(TH/6-1) Progress in simulating turbulent electron thermal transport in NSTX

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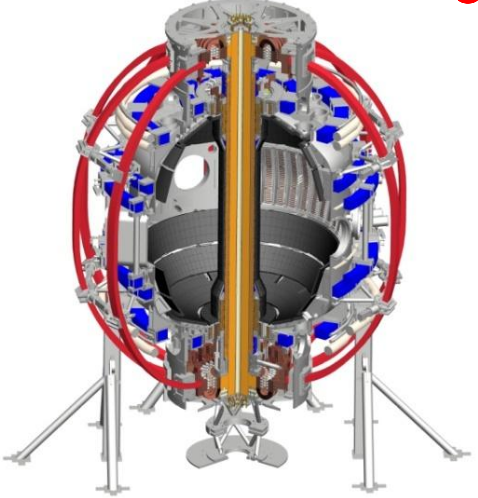

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Motivation: Understand mechanism(s) responsible for electron thermal transport over broad range of parameters

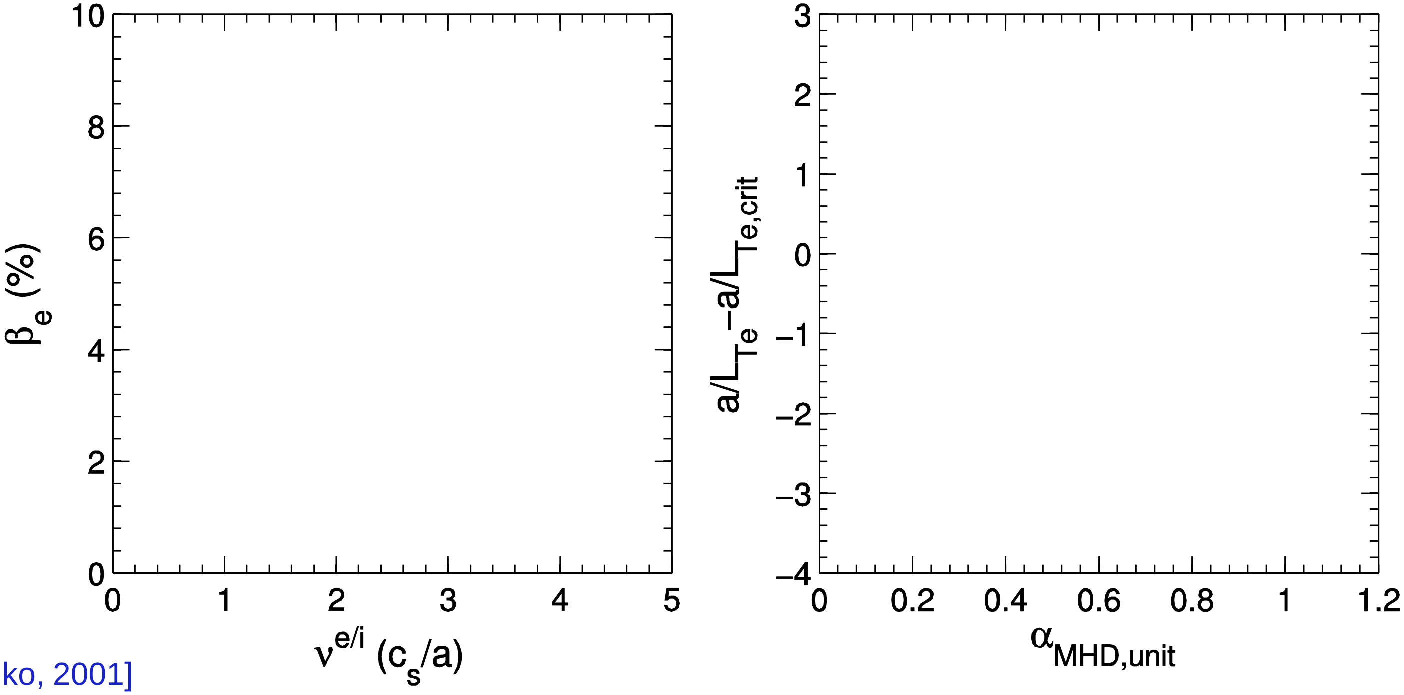
- Wide range of parameters accessible by spherical tokamaks (ST)
- H-mode ion thermal transport often near neoclassical in STs
- Observed confinement scaling $\Omega\tau_E \sim \nu_*^{-0.8}$ [Kaye EX/7-1, previous talk]

  $\Rightarrow$ does it extrapolate to future devices at lower ν_* (NSTX-U, ST-FNSF, …)?

- Considering core thermal gradient micro-instabilities (r/a~0.4-0.8)
  - Local GYRO simulations based on experimental profiles & equilibrium reconstructions

- Although important, not addressing:
  - Pedestal [Canik (EX/P7-16), Diallo (EX/P4-04), Kubota (EX/P7-21), Maingi (EX/11-2), Smith (EX/P7-18)]
  - Energetic particle driven instabilities [Belova, TH/P6-16; Crocker, EX/P6-2]

Broad range of parameters requires consideration of many micro-instabilities



[Jenko, 2001]

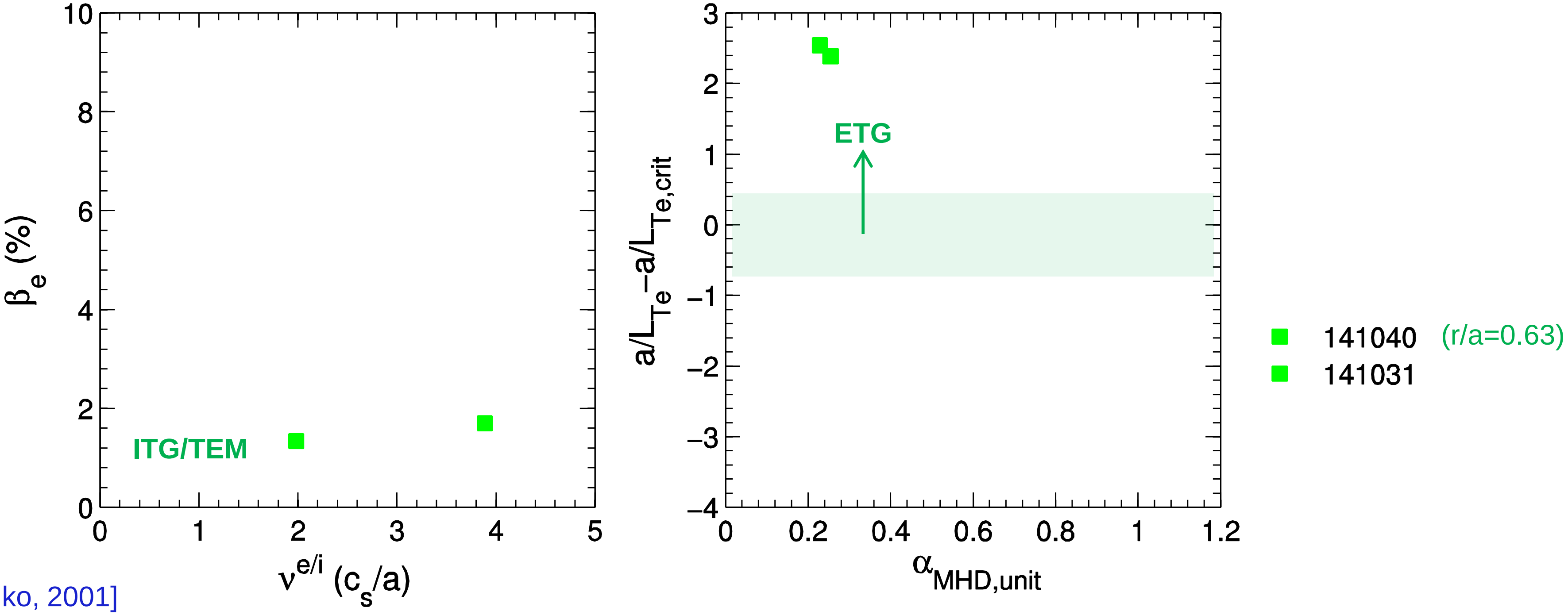
$$\left(\frac{R}{L_{Te}}\right)_{crit}^{etg} = \max\left\{\begin{matrix}(1+Z_{eff}T_e/T_i)\cdot(1.3+1.9s/q)\cdot(\cdots) \\ 0.8R/L_{ne}\end{matrix}\right\}$$

$$\alpha_{mhd,unit} = -q^2R\nabla\beta$$

$$\nabla\beta = \sum_s \nabla(n_sT_s)\cdot 2\mu_0/B_{unit}^2$$

Broad range of parameters requires consideration of many micro-instabilities

- “Electrostatic” **ITG/TEM** can be found at lower beta, often with $\gamma_E \sim \gamma_{lin}$
- **ETG** found for $a/L_{Te} > a/L_{Te,crit}$



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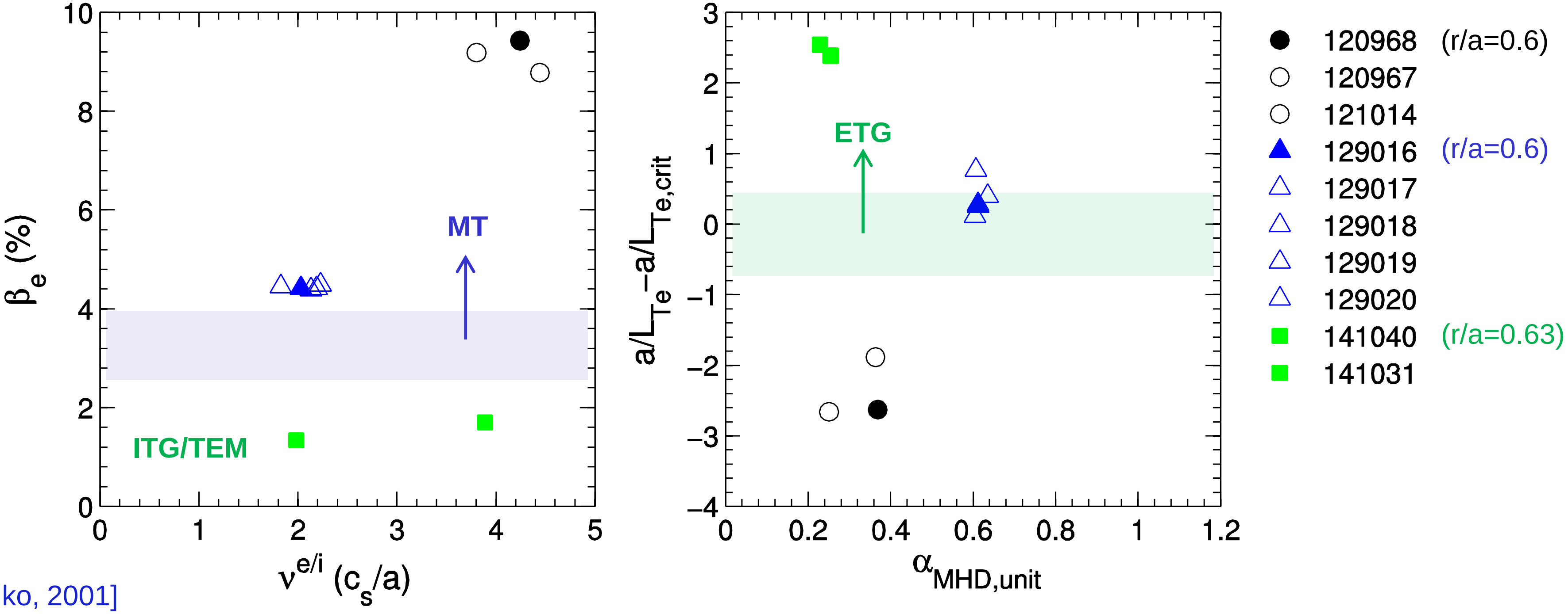
- **ETG** found for $a/L_{Te} > a/L_{Te,crit}$ (high and low β_e)
- Microtearing tearing (**MT**) found at sufficiently high β_e and ν_{ei}



[Jenko, 2001]

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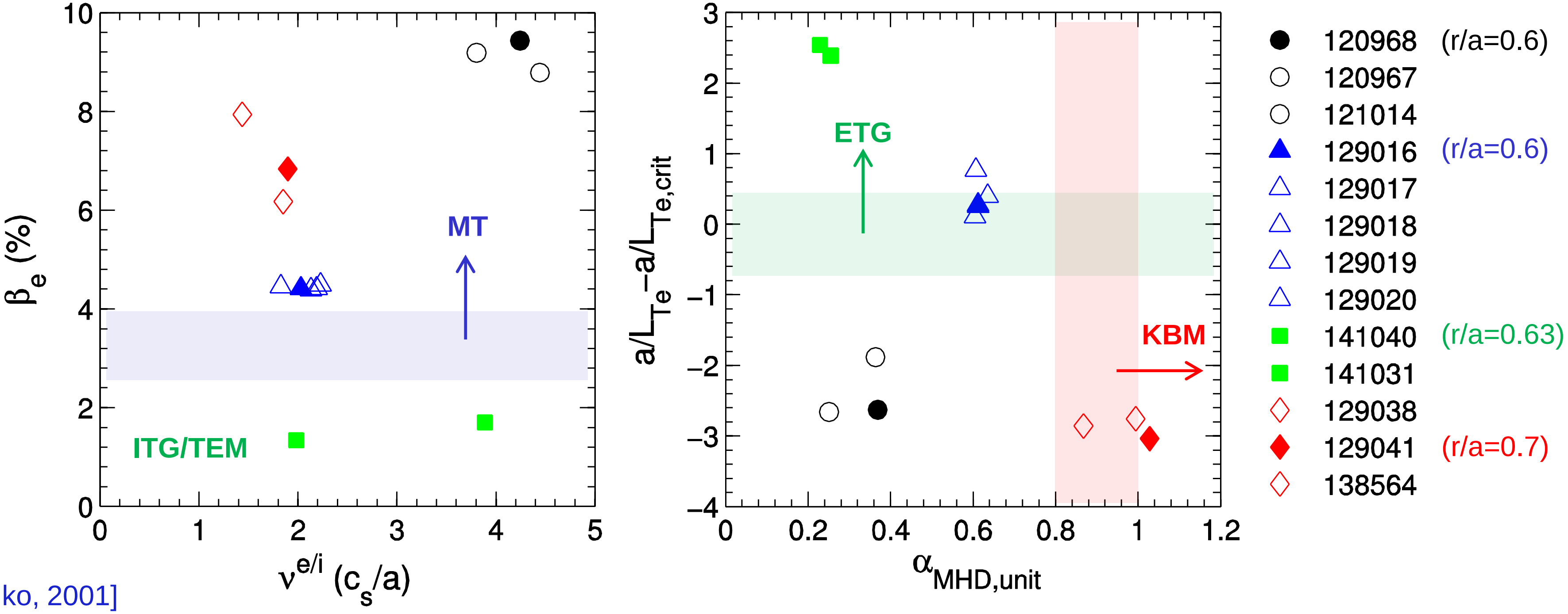
- “Electrostatic” **ITG/TEM** can be found at lower beta, often with $\gamma_E \sim \gamma_{lin}$
- **ETG** found for $a/L_{Te} > a/L_{Te,crit}$ (high and low β_e)
- Microtearing tearing (**MT**) found at sufficiently high β_e and ν_{ei}
- **KBM** unstable at high $\alpha_{mhd} \sim \nabla\beta$



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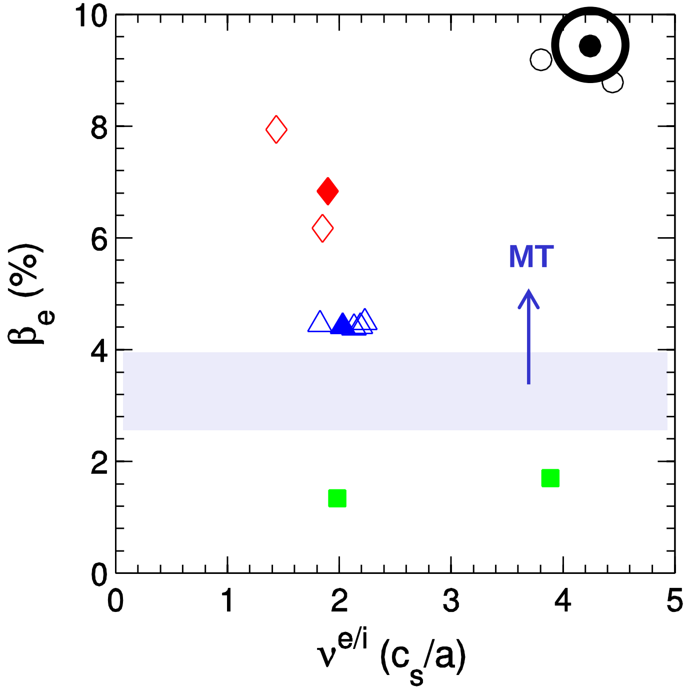
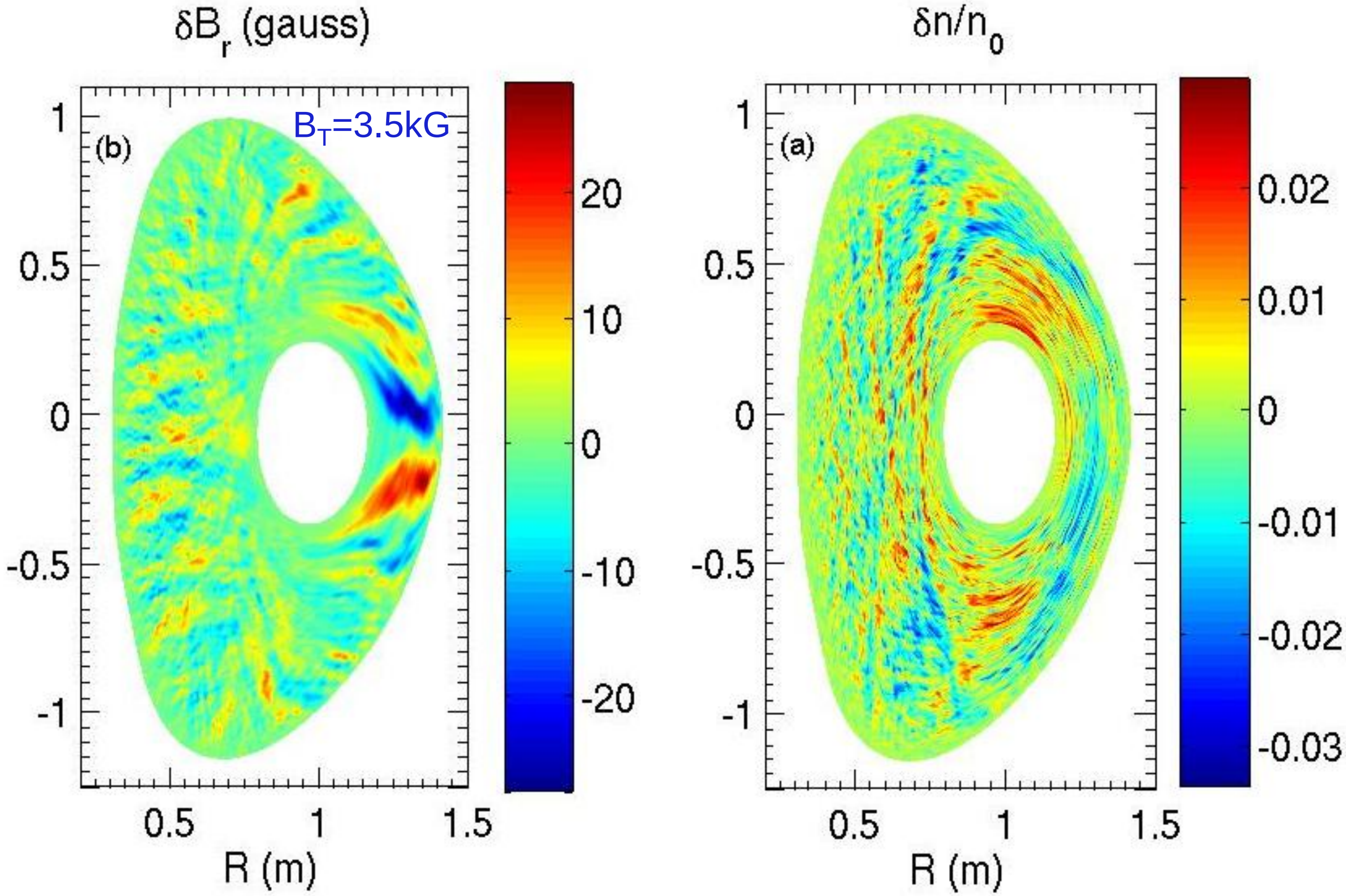
Outline

- Motivation
- **Microtearing simulations**
- ETG simulations
- TEM/KBM simulations
- Summary



First nonlinear microtearing (MT) simulations for NSTX predict large δB_r and dominant magnetic flutter transport

- $\chi_{e,em} \approx 6\ m^2/s$ from $\delta B_r/B \sim 0.15\%$ (rms)
  - Measurable phase fluctuation predicted for proposed polarimetry diagnostic [J. Zhang, 2012]
- Narrow density perturbations distinct from traditional ITG/TEM



$L_x, L_y = 80{,}100\ \rho_s$
$nx, ny = 540{,}16$
D only; φ, $A_{||}$
$\gamma_E=0$

Resolution constrained by
$\Delta r_{rat} = 1/k_\theta s$
$\Delta x \leq 0.2\ \rho_s$

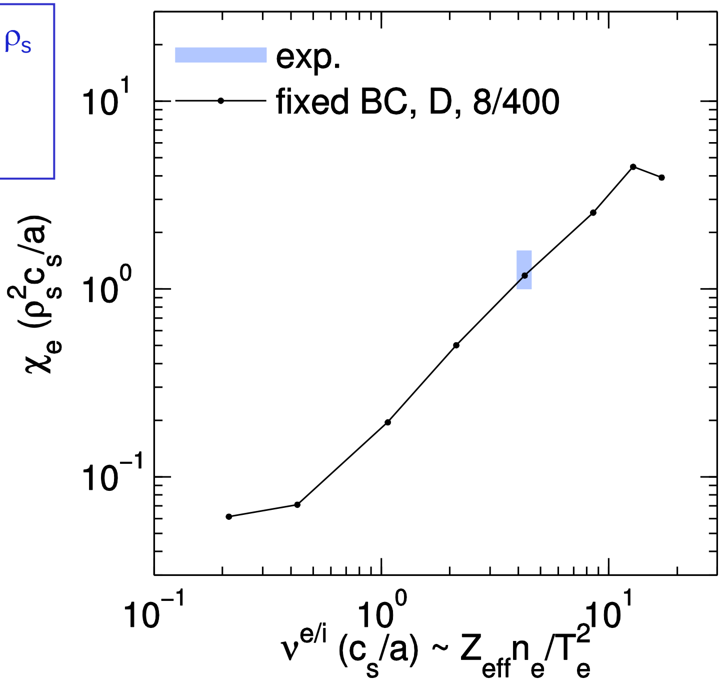
Toroidal mode numbers:
$n \approx 5$-40

W. Guttenfelder et al., Phys. Rev. Lett. (2011); Phys. Plasmas (2012).

MT transport increases with collisionality consistent with confinement scaling

- Possible component of confinement scaling in NSTX ($\Omega\tau_E \sim \nu_*^{-0.8}$)

$L_x, L_y = 80,60\ \rho_s$
$nx, ny = 400,8$
D only; φ, $A_{||}$
$\gamma_E = 0$



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- Possible component of confinement scaling in NSTX ($\Omega\tau_E \sim \nu_*^{-0.8}$)
  - ν scaling confirmed with different physical & numerical assumptions (magnitude varies)
  - Suppressible by experimental E×B shear ($\gamma_{E,exp} \approx \gamma_{lin,MT}$)

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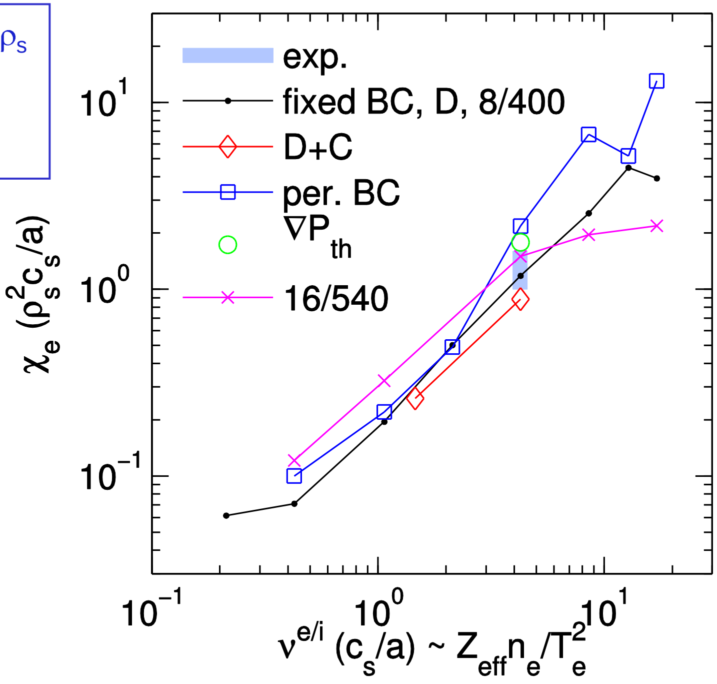

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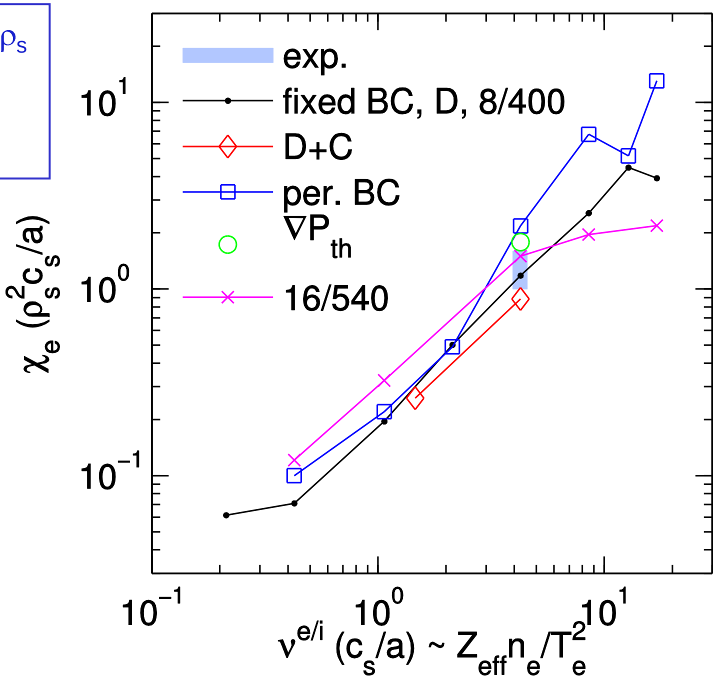

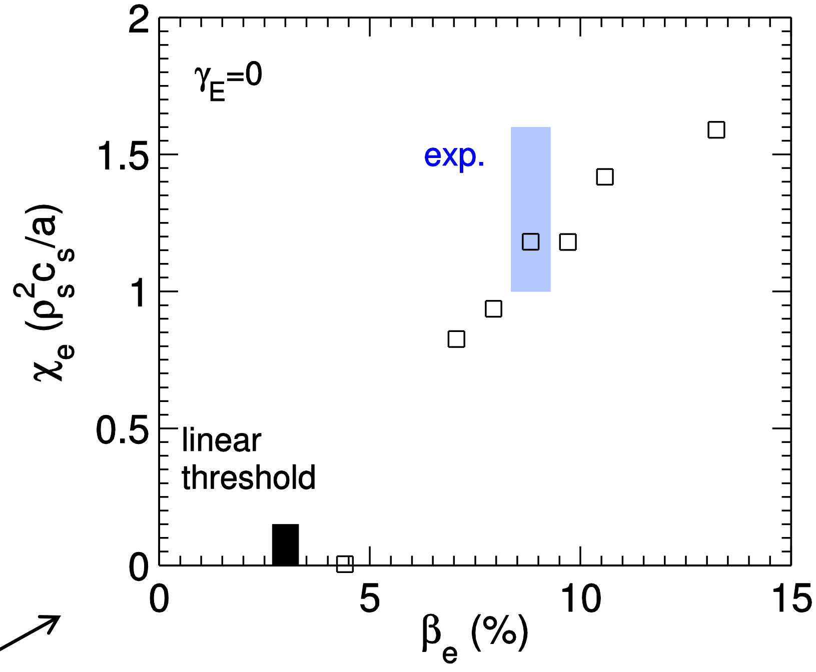

- Threshold behavior with a/L_{Te} and β_e
  - Beta scaling not consistent with weak confinement scaling, $\Omega\tau_E \sim \beta^{-0.1}$ [Kaye, 2007]
  - Useful to characterize threshold for (1) experimental interpretation, (2) relating to MT in conventional tokamaks [Jenko, (TH/6-4); Doerk, PRL (2011), PoP (2012); Petty et al. (ITR/P1-30)]

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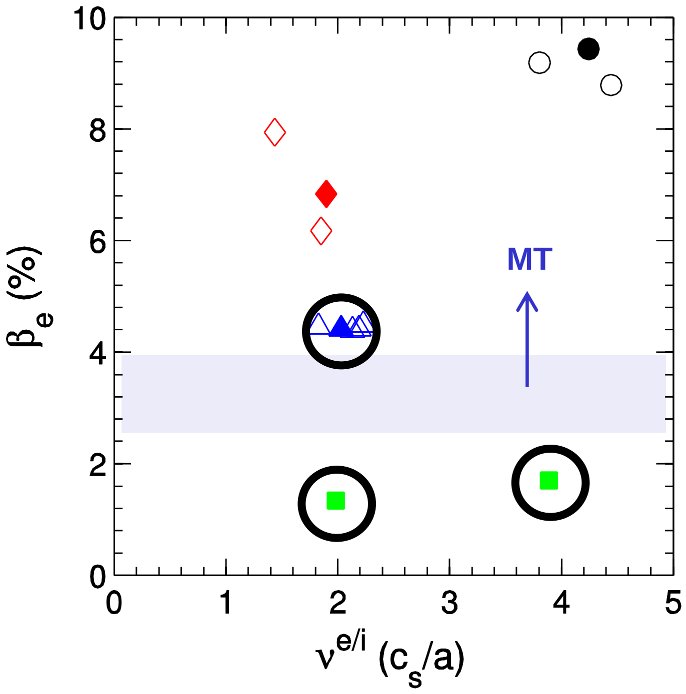
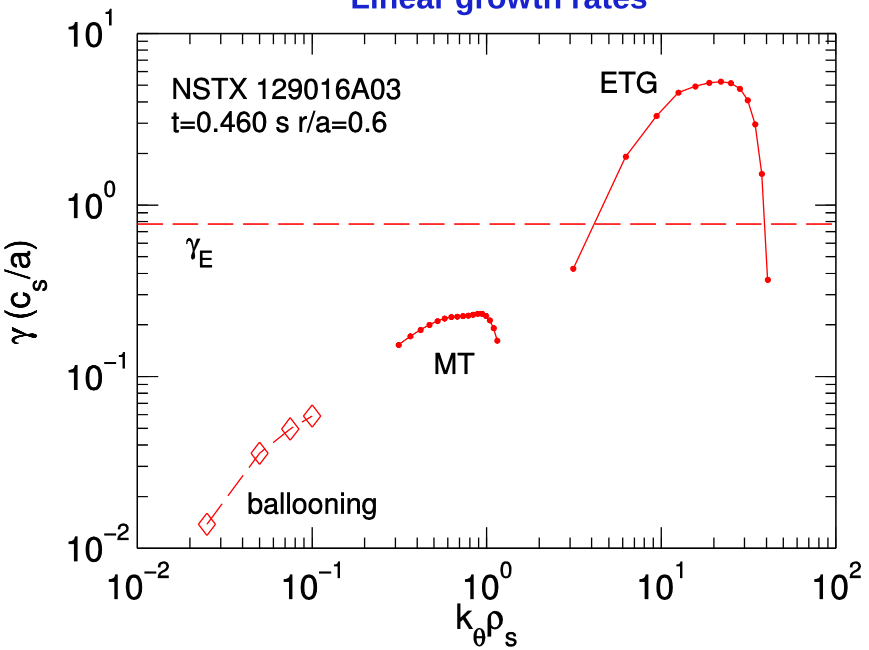


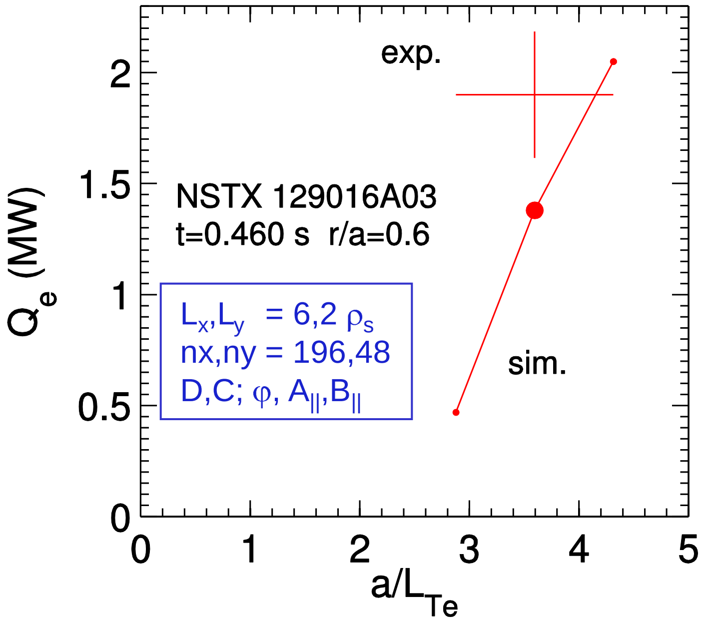
ETG transport significant in core of some high-β NSTX discharges

- High-ν_* discharge without Lithium [Kaye, EX/7-1 (previous talk); Maingi, EX/11-2]
- Microtearing (and ballooning) instabilities at ion scales, but $\gamma_E >> \gamma_{lin,ion}$
- ETG also unstable → significant nonlinear transport, Q_e~1-2 MW ($\chi_e \sim 10\ \rho_e^2 v_{Te}/L_{Te}$)
  - Relatively stiff ($a/L_{Te,crit}$~2.2)

Linear growth rates



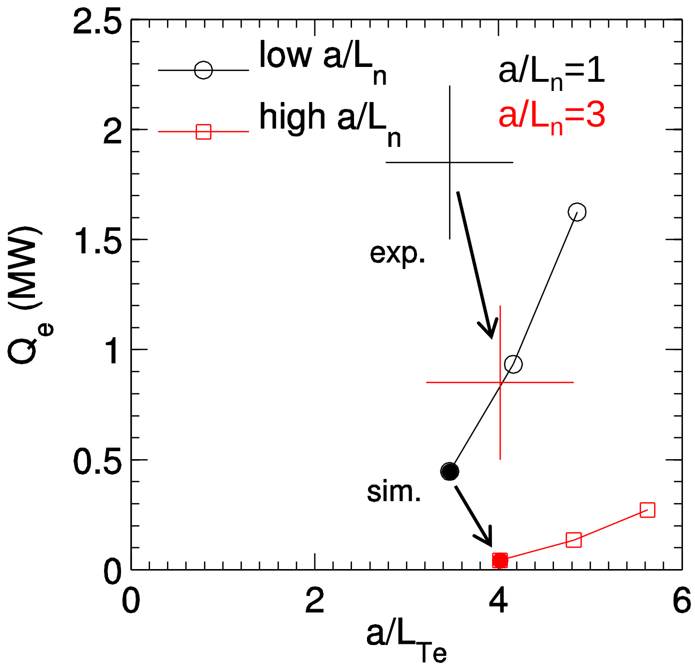
Predicted ETG transport



- Predicted ETG transport independent of ν_e ($\nu_e << \omega$)

Stiffness of ETG transport depends on ∇n

- Increase in core (r/a≈0.6) density gradient before/after large ELM leads to reduction in experimental transport and high-k scattering intensity [1]



[1] Y. Ren et al., Phys. Plasmas (2012); Phys. Rev. Lett. (2011).

Stiffness of ETG transport depends on ∇n

- Increase in core ($r/a \approx 0.6$) density gradient before/after large ELM leads to reduction in experimental transport and high-k scattering intensity [1]

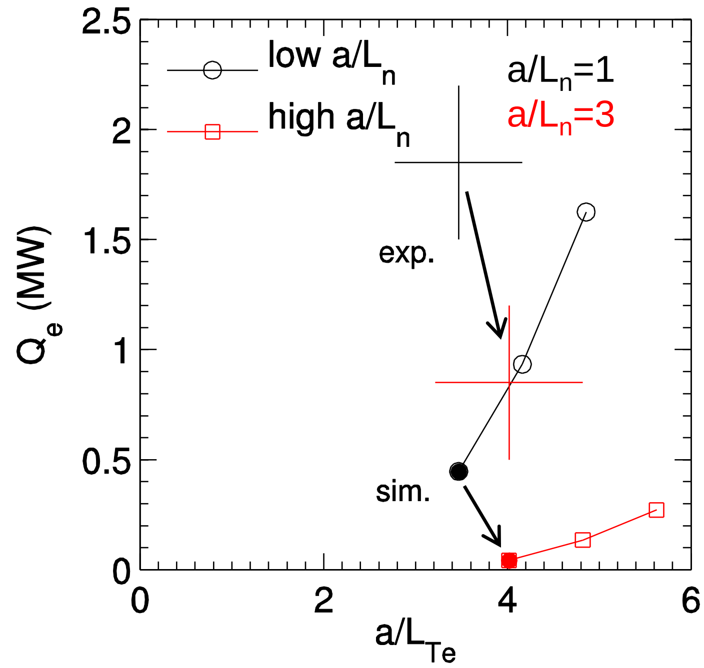
- Consider critical gradient model for ETG:

$$\chi_e = \underline{\frac{\rho_s^2 c_s}{a}} \cdot \left[\left(\frac{R}{L_{Te}}\right) - \underline{\left(\frac{R}{L_{Te}}\right)_{crit}} \right] \cdot \underline{F(s,q,\ldots)}$$

Little variation in $\rho_s^2 c_s/a \approx 1.4\ \mathrm{m^2/s}$

~25% increase in effective threshold

⇒ **Large a/L_n decreases ETG stiffness (F) regardless of threshold**



- Strong correlation between $Q_{e,ETG}$ and a/L_n also found in low-β ν_*-scan discharges with apparent nonlinear threshold $\eta_e = L_n/L_{Te} \sim 1.5\text{-}2.0$
- Higher density gradient causes electrostatic TEM to be unstable

[1] Y. Ren et al., Phys. Plasmas (2012); Phys. Rev. Lett. (2011).

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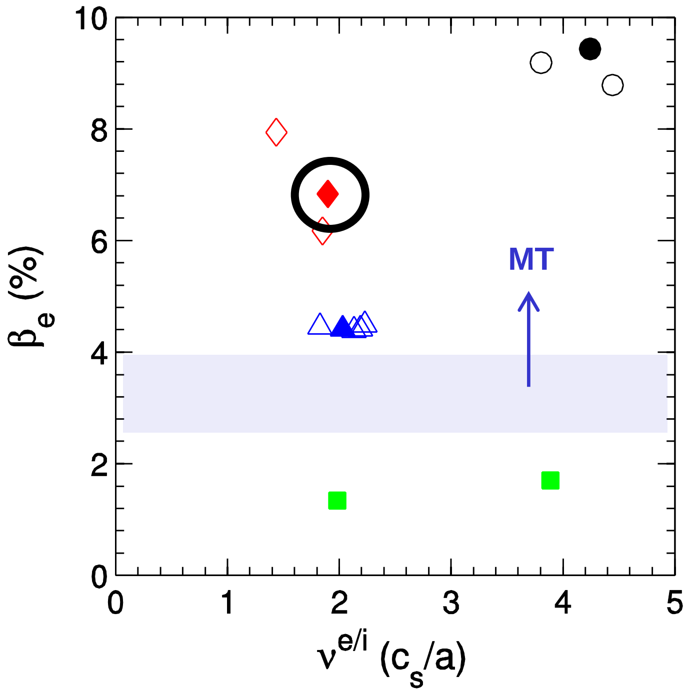
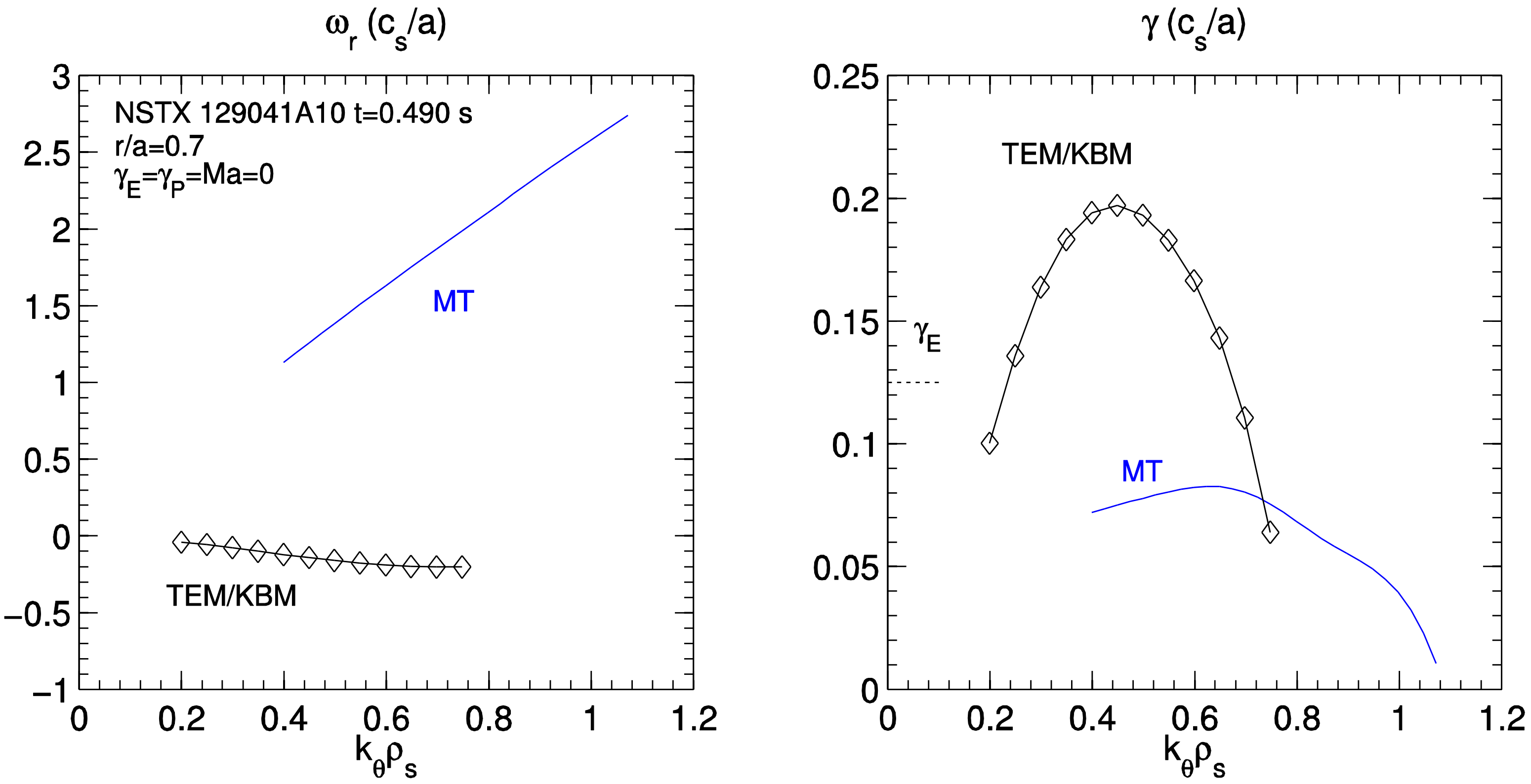


Different ion scale instabilities can overlap simultaneously

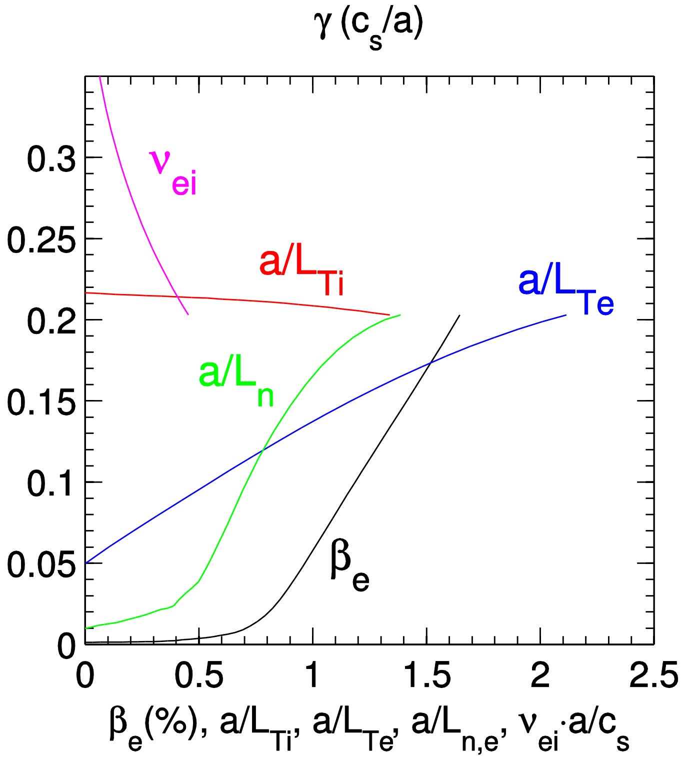
- Low ν_* discharge with Lithium (129041 [Kaye, Maingi]) shows microtearing unstable but subdominant to ballooning mode (r/a=0.7)
- Ballooning mode disappears in absence of compressional perturbations ($B_{||}$)



- What is the nature of these ion scale ballooning modes?

Ballooning mode scales like TEM, but very sensitive to beta like KBM

- Destabilized by a/L_{Te}, a/L_n, weakly dependent on a/L_{Ti}, stabilized by ν_e (like TEM)
  - $\gamma \sim 1/\nu_e$ scaling opposite to MT and confinement scaling



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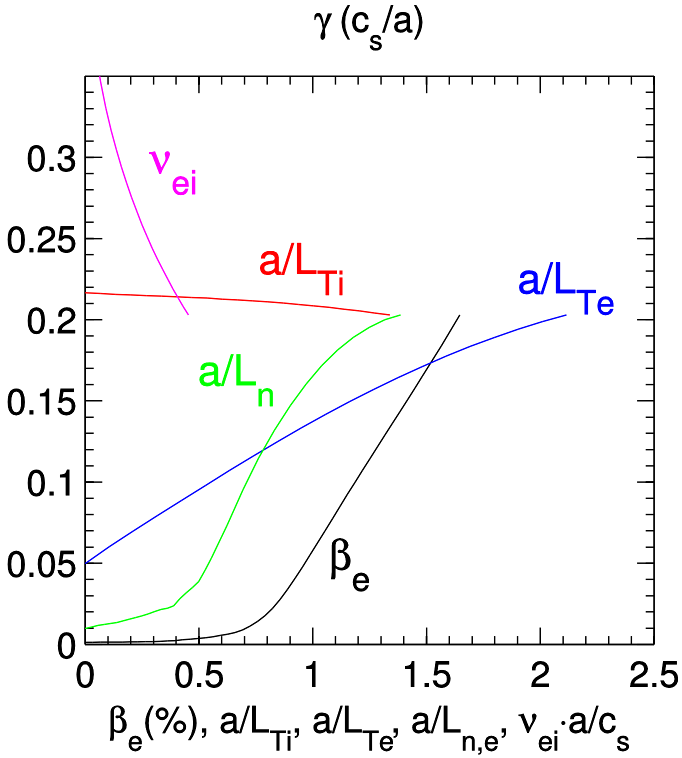
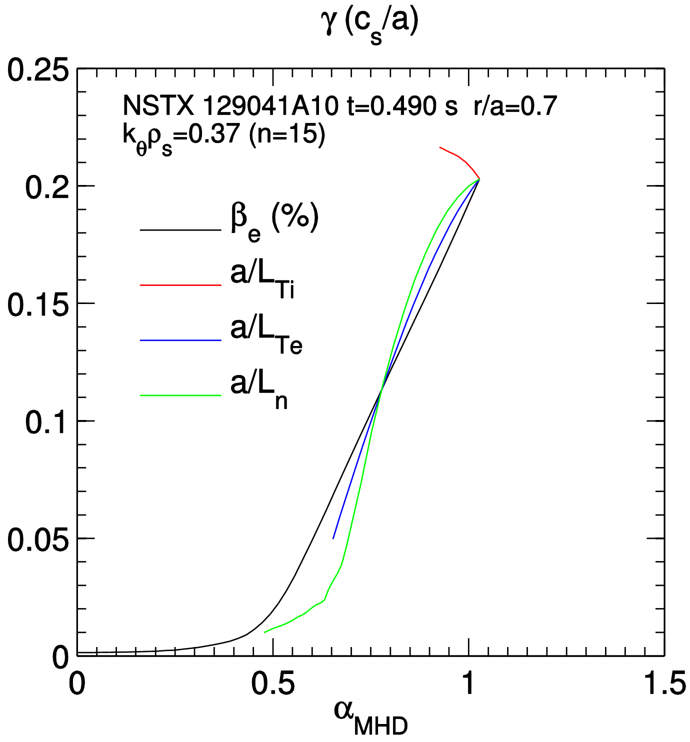
- Destabilized by a/L_{Te}, a/L_n, weakly dependent on a/L_{Ti}, stabilized by ν_e (like TEM)
  - $\gamma \sim 1/\nu_e$ scaling opposite to MT and confinement scaling
- Growth rate scaling largely unified by $\alpha_{mhd} = -q^2 R \nabla\beta$, $\nabla\beta \sim \beta_e \sum_s \frac{n_s}{n_e}\frac{T_s}{T_e}\left(\frac{a}{L_{n,s}} + \frac{a}{L_{T,s}}\right)$ → expected for ideal/kinetic ballooning mode (KBM)

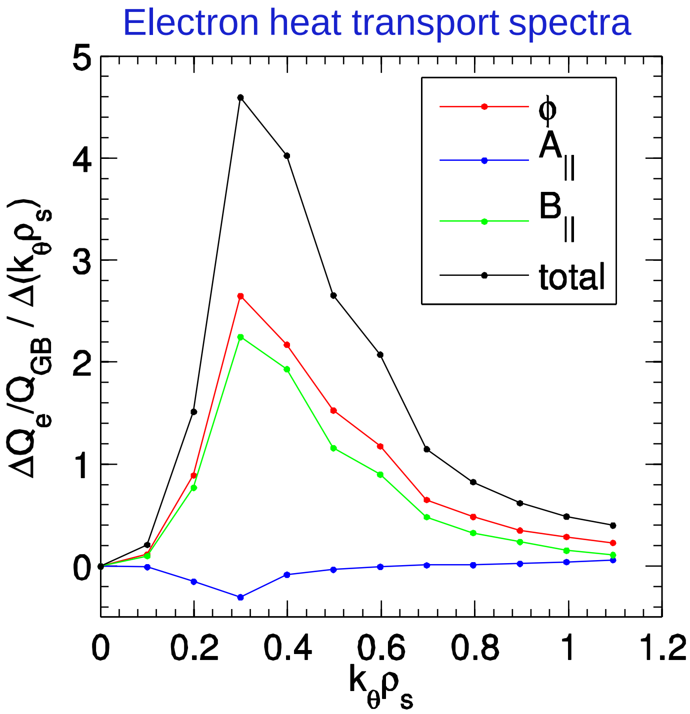




- Similar behavior predicted in linear pedestal simulations [Canik, EX/P7-16]

Nonlinear TEM/KBM simulations predict significant transport in all channels from both φ and $B_{||}$ perturbations

- $Q_{e,sim} \approx 2$ MW, $Q_{i,sim} \approx 1.5$ MW ($P_{NBI}=3$ MW)
- Nearly half of transport from $\delta B_{||}/B \sim 0.08\%$



Electron heat transport spectra

$L_x,L_y = 69,63\ \rho_s$
nx,ny = 140,12
D,C; $\varphi, A_{||}, B_{||}$
$\gamma_E=0$

- Including finite $dV_{||}/dr \rightarrow$ momentum transport $\Pi_{i,sim} \sim 0.3$ N·m ($\Pi_{i,exp} > 1$ N·m)
  - May reconcile scenarios with anomalous χ_e, χ_φ, near neoclassical χ_i [Kaye, NF (2009)]
  - Suppressible by experimental E×B shear

Summary: Many turbulence mechanisms predicted over broad range of parameter space (especially β)

(1) First nonlinear microtearing (MT) simulations predict significant electron transport from magnetic flutter (~B_r)

- $\gamma, \chi_e \sim \nu_e^{+1}$
- Stiff with β_e and a/L_{Te} (suppressible by E×B shear)

(2) ETG predicts significant electron transport, in some scenarios

- $\gamma, \chi_e \sim \nu_e^{0}$
- Stiffness depends on ∇n_e

(3) TEM/KBM simulations predict large transport in all channels from φ and $B_{||}$

- $\gamma \sim \nu_e^{-1}$
- Stiff with $\alpha_{MHD} \sim \nabla\beta$ (suppressible by E×B shear)

Unlikely that one mechanism or parameter can theoretically describe transport scaling → predictive modeling

Backup slides

Attempting to validate gyrokinetic simulations using NSTX experimental data

- Comparing to experimental transport and sensitivity to parametric variations

- Following nonlinear simulations based on 8 NSTX discharges:
  - H-mode ν_* scaling experiments, without Lithium wall conditioning
  - H-mode scan of Li-deposition for wall conditioning (will be referring to “pre-Li” and “post-Li”)
  - “Low beta” H-mode ν_* scaling
  - Reverse shear L-modes with electron internal transport barrier (e-ITB)

- Using Eulerian gyrokinetic code GYRO [1-3], almost all cases use:
  - Numerical equilibrium
  - Two ion species (D,C)
  - Fully electromagnetic perturbations (φ, $A_{||}$, $B_{||}$)
  - Cases usually run without and with toroidal flow/flow shear ($Ma \sim v_{Tor}$, $\gamma_P \sim dv_{||}/dr$, $\gamma_E \sim d(E_r)/dr$)

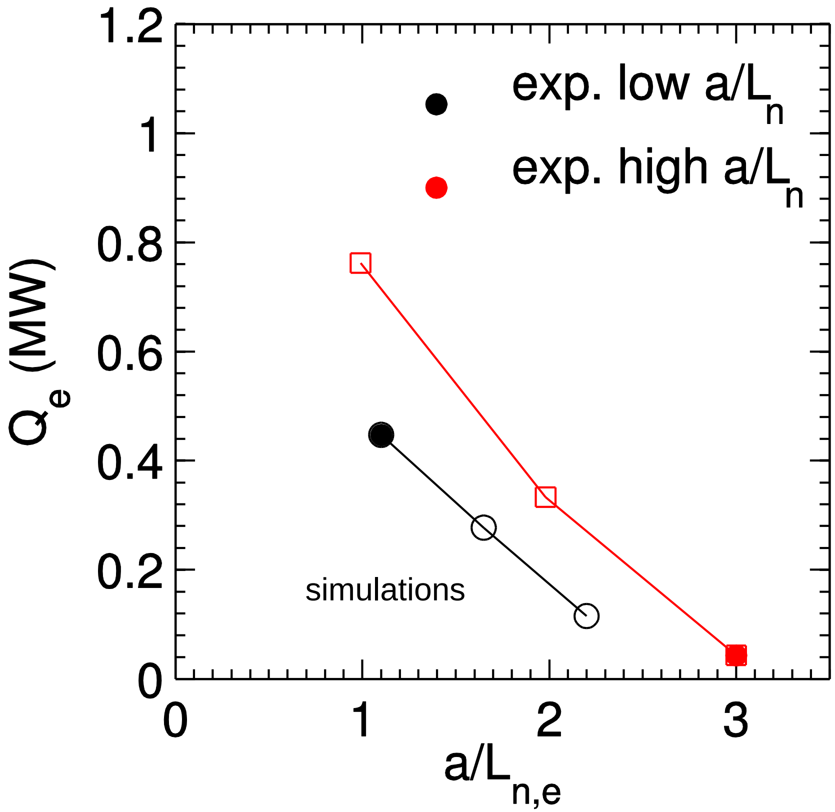
- Most simulations are *local* → **non-local/global effects ($\rho_* = \rho_s/a \sim 1/120$, $\rho_s/L \sim 1/50$) almost certainly will change results quantitatively**

[1] J. Candy, R.E. Waltz, J. Comput. Phys. **186**, 545 (2003); [2] J. Candy, E.A. Belli, General Atomics Report **GA-A26818** (2010).
[3] E.A. Belli, J. Candy, Phys. Plasmas **17**, 112314 (2010).

Increase in density gradient leads to reduction in experimental transport and high-k scattering intensity [1]

- Core (r/a≈0.6) a/L_n increased due to large ELM
- Local experimental transport and high-k scattering intensity reduced
- Scaling reproduced by nonlinear ETG simulations

$Q_{e,exp}$=0.8-1.8 MW



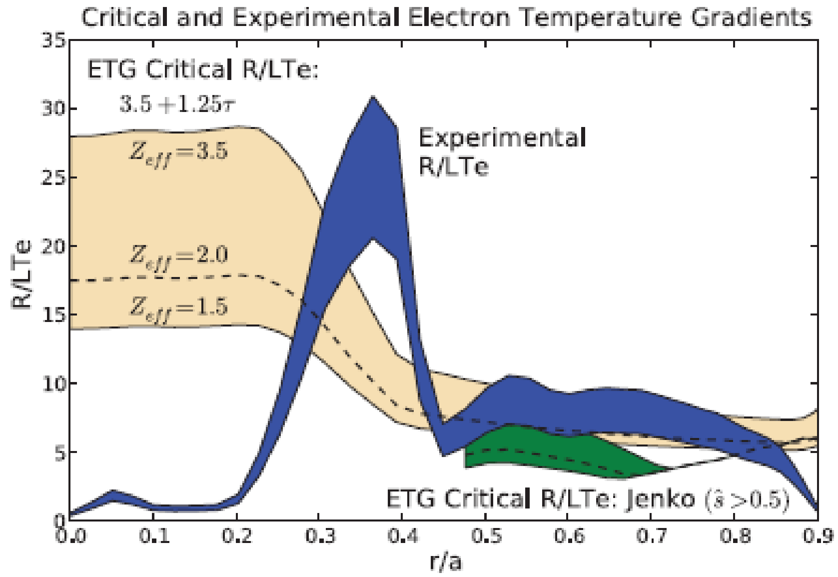
[1] Y. Ren et al., Phys. Plasmas (2012); Phys. Rev. Lett. (2011).

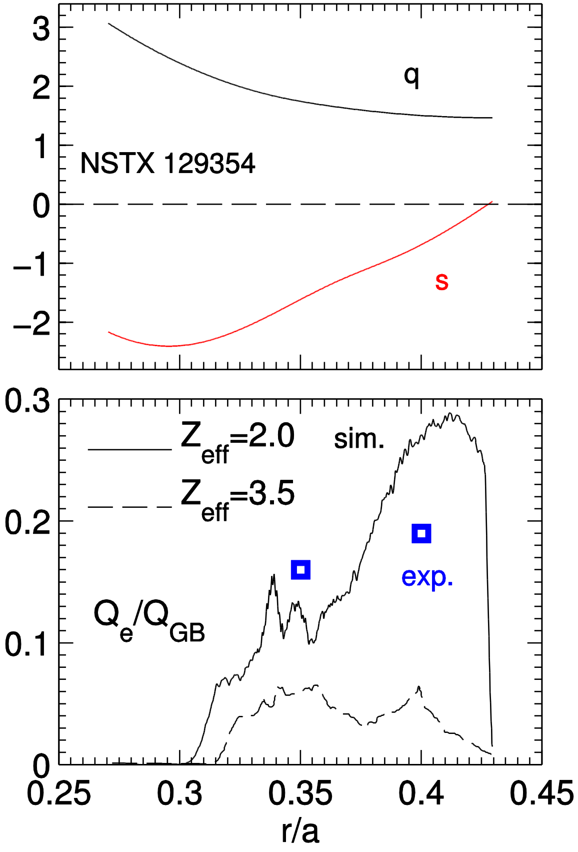
ETG transport minimized with strong negative magnetic shear in e-ITBs

- L-mode (RF) with e-ITB for strong negative magnetic shear (s<<0)
- ETG linearly unstable around transport barrier
- *Non-local* ETG simulations show transport reduced in region of min(s)
- Sensitive to uncertainty in Z_{eff} due to linear threshold, $(R/L_{Te})_{crit} \sim (1+Z_{eff}T_e/T_i)\cdot(\ldots)$

Non-local simulations

$L_x, L_y = 14.3, 2.4\ \rho_s$
nx,ny = 864,24

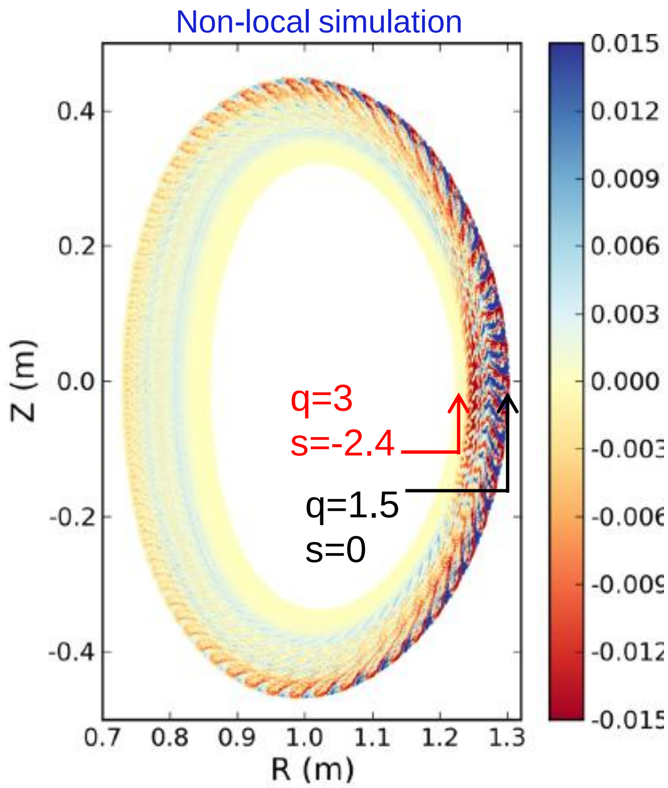


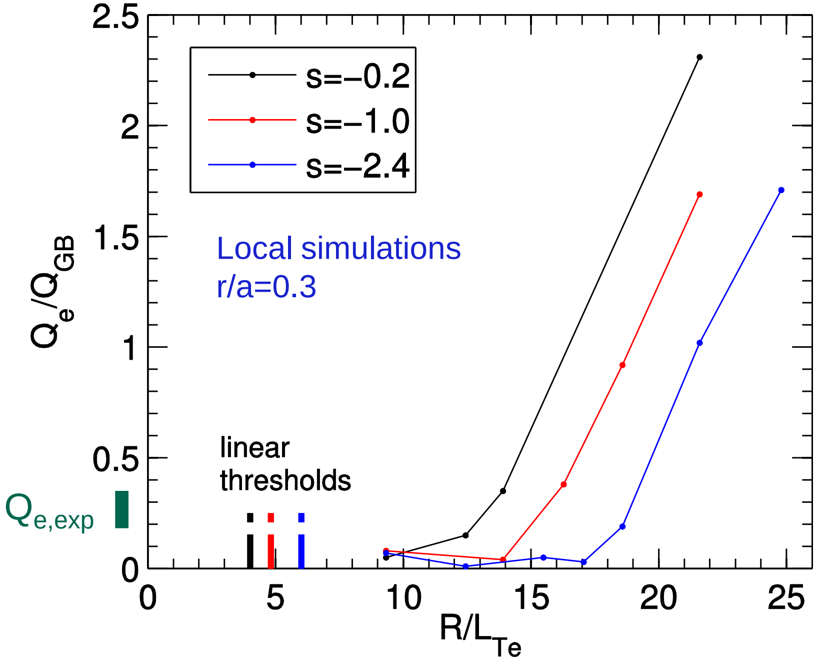


H. Yuh et al., Phys. Rev. Lett. **106**, 055003 (2011).
J.L. Peterson et al., Phys. Plasmas **19**, 056120 (2012).

ETG transport suppressed by large negative magnetic shear, consistent with formation of e-ITB

- e-ITB's in RF L-modes correlated with strong negative magnetic shear (s<<0)
- Negligible turbulence or transport near min(s) in "global" ETG simulations
- Effective nonlinear gradient for significant transport, R/L_{Te}~12-18 ($s = -0.2 \rightarrow -2.4$) much larger than linear thresholds, R/L_{Te}~4-6
  - Nonlinear upshift much larger than ITG "Dimits" shift, ~30% [Dimits, 2000; Mikkelsen, 2008]


Non-local simulation



H. Yuh et al., Phys. Rev. Lett. (2011). J.L. Peterson et al., Phys. Plasmas (2012).

Nonlinear TEM/KBM simulations predict significant transport, from both φ and $B_{||}$ perturbations

- Significant transport in all channels (heat, particles), nearly half from $\delta B_{||}/B \sim 0.08\%$
- Spectra peak around $k_\theta \rho_s \sim 0.3$, MT apparent early in $A_{||}$ but does not survive

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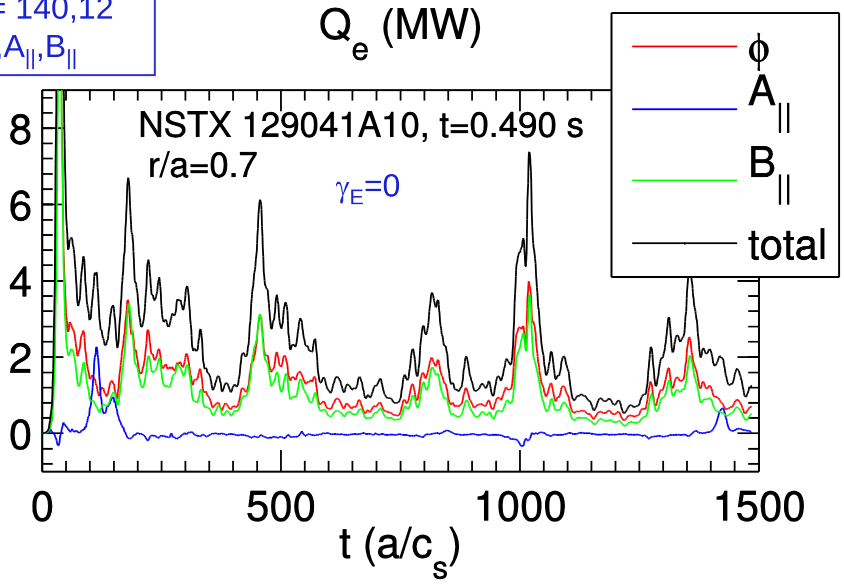

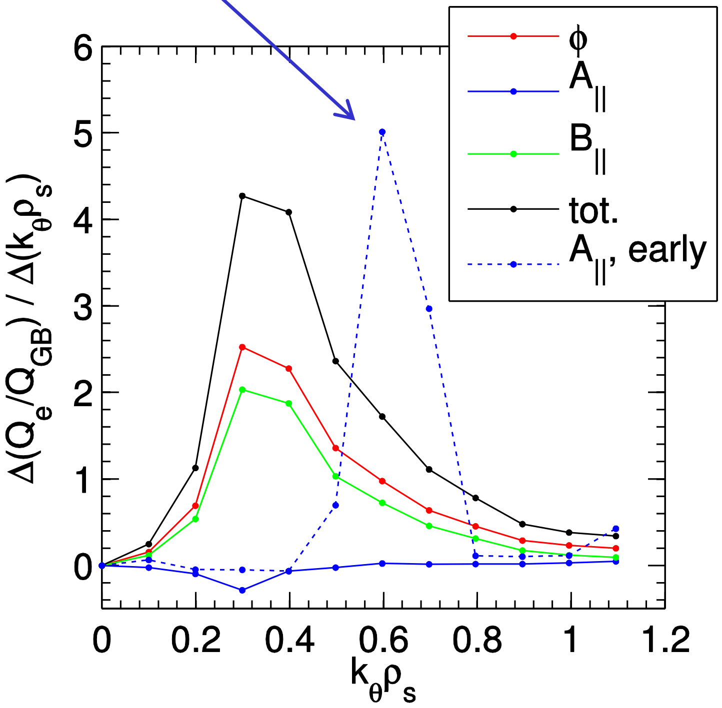

- Including finite $dV_{||}/dr$ & V_{Tor} →momentum transport ($\Pi_{i,sim} \sim 0.3$ N·m; $\Pi_{i,exp} \sim 1\text{-}1.5$ N·m)
  - May reconcile scenarios with anomalous χ_e, χ_φ, near neoclassical χ_i [Kaye, NF (2009)]
  - However, significantly suppressed when also including E×B shear