Observation of a Critical Gradient Threshold for Electron Temperature Fluctuations in the DIII-D Tokamak

Presented by

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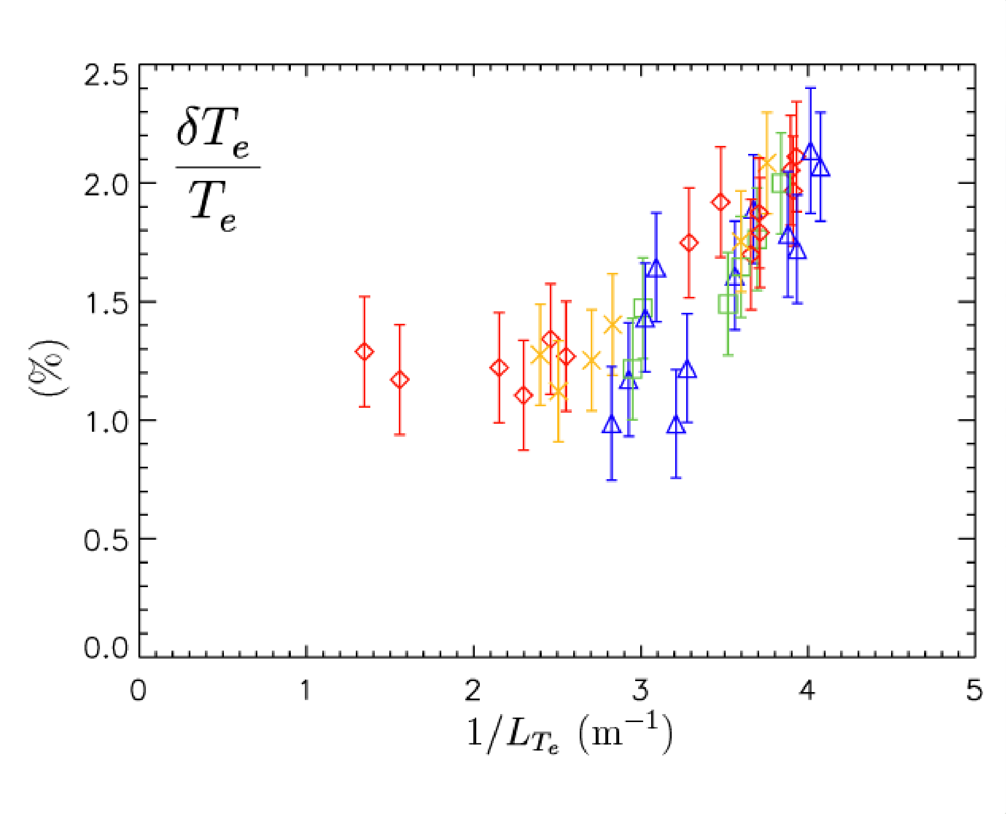

Presented at
54th American Physical Society Division of Plasma Physics Meeting
Providence, RI, USA

October 29, 2012

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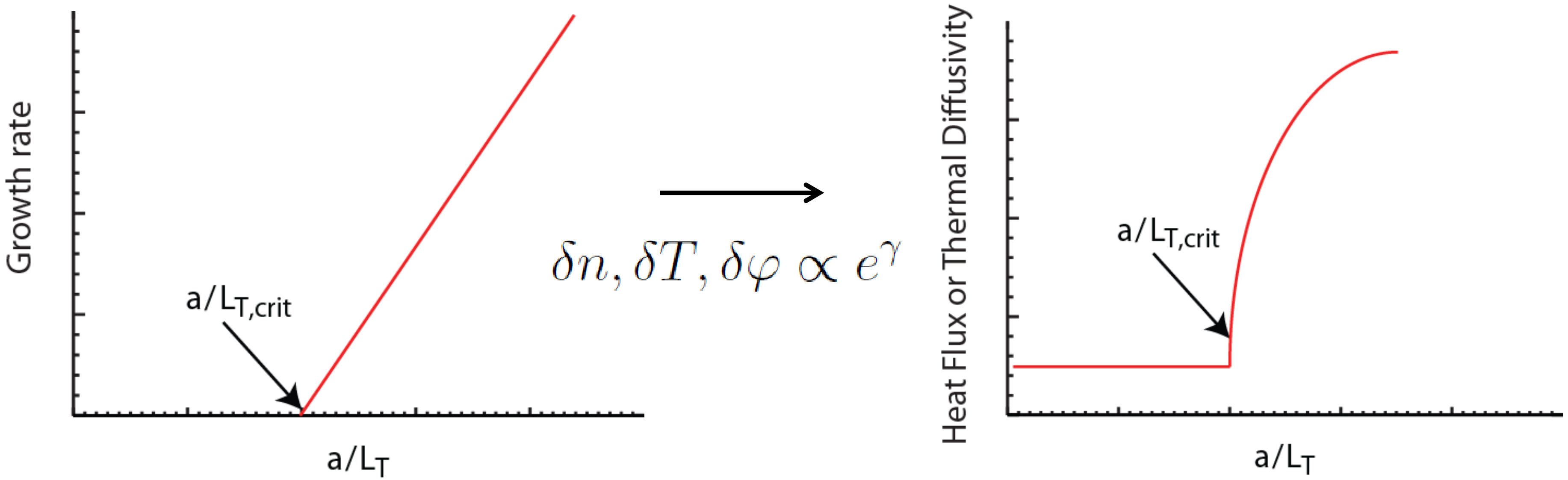
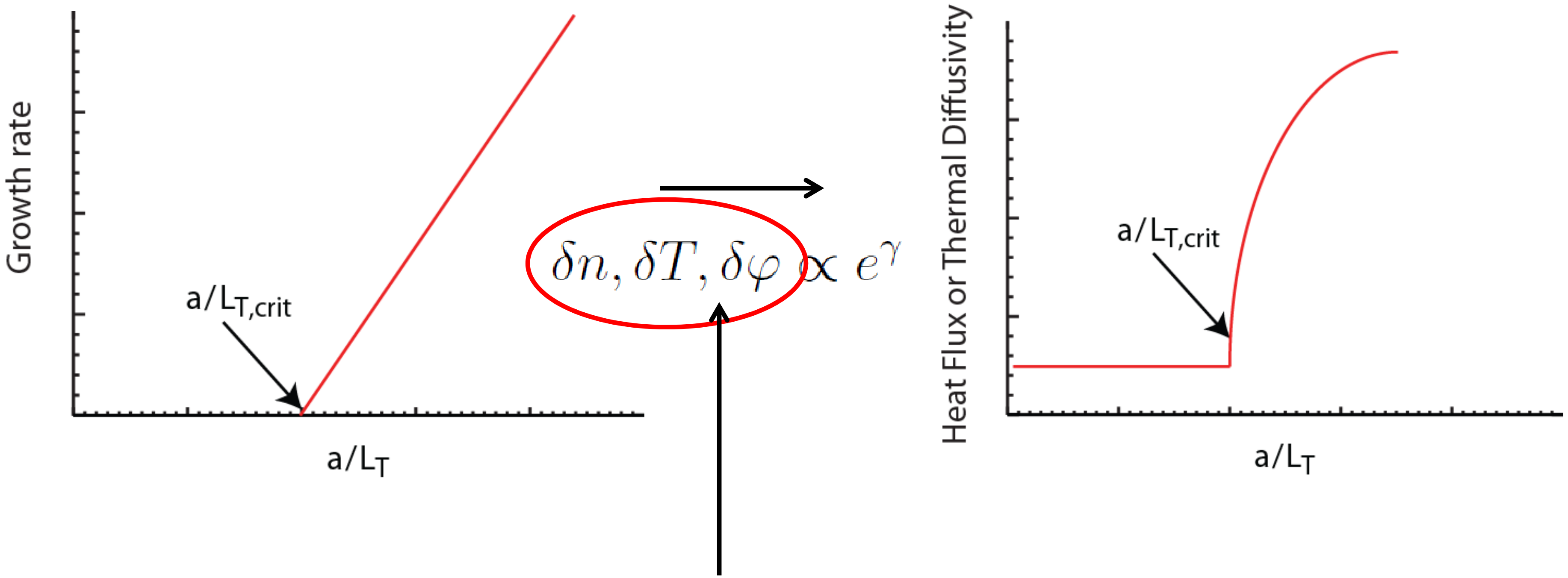
Motivation: Validation of the critical gradient paradigm for turbulence driven transport



$$\delta n, \delta T, \delta \varphi \propto e^{\gamma}$$

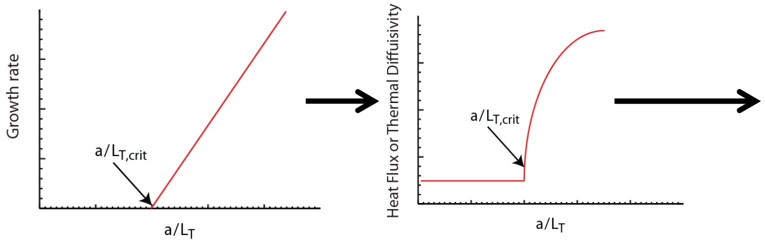
- **Gyroradius-scale mode becomes linearly unstable, explosive growth leads to large macroscopic change in heat fluxes and diffusivities**
- **Threshold can be up-shifted non-linearly, e.g. Dimits shift**

Motivation: Validation of the critical gradient paradigm for turbulence driven transport



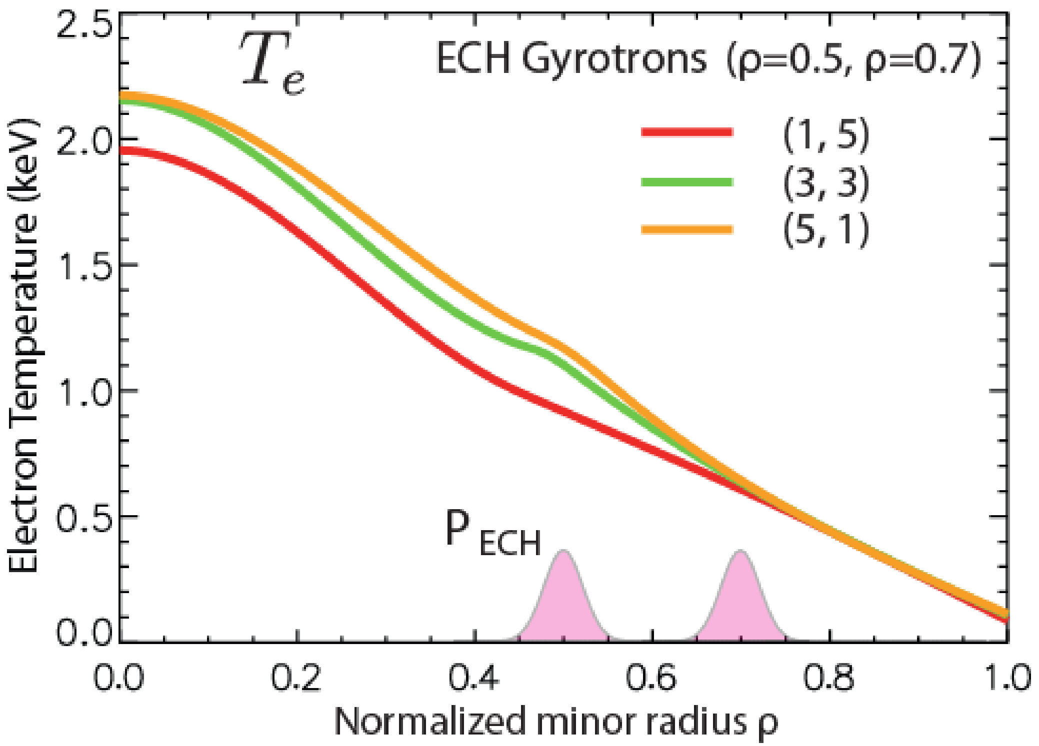
- **Direct validation of this picture requires systematic measurements of the turbulent fluctuations driven unstable by the new mode, which cause the increased transport**
  - Previous work restricted to indirect studies

Motivation: Critical gradient leads to stiff transport



Many previous studies of critical gradients and stiffness:

B. Coppi and N. Sharky, Nucl. Fusion 21, 1363 (1981)
F. Ryter et al., Phys. Rev. Lett. 86, 2325 (2001)
G.T. Hoang et al., Phys. Rev. Lett. 87, 125001 (2001)
D.R. Baker et al., Phys. Plasmas 8, 4128 (2001)
P. Mantica et al, Plasma Phys. Control Fusion 44, 2185 (2002)
D.R. Mikkelsen et al., Nucl. Fusion 42, 1376 (2003)
X. Garbet et al. Plasma Phys. Control. Fusion 46, 1251(2004)
F. Ryter et al., Phys. Rev. Lett. 95, 085001 (2005)
Y. Camenen et al., Plasma Phys. Control. Fusion 47, 1971 (2005)
P. Mantica et al., Phys. Rev. Lett. 102, 175002 (2009)
P. Mantica et al., Phys. Rev. Lett. 107, 135004 (2011)
and lots more



- **Local stiffness parameterizes incremental change in flux for incremental change in gradient:** $S = \frac{\nabla T_e}{Q_e}\frac{\partial Q_e}{\partial(\nabla T_e)}$
- **Global stiffness (i.e. profile resilience): little change to profiles with additional heating, strongly diminishing returns**

Summary of results

- **First direct, systematic observation of a critical gradient in a locally measured fluctuating turbulent quantity in a tokamak**
  - Critical gradient observed for both electron thermal transport and electron temperature fluctuations

$Q_e, \ \frac{\delta T_e}{T_e}$

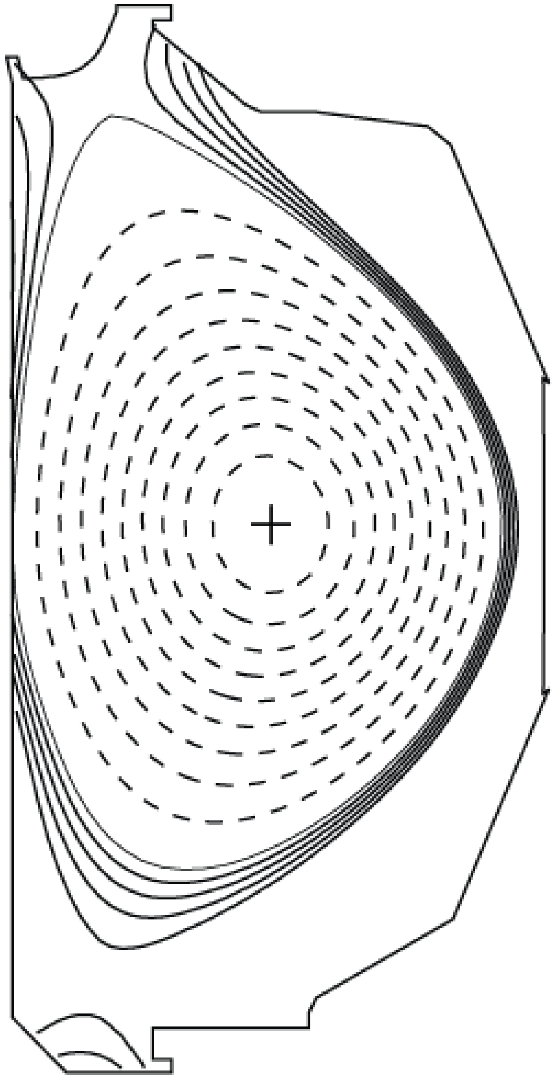
- **Evidence identifies threshold with ∇T_e driven trapped electron mode turbulence**

∇T_e -TEM

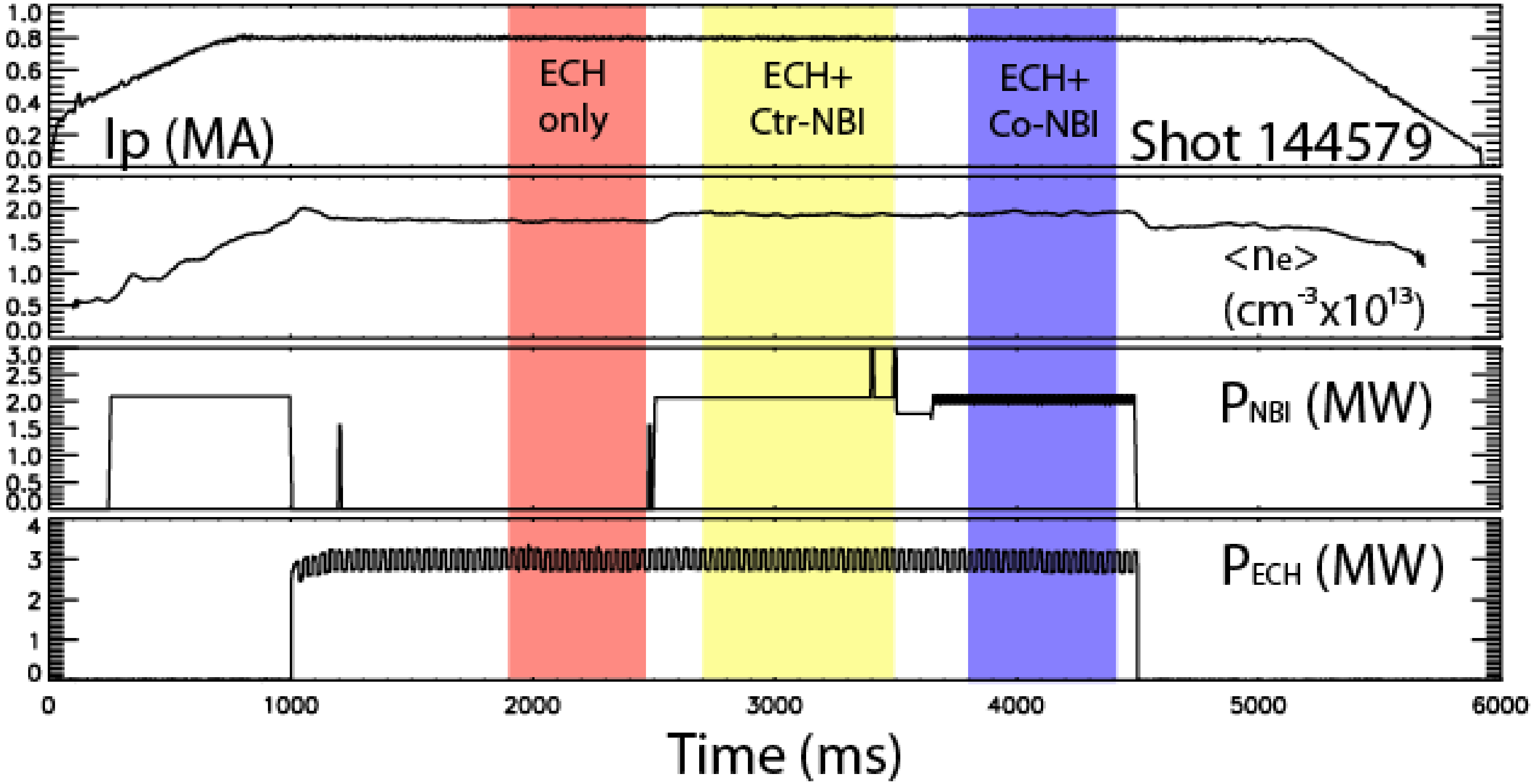
- **Supported by linear & non-linear calculations**
  - Linear gyrofluid calculations with TGLF
  - Nonlinear gyrokinetic simulations with GYRO

L-mode target discharge

- **Upper single null, diverted**
  - I_p=0.8 MA
  - B_T=-2 T
  - $\langle n_e \rangle \sim 2 \times 10^{13}$ cm^{-3}
  - R~1.7 m, a~0.6 m
- **ECH-only and NBI+ECH shots**
  - Rotation scan at fixed power
  - P_{ECH} ~ 3 MW, 1 gyrotron modulated
  - P_{NBI} ~ 2 MW
- **Turbulence measurements:**
  - T_e fluctuations , 2 radii per shot (CECE)
  - nT crossphase (CECE + reflectometry)
  - Density fluctuations (BES, DBS)



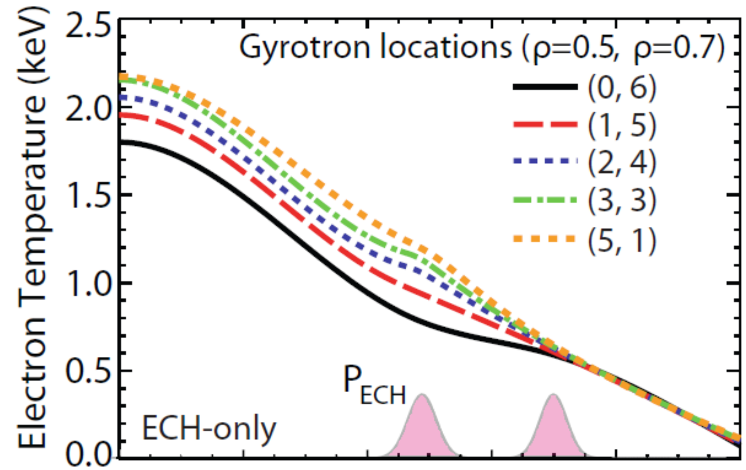
Steady-state time periods used to average profile and turbulence data

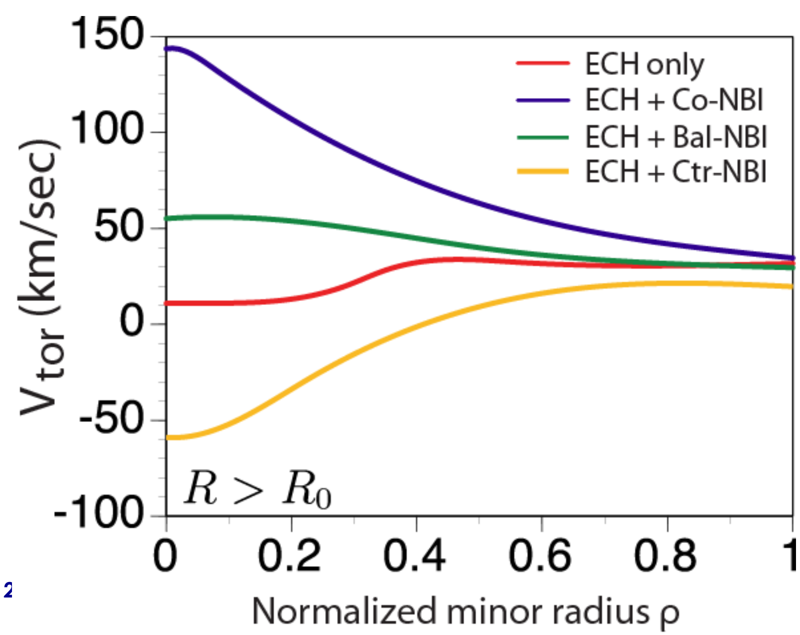


- **Highly reproducible, stationary discharges**
- **3 time periods per shot: ECH-only, ECH+Co-NBI, and either ECH+Bal-NBI or ECH+Ctr-NBI**

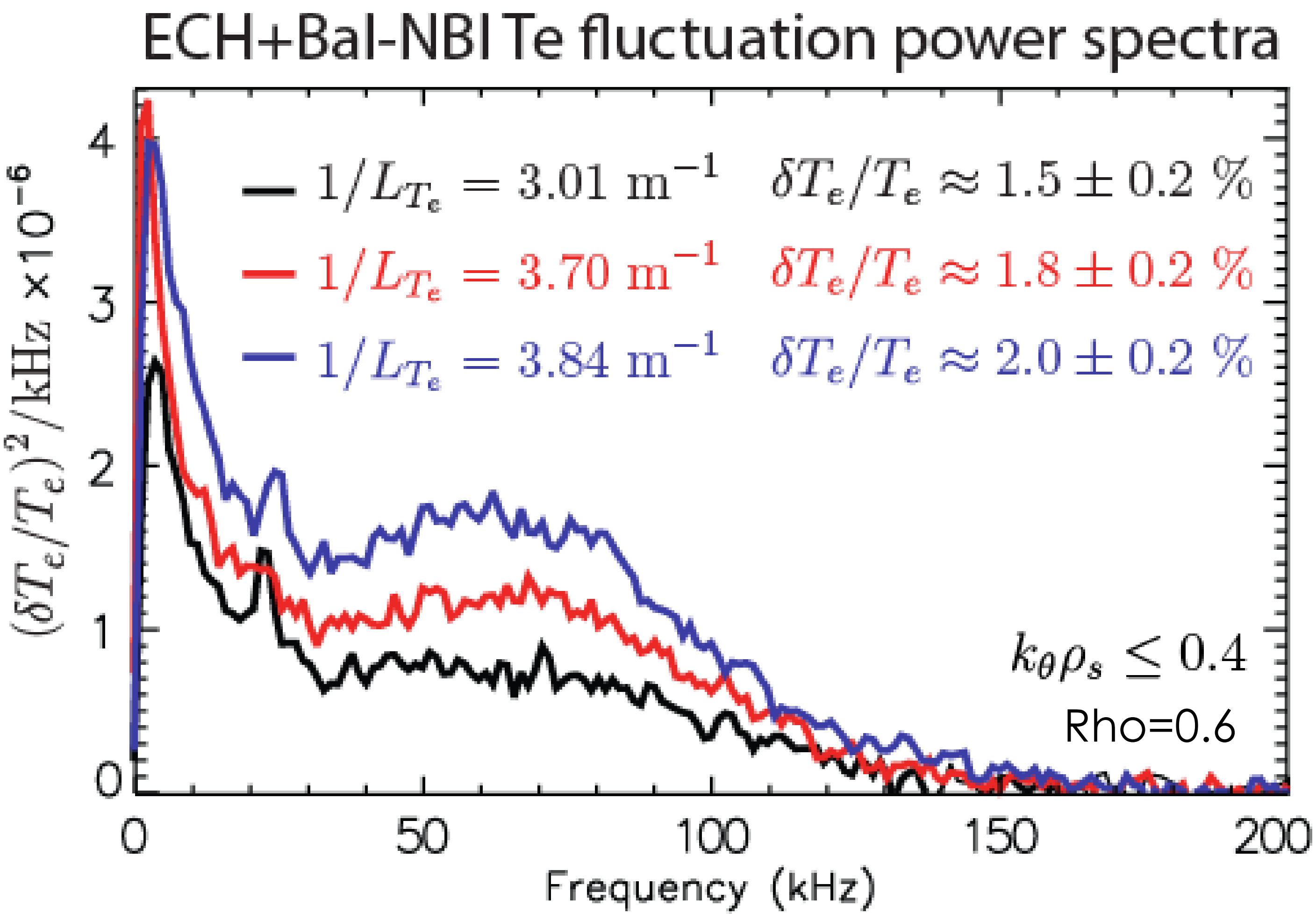
Local electron temperature gradient and rotation systematically varied in repeated L-mode discharges

- **ECH deposition locations modified shot-to-shot to locally scan ∇T_e at rho=0.6**
- **Fluctuation measurements acquired near rho=0.6 during ~500-800 ms steady-state periods**
- **Rotation (and flow shear) varied by changing NBI mix at fixed power**
- **Other profiles:**
  - For ECH only T_i lower everywhere, T_e lower in core (rho<0.5)
  - Density feedback controlled, well-matched
  - Z_{eff} higher with Ctr-NBI

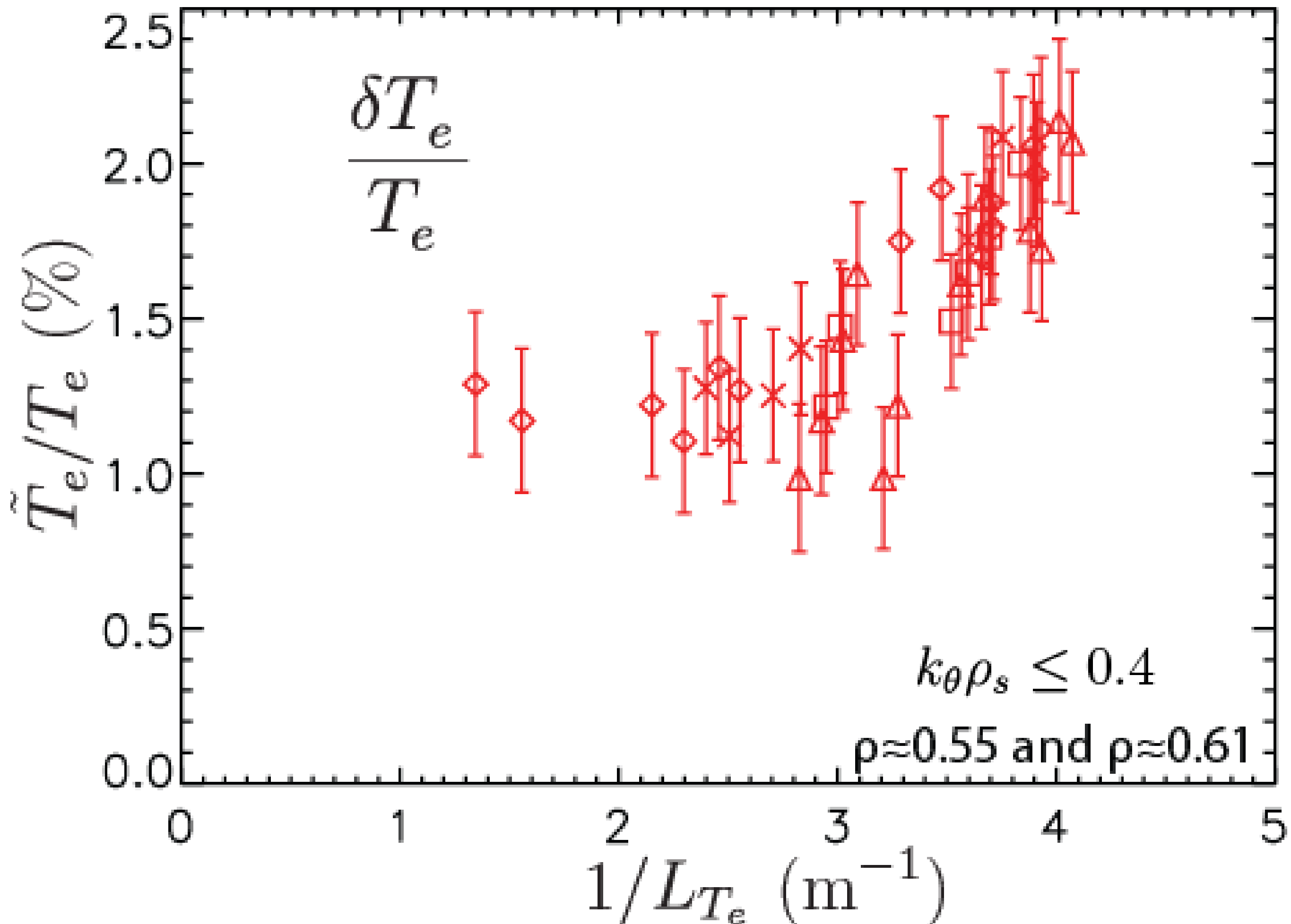




Long wavelength electron temperature fluctuations increase with $1/L_{Te}$



T_e fluctuations show critical gradient threshold in $1/L_{Te}$



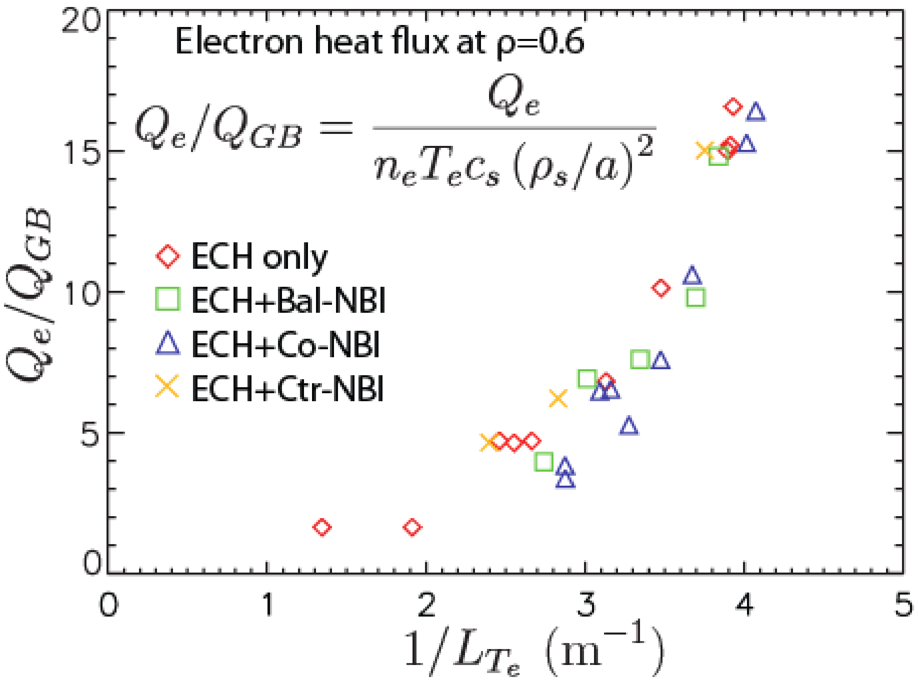
$$\tilde{Q}_e = \frac{3n_eT_e}{2B}k_\theta\left(\frac{|\tilde{n}_e|}{n_e}|\tilde{\varphi}|\gamma_{n_e,\varphi}\sin\alpha_{n_e,\varphi} + \frac{|\tilde{T}_e|}{T_e}|\tilde{\varphi}|\gamma_{T_e,\varphi}\sin\alpha_{T_e,\varphi}\right)$$ [1]

[1] A.J. Wootton et al., Phys. Fluids B 2, 2879 (1990)

Power balance inferred flux increases non-linearly with $1/L_{Te}$, limited rotation dependence

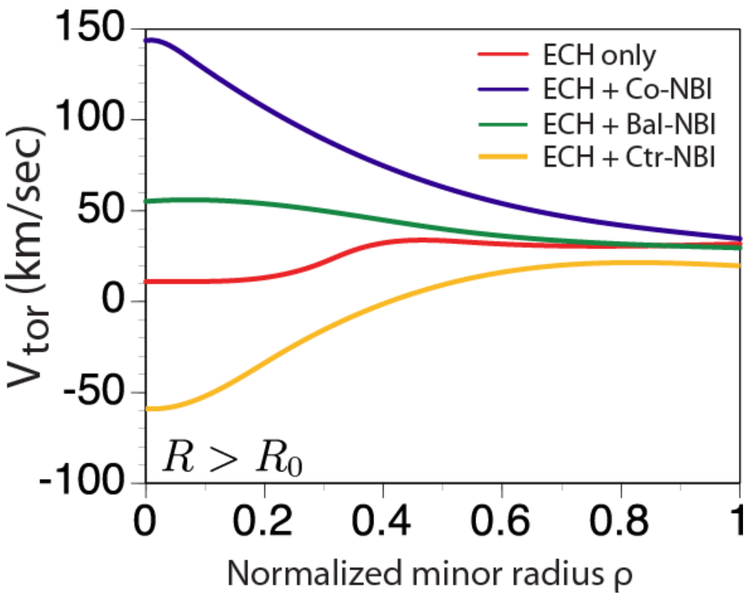
- **Electron heat flux similar to results from F. Ryter et al. Phys. Rev. Lett. 95, 085001 (2005), but also shows little rotation dependence**

- **Further transport and stiffness analysis reported in J.C. DeBoo et al., Phys. Plasmas 19, 082518 (2012)**



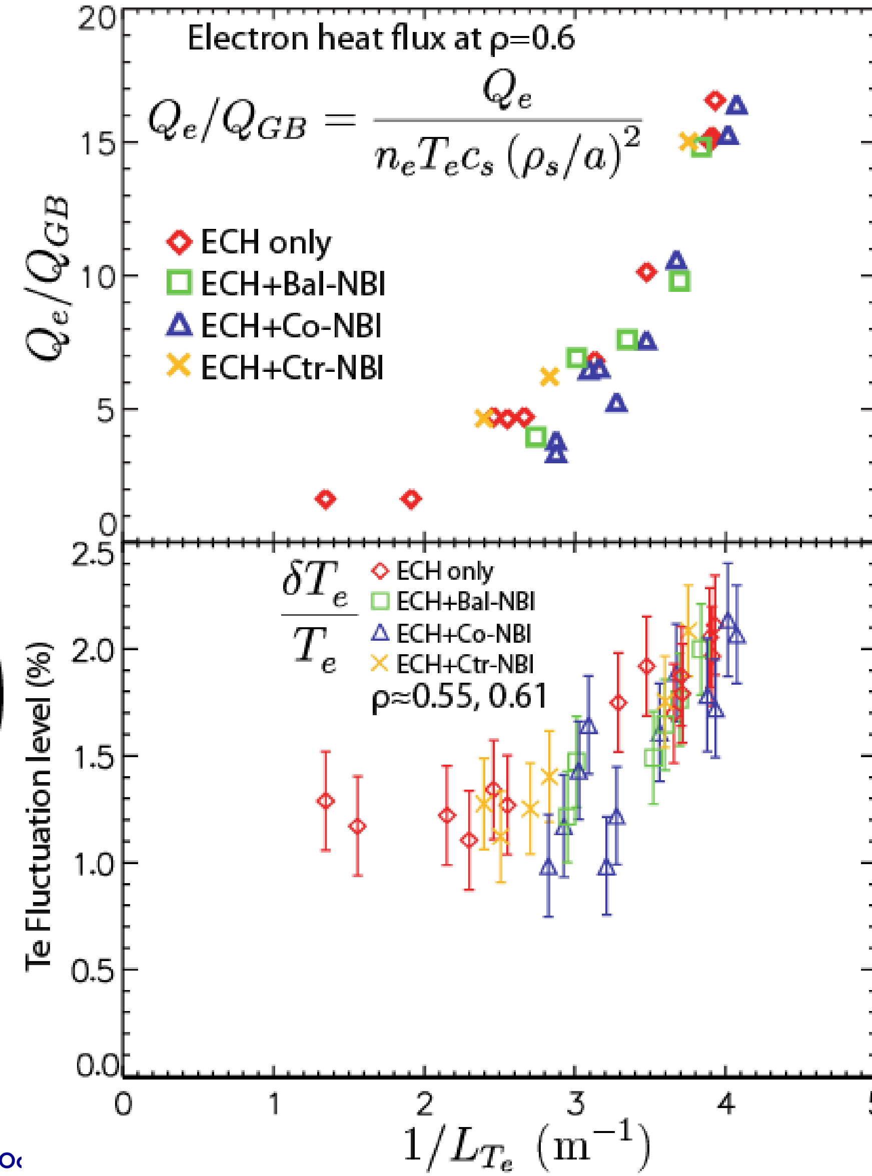
$$\tilde{Q}_e = \frac{3n_eT_e}{2B}k_\theta\left(\frac{|\tilde{n}_e|}{n_e}|\tilde{\varphi}|\gamma_{n_e,\varphi}\sin\alpha_{n_e,\varphi} + \frac{|\tilde{T}_e|}{T_e}|\tilde{\varphi}|\gamma_{T_e,\varphi}\sin\alpha_{T_e,\varphi}\right)$$

Simultaneous increase in T_e fluctuations and heat flux with little sensitivity to rotation or flow shear

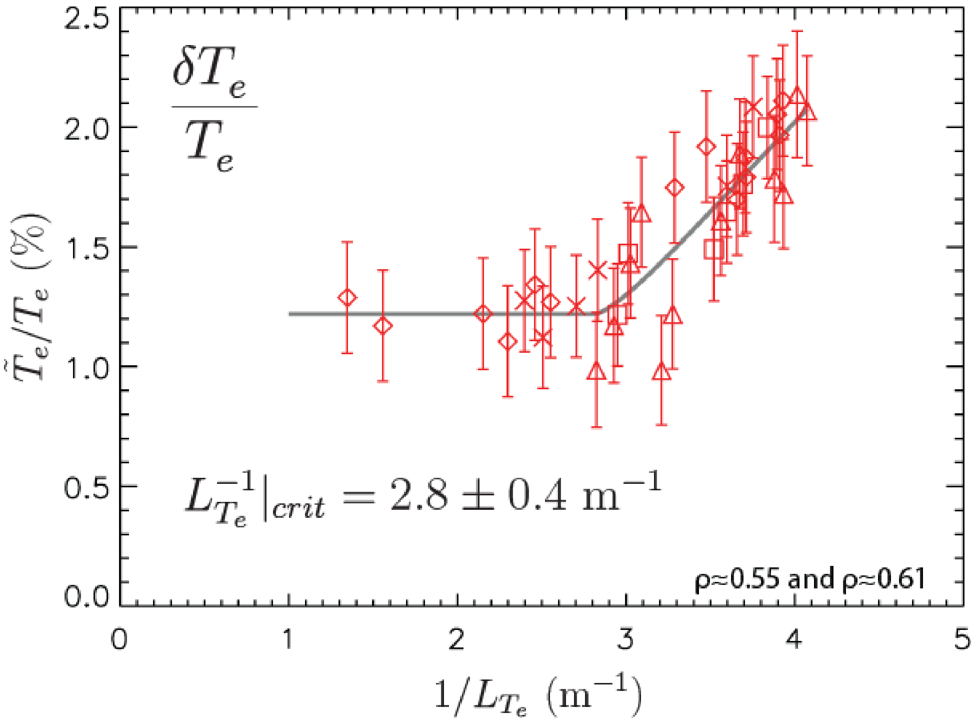


$$\tilde{Q}_e = \frac{3 n_e T_e}{2B} k_\theta \left(\frac{|\tilde{n}_e|}{n_e} |\tilde{\varphi}| \gamma_{n_e,\varphi} \sin\alpha_{n_e,\varphi} + \frac{|\tilde{T}_e|}{T_e} |\tilde{\varphi}| \gamma_{T_e,\varphi} \sin\alpha_{T_e,\varphi} \right)$$

- **δTe/Te can only partially account for Q_e increase**
  - Q_e increase >10x, $\delta T_e/T_e$ ~ 2x
  - Changes to transport crossphases, High-k (ETG) possible



Fit to model equation quantifies critical gradient value and uncertainty estimate



- **Functional form similar to models in F. Imbeaux and X. Garbet Plamsa Phys. Control. Fusion 44, 1425 (2002)**
- **Data varied within uncertainties; mean and standard deviation of fits to:**

$$\chi_e \propto \frac{\delta T_e^2}{T_e^2} = c_0 + c_1 \left(L_{T_e}^{-1} - L_{T_e}^{-1}|_{crit}\right)^{\ell} H\left(L_{T_e}^{-1} - L_{T_e}^{-1}|_{crit}\right)$$

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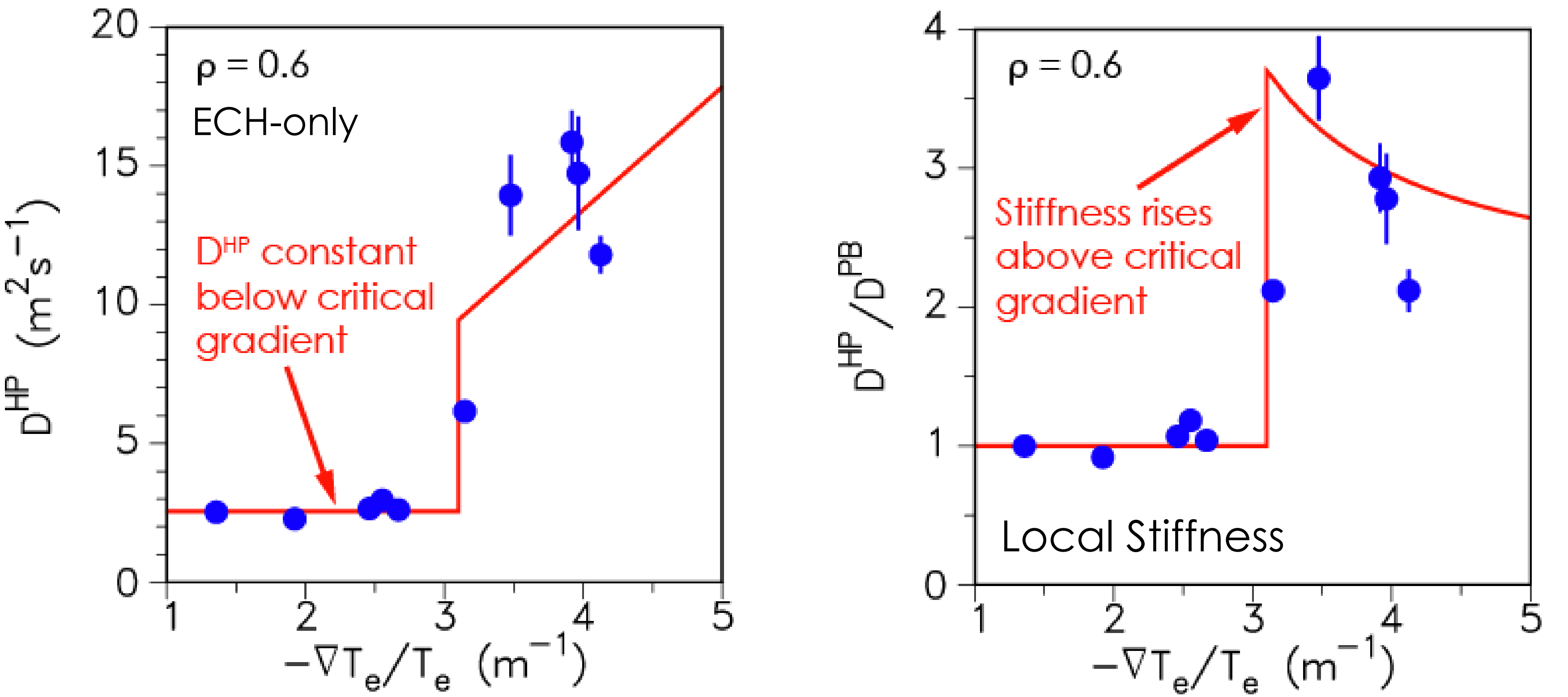
Heat pulse analysis shows critical gradient; stiffness parameter increased above threshold



- ECH-only threshold at $1/L_{crit}$=3.0 ± 0.2 m^{-1}, within uncertainties of temperature fluctuation threshold at 2.8 ± 0.4 m^{-1}
- See C. C. Petty NO4.00009 Wednesday for additional heat pulse analysis

Threshold identified

- **First direct, systematic observation of a critical gradient in a locally measured fluctuating turbulent quantity in a tokamak**
  - Critical gradient observed for both electron thermal transport and electron temperature fluctuations
    - Electron temperature fluctuations threshold
    - Electron thermal diffusivity threshold
      - Increase in local stiffness above threshold
    - Nonlinear increase in electron heat flux

$Q_e, \ \frac{\delta T_e}{T_e}$

- **Evidence identifies threshold with ∇T_e driven trapped electron mode turbulence**

∇T_e -TEM

- **Supported by linear & non-linear calculations**
  - Linear gyrofluid calculations with TGLF
  - Nonlinear gyrokinetic simulations with GYRO

What trends and characteristics can be observed in the turbulence measurements?

- First direct, systematic observation of a critical gradient in a locally measured fluctuating turbulent quantity in a tokamak
  - Critical gradient observed for both electron thermal transport and electron temperature fluctuations

- Evidence identifies threshold with ∇T_e driven trapped electron mode turbulence

∇T_e -TEM

- Supported by linear & non-linear calculations
  - Linear gyrofluid calculations with TGLF
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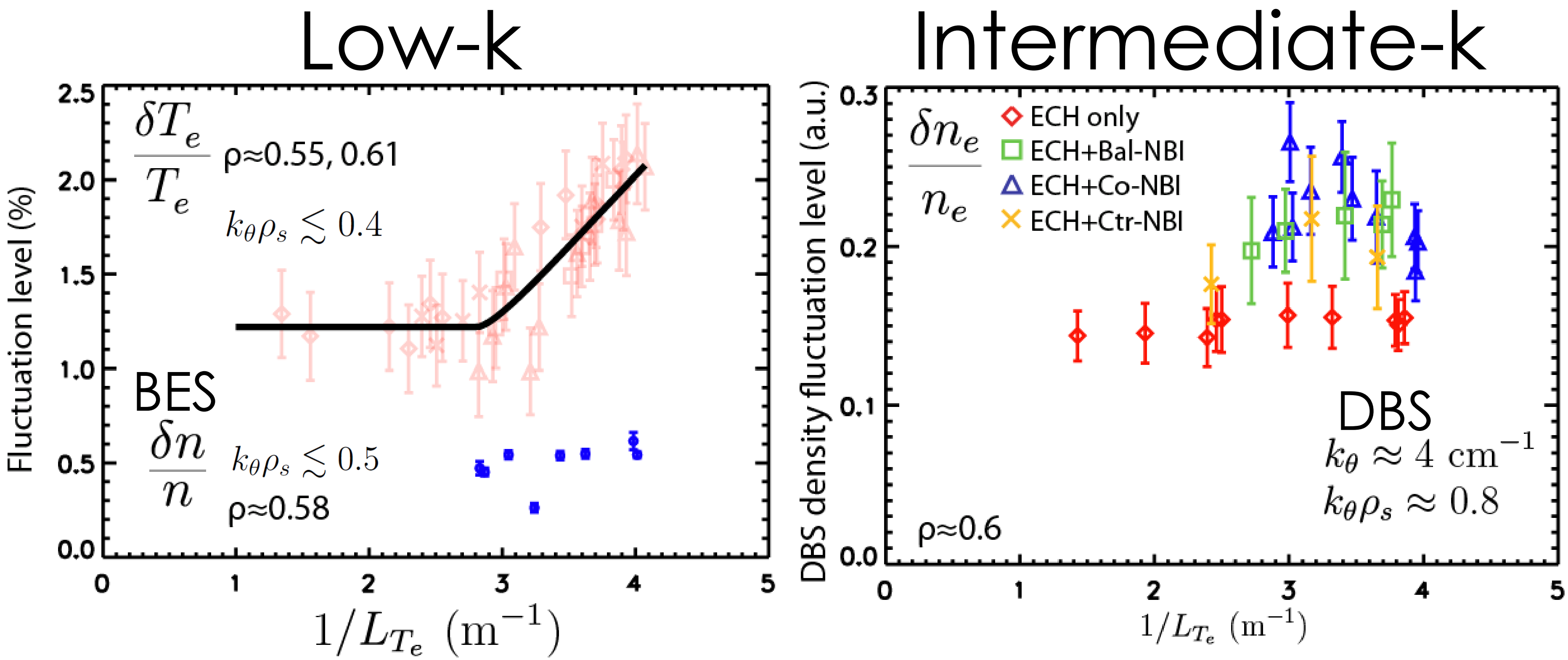
Density fluctuations show little change with $1/L_{Te}$, The ratio $(\delta T_e/T_e)/(\delta n_e/n_e)$ increases at low-k



- $1/L_{Te}$ threshold & $(\delta T_e/T_e)/(\delta n_e/n_e)$ trend consistent with transition to ∇T_e-TEM turbulence
- Intermediate-k fluctuations higher with NBI

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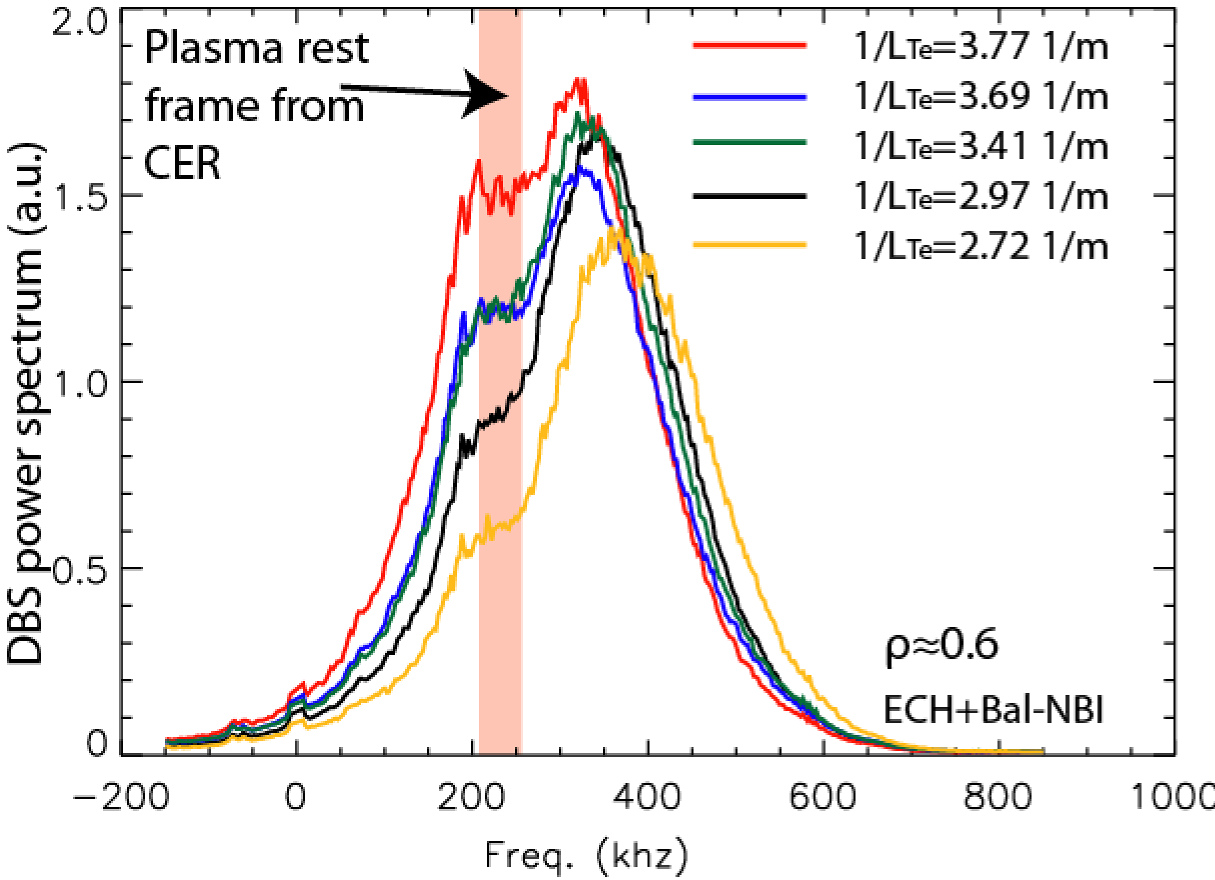
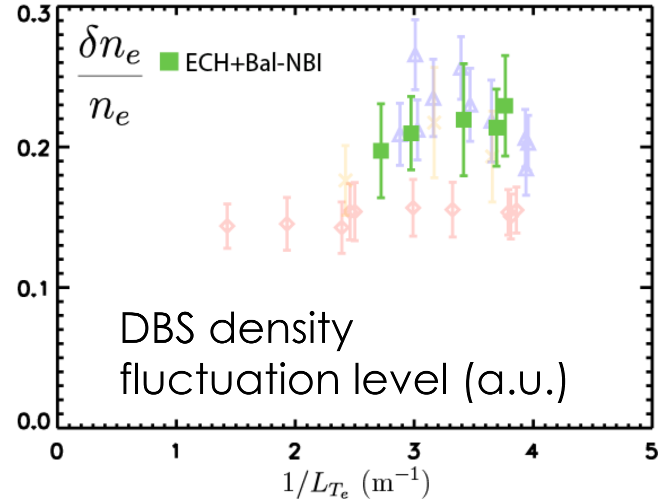
Changes to intermediate-k density fluctuation spectra consistent with new mode being driven at high $1/L_{Te}$

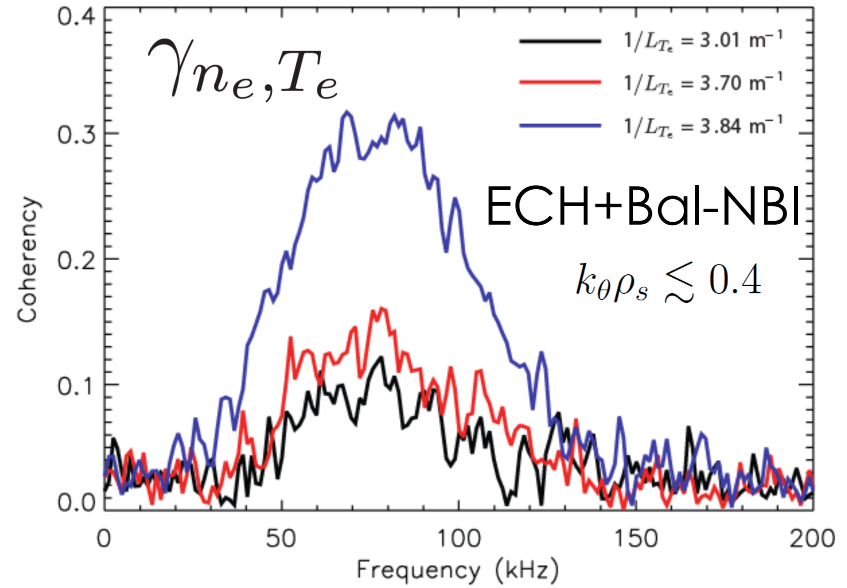


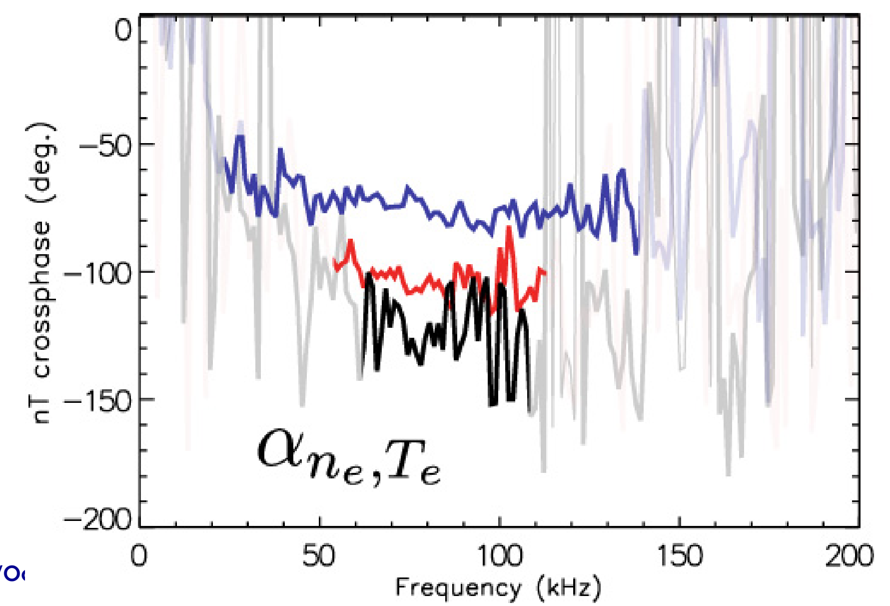


- **Frequency-localized increase in DBS spectrum with $1/L_{Te}$ in ECH+Bal-NBI plasmas**
  - Electron diamagnetic direction is negative direction
  - Increase on electron diamagnetic side of spectrum consistent with ∇T_e-TEM
- **Different behavior below critical gradient with the various NBI configurations**

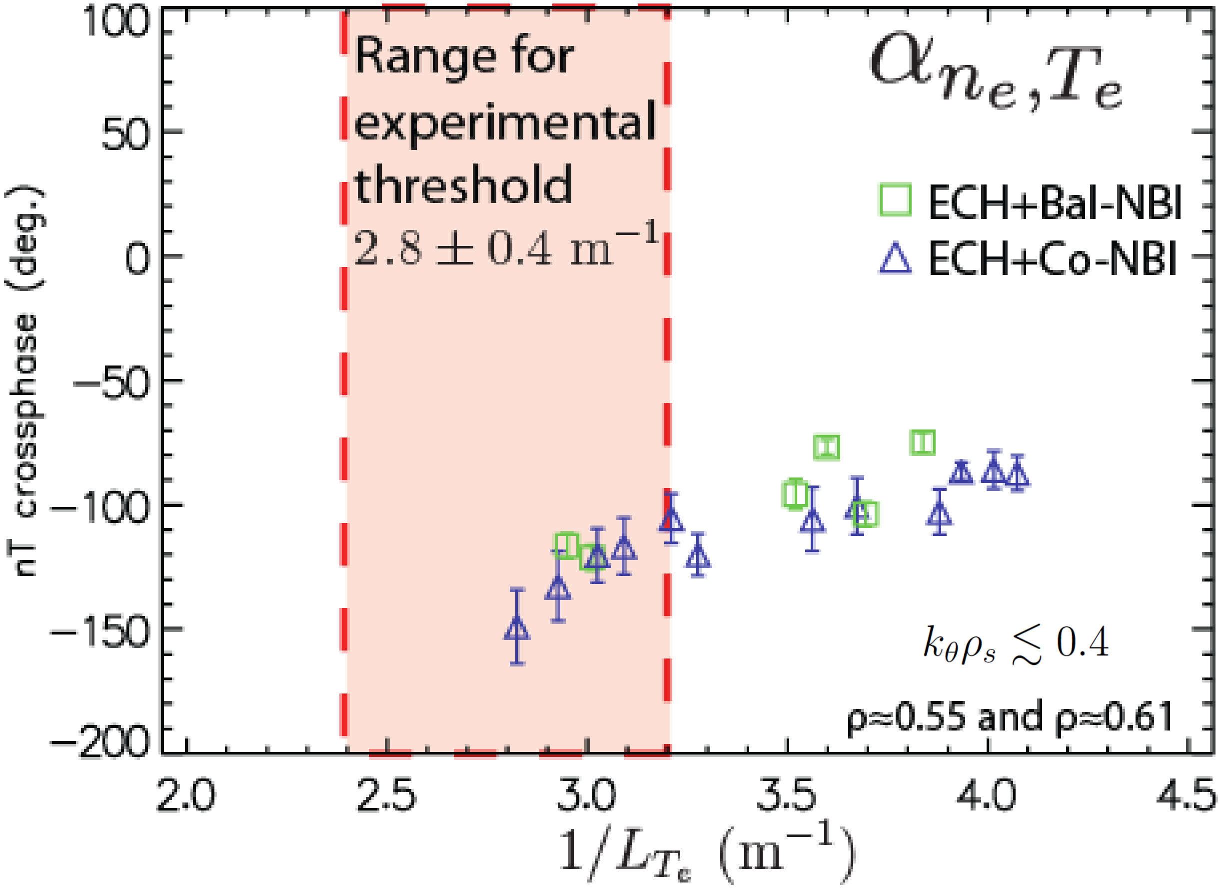
The crosspase angle between fluctuating quantities is a fundamental characteristic of plasmas instabilities

- **Crossphase measurements:**
  - Changes imply changes to dominant mode driving transport
  - Changes give reason to consider changes to transport crossphases
  - Strong, multi-field constraint for comparison to simulations
- **Coherency between electron temperature and density fluctuations increases with $1/L_{Te}$**
  - Coherent frequency range varies with rotation, consistent with a Doppler shift
- **Measured crossphase changes with $1/L_{Te}$**





nT crossphase changes with a/L_{Te}, implying change in dominant instability driving turbulent transport



- **ECH+Co-NBI and ECH+Bal-NBI quantitatively similar to previous results (White PoP 2010, Rhodes NF 2011, Wang PoP 2011), where changes to T_e/T_i and collisionality (with comparatively little $1/L_{Te}$ change) were attributed to ITG to TEM transition**

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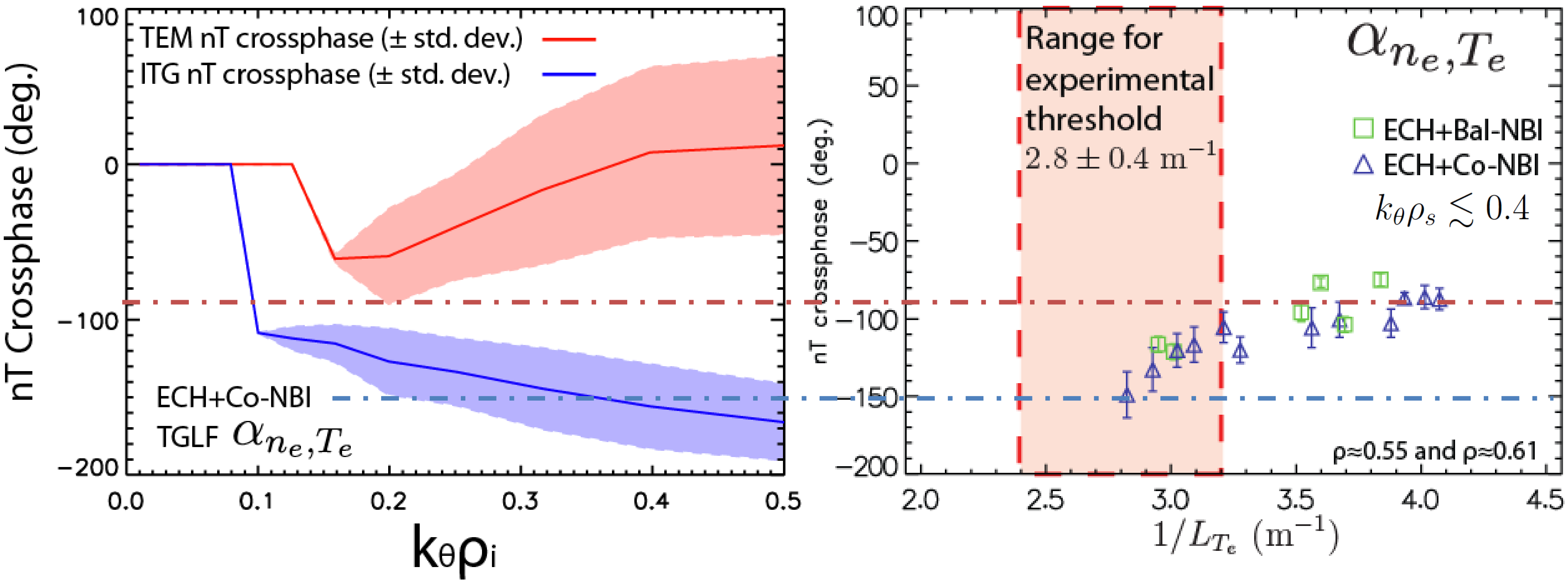
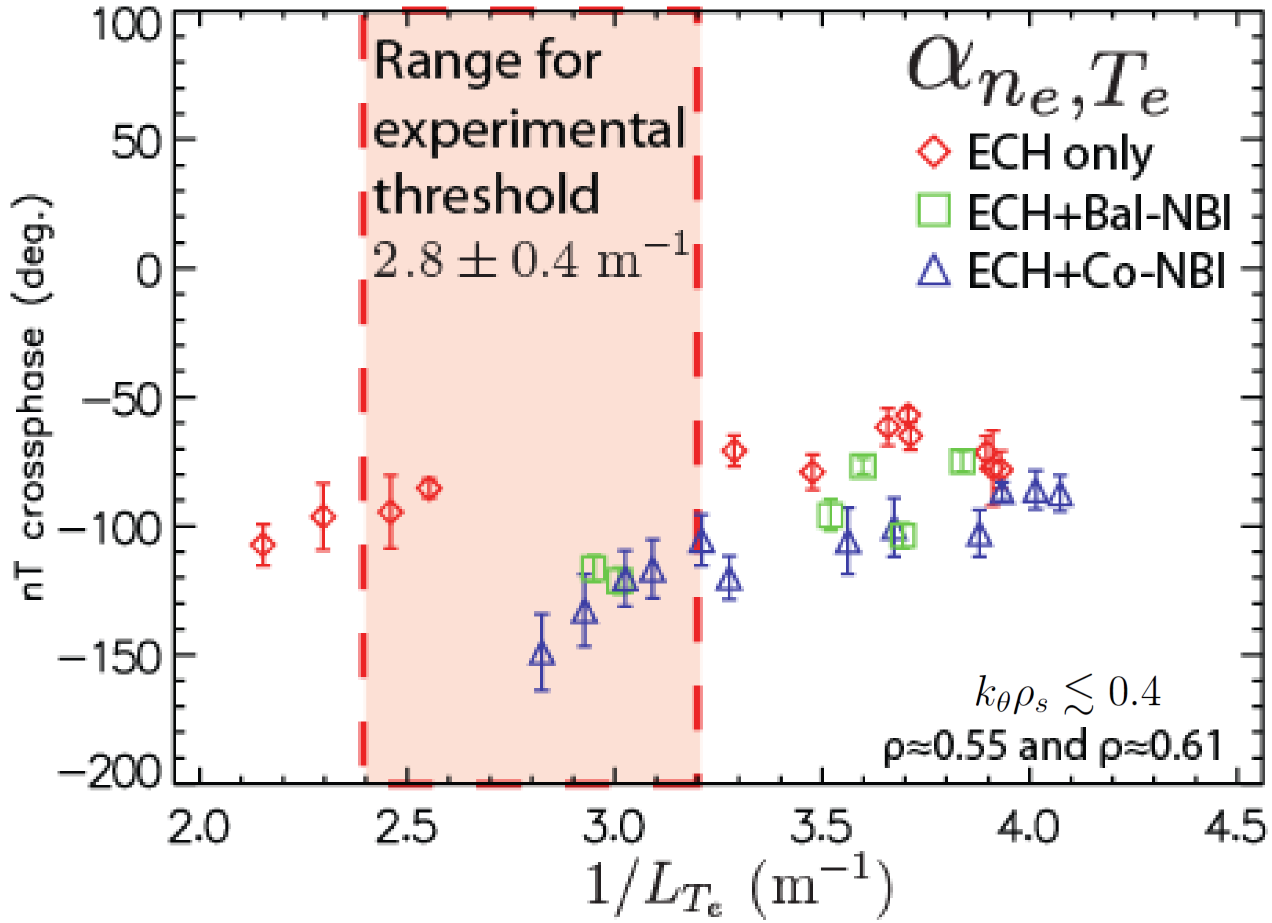
Predicted linear nT crossphase from TGLF consistent with interpretation of measurements in ECH+Co-NBI as transition from predominantly ITG to TEM



- **nT crossphase shows little trend with a/L_{Te} for each mode independently**
  - Interpretation: measured crossphase is weighted average

- **Crossphase measurements changed from $-149^o \pm 15^o$ to $-86^o \pm 7^o$; trend consistent with ITG below threshold in ECH+Co-NBI plasmas**

ECH-only plasmas exhibit different behavior, implying different instability below threshold



- **Measurement implies different instability behavior below threshold, current conjecture for ECH-only is ∇n_e-TEM**

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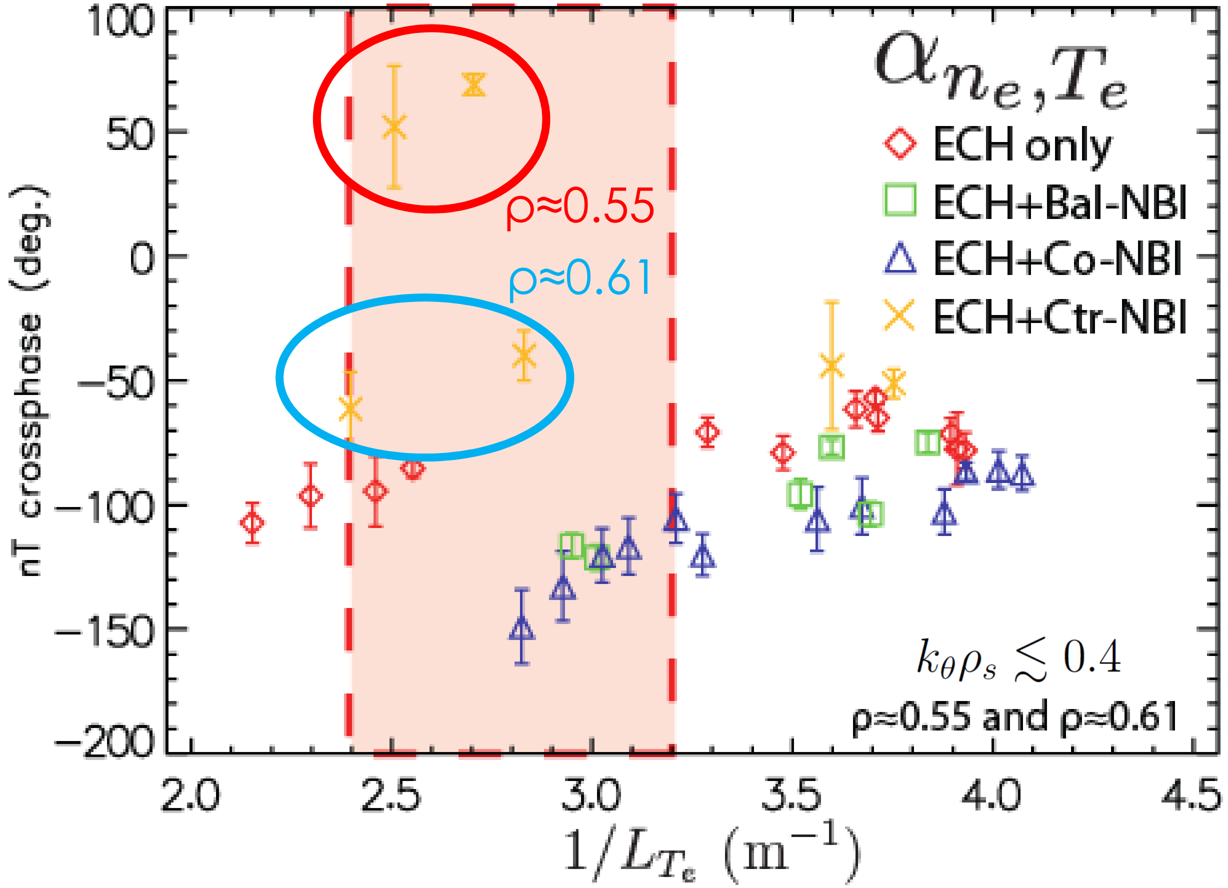
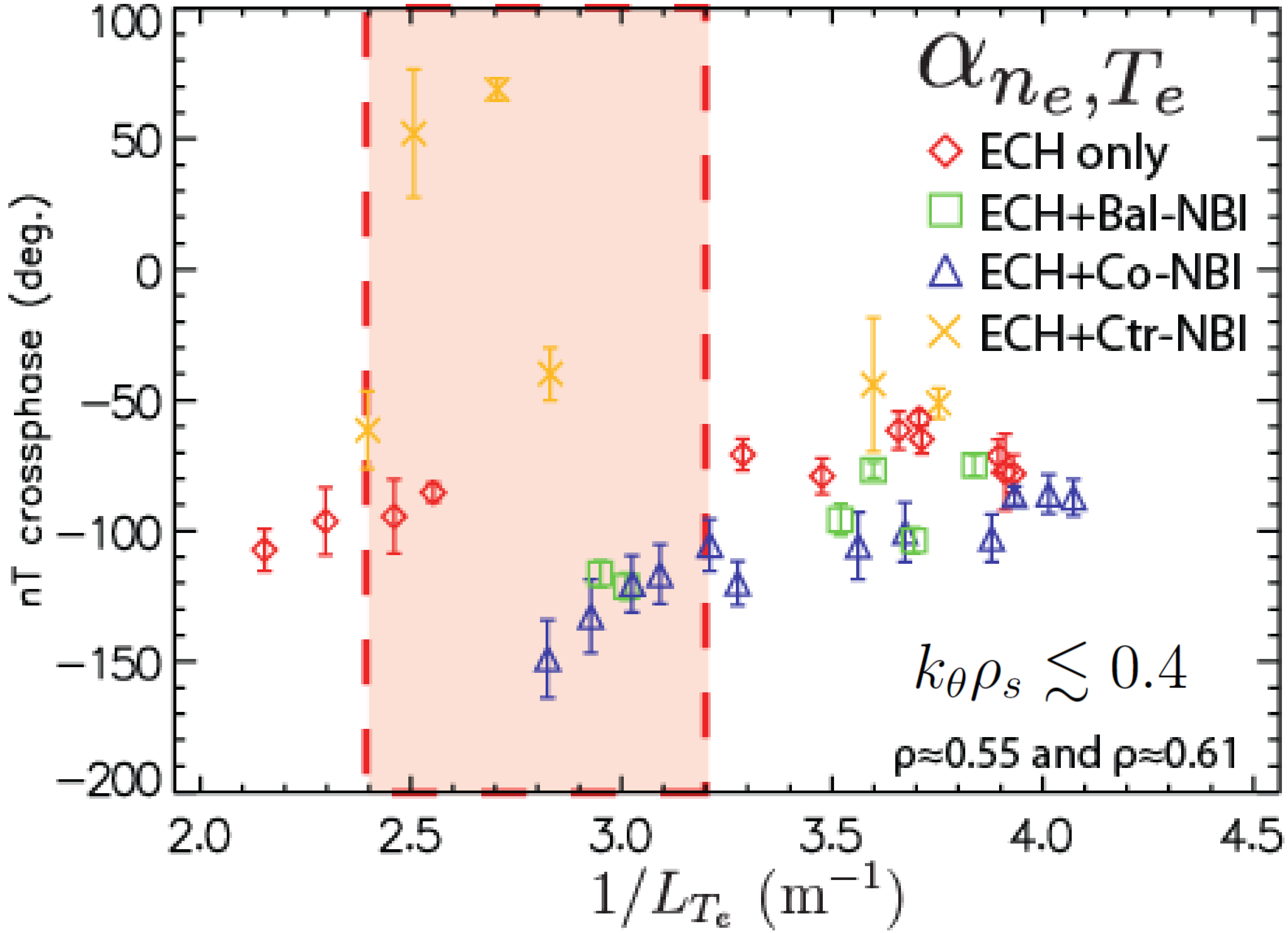
Different instability behavior also implied for ECH+Ctr-NBI by nT crossphase measurements



- **Significantly different behavior for ECH+Ctr-NBI at low $1/L_{Te}$**
  - Radial dependence: positive values both from inner location

All cases converge at high $1/L_{Te}$, implying common mode present in all four



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Accumulated evidence strongly constrains identification of ∇T_e -TEM

- First direct, systematic observation of a critical gradient in a locally measured fluctuating turbulent quantity in a tokamak
  - Critical gradient observed for both electron thermal transport and electron temperature fluctuations
- **Accumulated evidence identifies threshold with ∇T_e driven trapped electron mode turbulence**
  - $1/L_{Te}$ threshold
  - The ratio $(\delta T_e/T_e)/(\delta n_e/n_e)$ increases for low-k fluctuations
  - nT crossphase
    - Measurements imply common mode above threshold
    - Measured crossphase moves from ITG toward TEM in linear predictions
  - Spectral changes consistent with TEM

$\boldsymbol{\nabla T_e}$ -TEM

- Supported by linear & non-linear calculations
  - Linear gyrofluid calculations with TGLF
  - Nonlinear gyrokinetic simulations with GYRO

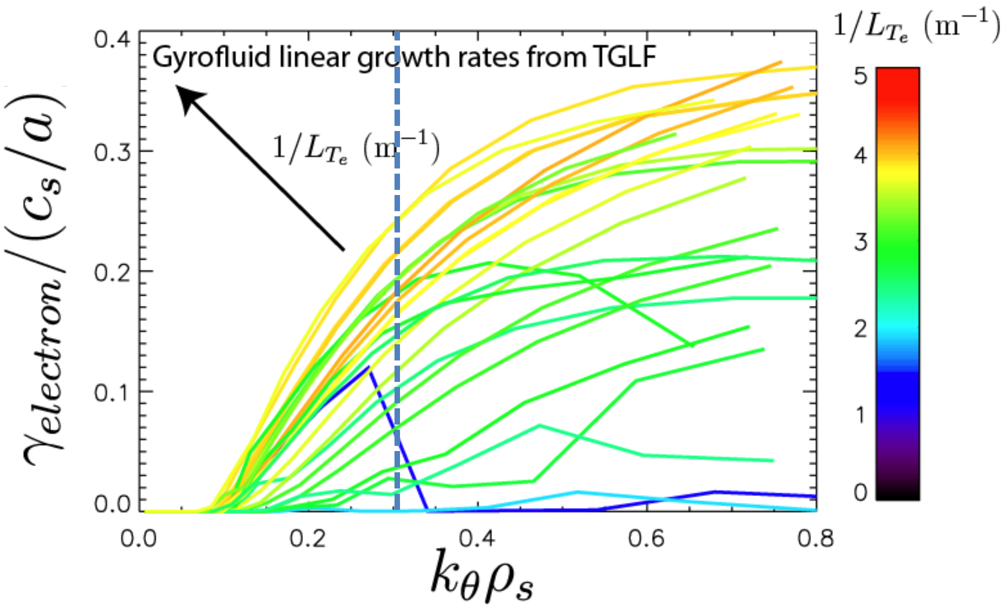
How to experimental results compare to linear and nonlinear predictions?

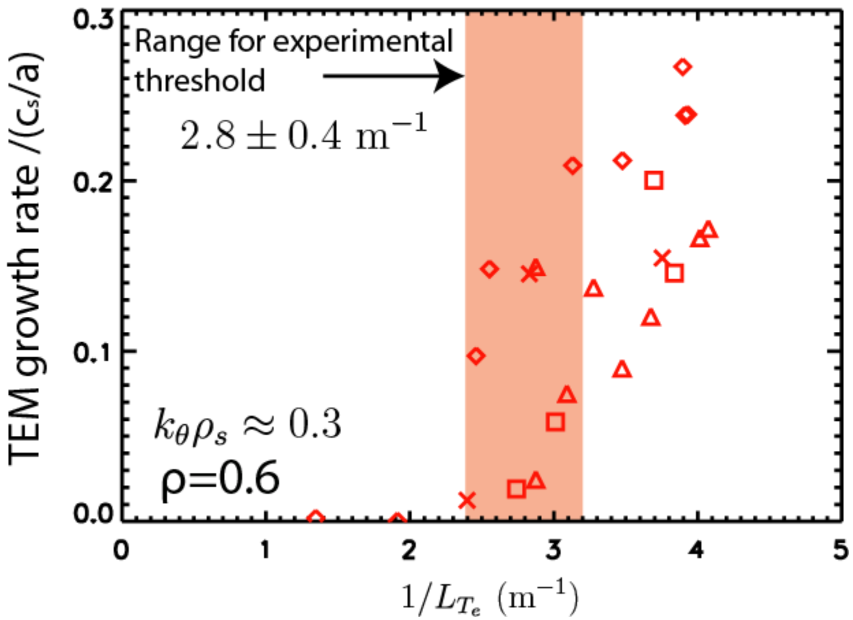
- **First direct, systematic observation of a critical gradient in a locally measured fluctuating turbulent quantity in a tokamak**
  - Critical gradient observed for both electron thermal transport and electron temperature fluctuations
- **Evidence identifies threshold with ∇T_e driven trapped electron mode turbulence**

∇T_e -TEM

  - $1/L_{Te}$ threshold
  - The ratio $(\delta T_e/T_e)/(\delta n_e/n_e)$ increases
  - nT crossphase
    - Common mode above threshold
    - Measured crossphase moves from ITG toward TEM in linear predictions
  - Spectral changes consistent with TEM
- **Supported by linear & non-linear calculations**
  - Linear gyrofluid calculations with TGLF
  - Nonlinear gyrokinetic simulations with GYRO

Growth rate spectrum of fastest growing linear modes propagating in electron diamagnetic direction generally increases with $1/L_{Te}$





Other measures $(\gamma(k), \langle\gamma\rangle, \gamma/k^2)$ similar

- **The Trapped-Gyro-Landau-Fluid (TGLF) code used for linear stability analysis**
  - Experimental profiles used as inputs
- **TEM growth rates consistent with experimental critical gradient**

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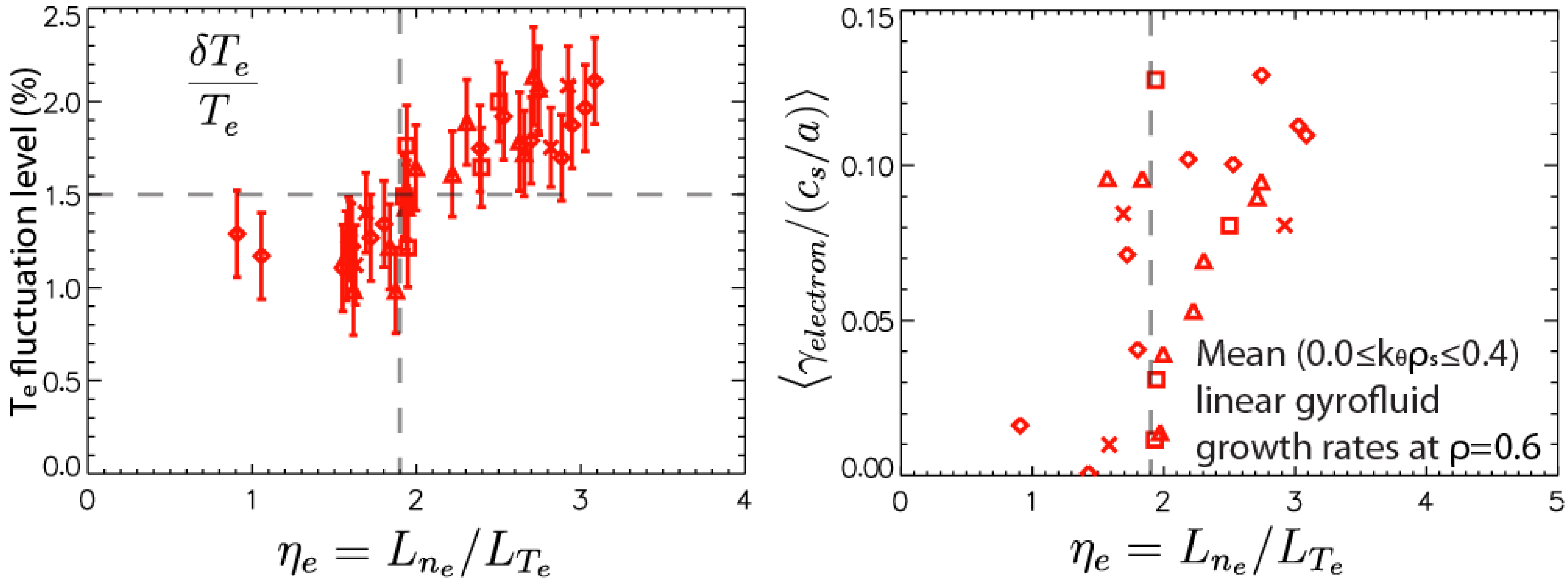
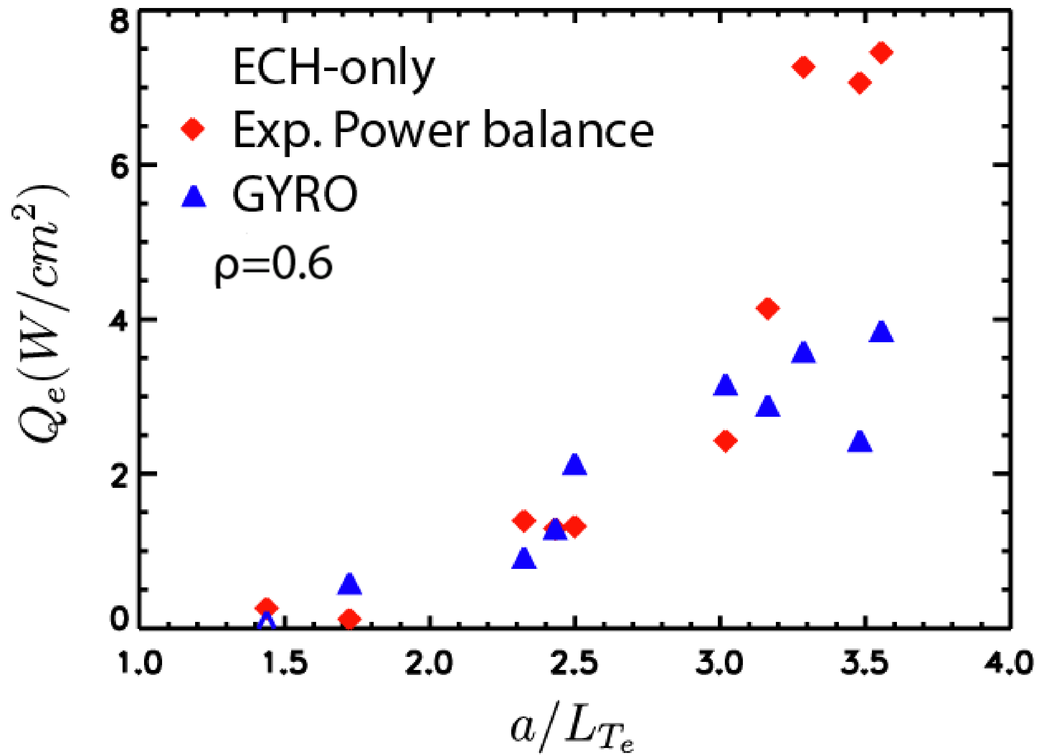
Density gradient affects linear stability calculations, instability above $\eta_e = L_{ne}/L_{Te} \sim 2$



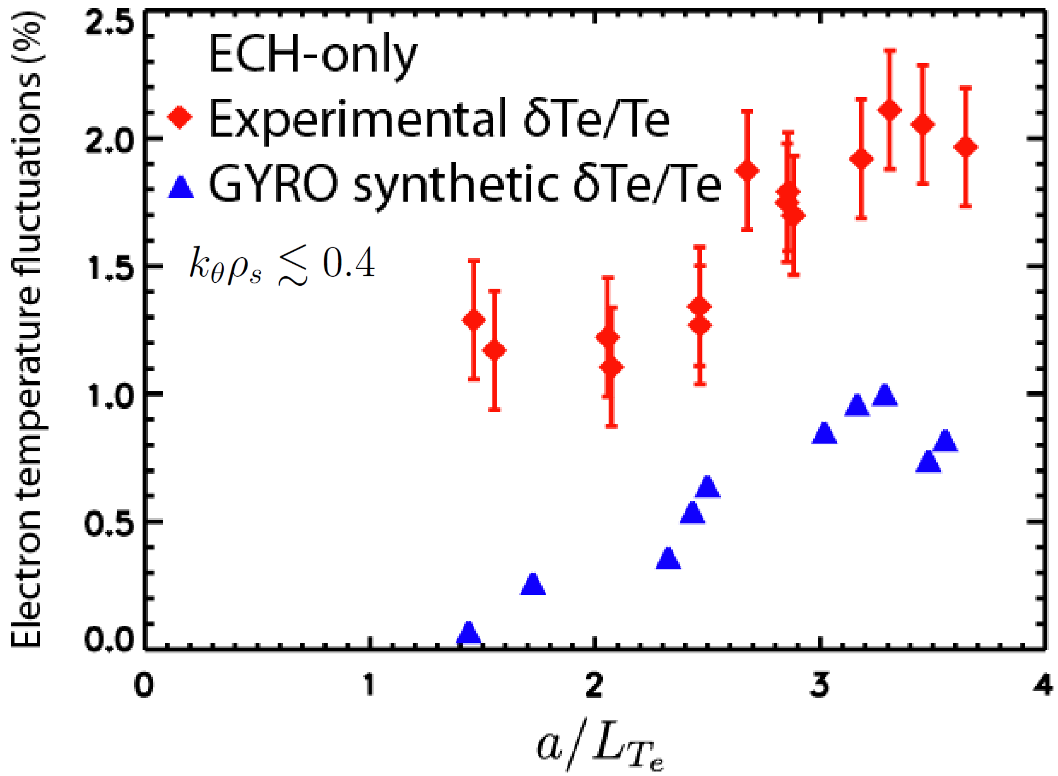
- **No large non-linear upshift of threshold ("Dimits shift") observed**
  - If an upshift exists, it's impact is smaller than the ~10% variations in other parameters that lead to scatter in the growth rate calculations
  - Consistent with simulations of with ∇T_e-TEM showing weak impact of zonal flows (Dannert PoP 2005, Ernst PoP 2009); opposite seen in simulations for ∇n_e-TEM (Ernst PoP 2004), ITG (Dimits PoP 2000), see also following talk

Nonlinear GYRO prediction for Q_e close to experimental values in ECH-only plasmas at low a/L_{Te}, but a shortfall exists at high a/L_{Te}



- **Global nonlinear gyrokinetic simulations with GYRO**
  - Electrostatic, with 3 kinetic species (electrons, deuterium, and carbon)
  - Wavenumbers up to $k_\theta \rho_s$ ~1.3 included; box widths ~100 ρ_s
- **Ion heat flux systematically under-predicted**

GYRO under-predicts δTe/Te, but shows similar trend with a/L_{Te}

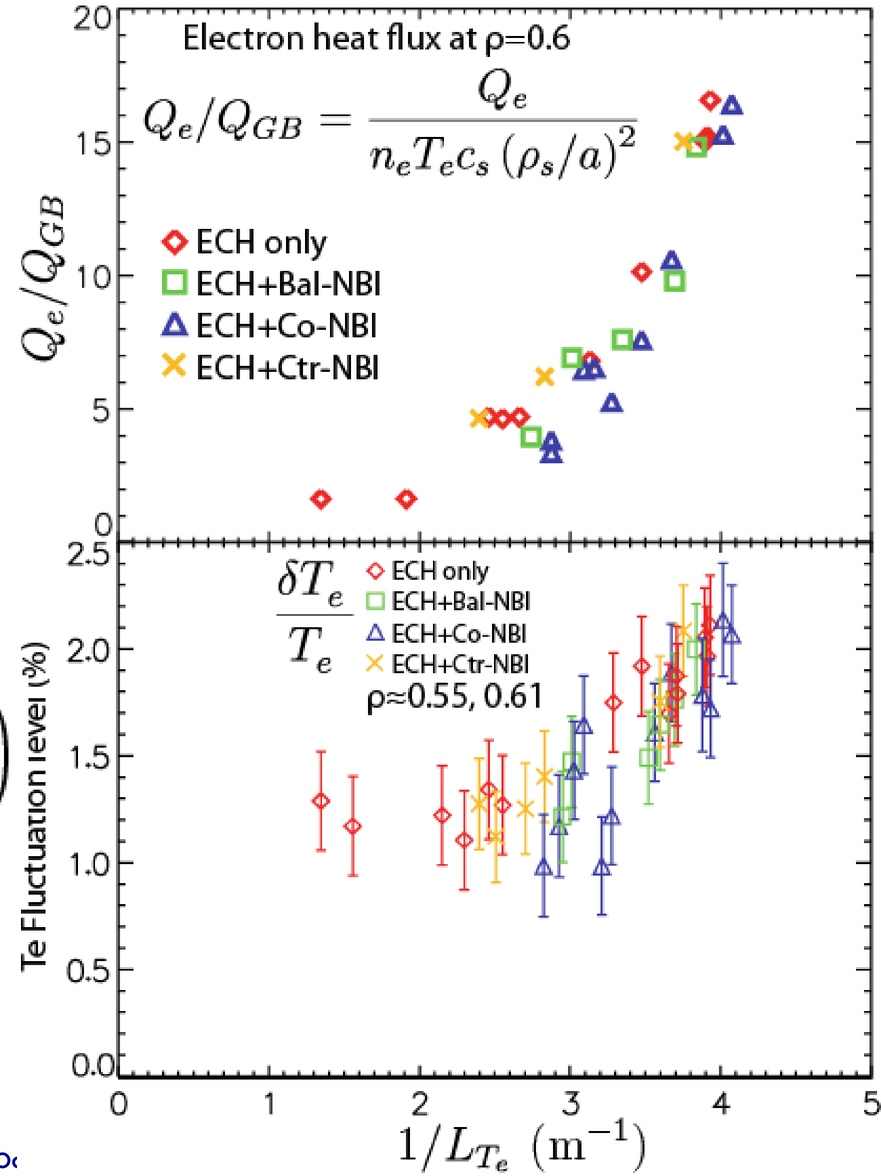


- Synthetic CECE diagnostic used on GYRO output (Holland PoP 2009)
- Even though Q_e is matched reasonably well at low a/L_{Te}, electron temperature fluctuations are under-predicted
- See S.P. Smith TP8.00004 Thursday for more GYRO, TGLF, and TGYRO results

Principle result

- Critical gradient observed for both electron thermal transport and electron temperature fluctuations

$$\tilde{Q}_e = \frac{3 n_e T_e}{2B} k_\theta \left(\frac{|\tilde{n}_e|}{n_e} |\tilde{\varphi}| \gamma_{n_e,\varphi} \sin \alpha_{n_e,\varphi} + \frac{|\tilde{T}_e|}{T_e} |\tilde{\varphi}| \gamma_{T_e,\varphi} \sin \alpha_{T_e,\varphi} \right)$$



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Summary of results

- **Observed effect of critical gradient threshold in multiple parameters**
  - $\delta Te/Te$, heat pulse analysis of χ_e, experimental power balance Q_e, local stiffness, linear growth rates
- **∇T_e-TEM identified as instability responsible for threshold**
  - $1/L_{Te}$ threshold, $(\delta T_e/T_e)/(\delta n_e/n_e)$, nT crossphase, spectral changes
- **Characteristics of ∇T_e-TEM:**
  - Low-k (ITG-scale) if driven strongly (***not*** strictly intermediate-k)
  - At low-k, $\delta T_e/T_e$ steadily increases above threshold, $\delta n_e/n_e$ does not
  - No significant non-linear upshift observed
- **Nonlinear GYRO predictions reproduce trends in Q_e and $\delta Te/Te$**
  - Q_e in reasonable agreement at low $1/L_{Te}$, shortfall at high $1/L_{Te}$
  - $\delta Te/Te$ under-predicted for all $1/L_{Te}$
  - Further synthetic diagnostic comparisons ongoing