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

Presented by

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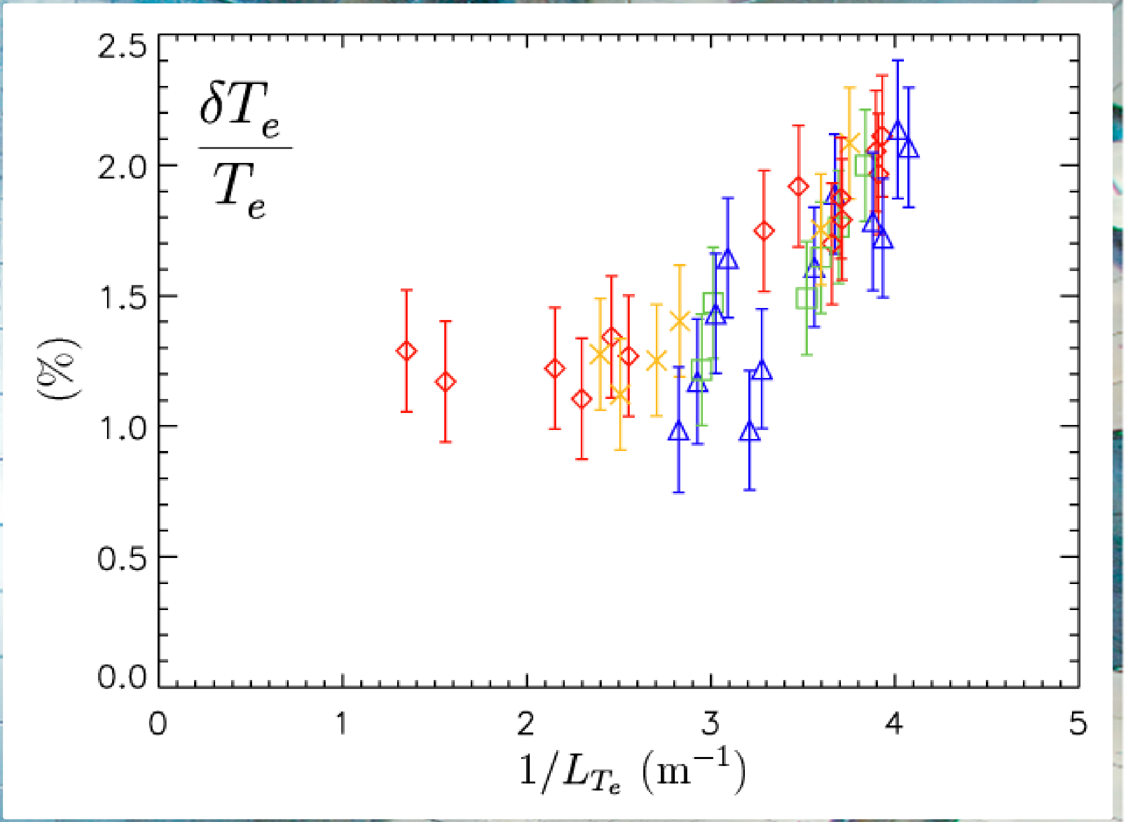


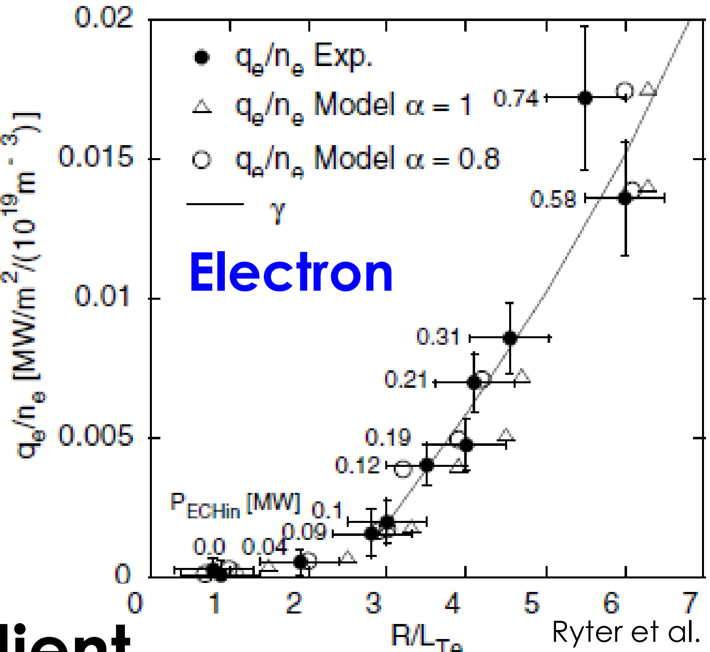
Presented at
NSTX Monday Physics Meeting
Princeton, NJ, USA

April 16, 2012

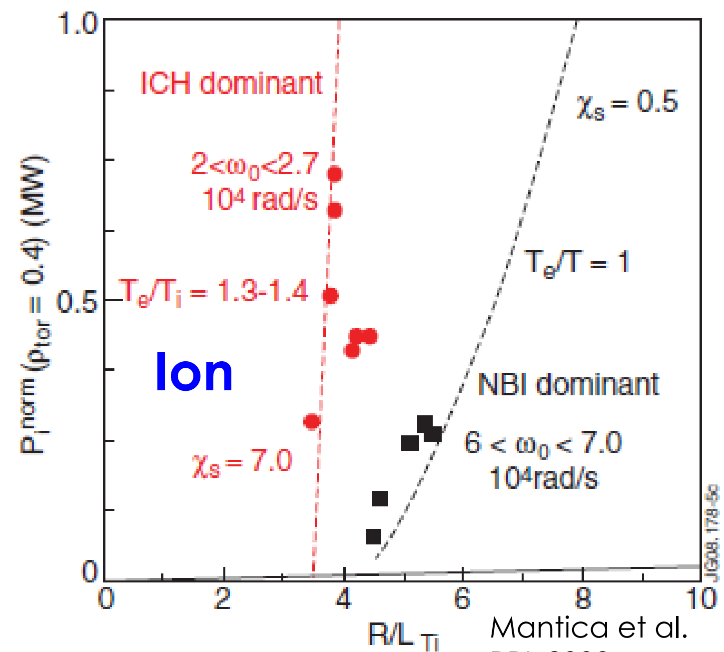
Stiff heat transport has been previously observed for both ions and electrons

- **Stiff heat transport results in little change to equilibrium with more heating, strong electron heating from alphas in burning plasmas**
- **Previous studies lacked fluctuation measurements—What is causing the increased transport and stiffness?**

Heat flux



Ryter et al. PRL 2005



Mantica et al. PRL 2009

Gradient

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

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Summary of results

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

- **Critical gradient observed in both electron thermal transport and electron temperature fluctuations**
  - First direct, systematic observation of a critical gradient in a locally measured fluctuating turbulent quantity in a tokamak
  - Previous experimental work (e.g. Ryter PRL 2005, Mantica PRL 2009) restricted to transport analysis; many examples of monotonic relationships or transient observations

γ

- **Gyrofluid growth rates consistent with critical threshold**
- **nT Crossphase also changes**

α_{n_e,T_e}

  - Crossphase in Bal- and Co-NBI cases consistent with previous work
  - Crossphase in ECH only and Ctr-NBI differ

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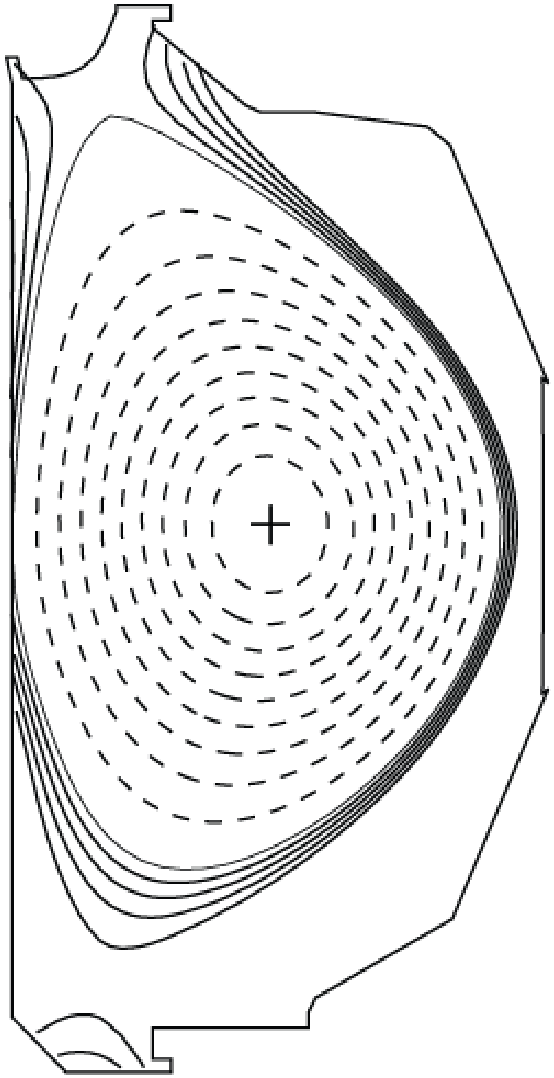
L-mode target discharge

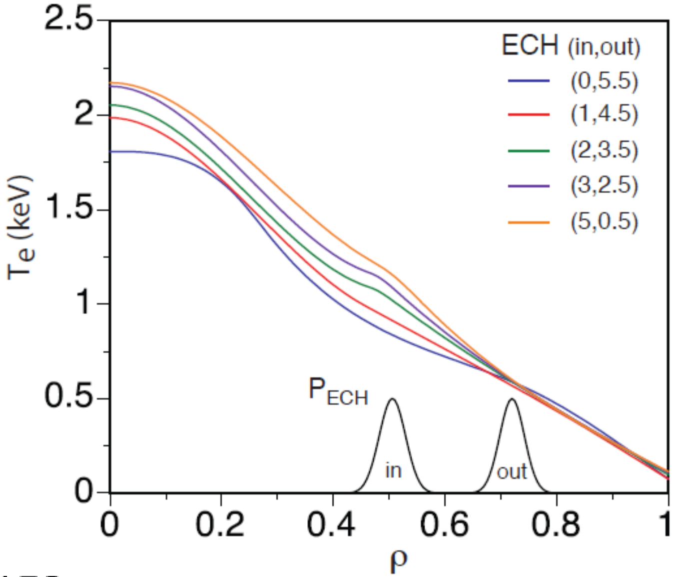
- **Upper single null, diverted**
  - I_p=0.8 MA
  - B_T=-2 T
  - $\langle n_e \rangle \sim 2x10^{13}$ cm^{-3}
- **ECH only and NBI+ECH shots**
  - Rotation scan at fixed power
  - P_{ECH} ~ 3 MW
  - P_{NBI} ~ 2 MW
- **Turbulence measurements:**
  - T_e fluctuations , 2 radii per shot (CECE)
  - nT crossphase (CECE + reflectometry)
  - Density fluctuations (BES, DBS)

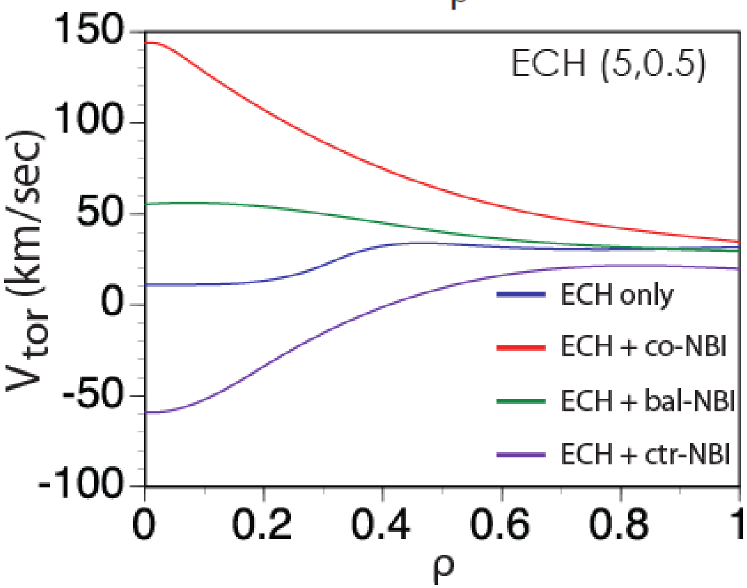


Local electron temperature gradient and rotation systematically varied in repeated L-mode discharges

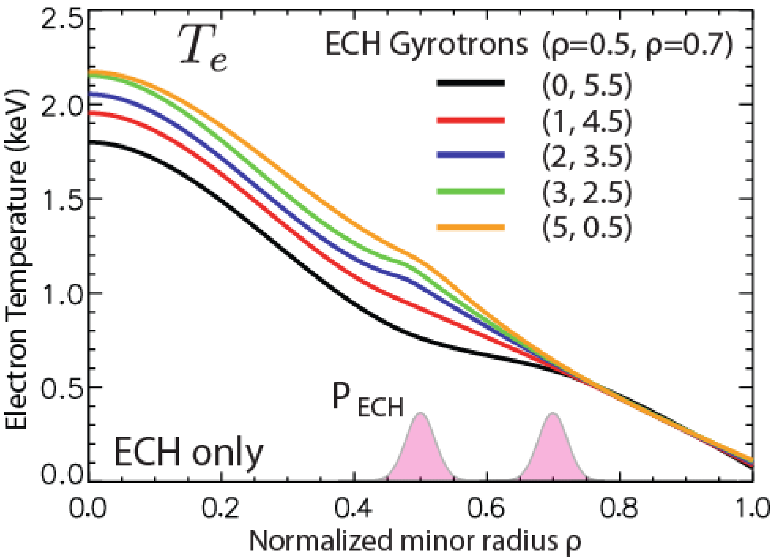
- **ECH deposition locations modified shot-to-shot to locally scan ∇T_e at rho=0.6**
- **Rotation varied by changing NBI mix at fixed power, ExB flow shear small in all cases**
- **Fluctuation measurements acquired during ~500-800 ms steady-state periods**

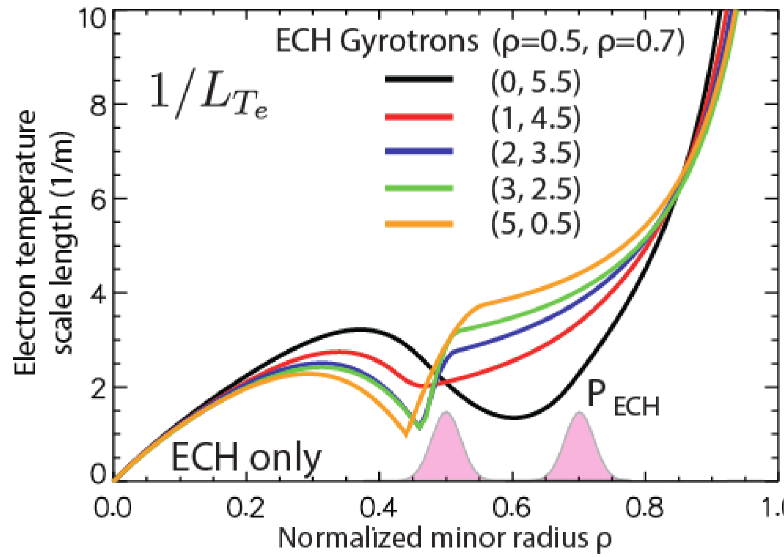
- **Other profiles:**
  - For ECH only T_i lower everywhere, T_e lower in core (rho<0.5)
  - Density well-matched
  - Z_{eff} higher with Ctr-NBI



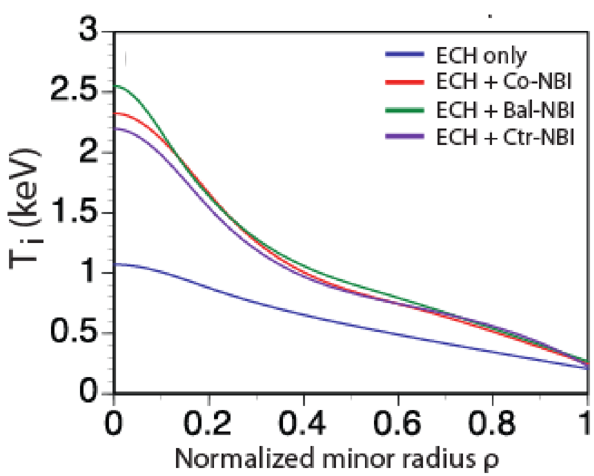


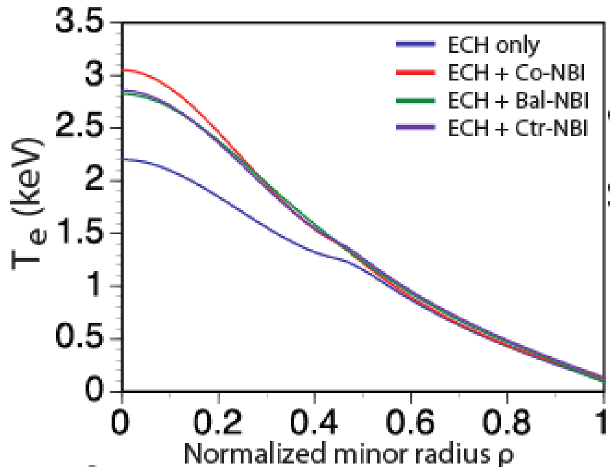
$1/L_{Te}$ systematically scanned, most other profiles well-matched

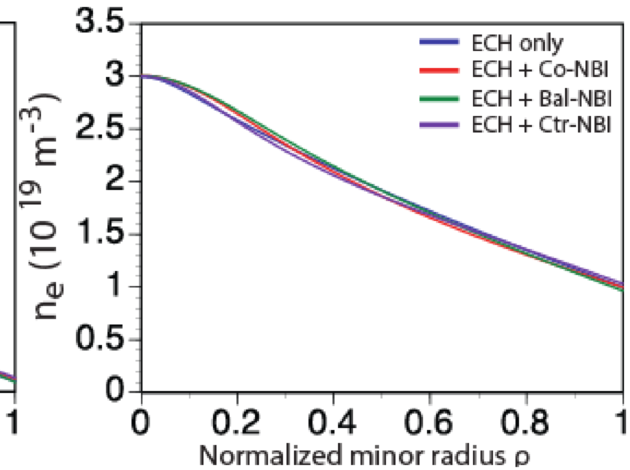




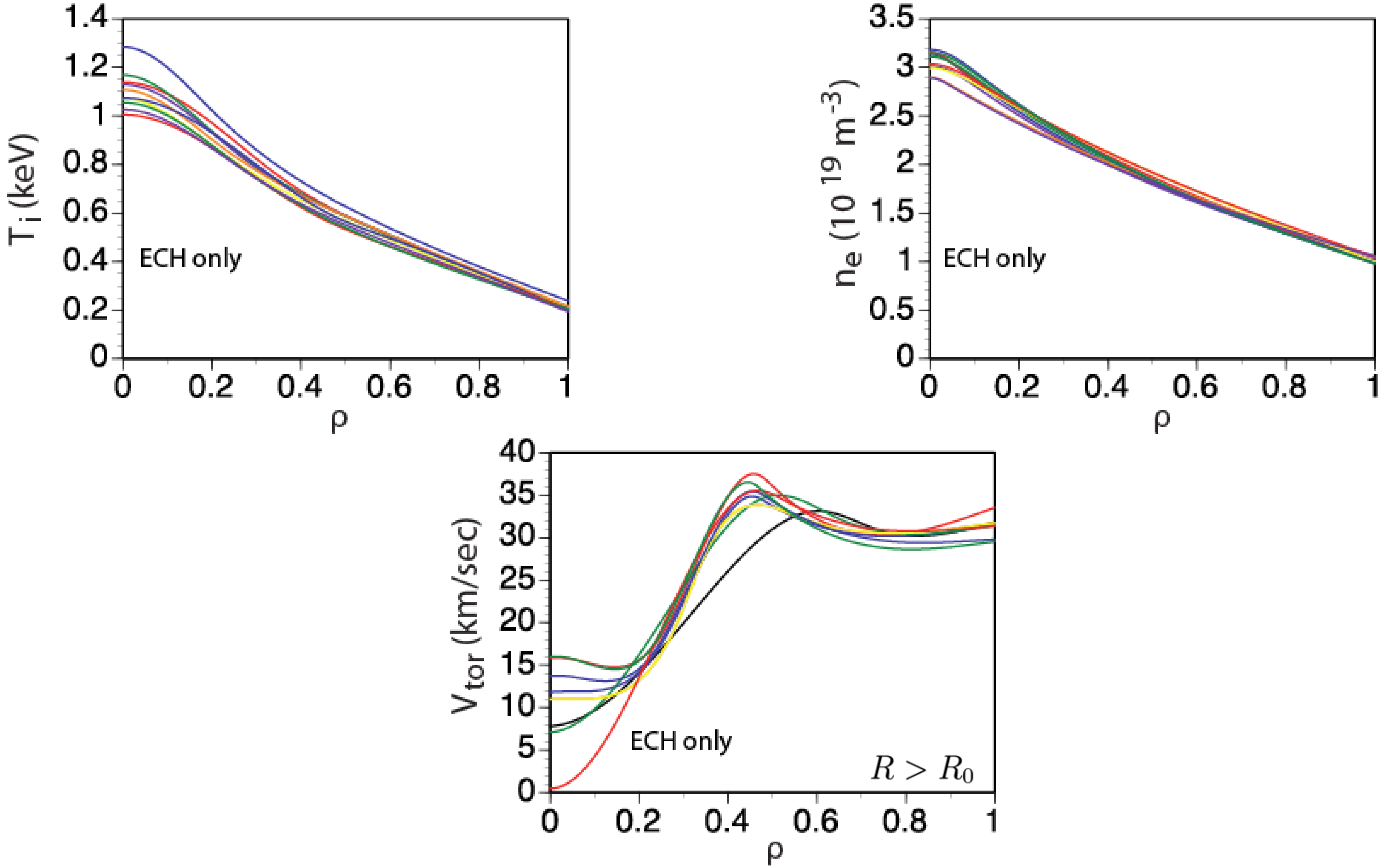
$R_0 \approx 1.7$ m
$a \approx 0.6$ m







Other profiles showed no systematic variations with ECH deposition scans for each NBI case



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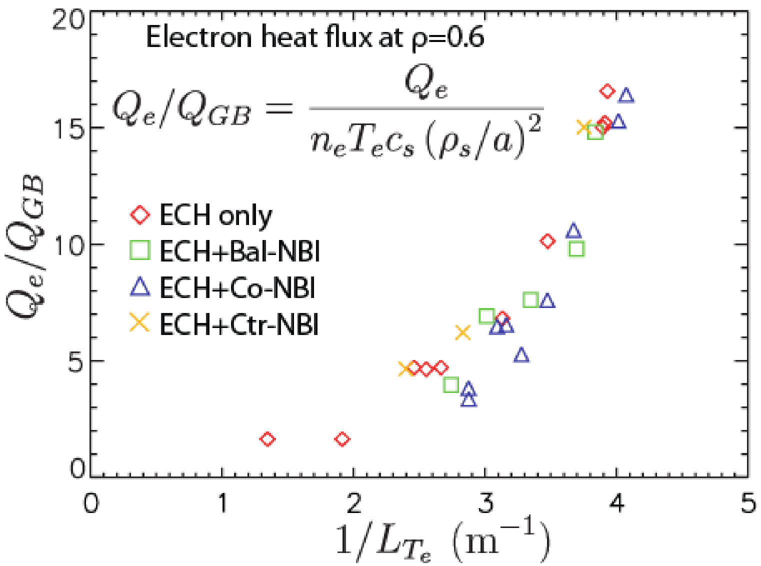
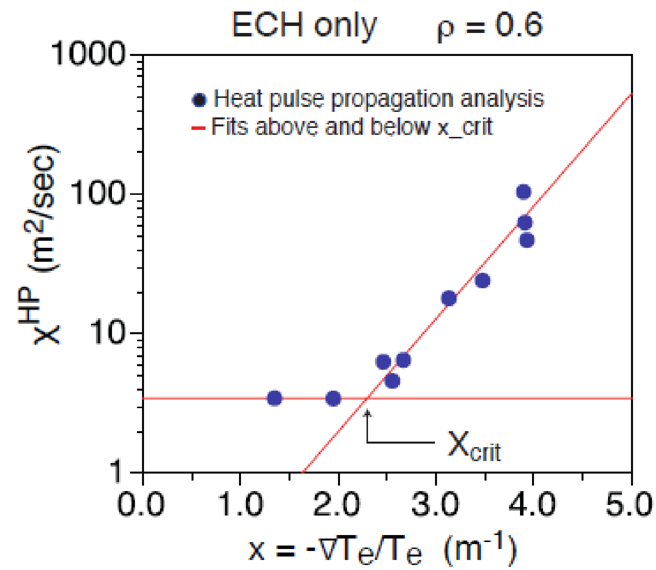
Transport analysis shows increase in stiffness with $1/L_{Te}$, limited rotation dependence

- **Electron heat flux similar to results from Ryter et al. PRL 2005, but shows little rotation dependence**

- **Transient heat pulse analysis shows critical gradient behavior in $1/L_{Te}$ dependence of electron thermal transport**

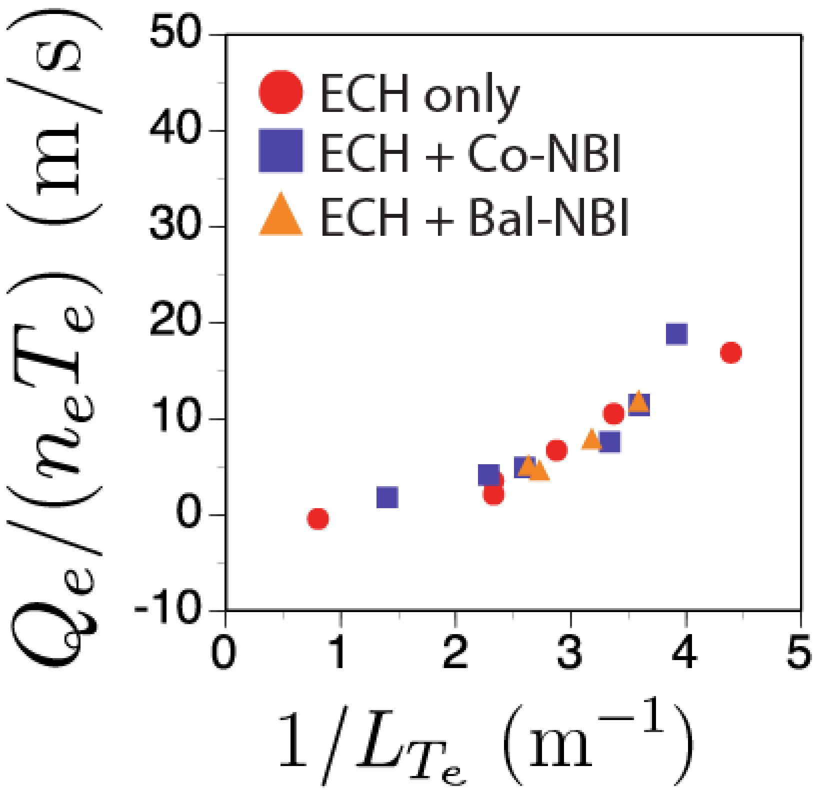
- **Further transport and stiffness analysis reported in DeBoo et al., "Electron Profiles Stiffness and Critical Gradient Studies," submitted to Phys. Plasmas**



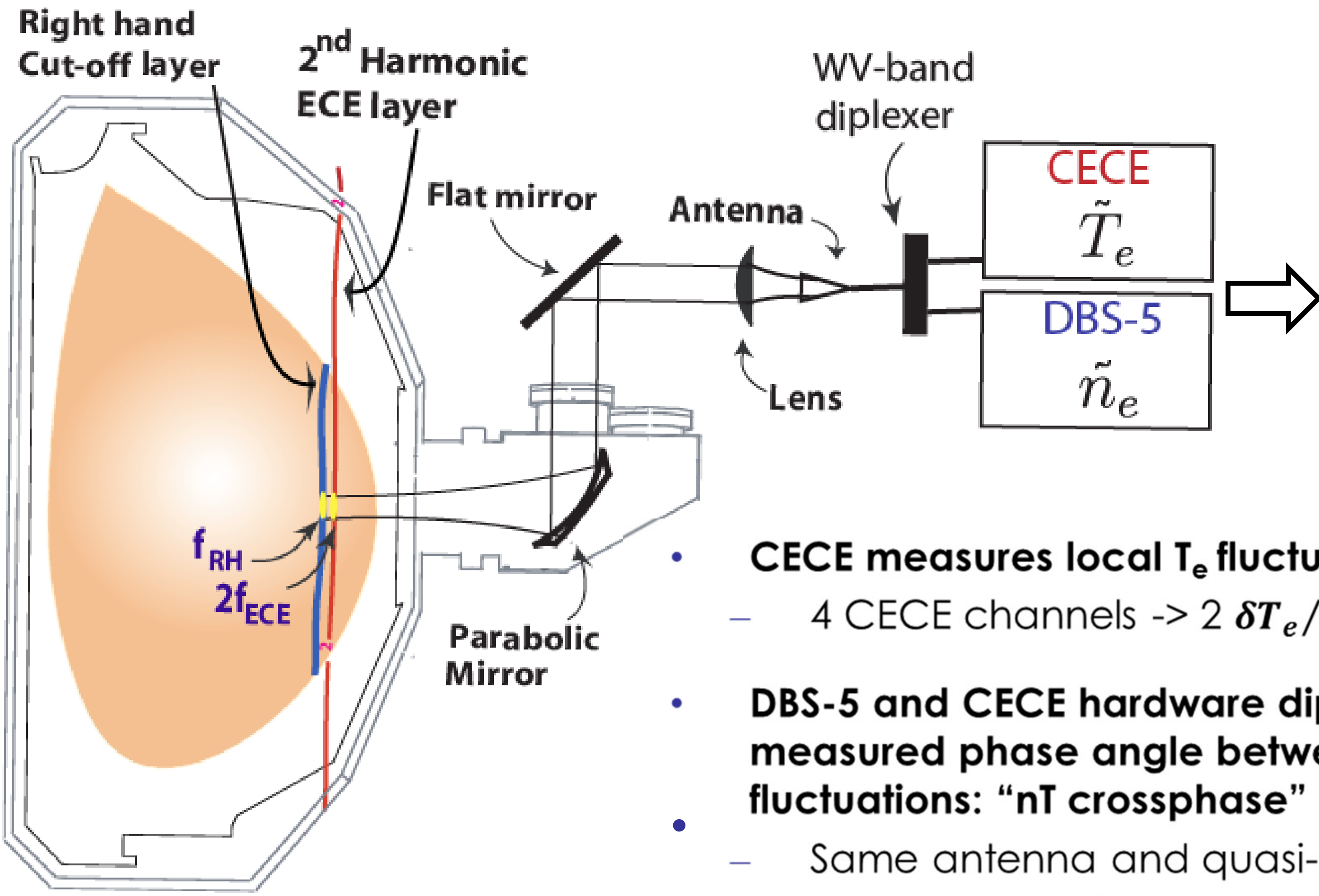


ECH variation experiment also performed at rho=0.4

- Electron heat transport less stiff at rho=0.4
- No critical gradient observed
- No CECE measurements for rho=0.4 experiment



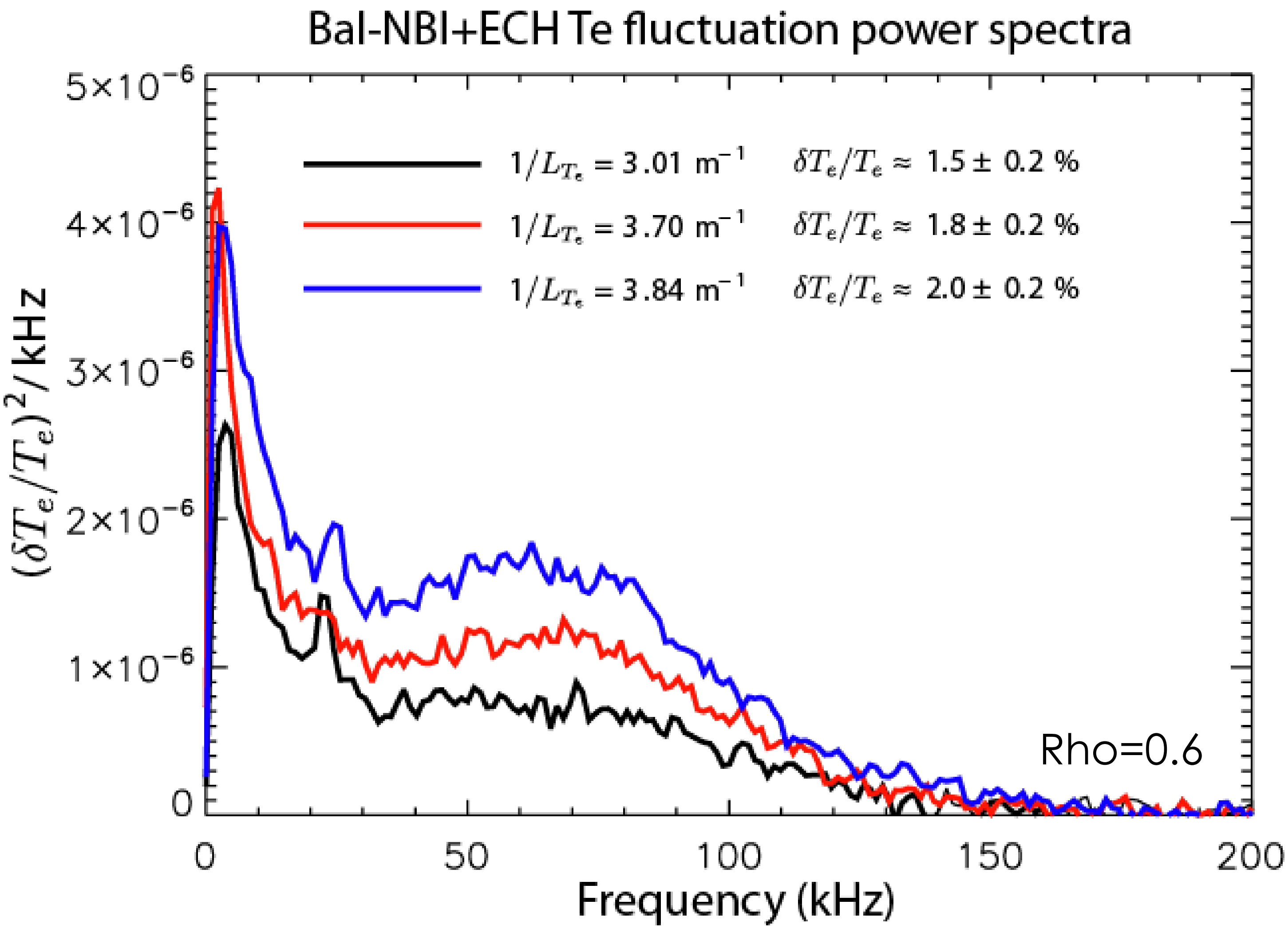
CECE measures T_e fluctuation levels
Reflectometer/CECE provide nT crossphase data



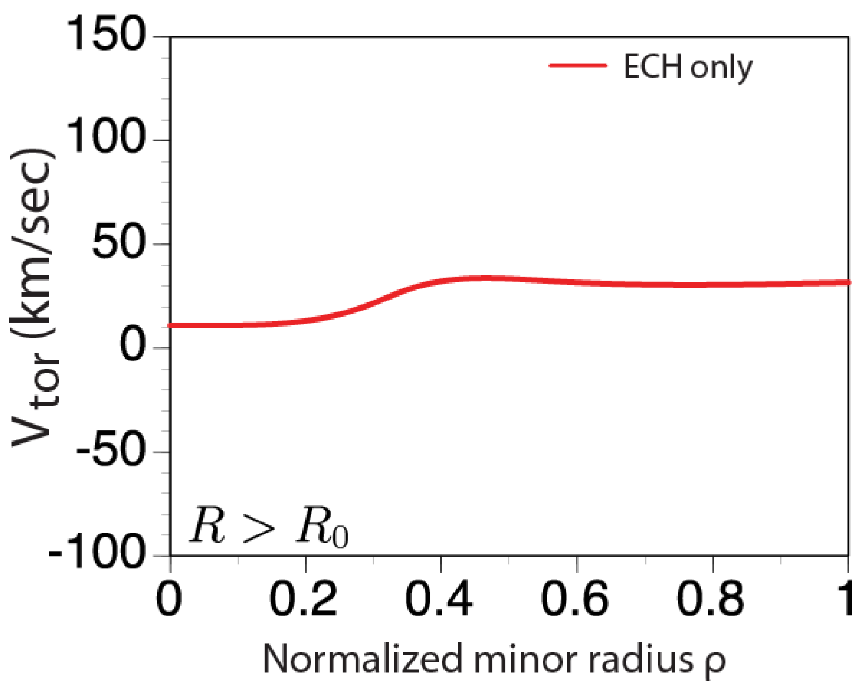
Crossphase between electron temperature and density fluctuations

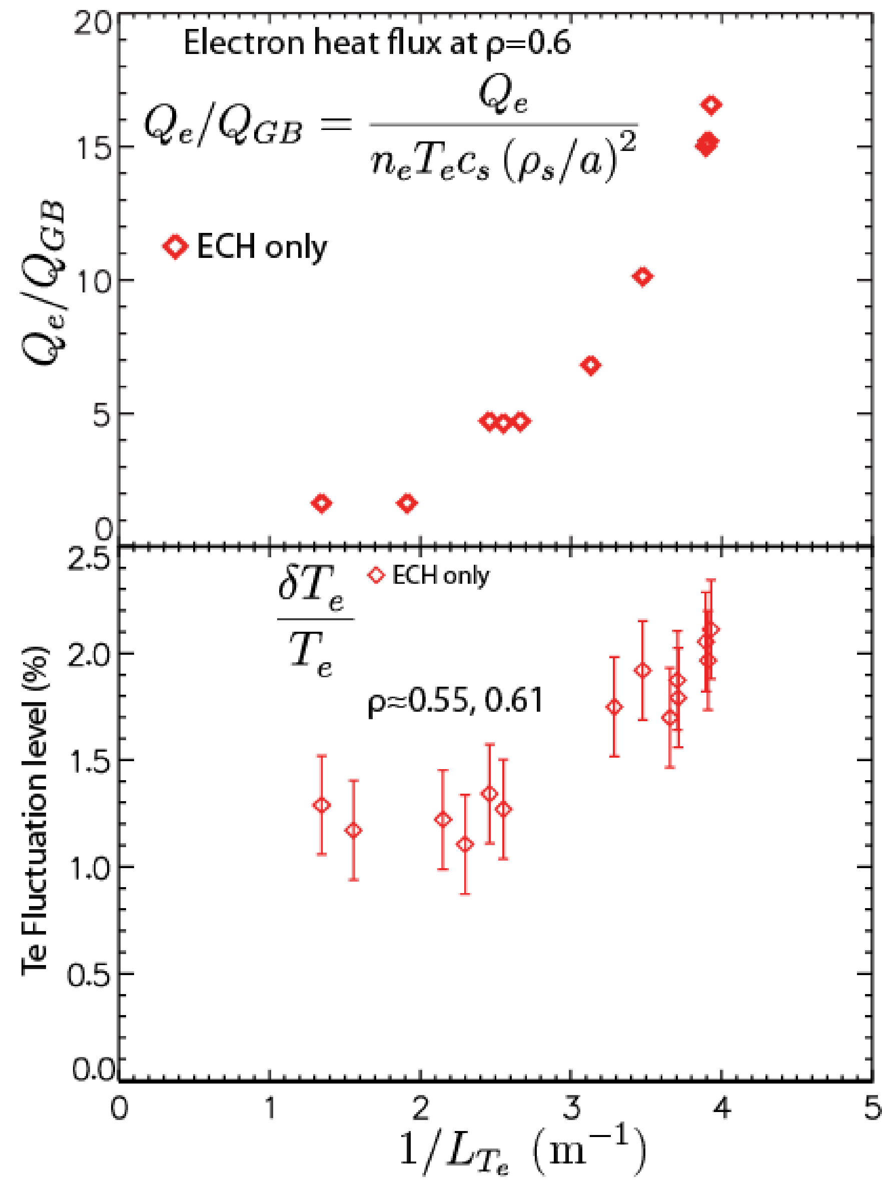
- **CECE measures local T_e fluctuations**
  - 4 CECE channels -> 2 $\delta T_e/T_e$ locations per shot
- **DBS-5 and CECE hardware diplexed together measured phase angle between n_e and T_e fluctuations: "nT crossphase"**
-
  - Same antenna and quasi-optical components
  - DBS-5 aligned for reflectometry
  - Both diagnostics sensitive to low-k ($k_\perp \rho_i < 0.5$)
  - Tuned to look at same plasma volume

Temperature fluctuations increase with $1/L_{Te}$



ECH-only has cases well below critical gradient





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

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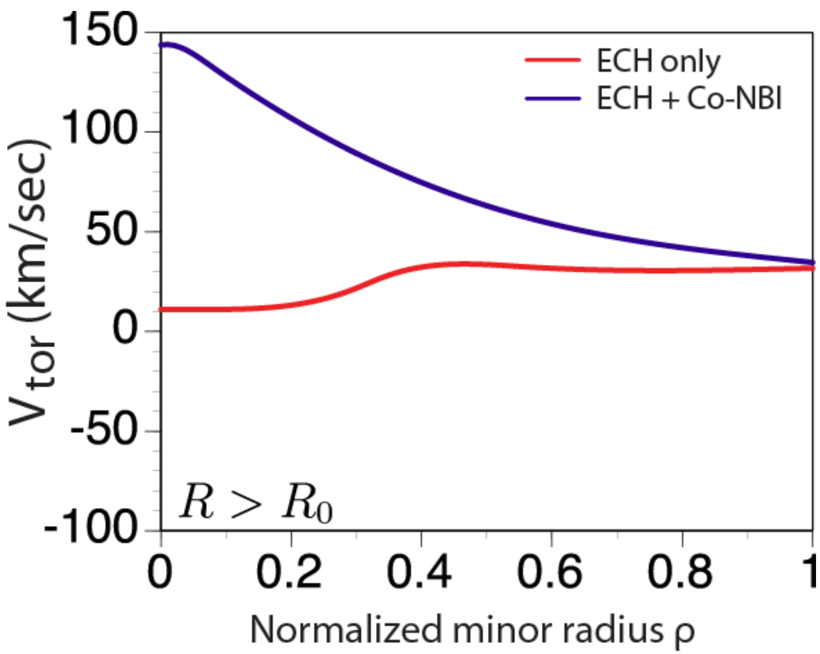
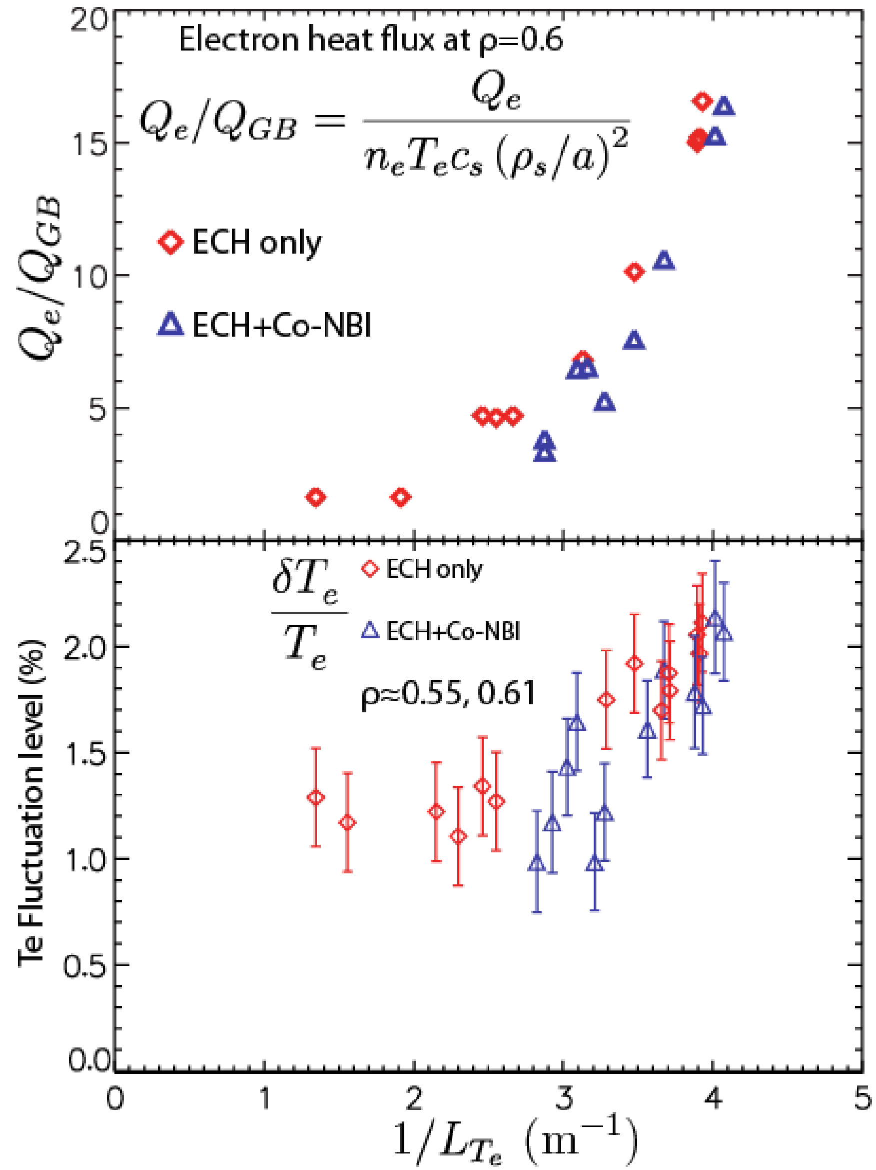
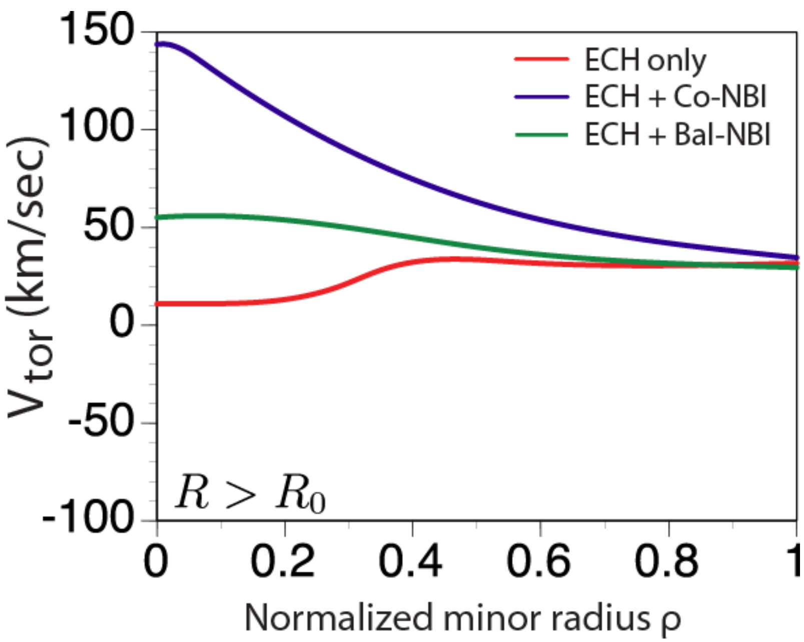
ECH+Co-NBI shows same trends with $1/L_{Te}$

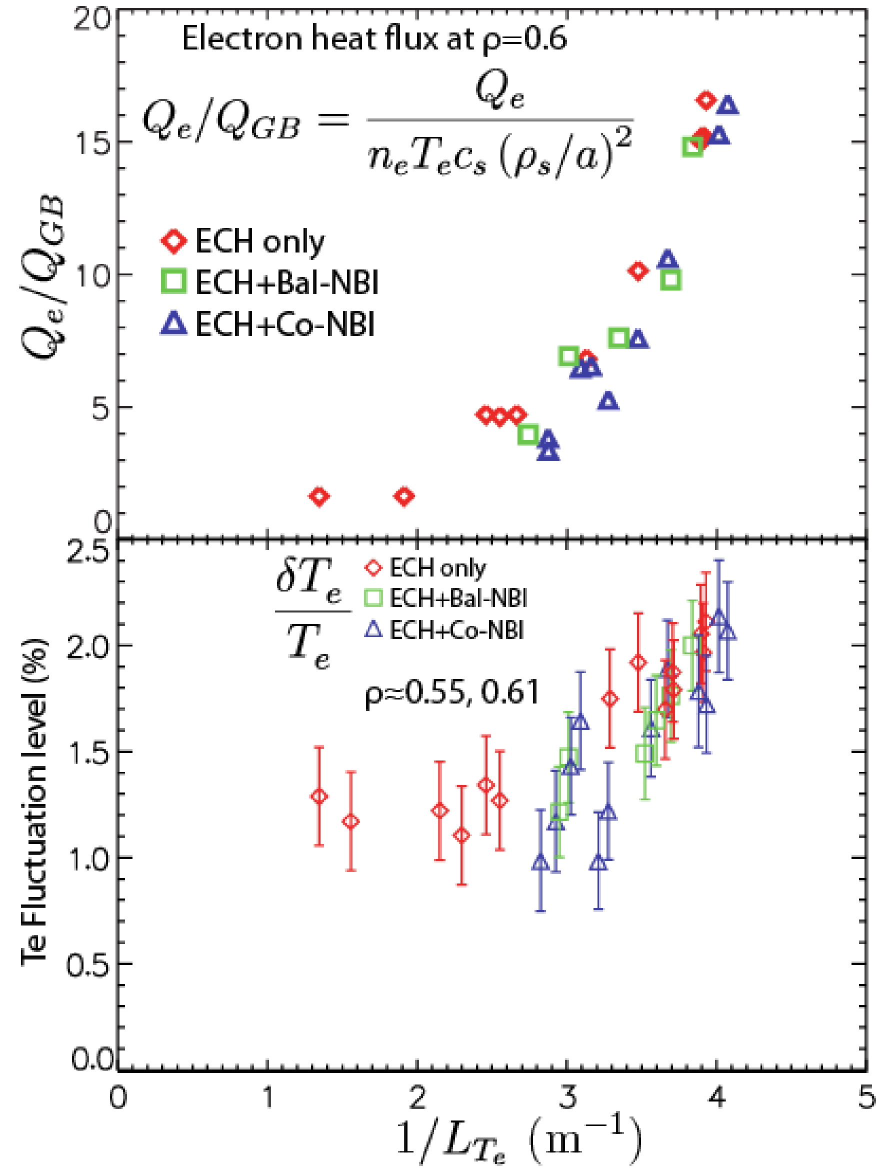




$$\tilde{Q}_e = \frac{3n_eT_e}{2B}k_\theta \left(\frac{|\tilde{n}_e|}{n_e}|\tilde{\varphi}|\gamma_{n_e,\varphi}\sin\alpha_{n_e,\varphi} + \frac{|\tilde{T}_e|}{T_e}|\tilde{\varphi}|\gamma_{T_e,\varphi}\sin\alpha_{T_e,\varphi} \right)$$

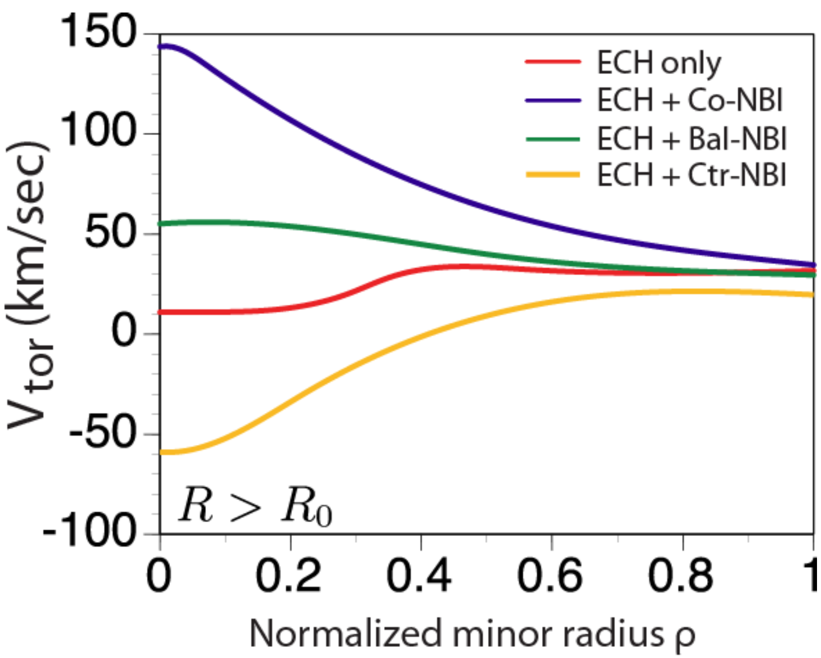
ECH+Bal-NBI shows same trends

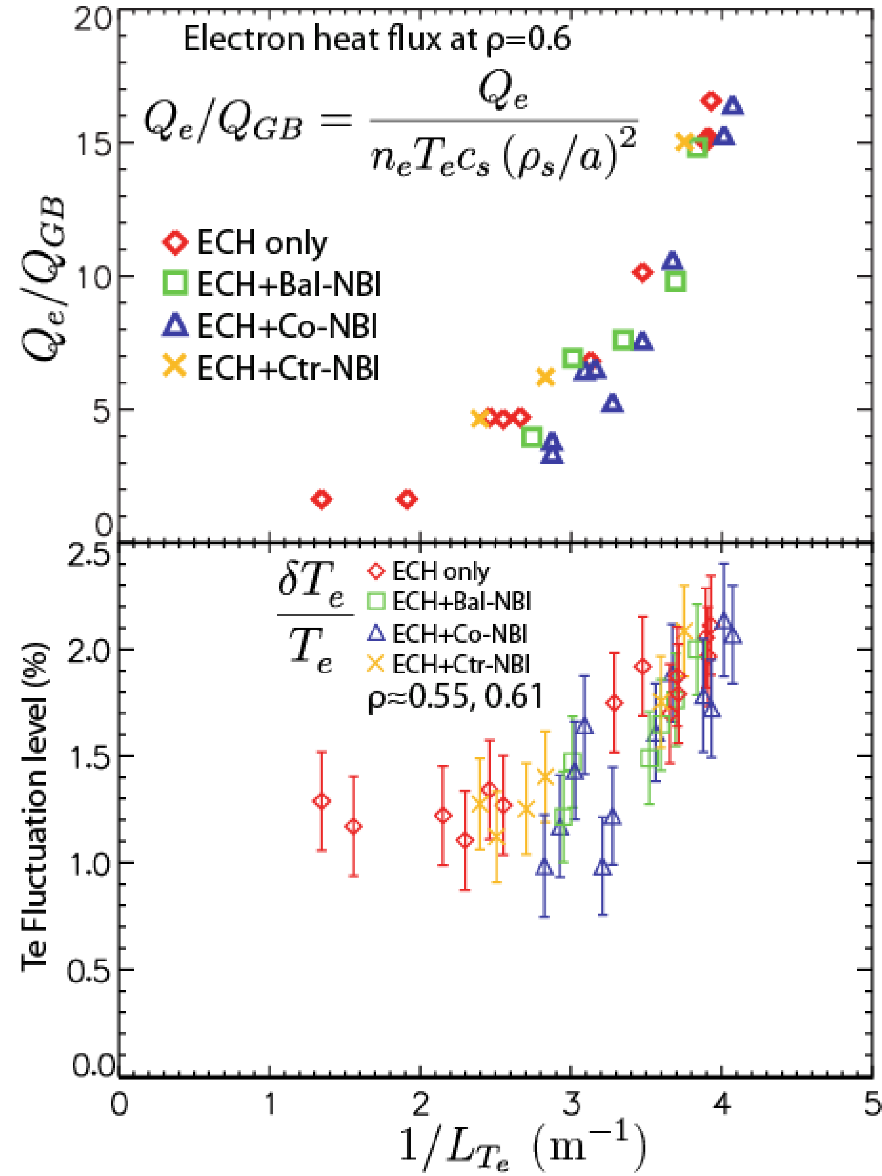




$$\tilde{Q}_e = \frac{3 n_e T_e}{2B} k_\theta \left(\frac{|\tilde{n_e}|}{n_e} |\tilde{\varphi}| \gamma_{n_e,\varphi} \sin \alpha_{n_e,\varphi} + \frac{|\tilde{T_e}|}{T_e} |\tilde{\varphi}| \gamma_{T_e,\varphi} \sin \alpha_{T_e,\varphi} \right)$$

ECH+Ctr-NBI shows same trends, also exhibits points below critical gradient for T_e 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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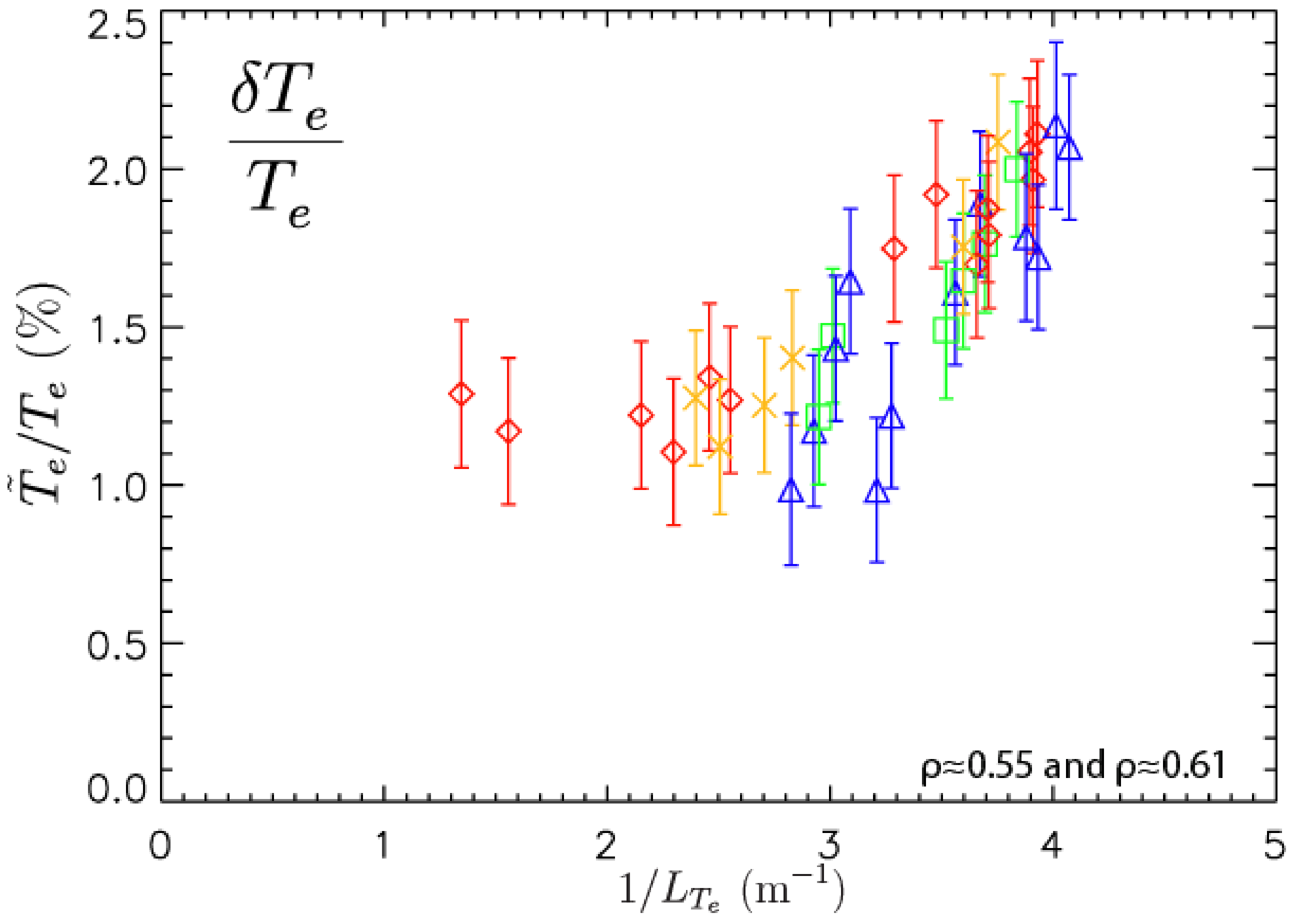
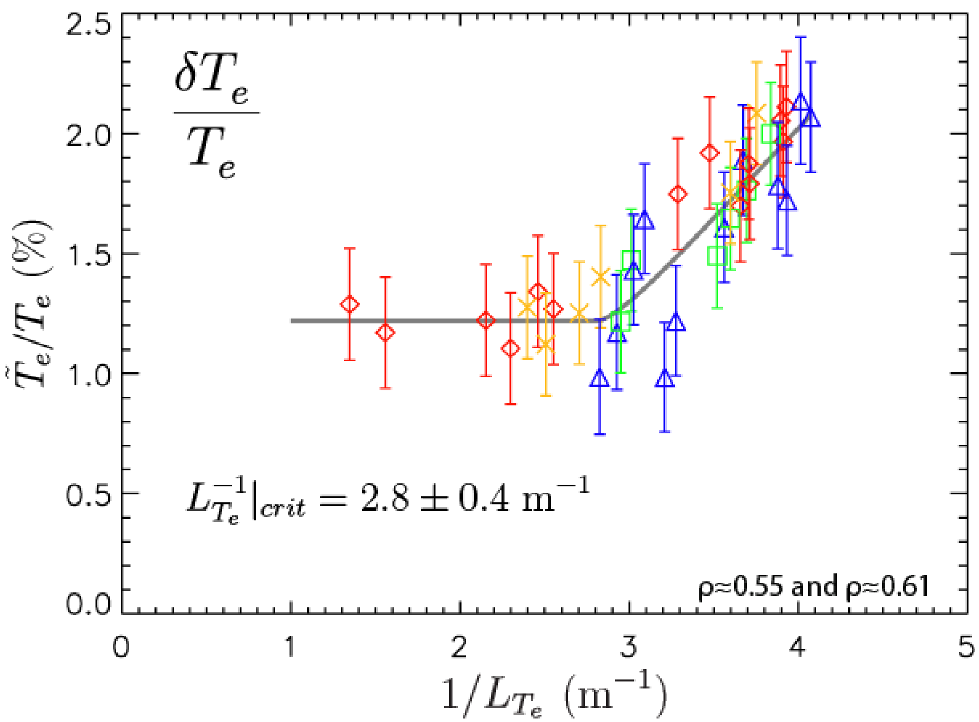
Temperature fluctuations show critical gradient threshold in $1/L_{Te}$, limited rotation dependence



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

Fit to model finds critical gradient value and uncertainty estimate



- **Functional form similar to models in F. Imbeaux and X. Garbet PPCF 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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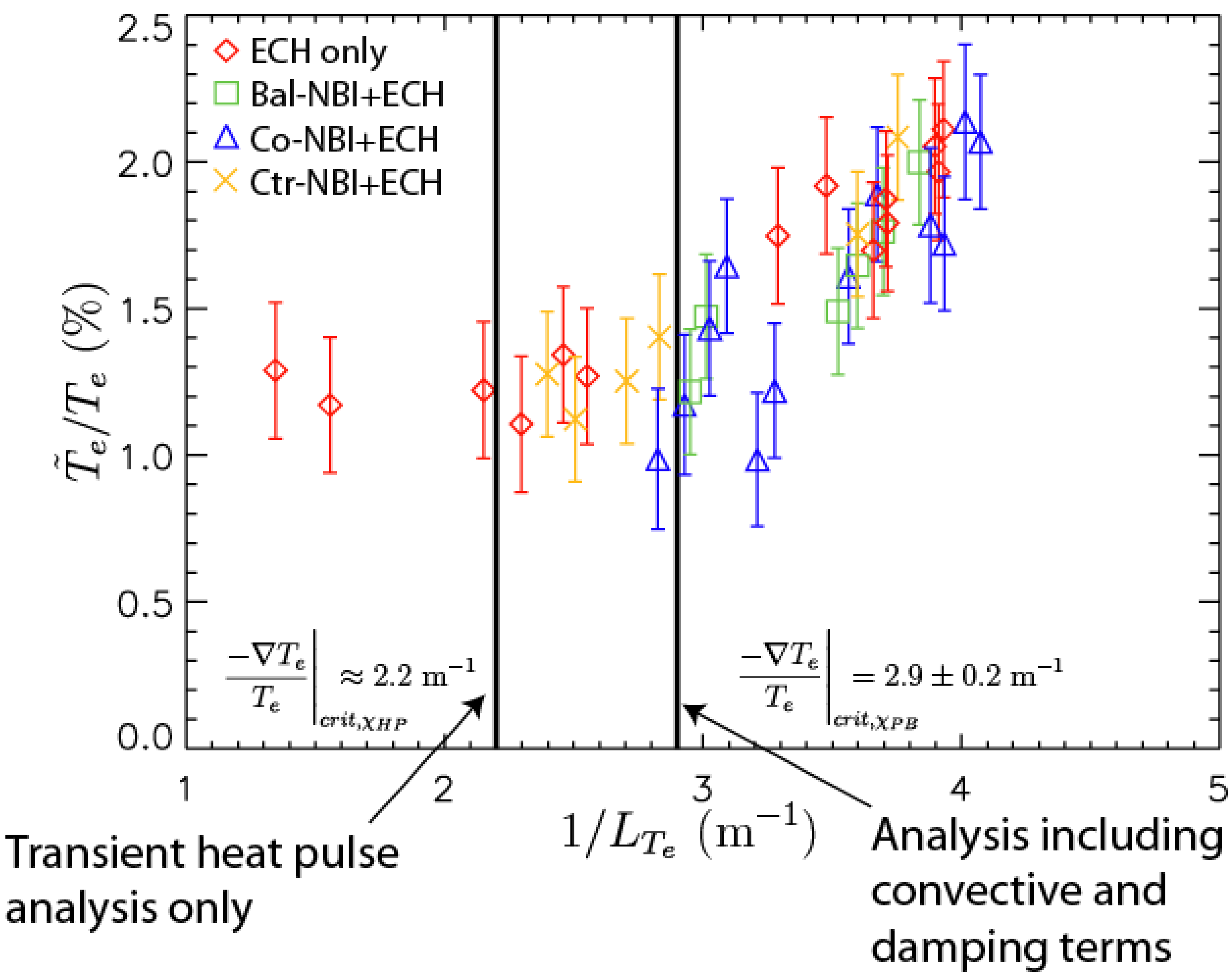
Analysis of electron thermal diffusivity from heat pulses also yields critical gradients



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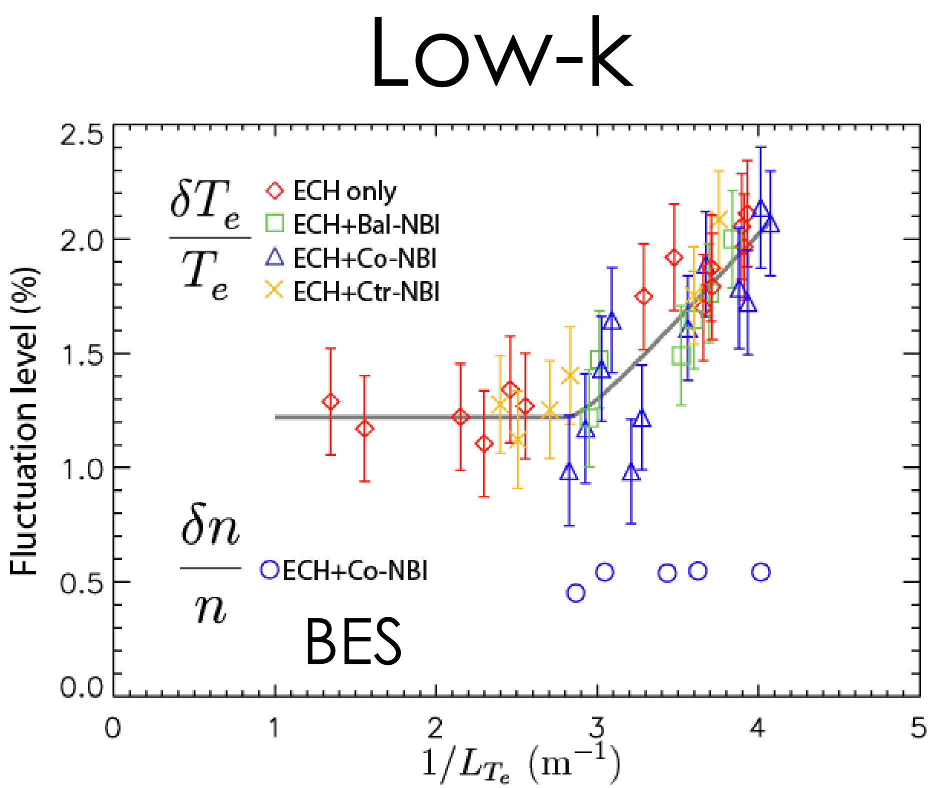
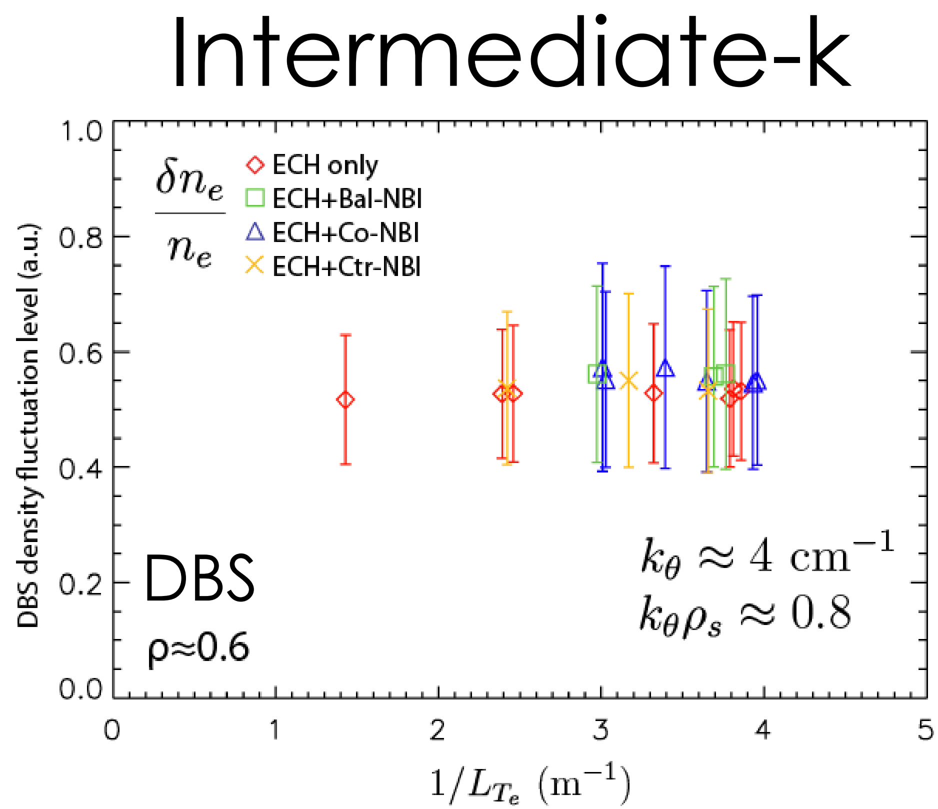
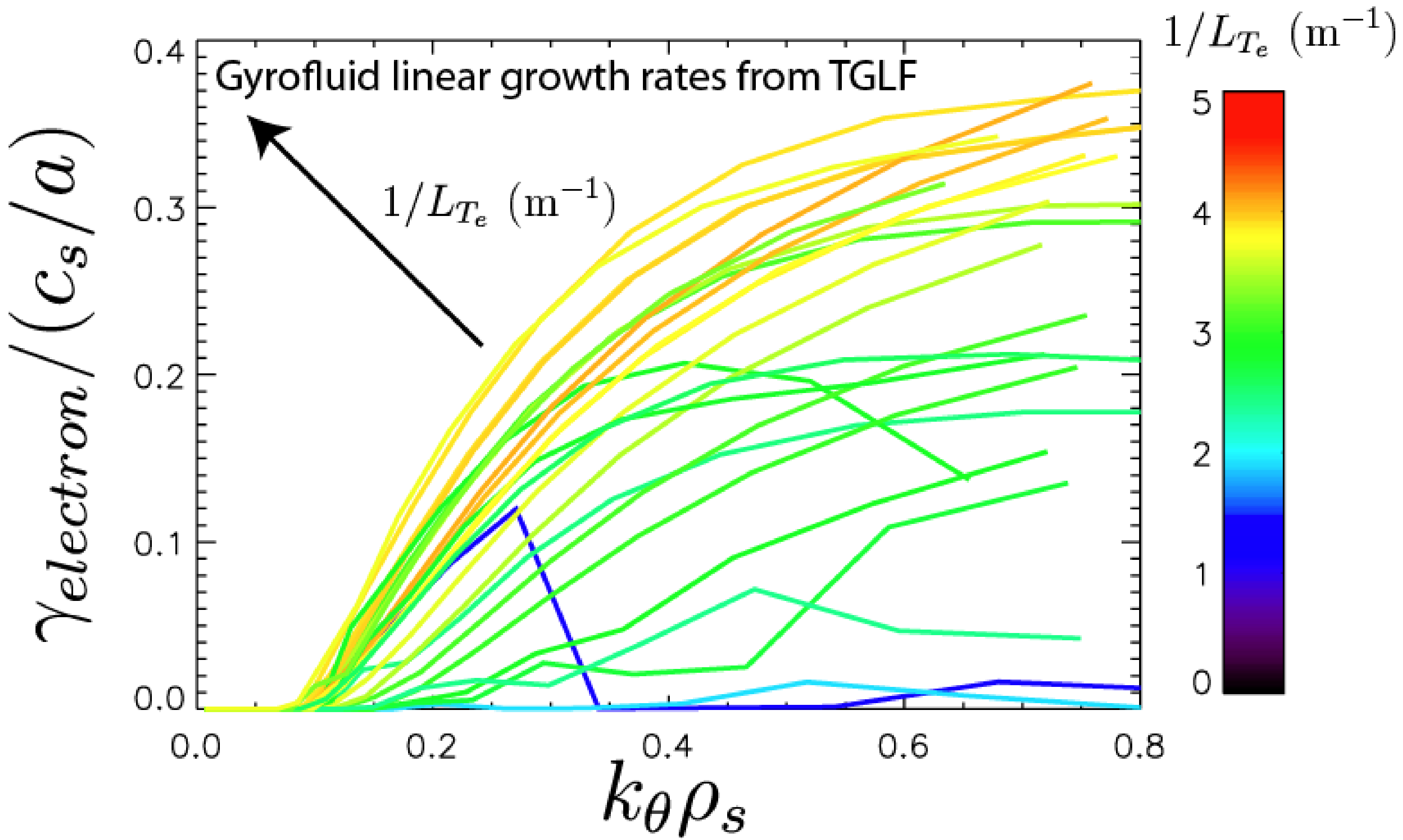
Density fluctuations show little change; the ratio $(\delta T_e/T_e)/(\delta n_e/n_e)$ increases





- **$1/L_{Te}$ threshold & $(\delta T_e/T_e)/(\delta n_e/n_e)$ change consistent with ∇T_e driven trapped electron mode turbulence**

Spectrum of fastest growing linear modes in electron diamagnetic direction generally increases with $1/L_{Te}$



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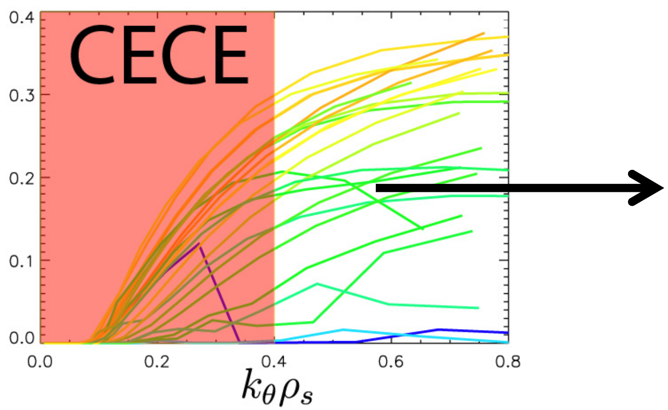
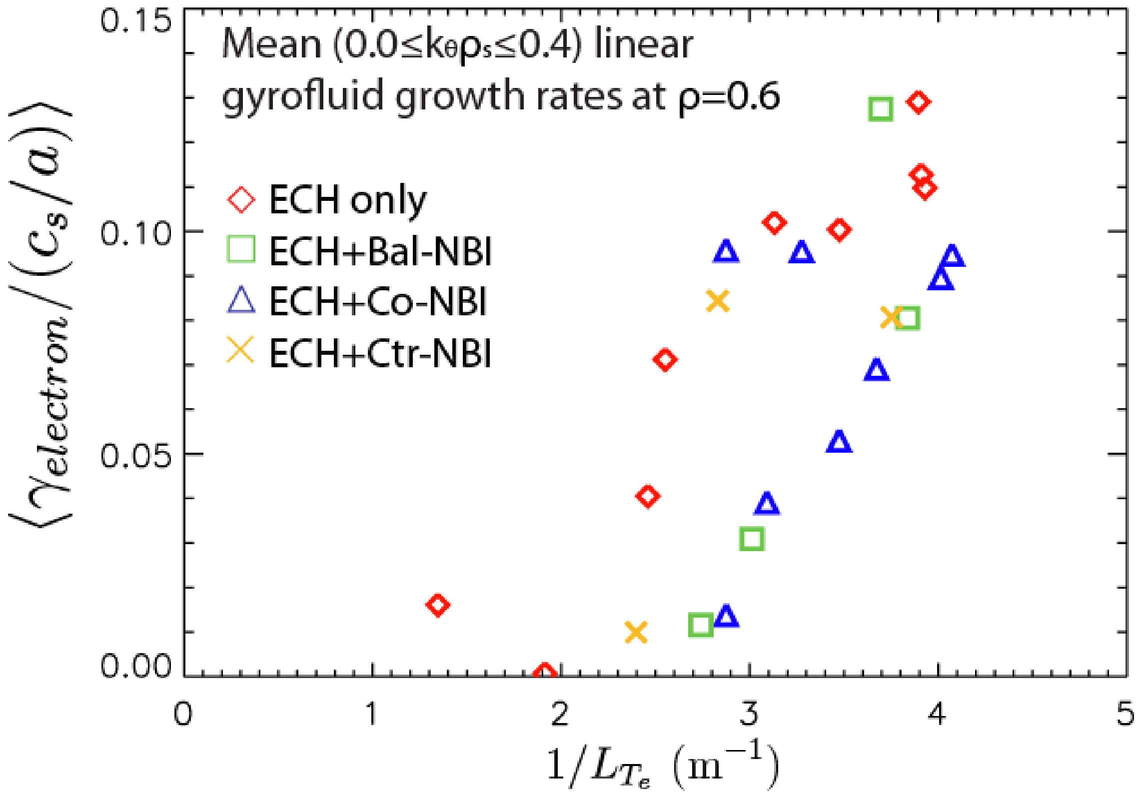
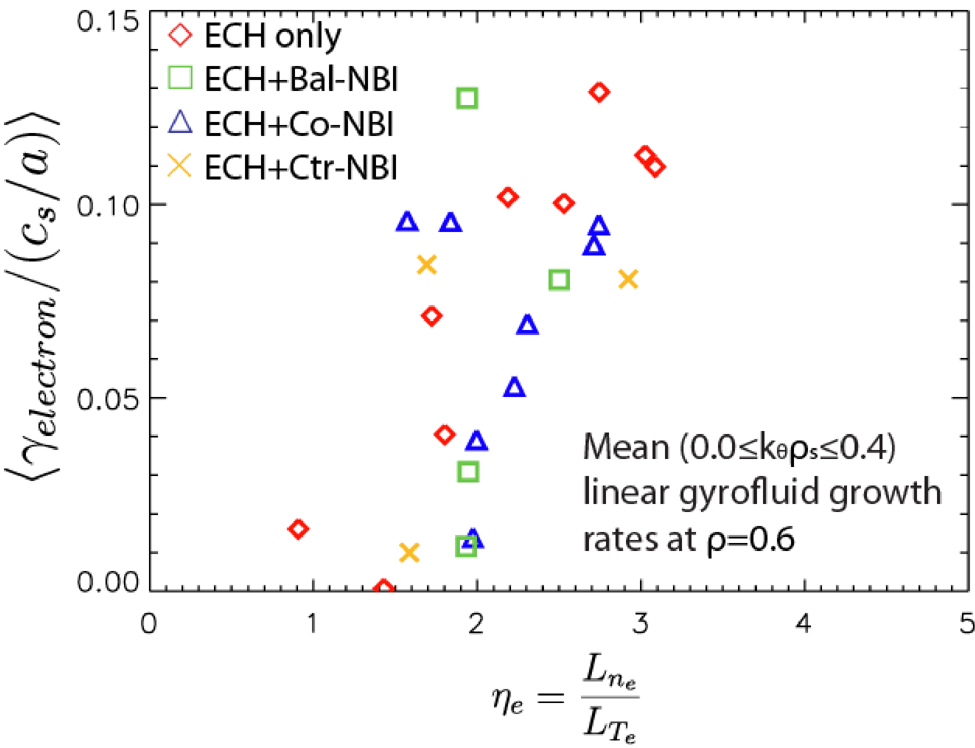
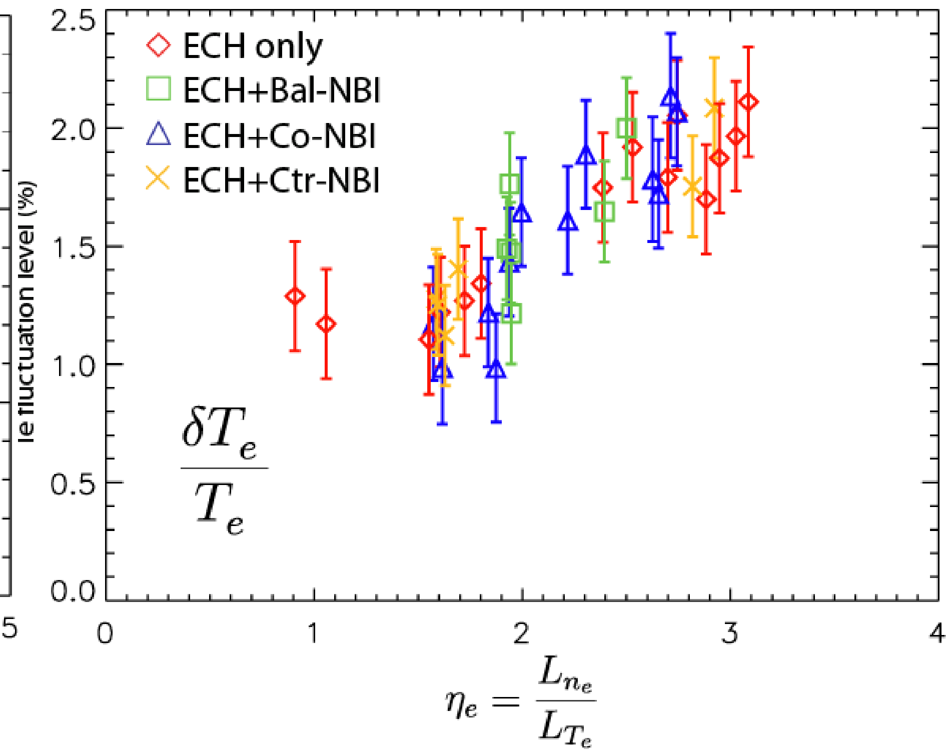
Mean growth rates over approximate CECE wavenumbers rapidly increase





Density gradient affects linear stability calculations, instability above η_e~2





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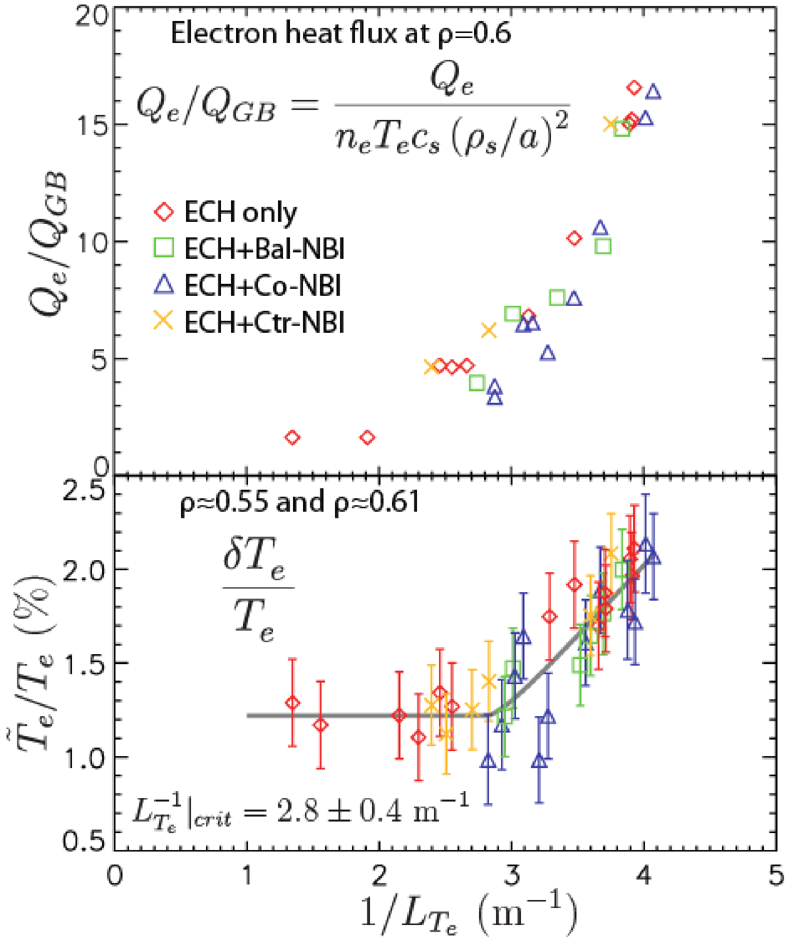
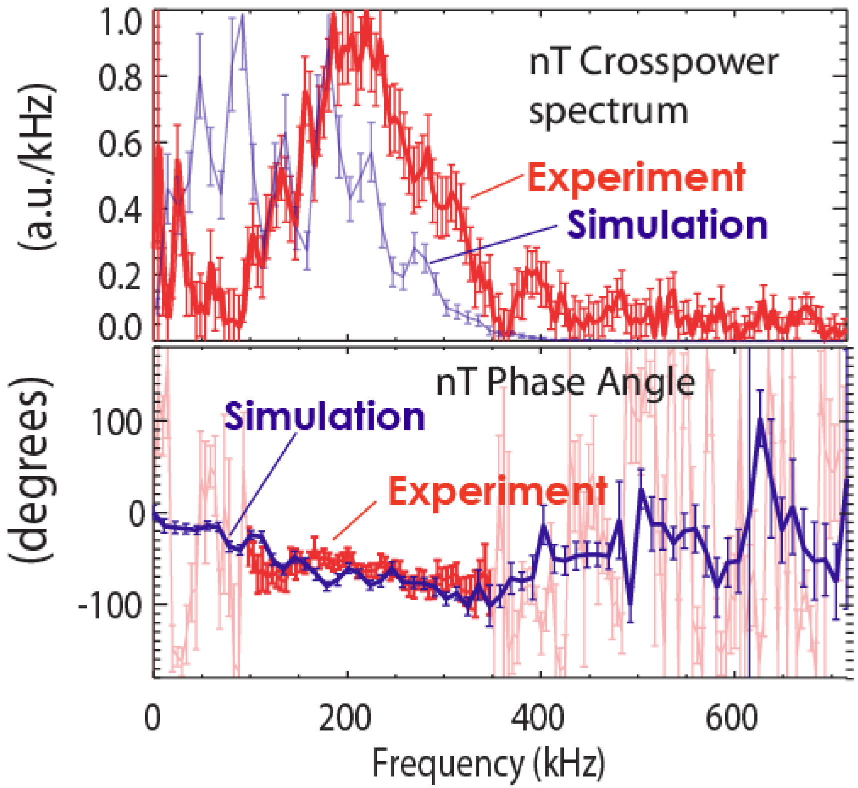
What causes the increased transport?

- **Heat flux increases by ~10x, but temperature fluctuations only increase by ~2x**
- **What else can contribute?**
- **nT crossphase can be measured**

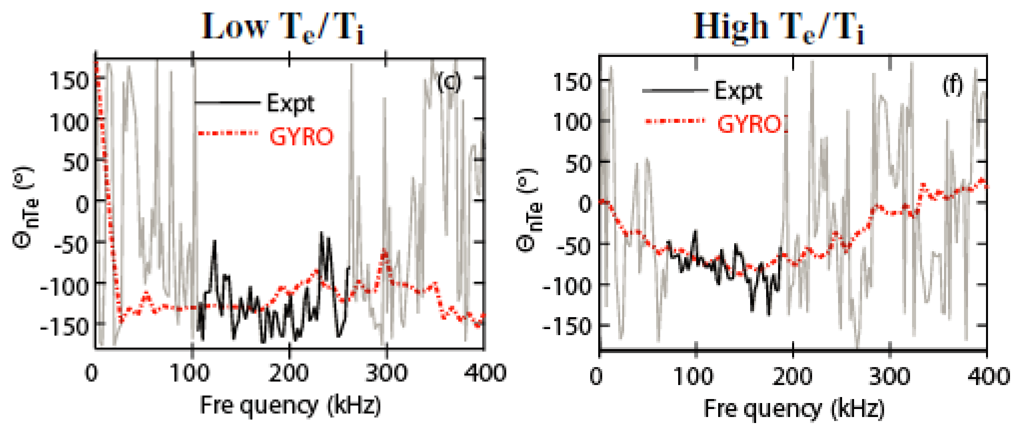


$$\tilde{Q}_e = \frac{3 n_e T_e}{2B} \sum_{k_\theta} k_\theta \left(\frac{|\tilde{n}_e|}{n_e} |\tilde{\varphi}| \gamma_{n_e,\varphi} \sin \alpha_{n_e,\varphi} + \frac{|\tilde{T}_e|}{T_e} |\tilde{\varphi}| \gamma_{T_e,\varphi} \sin \alpha_{T_e,\varphi} \right)$$

Crossphase in the core (r/a~0.5-0.6) of several beam-heated L-mode plasmas show quantitative agreement with gyrokinetic simulation



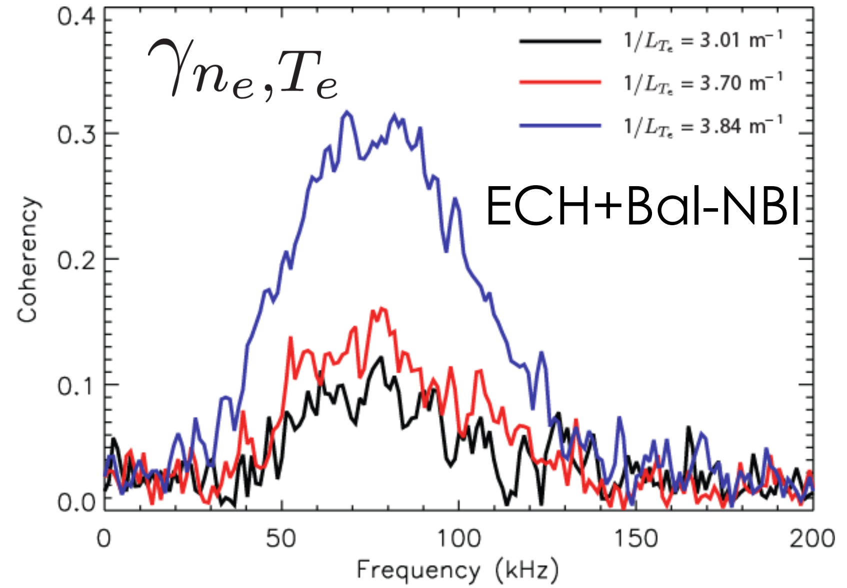
- Fig. from White PoP 2010



- Figs. from Rhodes NF 2011

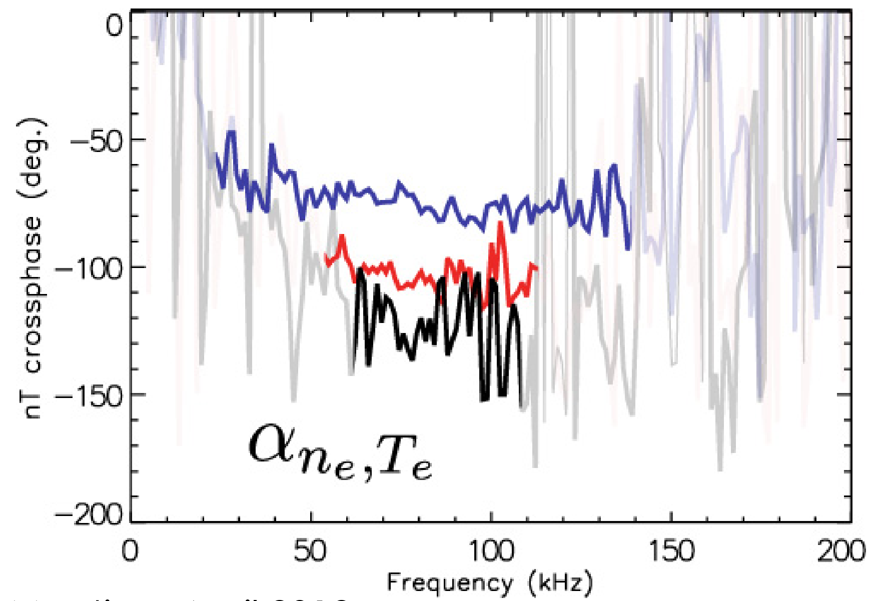
- **Quantitative agreement between experiment and GYRO has been found in Co-NBI + ECH heated plasmas, same experimental trend as for Ohmic+ECH**
- **Density-temperature crossphase measurement provides a multi-field constraint for validation studies**

nT crosshase varies with $1/L_{Te}$

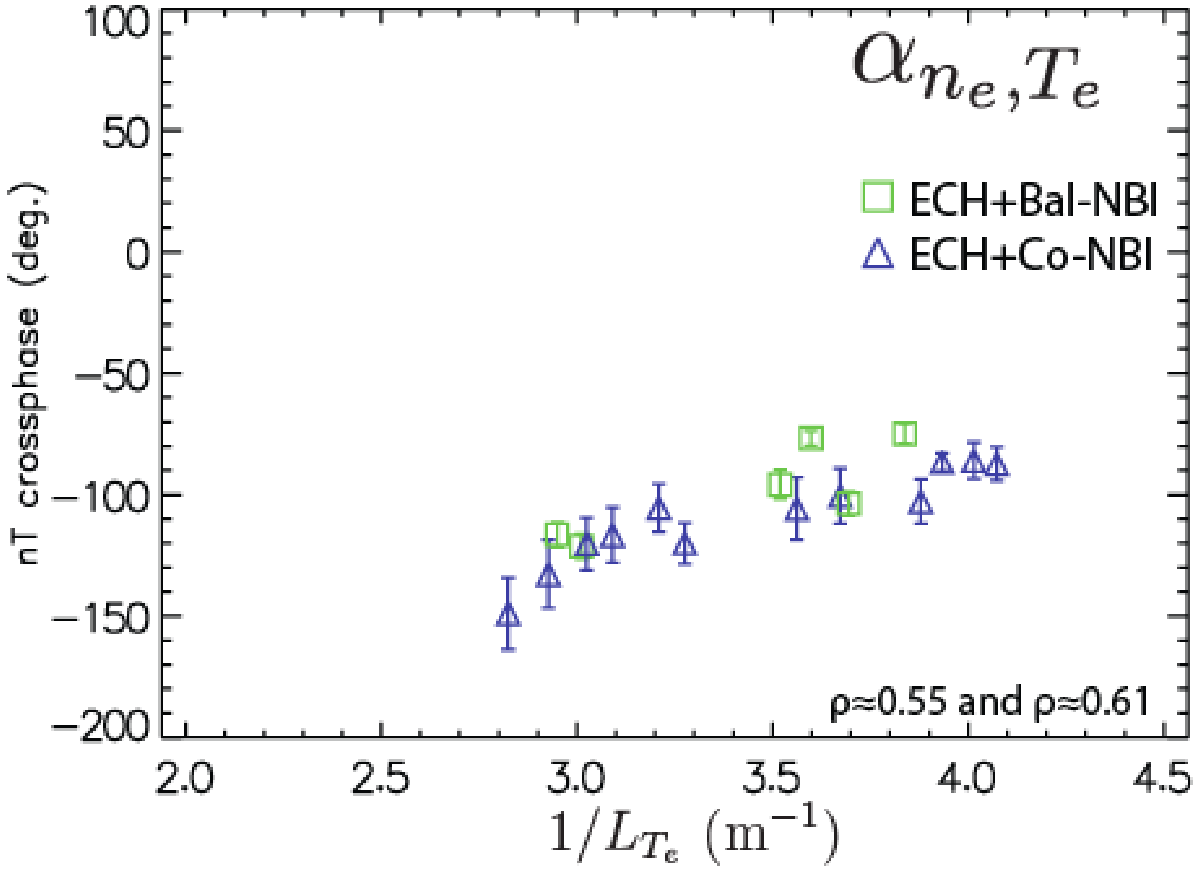


- **Coherency between electron temperature and density fluctuations increases with $1/L_{Te}$**
  - Coherent frequency range varies with rotation, consistent with a Doppler shift
- **Crossphase changes with $1/L_{Te}$**

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

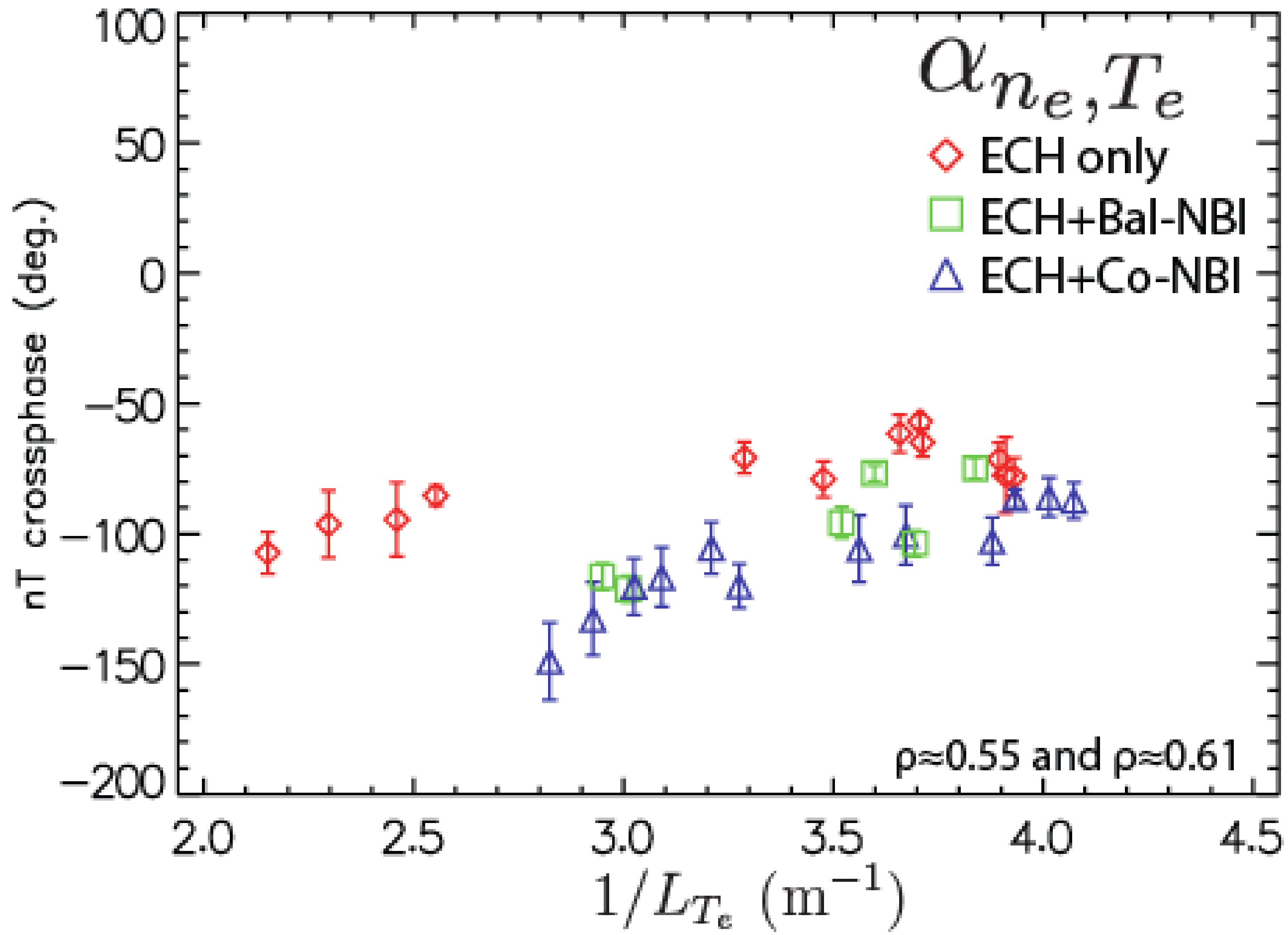


Averaged nT crossphase changes with a/L_{Te}



- **Co-NBI and Bal-NBI consistent with expectations from previous work, trend was attributed to change in dominant instability: ITG->TEM (White PoP 2010, Rhodes NF 2011, Wang PoP 2011)**

ECH only shows reduced trend



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

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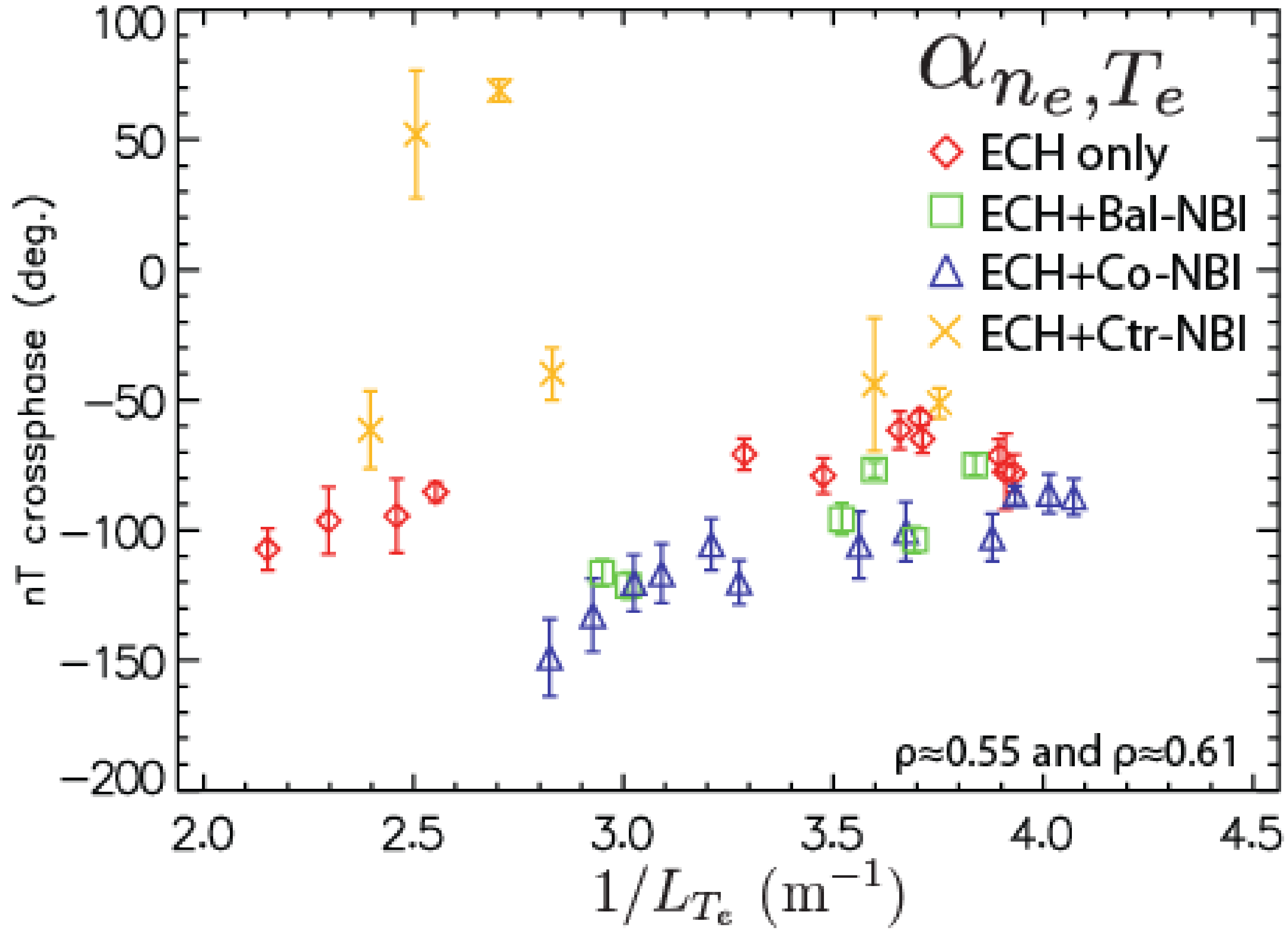
Significantly different behavior for ECH+Ctr-NBI at low $1/L_{Te}$
All cases converge at high $1/L_{Te}$



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

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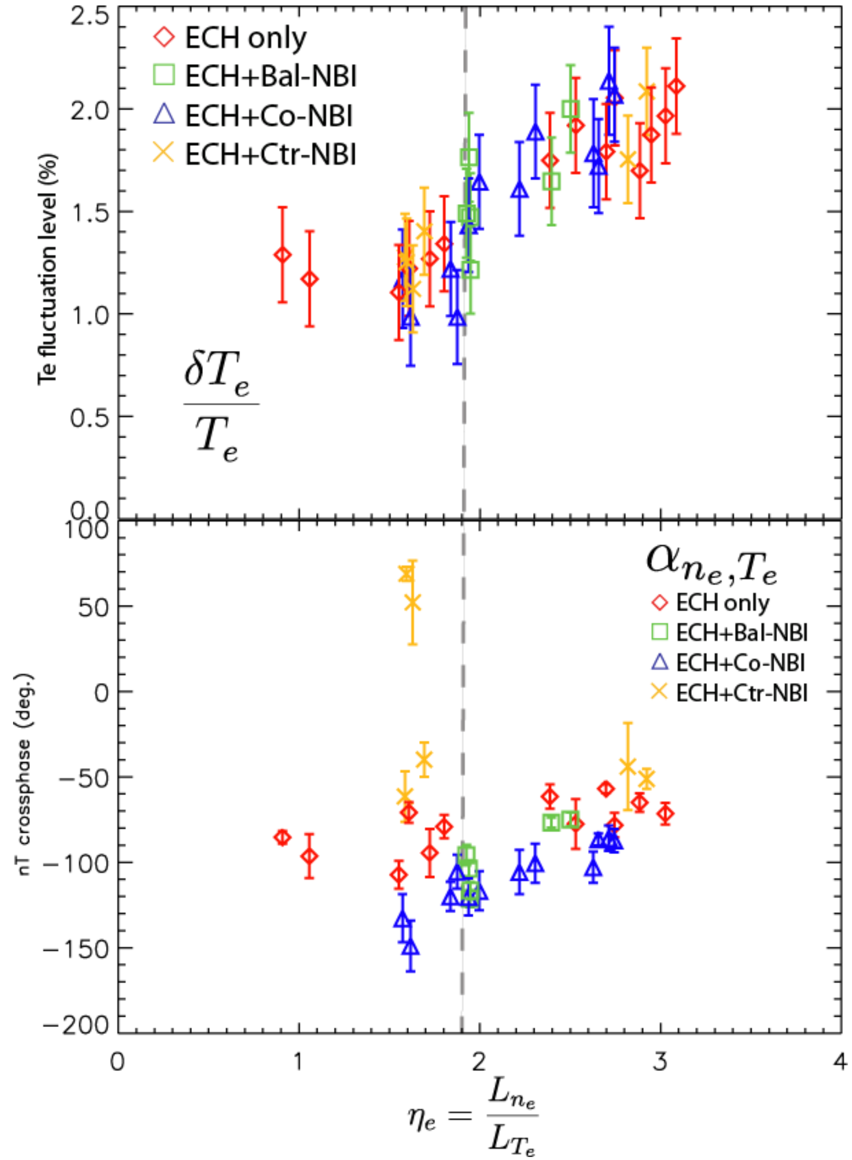
nT crossphase varies wildly below η_e=2, values similar above η_e=2



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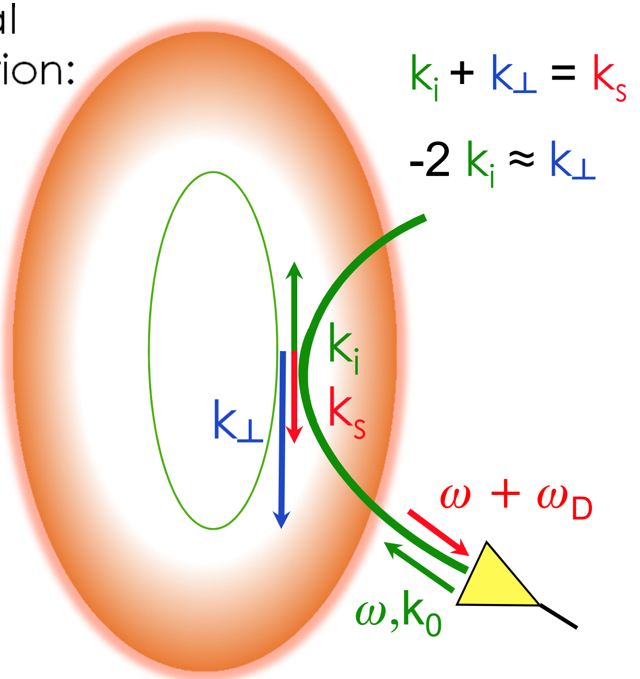
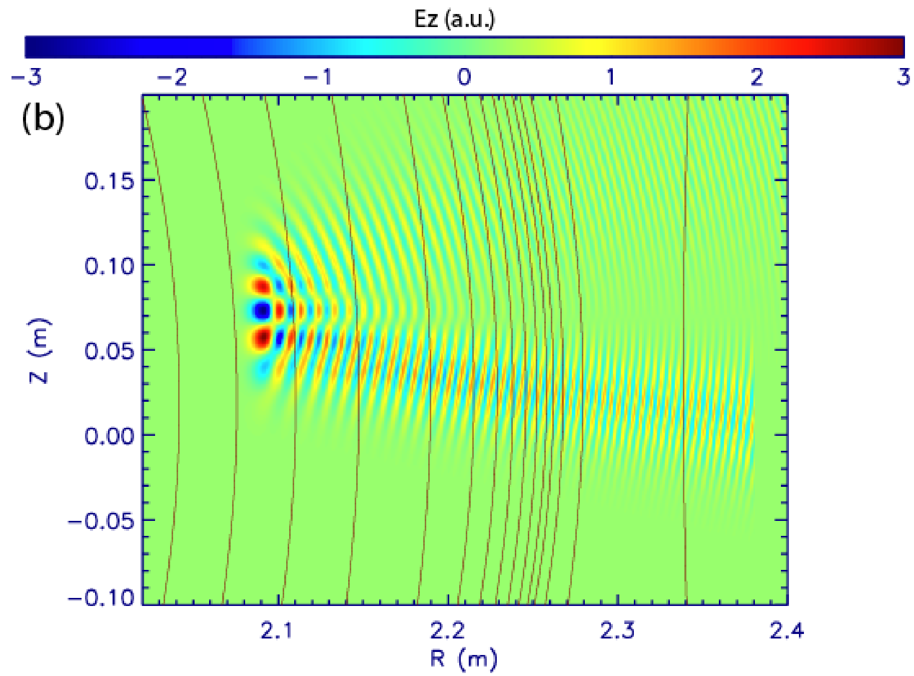
J. C. Hillesheim, NSTX Physics Meeting, April 2012

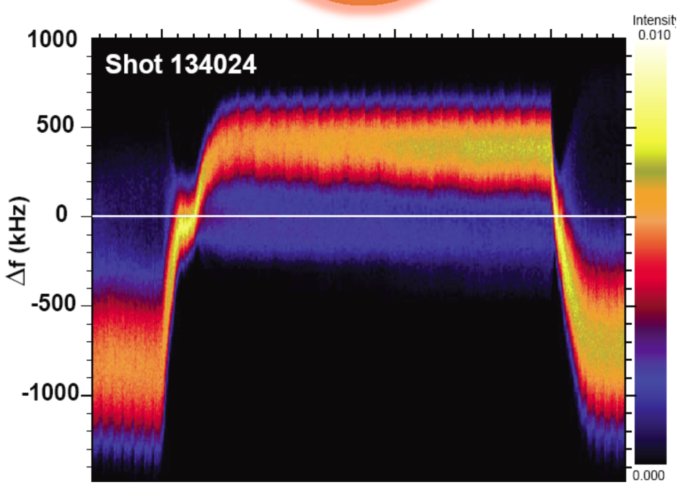
DBS measures the *radially localized* lab frame velocity and density fluctuation level

Poloidal Cross-section:



Full-wave simulation:





Counter-Beams

Co-Beams

- **Doppler shift in backscattered signal induced by lab frame velocity of the turbulence**

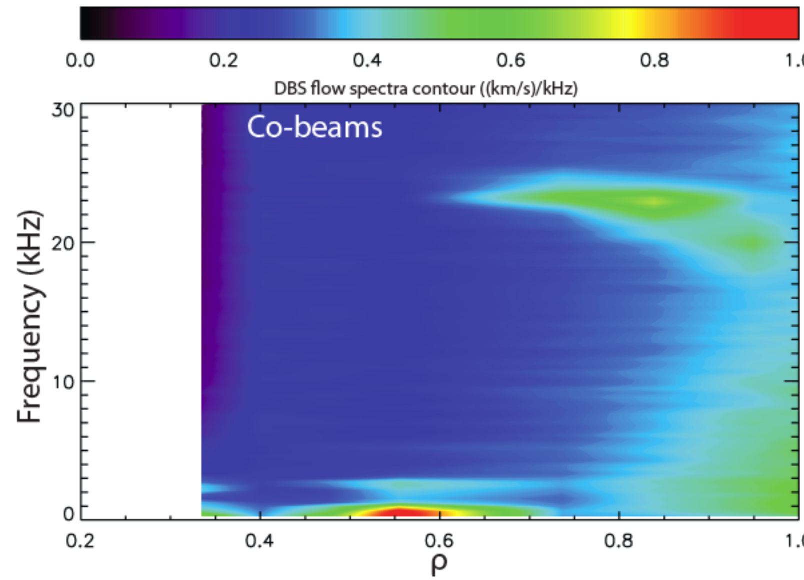
$$\omega_D \approx k_\perp v_{Lab}$$

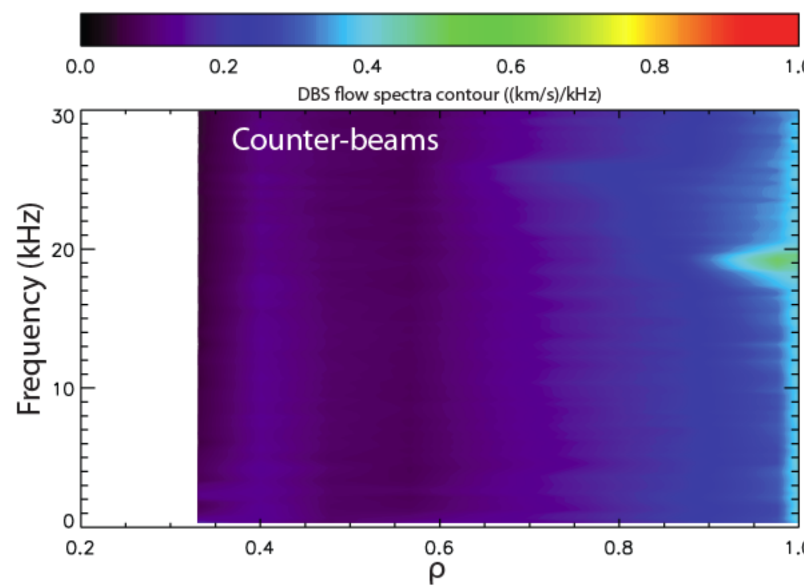
$$v_{Lab} = v_{E\times B} + \tilde{v}$$

J. C. Hillesheim, NSTX Physics Meeting, April 2012

Geodesic acoustic mode (GAM) and other low frequency zonal flows significantly weaker in ECH+Ctr-NBI

- **Contour plots from 8-channel Doppler backscattering system**
- **Both rotation & Z_{eff} differ**
- **GAM studied at DIII-D with DBS**
  - J. C. Hillesheim et al., Phys. Plasmas 19, 022301 (2012)
- **Zonal flow dynamics through L-H transition also studied**
  - L. Schmitz et al., Phys. Rev. Lett. 108, 155002 (2012)





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GAM typically disappears before L-H transition, limit cycle oscillations observed in slow transitions

- **Contour plots from 8-channel Doppler backscattering system**
- **GAM studied at DIII-D with DBS**
  - J. C. Hillesheim et al., Phys. Plasmas 19, 022301 (2012)
- **Zonal flow dynamics through L-H transition also studied**
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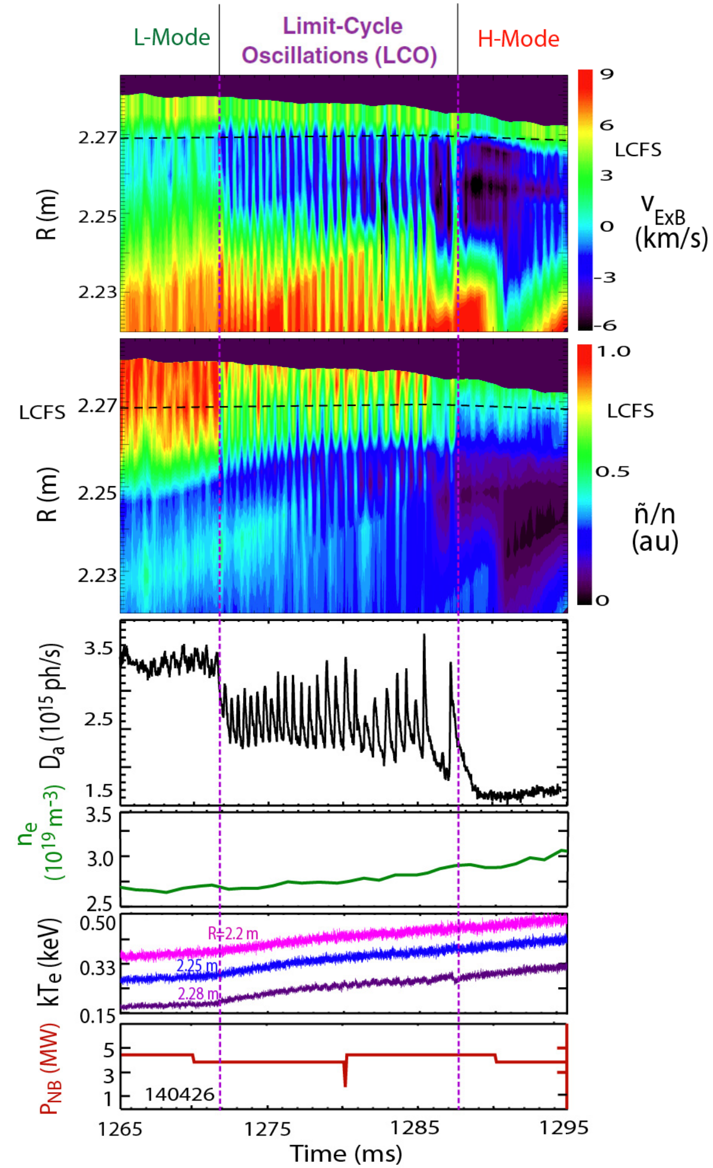

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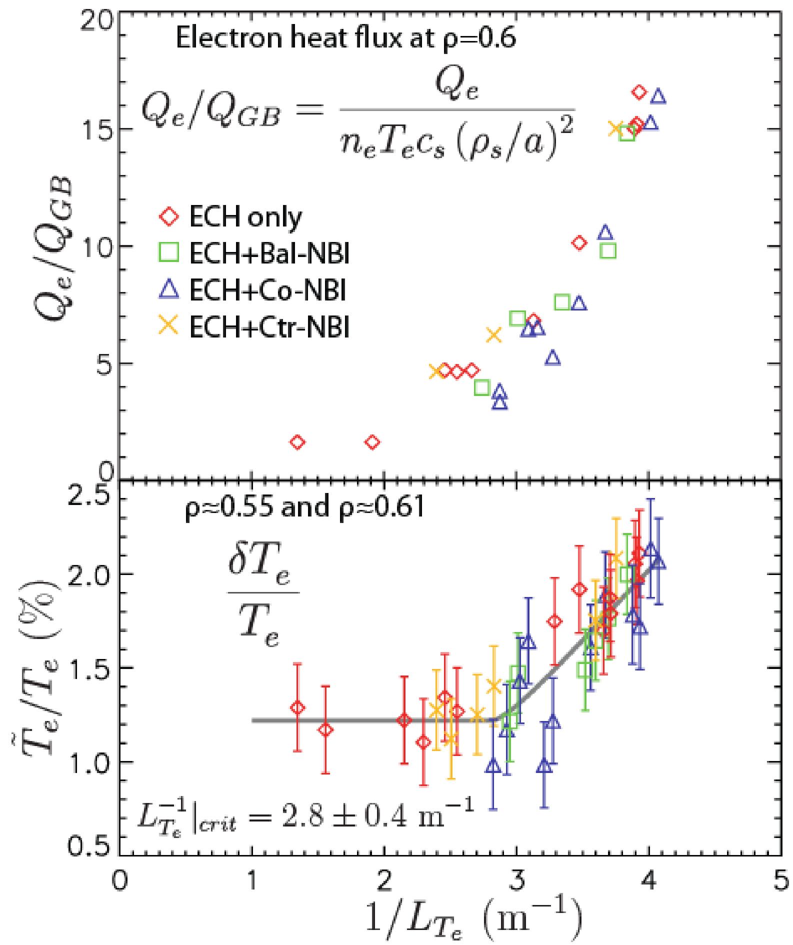
Principal result

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

- **Critical gradient observed in electron thermal transport and electron temperature fluctuations**

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

- **TGLF linear growth rates consistent with critical gradient**



Measurements consistent with ∇T_e driven trapped electron mode turbulence at high $1/L_{Te}$

- **Observed critical gradient in $1/L_{Te}$**
  - B.B. Kadomtsev et al., Nucl. Fusion 11, 67 (1971)
- **Measured nT crossphase consistent with TEM**
  - A. E. White et al., Phys. Plasmas 17, 056103 (2010), T. L. Rhodes et al., Nucl. Fusion 51, 063022 (2011), G. Wang et al., Phys. Plasmas 18, 082504 (2011)
- **Change in ratio of fluctuations consistent with TEM**
  - A. E. White et al., Phys. Plasmas 17, 020701 (2010)
- **Linear growth rates consistent with critical gradient**
- **Collisionality & Beta in TEM relevant regime**
  - $\nu^*\sim 0.1$ and $\beta<0.5\%$

Critical gradients found in several analyses—most are in agreement

- **Transport critical gradient values**
  - Electron temperature fluctuations $$L_{T_e}^{-1}|_{crit} = 2.8 \pm 0.4 \text{ m}^{-1}$$
  - Heat pulse electron thermal diffusivity $$L_{T_e}^{-1}|_{crit} \approx 2.2 \text{ m}^{-1}$$
  - Electron thermal diffusivity with convective and damping terms from heat pulse analysis $$L_{T_e}^{-1}|_{crit} = 2.9 \pm 0.2 \text{ m}^{-1}$$

$$R_0 \approx 1.7 \text{ m}$$
$$a \approx 0.6 \text{ m}$$

- **Instability threshold**
  - Electron temperature fluctuations and linear growth rates $$\eta_e \approx 2$$

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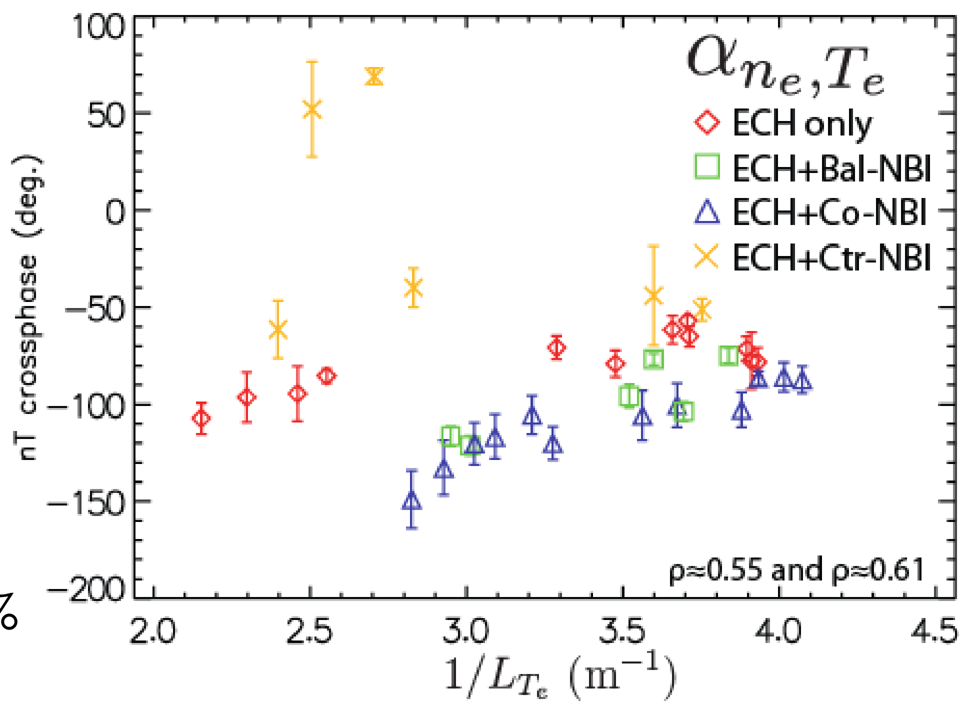
What constraints can be put on the transport crossphases?

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

- **Convective term can be argued to be small** $\rightarrow \sin \boldsymbol{\alpha_{n\varphi}} \approx \mathbf{0}$
  - Density profile shows little response during ECH scan
  - Particularly for ECH only, only particle source at edge
  - Previous simulations of similar plasmas show conductive term dominates, accounting for ~90% of Q_e



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Can low-k fluctuations completely account for the observed heat flux?

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

- **Consider only convective term**
  - Take average wavenumber to be $k_\theta = 1.5\ cm^{-1}$ $(k_\theta \rho_s \approx 0.3)$
  - To set a bound take $\gamma_{T\varphi} = 1$, $\sin \alpha_{T\varphi} = 1$
- **At highest 1/L_{Te}** $\frac{Q}{nT} \approx 45\ m/s$
- **Under above assumptions, this would require** $\frac{e|\tilde{\varphi}|}{T_e} \approx 2.5\%$

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Summary of results

- **Critical gradient observed in both electron thermal transport and electron temperature fluctuations** ($Q_e, \frac{\delta T_e}{T_e}$)
  - Stiffness increases above critical gradient
- **nT Crossphase also changes; indicates more subtle picture, with various instabilities active under the critical gradient** (α_{n_e,T_e})
  - Implies changes to transport crossphases plausible
- **Gyrofluid growth rates from TGLF consistent with linear instability critical threshold behavior** ($\langle\gamma_{electron}/(c_s/a)\rangle$)
- **Future work:**
  - Comparison to further gyrokinetic & gyrofluid predictions