Reduced Electron Thermal Transport in Low-Collisionality H-Mode Plasmas and the Role of Small-Scale Turbulence

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Understanding Electron Transport is Important for Burning Plasmas (α-particle Heating Controls T_e/T_i and Gradients)

- Electron transport is driven by multi-scale phenomena
- Gyrokinetic code results (GYRO, GENE) predict that intermediate/small-scale turbulence may be important (or possibly dominant) in H-Mode if ITG modes are close to marginal stability or shear-suppressed
- ECH-heated QH-mode plasmas in DIII-D provide an excellent test bed for electron transport physics (T_i and T_e decoupled, $0.5 < T_e/T_i < 1.2$)
- Local measurements of intermediate/smaller-scale density fluctuations ($k\rho_e \leq 0.2$) have become available (DBS) and provide critical tests and validation of Gyrokinetic predictive codes

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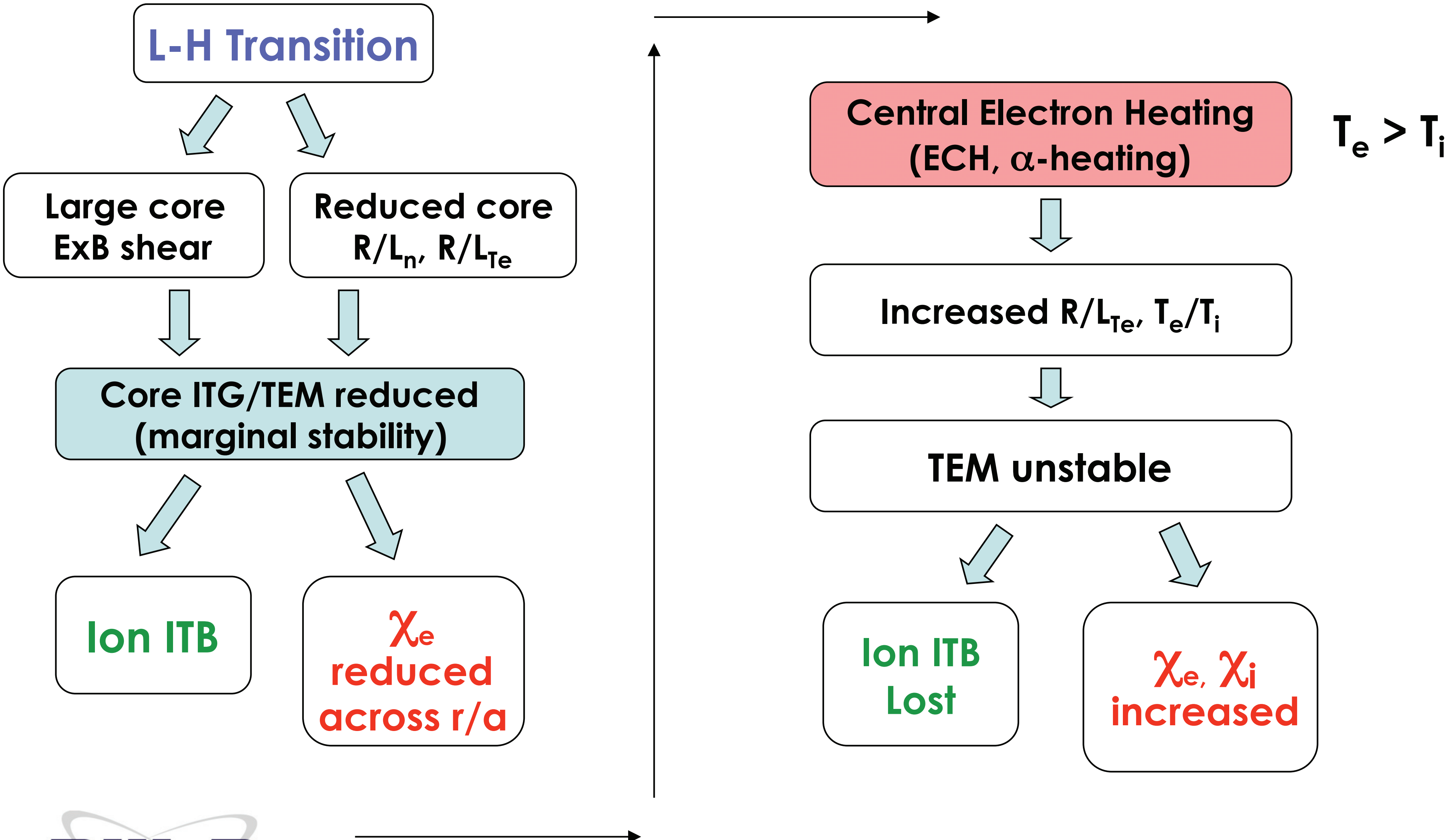
Core Electron Transport Depends Sensitively on Heating Profile (Auxiliary or α-heating)

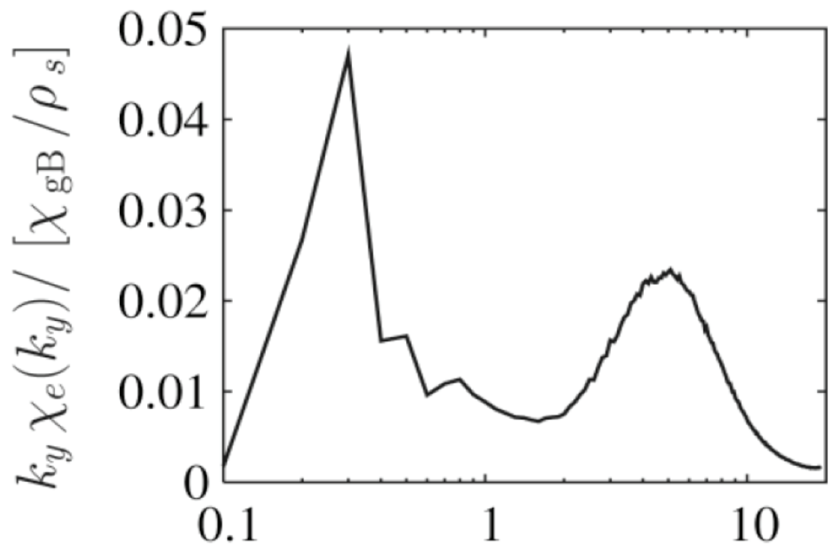


Intermediate/High-k Turbulence May Drive More Than 50% of Electron Thermal Flux When ITG is Near Marginal Stability

Cyclone ITG/TEM/ETG simulation; ITG marginally unstable: 50% of electron thermal flux driven for $k_\theta \rho_s \geq 0.5$.

$R/L_{T_e} = 6.9$ $\quad$ $R/L_{T_i} = 5.5$
$R/L_n = 0$

(Goerler and Jenko, PRL 2008)

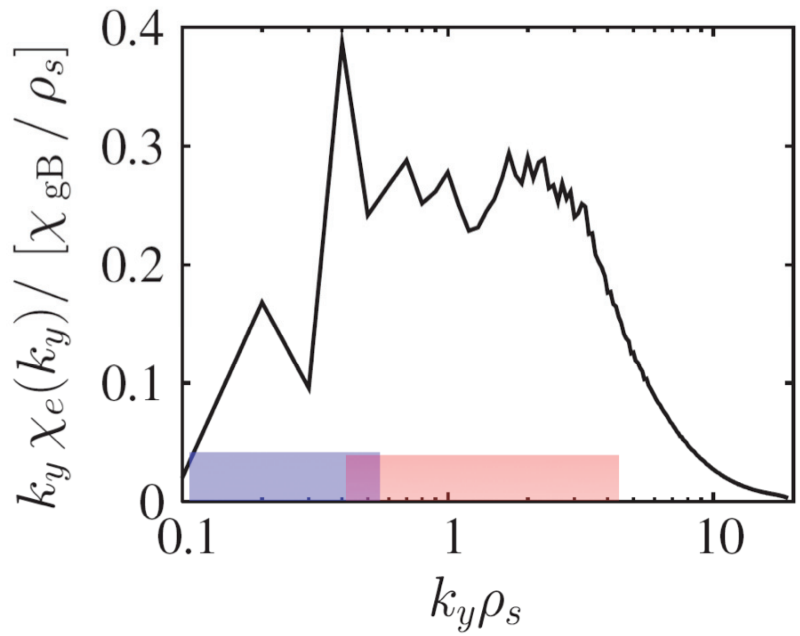


Coupled TEM/ETG simulation; ITG linearly stable: 70% of electron heat flux driven for $k_\theta \rho_s \geq 0.5$.

$R/L_{T_e} = 6.9$ $\quad$ $R/L_{T_i} = R/L_n = 0$

Accessible By BES and CECE

Accessible by Doppler Backscattering



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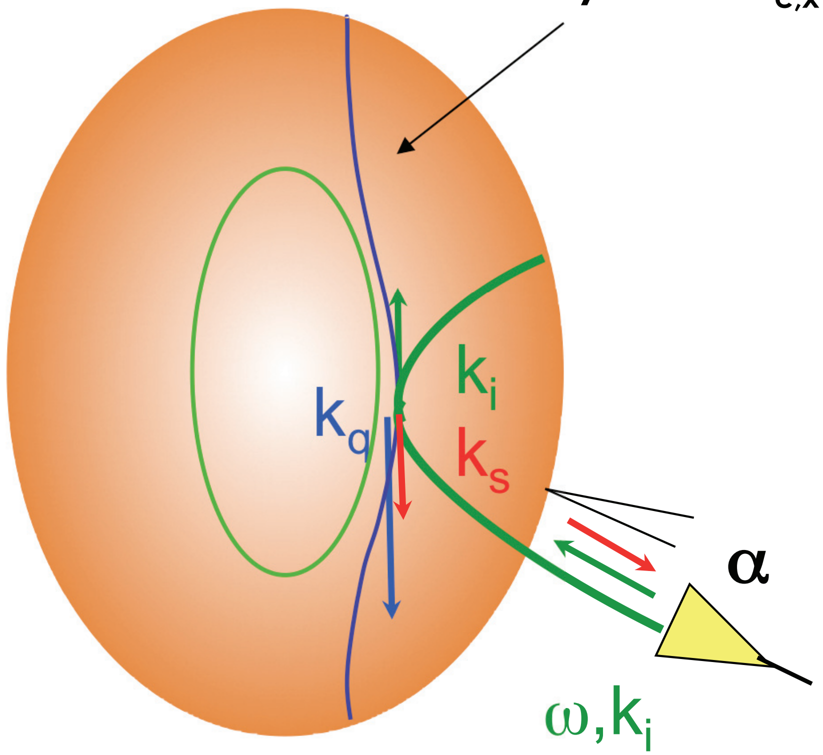
See also:
Candy et al., PPCF 49 (2007)
Waltz, et al., PoP 14 (2007)

Doppler Backscattering (DBS) Measures Local Density Fluctuation Level Versus Wavenumber

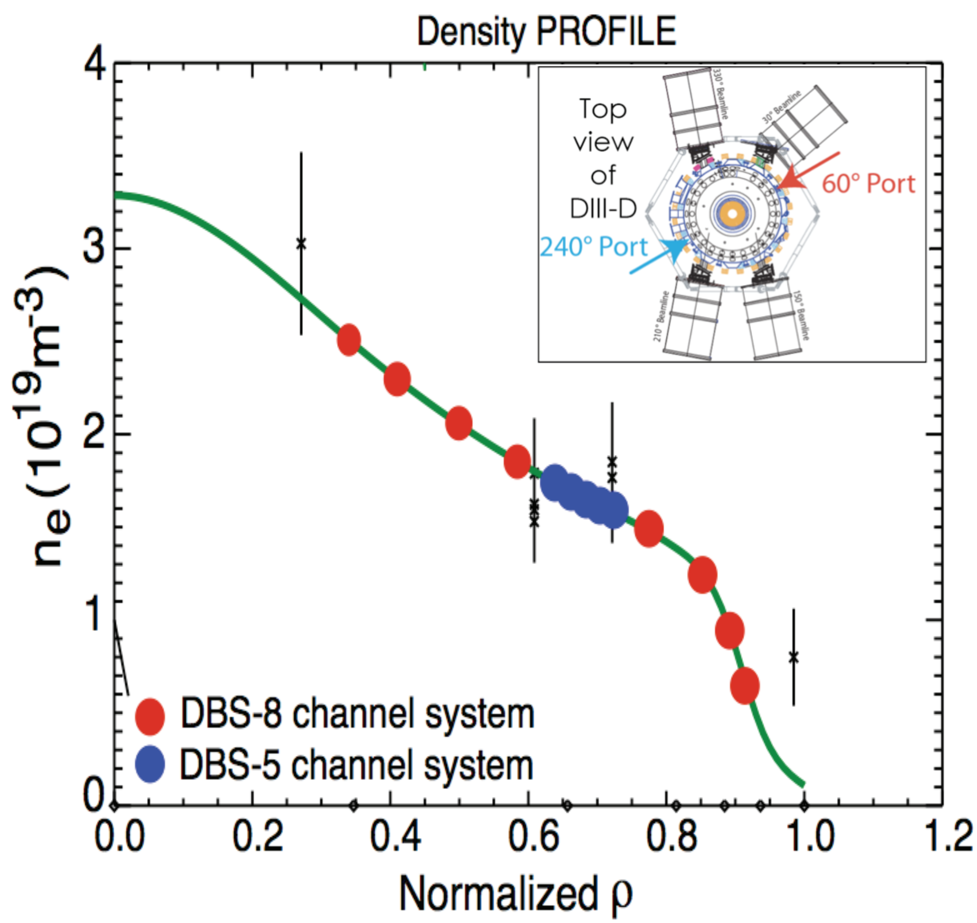


Backscattering off density fluctuations with $k_s = k_i - k_\theta$, $k_\theta = -2k_i$

Several effects localize backscattering to the cut-off layer

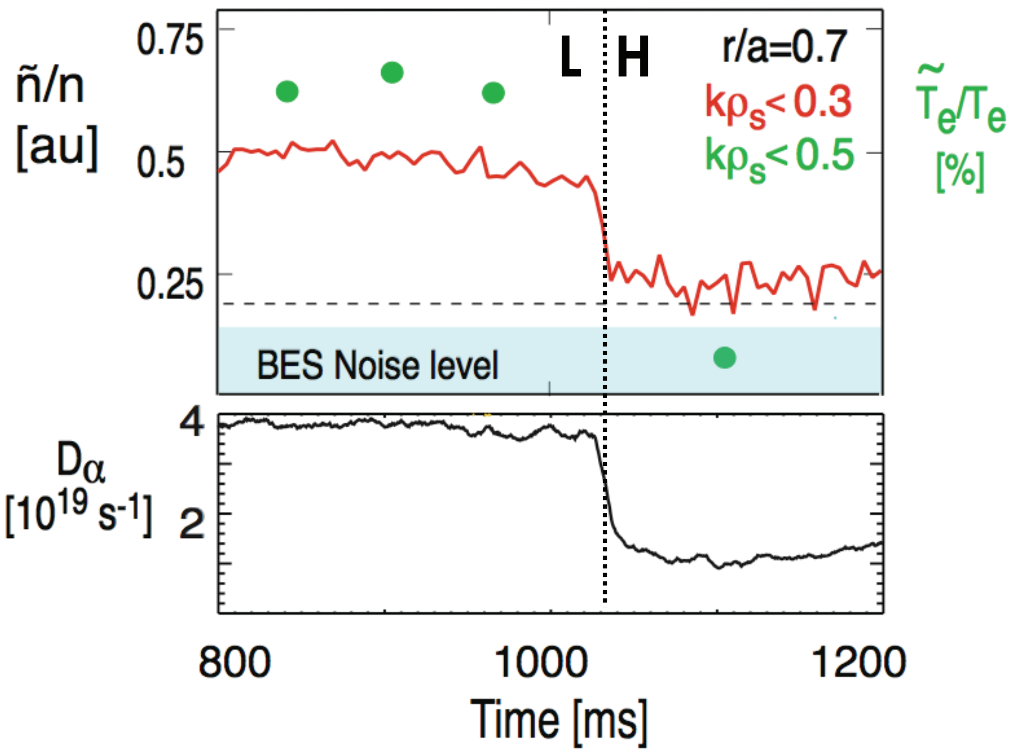
Fluctuation level vs. k_θ from back-scattered amplitude:

$\tilde{n}(k_\theta) \sim A(k_\theta)$



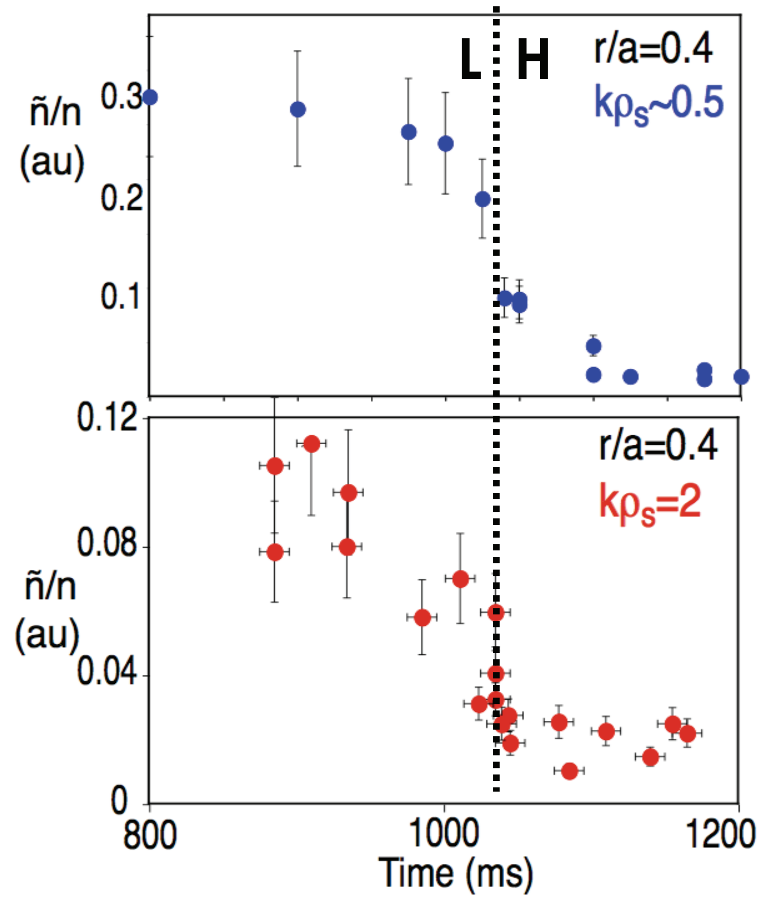
At the L-H Transition, Core Fluctuations ($0.4 \leq r/a \leq 0.8$) are Reduced for Low and Intermediate Wavenumbers

CECE ($\tilde{T}_e/T_e$)*, BES ($\tilde{n}/n$), r/a=0.7



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

Doppler Backscattering, r/a=0.4



Moderate reduction before L-H transition due to increasing E×B shear; ñ drops at transition within ~5-10 ms.

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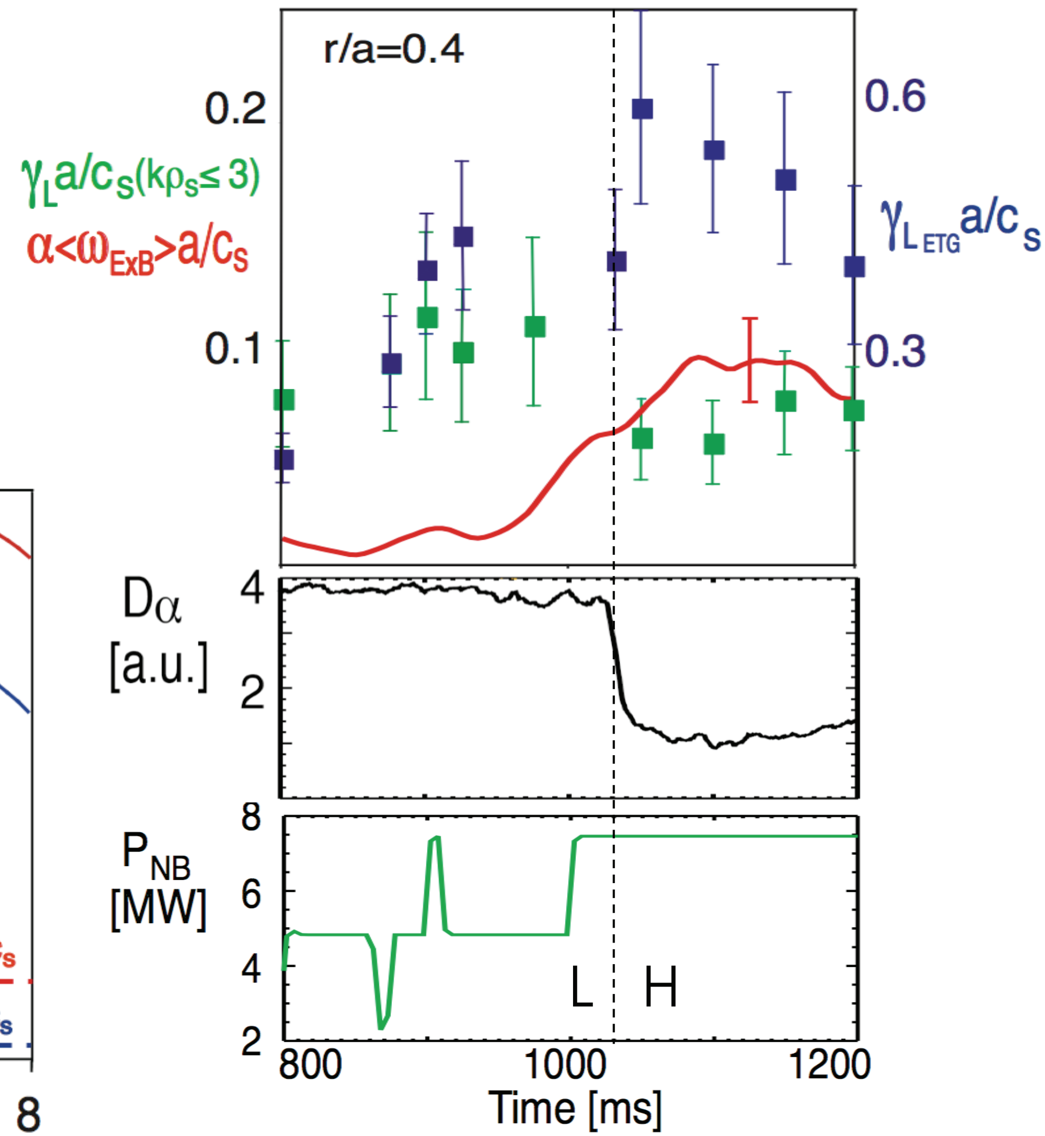
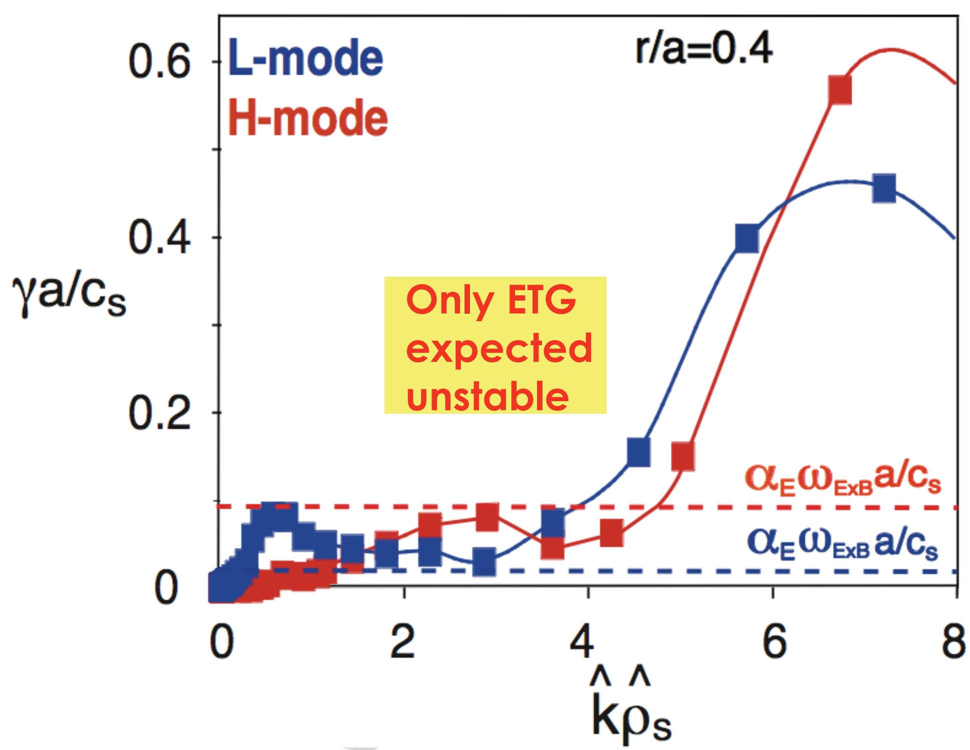
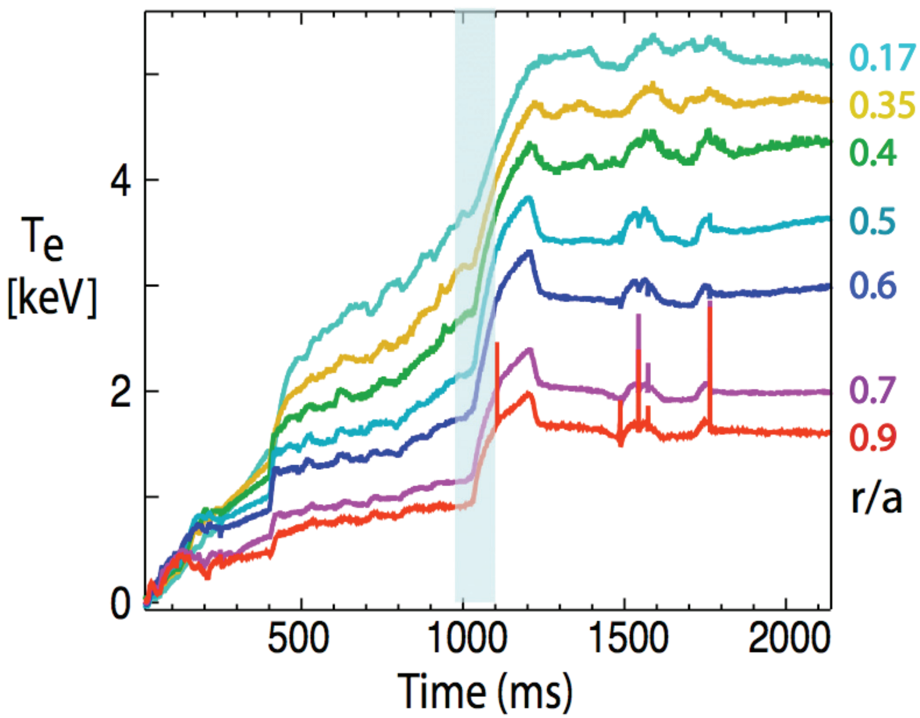
The E×B Shearing Rate Exceeds the Linear Growth Rate in the ITG/TEM Range in the Core Plasma in H-mode

Linear ITG growth rate γ_L and ETG growth rate $\gamma_{L\ ETG}$ calculated by TGLF. The radial electric field/ shear in the core is dominated by toroidal rotation ($E_r \sim v_\phi \times B_\theta$). Fluctuation suppression (quench rate $a_E\langle w_{E\times B}\rangle a/c_s > \gamma_L$) expected for $k_\perp \rho_s \leq 4$ in H-mode (r/a=0.4)

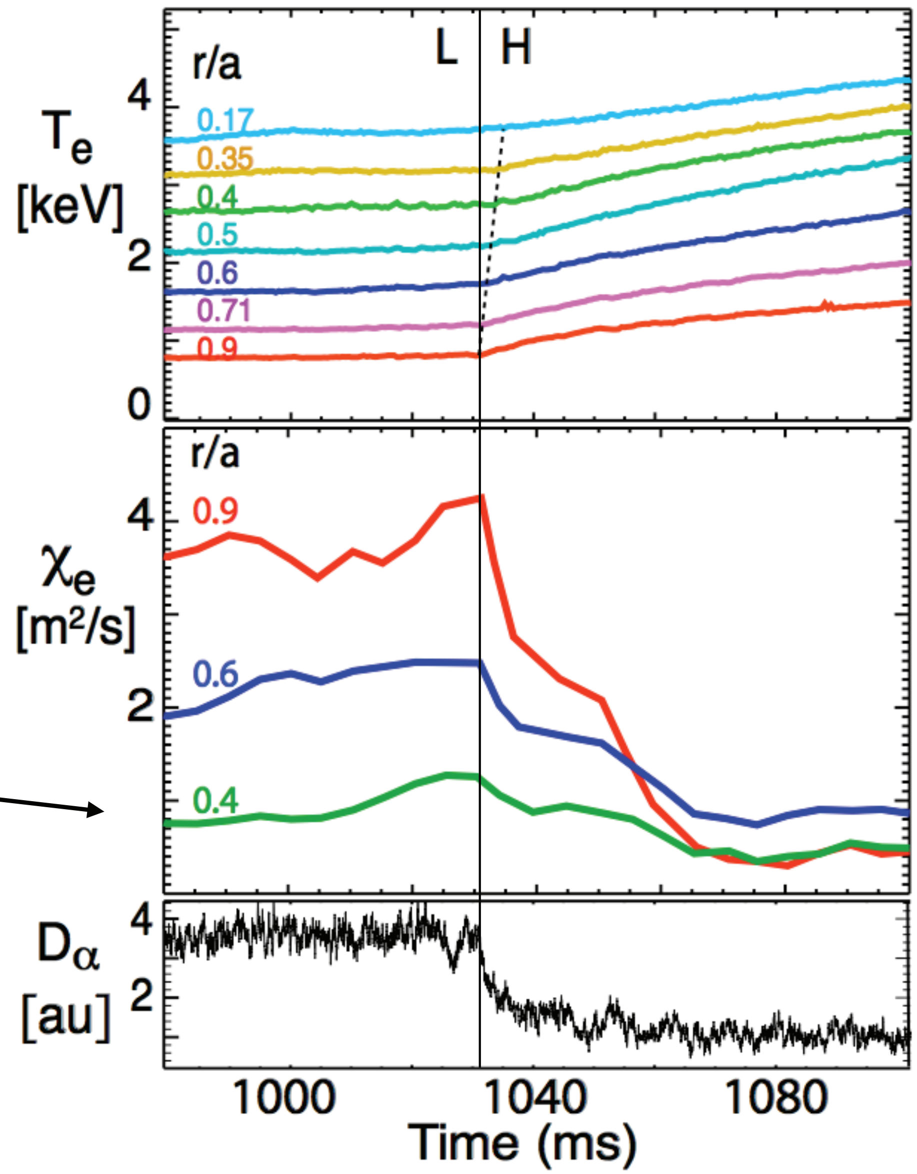




Core Electron Thermal Diffusivity Decreases Within ~10 ms of H-mode Edge Barrier Formation



L-H transition



Electron heat diffusivity (from TRANSP) decreases rapidly across minor radius

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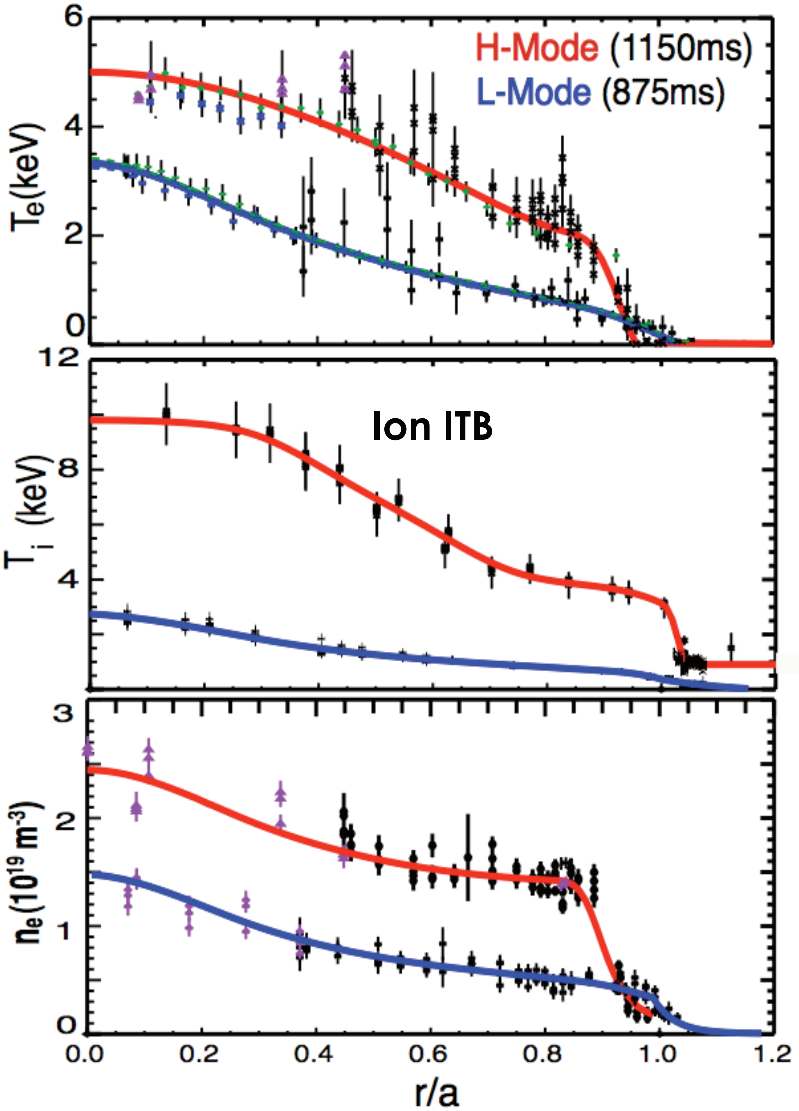
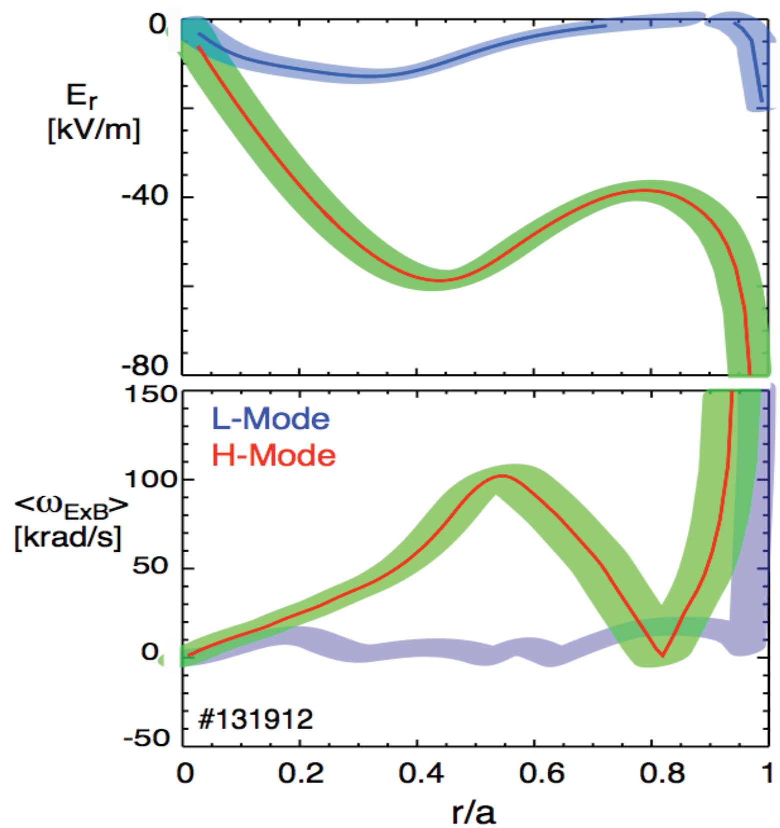
Strong Core E×B Shear Results in Ion ITB and Reduced Core Electron Transport (#131912)





Radial Electric Field

Waltz-Miller Shearing Rate

H-Mode (1150 ms): strong shear in the core plasma (r/a <0.7) in addition to the pedestal region

Low collisionality $\nu_e^*(0.4)$ ~0.04
Counter-NB injection; $T_e/T_i(0.4)$~0.6

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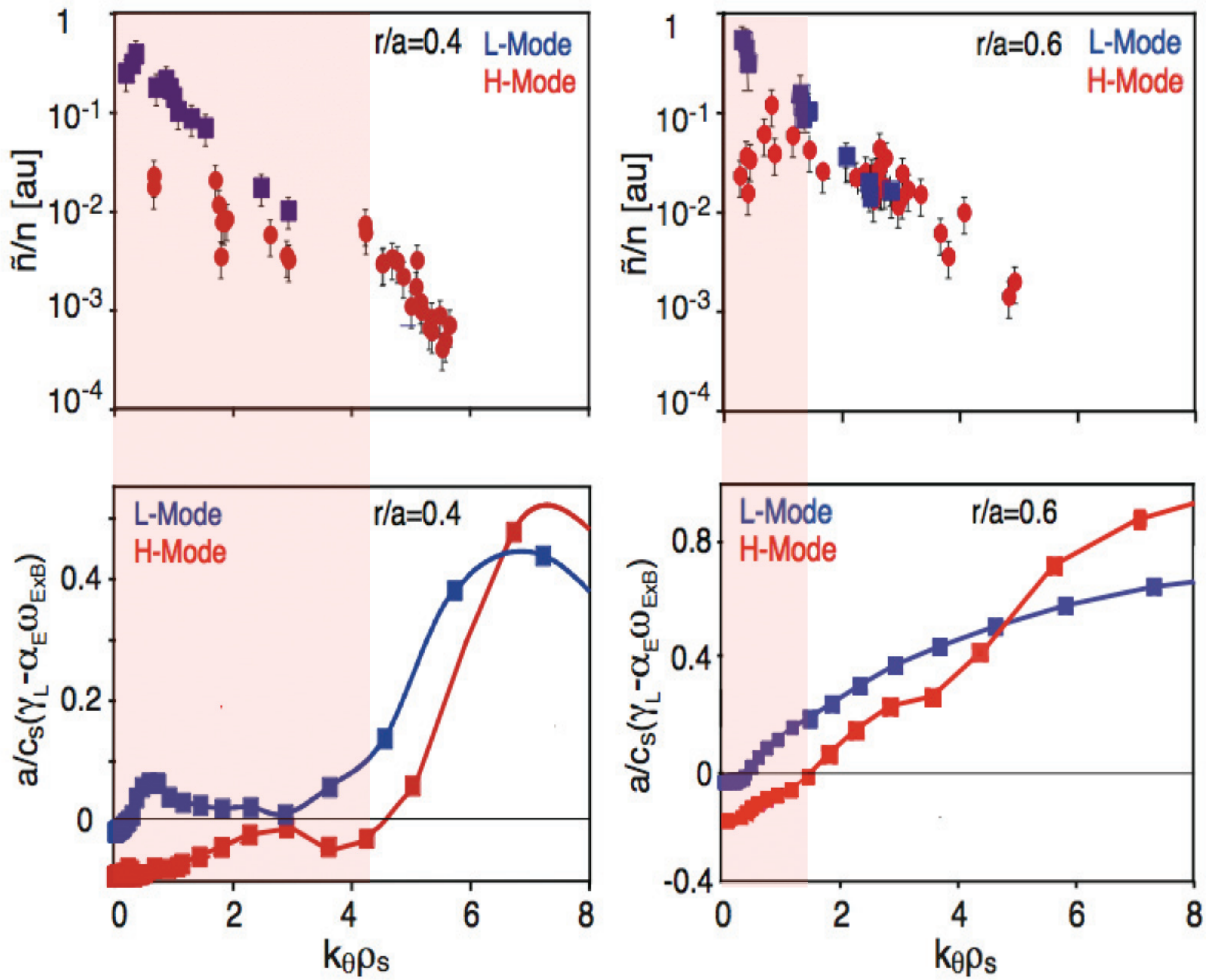
In H-mode, Core Fluctuations are Reduced in the Wavenumber Range Where $\gamma_L - \alpha \langle \omega_{ExB} \rangle < 0$

Exponential spectra in L-Mode:

$\tilde{n}/n \sim e^{-\zeta(k\rho_s)}$
(ζ =1.5…1.7)

Flattening/inversion of H-mode spectrum at low $k\rho_s$

TGLF growth rate of most unstable mode minus normalized shear quench rate $\alpha_E \omega_{ExB} a/c_s$



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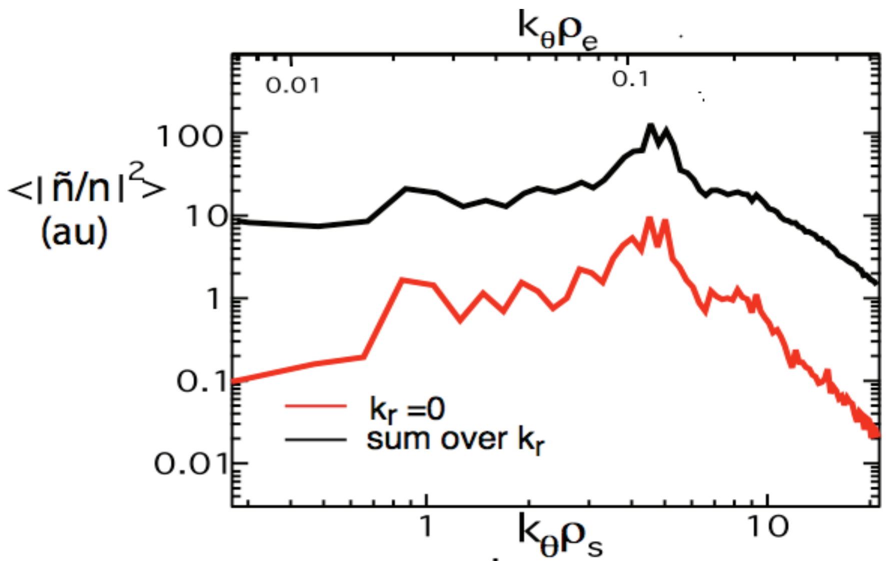
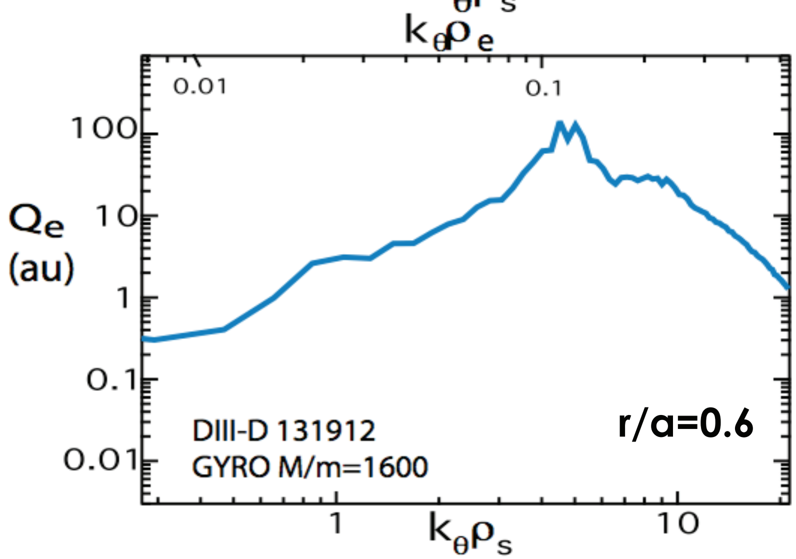
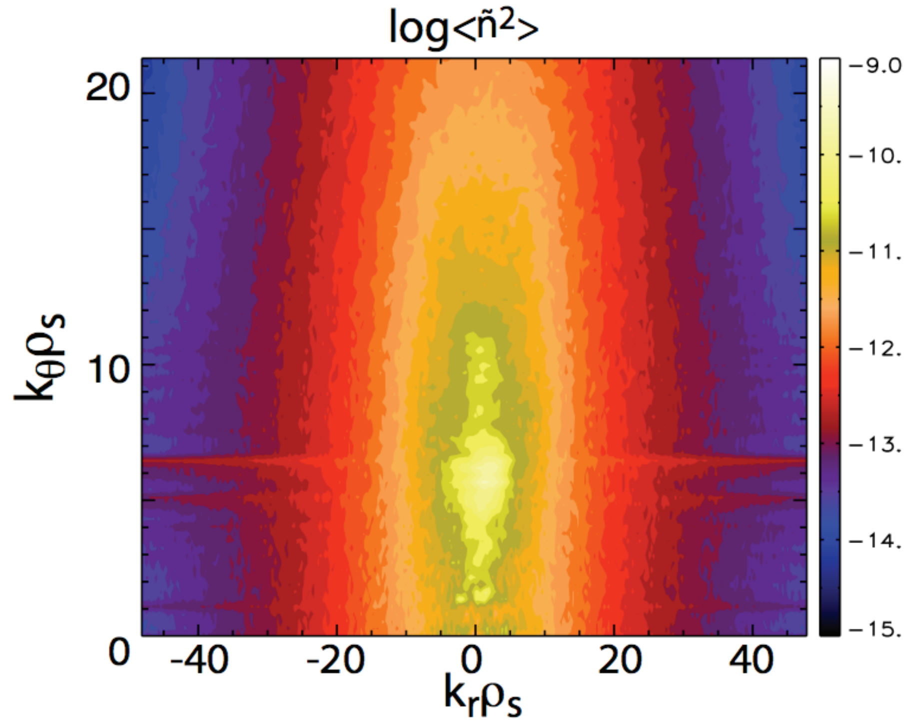
Initial Multi-scale GYRO Calculations Indicate Importance of ETG Range ($k_\theta\rho_s > 2$) for Electron Thermal Transport







Full multi-scale, electromagnetic, local simulation including pitch angle collisions, M/m=1600.
Fixed gradient simulation;
$Q_{e\ GYRO} = 0.28\ Q_{e,\ exp}$

Electron Heat flux almost entirely driven by modes with $k_\theta\rho_s > 2$

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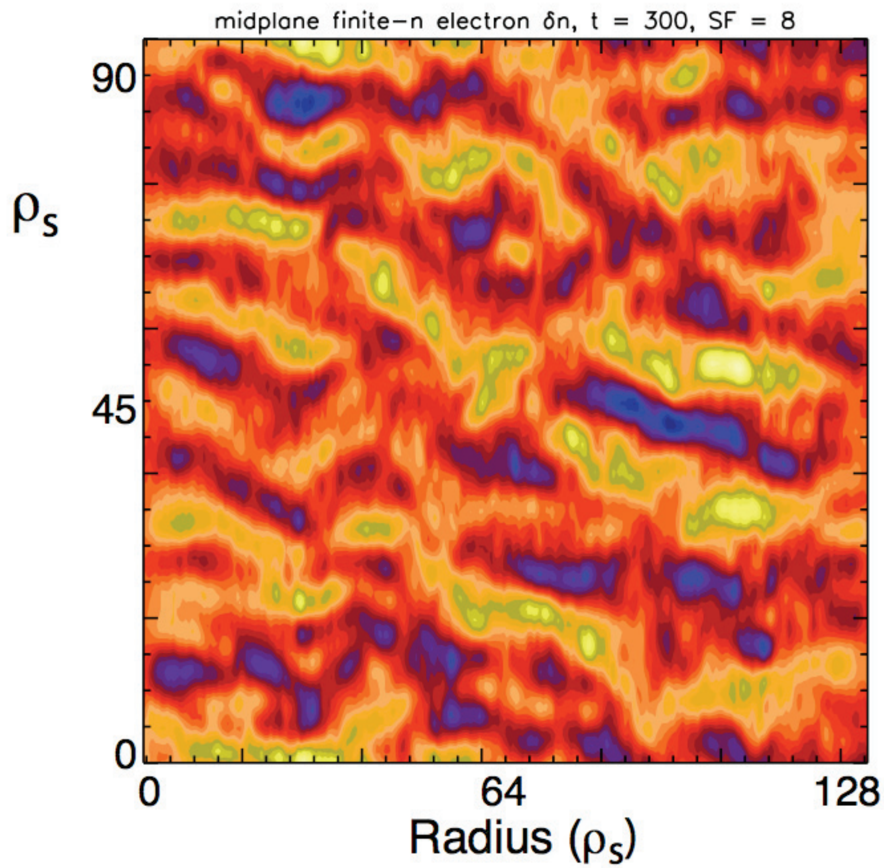
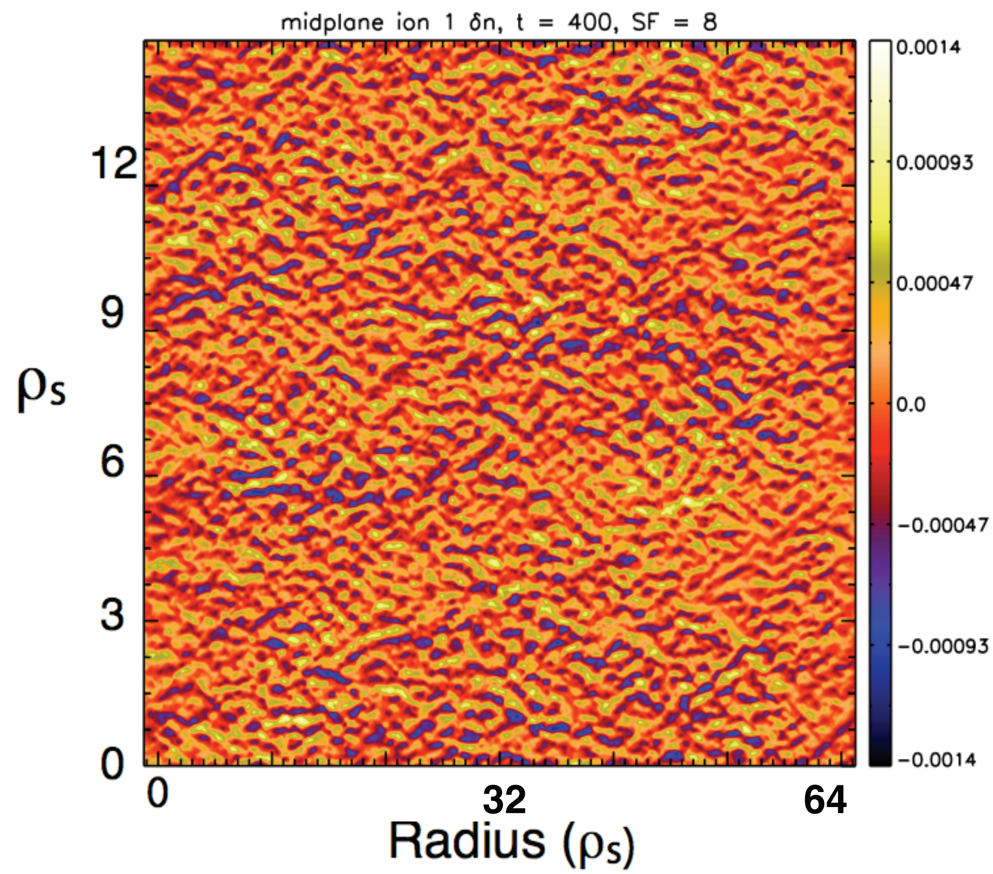
H-Mode Density Contours Show Small-scale Structures

Outboard Midplane Density Fluctuations

L-Mode, 128913



H-Mode, 131912



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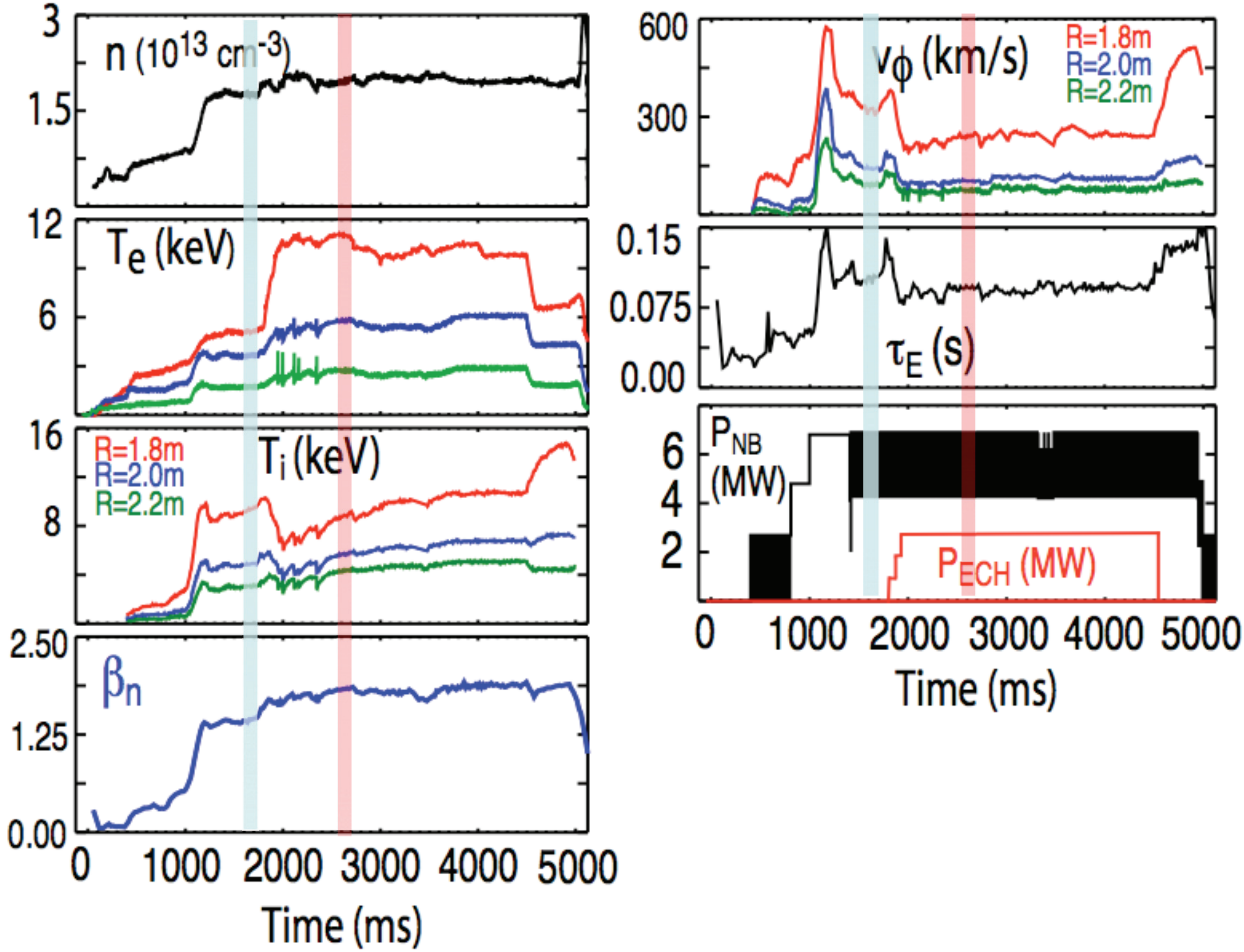
Both L-and H-Mode structures are radially elongated

$T_e/T_i > 1$ and $T_e(0) > 10$ keV Achieved in ECH-assisted QH-mode Plasma ("Simulates Central α-heating")

Reduced toroidal rotation and reduced central ion temperature with ECH

Collisionality $\nu^* \sim 0.02$-0.04 (comparable to ITER!)



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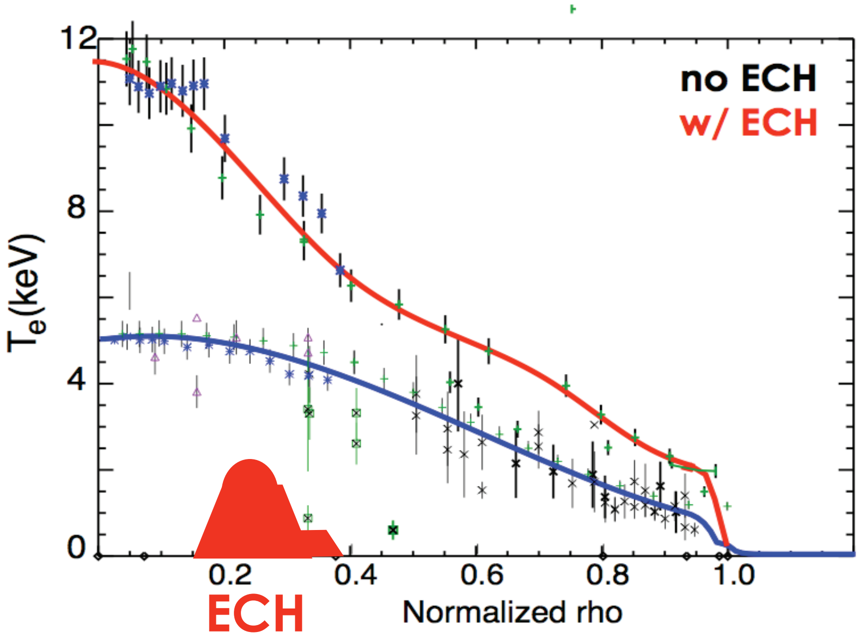
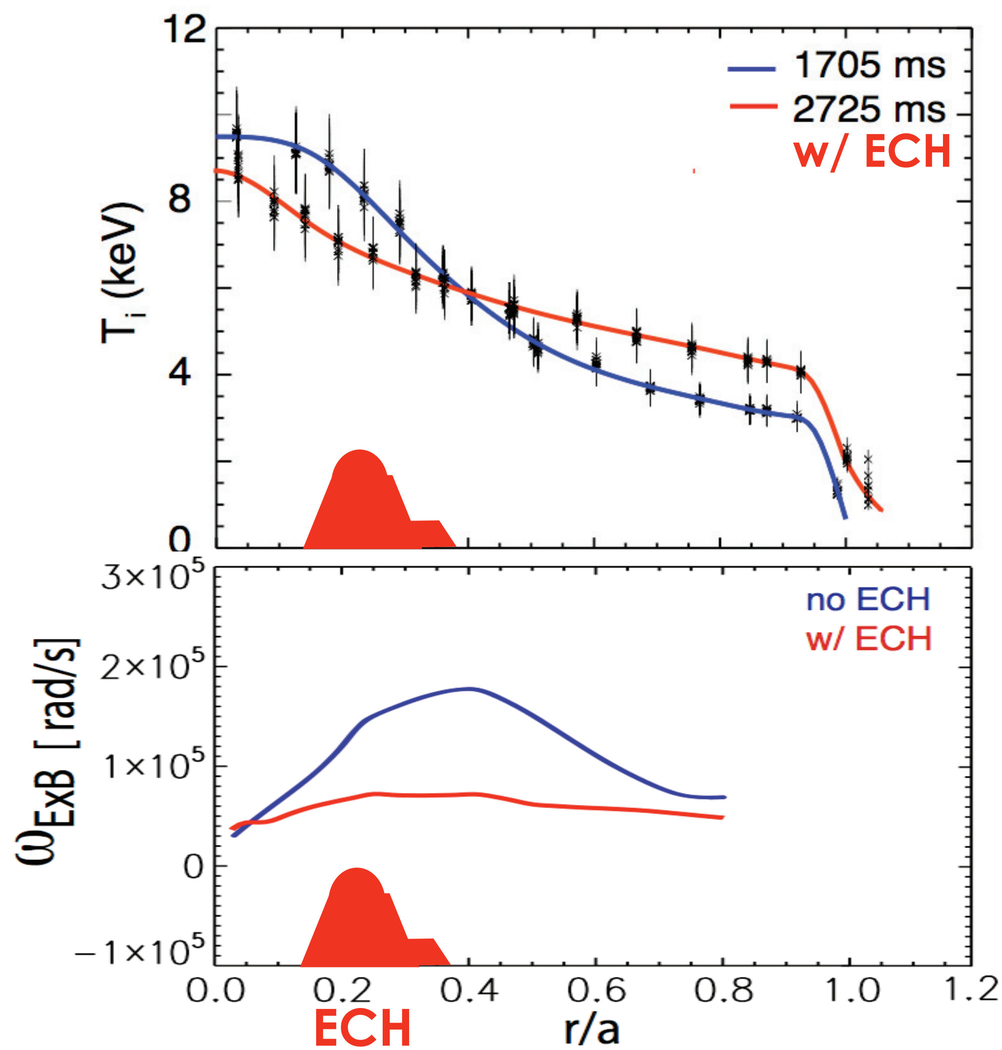
Large Increase in T_e and T_e/T_i with ECH (#141407, 2.7 MW): Decreased E×B Shear and Increased Ion Transport

Electron Temperature



r/a	0.3	0.5	0.7
T_e/T_i	0.62	0.65	0.66
T_e/T_i	1.21	1.07	0.8

Ion Temperature



- Ion (and electron) thermal transport increases with ECH

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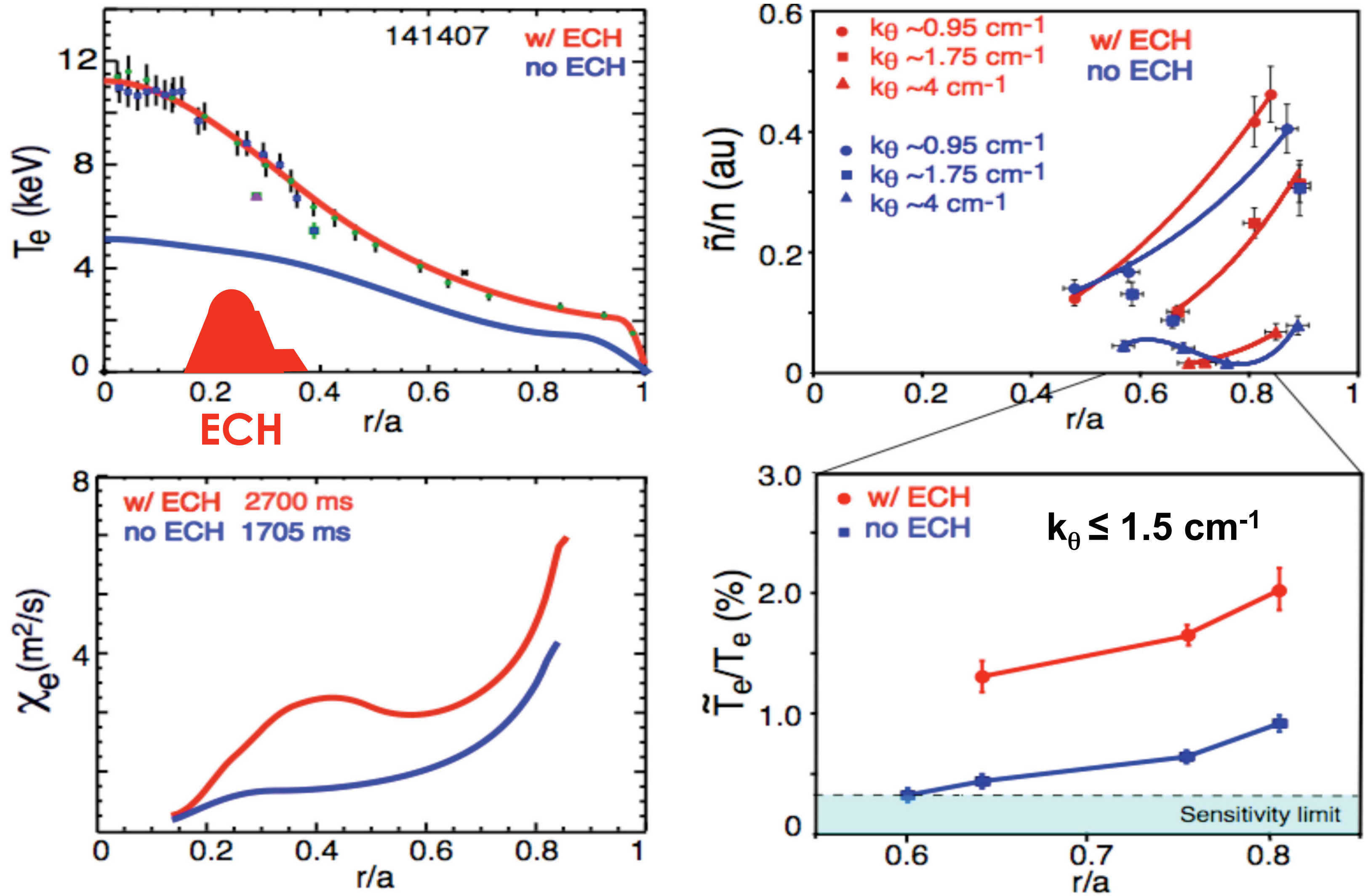
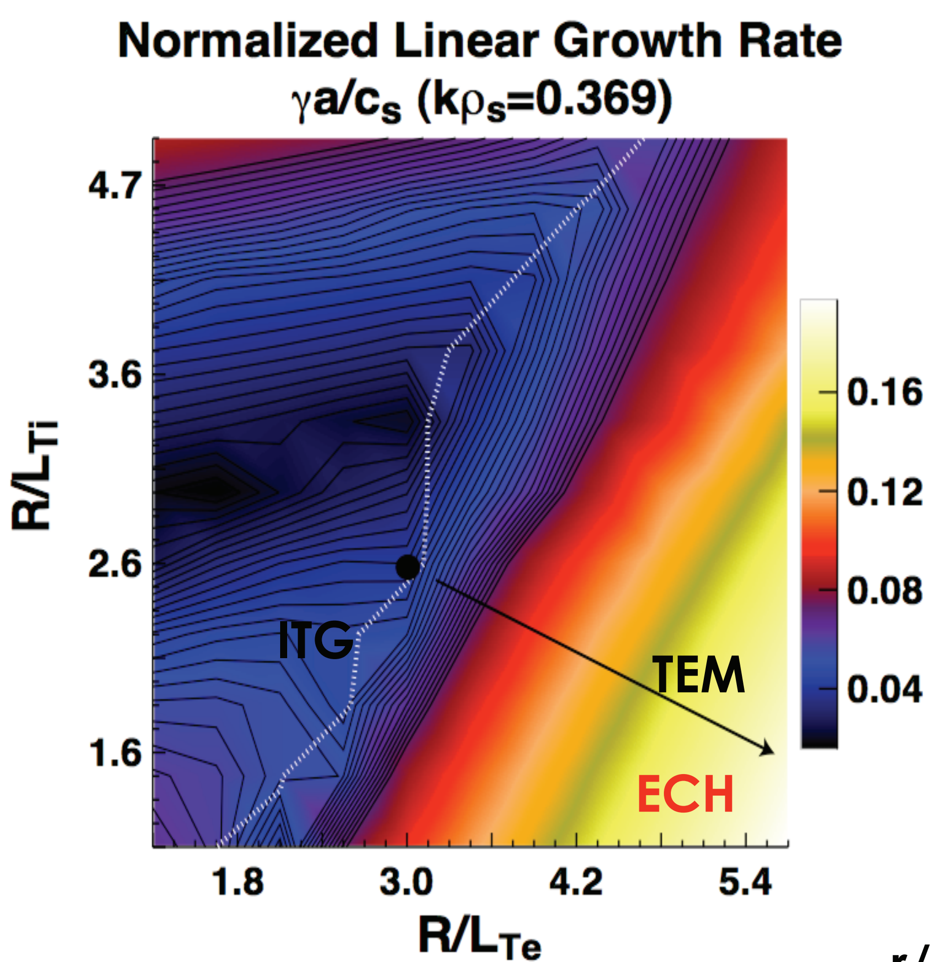
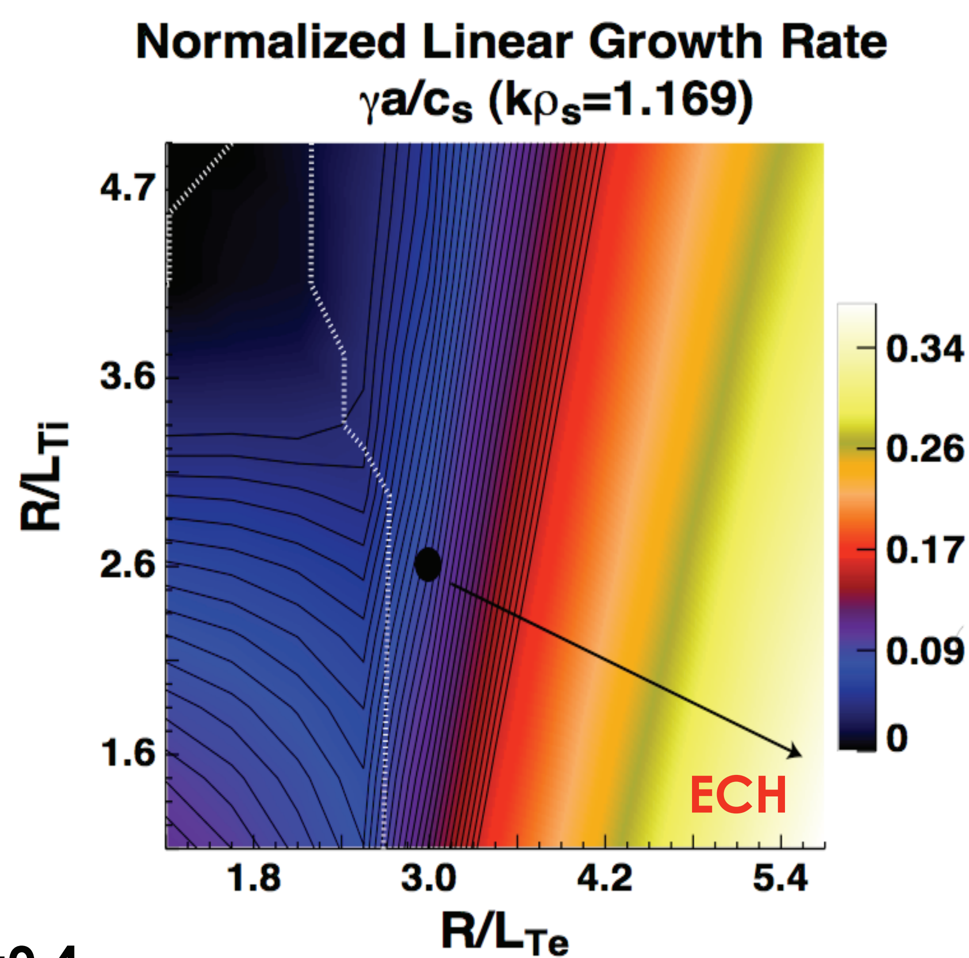
Electron Temperature Fluctuations, Diffusivity Increase Substantially With ECH, Suggesting TEM Dominance



At r/a=0.4, increasing R/L_{Te} with ECH Leads to TEM Transition, Increased Growth Rates (E×B Shear is Also Reduced)





r/a=0.4

Increased ion transport reduces R/L_{ti} and results in increased growth rate (feedback)

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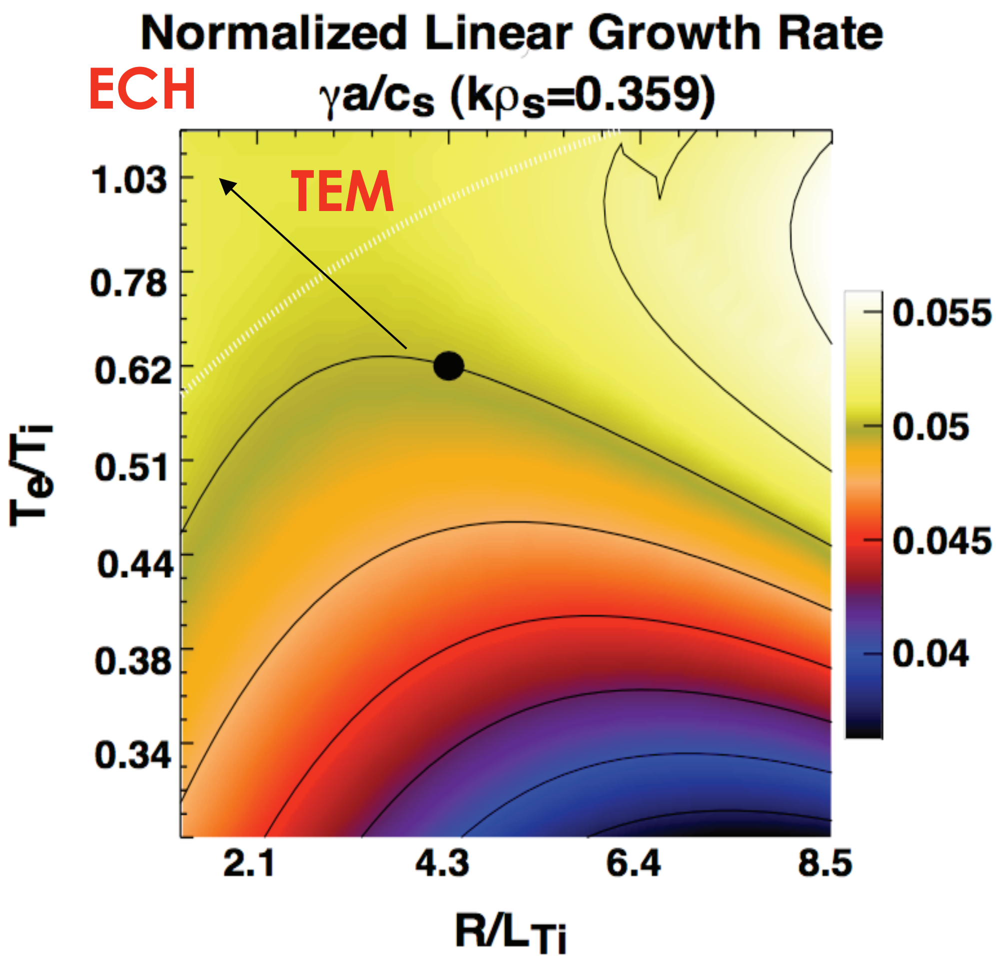
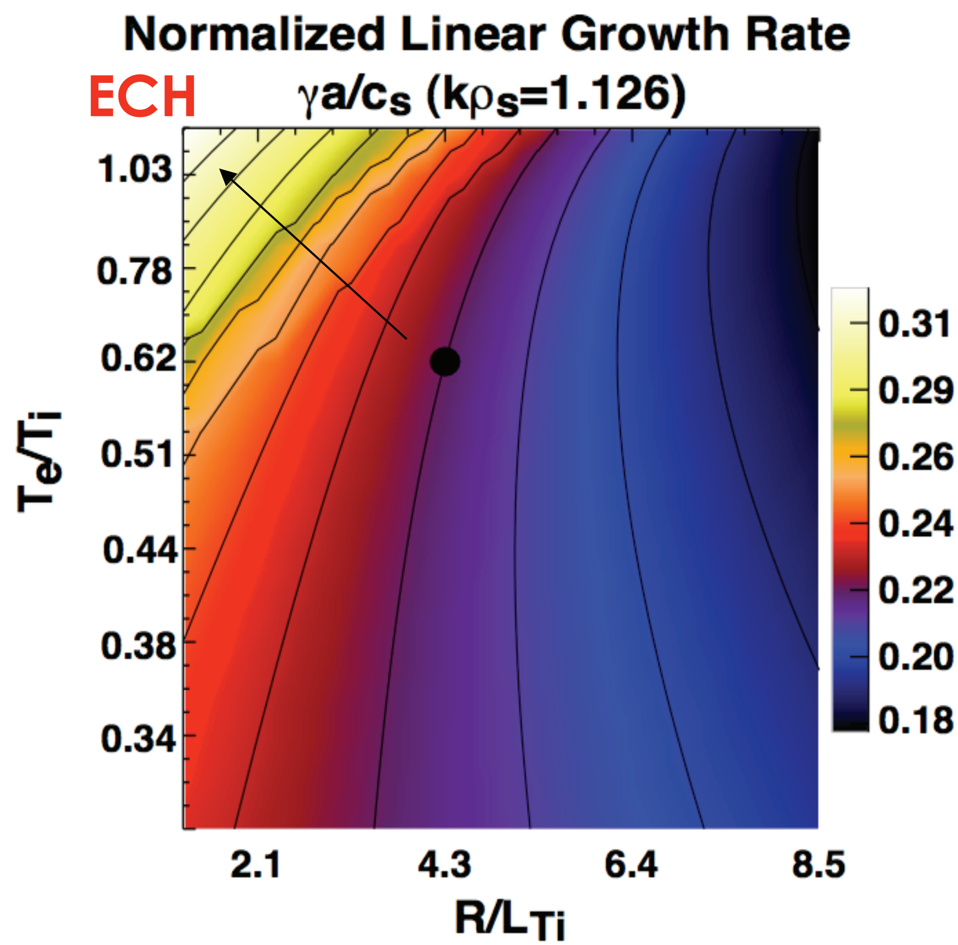
At r/a=0.6, Intermediate-k Growth Rates Increase Moderately with ECH (E×B Shear Reduction is Probably Dominant Effect)





r/a=0.6 $R/L_{Te}(0.6)$=5.5 (nearly constant)
Increased ion transport reduces R/L_{ti} and results in increased growth rate (feedback)

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Summary

- Core electron thermal transport and ITG/TEM core turbulence are substantially reduced across the L-H transition in low-collisionality H-mode plasmas, consistent with reduced linear growth rates and increased E×B shear
- The observed fluctuation reduction in the low-k wavenumber range Is qualitatively consistent with initial GYRO multi-scale simulations predicting the dominance of ETG-scale turbulence in the core. Fixed-flux runs are in preparation to allow quantitative comparisons to experimentally measured turbulence wavenumber spectra
- $T_e/T_i \sim 1$ has been achieved with central ECH in these plasmas. Significant TEM activity is predicted due to increased R/L_{te}, T_e/T_i, and reduced ExB shear. Experimentally, significantly increased electron temperature fluctuations and radial electron/ion transport are observed

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