Reduction of TEM/ETG-scale density fluctuations in the core and edge of H-mode DIII-D plasmas

Presented by L. Schmitz[1]

with

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Motivation

- **Understanding electron thermal transport in H-mode plasmas Is critical for next-step burning plasma experiments such as ITER. Electron transport is caused by large-scale as well as intermediate/ small scale turbulence.**
- **The role of ExB shear and Zonal Flows in regulating intermediate and small-scale turbulence is poorly understood.**
- **This talk presents evidence that**
  - large scale ($k_{\perp} r_s < 0.5$) **temperature fluctuations are significantly reduced** in H-mode plasmas
  - **intermediate scale density turbulence** ($0.8 \leq k_{\perp} r_s \leq 4$) **is also significantly reduced** across a large radial region in H-mode
  - Zonal Flows **regulate local turbulence levels** near rational q-surfaces (e.g. q=2, observed in L-mode)

These data provide a new perspective on the role of multi-scale and multi-field turbulence phenomena in regulating electron thermal transport.

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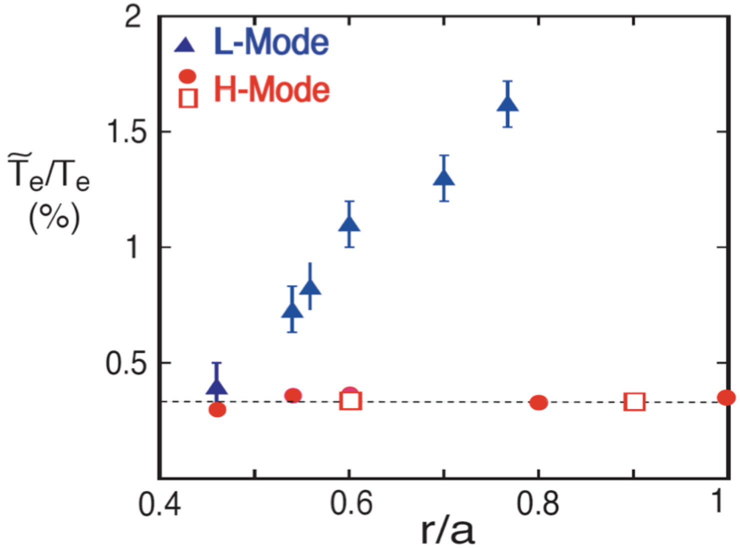
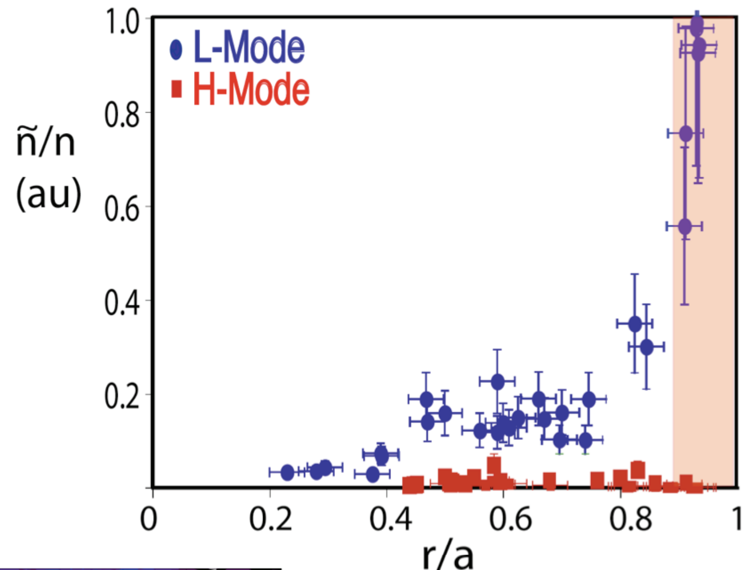
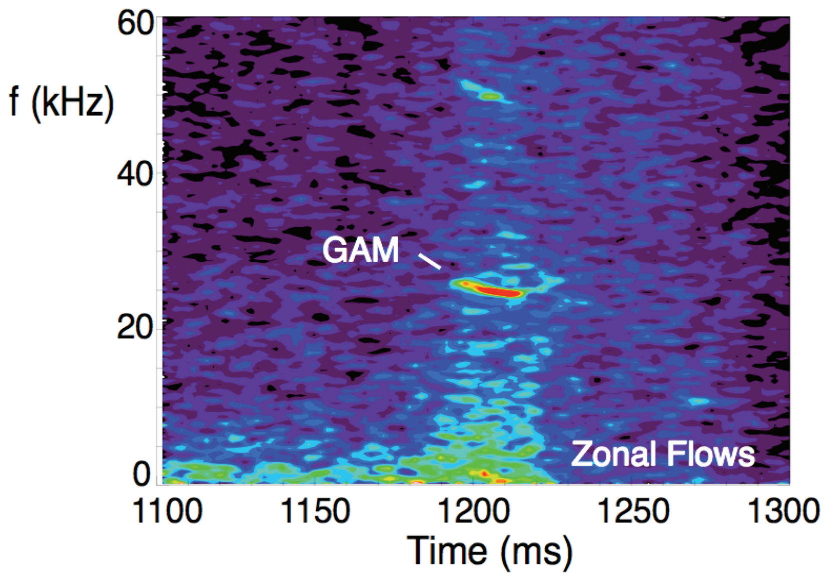
New measurement capabilities provide a fresh perspective on H-mode electron thermal transport and Zonal Flows

Radial profile of large-scale temperature fluctuations



Radial profile of Intermediate-scale density fluctuations





Interaction of Zonal Flow layers with intermediate scale turbulence

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Why are electron temperature fluctuations important?

Both density and electron temperature fluctuations can contribute to electron heat flux:

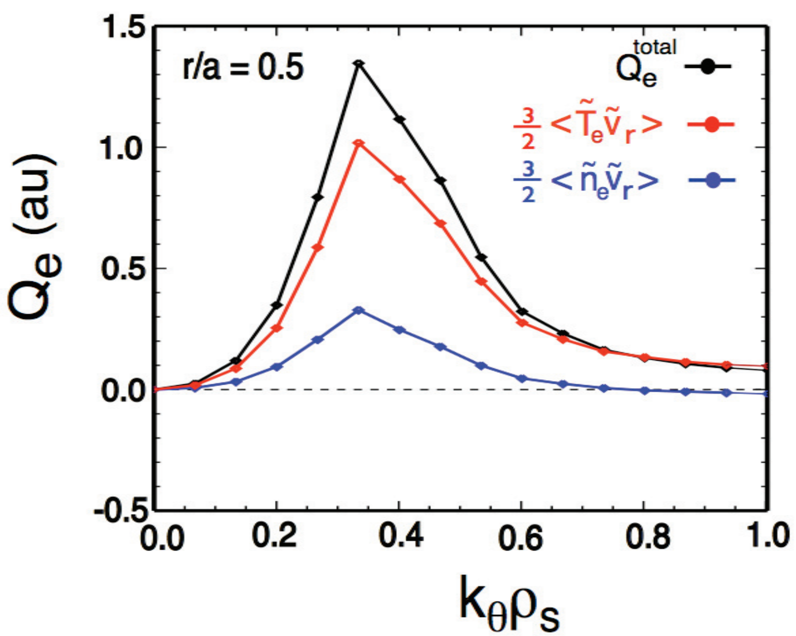
$$Q_e^{fl} = 3/2nk_B T_e / B_t (< (\tilde{T}_e/T)\,\tilde{E}_\theta > + < (\tilde{n}/n)\,\tilde{E}_\theta >)$$

For adiabatic electrons, ITG modes are not associated with temperature fluctuations. However, trapped particle effects can cause non-adiabaticity.

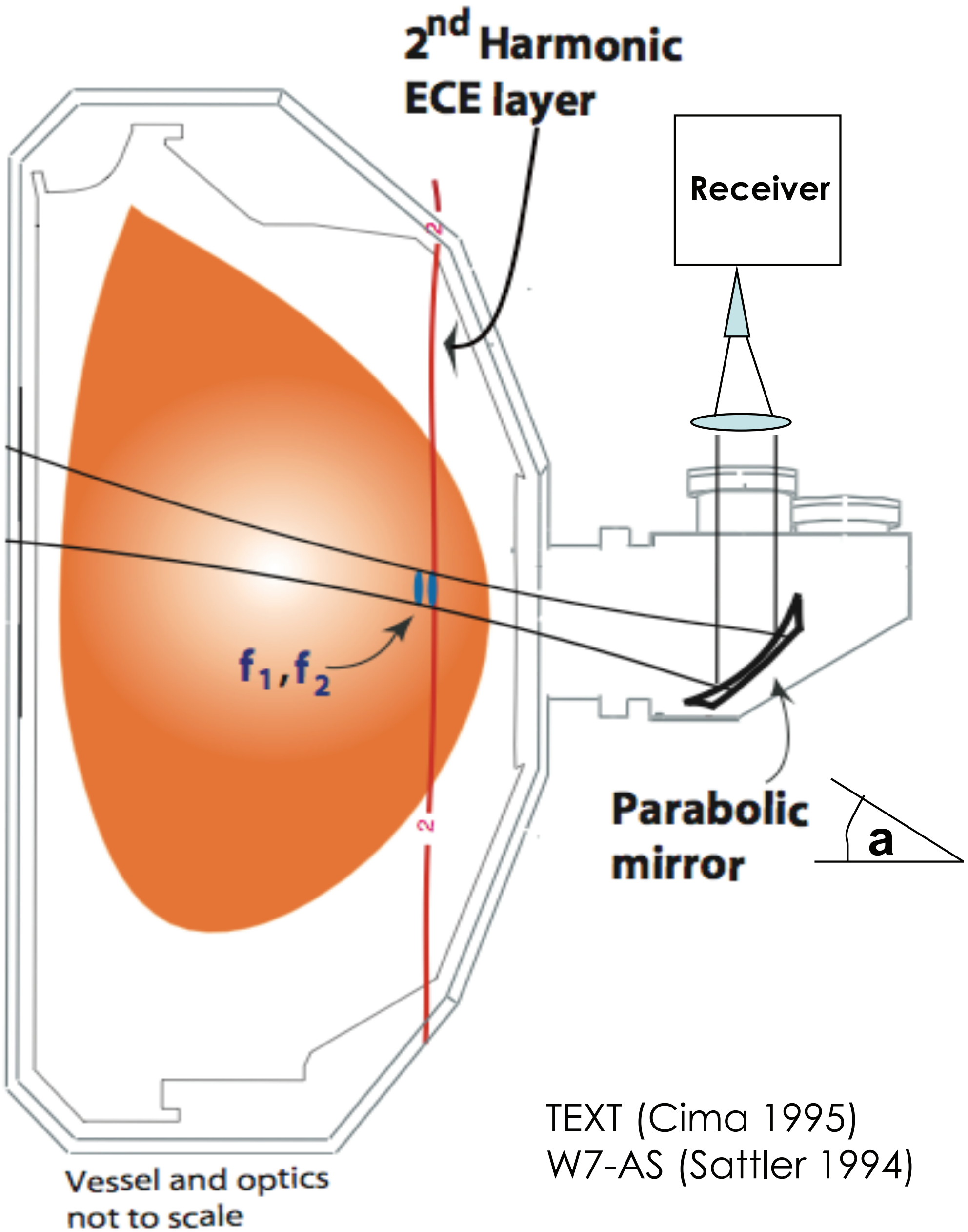
In DIII-D L-mode discharges, $\tilde{T}_e/T_e \sim \tilde{n}/n$ has been observed.*

Recent GYRO simulations:
$\tilde{T}_e$ can contribute ~ 80% to L-mode electron heat transport*

*A.E. White et al.
Phys Plasmas 15, 2008
+J. Kinsey, Nonlinear GYRO
Simulation Database



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



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

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

CECE sensitive to $k_q r_s \leq 0.5$

Turbulence Spectrum is Doppler-shifted due to ExB speed:

$$\omega \sim v_{E\times B} < k_\theta > \sin(\alpha)$$

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

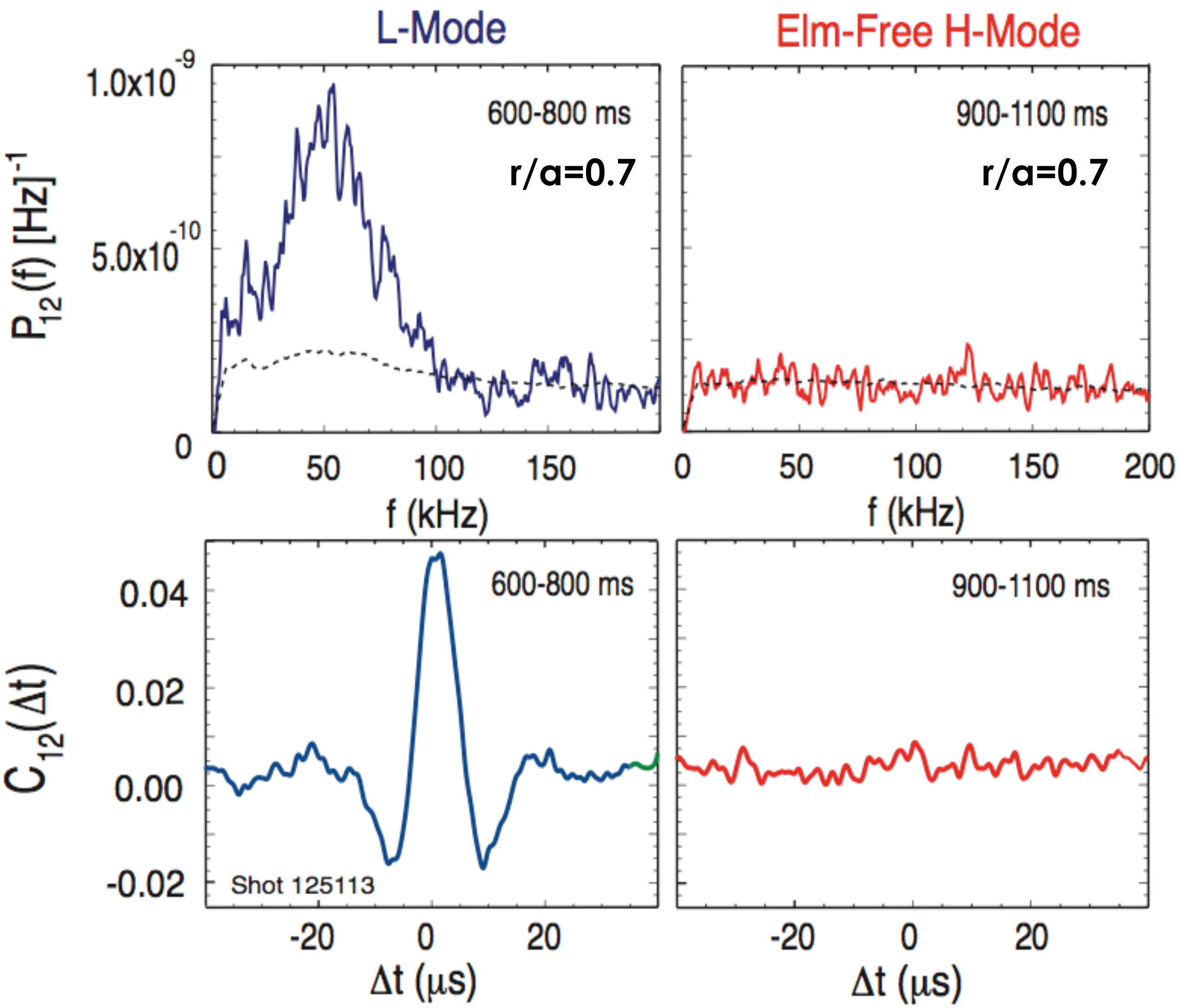
Temperature fluctuation spectrum shows L-mode feature consistent with ITG modes ($k_q \lesssim 1.7\ cm^{-1}$, $k_q r_s \lesssim 0.3$).

No feature is seen after

the L-H transition

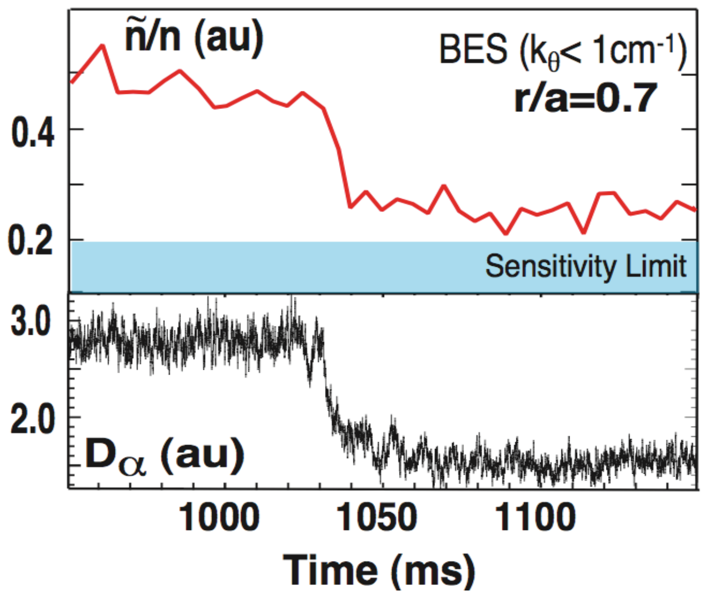
The normalized fluctuation level is directly determined from the correlation coefficient:

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

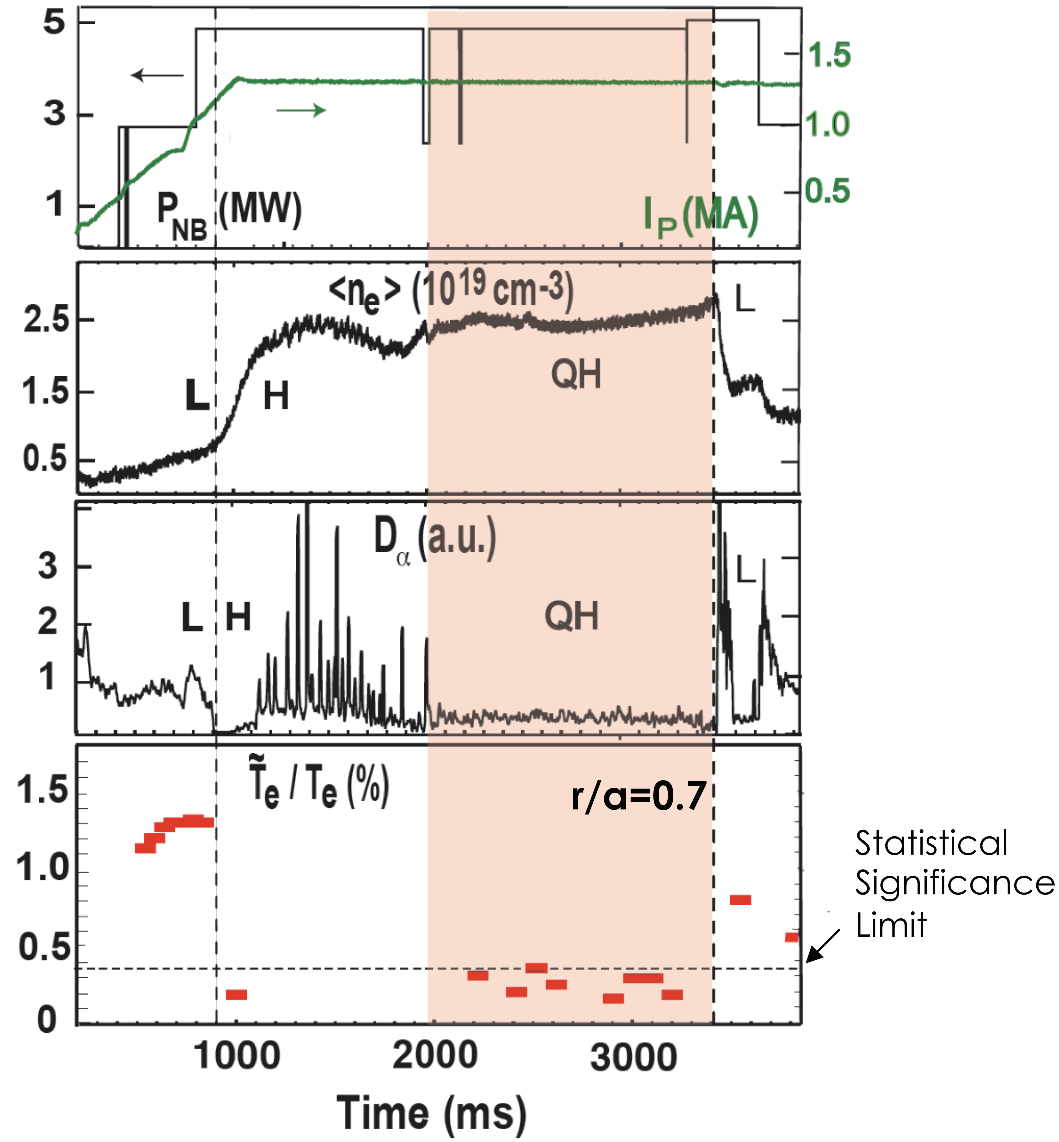


Correlation ECE and BES data show a similar decrease (≥ 75%) in $\tilde{T}_e/T_e$ and $\tilde{n}/n$ at the L-H transition

Density fluctuations (BES)



Temperature fluctuations*



QH:Quiescent (sustained ELM-free) H-mode

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

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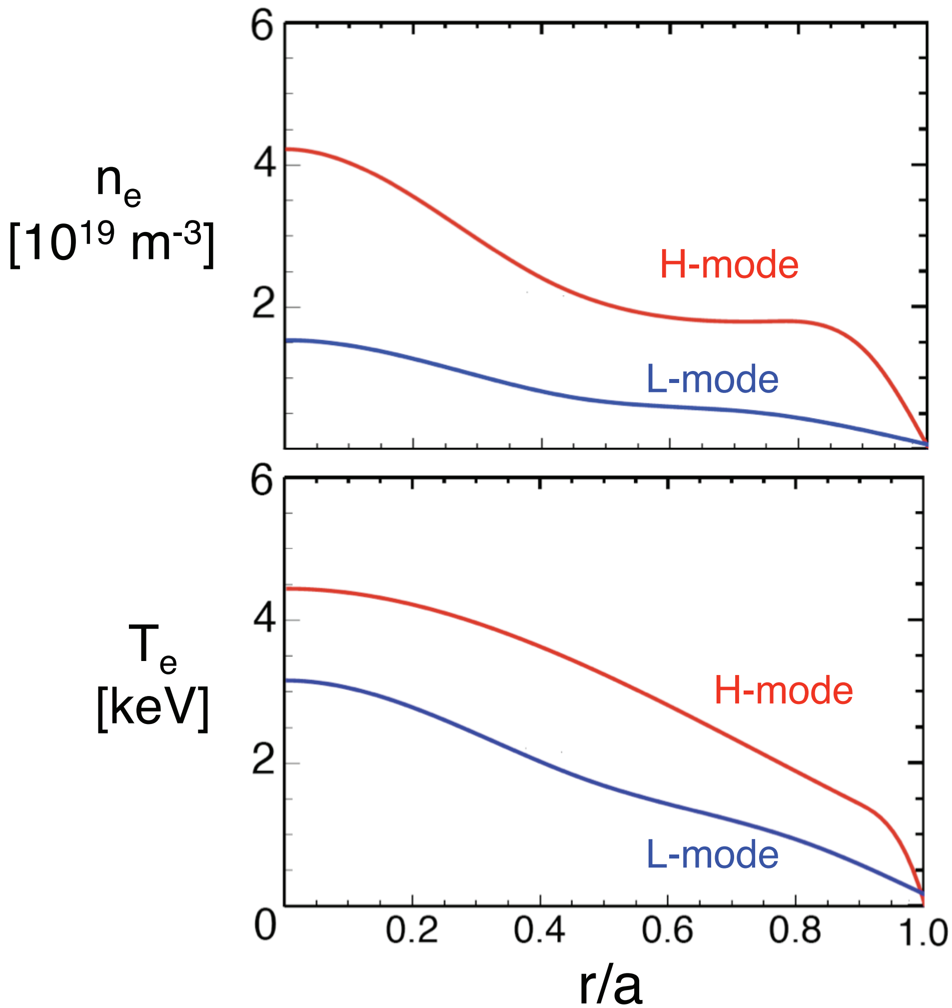
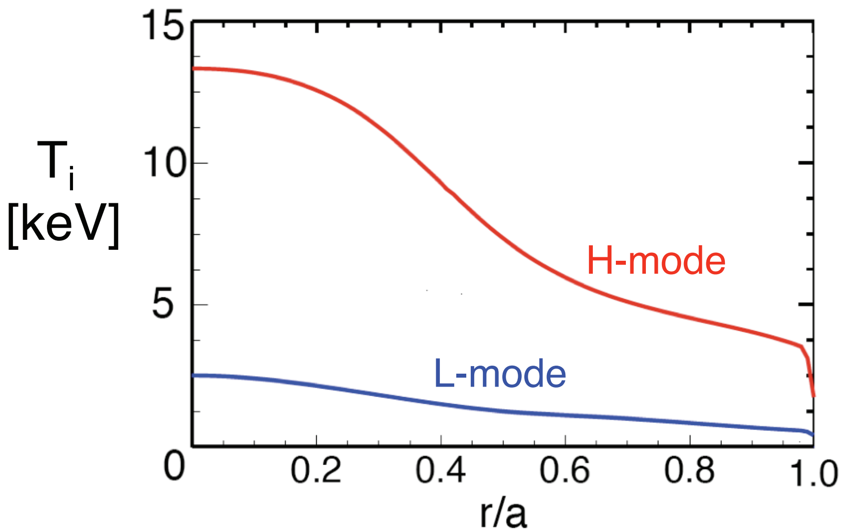
Radial density and temperature profiles, #125730





Counter-injected,
P_{NB}=7 MW (H-mode)

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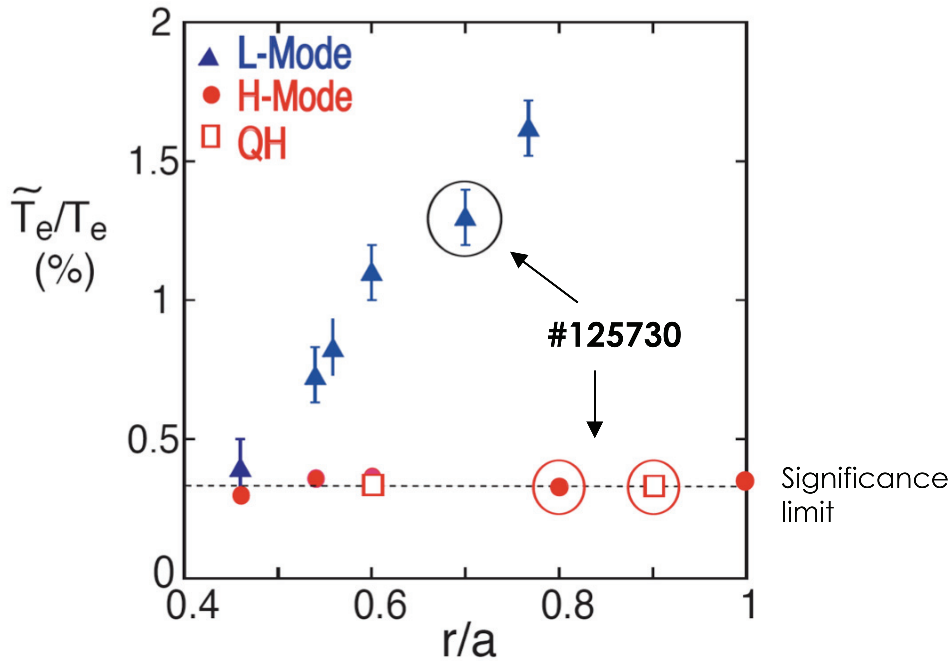
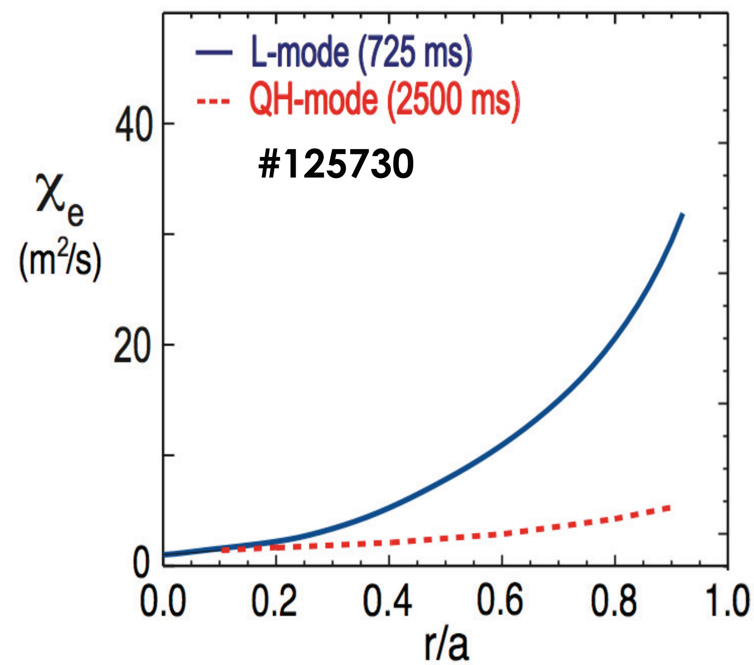
In H-mode, fluctuation levels and electron heat diffusivity are significantly reduced across a large radial region





Co- and counter-injected shots with Elm-free H-mode and quiescent H-mode (QH) are included.

- Fluctuations levels are reduced to the CECE-detection limit (0.25-0.33%) at all radii in H-mode
- Suppression of temperature fluctuations is consistent with ExB shear stabilization of ITG turbulence.

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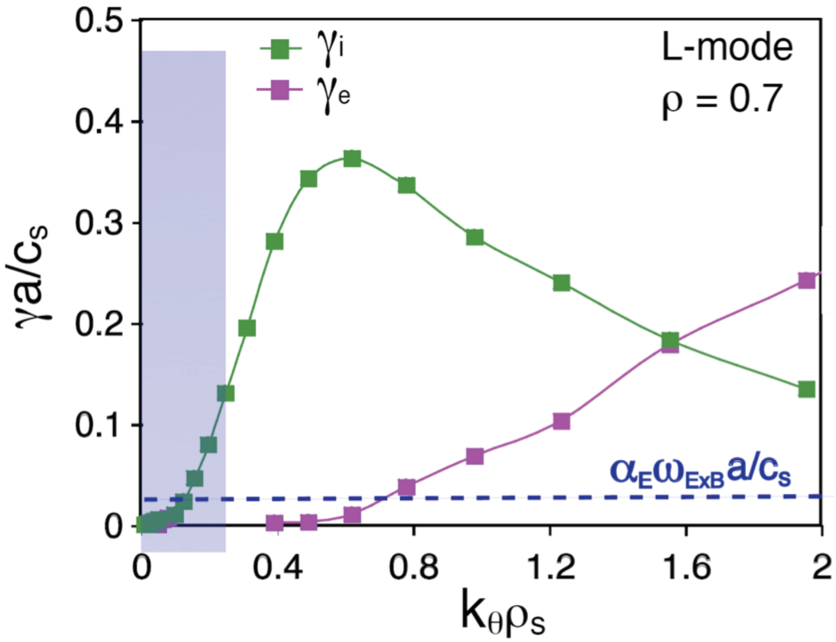
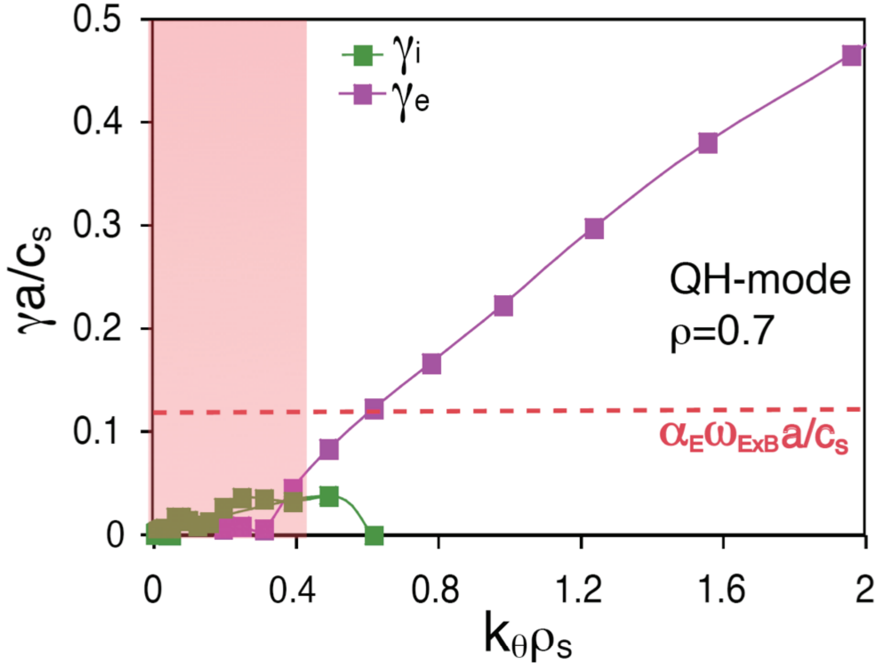
Linear Stability Calculations (TGLF) indicate that ITG modes are quenched in H-mode but TEM/ETG persist for $k\rho_s > 0.6$

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



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



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 ($a_E=0.3k^{1/2}$ is derived from GYRO ExB shear scans)*

#125730

In H-mode, $k\rho_s > 0.6$ is still expected unstable

*Kinsey, et al., Phys. Plasmas 14, 102306 (2007).

Wavenumber range accessible to CECE

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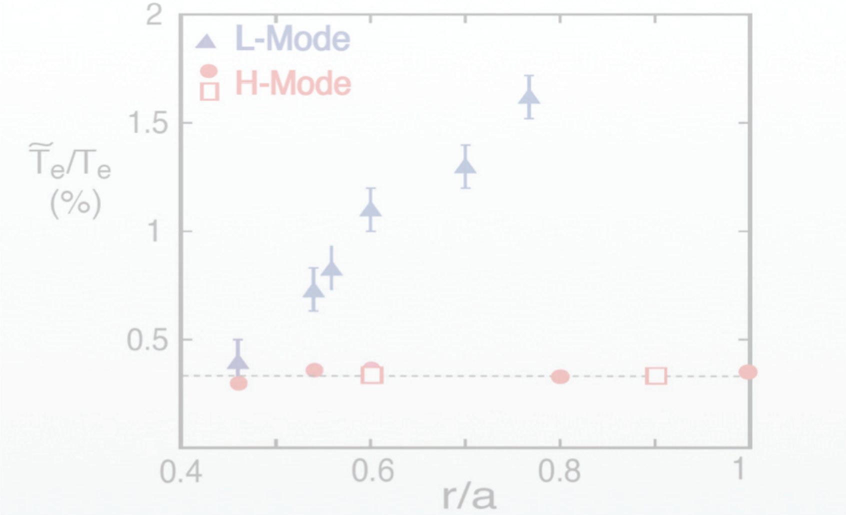
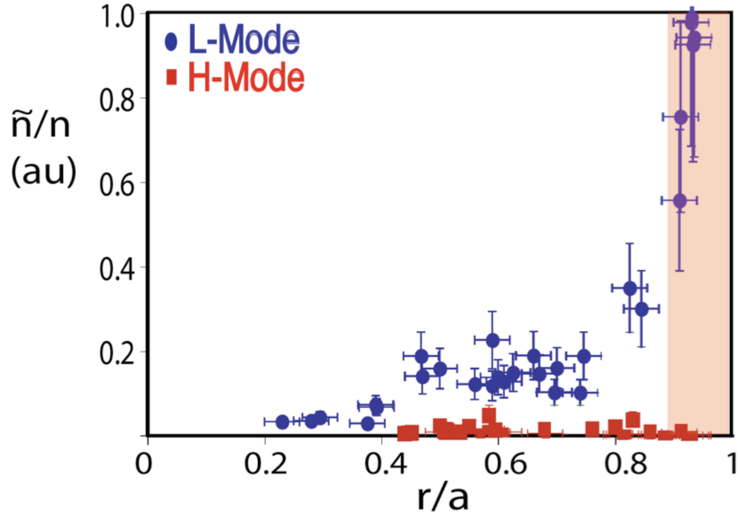
Conclusion: Electron Temperature fluctuations are associated with ITG modes, likely due to non-adiabatic electron response

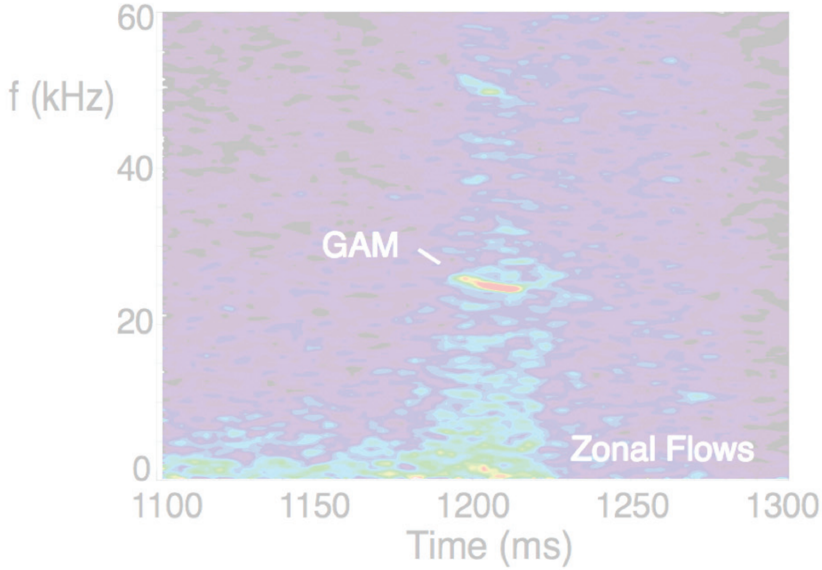
New measurement capabilities provide a fresh perspective on H-mode electron thermal transport and Zonal Flows

Radial profile of large-scale temperature fluctuations



Radial profile of Intermediate-scale density fluctuations





Interaction of Zonal Flow layers with intermediate scale turbulence

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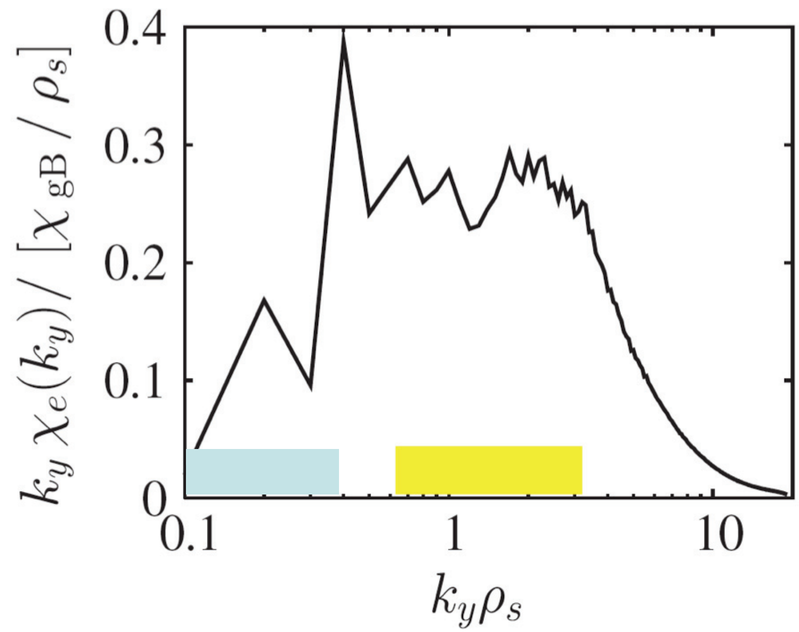
Intermediate/high-k turbulence may drive 50% or more of the electron heat flux once ITG modes are suppressed

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).

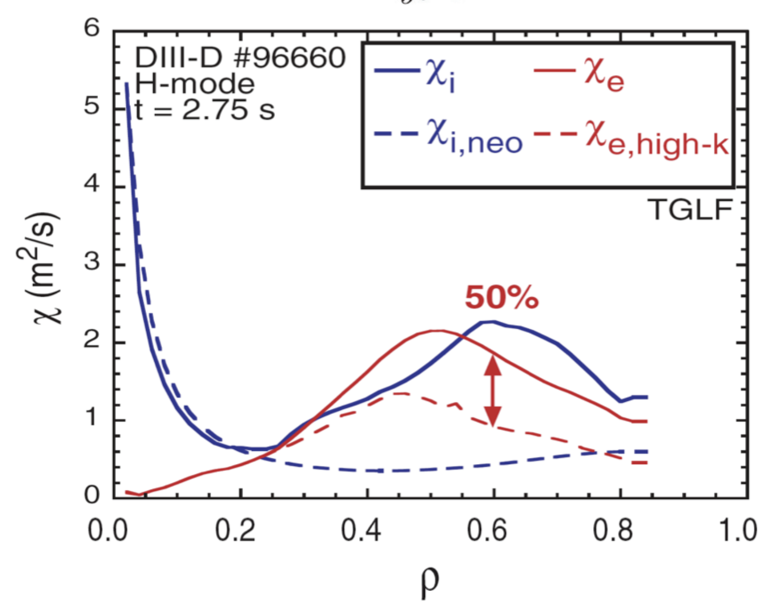
Accessible By CECE

Accessible by Doppler Backscattering



TGLF (Trapped gyro-Landau fluid) simulation of DIII-D H-mode plasma:
Calculates total electron diffusivity and diffusivity due to high-k modes

(J. Kinsey, Phys. Plasmas 15, 055908, 2008).



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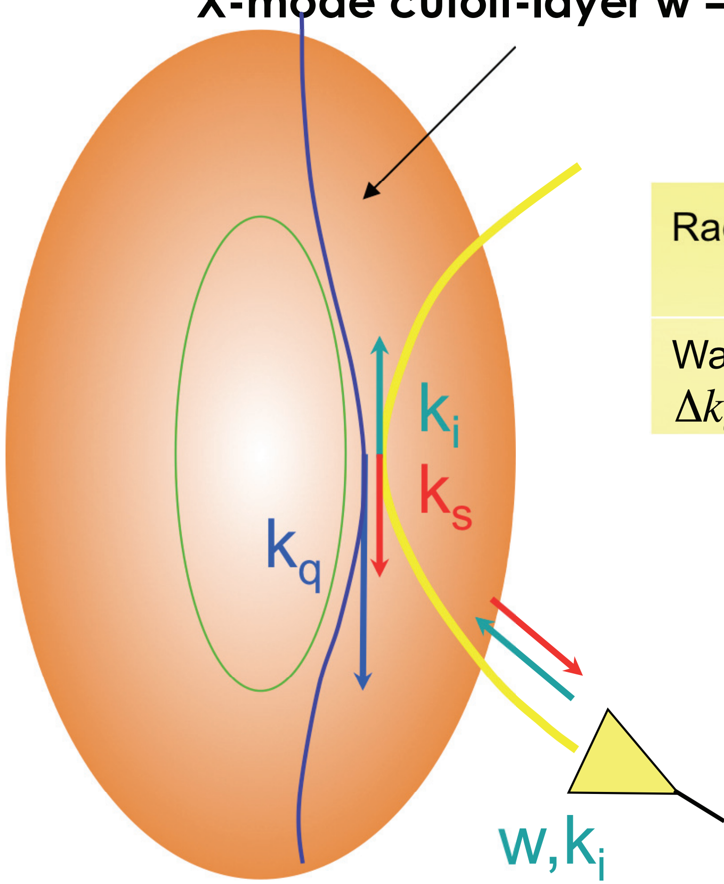
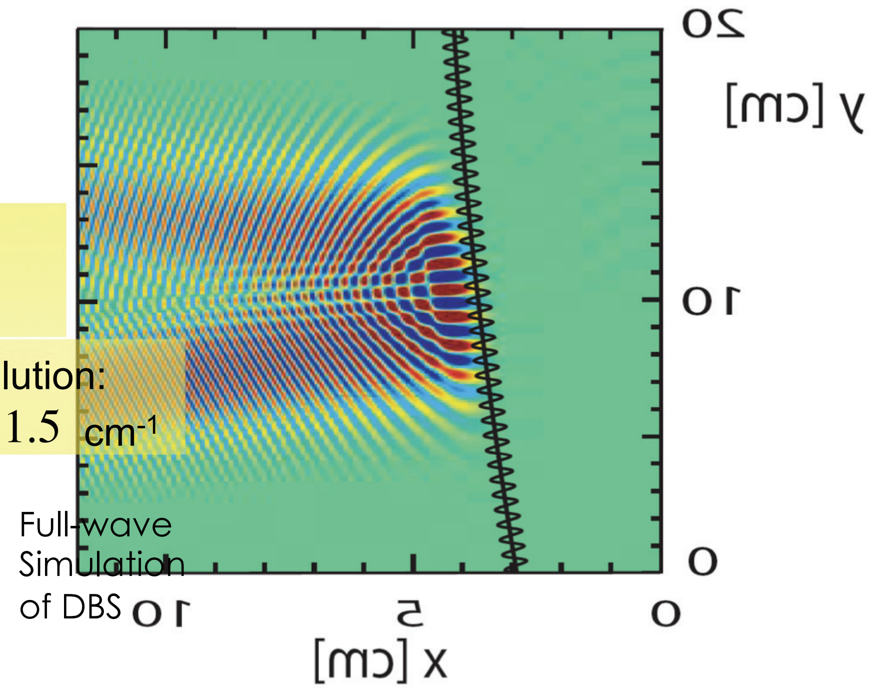
Doppler Backscattering (DBS) measures density fluctuations at a selective poloidal wavenumber



Radial resolution:
Dr < 1 cm

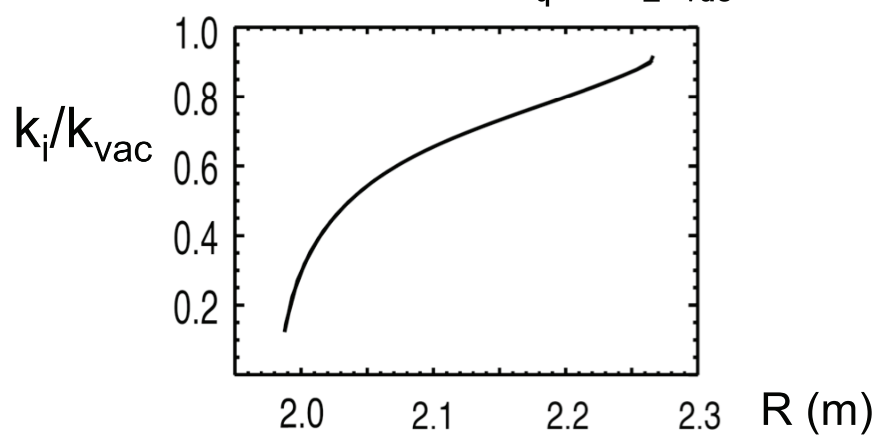
Wavenumber resolution:
$\Delta k_\theta \sim 2\sqrt{2}/W_o \leq 1.5$ cm^{-1}



Backscattering off density fluctuations with $k_q = k_s - k_i$, $k_q = -2k_i$

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

GENRAY Ray Tracing is used to determine Probed radius and probed $k_q = 2n_\perp k_{vac}$



Intermediate-scale fluctuations are reduced across the minor radius in H-mode

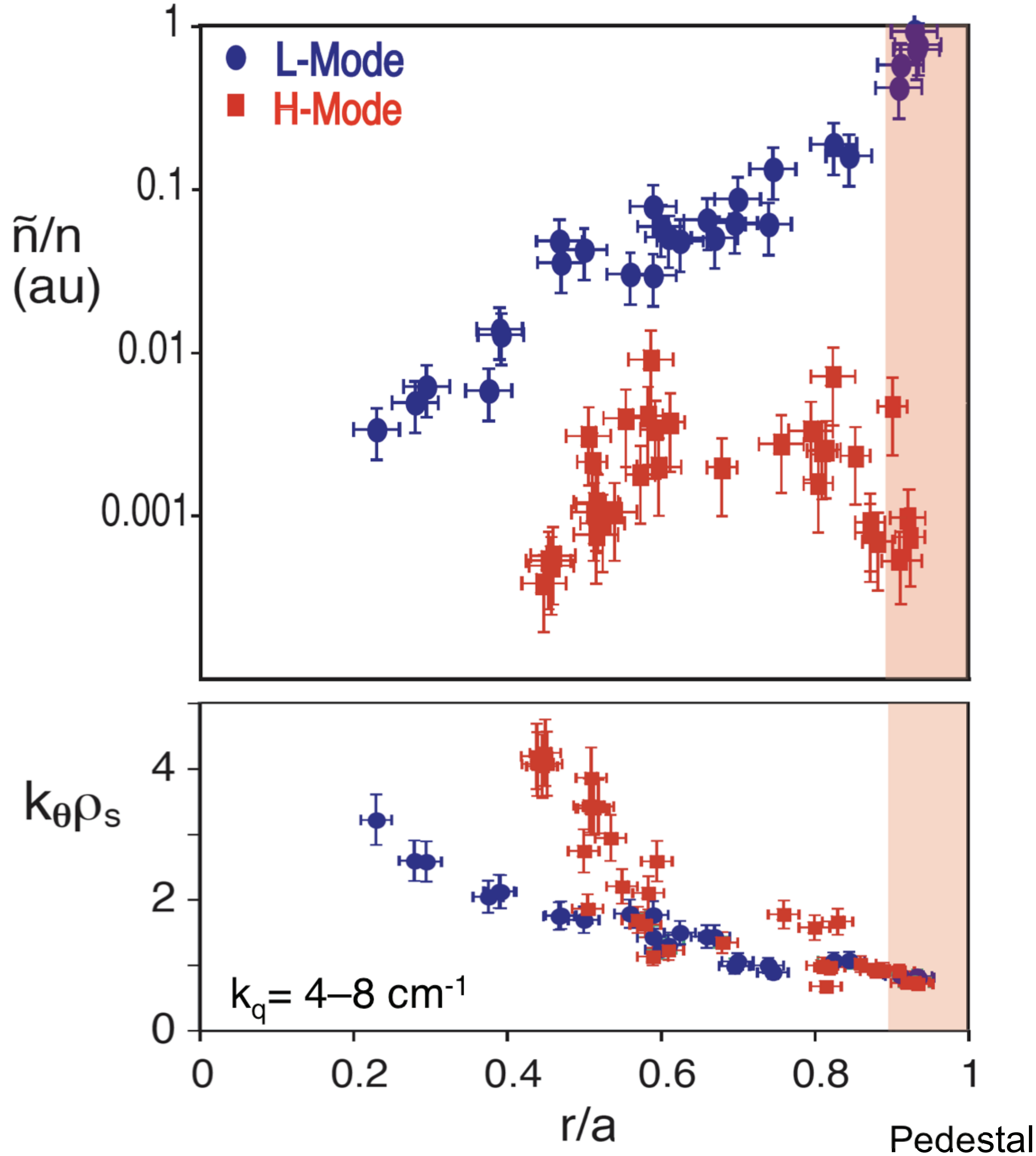
Low density, low collisionality counter-injected H-mode plasma

H-mode:
$T_e(0)$ = 4.5 keV,
$T_i(0)$ = 9 keV
$\langle n_e \rangle = 2\times10^{19}\ m^{-3}$

X-Mode Doppler Backscattering,
f = 50-70 GHz

Largest reduction is observed in the pedestal and inner core

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



Intermediate-scale fluctuations are reduced across the minor radius in H-mode

Largest reduction in the pedestal and inner core

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

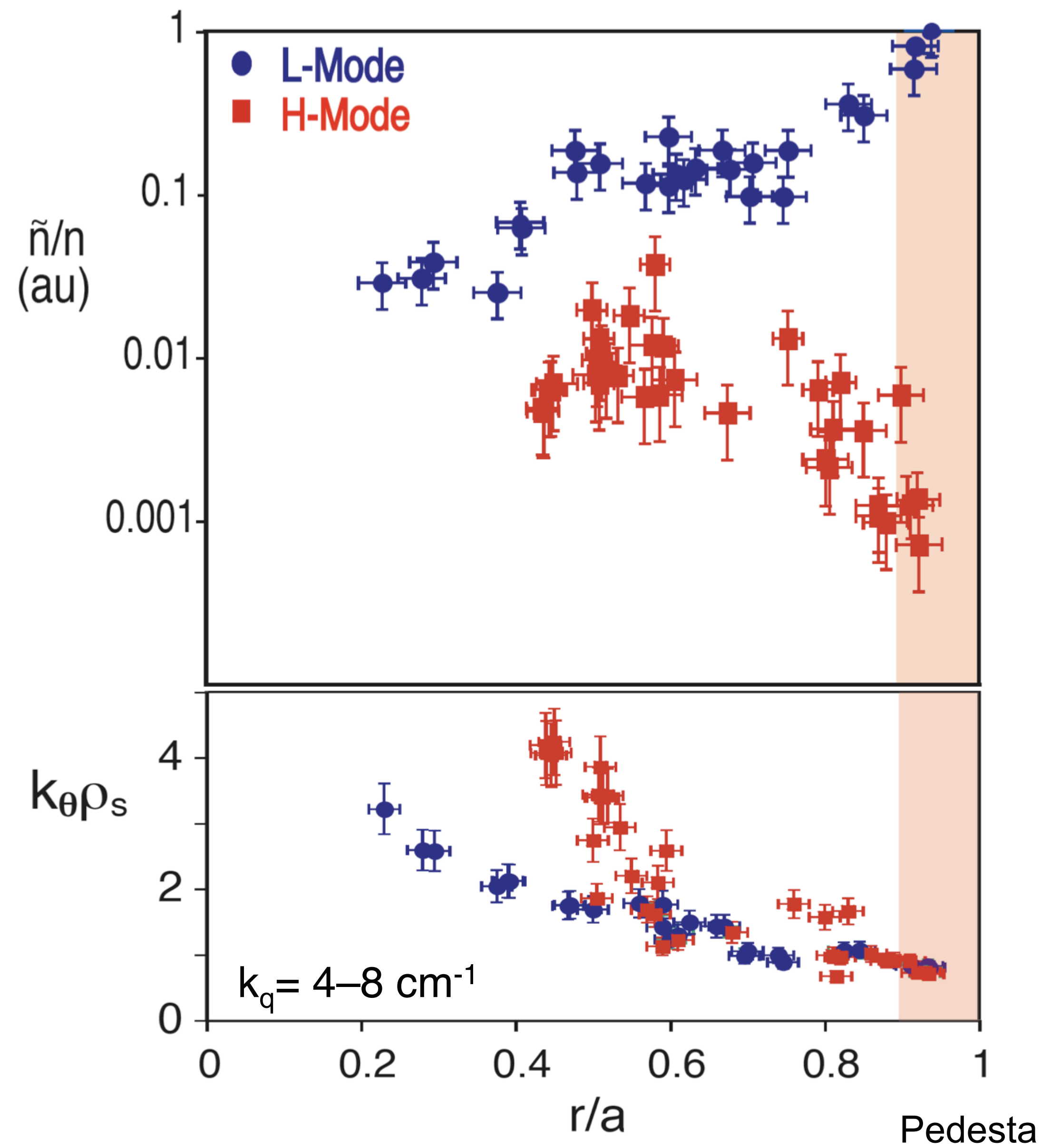
Correction for change $k_\perp r_s$ (using scaling from TORE SUPRA)*:

$$(\tilde{n}/n)^2 \sim (k_\perp r_s)^{-3.5}$$

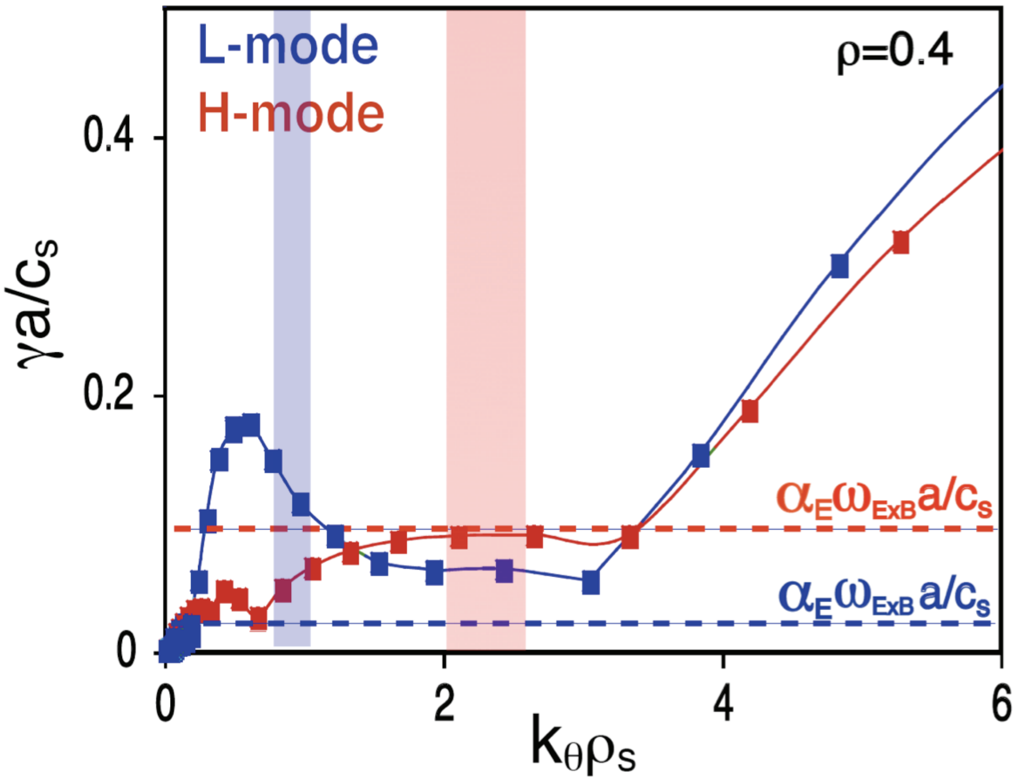
results in corrected levels:

$$\tilde{n}_{corr}/n = (\tilde{n}_{meas}/n)*(k_\perp r_s)^{1.75}$$

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



Linear stability calculations (TGLF) indicate that intermediate scale modes are suppressed in the H-mode core ($kr_s \lesssim 3$)



#131912

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

R/L_{Te}=4.3
R/L_n=2

R/L_{Te}= 2
R/L_n=1.7

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

Wavenumber range accessible by DBS

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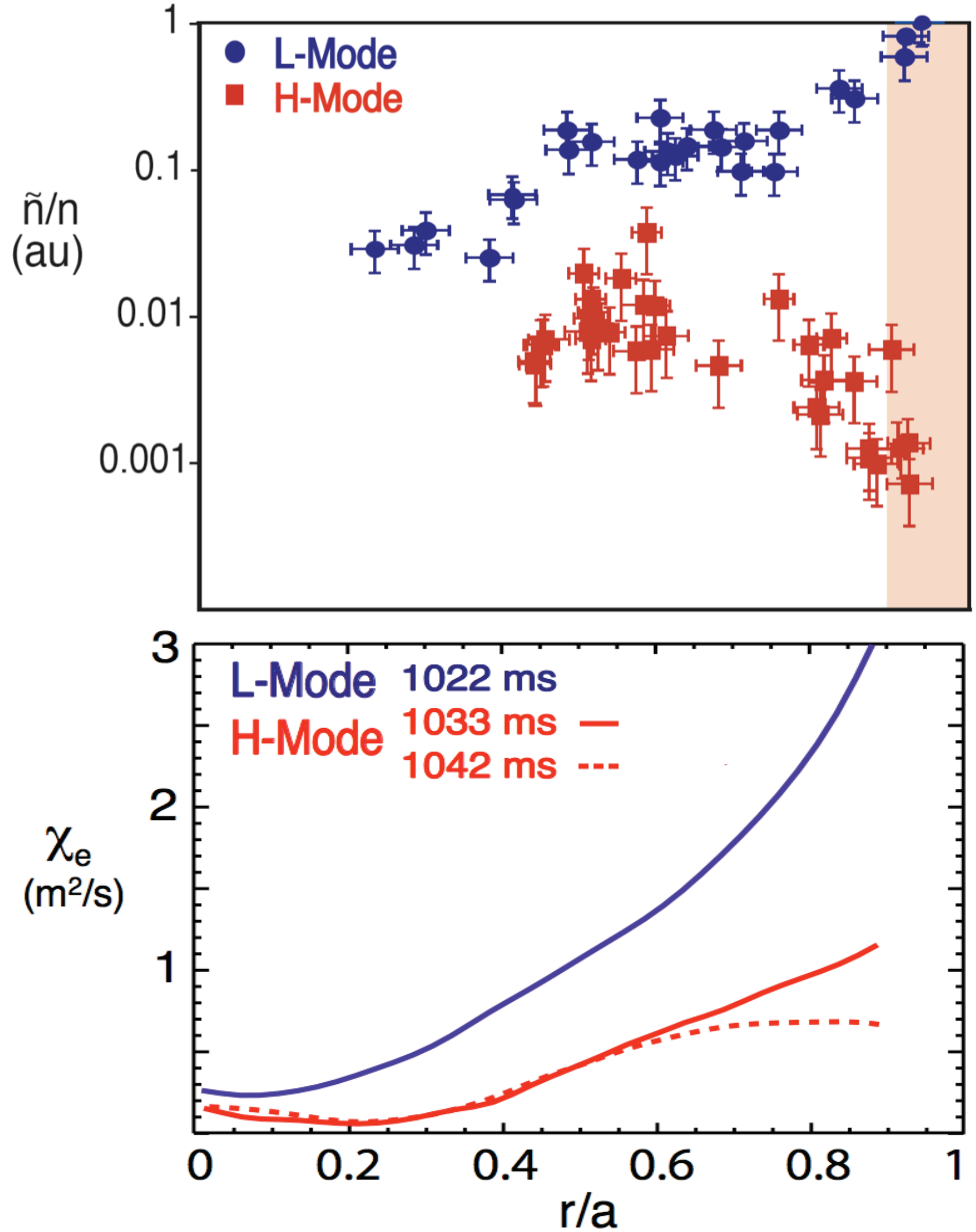
Electron heat diffusivity decreases rapidly at the L-H transition across the minor radius

- Fluctuation reduction across the minor radius in H-mode

- Rapid reduction of of χ_e in the pedestal and core plasma within 5 -10 ms of the L-H transition.

  Initial results from quasilinear transport code (TGLF) indicate that the residual electron transport is due to intermediate/high-k modes.



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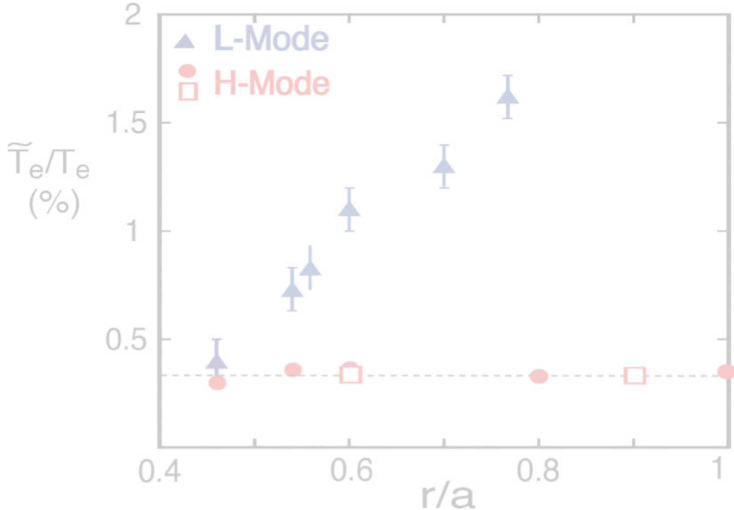
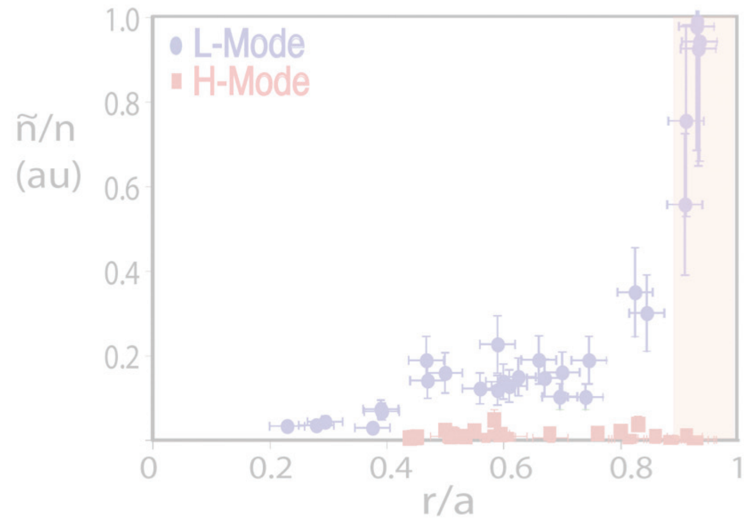
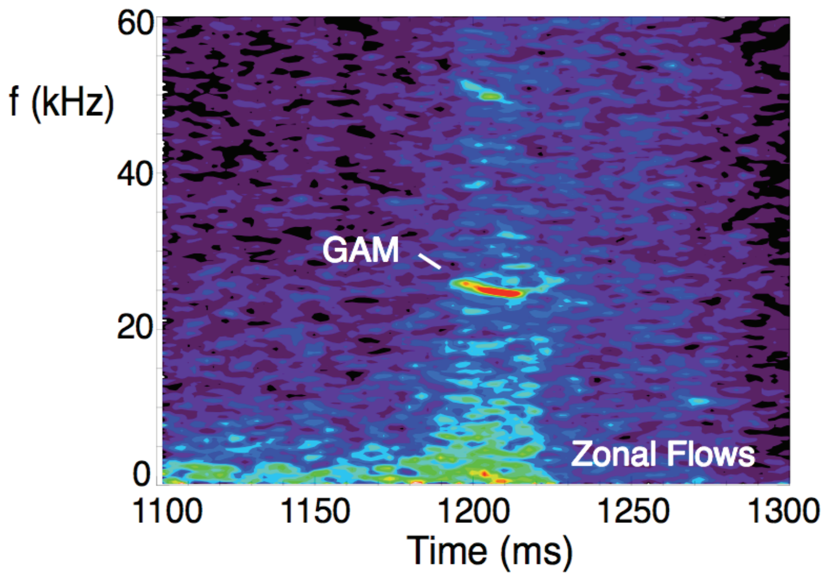
New measurement capabilities provide a fresh perspective on H-mode electron thermal transport and Zonal Flows

Radial profile of large-scale temperature fluctuations



Radial profile of Intermediate-scale density fluctuations





Interaction of Zonal Flow layers with intermediate scale turbulence

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Turbulence self-regulation by Zonal Flows

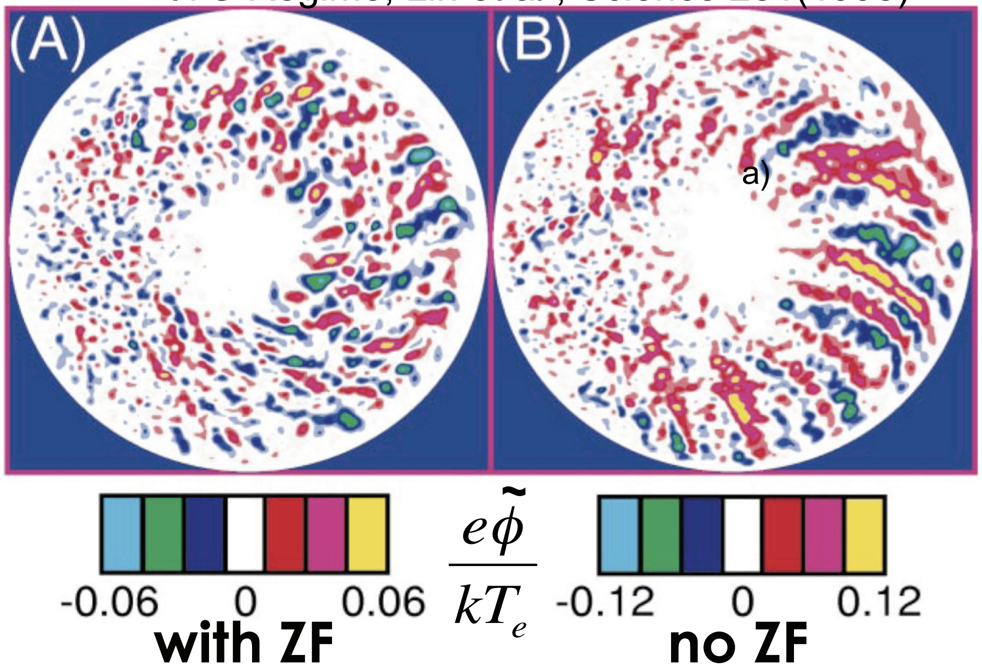
Two types of self-generated Zonal Flows:

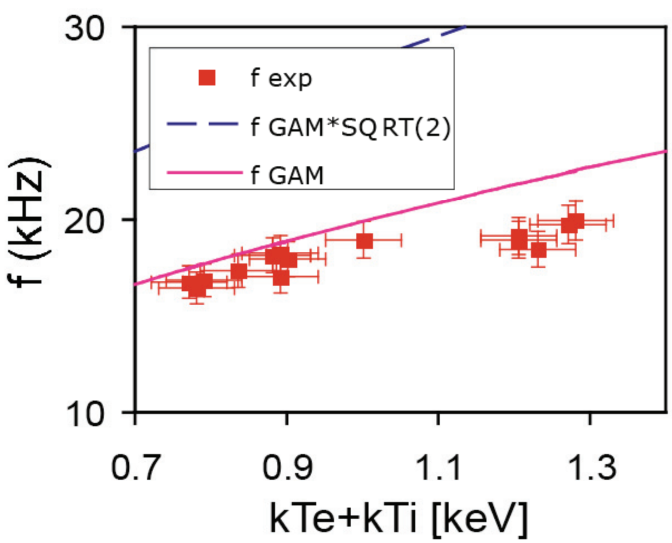
Low frequency Zonal Flows:
$n=0$, $m \approx 0$ (finite k_r): axisymmetic, radially sheared flows

Geodesic Acoustic Modes (GAMs):
$m=0$, $n=0$ electrostatic mode coupled to $m=1$, $n=0$ pressure perturbation:

$$\omega_{GAM} \sim \sqrt{2}c_s / R(1 + 1/2q^2)^{1/2}$$

ITG Regime, Lin et al., Science 281(1998)





DBS GAM data

Strong Zonal Flows are observed in an electron transport barrier near the q=2 surface (L-mode)

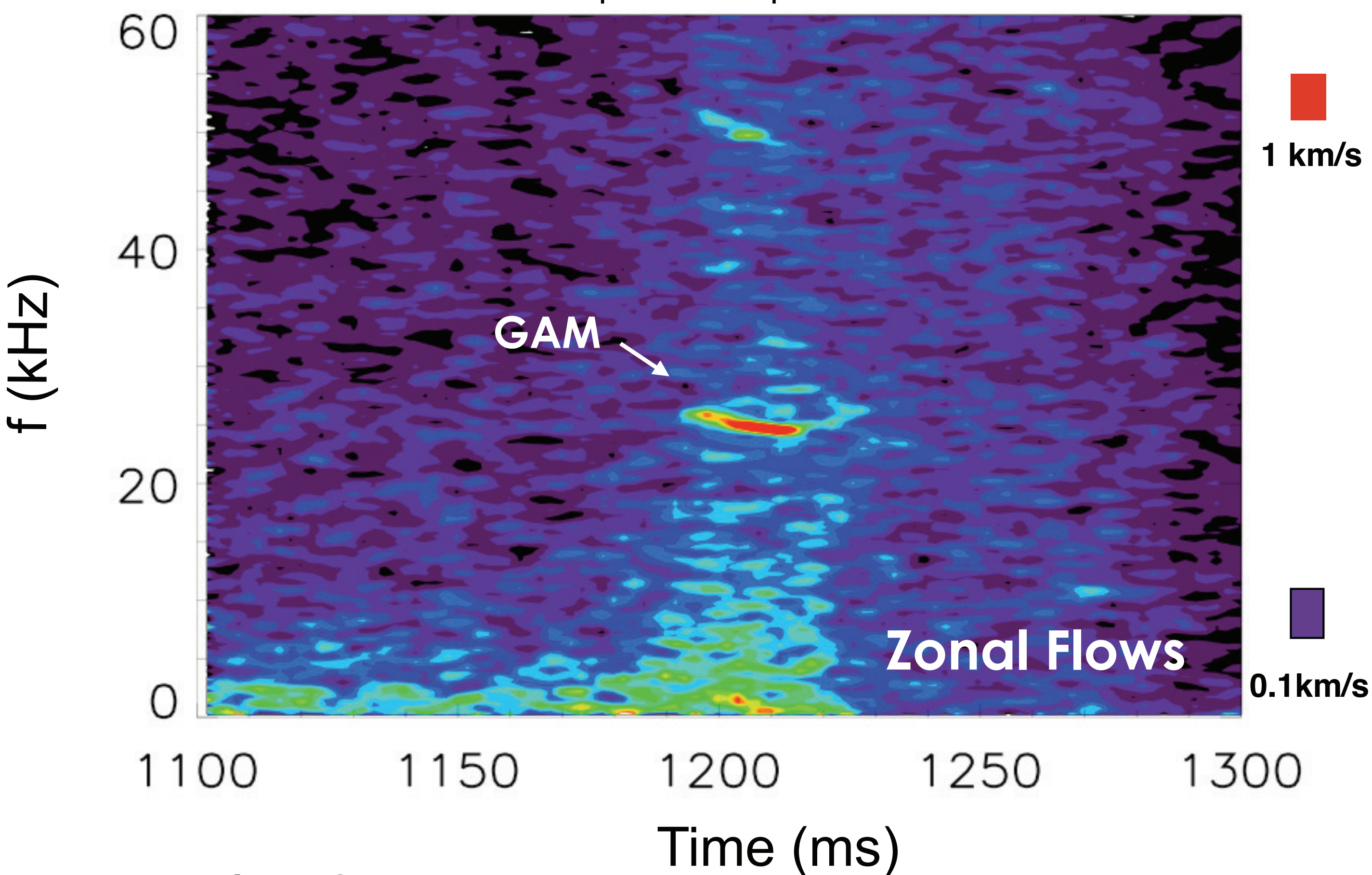
ZMF (zero-mean frequency) and low frequency Zonal Flows are observed near the q = 2 surface (r/a ~ 0.5)

A localized GAM is transiently observed at the same radius

#133678, co-injected 7 MW

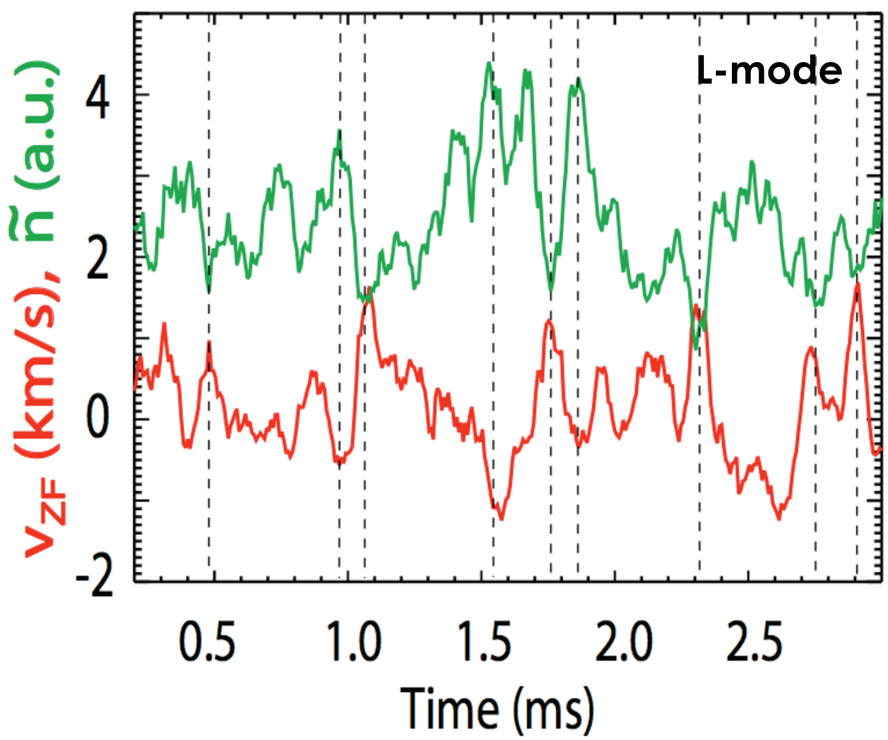
DBS flow cross spectrum

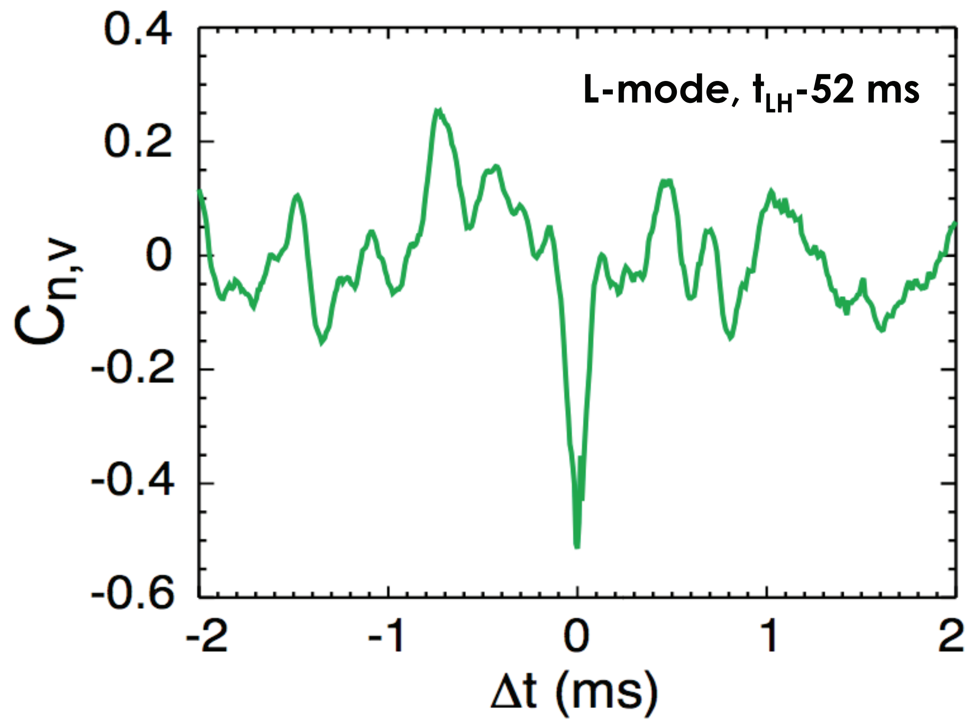
$A_v(f,t)=(v_q(f,t,x)v_q^*(f,t,x+Dx))^{1/2}$



r/a ~0.5

Zonal Flow is 180° out of phase (anti-correlated) with the intermediate-scale density fluctuation amplitude





r/a ~ 0.47
Probed $k_q \sim 6\ cm^{-1}$, $k_q r_s \sim 3$

- Flow and density fluctuation amplitude are out of phase (180°) in L-Mode

Firstexperimental evidence of Zonal Flow interaction with Intermediate scale turbulence

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Summary

- **Core density and electron temperature fluctuations (ITG/TEM-scale, $k_\perp r_s < 0.5$) are significantly reduced in H/QH-Mode. Suppression is consistent with ExB shear suppression of ITG modes.**

- **Intermediate scale density fluctuations are significantly reduced across the L-H transition (≥ 10x across the minor radius in counter-injected, low collisionality H-Modes).**
  - The observed H-mode core suppression is consistent with ExB shear suppression (TGLF results).
  - The electron heat diffusivity is rapidly and significantly reduced in the plasma core after the L-H transition.

- **Strong Zonal Flows (low frequency ZF and GAM) are observed near rational q-surfaces in the core plasma (L-mode). The ZF amplitude is 180ª out of phase (anti-correlated) with the intermediate-k density fluctuation level.**