# Direct Comparison of GPI and BES measurements of Edge Fluctuations in NSTX

Y. Sechrest[1], D. Smith[2], T. Munsat[1], S. J. Zweben[3] ([1] CU-Boulder, [2] UW-Madison, [3] PPPL)

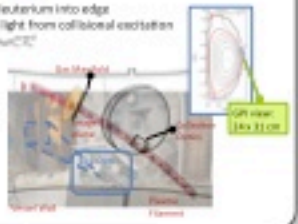
## Overview

Motivation: Compare fluctuations measured by Gas Puff Imaging (GPI) and Beam Emission Spectroscopy (BES) in MHD-quiescent, ELM-Free, H-mode plasmas

- Diagnostics measure plasma fluctuations in the pedestal, edge, and Scrape-off layer (SOL)
- Close proximity of viewing areas allows for direct comparison
  - Intensity fluctuations are found to be strongly correlated
  - Fluctuation statistics similar, but large difference in RMS levels
  - Correlation lengths and Decorrelation times give mixed agreement
- BES Sensitive to GPI Puff
  - Mean signal increases by as much as a 2x
  - Increased fluctuations in 5-10 kHz band observed during gas puff

## Gas Puff Imaging

- Discharges neutral deuterium into edge
- Images $D_\alpha$ (656 nm) light from collisional excitation
- $I \propto n_e n_0 f(n_e, T_e) \approx n_e n_0 C T_e^{0.5}$
- Resolution:
  - Rad. 2 +/- 1 cm
  - Pol. 8.5-2 cm
- 400 kHz framerate
- Probes $k_\perp \rho_s \leq 2.0$




## Beam Emission Spectroscopy

- Measures $D_\alpha$ emission from collisional excitation of heating beam neutrals
- $I \propto n_e n_0 T_e^{0.5}$
- Resolution approx. 2-3 cm
- 2 MHz sampling rate
- Probes $k_\perp \rho_s \leq 3.5$

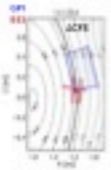
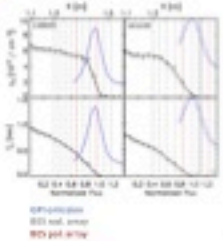


Figure (right) illustrates relative positioning. BES and GPI views shown in cylindrical coordinates. Actual views separated by ~36 degrees toroidally

## Plasma Conditions

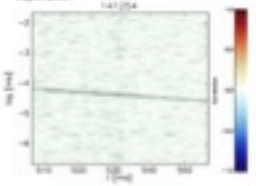
- GPI emission localized to gradient region and near SOL
- GPI $n_e$ and $T_e$ exponents vary with plasma parameters
- Most time traces taken at 0.85 normalized flux
  - Density ~ 2.0-4.0x10$^{13}$ cm$^{-3}$
  - Temp. ~ 100-200 eV
  - GPI Alpha ~ 0.6-0.7
  - GPI Beta ~ 0.03-0.1
- **GPI and BES predominantly density fluctuations**



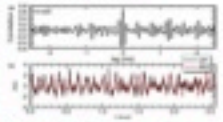
GPI poloidal array
BES rad. array
BES pol. array

## Cross-diagnostic correlation and coherence are strong

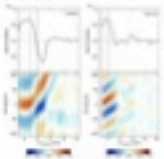
Strong Correlation persists in time:
- Time-lagged cross-correlation vs. time
- Timebases have offset and linear drift
- Align BES timebase using linear fit to persistent correlation feature
- Unable unravel time offset due to physical separation



Strong GPI/BES Cross-Correlation:
- Strong Correlations, R>0.7
- Raw traces clearly exhibit similarity



Corr. Vs. Radius:
- Radially extended
- Phase shift vs. R



Moderate Strength Coherence between 5-10 kHz:
- Top left: Cross-diagnostic Coherence, typically 0.6-0.8
- Top right: Cross-power (black) with envelopes of GPI (blue) and BES (red)
- Bottom left: Cross Phase
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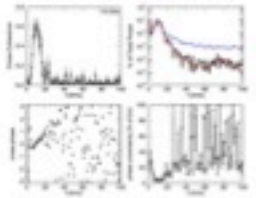
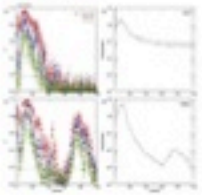
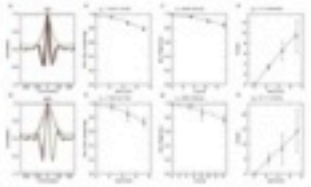


## Good Agreement Between Correlation Lengths and Times

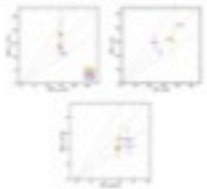
Coherence and Autopower:
- Similar features below 50 kHz
- 30 kHz feature seen in some shots, not present in GPI
  - Likely below noise floor
- Focus on < 50 kHz





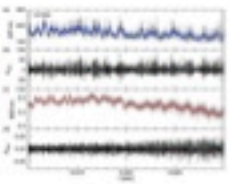
Estimating $L_{vcc}$ and $\tau_c$:
- BP Filtered fluctuations, 4-50 kHz
- Envelope calculated with Hilbert Transform
- Envelope decay at zero time lag yields $L_{vcc}$
- Decay of Envelope peak vs. time of peak yields $\tau_c$
- Linear fit to time of peak vs. separation gives $V_{tor}$

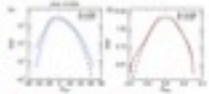
Good agreement for $L_{vcc}$, $\tau_c$, $V_{tor}$:
- Correlation functions:
  - 4 ms time blocks
  - averaged over 60 res.
- $L_{vcc}$ fall between 10-20 cm
- $\tau_c$ between 20-40 microsec
- BES $V_{tor}$ consistently lower



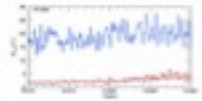
## Fluctuation Statistics Differ Between Diagnostics

Defining Mean/fluctuating quantities:
- Frequencies below ~4 kHz in BES signal sensitive to beam oscillations
- Mean I : low pass filtered at 4 kHz
- Fluctuation: $\delta I = I - \bar{I}$



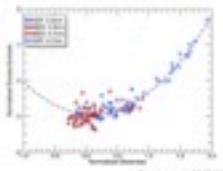


Similar fluctuation PDFs:
- PDFs for ~0.85 normalized flux
- BES near Gaussian, GPI slight skew



Large difference in RMS levels:
- BES fluctuations normalized to mean
- GPI relative fluctuations ~3x larger
- Not Temperature fluctuations
- "shadowing", underlover estimating?

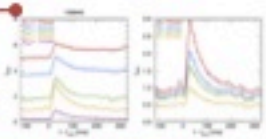
Skewness and Kurtosis:
- GPI moments
  - Follow quadratic trend, reported previously*
  - Dashed line 2nd order polynomial fit
- BES moments
  - Group near Gaussian
  - Does not clearly align with quadratic trend
- Distributions depend on $n_e$ and $T_e$, distributions in complex way

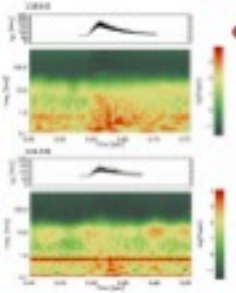


*Carter, et al. PRL 2009

## Gas Puff Effects

Mean BES increases with Puff:
- Left: Mean BES vs. rad. Channel
- Right: Mean BES vs. pol Channel
- Time t=0 is start of gas discharge
- Significant increase, up to 3x
- *DEGAS 2 simulations suggest increased neutral density, D alpha light insufficient to explain change*

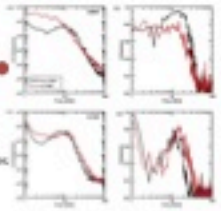




Increased 5-10 kHz fluctuation:
- Continuous wavelet transform, analogous to windowed FFT
- Fluctuation normalized to mean
- Strong Beam fluctuation at 800 Hz
- 138800 shots
  - show clear increase in 5-10 kHz concurrent with GPI puff
- 141200 shots
  - 5-15 kHz band has feature independent of gas puff
  - 5-10 kHz increase not as clear



Average Spectra show similar increase:
- twenty time blocks of ~3 ms in length
  - **60-0 ms before** GPI puff
  - 30-90 ms after GPI puff
- Increase between 5-10 kHz clearly visible
- Difference in coherence for 138805 series
- No consistent changes seen in $L_{vcc}$ estimates



## Summary

- Edge fluctuations in MHD-quiescent, ELM-free, H-mode plasmas compared
- Many similarities observed between diagnostics, as expected
  - Strong cross-diagnostic correlation, R > 0.7
  - Moderate coherence between 5-10 kHz , $\gamma^2$ = 0.6-0.8
  - Similar Probability Distributions at 0.85 Normalized Flux
  - Good agreement between $L_{vcc}$, $\tau_c$, $V_{tor}$
- Some differences remain unexplained:
  - Fluctuation levels differ by ~3x
- Gas Puff Effects:
  - Increased BES fluctuations in 5-10 kHz band concurrent with GPI puff

## Acknowledgements

We would like to acknowledge the NSTX team and Daren Stotler for their contributions. This work was supported by DOE Grants DE-SC0001968 and DE-FG03-08ER54999.

U.S. Department of Energy Office of Science

NSTX-U

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  - Good agreement between correlation lengths, times, and TDE velocities

- Increased fluctuations in 1-10 kHz band observed in BES during gas puff

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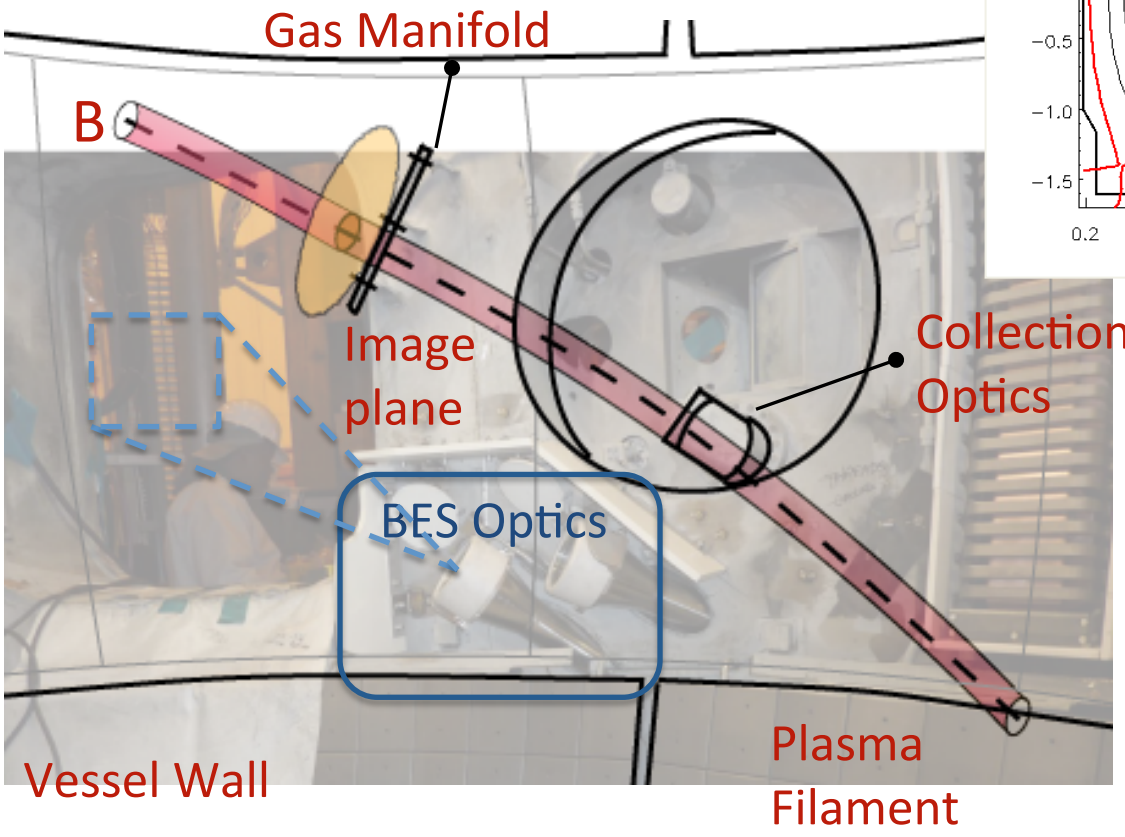


GPI view: 24 x 31 cm

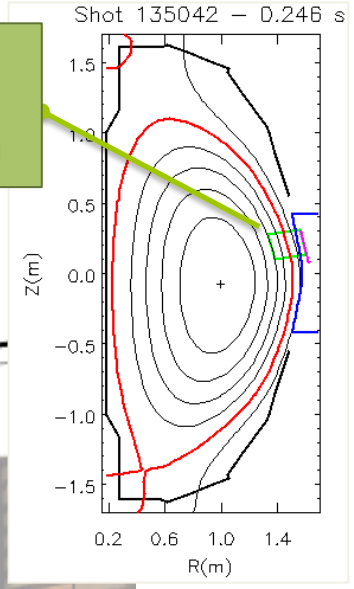

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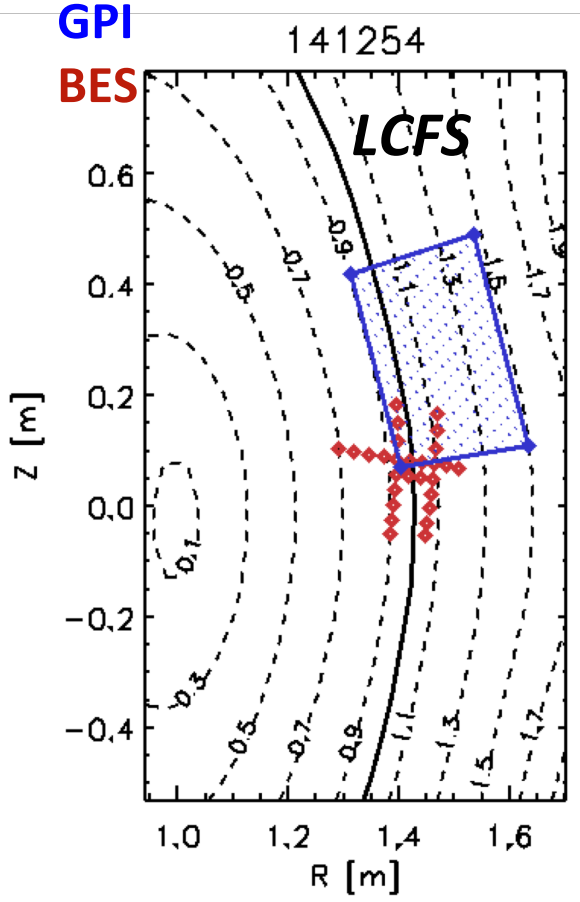
Figure (right) illustrates relative positioning.
BES and GPI views are plotted in cylindrical coordinates over contours of constant poloidal flux.
Toroidal separation is ~16 degrees.



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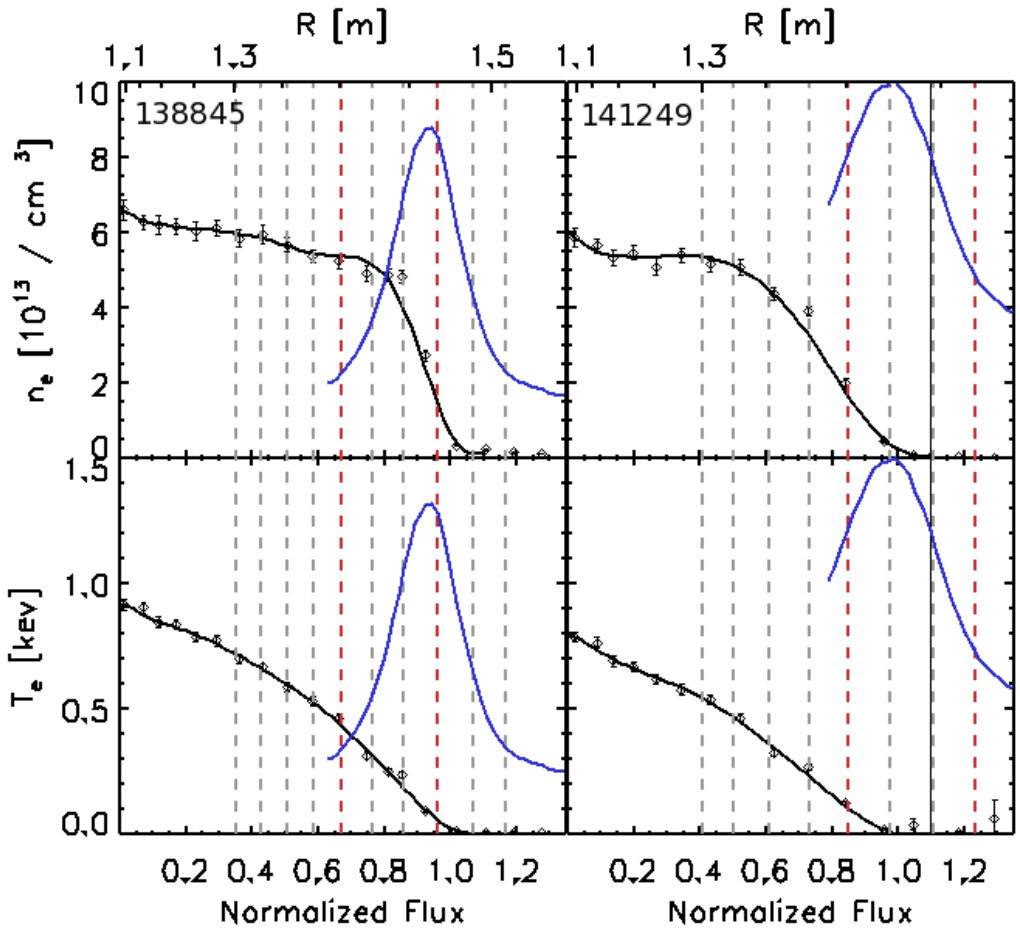


**GPI emission**

**BES rad. array**

**BES pol. array**

# Cross-Diagnostic Correlations and Coherence are strong

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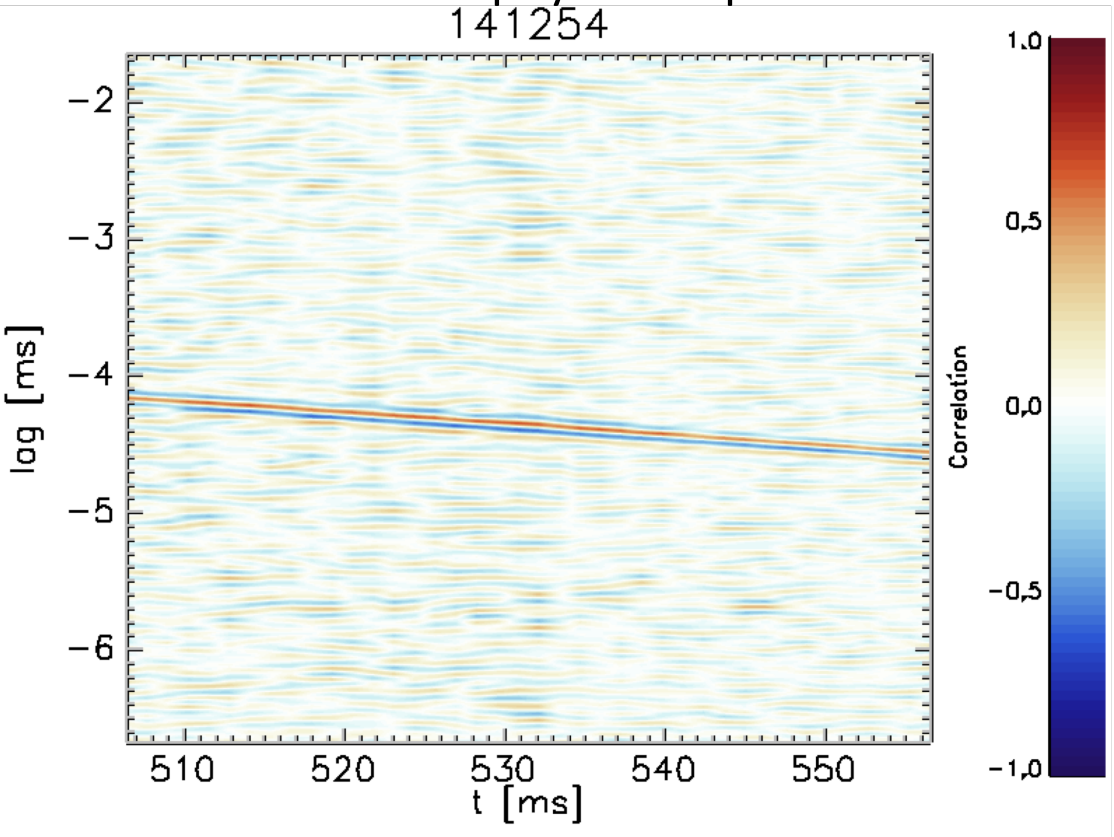
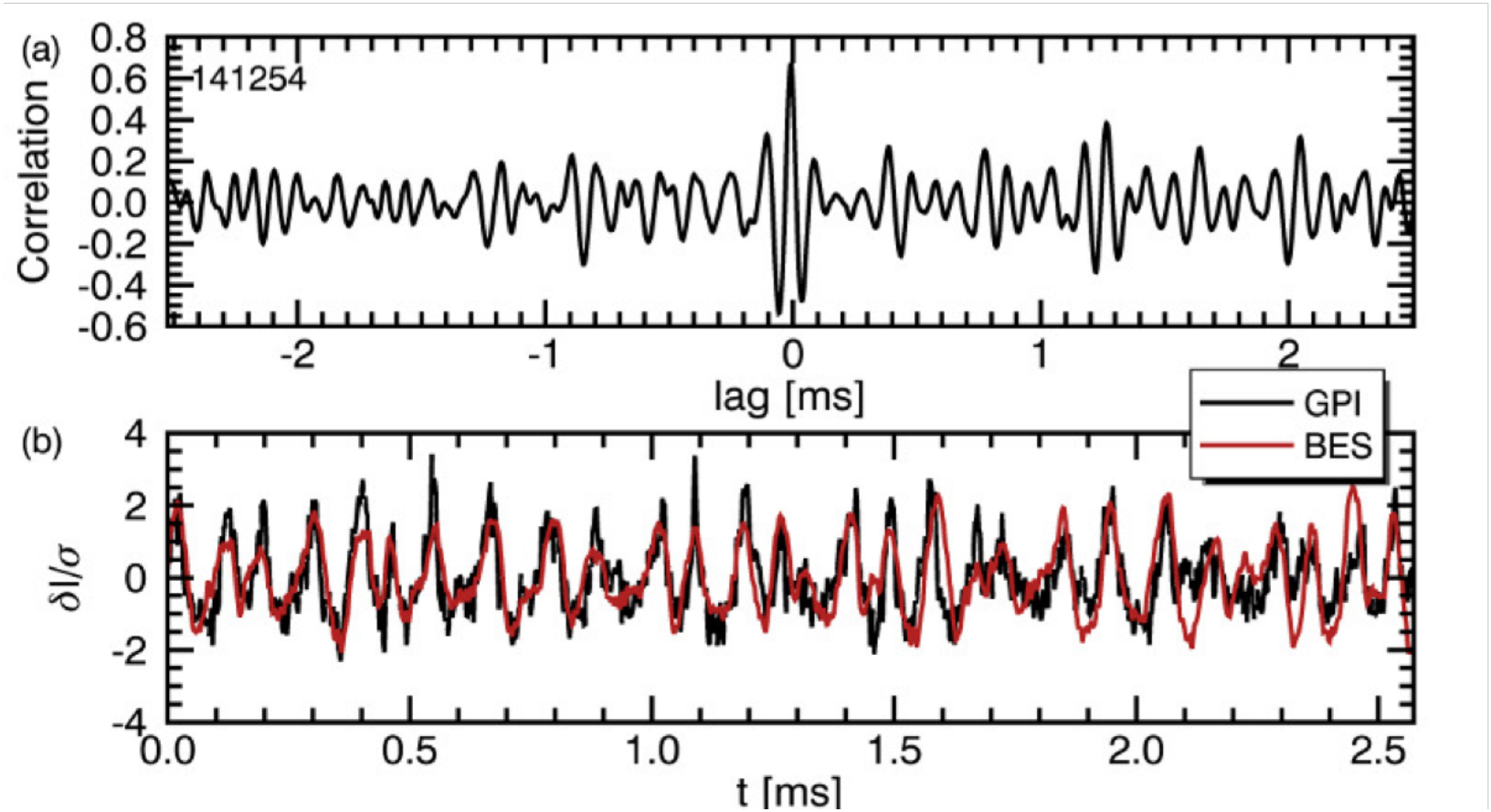


## Strong GPI/BES Cross-Correlation:

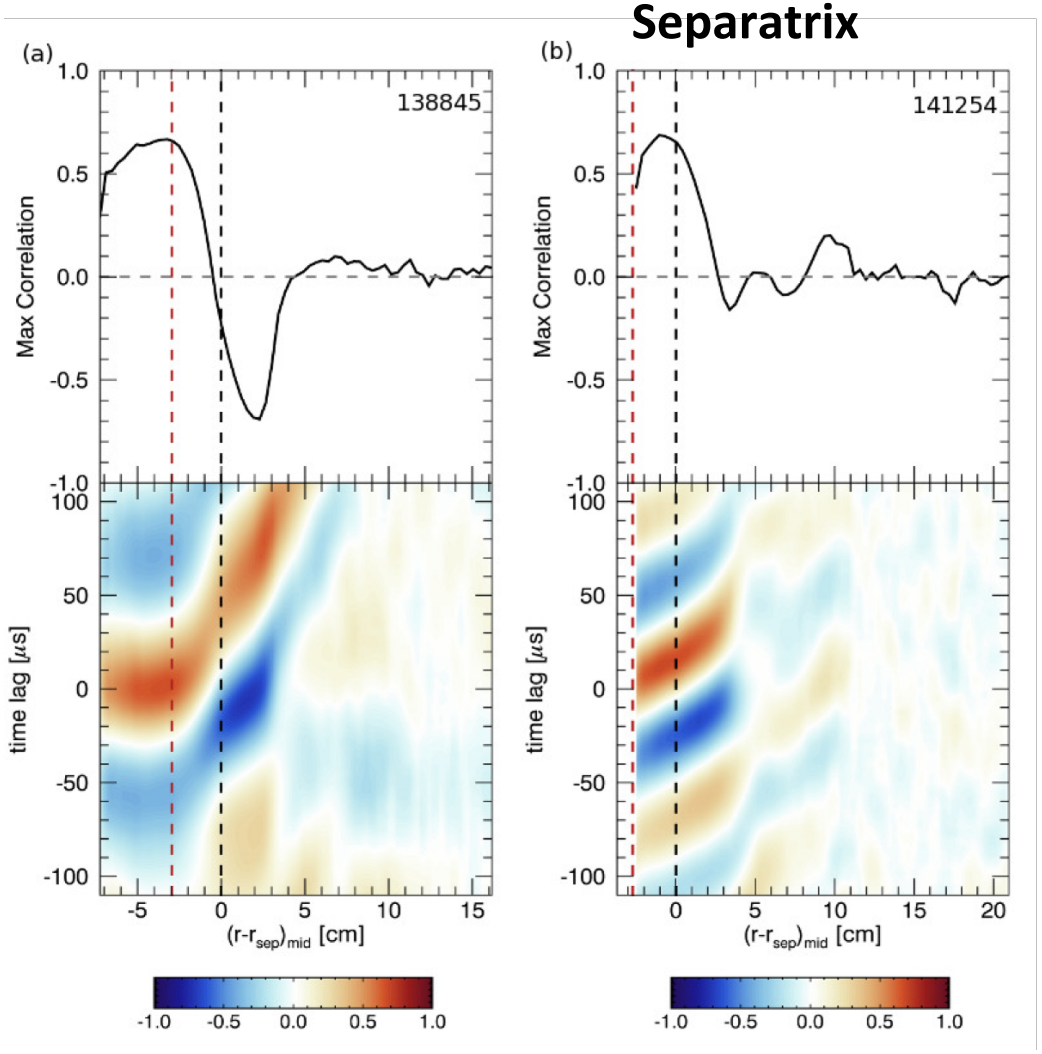
•Signals at intersection of BES rad. & inner pol. Arrays

•Normalized fluctuations clearly exhibit similarity



## Radial Structure:

- Top:
  - Corr. Vs. R at time-lag of strongest corr.
- Bottom:
  - Corr. Vs. time-lag and radius.
- Radially extended
- Phase shift vs. R



## Moderate Strength Coherence between 5-20 kHz:

- Top-left: Cross-diagnostic Coherence, typically 0.6-0.8
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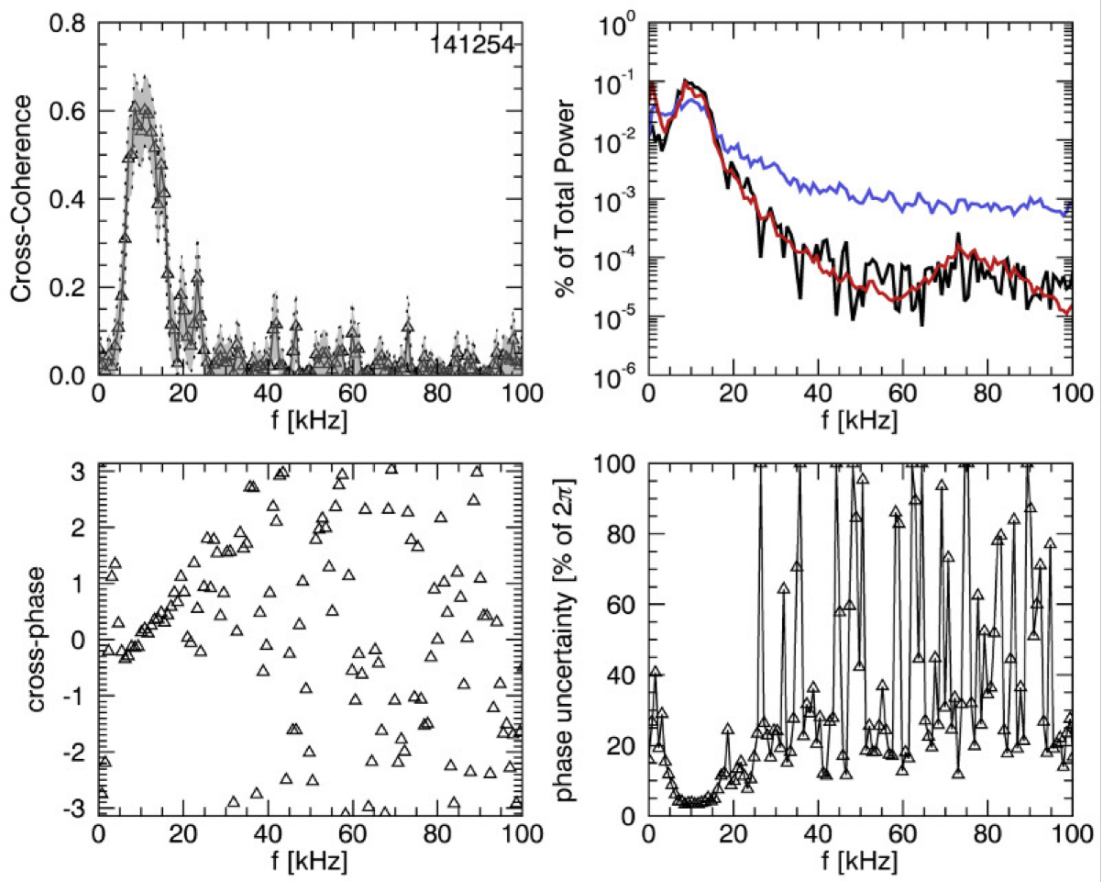

# Good Agreement Between Correlation Lengths and Times

**Coherence and Autopower:**

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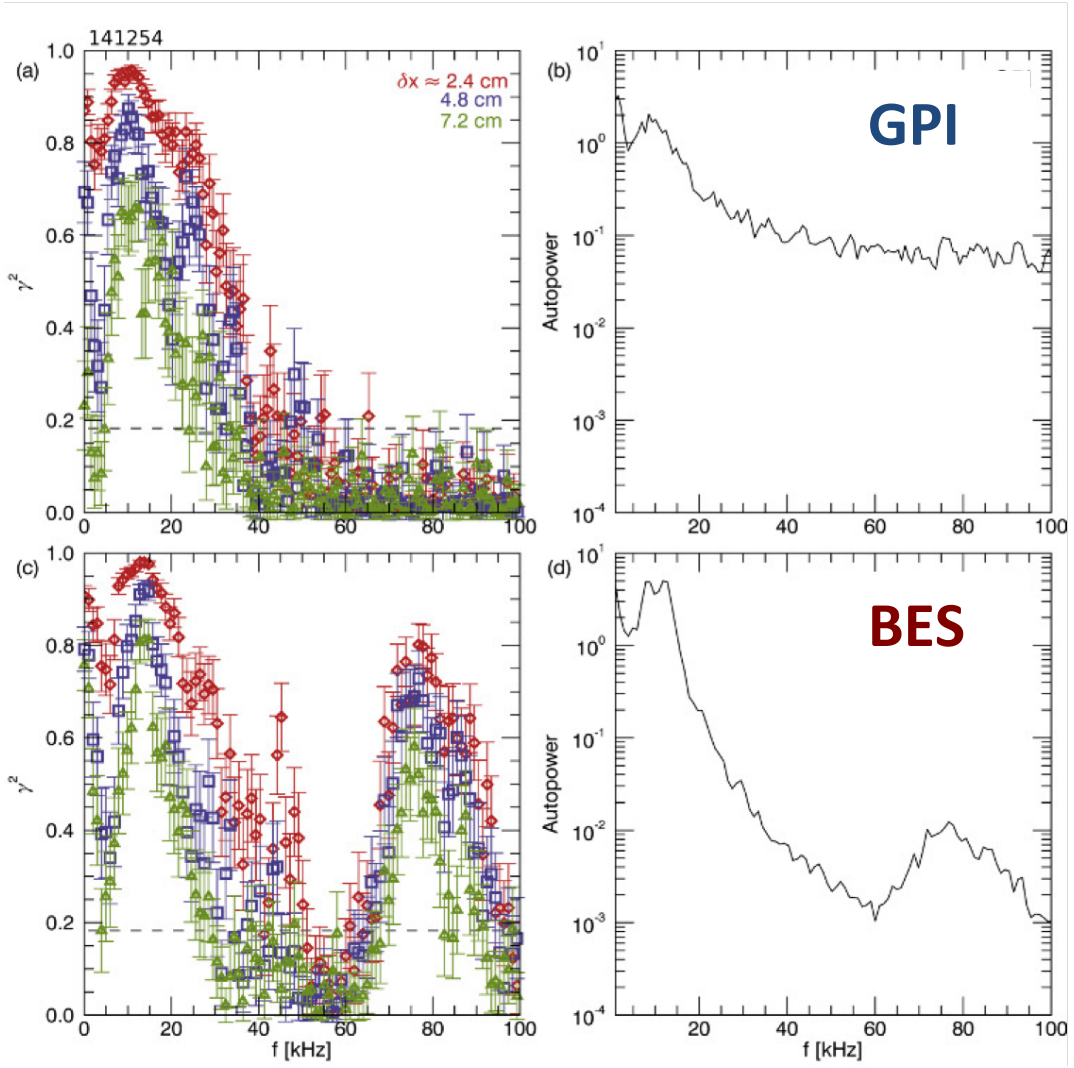
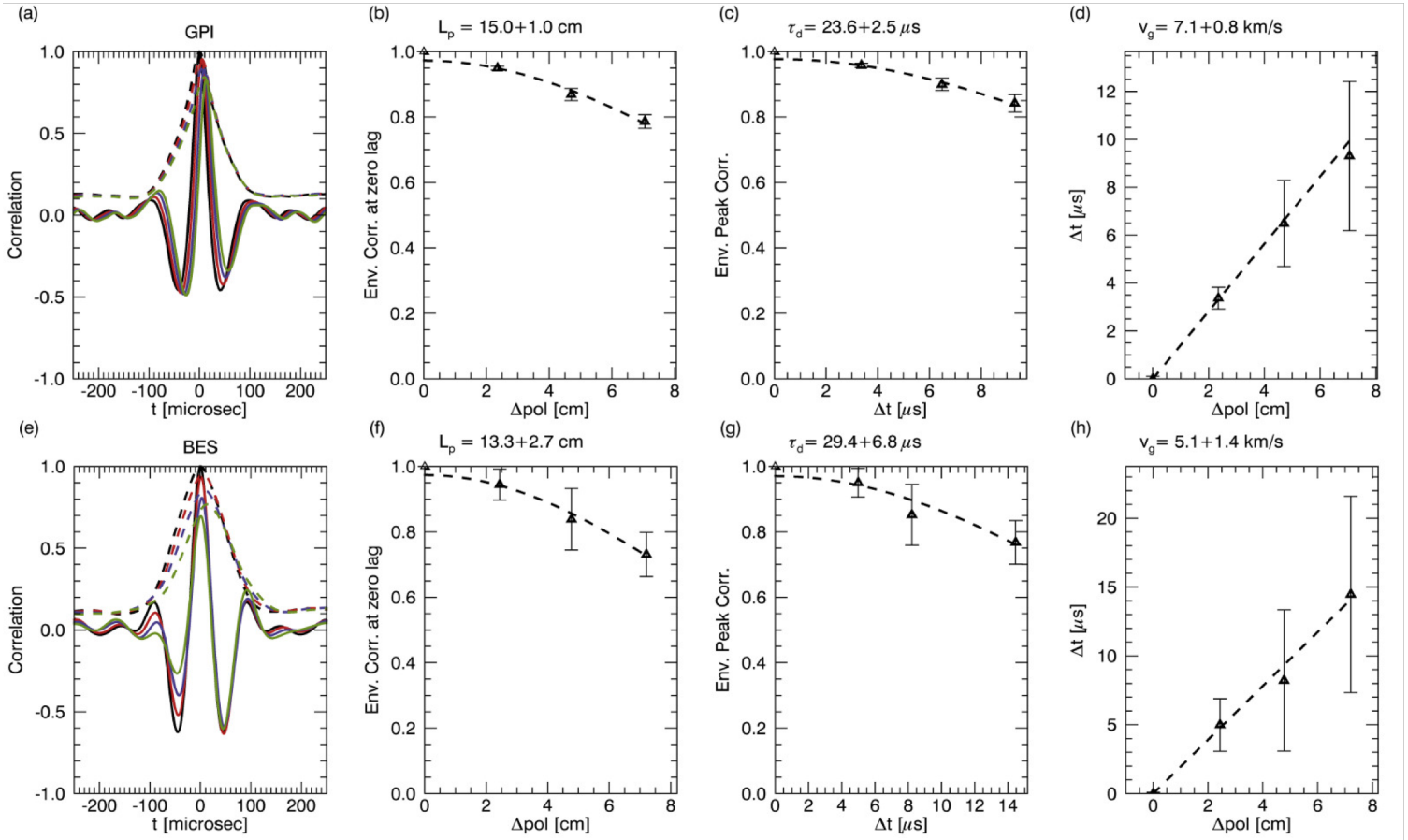
  - Likely below noise floor
- Focus on < 50 kHz



**GPI**

**BES**




## Estimating $L_{POL}$ and $\tau_C$:

- BP filtered fluctuations, 4-50 kHz
- Envelope calculated with Hilbert Transform
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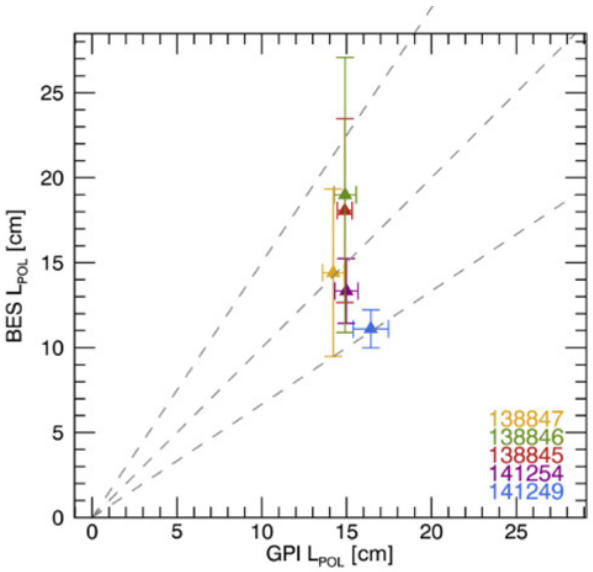
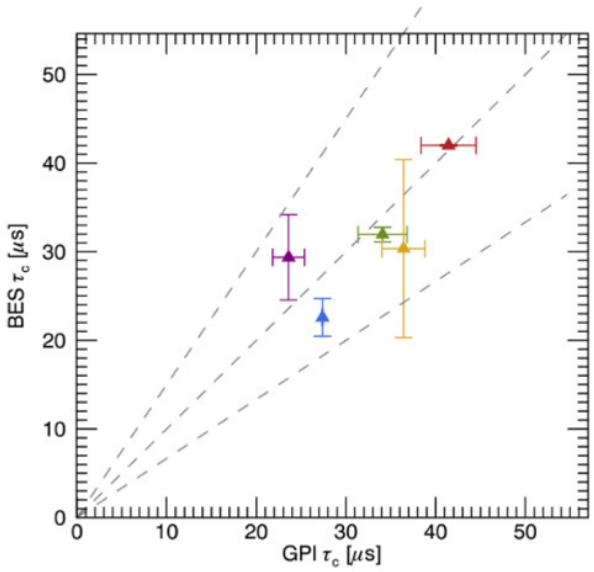
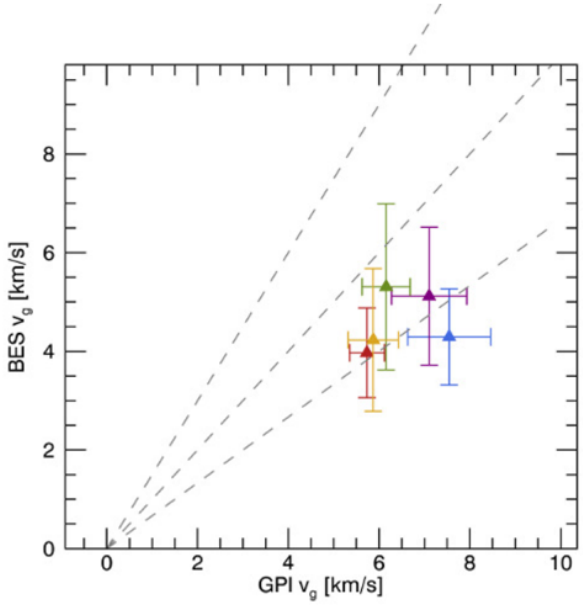


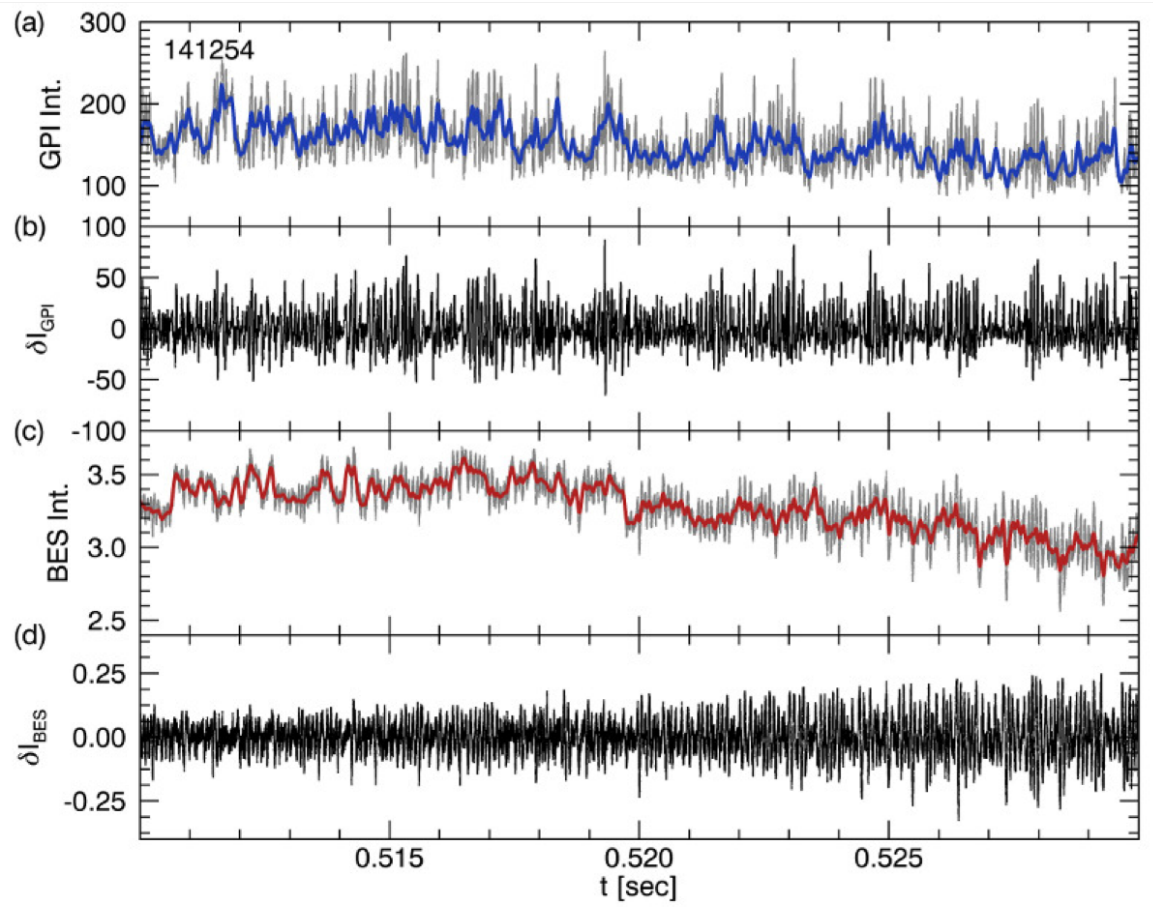

## Good agreement for $L_{POL}$, $\tau_C$, $V_{TDE}$ :

- Correlation functions:
  - 4 ms time blocks
  - averaged over 60 ms
- $L_{POL}$ fall between 10-20 cm
- $\tau_C$ between 20-40 microsec
- BES $V_{TDE}$ consistently lower

# Fluctuation statistics similar, but RMS levels differ

**Defining Mean/Fluctuating quantities:**

- Frequencies < 4 kHz in BES signal sensitive to beam oscillations
- Mean $\bar{I}$ : low pass filtered at 4 kHz
- Fluctuation: $\delta I = I - \bar{I}$



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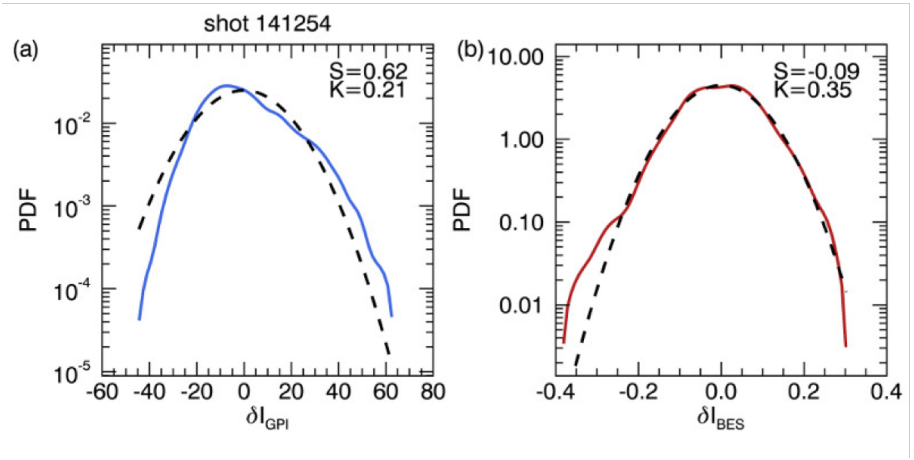
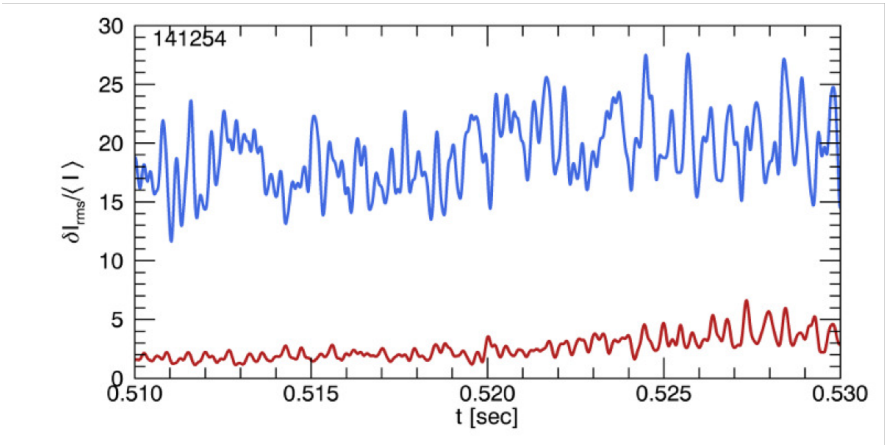



## Large difference in Normalized fluctuation

- GPI relative fluctuations ~8x larger
- Explanations:
  - Temperature fluctuations unlikely
  - Imprinting of fluctuations on neutrals



## Skewness and Kurtosis:

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  - Follow quadratic trend, reported previously*
  - Points near Gaussian, but slight skew for r=-2.9 cm
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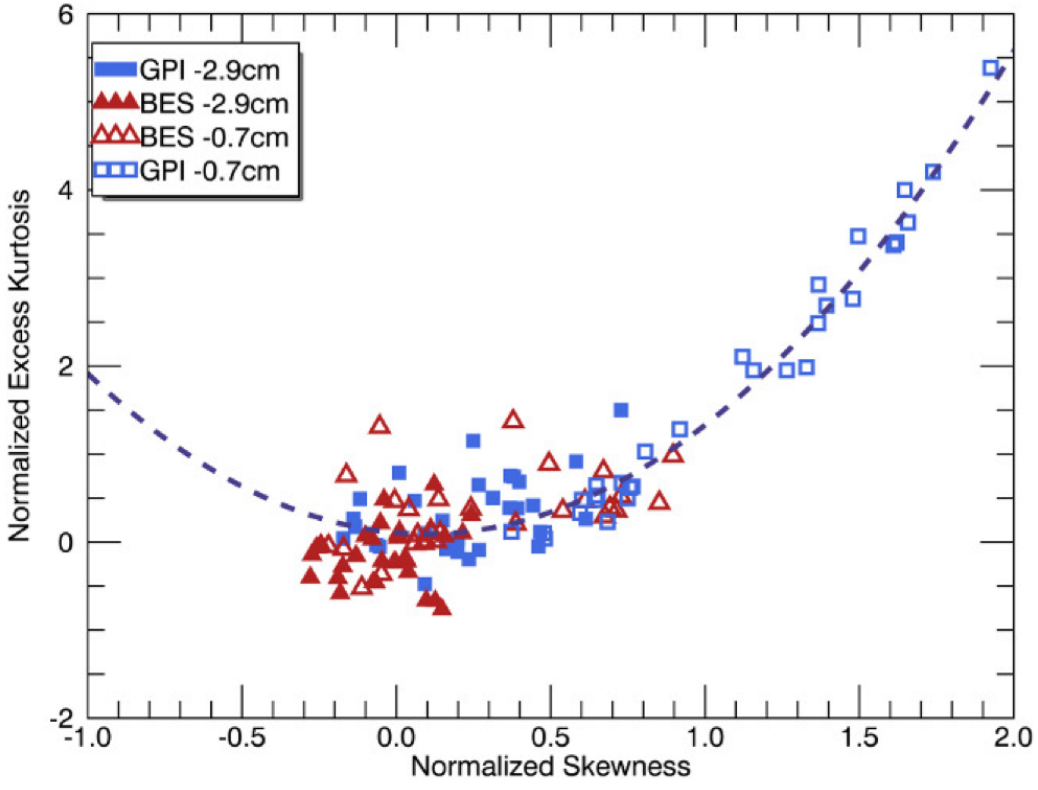

# Gas Puff Effects

**Mean BES increases with Puff:**

- Left: Mean BES vs. rad. Channel
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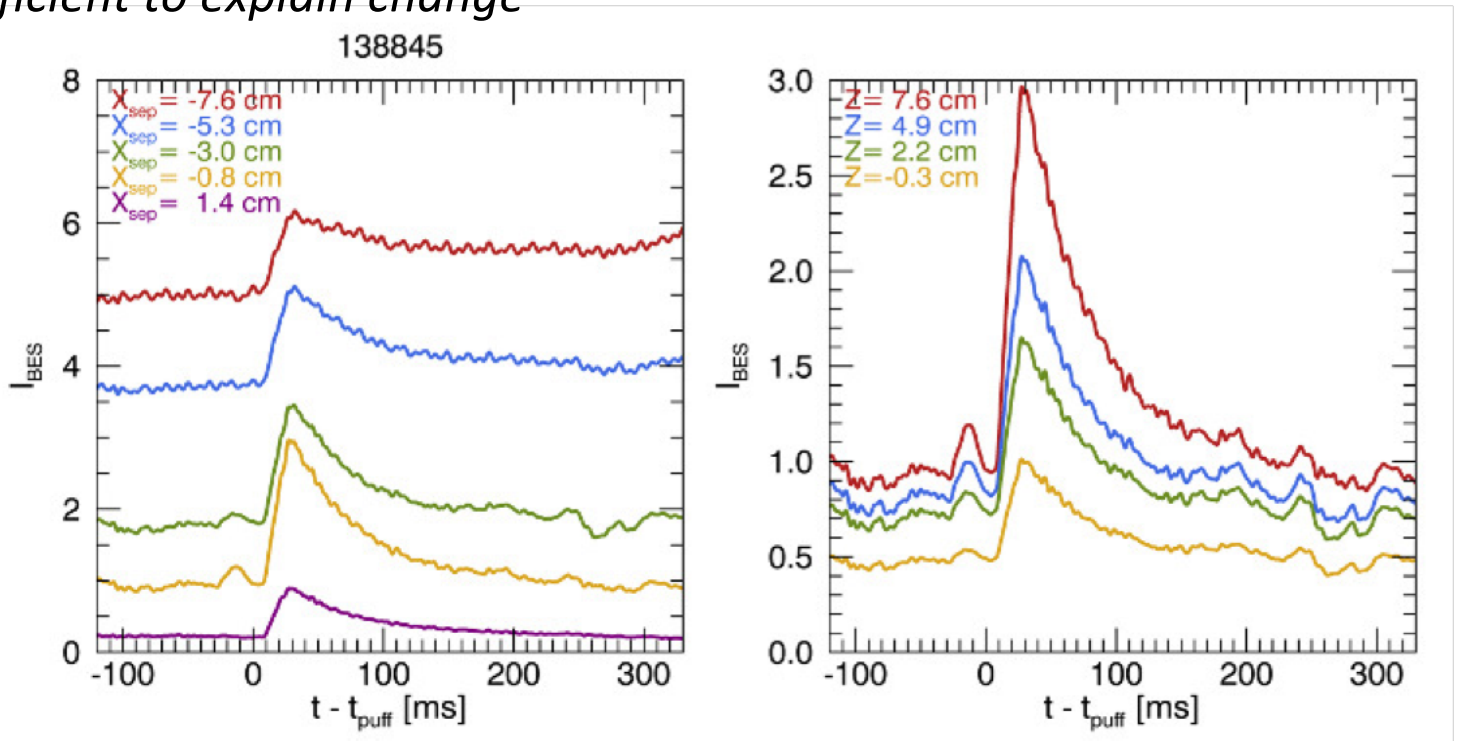
- Significant increase, up to 3x
- *DEGAS 2 simulations suggest increased neutral density, D alpha light insufficient to explain change*



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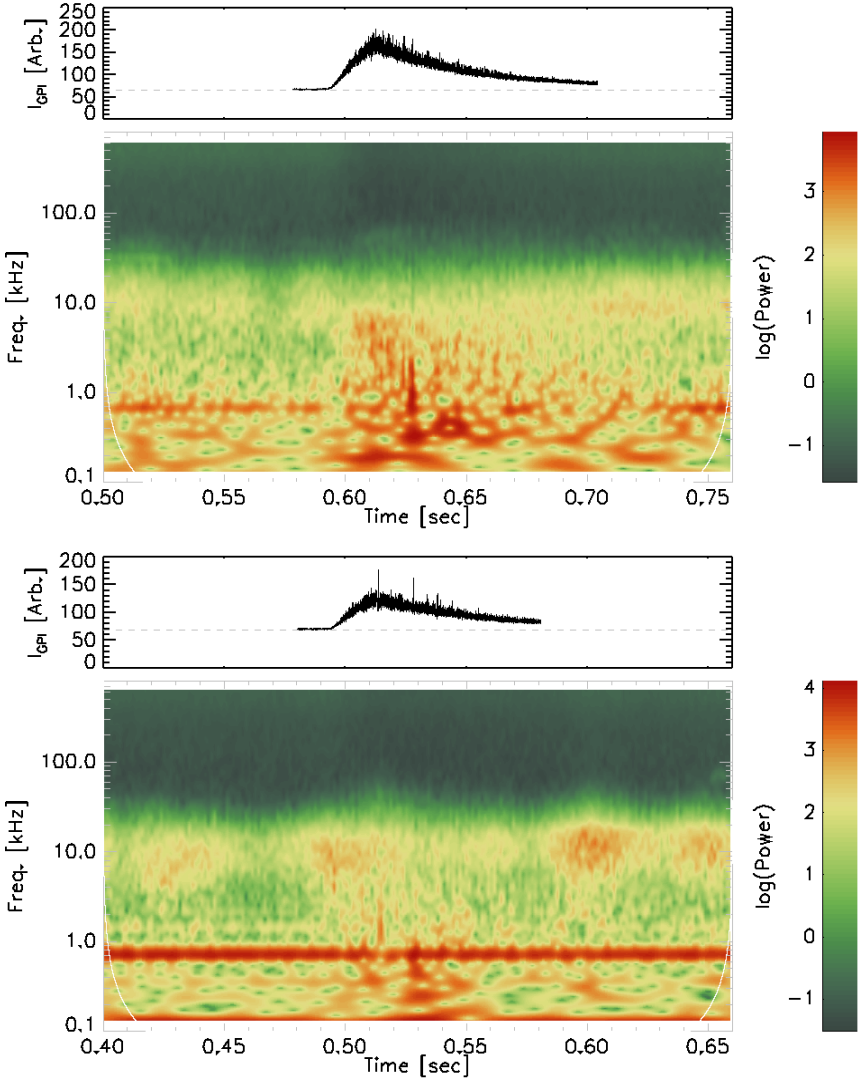

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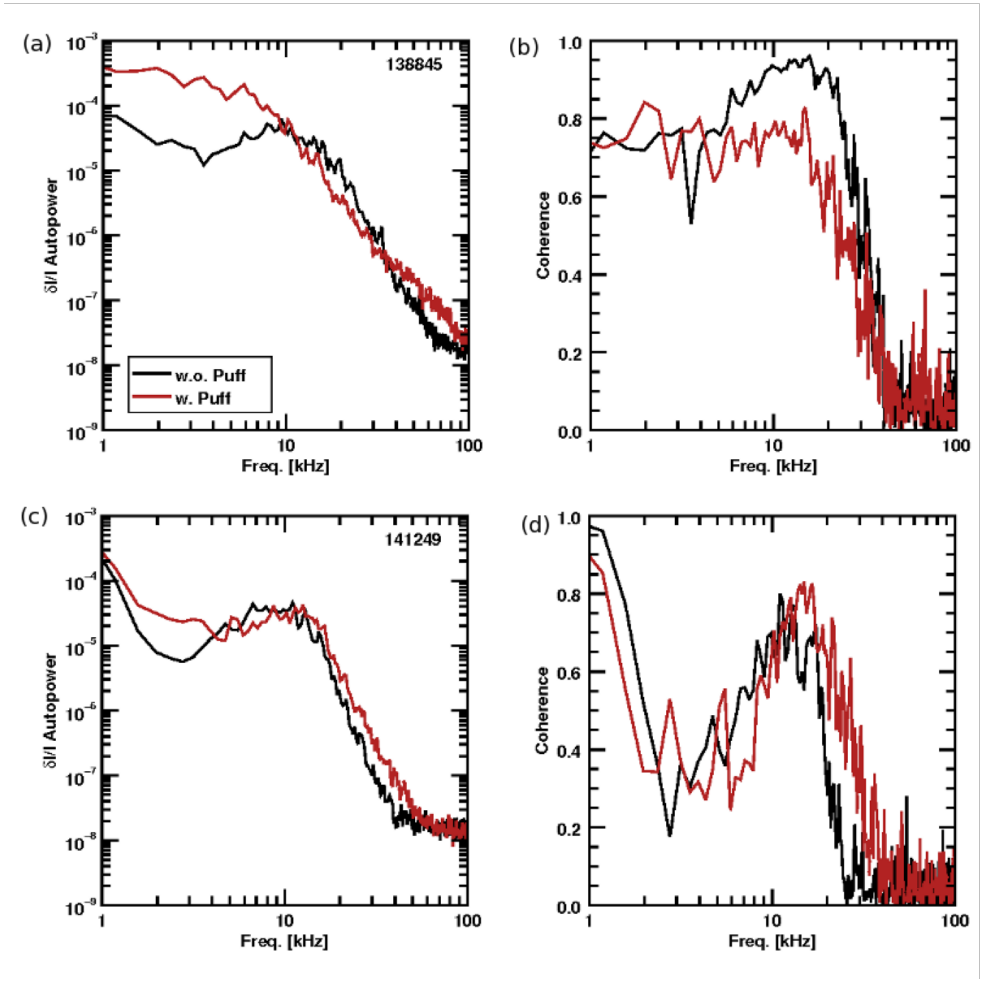
  - **60-0 ms before** GPI puff
  - **30-90 ms after** GPI puff
- Increase between 1-10 kHz clearly visible
- Right: BES coherence, ~5 cm pol. Separation
- 138845 coherence suppressed near 10 kHz
- No consistent changes seen in $L_{POL}$ estimates



# Summary

- Edge fluctuations in MHD-quiescent, ELM-free, H-mode plasmas compared
- ***Many similarities observed between diagnostics***
  - Strong cross-diagnostic correlation, $R > 0.7$
  - Moderate coherence between 1-20 kHz , $\gamma^2 = 0.6\text{-}0.8$
  - Similar Probability Distributions at 0.85 Normalized Flux
  - Good agreement between $L_{POL}$, $\tau_{C,}$ $V_{TDE}$
- Some differences remain unexplained:
  - Fluctuation levels differ by ~8x
- Gas Puff Effects:
  - Increased BES fluctuations in 1-10 kHz band concurrent with GPI puff

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