TH/P3-14: Measurement and prediction of momentum transport in spherical tokamaks

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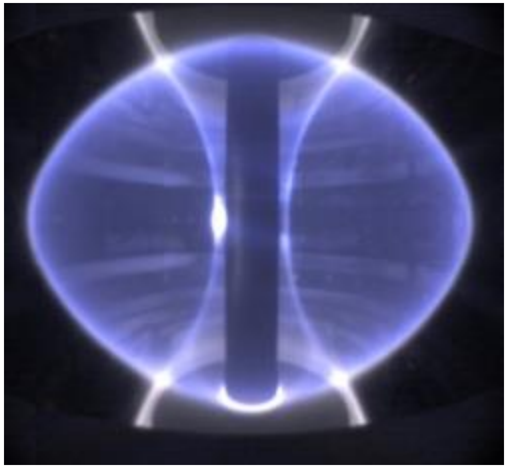
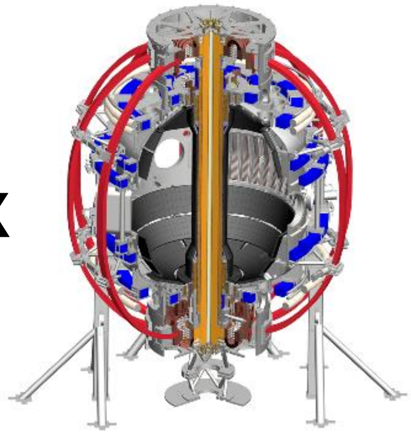
IAEA FEC 2016, Kyoto, Japan



MAST



NSTX

OVERVIEW

- To predict rotation profile (important for macro- and micro-instabilities) need to understand torques sources/sinks and momentum transport [Ida & Rice NF (2014)]

- Here, investigating momentum pinch in low aspect ratio, high beta spherical tokamak plasmas (NSTX & MAST) as an additional constraint on theory (stems out of ITPA T&C activity)

- **<u>Summary:</u>**
  - Previous NSTX H-mode experiments inferred momentum pinch comparable to conventional tokamaks, $(RV_\varphi/\chi_\varphi)_{exp}$ ~ (-1) – (-10)
  - However, local, quasi-linear GK theory predicts negligible pinch $(RV_\varphi/\chi_\varphi)_{sim}$ ~ 0 – (-1) in NSTX H-modes due to electromagnetic and low aspect ratio effects on mode-symmetry

  - MAST L-mode experiments (i.e. lower beta) were conducted, analysis not inconsistent with significant pinch, $(RV_\varphi/\chi_\varphi)_{exp}$ ~ (-1) – (-9)
  - However, non-stationary conditions also allow for weaker or outward pinch, $(RV_\varphi/\chi_\varphi)_{exp}$ ~ (-2) – (5)
  - Local, quasi-linear GK theory predicts weak pinch $(RV_\varphi/\chi_\varphi)_{sim}$ ~ (-1) similar to NSTX H-modes, too much uncertainty in experiments to constrain predictions

Toroidal angular momentum transport considered as sum of diffusion ($-\chi_\varphi \nabla\Omega$), convection ($V_\varphi \Omega$) and residual stress ($\Pi_{RS}$)

- Transport equation: $$\frac{\partial}{\partial t}\left(n_i m_i \langle R^2 \rangle \Omega\right) + \nabla \cdot \Pi_\varphi = T$$

Ignoring residual stress contributions throughout this work

- Assumed transport form: $$\Pi_\varphi = nmR^2\left(-\chi_\varphi \nabla\Omega + V_\varphi \Omega\right) + \Pi_{RS}$$

- Can identify different physical mechanisms by how they break symmetry of microinstability [Peeters, NF (2011); Angioni, PFR (2012); Diamond, NF (2013)]

- Pinch expected due to Coriolis effect (Peeters, 2007), or equivalently turbulent equipartition (Hahm, 2007) + thermoelectric force (Peeters, 2009)

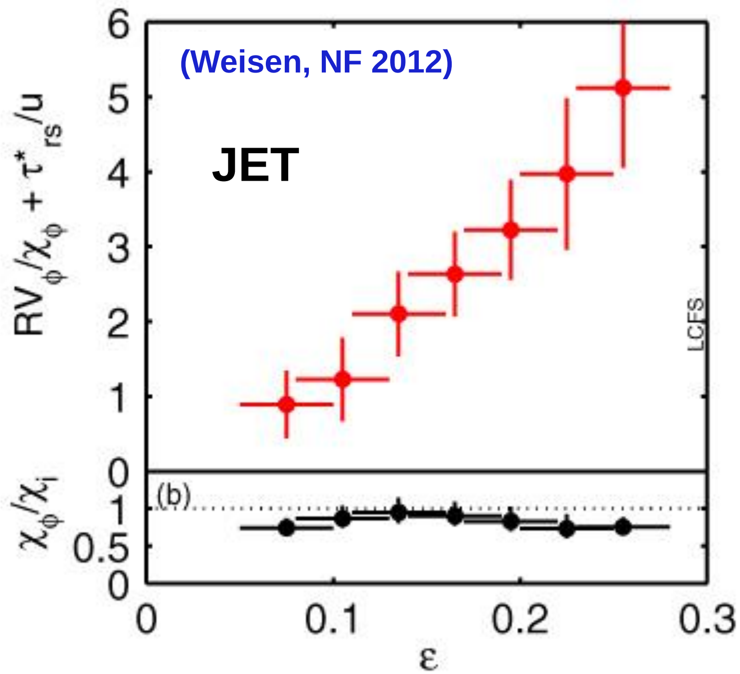
$$\hat{\Pi}_\varphi = \hat{\chi}_\varphi \left(\hat{u}' + \frac{RV_\varphi}{\chi_\varphi} \hat{u} \right)$$

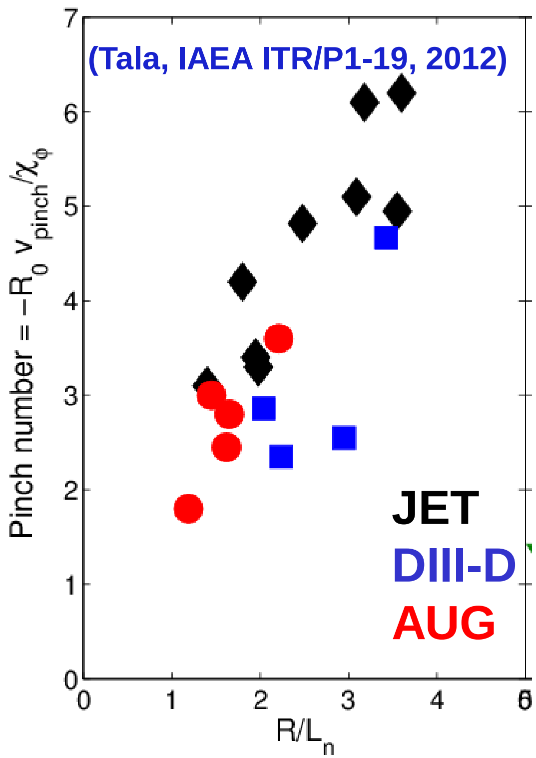
$$\hat{u}' = \frac{-R^2 \nabla\Omega}{c_s}$$

$$\hat{u} = \frac{R\Omega}{c_s}$$

Momentum pinch measured and predicted in conventional tokamaks

- Measurements in many machines from both perturbative experiments (NBI, 3D coils) and statistical regression analysis

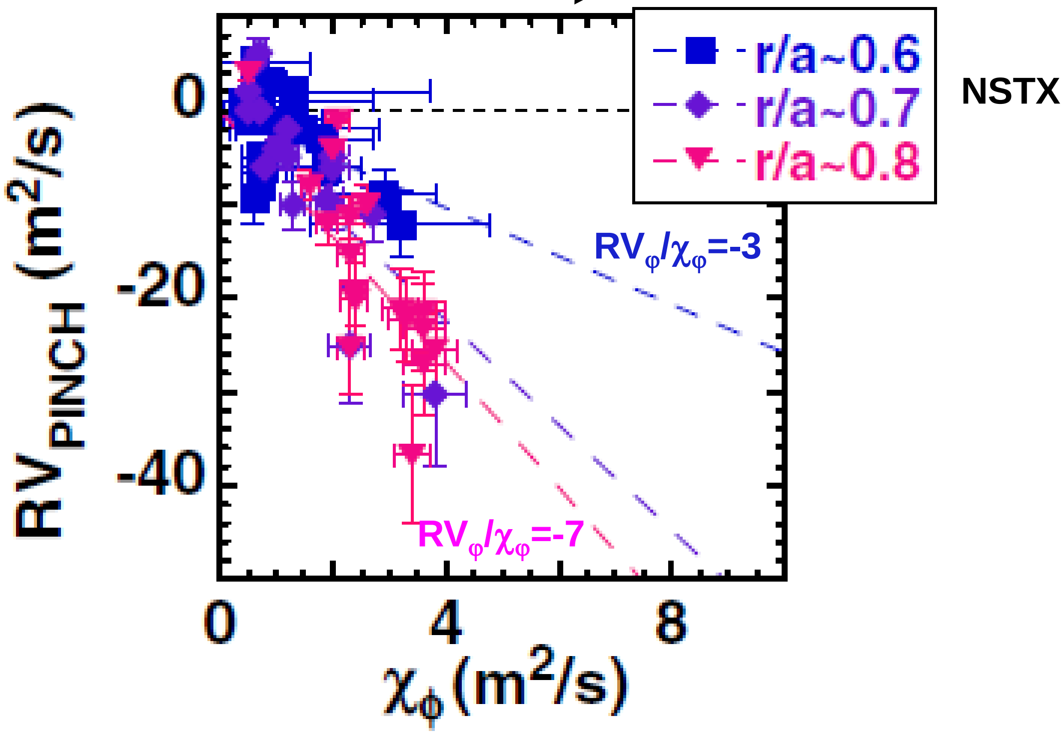




- Increase in (inward) pinch observed with ε=r/R and R/L_n, also predicted by ITG theory (Peeters, PRL 2007; PoP 2009)

Perturbative NSTX H-mode experiments indicate existence of an inward momentum pinch, $RV_\varphi/\chi_\varphi \approx -(1\text{-}7)$

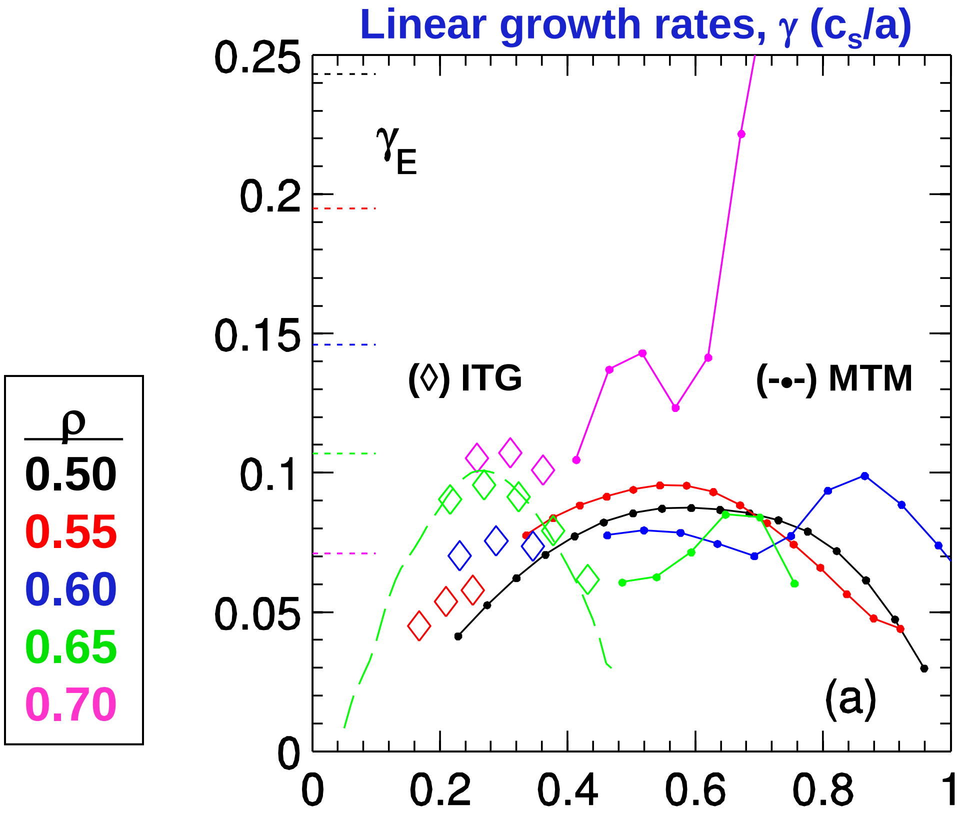
(Solomon, PRL 2008, PoP 2010;
Kaye, NF 2009; Yoshida, NF 2012)



- Local, linear gyrokinetic simulations of ITG turbulence describe pinch and scaling in conventional tokamaks ⇒ **does this hold for STs?**

Higher beta NSTX H-modes often dominated by microtearing modes (MTM) with sub-dominant ballooning modes

- Most cases have $\gamma_{MTM} > \gamma_{ballooning}$ (Π_φ=0 for MTM)
- Sub-dominant modes can be ITG, KBM or compressional ballooning modes – calculate pinch *assuming* they contribute to transport



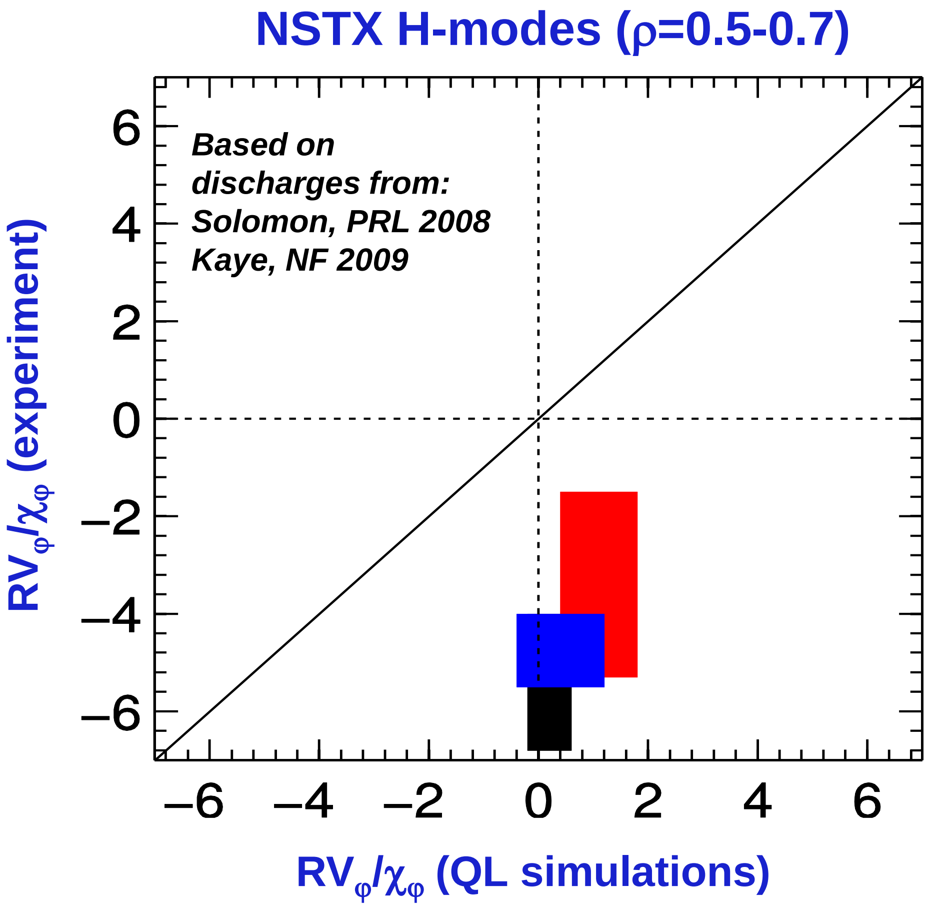
Linear GYRO simulations
[(Candy, Waltz, 2003)]()
3 species: D,C,e
EM: φ, $A_{||}$, $B_{||}$
Equilibrium reconstruction

β_T=12%, β_N=3.5

Guttenfelder, 2016 (Phys. Plasmas, *in review*)

Negligible or outward momentum convection predicted from ES and EM ballooning modes in NSTX

- Weak/outward pinch consequence of parallel mode structure response at high beta, low aspect ratio, see:
  - Peeters, PoP (2009)
  - Kluy, PoP (2009)
  - Hein, PoP (2011)
  - Guttenfelder, PoP (2016)



Momentum pinch coupled to symmetry breaking in parallel mode structure

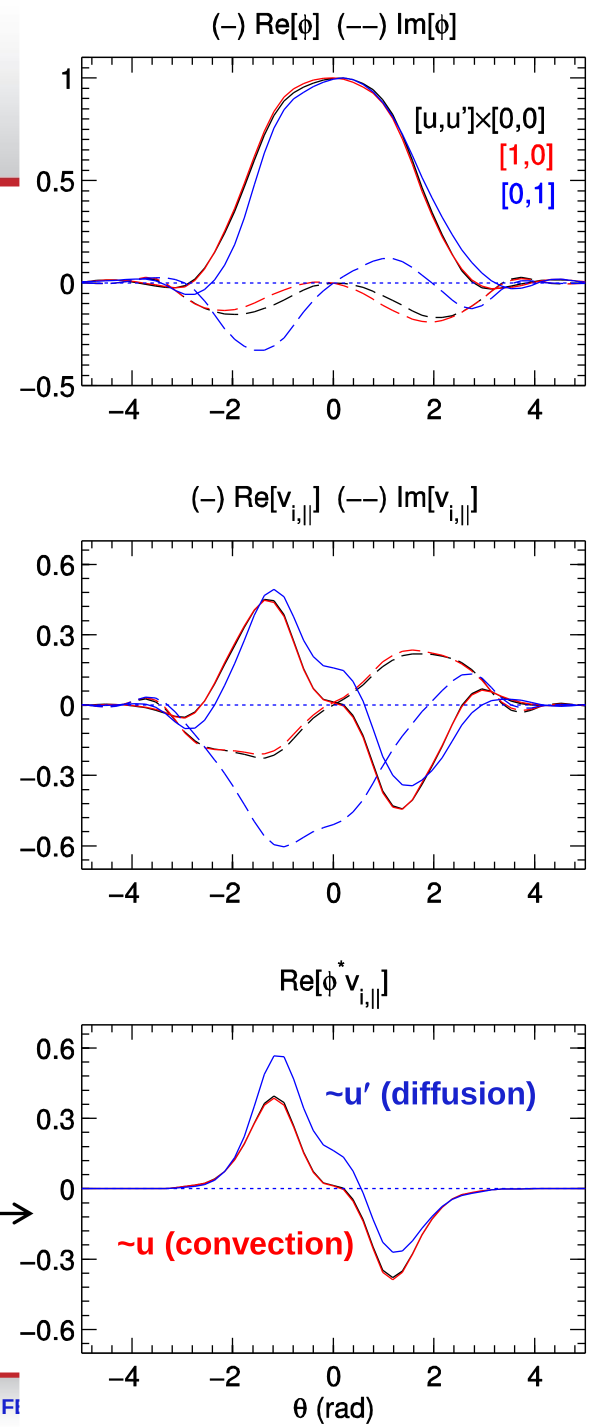
- Component of curvature drift in lab frame (M<1 smaller than curv. drift)

$$v_\kappa \approx \frac{mv_\parallel^2}{eBR} \rightarrow \frac{2m\left(v_\parallel + u_0\right)^2}{eBR} = \frac{mv_\parallel^2}{eBR} + \frac{2mv_\parallel u_0}{eBR} + \frac{mu_0^2}{eBR}$$

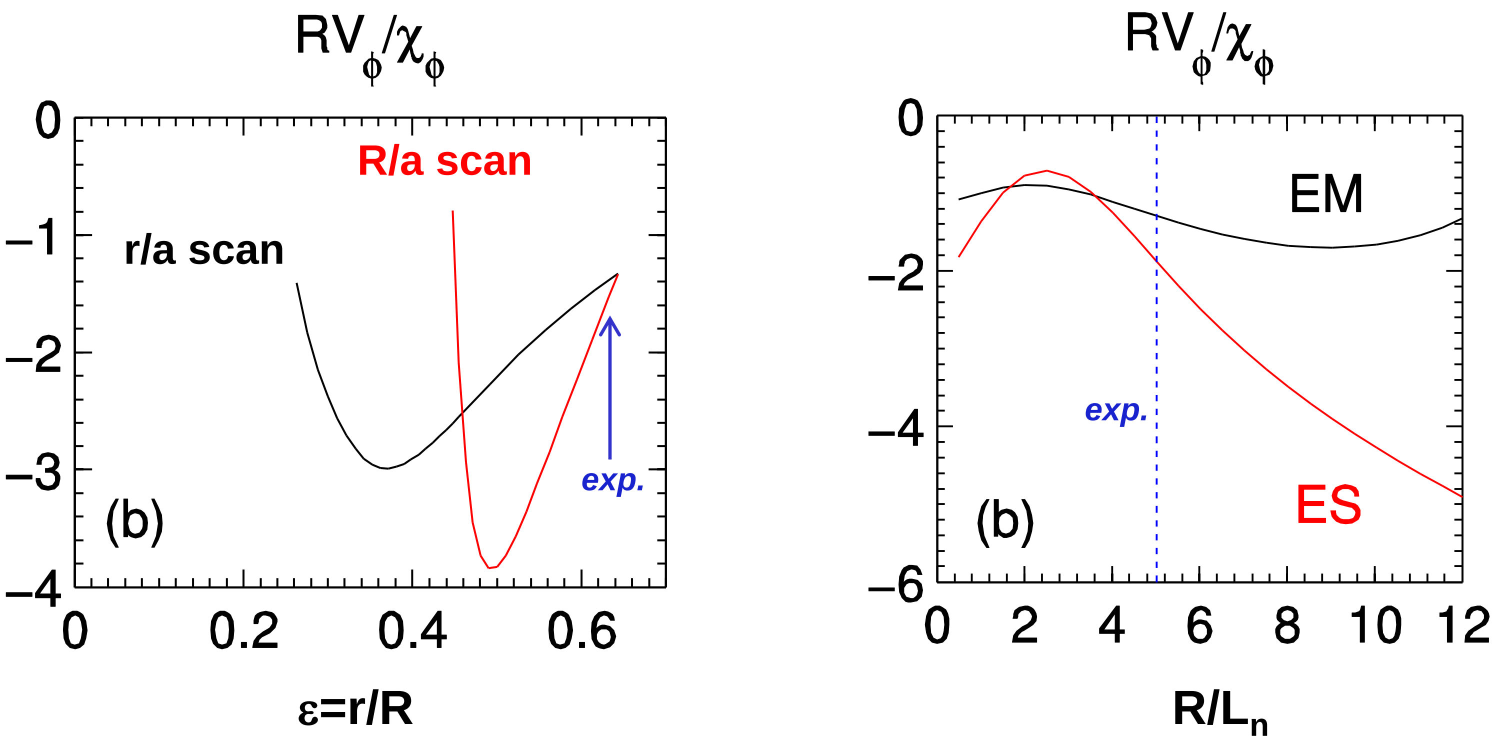
Curvature (v_κ) | Coriolis ($\sim M \cdot v_\kappa$) | Centrifugal ($\sim M^2 \cdot v_\kappa$)

- Does not influence stability, but toroidal flow couples δn, δT with δu → can cause momentum transport if eigenfunctions develop parallel asymmetry

- **Parallel asymmetry from u>0 very small in NSTX due to strong particle trapping & toroidicity → little convective transport** →



A larger (inward) pinch can be found: (i) at increased aspect ratio, (ii) in purely ES limit at high ∇n



- Above simulations based on NSTX L-mode discharge (Ren, NF 2013)
- Variation in pinch related to changes in parallel mode structure and symmetry (Guttenfelder, PoP 2016)
- Can’t do aspect ratio scan, can try to do similar analyses at lower beta…

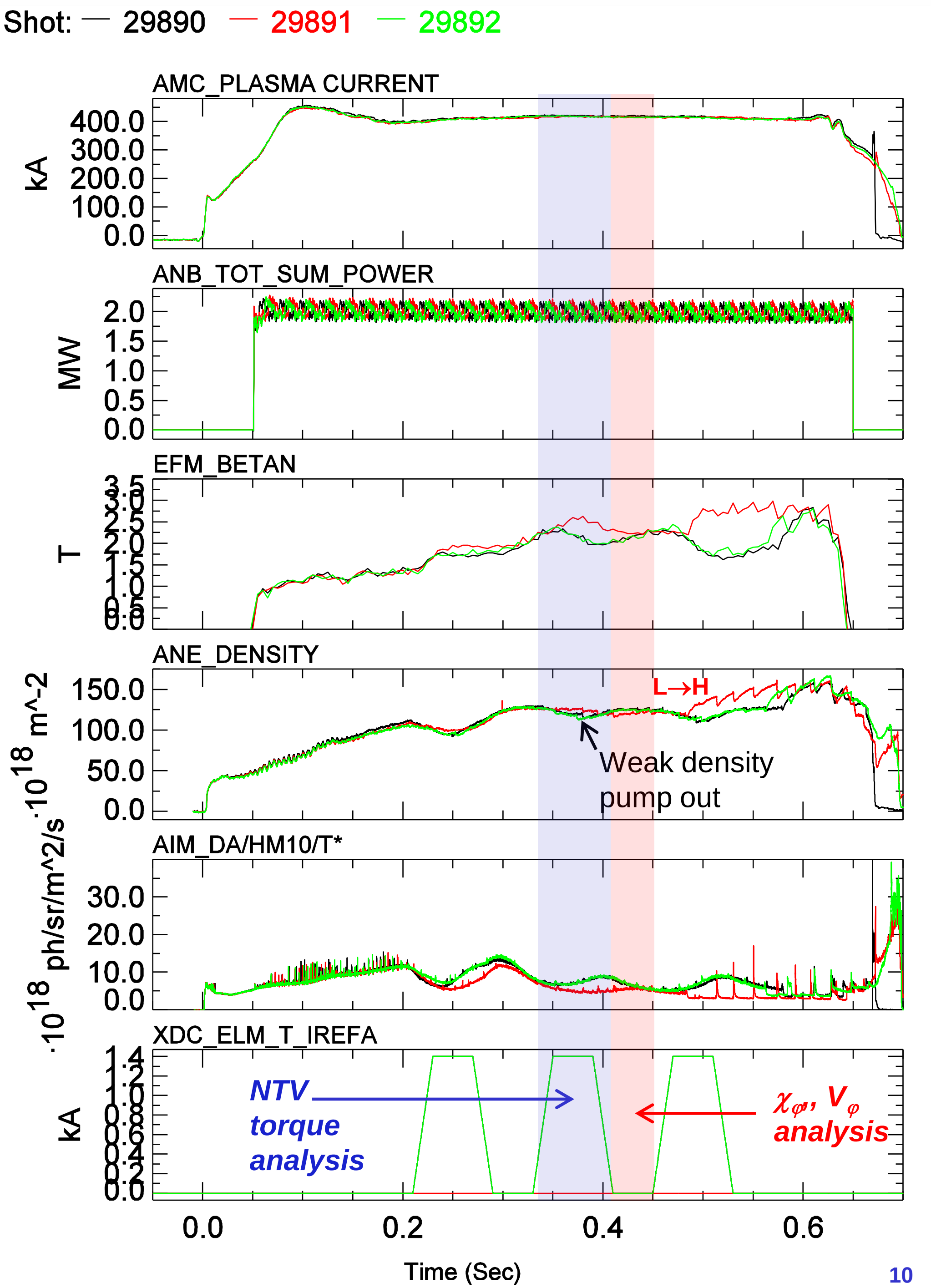
MAST L-mode experiment conducted in 2013

- 2 MW LSN L-mode
  - $\langle n_e \rangle = 2.3\times10^{19}\ m^{-3}$
  - B_T=0.5 T, I_p=0.4 MA ($q_{95}\approx5$)
  - **β_N~2, β_T~4%**

- Using applied 3D fields (n=3) to perturb rotation
  - **29890/ 29892 – three n=3 field pulses applied to brake rotation**
  - **29891 – no nRMP pulses**

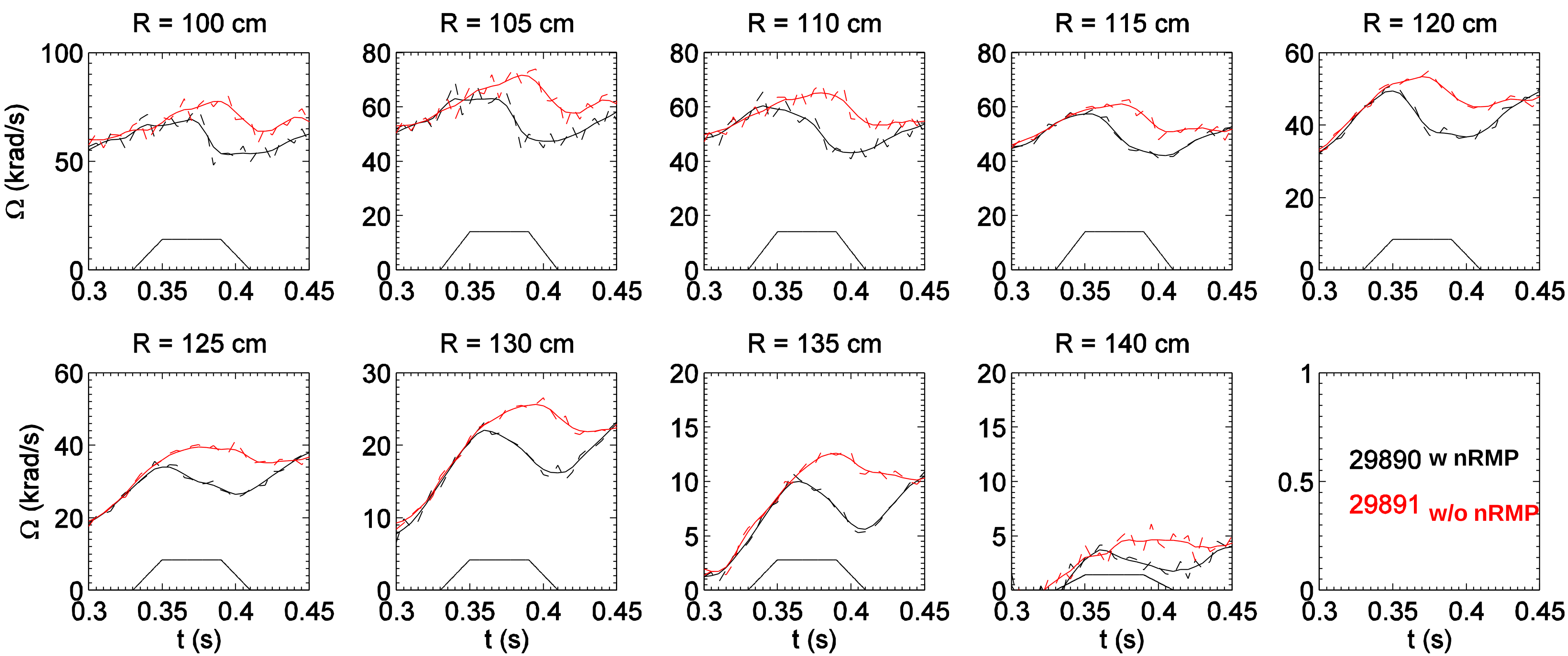
- Weak density pump out w/ nRMP, drop in β_N

- Without nRMP, eventual transition into H-mode (t~0.47 s)



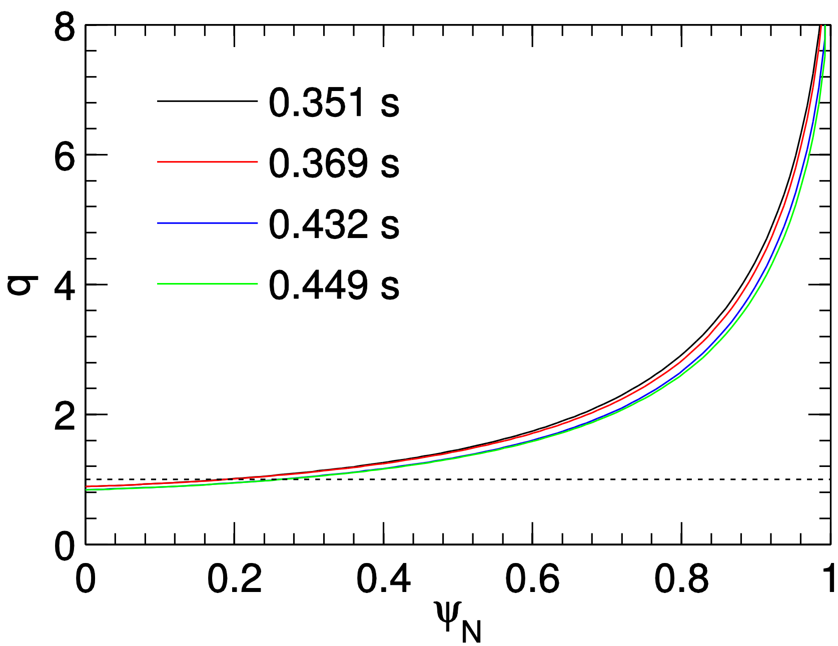
Changes in toroidal rotation due to 3D fields clearly observed

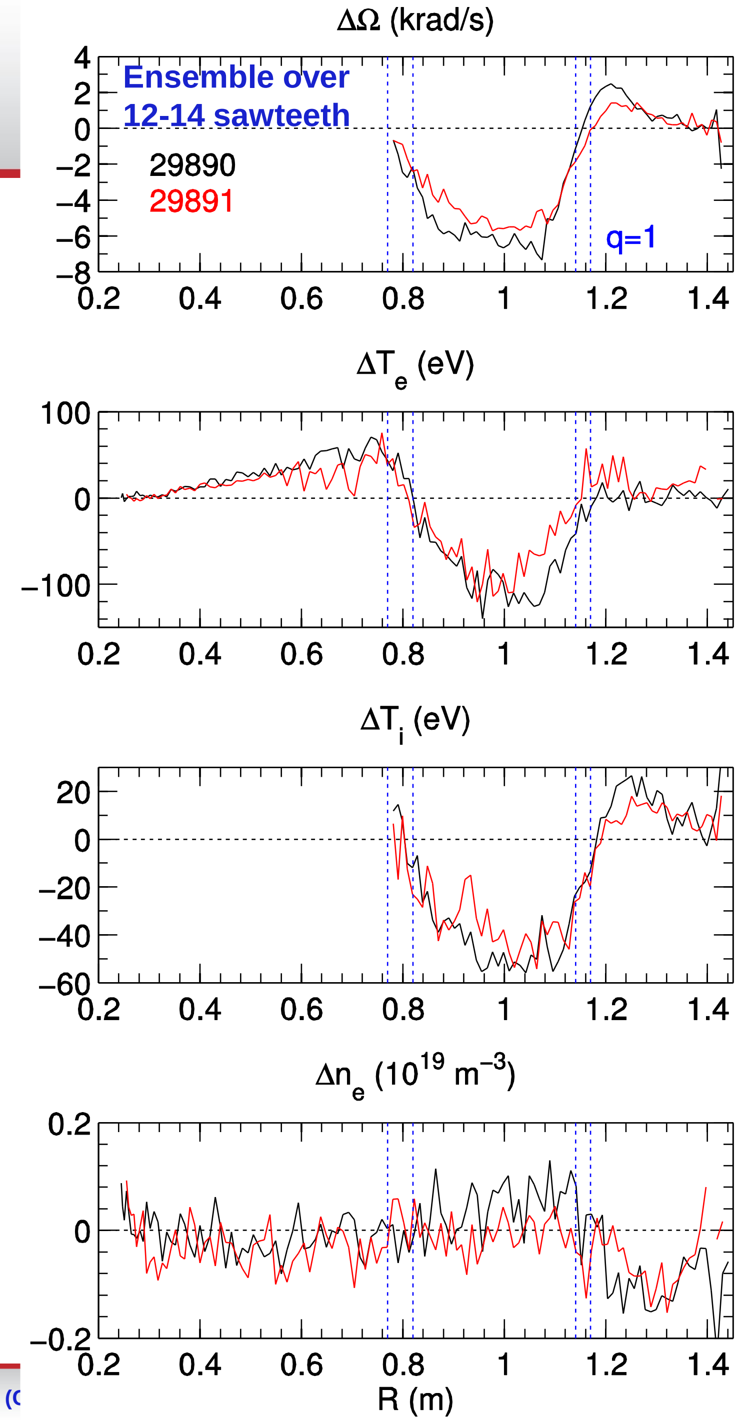
- Non-stationary conditions -- control shot (29891) provides a baseline for analysis (will impact analysis discussed later)
- Filtering to remove faster sawteeth oscillations(Δt_{ST}~6-12 ms)
  - $\Delta\Omega_{ST}$~2-6 krad/s < $\Delta\Omega_{3D}$~10-20 krad/s



Effect of sawteeth on rotation weaker than applied 3D fields

- Sawteeth cause ~6 krad/s (~8%) deceleration inside inversion radius
- q=1 surface ψ_N~0.19-0.26 (R_{out}~114-118 cm) consistent with ΔT_e inversion
  - ΔT_e ~ 120 eV (~16% of $T_{e,0}$~750)
  - ΔT_i ~ 50 eV (~6% of $T_{i,0}$~800)





Method to infer χ_φ and V_φ from transient rotation response *after* RMP turn-off

- TRANSP solves for momentum flux, Π, using the flux-surface-averaged toroidal angular momentum transport equation (Goldston, Varenna 1985), plus NUBEAM calculations for torque sources & sinks:

$$\frac{\partial}{\partial t}\left(\sum_i n_i m_i \langle R^2 \rangle \Omega\right) + \frac{1}{V'}\frac{\partial}{\partial \rho}\left[V' \cdot \Pi\right] = \sum T_{source} - \sum T_{sink}$$

- *Assuming* momentum flux composed of only diffusive and convective contributions:

$$\Pi = \sum_i n_i m_i \left[-\langle R^2 (\nabla\rho)^2 \rangle \chi_\varphi \frac{\partial \Omega}{\partial \rho} + \langle R^2 \rangle \langle \nabla\rho \rangle V_\varphi \Omega \right]$$

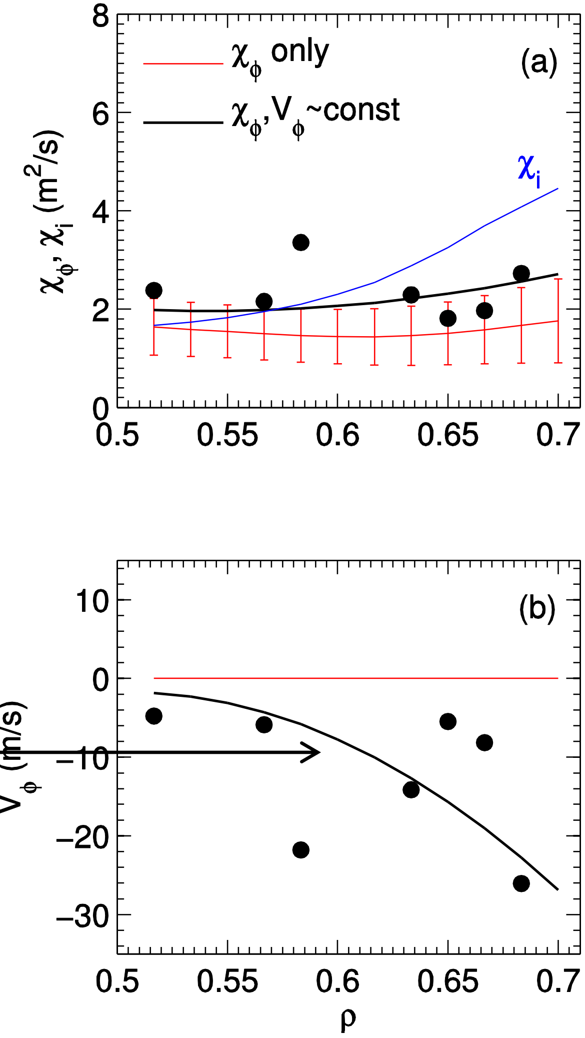
we can use $\Pi(\rho,t)$, $d\Omega/d\rho(\rho,t)$, and $\Omega(\rho,t)$ in a nonlinear least squares fit algorithm to determine best fit $\chi_\varphi(\rho)$, $V_\varphi(\rho)$ (assumed constant in time)

  – Using time window (0.41-0.45 s) after removal of NTV torque (T_{NTV}=0)

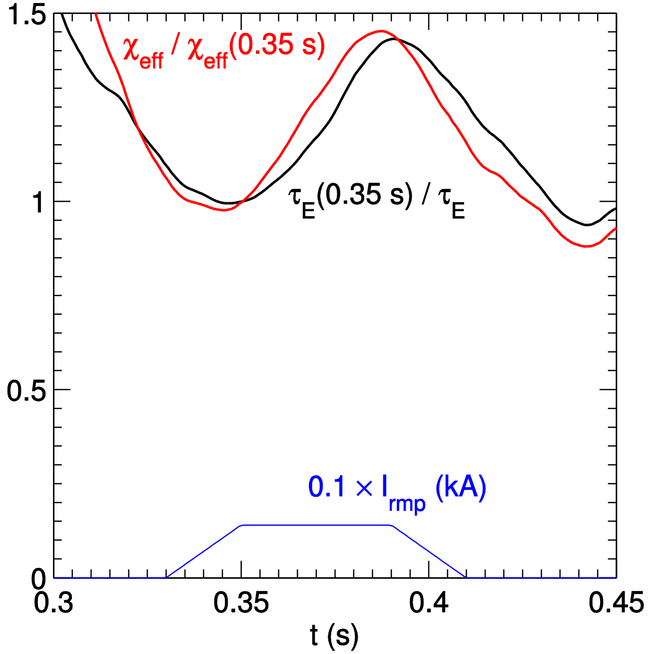
- Note: method only valid if $d\Omega/d\rho(t)$ and $\Omega(t)$ are sufficiently decorrelated

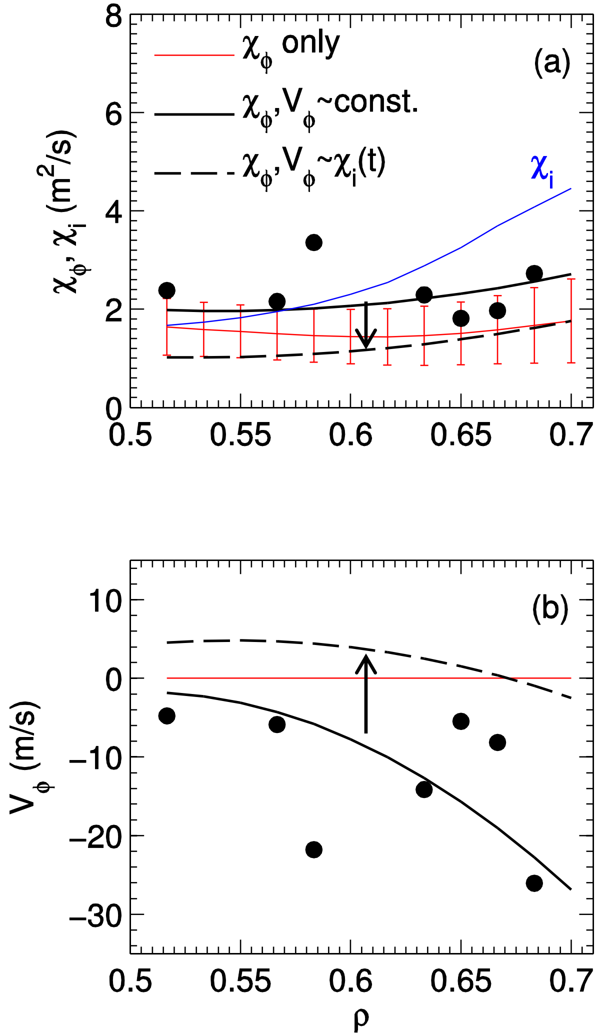
Inward momentum pinch inferred from transient recovery

- **χ_φ, V_φ assumed constant in time**
- Using both χ_φ and V_φ improves the quality of fit (χ_ν^2 smaller than χ_φ-only fit)
- At locations where there is a strong Ω-$\nabla\Omega$ linear correlation, method is ill-posed $\Rightarrow$ χ_φ & V_φ tend to large values
- Can fit entire analysis region simultaneously using polynomial profiles
  - Best fit (lowest χ_ν^2) using quadratic



Energy confinement and local thermal transport is non-stationary during analysis window

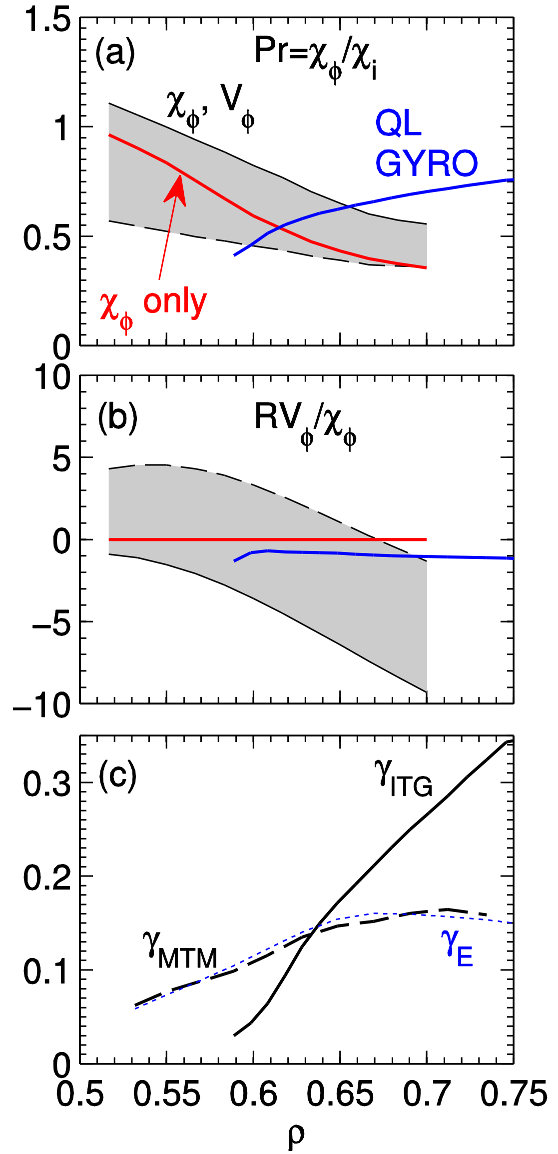




- $\tau_{E,th}$ drops ~40%, χ_{eff} increases 40%
- Inferred pinch becomes smaller or outward assuming χ_φ, $V_\varphi \sim \chi_i(t) \sim 1/\tau_E(t)$

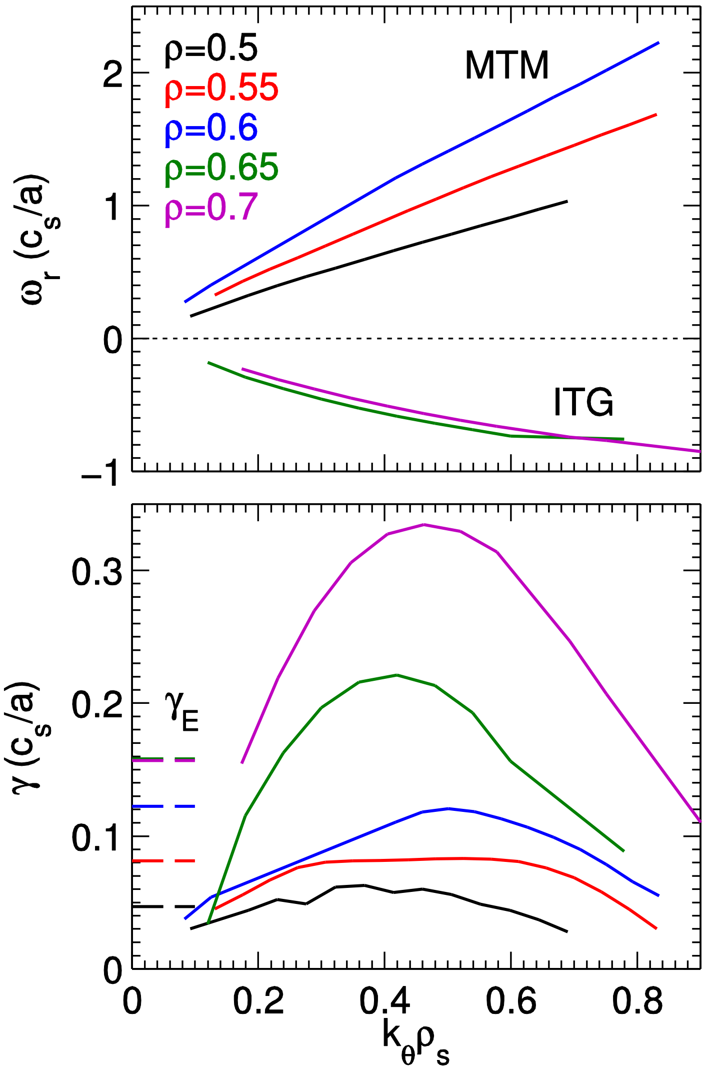
Resulting pinch parameter covers broad range, too much uncertainty to constrain quasi-linear predictions

- Prandtl number varies between Pr_{exp}=0.4-1.1
  - Quasilinear Prandtl number from unstable ITG Pr_{ITG}~ 0.5-0.8, in range of experimental inference
- Pinch parameter ranges between $(RV_{\varphi}/\chi_{\varphi})_{exp}$=(-1)-(-9) assuming fixed coefficients, or $(RV_{\varphi}/\chi_{\varphi})_{exp}$=(-1)-(5) for time-varying coefficients
  - Quasilinear pinch parameter is very small, $(RV_{\varphi}/\chi_{\varphi})_{ITG}$~ -1
  - Similar to weak pinch predicted in NSTX L and H-modes
- **Too much experimental uncertainty to constrain pinch predictions**



Linear GYRO* simulations used to predict unstable modes and corresponding momentum pinch

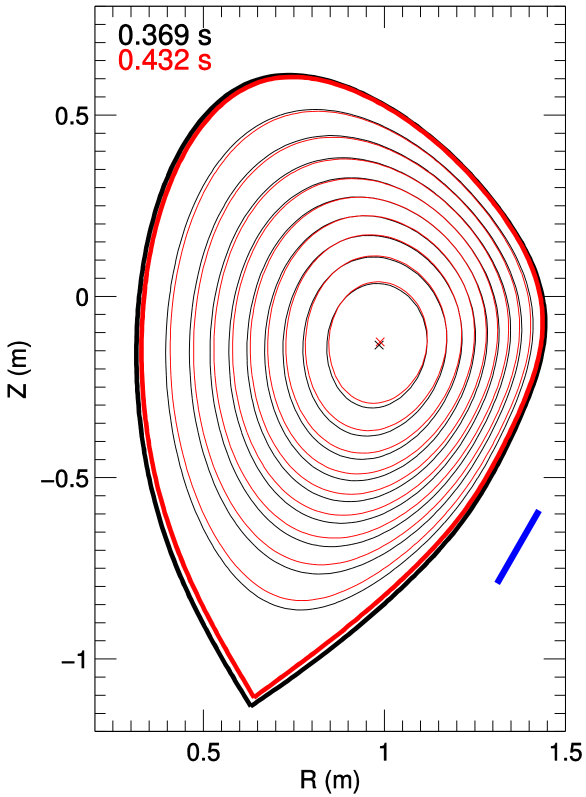
- Broad spectrum of microtearing modes (MTM) predicted ρ=0.5-0.6
  - Even in L-mode, beta relatively high (β_N=2, β_T=4%)
- However, no momentum transport predicted from MTM
- Electrostatic ITG becomes dominant ρ>0.6
- Can compute quasi-linear Prandtl number and momentum pinch for ITG mode (previous slide)

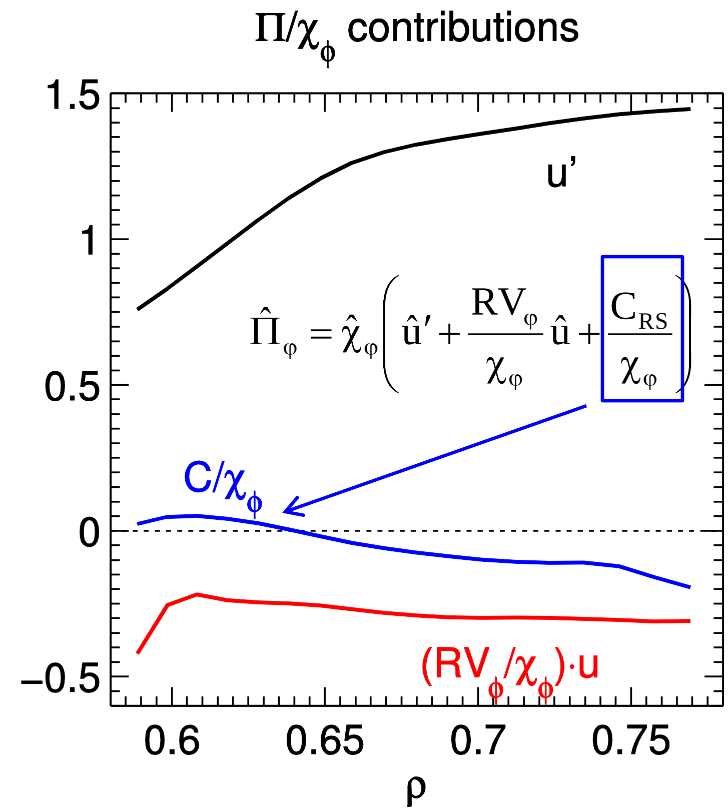


***Linear GYRO simulations**
<u>(Candy, Waltz, 2003) using:</u>
3 species: D,C,e
EM: φ, $A_{||}$, $B_{||}$
Equilibrium reconstruction

Have also begun investigating theoretical residual stress contributions

- Quasilinear residual stress from strong up-down asymmetry (Camenen, PRL 2009) predicted to be smaller than diffusive or convective contributions





- Also investigating residual stress sources due to finite ρ_*~1/100 with global GTS sims, e.g. profile shear ~ $\omega_r'\cdot\rho_*$ (Camenen, NF 2011), intensity shear ~ $d(\gamma_{ITG}-\gamma_E)/dr\cdot\rho_*$ (Gurcan, PoP 2010), zonal flow shear (Wang, FEC2016 TH/P3-12; PoP 2010)

Summary & future work

- Previous NSTX H-mode experiments inferred momentum pinch comparable to conventional tokamaks, $(RV_\varphi/\chi_\varphi)_{exp}$ ~ (-1) – (-10)
- However, local, quasi-linear GK theory predicts negligible pinch $(RV_\varphi/\chi_\varphi)_{sim}$ ~ 0 – (-1) in NSTX H-modes due to electromagnetic and low-aspect-ratio effects on mode-symmetry

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- Local, quasi-linear GK theory predicts weak pinch $(RV_\varphi/\chi_\varphi)_{sim}$ ~ (-1) similar to NSTX H-modes - **too much uncertainty in experiments to constrain MAST L-mode predictions**

- Future NSTX-U L-mode experiments are planned to continue investigation of momentum pinch and residual stress contributions