Energy Exchange Dynamics across L-H Transitions in NSTX

Ahmed Diallo

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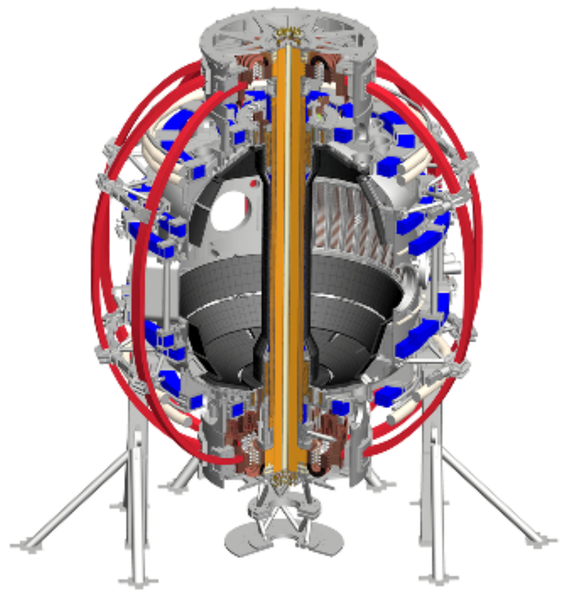
2017 APS-DPP Meeting
Milwaukee, WI



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

L-H transition is defined as …

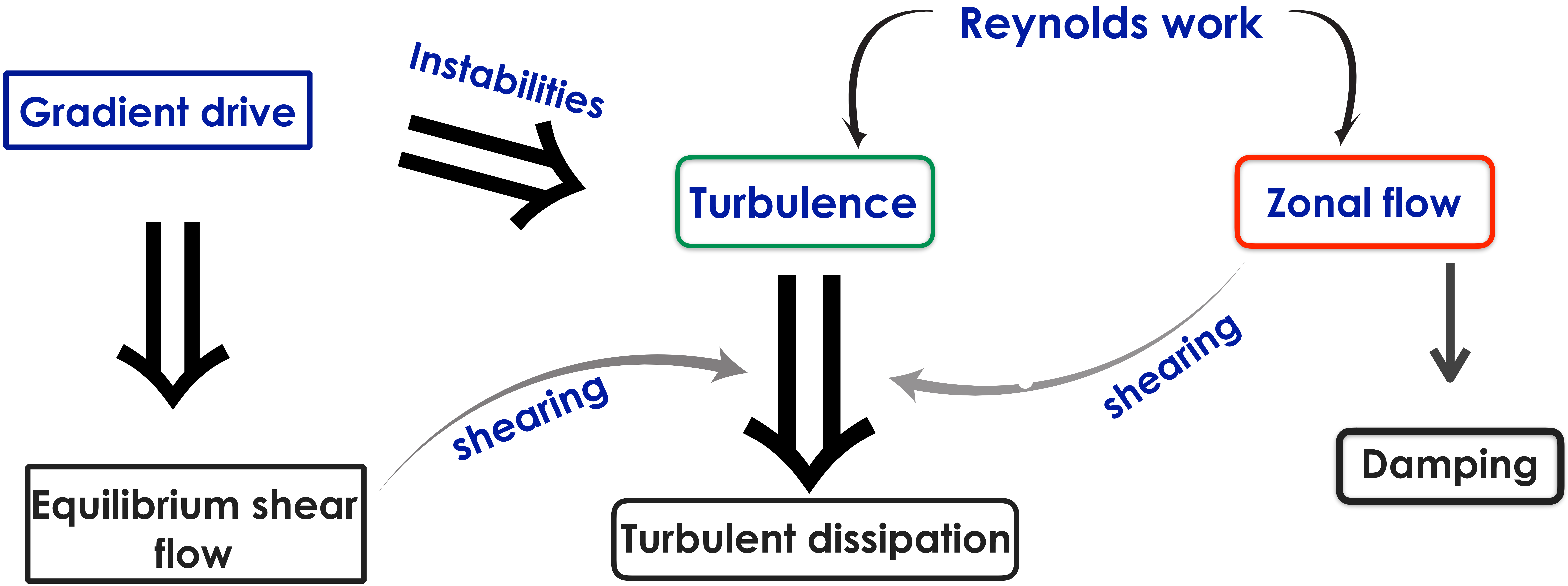
- It is the sudden transition to a state of good energy confinement:
  - Expected mode of operation for ITER.

- It appears as heating power increases past some threshold.

Wagner PRL (1982)

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

General paradigm leading to L-H transition: energy balance



Two main mechanisms can occur for turbulence suppression by flow shear

non-zonal ExB energy

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

→

Zonal ExB energy

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

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

Diamond et.al, Phys. Rev. Lett. 72, 2565 (1994).

2. Flow shear depletes the turbulence in other ways

Biglari, Diamond,and Terry, Phys. Fluids B 2, 1 (1990)

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

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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.

Biglari, Diamond,and Terry, Phys. Fluids B 2, 1 (1990)

Outline

- Previous results on energy transfer during the L-H transition
- Description of the NSTX gas-puff imaging system
- Tests of novel velocimetry technique using synthetic data
- Energy transfer dynamic across the L-H transition
- Summary

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

- Studies on EAST 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:

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

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

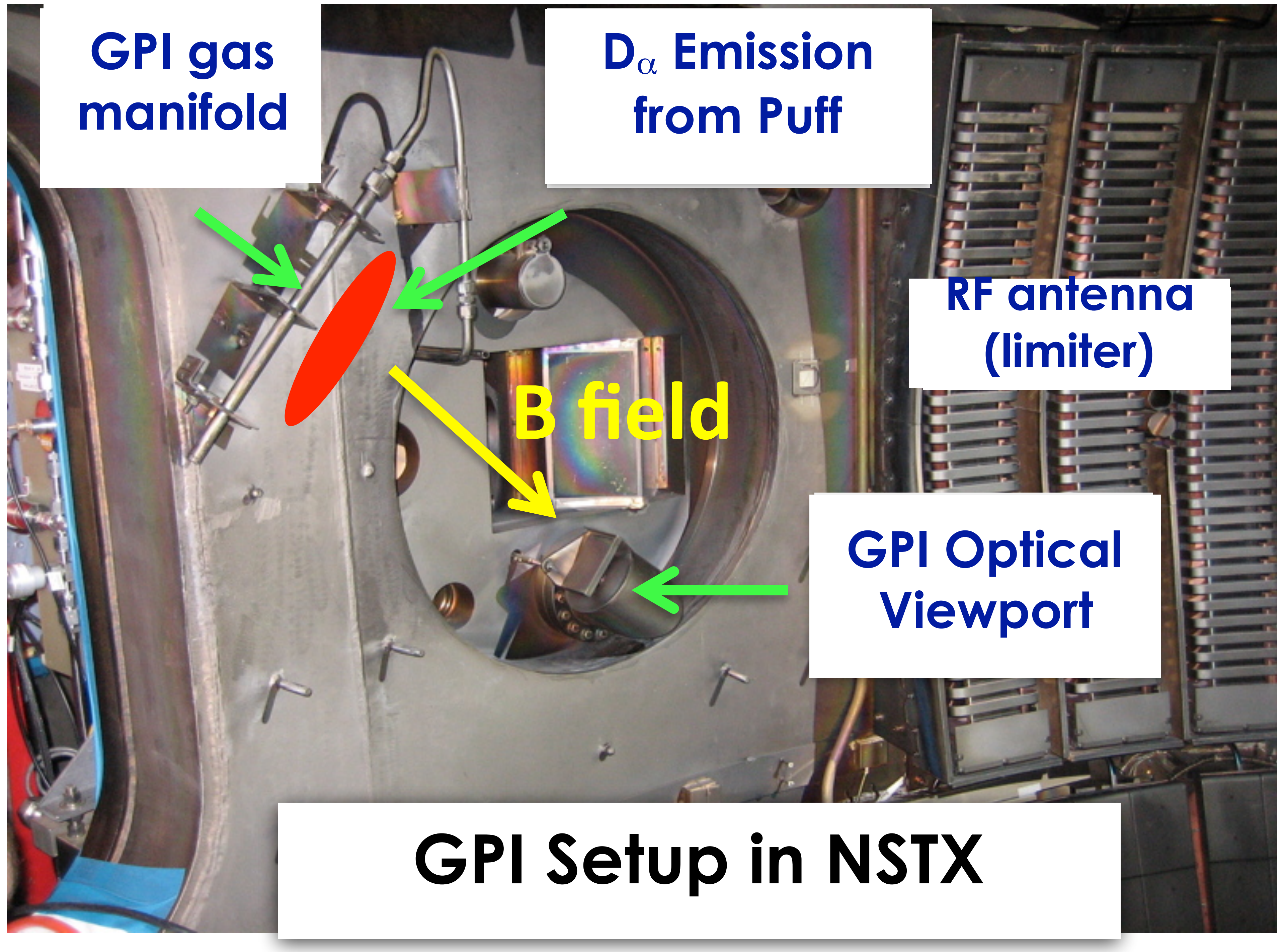
Cavedon et al. Nucl. Fusion 57 (2017) 014002

- JFT-2M showed that the observed Reynolds force is far too low to drive the 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

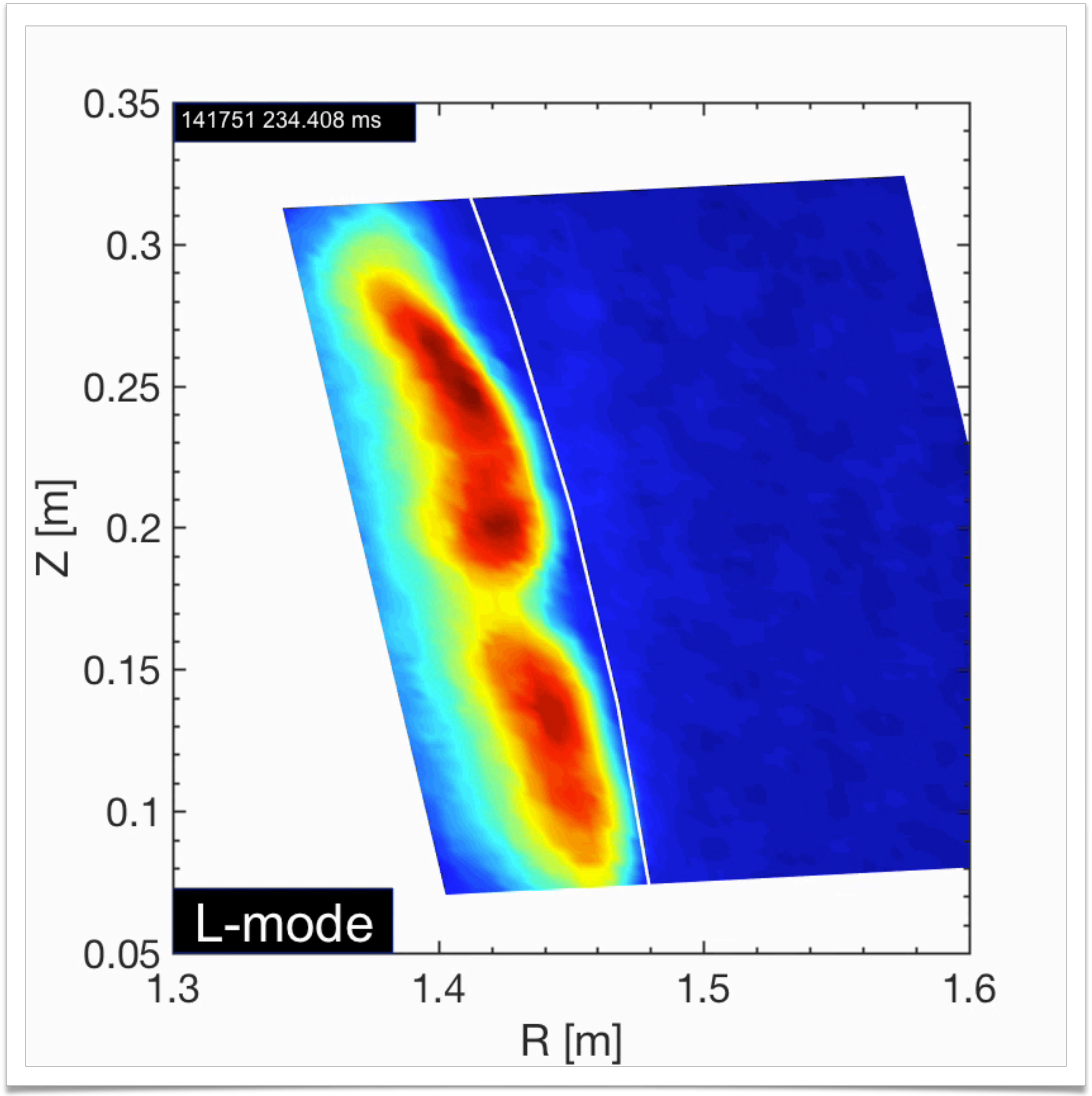
Zweben et al., Rev. Sci. Instrum. 88, 041101 (2017)



GPI Setup in NSTX

GPI provides edge turbulence images

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

- 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

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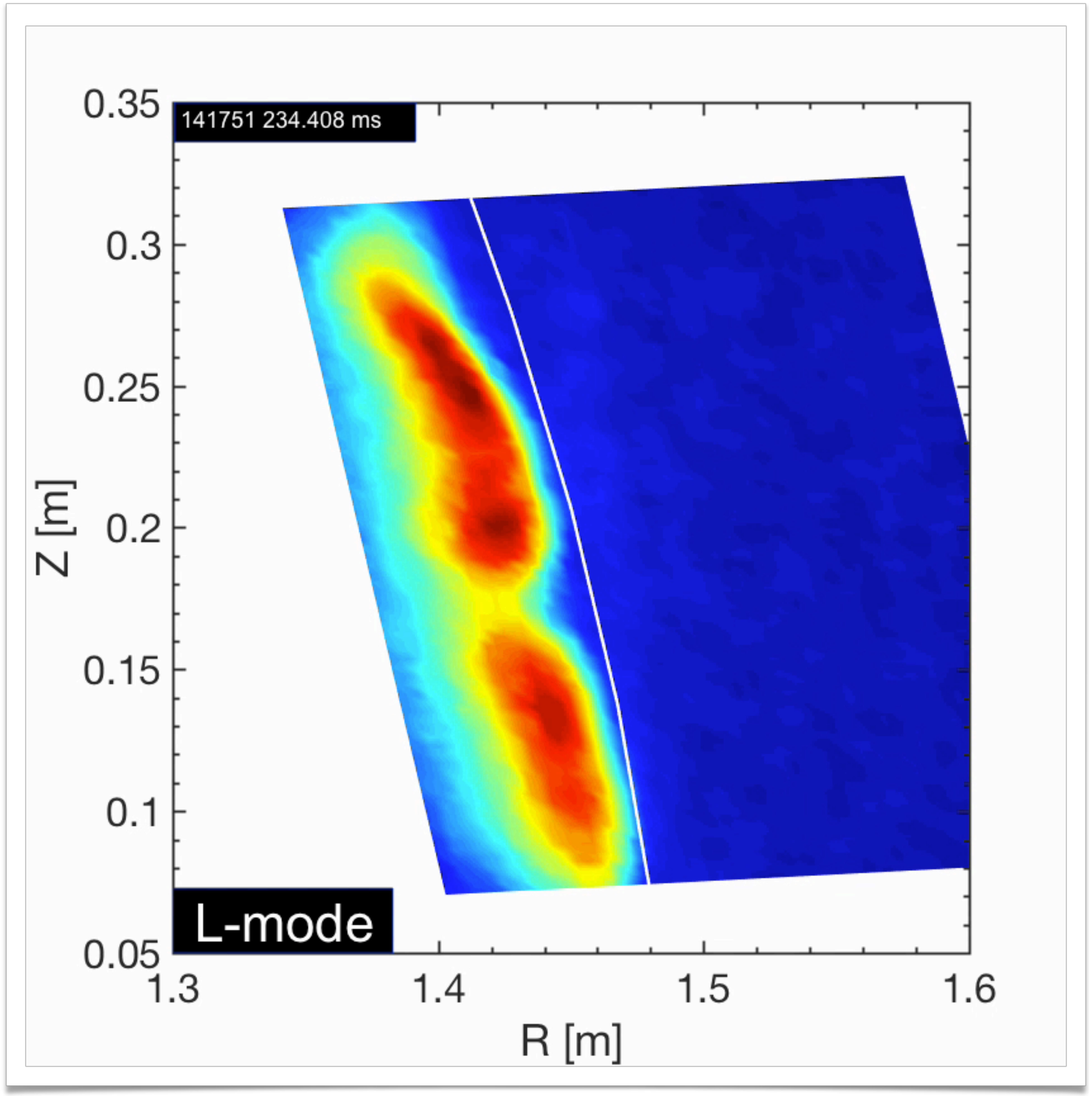

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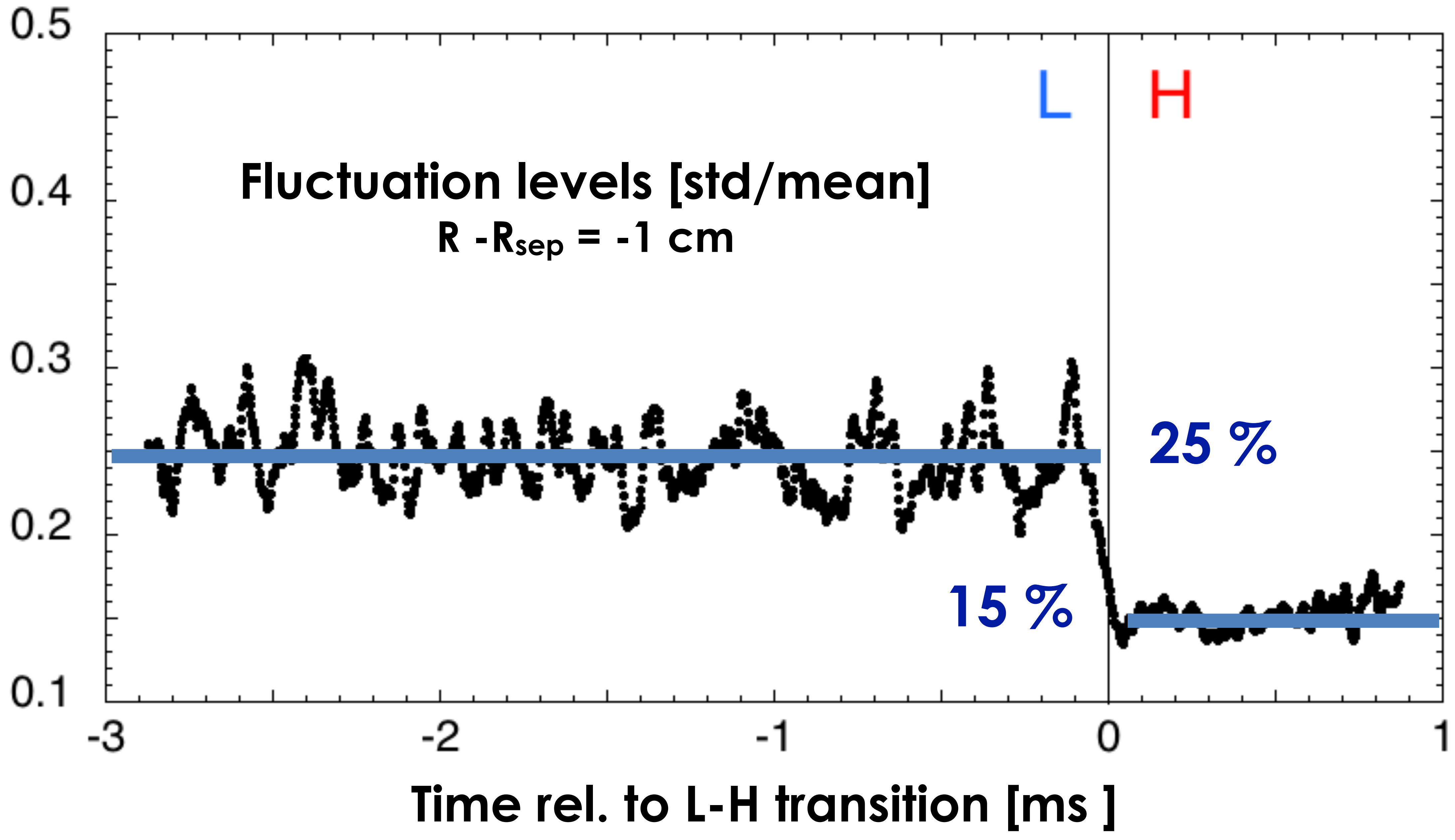
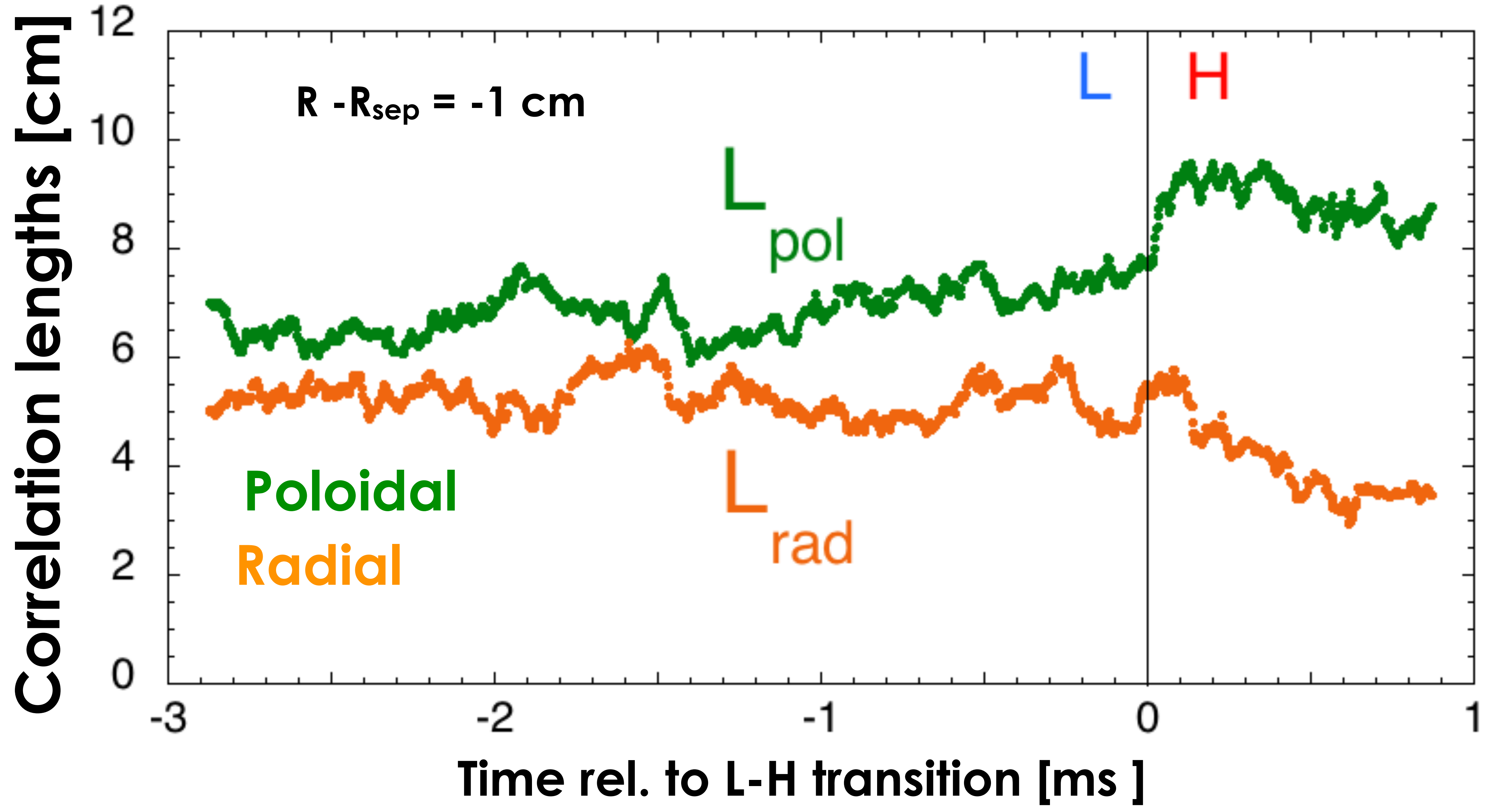
- L-H transition as a sudden (~100 μs) decrease in edge turbulence

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





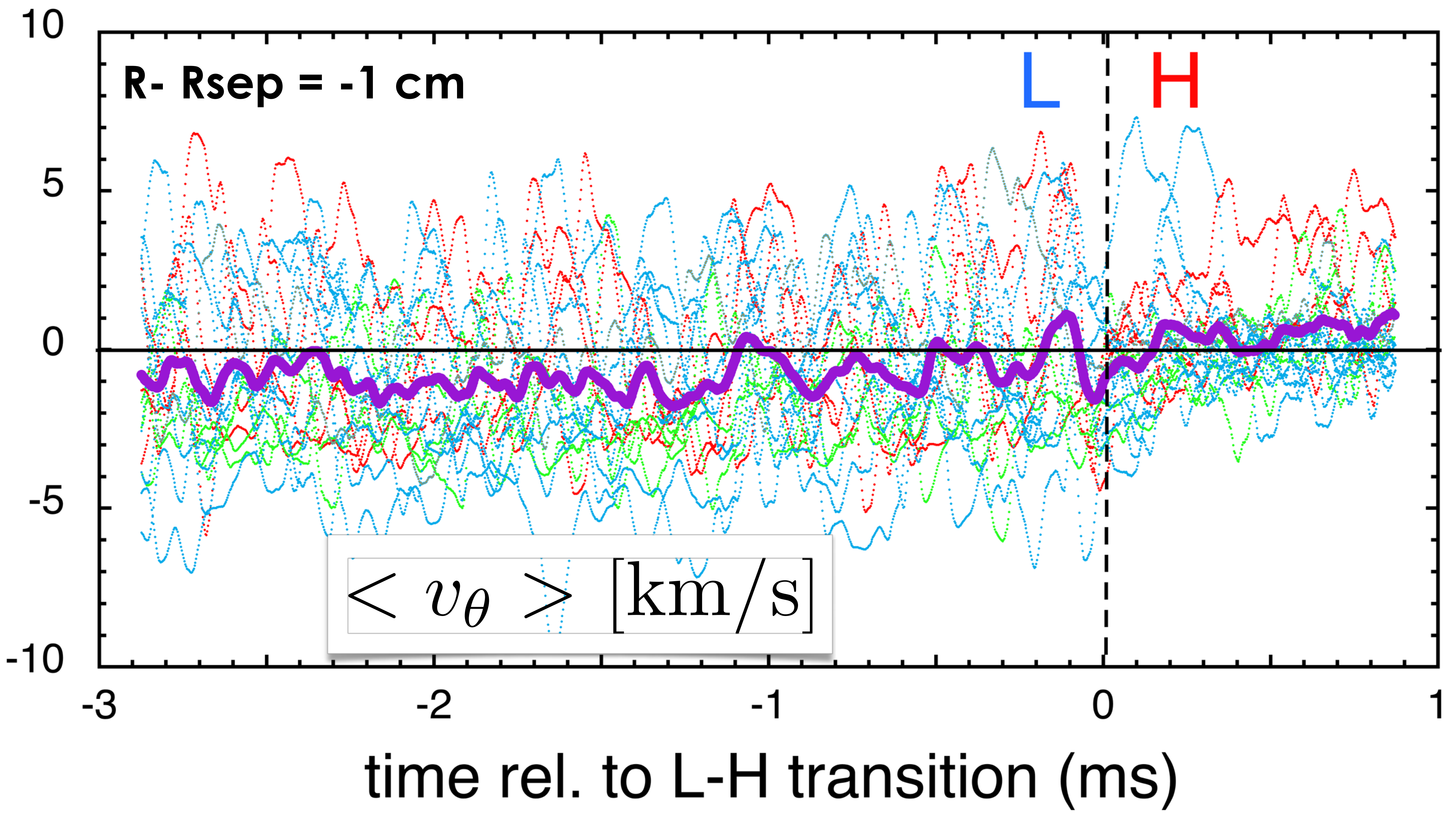
All turbulence quantities (averaged over 17 discharges)
nearly constant at all radii up to 3 cm inside the separatrix during 3 msec before transition

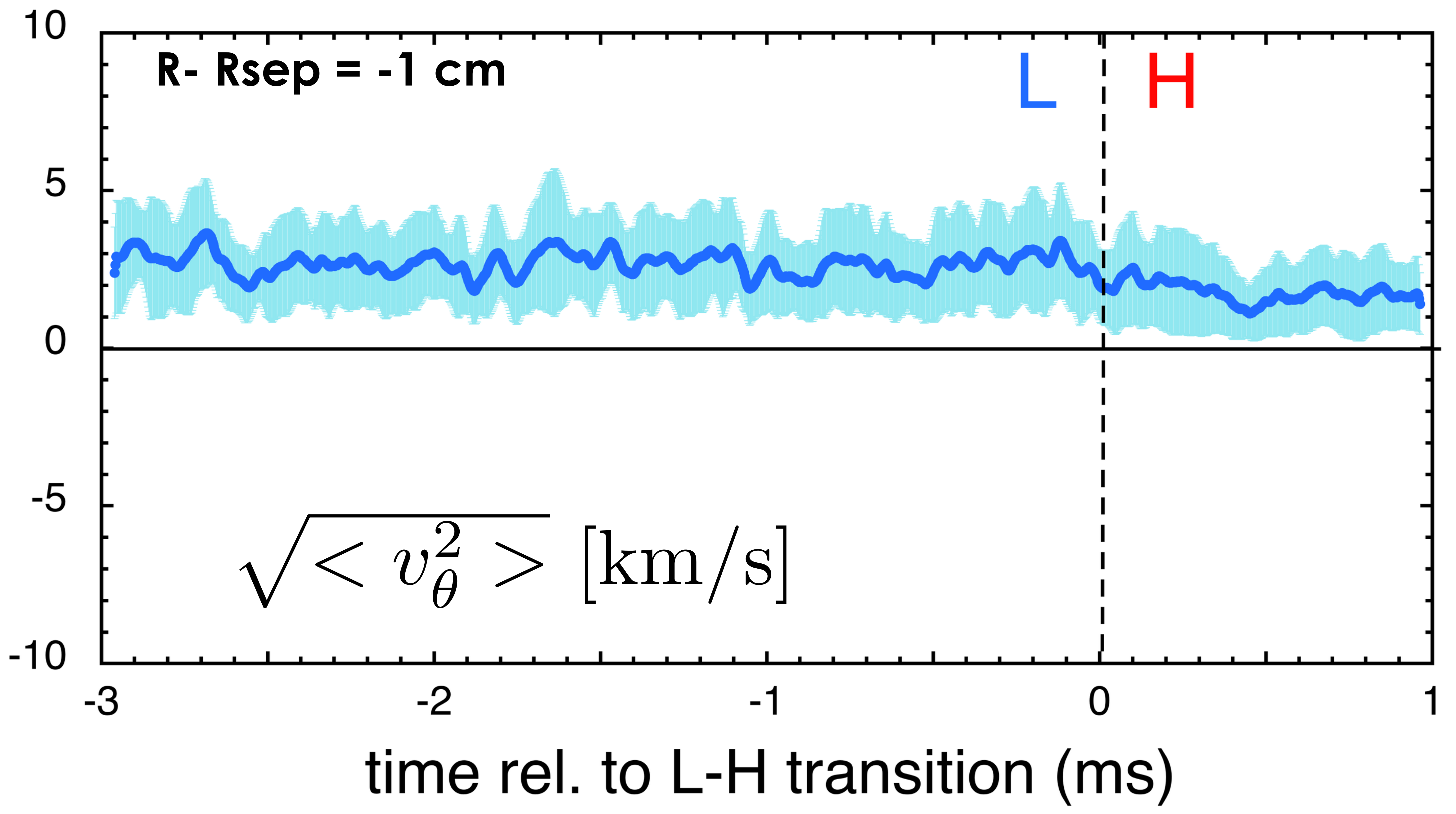
What causes the drop in fluctuation levels across the L-H transition?

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





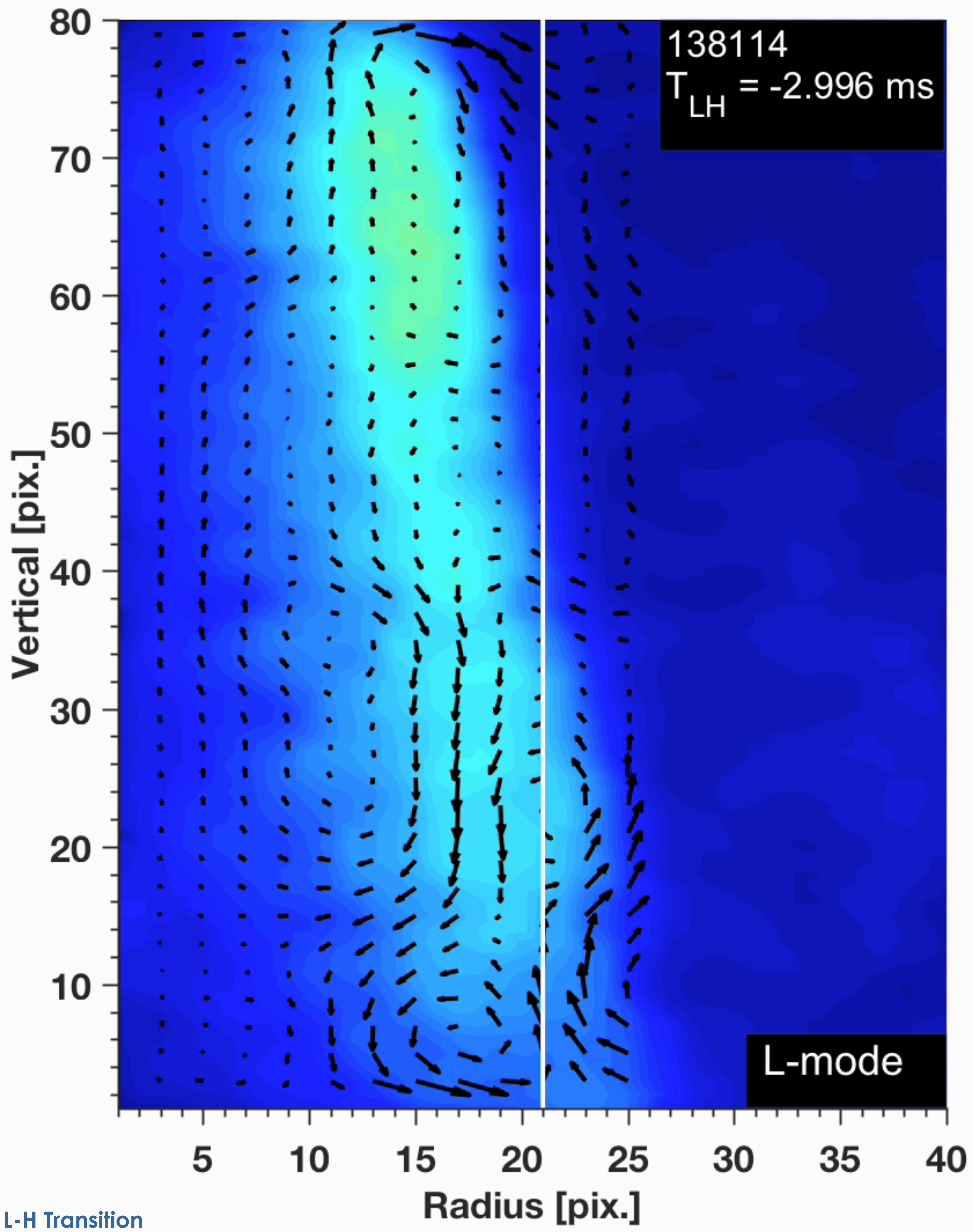
These quantities are averaged in poloidal angles and in time (over 30 μs) and over multiple shots

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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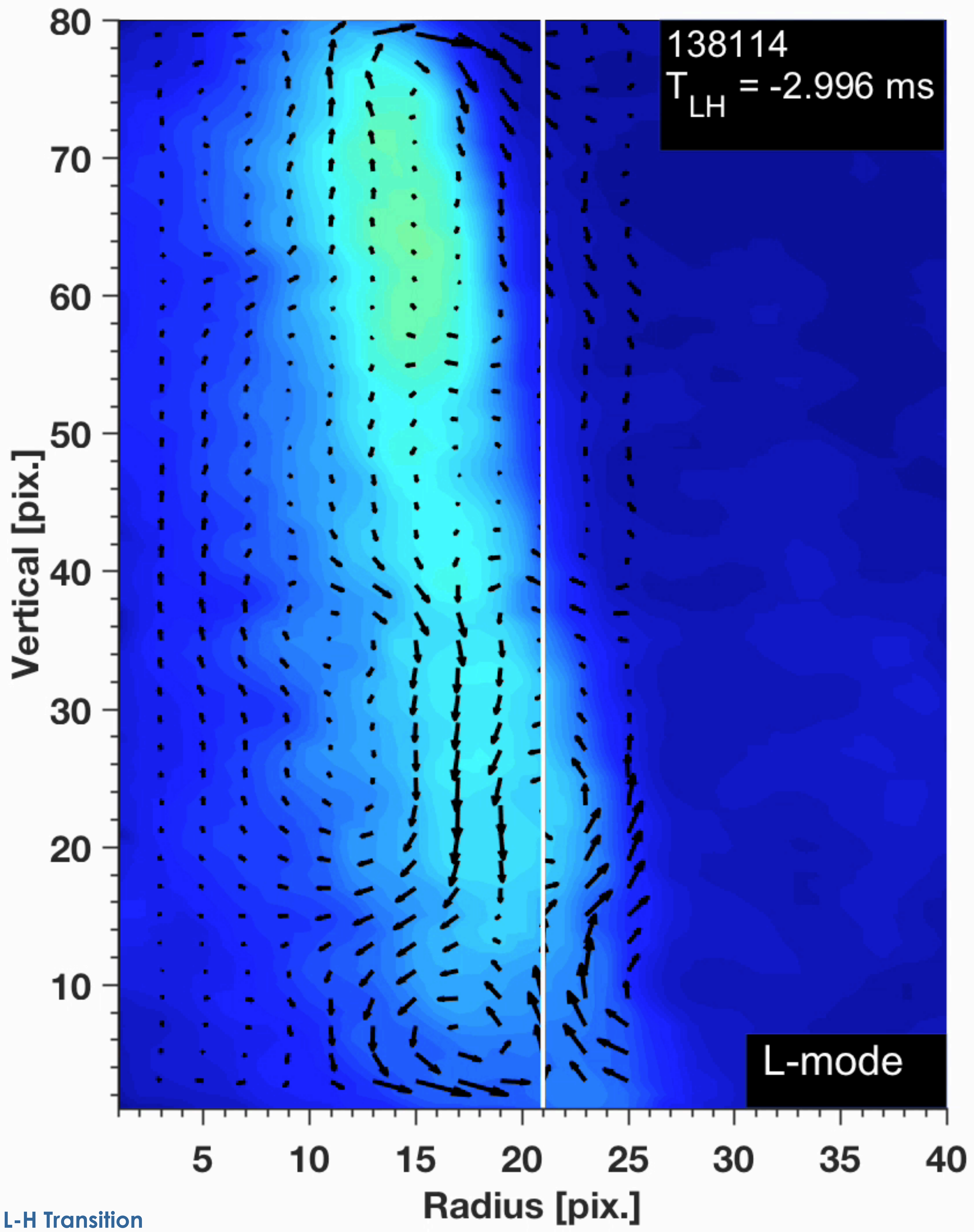

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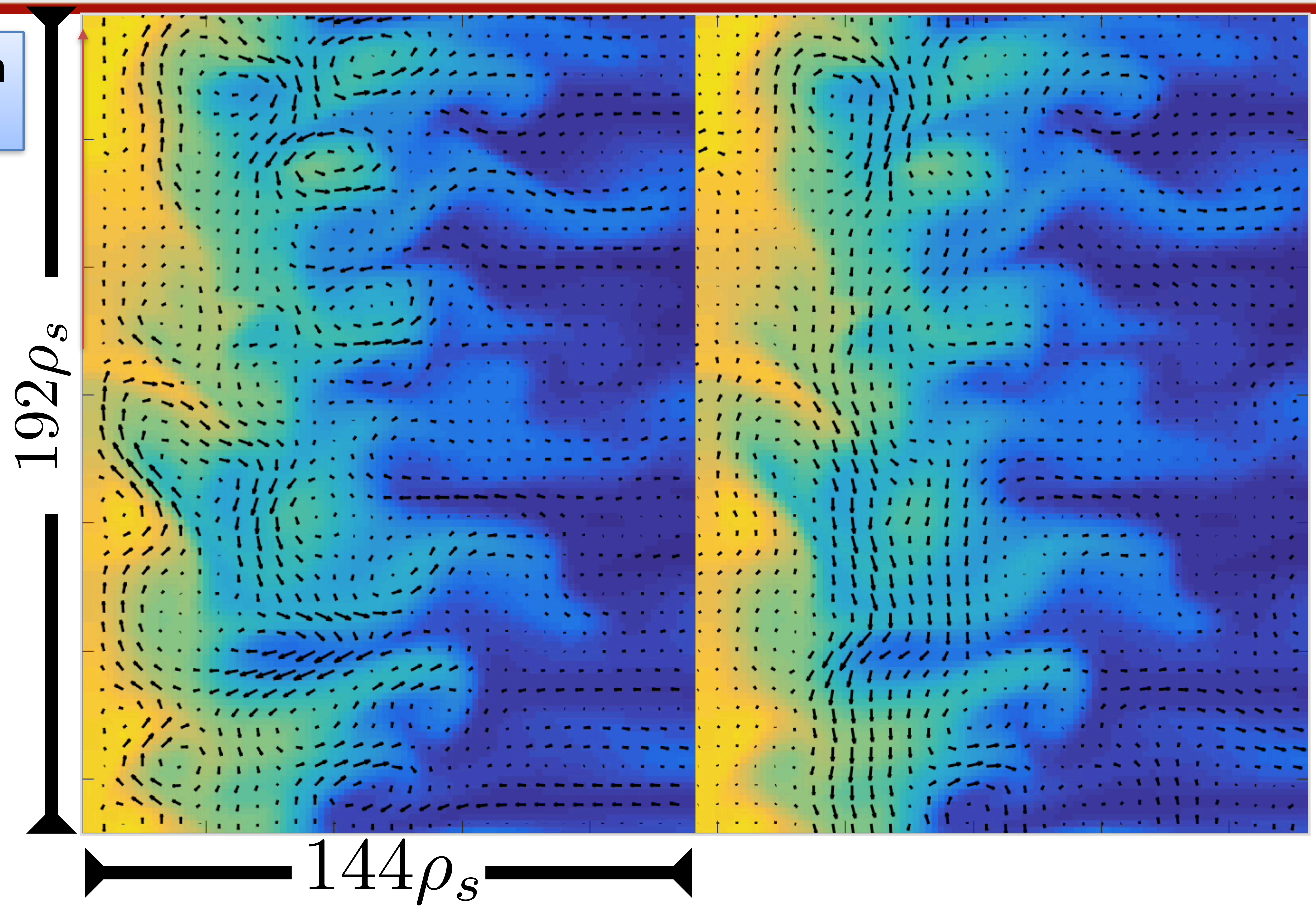
Comparison between ExB velocities and velocities determined from velocimetry

ExB velocities from simulations

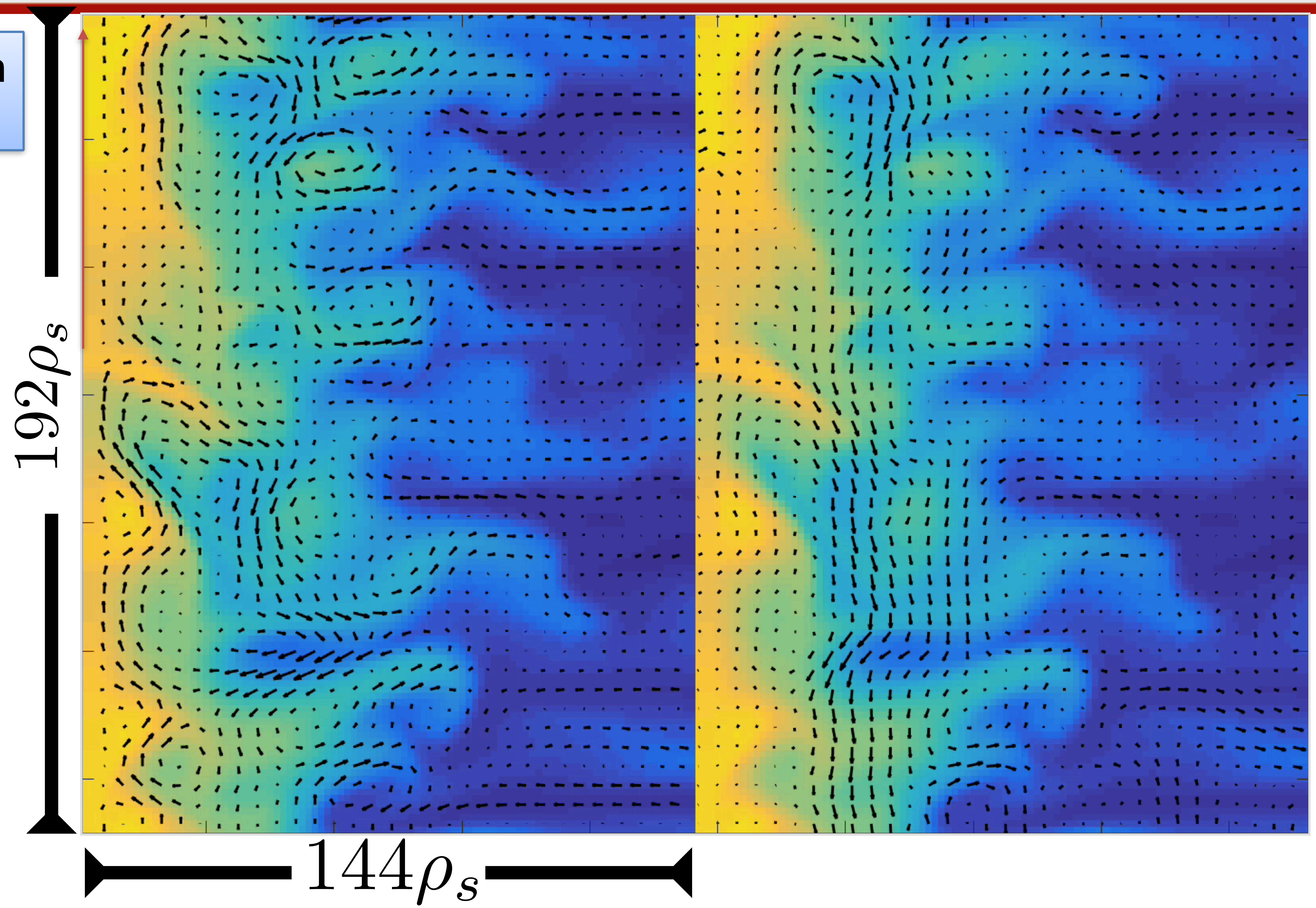
Velocities determined from velocimetry



Synthetic data obtained from BOUT++ simulation courtesy N. Bisai, IPR

Comparison between ExB velocities and velocities determined from velocimetry

ExB velocities from simulations



Velocities determined from velocimetry

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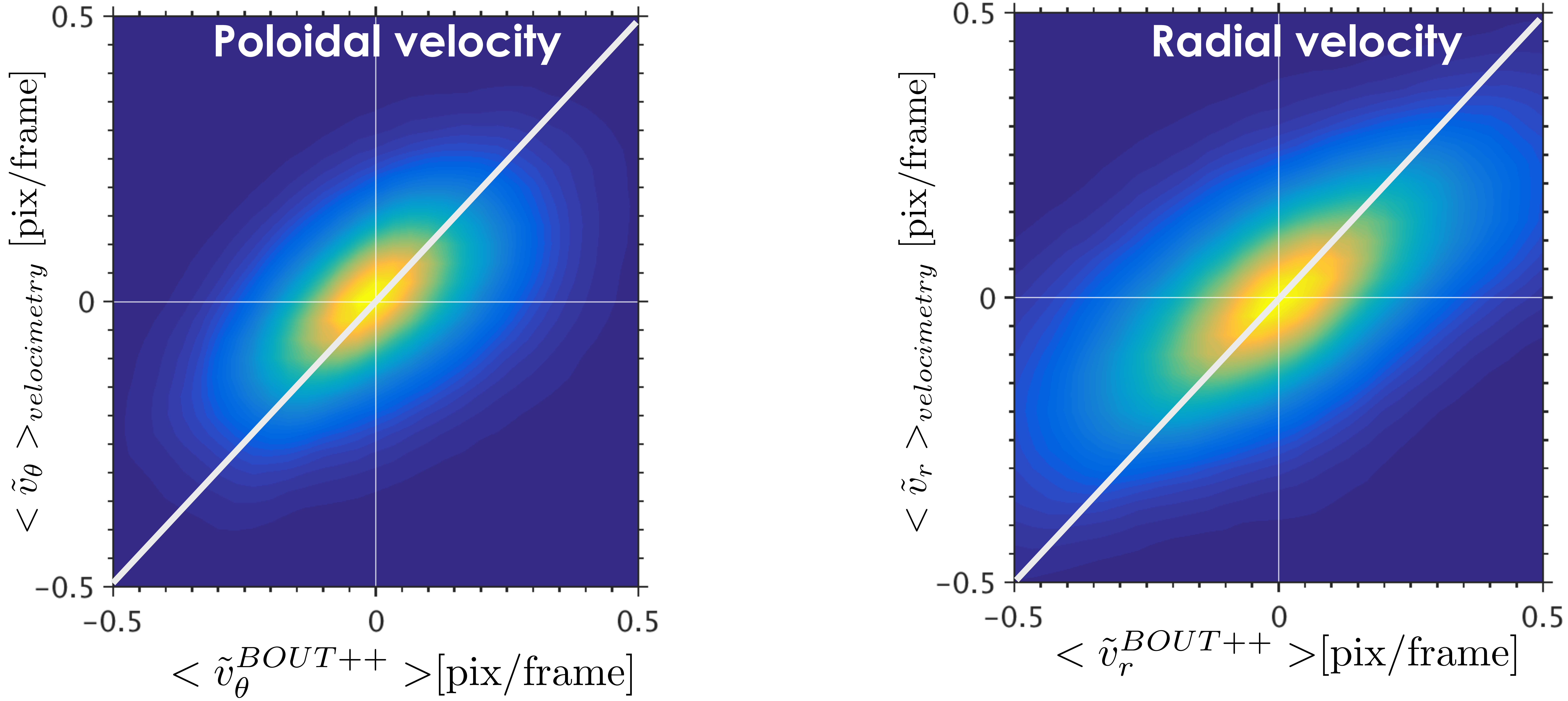
Novel velocimetry analysis agrees with the fluctuating components of the ExB velocity from BOUT++



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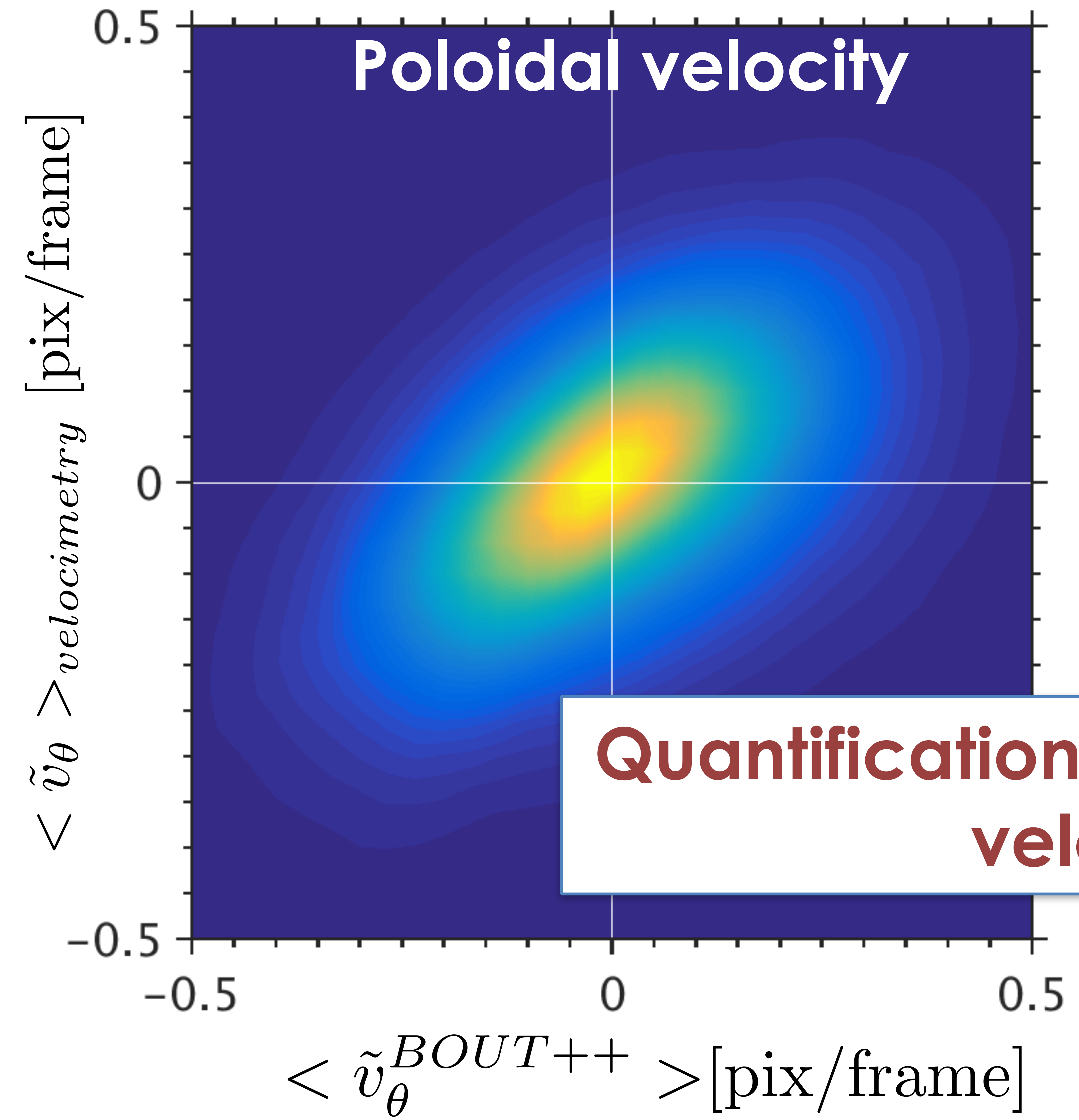
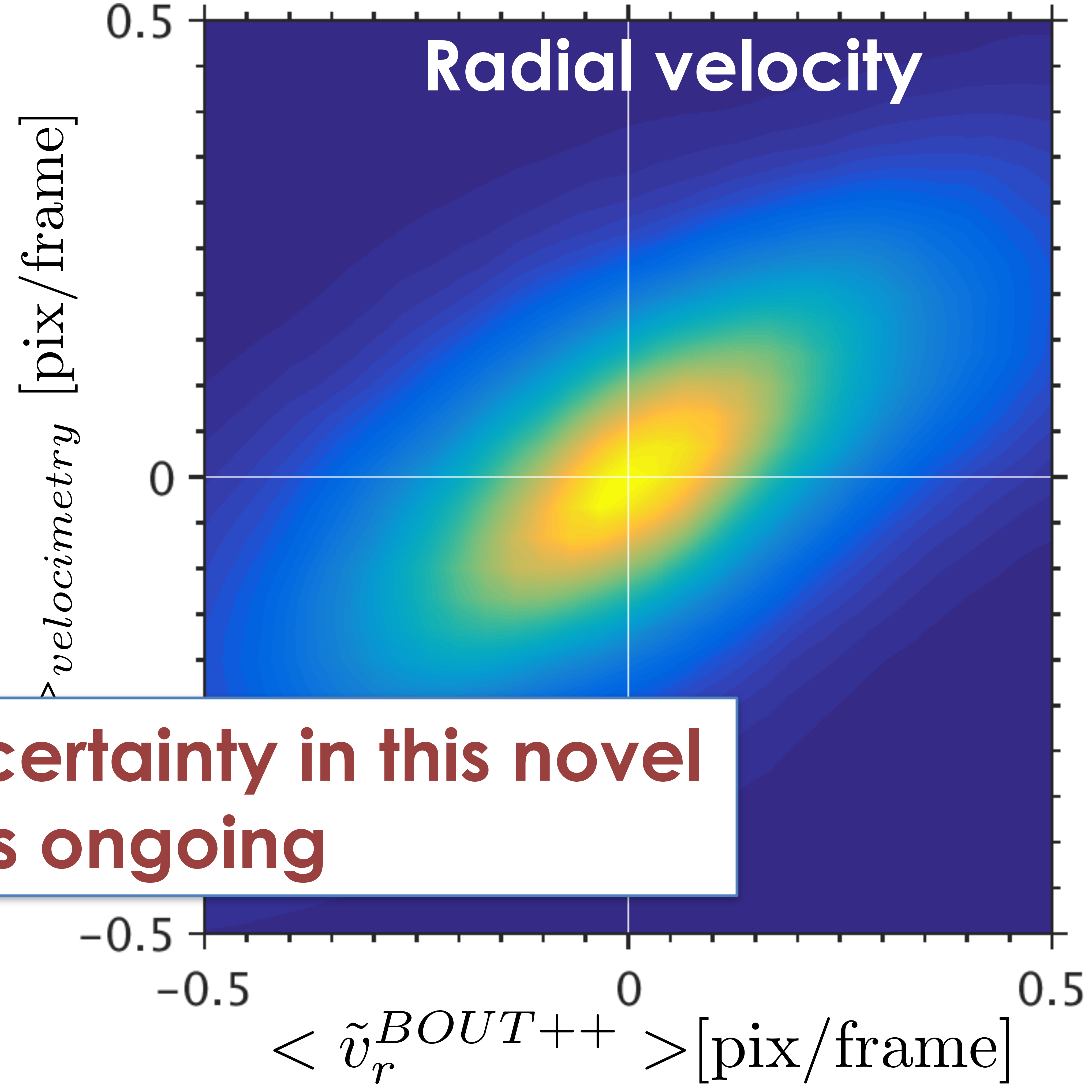
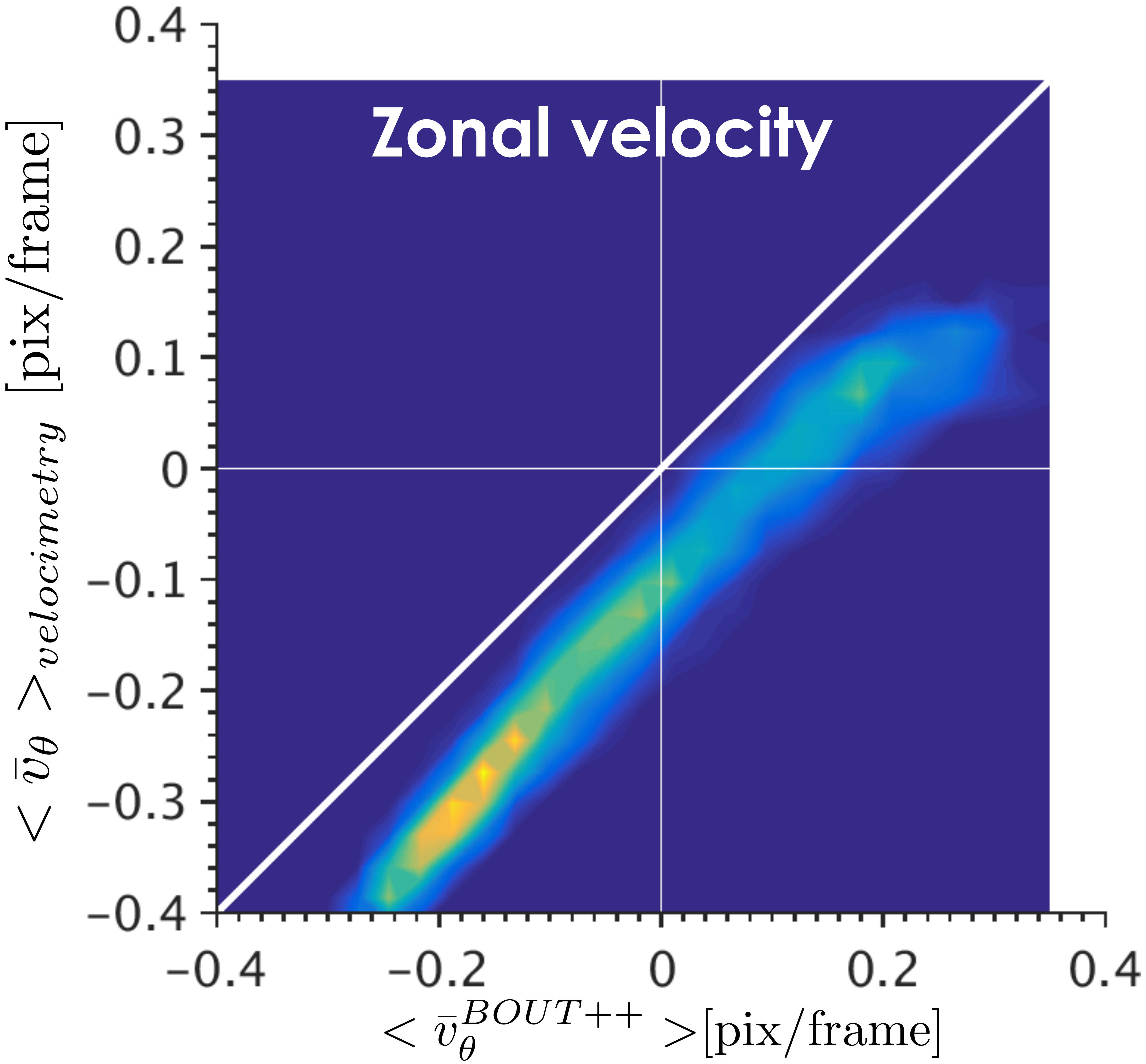




Quantification of the uncertainty in this novel velocimetry is ongoing

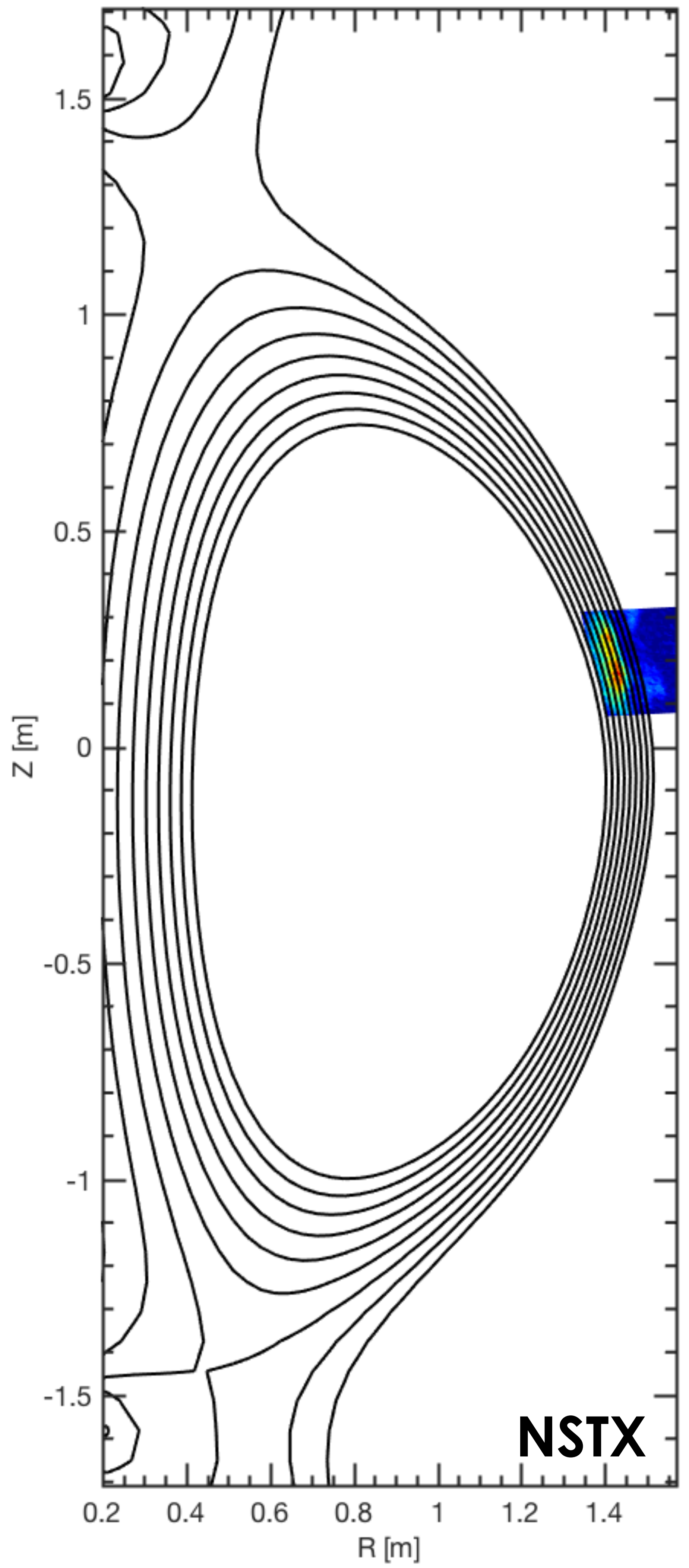
Velocimetry analysis captures poloidally averaged mean flow from synthetic data with fixed offset



- **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

We decompose the velocity field into zonal and non-zonal components



- 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 dynamic across the L-H transition**
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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

$$\frac{n_0 m_i \langle \tilde{v}_\theta^2 \rangle}{2}$$

P>0

P<0

Zonal ExB energy

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

Negative Production term

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

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})

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

+

non-zonal ExB energy

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

Zonal ExB energy

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

Production term

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

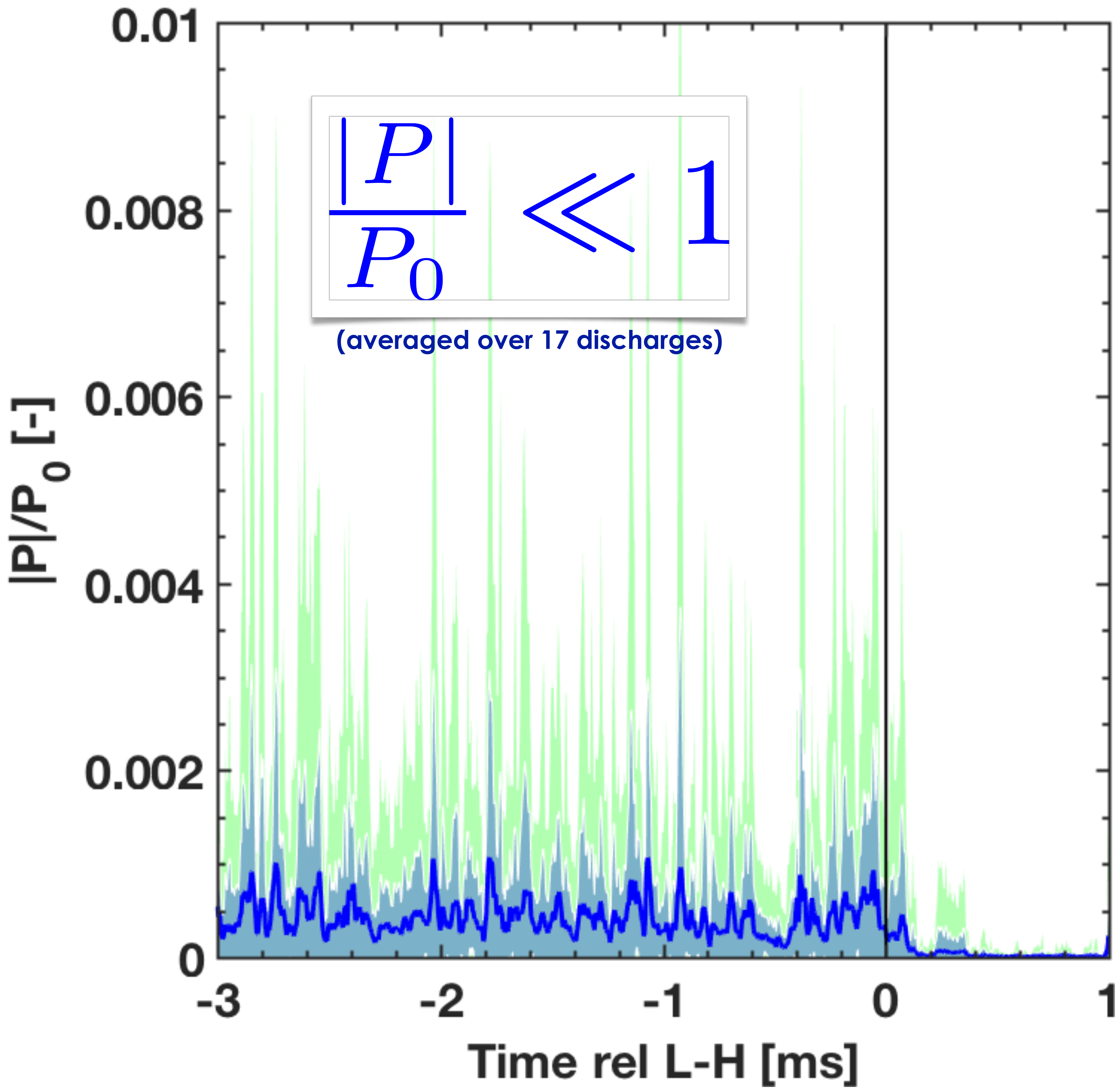
Turbulence energy (E_{Turb})

γ = **Growth rate**

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 turbulence 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 evaluated for NSTX

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

- 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

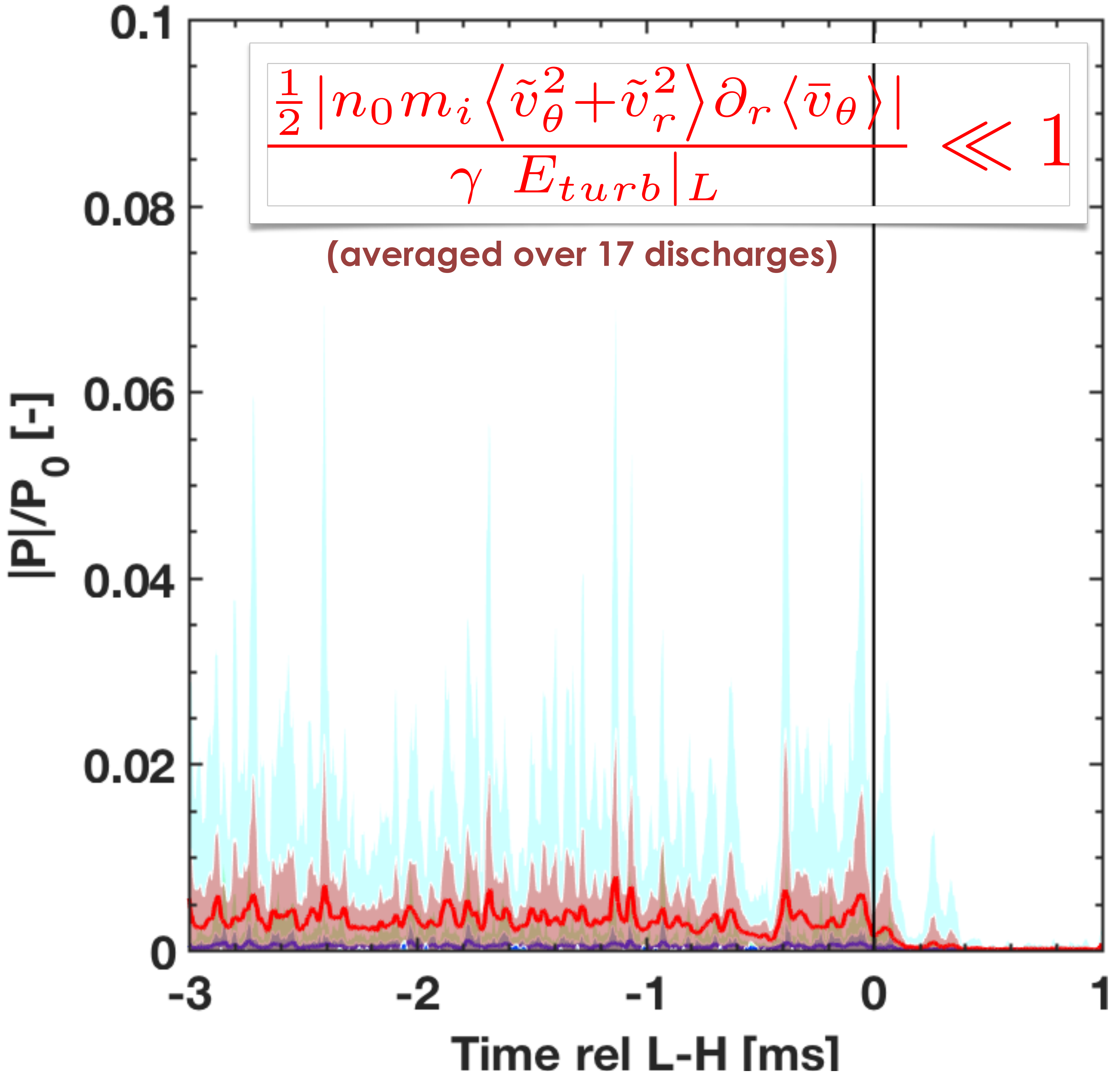
$$\frac{|P|}{P_0} \doteq \frac{|n_0 m_i \langle \tilde{v}_\theta \tilde{v}_r \rangle \partial_r \langle \bar{v}_\theta \rangle|}{\gamma \; E_{turb}|_L}$$

Using the triangle inequality:

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

$$\frac{|P|}{P_0} \leq \frac{\frac{1}{2} |n_0 m_i \left\langle \tilde{v}_\theta^2 + \tilde{v}_r^2 \right\rangle \partial_r \langle \bar{v}_\theta \rangle|}{\gamma \; E_{turb}|_L}$$

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



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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

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

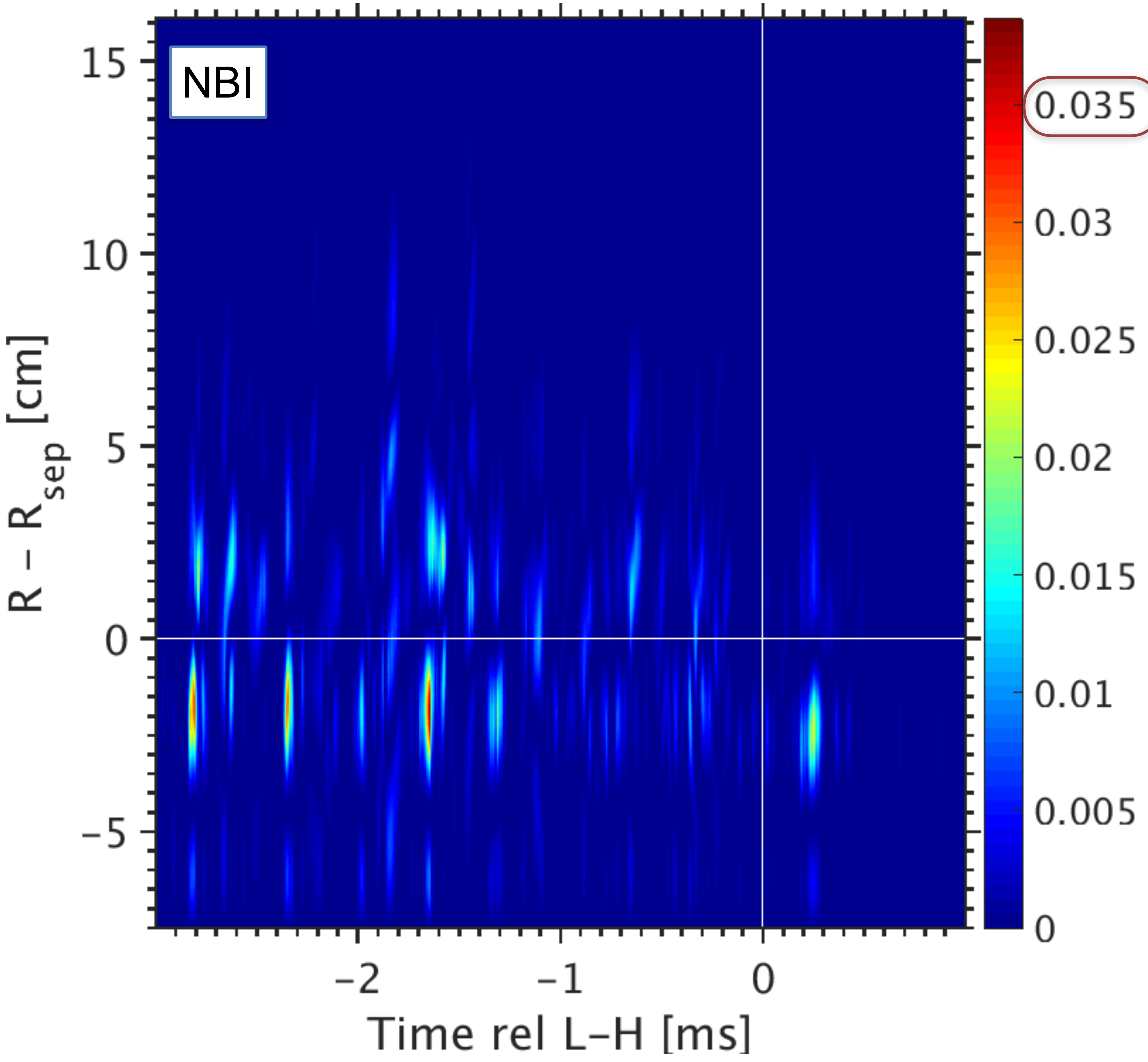
Zonal ExB energy

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

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

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

Turbulence fluctuation energies

Zonal ExB energy

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

Poloidal flow damping rate*

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

NSTX parameters

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

Turbulence Dissipation

$$\nu E_z$$

For the cases where $\gamma \; \tau_{lh} \gg 1$

(slow transition criteria)

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

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

γE_{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

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Poloidal flow damping rate*

νE_z

Turbulence Dissipation

For the cases where $\gamma\ \tau_{lh} \gg 1$

(slow transition criteria)

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

Assuming interchange or drift wave turbulence

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

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

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

Too weak to perturb the turbulent energy balance

Summary:Energy balance

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

Thermal free energy(E_{th})

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

+

non-zonal ExB energy

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

Turbulence energy (E_{Turb})

⟷

Zonal ExB energy

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

Production term

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

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

- 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

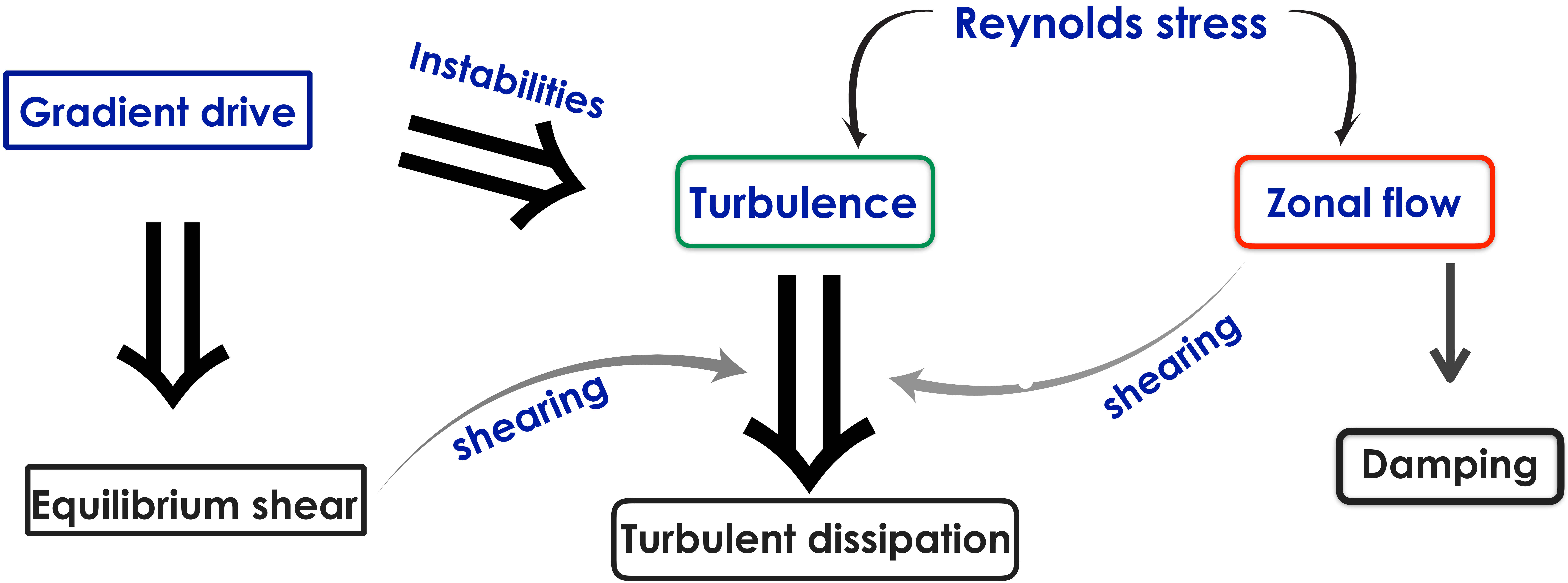
- Energy-transfer mechanism appears much too weak to explain the rapid turbulence suppression at the L-H transition.

  Uncertainties in 2D velocimetry may be order unity, but the energy transfer mechanism is ~100x too small to explain the turbulence suppression.

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

Supplementary material

Summary: energy balance



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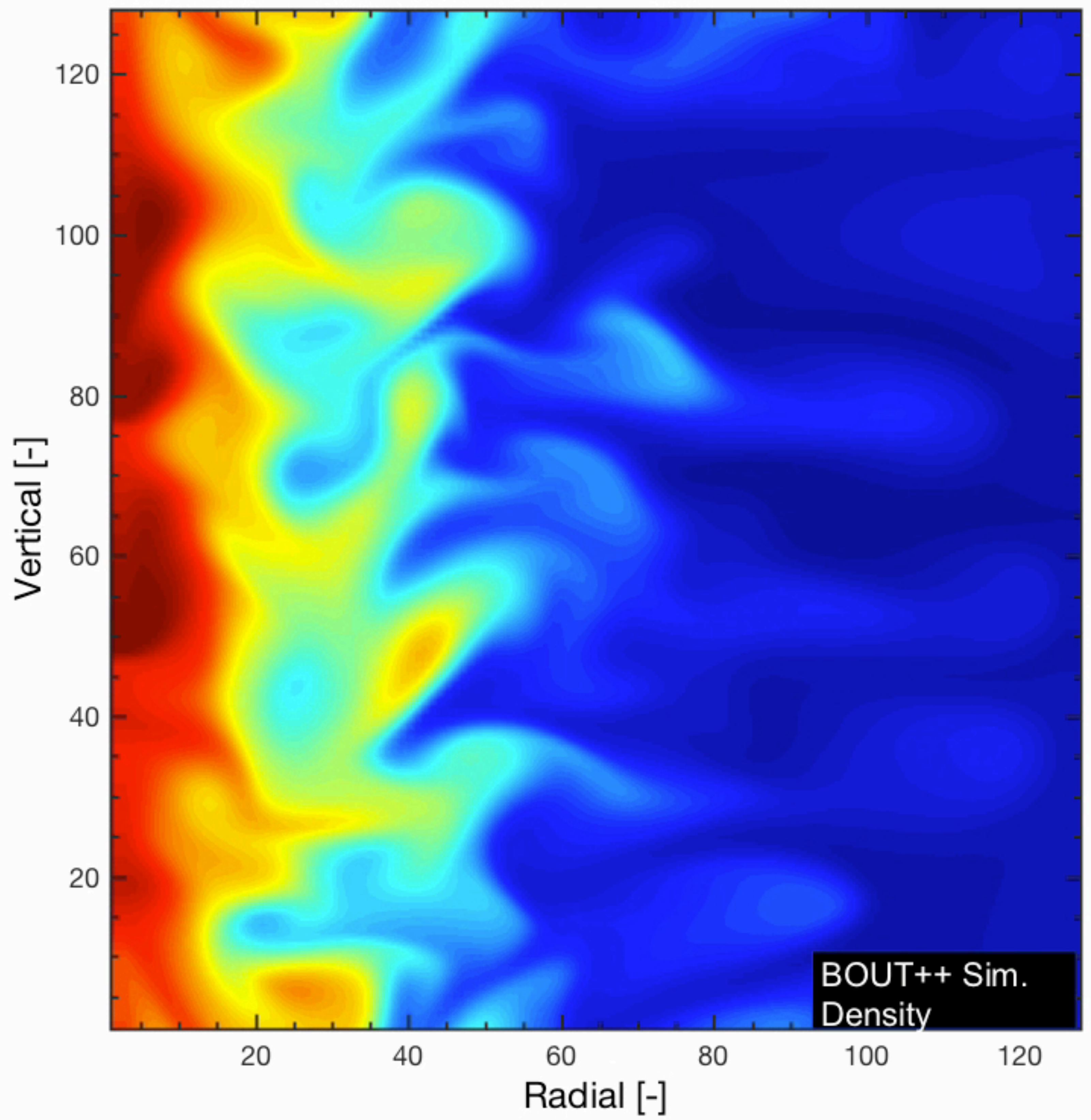
BOUT++ simulations for testing velocimetry

Density

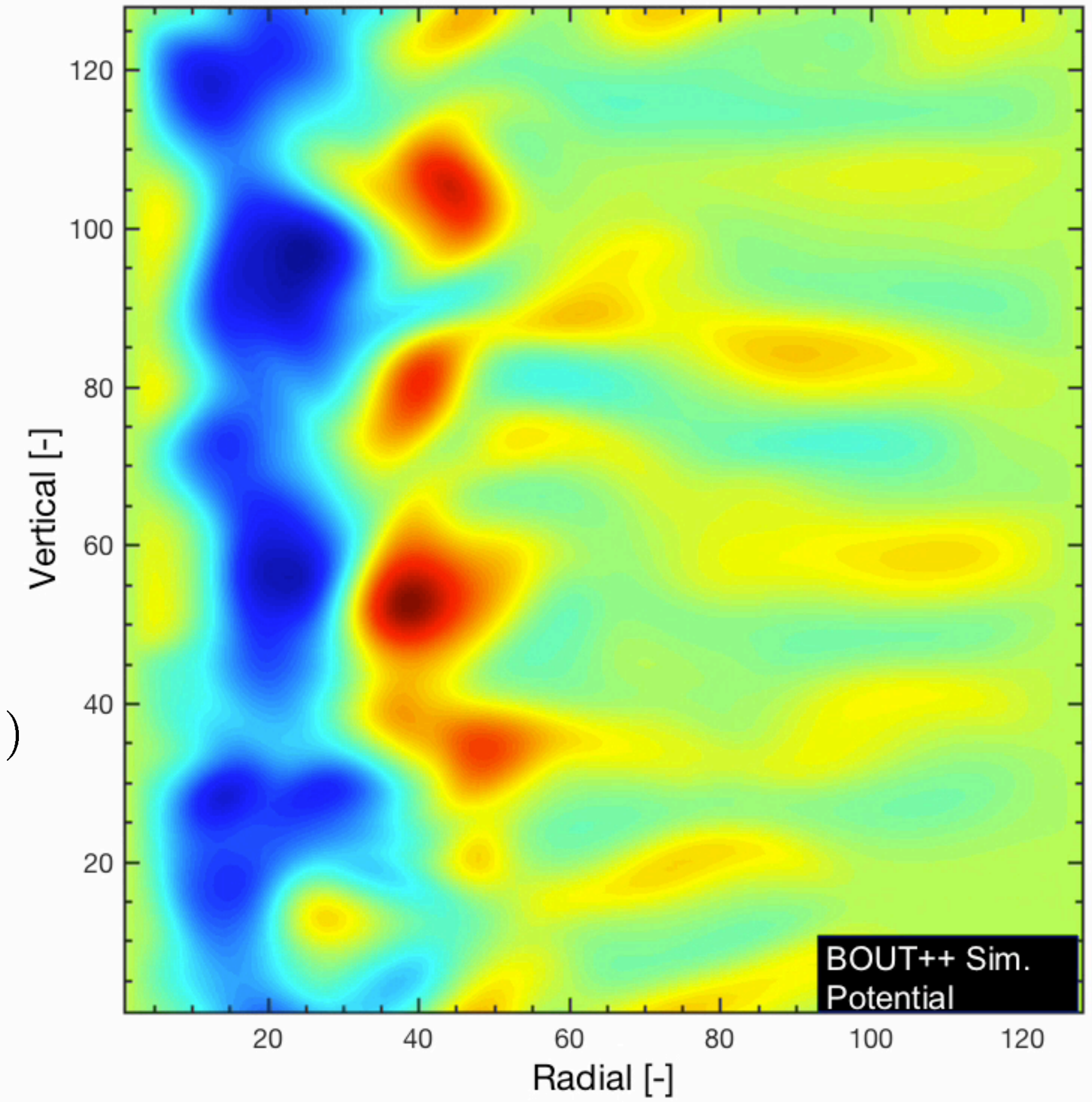


Box length :: $l_x \times l_y = 192\rho_s \times 192\rho_s$
Grid points :: $n_x \times n_y = 128 \times 128$

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 :: $1.0 \times 10^{-4} \ (/n_0 c_s)$
Neutral source (for UTE0) :: $1 \times 10^{-5}(/n_0 c_s)$

Potential



Courtesy N. Bisai, IPR

BOUT++ simulations for testing velocimetry

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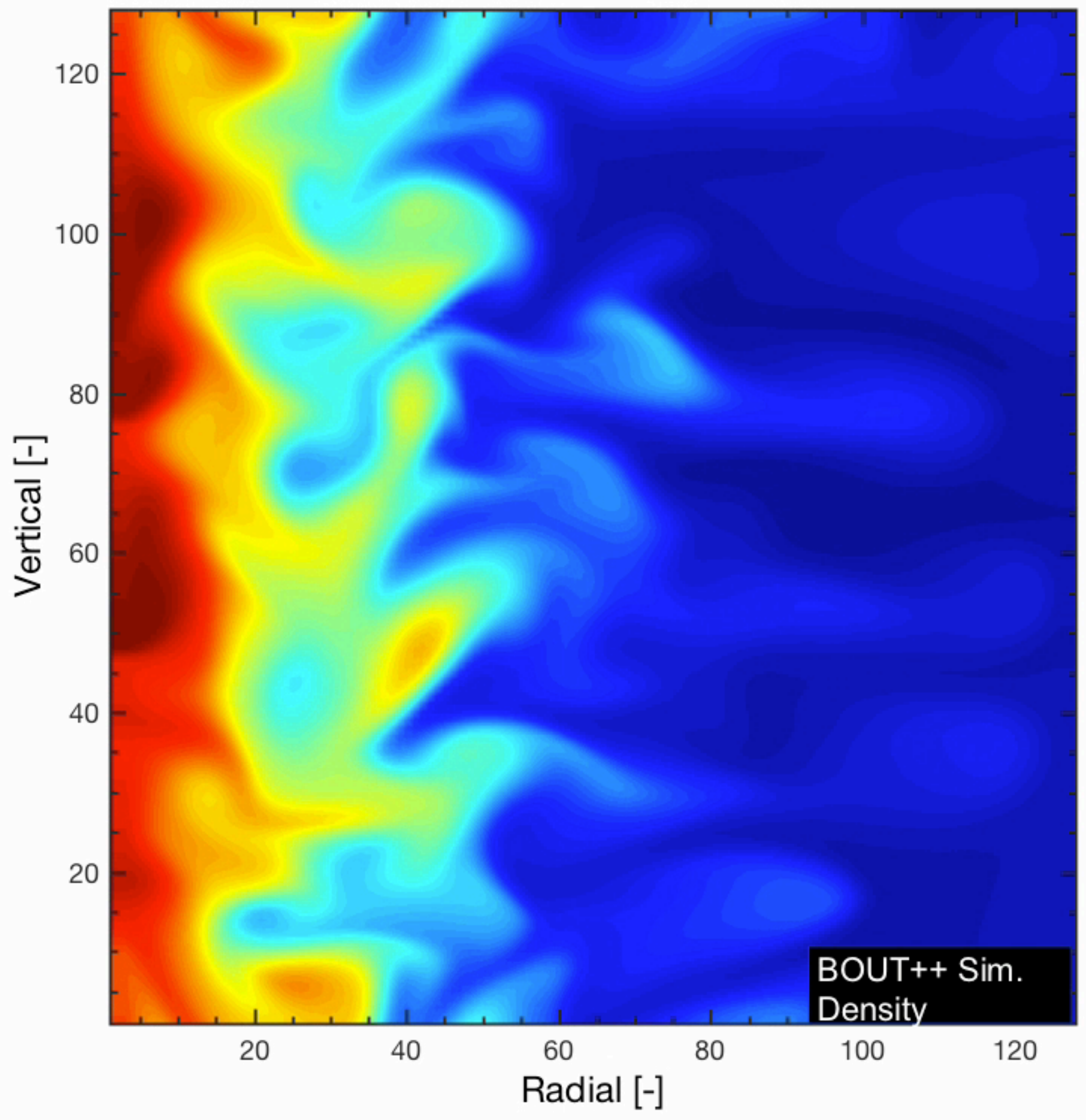

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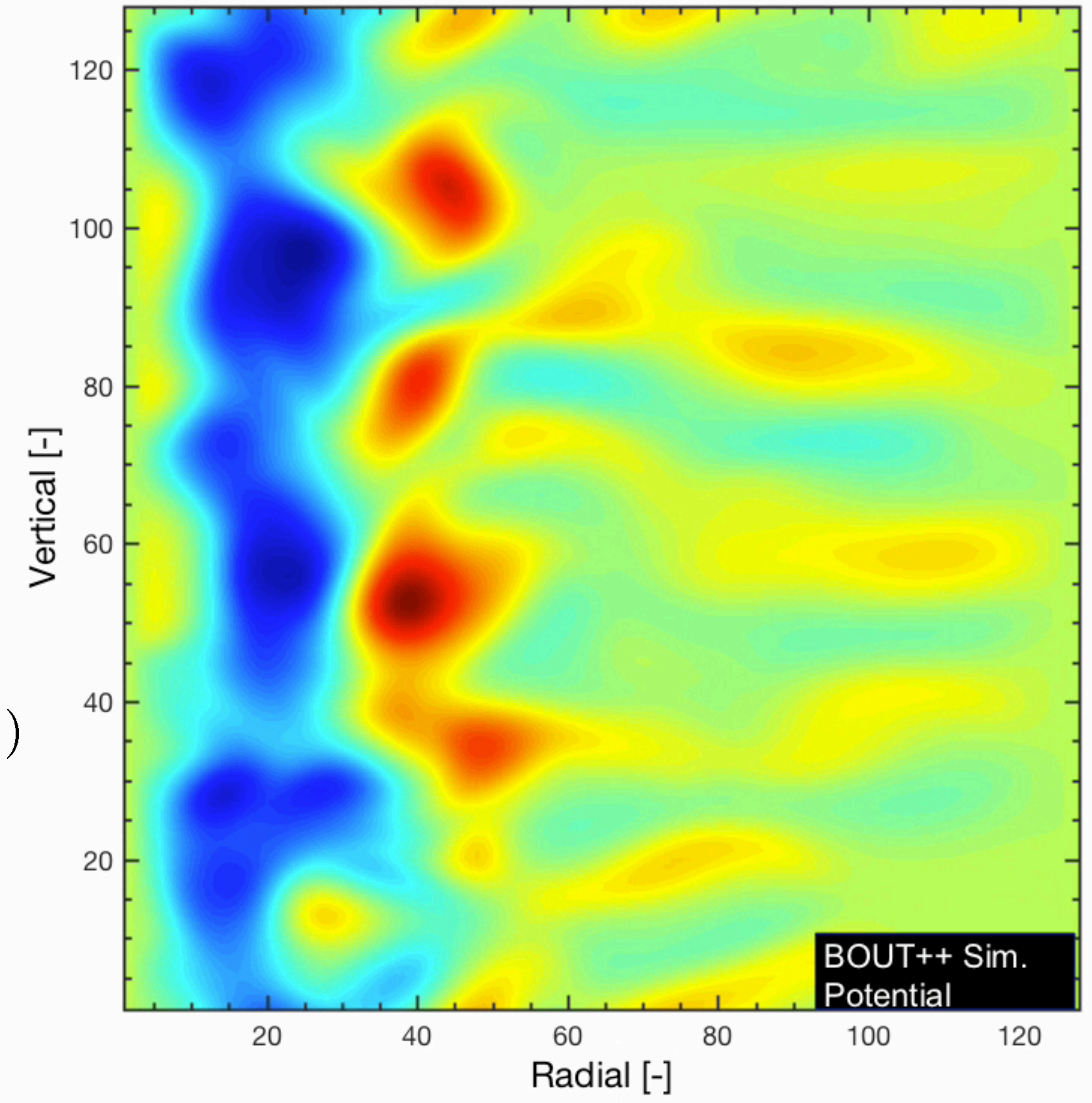
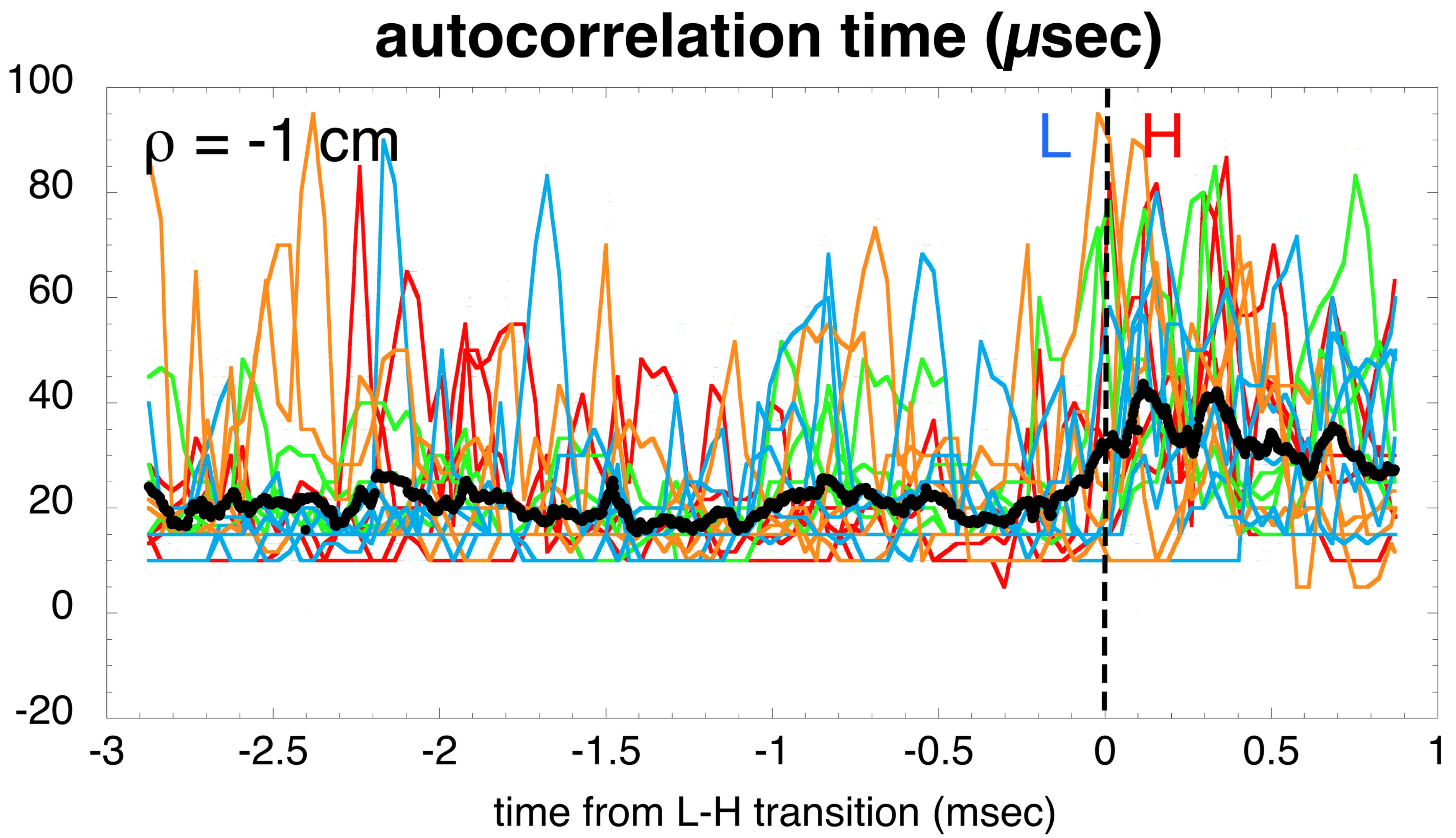
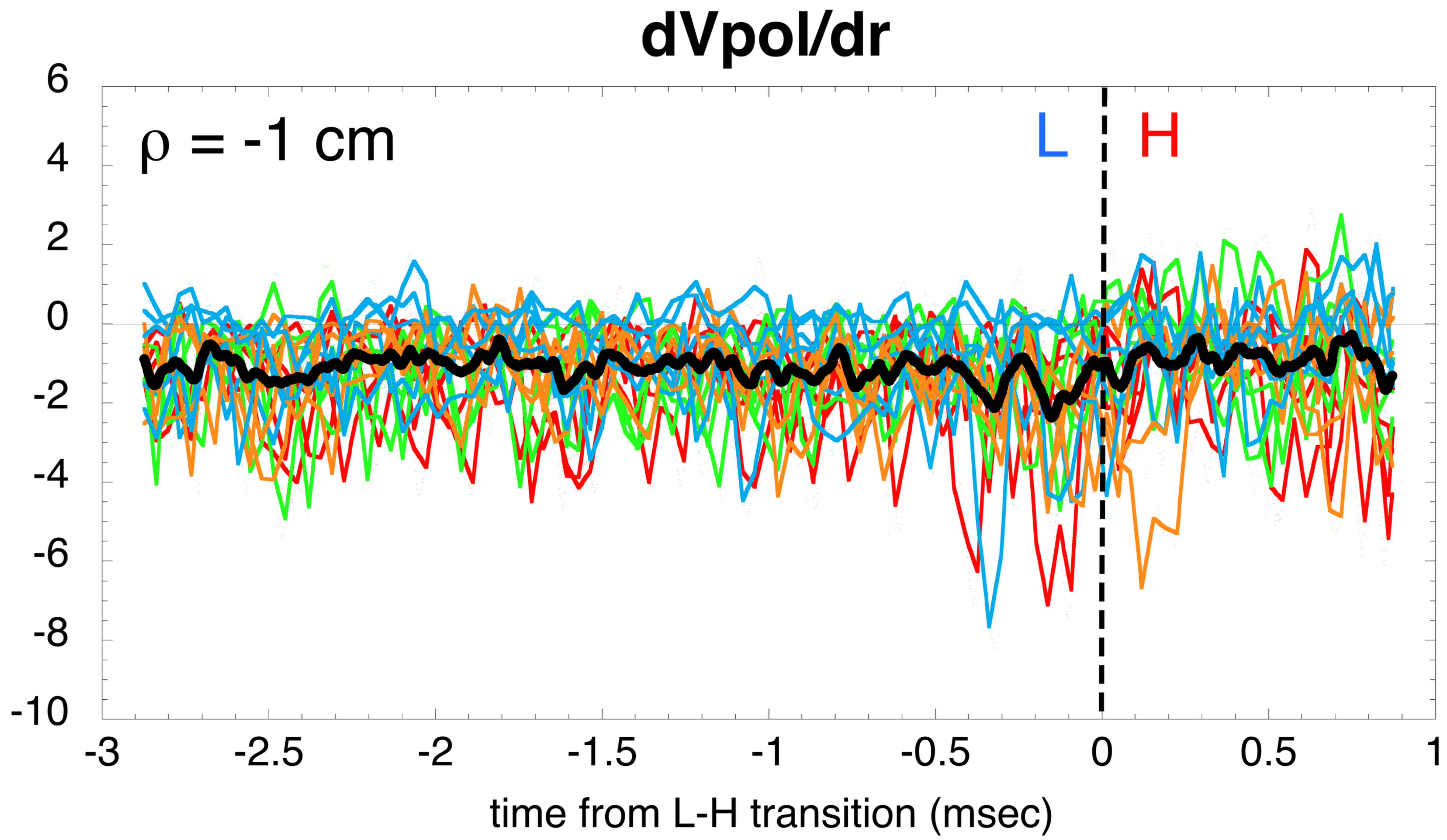


Courtesy N. Bisai, IPR

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