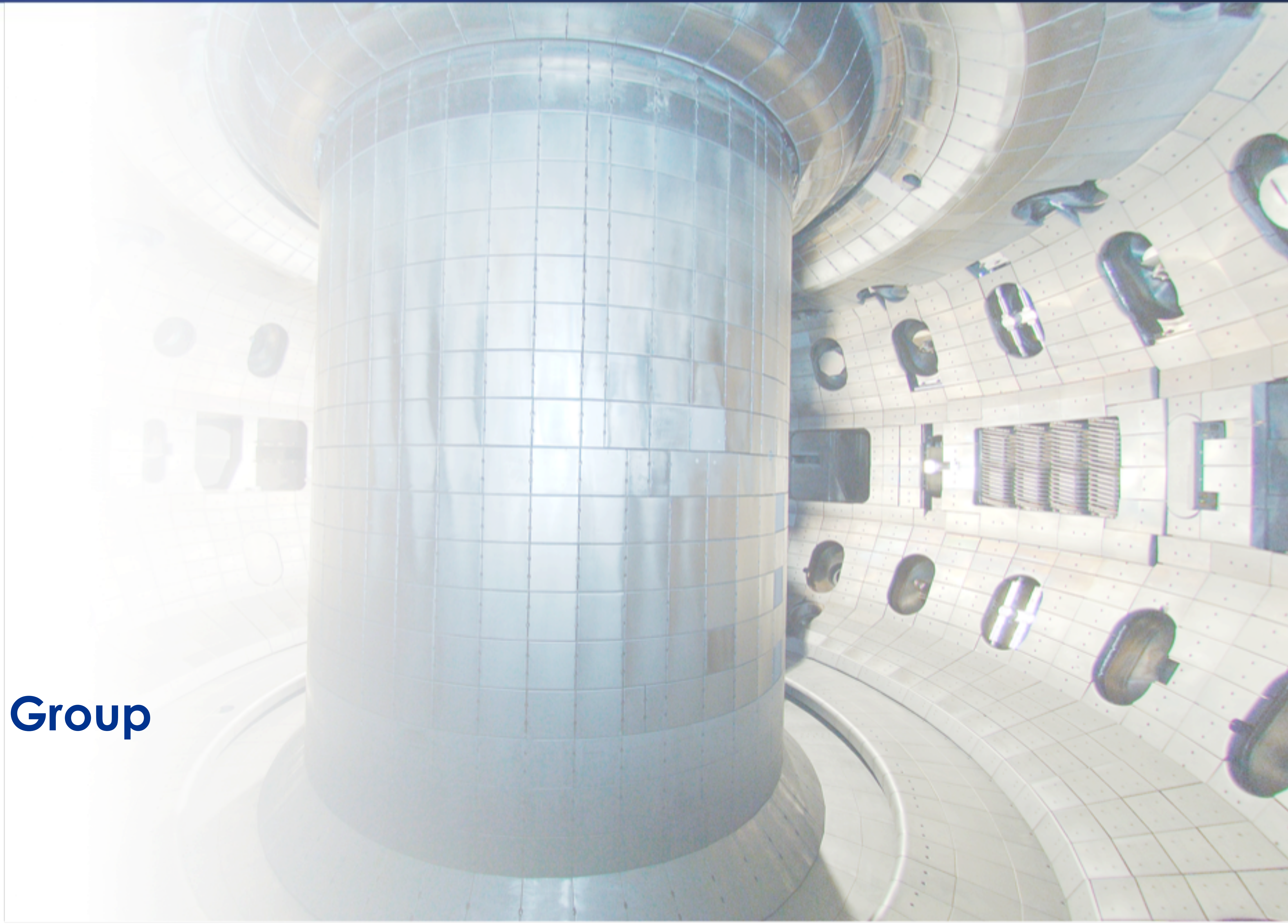
The Influence of Rotation on Burning Plasma Performance in Tokamaks

by

C. Chrystal[1]

[1]General Atomics



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Thank You to All my Coauthors

- K. H. Burrell[1], J. S. deGrassie[1], S. R. Haskey[2], J. Ferreira[3], C. Giroud[4], B. A. Grierson[2], S-P. Pehkonen[5], C. C. Petty[1], A. Salmi[5], W. M. Solomon[1], G. M. Staebler[1], T. Tala[5]

[1]General Atomics
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[3]Instituto de Plasmas e Fusão Nuclear
[4]Culham Centre for Fusion Energy
[5]VTT Technical Research Centre of Finland

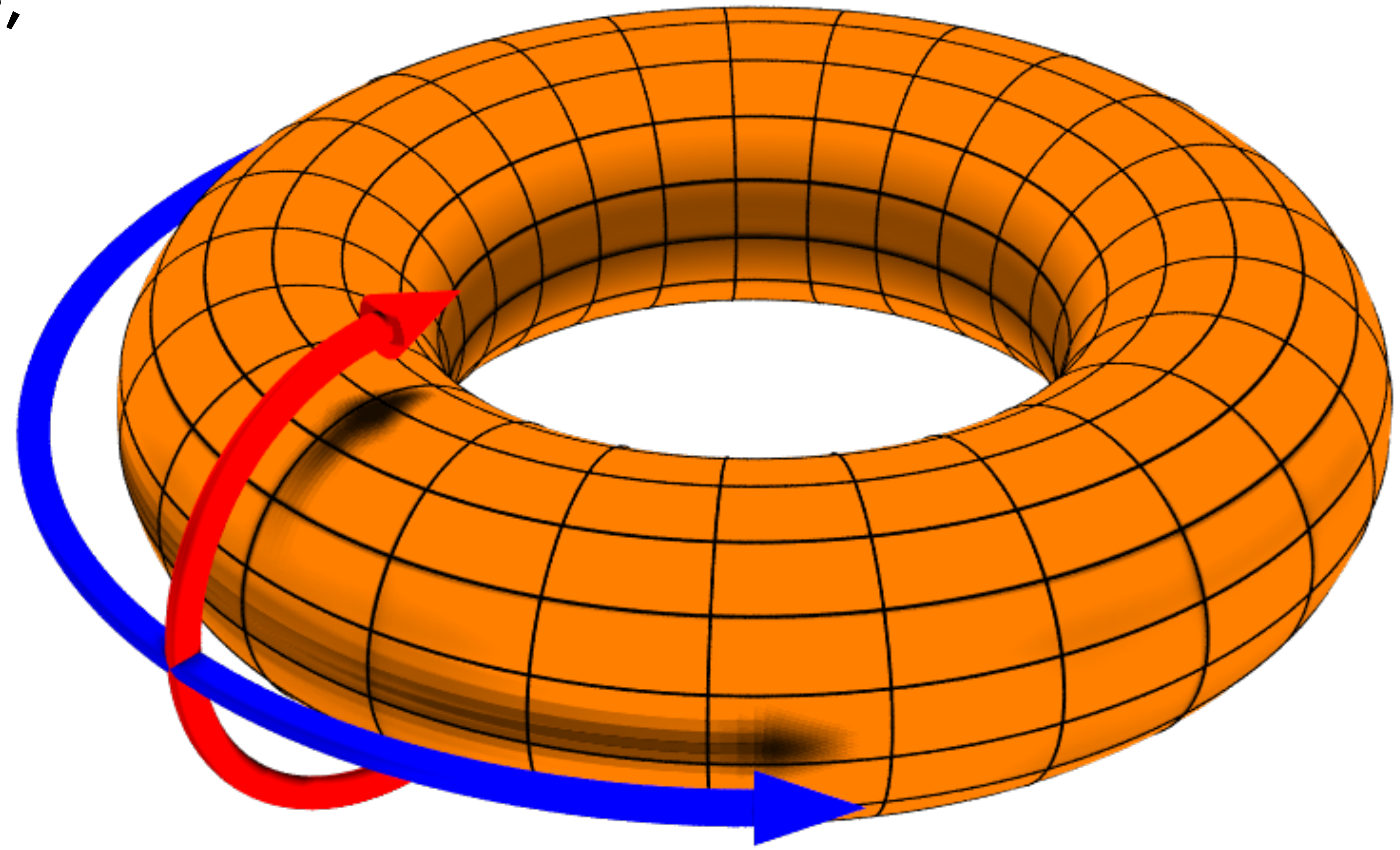
- Also, thank you to a large number of scientists whose excellent work I have referenced as part of the review

- Lastly, thank you to the organizing committee for inviting me to give this talk

Rotation (Flow) Is Essential to Understanding Toroidal Fusion Plasma Performance

- Rotation contributes to radial force balance, is important for the determination of the radial electric field

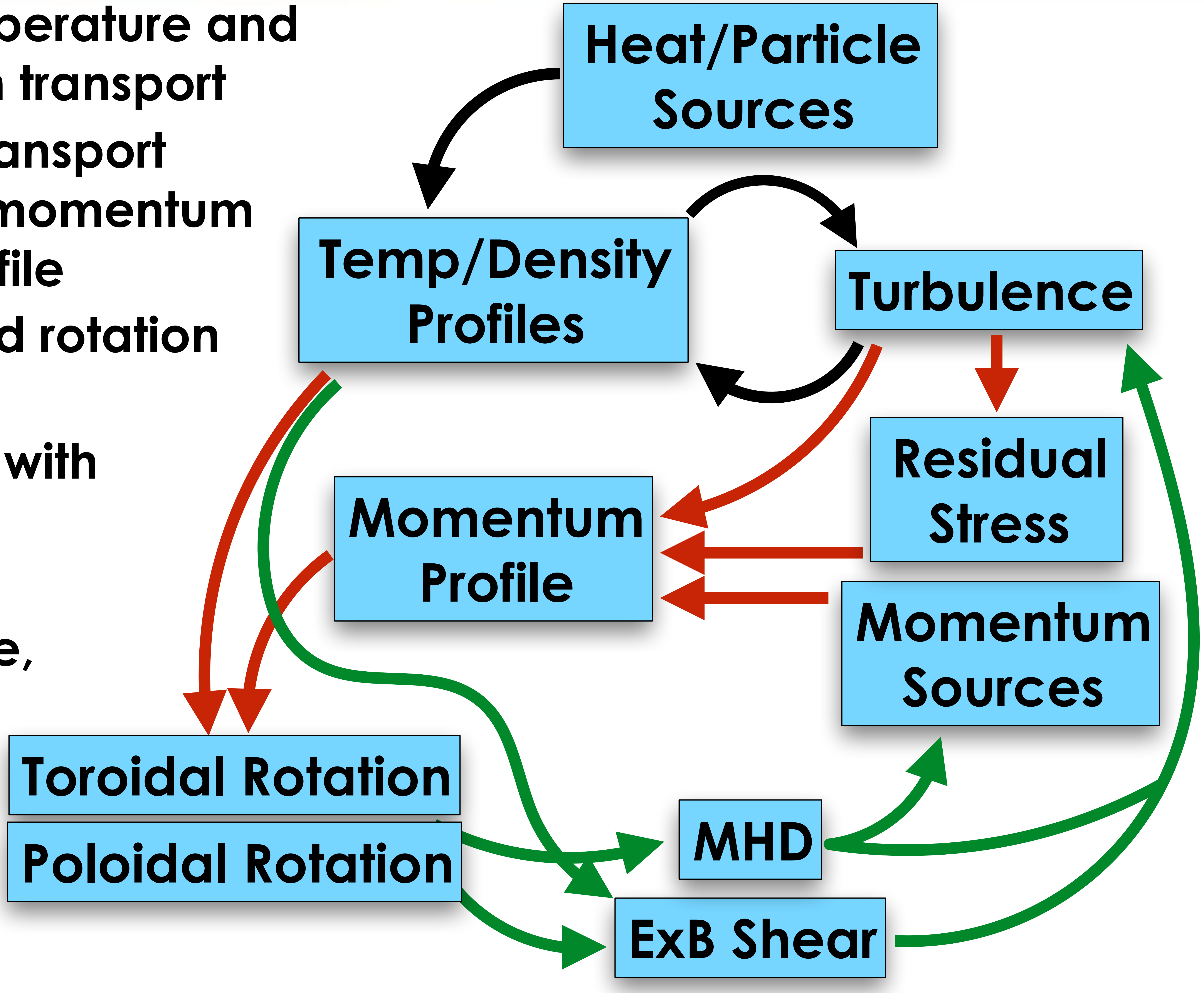
$$E_r = \frac{\nabla P}{nZe} + V_\varphi B_\theta - V_\theta B_\varphi$$



- ExB shear affects turbulence and
- transport
- Rotation can be driven but is also spontaneous, and plays a part in the plasma's self-organization into different states (e.g. H-mode)
- Plasma flow and magnetic geometry combine to form MHD phenomenon and the plasma's reaction to 3D fields

Understanding Rotation and Momentum Transport Is a Complex, Nonlinear Problem

- Initial turbulence generation by temperature and density profiles is key for momentum transport
- Turbulence generates momentum transport and residual stress, combining with momentum sources to generate momentum profile
- Particle and momentum profiles yield rotation profile
- Rotation affects MHD and combines with pressure to yield ExB shear
  - Both poloidal and toroidal matter!
- MHD and ExB shear affect turbulence, feeding back on rotation through multiple complex pathways
- Note: Sign of rotation matters! Neutrals ignored!



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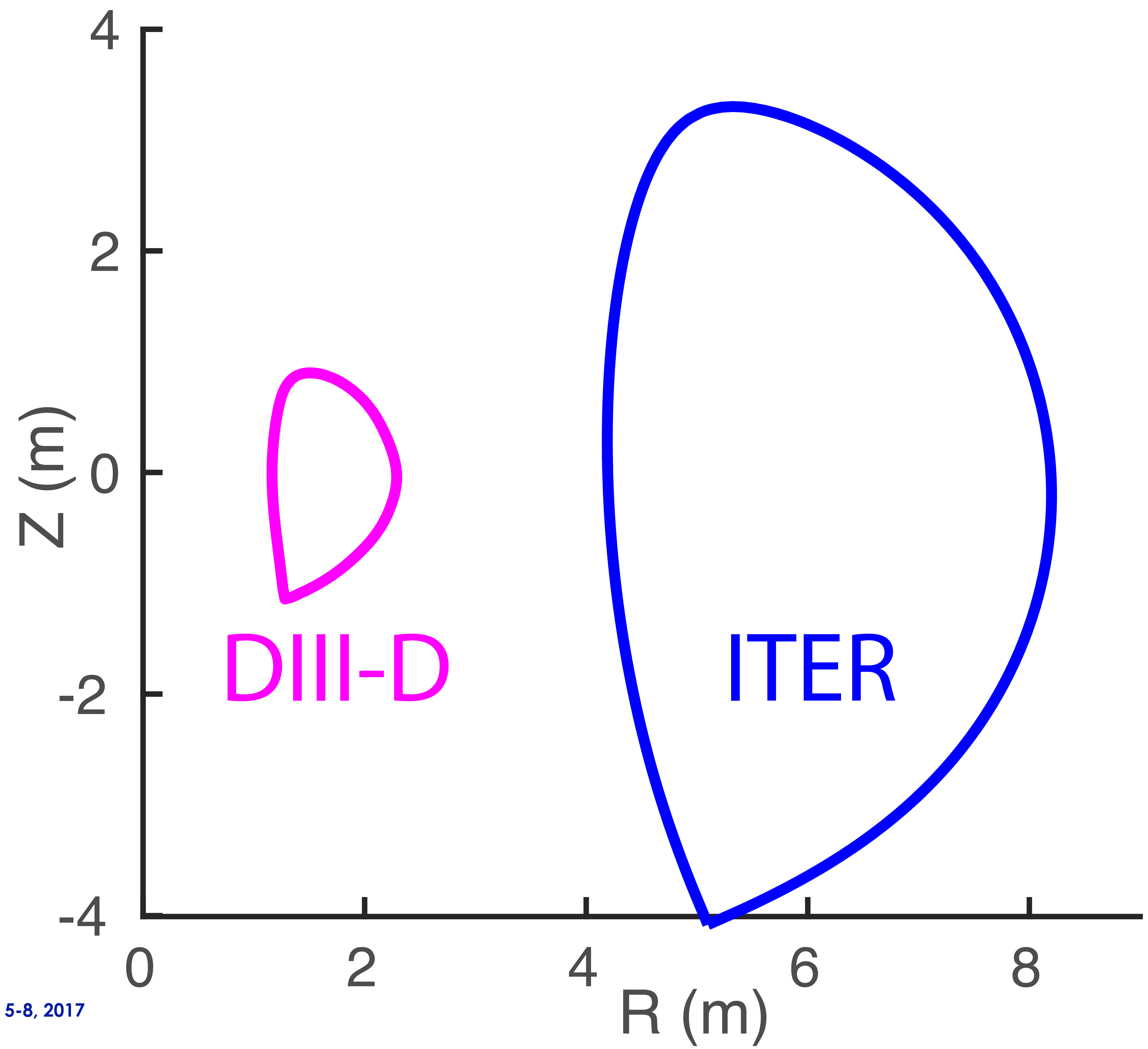
To Simplify, Current Focus Will Be on Burning Plasma Tokamaks

- **If no limits are applied, the subject of rotation is too broad to cover well**
- **Ultimate goal of any long-lived fusion production is a burning plasma**
- **Based on dominant research direction, burning plasma = large tokamak = ITER**
  - ITER serves in this talk as a model for a burning plasma, but a burning plasma does not have to be ITER (or a tokamak)
- **Large tokamaks have large volume, large moment of inertia, small relative neutral beam torque**
  - We cannot apply an overwhelming source of momentum as is possible with many current tokamaks



Outline

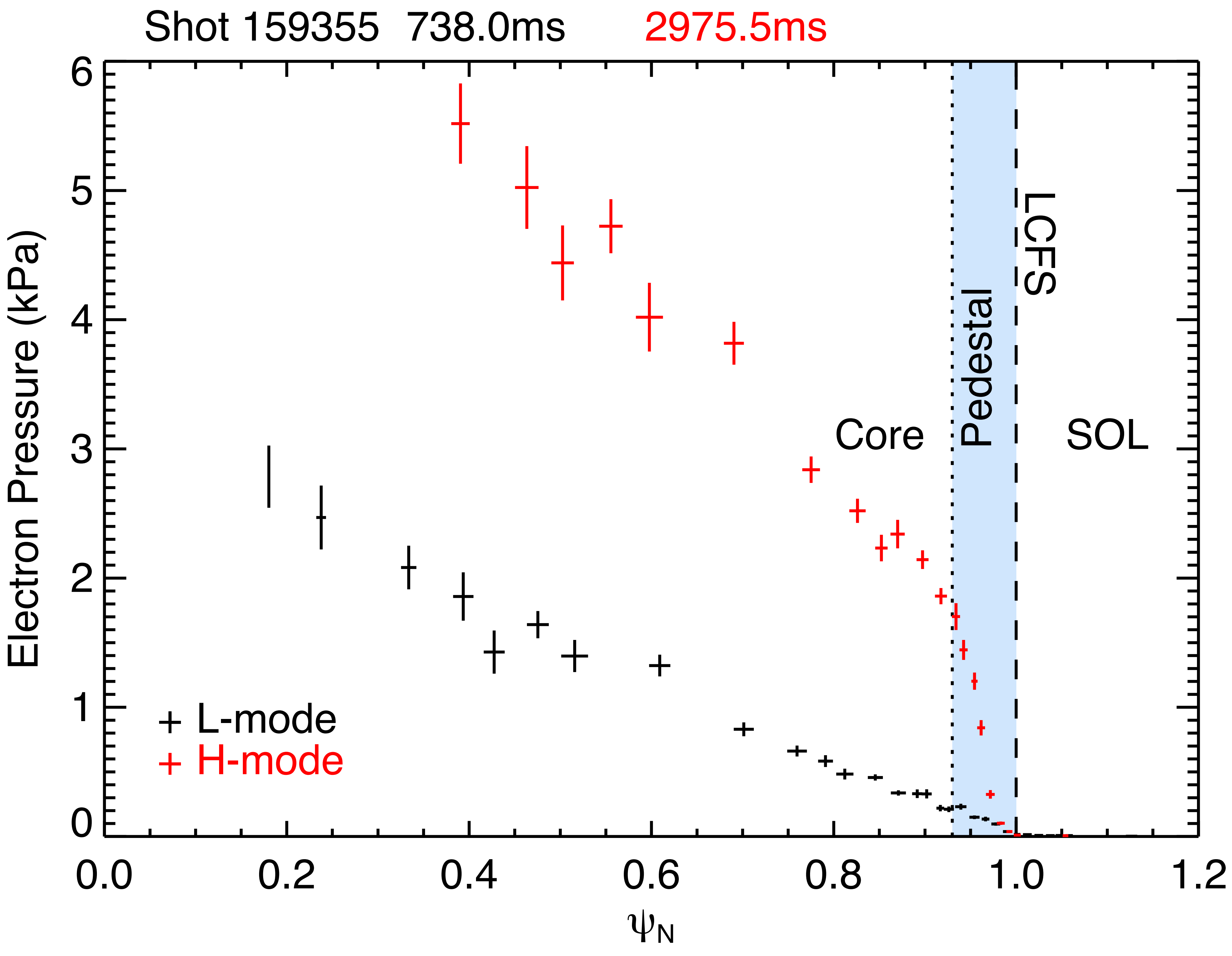
- Introduction to plasma rotation for tokamaks devices

- Critical rotation understanding needed for burning plasmas

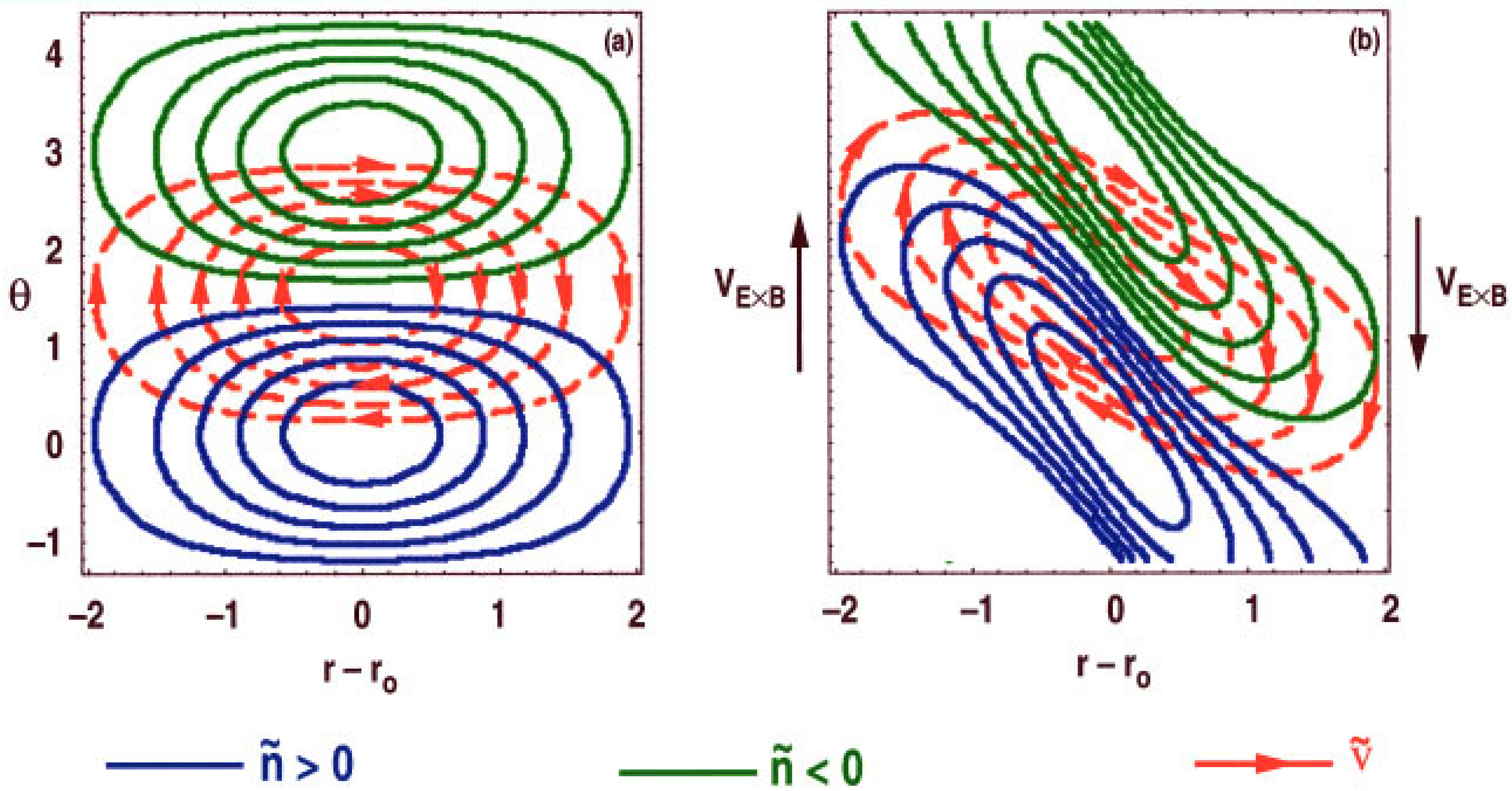
- Recent work at DIII-D on predicting ITER rotation

ExB Shear Directly Affects Turbulent Transport and Access to Certain Operating Regimes

- **ExB shear reduces radial transport through a nonlinear process that results in decorrelation of turbulence**



Courtesy D. Eldon

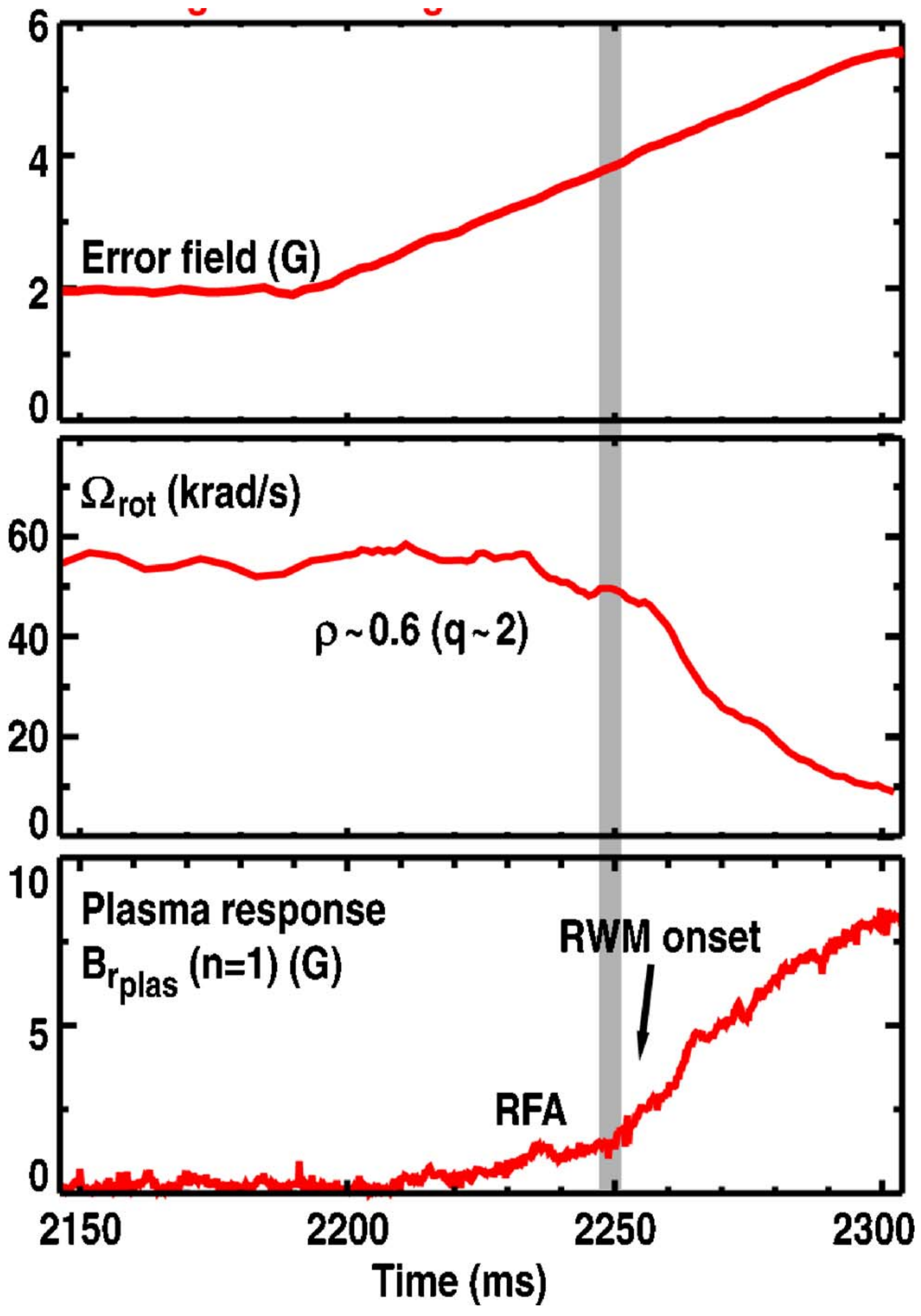


Burrell, Phys. Plasmas **4**, 1499 (1997)

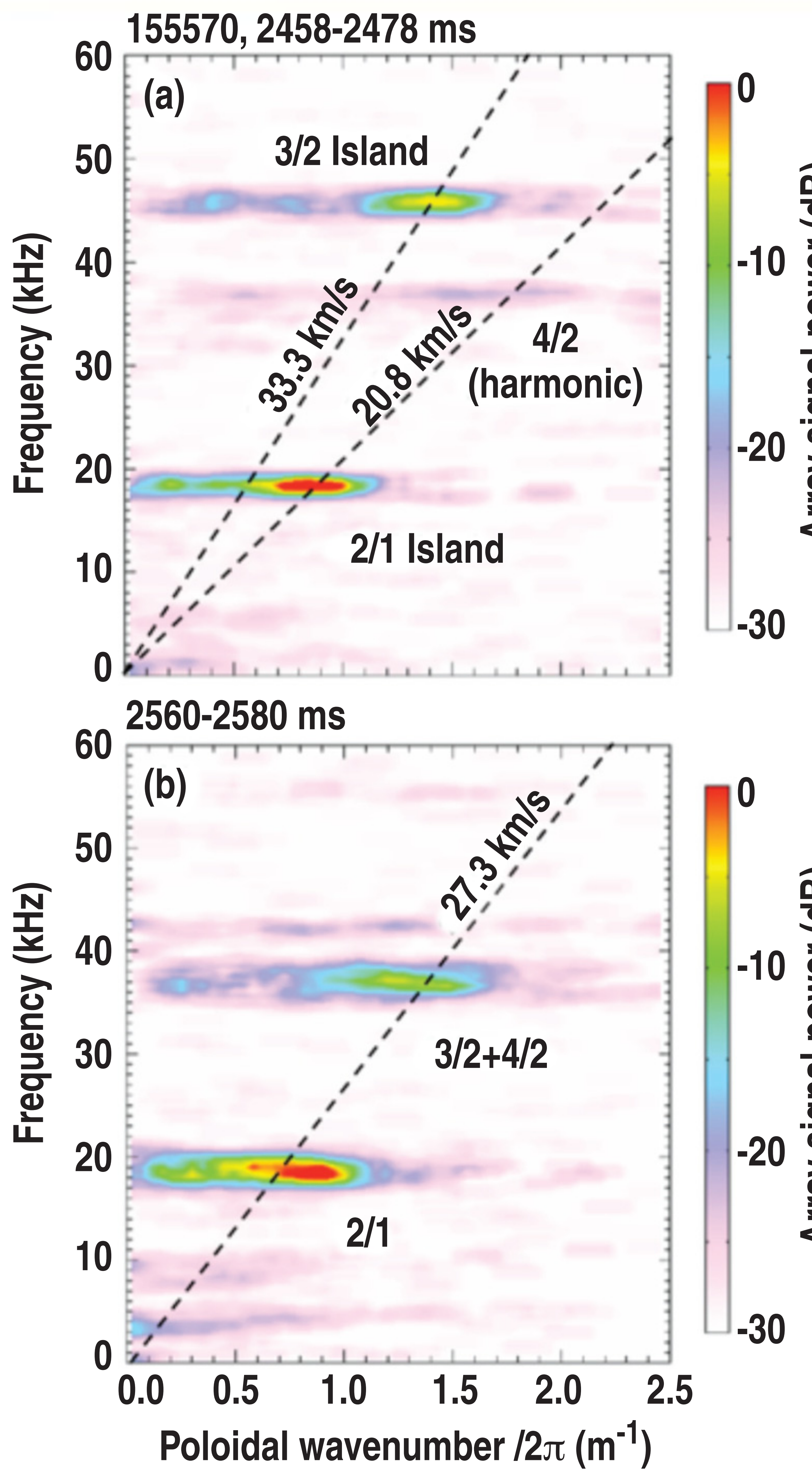
- **H-mode is caused by a feedback: more pressure gradient => more ExB shear => less radial transport**
- **Step pressure gradient creates E_r "well" that is key to global confinement and stability**

Rotation Influences Interaction of Plasma State with Static 3D Structures

- **MHD modes interact with 3D field structures and provide a torque that is rotation dependent**
  - Rotation determines interaction between static structures and rotating mode in the plasma
- **Mode locking allows MHD amplitude to grow and can result in disruptions**
  - Disruptions a potential show-stopper (No, I haven't forgotten stellarators)
- **Stability for some MHD is dependent on rotation, e.g. RWM**
- **Rotation shear can be important for the interaction of multiple MHD structures**



Strait Phys. Plasmas **14**, 056101 (2007)



Tobias,Phys. Plasmas **23**, 056107 (2016)

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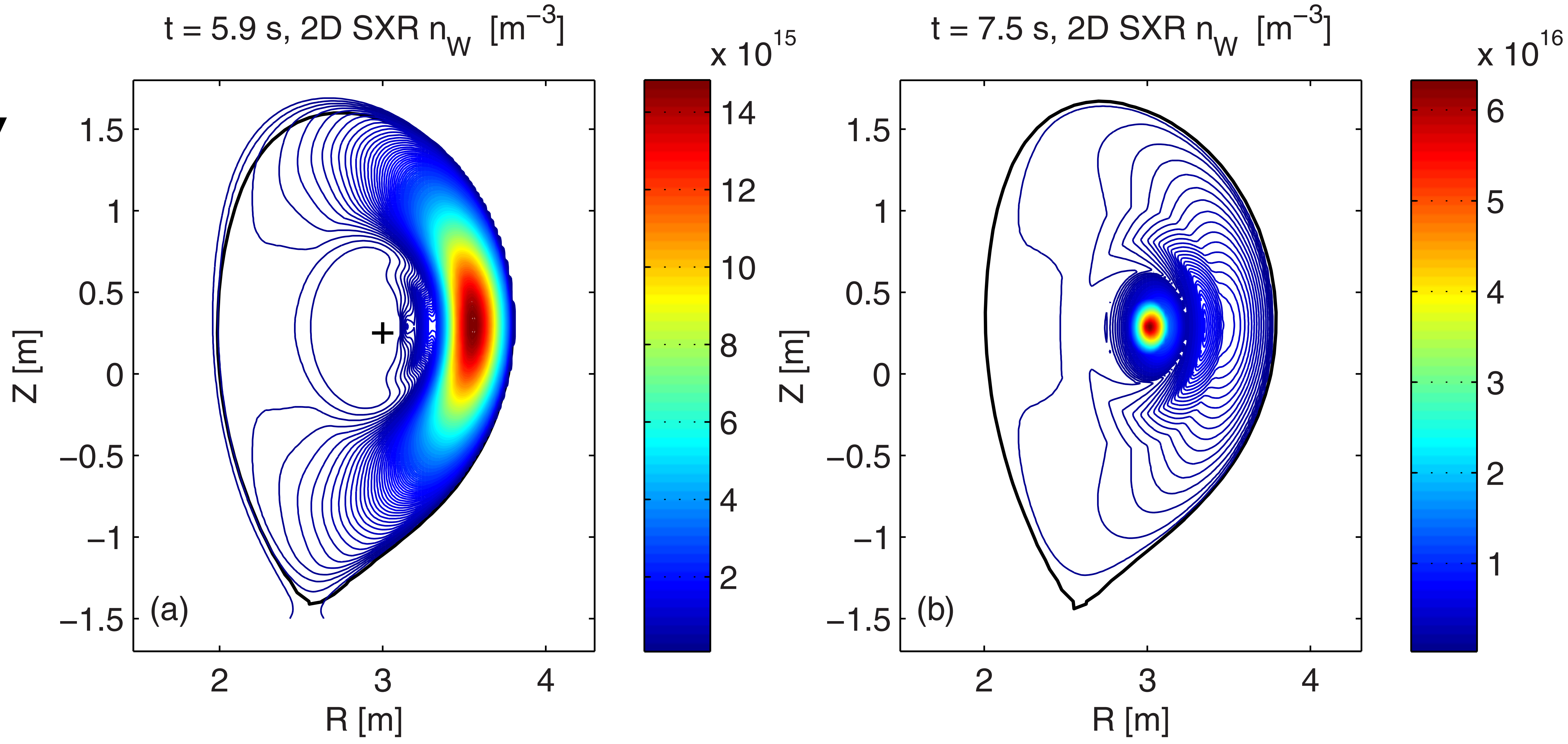
Toroidal Rotation Influences High-Z Impurity Transport via Centrifugal Force

- **Centrifugal force important when rotation is comparable to thermal speed**
  - $V_{th} \sim 1/m^{1/2}$, easier to satisfy with high-Z impurities
- **High-Z transport important because of potential for debilitating radiated power from the core**
- **Higher rotation yields asymmetry that enhances neoclassical pinch of impurities at lower collisionality[1]**
- **Low toroidal rotation can create more favorable high-Z impurity distribution[1]**



[1] Angioni, Nucl. Fusion **54** 083028 (2014)

Momentum Transport Is the Formalism Through Which the Complexity of Rotation Is Interpreted

- **Rotation does not have a conservation law, momentum does, rotation is a consequence of momentum balance**
- **For toroidal rotation:**

$$\frac{\partial}{\partial t} mnR^2\omega = -\nabla \cdot \mathbf{\Pi} + \tau$$

  – Looks simple enough, but momentum flux is complex, sources are not well known

Difficult to evaluate without probes

$$\frac{\partial}{\partial t} mnR^2\omega = -\nabla \cdot [-nmR^2(\chi \nabla \omega - V_\varphi \omega \hat{r})] + \tau_{\mathrm{NBI}} + (-\nabla \cdot \mathbf{\Pi}_{\mathrm{RS}} + \tau_{\mathrm{int}})$$

Transport coefficients hide complex dependencies

$$\chi = \chi(\omega, \nabla\omega, n, \nabla n, T, \nabla T, \ldots)$$
$$V_\varphi = V_\varphi(\omega, n, \nabla n, T, \nabla T, \ldots)$$

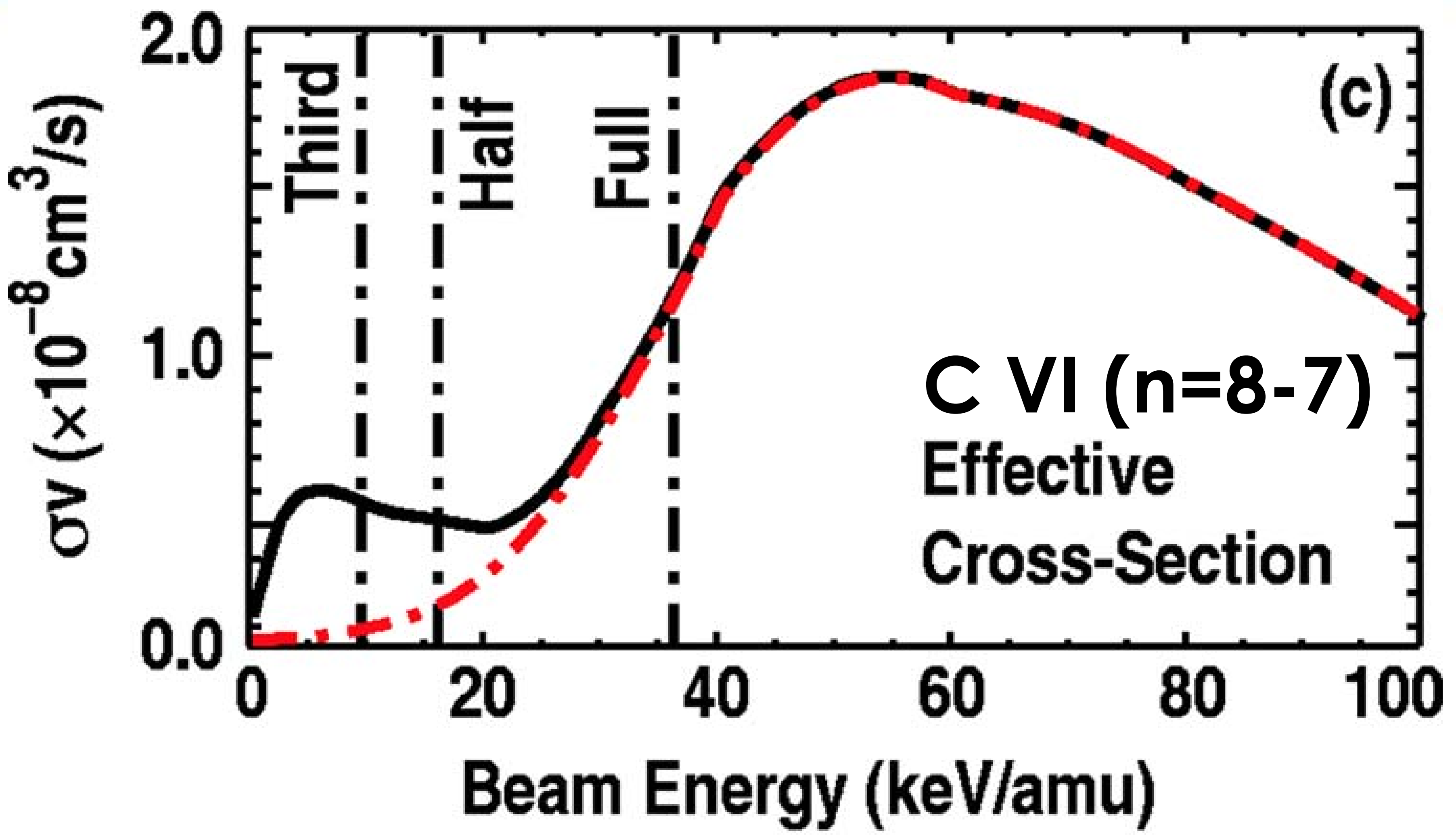
We must put our trust in NUBEAM

Many potential physics effects contained here

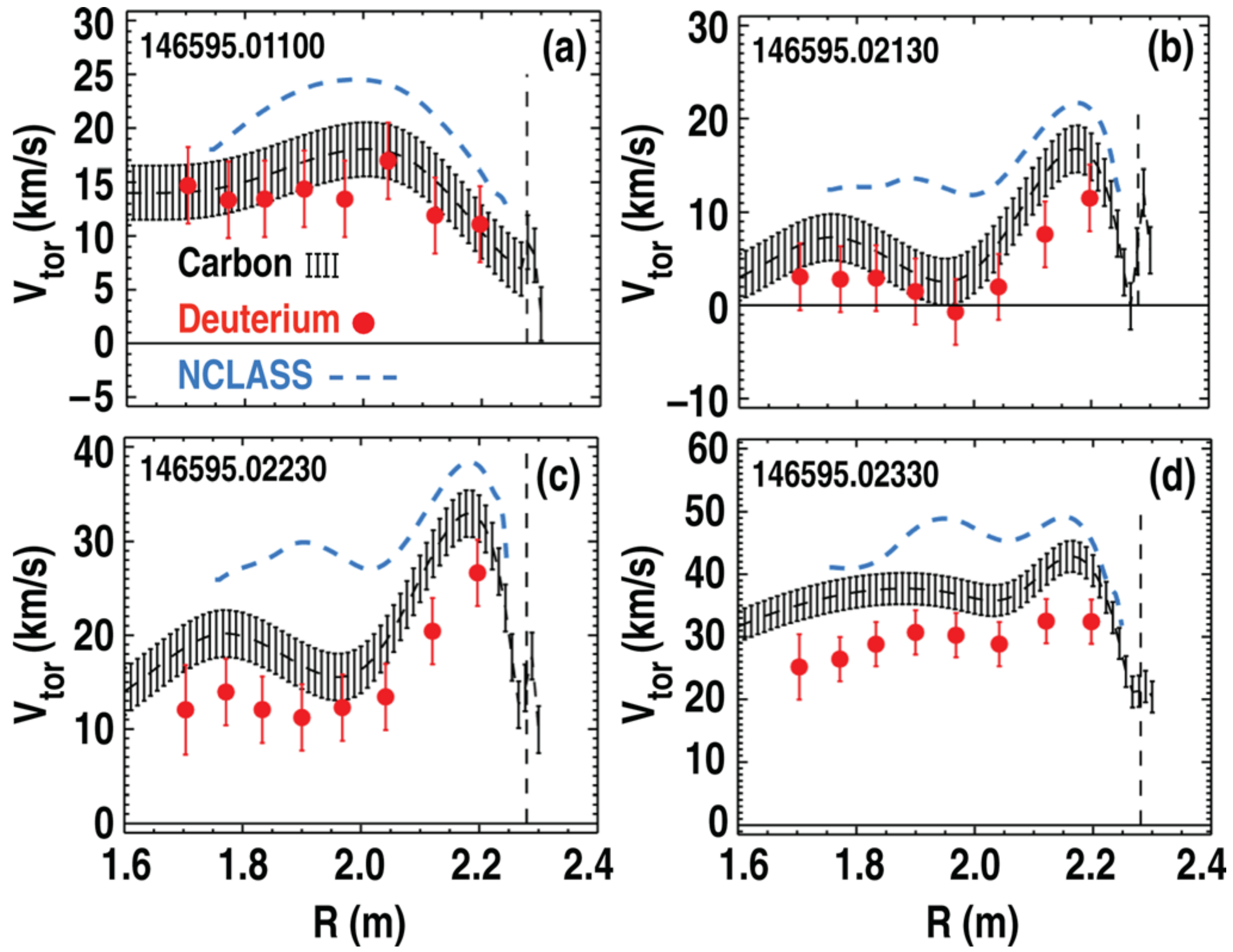
- **Poloidal rotation has similar complexities plus poloidal damping**

The Measurement of Toroidal Rotation Is Not Trivial

- **Mach probes cannot survive high pressure regions**
- **Measurement of impurity toroidal rotation is routine**
  - Typically user charge exchange (CER on DIII-D)
  - Charge exchange requires correction due to energy dependent cross section for charge exchange process



Solomon, Phys. Plasmas **13**, 056116 (2006)

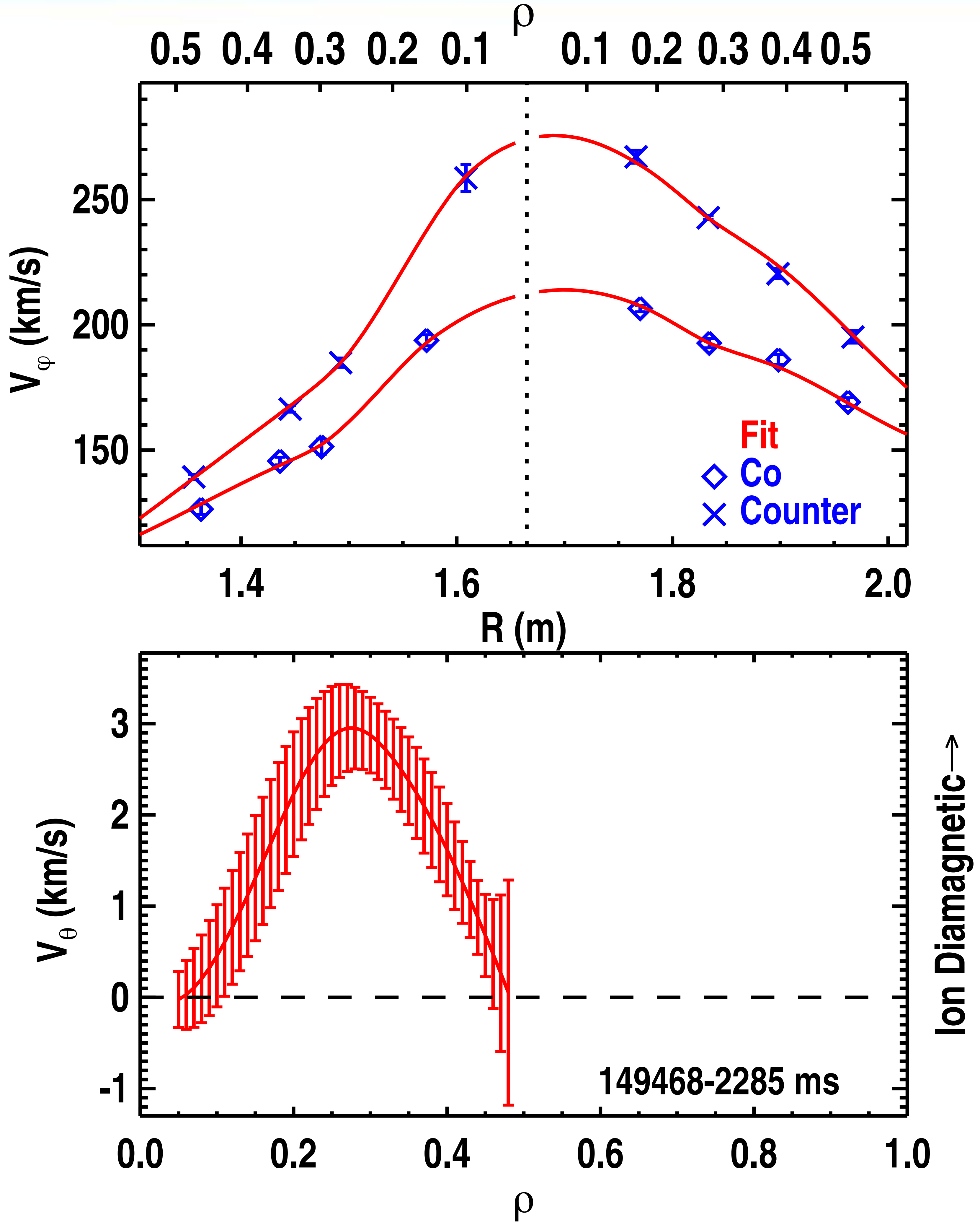


- **Momentum studies requires knowing the rotation of the bulk of the plasma => needs more difficult to measure main-ion rotation**
  - Assuming standard beam/plasma composition
  - Main-ion poloidal rotation rare, essentially impossible for standard beam/plasma composition

Grierson, Phys. Plasmas **19**, 056107 (2012)

Measurement of Poloidal Rotation Is Difficult and Requires Subtle Distinctions

- **Poloidal rotation for impurities is <u>very</u> different from main-ion poloidal rotation**
  - This is somewhat moot, goal is usually to get E_r, only need complete set of measurements from one species
- **Energy dependent charge exchange cross section is difficult to correct due to finite lifetime effect[1]**
  - Assuming standaard beam orientation
- **New measurement techniques have increased accuracy[2-4]**
- **ExB flow is in the perpendicular direction but is not itself the poloidal flow, can be seen in turbulence advection, not turbulence phase velocity**
  - Velocimetry with beam emission spectroscopy or gas puff imaging non-trivial, doppler shift from doppler backscattering usually assumes small phase velocity



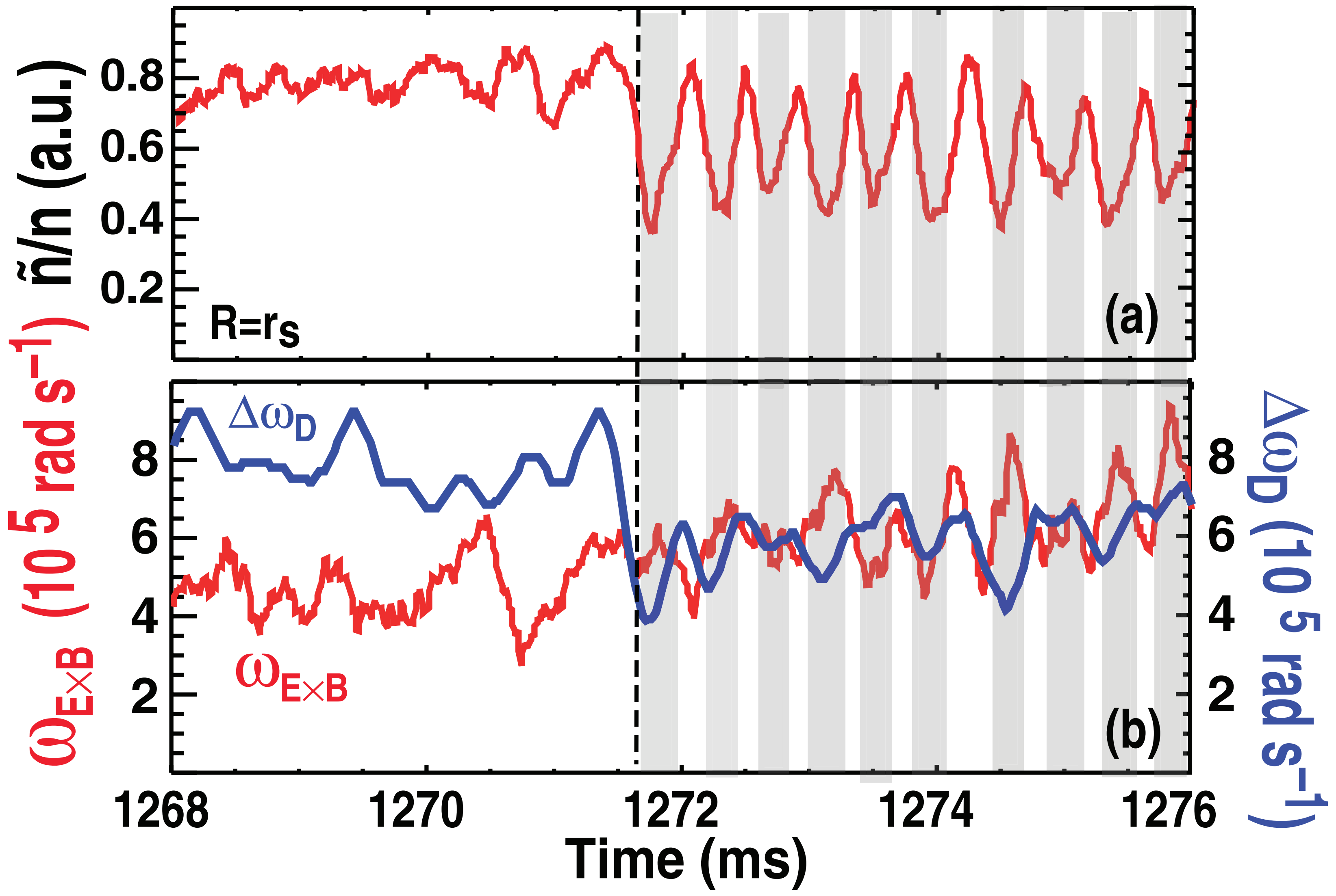
[1] Bell, AIP Conf. Proc. **547**, 39 (2000)
[2] Chrystal, Rev. Sci. Intrum. (2012) and (2014)
[3] Camenen, EPS (2012) and Bortolon, Nucl. Fusion (2013)
[4] McDermott, TTF (2017)

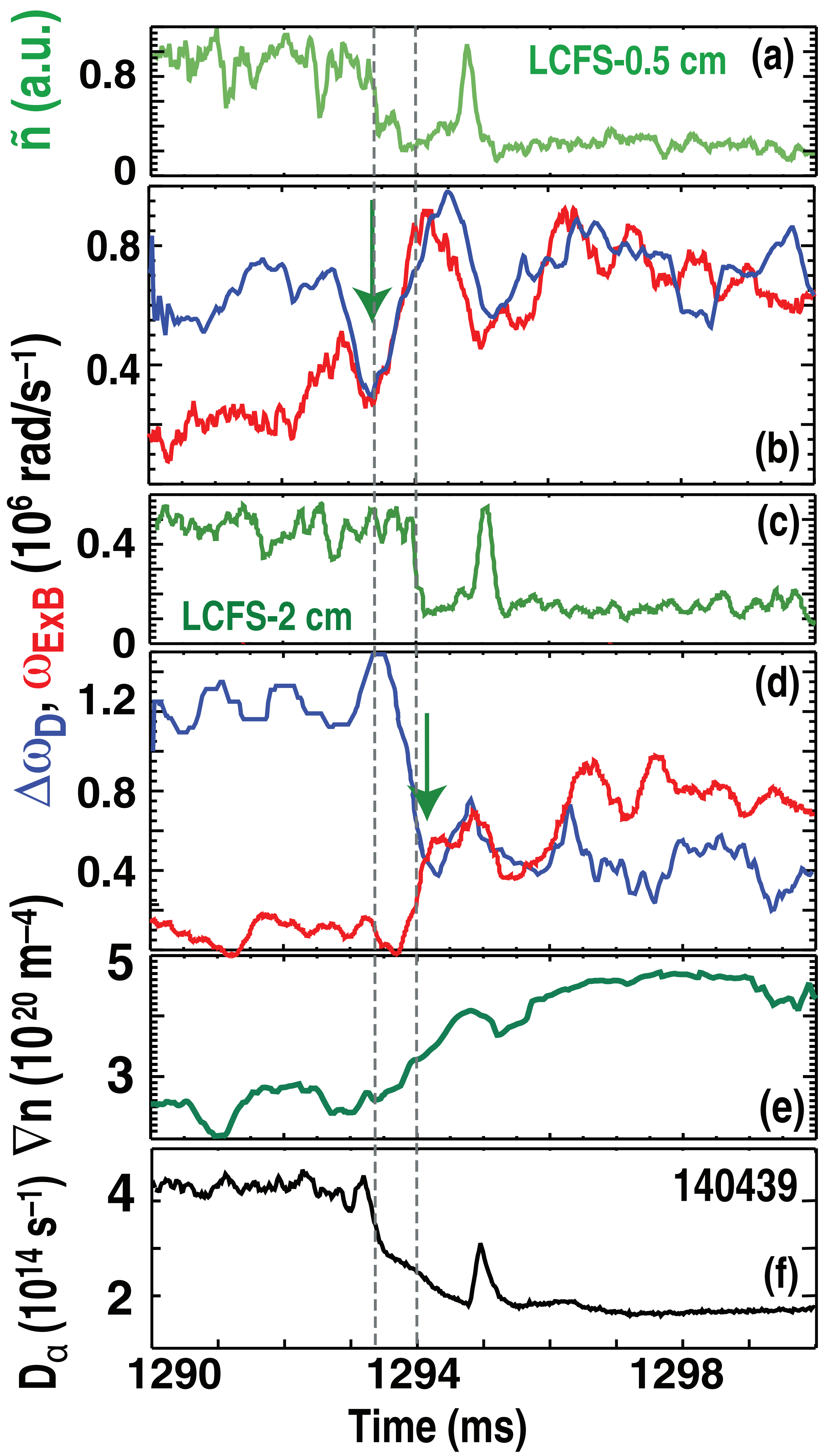
Outline

- Introduction to plasma rotation for tokamaks devices
- Critical rotation understanding needed for burning plasmas
- Recent work at DIII-D on predicting ITER rotation

Interaction Between Rotation and Rotation Drive Key to Understanding H-mode Transition

- **Mechanism of H-mode transition needs to be understood to have predictive capability**
  – H-mode is known to be locked in by steep pressure gradient and E_r well, transition itself still a subject of investigation
- **Turbulence generated zonal flows reducing turbulence until pressure gradient can lock in is a very promising model[1]**
  – Some results at without any phase shift are very intriguing
- **What will the H-mode power threshold be for ITER? In ITER with a helium plasma?**
- **Interaction of flow and turbulence at critical point must be understood for success and survivability of a burning plasma**





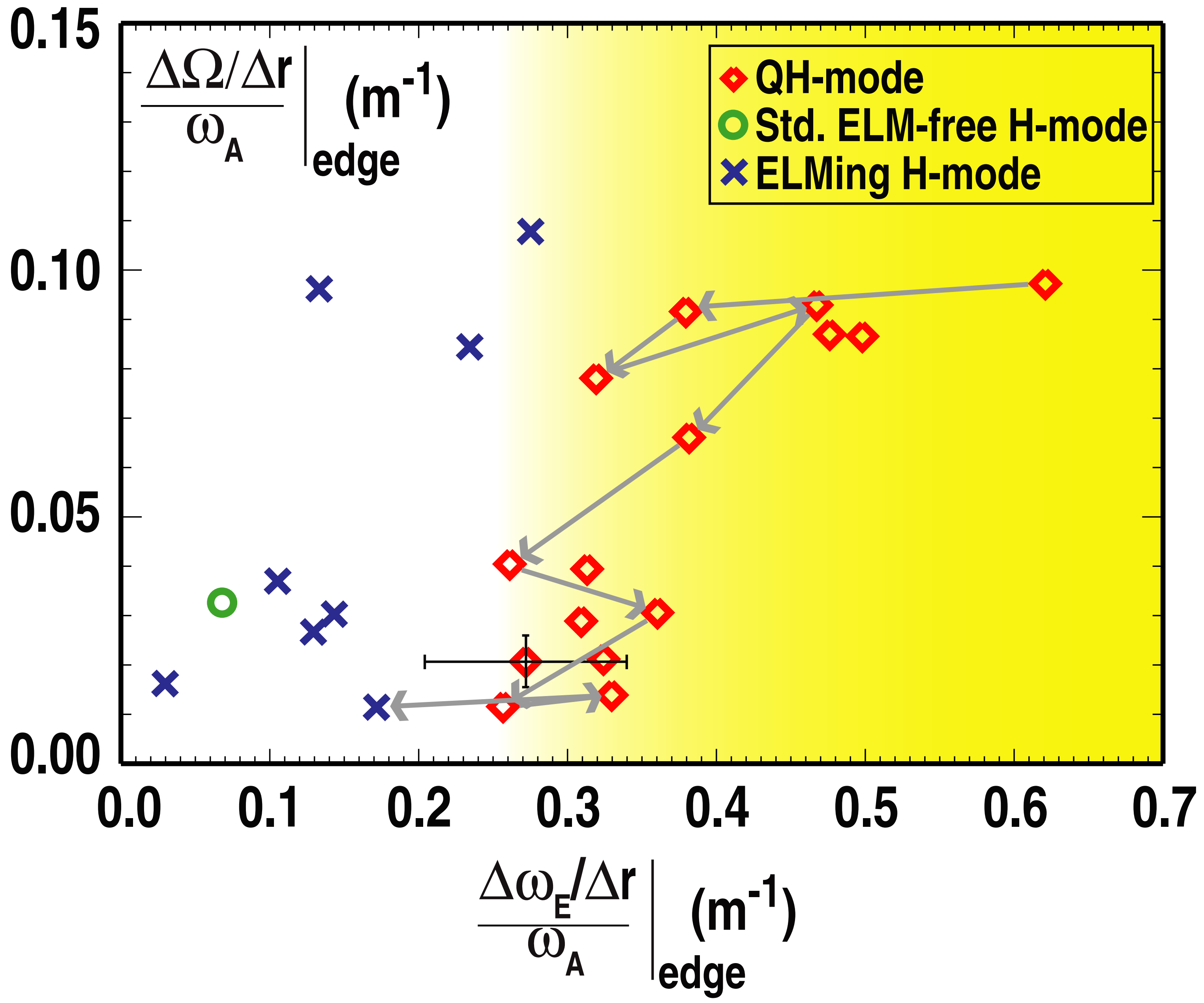
C. Chrystal/APTWG/June 5-8, 2017

[1] Schmitz, Nucl. Fusion **57**, 025003 (2017)

Candidates for ELM-free Operation Require Particular Rotation in Pedestal

- **Avoiding ELMs with H-mode confinement is, essentially, necessary for ITER's success**
  - There are several schemes for accomplishing this
- **RMP ELM suppression is lost when neutral beam torque is reduced, results consistent with $E_r=0$ moving, preventing island creation[2]**
- **QH-mode requires significant ExB shear in the pedestal to be created (can exist with near zero torque)[1,2]**

- **Will rotation in pedestal satisfy unique conditions for these operating modes?**

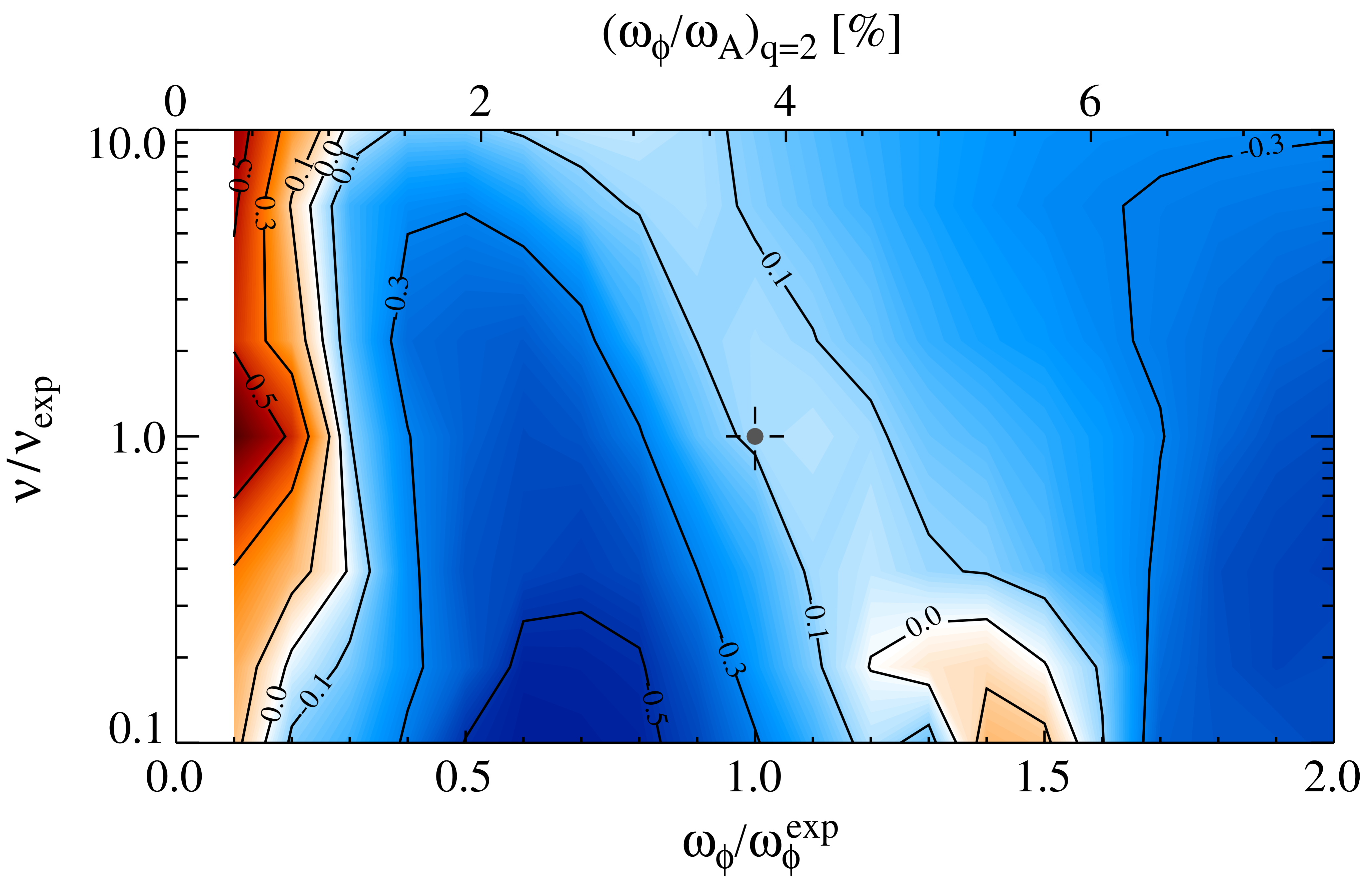


C. Chrystal/APTWG/June 5-8, 2017

[1] Garofalo, Nucl. Fusion **51**, 083018 (2015) [2] Chen, Nucl. Fusion **56**, 076011 (2016) [3] Moyer, APS 2016

Rotation Shield Plasma from Error Fields and Decreases Susceptibility to MHD

- **Rotation profiles can set MHD stability or determine discharge viability in the event of MHD being destabilized by another cause (e.g. NTM)**
- **RWM known to be a potential problem at low rotation, low rotation not a sufficient condition, requires detailed study of delta-W that depends on the rotation itself**
- **Higher rotation increases n=2 overlap field needed to generate tearing mode**[1]

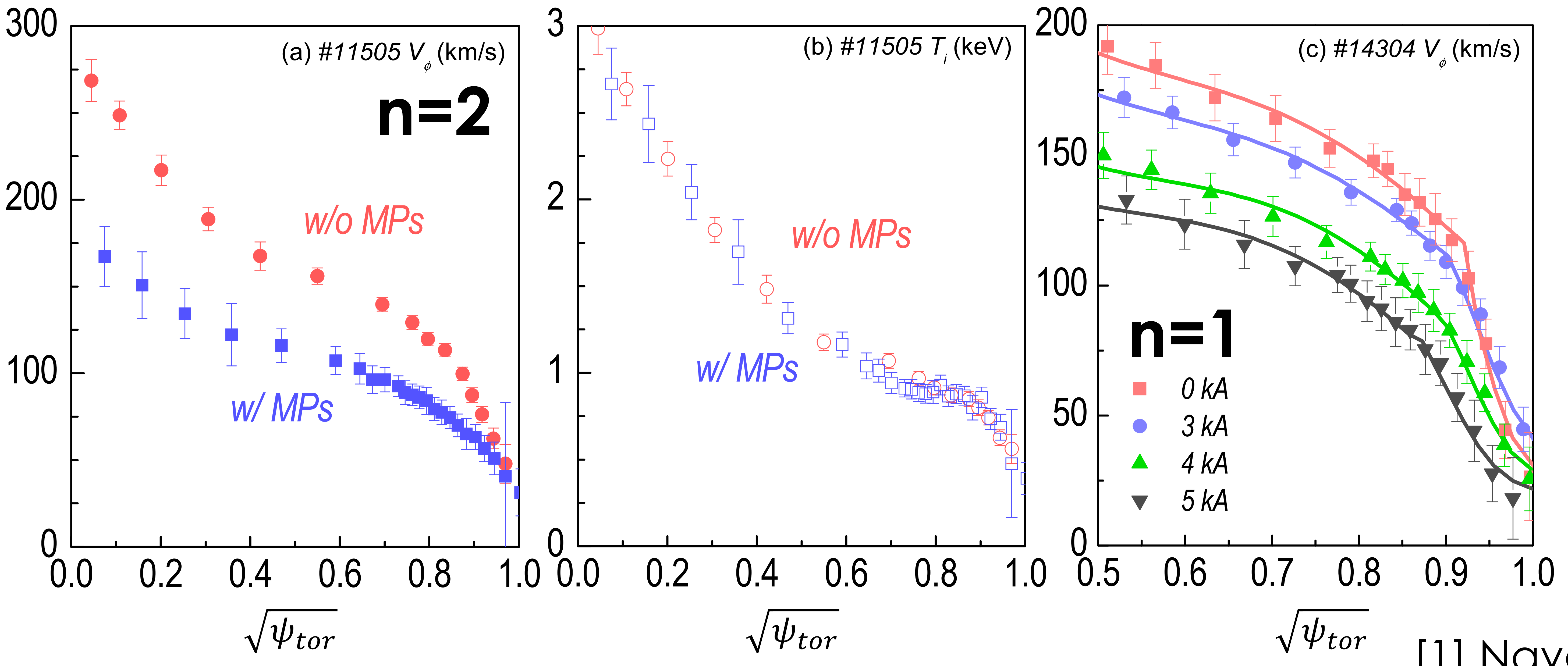


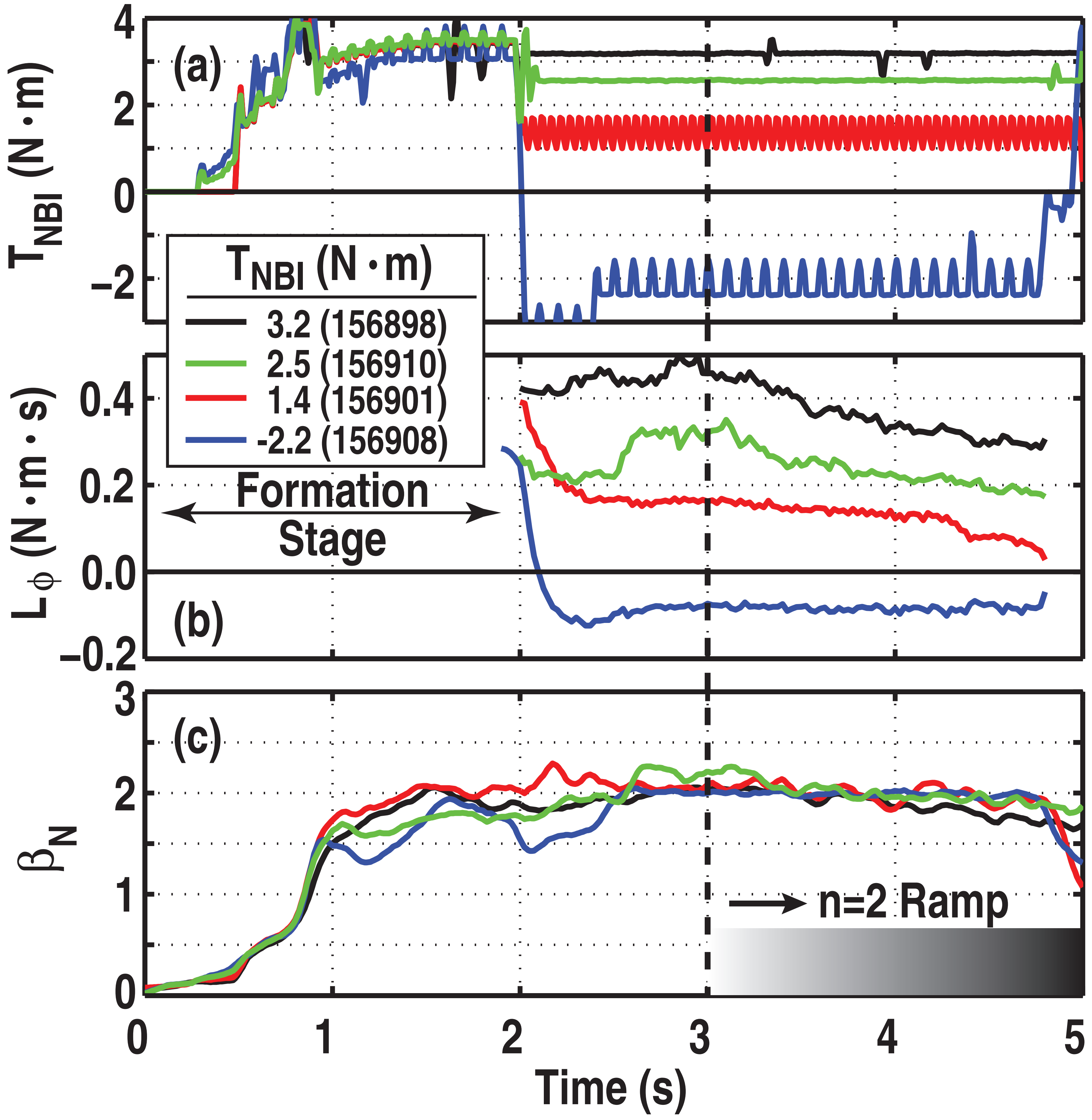
Berkery Phys. Rev. Lett. **104**, 035003 (2010)

[1] Lanctot, Phys. Plasmas **24**, 056117 (2017)

3D Fields Influence Rotation by Creating Non-ambipolar Transport

- Field ripple has been shown to reduce rotation[1], but high n test blanket module work saw a small effect after n=1 compensation[2]
- Non-dominant error fields (n=2) clearly reduce rotation[3,4]
- 3D field effects described by NTV theory, non-ambipolar transport brings plasma to an offset rotation
- Can NTV be used to create desirable rotation profiles?

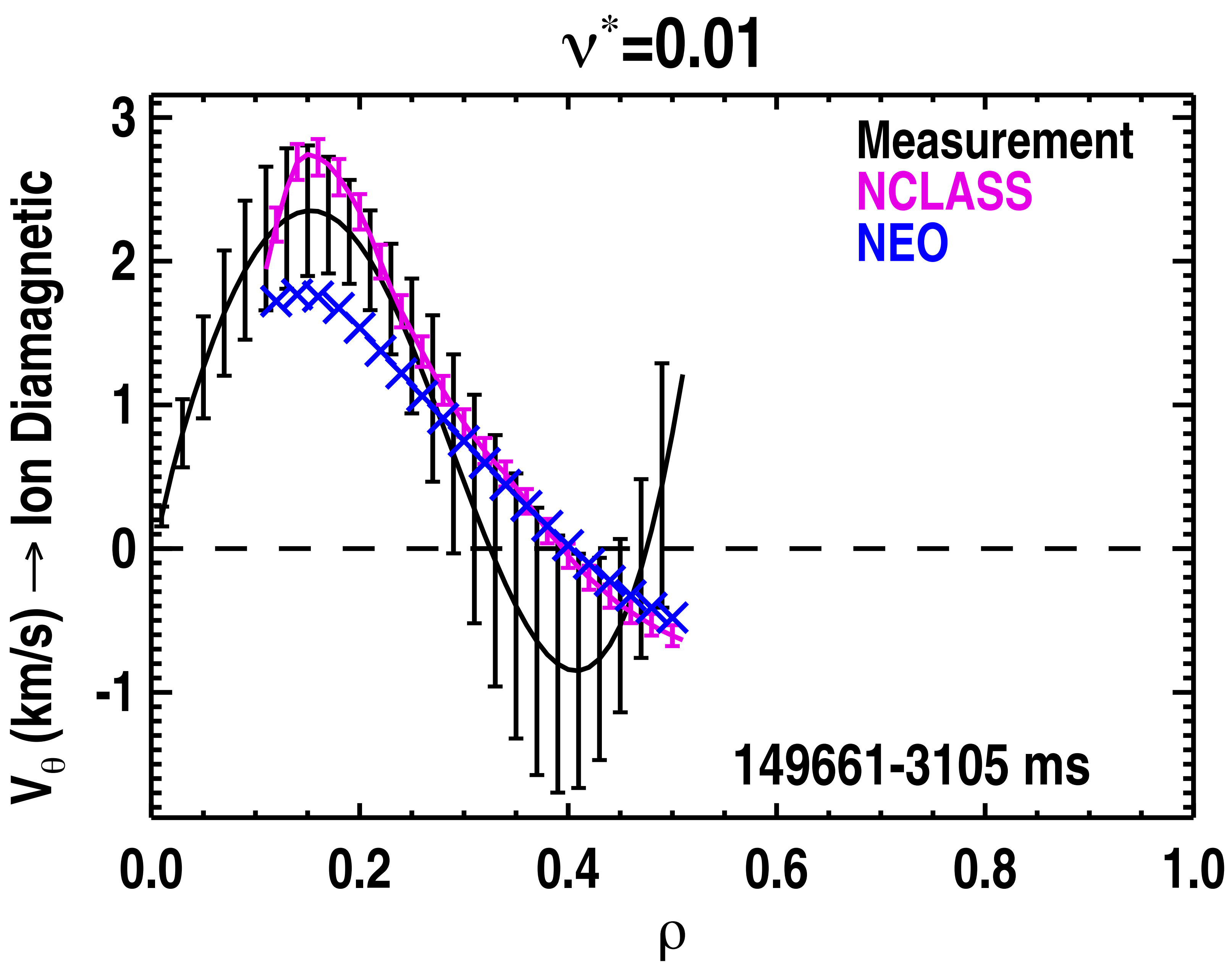


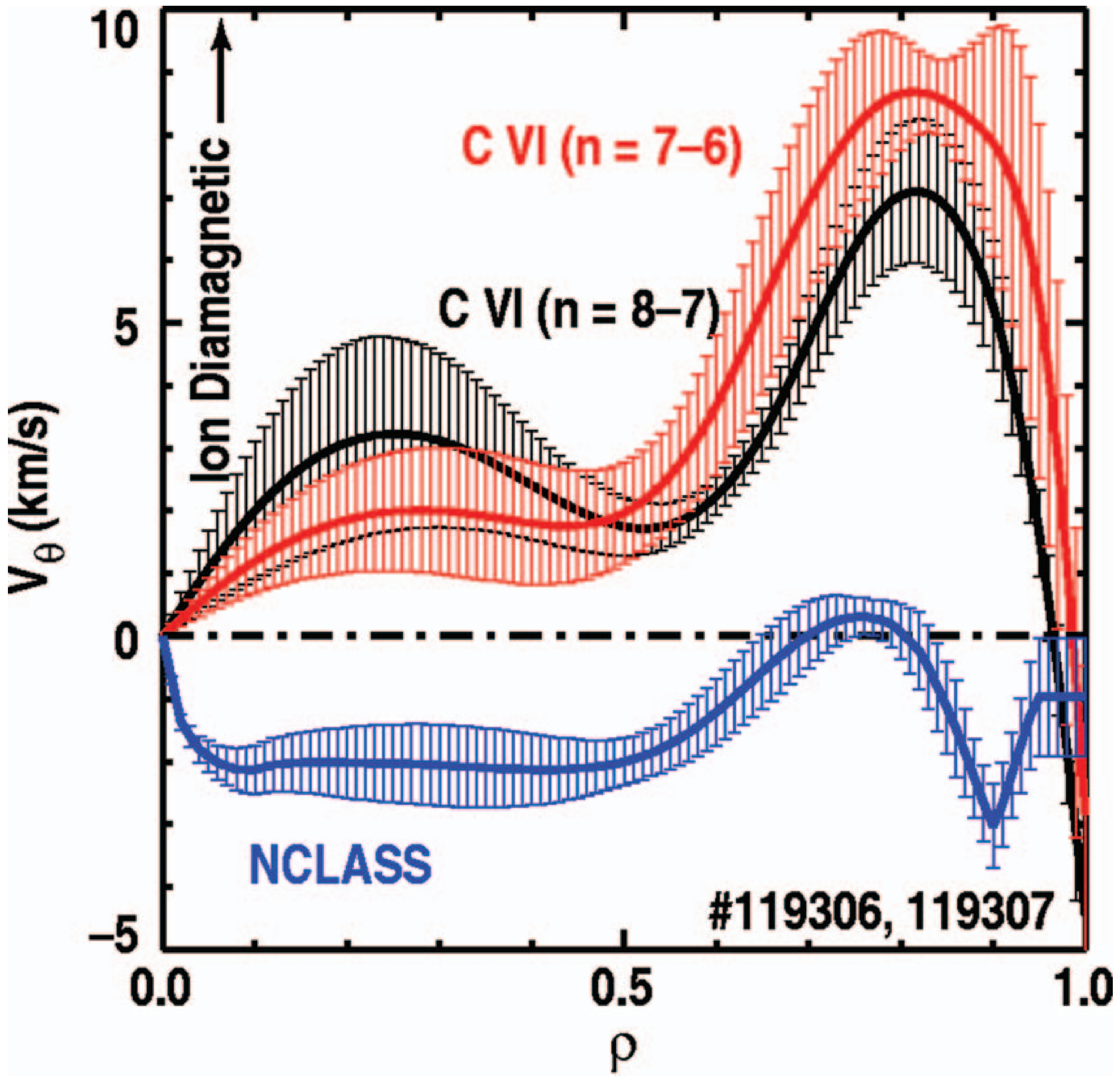


[1] Nave, Plasma Phys. Control. Fusion **54**, 074006 (2012)
[2] Lanctot, Nucl. Fusion **57**, 036004 (2017)
[3] Paz-Soldan, Nucl. Fusion **55**, 083012 (2015)
[4] Lee, Phys. Plasmas **23**, 082510 (2016)

Predictive Capability for Poloidal Rotation Needs to Be Developed

- **Past experiments with poloidal rotation have shown a mixed set of results when comparing to neoclassical theory[1]**
  - Alternative, comprehensive calculations needed for testing
- **Typically assumed that damping makes rotation neoclassical, evidence suggests low collisionality/large drive (turbulence, NBI, etc.) can make this assumption false**
- **Poloidal rotation driven by residual stress could easily change E_r in ITER**
  - 1 km/s V_{pol}, (a reasonable error bar) is a 10% contribution to E_r when V_{tor} is 100 km/s (ω is 16 krad/s)





Solomon, Phys. Plasmas **13**, 056116 (2006)

[1] Too many to reference here

Outline

- Introduction to plasma rotation for tokamaks devices
- Critical rotation understanding needed for burning plasmas
- **Recent work at DIII-D on predicting ITER rotation[1,2]**

[1] Chrystal, Phys. Plasmas **24**, 042501 (2017)
[2] Chrystal, Phys. Plasmas **24**, 056113 (2017)

Dimensionless Parameter Scans Increase Basic Understanding of the Complex Intrinsic Torque and Momentum Transport

- **Dimensionless parameter scans study plasma dynamics in terms of fundamental plasma parameters shared by different size tokamaks[1,2]**
  - Previously used to study energy transport, and other complex phenomena
- **Dependencies on these parameters are studied one at a time, results then "scaled up" to ITER**

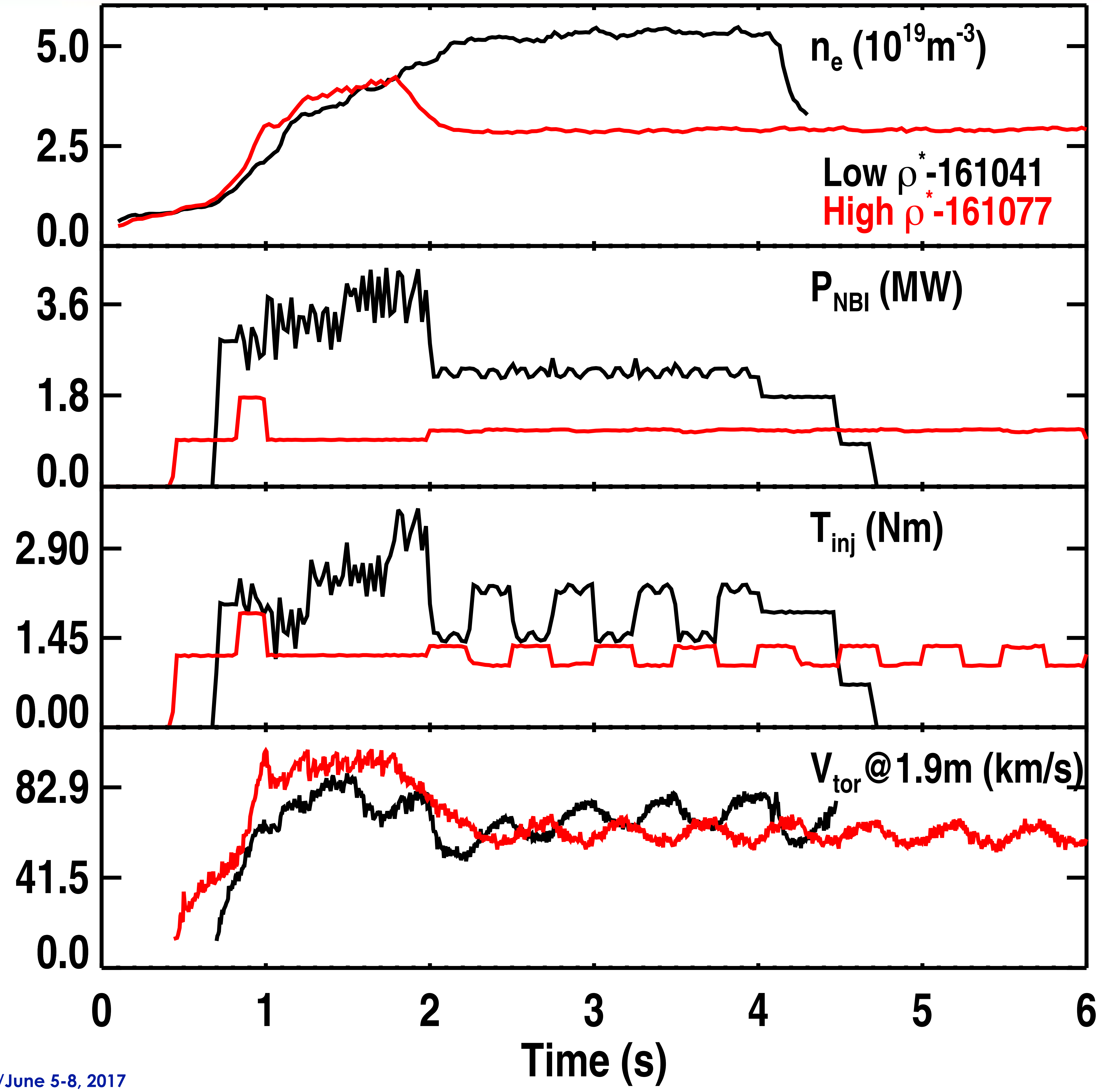
$$\rho^* \sim \frac{\sqrt{T}}{Ba} \qquad \nu^* \sim \frac{naq}{T^2}$$

- **Normalized gryoradius (ρ*) and collisionality (ν*) are key differences between current operation and ITER**
  - ρ^* for ITER cannot be matched on current machines
  - ν^* is rarely matched

[1] Petty, Phys. Plasmas **15**, 080501(2008)
[2] Luce, Plasma Phys. Control. Fusion **50**, 043001 (2008)

Dimensionless Parameter Scans Are Used to Determine ρ^* and ν^* Dependencies of Intrinsic Torque

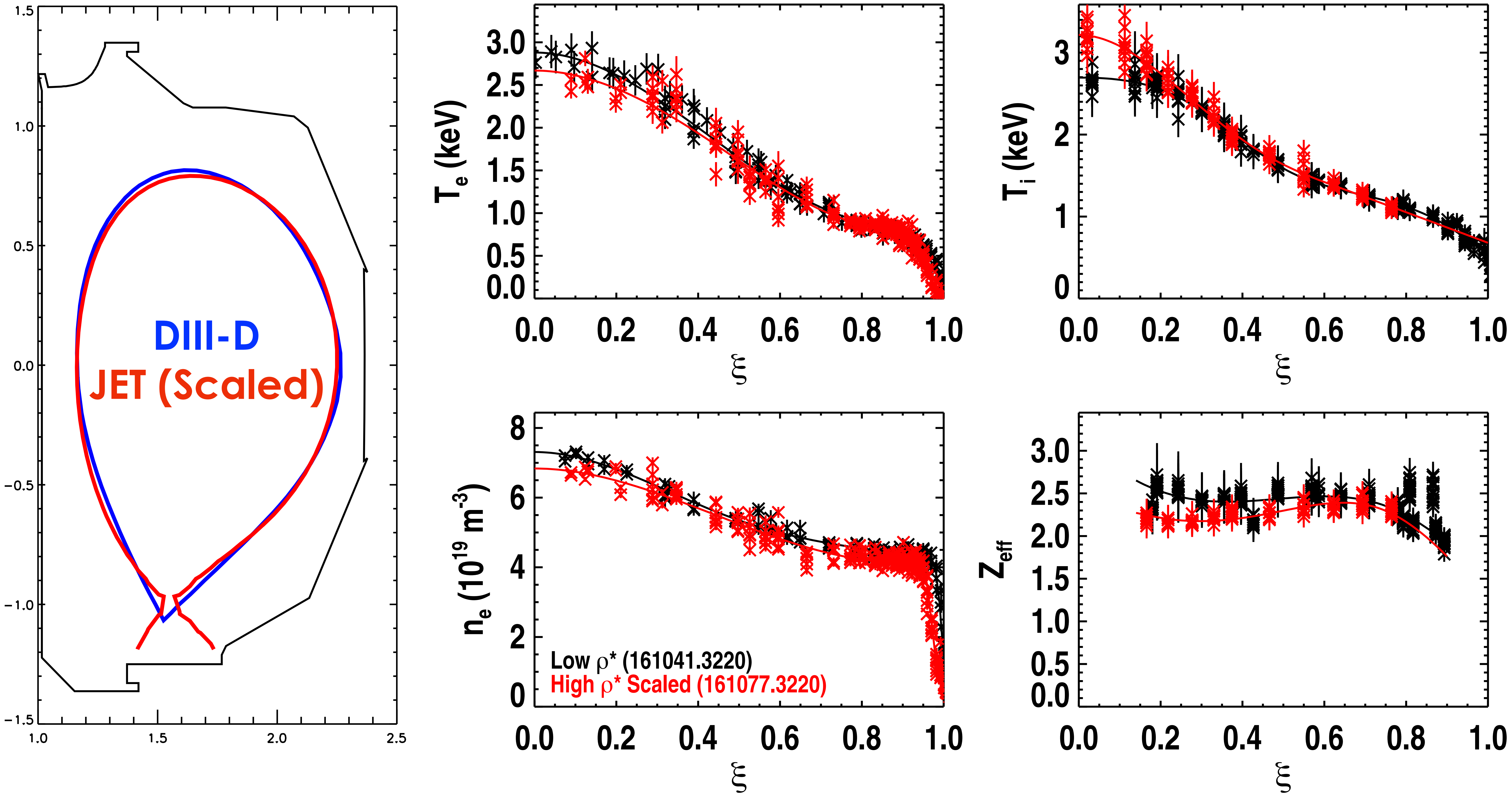
- **Vary one dimensionless parameter at a time**
- **B_T is varied, other parameters scaled with prescribed proportions**
  - For ρ^*: $I_p \sim B_T a$, $n \sim B_T^{4/3} a^{-1/3}$, $T \sim B_T^{2/3} a^{1/3}$
  - For ν^*: $I_p \sim B_T a$, $n \sim a^{-2}$, $T \sim B_T^2 a^2$
- **NBI torque is modulated, change in rotation related to intrinsic torque size relative to NBI torque steps**



Good Dimensionless Parameter Matches Were Obtained in ρ^* and ν^* Scans

- **Profiles of high field (low ρ^*, low ν^*) are compared to scaled versions of low field (high ρ^*, high ν^*), agreement shows only ρ^* or ν^* was varied**

- **ρ^* scan was designed as multi-machine scan to help extrapolation to ITER**
  - ITPA joint experiment



Good Dimensionless Parameter Matches Were Obtained in ρ* and ν* Scans

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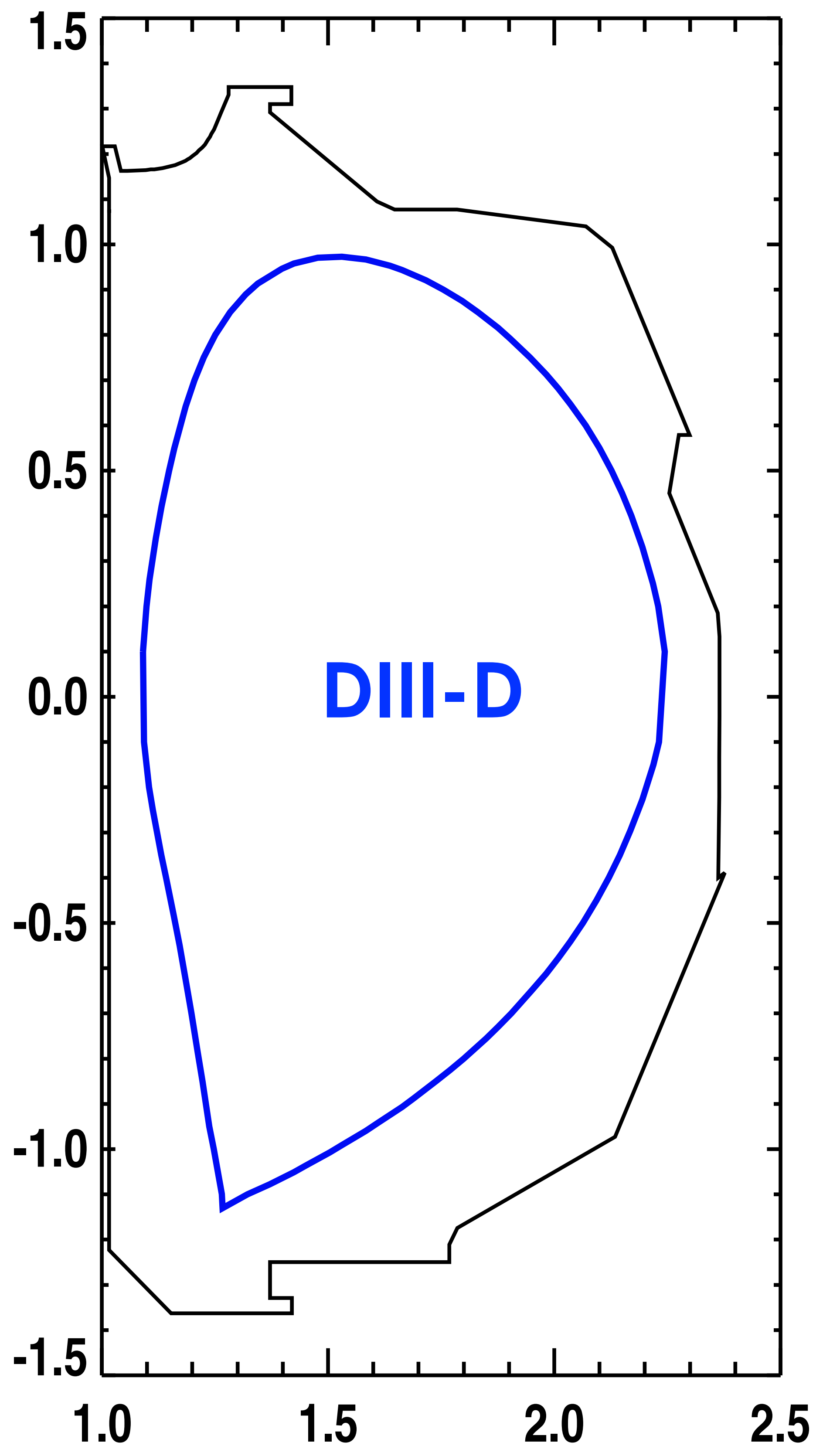
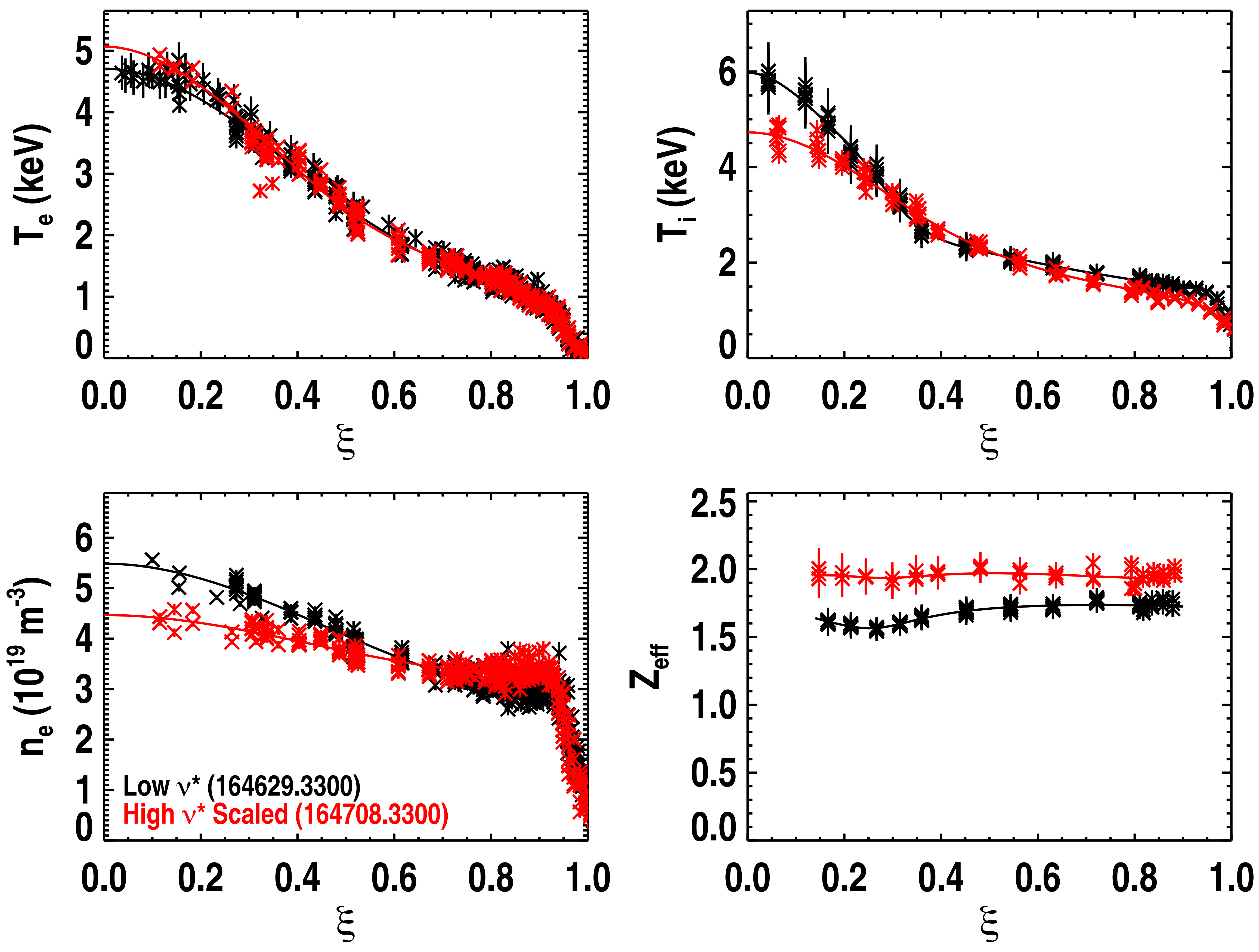
- **ρ* scan was designed as multi-machine scan to help extrapolation to ITER**
  - ITPA joint experiment

- **ν* scan only performed in DIII-D**

- **Density peaking changes with ν*, match at outer radii was prioritized**





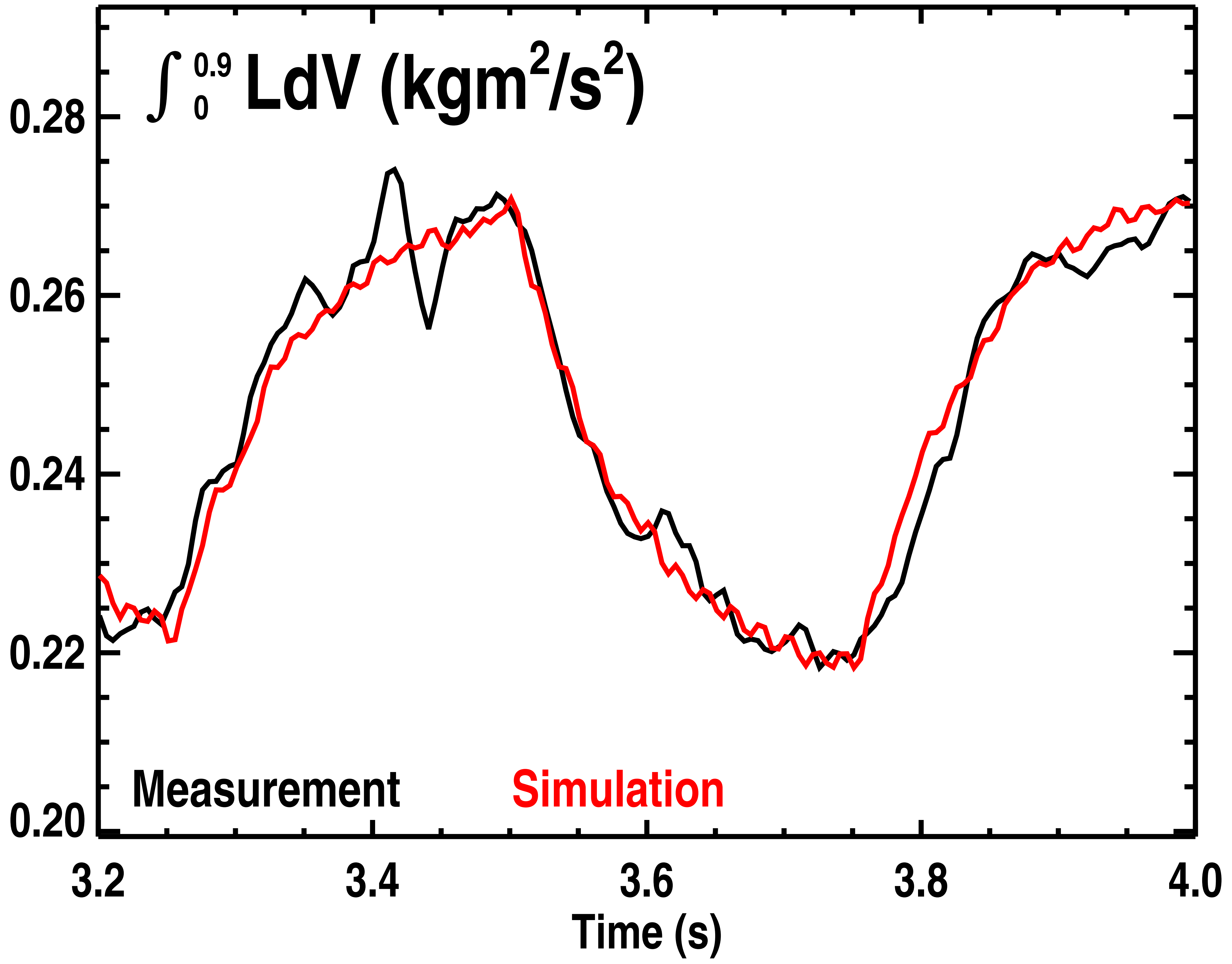
Intrinsic Torque and Momentum Confinement Time Are Found by Modeling Time History of Angular Momentum

- **Data is fit to simple momentum conservation equation, intrinsic torque and momentum confinement time are separated by time response to known torque steps[1]**
  - TRANSP+NUBEAM used to calculate torque steps and track angular momentum

Input

$$\int_0^r \left(\frac{\partial L}{\partial t} - \tau_{\rm NBI}\right) dV = \int_0^r \tau_{\rm int}\, dV - \frac{1}{t_\varphi}\int_0^r L dV$$

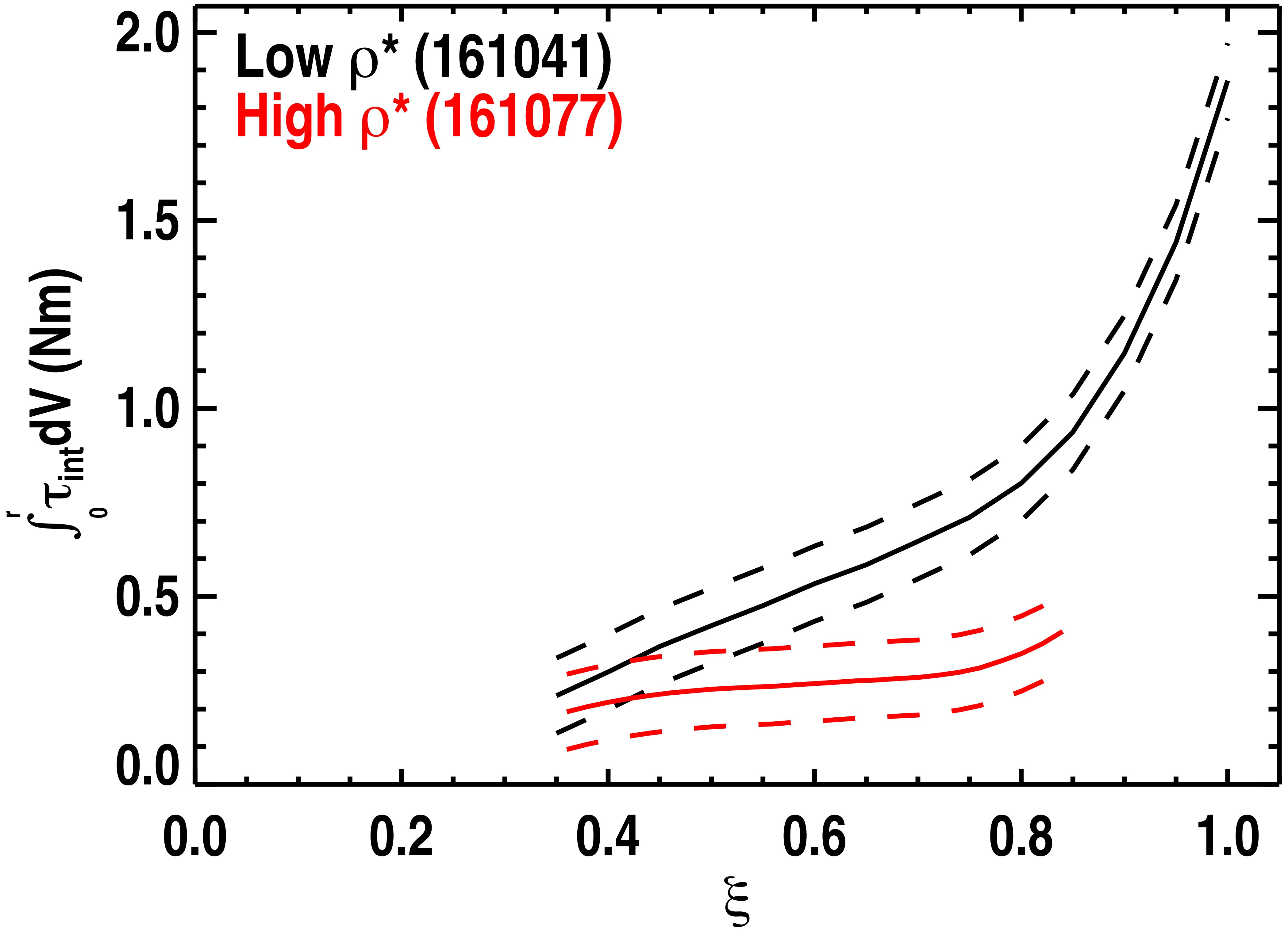
Fit

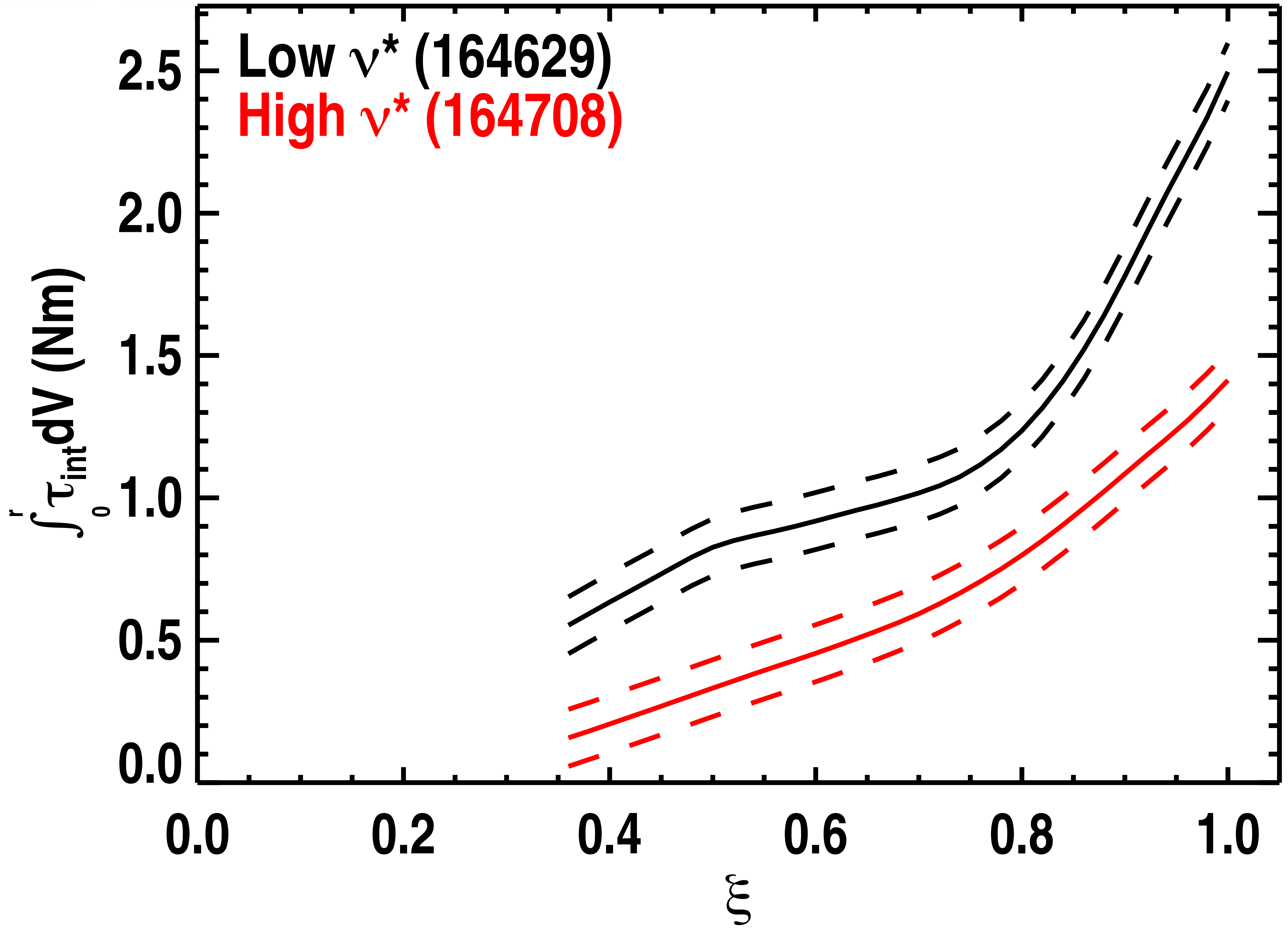


- **Confinement time and intrinsic torque assumed constant in time**
  - Perturbation amplitude is ~10% and intrinsic torque does not appear to vary with absolute rotation

[1] Solomon, Nucl. Fusion **49**, 085005 (2009)

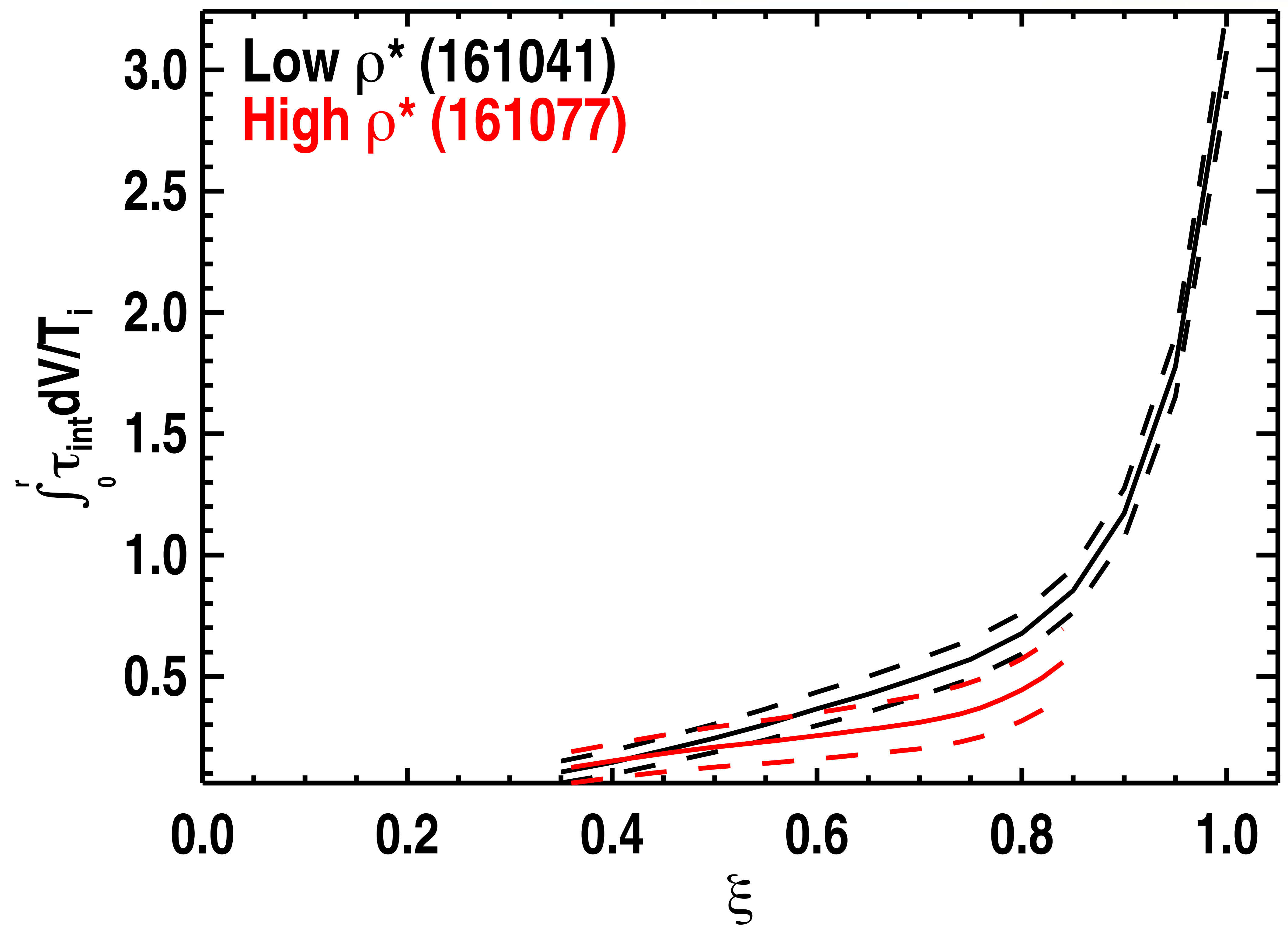
Normalized Intrinsic Torque Increases with Decreasing ρ* and Decreases with Decreasing ν*

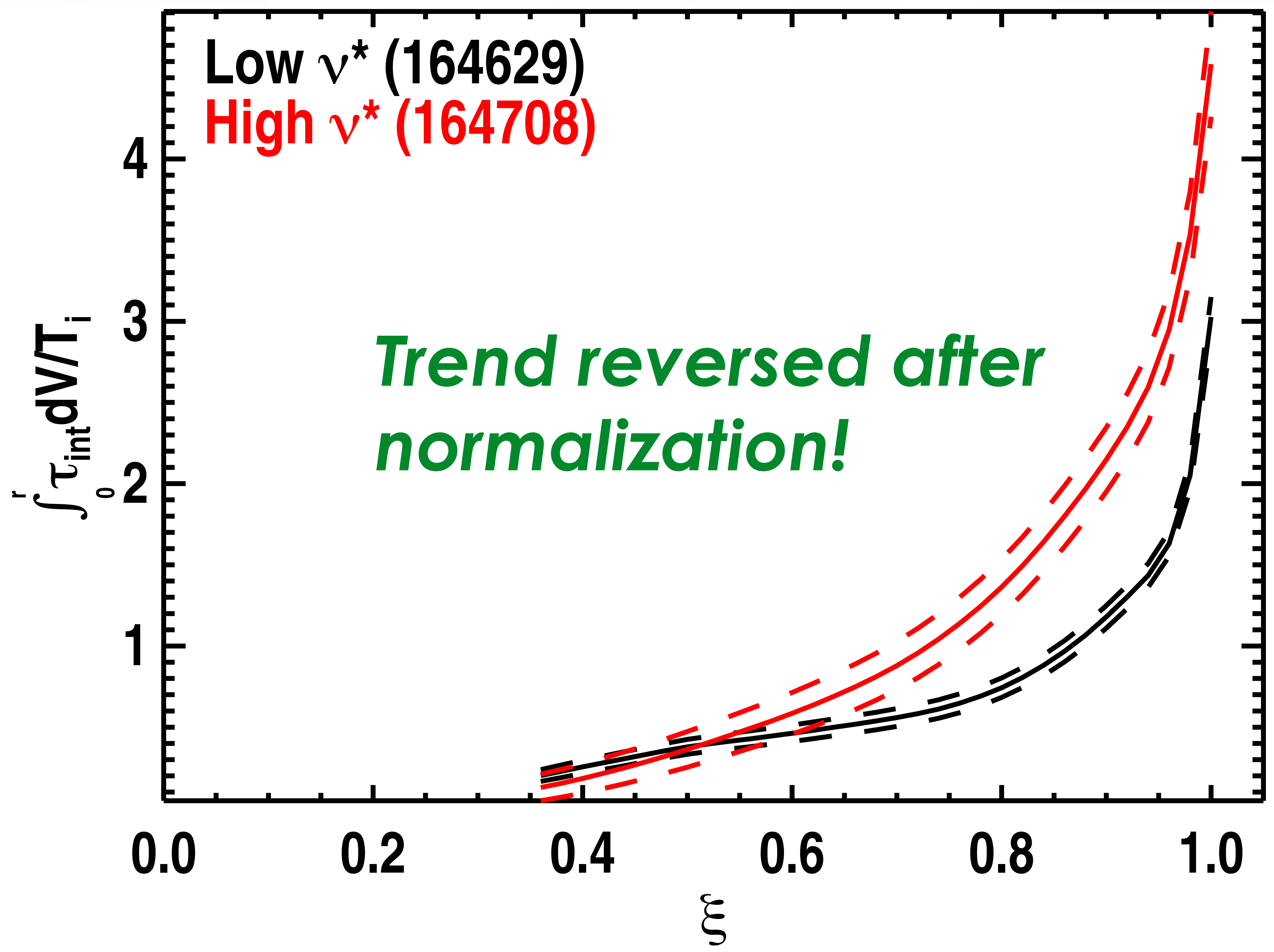




- Intrinsic torque is ~1 Nm, in agreement with previous measurements

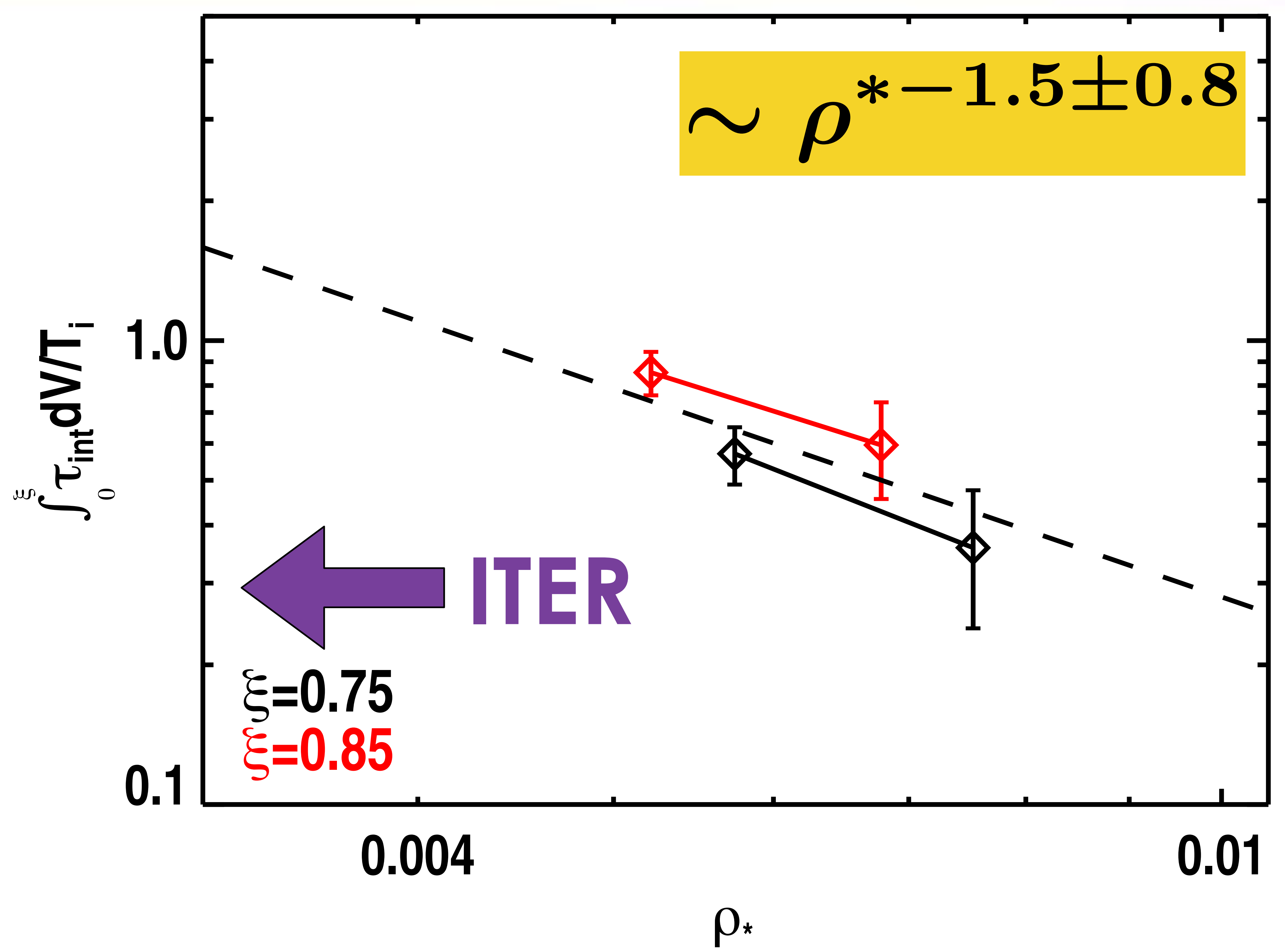
Normalized Intrinsic Torque Increases with Decreasing ρ^* and Decreases with Decreasing ν^*

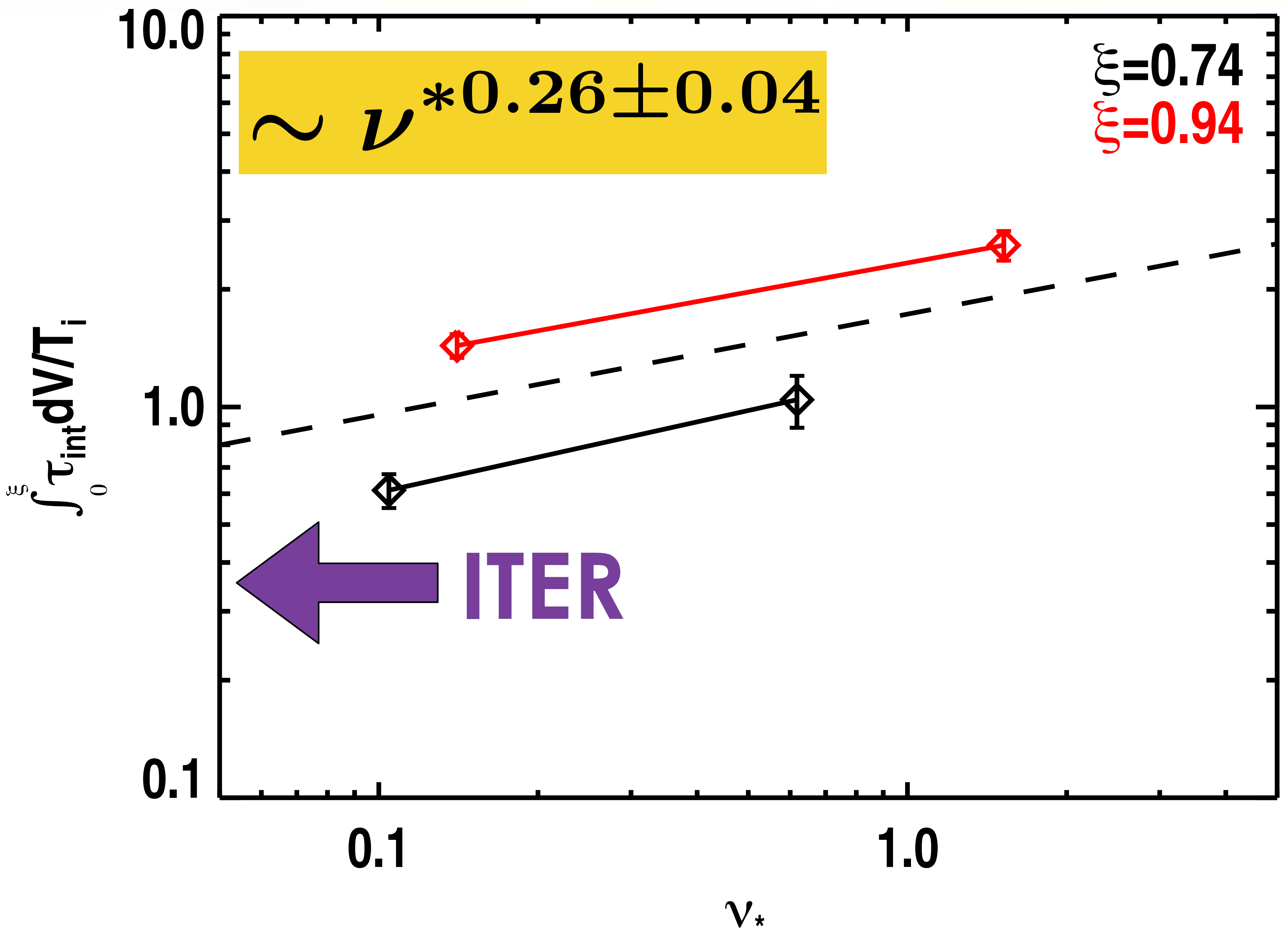




- Intrinsic torque is ~1 Nm, in agreement with previous measurements
- Must work with dimensionless parameters to determine scaling, normalize intrinsic torque with T_i (simplest quantity with same units, discussed more later)

Normalized Intrinsic Torque Increases with Decreasing ρ^* and Decreases with Decreasing ν^*

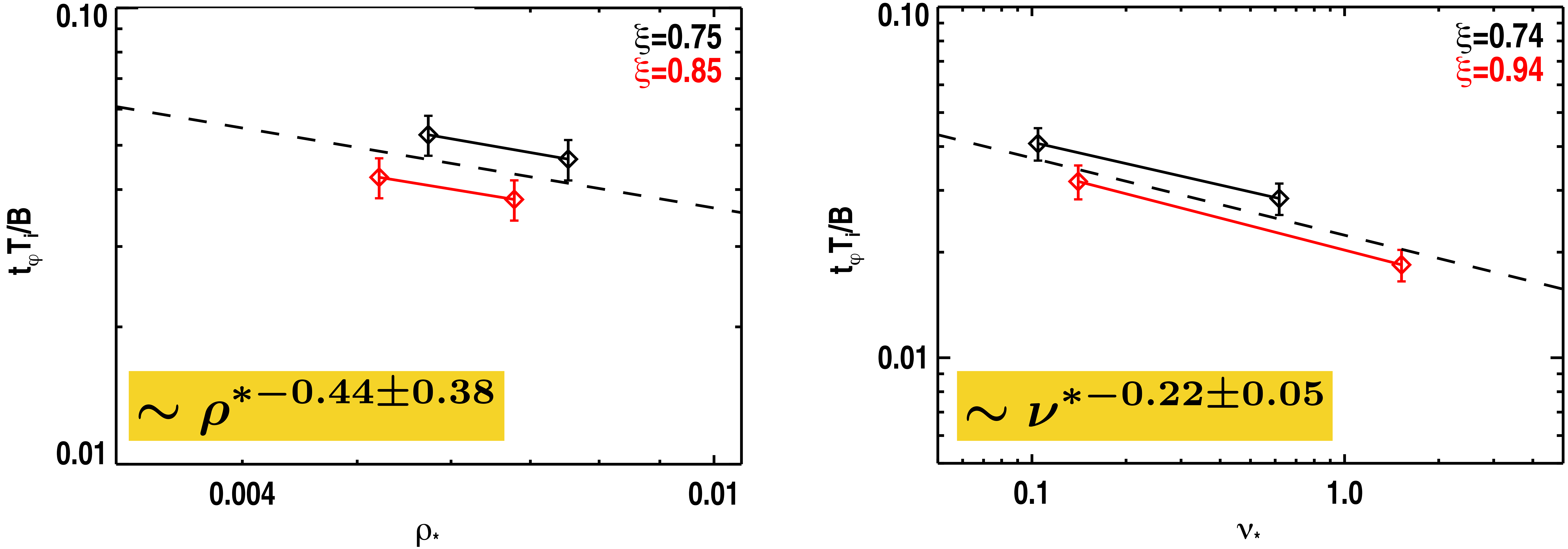




- Intrinsic torque is ~1 Nm, in agreement with previous measurements
- Must work with dimensionless parameters to determine scaling, normalize intrinsic torque with T_i (simplest quantity with same units, discussed more later)
- Net scaling is unexpectedly "favorable": increases for ITER's lower ρ^*, ν^*

Normalized Momentum Confinement Time Increases with Decreasing ρ^* and ν^*

- Same analysis that gave intrinsic torque also gave momentum confinement time



- Normalization is the Bohm-time, a^2B/T
- Scaling is (as expected) “favorable”: increasing for ITER’s lower ρ^*, ν^*

Scalings Predict a 10 krad/s Boundary Condition for ITER Rotation

- **Total intrinsic torque from low shot projected to ITER (scenario 1 of [1])**
  - $\boldsymbol{\rho}^*$ and $\boldsymbol{\nu}^*$ in ITER are 30% of DIII-D values
  - q (3.5), β (1.4) scalings are ignored, they are similar to ITER

$$\int_0^a \tau_{\mathrm{ITER}} dV = \frac{\int_0^a \tau_{\mathrm{D3D}} dV}{N_{\mathrm{D3D}}} \left(\frac{\rho^*_{\mathrm{ITER}}}{\rho^*_{\mathrm{D3D}}}\right)^{-1.5} \left(\frac{\nu^*_{\mathrm{ITER}}}{\nu^*_{\mathrm{D3D}}}\right)^{0.26} N_{\mathrm{ITER}}$$

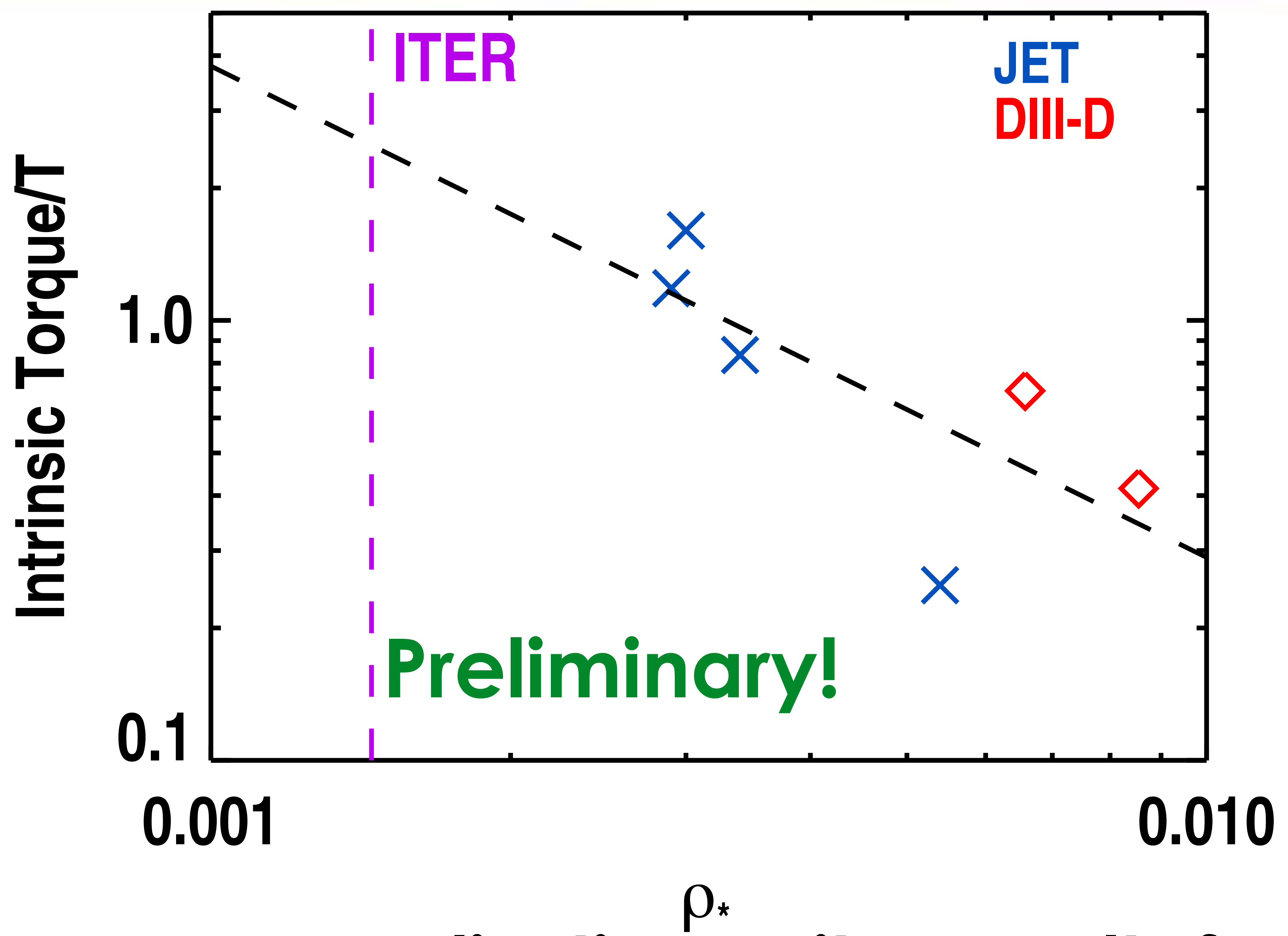
- **Total intrinsic torque prediction is 33 Nm**
  - Coincidentally, approximately the same as ITER NBI torque
- **Similar method yields a momentum confinement time of 1.2 s**

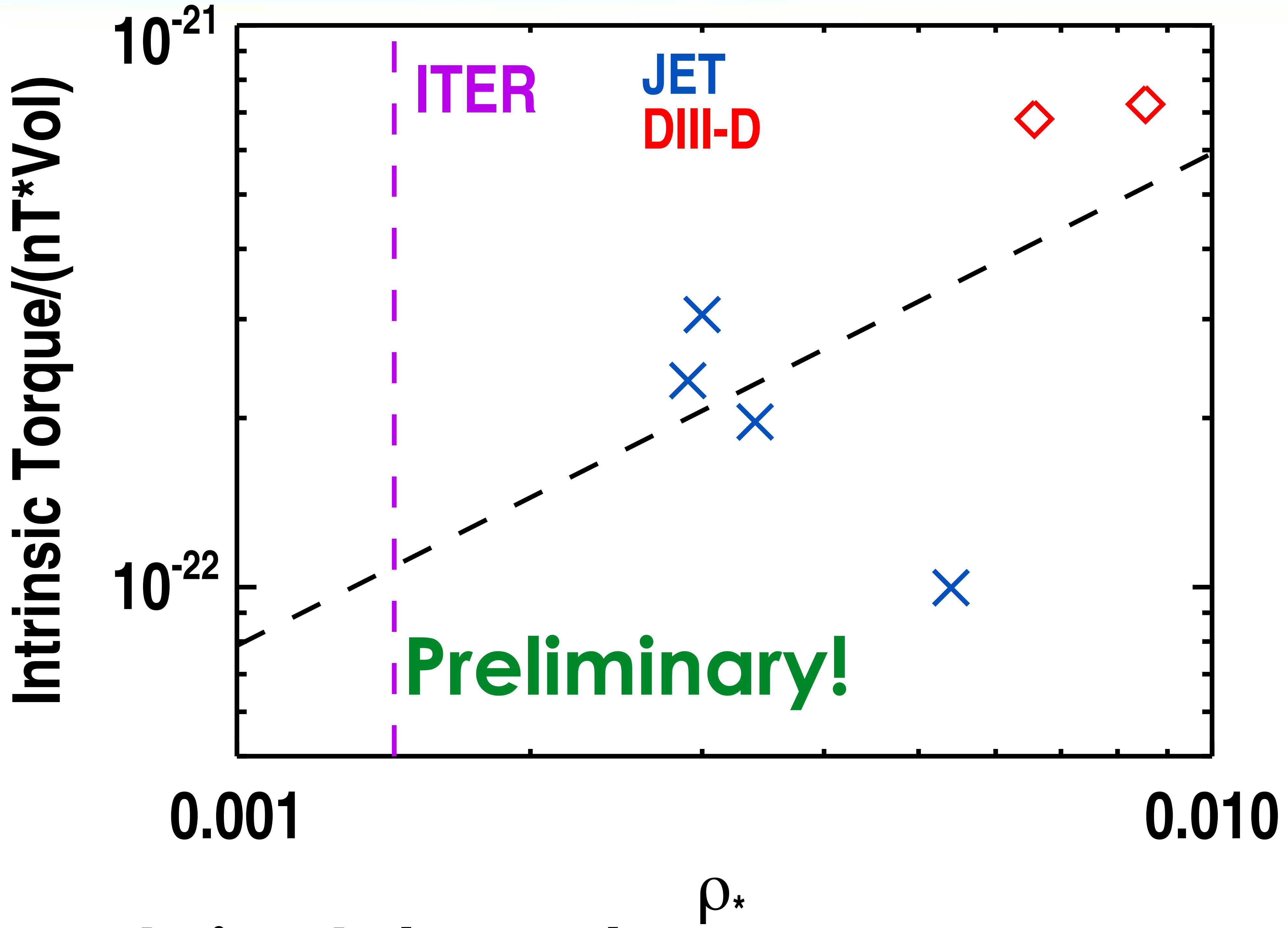
$$\langle\omega\rangle \int_{0.8}^{1} nmR^2 dV \equiv \int_{0.8}^{1} nmR^2 \omega dV = t_\varphi \int_{0.8}^{1} \tau_{\mathrm{int}} dV$$

- **<ω>=10 krad/s (60 km/s) boundary condition calculated with ONLY edge portion of intrinsic torque; will be part of future ITER prediction**

[1] Green, Plasma Phys. Control. Fusion **45**, 687 (2003)

Results from JET Show a Similar Trend and Support Temperature Normalization





- **A proper normalization unites results from different size tokamaks**
- **JET portion shows best match when normalizing with T_i (final analysis ongoing)**
- **Total thermal energy is expected normalization for residual stress, but match is poor**

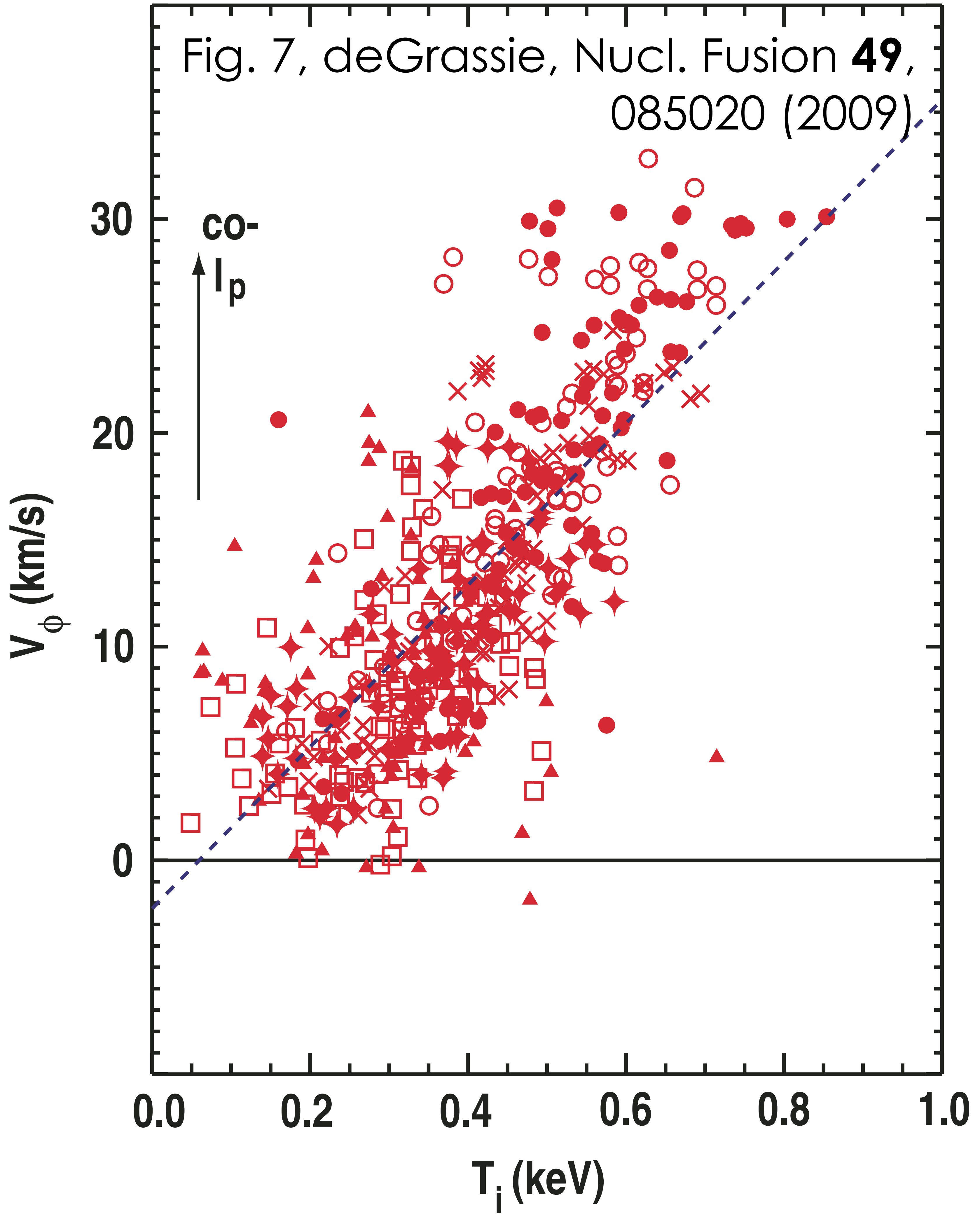
This work was conducted under the auspices of the ITPA Transport and Confinement Topical Group

Extensive Nature of Intrinsic Torque Similar to Previous Intrinsic Rotation Results

- **Previous results showed edge intrinsic rotation was best correlated with T_i[1]**
- **For self similar profiles, constant volume:**

$$\tau_{\rm int} \sim L_{\rm int}/t_\varphi \sim nV_{\rm int}/t_\varphi$$
$$\Rightarrow nT_i/t_\varphi$$
$$\Rightarrow \tau_{\rm int}/T_i \sim n/t_\varphi$$

  – Self similar if, for instance, $RV_{pinch}/\chi=-4+R/L_n$ in [2]
  – Ignoring special case of rotation reversals
- **This scaling is seen in recent experiments:**
  In ρ^* scan $n/t_\varphi \sim \rho^{*-1.06}$, measured to be $\rho^{*-1.49}$
  In ν^* scan $n/t_\varphi \sim \nu^{*0.47}$, measured to be $\nu^{*0.26}$
- **Note, no dependence of intrinsic rotation on ρ^* does not mean intrinsic torque has no dependence**
  – Soon to be analyzed experiments have investigated this



[1] deGrassie, Nucl. Fusion **49**, 085020 (2009)
[2] Peeters, Phys. Rev. Lett. **98**, 265003 (2007)

Studies of Energy Tranport Provide a Useful Reference for the Study of Momentum Transport

- **Same basic conservation equation**

$$\frac{\partial}{\partial t}\left(\frac{3}{2}nT\right) = -\nabla Q + S + \Gamma\left(\nabla T + \frac{T}{n}\nabla n\right) - \nabla\left(\frac{5}{2}\Gamma T\right)$$

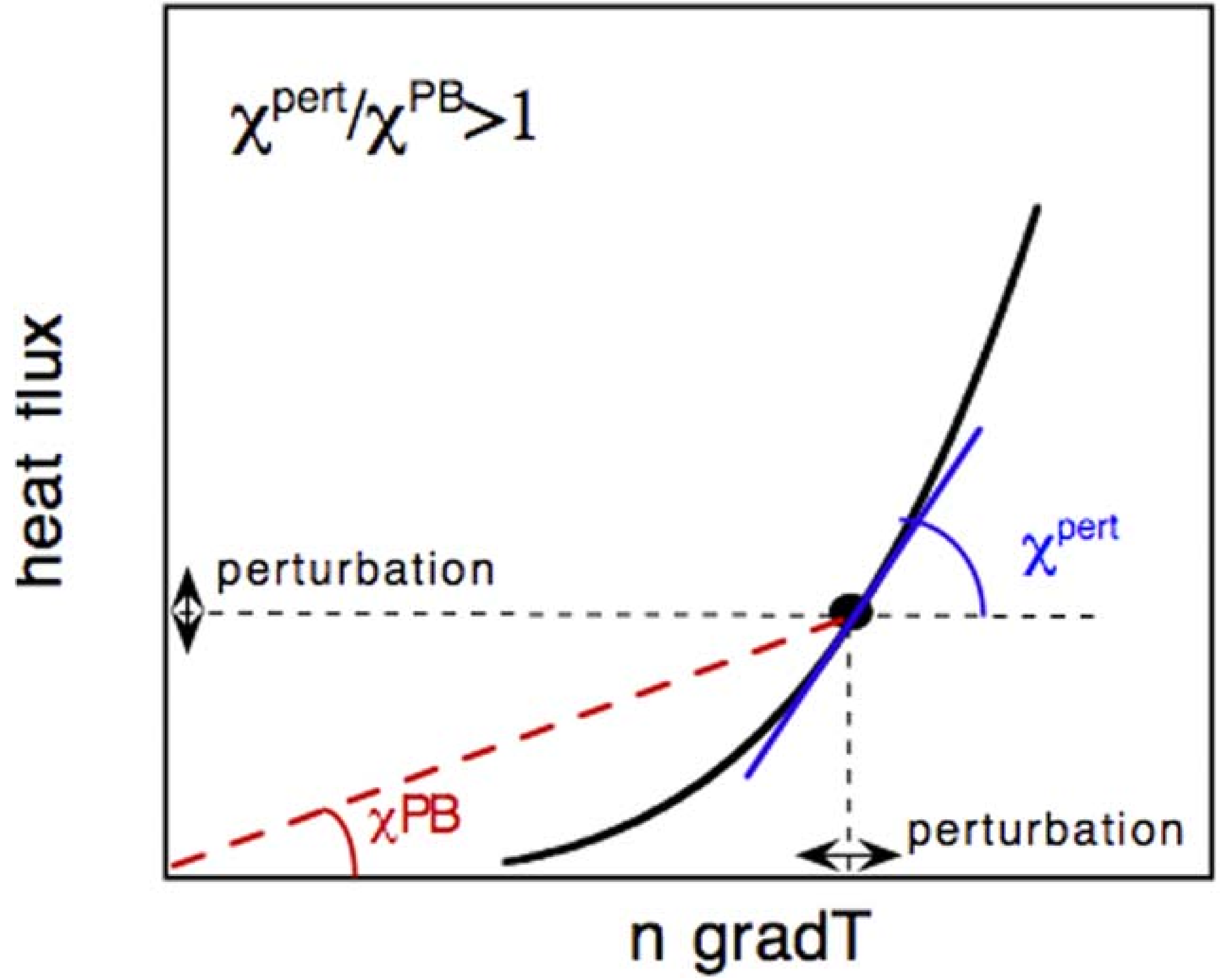
- **Flux can be written as function of diffusion, pinch**

$$Q \equiv -n\chi\nabla T + VnT$$

- **Transport coefficients are complex functions of plasma parameters**

$$\chi = \chi(n, \nabla n, T, \nabla T, ...)$$

- **Need to study both "power-balance" and "incremental" transport**
  - PB depends on all parameters => equilibrium solution
  - INC is local response => perturbed solution

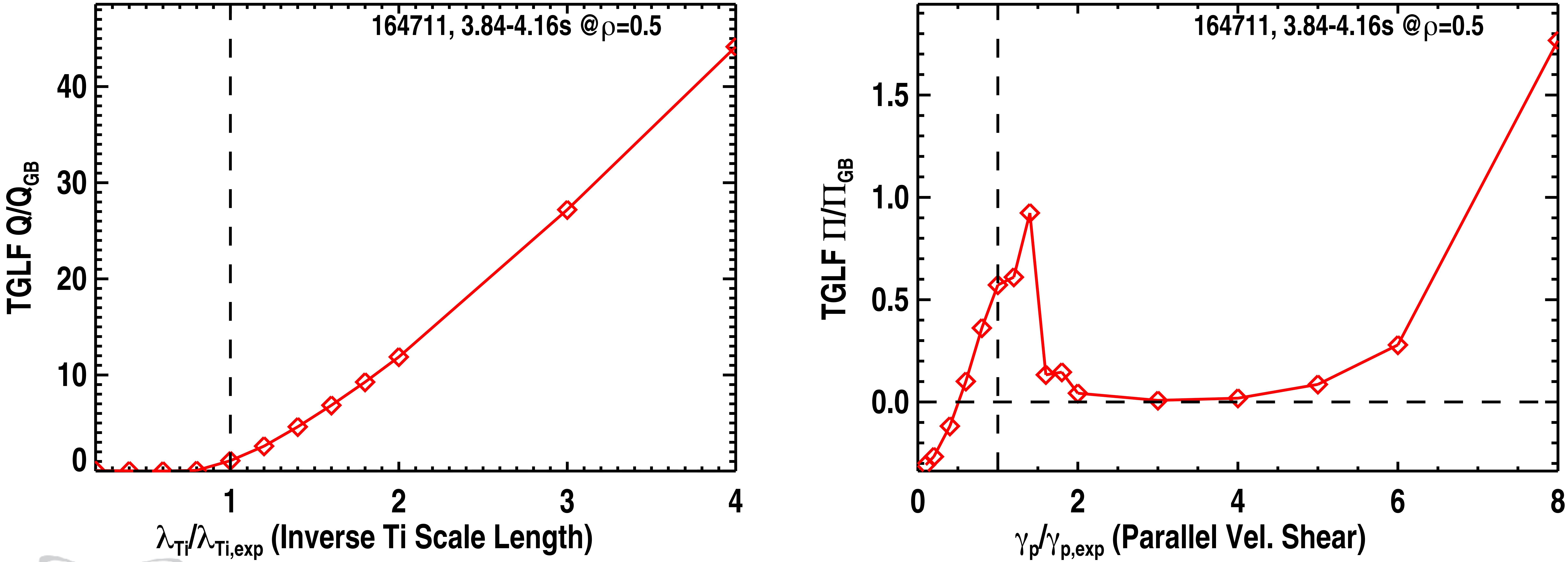


Mantica, C. R. Physique **7**, 634 (2006)

Momentum Transport Can Be More Complicated and Less Intuitive than Transport in Other Channels

$$mnR^2\frac{\partial\omega}{\partial t} = -\nabla\cdot\mathbf{\Pi} + \tau \qquad \mathbf{\Pi} = nmR^2(-\chi_{\mathrm{PB}}\nabla\omega + V_{\mathrm{PB}}\omega\hat{r})$$

- **Unlike energy transport, rotation gradient can drive ExB shear, $\chi_{\mathrm{inc}} < 0$ possible**



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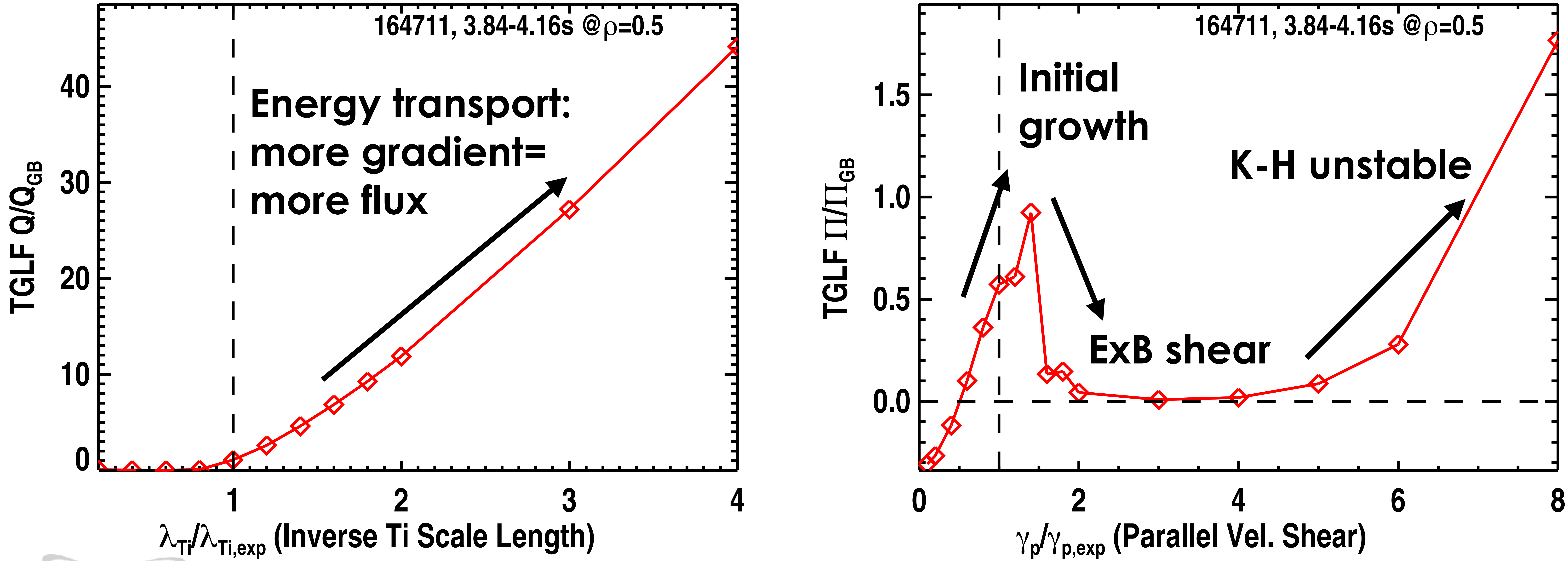

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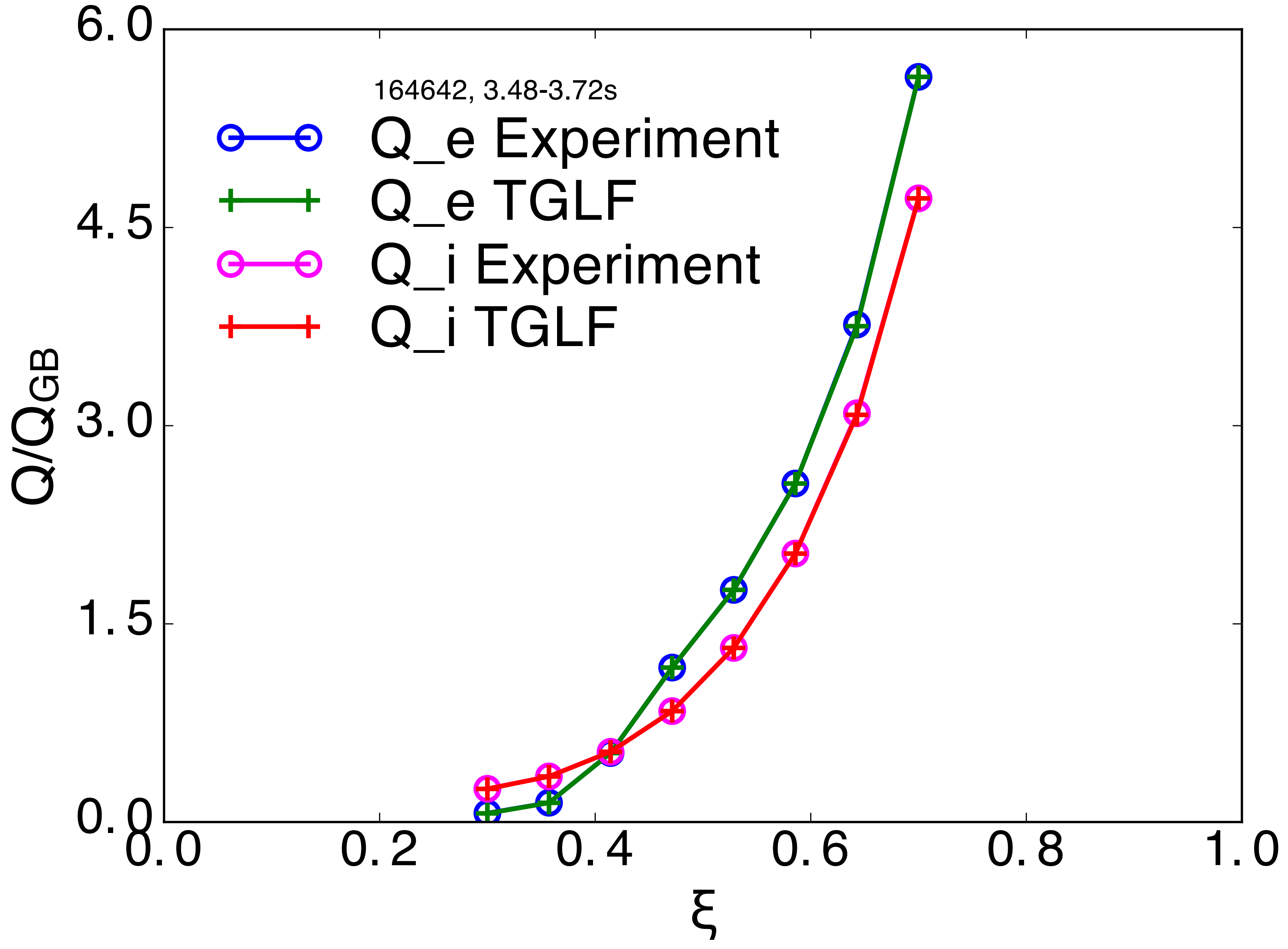
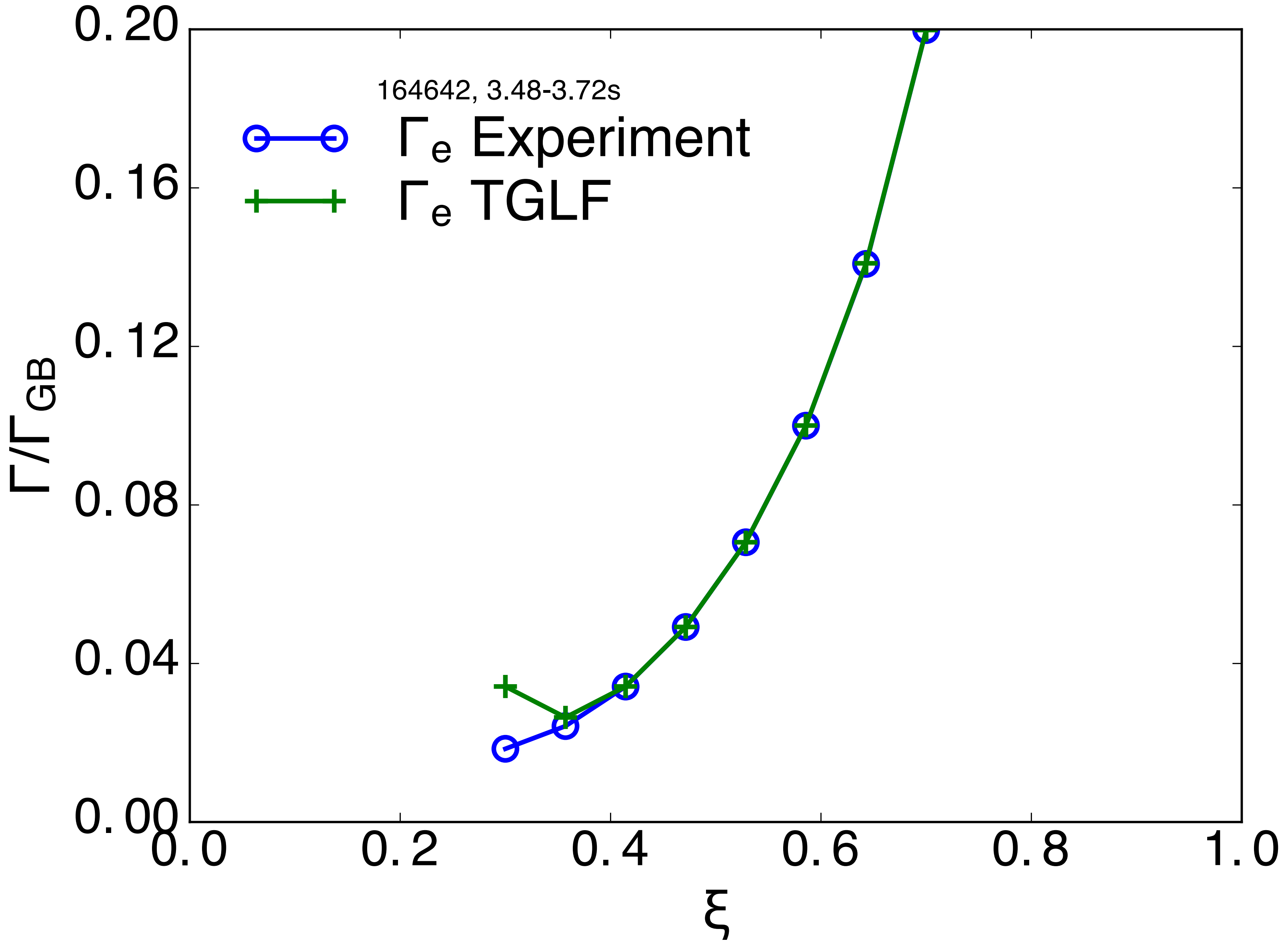
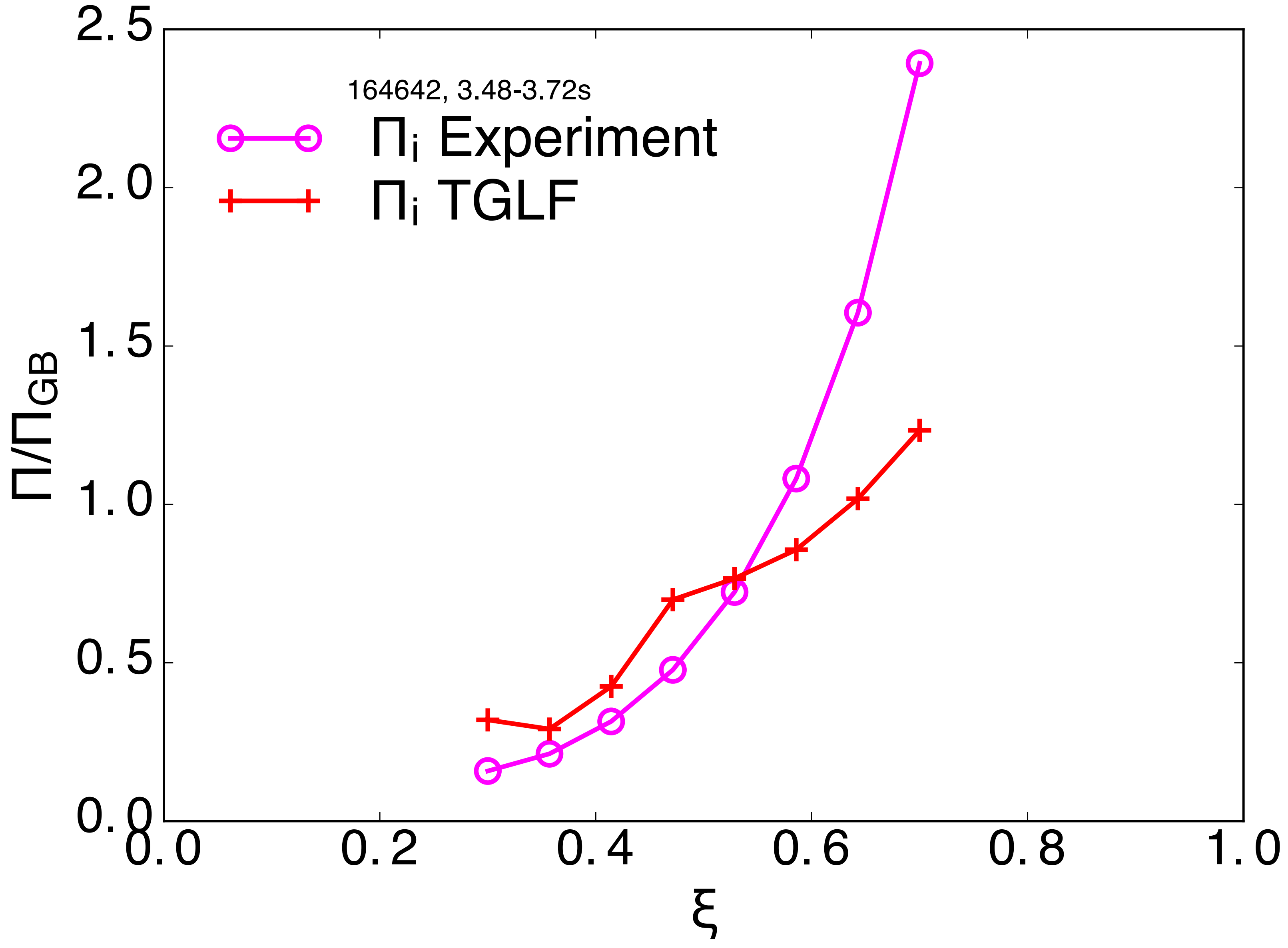
Gyrokinetic Simulations with TGLF and TGYRO Are Used to Compare Momentum Flux from Theory and Experiment

- **TRANSP+NUBEAM used to determine experimental flux**
- **TGLF determines flux, significant low-k turbulence needed to get significant momentum flux, diamagnetic velocities are ignored (high rotation ordering)**
- **TGYRO ensures energy and particle flux match to generate low-k turbulence, profiles results are close to the measurements**

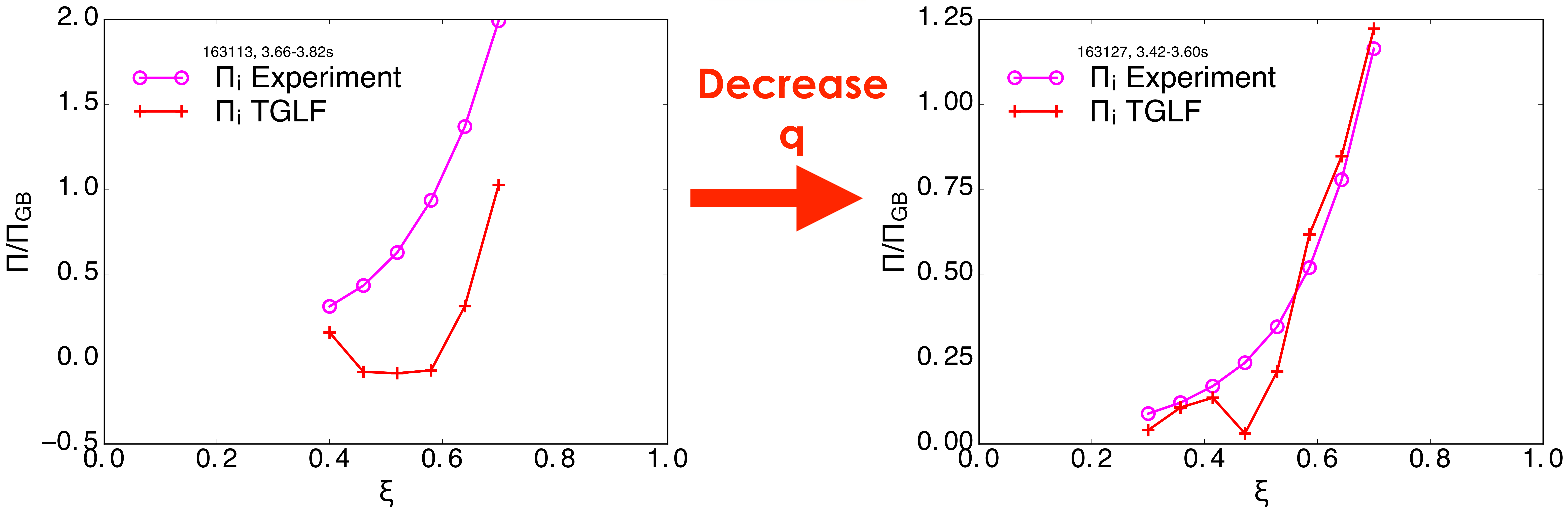






- **Additional dimensionless parameters (q, T_e/T_i) found to be important**

Power Balance Momentum Flux Prediction Improves as Parameters Move Closer to ITER



- **TGLF prediction improved significantly when lowering q**

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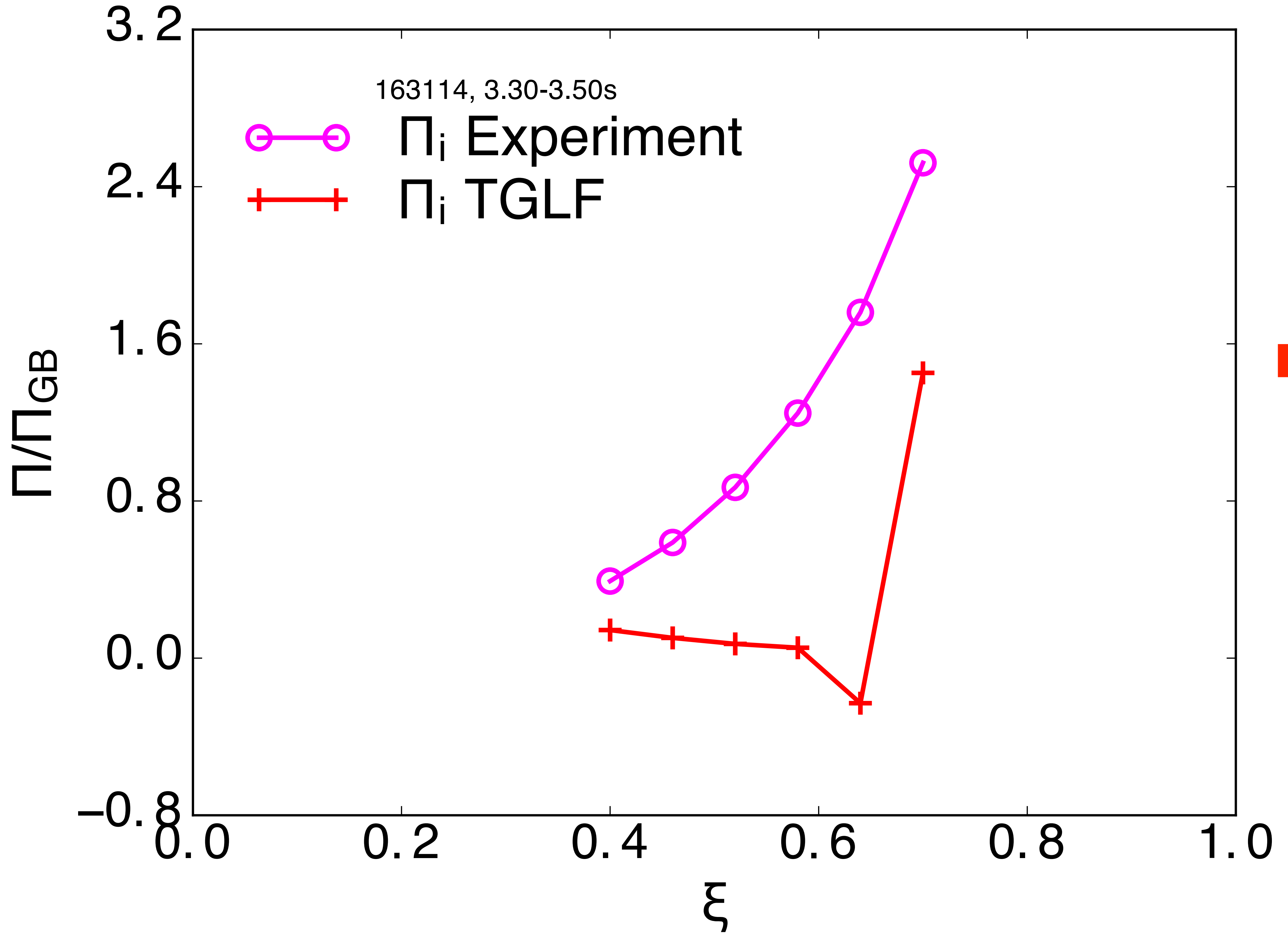
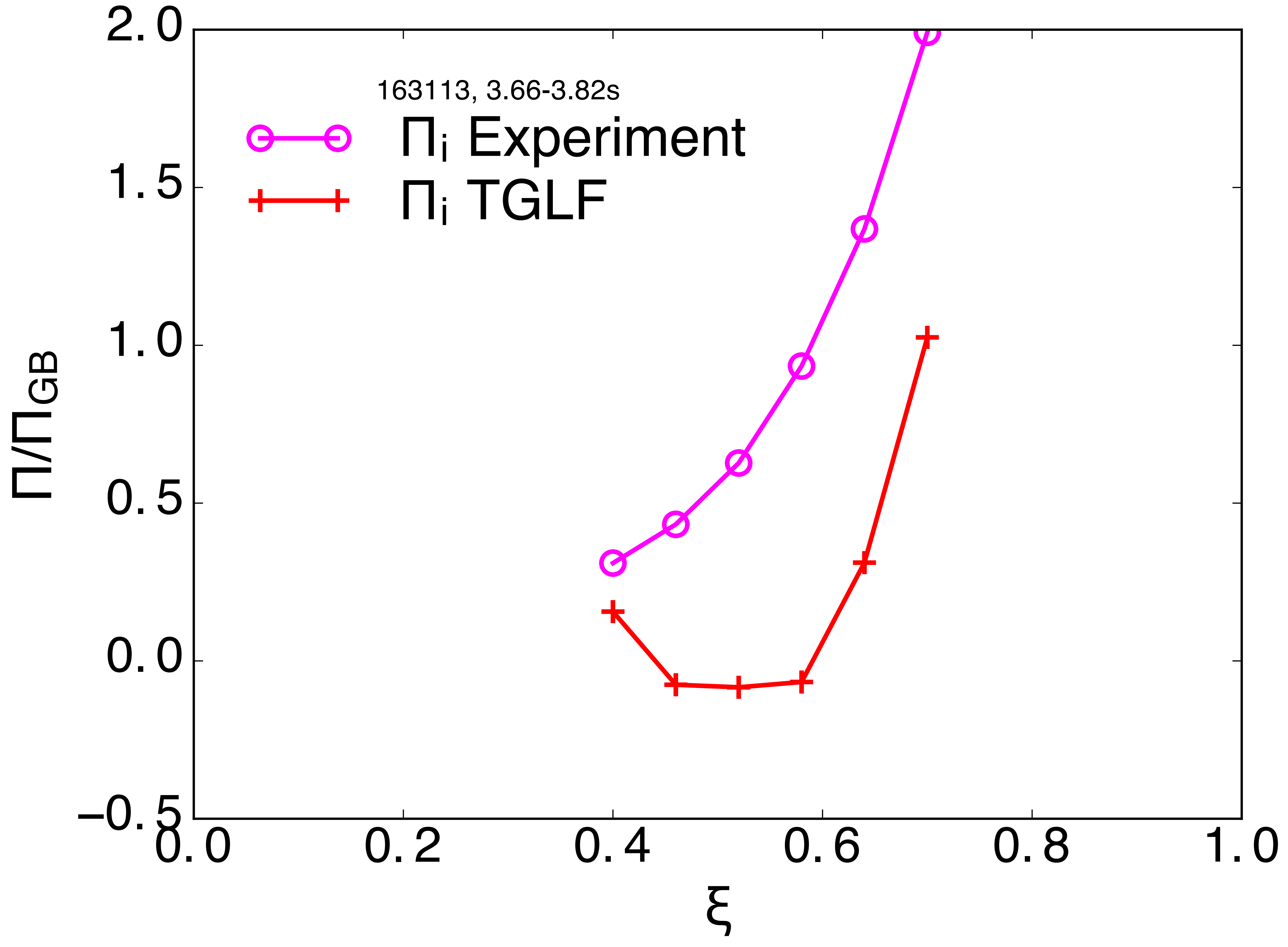


T_e/T_i
0.8 ➜ 1



- **TGLF prediction improved significantly when lowering q**
- **Prediction equally poor when raising T_e/T_i**

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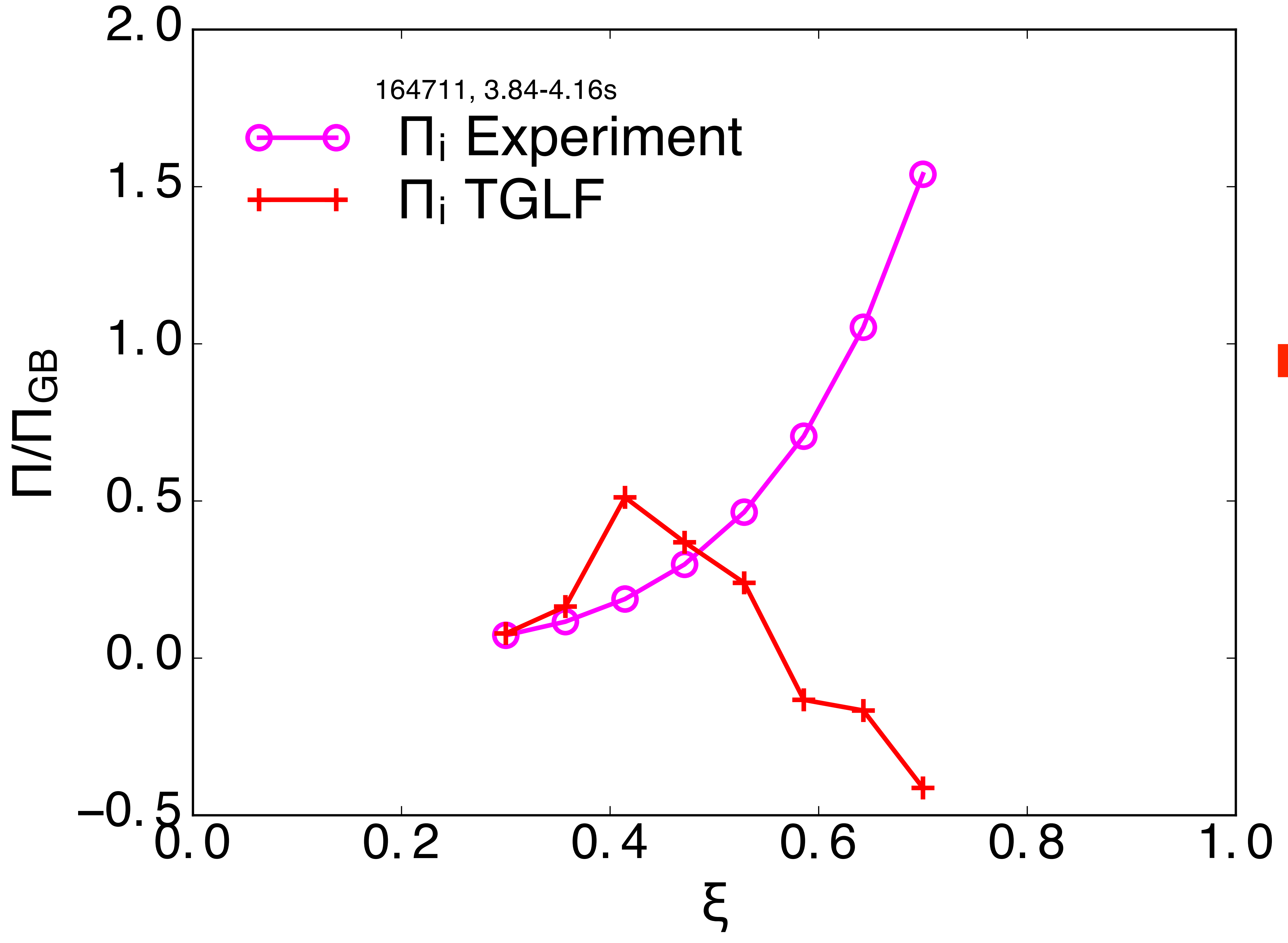

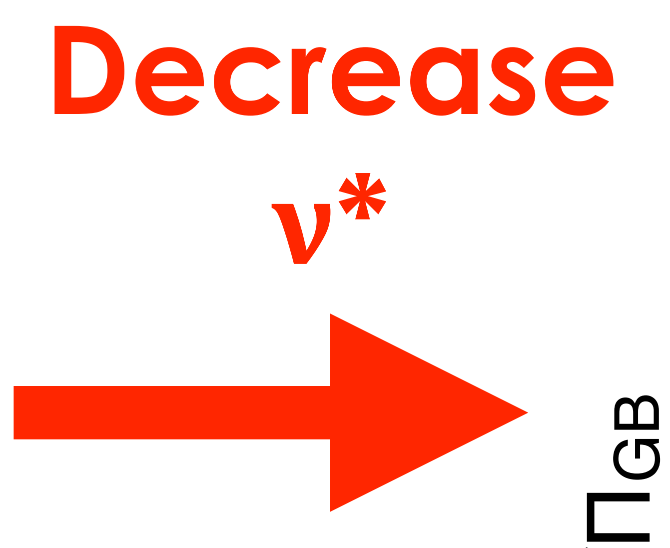

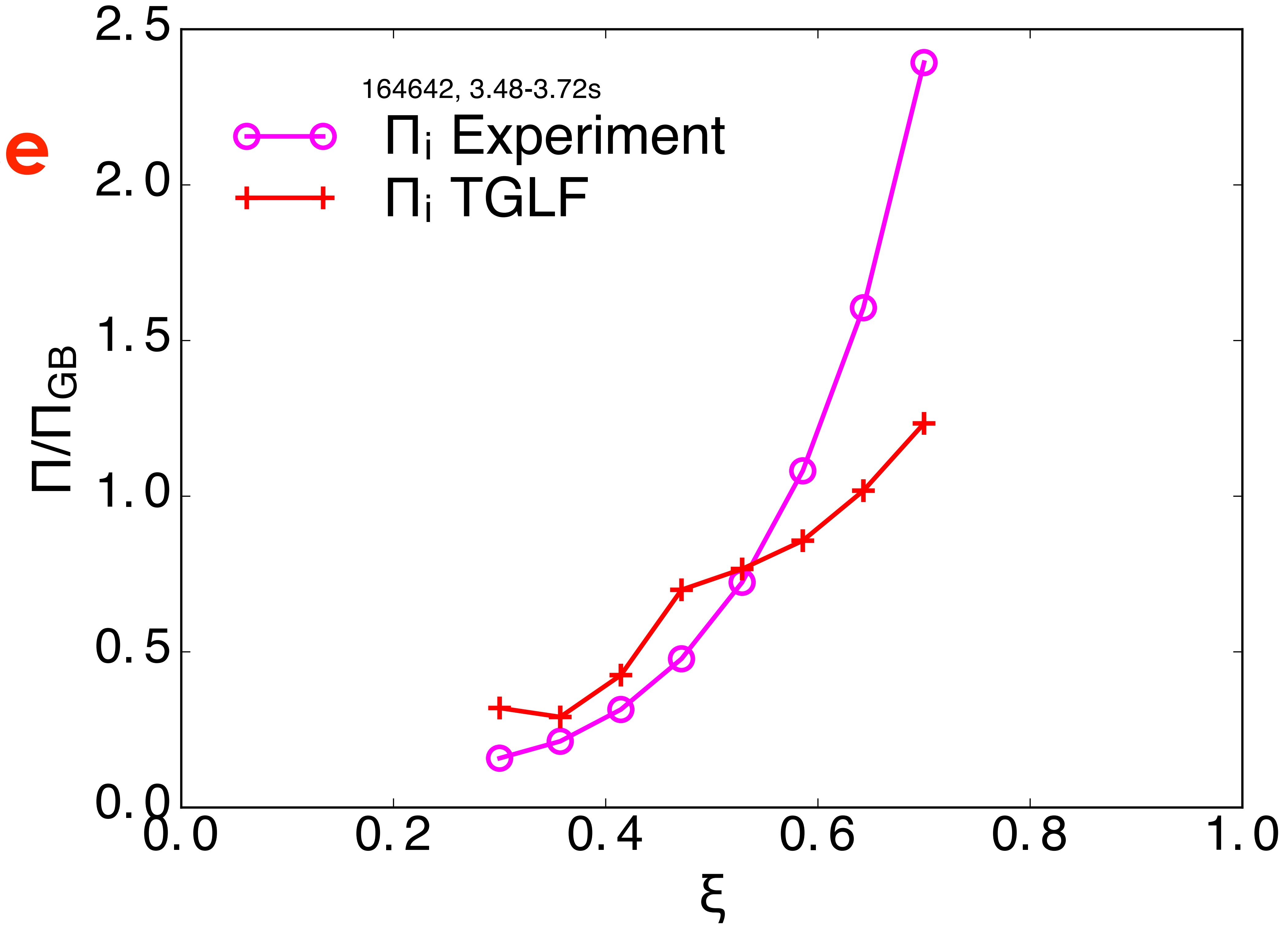

- **TGLF prediction improved significantly when lowering q**
- **Prediction equally poor when raising T_e/T_i**
- **Prediction improves when ν* is lowered**

Torque Perturbation in these Experiments Allow Further Study of Incremental Transport Coefficients

- **Perturb momentum source with co/counter NBI, other parameters nearly constant**
  - Allows temperature, density dependencies of coefficients and residual stress to be ignored

$$nmR^2\partial\tilde{\omega}/\partial t-\tilde{\tau}=-\nabla\cdot\tilde{\mathbf{\Pi}},\quad \tilde{\mathbf{\Pi}}=nmR^2(-\chi_{\mathrm{inc}}\nabla\tilde{\omega}+V_{\mathrm{inc}}\tilde{\omega}\hat{r})$$

- **Fourier transform isolates plasma response at driven frequency, amplitude and phase solve indeterminacy, incremental transport coefficients then calculated**

$$\tilde{\Pi}=\bar{\Pi}\cos(2\pi ft+\phi_{\Pi}),\quad \tilde{\omega}=\bar{\omega}\cos(2\pi ft+\phi_{\omega})$$

$$\chi_{\mathrm{inc}}\bar{\omega}\frac{\partial\phi_{\omega}}{\partial r}=\frac{\int_0^r(d\mathrm{Vol}/dr)\bar{\Pi}\cos\phi_{\Pi}dr\sin\phi_{\omega}-\int_0^r(d\mathrm{Vol}/dr)\bar{\Pi}\sin\phi_{\Pi}dr\cos\phi_{\omega}}{(d\mathrm{Vol}/dr)nm\langle R^2(\nabla r)^2\rangle}$$

$$\frac{V_{\mathrm{inc}}}{\nabla r}\bar{\omega}-\chi_{\mathrm{inc}}\frac{\partial\bar{\omega}}{\partial r}=\frac{\int_0^r(d\mathrm{Vol}/dr)\bar{\Pi}\cos\phi_{\Pi}dr\cos\phi_{\omega}-\int_0^r(d\mathrm{Vol}/dr)\bar{\Pi}\sin\phi_{\Pi}dr\sin\phi_{\omega}}{(d\mathrm{Vol}/dr)nm\langle R^2(\nabla r)^2\rangle}$$

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- **Fourier transform isolates plasma response at driven frequency, amplitude and phase solve indeterminacy, incremental transport coefficients then calculated**

Diffusion depends on phase of perturbation

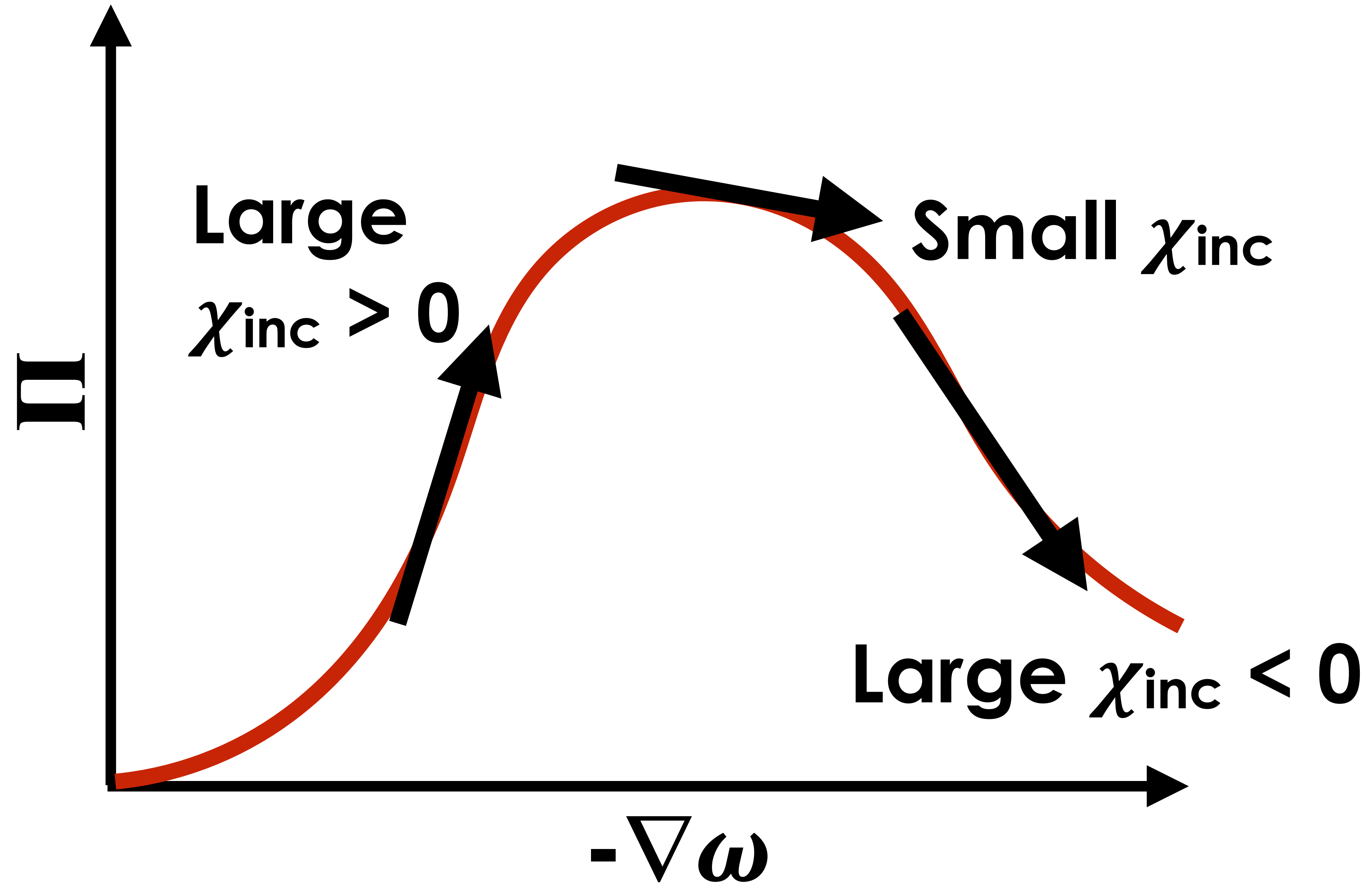
$$\chi_{\rm inc}\bar{\omega}\frac{\partial\phi_\omega}{\partial r} = \frac{\int_0^r ({\rm dVol}/dr)\bar{\Pi}\cos\phi_\Pi dr\sin\phi_\omega - \int_0^r ({\rm dVol}/dr)\bar{\Pi}\sin\phi_\Pi dr\cos\phi_\omega}{}$$

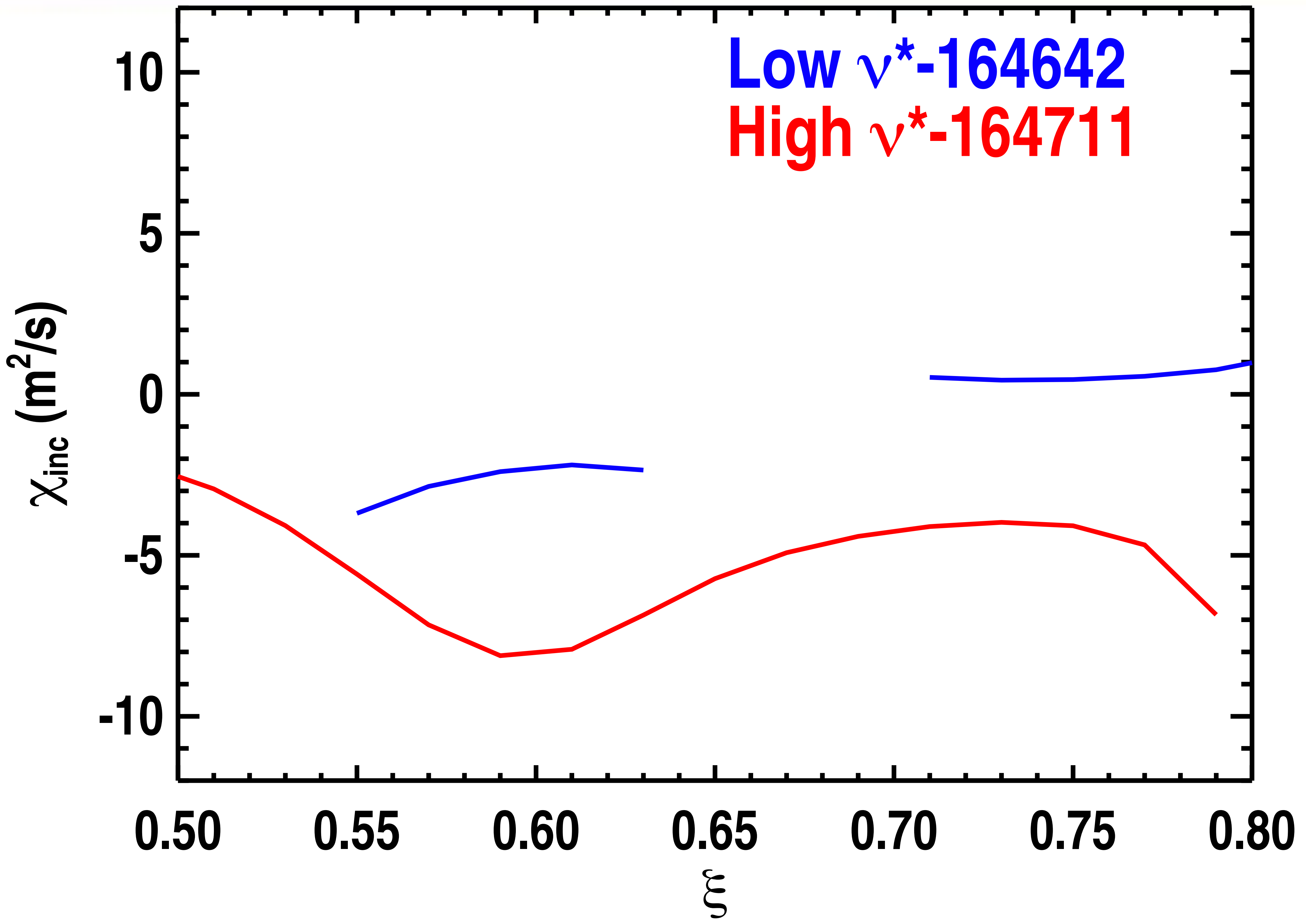
Pinch depends on ampltiude of perturbation

$$\frac{V_{\rm inc}}{\nabla r}\bar{\omega} - \chi_{\rm inc}\frac{\partial\bar{\omega}}{\partial r} = \frac{\int_0^r ({\rm dVol}/dr)\bar{\Pi}\cos\phi_\Pi dr\cos\phi_\omega - \int_0^r ({\rm dVol}/dr)\bar{\Pi}\sin\phi_\Pi dr\sin\phi_\omega}{({\rm dVol}/dr)nm\langle R^2(\nabla r)^2\rangle}$$

- **Power balance and incremental coefficients can differ, no guarantee a solution can capture incremental and average dynamics**
  - $V_{\rm inc}$ not easily relatable to power balance pinch

Measured Incremental Diffusivity Gets Smaller with Smaller q and ν* in Dimensionless Parameter Scans





- **Momentum confinement is less sensitive to rotation gradient when χ_{inc} is small**
- **Higher Te/Ti appears more problematic**
  - Needs nonlinear gyrokinetics, beyond the scope of this work, see Wang talk in this session
- **ITER's q and ν* is a more forgiving regime to model**

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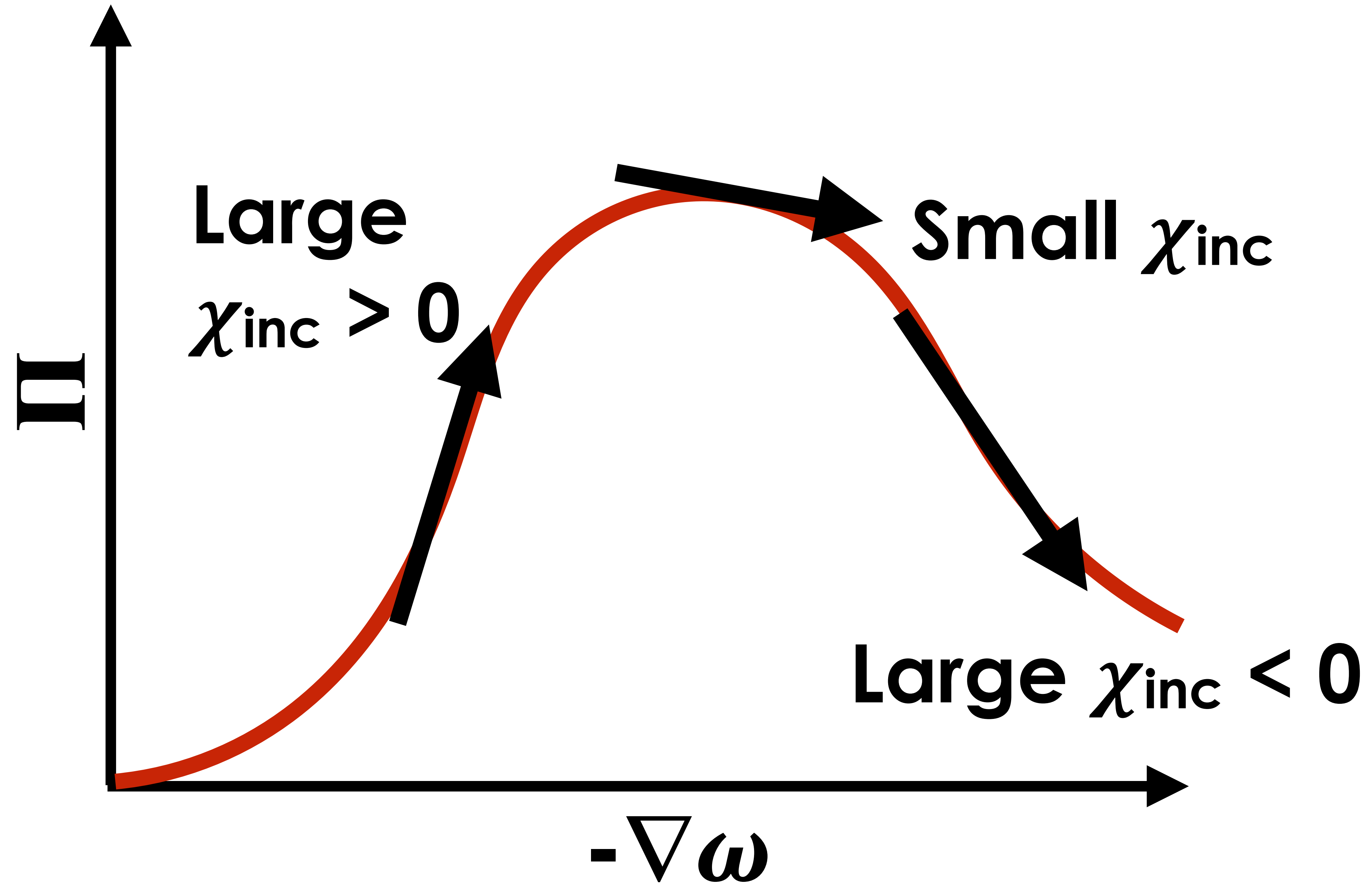

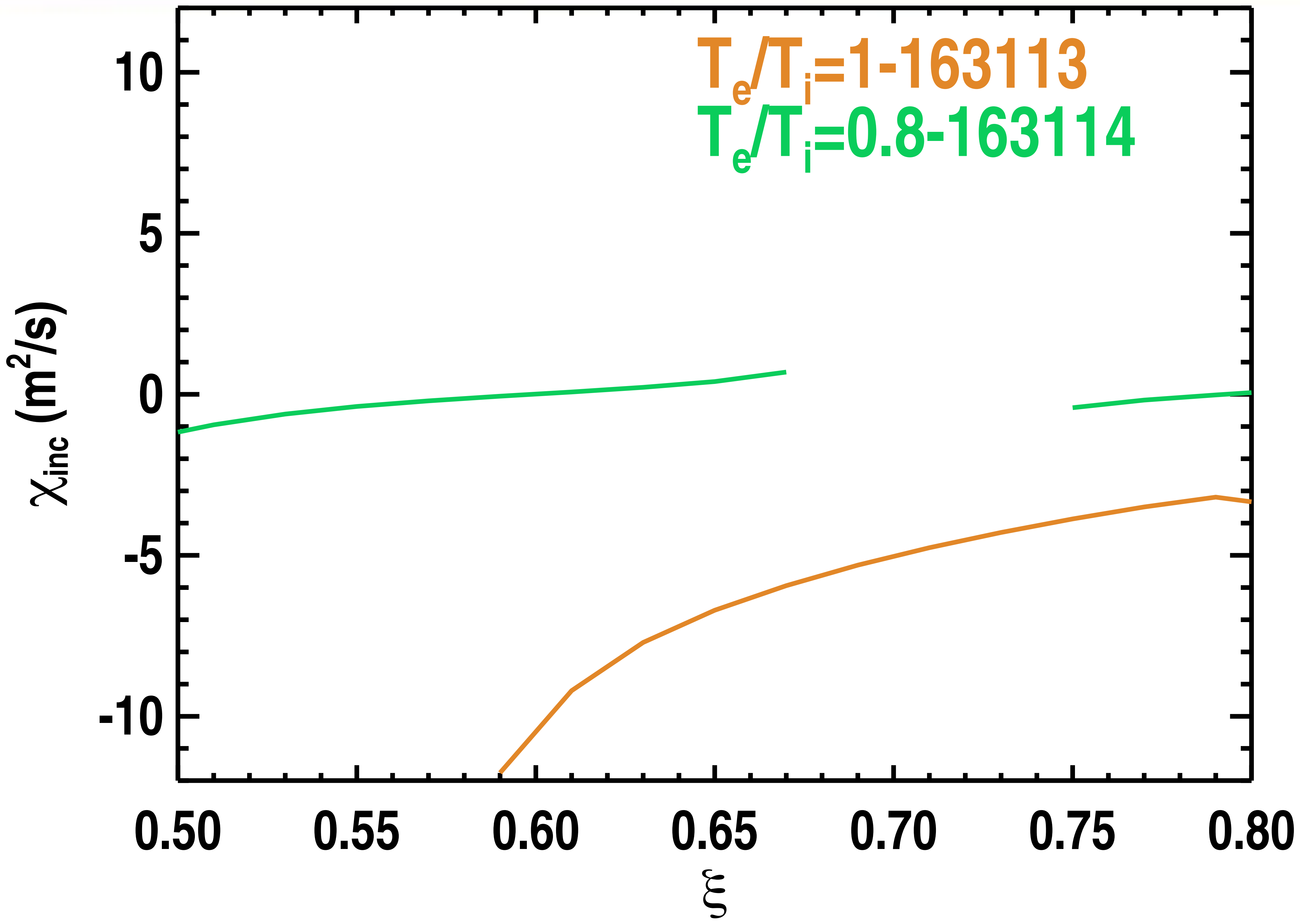

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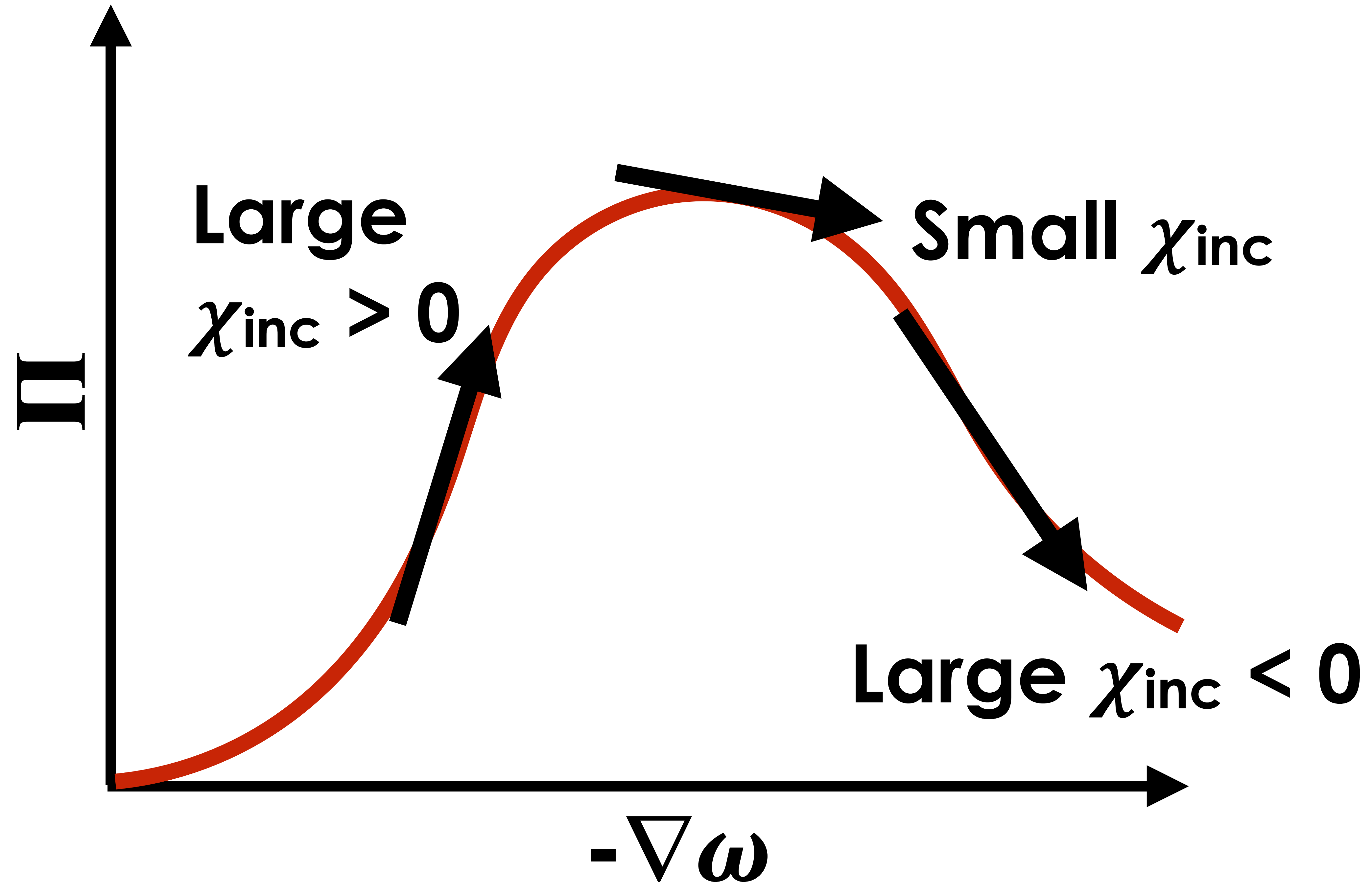

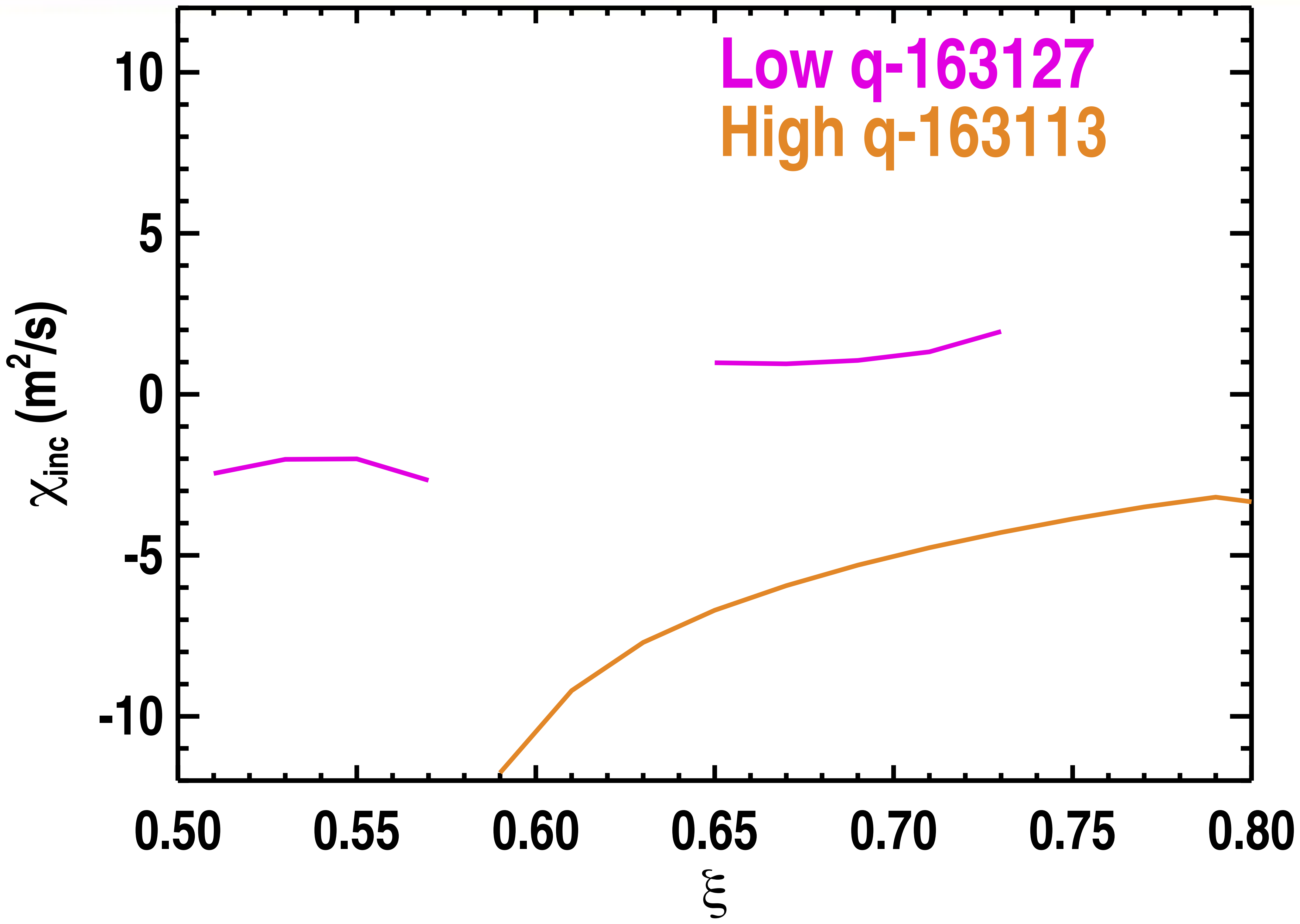

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Incremental Transport Comparisons with TGLF Improve for Lower q and Lower ν*

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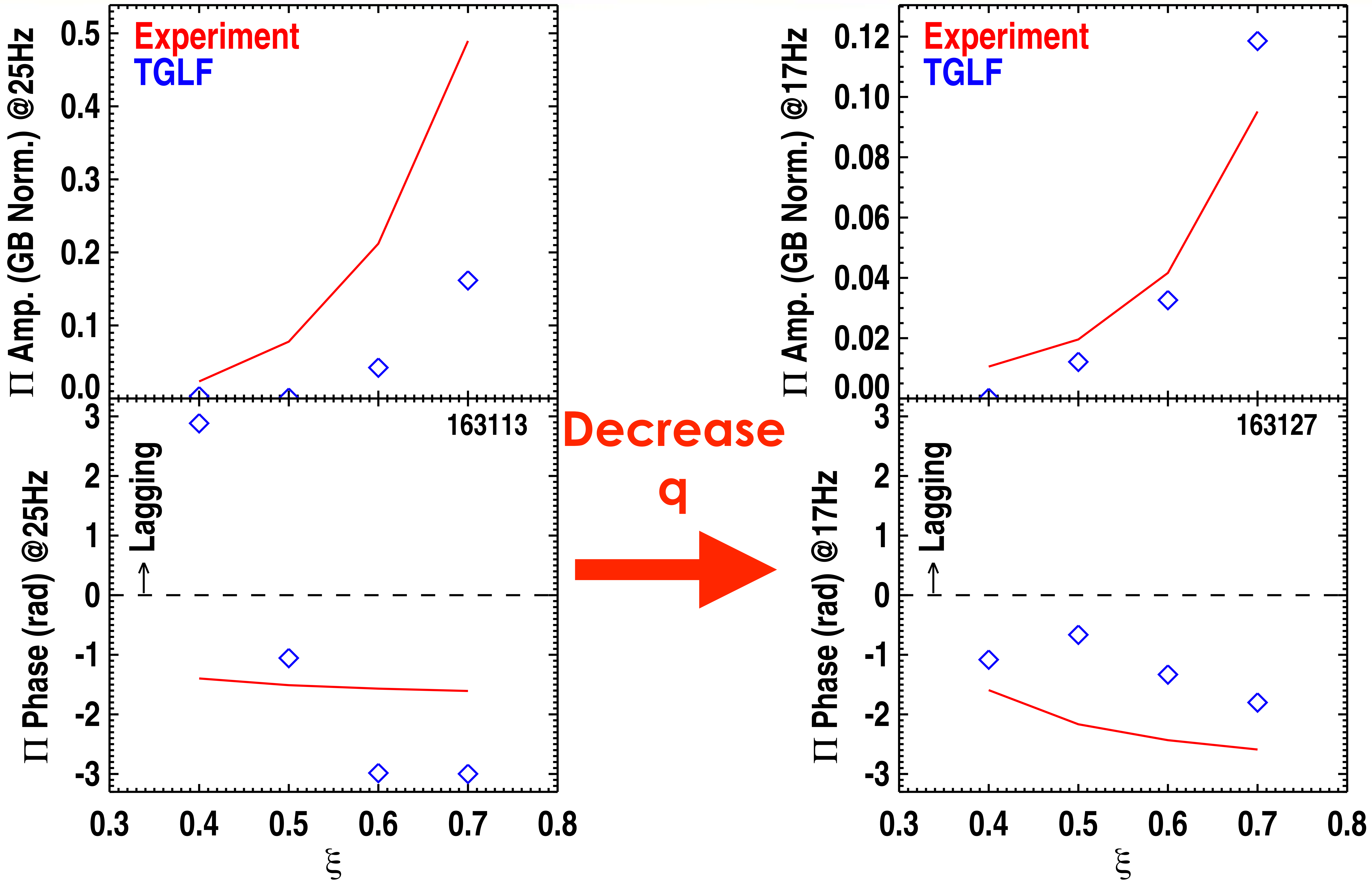

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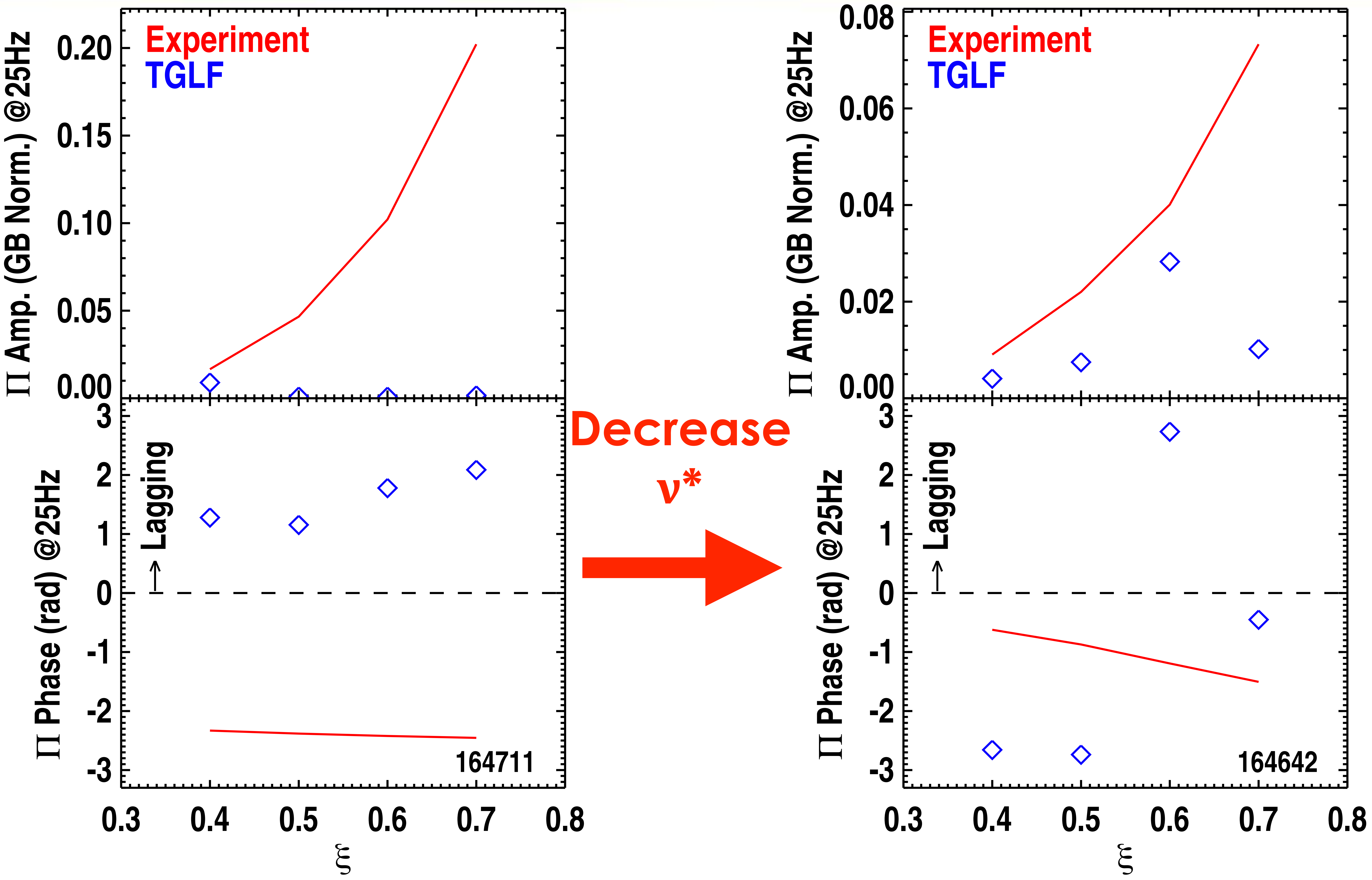

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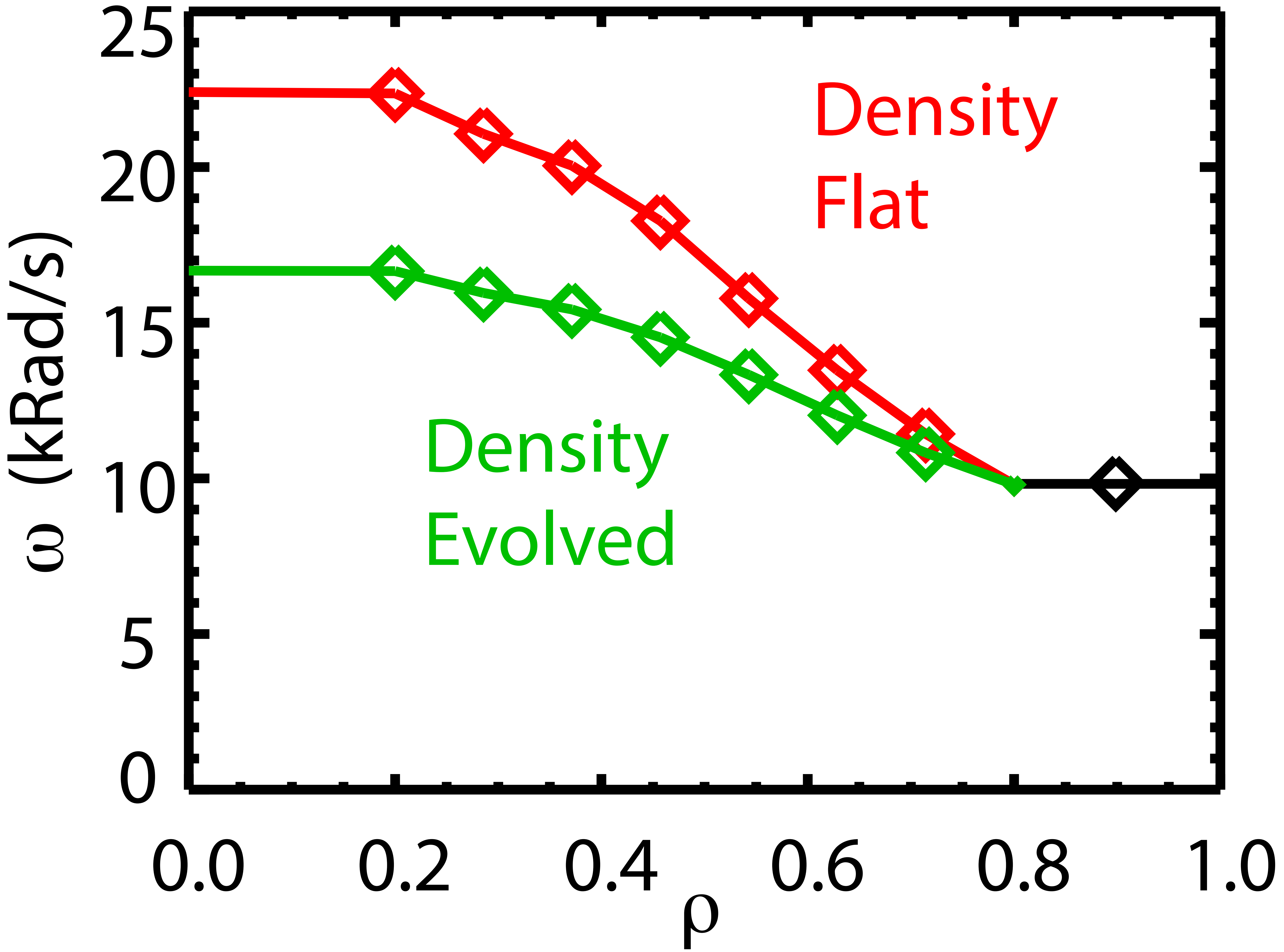
Rotation Profile Predicted for ITER with Edge Intrinsic Torque Boundary and TGLF Transport Increases Performance

- **10 krad/s B.C., TGLF/TGYRO used to predict core rotation from NBI**
  - Previous comparisons increase confidence

- **Flat density has higher rotation, self-consistent particle transport has lower rotation, higher Q_{DT}**
  - This rotation yields ~35 kV/m Er, 3X grad-pressure term[1], simulations used high ExB ordering



[1] Budny , Nucl. Fusion **48**, 075005 (2008)
[2] Liu, Nucl. Fusion **49**, 035004 (2009) [3] Berkery, Phys. Rev. Lett. **104**, 035003 (2010)

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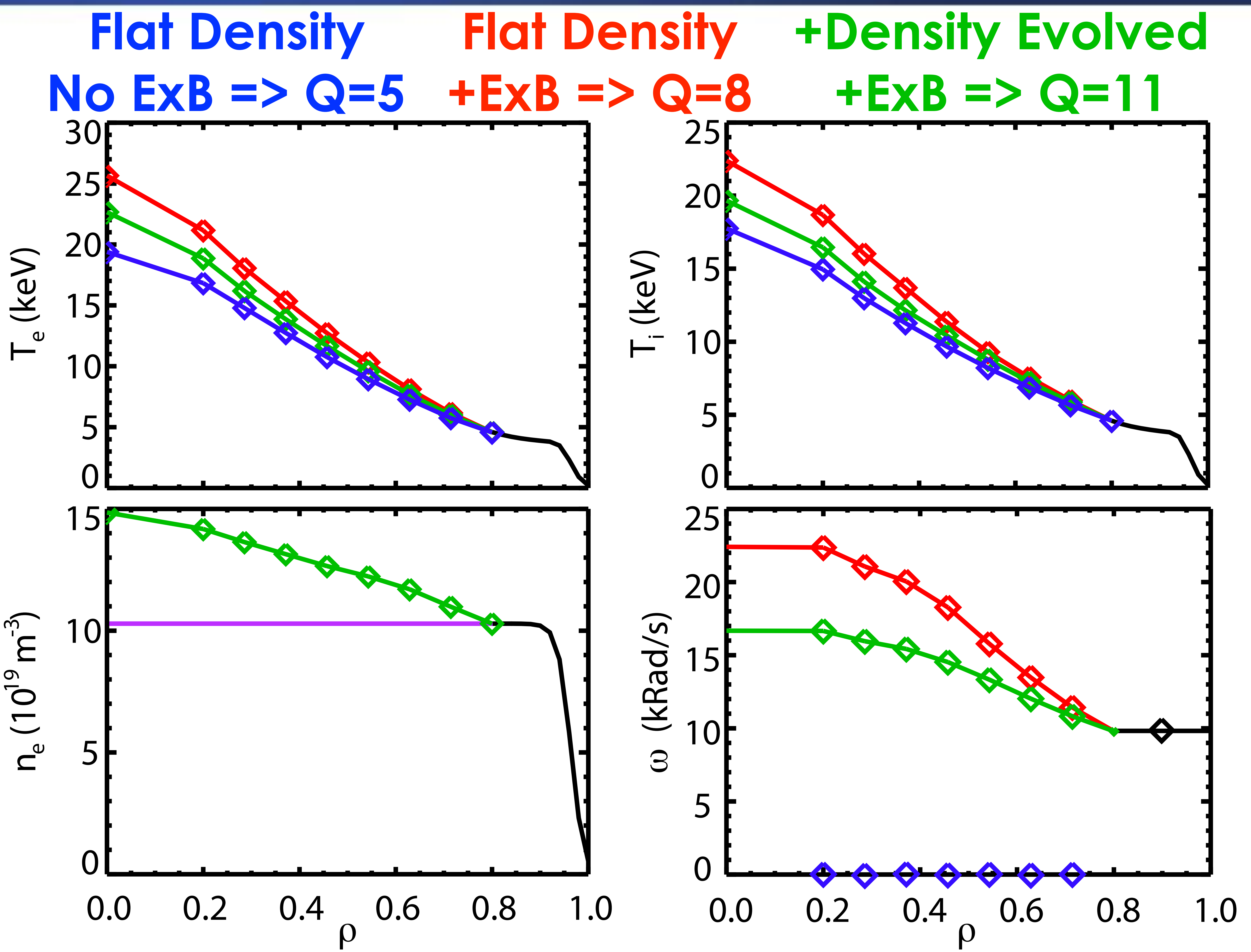
- **Alfvén Mach number=0.01, further study needed to determine RWM stability[2,3]**



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Rotation Is a Complex Nonlinear Problem at the Root of Determining Burning Plasma Performance

- **The interaction of rotation and plasma dynamics is an extremely rich subject, and even when focusing on just the most critical needs of burning plasma design, there are several important area where increased understanding is needed**
  - H-mode transition physics
  - MHD stability and interaction with rotation
  - 3D field effects on rotation
- **Dimensionless parameter analysis predicts intrinsic rotation that will be significant in ITER, motivating further study of this area**
- **Confidence in rotation predictions needed to determine possibilities of harmful MHD or ELM operating scenarios**
- **Transport models show significant effects of ExB shear on overall ITER performance with significant room leftover for the influence of poloidal rotation**
  - Especially in light of recent multiscale results[1]

[1] Holland, Nucl. Fusion **57**, 066043 (2017)