Predicting the Rotation Profile in ITER

by

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in collaboration with

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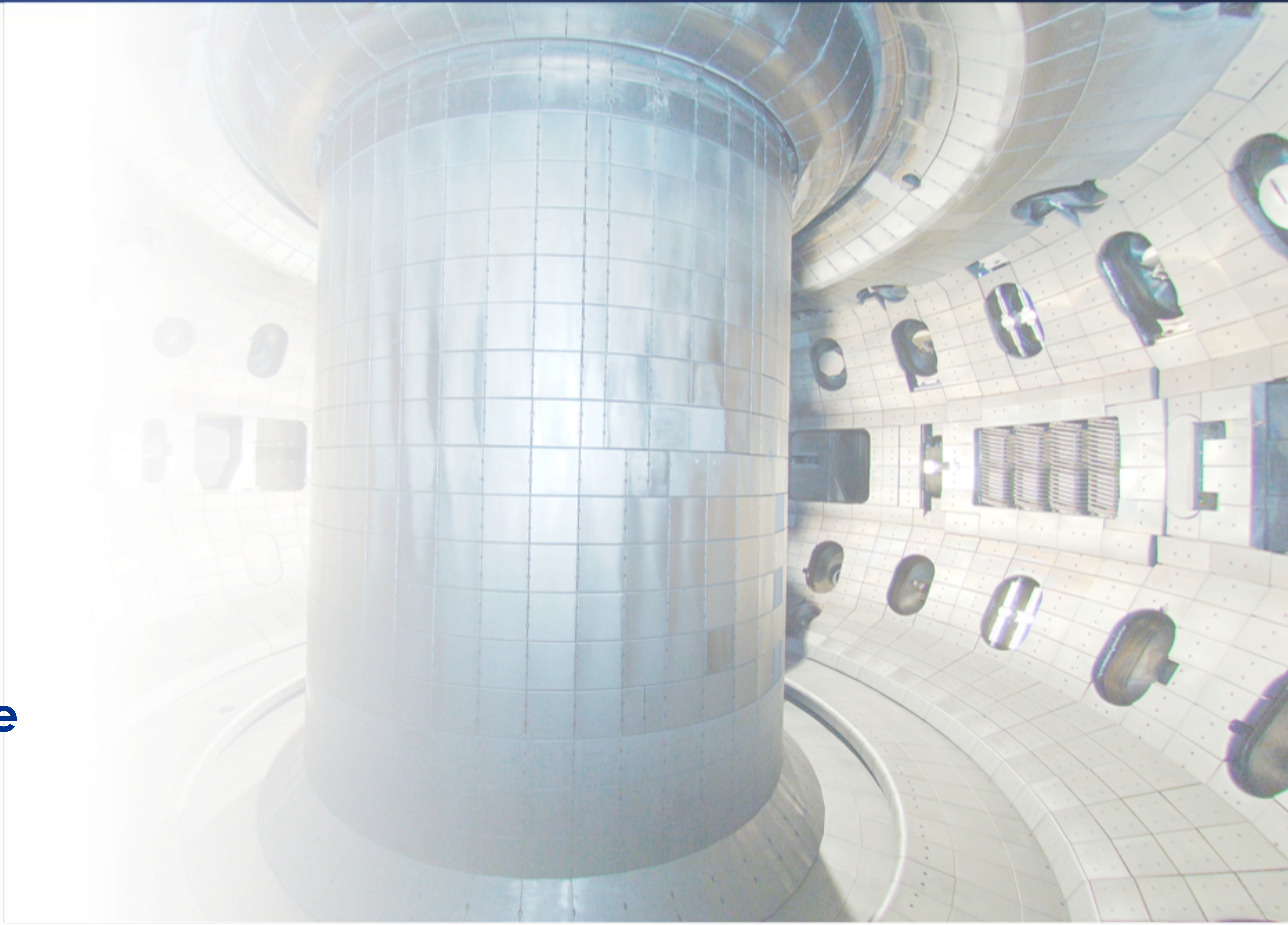

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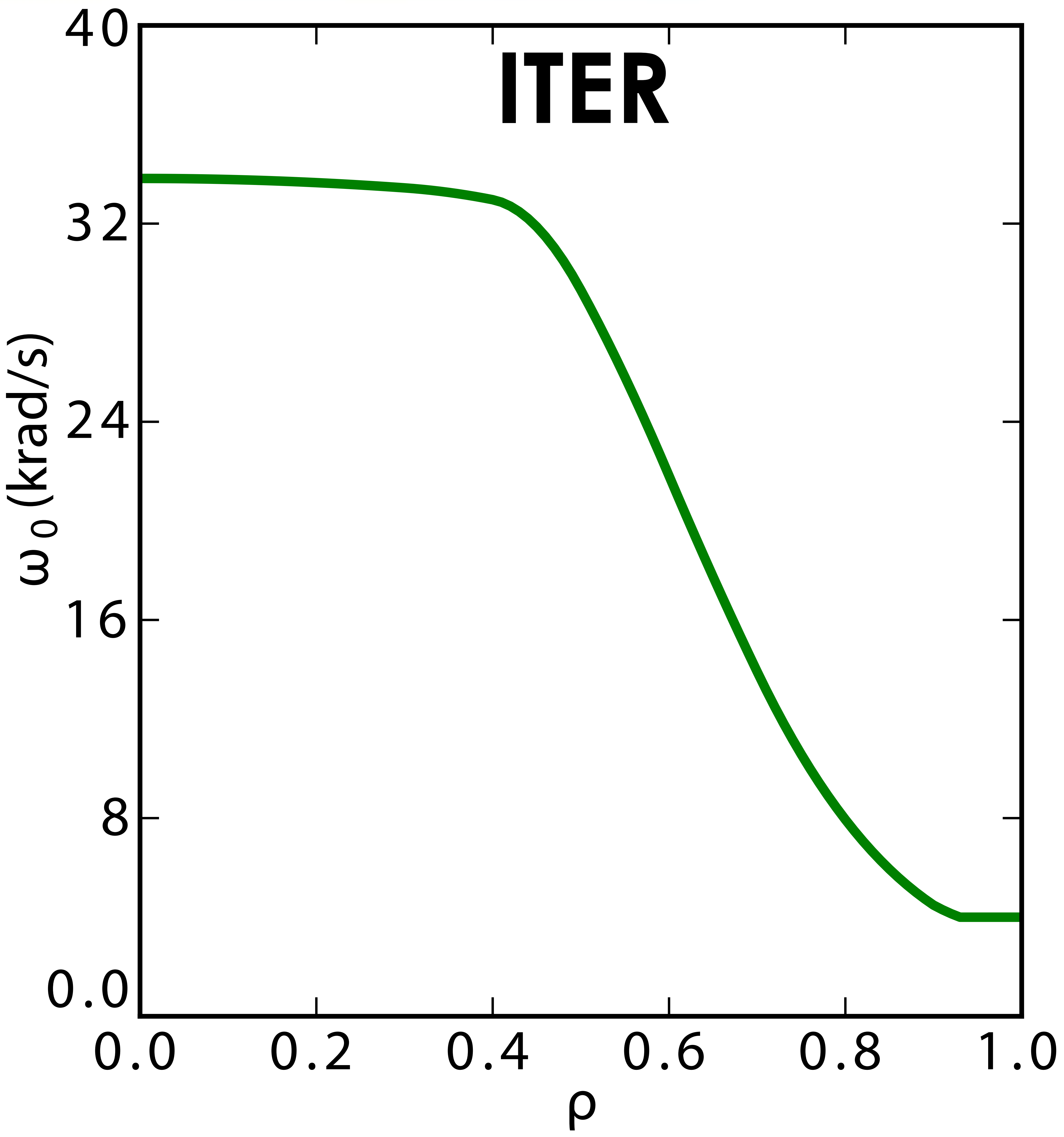
Rotation Is Important for Determining Stability and Performance in Tokamaks, Affects Predictions of ITER Performance

- **Rotation is important for determining ExB shear, MHD stability, transport of high-Z particles**
  - All key for determining fusion power output
- **Also key for ITER is affect of pedestal rotation on access to ELM free H-mode via QH-mode[1] and RMP ELM suppression[2]**
  - Scaling arguments offer favorable prospect of RMP ELM suppression

ITER modeling has shown a doubling of fusion power when taking rotation into account due to ExB shear suppression of turbulence

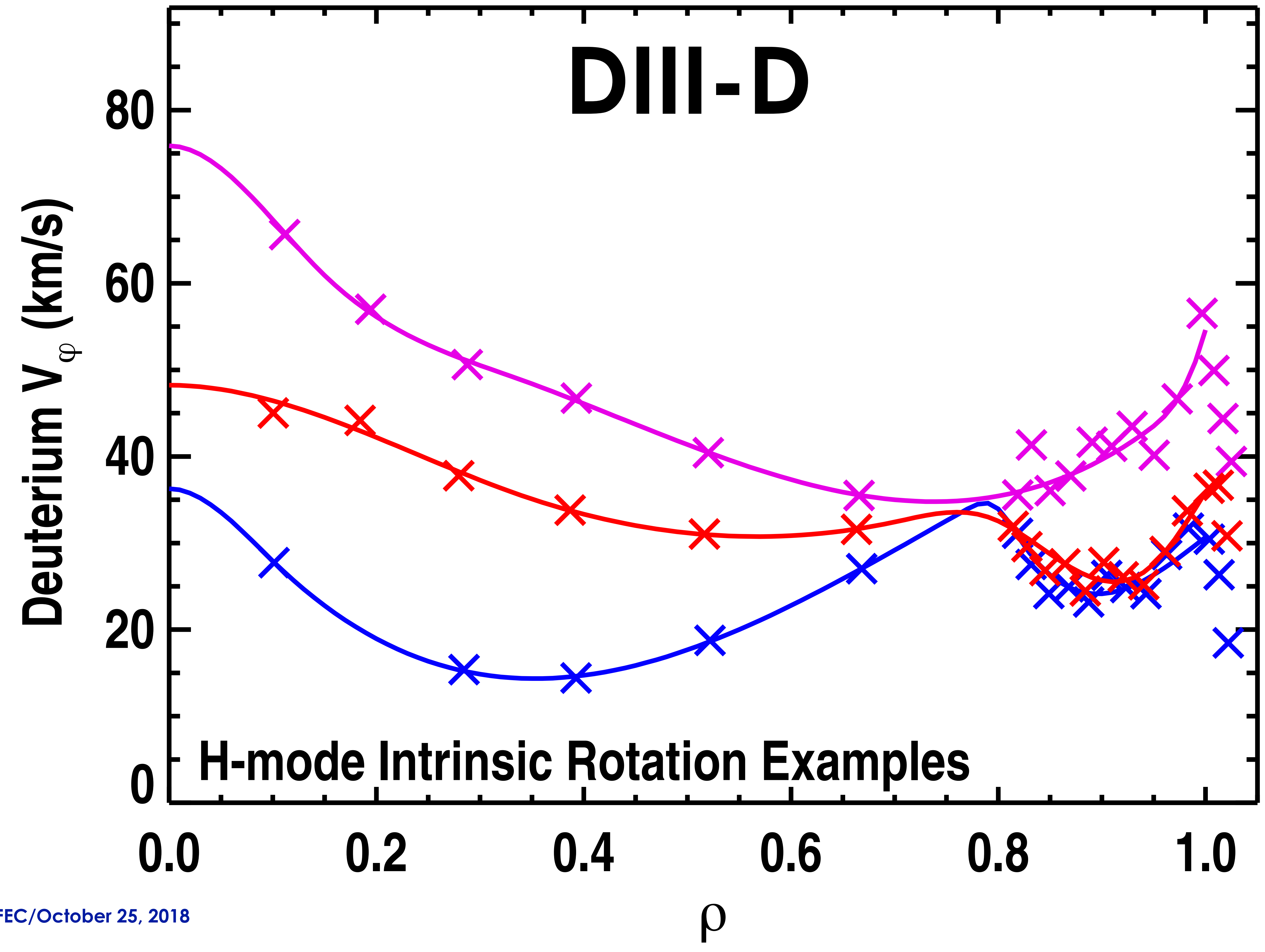


[1] Garofalo, Nucl. Fusion **51**, 083018 (2011)
[2] Moyer, Phys. Plasmas **24**, 102501 (2017)

Determining Rotation in ITER Is Difficult Due to the Presence of Many Similar Size Momentum Sources

- Momentum source in many current tokamaks dominated by NBI
- ITER's larger moment of inertia means non-NBI sources need to be well understood because NBI torque will not be dominant

- Intrinsic rotation profiles display features caused by many physical effects that may be present in ITER



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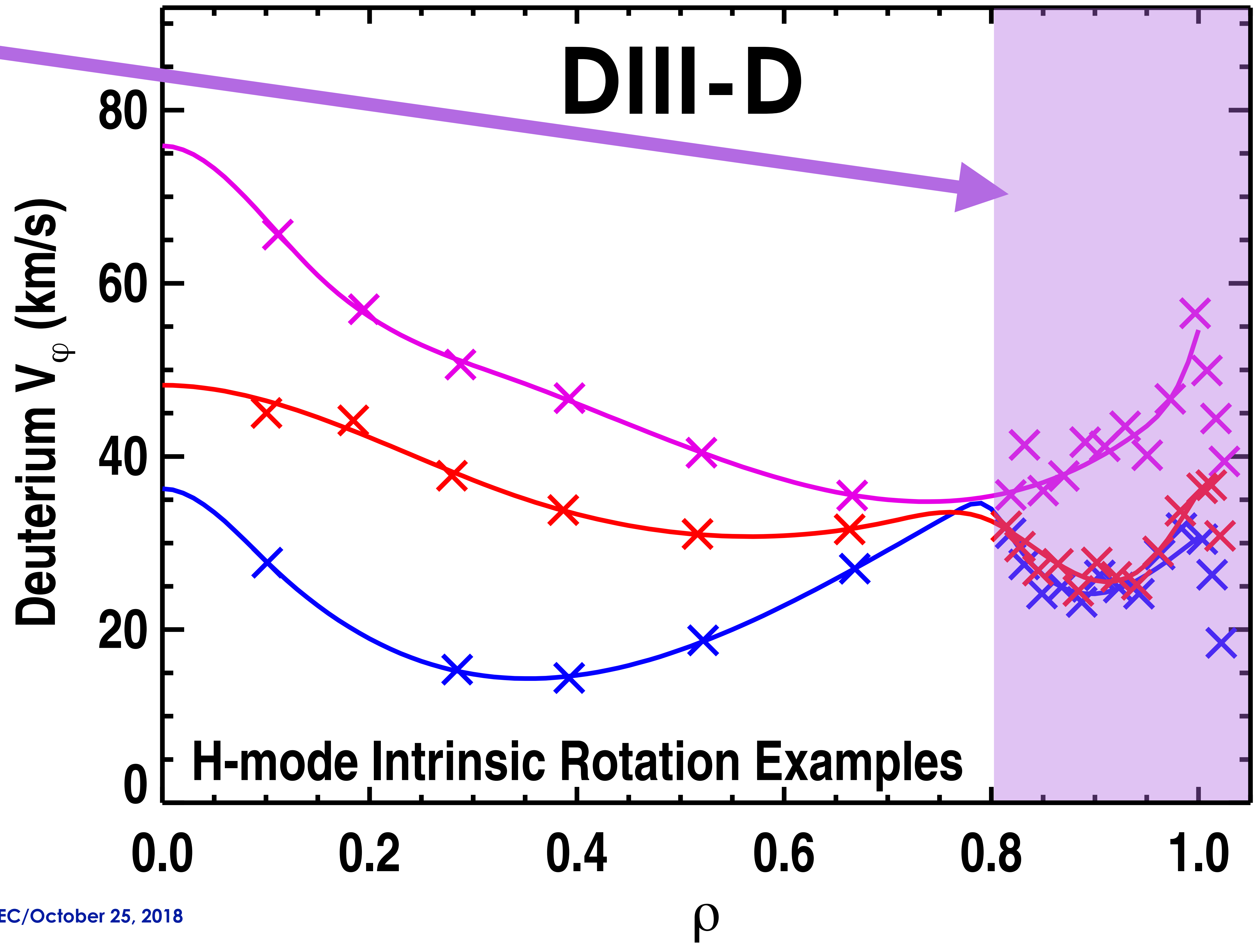
Co-current LCFS feature:
- -Orbit loss
- -Co/counter current transport
- -Residual stress
- -Neutral particles
- -Fast-ion loss
- -Field ripple/NTV



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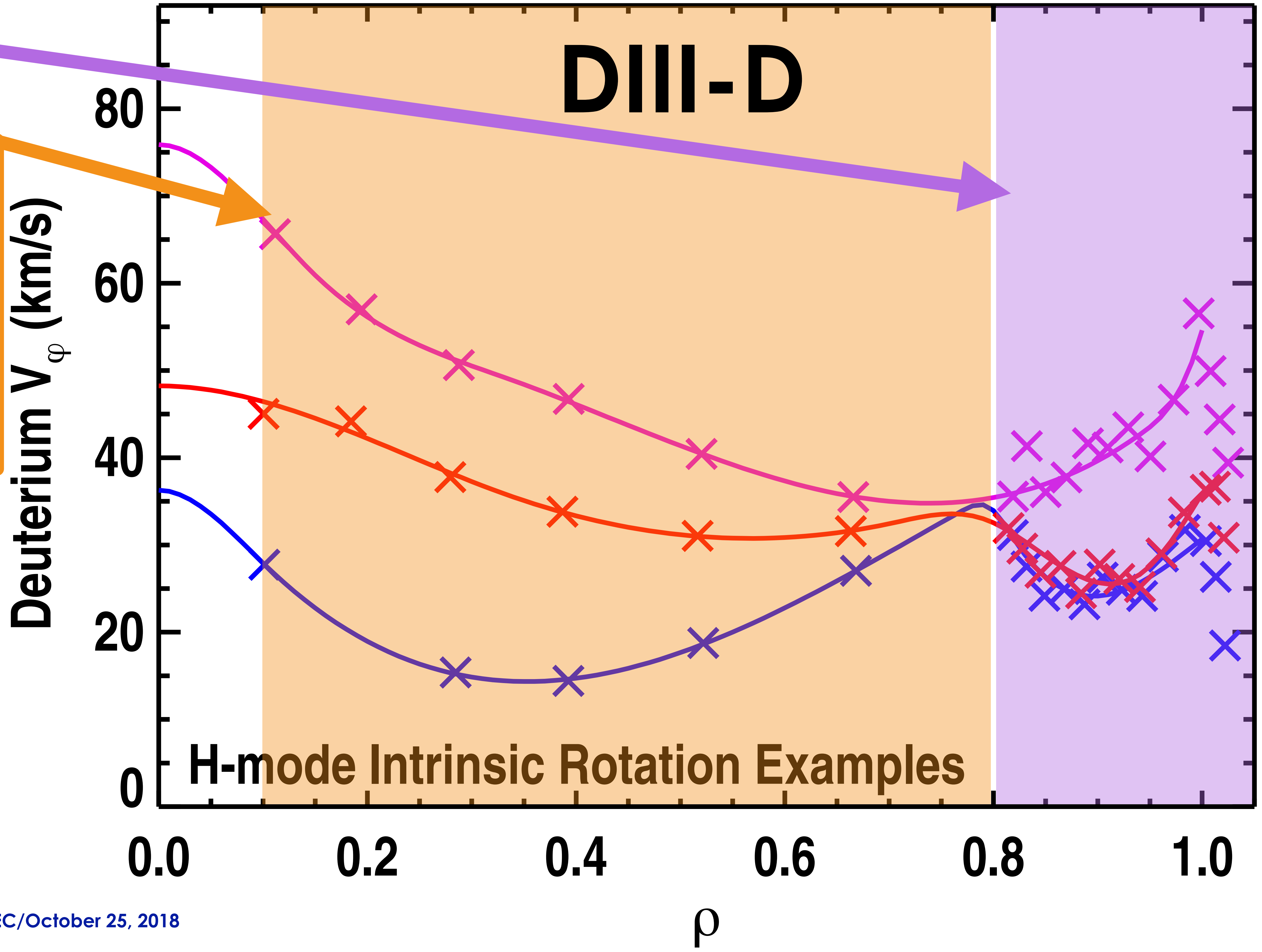
- -Beam torque
- -MHD/NTV



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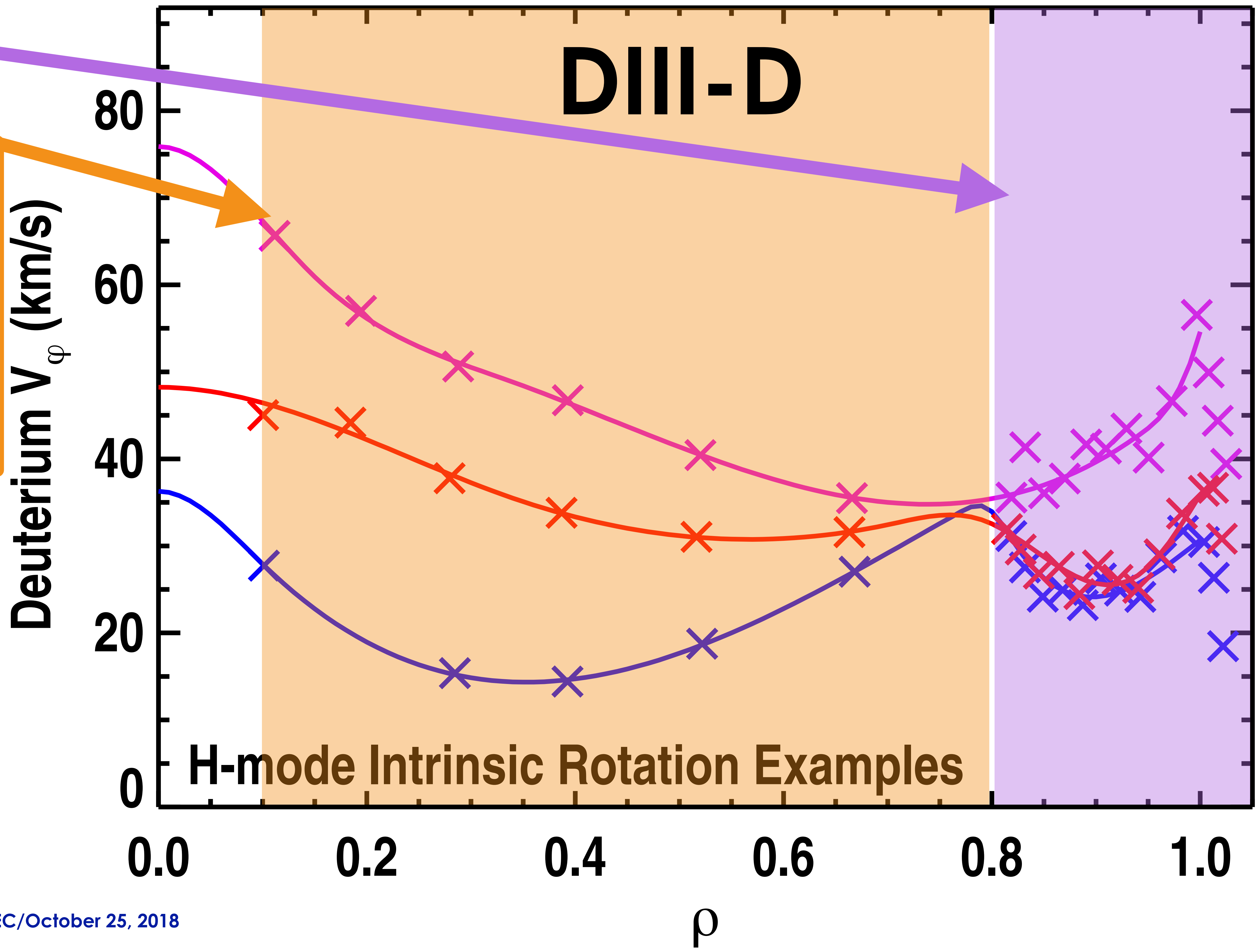


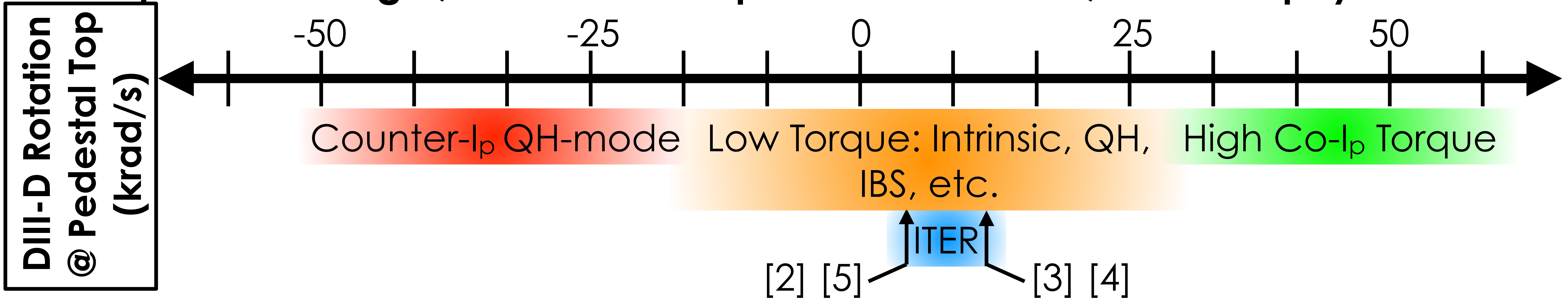
- ***Evaluating 3D field torques requires rotation profile, subject of future work after "initial condition" is laid down***

Outline

- **DIII-D investigation of LCFS co-current feature in intrinsic rotation plasmas**
  - Fast-ion effects on ρ_* scaling
  - Neutral particle effects on intrinsic momentum transport
- **ITER prediction based on co-current feature and core NBI**
- **Implications for RMP ELM suppression and conclusion**

ρ_* Scaling of Intrinsic Co-current Rotation Feature Is Key for Predicting ITER Rotation Boundary Condition

- **Low ρ_* operating regime of ITER cannot be achieved in current tokamaks**
- **Robust co-current rotation near LCFS is a boundary condition, investigated by: empirical scaling[1,2], dimensionless parameters scans[3], reduced physics models[4,5]**



- **Similar predictions: 4-10 krad/s, but discrepancy exists between databases ($M \sim \rho_*^{1}$) and dimensionless parameter scan ($M \sim \rho_*^{-1}$)**
  - Databases vary ρ_* more widely, dimensionless parameter scan varies ρ_* alone BUT had significant fast-ion population
- **Dimensionless parameter scan (intrinsic torque) results need to be verified in intrinsic rotation conditions**

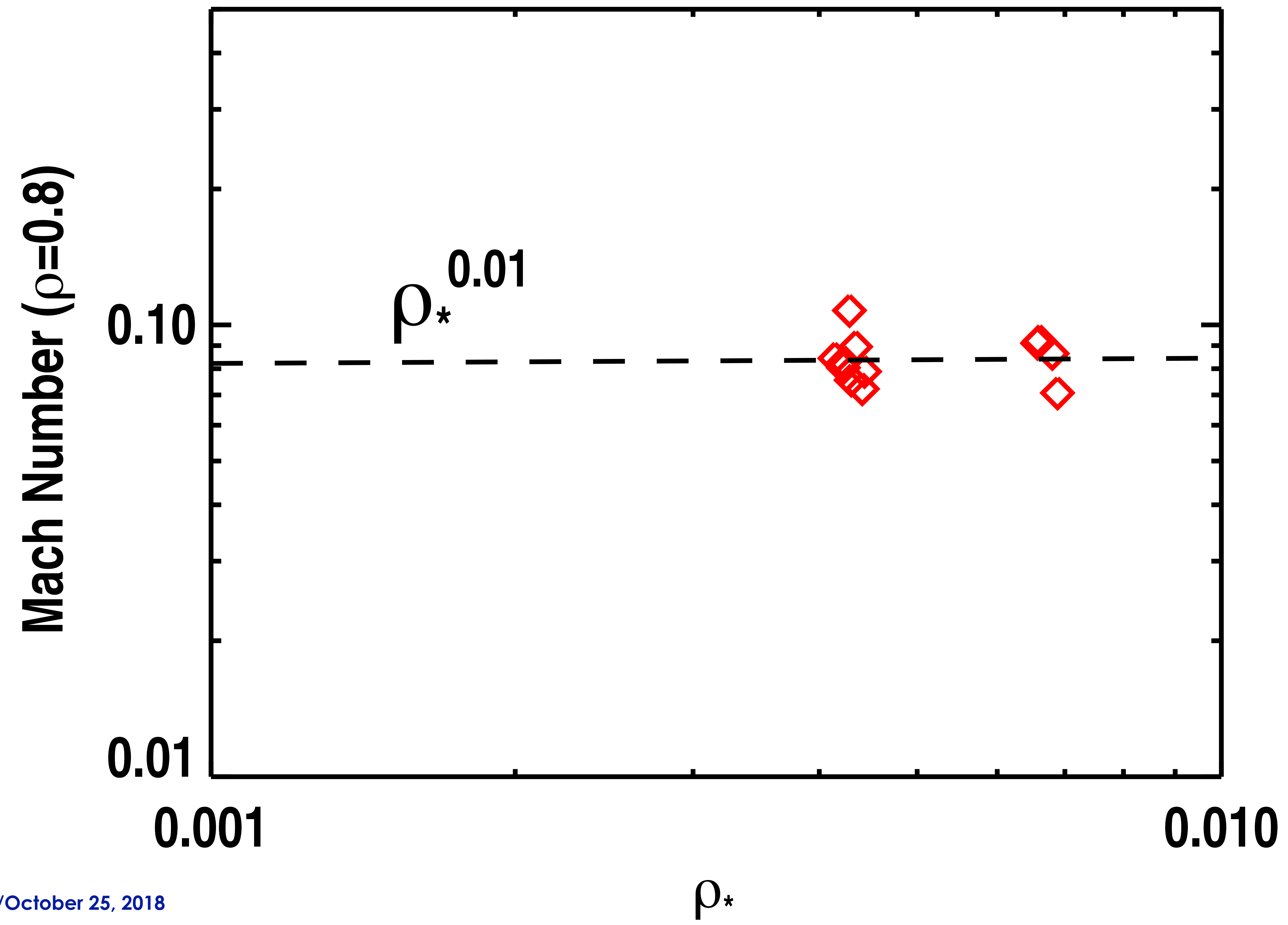
[1] Rice, Nucl. Fusion **47**, 1618 (2007)
[2] deGrassie, Phys. Plasmas **23**, 082501 (2016)
[3] Chrystal, Phys. Plasmas **24**, 042501 (2017)
[4] Rice, Nucl. Fusion **57**, 116004 (2017)
[5] Ashourvan, Phys. Plasmas **25**, 056114 (2018)

Measured Scaling of Intrinsic Rotation in ECH H-modes Has Smaller Discrepancy and Increases Confidence in ITER Prediction

- **No significant scaling of intrinsic Mach number measured with in dimensionless parameter scan, defying both possible expectations**
  - Fundamentally different from observing variation with Mach number in a database

- **Expectation was $M \sim \rho_*^{-1\pm0.9}$, new result not quite within error bar, perhaps edge plasma factors or Z_{eff} changes are the cause of variation in results**
  - Other dimensionless parameters matched

- **Adjust previous intrinsic torque based ITER prediction of ~10 krad/s: result is 3 krad/s, very near the previous predictions (4-10 krad/s)**



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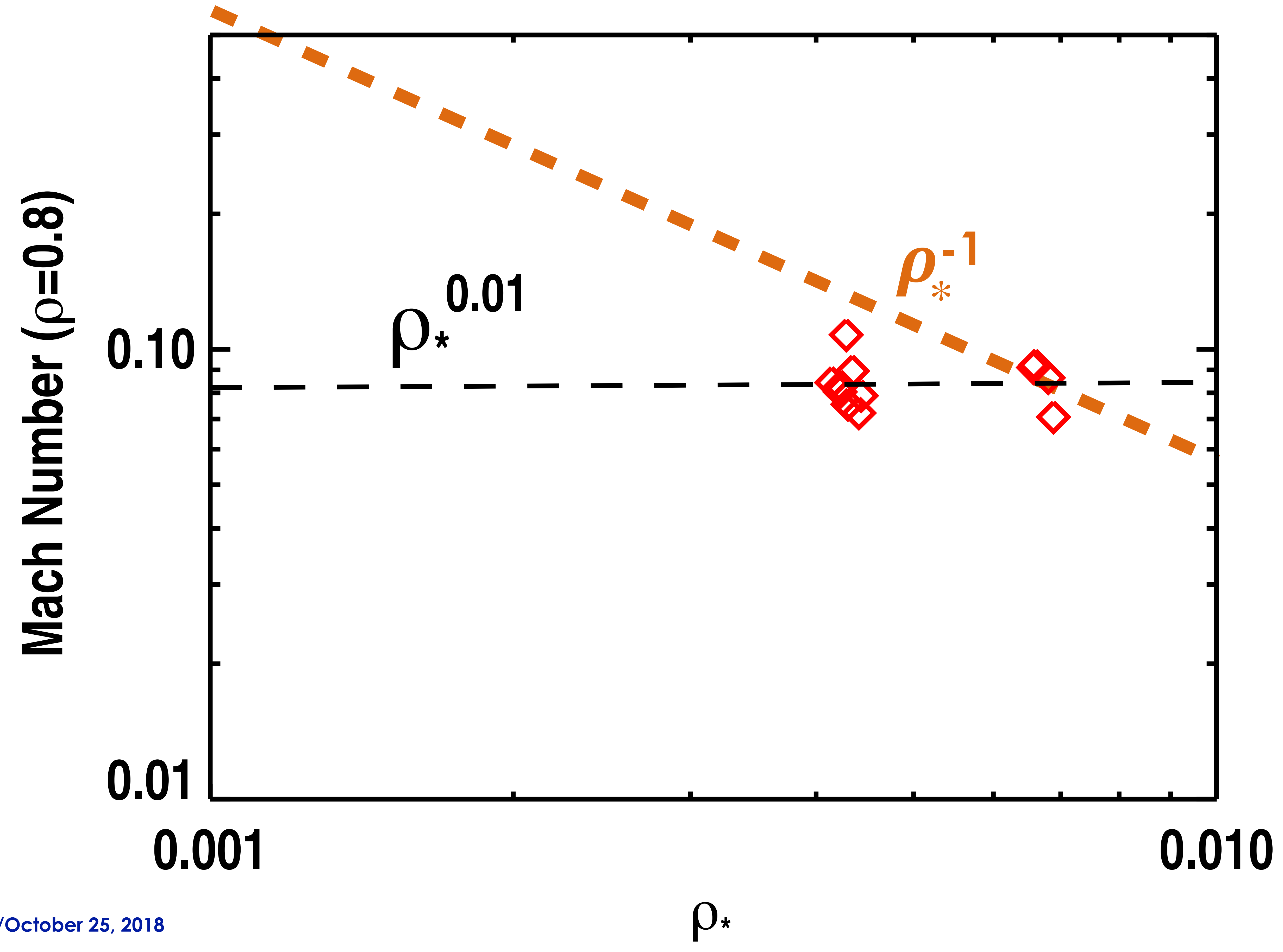

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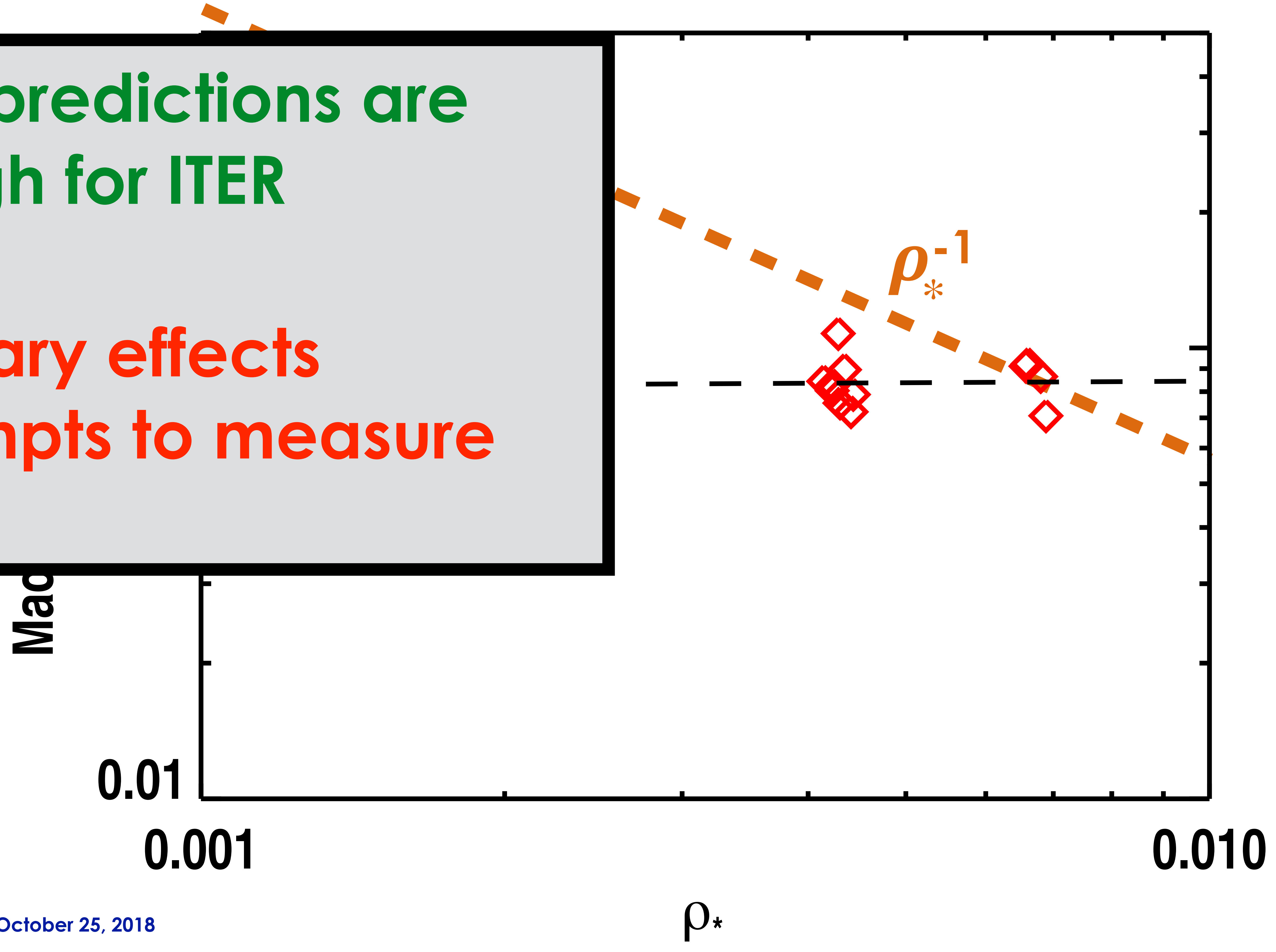
- Intrinsic rotation predictions are consistent enough for ITER prediction
- Are there boundary effects influencing attempts to measure the ρ_* scaling?

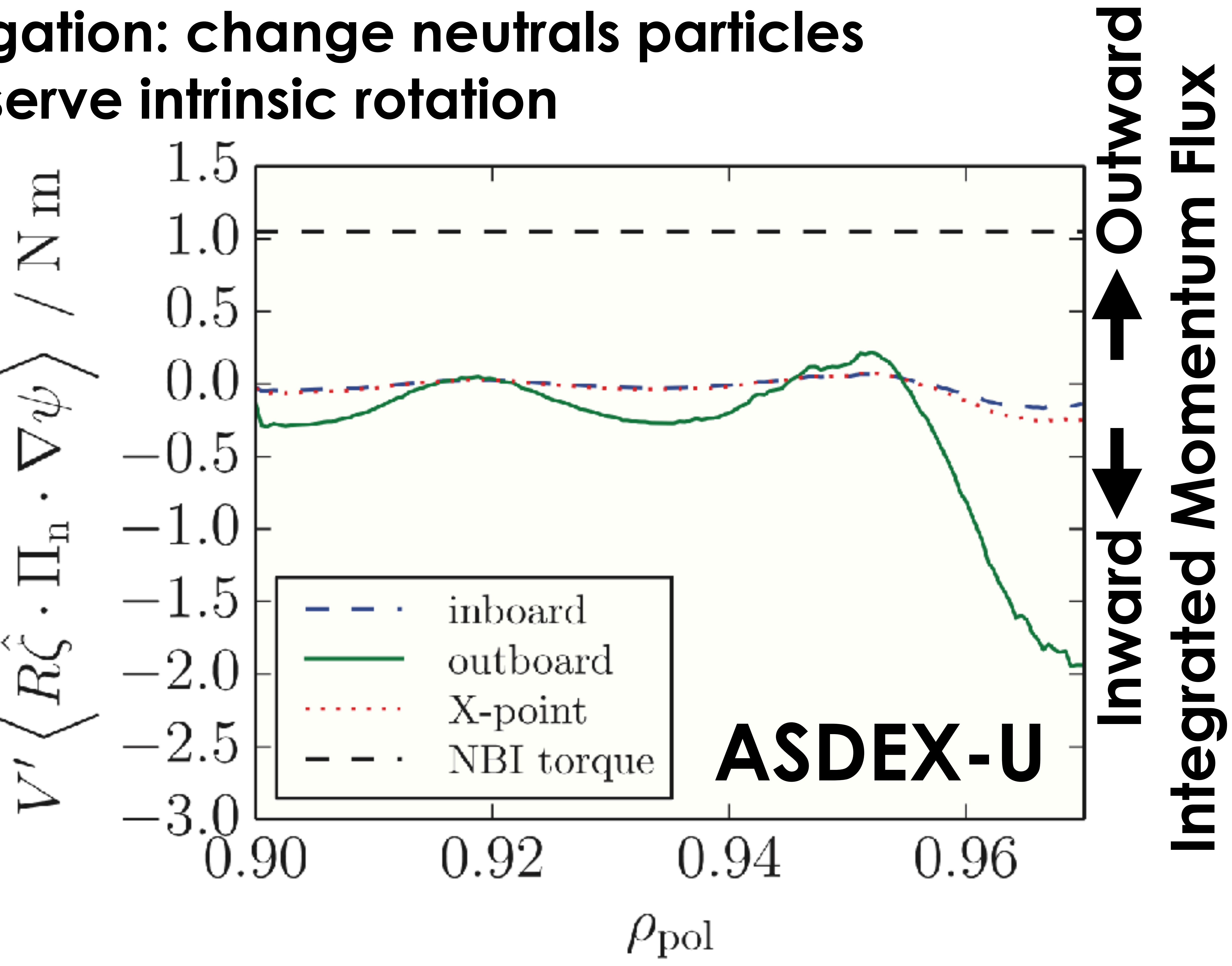


Momentum Transport from Neutrals in Pedestal Is a Hidden Variable that May Affect Current Tokamaks Much More than ITER

- **Neutral particles in pedestal are a hidden variable for most current experiments because they are rarely measured, may be corrupting ITER predictions**
- **Experiment in DIII-D made proxy investigation: change neutrals particles significantly through SOL conditions, observe intrinsic rotation**

$$M_{\mathrm{ped}} \sim f\left(\frac{n_{\mathrm{nuet}}}{n_e}, \frac{n_{\mathrm{neut}}}{a\nabla n_{\mathrm{neut}}}\right)$$

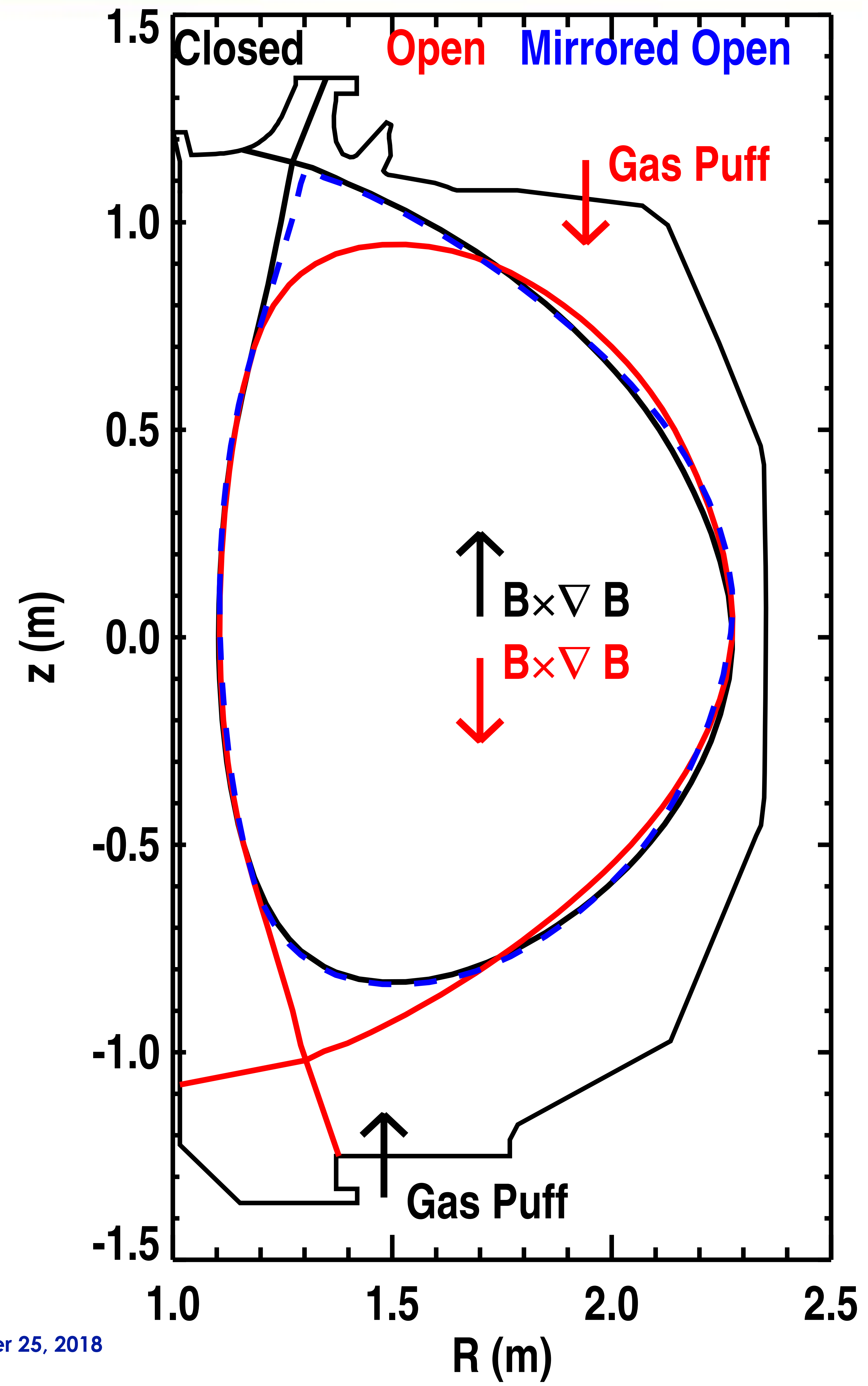
- **Basic idea: neutrals affect rotation via charge exchange and ionization, effect is much reduced in ITER due to decreased neutral penetration into plasma**



Omotani, Nucl. Fusion **57**, 066048 (2017)

Proxy Investigation Uses Divertor Closure to Change Neutral Trapping, Effect Shown by SOLPS Modeling

- **DIII-D upper divertor can be made significantly more closed than lower divertor**
- **Create similar intrinsic rotation discharges (ECH H-modes) in these two configurations**
  - Measure main-ion rotation from core to LCFS with main-ion CER



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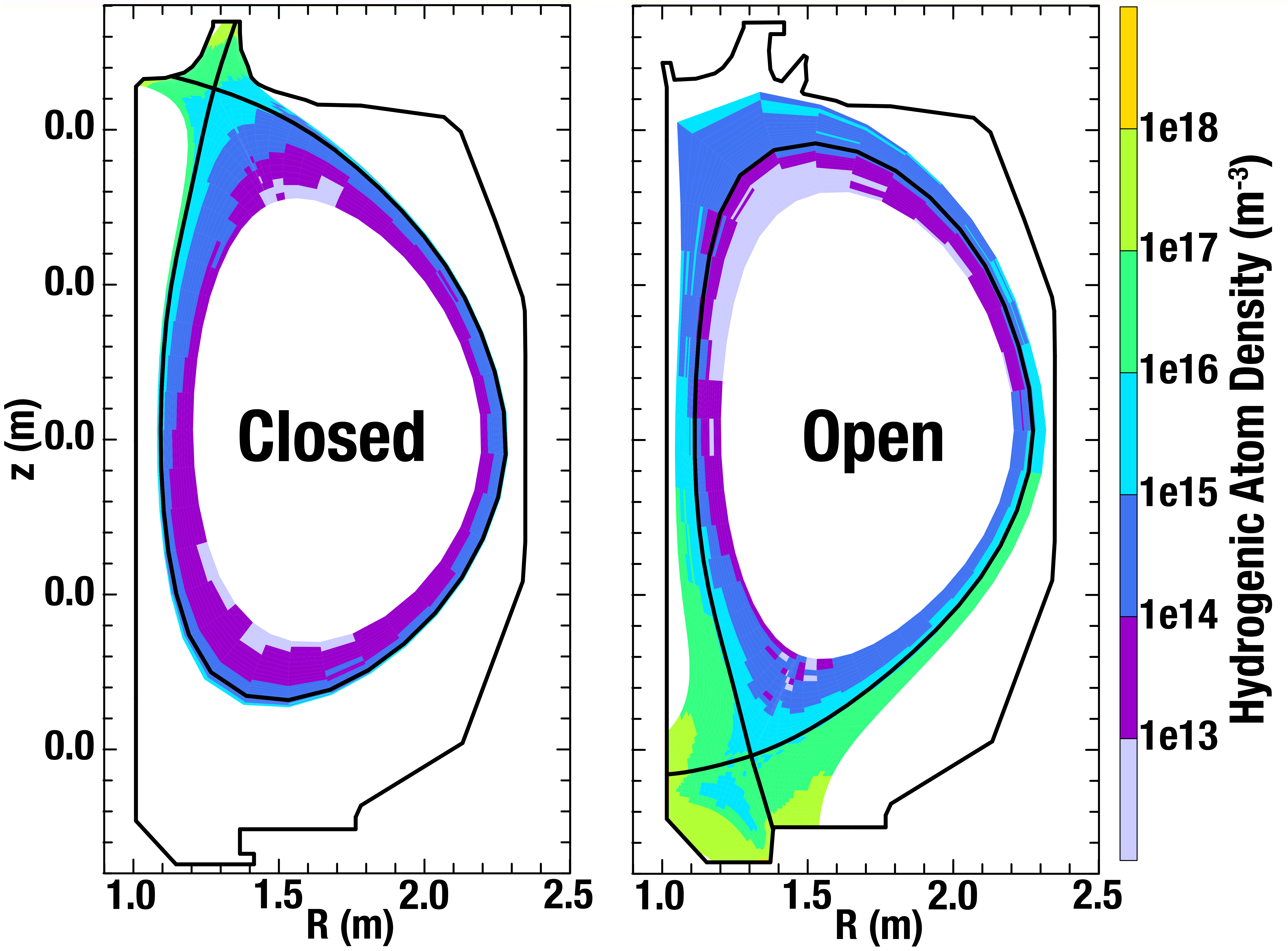

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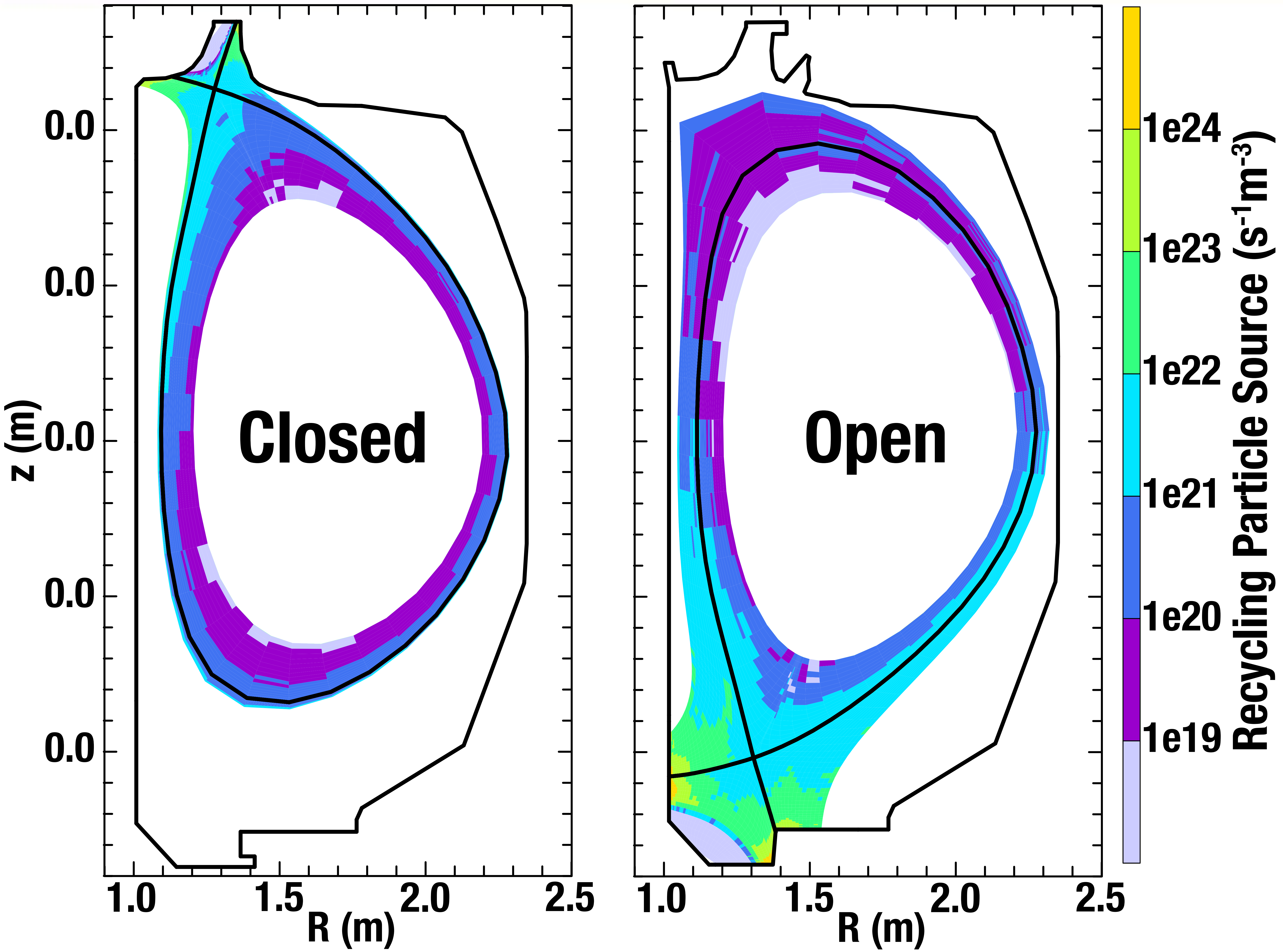

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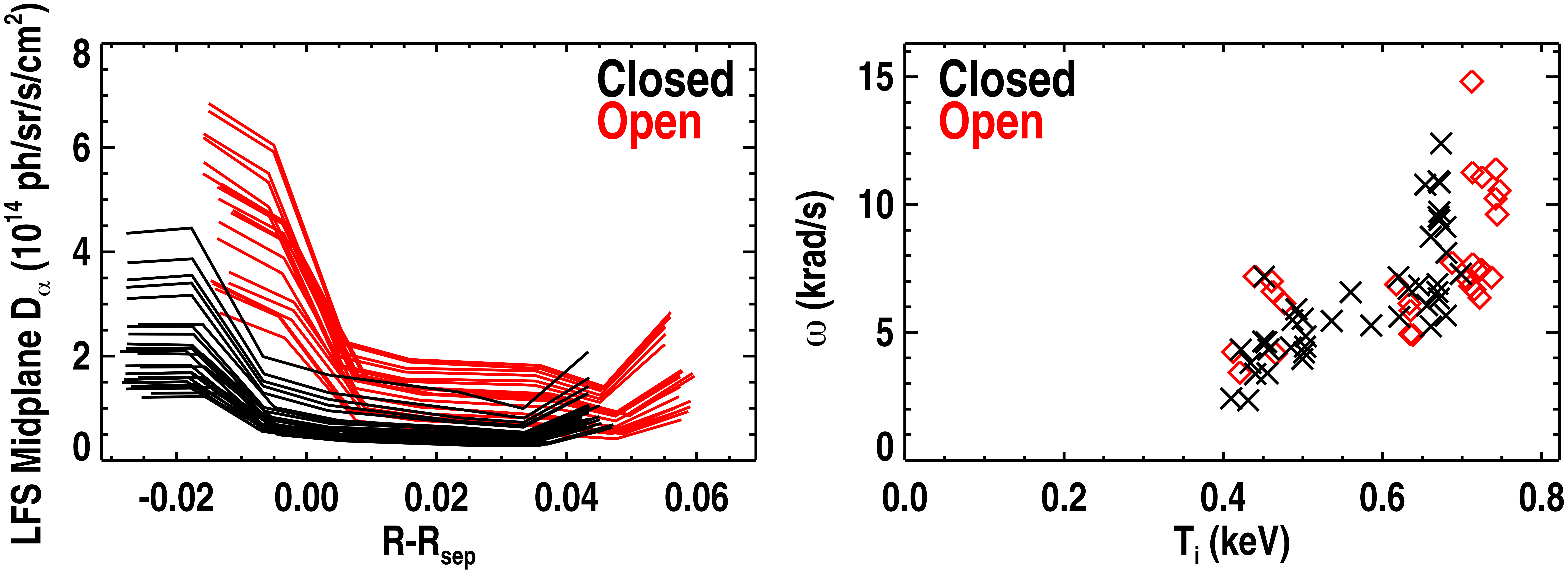
Across Database of Open/Closed Plasmas, Pedestal Top Rotation Constant While Midplane Neutral Emission Changes

- Pedestal top intrinsic rotation (carbon) gives basic indication of changes in edge/ pedestal rotation
- For the parameters varied in these discharges, main trend is expected to be with T_i



- Neutrals appear to have little effect because rotation data sets essentially the same while midplane neutral emission clearly increase for open cases

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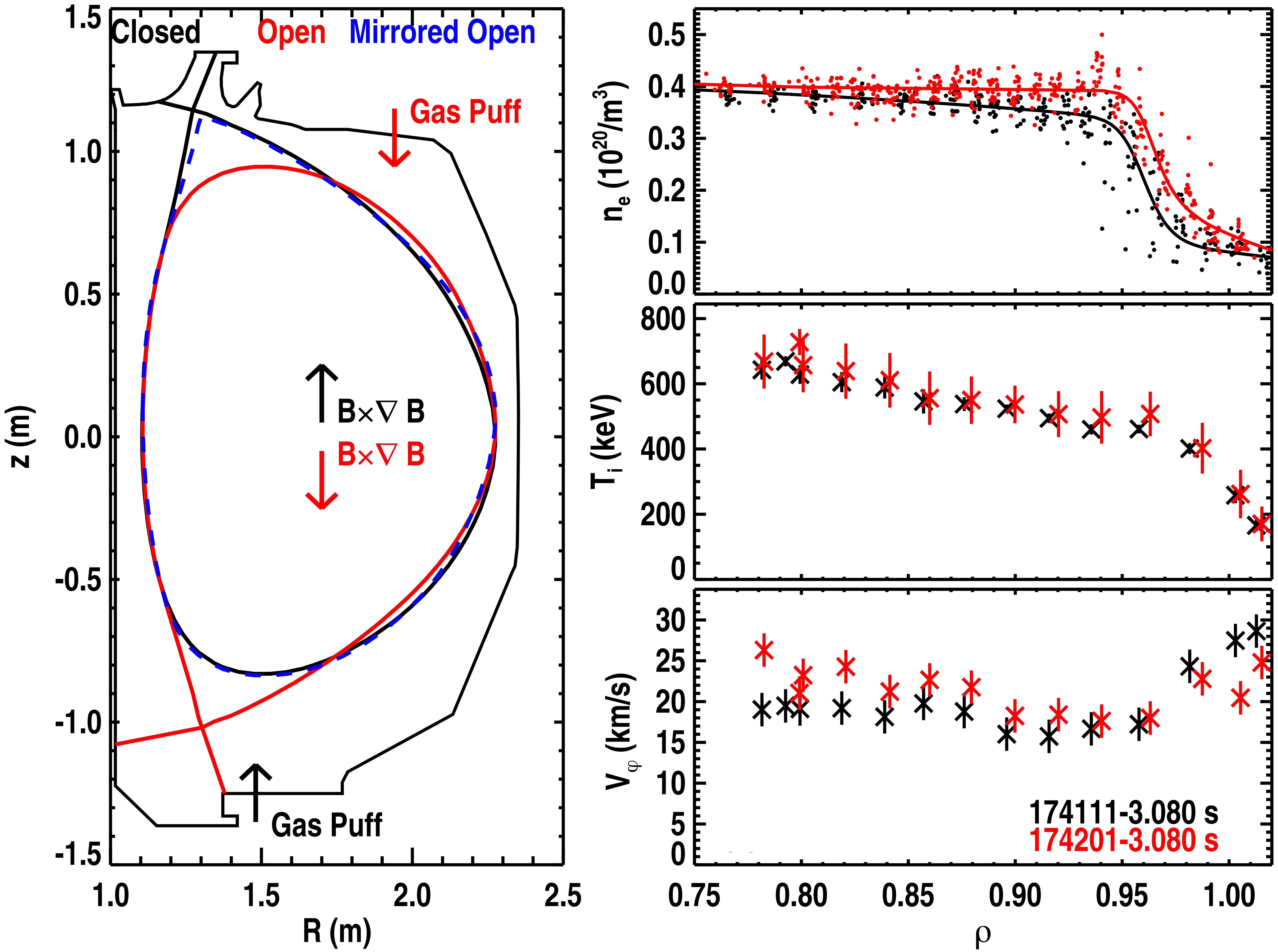
DIII-D Intrinsic Rotation in Open/Closed Divertors Do Not Change Significantly with Changes in Pedestal Fueling

- **Divertor closure affects amount of neutral fueling near LCFS as seen by SOLPS modeling and density profile results, even when other parameters are the same**
  - Density profiles changes are significant given the same I_p, β, etc.

- **Main-ion intrinsic rotation is largely unaffected compared to normal experimental variation**

- **Edge neutrals have no significant effect on intrinsic rotation**



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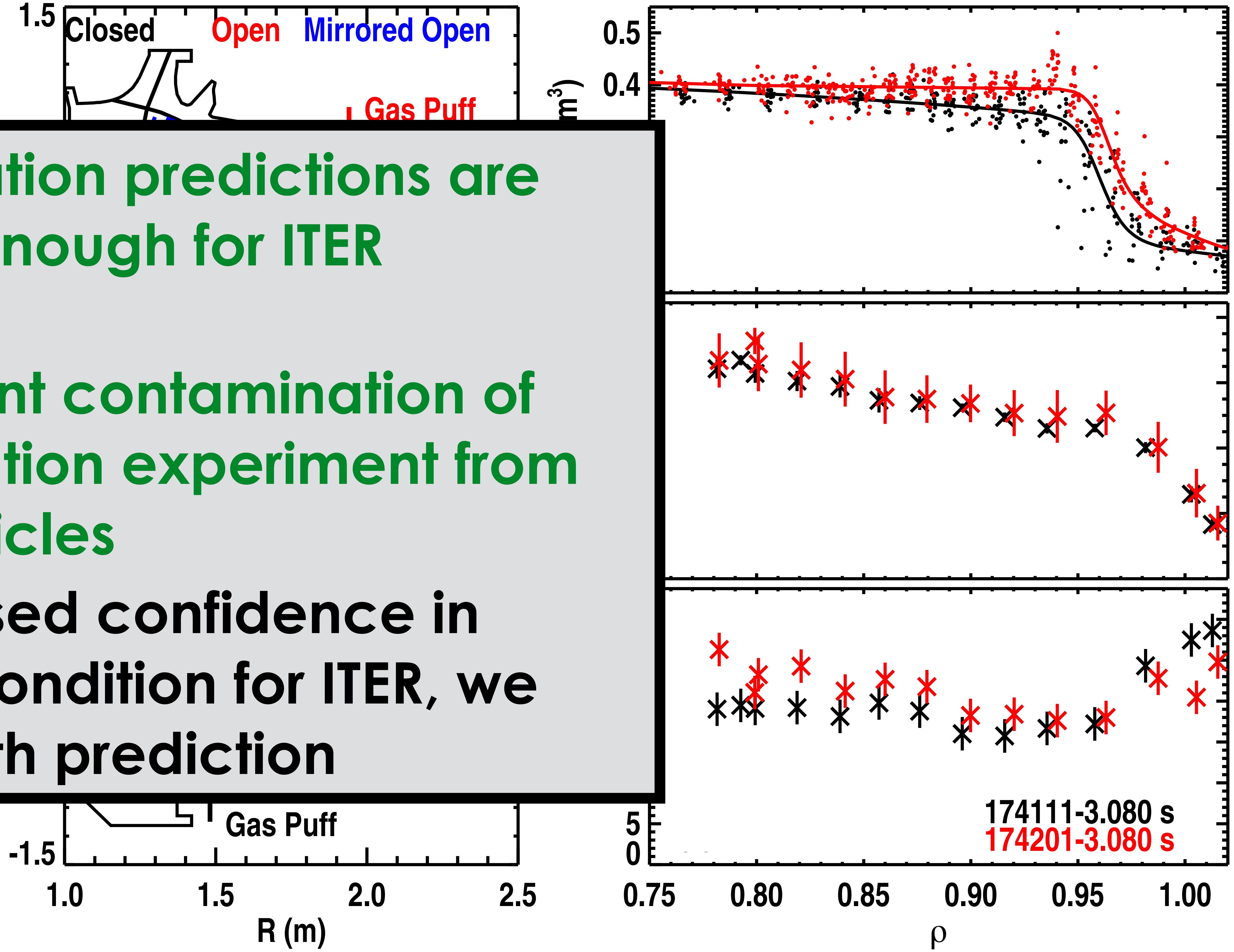
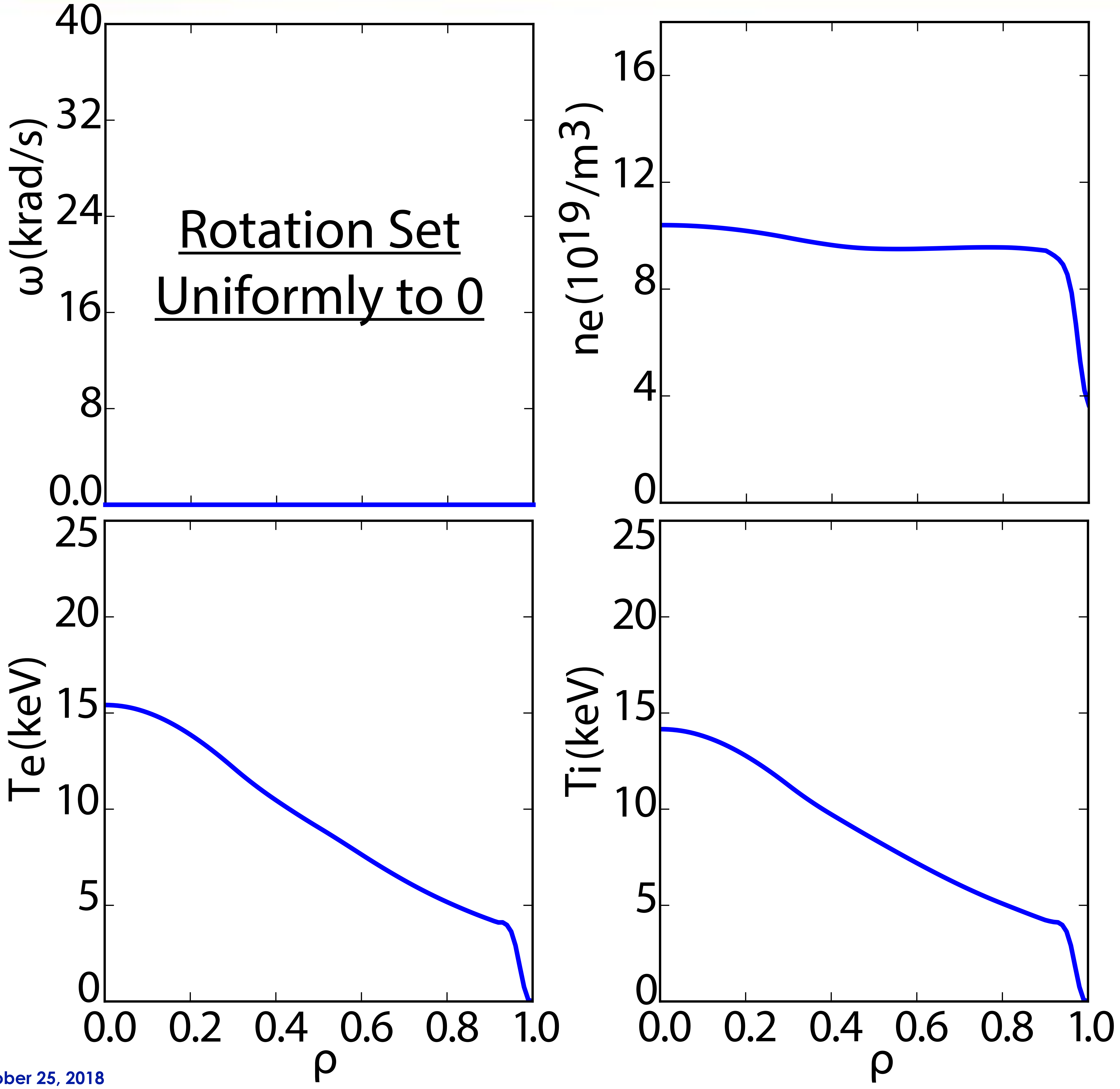


- **Intrinsic rotation predictions are consistent enough for ITER prediction**
- **No significant contamination of intrinsic rotation experiment from neutral particles**
- **With increased confidence in boundary condition for ITER, we proceed with prediction**

Initial ITER Modeling Done Without Rotation Is Baseline for Evaluating Effect of Rotation

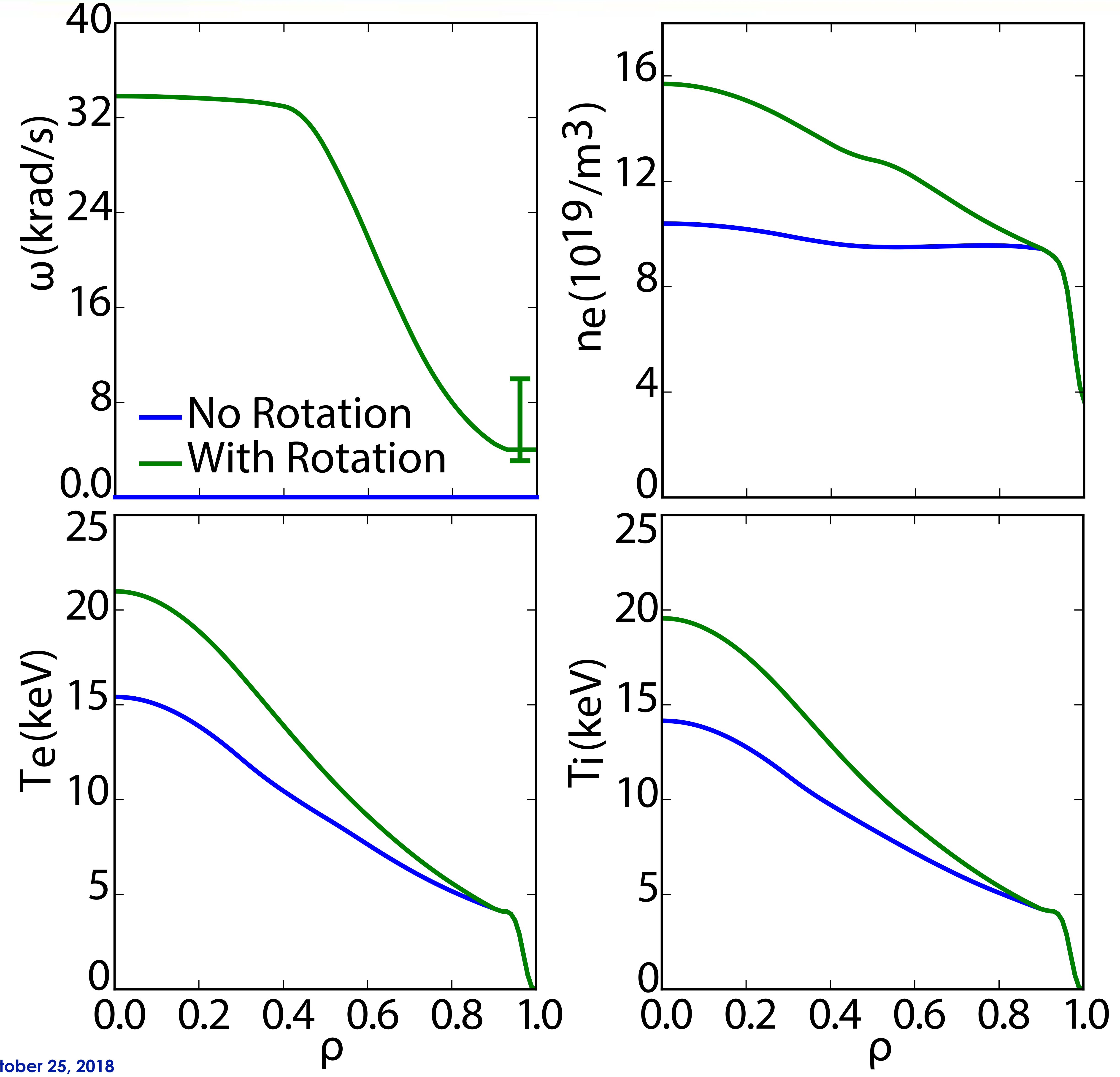
- **Predictive TRANSP determines sources**
  - ITER baseline scenario (15 MA), EPED pedestal
  - 35 N•m and 33 MW NBI, 10 MW ICRF, 6 MW ECCD (at q=3/2, 2 surfaces)
- **Core solution with TGYRO with TGLF+NEO transport**
- **Next, use edge rotation boundary condition and also solve transport in momentum channel with NBI**
  - TGLF momentum transport worked well in DIII-D[1] at lower collisionality and q



[1] Chrystal, Phys. Plasmas **24**, 056113 (2017)

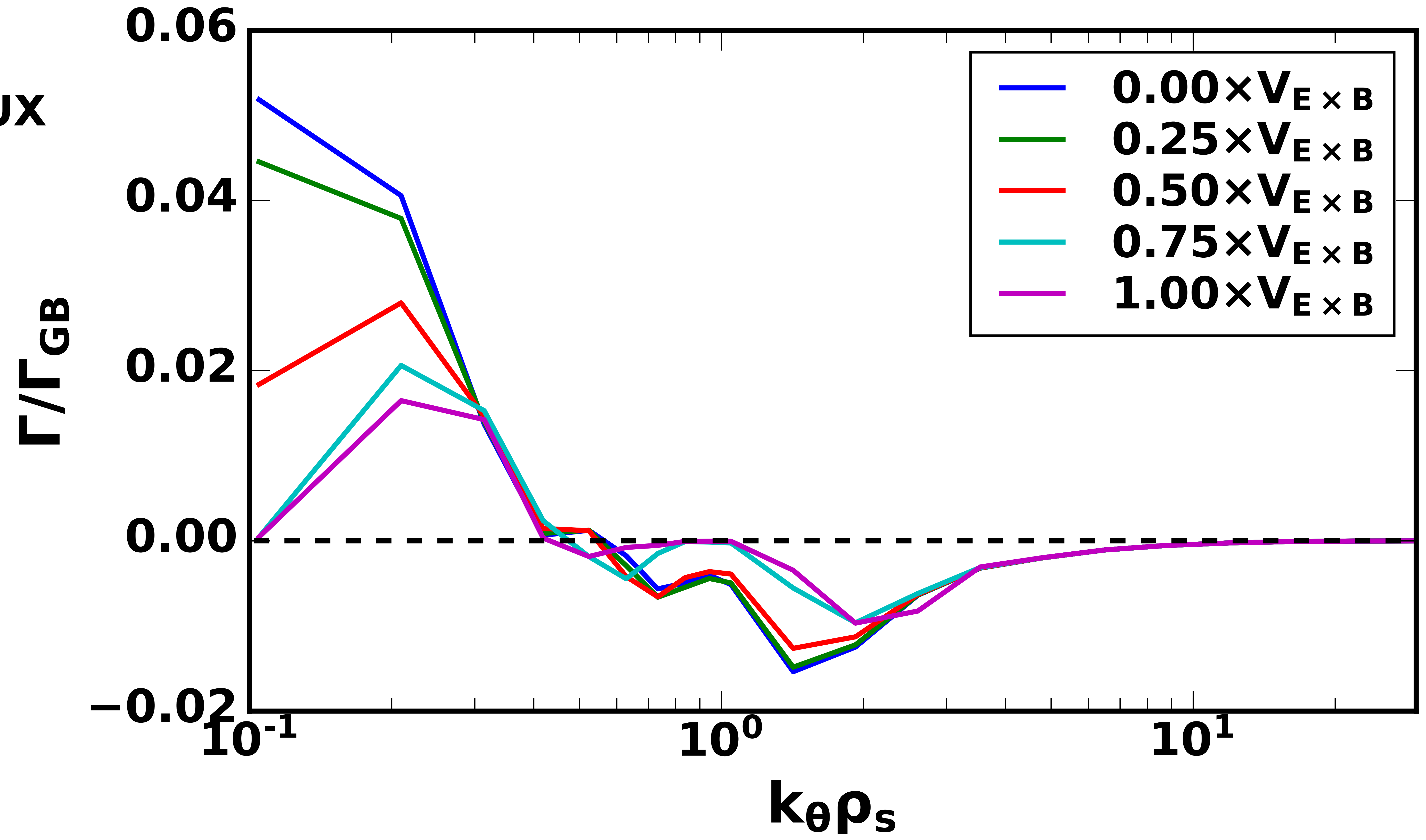
Core Rotation Shear in ITER Is Predicted to Significantly Improve Fusion Performance

- **Rotation boundary condition of 4 krad/s is used, relatively modest value within 3-10 krad/s range of predictions**
- **Core rotation determined from TGLF momentum flux and 35 N•m source**
- **Deuterium Mach numbers are modest: M_{core}~0.2, M_{ped}~0.04**
  - Significant for heavy impurity transport
- **Q_{fus} approximately doubles due to density peaking and increased temperatures caused by rotation shear**
  - Grains of salt: Q values are idiosyncratic to the impurities and radiated power, there are nonlinearities and initial condition is important, residual stress not included in core (see Grierson EX/P6-3 this afternoon)



Performance Improvement From Rotation Shear Is Due to Reduction of Low-k Turbulence and Increase in Density Peaking

- In simulation with rotation, low-k turbulence => outward particle flux, intermediate-k => inward particle flux
- Without ExB shear, total flux would be outward, force TGYRO to flatten density profile
- ExB shear suppresses low-k turbulence more strongly, so flux is balanced even with a peaked density profile



- Increased T_e due to reduced transport further destabilizes intermediate-k turbulence, increasing inward particle flux, as seen in similar studies[1]

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[1] Grierson, Phys. Plasmas **25**, 022509 (2018)

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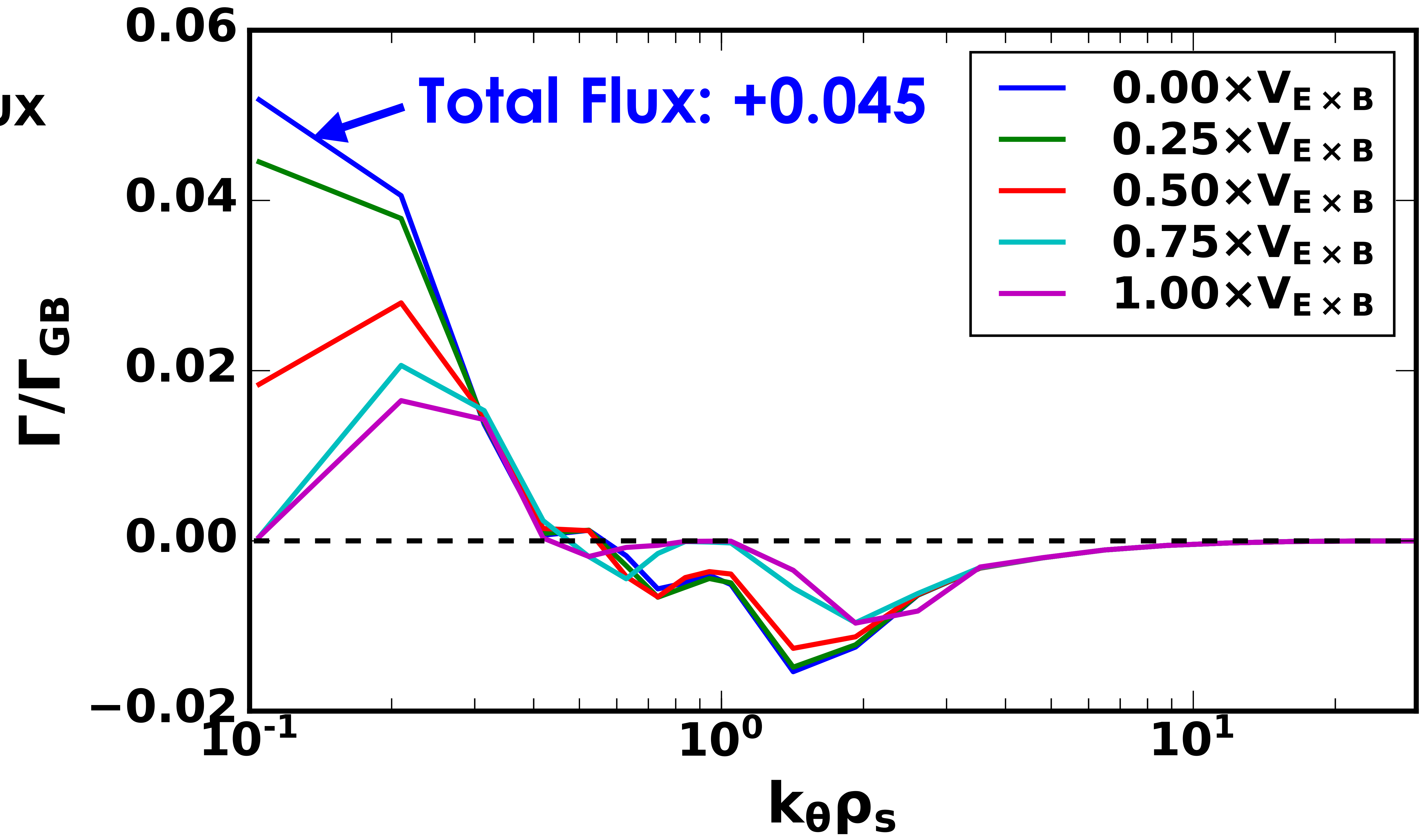

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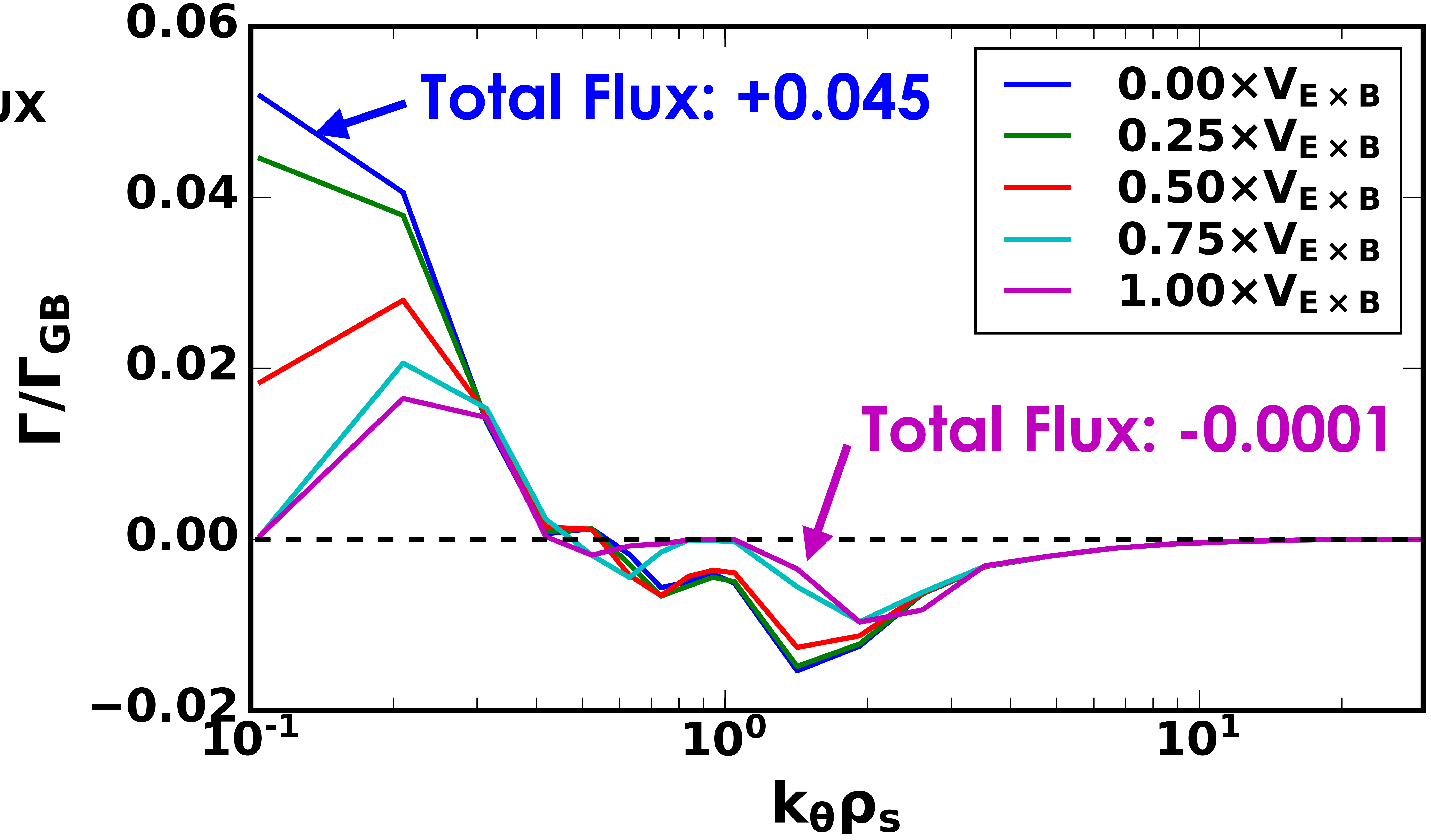

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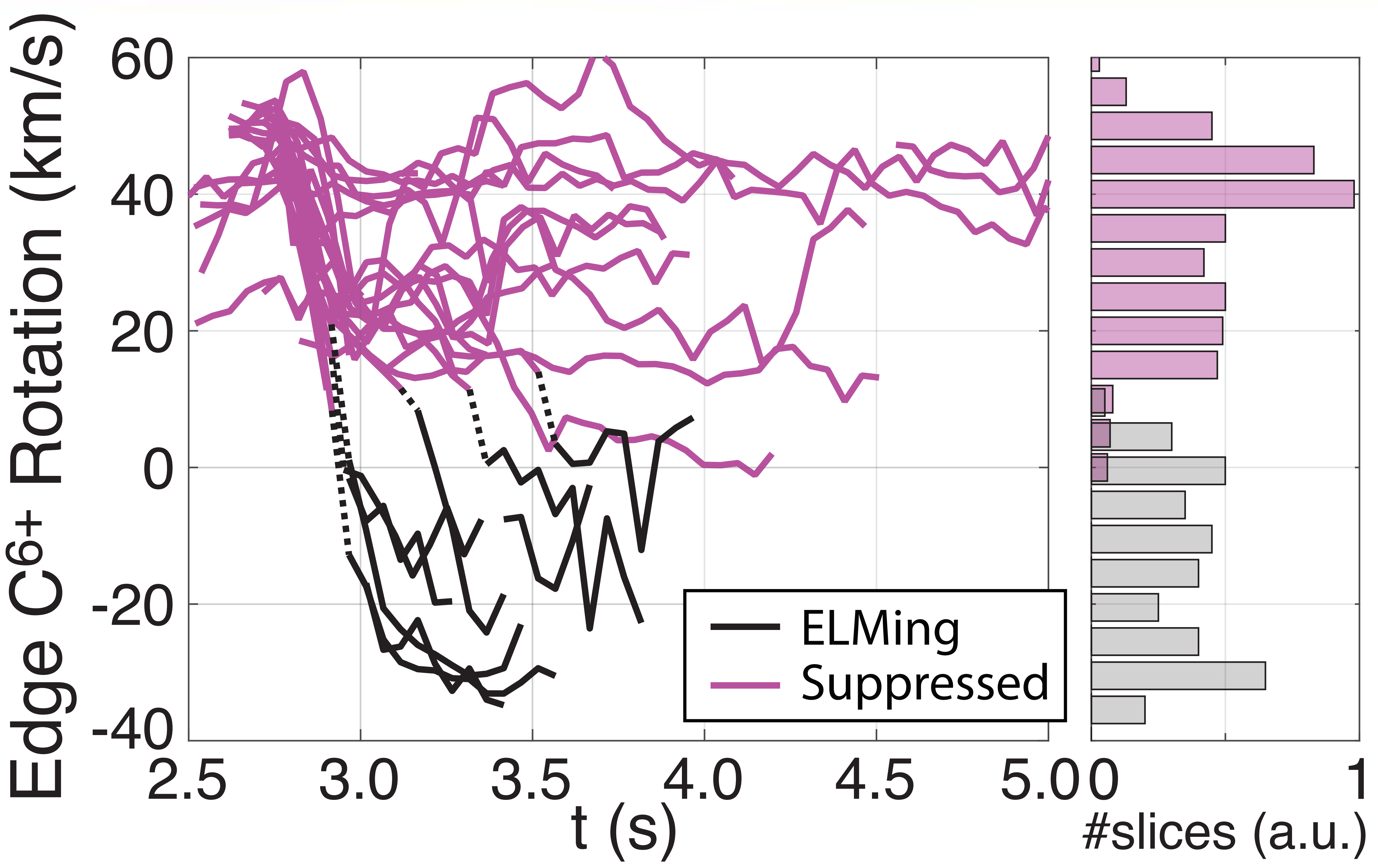
[1] Grierson, Phys. Plasmas **25**, 022509 (2018)

Simple Scaling Relation Offers Favorable Prospect of Achieving RMP ELM Suppression in ITER

- **Low rotation RMP ELM suppression is hard to achieve, hypothesized to be a result of inward movement of E_r=0[1]**
  - $\omega_{\perp,e}$ also hypothesized[2], movement is typically correlated with E_r=0 movement
- **Relation for E_r=0, divergence free flow:**

$$\mathbf{V} = k(\psi)\mathbf{B} + \omega(\psi)R\hat{\varphi} \Rightarrow -\frac{\nabla P}{nZe} = \omega R B_\theta$$

- **ITER needs less rotation because of:**
  - Larger gradient scale length (larger size)
  - Larger poloidal field



- **5-9 krad/s of pedestal top rotation is lower limit for suppression in DIII-D, translates to 0.2-0.5 krad/s for ITER, <3 krad/s prediction**
  - Effect of RMP field on rotation prediction still needed to fully answer this question

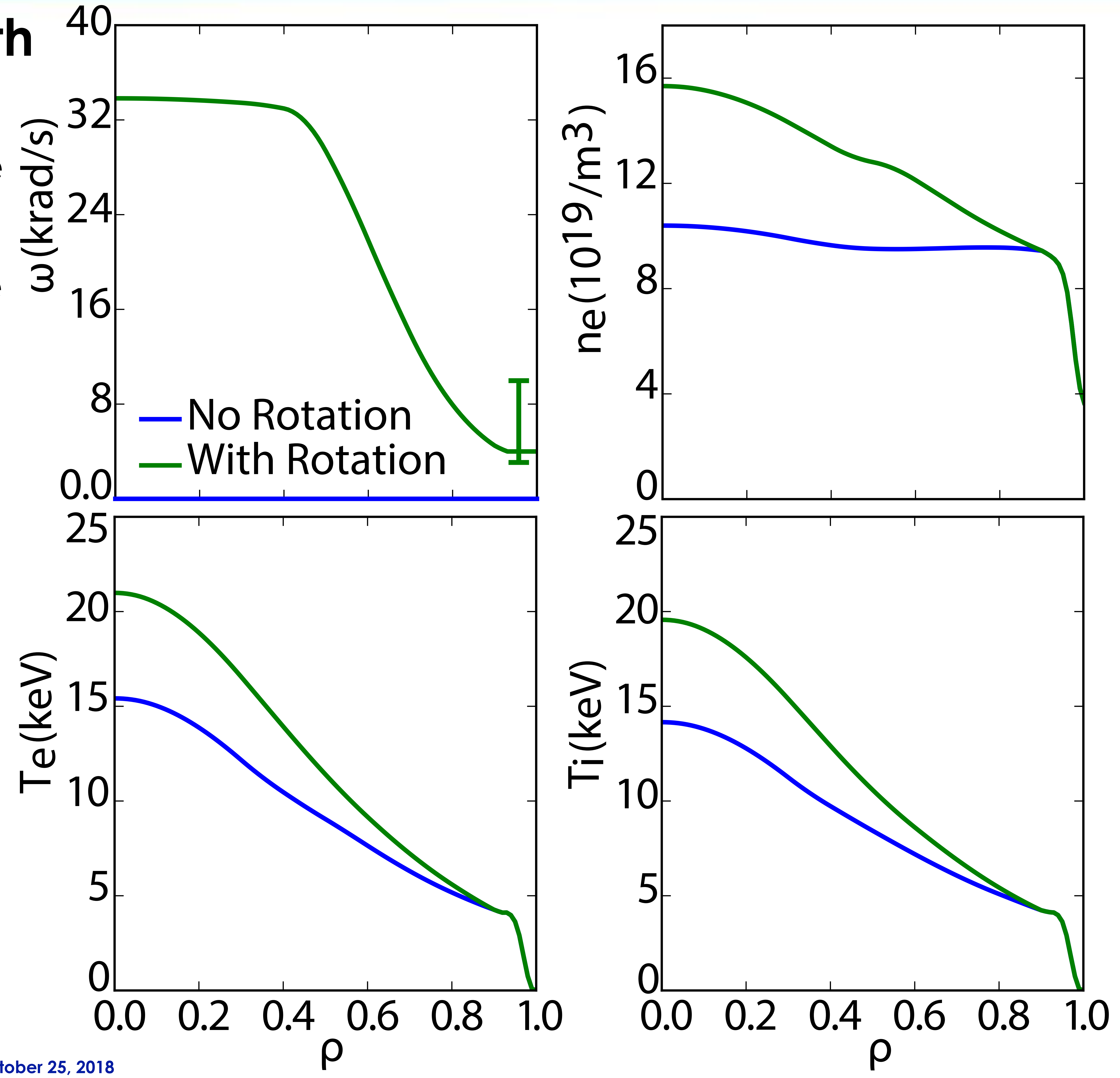
[1] Paz-Soldan, Nucl. Fusion (in review)
[2] Moyer, Phys. Plasmas **24**, 102501 (2017)

Conclusions

- **Edge rotation prediction for ITER is made with increased confidence: 3-10 krad/s**
  – Fast-ion effect on results is relatively small while reducing discrepancies between predictions
  – Neutral particle induced transport found to be small

- **ITER, though large and with relatively small NBI torque, will still have significant enough ExB to decrease turbulent transport**
  – Prospect of RMP ELM suppression is good

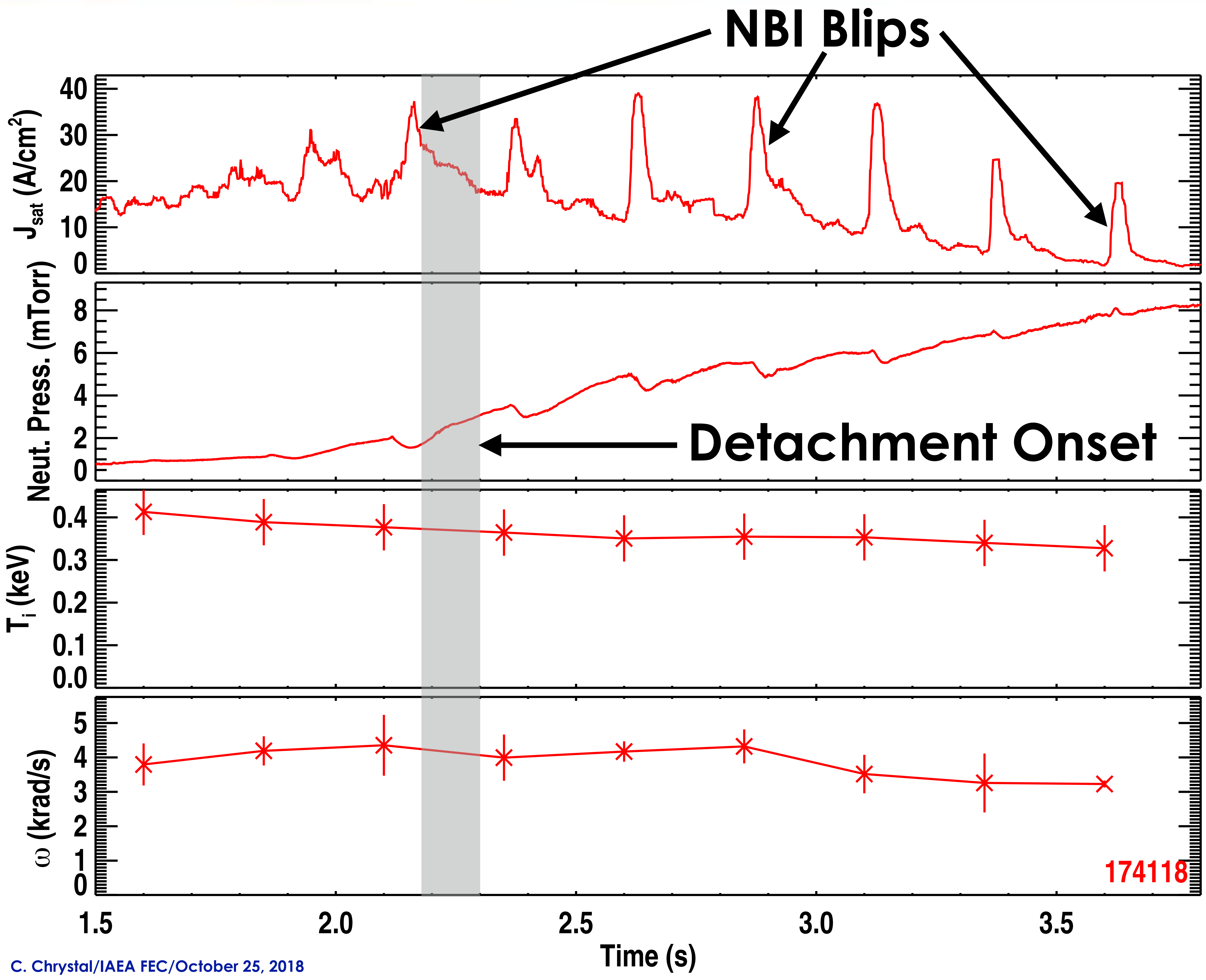
- **These rotation predictions must now be integrated with effects from intrinsic and applied 3D fields**



BACKUP SLIDES

Intrinsic Rotation Does Not Vary with Gross Change in Neutrals Associated with Divertor Detachment

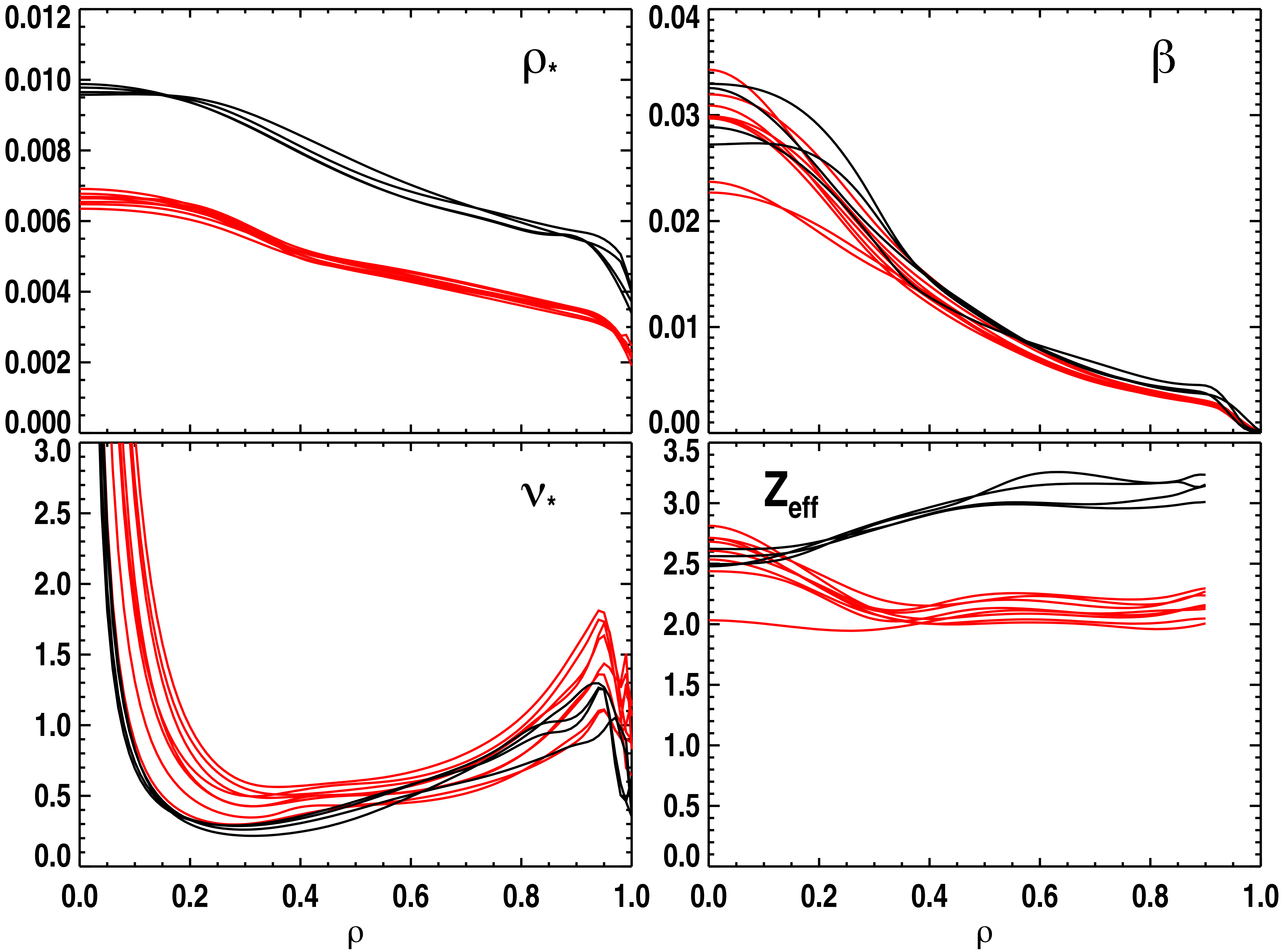
- **Detached divertors have higher neutral particle pressures**
- **These conditions were created with significant main-chamber gas fueling in order to increase plasma density**
- **These changes are expected to increase neutral densities inside the confined plasma, but this causes no significant change to the intrinsic rotation**
  - So long as T_i does not begin to drop
- **This result supports conclusions drawn from open/closed divertor comparisons**



Dimensionless Parameter Scan Executed in ECH H-modes in DIII-D Achieved Desired Variation in ρ_*

- **ρ_* was decreased by ~30%, the expected range achievable in DIII-D with limitations on field variation due to ECH absorption**

- **Change in Z_{eff} is likely due to a change in carbon source due to a hard to control change in boundary conditions**
  - This is a potential confounding factor for the results, though previous work has not seen causal changes in intrinsic rotation with Z_{eff}



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Simple Scaling Relation Offers Favorable Prospect of Achieving RMP ELM Suppression in ITER

- **RMP ELM Suppression at low rotation is thought to be difficult due to the movement of the E_r=0 crossing to lower minor radius**
- **Using the divergence-free form of velocity:**

$$\mathbf{V} = k(\psi)\mathbf{B} + \omega(\psi)R\hat{\varphi}$$

a relation for E_r=0 can be made into scaling requirement for Mach number

$$-\frac{\nabla P}{nZe} = \omega R B_\theta \Rightarrow -\frac{\nabla P}{nZe} = \omega R B_\theta \left(\frac{R\sqrt{T/m}/B/a}{R\sqrt{T/m}/B/a}\right)$$

$$M\epsilon = -\rho_* q(\lambda_T^{-1} + \lambda_n^{-1})$$

  - ω is the toroidal rotation frequency if poloidal rotation is zero, B approximated as toroidal field to make factor of q
  - We will assume the normalized gradient scale lengths will NOT change in ITER
- **5-9 krad/s of pedestal top rotation is current lower limit for RMP ELM suppression in DIII-D, yields a lower limit of 0.2-0.5 krad/s for ITER, <3 krad/s prediction**
  - Effect of RMP ELM suppression on rotation prediction still needed to fully answer this question