Connections between intrinsic rotation, density peaking, and plasma turbulence regimes in ASDEX Upgrade

Presented by R. M. McDermott

With Contributions from
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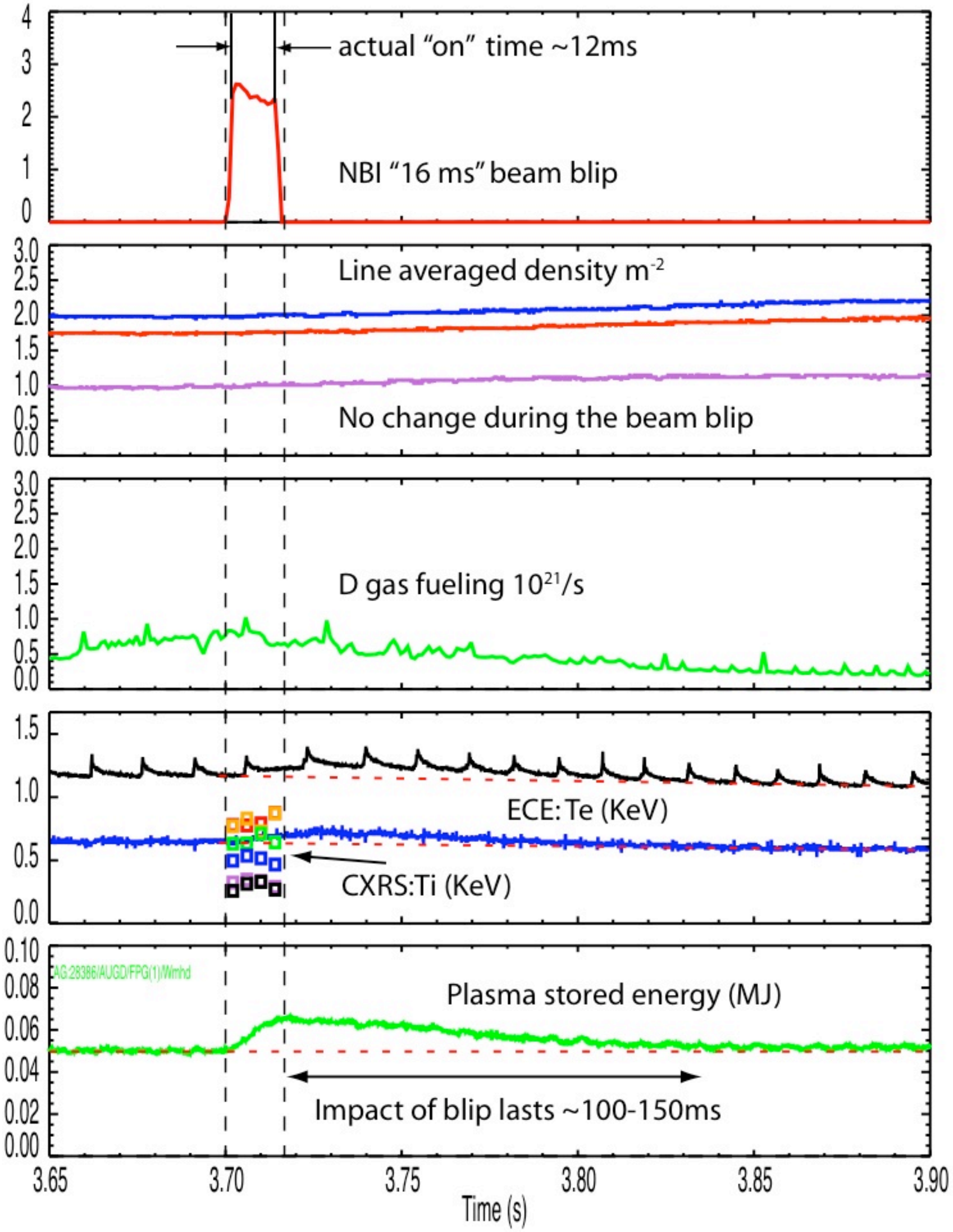
Motivation and Overview

- Tokamak transport is turbulence dominated
- Turbulent channels (energy, particle, momentum) are intricately connected
- No theory of tokamak transport complete without understanding and inclusion of these interactions

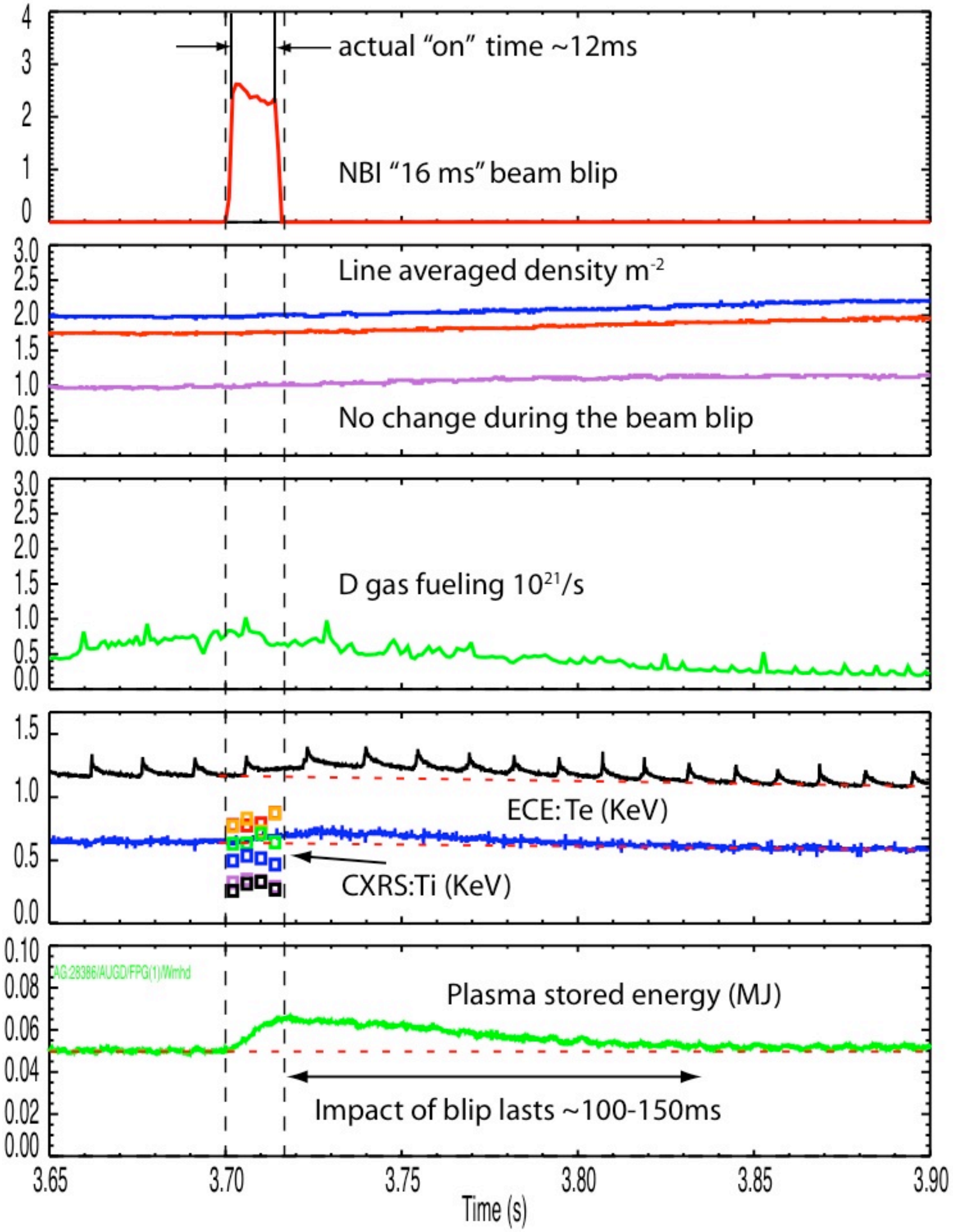
- In this talk: Consistent connections between turbulence driven particle and momentum transport observed in
  - Intrinsic rotation database
  - Rotation changes across linear to saturated Ohmic confinement (LOC-SOC) regime
  - NBI H-modes + ECRH Power

Intrinsic V_φ measured via non-perturbative NBI blips

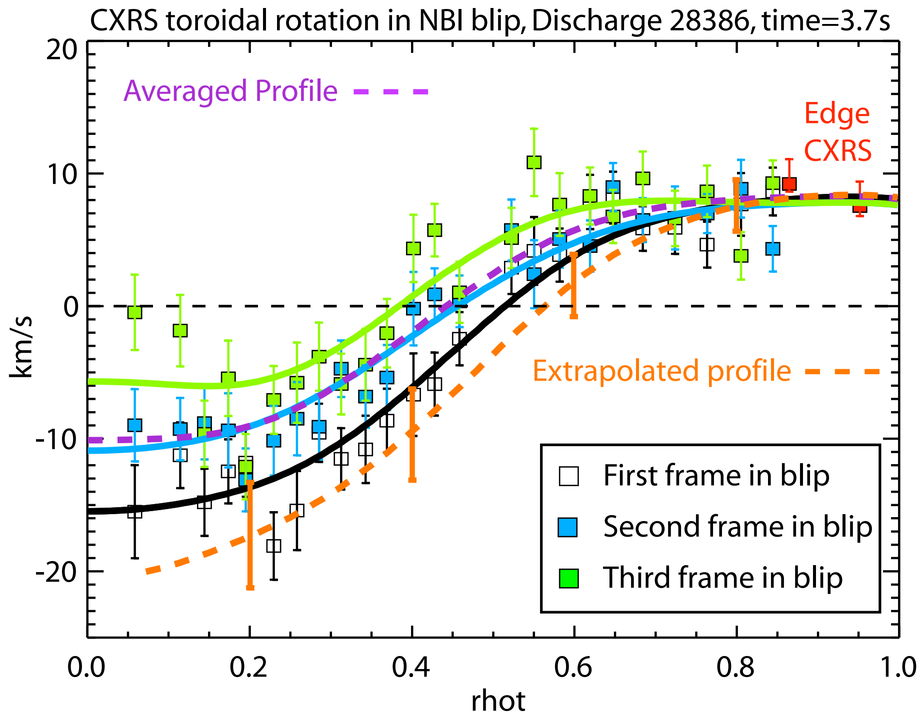


- 12-16ms NBI blips
  - Minimal impact on plasma
  - No effect observed on n_e
  - Effect on T_e and W_p (100-150ms)

Intrinsic V_φ measured via non-perturbative NBI blips

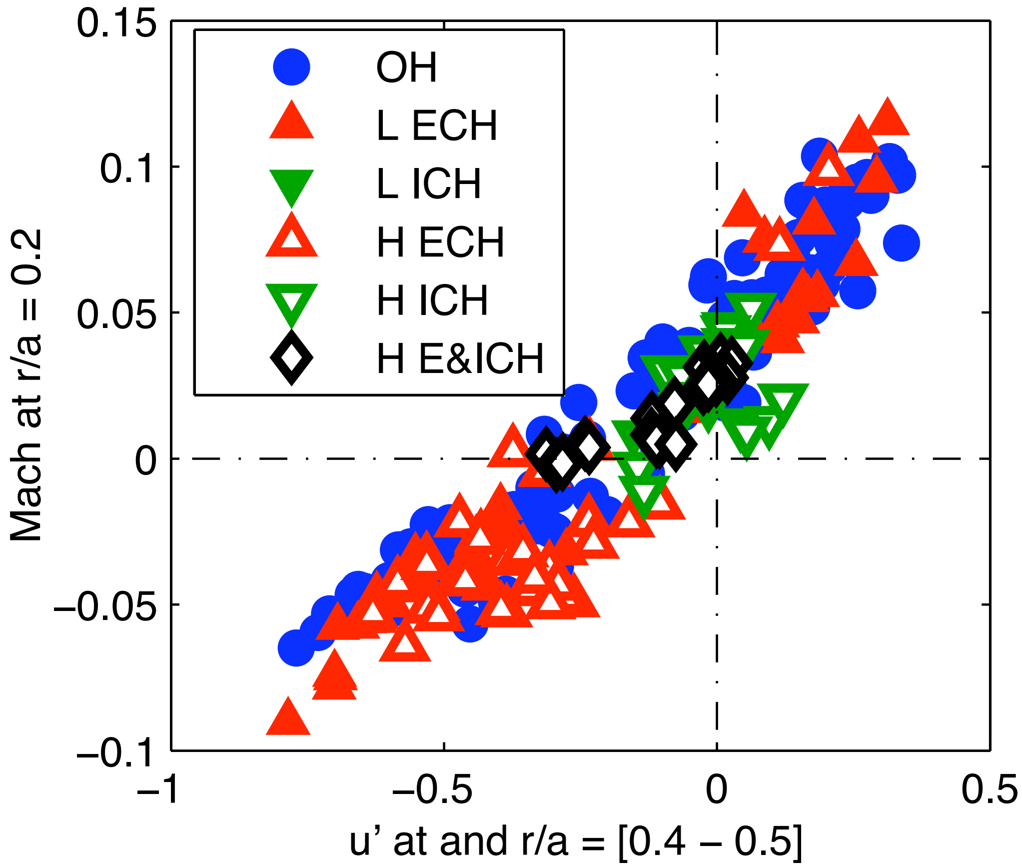


- CXRS B^{5+} / C^{6+} ~ t_{int} = 4ms
  - Intrinsic rotation obtained via averaging or linear backward extrapolation
  - V_D calculated with NC correction gives typically 3% difference



Near perfect correlation of core Mach with mid-radius rotation gradient

- Rotation database developed using NBI blip technique
  - Ohmic L-mode and ECRH and ICRH L- and H-mode plasmas
- Core Mach strongly correlated (94%) with normalized V_φ gradient at mid-radius, U'
- Correlation holds for ALL cases regardless of confinement or heating method



$$U' = -(R/v_{thi})\frac{dV_\phi}{dr}$$

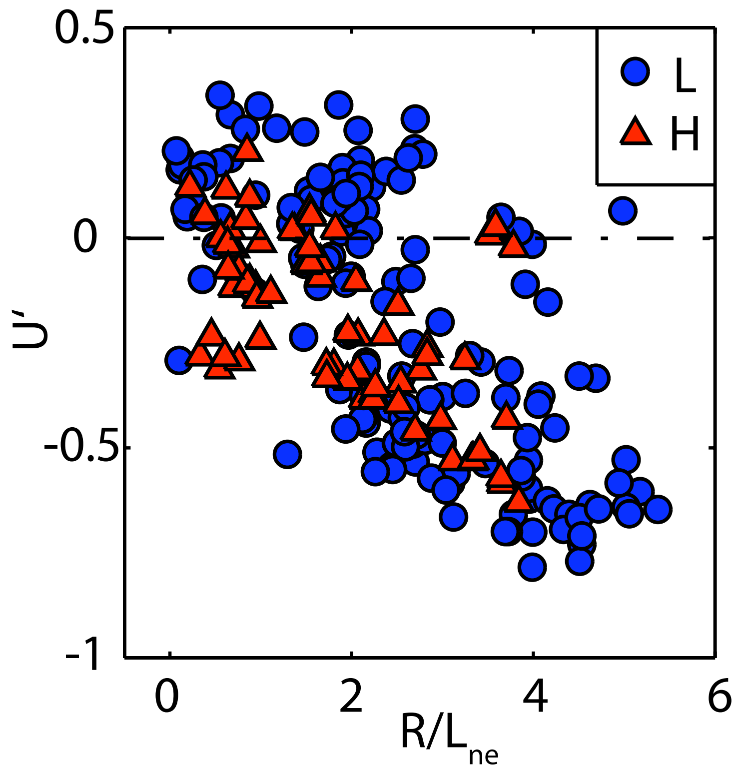
McDermott, *et al* PPCF **53** 124013 (2011) & Angioni, *et al* PRL **107** 215003 (2011)

U' correlates best with R/L_{ne}

- Normalized rotation gradient

  Correlates best with R/L_{ne} (70%)

  - Peaked density ↔ hollow rotation
  - Flat density ↔ peaked rotation



Angioni, *et al* PRL **107** 215003 (2011)

Database suggests connection between momentum and particle transport

- Normalized rotation gradient

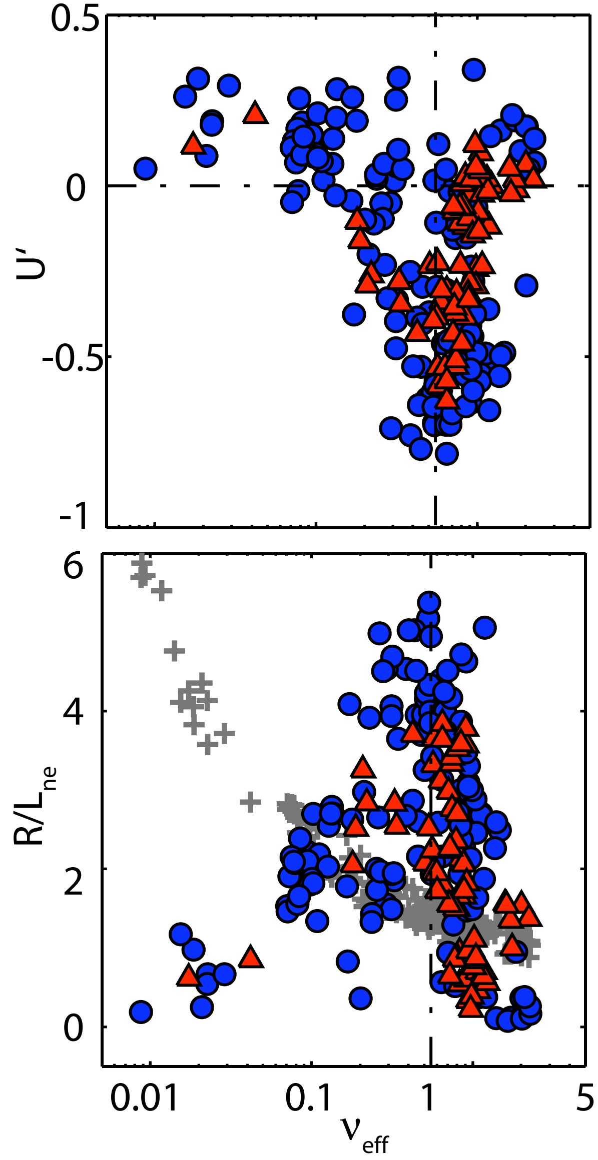
  Correlates best with R/L_{ne} (70%)

  - Peaked density ↔ hollow rotation
  - Flat density ↔ peaked rotation

- U' and R/L_{ne} show opposing non-monotonic dependence on υ_{eff}

$$\upsilon_{eff} = \frac{\upsilon_{ei}}{C_s/R}$$

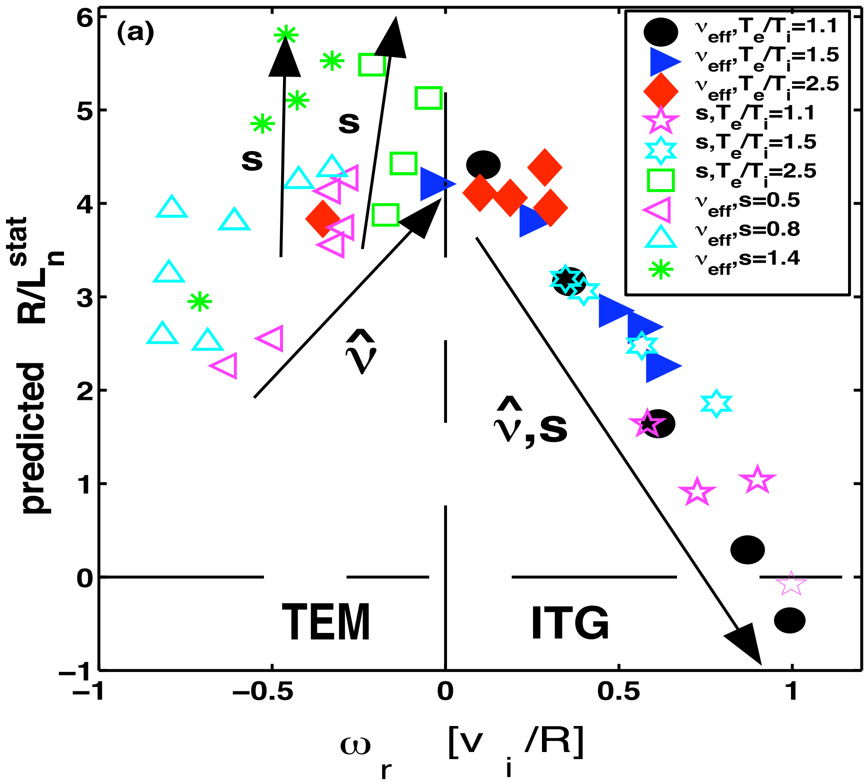
- Minimum in Mach and maximum in R/L_{ne} occur at same υ_{eff}
  - Connection between particle and momentum transport



Angioni, *et al* PRL **107** 215003 (2011)

Particle transport consistent with theoretical predictions

- Robust explanation for R/L_{ne}
  - Maximal R/L_{ne} in TEM regime near ITG/TEM border
  - R/L_{ne} increase with q_{95} predicted due to increase in magnetic shear (TEM)



Fable, PPCF 52 015007 2010

Particle transport consistent with theoretical predictions

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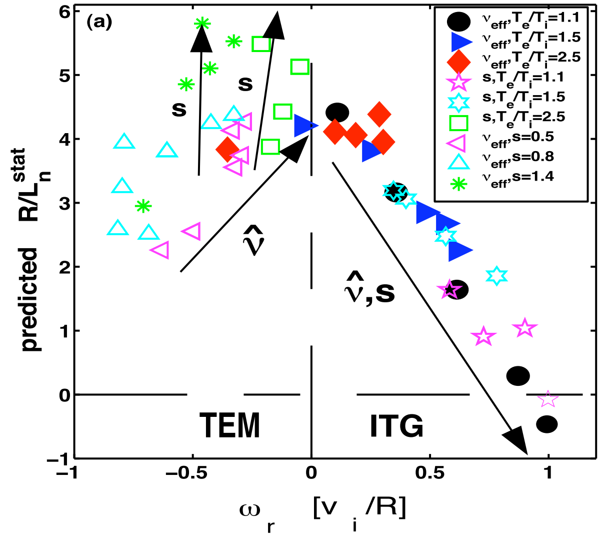
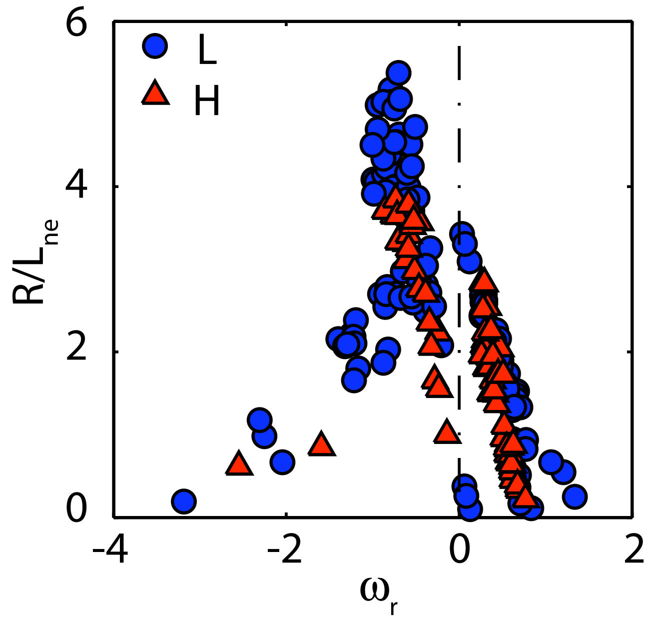
  - Maximal R/L_{ne} in TEM regime near ITG/TEM border
  - R/L_{ne} increase with q_{95} predicted due to increase in magnetic shear (TEM)

- Database consistent with theoretical turbulent particle transport
  - Magnetic shear trend also reproduced

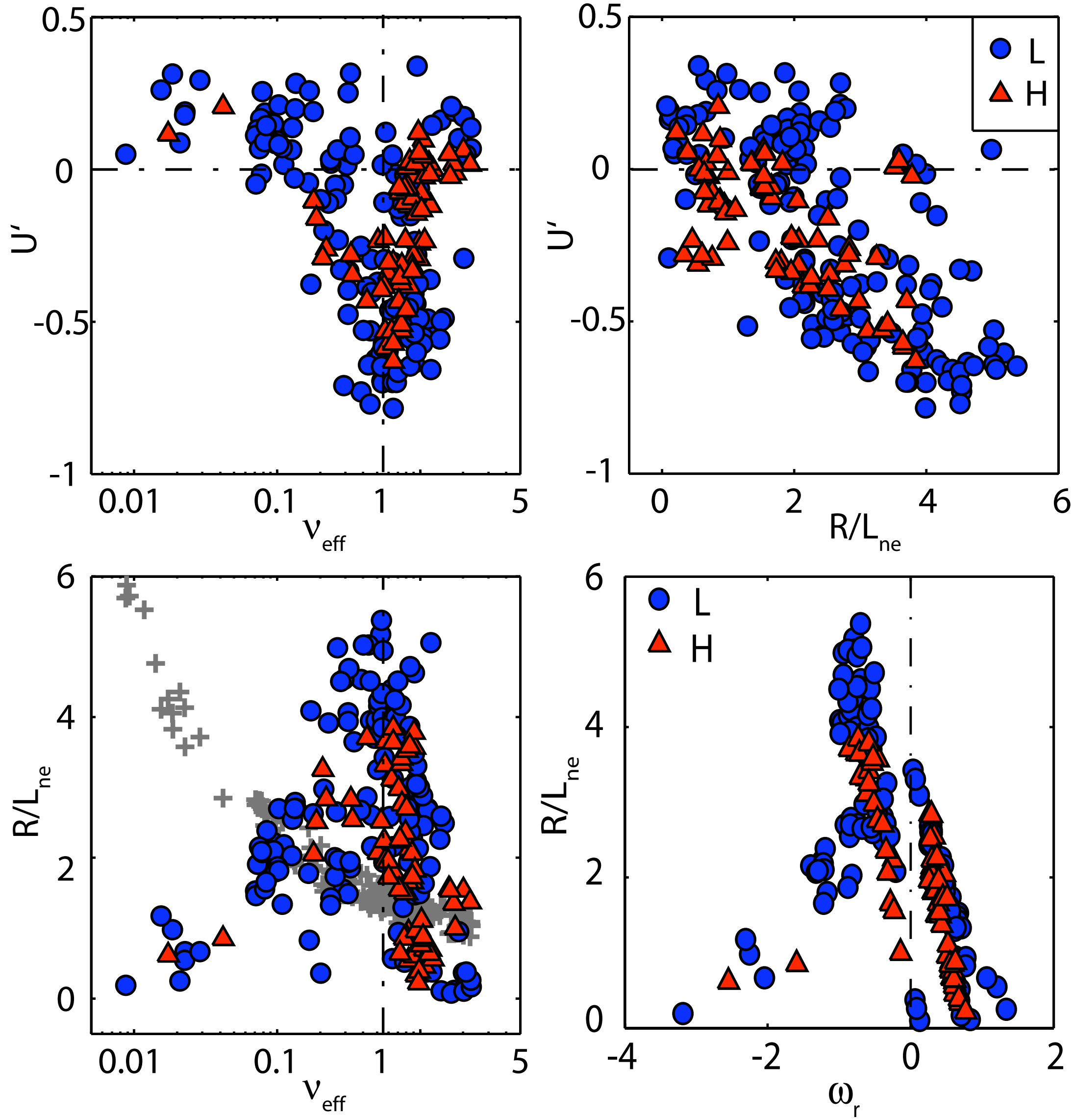




Fable, PPCF 52 015007 2010, Angioni, *et al* PRL **107** 215003 (2011)

Hollow rotation occurs with strong R/L_{ne}

- Negative u’ (hollow profile) occurs concurrent with strong R/L_{ne} and leads to cntr-current rotation in the core
  - Strong R/L_{ne} occurs near ITG/TEM boundary



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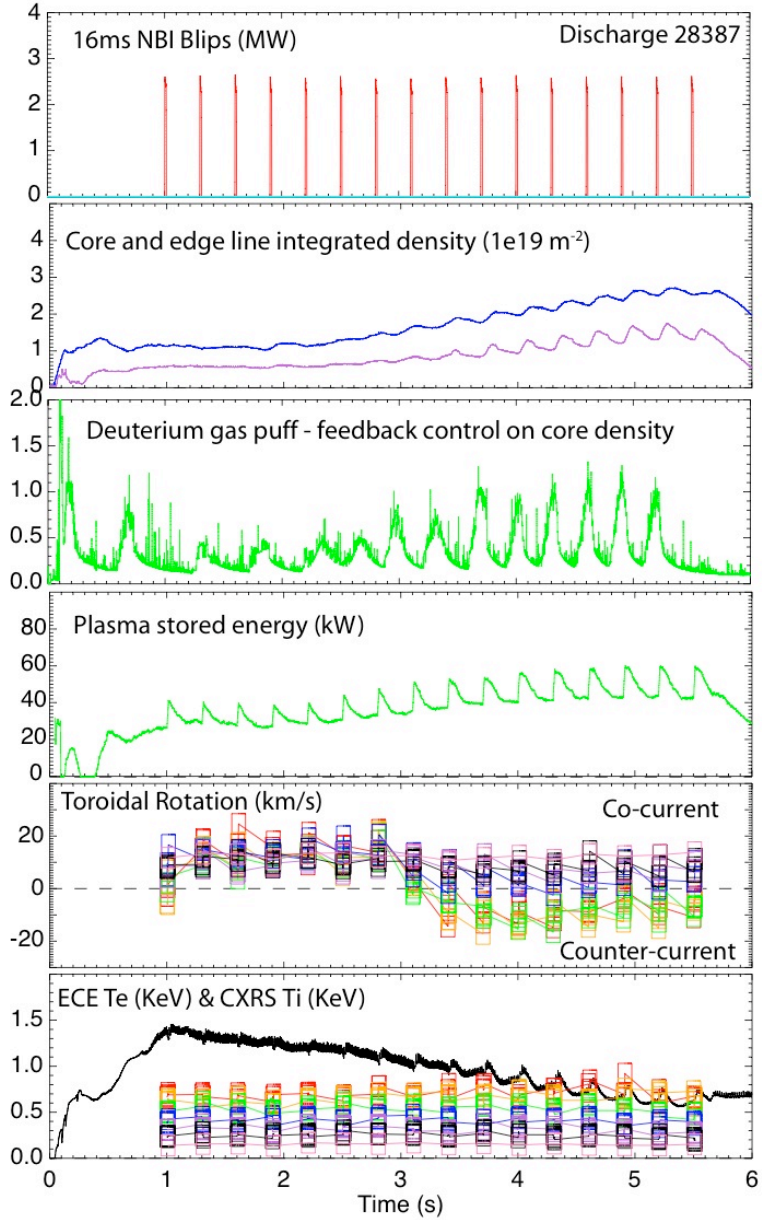
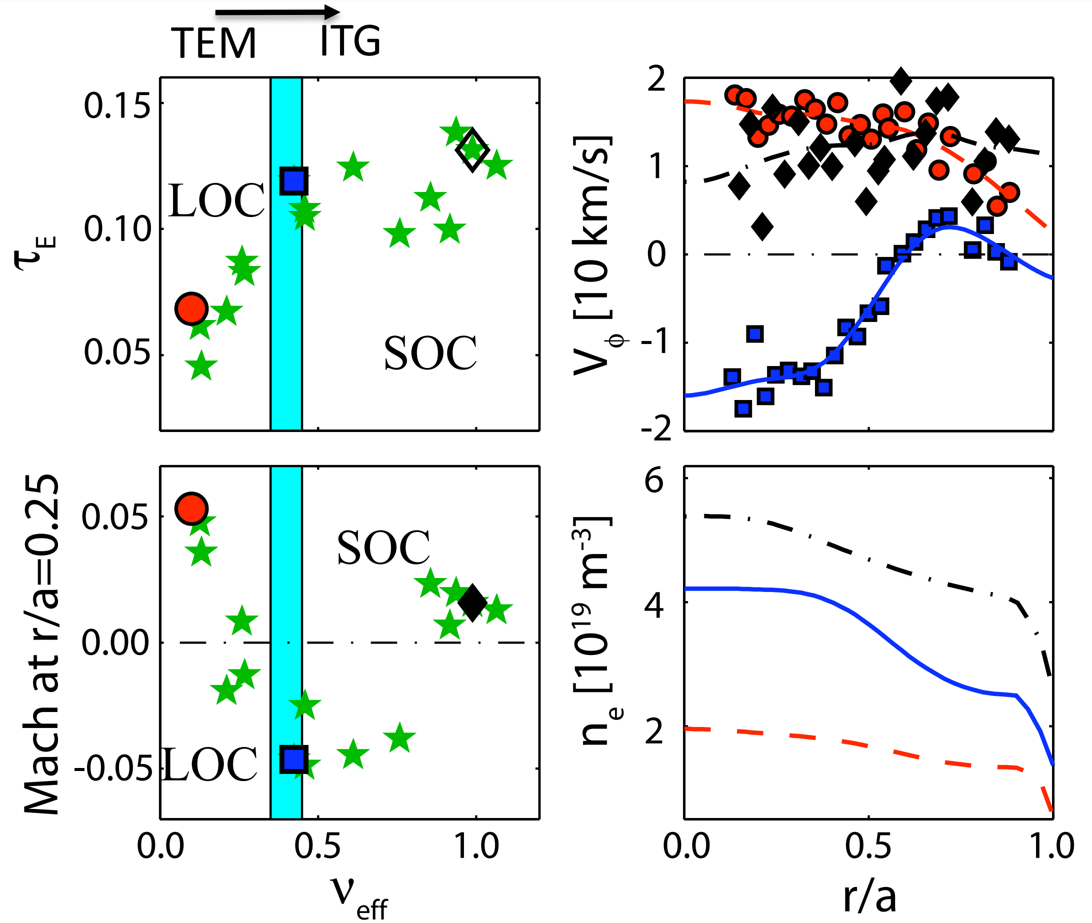
Rotation reversals observed within individual discharges

Expansion of intrinsic database:

- Ohmic L-mode discharges with n_e ramps performed to study V_φ across TEM/ITG and LOC-SOC boundaries
- V_φ switches co-current to counter-current with increasing n_e
    - Second switch to co-current with further increased n_e



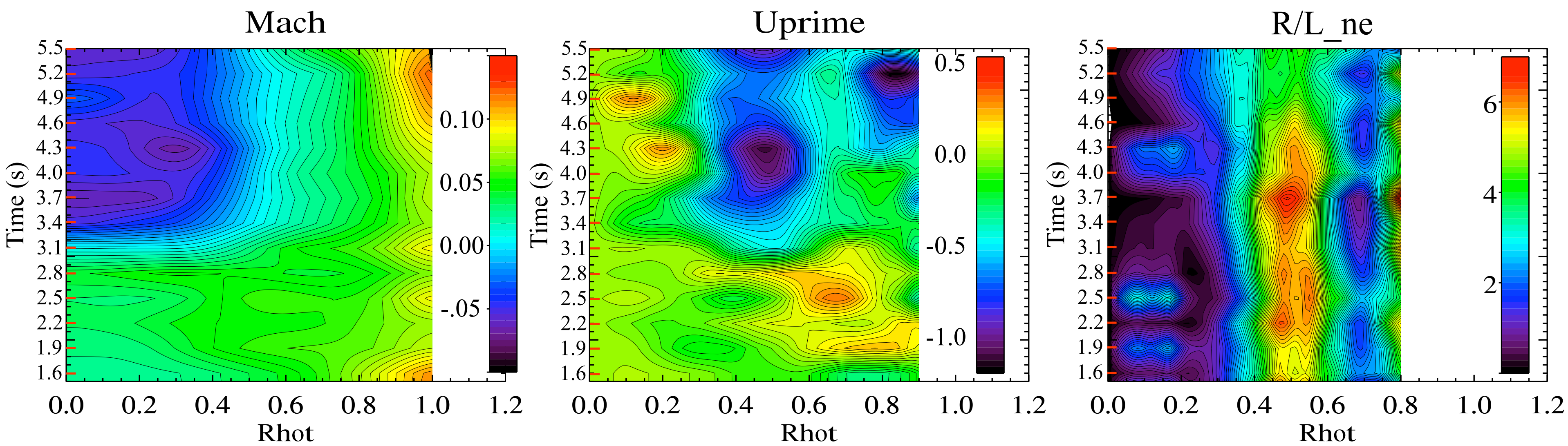
Double V_φ reversal connected to R/L_{ne}



- Connection between energy confinement, intrinsic rotation, and turbulent particle transport!
- Double reversal of rotation with correlates with R/L_{ne} behavior

Core V_φ linked to mid-radius behavior

- Rotation $0<\rho_\varphi<0.4$ changes occurs simultaneously
  - Time resolution (300ms)
- R/L_{ne} at mid-radius evolves before/during LOC-SOC transition
  - υ_{eff} also increasing with time

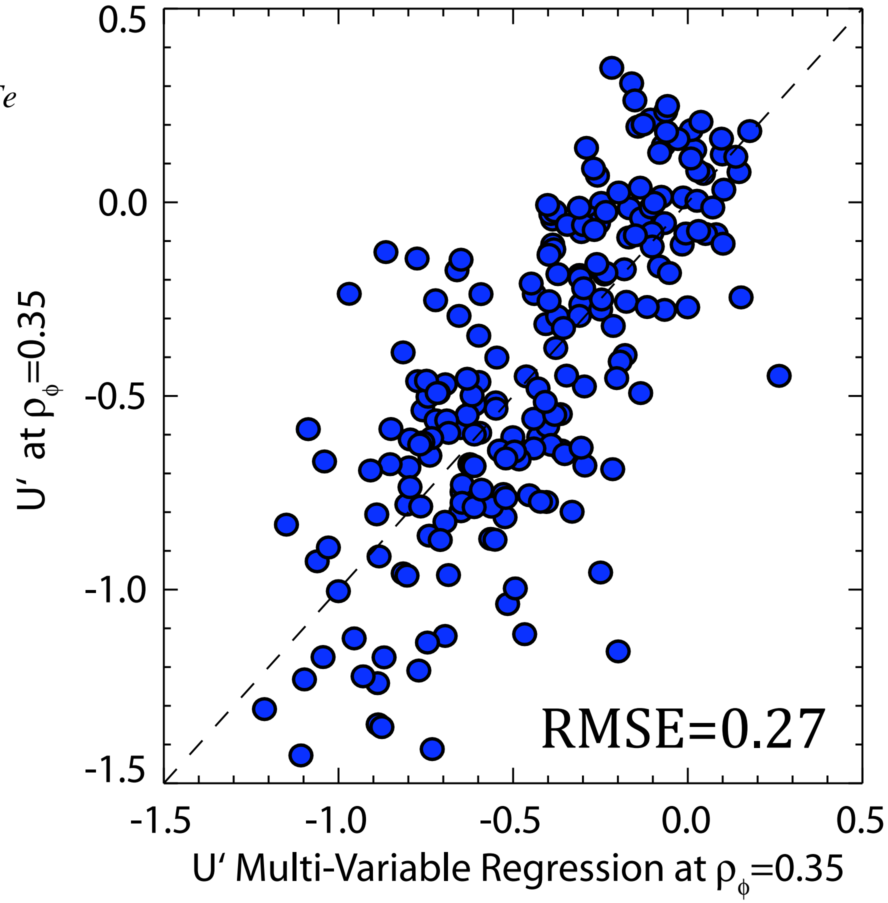


Multi-variable regression indicates R/L_{ne}, ν_{eff}, & R/L_{Ti}

$$U' = -\boxed{(0.16 \pm .02)R/L_{ne}} - \boxed{(0.11 \pm .02)\upsilon_{eff}}$$
$$-\boxed{(0.09 \pm 0.03)R/L_{Ti}} - (0.01 \pm 0.01)R/L_{Te}$$
$$-(0.04 \pm .02)q_{95} + (11.5 \pm 10.5)\rho^{*} + C$$

Variable: (V)	Significance: (A_x/σ_x)	Relevance: A_xStd_dev (V)
R/L_{ne}	-6.6	-0.17
υ_{eff}	-5.3	-0.11
R/L_{Ti}	-3.1	-0.08

- **R/L_{ne}** – Most statistically significant & relevant variable
  - followed by υ_{eff} & R/L_{Ti}



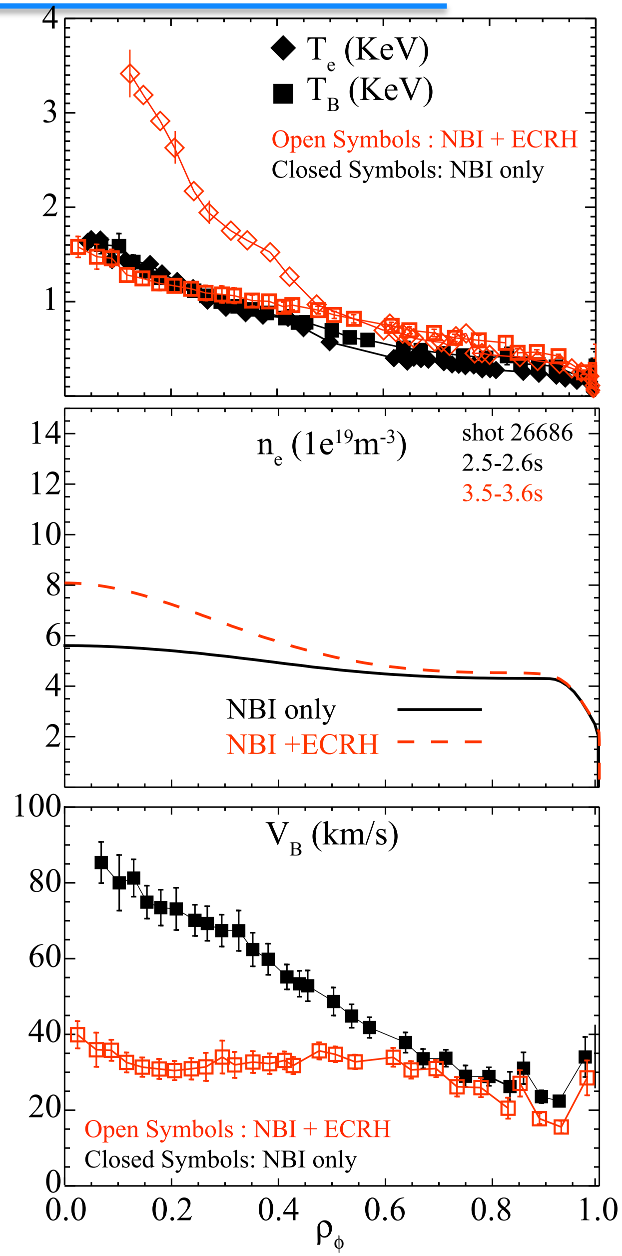
Similar behavior seen in NBI H-modes

- AUG NBI H-modes ITG dominated
  - Sufficient ECRH increases T_e - turbulence regime switches to TEM
  - Turbulence change causes n_e peaking
  - Rotation flattens and can become hollow

- Qualitatively consistent with intrinsic rotation database observations!
- Requires transport analysis to confirm presence of residual stress torque

For more details: Angioni, TH/P2-21

McDermott PPCF **53** 035007, 2011, McDermott PPCF **53** 124013, 2011



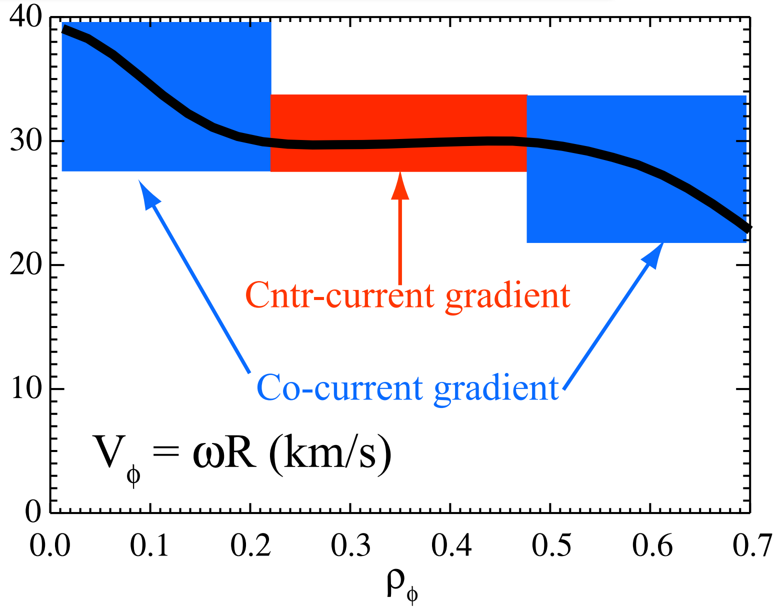
Transport analysis indicates presence of RS torque same order of magnitude as NBI!

External torque   Intrinsic torques

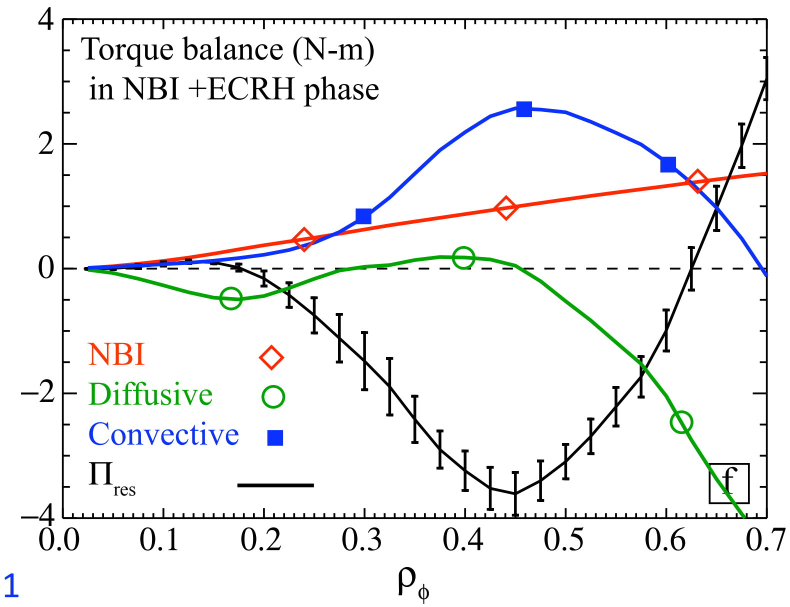
$$\int \left(\eta_{NBI} + \Pi_{RS}\right) dVol \quad +$$

$$m_{eff} n_e R \left\langle \frac{\partial Vol}{\partial r} \right\rangle \left[\chi_\phi \frac{d\langle V_\phi \rangle}{dr} - V_{Con} \langle V_\phi \rangle \right] = 0$$

Diffusion   Convection



- Diffusive flux ~ 0 due to $\nabla V_\varphi \sim 0$
- NBI and convection both inward
- Counter-current Π_{RS} needed to explain rotation profiles
  - Same order of magnitude as torque from 1-2NBI sources!



McDermott PPCF **53** 035007, 2011, McDermott PPCF **53** 124013, 2011

Size of residual stress scales with R/L_{ne}

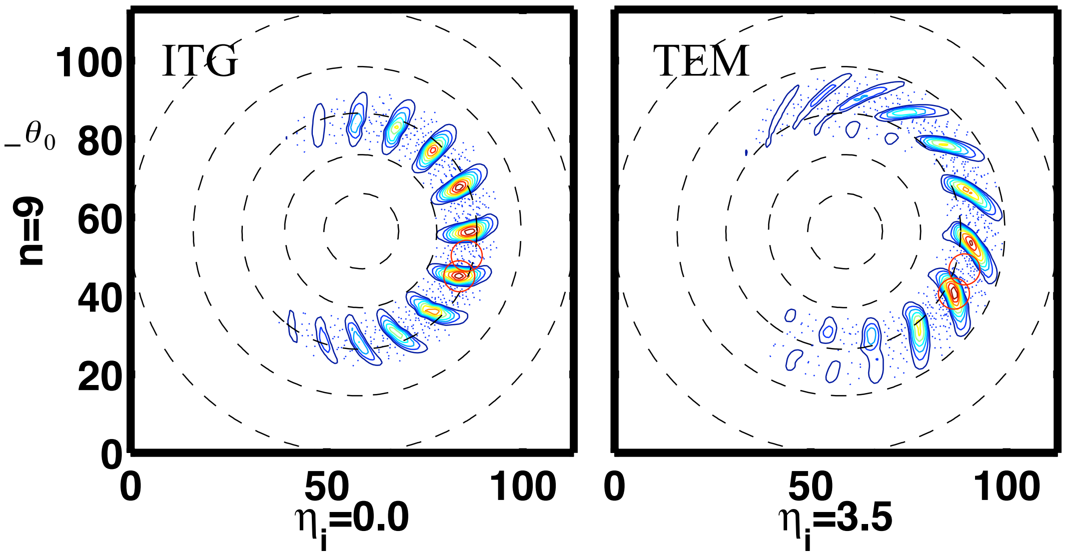
- Momentum transport equation in intrinsic scenarios:

$$\Gamma_{RS} + \chi_{\phi} u' + RV_C u = 0$$

- If convection contribution is small expect residual stress to shown similar dependencies to u' → $\Gamma_{RS} \propto R/L_{ne}$
- Test Γ_{RS} dependence using local linear gyrokinetic simulations (GS2)

$$u'_{prediction} = -\left(\frac{RV_C}{\chi_\phi}\right)_{GS2} u_{D,meas.} - \left(\frac{\Gamma_{RS}}{\chi_\phi}\right)_{GS2\_\theta_0}$$

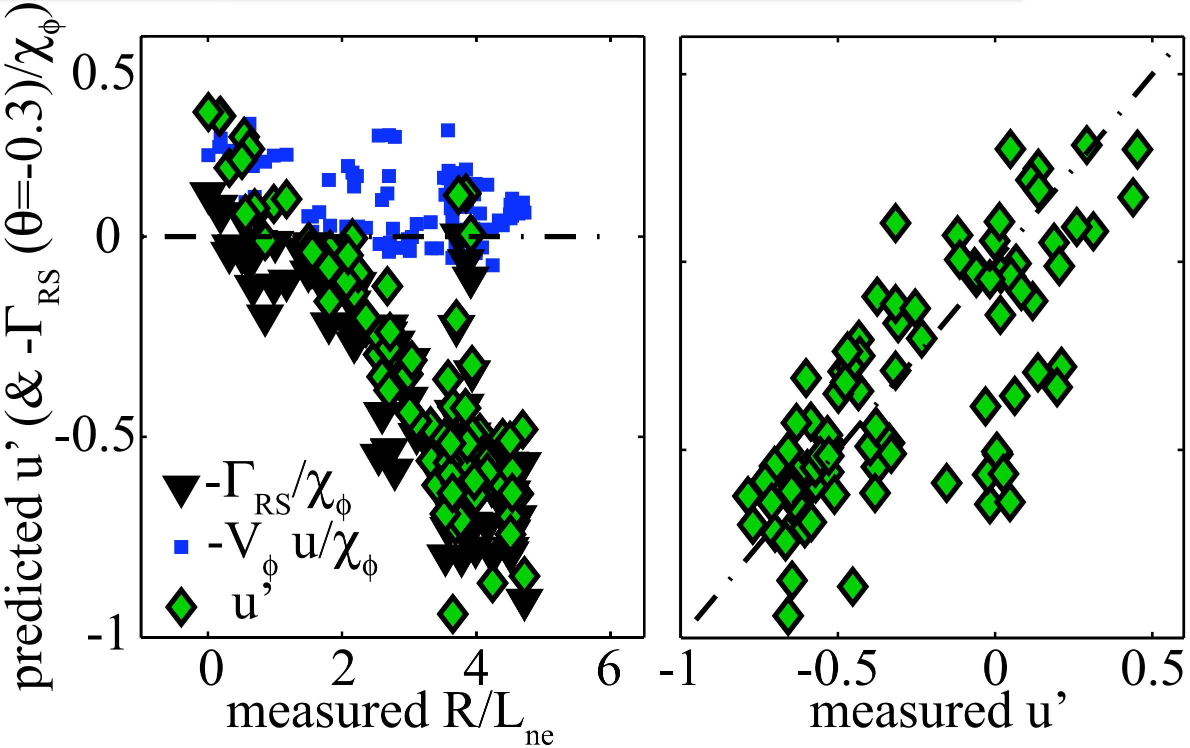
Real part of potential ϕ



Courtesy of A. Bottino, ORB5

Residual stress and intrinsic rotation calculation dominated by R/L$_{ne}$

- Predicted Γ_{RS}/χ_φ dependent on R/L$_{ne}$ and sets u'
  - Coriolis pinch small fixed offset

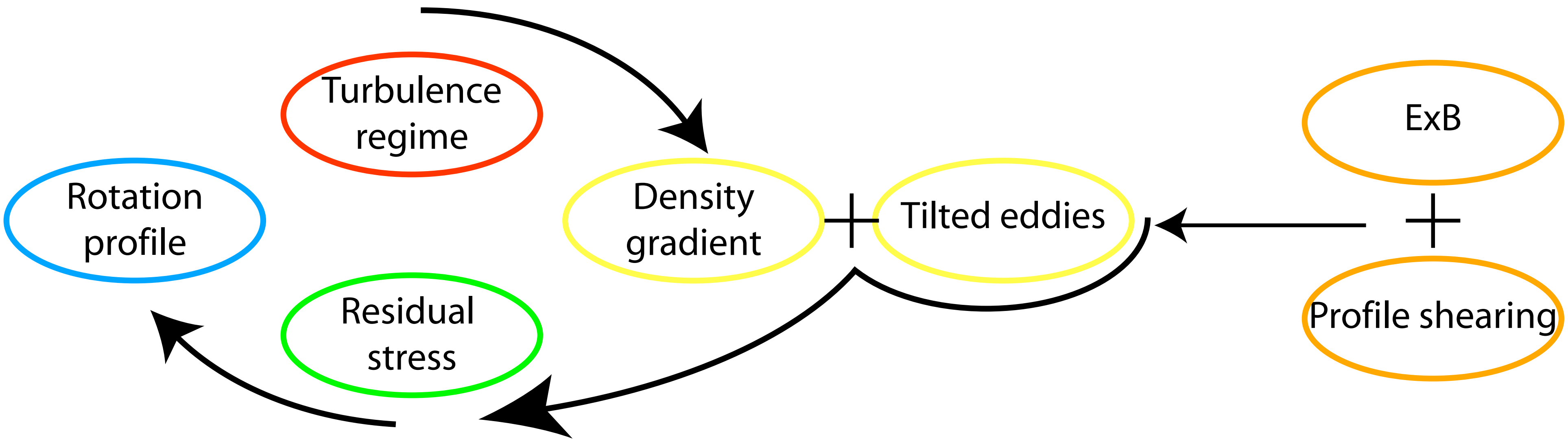


Angioni, *et al* PRL **107** 215003 (2011)

- Quantitative agreement of u' with θ_0=-0.3 rad for TEM data points
  - ITG points fit best to -0.15rad
  - Combination ExB (same tilt direction for both ITG & TEM) and profile shearing (tilt direction opposite for ITG & TEM)

Consistent story

- ITG to TEM turbulence regime
  - peaked n_e profiles
  - Increased residual stress momentum flux (cntr-current torque)
  - Cntr-current rotation gradient and hollow rotation profile



Summary and Conclusions

- Connection between turbulent particle and momentum transport
  - Hollow V_φ profiles (counter-current directed residual stress torque) occur only with strong R/L_{ne}, which occurs near the ITG-TEM boundary
  - Observed in intrinsic rotation database, Ohmic L-modes across LOC-SOC, and NBI H-modes with ECRH power

- Predicted u' from linear gyro-kinetic calculations with constant tilting angle dominated by Γ_{RS} ,which shows strong dependence on R/L_{ne}
  - Quantitative agreement for TEM dataset with -0.3rad tilt angle & ITG with -0.15rad
  - Combination of ExB and profile shearing qualitatively consistent

- Next step non-linear simulations to confirm Γ_{RS} results
- Expansion of AUG database to wider range of topologies and parameters
- Inter-machine intrinsic V_φ comparison using same analysis techniques