Measurements of Reduced Low-k Electron Temperature and Intermediate Scale Density Fluctuations in H and QH-mode

by
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Outline

- **Reduced core electron temperature fluctuations in H and QH-Mode plasmas (ITG scale, $k_\perp r_s < 0.5$)**
  - Principle of Correlation-ECE Diagnostic (CECE)
  - Experimental Results/TGLF Linear Stability Results
- **Intermediate scale fluctuations are significantly reduced across the L-H Transition**
  - Principle of Doppler Backscattering Diagnostic (DBS)
  - Intermediate-k Fluctuation Levels/TGLF Results
- **Interaction of Zonal Flows with Intermediate-k fluctuations**
  - GAM and ZF Spectra in DIII-D
  - Modulation of density fluctuations

Motivation

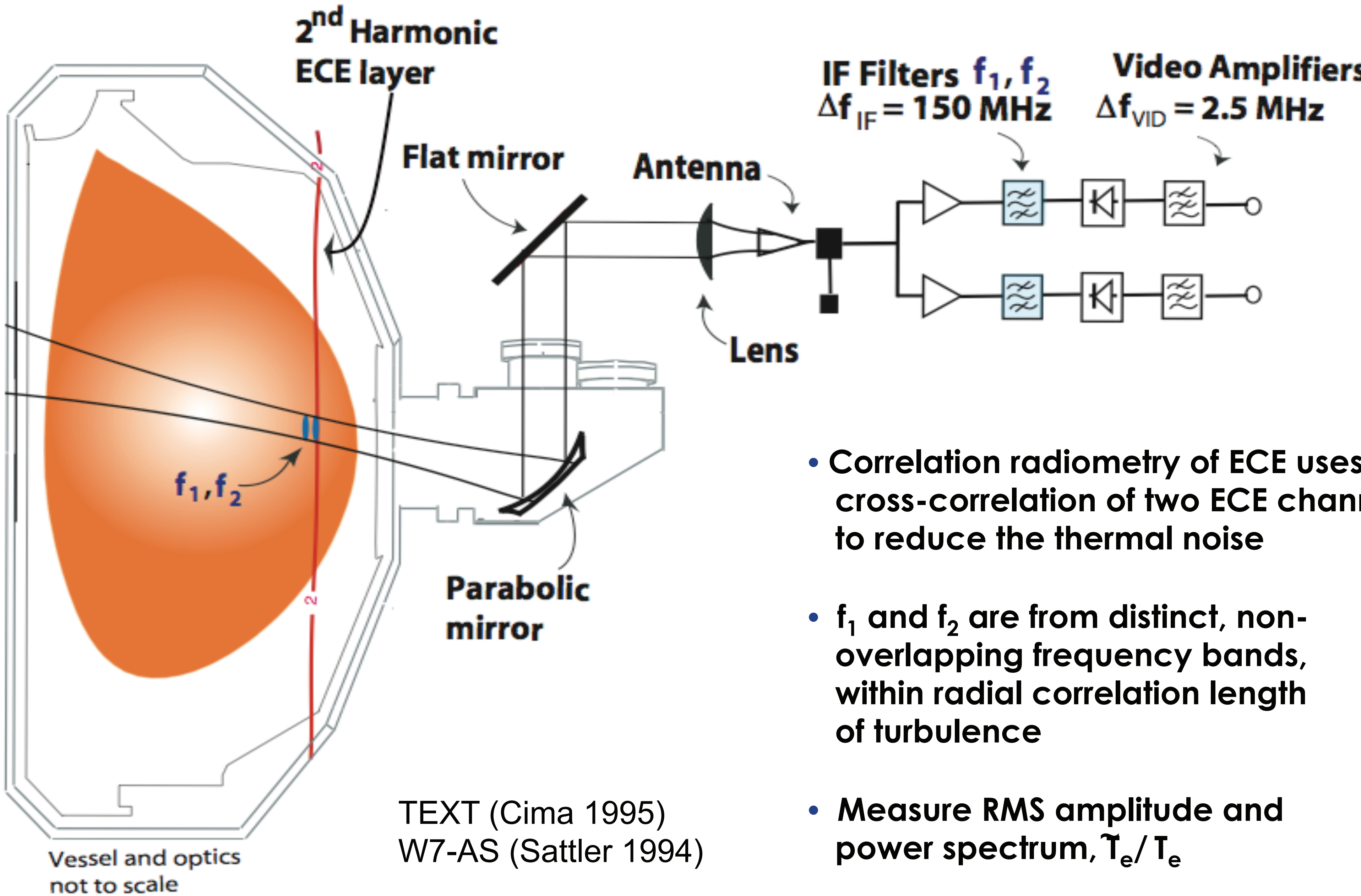
- **Electron transport and electron channel physics is important in burning plasmas**
  ($T_e \geq T_i$: a particles mainly heat electrons)

- **Contribution of $\tilde{T}e$ fluctuations to core plasma transport has not been investigated previously**

- **Electron transport driven by ETG/TEM modes can be dominant once ITG turbulence ($k_\perp r_s < 0.5$) is quenched in H-Mode** $(\chi_i \sim \chi_{i,neo})$

- **Combined ETG/TEM Gyrokinetic Simulations show large scale radial structures (streamers) and significant electron heat transport at intermediate/ high wavenumber ($k_\perp r_s \geq 1$).**

Correlation Electron Cyclotron Emission (CECE) diagnostic measures local, low-k electron temperature fluctuations



TEXT (Cima 1995)
W7-AS (Sattler 1994)

- **Correlation radiometry of ECE uses cross-correlation of two ECE channels to reduce the thermal noise**
- **f_1 and f_2 are from distinct, non-overlapping frequency bands, within radial correlation length of turbulence**
- **Measure RMS amplitude and power spectrum, $\tilde{T}_e / T_e$**

Correlation ECE data show a substantial decrease (>75%) in $\tilde{T}_e/T_e$ at the L-H transition and during QH-mode+

Counter-injected QH-mode shot #125116

In L-mode:

$$\tilde{T}_e/T_e \sim \tilde{n}/n \ ^*$$

+ L. Schmitz, A.E. White, et al., Phys. Rev. Lett. 100, (2008)

*A.E. White, L. Schmitz, et al., Phys. Plasmas (2008)

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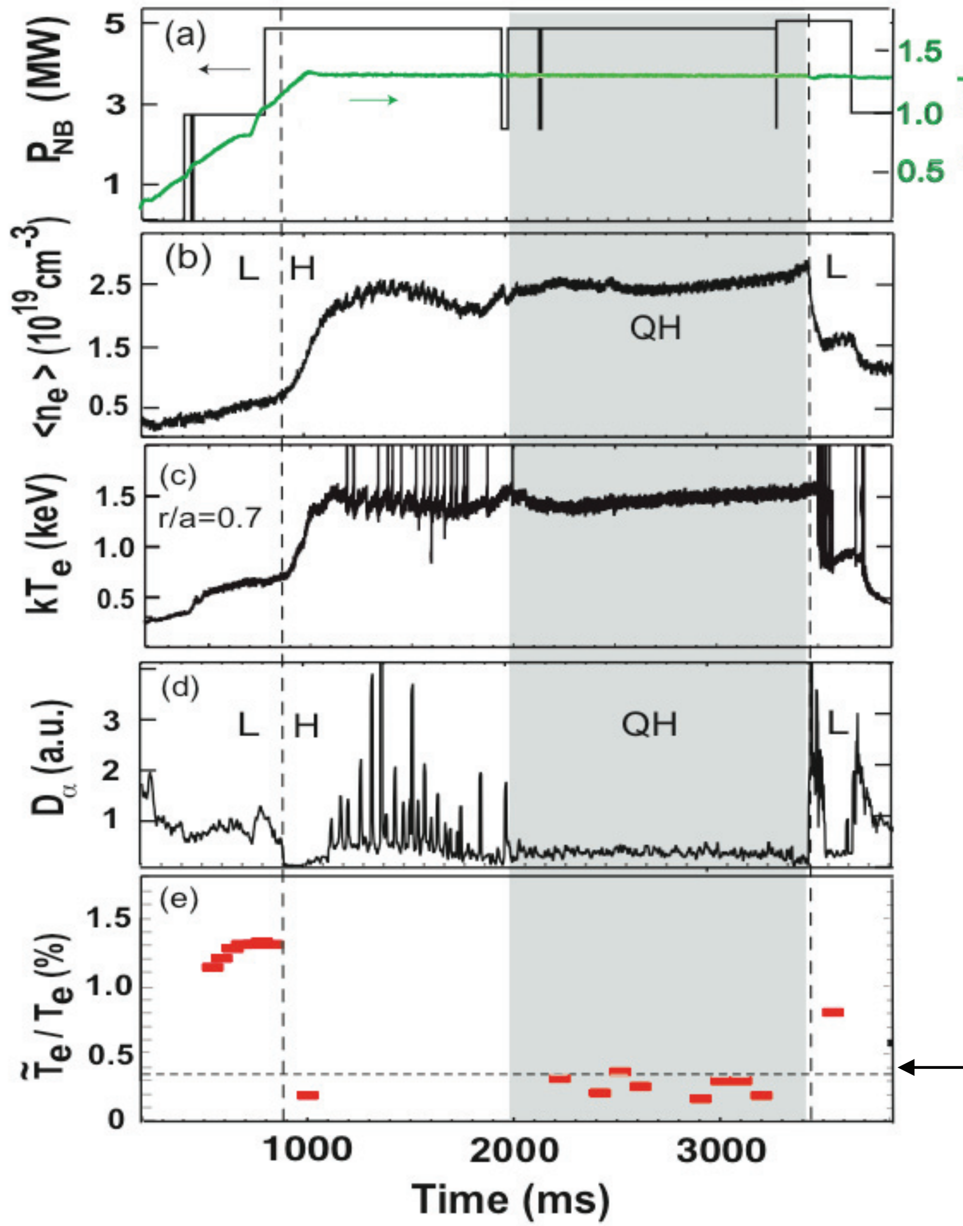

Statistical Significance Limit

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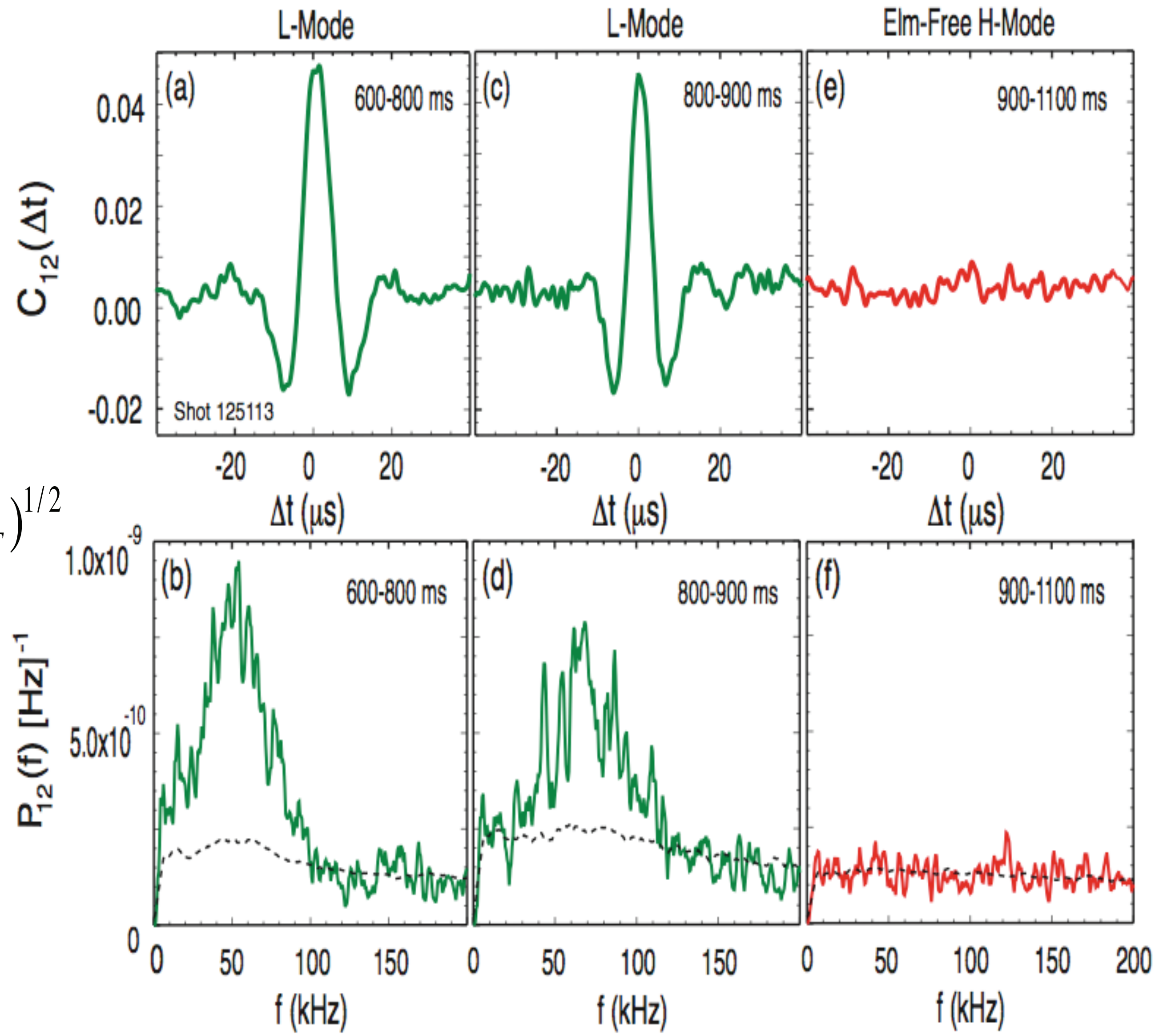
CECE correlation coefficient ($\sim\tilde{T}_e/T_e$) and cross-power spectra decrease across L-H transition

$\tilde{T}_e/T_e$ is directly determined from the correlation coefficient:

$$\tilde{T}_e/T_e = [C_{12}(0)]^{1/2} \times (\Delta f_{vid}/\Delta f_{IF})^{1/2}$$

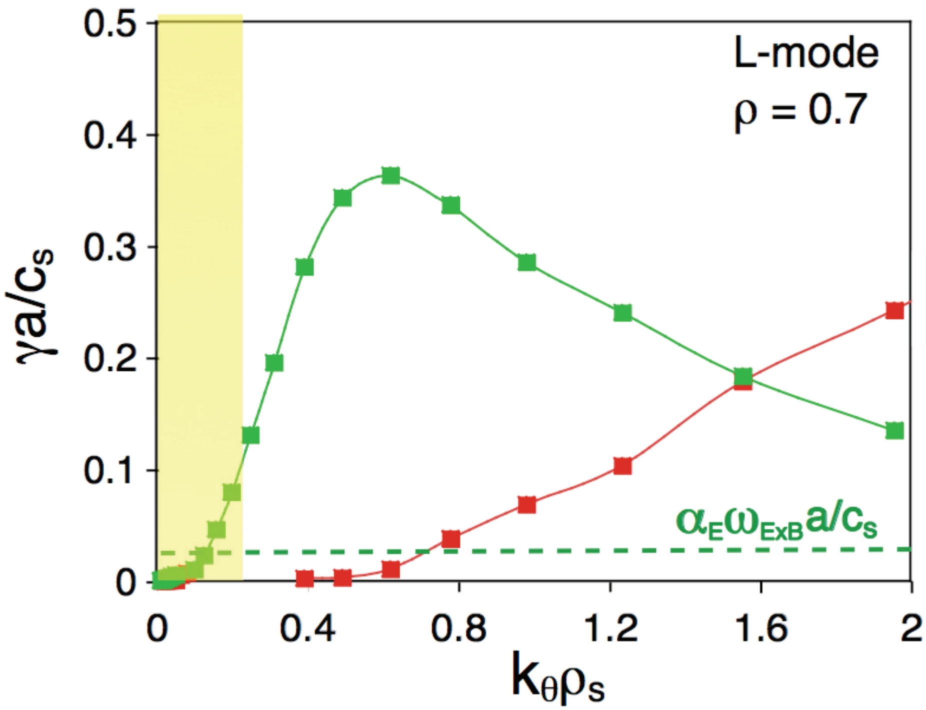
Spectral shape is dominated by ExB speed:

$$f_{max} \sim v_{E\times B} < k_\theta > /2\pi$$

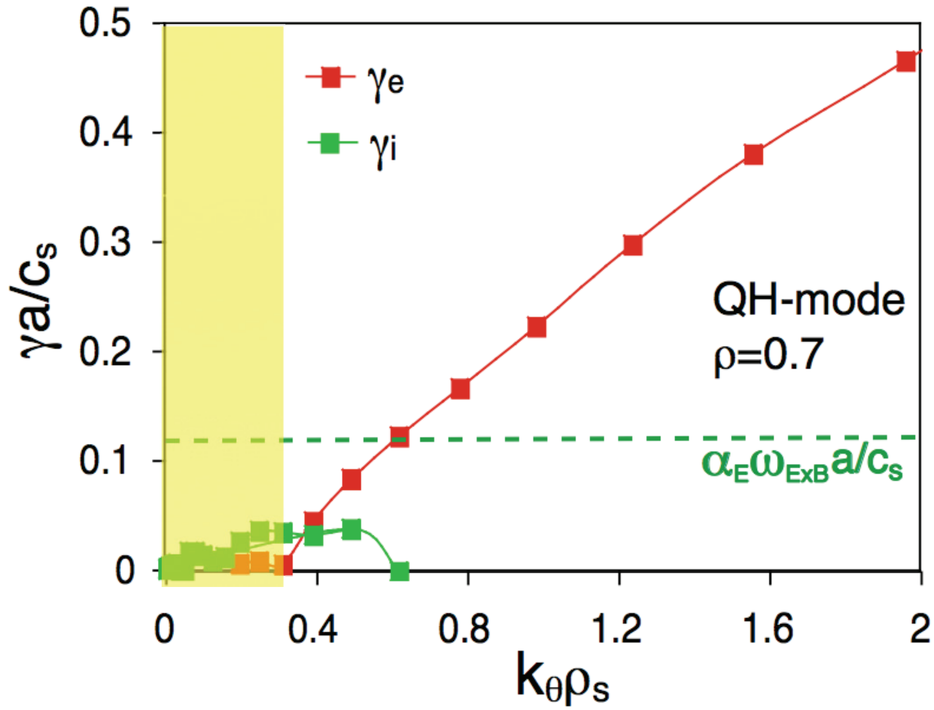


Linear Stability Calculations (TGLF) indicate that ITG modes are quenched in QH-mode but TEM/ETG persist for $kr_s > 0.6$

$R/L_{Te}=6.3$ $R/L_{n}=1.5$



$R/L_{n}=1$ $R/L_{Te}=4$



ITG and TEM/ETG linear growth rate exceed flux-surface-averaged ExB shearing rate $w_E=0.3\ k^{1/2}\langle w_{ExB}\rangle$ in L-mode

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In QH-mode, $kr_s > 0.6$ is still expected unstable

Wavenumber range accessible to CECE

Conclusion: Electron Temperature fluctuations are feature of ITG modes, possibly due to non-adiabatic electron response

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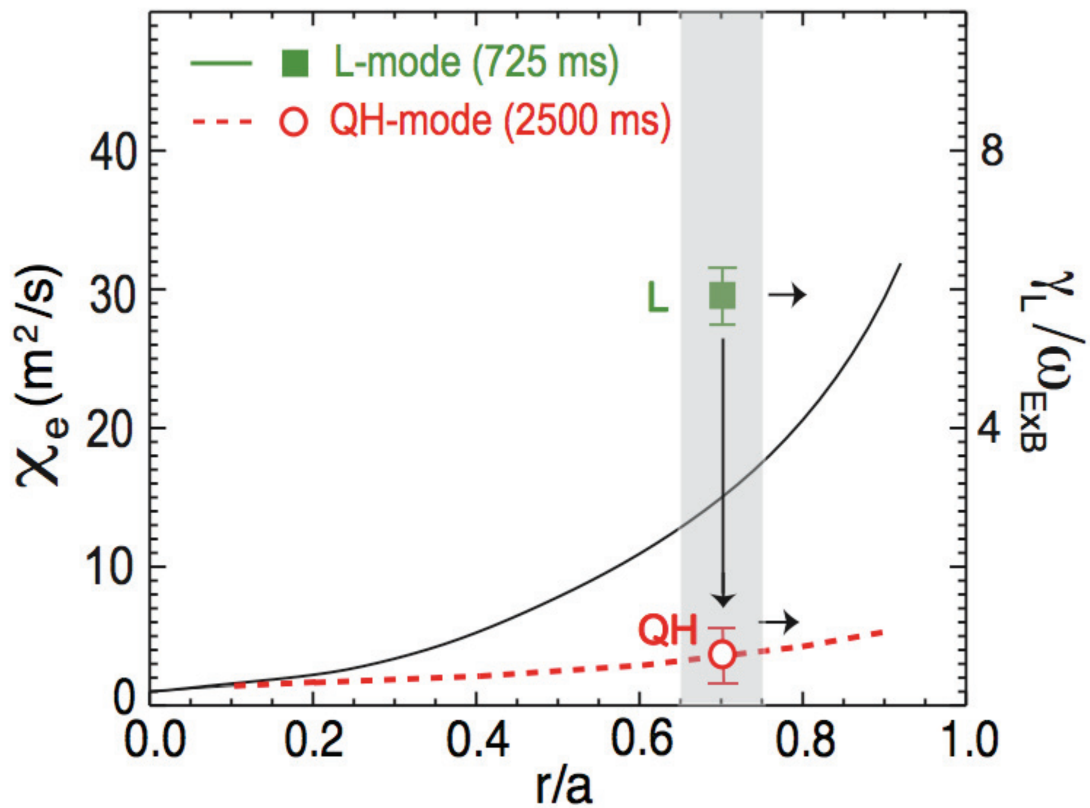
In QH-mode, the electron heat diffusivity is significantly reduced across the minor radius

Electron heat flux due to temperature and density fluctuations depends on the relative phasing of $\tilde{T}$, $\tilde{n}$, and $\tilde{E}_q$:

$$Q_e^{fl} = 3/2nk_BT_e/B_t(<(\tilde{T}_e/T)\tilde{E}_\theta> + <(\tilde{n}/n)\tilde{E}_\theta>)$$

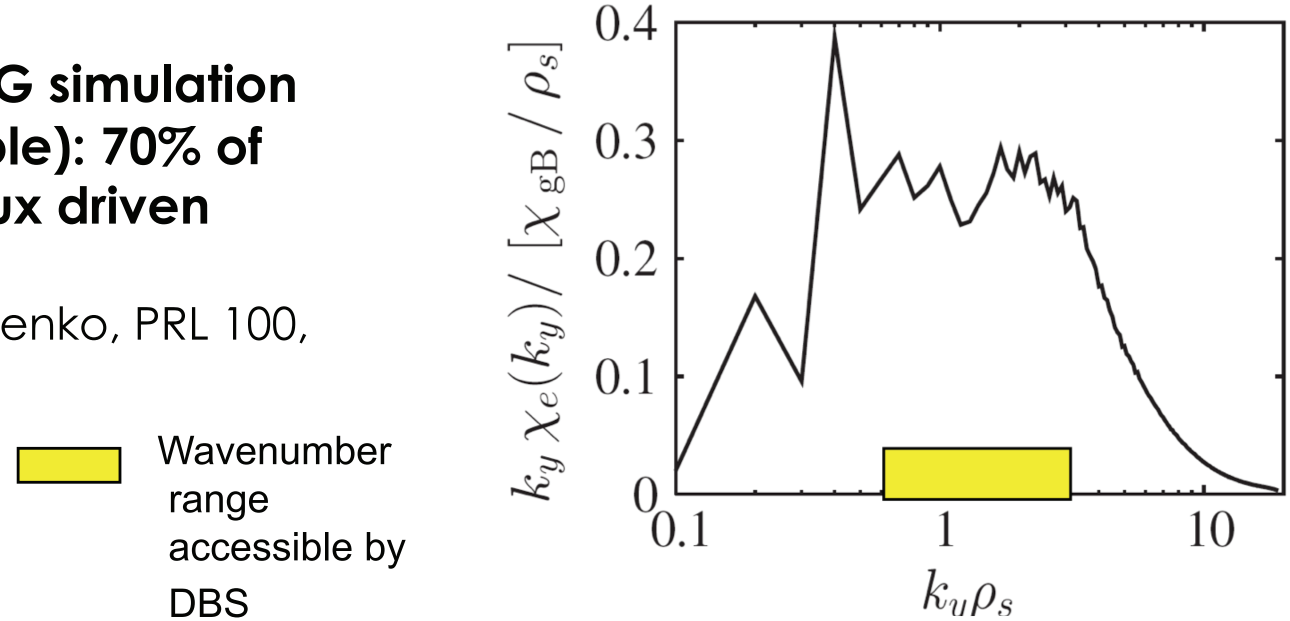
Recent GYRO simulations show that $\tilde{T}_e$ can contribute substantially (> 50%) to L-mode electron heat transport.*

*(A.E. White et al. Phys Plasmas 15, 2008)

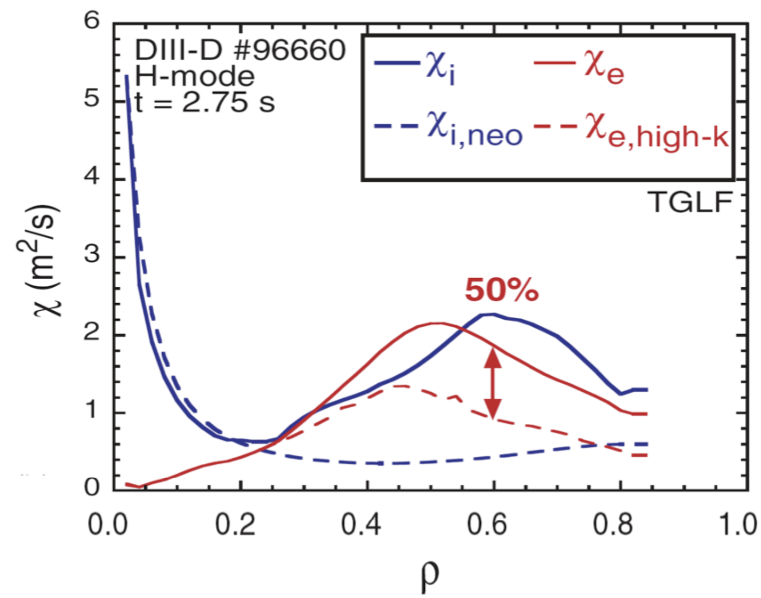


Intermediate/ high-k turbulence may drive 50% or more of the electron heat flux once ITG modes are suppressed

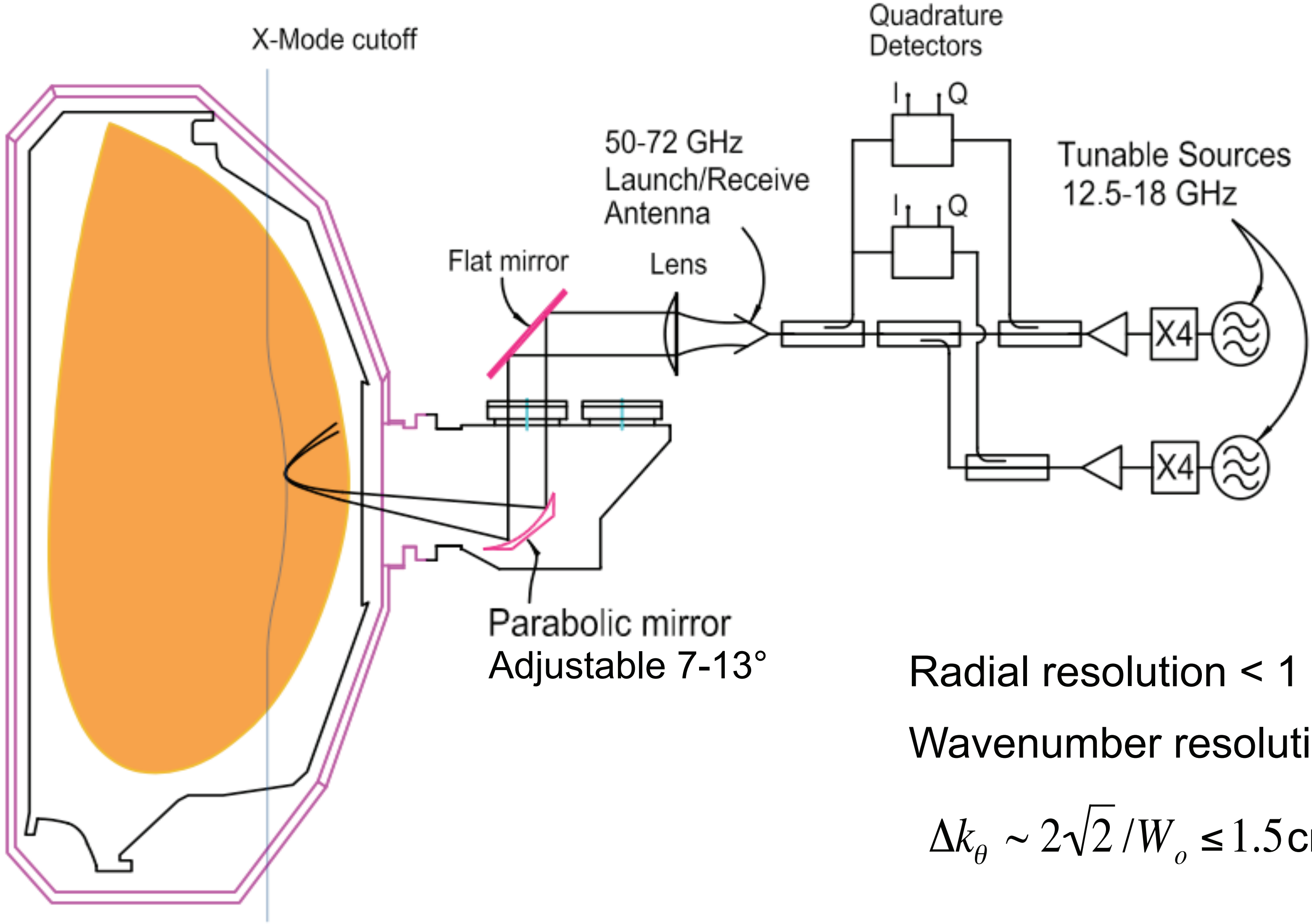
Coupled TEM/ETG simulation (ITG linearly stable): 70% of electron heat flux driven for $k_q r_s \geq 0.5$.
(T. Goerler and F. Jenko, PRL 100, 185002, 2008).



TGLF (Trapped gyro-Landau fluid) simulation: 50% of H-mode electron heat flux in DIII-D is driven by high -k modes
(J. Kinsey, Phys. Plasmas 15, 055908, 2008).



Doppler Backscattering Diagnostic (DBS) measures intermediate scale density fluctuations ($0.5 < k_\theta r_s < 4$)



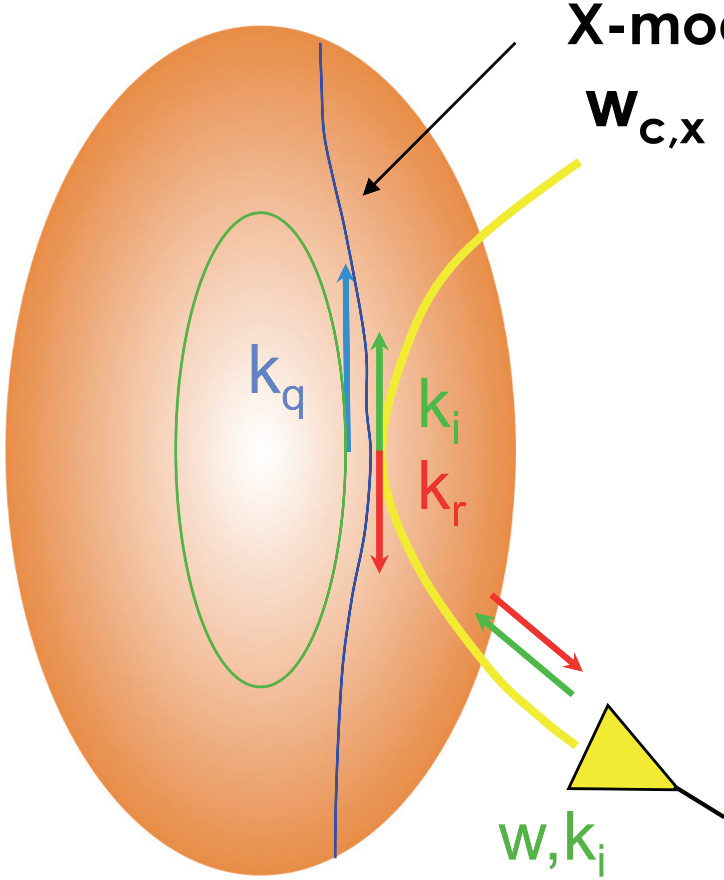
Radial resolution < 1 cm

Wavenumber resolution:

$$\Delta k_\theta \sim 2\sqrt{2}/W_o \leq 1.5 \text{cm}^{-1}$$

Principle of Doppler Backscattering (DBS)

X-mode cutoff layer w = $w_{c,x}$

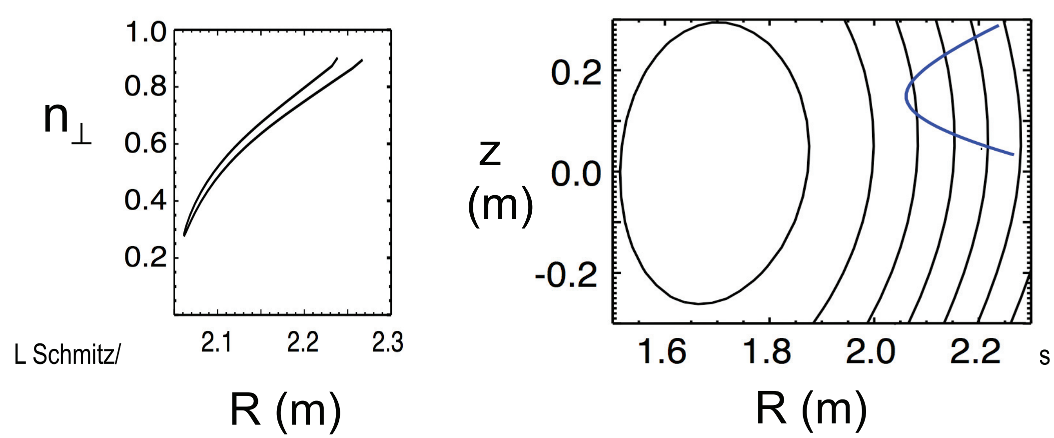


$k_q = -2k_r$

Backscattering off density fluctuations with $k_q = -2k_r = 2k_i$

Poloidal turbulence velocity obtained from frequency shift:
$v_{fl} = v_{ExB} + v_{ph} = w_{Doppler} / 2k_i$

GENRAY Ray Tracing is used to determine Backscattering location and $k_i = n_\perp k_{vac}$



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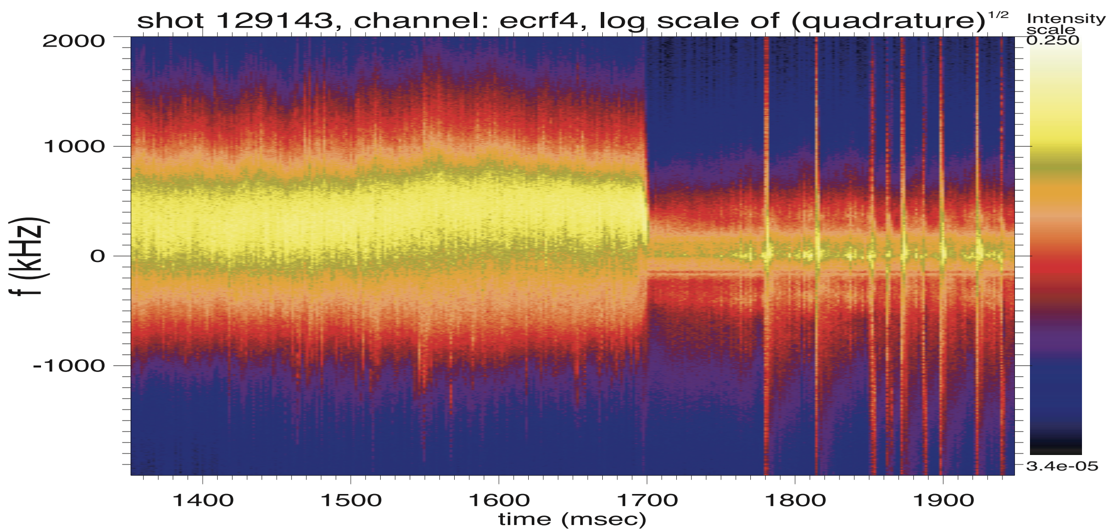
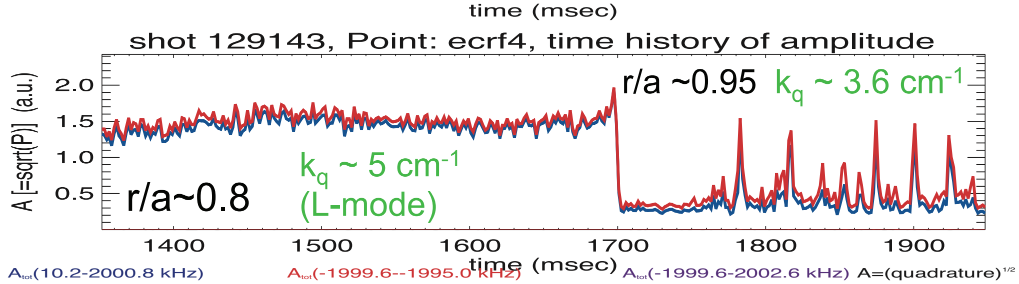
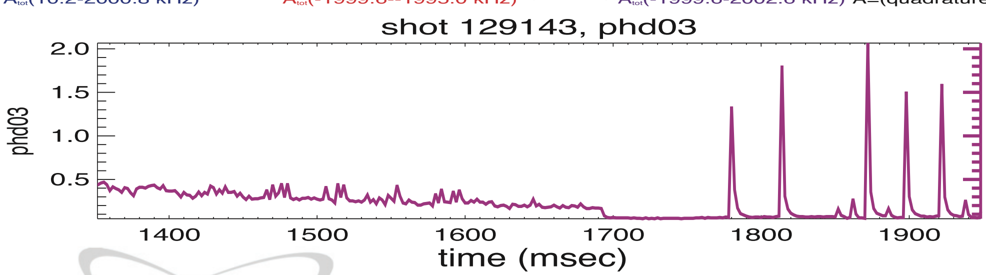
Low and intermediate-k fluctuation spectra for low rotation L-H transition

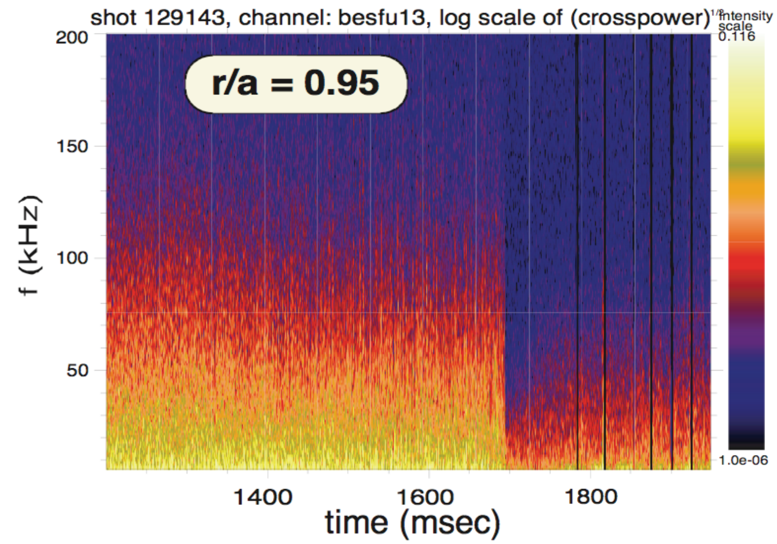
Doppler Backscattering (k_θ ~ 3.5-5 cm^{-1})

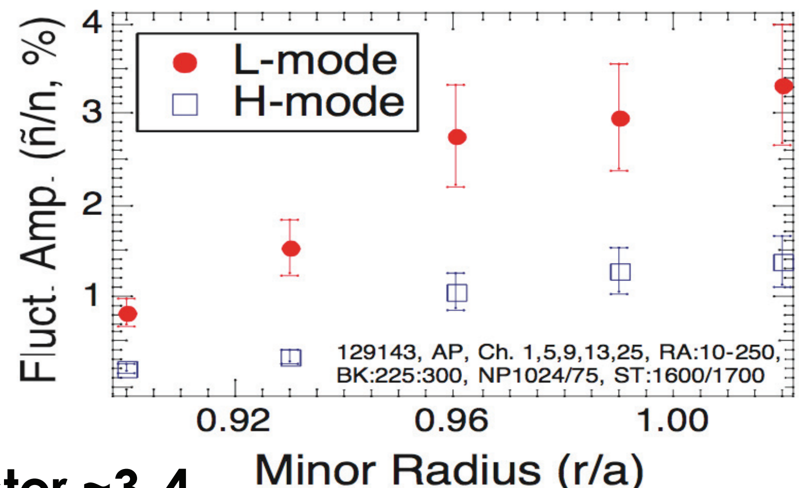






BES ($k_\theta \leq$ 3 cm^{-1})





ñ/n reduced by factor ~3-4

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DBS shows 30-80% reduction of intermediate-k fluctuations across the L-H transition

Co-injected Plasma,
B=2T, I_p=1 MA,
P_{NB}=3 MW

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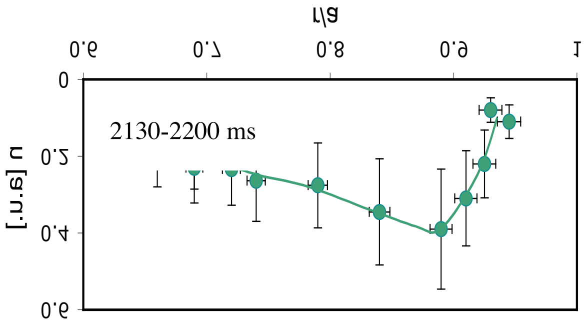
Rapid decrease
Within 1 ms

Pedestal Top:
Rapid decrease
Within 0.1 ms



$k_\perp$~7-11 cm^{-1}
0.3<r/a<0.6 (est.)
$k_q r_s$ ~ 2.5

$k_\perp$ ~ 5-7 cm^{-1}
0.7 ≤ r/a ≤ 0.9
$k_q r_s$ ~ 1

$k_\perp$ ~ 3.5 cm^{-1}
r/a~0.95
$k_q r_s$ ~ 0.5

BES Data:
$k_\perp$ ~ 0-3 cm^{-1}
$k_q r_s$ ~ 0.1-0.2

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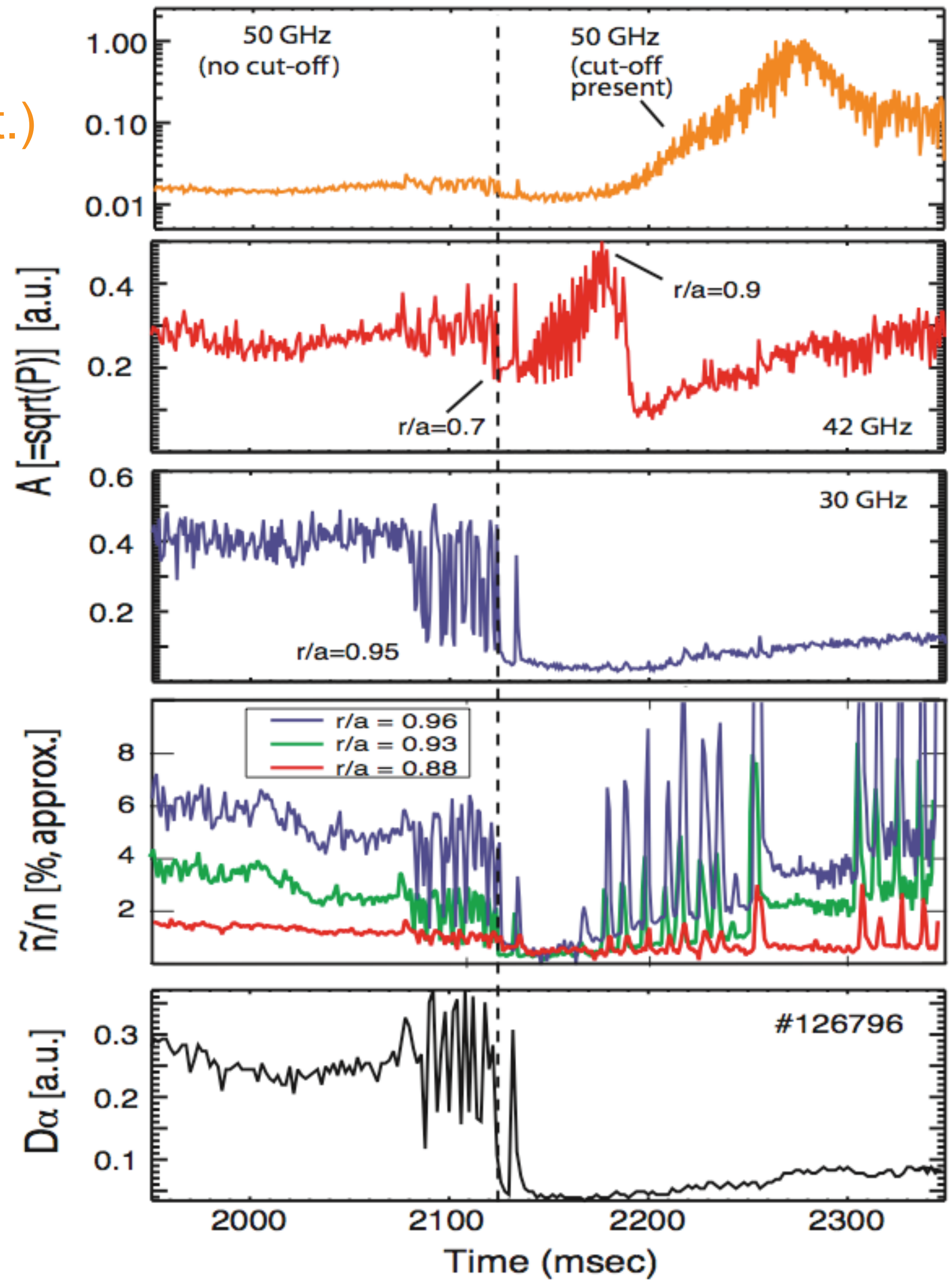
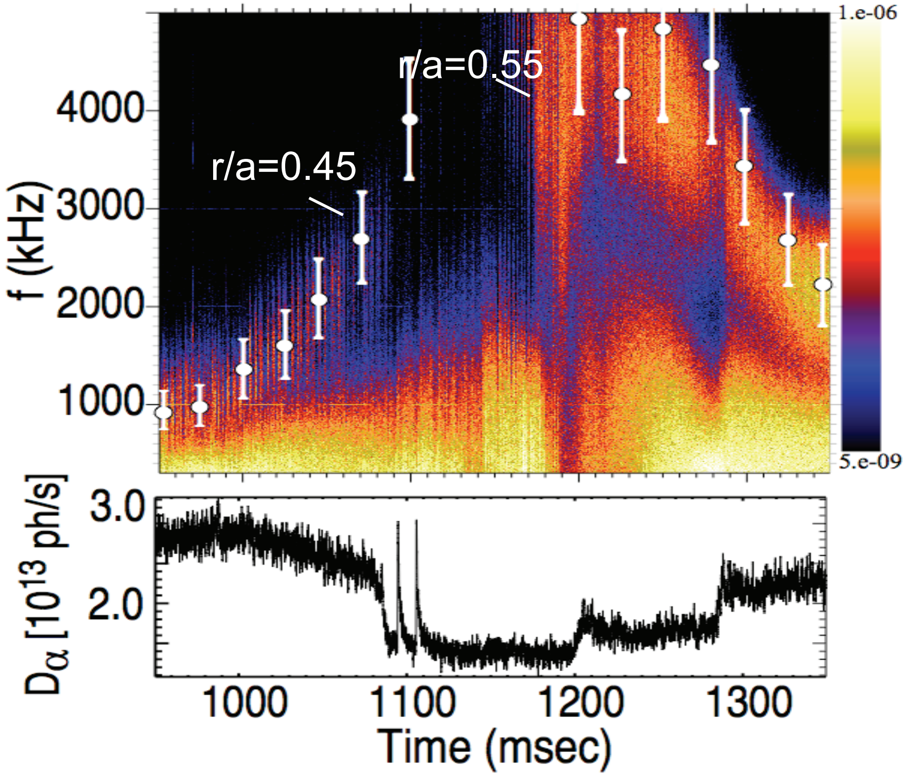
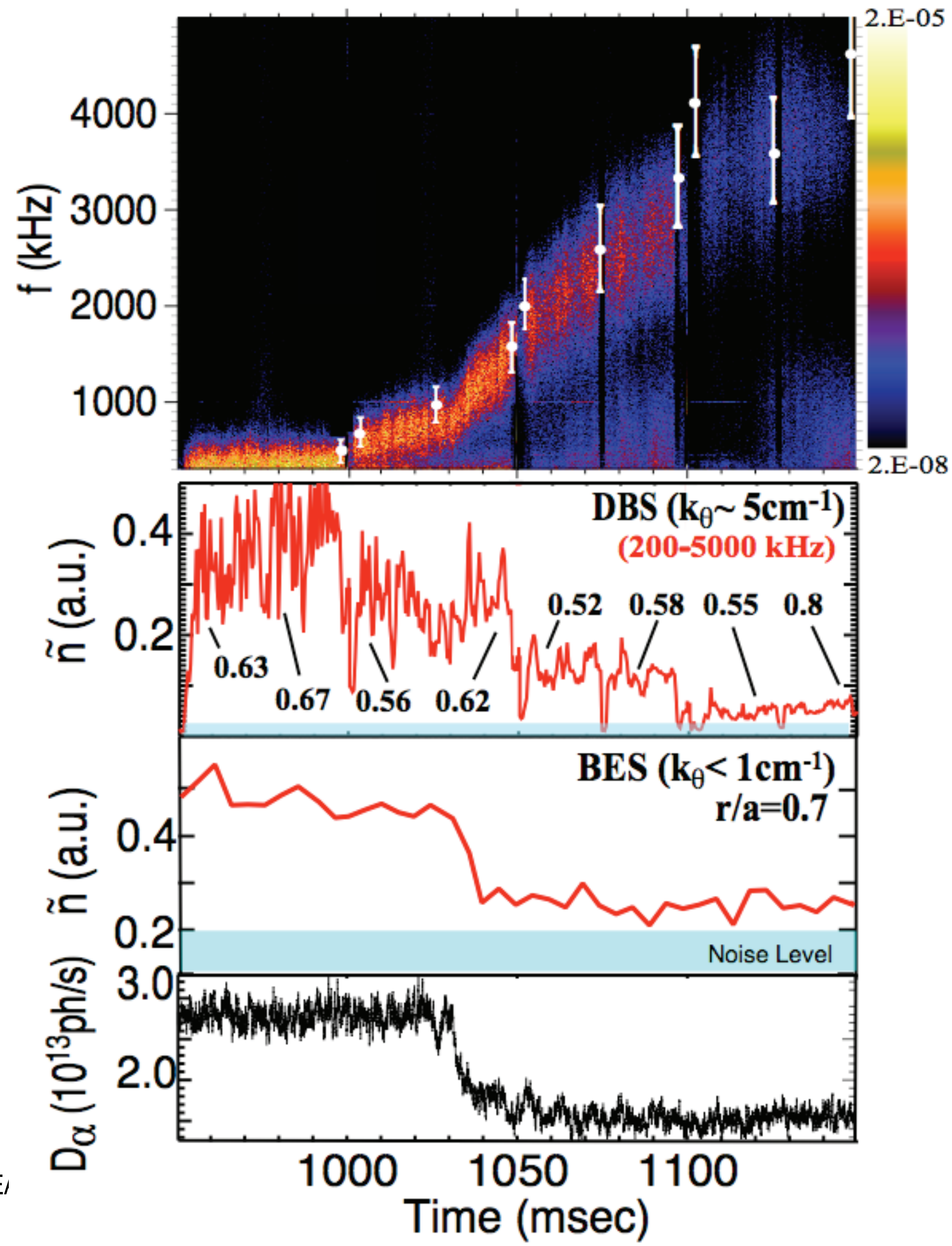


Very pronounced fluctuation reduction in low-density, counter -injected QH-mode plasma (suppression for r/a < 0.5)





Reduction observed ~ 10 ms after D_α drop.

DBS Doppler shift agrees well with shift from CER data (shown in white)

Scanned frequency to cover $0.5 \le r/a \le 0.8$

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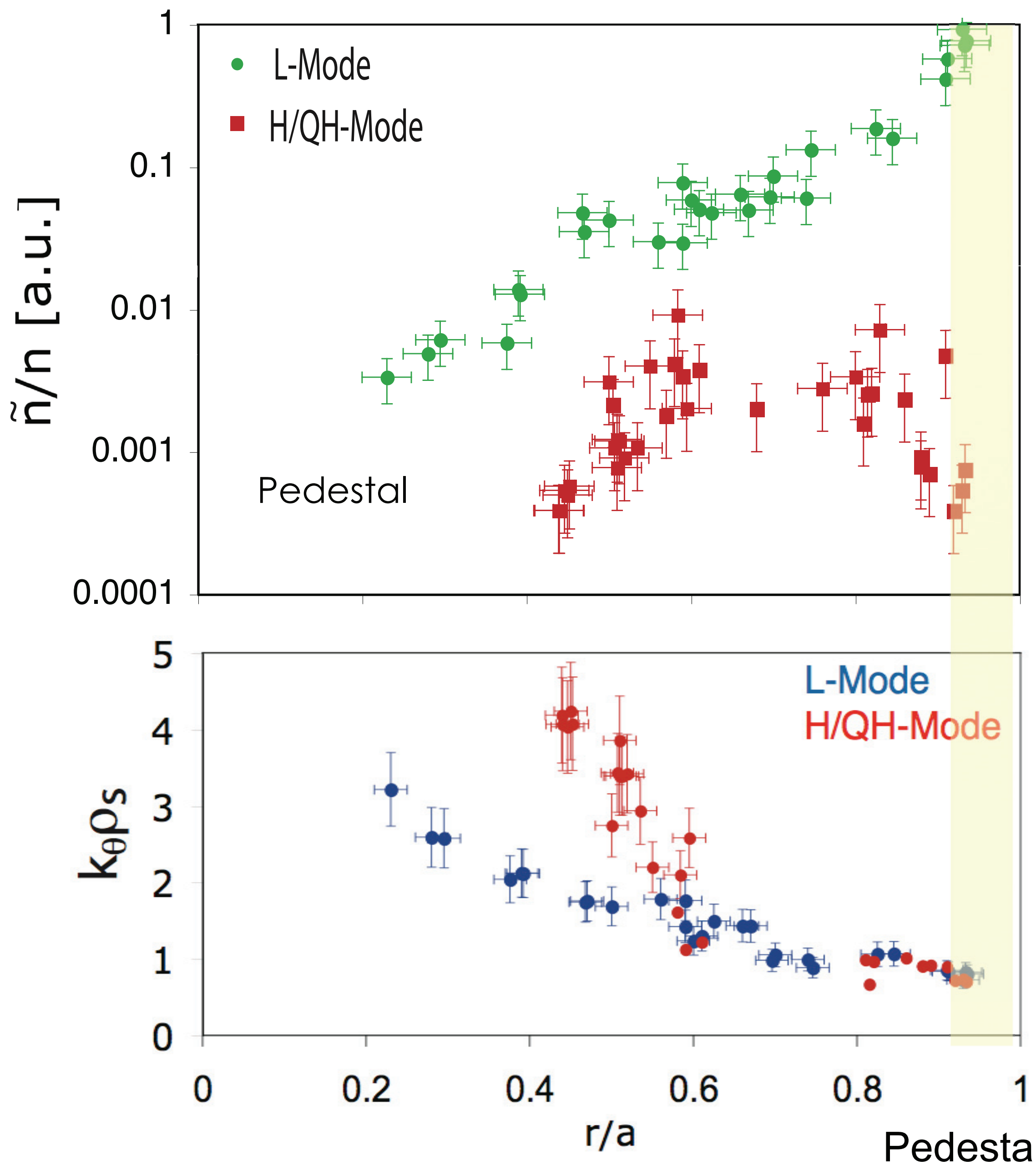
Largest reduction of H and QH-mode fluctuation level is found in pedestal region and inner core (r/a <0.5)

The probed $k_{\perp} r_s$ increases towards the plasma center:

Fluctuation levels need be be normalized since fluctuation spectrum is predicted to scale* as $\tilde{n}/n \sim (k_{\perp} r_s)^{-7/4}$

*P. Hennequin, R. Sabot, et al., PPCF 46, B121 (2004).



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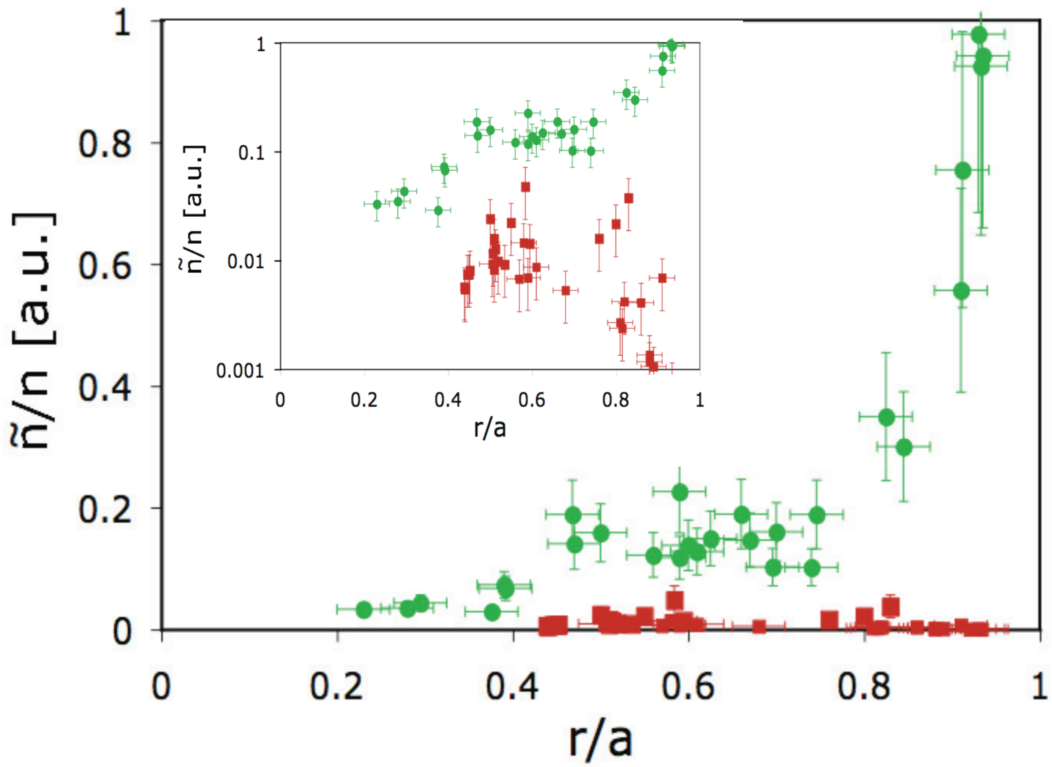
Profile of normalized fluctuation level based on scaling $\tilde{n}/n \sim (k_\perp r_s)^{-7/4}$

$\tilde{n}/n = \tilde{n}/n_{meas.} * (k_\perp \rho_s)^{7/4}$



L-Mode (0.7-0.97s)
H/QH-Mode (1.07-1.4s)
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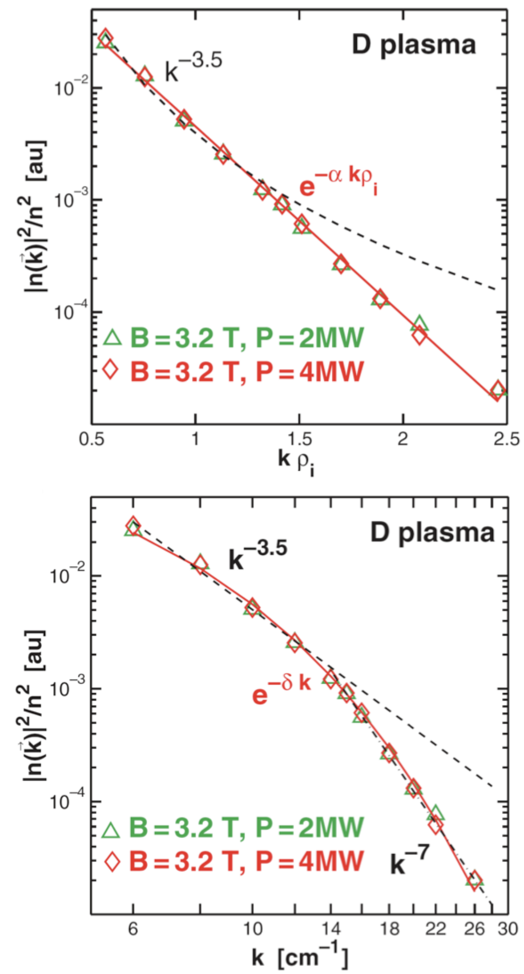
Relative fluctuation level $\tilde{n}/n$ is normalized to L-Mode edge value

Scaling from TORE SUPRA*:
$(\tilde{n}/n)^2 \sim (k_\perp r_s)^{-3.5}$



*P. Hennequin, R. Sabot, et al., PPCF 46, B121 (2004).

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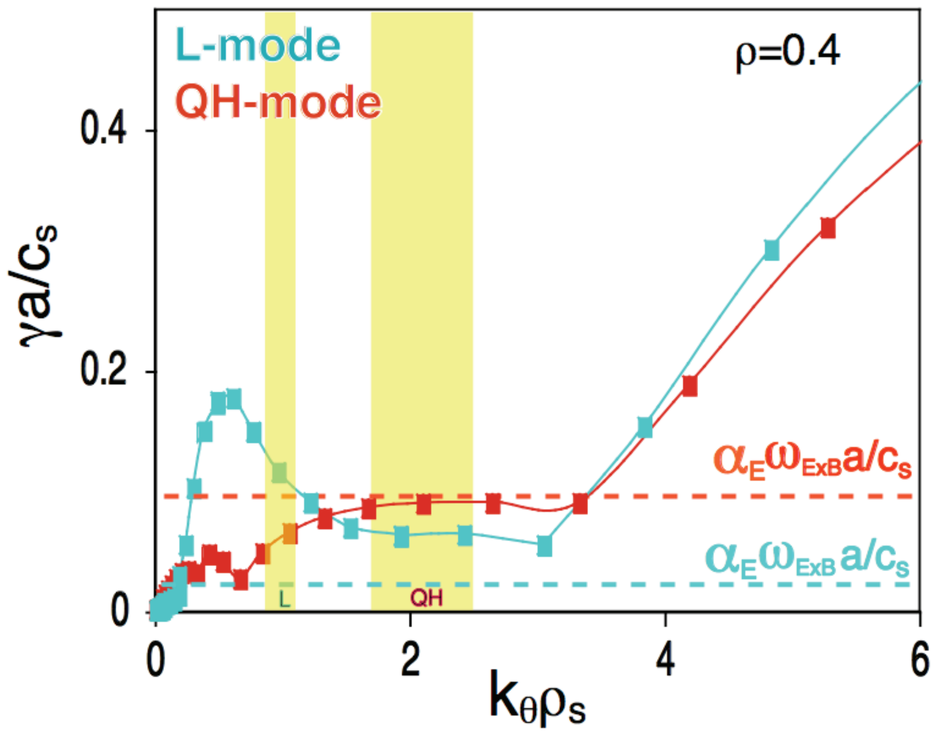
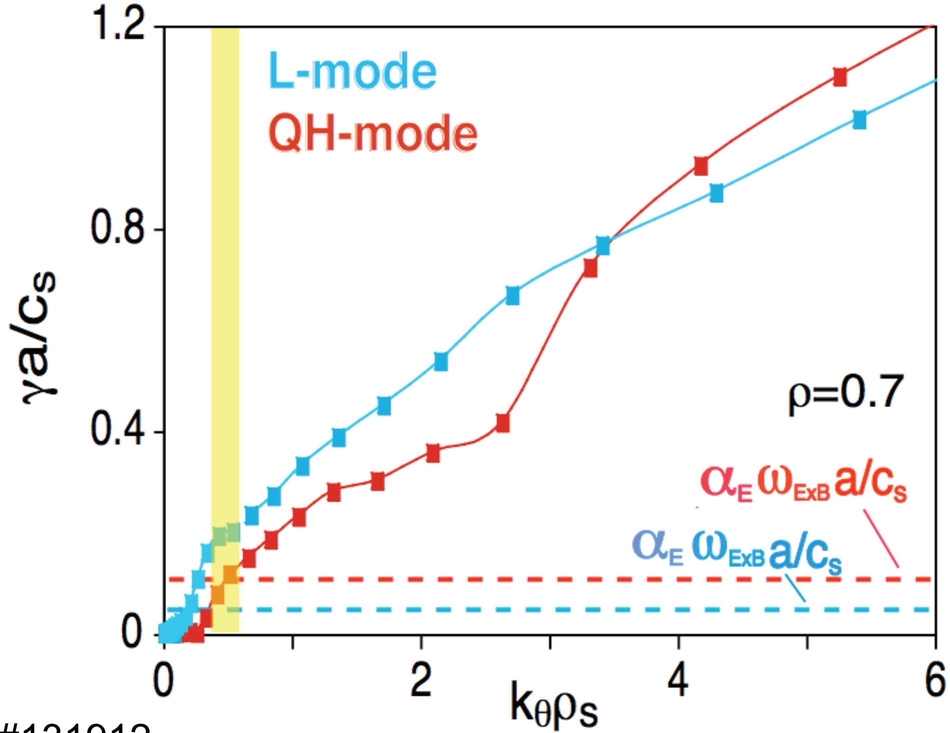
Linear stability calculations (TGLF) indicate intermediate scale stability in QH-mode core plasma ($kr_s \lesssim 3$)

$R/L_{Te}=4.3$ $R/L_n=2$ (L-mode) $R/L_{Te}= 2$ $R/L_n=1.7$ (QH-mode)



$R/L_{Te}=4.9$ $R/L_n=2.1$ (L-mode) $R/L_{Te}=4.4$ $R/L_n=1$ (QH-mode)



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Most unstable mode is shown. TEM/ETG is marginally stable for r/a=0.4 ($kr_s \leq 3$).

Calculations confirm linear instability in QH-mode for r/a> 0.55 ($kr_s \geq 0.5$).

Shearing rate:

$$w_E = a_E \langle w_{E\times B} \rangle, \quad a_E = 0.3k^{1/2}$$

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Wavenumber range accessible by DBS

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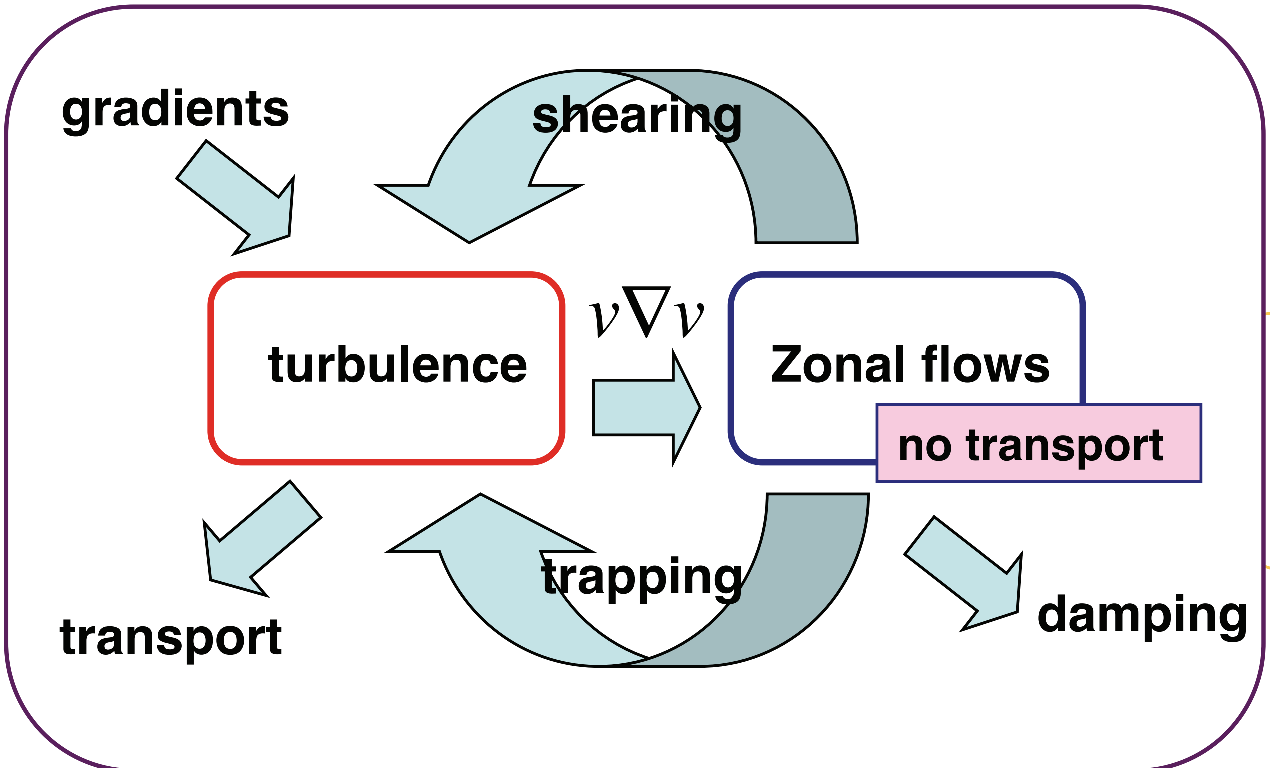
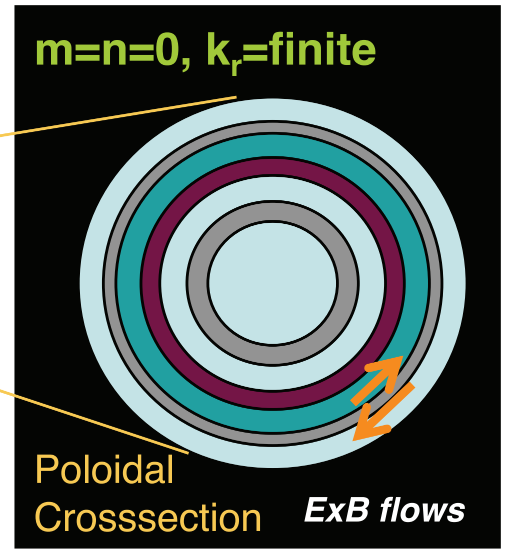
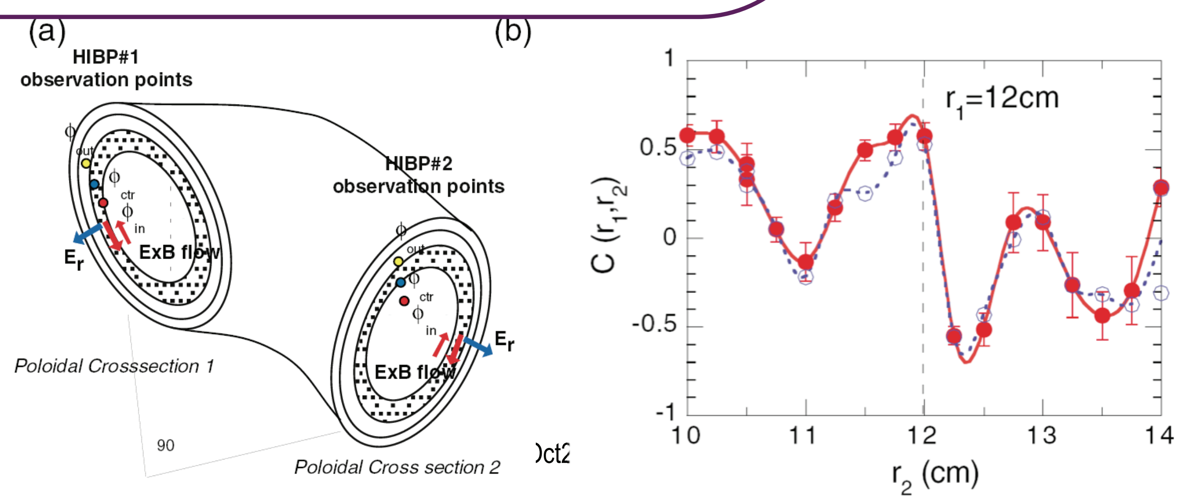
Generation of Zonal Flows and interaction with turbulence







HIBP data (A. Fujisawa et al., PRL 2004)

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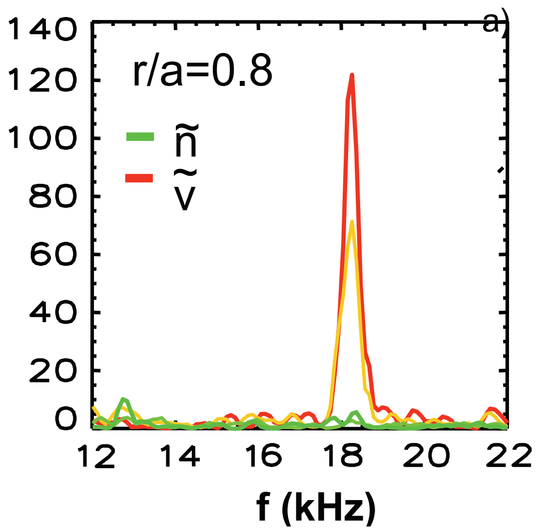
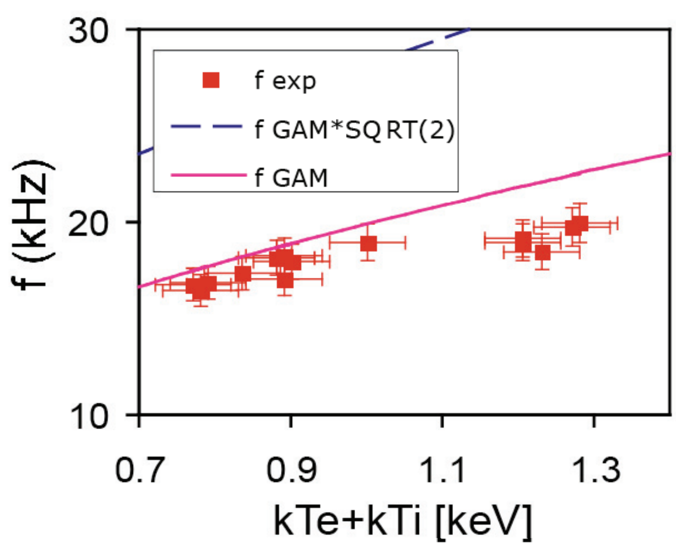
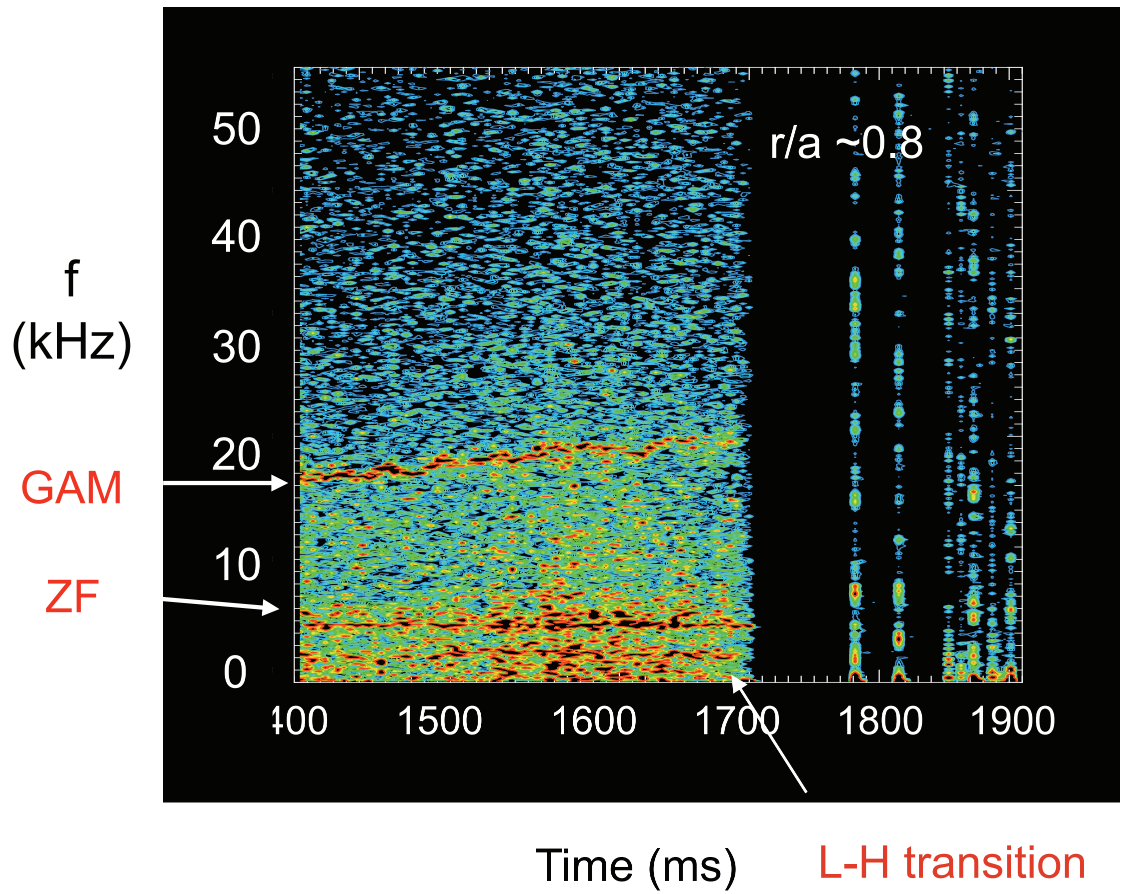
Observation of GAMs and Low Frequency Zonal Flows (ZF) in DIII-D L-Mode Plasma by Doppler Backscattering







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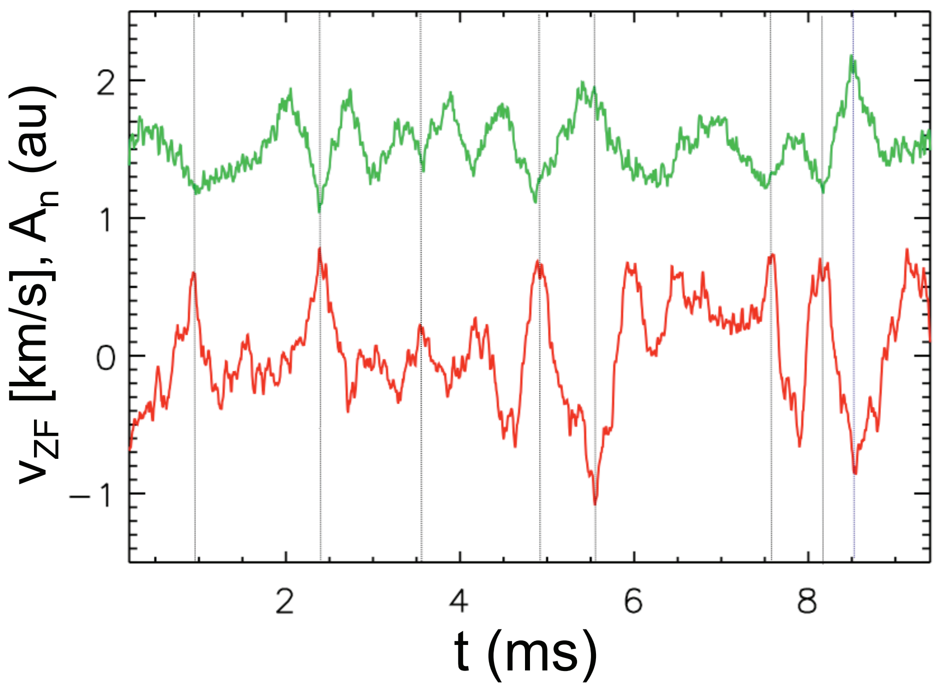
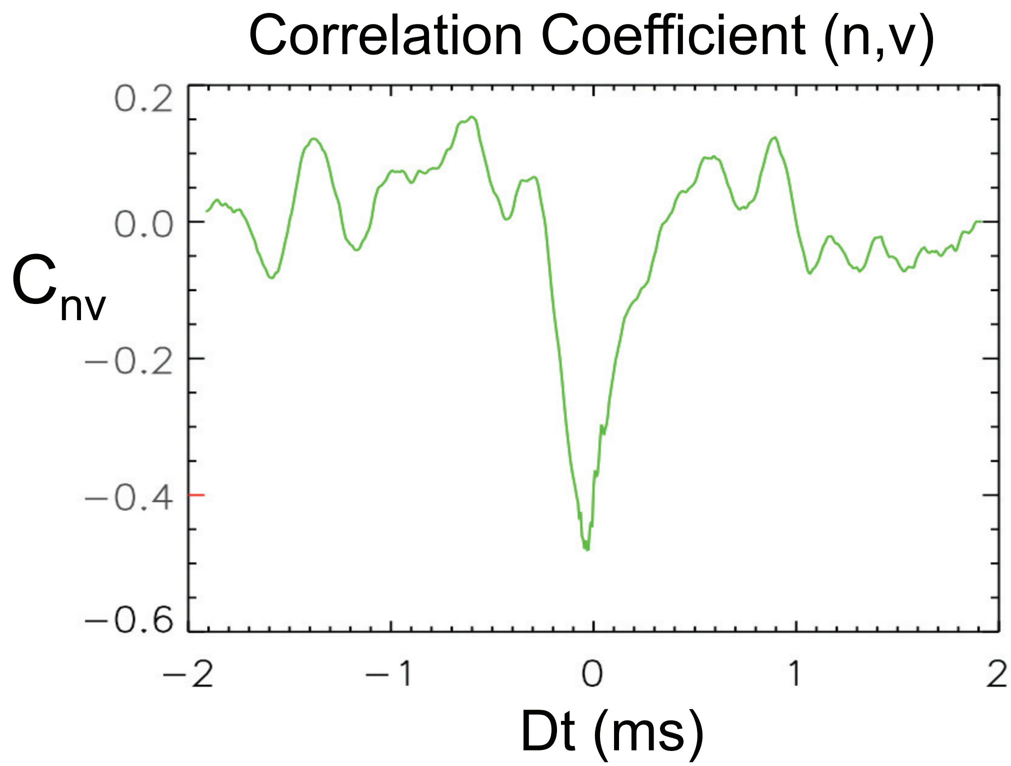
Strong Zonal Flows modulate Intermediate-scale density fluctuation amplitude





Low frequency flow fluctuations v: 0.2-3 kHz
High frequency density fluctuation amplitude A_n: 7.5-75 kHz

Density fluctuation probed poloidal wavenumber: $k_q \sim 5\ cm^{-1}$

- **Strong Anticorrelation between flow and density fluctuation envelope in L-mode core plasma.**

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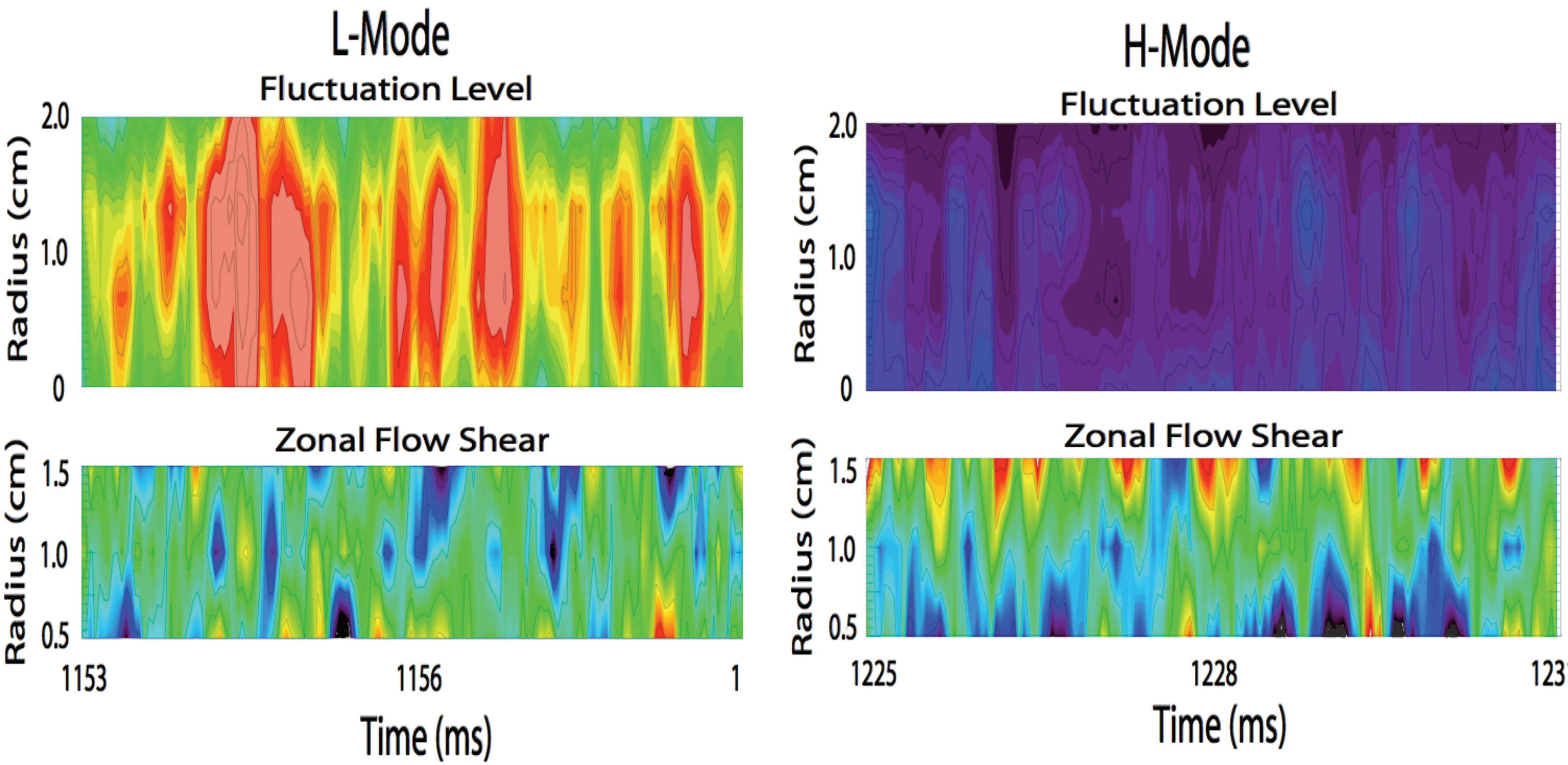
Reduced fluctuation level and enhanced Zonal Flow shear in H-Mode (core plasma)



4-channel DBS system

133678, r/a=0.5, H-mode transition at 1220 ms

Probed $k_q \sim 5.5\text{-}6\ cm^{-1}$

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Summary

- Electron temperature fluctuations in the ITG regime are substantially reduced in H/QH-mode as large-scale turbulence is shear-stabilized.
- Intermediate scale turbulence is observed to be suppressed in the core of low density counter-injected H- and QH-mode plasmas and is reduced for r/a > 0.5, in agreement with TGLF linear stability calculations. Moderate turbulence reduction has been observed at the L-H transition in other plasma regimes for r/a > 0.5. The reduction is most pronounced at the top of the pedestal.
- Transport Calculations with TGLF/XPTOR and GYRO simulations are in progress to obtain estimates for the contribution of low-k and intermediate-k modes to electron heat loss in L/H-mode.
- Experiments have started to investigate the role of Zonal Flows and Zonal Flow Shear for intermediate-scale turbulence regulation. A 4-channel DBS system has been implemented at DIII-D to obtain simultaneous radial profiles of flows and fluctuation levels with high time resolution.