluate the sign of production term: does turbulence drive flows or vice versa?

  In NSTX, energy is transferred from mean flows to turbulence

- **Is the absolute value of the production term big enough to explain the rate of change of the thermal free energy?**

Recall: This energy balance between flow and turbulence

non-zonal ExB energy

$$\frac{n_o m_i \left\langle \tilde{v}_\theta^2 \right\rangle}{2}$$

Zonal ExB energy

$$\frac{n_o m_i \left\langle \bar{v}_\theta \right\rangle^2}{2}$$

Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

Thermal free energy is an additional reservoir for the turbulence energy

*Stoltzfus-Dueck, PoP **23** 054505 (2016)*

NP10.00024: Stoltzfus-Dueck, Wed 9:30a

Turbulence energy (E_{Turb})

Thermal free energy

$$\frac{n_{e0}T_{e0}}{2}\left(\frac{\tilde{n}_e}{n_{0e}}\right)^2$$

+

non-zonal ExB energy

$$\frac{n_o m_i \left\langle \tilde{v}_\theta^2 \right\rangle}{2}$$

$\longleftrightarrow$

Zonal ExB energy

$$\frac{n_o m_i \left\langle \bar{v}_\theta \right\rangle^2}{2}$$

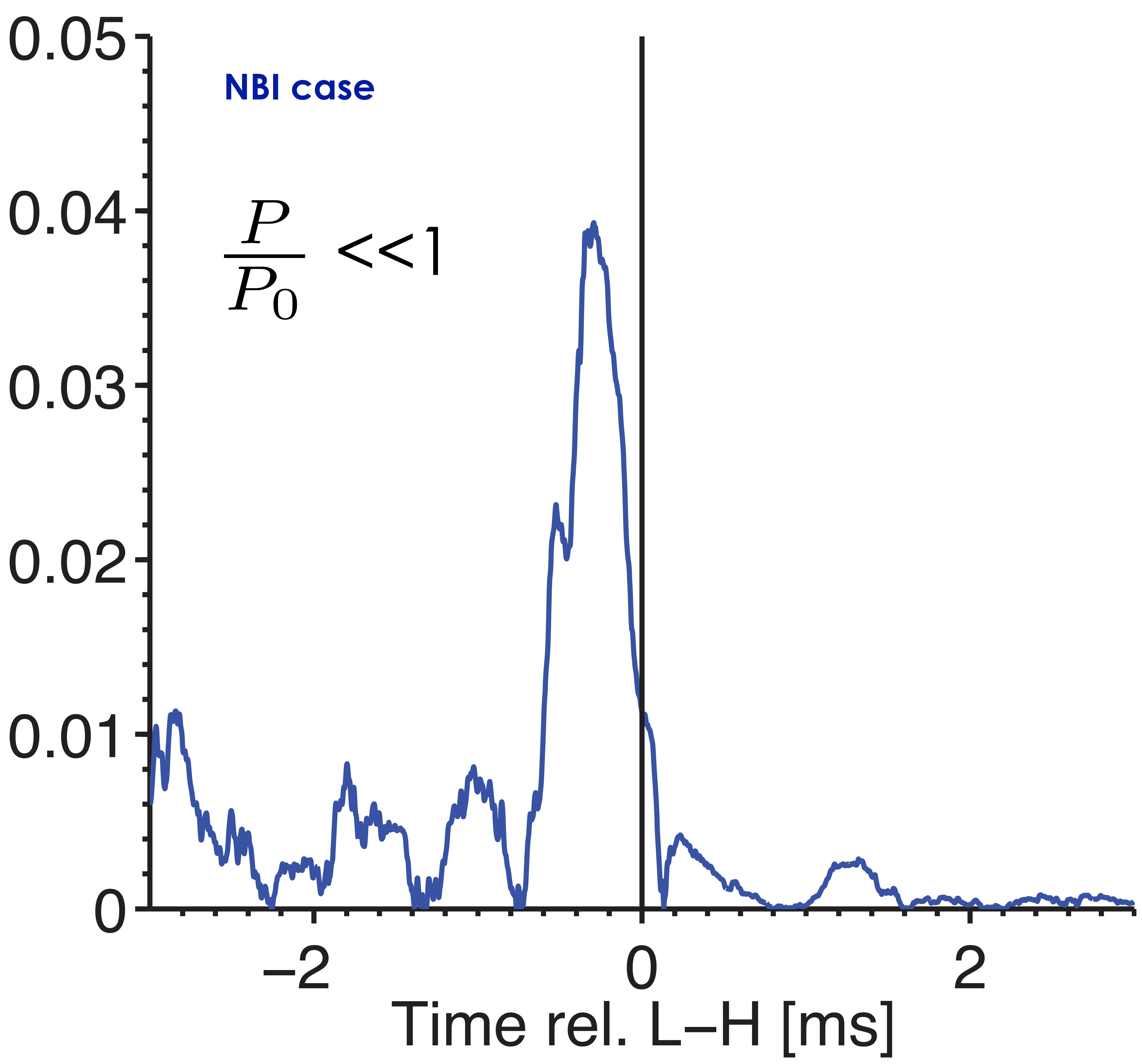
Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

Compare the rate of change of the thermal free energy over the L-H transition to the absolute value of the production term

$$\frac{P}{P_0} = \frac{\left| n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta > \right|}{\left(E_{turb}|_L - E_{turb}|_H\right)\tau_{L\rightarrow H}^{-1}}$$

Production term is much less than the observed rate of change of the thermal free energy



$$\frac{P}{P_0} = \frac{\left| n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta > \right|}{(E_{turb}|_L - E_{turb}|_H)\tau^{-1}_{L\rightarrow H}}$$

- **Ratio NEEDS to be around 1 to have turbulence suppression.**
- **Ratio is much less than 1 so inconsistent with the turbulence depletion.**

$\frac{P}{P_0}$ <<1

Results are qualitatively similar for RF and Ohmic cases.

We test the suppression of turbulence via energy transfer from turbulence to mean flow

- Is the absolute value of the production term big enough to explain the rate of change of the thermal free energy?

Production term is 100x smaller than the observed rate of change of the thermal free energy

NSTX results do not support that energy transfer to flows directly depletes the turbulent fluctuations

- We consider the following energy balance to evaluate the turbulence depletion:
  - Most experimental results neglected the thermal free energy

Thermal free energy — non-zonal ExB energy — Zonal ExB energy

$$\frac{n_{e0}T_{e0}}{2}\left(\frac{\tilde{n}_e}{n_{e0}}\right)^2 + \frac{n_0 m_i\left\langle \tilde{v}_\perp^2 \right\rangle}{2} \longleftrightarrow \frac{n_0 m_i \langle \bar{v}_E \rangle^2}{2}$$

Production term

$$n_o m_i < \tilde{v}_\theta \tilde{v}_r > \partial_r < \bar{v}_\theta >$$

- **The turbulence quantities change across at the L-H transition but not *before*, so the changes do not help identify the L-H mechanism.**
- **Energy-transfer mechanism appears much too weak to explain the rapid turbulence suppression at the L-H transition.**
  - Uncertainties in 2D velocimetry may be order unity, but the energy transfer mechanism is ~100x too small to explain the turbulence suppression.
  - Future work will attempt to quantify the uncertainties in 2D velocimetry.

Supplementary material

We test the suppression of turbulence via energy transfer from turbulence to mean flow

- Is the absolute value of the production term big enough to explain the rate of change of the thermal free energy?

Production term is much less than the observed rate of change of the thermal free energy

- Does the energy in the mean flow increase as much as the turbulence energy drops?

Does the zonal flow absorb a significant fraction of the total turbulence energy?

Stoltzfus-Dueck, PoP 23 054505 (2016)

Turbulence fluctuation energies

Thermal free energy

non-zonal ExB energy

$$\frac{n_{e0} T_{e0}}{2} \left(\frac{\tilde{n}_e}{n_{e0}} \right)^2 + \frac{n_0 m_i \langle \tilde{v}_\theta^2 \rangle}{2}$$

Zonal ExB energy

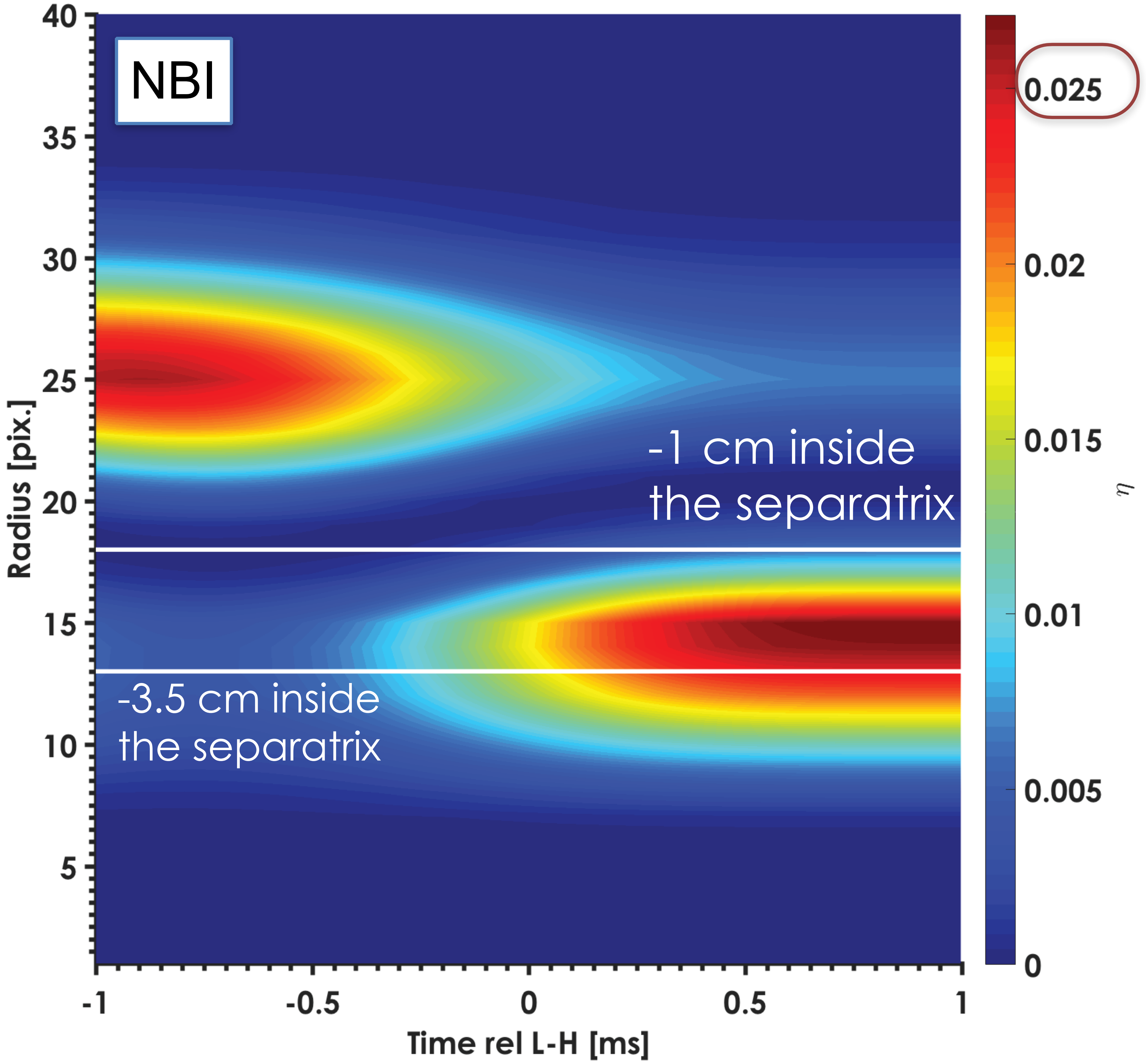
$$\frac{n_o m_i \langle \bar{v}_\theta \rangle^2}{2}$$

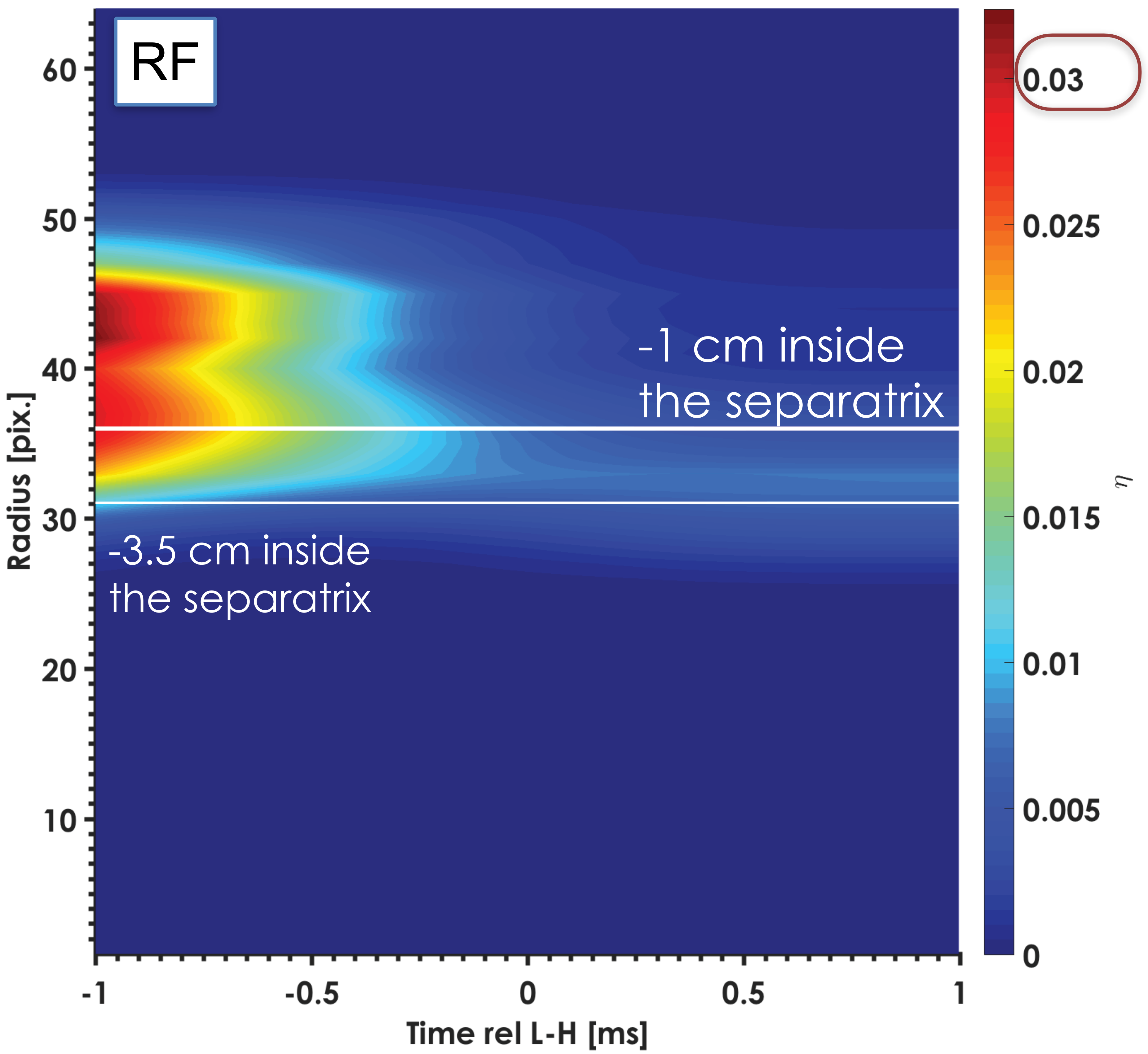
For zonal flows to take most of the turbulence energy:

$$\frac{\left(\langle \bar{v}_\theta^2 \rangle / c_s^2 \right) [H]}{(\tilde{n}_e / n_{e0})^2 [L]} \gtrsim 1$$

Kinetic energy in the mean flow is always much smaller than the L-mode thermal free energy in all discharges

$$\eta \doteq \frac{\langle \bar{v}_\theta \rangle^2 / c_s^2}{(\tilde{n}_e / n_{e0})^2_{\text{L-mode}}}$$

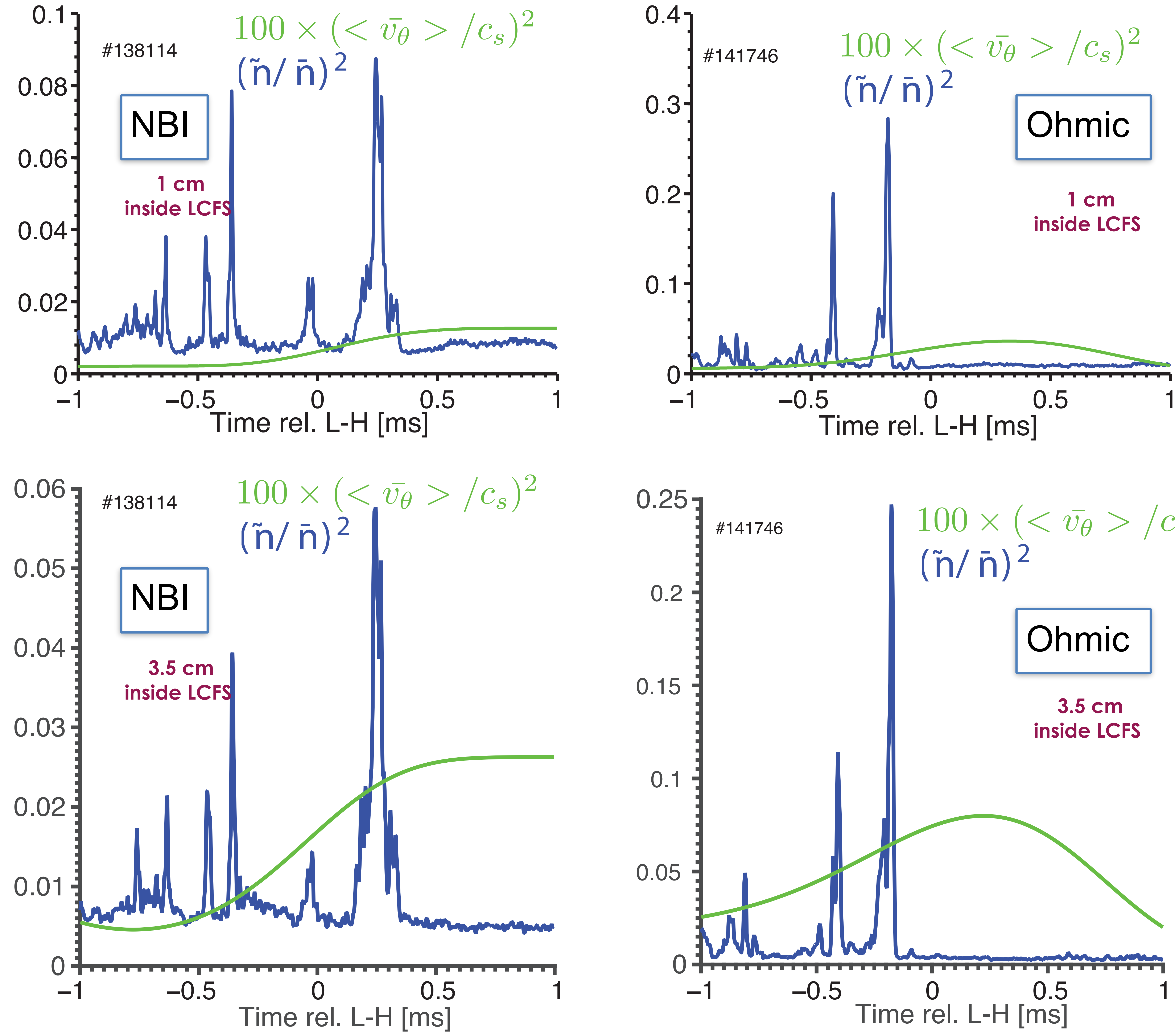




$$\eta \ll 1$$

Too weak to explain the rapid turbulence suppression at the L-H transition.

The kinetic energy in the mean flow remains smaller than the thermal free energy at two radii (1 cm & 3.5 cm) inside the LCFS



The sum of the two turbulent fluctuation energies needs to be exhausted in order to deplete the turbulence

STOLTZFUS-DUECK, PoP **23** 054505 (2016)

Electron parallel conduction
fast timescale

$$j_{||}\nabla_{||}\varphi$$

Thermal free energy — non-zonal ExB energy — Zonal ExB energy

$$\partial_t\left(\frac{T_{e0}}{2n_{e0}}\tilde{n}_e^2+\frac{n_0 m_i\left\langle\tilde{v}_E^2\right\rangle}{2}+\frac{n_0 m_i\langle\bar{v}_E\rangle^2}{2}\right)=\mathrm{sources}+\mathrm{sinks}$$

slow time scale

Production term

$$n_0 m_i\left\langle\tilde{v}_r\tilde{v}_\theta\right\rangle\partial_r\left\langle\bar{v}_\theta\right\rangle$$

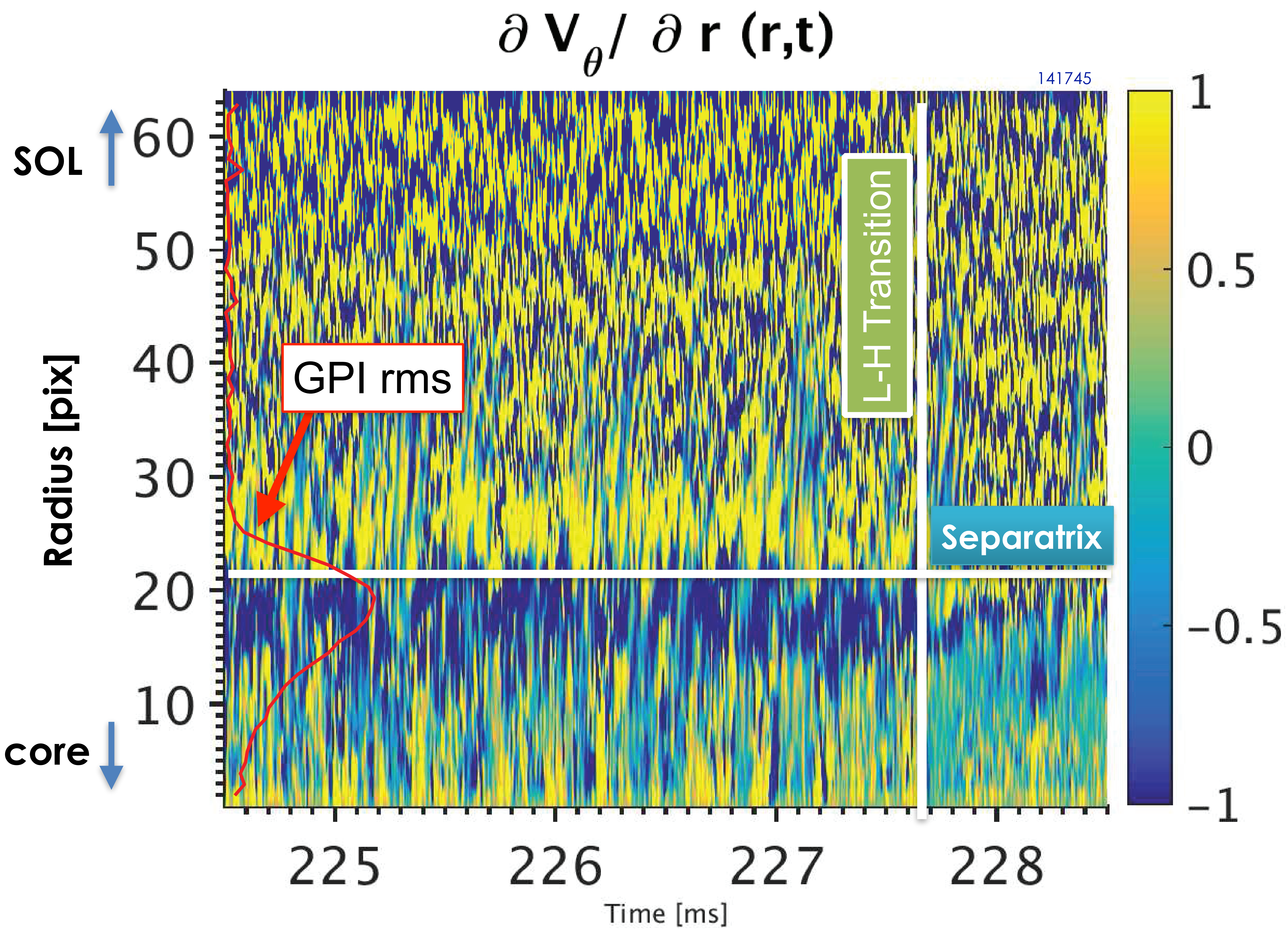
Moves as a single unit
given the fast time scales $t\sim\frac{qR}{v_{the}}$

$$\left(\frac{T_{e0}}{2n_{e0}}\tilde{n}_e^2+\frac{n_0 m_i\left\langle\tilde{v}_E^2\right\rangle}{2}\right)$$

For energy transfer to mean flows to deplete the turbulence, we must have

$$\frac{\left\langle\bar{v}_\theta^2\right\rangle/c_s^2}{(\tilde{n}_e/n_{e0})^2}\gtrsim 1$$

Radial gradient of the poloidal velocity



Approach for the decomposition of the velocity field components

- Reynolds decomposition should be applied to the whole flux surface.
- However, GPI view is limited to a 30 x 24 cm patch of the flux surface
  – The flux-surface average is replaced by a temporal average

- For each velocity component, $v_i = \bar{v}_i + \tilde{v}_i, \; i \in [r, \theta], \; \forall t$

$$\text{High-pass filter of } v(r, \theta, t) \text{ at 1 kHz} \longrightarrow \tilde{v}(r, \theta, t)$$

$$\text{Low-pass filter of } v(r, \theta, t) \text{ at 1 kHz} \longrightarrow \bar{v}(r, \theta, t)$$

This cutoff frequency was chosen to include the poloidally oscillating flow (2 - 5 kHz) described in ref. Zweben et al. PoP (2010) into the non zonal component.

Variations (1 - 2 kHz) around this cutoff do not qualitatively change the results presented here.

Production term conservatively transfers energy between non-zonal and zonal energy

Simplified energy balance equations

$$\partial_t \left(E_n + E_\sim\right) = \int dV \left[\frac{Q}{L_n} - \eta j^2 - T_{e0} \left\langle \phi \right\rangle \kappa(n_e) - n_0 m_i \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle \partial_r \left\langle \bar{v}_\theta \right\rangle\right]$$

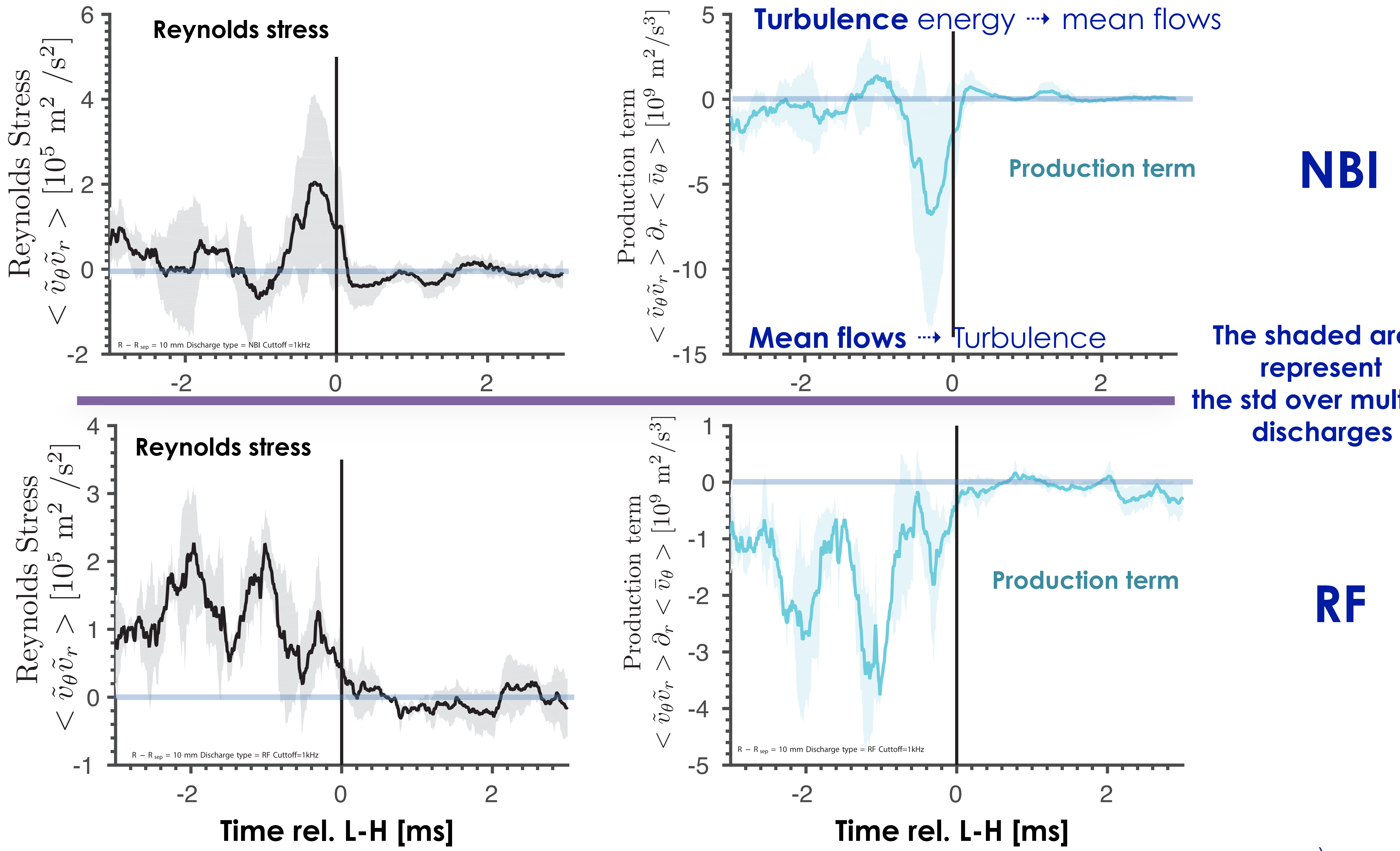
GAM physics

Production term

$$\partial_t E_z = \int dV \left[T_{e0} \left\langle \phi \right\rangle \kappa(n_e) + n_0 m_i \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle \partial_r \left\langle \bar{v}_\theta \right\rangle\right]$$

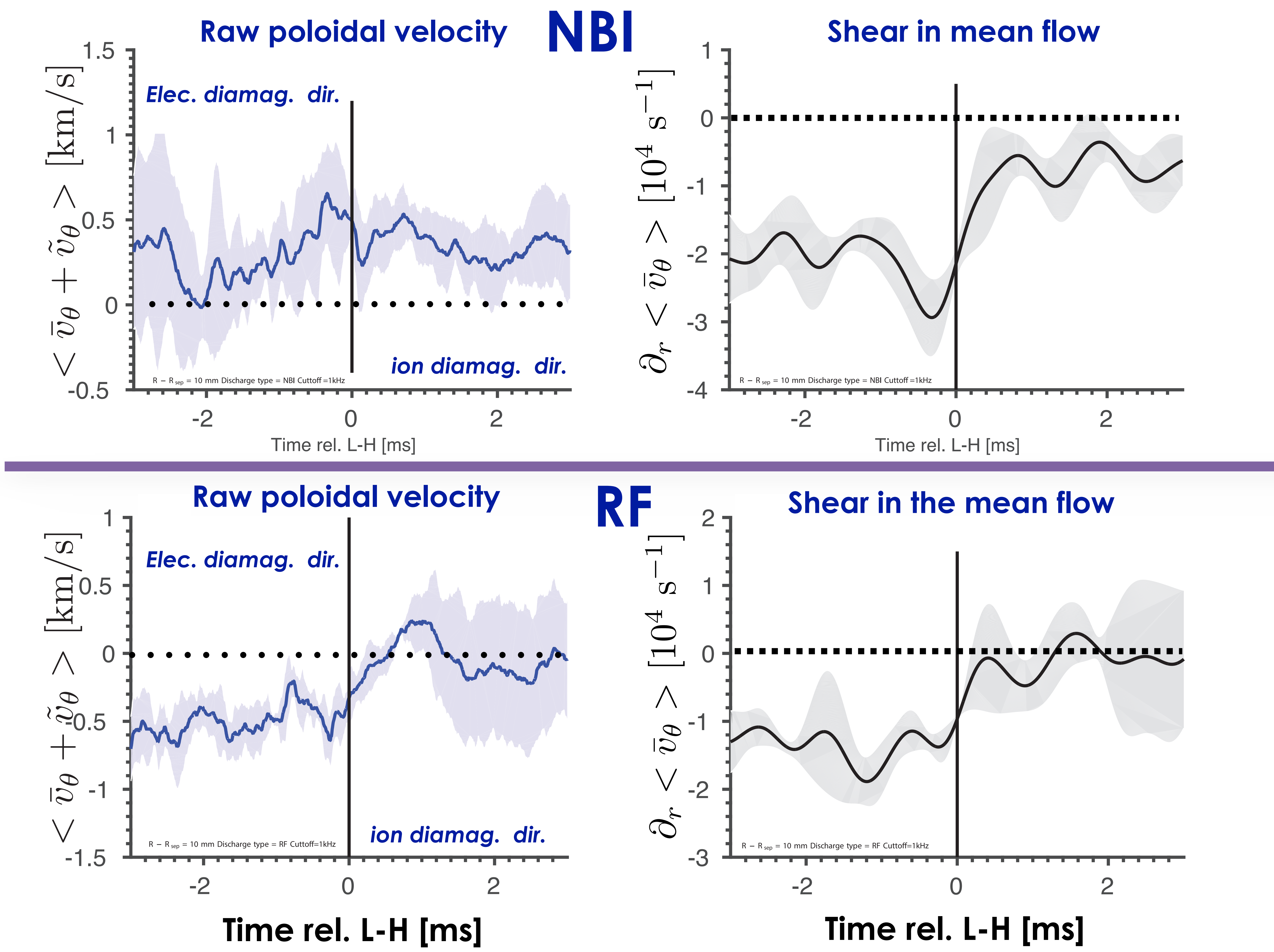
Equations capture the energy transfer that plays a key role in many models of the L-H transition.

Energy is transferred from mean flows to turbulence

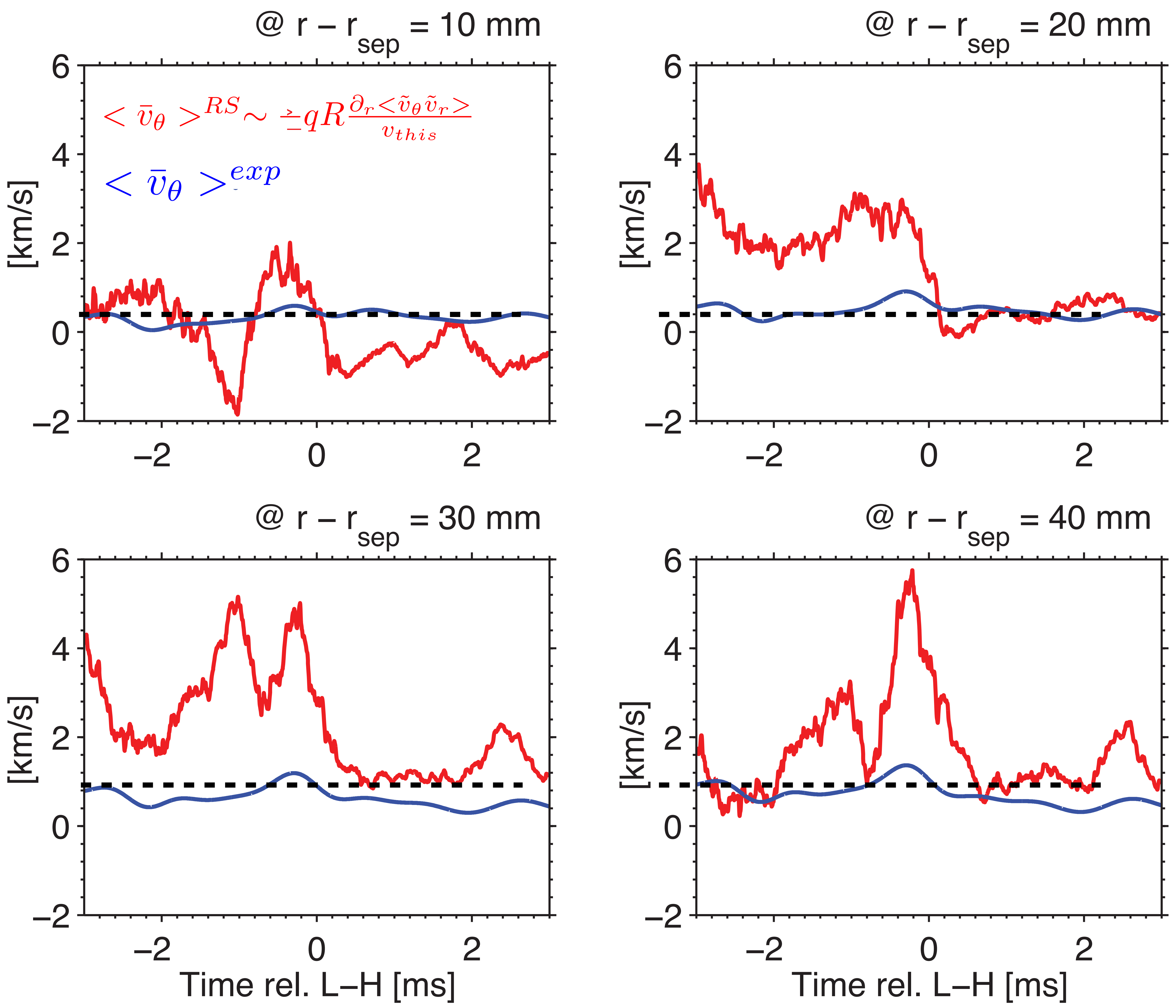


The shaded area represent the std over multiple discharges

The inferred absolute shear in the mean flow decreases across the L-H transition, which is inconsistent with the shear model



Reynolds stress-driven mean flow and the measured mean flow are of the same order of magnitude



- Crude estimate the Reynolds stress-driven flow
  - Assuming flow damping at ion transit rate

- **Contribution of the Reynolds stress to the mean flow cannot necessarily be discarded.**

Poloidal Flow