NSTX-U is sponsored by the
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Energy Exchange Dynamics across L-H Transitions in NSTX

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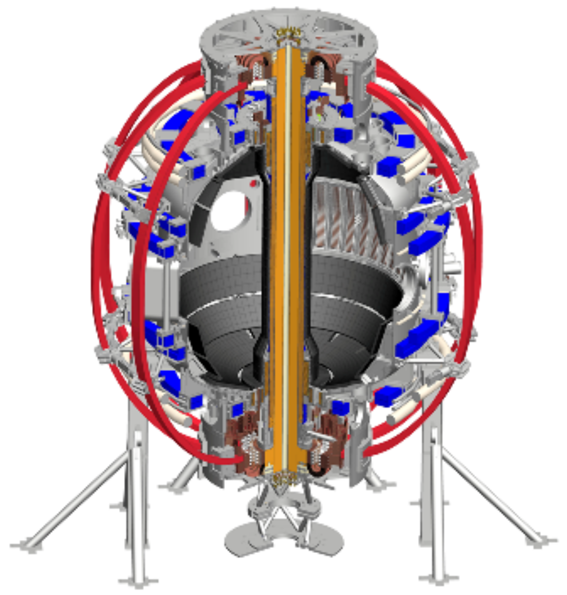
Milwaukee, WI



Supported by U.S. DoE under contract DE-AC02-09CH11466

L-H transition is defined as …

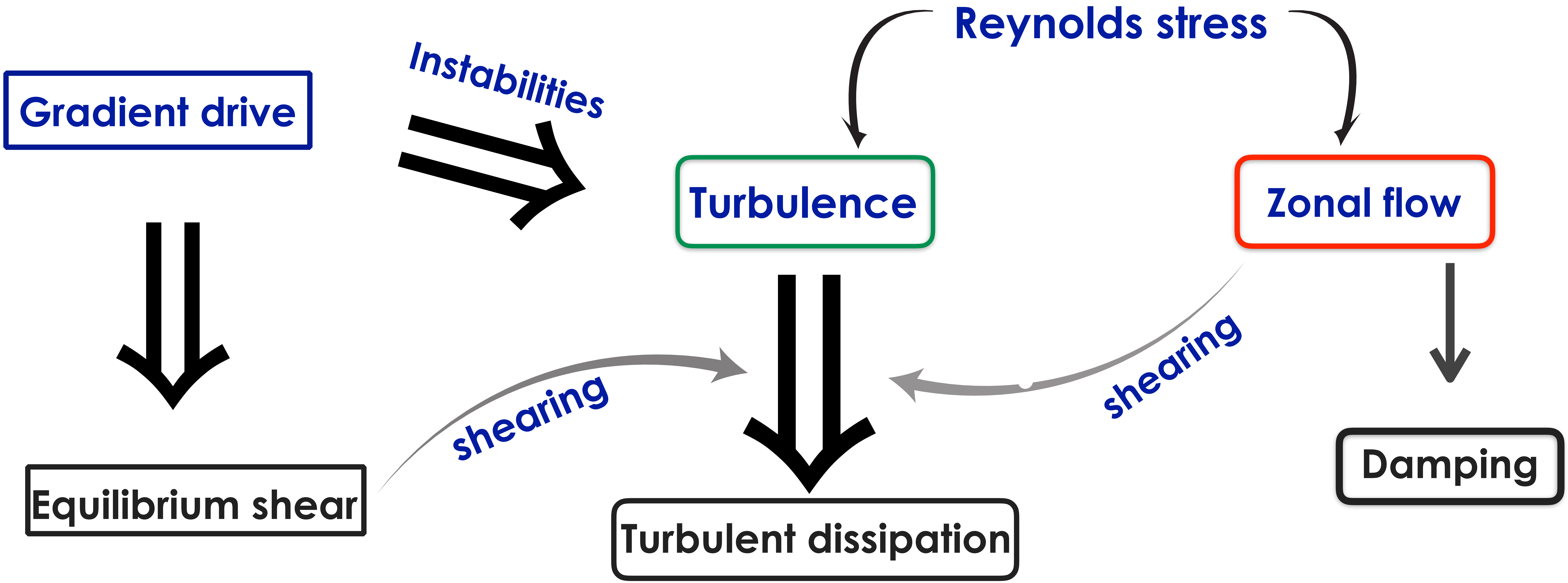
- It is the sudden transition to a state of good energy confinement:
  - Expected mode of operation for ITER.

- It appears as heating power increases past some threshold.

Wagner PRL (1982)

While H-mode has been discovered 35 years ago, its triggering mechanism is not yet understood

General paradigm leading to L-H transition: energy balance



Suppression of turbulence by sheared flow: Focus of this talk

Two main mechanisms can occur for turbulence suppression by flow shear

non-zonal ExB energy

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

Zonal ExB energy

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

1 Energy transfer to flows *directly* depletes the turbulent fluctuations.

2 Flow shear depletes the turbulence in other ways

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NSTX L-H transitions are inconsistent with the depletion of turbulence due to energy transfer to zonal flows

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   NSTX L-H transitions are inconsistent with the depletion of turbulence due to energy transfer to zonal flows

2. Flow shear depletes the turbulence in other ways

   NSTX data cannot rule out such mechanisms.

Outline

- Previous results on energy transfer during the L-H transition
- Description of the NSTX gas-puff imaging system
  - Turbulence quantities across the L-H transition of 17 discharge database
- Test of novel velocimetric approach against BOUT++ simulation
- Energy transfer dynamic across the L-H transition
- Summary

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

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

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

- Work on C-Mod using gas-puff imaging (GPI) provided a timeline for the L-H transition:
  - First peaking of the normalized Reynolds power
  - Then the collapse of the turbulence
  - Finally the rise of the diamagnetic electric field shear

  Cziegler et al. PPCF 2014

- 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

Other experimental investigations do not show a key role for Reynolds stress

- AUG showed experimental evidence of the role of the neoclassical flows in the L–H transition physics.
  - Poloidal flows were close to neoclassical over almost the entire L-H transition, including I-phase

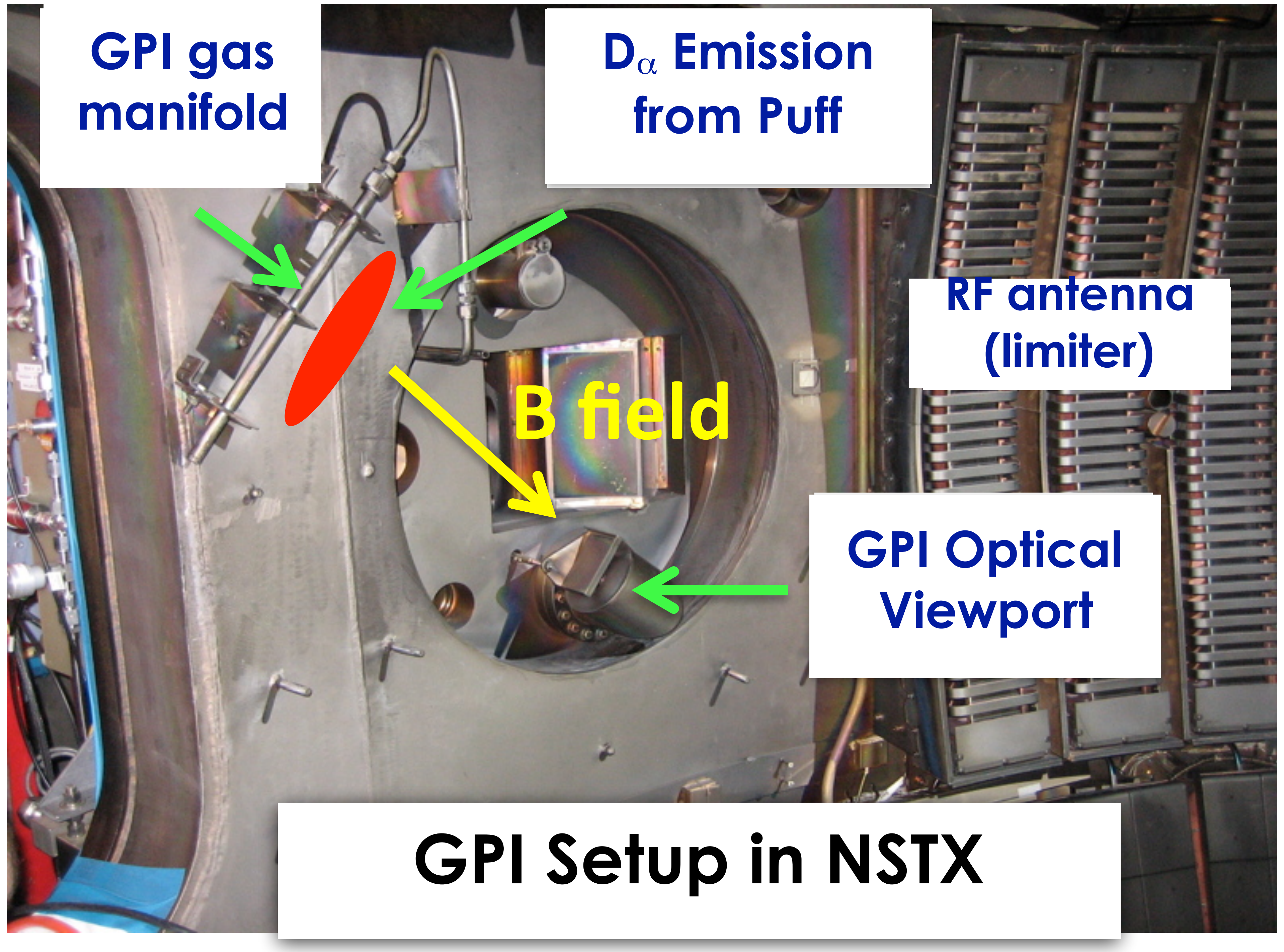
Cavedon et al. Nucl. Fusion 57 (2017) 014002

- JFT-2M showed that the observed Reynolds force is far too low to drive the present E × B flow modulation

Kobayashi et al. Nucl. Fusion 54 (2014) 073017

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

Zweben et al., Rev. Sci. Instrum. 88, 041101 (2017)



GPI provides edge turbulence images

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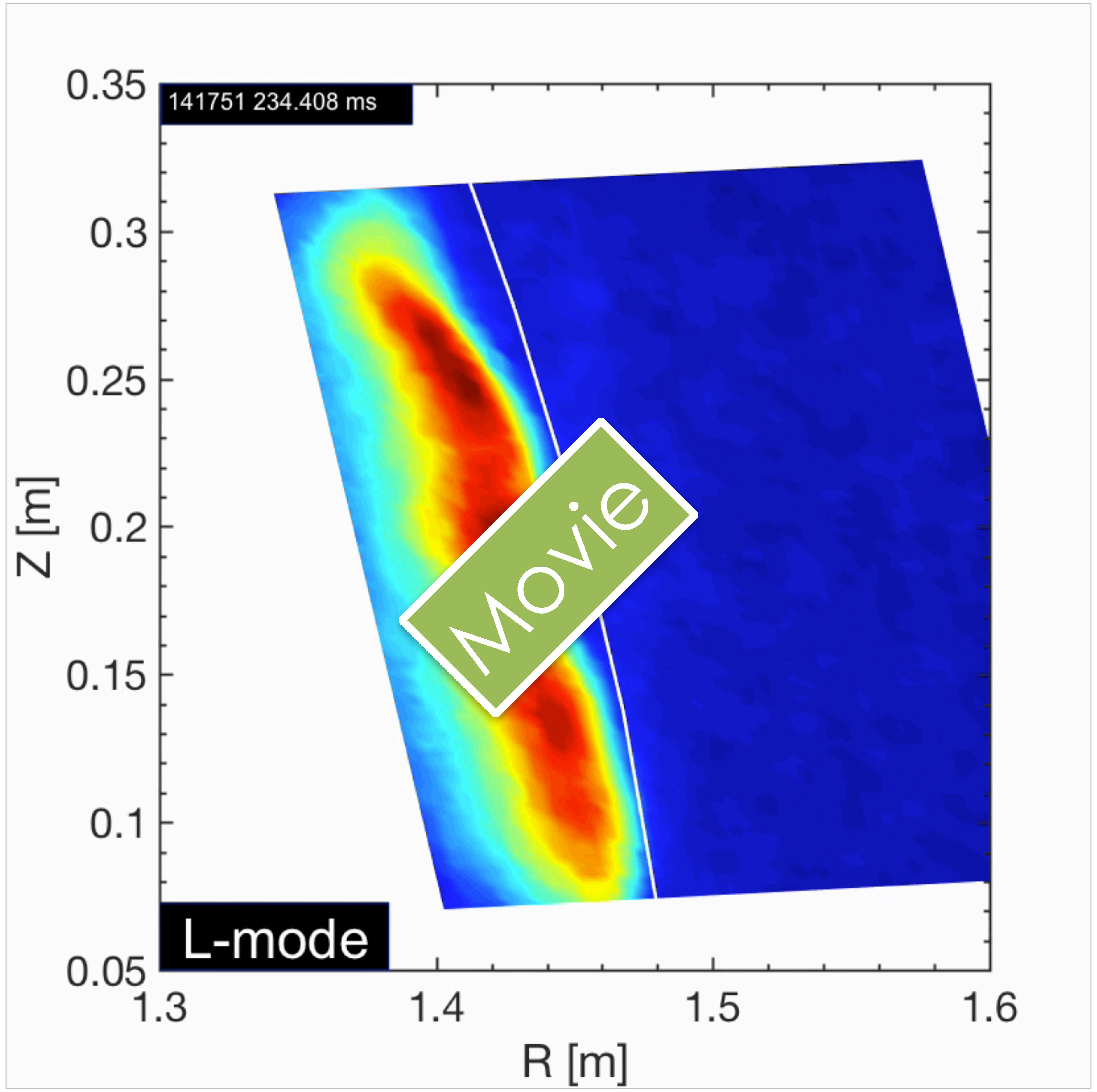
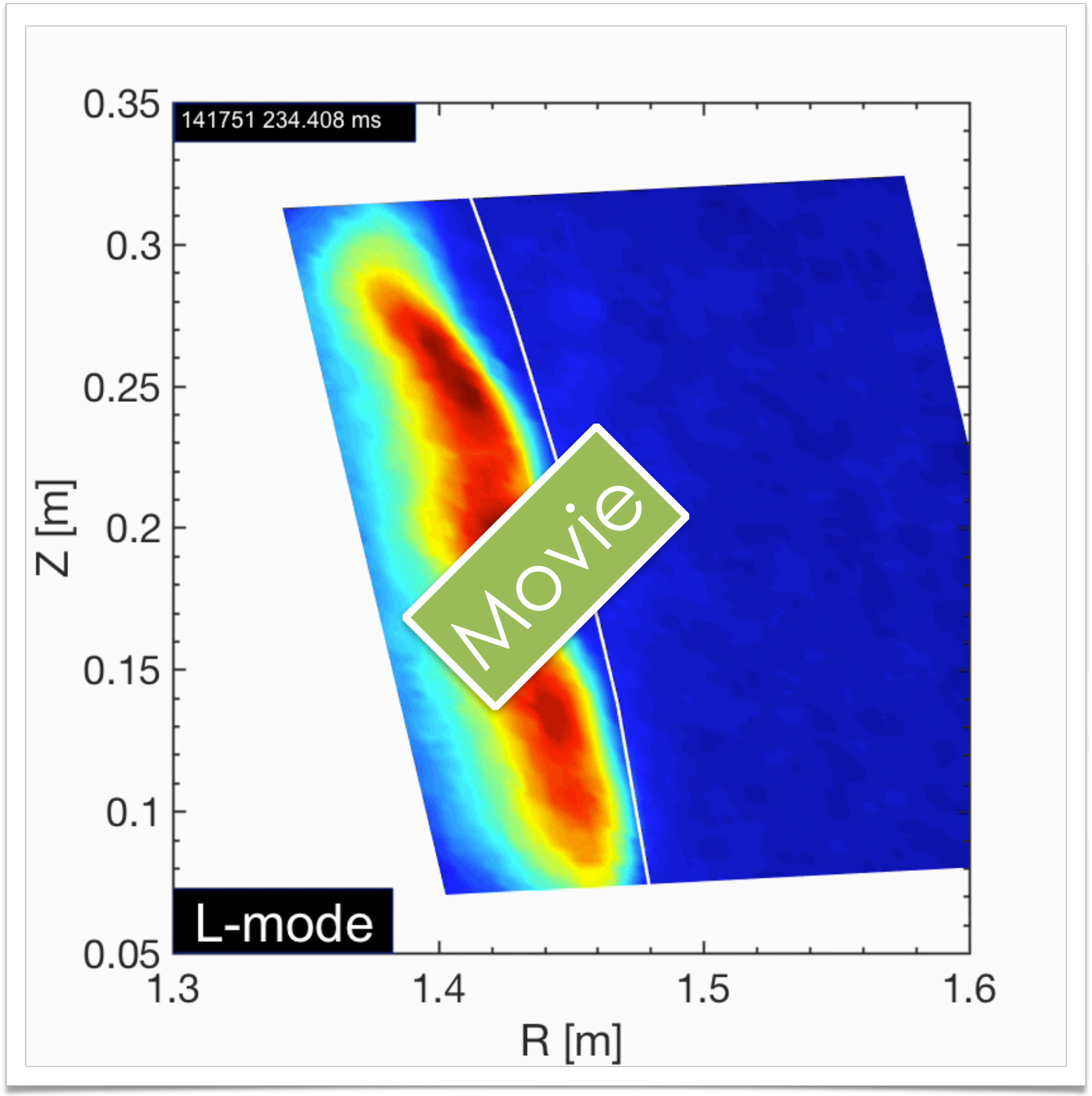


Zweben PoP (2010) for detailed description

GPI provides edge turbulence images

- **Views neutral D_α light emission**
- **Temporal resolution ~ 2.5 μs;**
- **Spatial resolution ~ 1 cm over 24 x 30 cm**
- **L-H transition as a sudden (~100 μs) decrease in edge turbulence**

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



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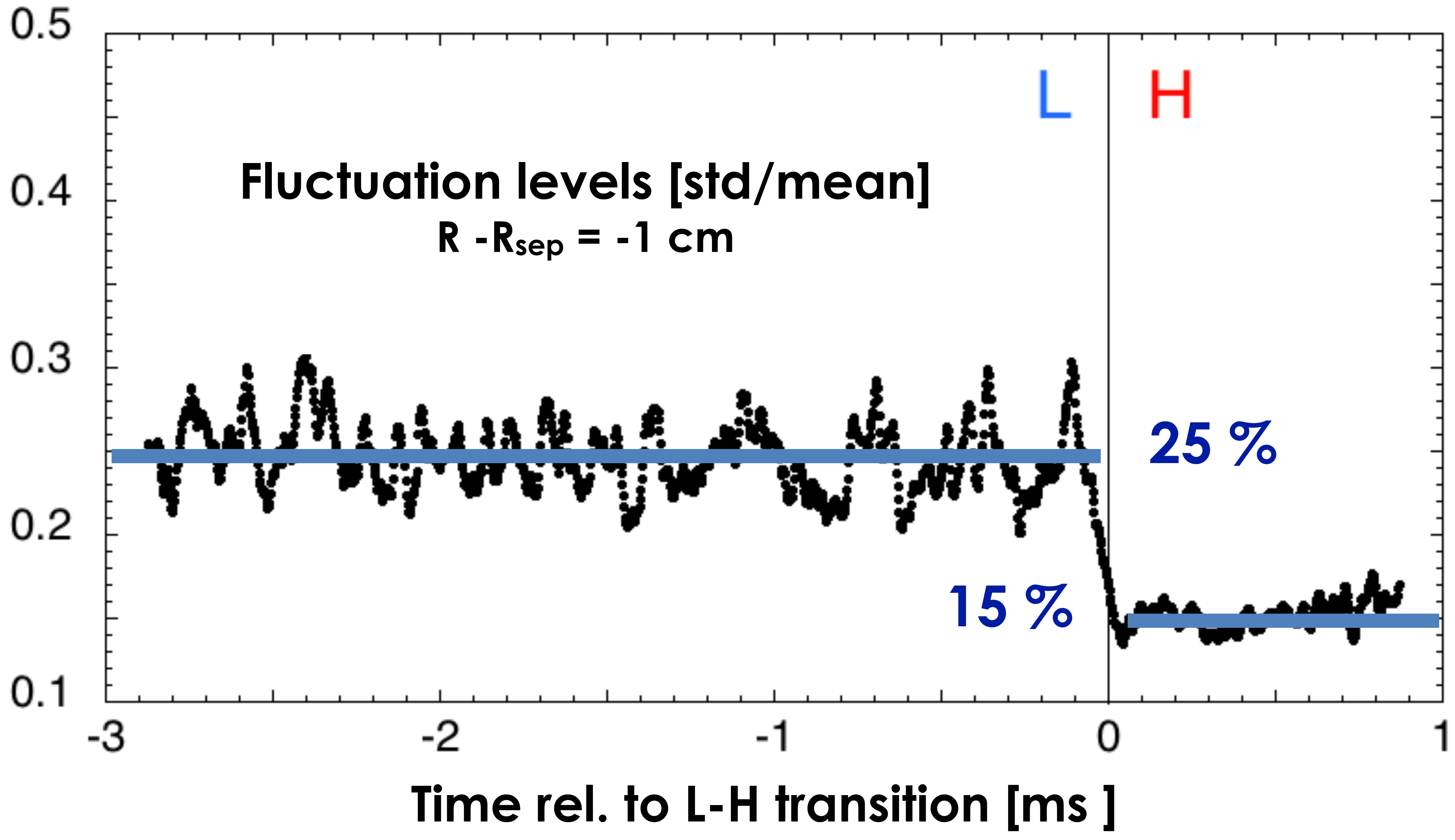
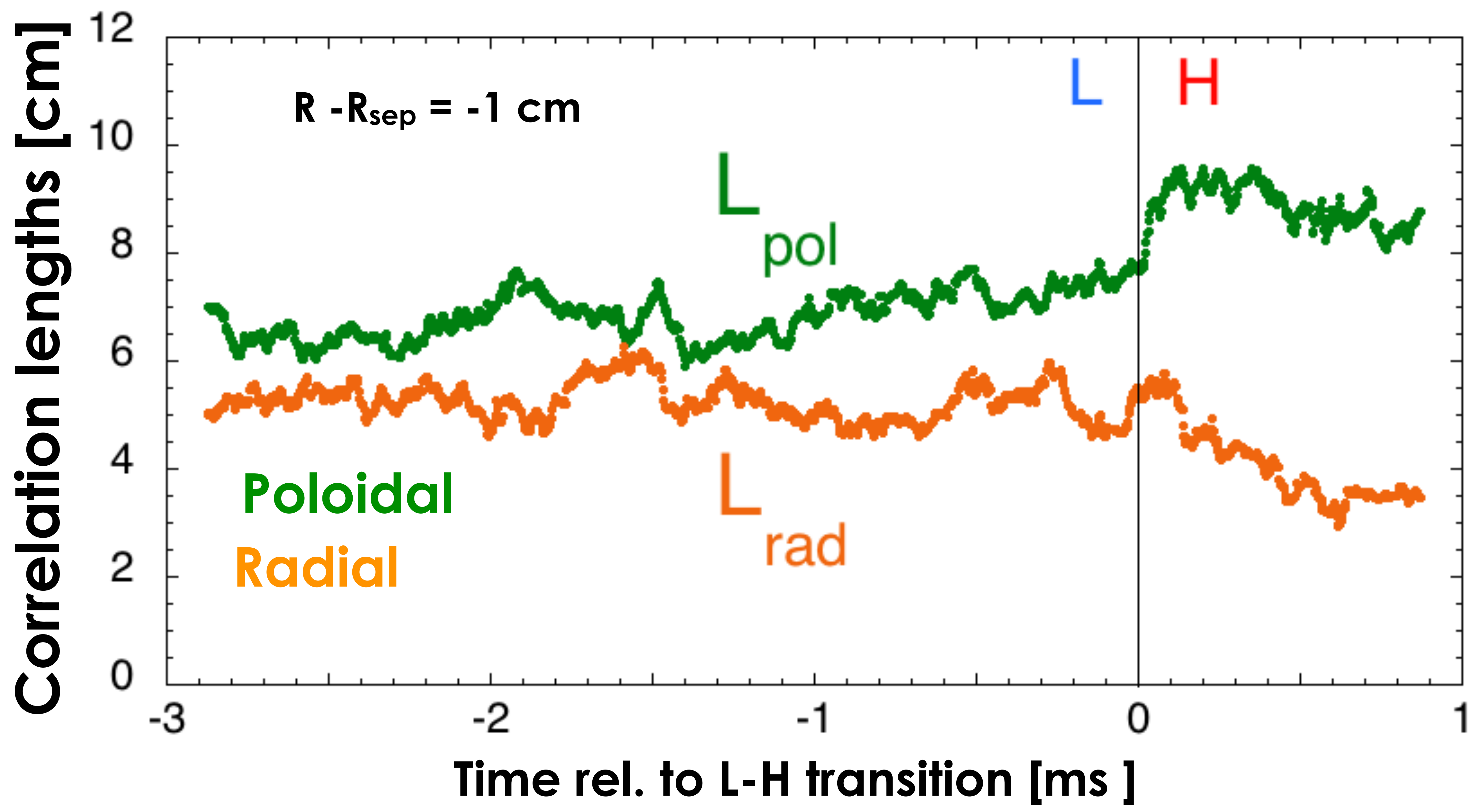
Clear drop in fluctuation levels across the L-H transition, but no systematic change of turbulence quantities preceding the transition





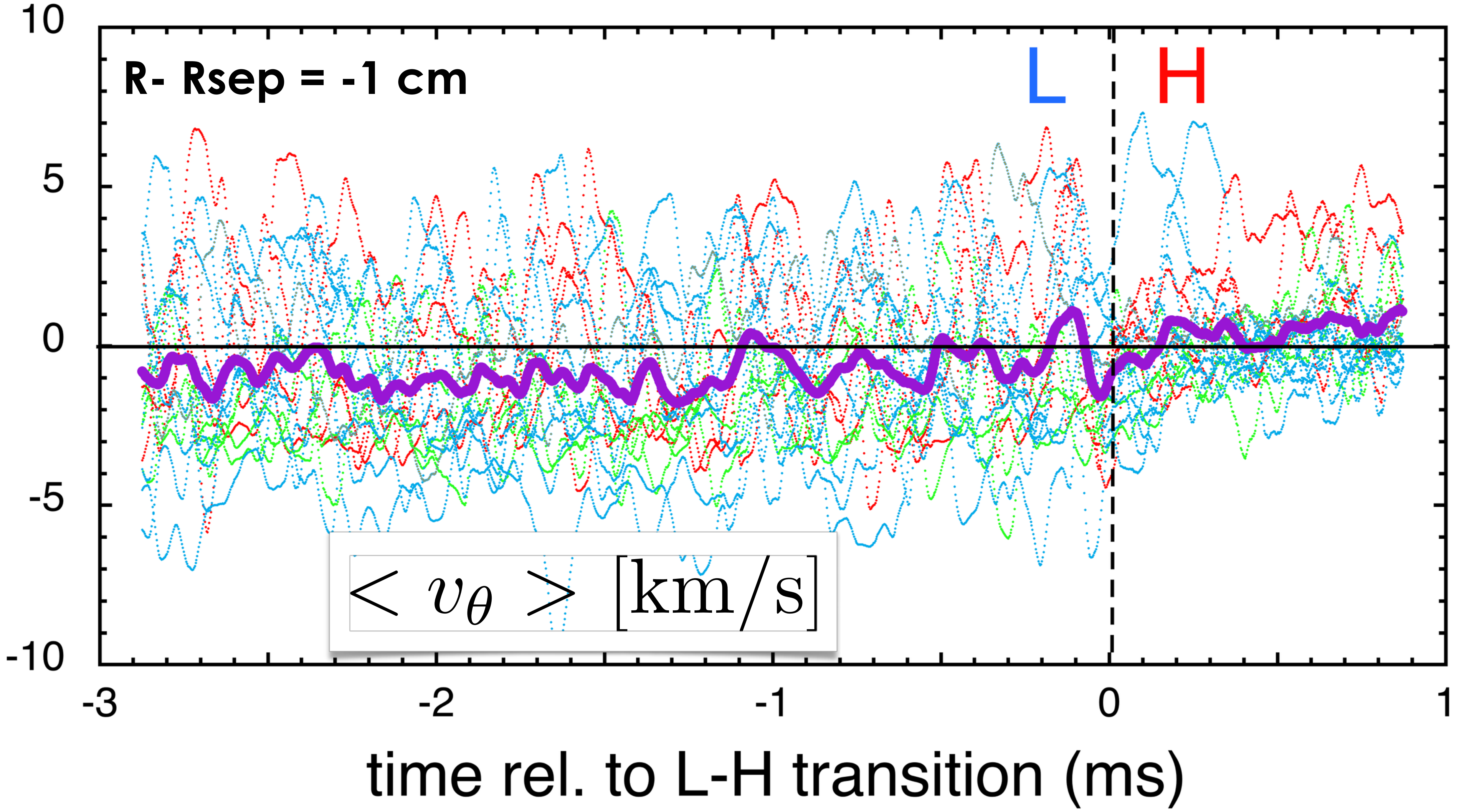
All turbulence quantities (averaged over 17 discharges) nearly constant at all radii up to 3 cm inside the separatrix during 3 msec before transition

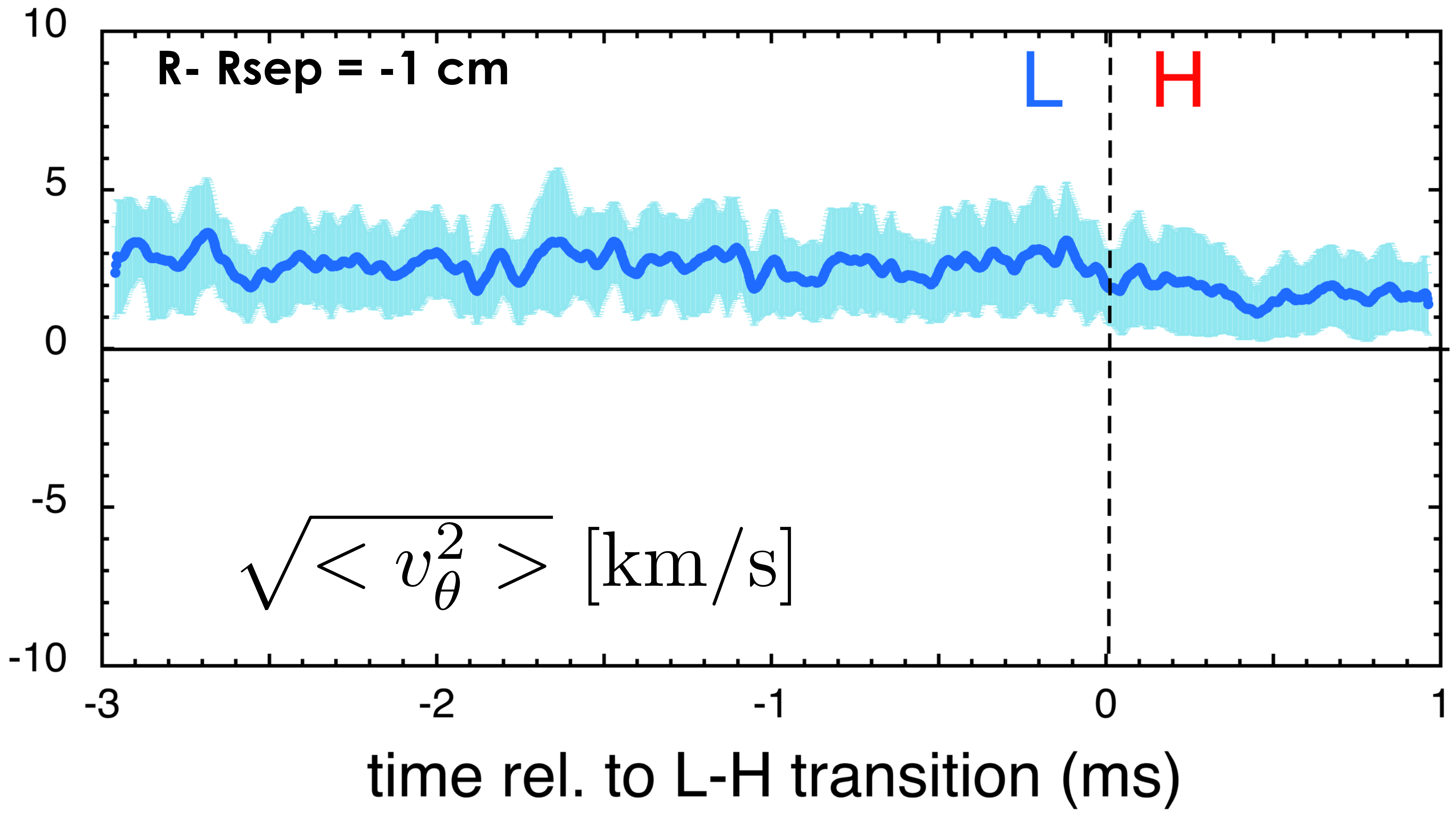
What causes the drop in fluctuation levels across the L-H transition?

Can direct energy transfer from turbulence to mean flow explain this?

Poloidally-averaged velocities and kinetic energies do not exhibit changes prior to the L-H transition

It is expected that flow shear suppression of turbulence would show some detectable change in the flow just before the L-H transition





velocities from time-delayed cross-correlation search code

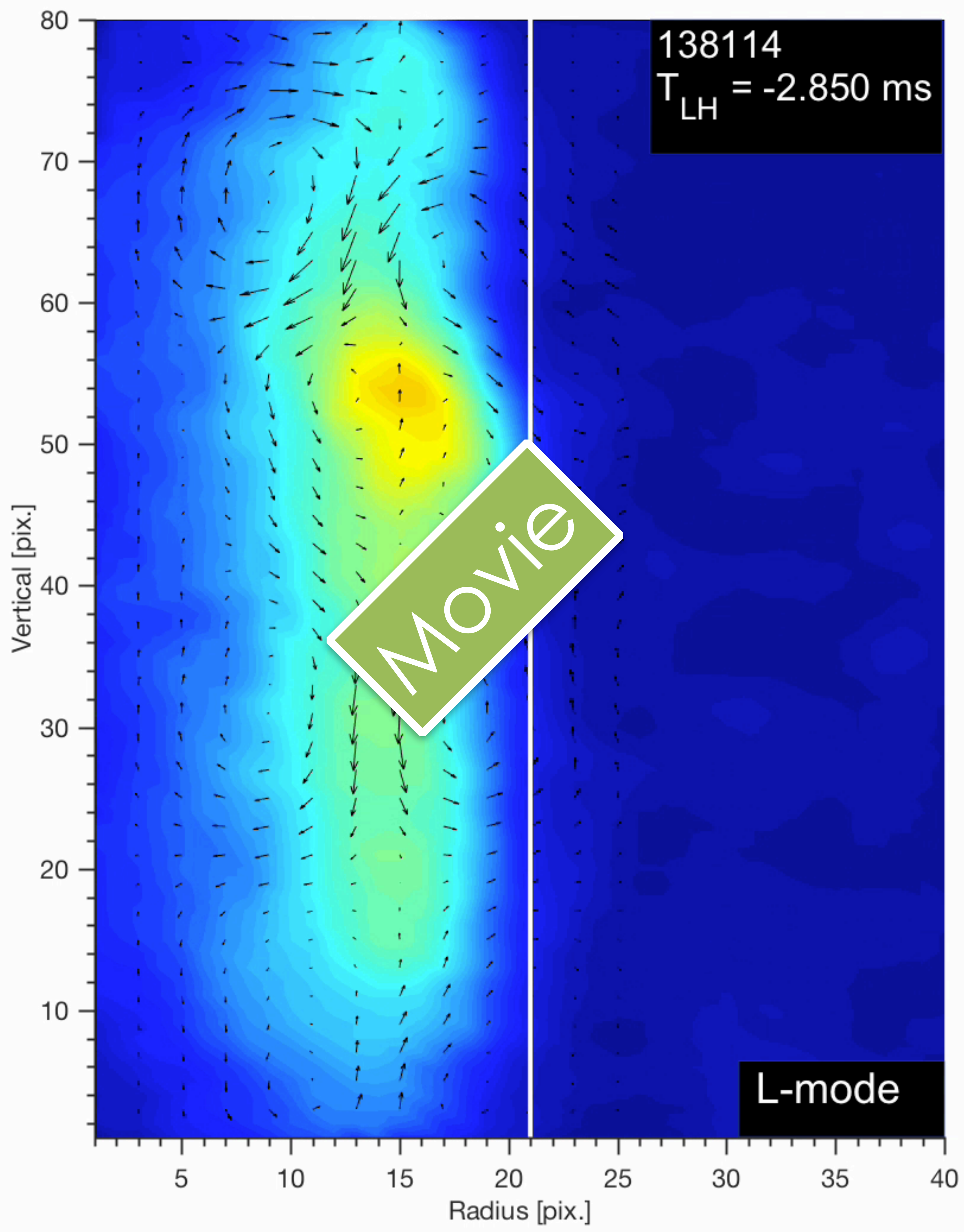
These quantities are averaged in poloidal angles and in time (over 30 μs) and over multiple shots

A novel velocimetric approach was applied to GPI

- **Method: a robust generalization of optical flow that enforces divergence-free velocity**
  Stoltzfus-Dueck - in preparation

- **This approach has a time resolution limited only by the frame rate, and an effective spatial resolution set by the intensity structure size**

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



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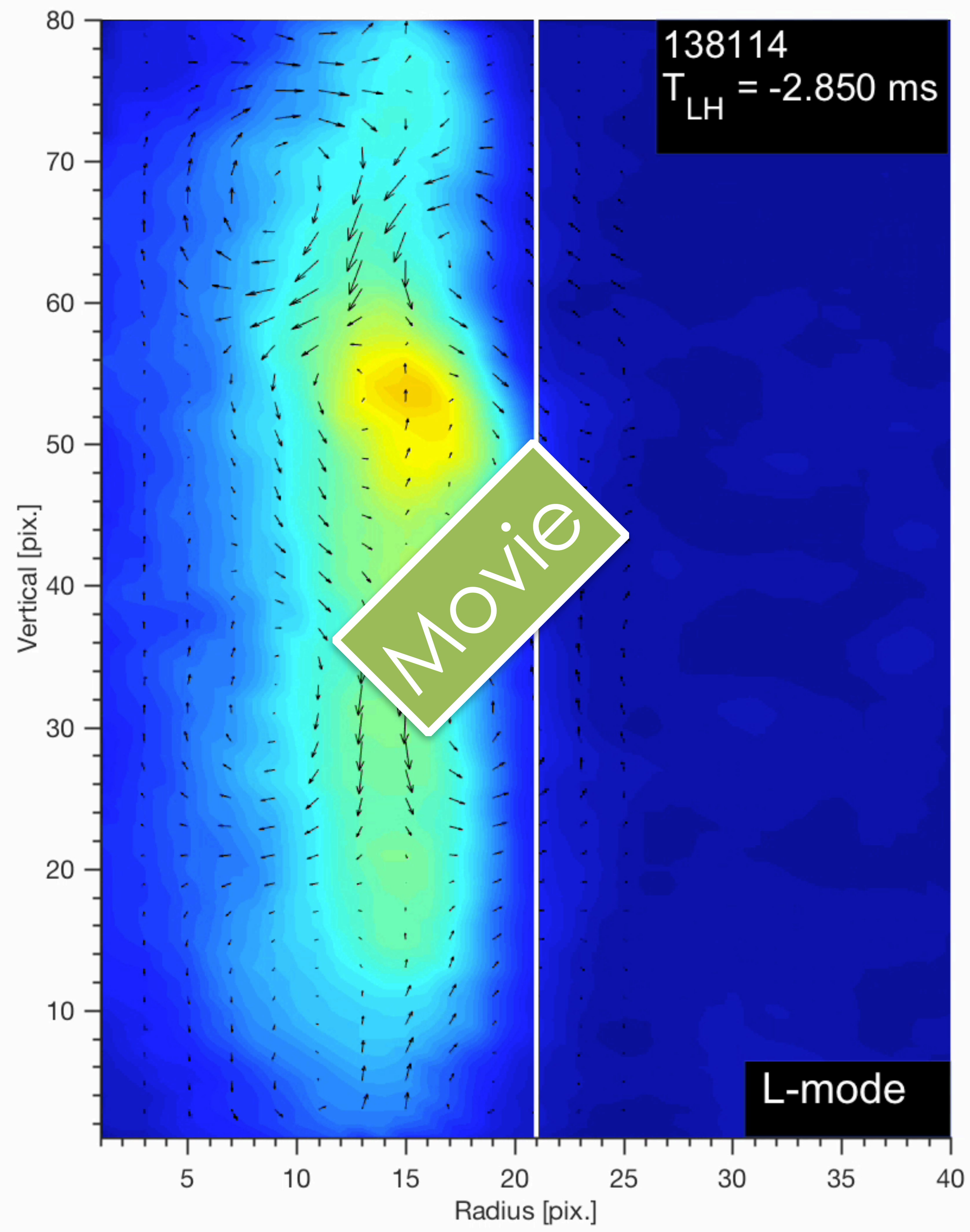

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Test of novel velocimetry against BOUT++ simulations

BOUT++ simulation
courtesy N. Bisai, IPR

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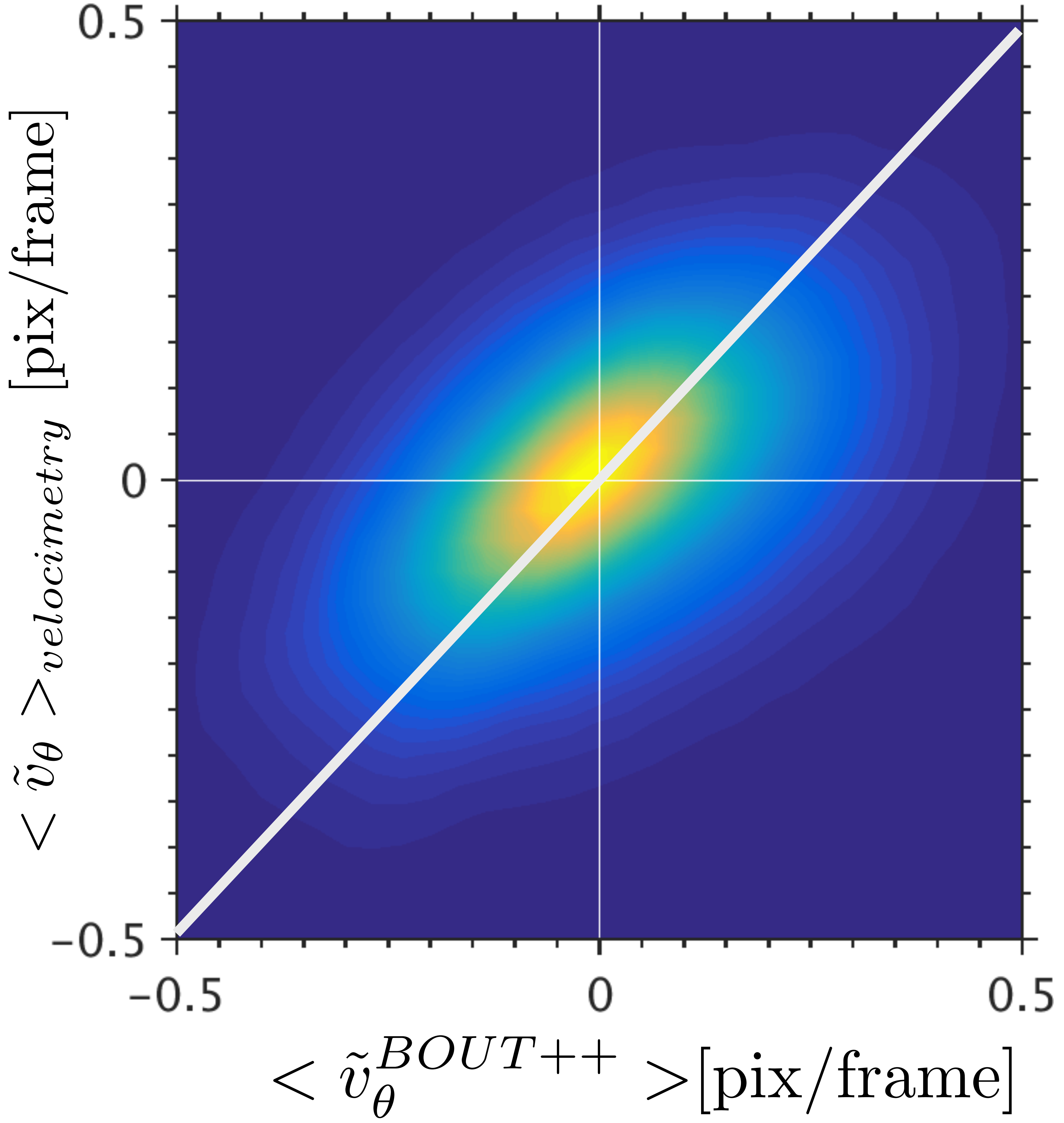
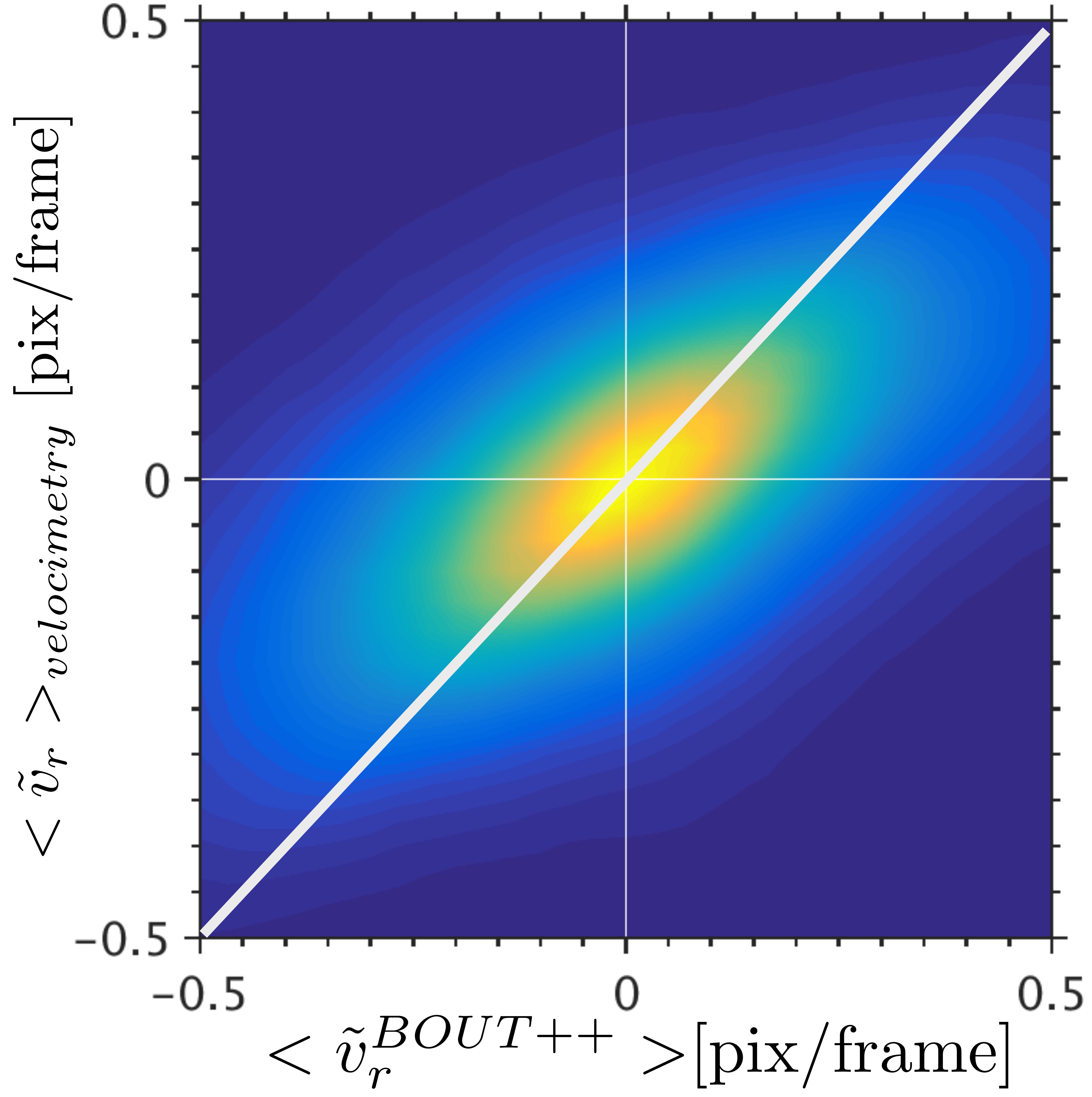
Novel velocimetry analysis agrees with the fluctuating components of the ExB velocity from BOUT++





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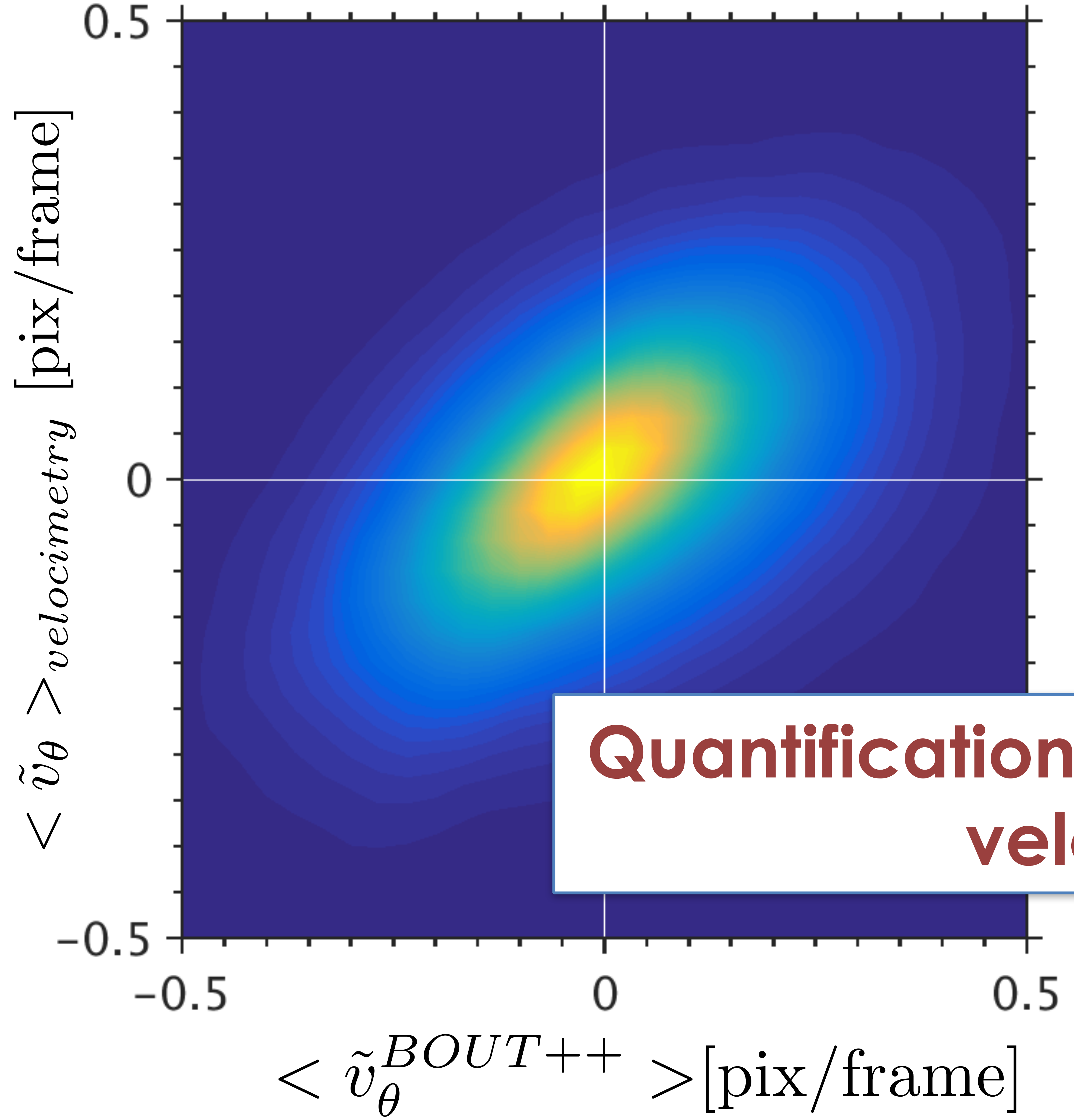
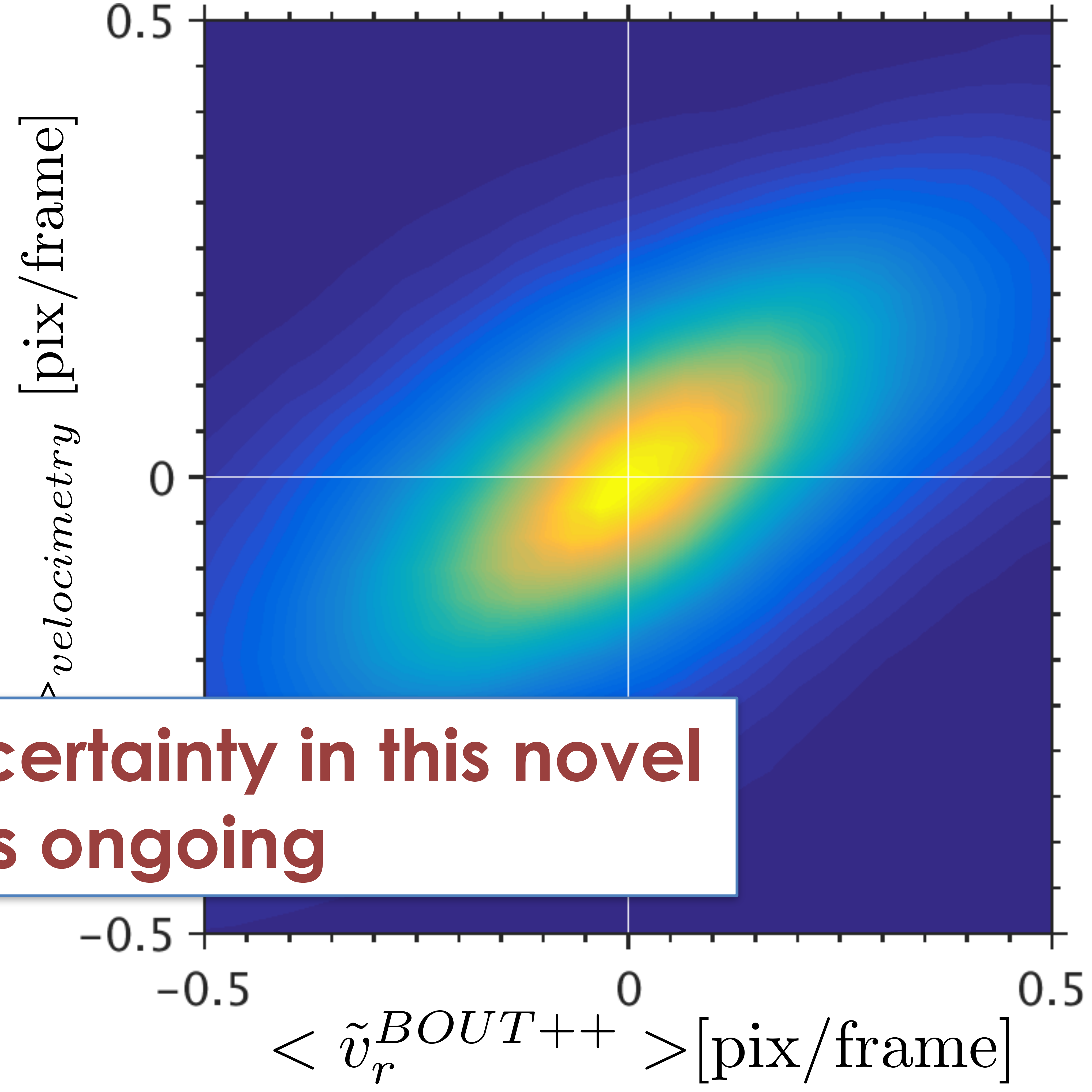
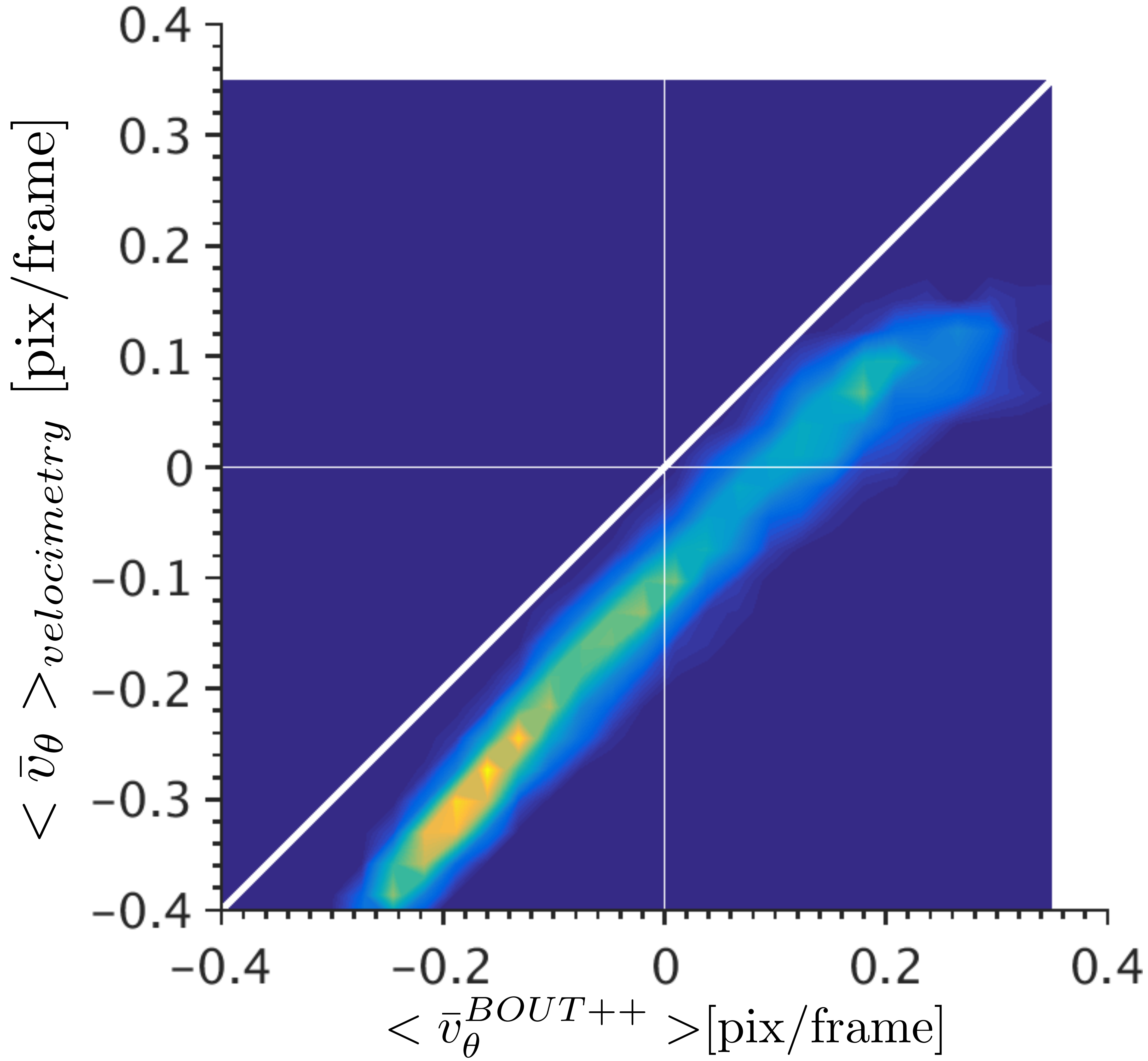




Quantification of the uncertainty in this novel velocimetry is ongoing

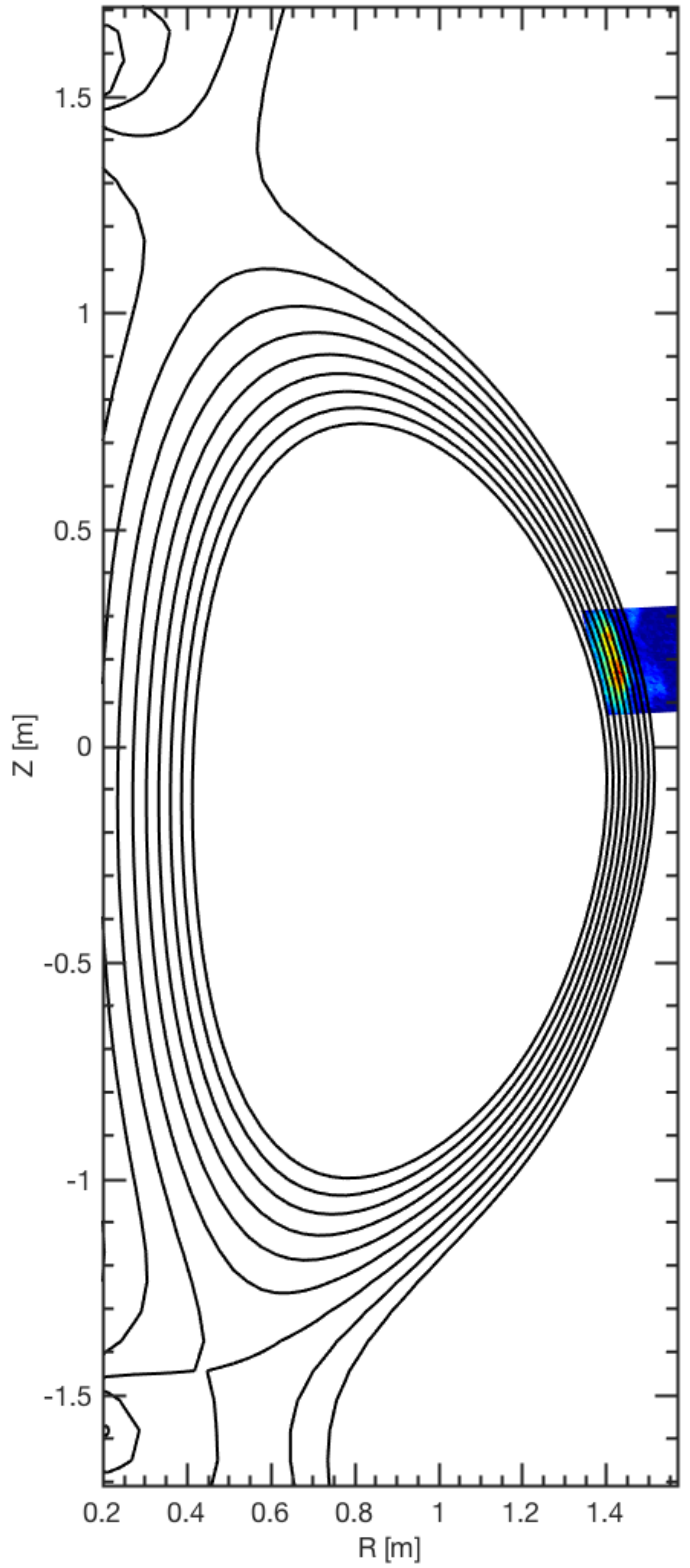
Velocimetry analysis captures poloidally averaged mean flow from BOUT++ with fixed offset



- **Apparent rigid shift was found to be due to drift wave propagation.**
- **Such a shift does not change our principal conclusions**

See Stotler's presentation on GPI for XGC1
TP11.0084- Thurs AM

Approach for the decomposition of the velocity field components



- Goal is to determine the zonal component of flows
  - Zonal fluctuations tend to have lower frequencies than non-zonal
- Reynolds decomposition should be applied to the **whole flux surface**
- However, GPI view is limited to a 24 x 30 cm patch of the flux surface

Low-pass frequency filter should be able to approximately separate the zonal **(~lower-frequency)** from non-zonal **(~turbulent, higher-frequency)** components.

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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

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

P>0

$$\longrightarrow$$

$$\longleftarrow$$

P<0

Zonal ExB energy

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

Negative Production term

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

A positive production term indicates the depletion of turbulence

Thermal free energy is an additional reservoir for the turbulence energy

See paper for details
Stoltzfus-Dueck, PoP ***23*** *054505 (2016)*

$$\gamma E_{th}$$

Thermal free energy(E_{th})

non-zonal ExB energy

Zonal ExB energy

$$\underbrace{\boxed{\frac{n_{e0}T_{e0}}{2}\left(\frac{\tilde{n}_e}{n_{0e}}\right)^2} + \boxed{\frac{n_o m_i \left\langle \tilde{v}_\theta^2 \right\rangle}{2}}}_{\text{Turbulence energy } (E_{Turb})} \longleftrightarrow \boxed{\frac{n_o m_i \left\langle \bar{v}_\theta \right\rangle^2}{2}}$$

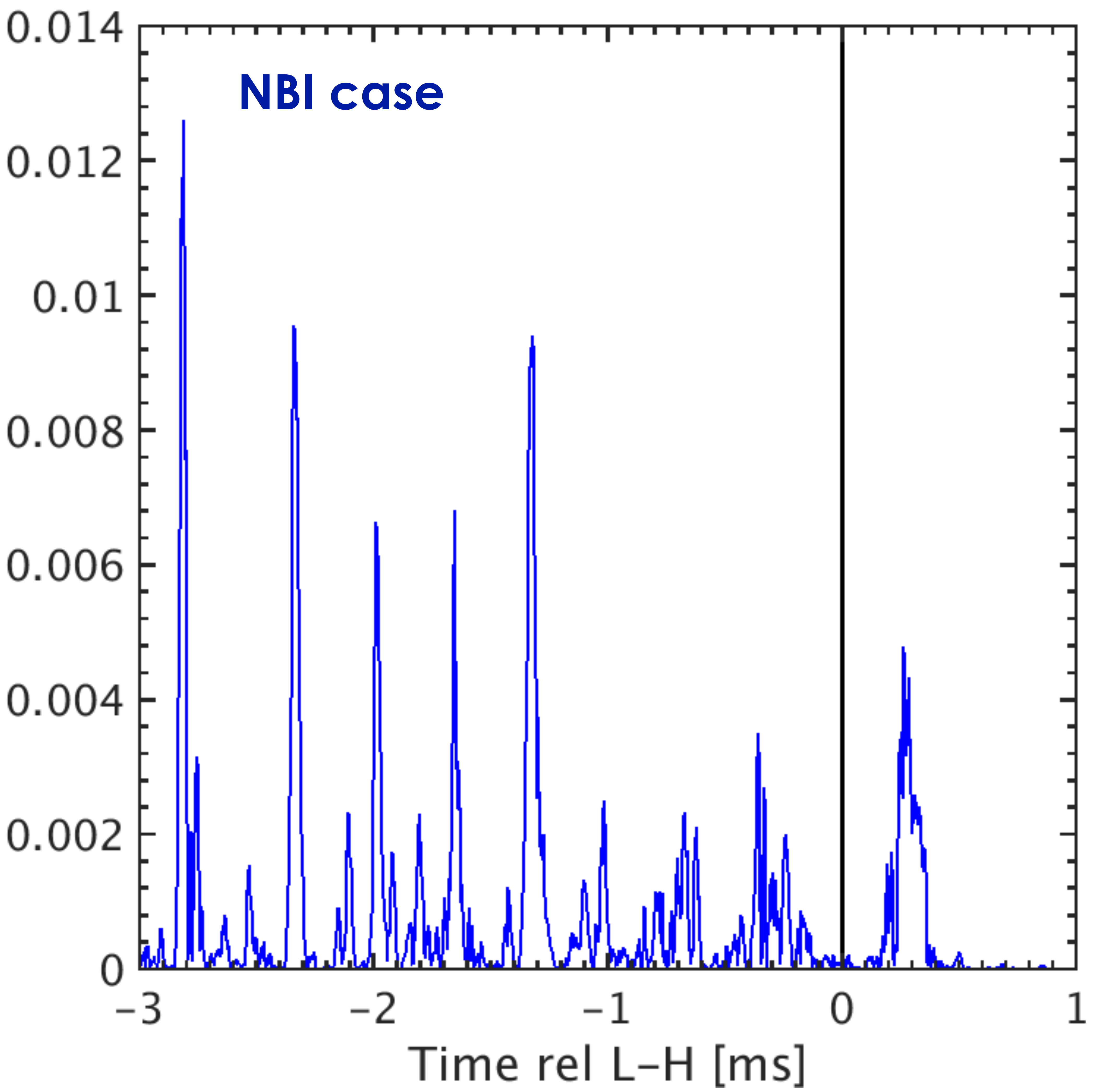
Production term

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

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 affect the thermal free energy?

Production term is much less than the turbulent free-energy supply



$$\frac{|P|}{P_0} \doteq \frac{|n_0 m_i \langle \tilde{v}_\theta \tilde{v}_r \rangle \partial_r \langle \bar{v}_\theta \rangle|}{\gamma \ E_{turb}|_L}$$

Assuming interchange or drift wave turbulence

$$\gamma \sim 10^5 s^{-1}$$

- Ratio needs to be around 1 to cause turbulence suppression.
- Ratio is much less than 1 so inconsistent with the turbulence depletion.

Assuming uncertainties in Reynolds stress estimate, what is an upper bound the production term?

Simplified estimates of the Reynolds work provide an upper bound for the production term

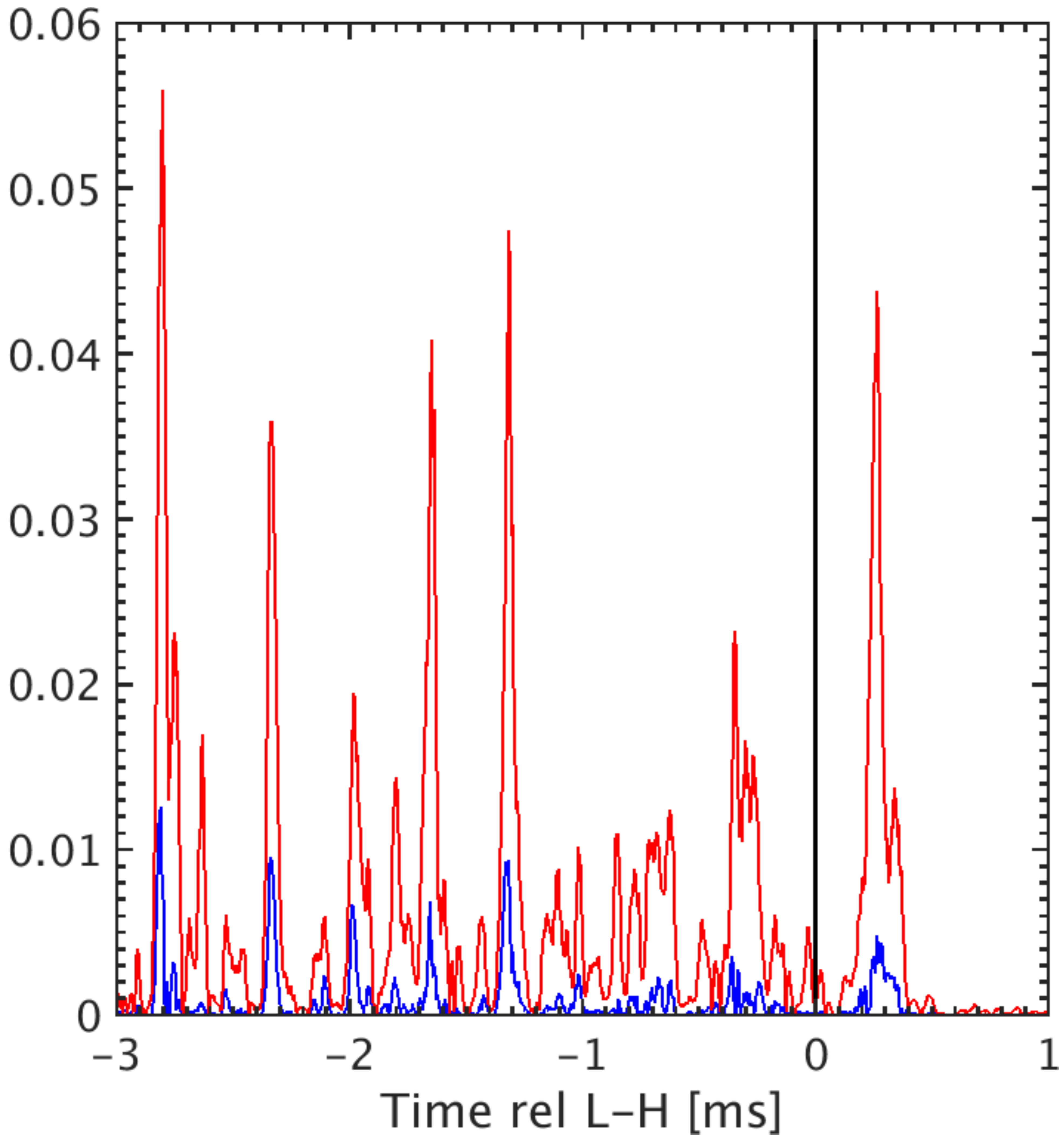
$$\frac{|P|}{P_0} \doteq \frac{|n_0 m_i \langle \tilde{v}_\theta \tilde{v}_r \rangle \partial_r \langle \bar{v}_\theta \rangle|}{\gamma \ E_{turb}|_L}$$

Using the triangle inequality:

$$2\langle \tilde{v}_\theta \tilde{v}_r \rangle \leq \left\langle \tilde{v}_\theta^2 \right\rangle + \left\langle \tilde{v}_r^2 \right\rangle$$

$$\boxed{\frac{P}{P_0} \leq \frac{|n_0 m_i \left\langle \tilde{v}_\theta^2 + \tilde{v}_r^2 \right\rangle \partial_r \langle \bar{v}_\theta \rangle|}{\gamma \ E_{turb}|_L}}$$

Simplified estimates of the Reynolds work provide an upper bound for the production term



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Using the triangularity inequality:

$$2\left\langle \tilde{v}_\theta \tilde{v}_r \right\rangle \leq \left\langle \tilde{v}_\theta^2 \right\rangle + \left\langle \tilde{v}_r^2 \right\rangle$$

$$\boxed{\frac{P}{P_0} \leq \frac{|n_0 m_i \left\langle \tilde{v}_\theta^2 + \tilde{v}_r^2 \right\rangle \partial_r \langle \bar{v}_\theta \rangle|}{\gamma \ E_{turb}|_L}}$$

Production term remains less than the turbulent free-energy supply

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

- 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

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

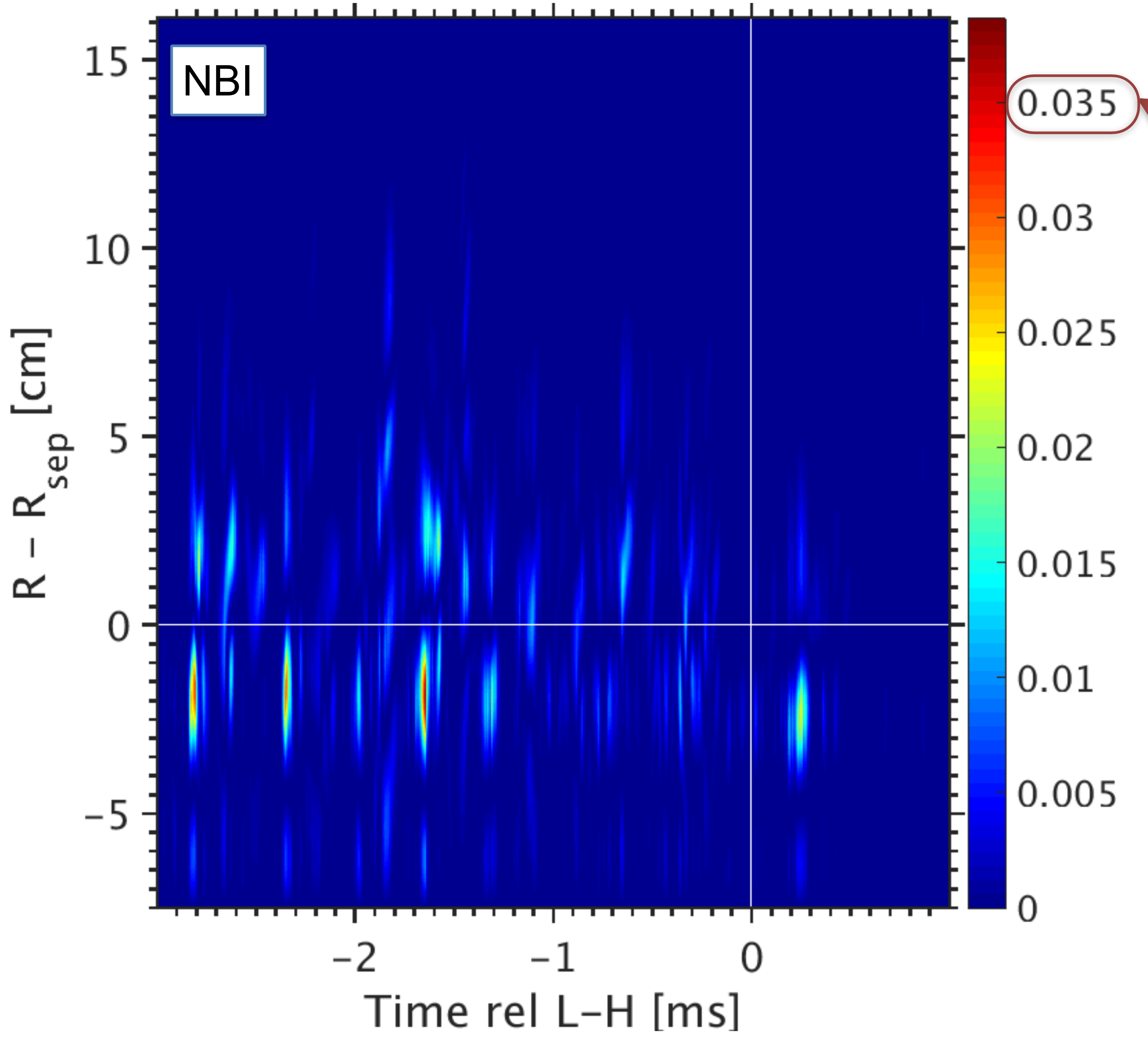
Zonal ExB energy

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

For zonal flows to take most of the turbulence energy:

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

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



$$\eta \doteq \frac{\langle \bar{v}_\theta \rangle^2 / c_s^2}{(\tilde{n}_e / n_{e0})^2} \Longrightarrow \frac{\langle \bar{v}_\theta \rangle^2 / c_s^2}{\left(<\tilde{I}^2>_{[L]} / \bar{I}^2 \right)}$$

$$\eta \ll 1$$

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

Does enough energy pass through poloidal flow damping to disturb the turbulent energy balance?

$$\gamma E_{th}$$

Thermal free energy

non-zonal ExB energy

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

Turbulence fluctuation energies

Zonal ExB energy

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

Poloidal flow damping rate*

*Hassam & Kulsrud Phys. Fluid 21 2271 (1978)

$$\nu E_z$$

$$\nu \sim 10^4 \text{ Hz}$$

Turbulence Dissipation

Slow transition criteria:

$$\boxed{\frac{\nu}{\gamma}\frac{E_z}{E_{th}} \gtrsim 1}$$

Does enough energy pass through poloidal flow damping to disturb the turbulent energy balance?

$$\gamma E_{th}$$

Thermal free energy

non-zonal ExB energy

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

Turbulence fluctuation energies

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Poloidal flow damping rate*

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Turbulence Dissipation

Slow transition criteria:

$$\frac{\nu}{\gamma}\frac{E_z}{E_{th}} \gtrsim 1$$

Assuming interchange or drift wave turbulence

$$\gamma \sim 10^5 s^{-1}$$

$$\eta = \frac{E_z}{E_{th}}$$

$$\boxed{\frac{\nu}{\gamma}\eta \sim 3.6 \cdot 10^{-3}}$$

Too weak to perturb the turbulent energy balance

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

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

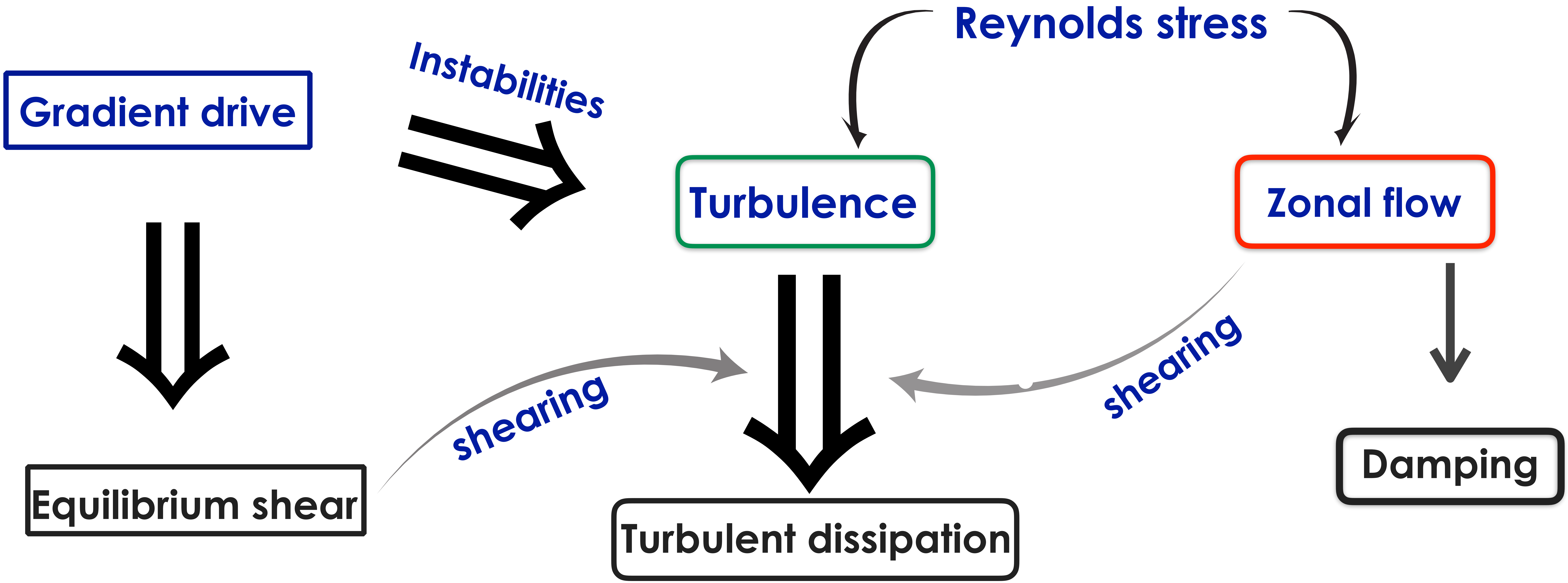
Production term

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

- **The turbulence quantities change across at the L-H transition but not *before*, so the changes do not help identify the L-H trigger mechanism.**
  - **Poloidal velocities do not change prior to the L-H transition**

- **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.**

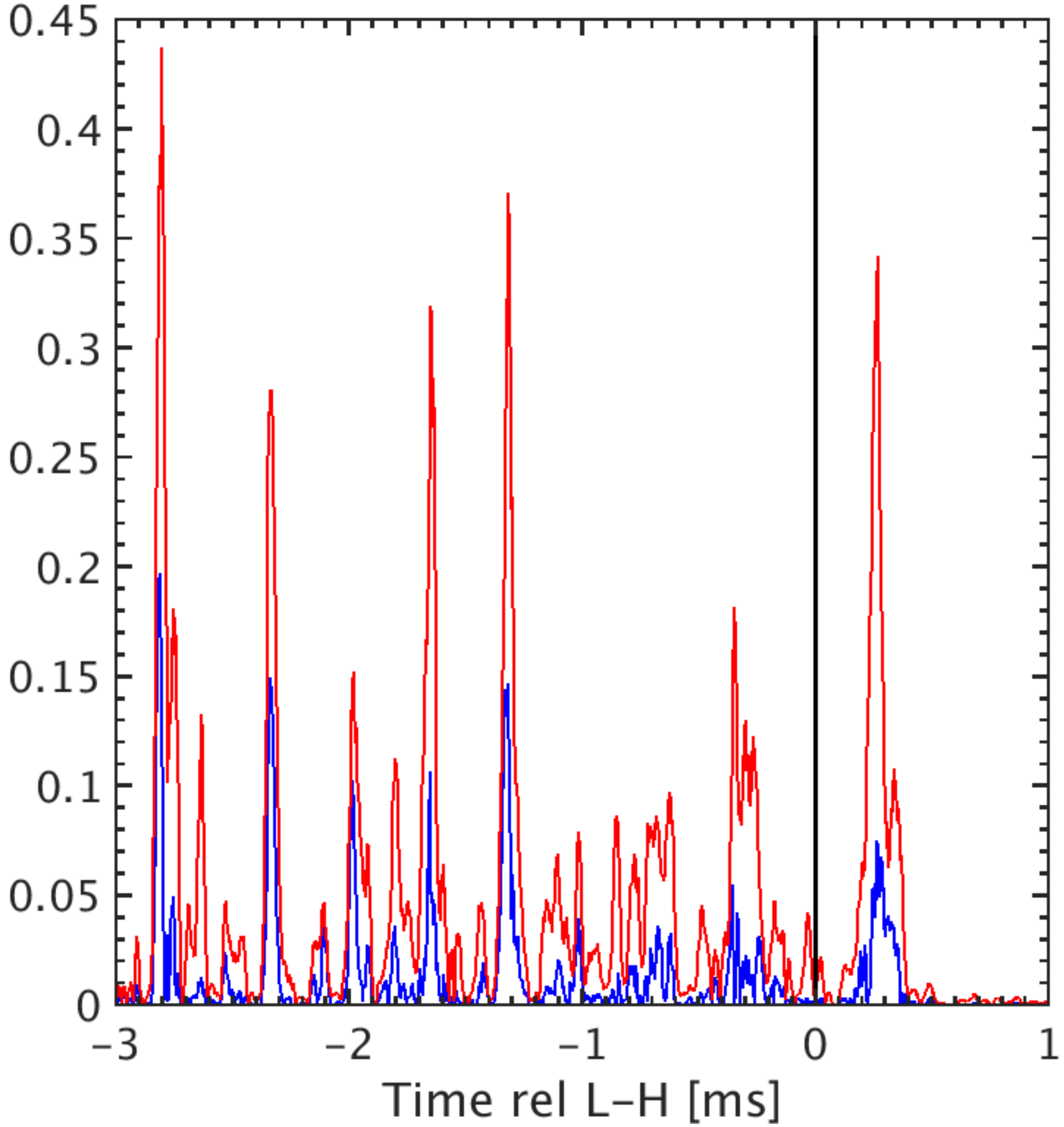
Summary: energy balance



Analysis does not rule out Zonal flow playing a role in affecting the turbulence dissipation channel

Supplementary material

Simplified estimates of the Reynolds work provide an upper bound the production term



$$\frac{P}{P_0} \doteq \frac{|n_0 m_i \langle \tilde{v}_\theta \tilde{v}_r \rangle \partial_r \langle \bar{v}_\theta \rangle|}{0.5(E_{turb}|_L - E_{turb}|_H)\tau_{L-H}^{-1}}$$

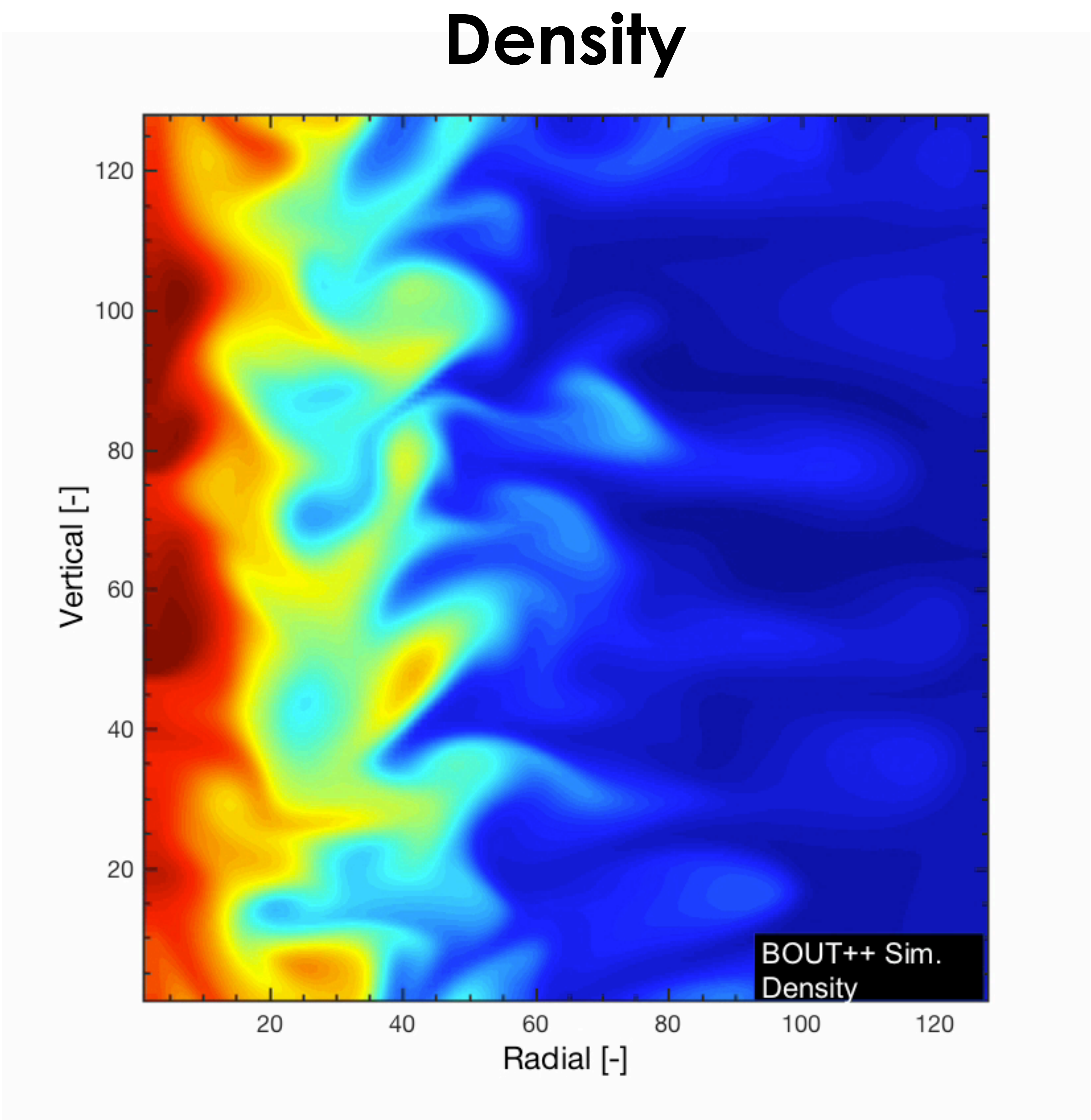
Using the triangularity inequality:

$$2\langle \tilde{v}_\theta \tilde{v}_r \rangle \leq \left\langle \tilde{v}_\theta^2 \right\rangle + \left\langle \tilde{v}_r^2 \right\rangle$$

$$\boxed{\frac{P}{P_0} \leq \frac{|n_0 m_i \left\langle \tilde{v}_\theta^2 + \tilde{v}_r^2 \right\rangle \partial_r \langle \bar{v}_\theta \rangle|}{(E_{turb}|_L - E_{turb}|_H)\tau_{L-H}^{-1}}}$$

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

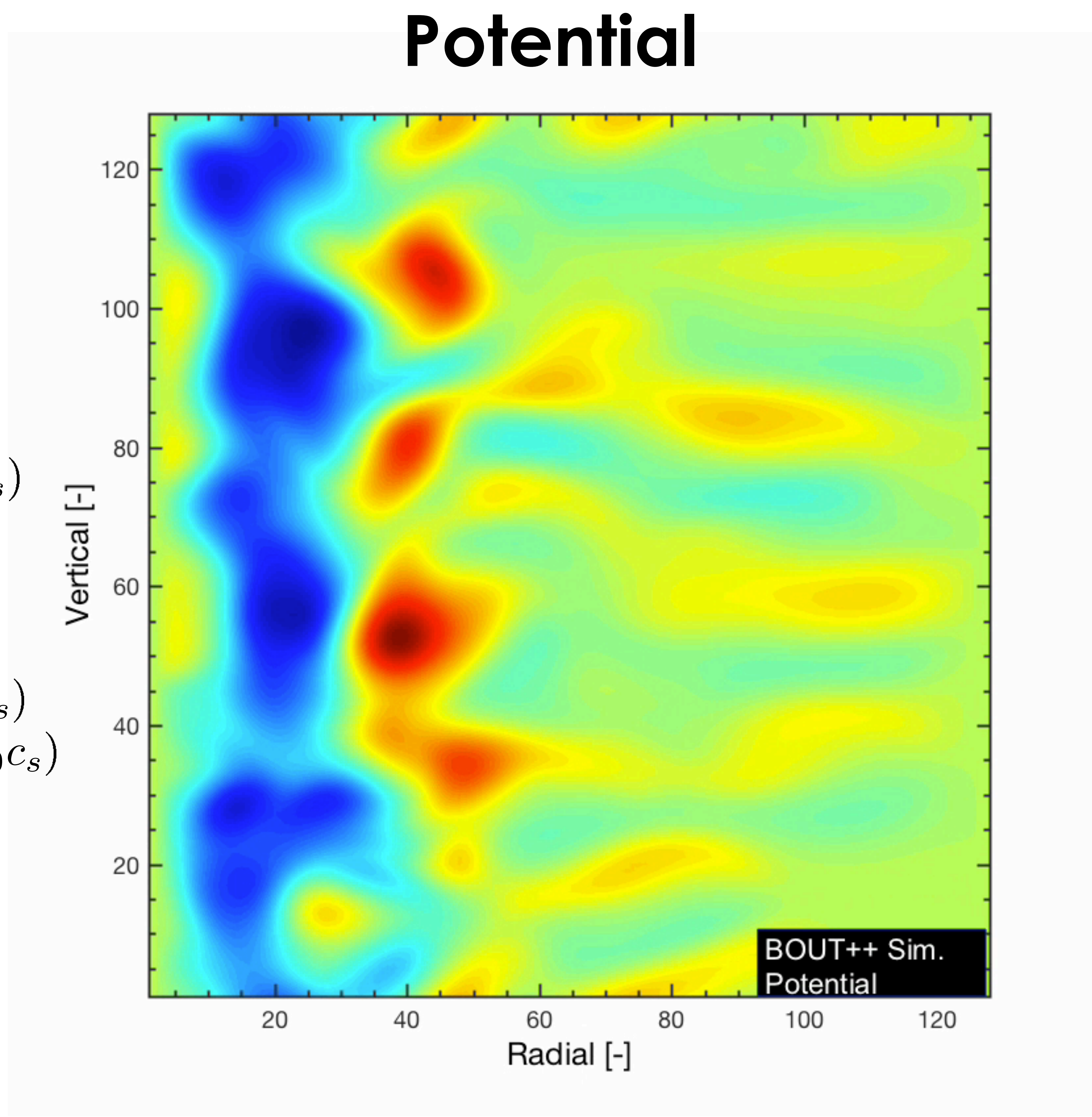
BOUT++ simulations for testing veleocimetry



Box length :: $l_x \times l_y = 192\rho_s \times 192\rho_s$
Grid points :: $n_x \times n_y = 128 \times 128$

Sheath Conductivity :: $\sigma = 2.0 \times 10^{-4}$
Particle Diffusions coefficient :: 0.01 $(/\rho_s c_s)$

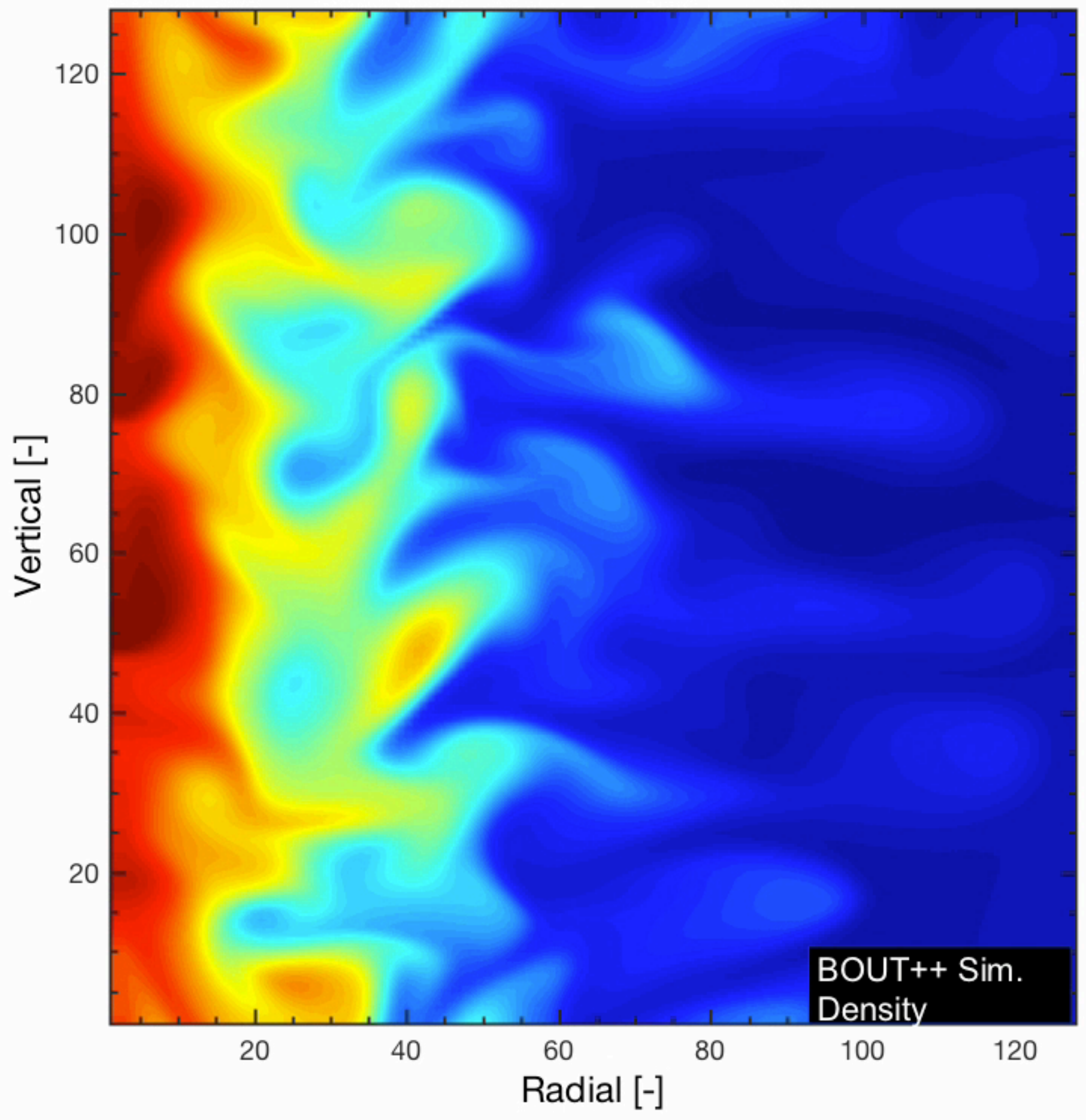
Viscosity :: $0.01(/\rho_s c_s)$
Neutral diffusion :: 0.4 $(/\rho_s c_s)$
Particle flux from core :: 1.0×10^{-4} $(/n_0 c_s)$
Neutral source (for UTE0) :: $1 \times 10^{-5}(/n_0 c_s)$



Courtesy N. Bisai, IPR

BOUT++ simulations for testing veleocimetry

Density



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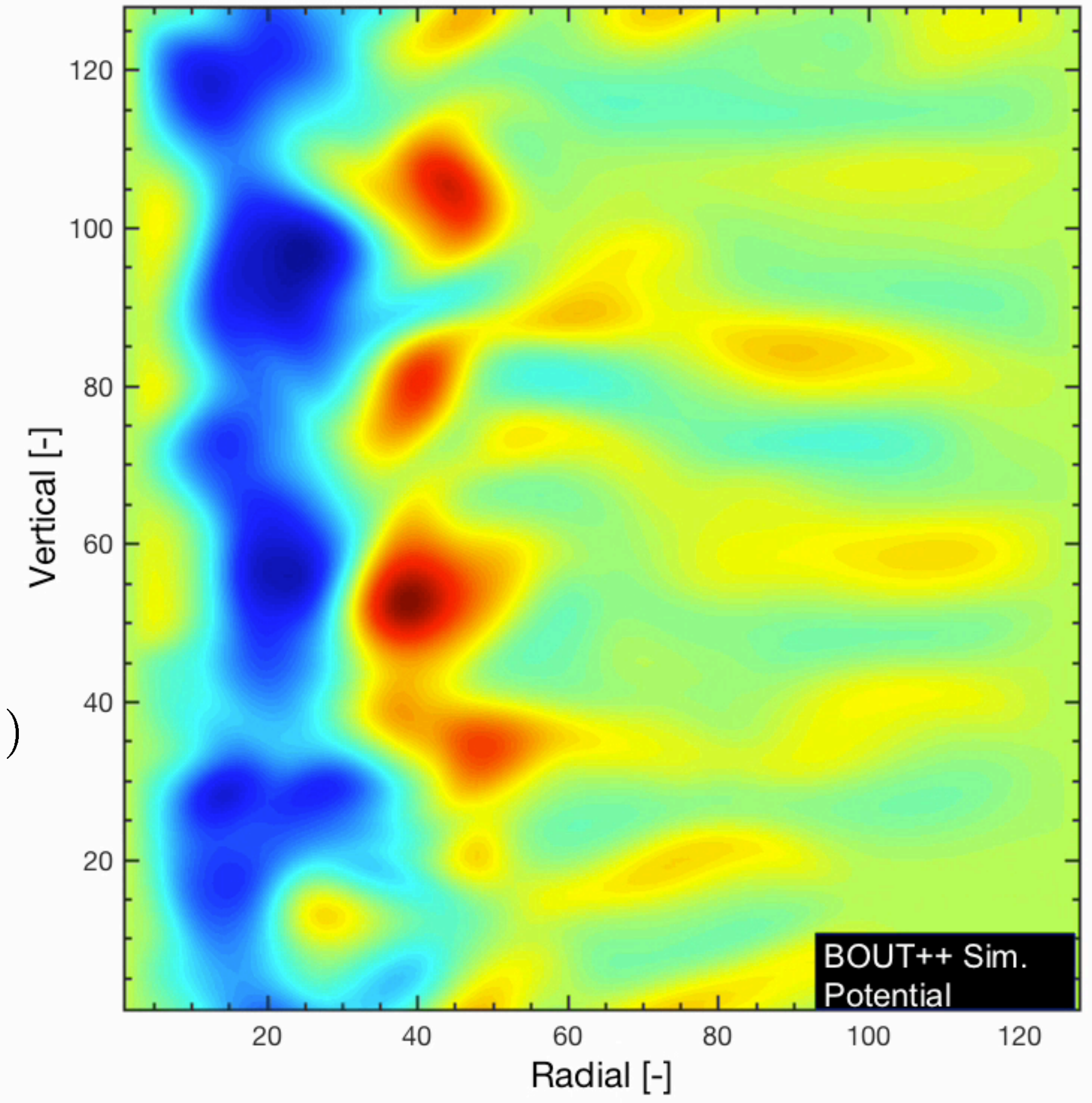
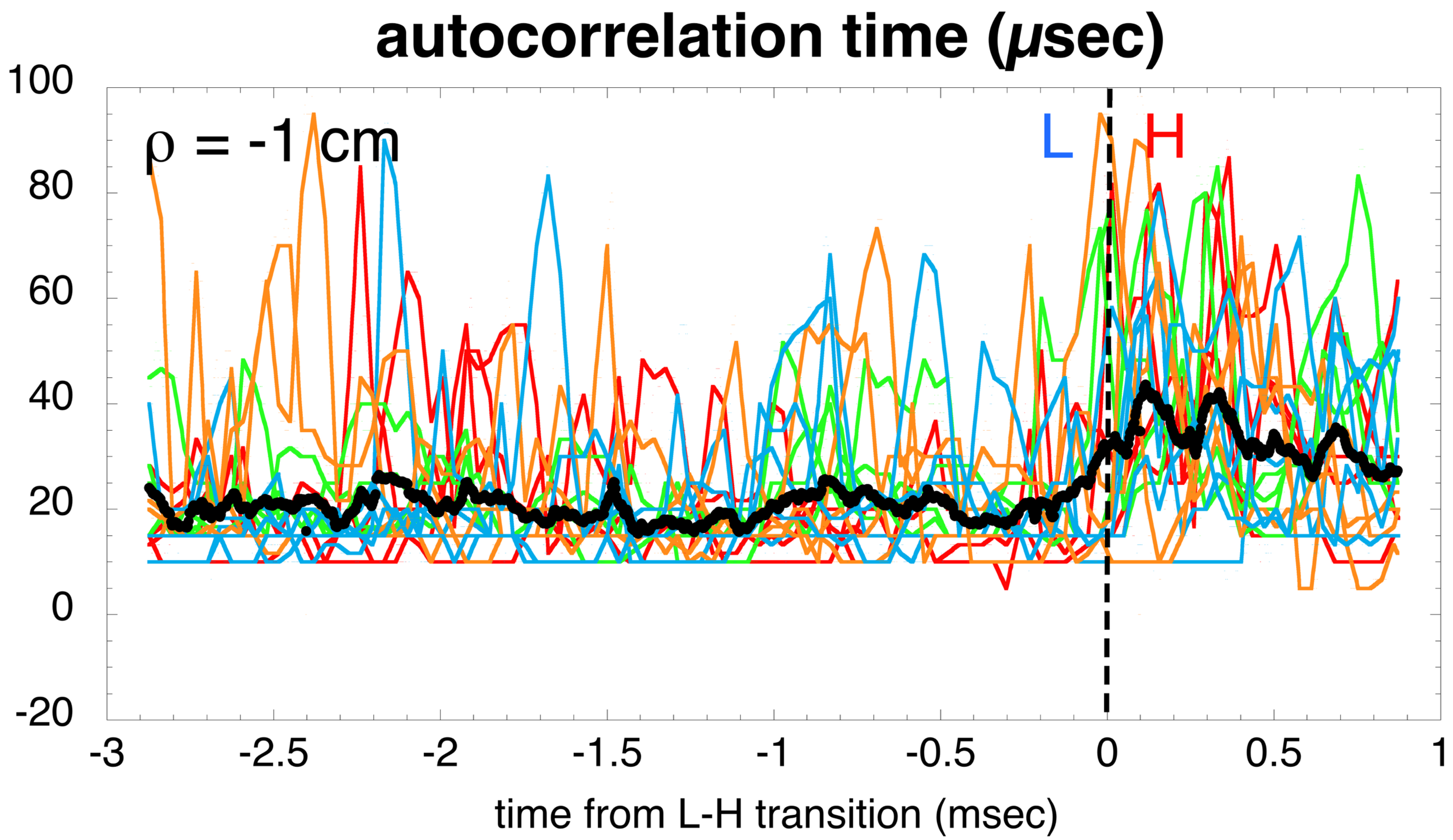
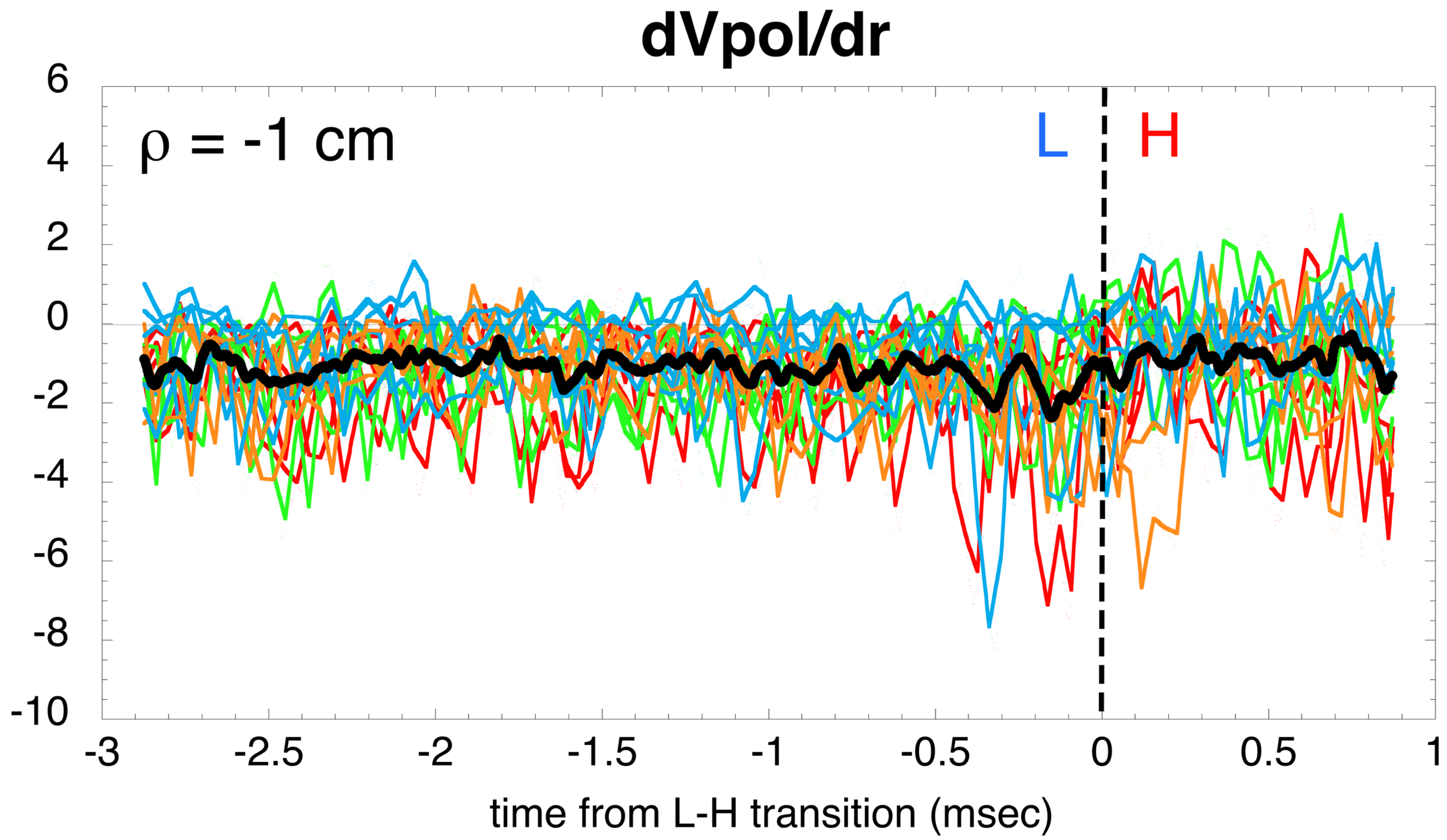
Potential



Courtesy N. Bisai, IPR

L-H transition is associated with an increase of the autocorrelation time





- Average autocorrelation time =22 μsec in L and 34 μsec in H-mode
- Average dV_{pol}/dr= - 1.1 km/s/cm in L and - 0.85 km/s/cm in H-mode

Velocity shear estimates