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Gyrokinetic predictions of momentum and impurity transport in NSTX

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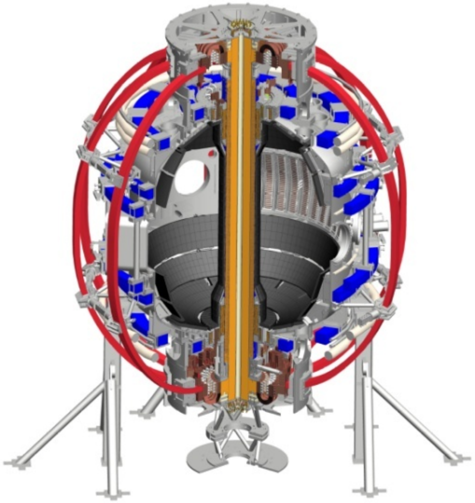

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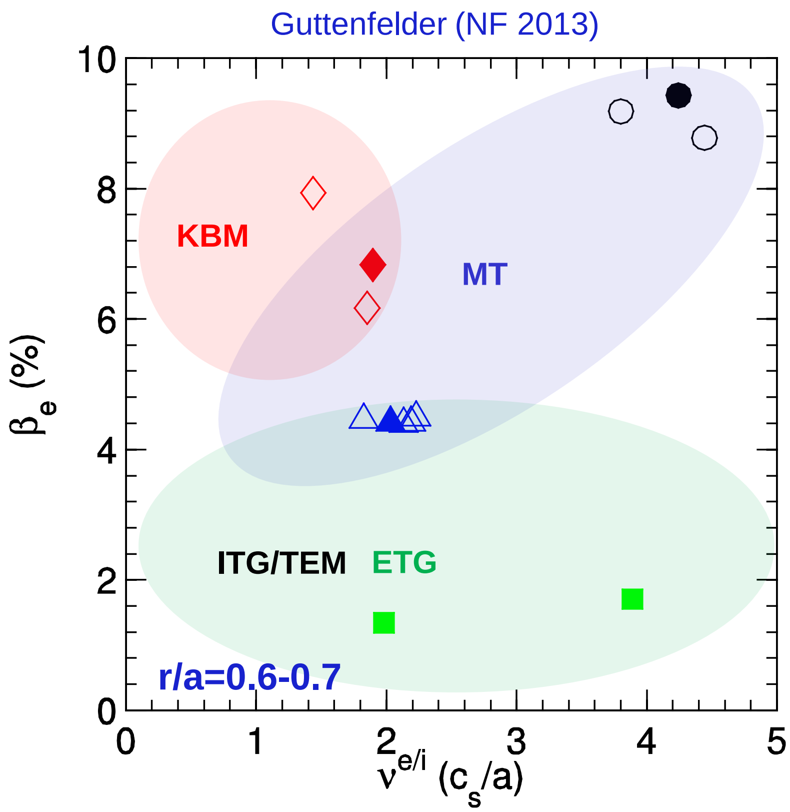
Broad range of parameters in NSTX requires consideration of many micro-instabilities



Transport Mechanism	Transport channel affected			
	ion energy	electron energy	particle/ impurity	momentum
ITG	×	×	×	×
TEM	×	×	×	×
KBM	×	×	×	×
MT		×		
ETG		×		

- All of them of interest for electron thermal transport
- Only ion scale ballooning instabilities (ITG, TEM, KBM) expected to transport momentum and impurity

⇒ Investigate multiple transport channels to help constrain theory

Summary

Momentum transport

- NSTX L-modes governed by ITG/TEM, linear simulations predict:
  - Prandlt number (Pr~0.2-0.8) generally consistent with experimental analysis (~0.5)
  - Relatively weak inward pinch ($RV_{\varphi}/\chi_{\varphi}$~ - 1) insensitive to many parameters except R/a
- NSTX n=3 magnetic perturbation H-mode experiments dominated linearly by microtearing (r/a=0.6-0.8)
  - Sub-dominant KBM exists, Pr~0.3-0.6 similar to experiment
  - Predicted $RV_{\varphi}/\chi_{\varphi}$~ -1 → +2 small/outward compared to stronger inward experimental values (-7 → -1), relatively insensitive to parameter variations

Impurity transport

- In lithiated H-mode cases where impurity carbon transport appears to be anomalous:
  - KBM modes (sub-dominant to microtearing) predict inward carbon pinch opposite to experiment

⇒ **Local linear theory does not appear to explain momentum & impurity transport trends in NSTX – future work to investigate nonlinear and global (finite-ρ_*) effects**

Momentum Transport

Interpretation of toroidal angular momentum transport often assumes diffusive and convective components

- Transport equation:

$$\frac{\partial}{\partial t}\left(n_i m_i \left\langle R^2 \right\rangle \Omega\right) + \nabla \cdot \Pi_\varphi = S_\Omega \rightarrow \sum_s (\cdots)$$

- *Assumed* transport form:

$$\Pi_\varphi = -nmR\chi_\varphi (R\nabla\Omega) + nmV_\varphi (R\Omega)$$

Prandtl number $\boxed{\mathrm{Pr} = \frac{\chi_\varphi}{\chi_i}}$

$$\hat{\Pi}_\varphi = \hat{\chi}_\varphi \left(\hat{u}' + \frac{RV_\varphi}{\chi_\varphi} \hat{u} \right)$$

Pinch parameter $\boxed{\frac{RV_\varphi}{\chi_\varphi}}$

$$\hat{u}' = \frac{-R^2\nabla\Omega}{c_s} \qquad \hat{u} = \frac{R\Omega}{c_s}$$

- Can also have residual stress Π_{RS} contributions (from up-down asymmetric flux surfaces, finite ρ_* profile effects) leading to intrinsic torque → intrinsic rotation when $u' = u = 0$
  - Perhaps less important in core with large beam torque (co-NBI in NSTX)

Steady state Prandtl numbers $\chi_\varphi/\chi_i < 1$ for NSTX L- mode and H-mode discharges

- Pr=$\chi_\varphi/\chi_i \approx 0.3$-1.0 over many radii and discharges (assumes V_φ=0)

- $\chi_\varphi > \chi_{\varphi,NC}$ for both L and H

  In L-mode $\chi_i > \chi_{i,NC}$

$$\mathrm{Pr} = \frac{\chi_\varphi}{\chi_i} \approx \frac{\chi_{\varphi,\mathrm{turb}}}{\chi_{i,\mathrm{turb}}}$$

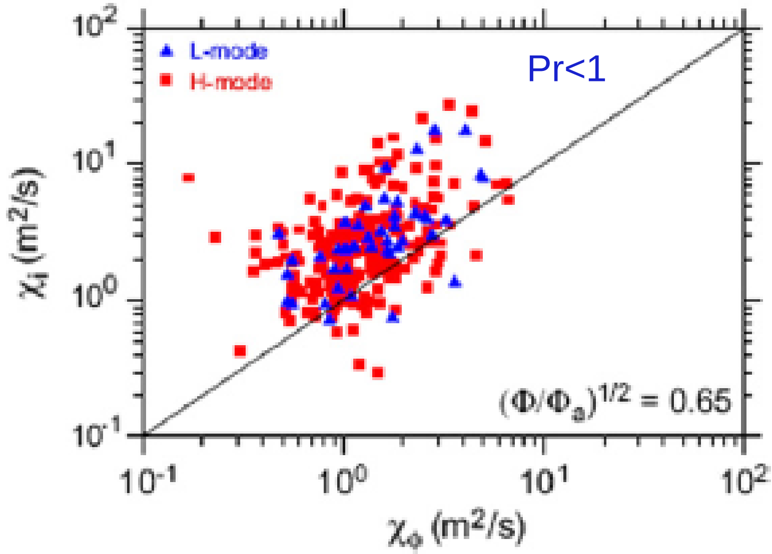
  In H-mode $\chi_i \approx \chi_{i,NC}$

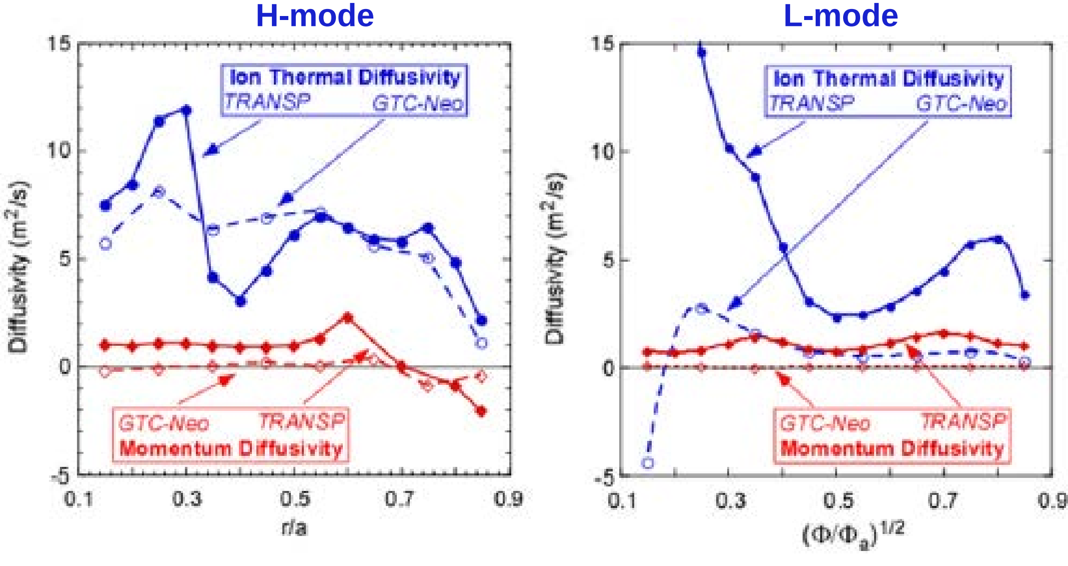
$$\mathrm{Pr} = \frac{\chi_\varphi}{\chi_i} = \frac{\chi_{\varphi,\mathrm{turb}}}{(\chi_{i,NC} + \cancel{\chi_{i,\mathrm{turb}}})} \xrightarrow{} \sim 0$$

$\Rightarrow$ Pr less useful in H-mode?

- RV_φ/χ_φ less ambiguous

Steady state transport analysis (Kaye et al., 2009)

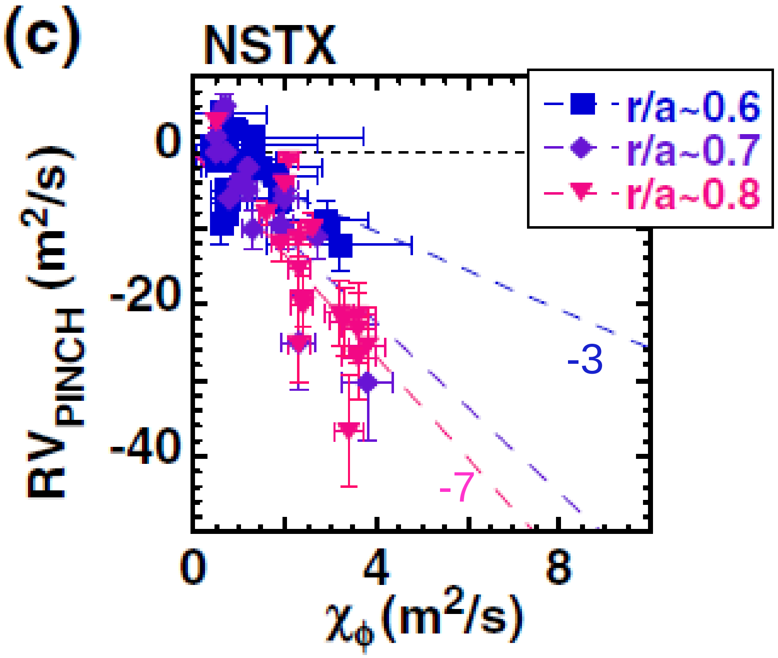




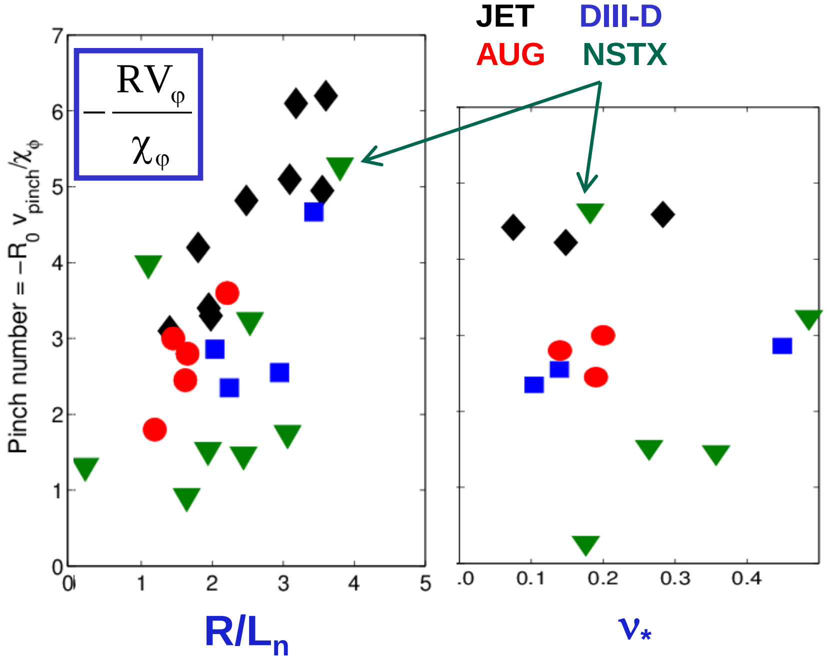
Perturbative H-mode experiments indicate existence of an inward momentum pinch

- $RV_\varphi/\chi_\varphi \approx$ -(1-7) for many NSTX discharges & radii
  - Pr~0.3-0.5, smaller than other machines (Pr~0.6-2.0) (Yoshida, NF 2012)
- Possible dependence on density gradient (R/L_n), less clear with collisionality (ν*), but a lot of scatter

(Solomon et al., PRL 2008, PoP 2010; Yoshida et al., NF 2012)



(Tala et al., IAEA 2012)



Q: What are the relevant momentum transport mechanism(s) in NSTX?

Method for predicting quasi-linear Prandtl (χ_φ/χ_i) and Pinch numbers (RV_φ/χ_φ)

- Local linear GYRO simulations run between r/a=0.6-0.8 ($\rho_{tor}\approx 0.5$-0.7), with
  - deuterium, carbon, electrons
  - φ, $A_{||}$, $B_{||}$
  - numerical equilibrium (EFIT/LRDFIT)
  - n_e profiles from averaged inboard/outboard measurements (no centrifugal effects in GYRO)

- Pr and RV_φ/χ_φ determined using momentum flux from different combinations of u, u′

$$\hat{\Pi}_\varphi = \hat{\chi}_\varphi \hat{u}' + (\hat{R}\hat{V}_\varphi + \hat{R}\hat{\Gamma}_p)\hat{u} + \hat{\Pi}_{\varphi,RS}$$

$$\Pr = \frac{\hat{\chi}_\varphi}{\hat{\chi}_i} = \frac{\hat{\Pi}_\varphi(0,u') - \hat{\Pi}_\varphi(0,0)}{\hat{u}'} \cdot \frac{a/L_{Ti}}{\hat{Q}_i}$$

$$\left(\frac{RV_\varphi}{\chi_\varphi}\right) = \left[\frac{\hat{\Pi}_\varphi(u,0) - \hat{\Pi}_\varphi(0,0)}{\hat{u}} - \underline{\hat{m}\hat{R}\hat{\Gamma}_p(u,0)}\right] \cdot \frac{\hat{u}'}{\hat{\Pi}_\varphi(0,u') - \hat{\Pi}_\varphi(0,0)}$$

Following Peeters et al.
PRL (2007)
Nucl. Fusion (2011)

- Subtracting particle convection contribution

Transport of toroidal angular momentum calculated from delta-f gyrokinetics (GYRO*)

- Transport calculated for toroidal momentum from correlation of perturbed distribution function and effective radial drifts from all EM fields

$$\delta f_s(\vec{x}) = -\frac{e\delta\varphi(\vec{x})}{T_s}F_{s0} + H_s(\vec{R}) \qquad (3.22)$$

$$\Pi_s = \underset{\substack{\text{flux}\\\text{surface}\\\text{average}}}{\oint} \int d^3v\,\underline{H_s^*(\vec{R})}\left\langle \underline{[m_s R(\vec{V}_0+\vec{v})\cdot\vec{e}_\varphi]}\,\underline{\frac{c}{B}\vec{b}\times\nabla\left[\delta\varphi(\vec{x}) - \frac{1}{c}(\vec{V}_0+\vec{v})\cdot\delta\vec{A}(\vec{x})\right]}\cdot\nabla r\right\rangle_{\substack{\text{gyro}\\\text{average}}} \qquad (3.55)$$

Electrostatic
E×B drift

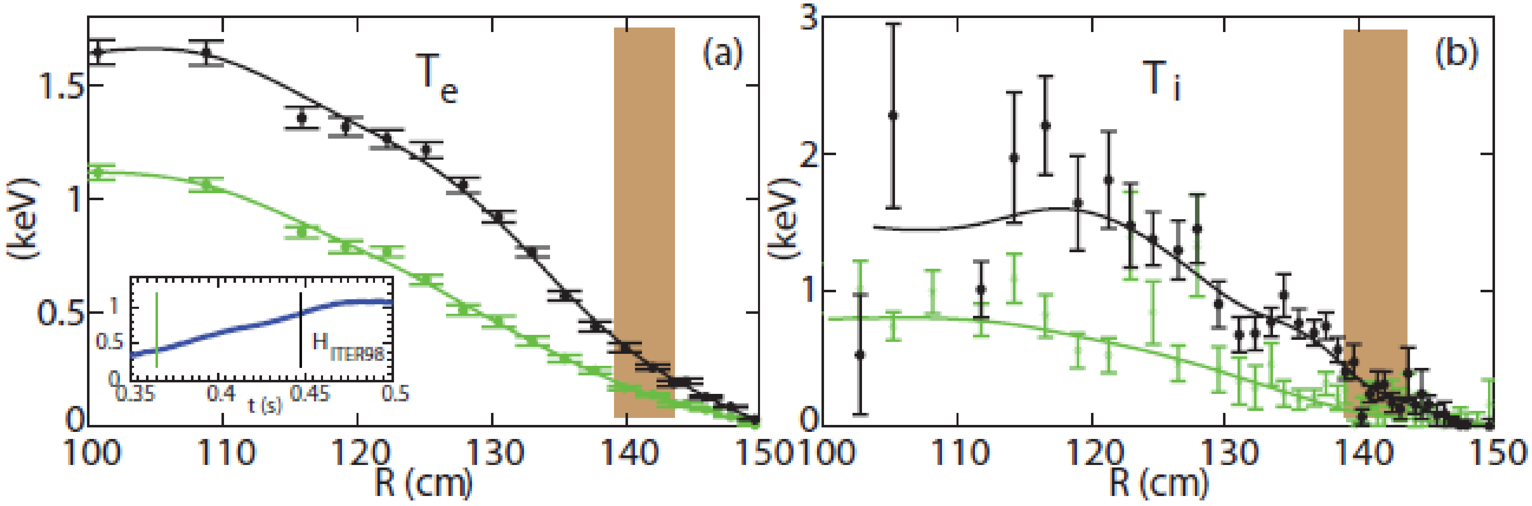
Drifts from shear ($v_{||}\nabla A_{||}$~ $v_{||}B_r$) and compressional ($v_\perp\nabla A_\perp$~$v_\perp B_{||}$) magnetic perturbations

- *EM contributions are important in NSTX H-modes*

*Candy & Belli, GYRO Technical Guide, https://fusion.gat.com/theory/Gyro

Example from NSTX L-mode (Ren, NF 2013)

- Low k_θ stability dominated by ITG/TEM
- No perturbative momentum experiments in this case, but it provides a basis for comparing to conventional tokamaks
- MAST perturbative L-mode experiments were run this year (analysis ongoing)

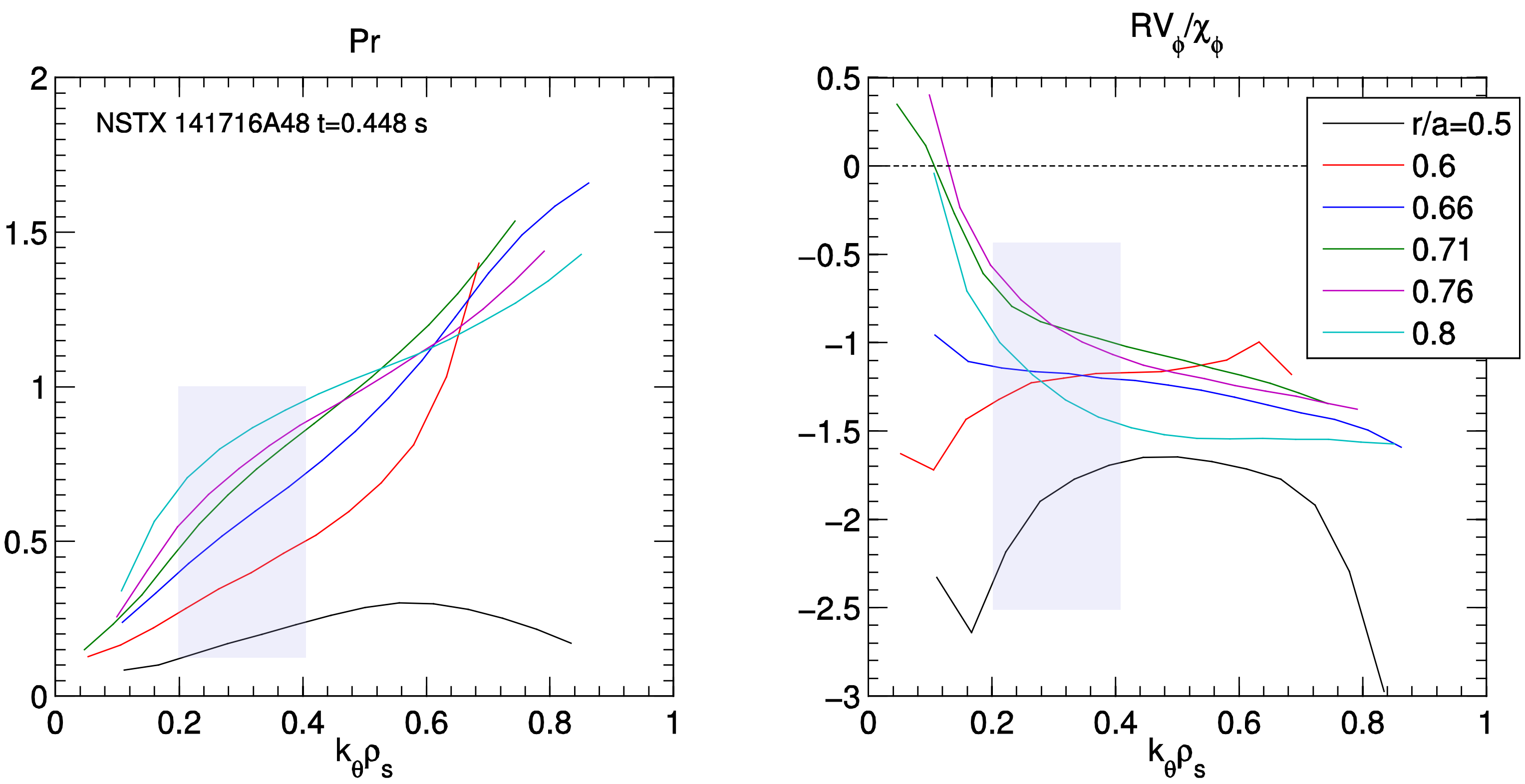


B_T=0.55 T, I_p=0.9 MA, P_{NBI}=2 MW, $\langle n\rangle \approx 3\times10^{19}$ m^{-3}

Quasilinear Prandtl number increases with radius, relatively weak momentum pinch predicted

- Range of Pr~0.2-0.8 generally consistent with experiment (~0.5)
  - NL spectrum peak around $k_\theta\rho_s$~0.3
- Small inward pinch RV_φ/χ_φ ~ -(1-2)

⇒ Investigate sensitivity to various parameters



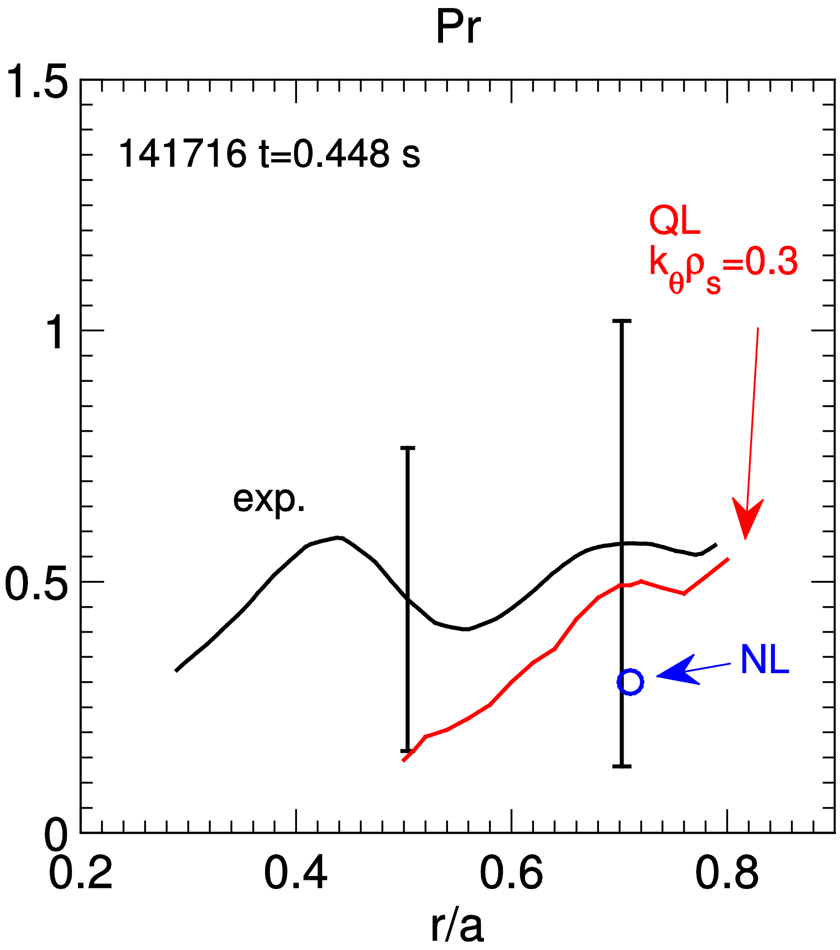
Quasi-linear and non-linear "effective" Pr number in range of experimental values

- Comparing "effective" Pr number (ignoring small pinch which lowers quasilinear Pr)

$$\Pr_{\text{eff}} = \frac{\hat{\chi}_{\varphi}^{\text{eff}}}{\hat{\chi}_{i}}, \qquad \hat{\chi}_{\varphi}^{\text{eff}} = \chi_{\varphi}\left(1+\frac{RV_{\varphi}}{\chi_{\varphi}}\frac{u}{u'}\right)$$

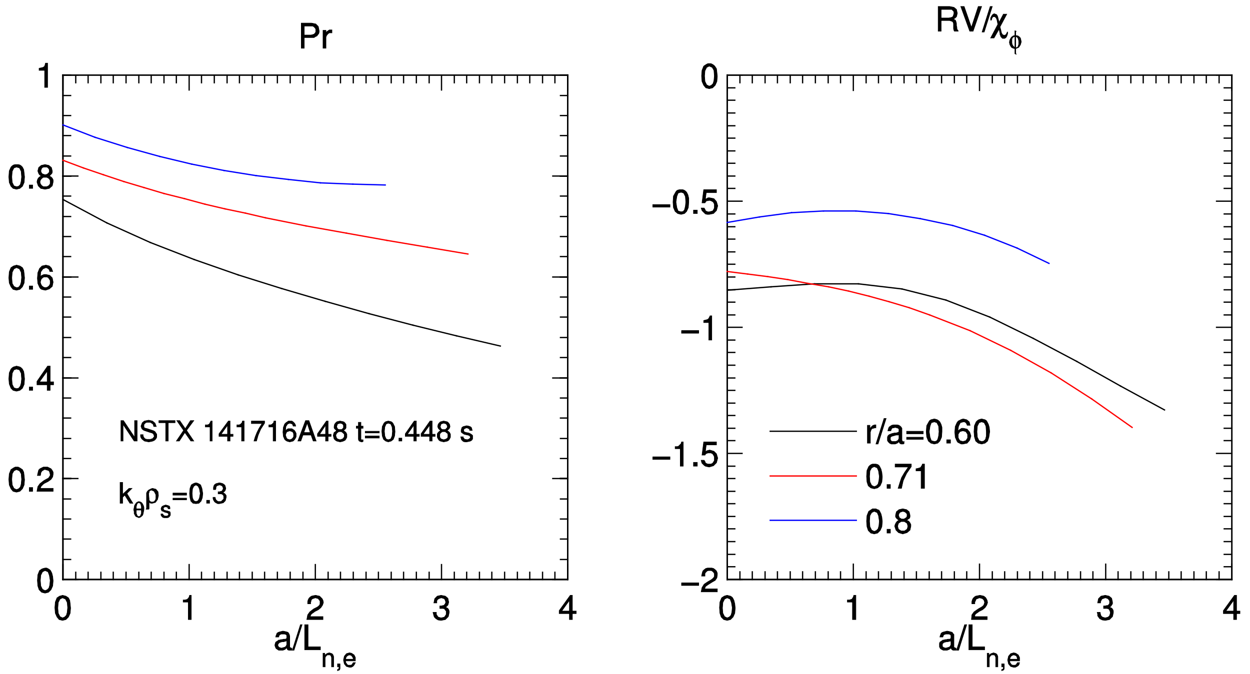
- Large uncertainty in χ_i due to power balance (e-i coupling, T_i uncertainties)
- Quasilinear estimates reasonably close
- Nonlinear simulation predicts lower effective Pr

⇒ Investigate sensitivity to various parameters



Pinch remains relatively small even for increased density gradient ($a/L_n = -a\nabla n/n$)

- Weaker dependence than predicted for ITG in conventional tokamaks

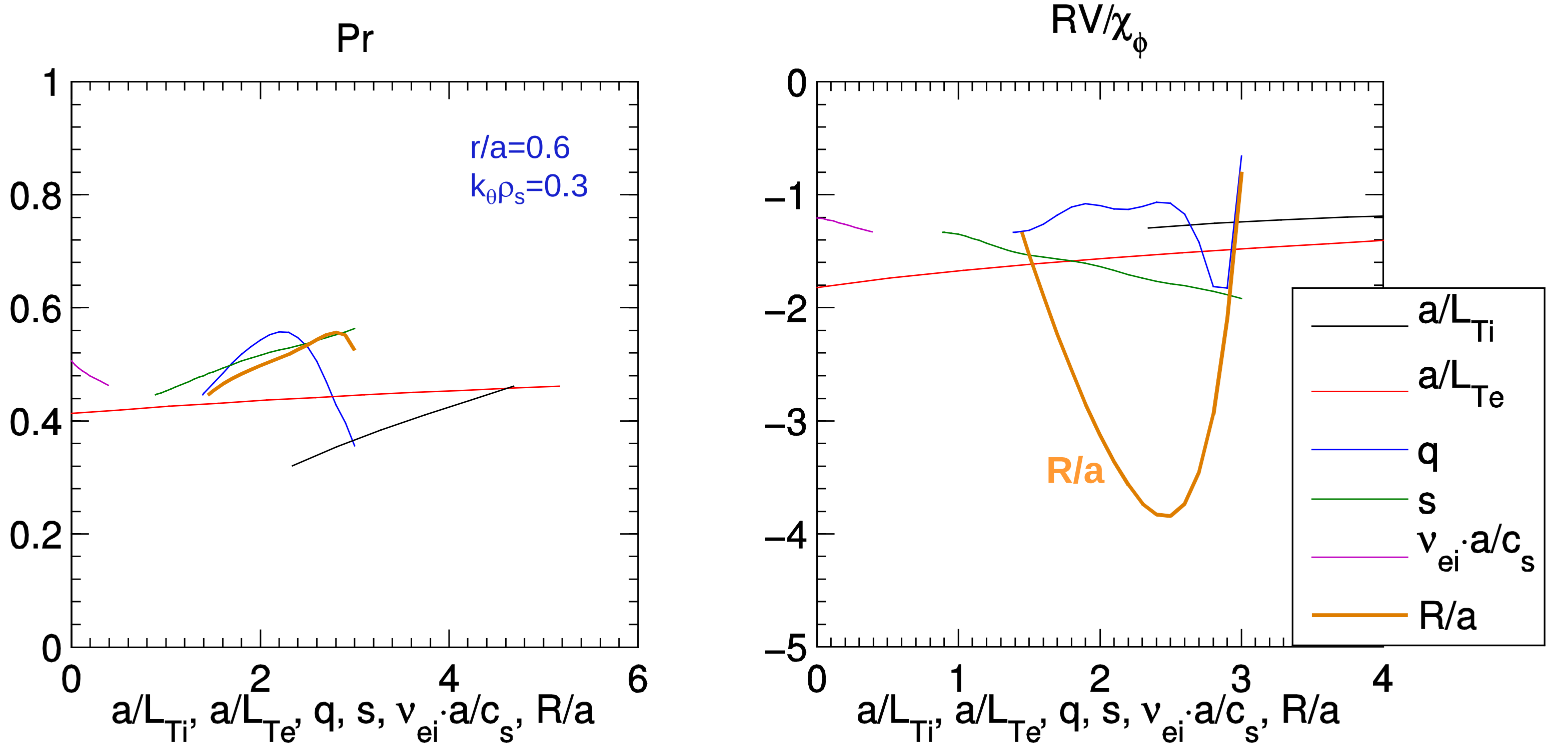


- Growth rates at r/a=0.6 increase with a/L_n
  - TEM-like at r/a=0.6
  - ITG-like at r/a=0.8

→ Weaker pinch consistent with smaller RV_φ/χ_φ reported for TEM conditions at higher aspect ratio [Kluy et al., 2009]

Pinch predicted to be weakly dependent on many parameters except aspect ratio (R/a)

- Prandtl number remains constant ~0.4-0.6
- RV_φ/χ_φ relatively insensitive to $a/L_{Ti,e}$, q, s, ν_{ei}
- Becomes much larger (inward) for increased aspect ratio (R/a)

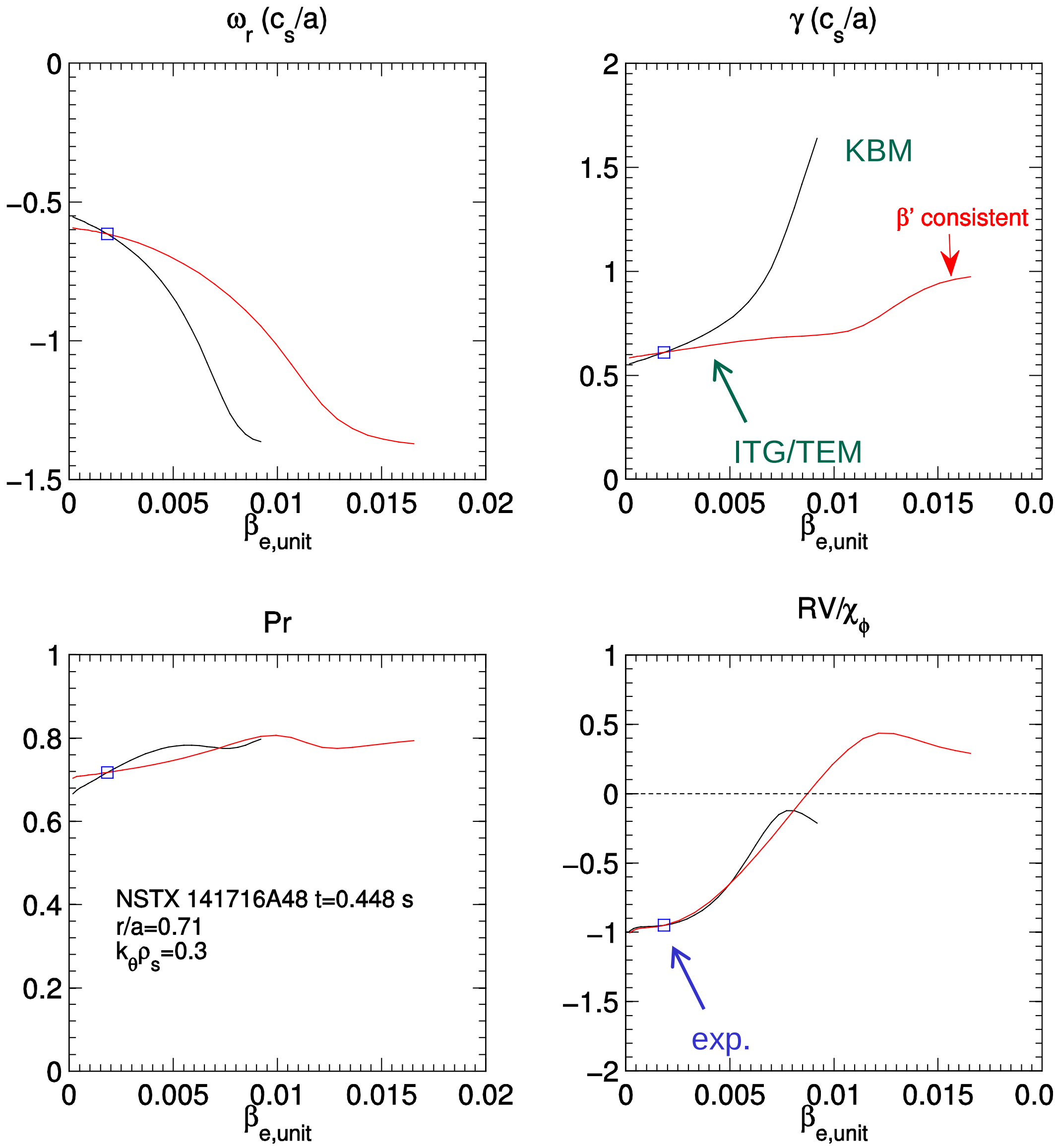


- q, s, R/a scans using local Miller equilibrium model ⇒ not consistent with any particular global equilibrium

Growth rates increase with beta, eventually transition to KBM (preview for H-modes)

- ITG/TEM growth rates *increase* with β_e, opposite to traditional results (e.g. “cyclone base case”)
- Eventually transitions to KBM (similar to hybrid ITG/KBM [Belli, Candy 2010])
    - Increasing β'_{eq} consistently is stabilizing [Bourdelle, 2003]

- Pr remains ~constant
- Pinch goes toward zero, even positive/outward (depending on β'_{eq})
    - similar to EM behavior predicted in conventional aspect ratio [Hein, 2010]

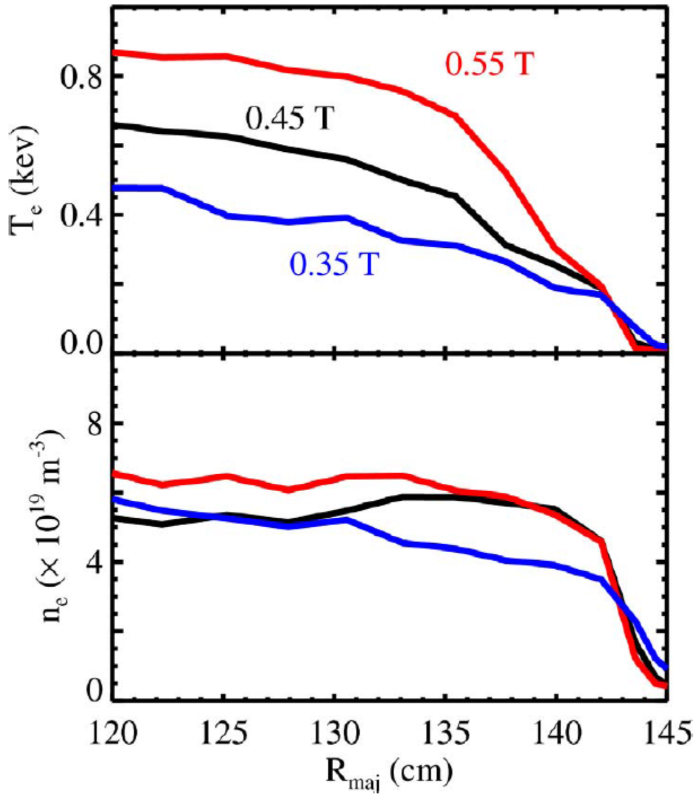


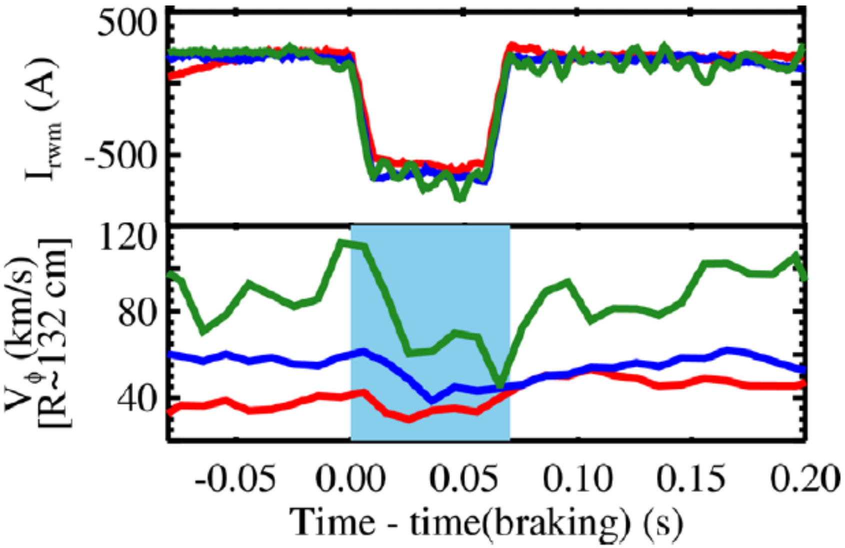
NSTX H-modes

- Simulations run for 7 NBI H-modes with n=3 perturbations [Solomon, 2010]

B_T=0.35-0.55 T I_p=0.7-1.1MA

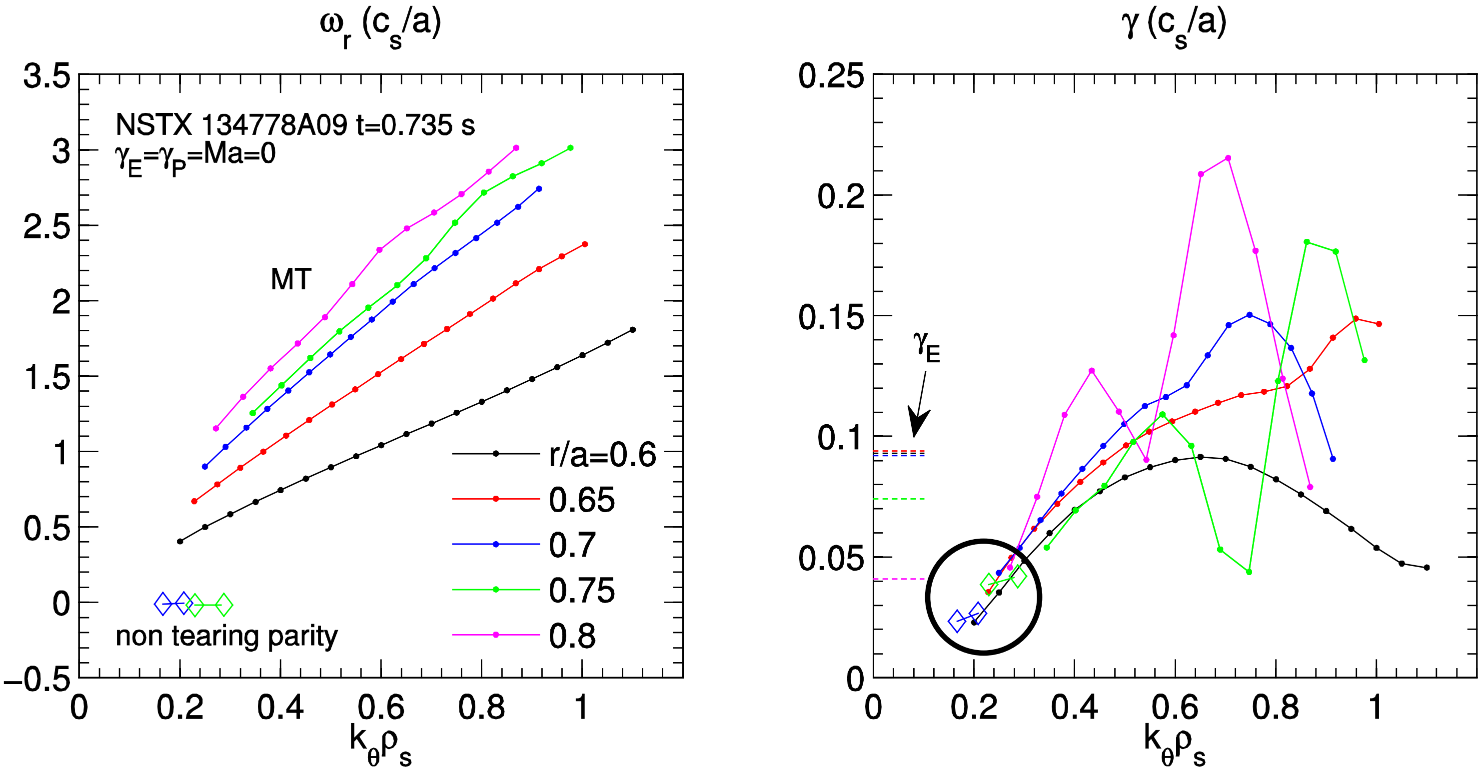
P_{NBI}=4-6 MW $\langle n \rangle \approx 4\text{-}6 \times 10^{19}$ m^{-3}





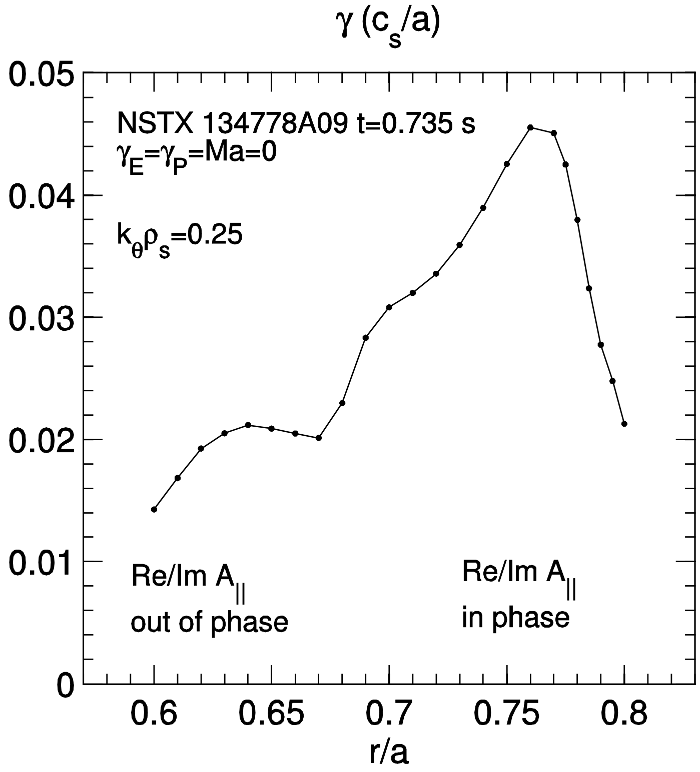
Most cases show broad spectra of microtearing modes

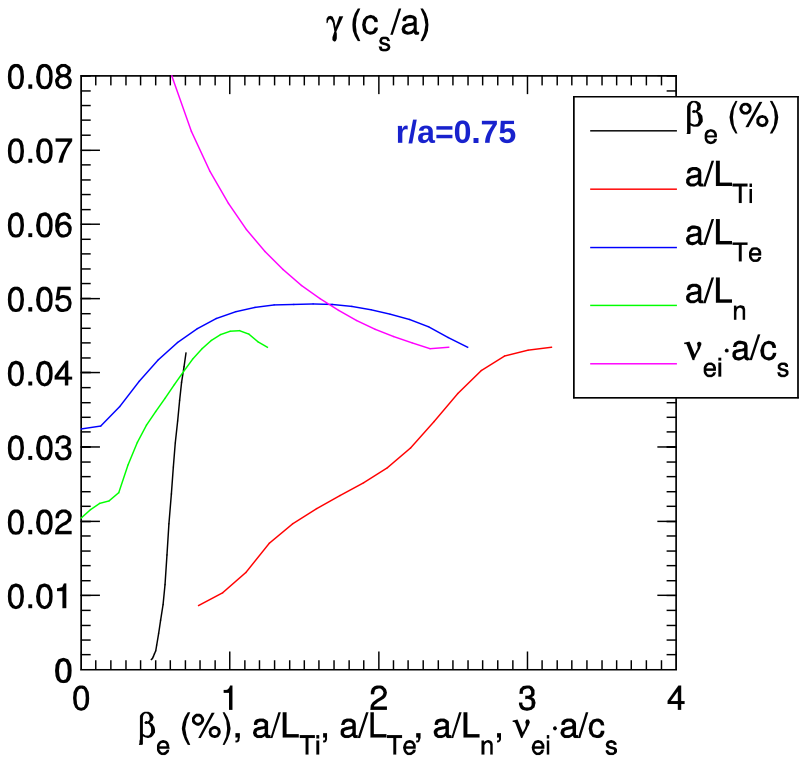
- Apparent in eigenfunctions (not shown) and near linear dispersion $\omega \approx \omega_{*e}$
  - Microtearing only transports electron energy
- Often see hints of subdominant ballooning modes (◊)
  - Unknown whether they survive nonlinearly
- E×B shearing rates comparable to γ_{lin} (γ_{lin}/γ_E ↑ as r/a ↑)



Ballooning modes exist over $0.6 \leq r/a \leq 0.8$, exhibit KBM behavior

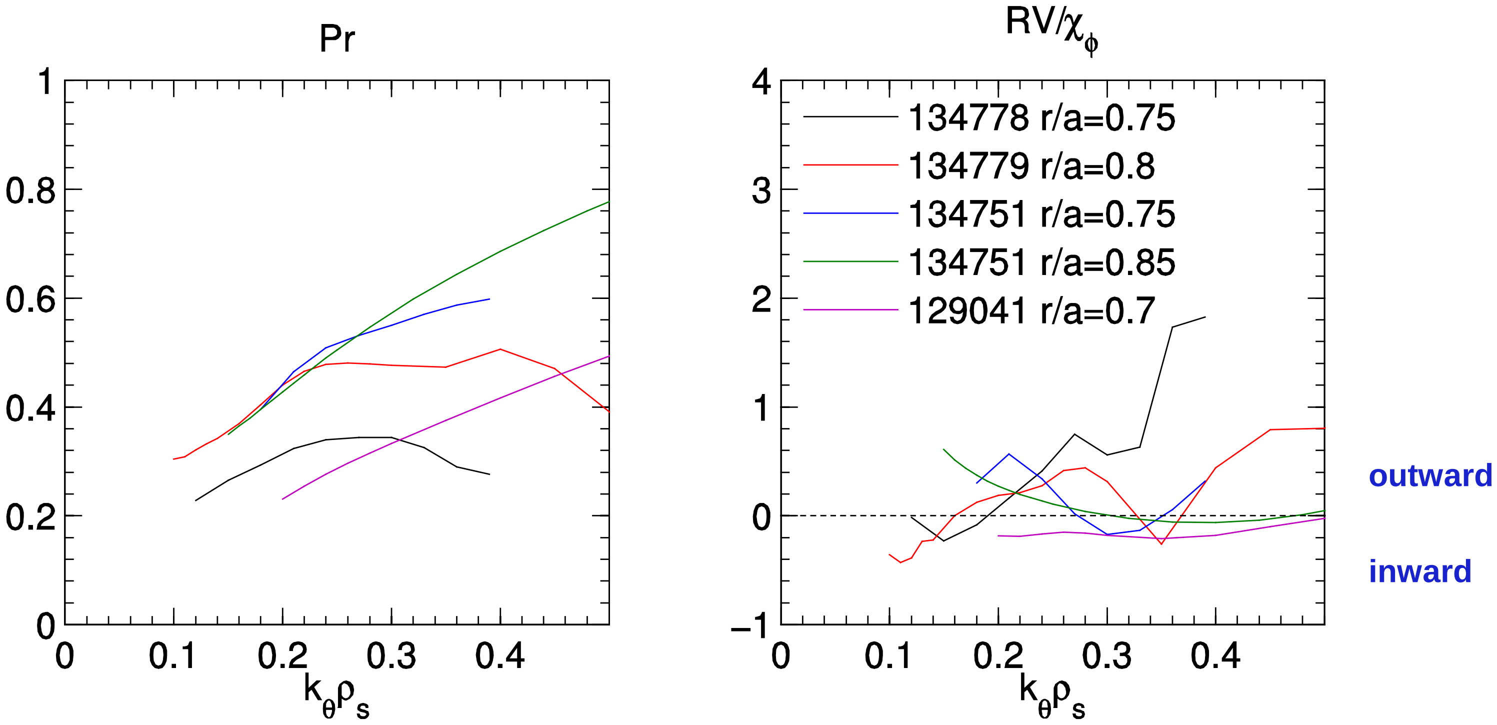
- Very sensitive to $\beta_e \rightarrow$ KBM ($\alpha_{MHD,unit}>0.6$)
  - Unstable from a/L_{Ti} - similar to hybrid ITG/KBM behavior found by Belli, Candy [2010]
  - Similar hybrid-KBM modes often predicted in NSTX H-modes [Guttenfelder, NF 2013; Canik, NF 2013]
- Transport contributions come from both φ and $B_{||}$; also D and C ($Z_{eff}\approx3$, $n_c m_c \sim 0.7 n_d m_d$)





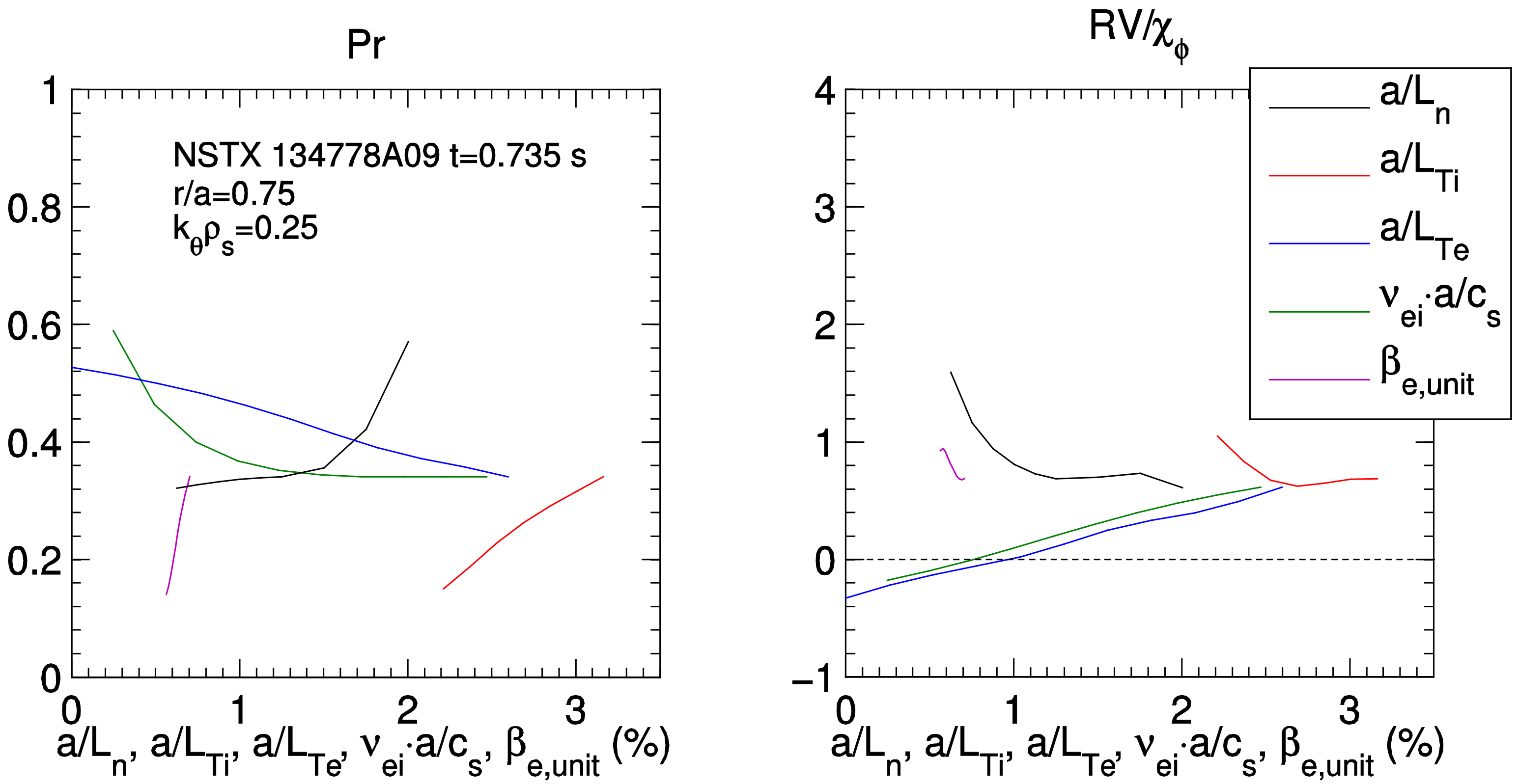
Small Prandtl numbers over KBM range of $k_\theta\rho_s$, small/outward Pinch parameter

- Interpreted Pr would be smaller for $\chi_{i,nc}>\chi_{i,turb}$
- Small/outward RV_φ/χ_φ
  - consistent with KBM predictions using conventional tokamak parameters [Hein, 2010]
- Small/positive RV_φ/χ_φ predicted in multiple cases, never approaches larger inward experimental values (-7)



Pinch parameter shows minor changes with parameters, always remains near zero or outwards

- Never approaches larger inward experimental values (-7)



- What else is missing?

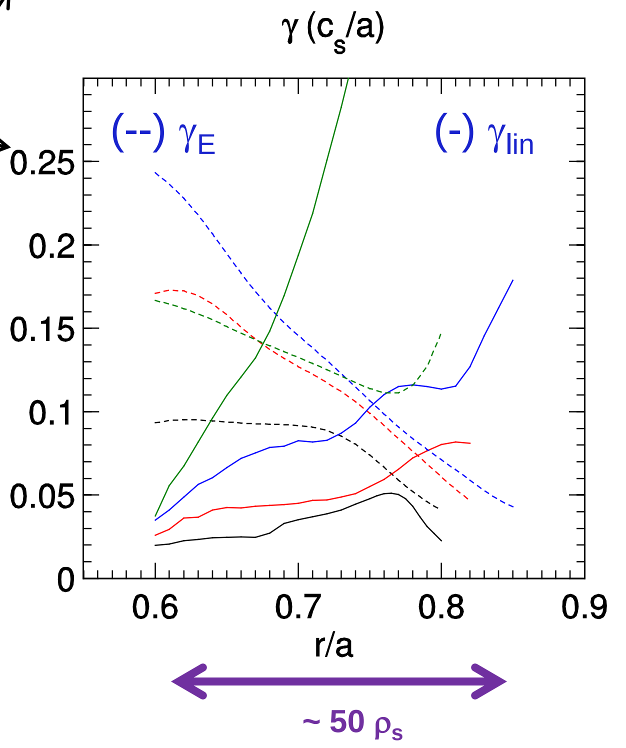
Additional considerations

- Nonlinear transport possibly different from quasilinear (simulations beginning)
- Perpendicular (E×B) flow shear (Dominguez, Casson, Waltz)

$$\Pi_\varphi = (\chi_\varphi u' + \chi_{\varphi\perp}\gamma_E) + (RV_\varphi + R\Gamma_p)u + \Pi_{\varphi,RS}$$

- Influence of particle flux
- Finite ρ_* effects: profile shear, non-local effects, influence from pedestal
- Centrifugal effects on transport and stability
  - GKW work in progress (Buchholtz, Hornsby, Peeters)

⇒ Mechanism(s) for strong observed inward pinch remains unresolved



Impurity Transport

Occasional evidence for non-neoclassical impurity transport in Lithium conditioned H-modes (Scotti, NF 2013)

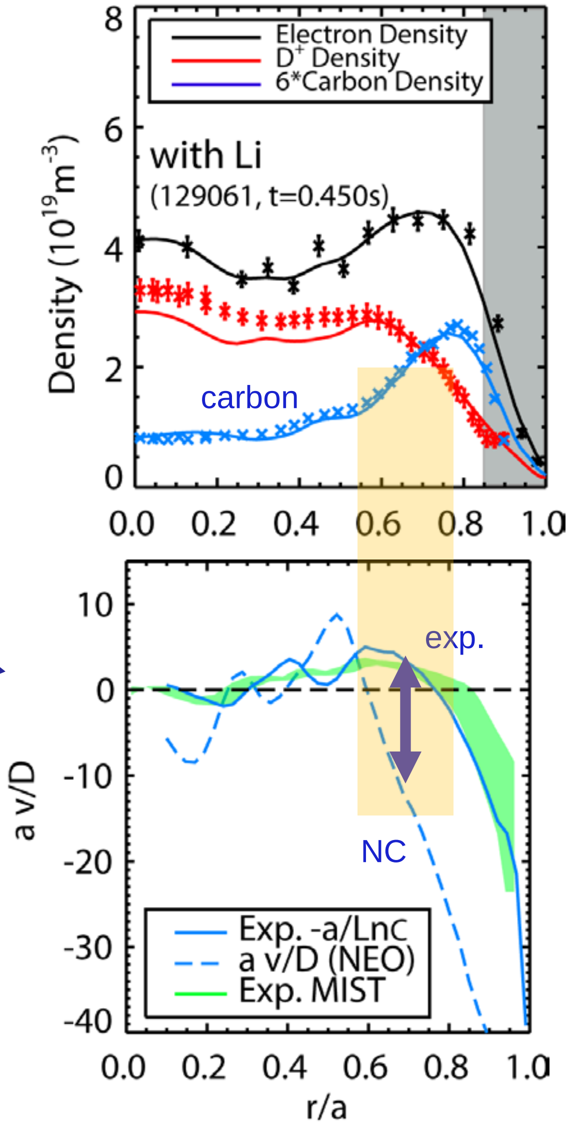
- Impurity transport often close to neoclassical levels in H-modes [Delgado-Aparicio, NF 2009, 2011; Clayton, PPCF 2012]

- With lithium wall conditioning, ELMs are suppressed and carbon accumulates
  - Lithium does NOT accumulate (better scrape-off layer screening + neoclassical $D_{Li}>>D_c$)

$$\Gamma_c = -D_c \nabla n_c + V_c n_c \approx 0 \;\Rightarrow\; \boxed{\frac{aV_c}{D_c} = -\frac{a}{L_{n,c}}}$$

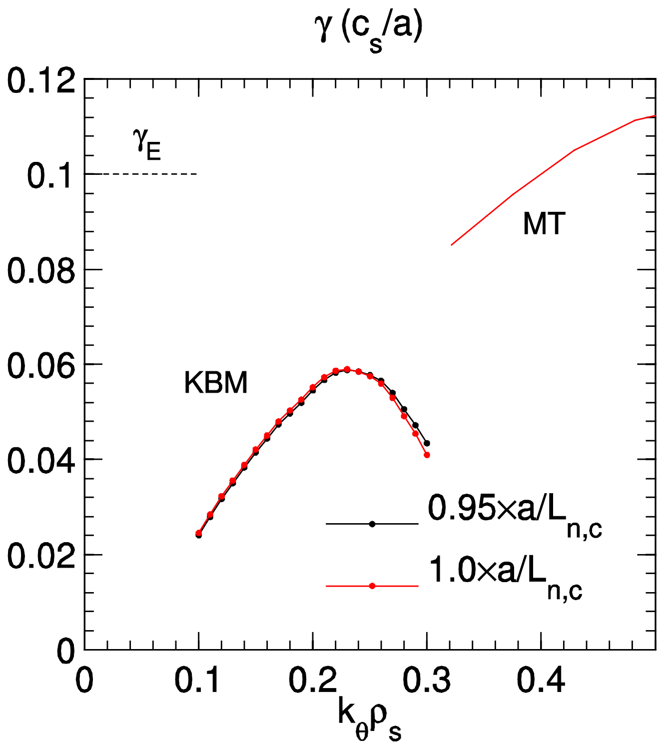
- Profile shape can diverge significantly from neoclassical theory (don't have quantitative source in these cases)

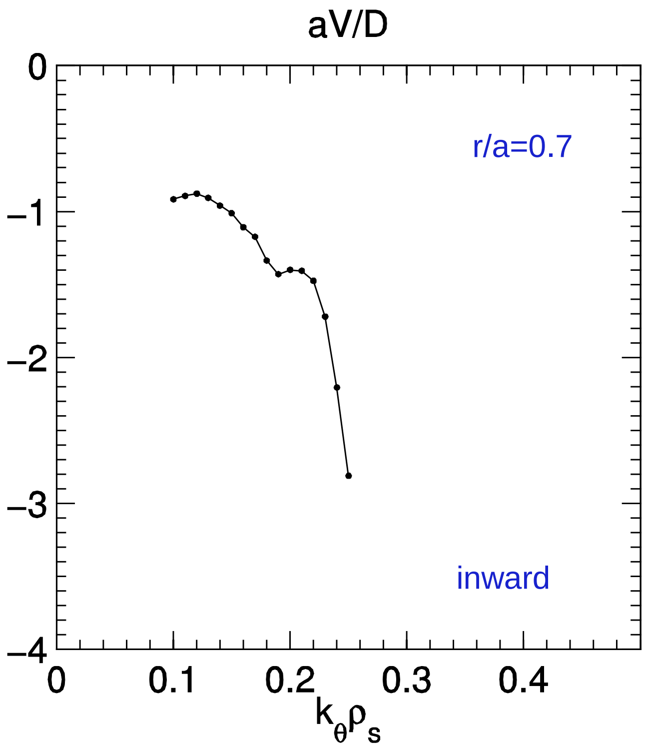
Q: Can ballooning modes influence impurity transport in NSTX H-modes?



Microtearing modes dominate, sub-dominant KBM modes predict inward carbon pinch

- Microtearing dominates (no particle flux)
- Weaker hybrid-KBM ($\gamma_{KBM}<\gamma_E$) – unknown if this survives nonlinearly
- KBM predicts inward carbon pinch (r/a=0.6-0.7)
  - – Opposite to experiment, similar to neoclassical





Inward carbon pinch predicted for KBM over a range of parameters

- Direction of carbon convection insensitive to ν_{ei}, a/L_{Ti}, a/L_{Te} , and u'
- Outward carbon convection predicted as beta is reduced and mode transitions to ITG/TEM

⇒ Does not appear to reconcile non-neoclassical impurity profile