Validation of Theoretical Models of Intrinsic Torque in DIII-D and Projection to ITER by Dimensionless Scaling

by
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[1]PPPL, [2]GA, [3]UCSD, [4]VTT, [5]IST, [6]CCFE

Presented at the
26th IAEA Fusion Energy Conference
Kyoto, Japan

October 17-22, 2016

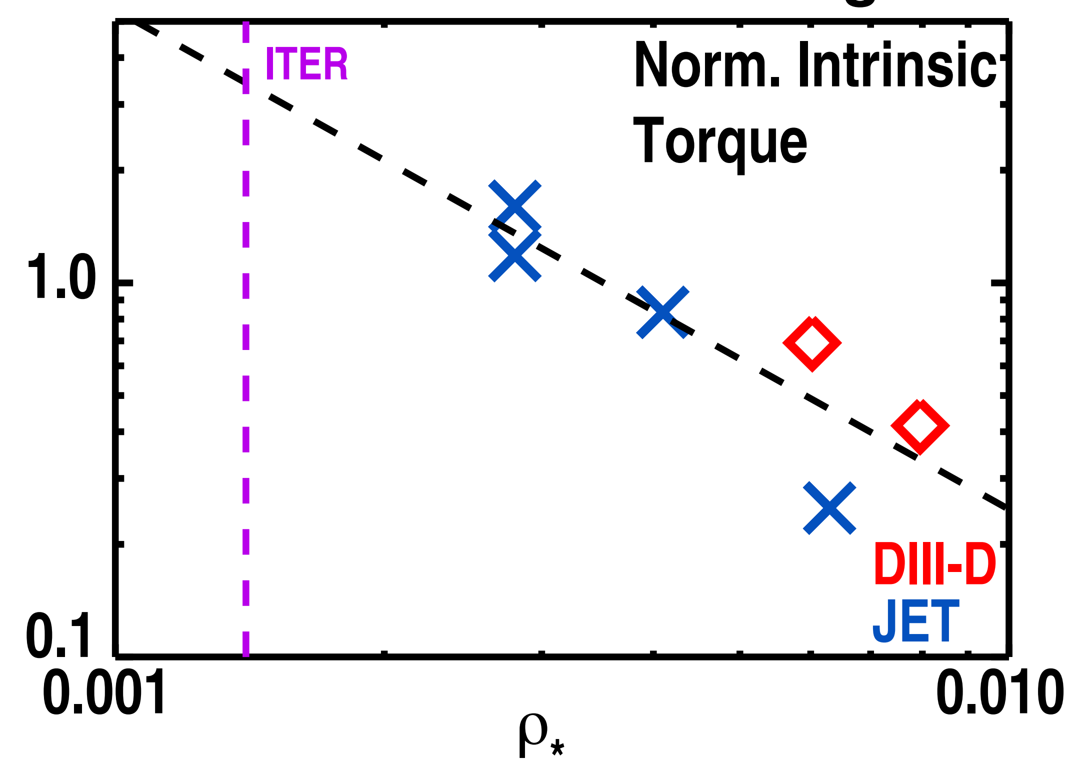
DIII-D NATIONAL FUSION FACILITY

PPPL

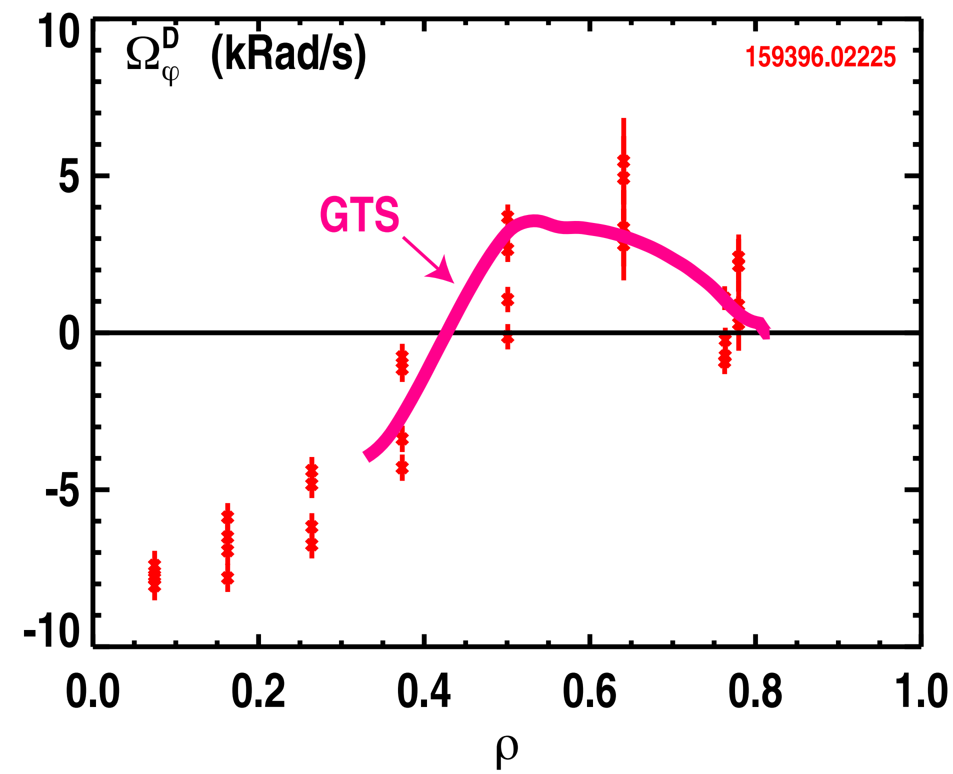
Experiments on DIII-D have Advanced the Predictive Capability for Intrinsic Rotation in ITER

- **Toroidal rotation in ITER is expected to be strongly influenced by intrinsic sources**
- **Empirical dimensionless scalings provide extrapolation from multi-machine databases**
- **First-principles based predictions require momentum diffusion, pinch and residual fluxes *plus* boundary condition**

Dimensionless Scaling



Intrinsic Rotation



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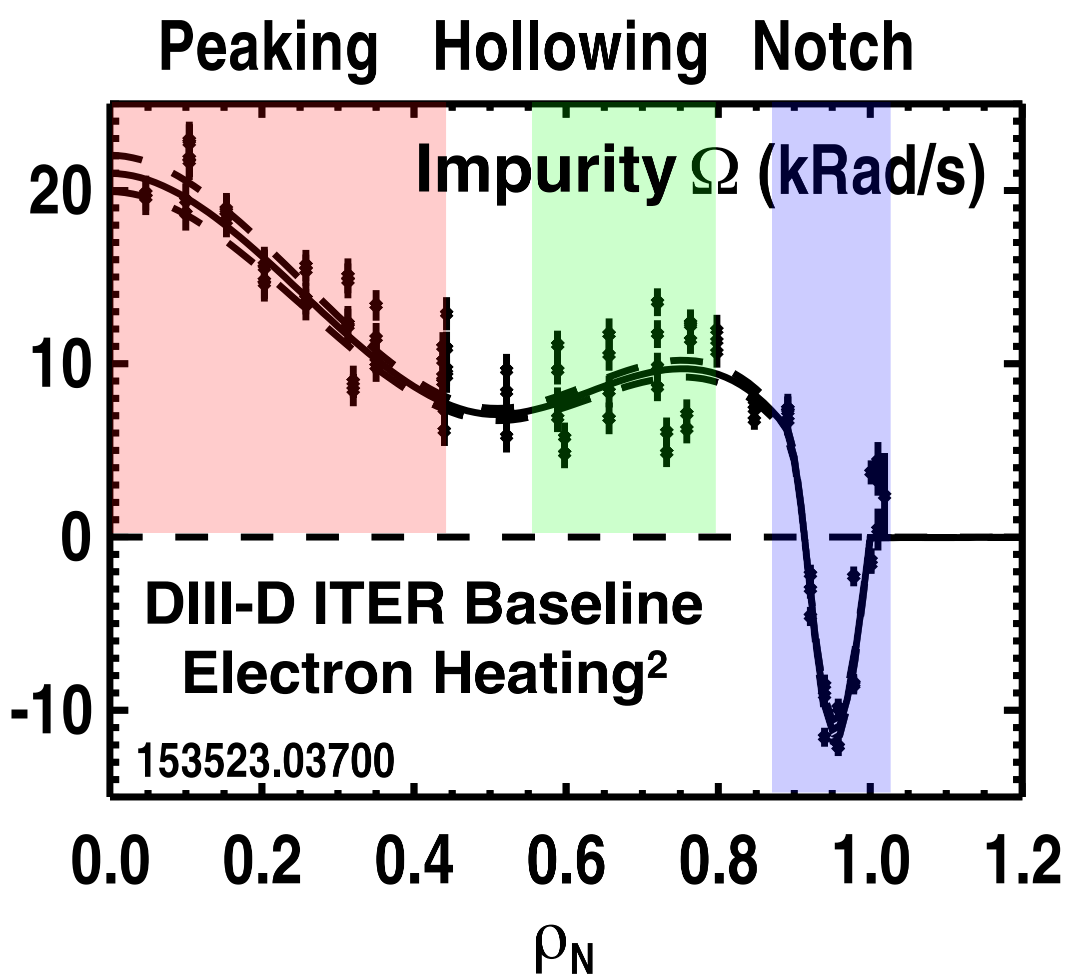
Prediction of Toroidal Rotation Required to Assess Stability, Transport, ELM Suppression for ITER



- Can we predict overall angular momentum?
- Can we predict the core gradients and structure?
- What is the role of the boundary condition?

- Overall rotation for MHD stability, W transport
- Core rotation gradients for E_r shear and confinement improvement
- Rotation and E_r in the pedestal for RMP ELM suppression[1] and access to QH-mode

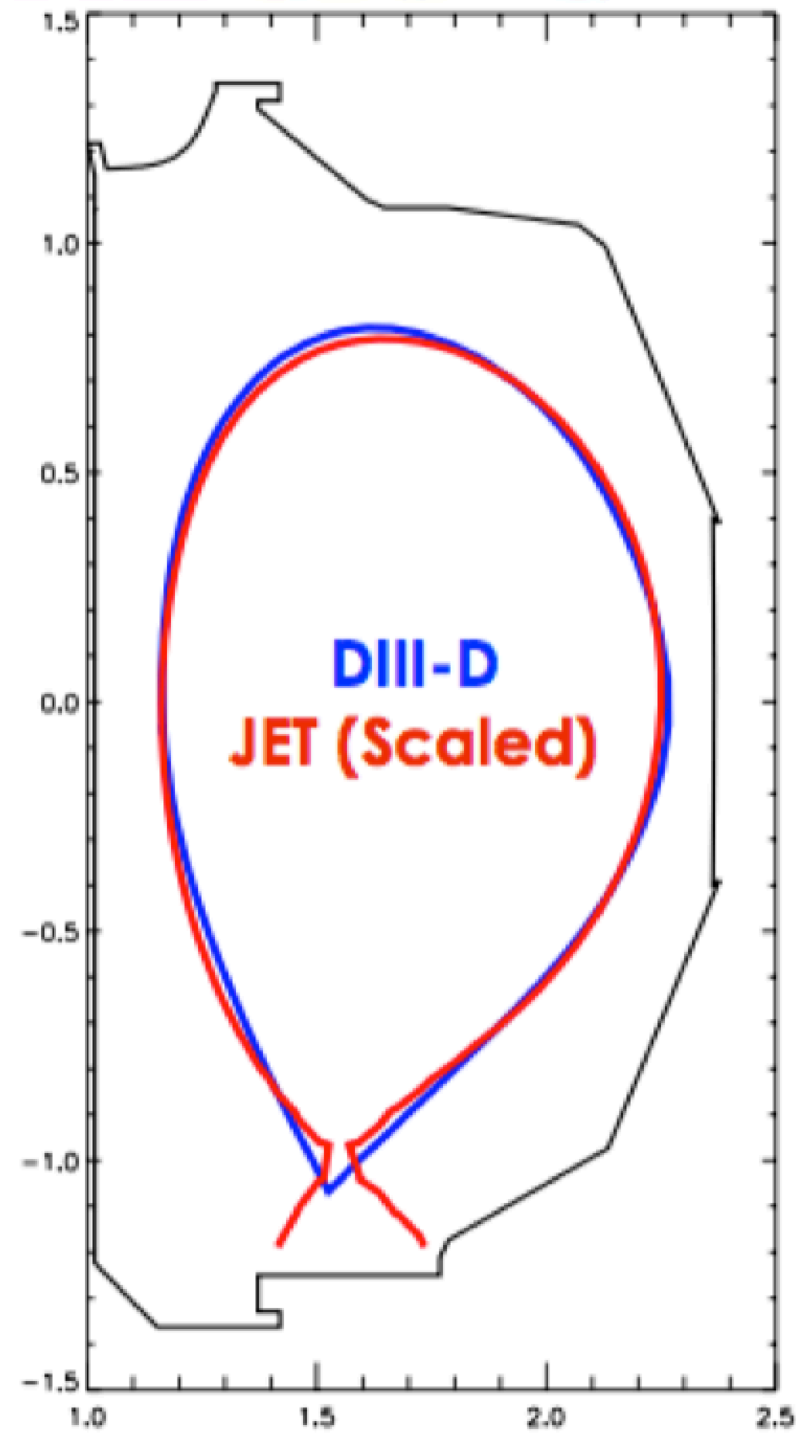
[1]C. Paz-Soldan EX/1-2
[2]C. Holland TH/6-1

Outline

- **Dimensionless scaling of intrinsic torque**
- Testing physics based models of core intrinsic rotation profile
- Dependence of Edge Flow on Geometry

Joint Experiment[1] with JET and ASDEX-U Tests ϱ* Scaling of Intrinsic Torque

- ϱ* for DIII-D, JET, ITER 0.01, 0.004, 0.002 (÷2.5, ÷2.0)
- Dimensionless parameter scan used to match conditions[2]



[1]T. Tala (EPS 2016)
[2]Petty, *Phys. Plasmas* **15** 080501 (2009)
[3]W.M. Solomon, *Phys. Plasmas* **17** 056108 (2010).

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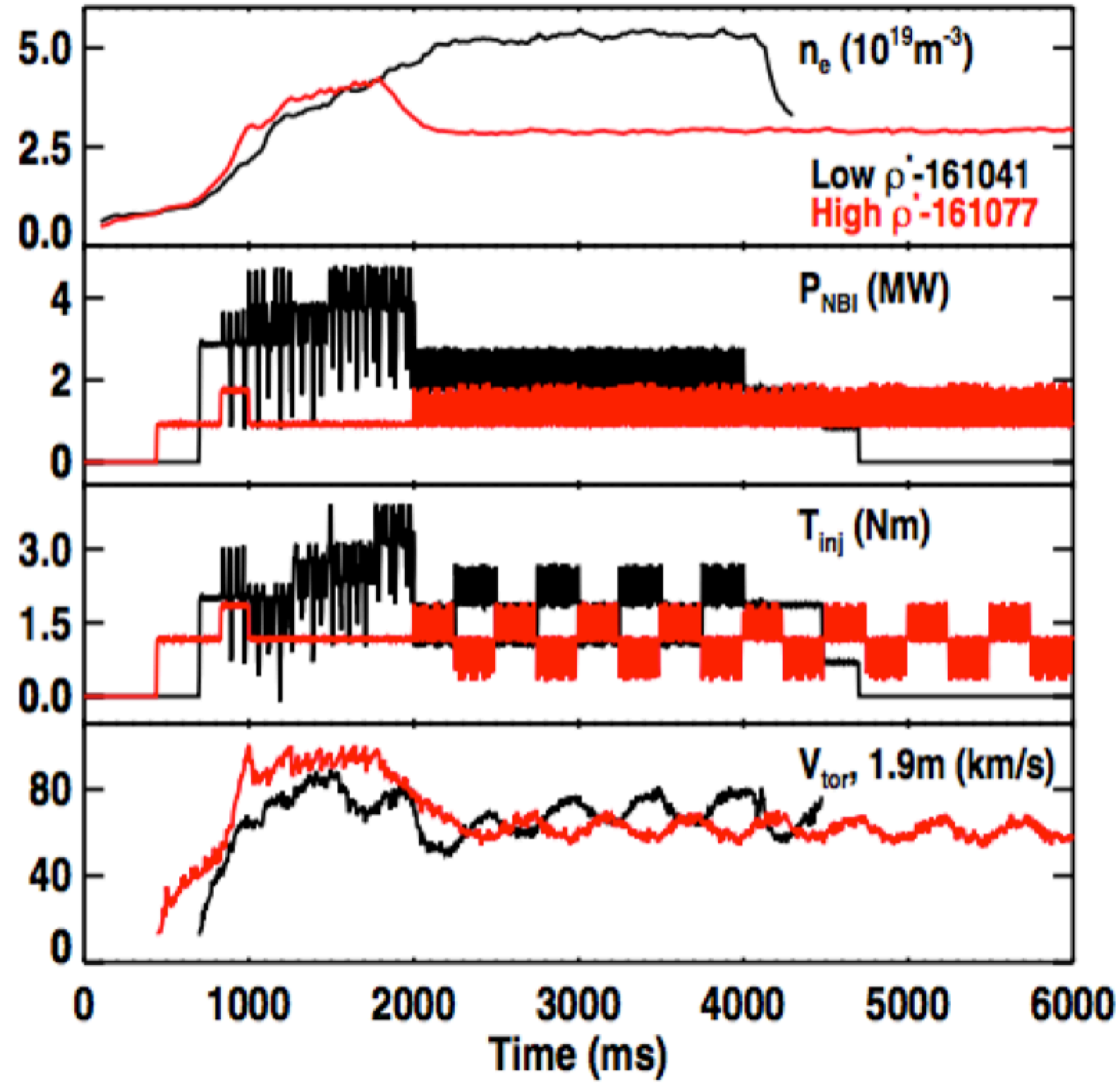
- ϱ* for DIII-D, JET, ITER 0.01, 0.004, 0.002 (÷2.5, ÷2.0)
- Dimensionless parameter scan used to match conditions[2]
- Torque perturbation method used to extract intrinsic torque[3]



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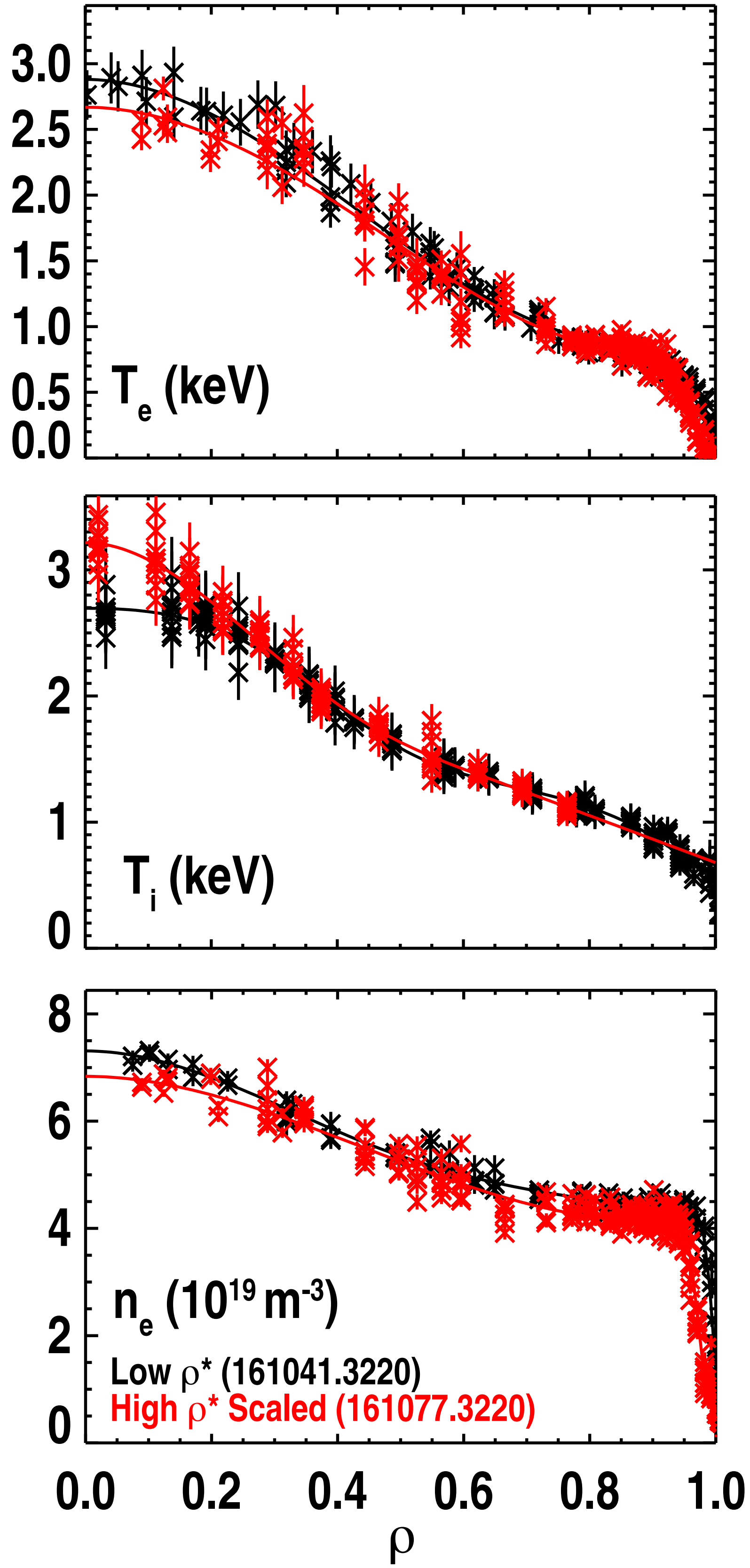
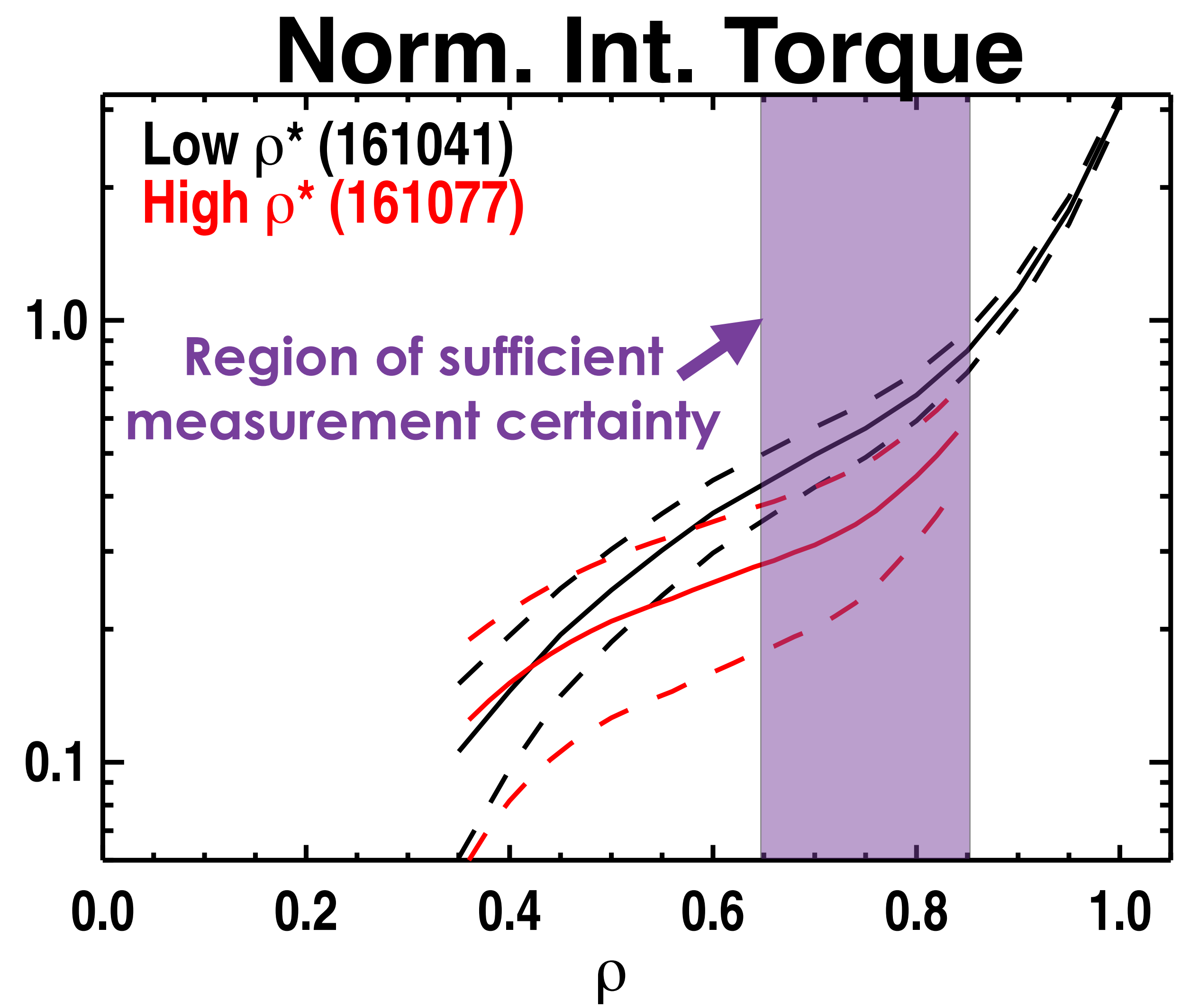
Dimensionless Match Obtained on DIII-D for Factor of 1.4 Variation in ϱ*

- ELMy H-mode conditions
  - Low ϱ* 2.2 T (Un-Scaled)
  - High ϱ* 1.4 T (scaled)
- I_p scaled with B_T, $n \sim B_T^{4/3}$, $T \sim B_T^{2/3}$ same β_N, q_{95}
- Good confinement $H_{98(y,2)} \sim 1.0$

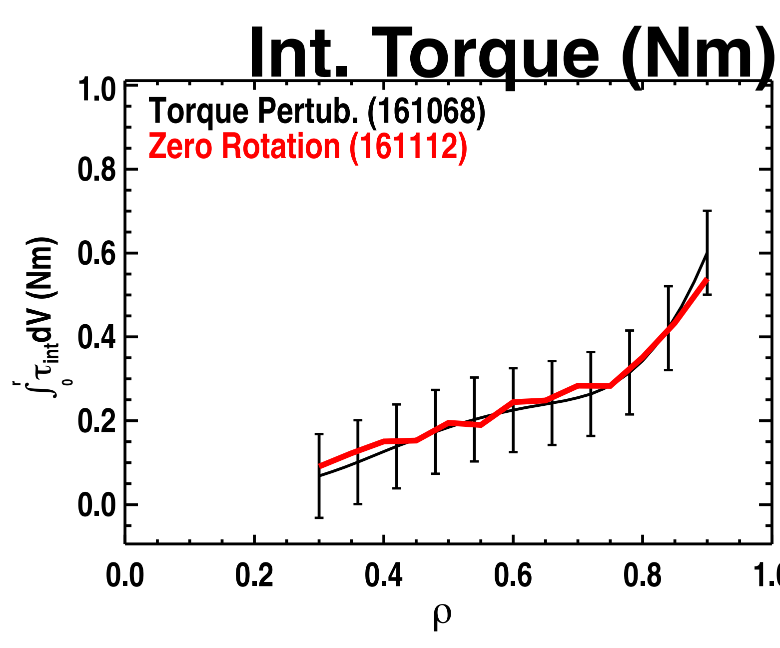


Intrinsic Torque Dominantly in Outer Region and Increases When Reducing ϱ^*

- Higher torque at low ϱ^* projects favorably to ITER
- Shape consistent with previous studies of intrinsic torque[1]



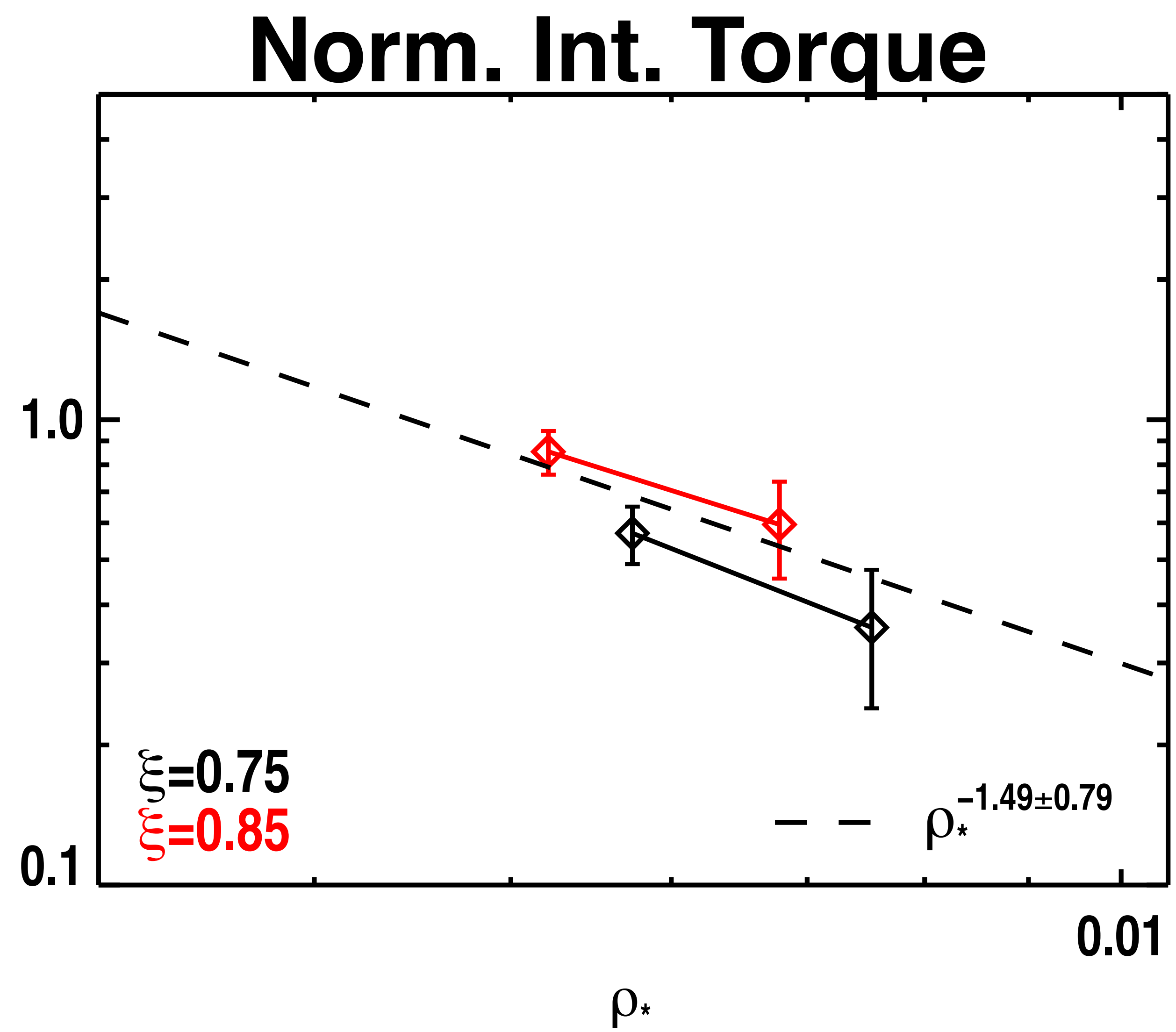
- Measurement cross-validated with zero rotation technique[2]



[1]W.M. Solomon, *Nucl. Fusion* **51** 073010 (2011)
[2]W.M. Solomon, *Nucl. Fusion* **49** 085005 (2009).

Projecting the DIII-D Intrinsic Torque to ITER Yields Approximately 45 Nm of Intrinsic Torque — More than NBI Torque

- **ITER has 33 Nm of available neutral beam torque**
- **Intrinsic torque is near available torque from NBI**
- **Projection to ITER scaled using T_i to dimensionalize**
- **Predicted[1] toroidal rotation from $\tau_{NBI}+\tau_{int}$ $\langle\Omega\rangle \approx 12$ kRad/s**
  - 1% of Alfven speed, marginal for RWM stability

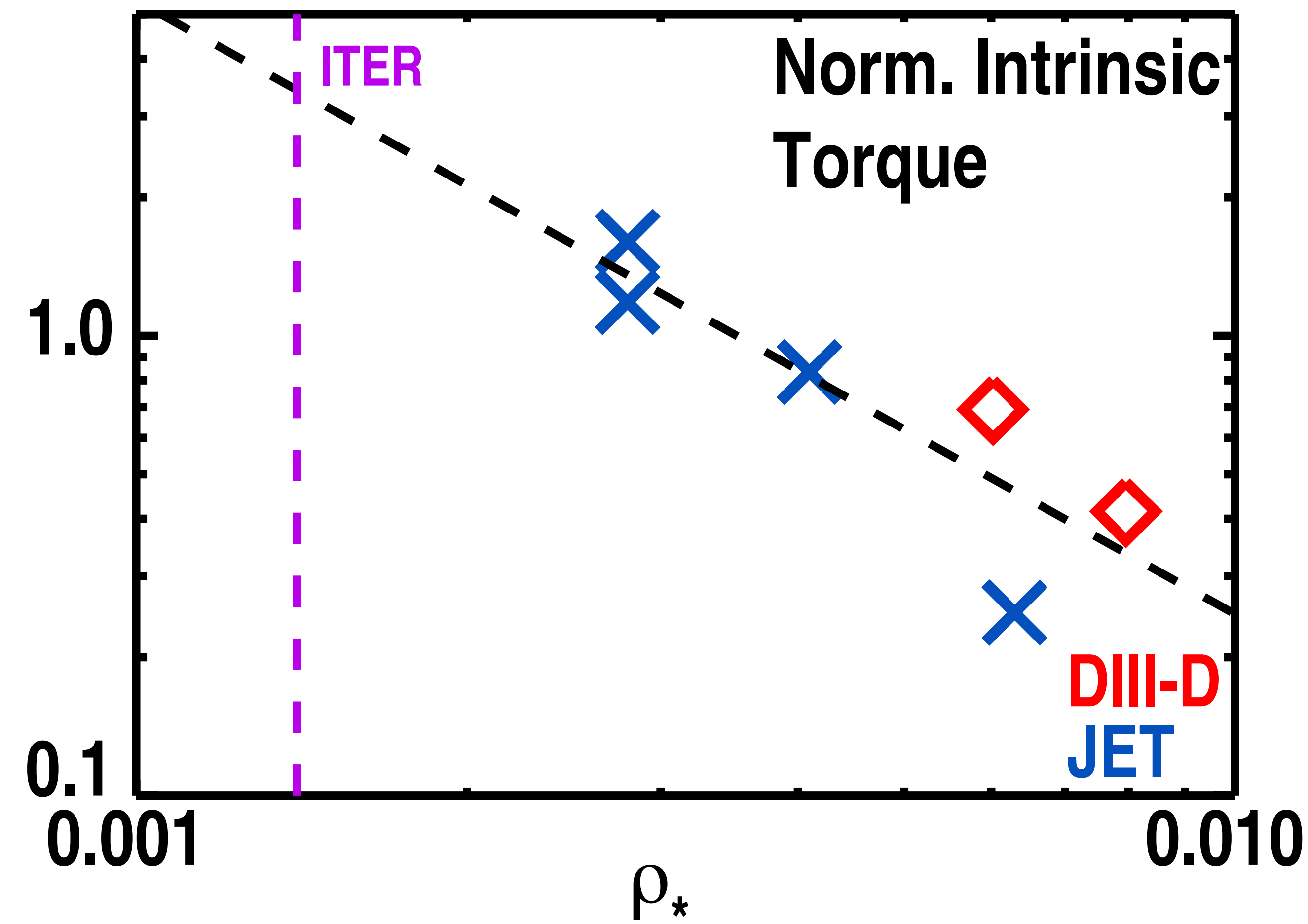


$$\tau_{ITER} = \frac{\tau_{DIII-D}}{T_{i,DIII-D}}\left(\frac{\rho^*_{ITER}}{\rho^*_{DIII-D}}\right)^{-1.5} T_{i,ITER}$$

[1]C. Chrystal *Phys. Plasmas* (submitted)

Multi-machine Intrinsic Torque Scaling Confirms DIII-D Results and Normalization

- Similar experiments executed on JET and ASDEX-U[1]
- Scaling with ion temperature best organizes data set[1,2]
- Projection to ITER with multiple parameters in progress[2]



We Project Relatively Low Toroidal Rotation

→ Finite performance improvement for ITER[2]

→ Details of the rotation profile matter

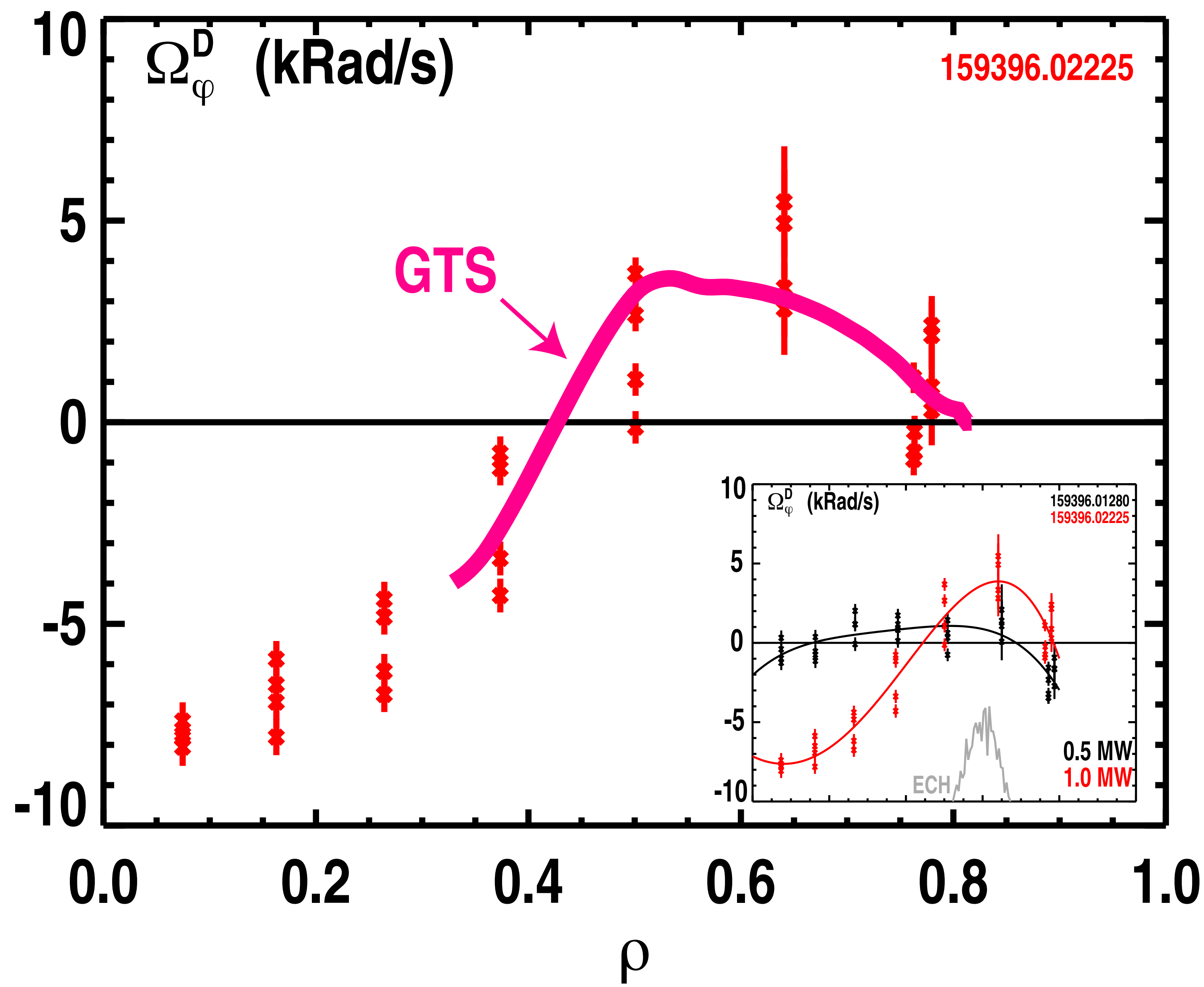
[1]T. Tala (EPS 2016)
[2]C. Chrystal (APS 2016)

Outline

- Dimensionless scaling of intrinsic torque
- **Testing physics based models of core intrinsic rotation profile**
- Dependence of Edge Flow on Geometry

Electron Heating Causes a Rotation Reversal and Global NL GTS Simulation Captures both *Shape* and *Magnitude*

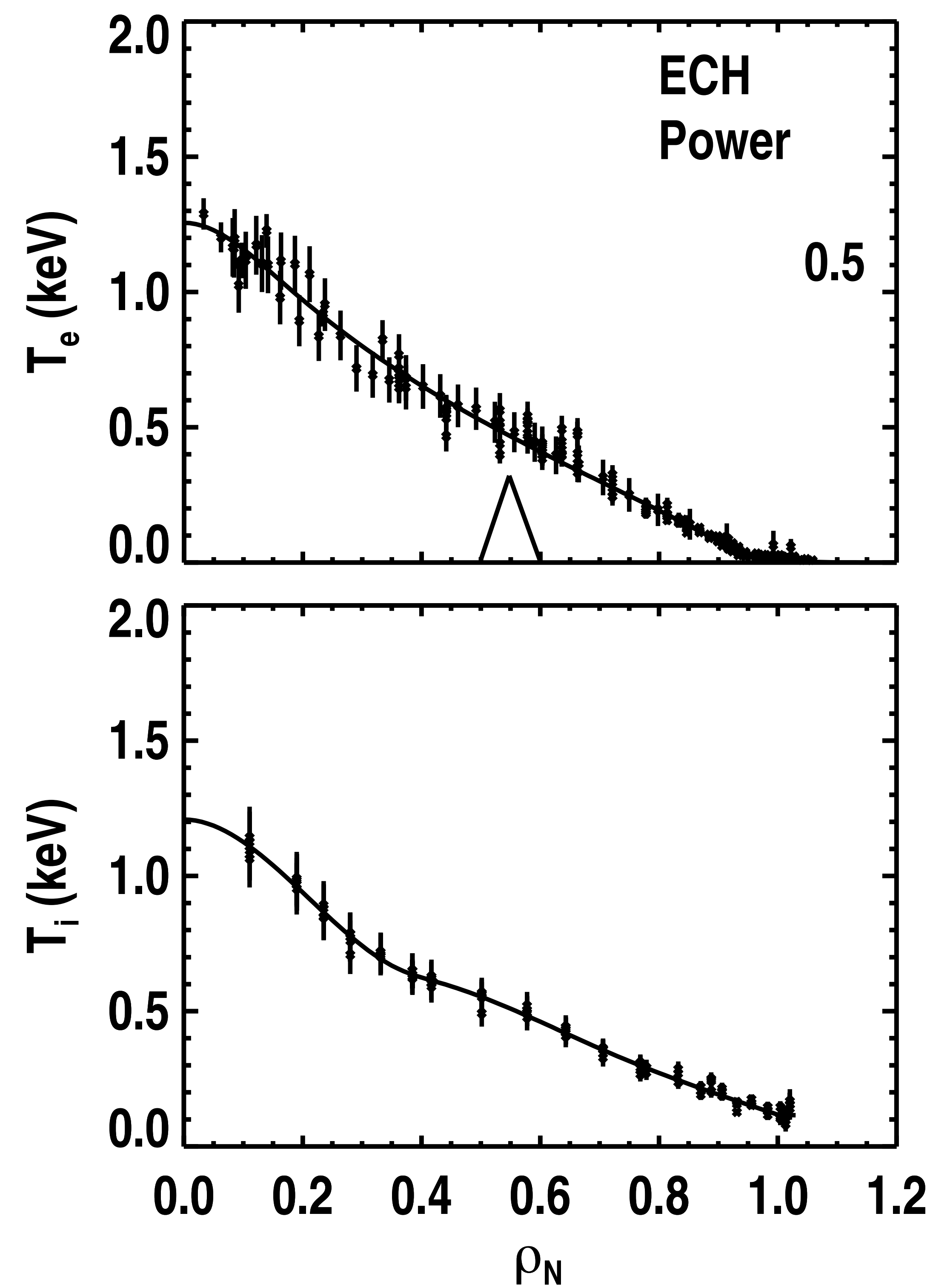
- **Rotation reversal occurs because of turbulence residual stress**
- **Validation of residual stress required to predict ITER rotation**
- **Simulations indicate low-k ITG with zonal flow E×B and global effects responsible[1]**



[1]W.X. Wang TH/P3-12

Rotation Profile Reversal Correlates with Onset of Temperature Profile Resilience and Confinement Degradation

- **Density $\langle n_e \rangle$ 2.5-3.0×$10^{19}m^{-3}$ and no NBI promotes T_e~T_i**
- **Direct electron heating raises both temperatures**
- **Between 0.5→1.0 MW power degradation sets in**



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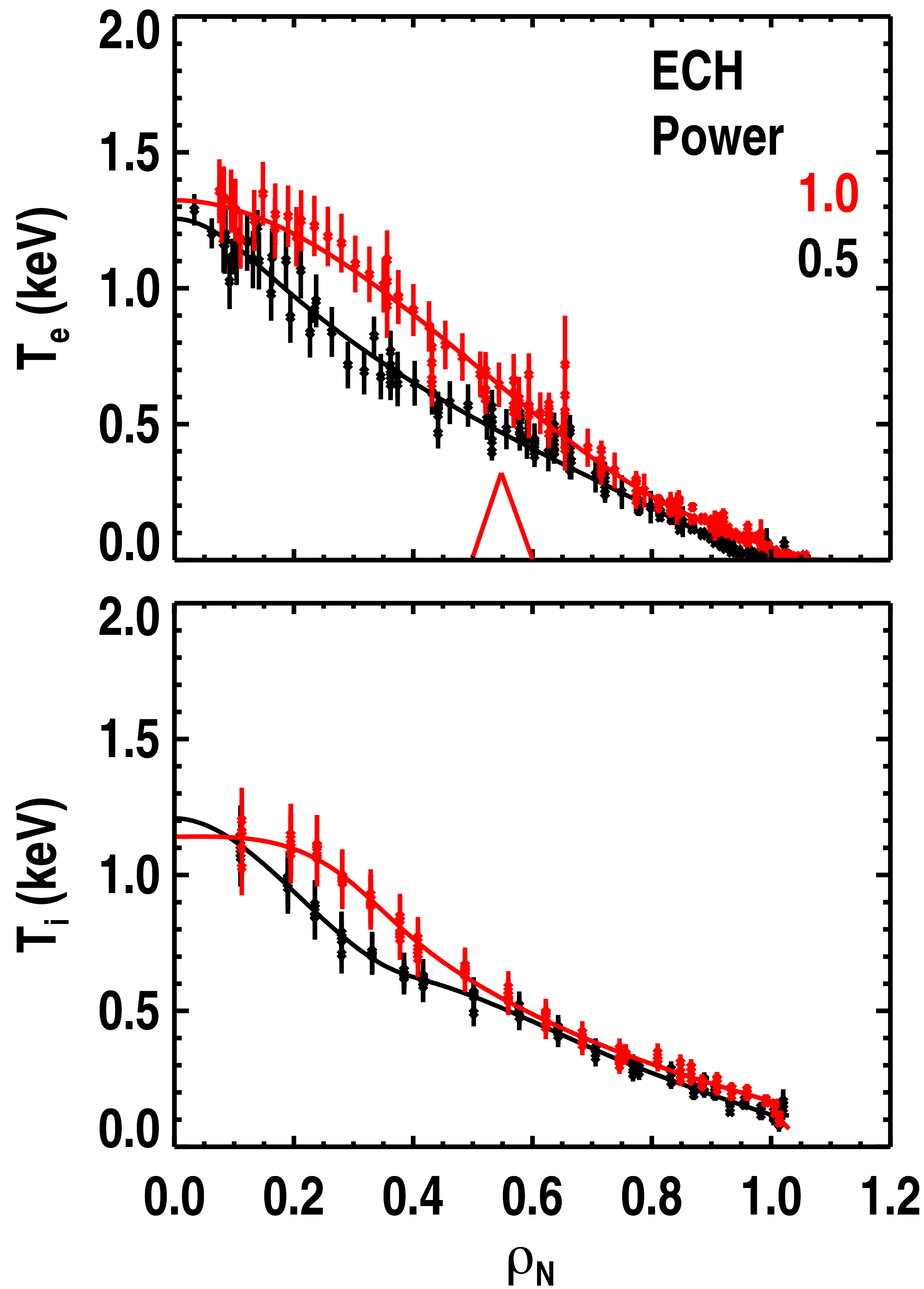

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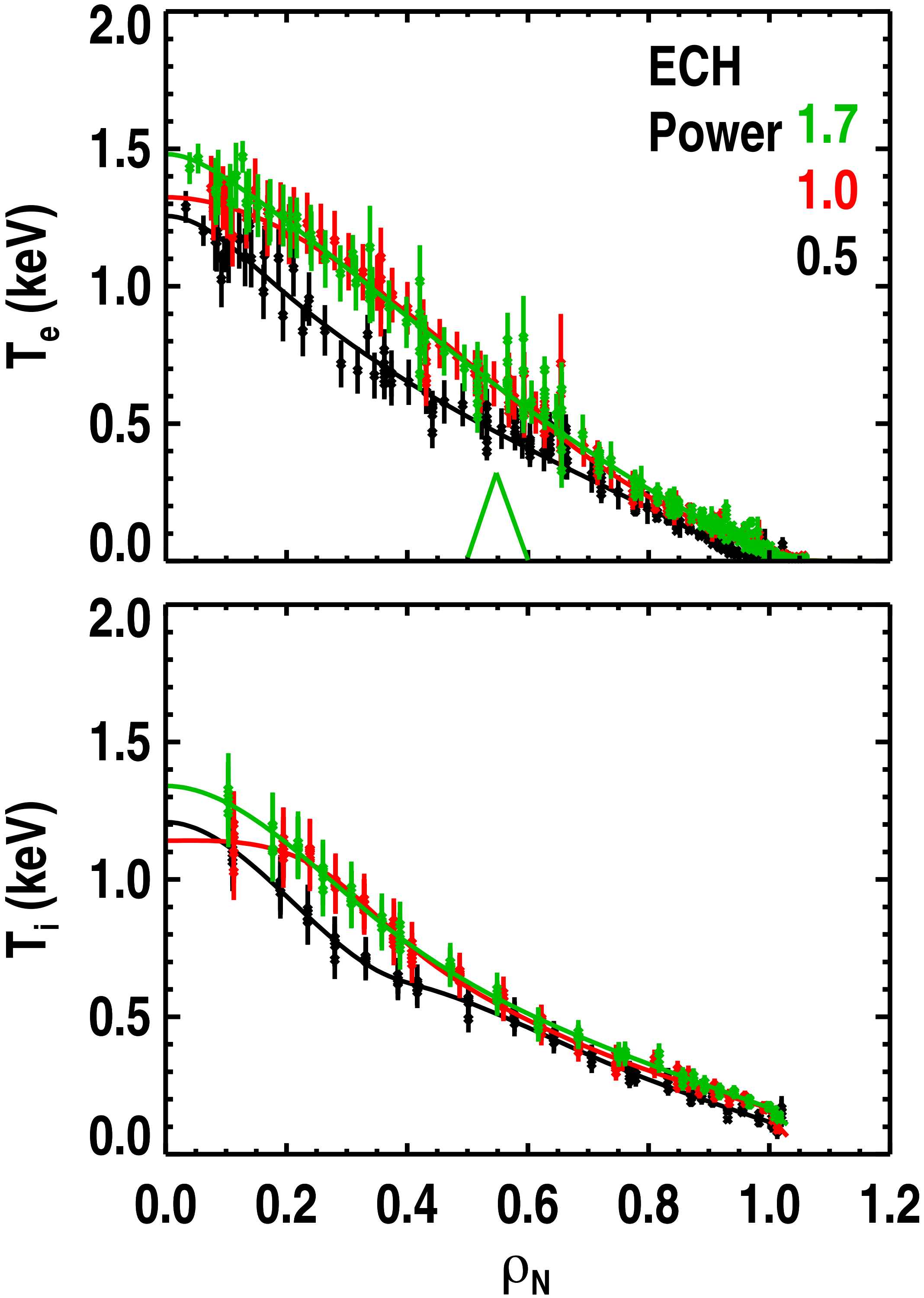

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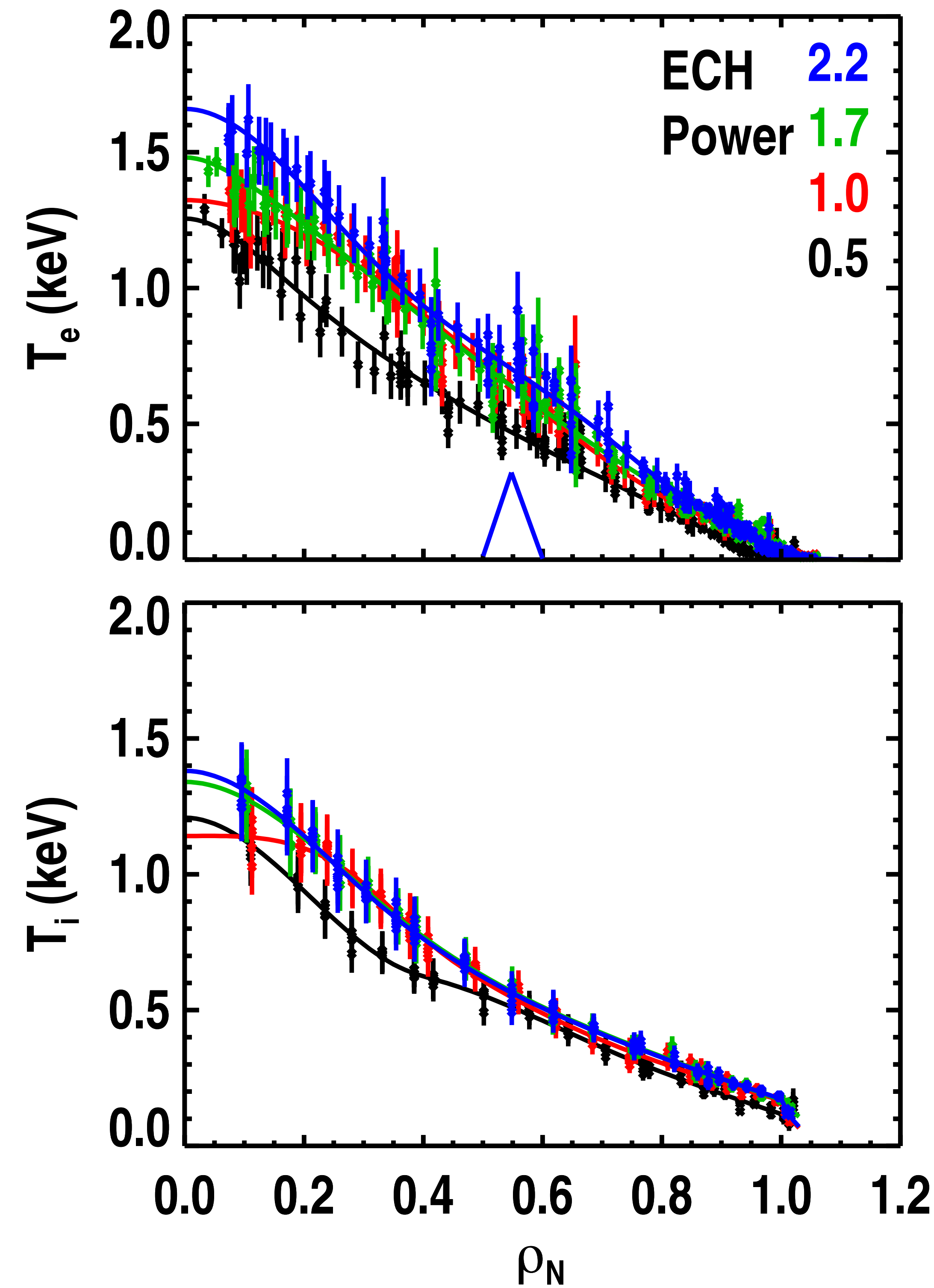
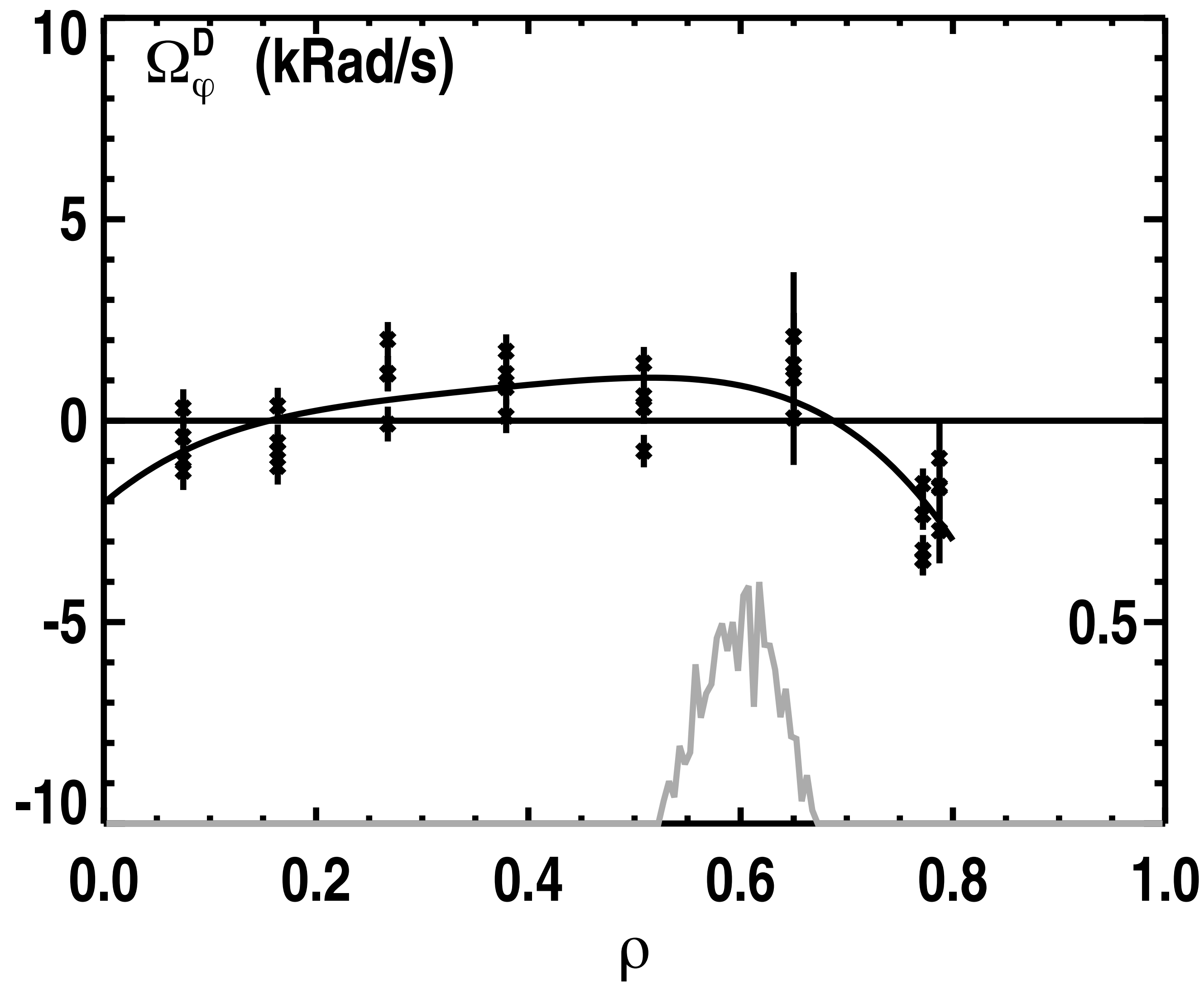


Rotation Profile from Main-ion CER Show Rotation Reversal When Power Degradation Sets In

- **On DIII-D direct measurements of the main-ion (D) toroidal flow available[1]**
  - Other machines use impurities
- **Deuterium carries energy, momentum fluxes**
- **Location where rotation *gradient* changes indicates non-diffusive flux**
  - Not necessarily the sign (+/-) of rotation velocity



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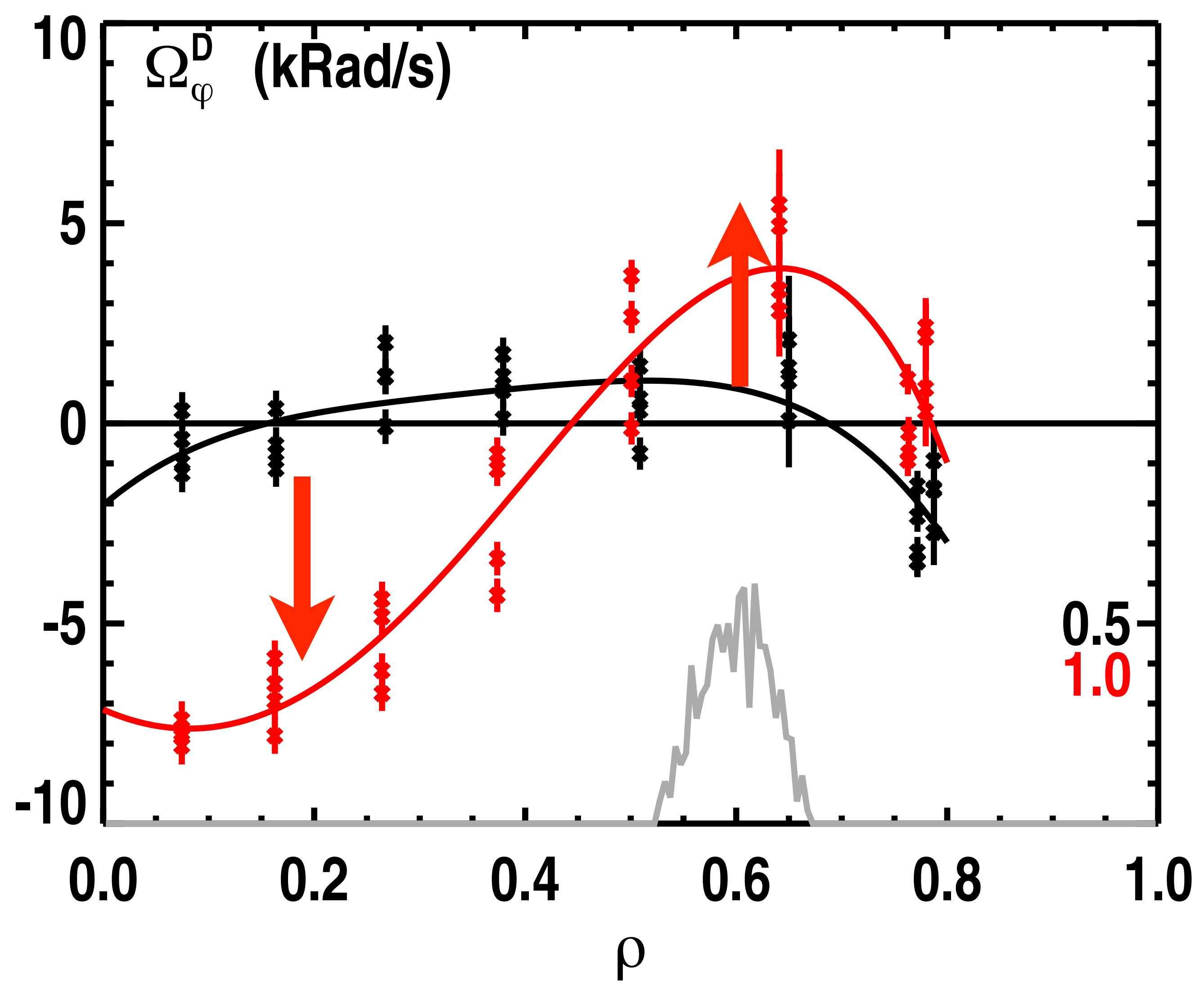

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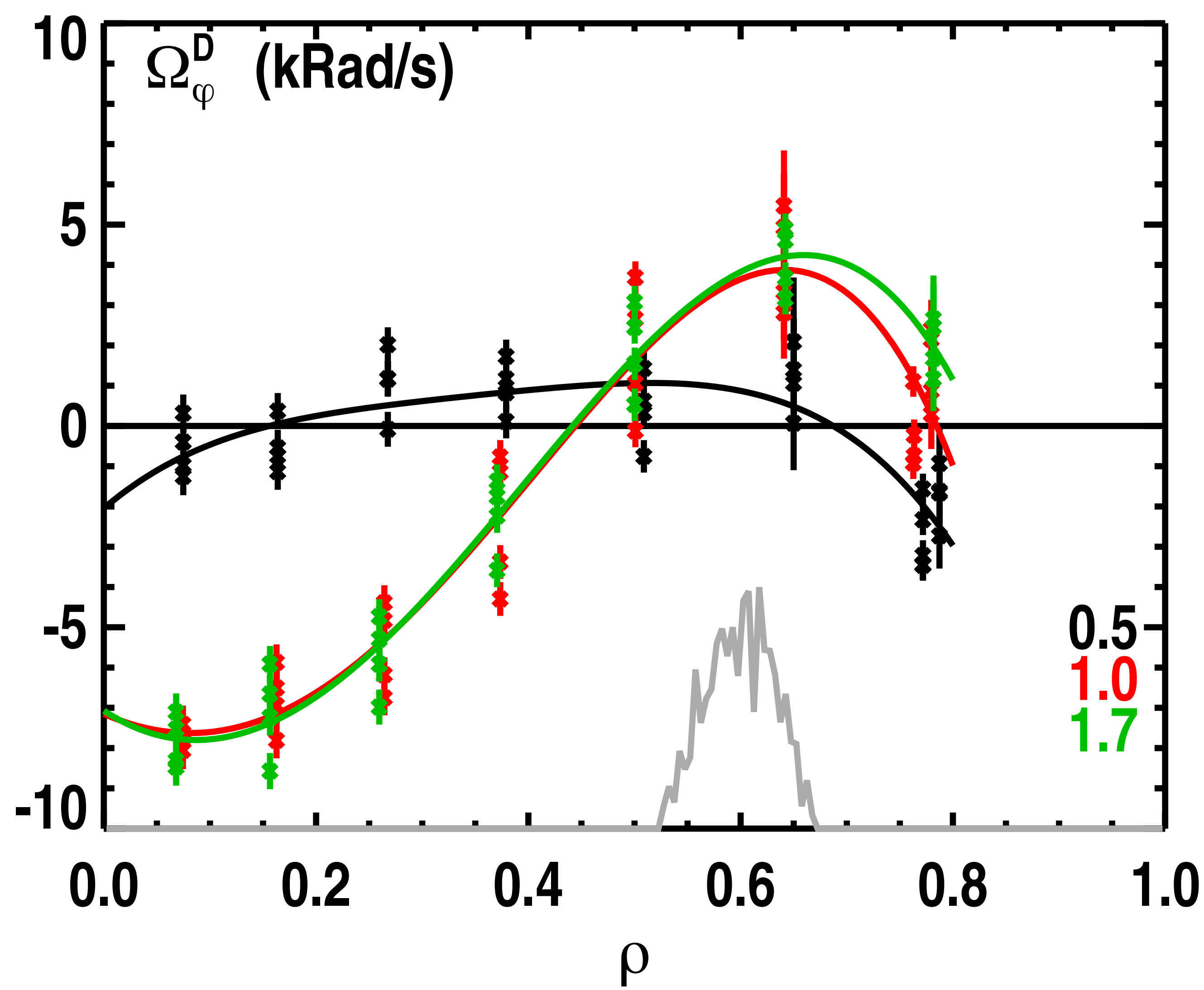

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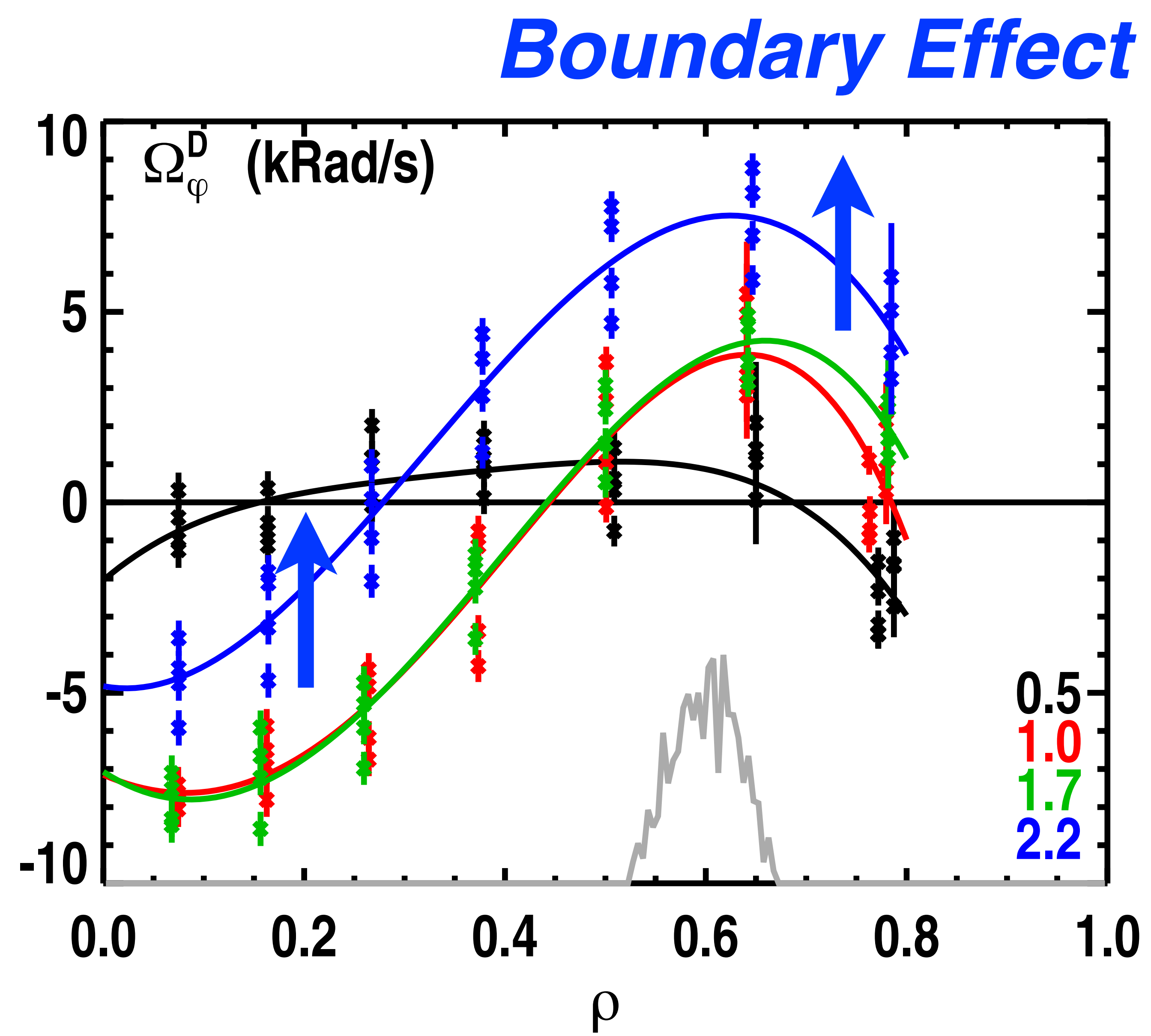

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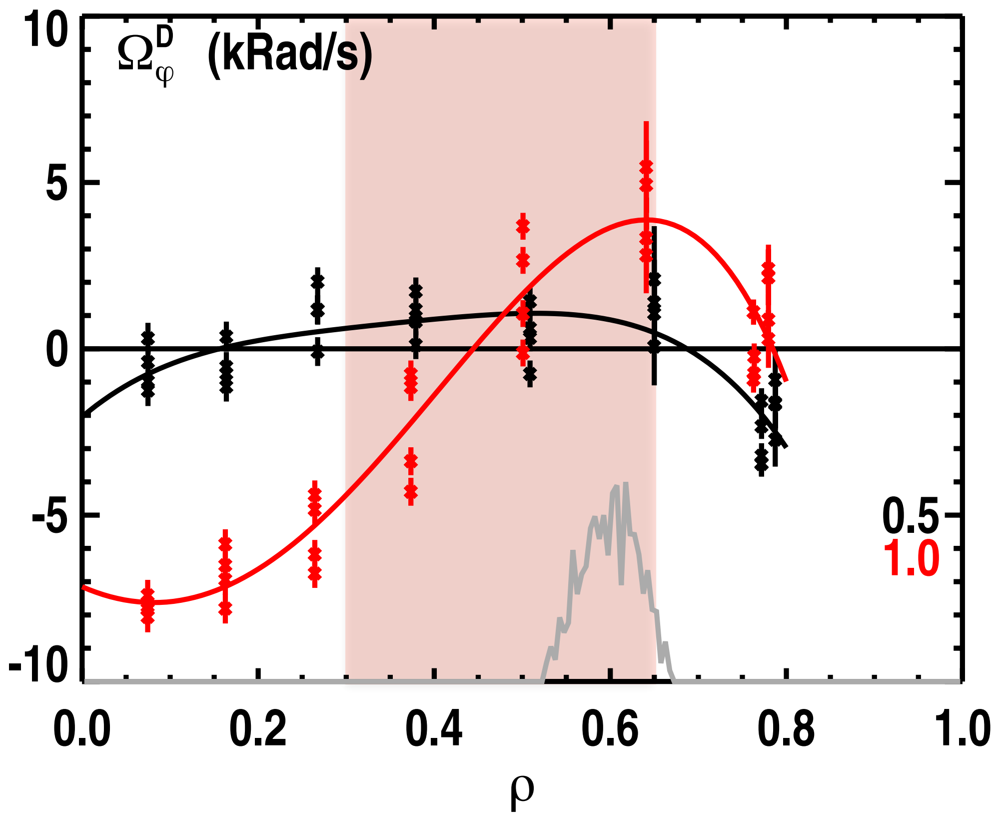
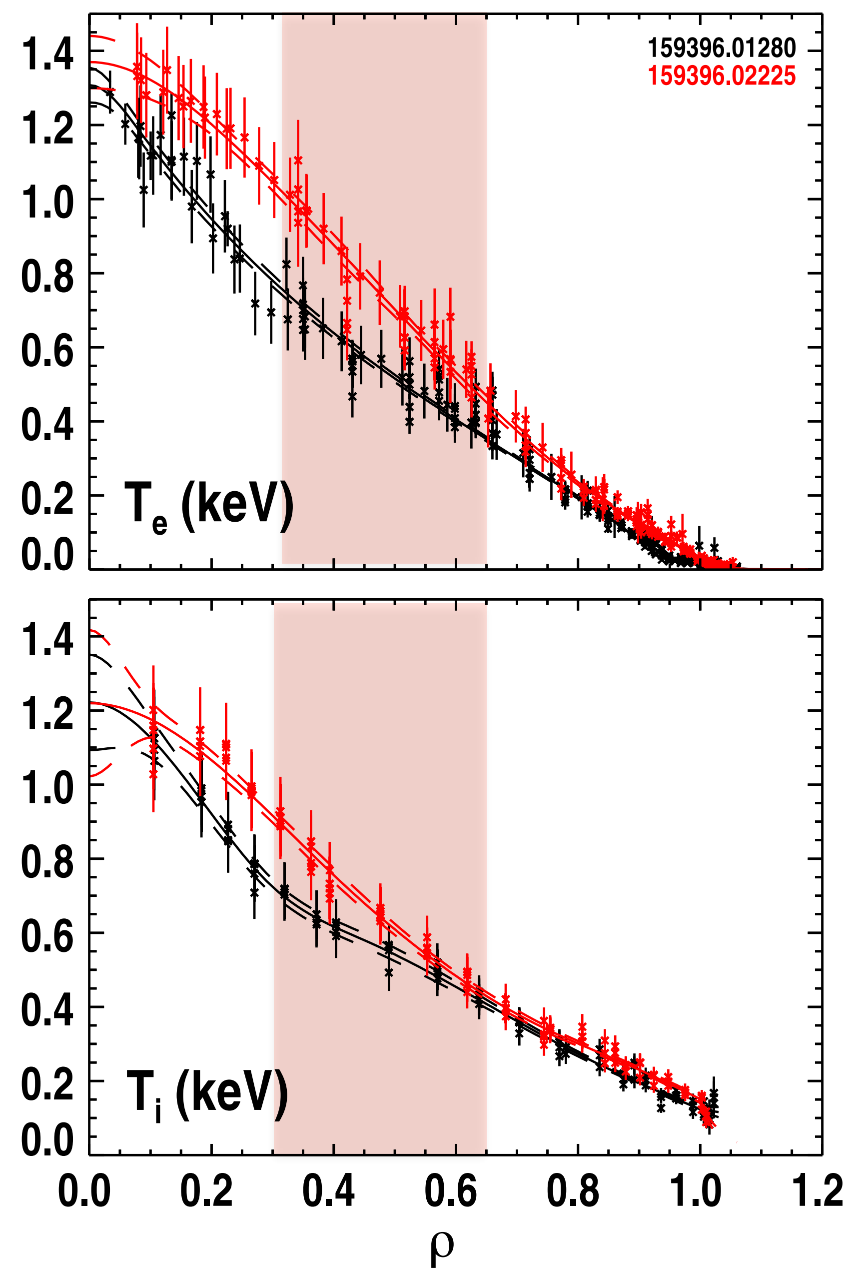
At Onset of Power Degradation Plasma Becomes Linearly Unstable to ITG at Radius where Rotation Gradient Increases

- **Direct electron heating raises both T_e, T_i with clear increase of a/L_{Ti} at mid-radius**
- **TGLF[1] indicates excitation of ITG[2] turbulence**





[1]G.M. Staebler et. al. Phys. Plasmas **12** (2005)
[2]C.L. Retting, et. al. Phys. Plasmas **8** (2001)

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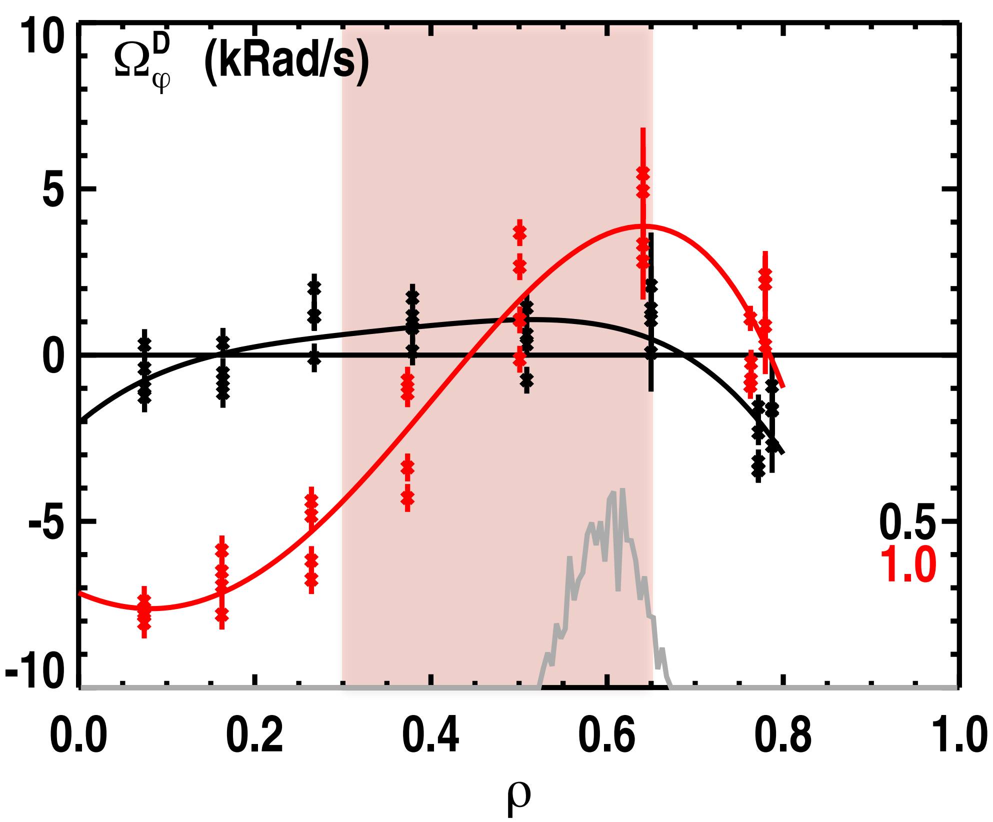

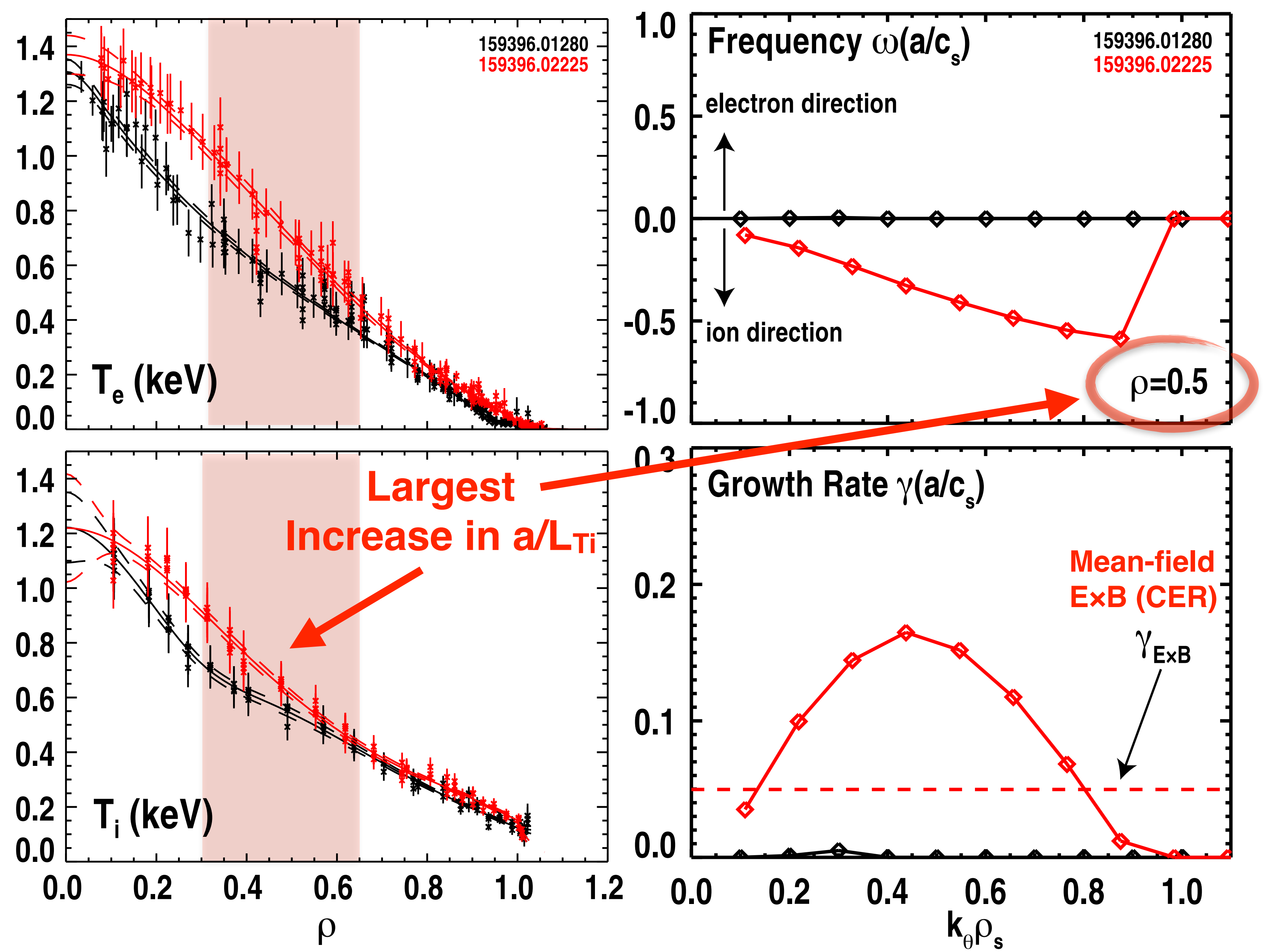

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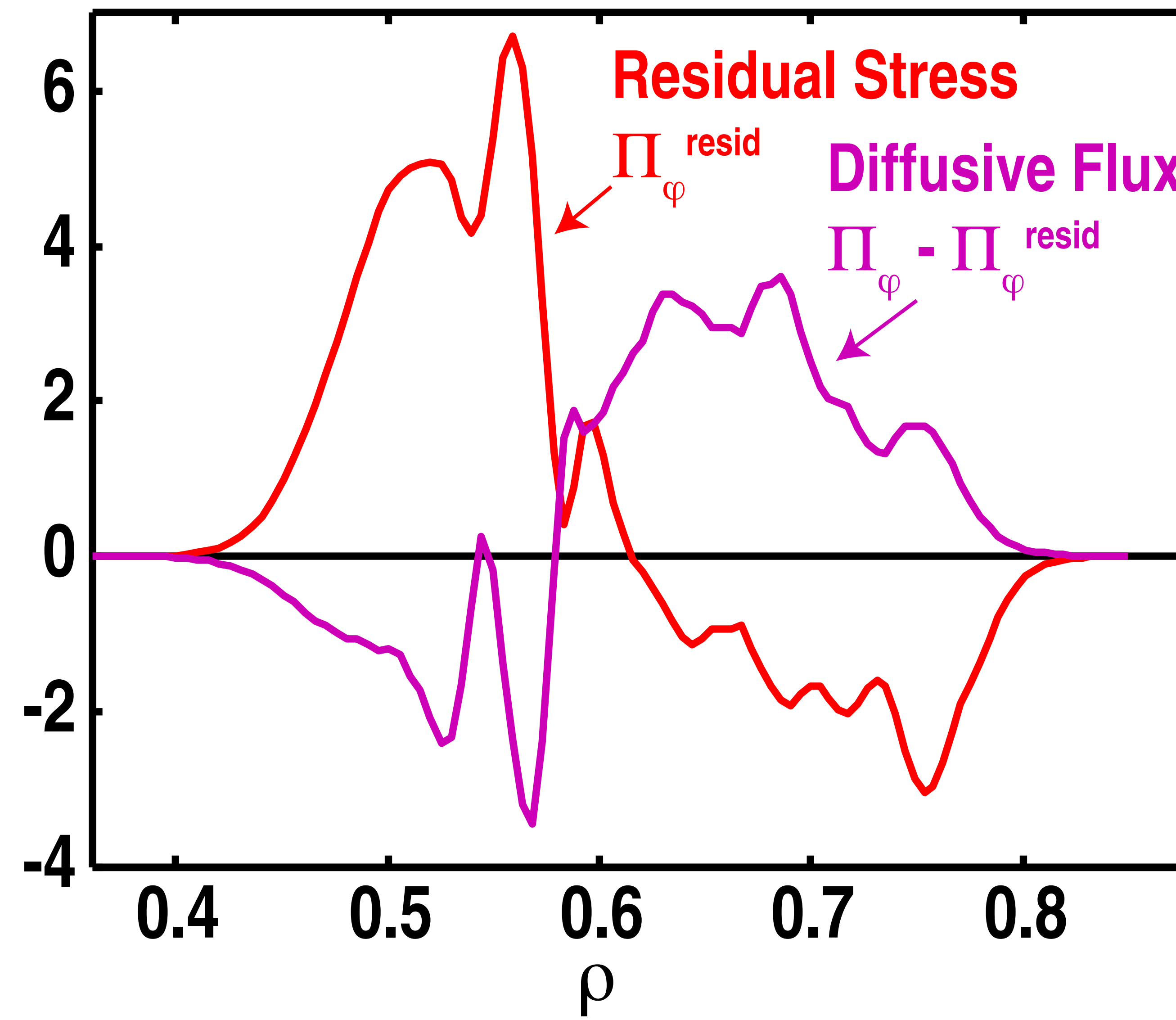
Global Nonlinear Gyrokinetic Simulation Shows Rotation Profile is Balance of Residual Stress and Diffusion

$$\Pi_\varphi = -m_i n_i \langle R^2 |\nabla\rho|\rangle \left(\chi_\varphi \frac{d\Omega}{d\rho} - V_p \Omega_\varphi\right) + \Pi^{Resid.}$$

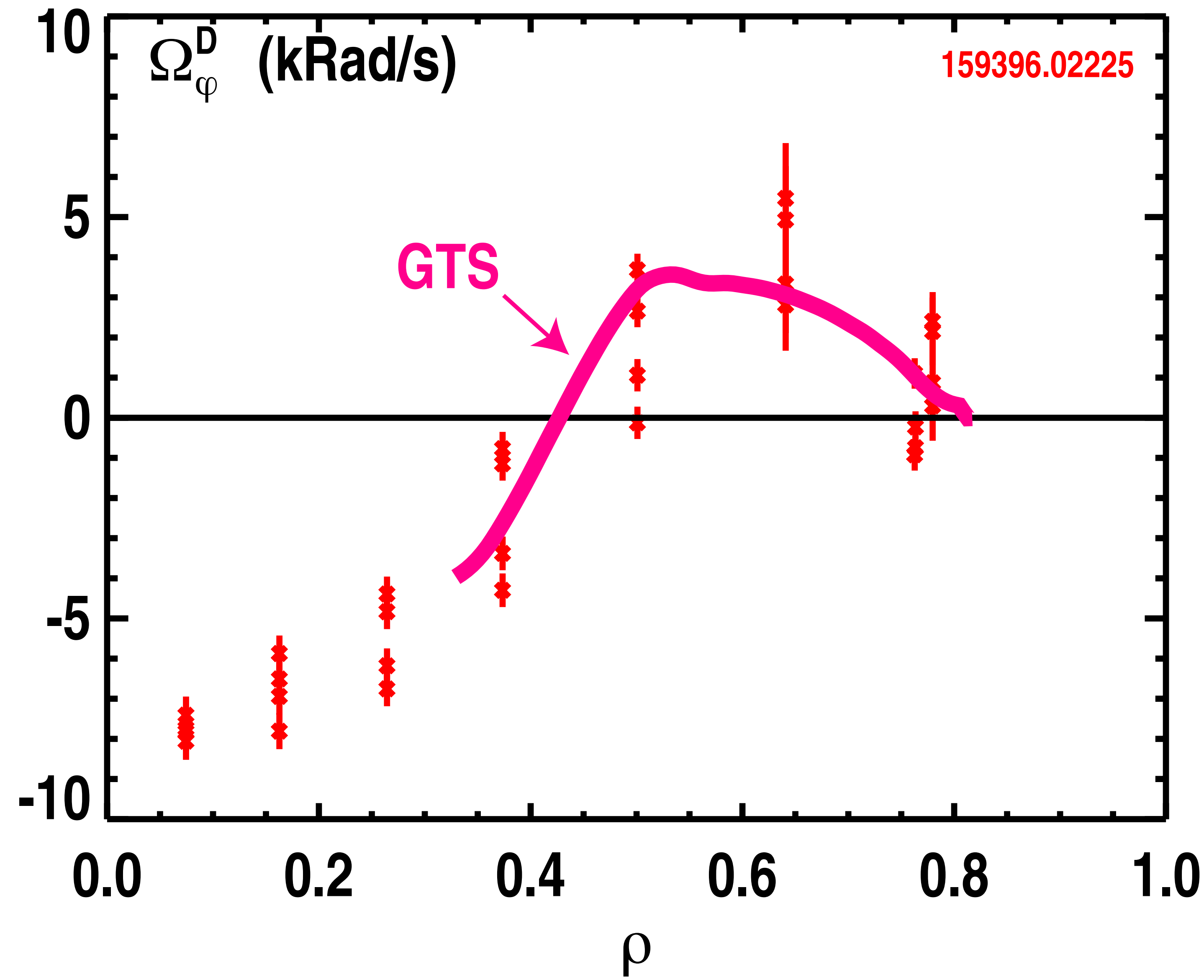
- **Momentum flux decomposed by series of simulations**[1]
  - Three simulations produce $\Pi^{resid.}$, V_p, χ_ϕ
- **Residual stress balanced by momentum diffusion**[2]
  - Momentum pinch small
- **Spatial integration of $\Pi_\phi \equiv 0$ + B.C. predicts intrinsic rotation profile**



[1]W.X. Wang Phys. Plasmas **13** (2006)
[2]W.X. Wang APS (2016)

Prediction of Intrinsic Rotation Profile from Electrostatic Turbulence Matches Both Shape and Magnitude of Experiment

- **Prandtl number used to relate energy and momentum flux**
  - Rotation profile and χ_ϕ is not available in *ab. initio.* prediction
  - Experiment and theory Pr = $\chi_\phi/\chi_i \approx 0.7$
- **Qualitative shape and quantitative magnitude in agreement with experiment**



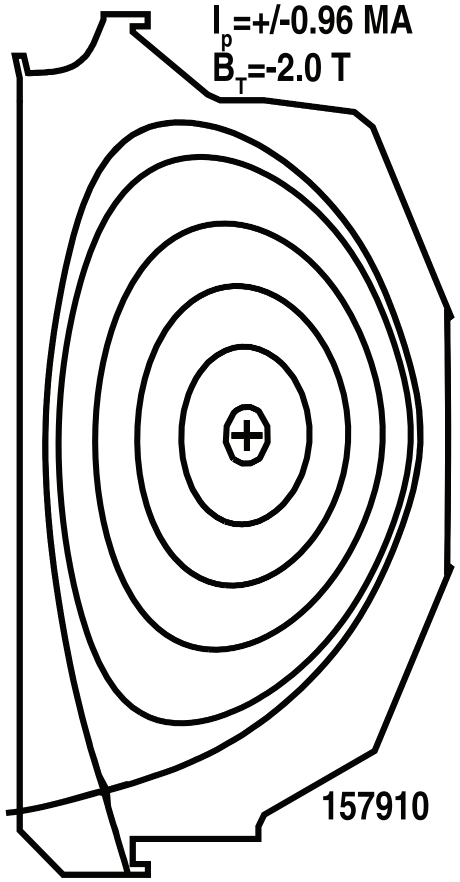
Global Nonlinear GTS Simulation can Predict Intrinsic Rotation Profile from Electrostatic Fluctuation-Induced Residual Stress

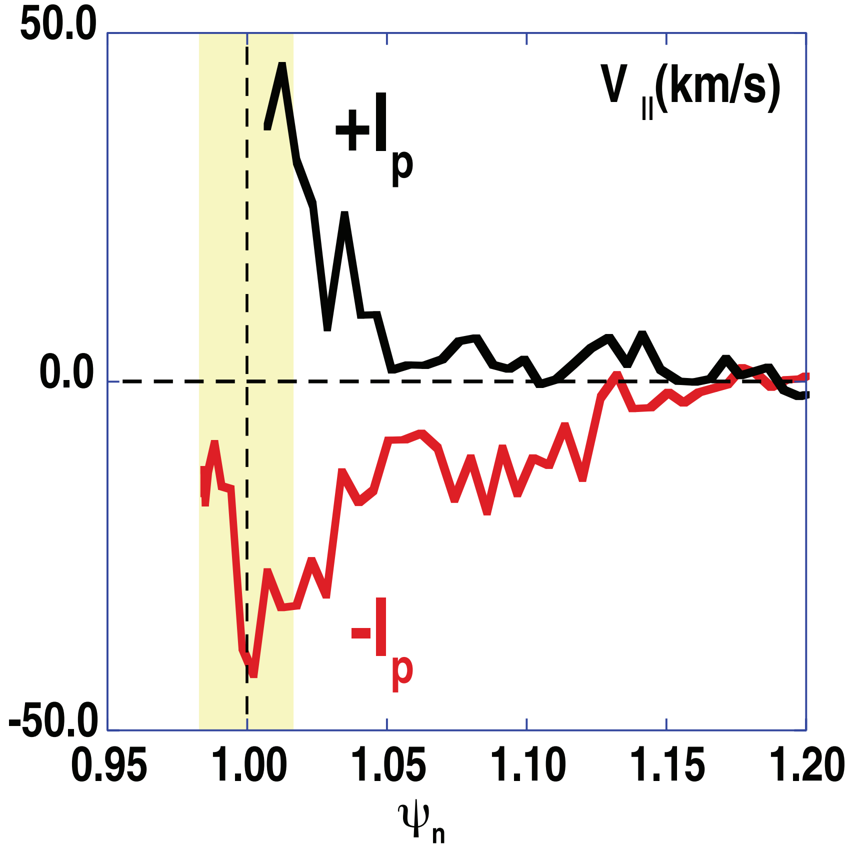
Outline

- Dimensionless scaling of intrinsic torque
- Testing physics based models of core intrinsic rotation profile
- **Dependence of Edge Flow on Geometry**

Edge Velocity "Layer" Exhibits Novel Dependece on Boundary Shape - Maximized for ITER Configuration

- **Edge velocity w/pinch possible source of intrinsic co-current angular momentum**
- **Inverting plasma shape test orbit-loss mechanism**
- **Find $V_{||}$ always co-Ip and maximized for LSN, favorable ∇B[1]**
  - Same as ITER configuration





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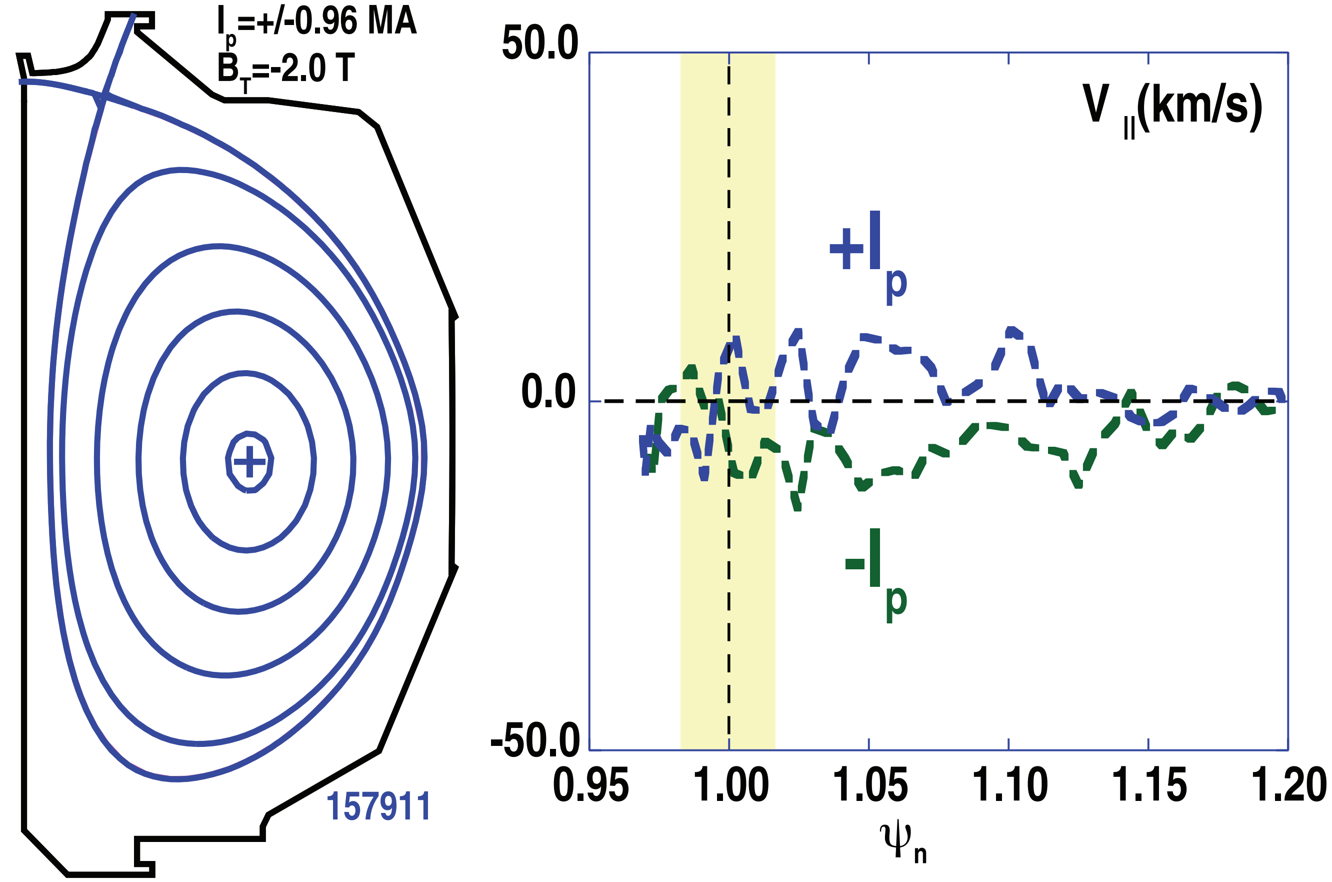

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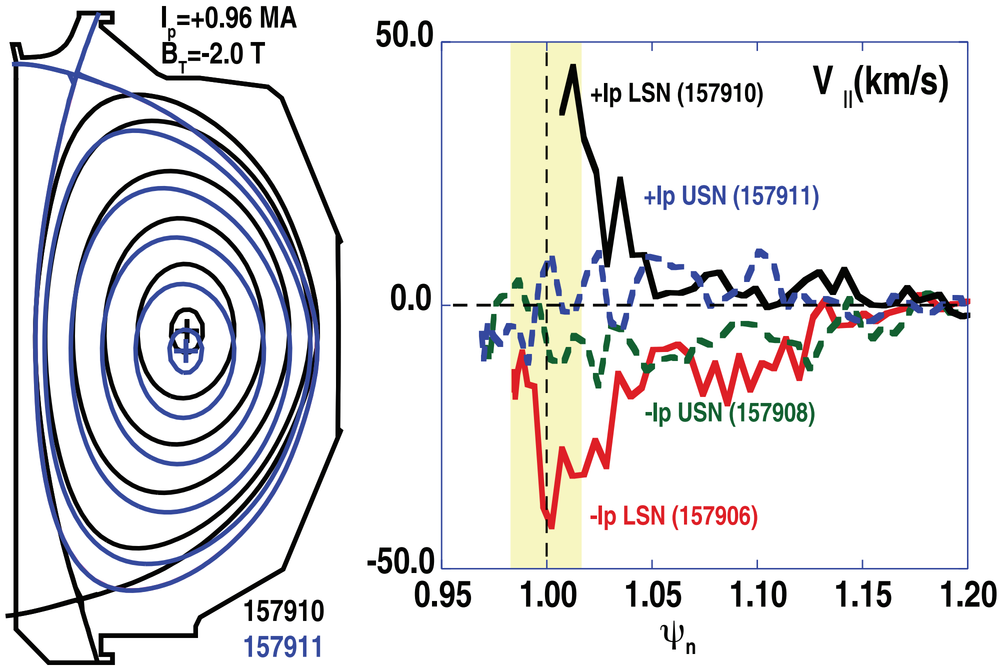
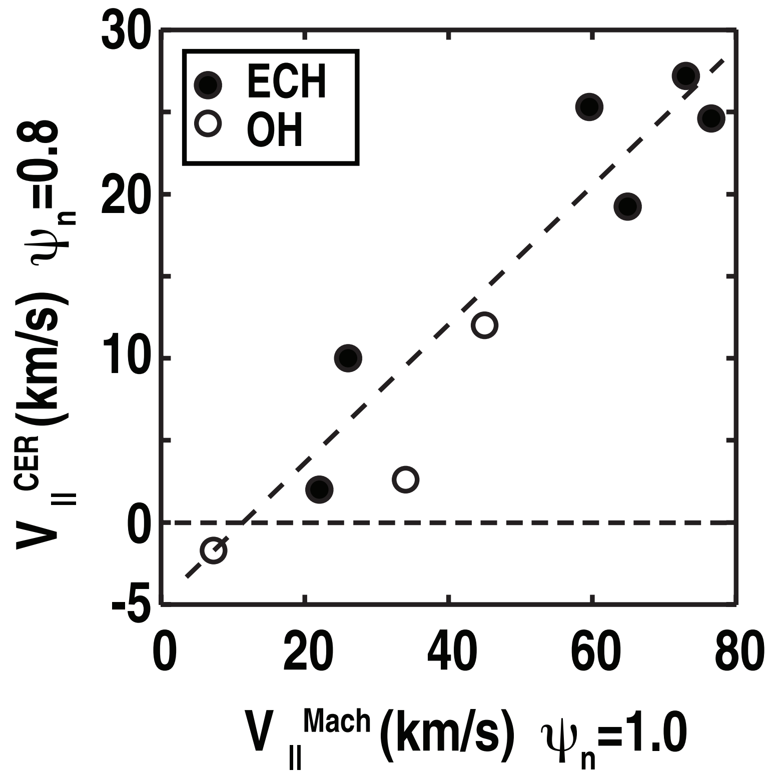
  - Same as ITER configuration
- **Core rotation correlates with edge rotation layer[1,2]**

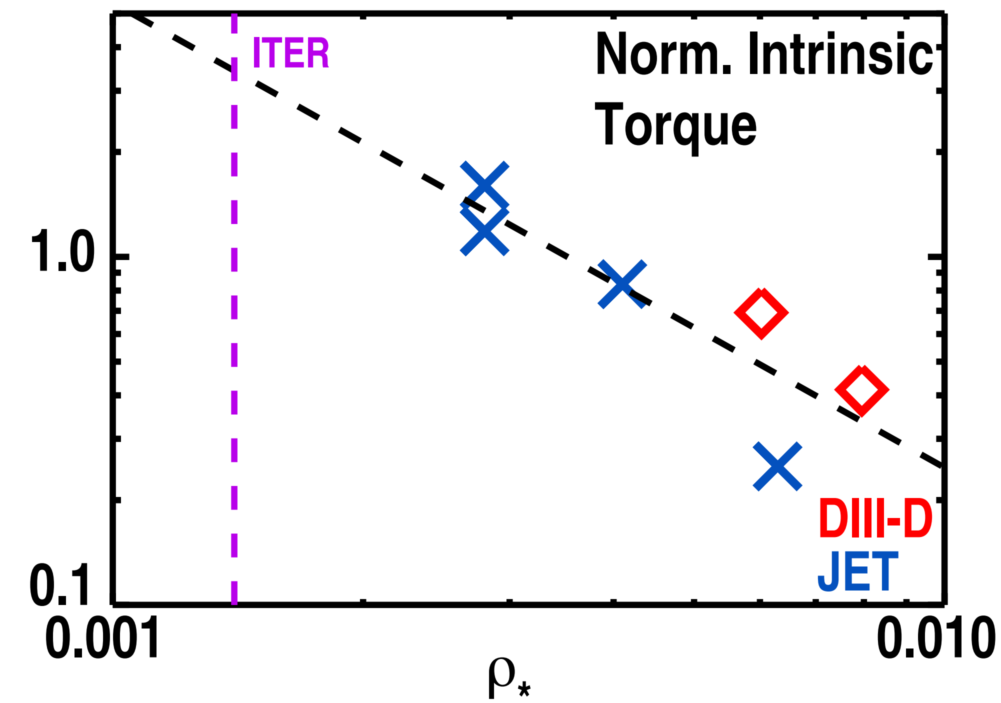


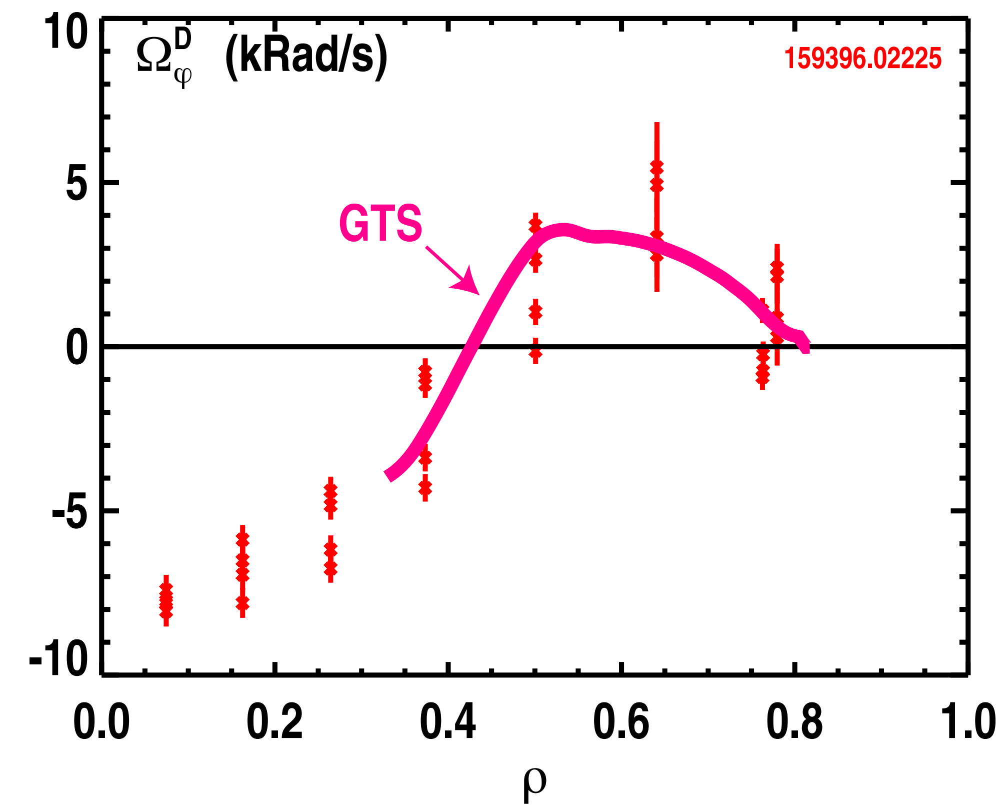


[1]Boedo *et. al.* Phys. Plasmas accepted (2016)
[2]S.R.Haksey APS-DPP (2016)

Rotation Experiments on DIII-D Are Producing Scalings and First-principles-based Validation of Momentum Transport for ITER

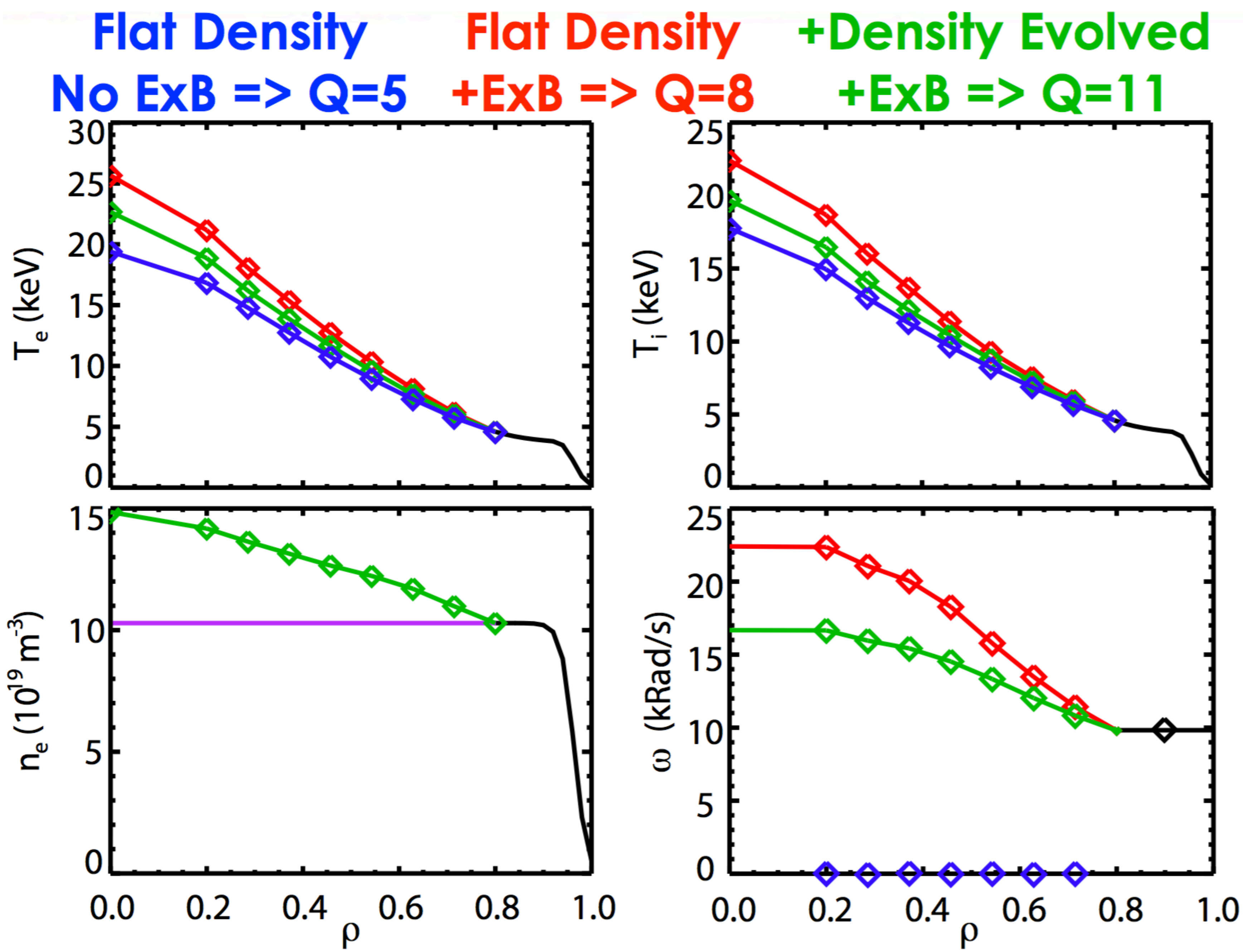
- Scaling of increased intrinsic torque towards ITER ρ* observed on DIII-D and projects twice as much torque from NBI only
- Successful capture of hollow intrinsic rotation demonstrates ability to predict rotation profile self-organization
- Edge rotation where intrinsic torque is maximized correlates with core rotation





Bonus Slides

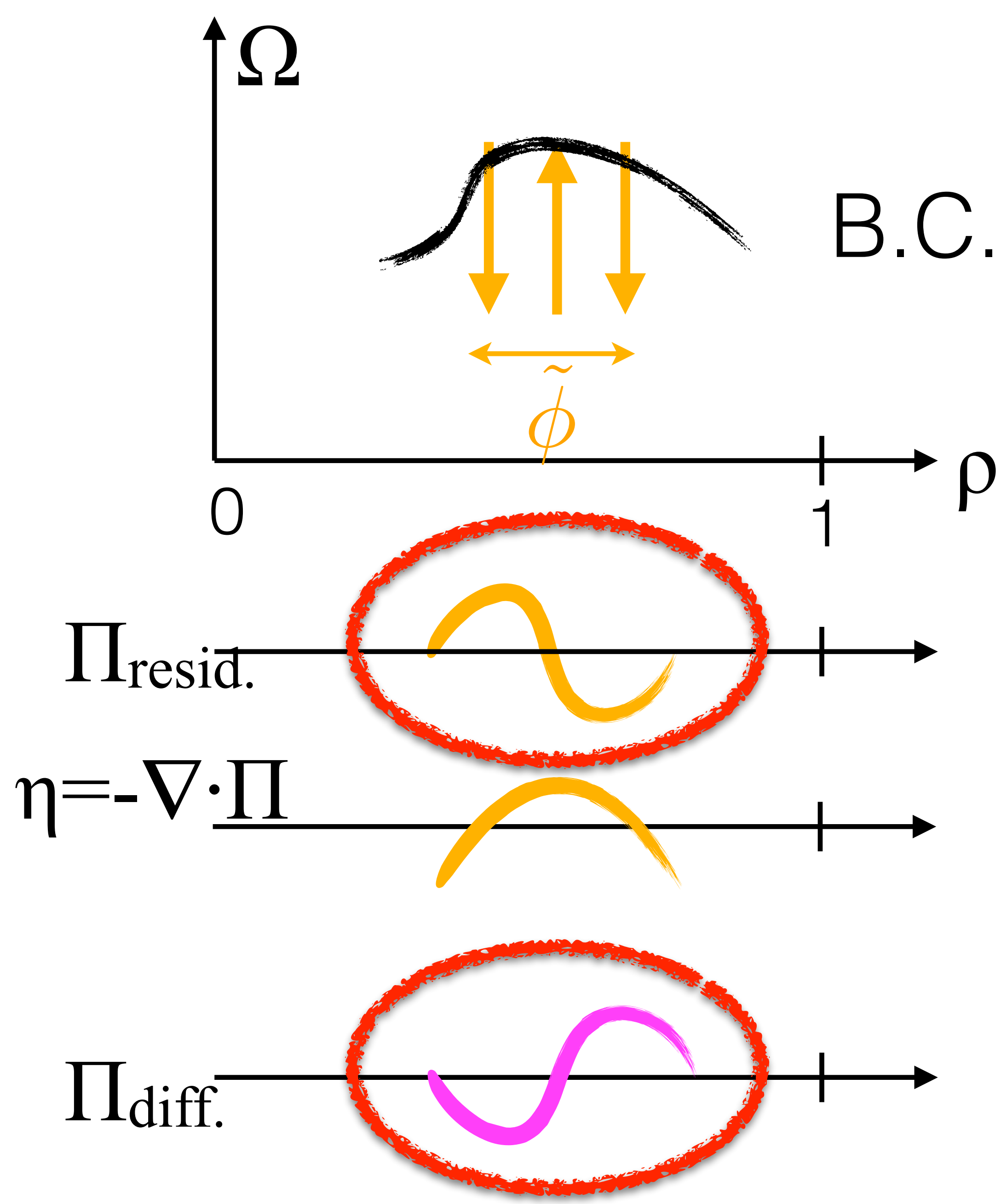
Predicted Intrinsic Rotation Improves ITER Performance via Direct E×B and Indirect Multi-Channel Effect (Density Peaking)



C. Chrystal APS-DPP (2016) Invited Talk

How Does an Intrinsic Rotation Gradient Appear?

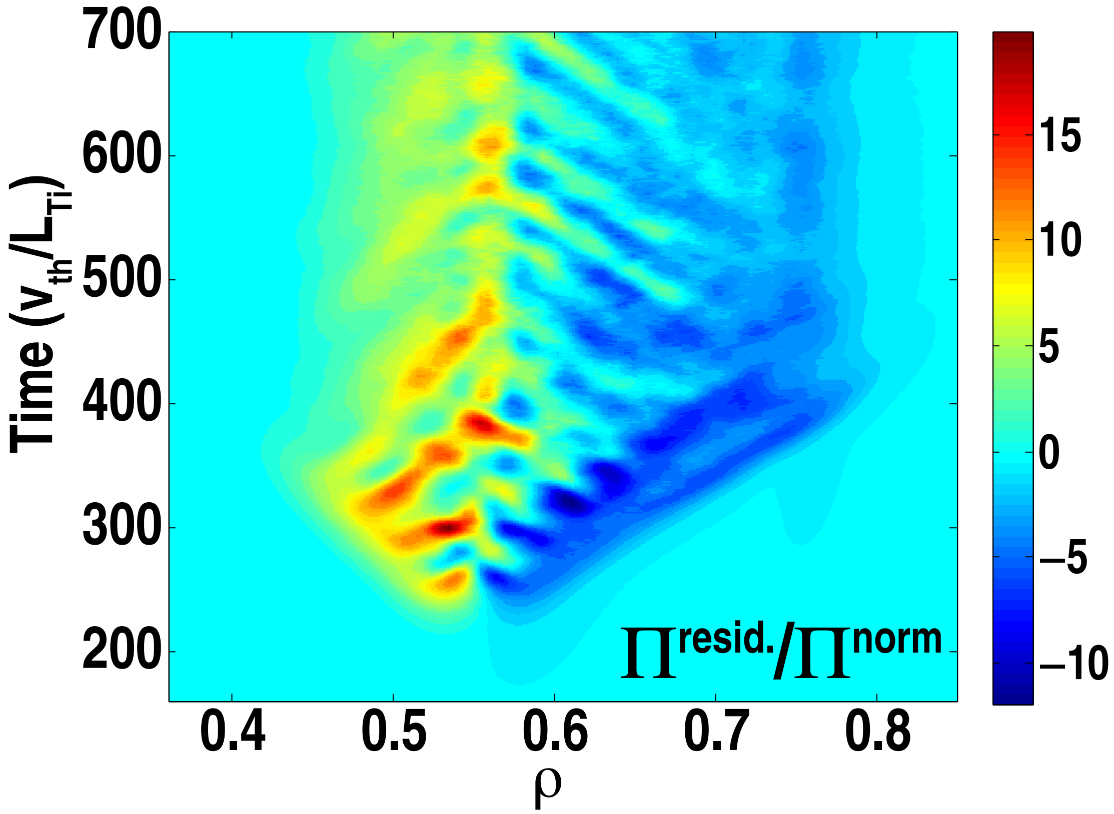
- **Need a mechanism to break the toroidal symmetry**
  - mean E×B shear, ZF E×B shear, up/down asymmetry, profile and turbulence intensity variation
- **Intrinsic torque generated by residual stress $\Pi_{resid.}$**
  - Low-k turbulence in the presence of symmetry breaking
- **Both diffusion and pinch can balance residual stress**
  - here Ω adjusts with local rotation gradient creating $\Pi_{diff.}$ until total $\Pi = 0$

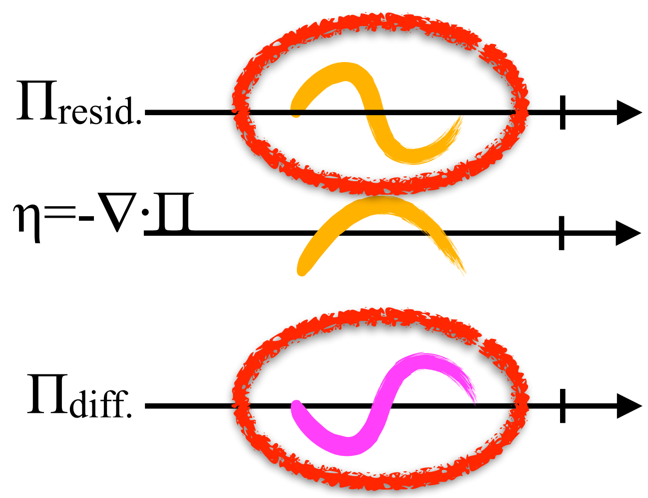


Residual stress and momentum diffusion balance

Balance of Residual Stress and Momentum Diffusion Responsible for Steady-State Experimental Rotation Profile

- **Qualitative balance residual stress and momentum diffusion producing a rotation “hollowing" is realized in GTS simulation**
- **But quantitative, first-principles prediction of rotation profile requires additional information**
  - Cannot use experimental rotation profile to derive diffusive flux, needs Pr





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