NSTX-U

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Survey of microinstability and simulated turbulent transport in NSTX

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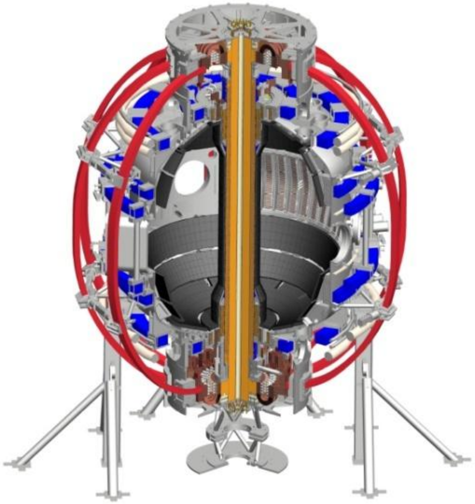

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Motivation: Understand mechanism(s) responsible for thermal, momentum, particle transport over broad range of parameters

- 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, IAEA 2012 EX/7-1]

  $\Rightarrow$ 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 [IAEA 2012: Canik (EX/P7-16), Diallo (EX/P4-04), Kubota (EX/P7-21), Maingi (EX/11-2), Smith (EX/P7-18)]
  - Energetic particle driven instabilities [IAEA 2012: Belova, TH/P6-16; Crocker, EX/P6-2]

Attempting to validate gyrokinetic simulations using NSTX experimental data

- Comparing to experimental transport and sensitivity to parametric variations

- Following simulations based on many NSTX discharges:
  - H-mode ν_* scaling experiments, without Lithium wall conditioning [Kaye NF 2007; IAEA 2012]
  - H-mode scan of Li-deposition for wall conditioning (will be referring to "pre-Li" and "post-Li") [Maingi PRL 2011, IAEA 2012]
  - "Low beta" H-mode ν_* scaling [Ren PoP 2012]

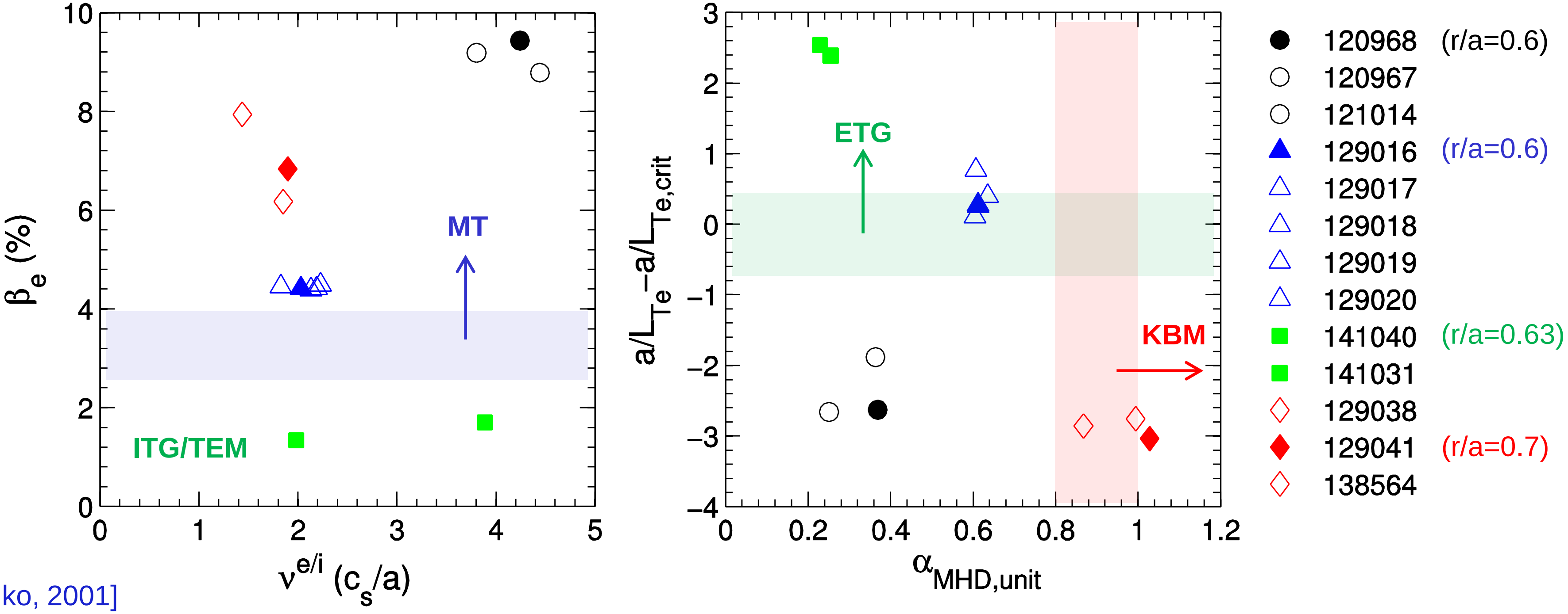
- Using Eulerian gyrokinetic code GYRO [1-3], almost all cases use:
  - Numerical equilibrium
  - Two ion species (D,C)
  - Fully electromagnetic perturbations (φ, $A_{||}$, $B_{||}$)
  - Cases usually run without and with toroidal flow/flow shear ($Ma \sim v_{Tor}$, $\gamma_P \sim dv_{||}/dr$, $\gamma_E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

- All 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).

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 $a/L_{Te} > a/L_{Te,crit}$ (high and low β_e)
- Microtearing tearing (**MT**) found at sufficiently high β_e and ν_{ei}
- **KBM** unstable at high $\alpha_{mhd} \sim \nabla\beta$



[Jenko, 2001]

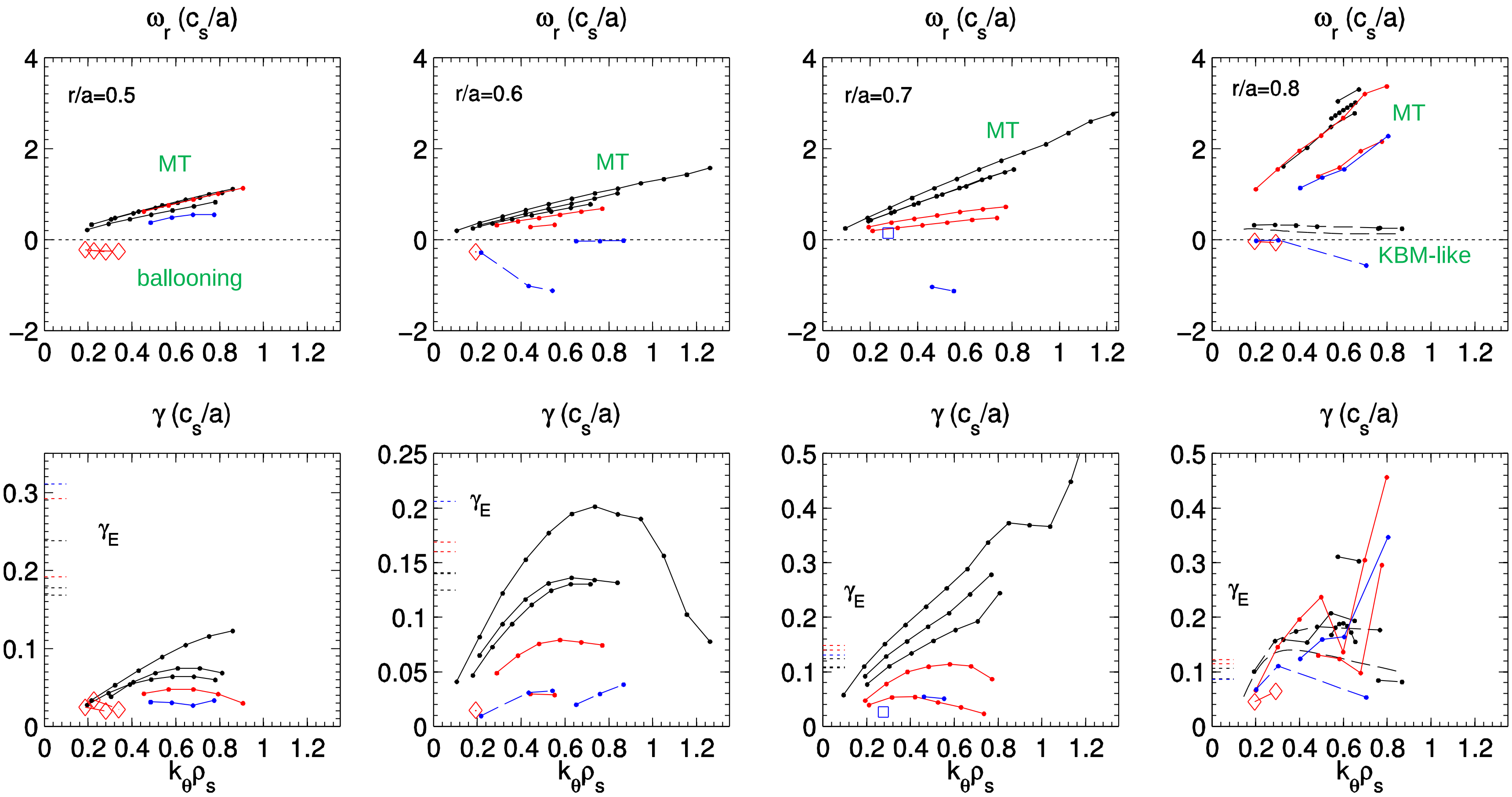
$$\left(\frac{R}{L_{Te}}\right)_{crit}^{etg} = \max\left\{\begin{array}{c}(1+Z_{eff}T_e/T_i)\cdot(1.3+1.9s/q)\cdot(\cdots)\\ 0.8R/L_{ne}\end{array}\right\}$$

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

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

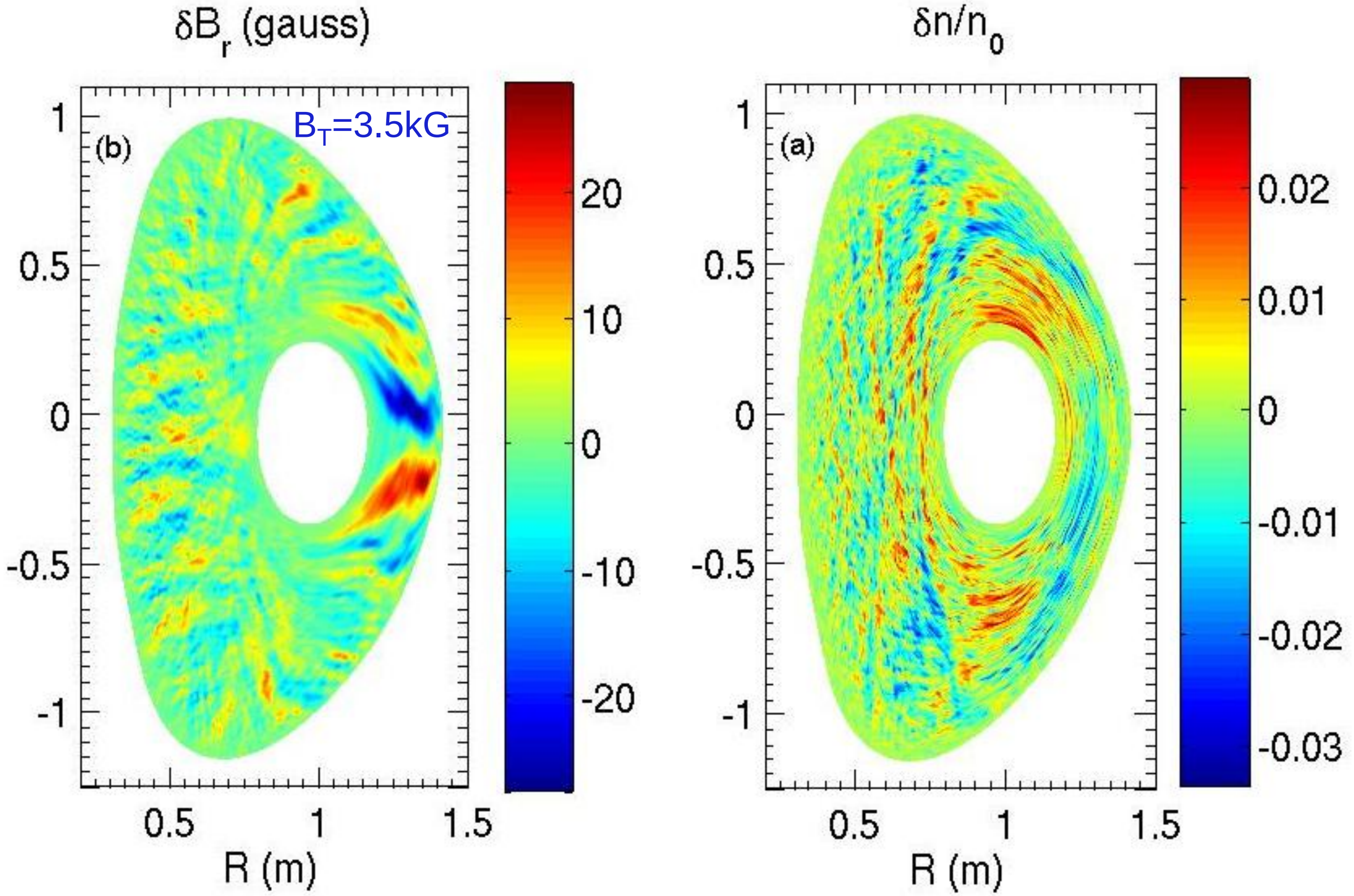
Microtearing prevalent in older ν_* discharges (2006 data, without Li wall conditioning)

- Color coding in plots: 3 high ν_*, 2 med ν_*, 2 low ν_* [Kaye NF 2007]
- Microtearing dominates r/a=0.5-0.8; ETG almost entirely stable throughout (not shown)
- At r/a=0.8 other ballooning modes (KBM) compete with MT (more later)
- $\gamma_{lin,max}/\gamma_E$ increases with r/a



Nonlinear microtearing (MT) simulations for high ν_* discharge predict large δB_r and dominant magnetic flutter transport

- $\chi_{e,em}$≈6 m^2/s from $\delta B_r/B$~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 ρ_s
nx,ny = 540,16
D only; φ, $A_{||}$
γ_E=0

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

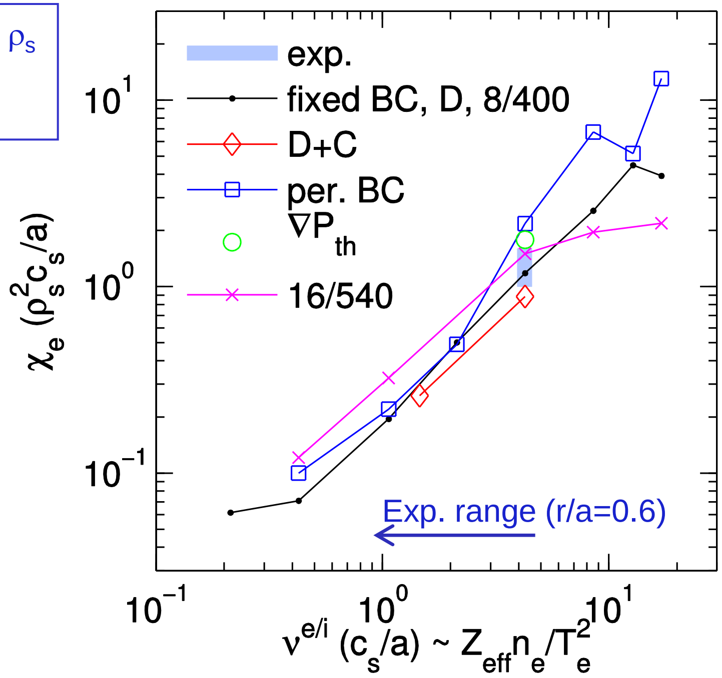
Toroidal mode numbers:
n≈5-40

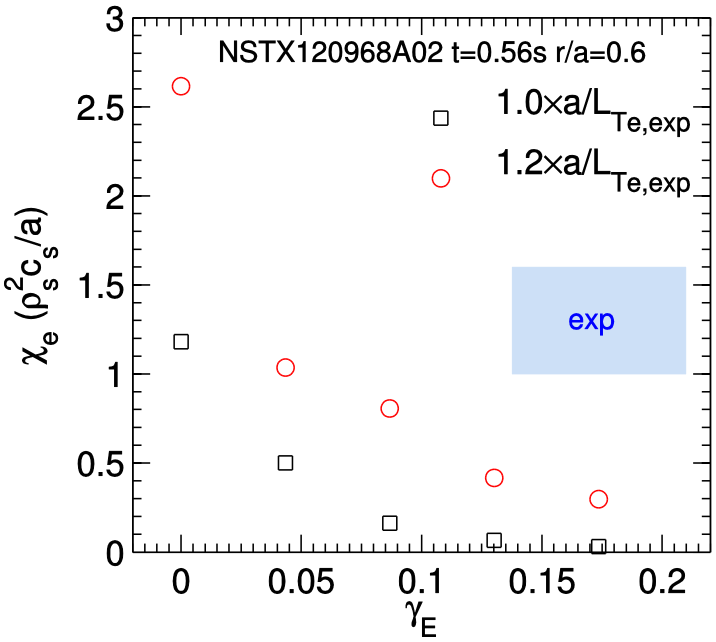
W. Guttenfelder et al., Phys. Rev. Lett. (2011); Phys. Plasmas (2012).

MT transport increases with collisionality consistent with confinement scaling

- Possible component of confinement scaling in NSTX ($\Omega\tau_E \sim \nu^{*-0.8}$)
- However, also suppressed by E×B shear ($\gamma_{E,exp} \approx \gamma_{lin,MT}$)

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

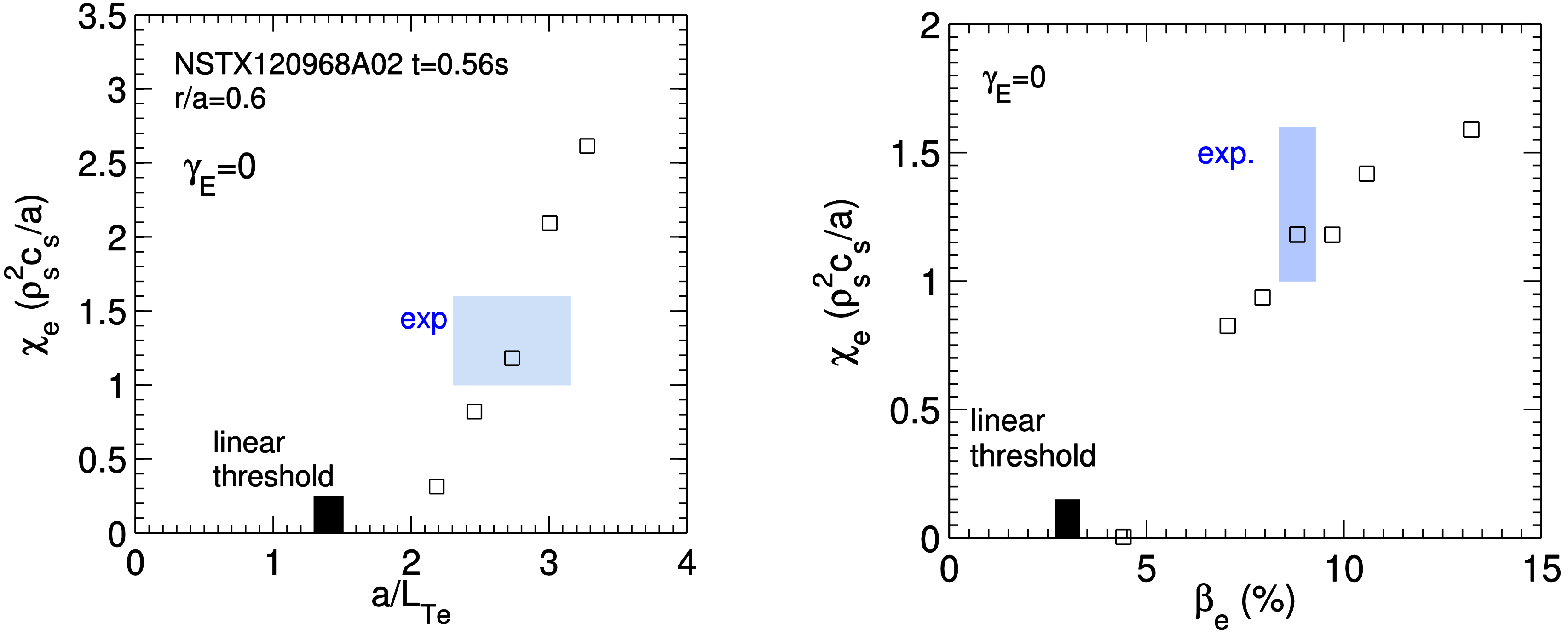




- Scaling of MT transport with ν_e confirmed for different physical and numerical assumptions: addition of impurity species (C), periodic boundary condition, equilibrium pressure gradient, perpendicular resolution (all without E×B shear)

Microtearing transport also stiff with ∇T_e and β_e

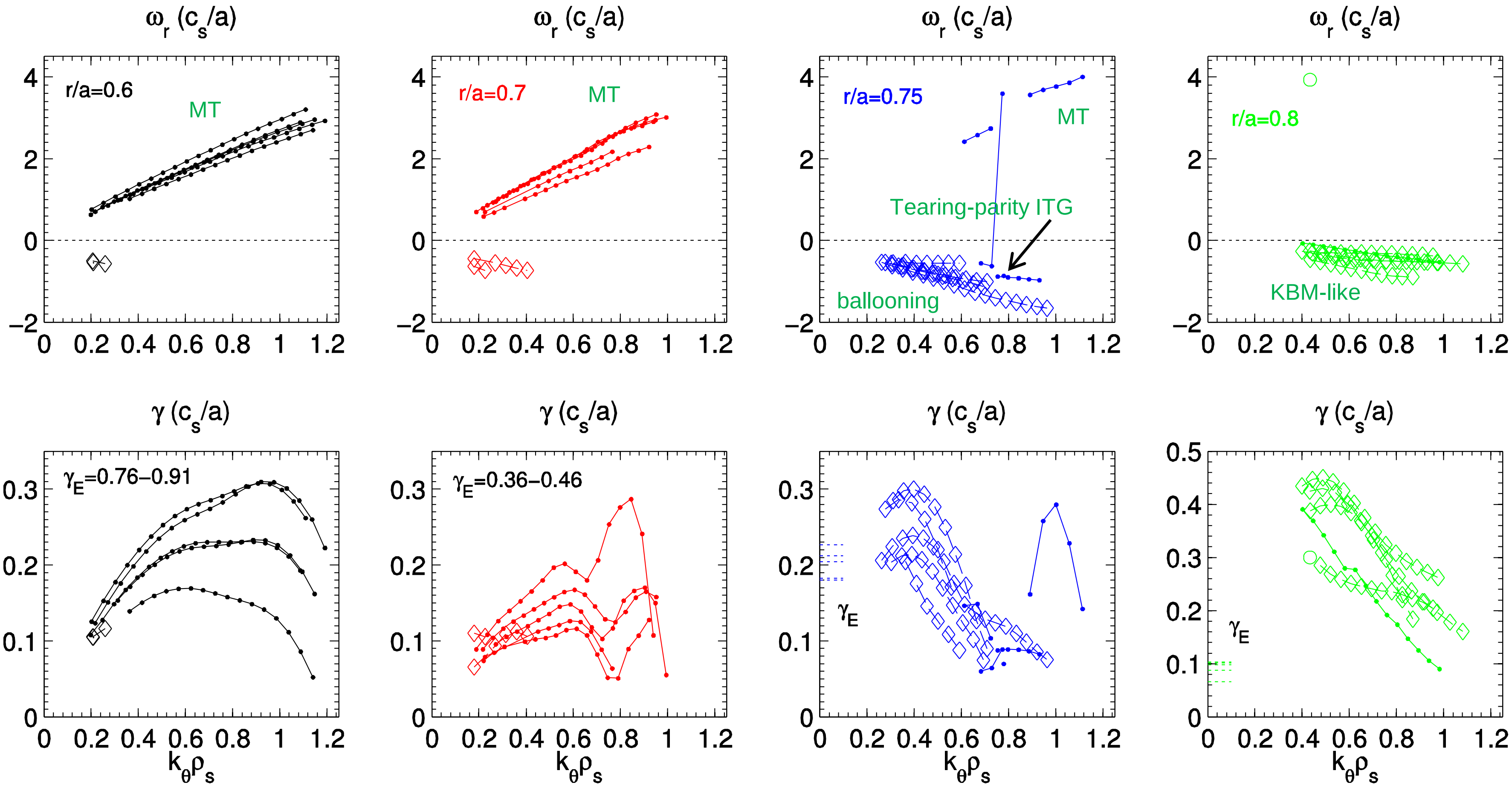
- Beta scaling not consistent with weak confinement scaling, $\Omega\tau_E \sim \beta^{-0.1}$ [Kaye, 2007]
- Useful to characterize threshold scaling for experimental interpretation and relating to MT as found conventional tokamaks [Doerk, PRL (2011), PoP (2012)]



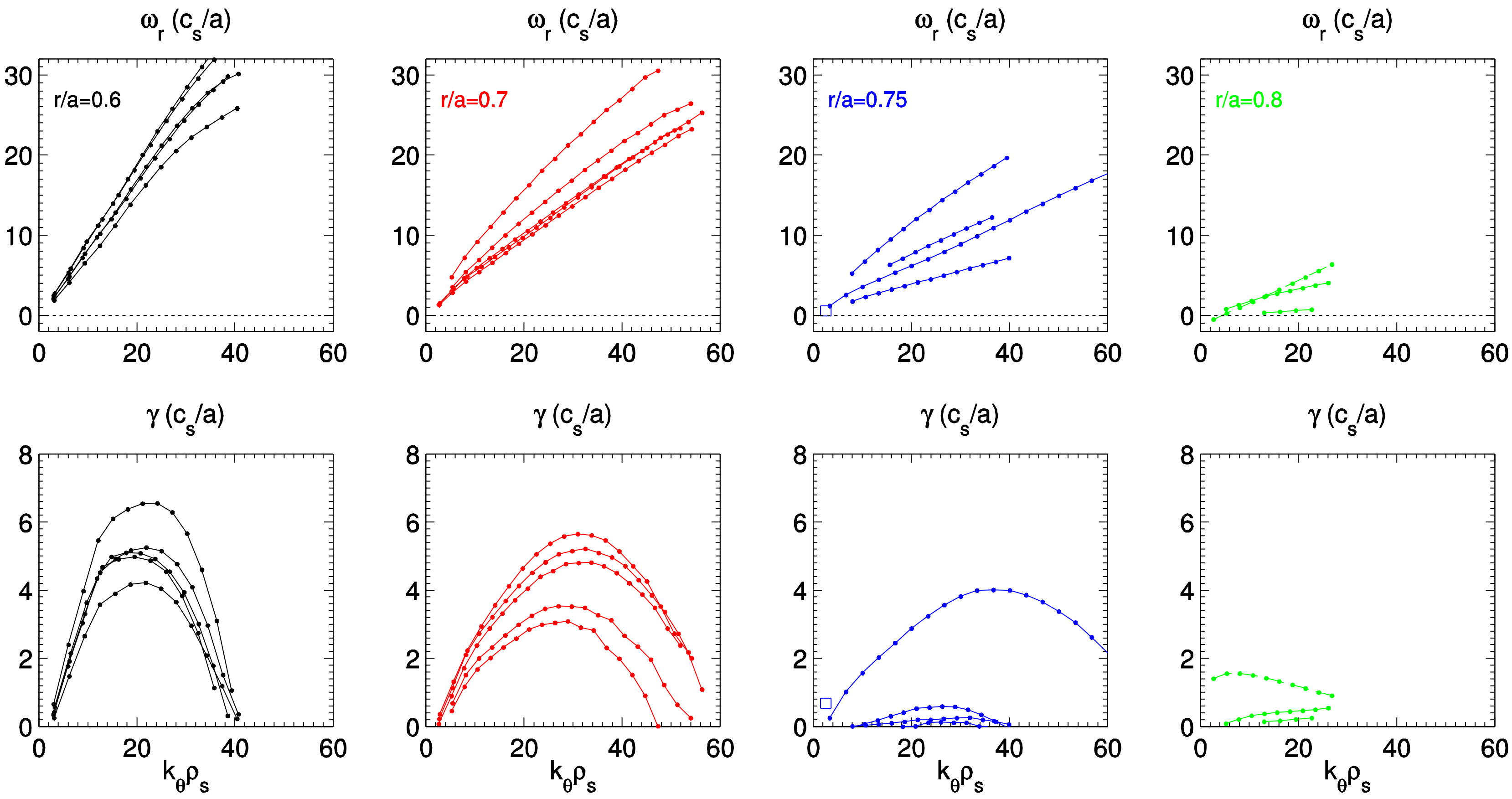
⇒ Confinement scaling unlikely described by any individual theory parameter (e.g. ν_e, β, ...), requires transport modeling

Microtearing also unstable in “pre-Lithiated” shots from Li deposition scan (2008 data, Maingi PRL 2011, IAEA 2012)

- Five similar discharges (129016-129020), MT strongest at r/a=0.6-0.7
- Ballooning modes dominate at r/a=0.75-0.8 (different from 2006 data)
- Very strong E×B shear at r/a=0.6-0.7…



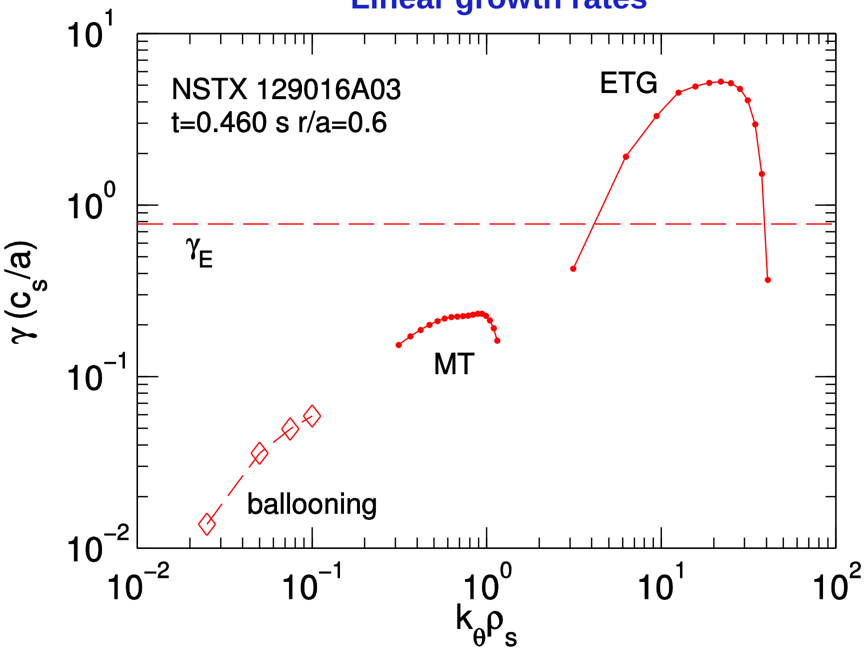
ETG strongly unstable at r/a=0.6-0.7 in “pre-Li” discharges



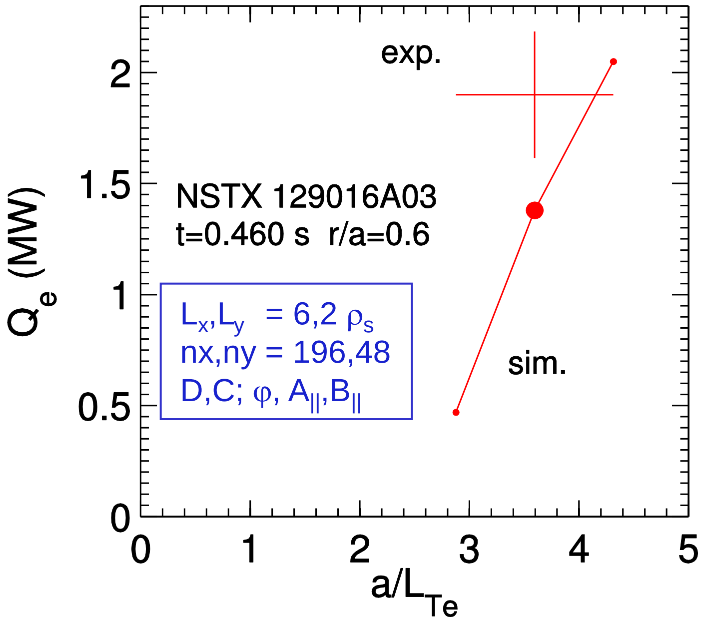
Nonlinear ETG transport significant in core of “pre-Li” discharges

- Microtearing (and ballooning) instabilities at ion scales, but $\gamma_E >> \gamma_{lin,ion}$
- ETG nonlinear transport, Q_e~1-2 MW (χ_e~10 $\rho_e^2 v_{Te}/L_{Te}$)
- Relatively stiff ($a/L_{Te,crit}$~2.2)

Linear growth rates

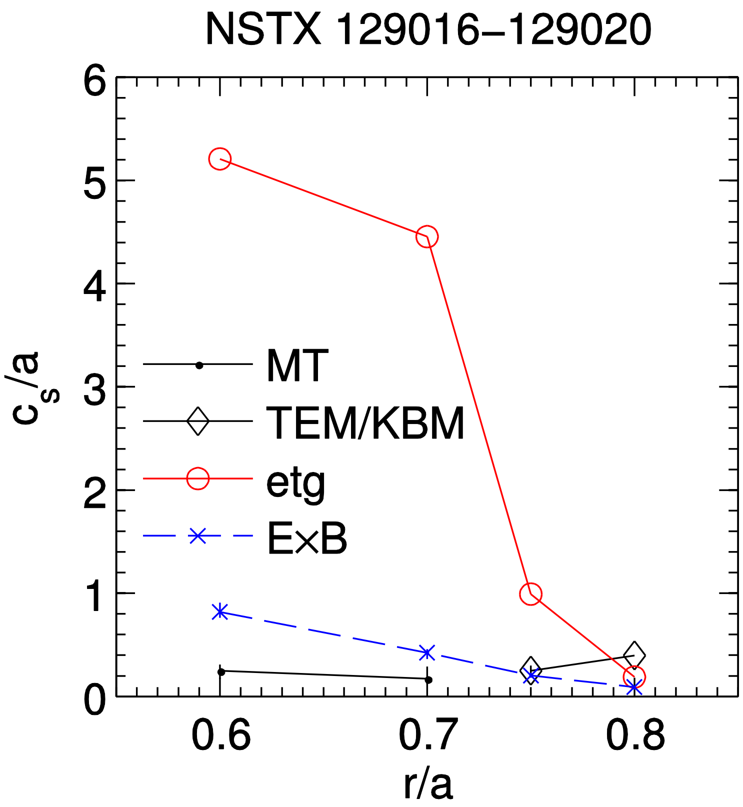


Predicted ETG transport



Multiple instabilities & profile variations (non-local effects at ρ_i scales) important to theoretically describe entire discharge

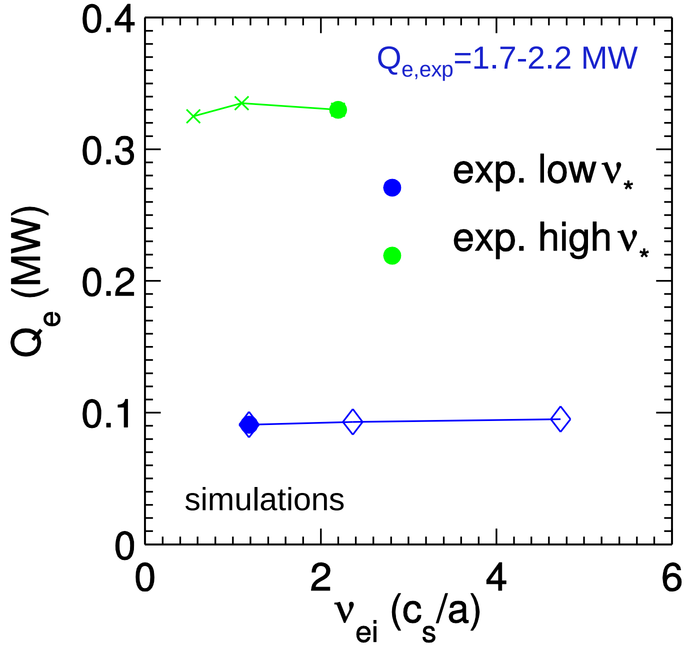
- Even over limited range of r/a=0.6-0.8, stability changes from ETG dominant (at ρ_e scales) to ballooning dominant (at ρ_i scales)
- Profile effects will matter for ion scales, $\rho_i/L \sim 1/50$
- Ideally would use multi-scale, global simulations – too expensive computationally



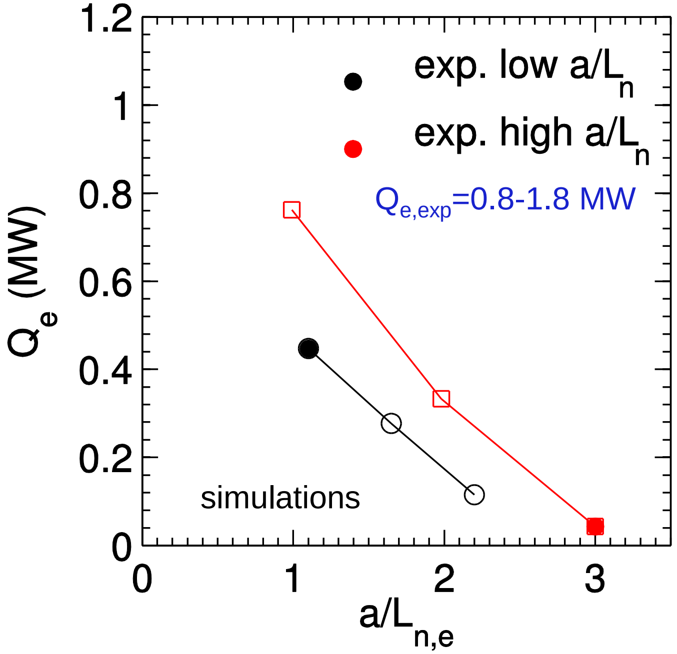
Maximum linear growth rates (ion and electron scale) and E×B shearing rates (averaged over 5 discharges)

Nonlinear ETG transport independent of ν_e, suppressed by ∇n

ν_* scaling experiment
lower n_e & P_{NBI} → lower beta



Change in core (r/a≈0.6) density gradient before/after large ELM



- Weak dependence follows linear stability ($\nu_e \ll \omega$)
- Not consistent with confinement scaling, $\Omega\tau_E \sim \nu_*^{-0.8}$

- Partially described by linear ETG threshold
- ∇n stabilization observed in reduction of high-k scattering intensity
- Higher density gradient causes electrostatic TEM to be unstable

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

Stiffness of ETG transport depends on ∇n

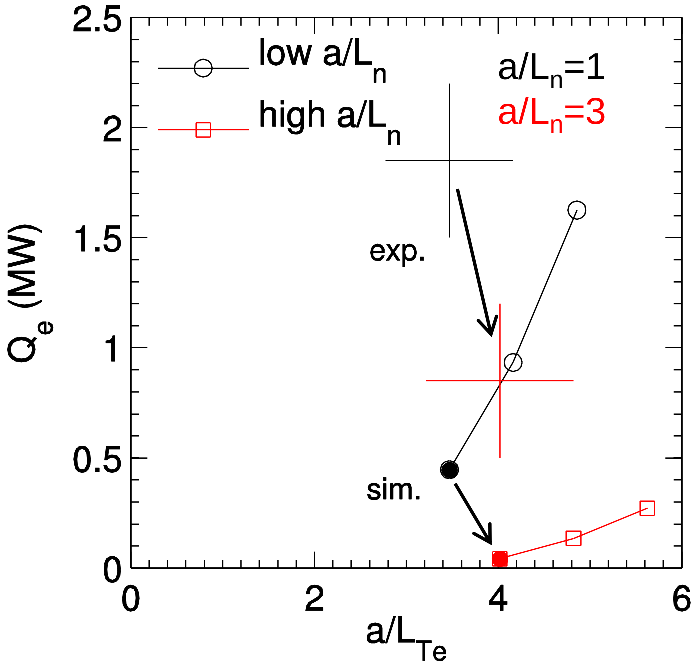
- Consider critical gradient model for ETG:

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

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

~25% increase in effective threshold →

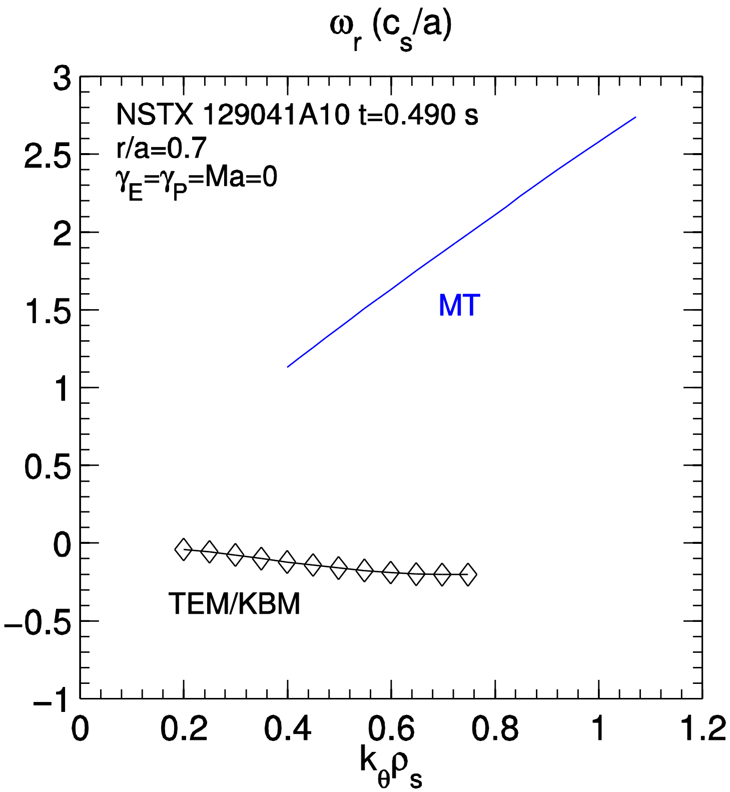
⇒ **Large a/L_n decreases ETG stiffness (F) regardless of threshold**

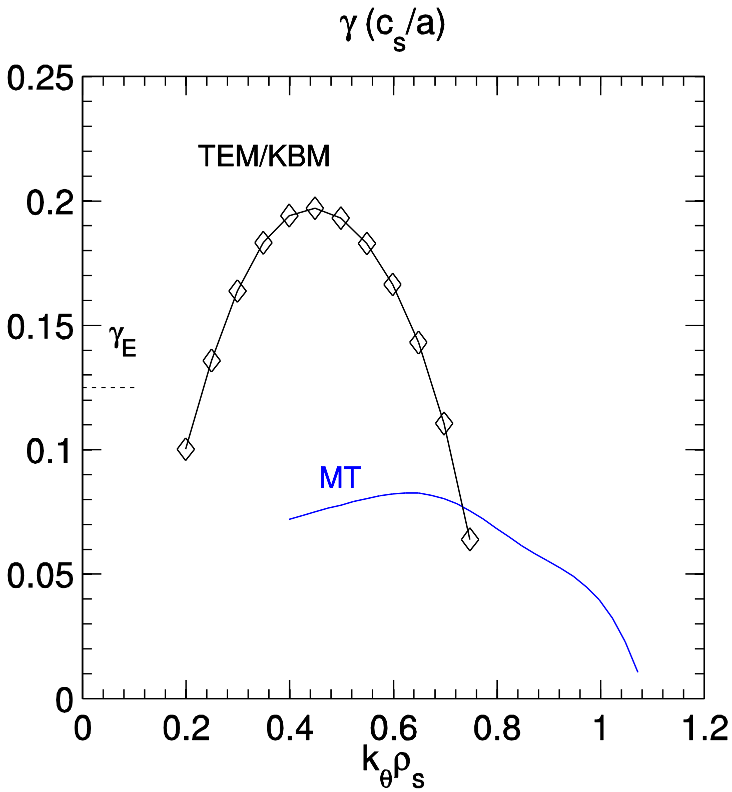


- Strong correlation between $Q_{e,ETG}$ and a/L_n also found in low-β ν_*-scan discharges with **apparent nonlinear threshold $\eta_e = L_n/L_{Te} \sim 1.5\text{-}2.0$**

Different ion scale instabilities often 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 ($B_{||}$)

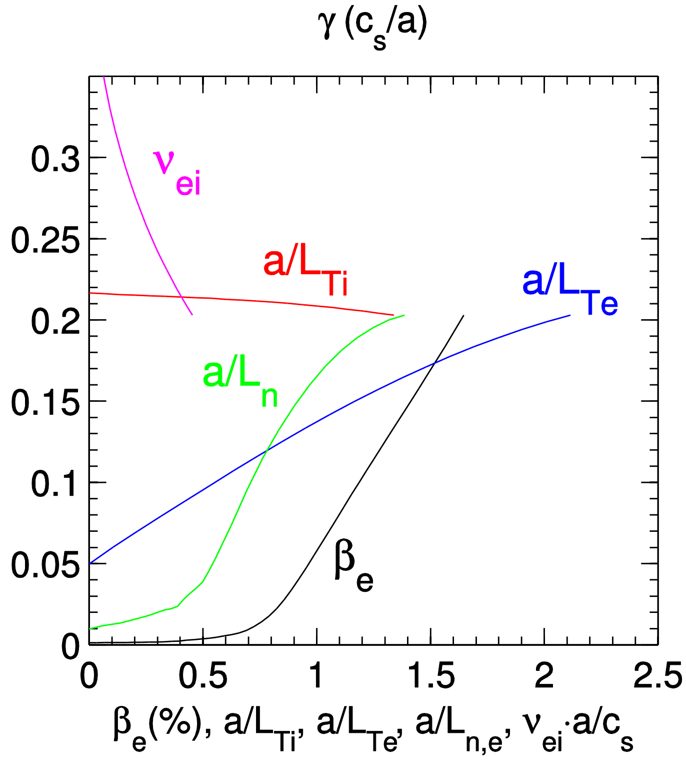


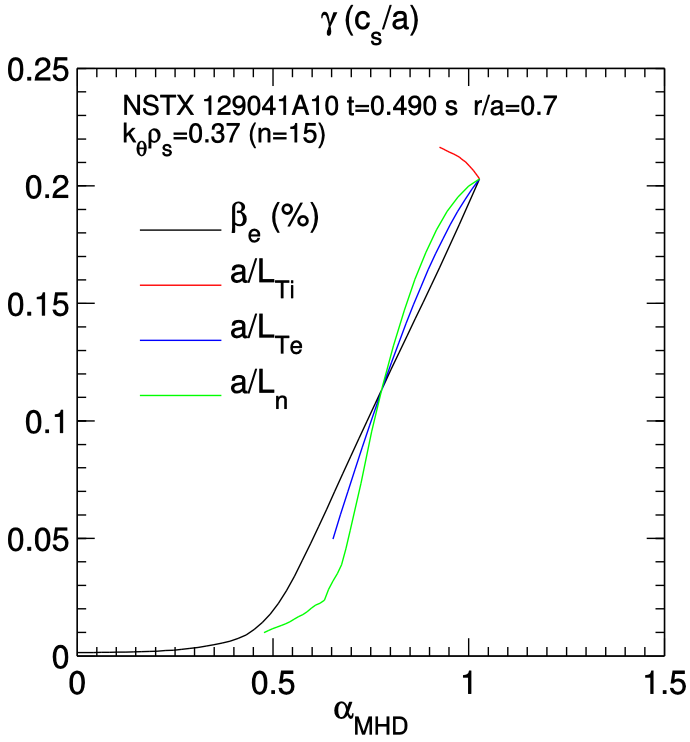


- What is the nature of these ion scale ballooning modes?

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
- Growth rate scaling largely unified by $\alpha_{mhd} = -q^2R\nabla\beta$, $\nabla\beta \sim \beta_e \sum_s \frac{n_s}{n_e}\frac{T_s}{T_e}\left(\frac{a}{L_{n,s}}+\frac{a}{L_{T,s}}\right)$
  → expected for ideal/kinetic ballooning mode (KBM)



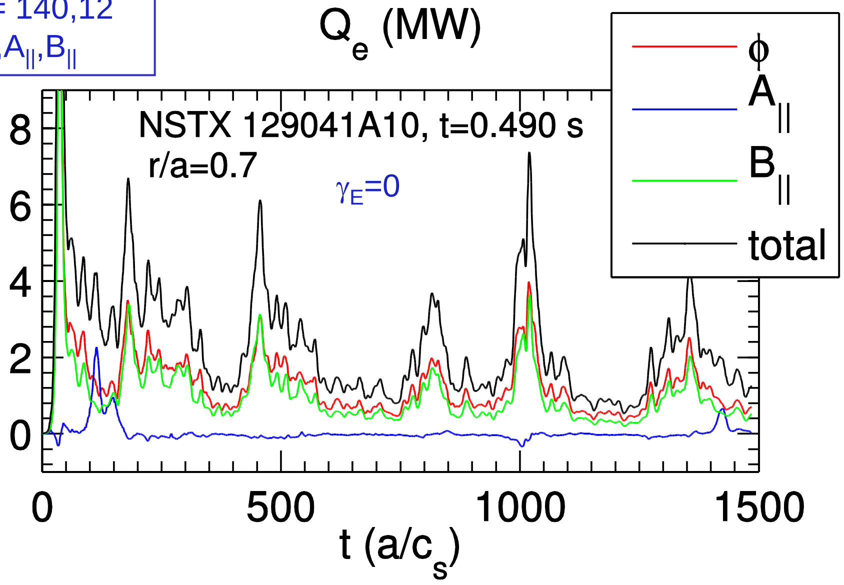


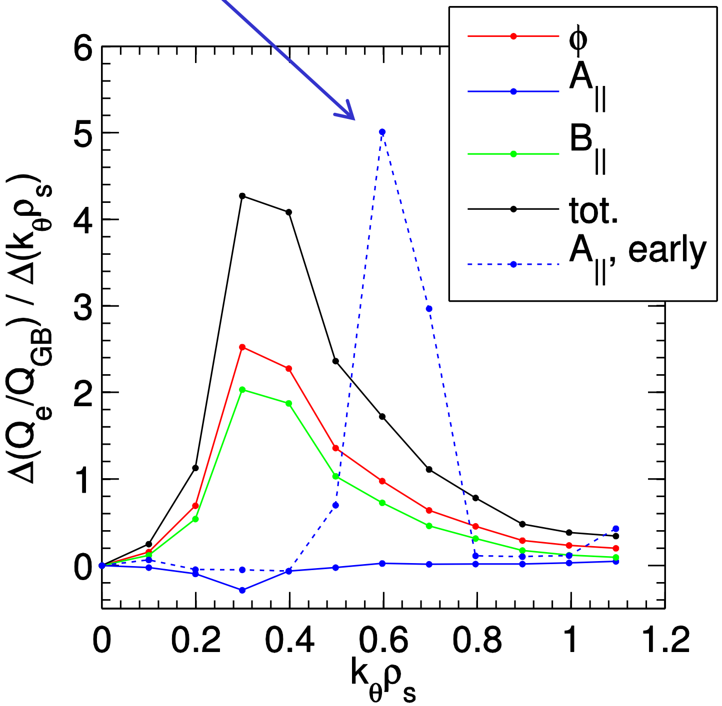
- Similar behavior predicted in linear pedestal simulations [Canik, EX/P7-16]

Nonlinear TEM/KBM simulations predict significant transport, 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

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





- 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

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

(1) Nonlinear microtearing (MT) simulations predict significant electron transport from magnetic flutter ($\sim B_r$)

- $\gamma, \chi_e \sim \nu_e^{+1}$
- 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