Hysteresis as a Probe of Turbulent Bifurcation in Intrinsic Rotation Reversals on Alcator C-Mod

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Outline

- **Why study hysteresis?**

  What is rotation reversal hysteresis, and what can it tell us about turbulence?

- **Experimental characterization of hysteresis on C-Mod**

  What is experimentally observed in hysteresis, and can we infer any changes in turbulence?

- **Understanding observations through quasilinear modelling**

  Can we use reduced models to identify a candidate theory for the reversal, despite the complexity of plasma turbulence?

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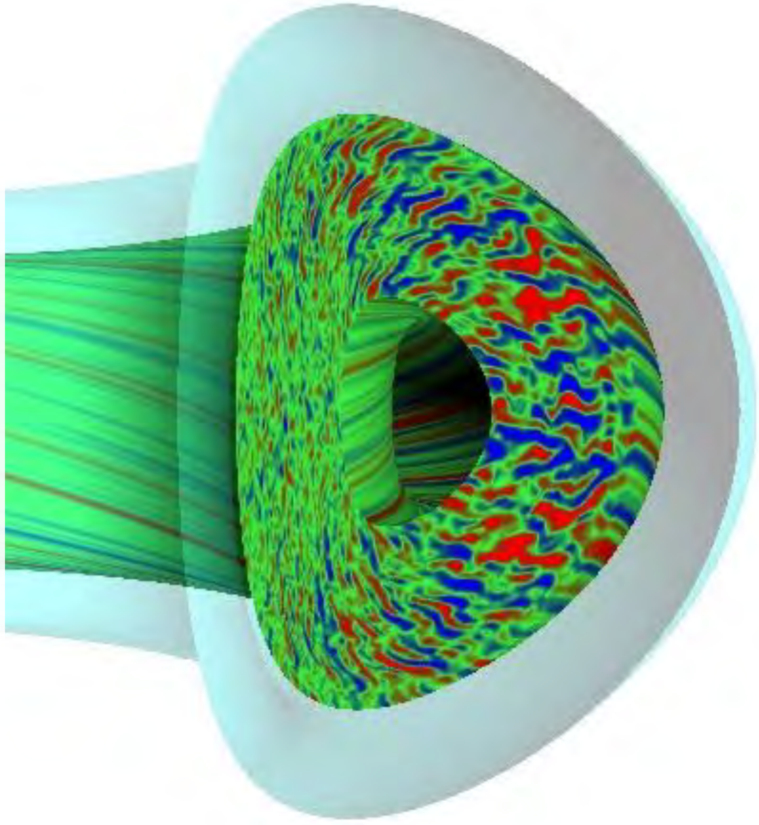
Focus: Turbulent Transport of Heat and Momentum in Tokamaks

Two Major Questions:

- **Energy Confinement** – How does turbulence influence transport of injected power in the tokamak?

- **Toroidal Rotation** – When do large-scale coherent flows form from turbulence in tokamaks?
  - *Fusion energy context:* How is this interrelated with energy confinement?

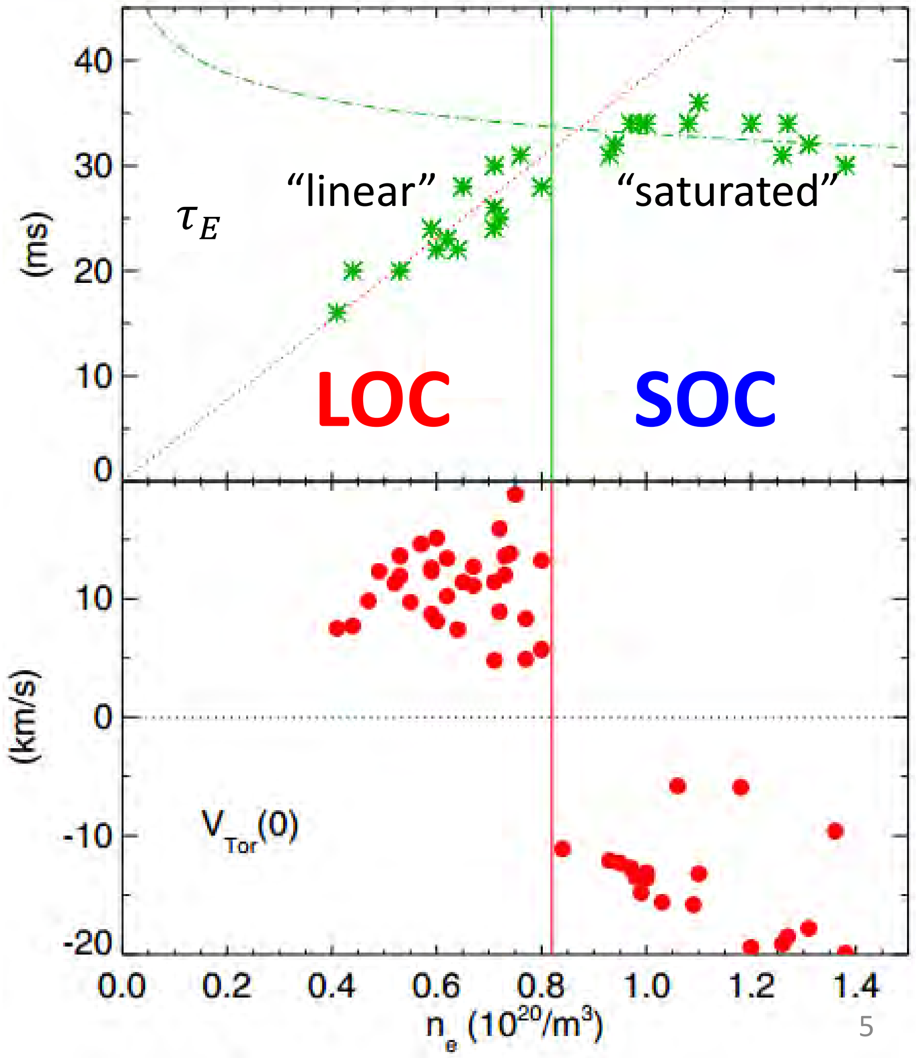


https://fusion.gat.com/theory/Gyromovies

Introduction: A Tale of Two Transitions in Tokamak Turbulence

- **LOC/SOC transition** is a universally observed transition in confinement time found in L-mode plasmas
- **Intrinsic Rotation Reversal** is a spontaneous reorganization of toroidal rotation in plasmas with no external momentum input
- Rich phenomenology observed (impurity asymmetry, density profile peaking, cold pulse propagation, etc…)[1]
  - *How are these transitions linked? Can we build a qualitative understanding of the underlying turbulent state?*

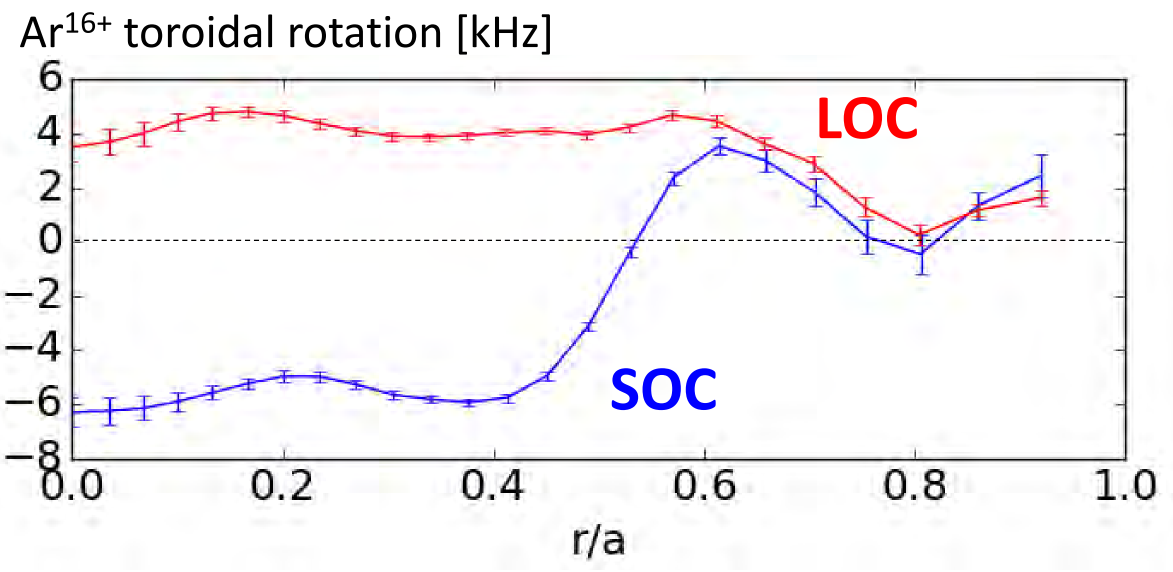
Rice NF 2013



[1]Rice NF 2013

Background: Understanding of Drift Wave Turbulence Necessary to Characterize LOC/SOC

- Gyrokinetic drift wave turbulence is responsible for most heat and particle transport in tokamaks
- Observed rotation profiles require a non-zero residual stress, driven by turbulence[1]
- LOC/SOC and reversal thought to be linked to a transition in DW turbulence from **TEM to ITG**[2,3]
- Studies based on linear stability alone have been inconclusive



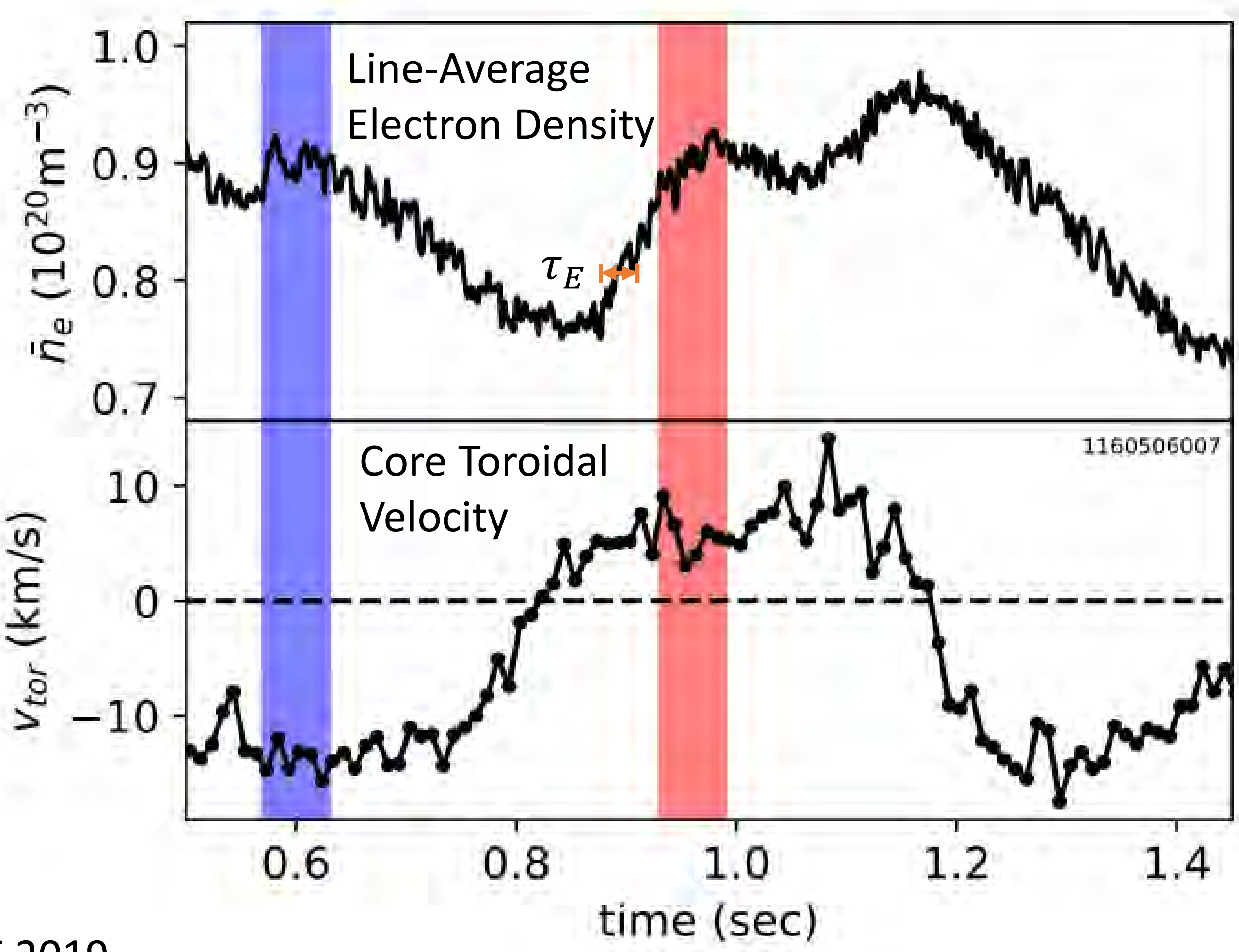
$$\frac{\Pi_{r\phi}}{\langle n\rangle} = -\chi_\phi \langle v_\phi\rangle' + V\langle v_\phi\rangle + \pi^R_{r\phi}$$

momentum flux = diffusion + pinch + residual

[1]Diamond NF 2013
[2]Diamond PoP 2008
[3]Camenen PPCF 2017

Motivation: Hysteresis Experiments Provide Controlled Probe of Turbulent Transition!

- Reversals exhibit **hysteresis,** so the same mean plasma parameters manifest different (bifurcated) rotation states
- *This Work*[1]:
    1. The physics of the dominant linear instability alone is **not enough** to explain the link between transitions
    2. A candidate **subdominant mode transition** found through quasilinear modelling which is consistent with the observed transport



[1]Cao et al NF 2019

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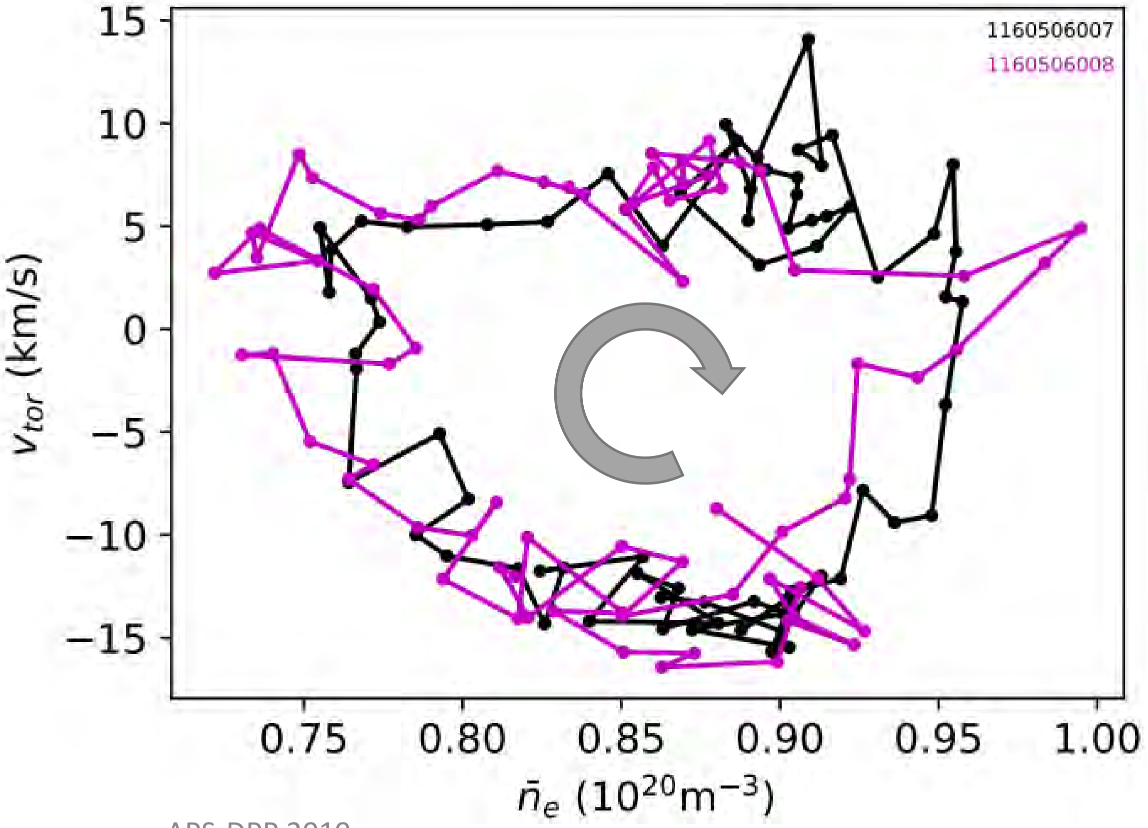
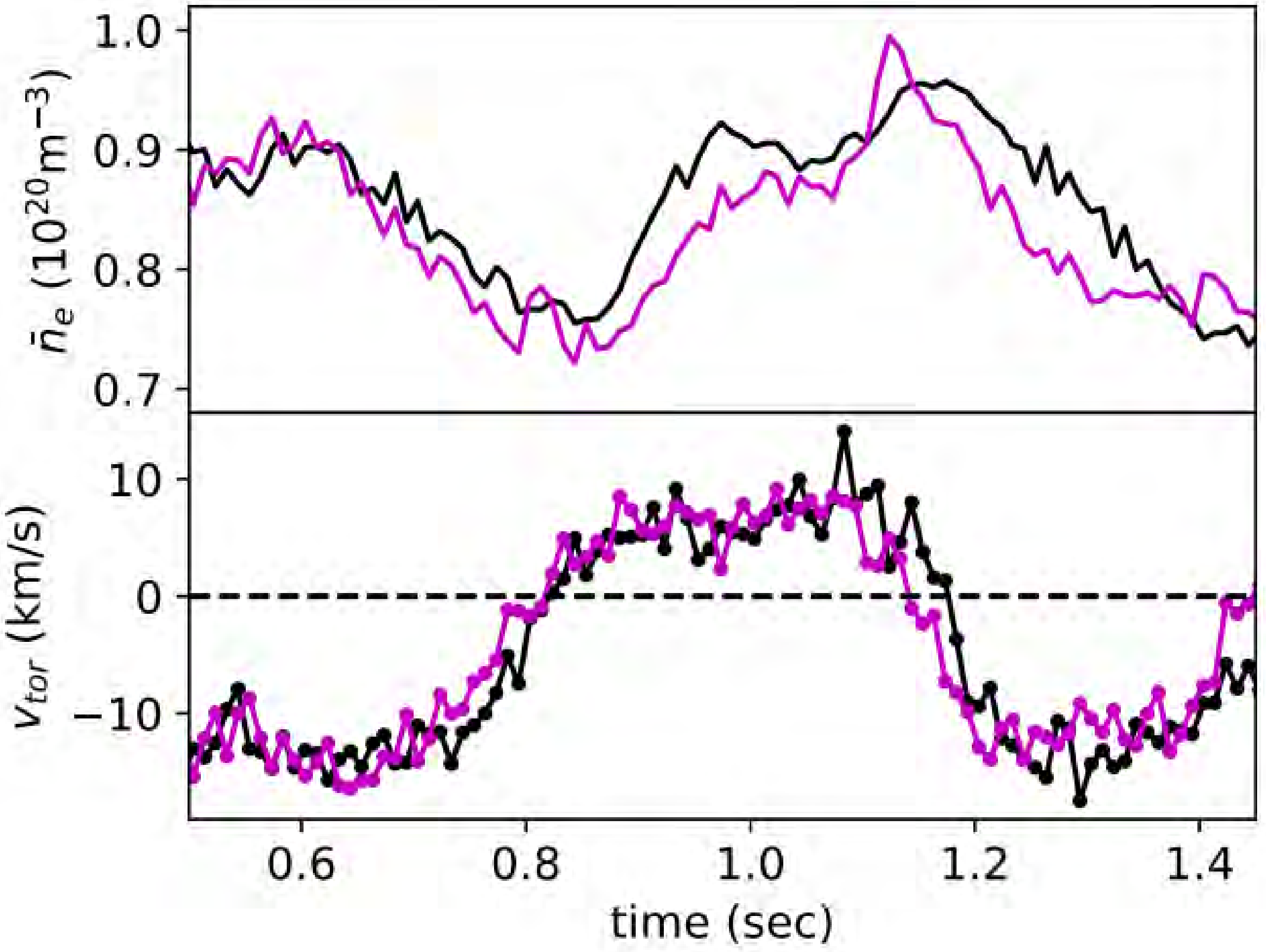
Experiments show hysteresis is a reproducible phenomenon across multiple shots

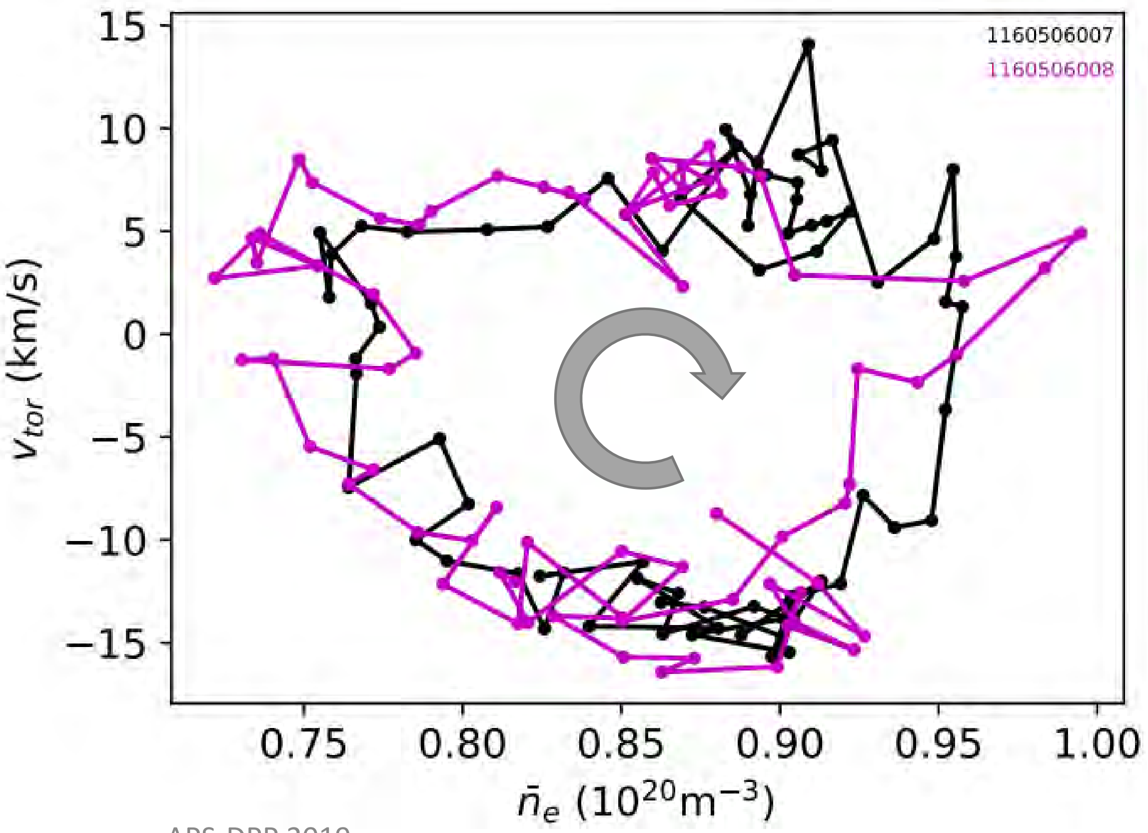
5.4 T, 0.8 MA

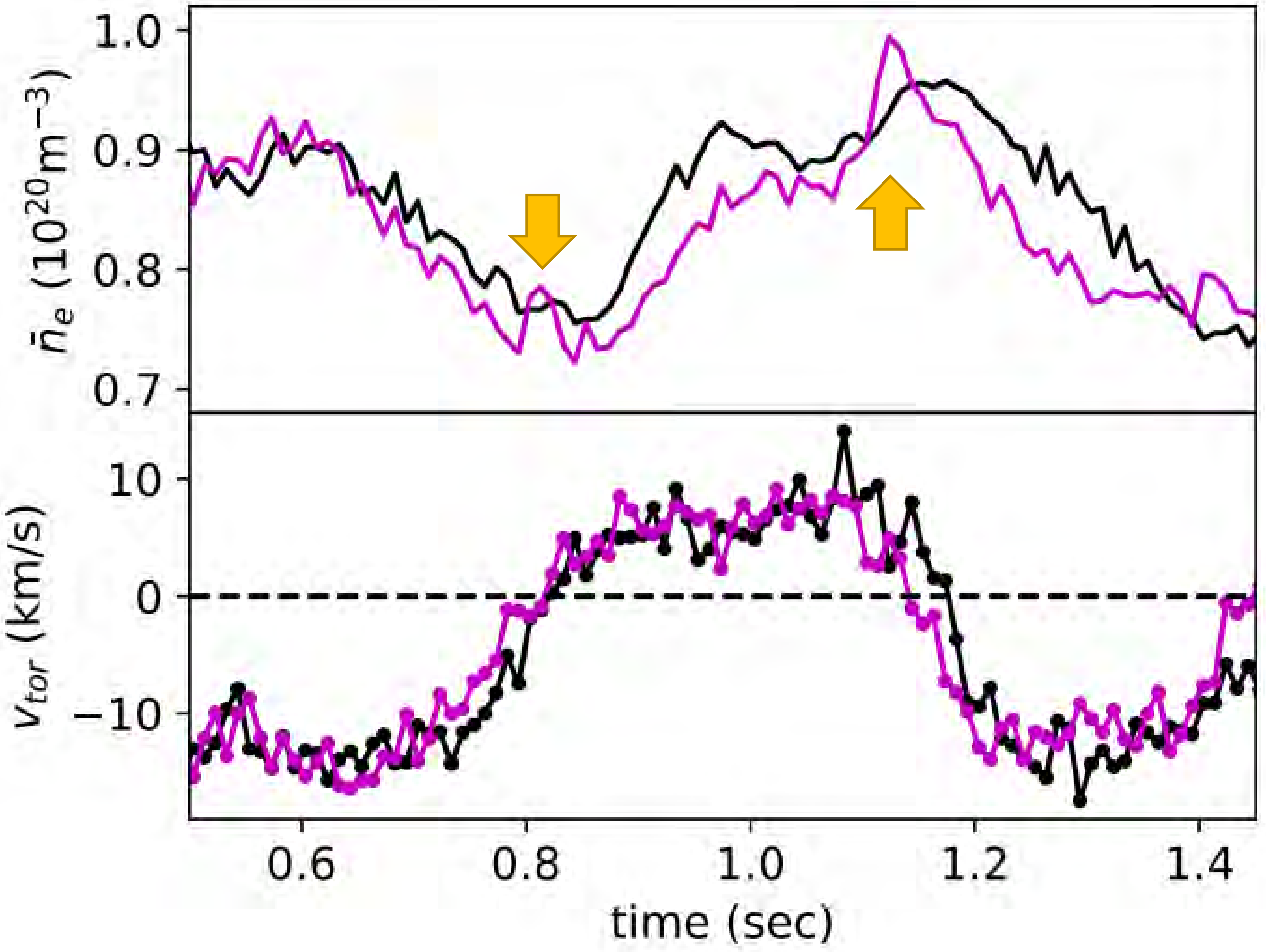




Experiments show hysteresis is a reproducible phenomenon across multiple shots

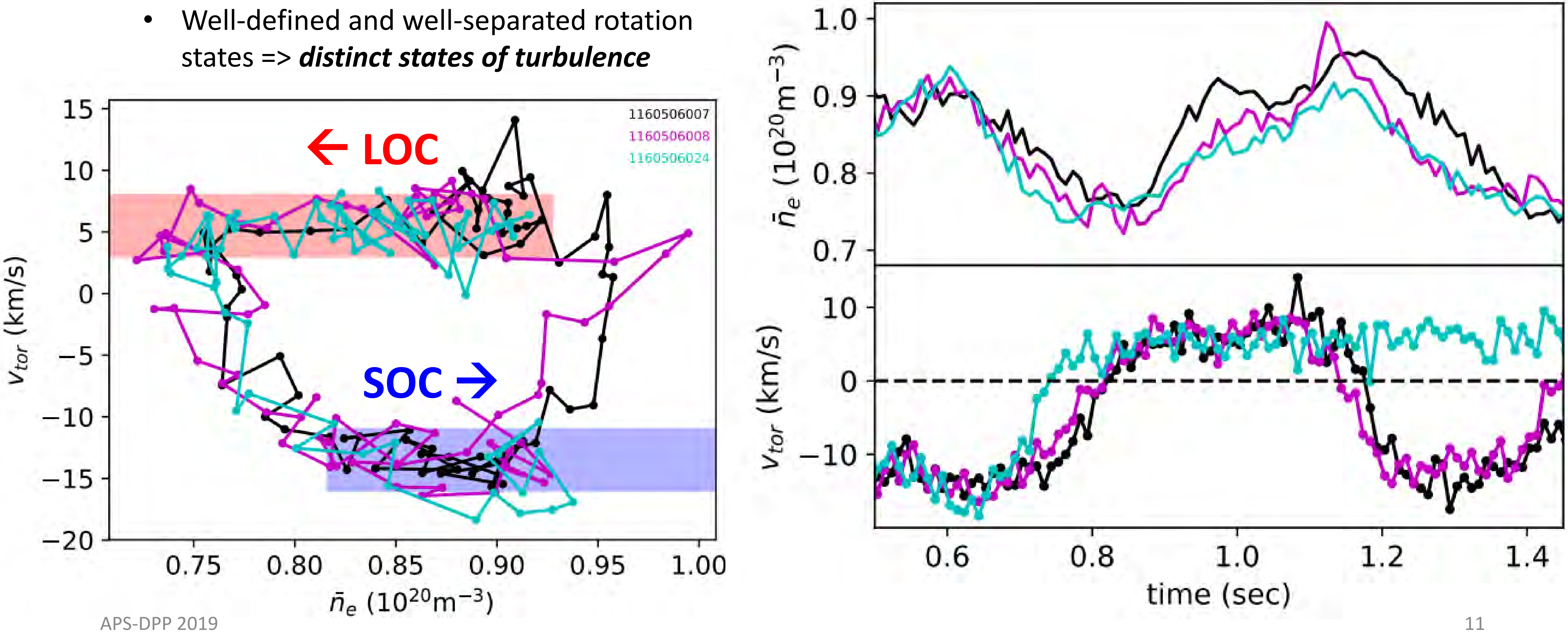
- Hysteresis robust to perturbative LBO





Experiments show hysteresis is a reproducible phenomenon across multiple shots

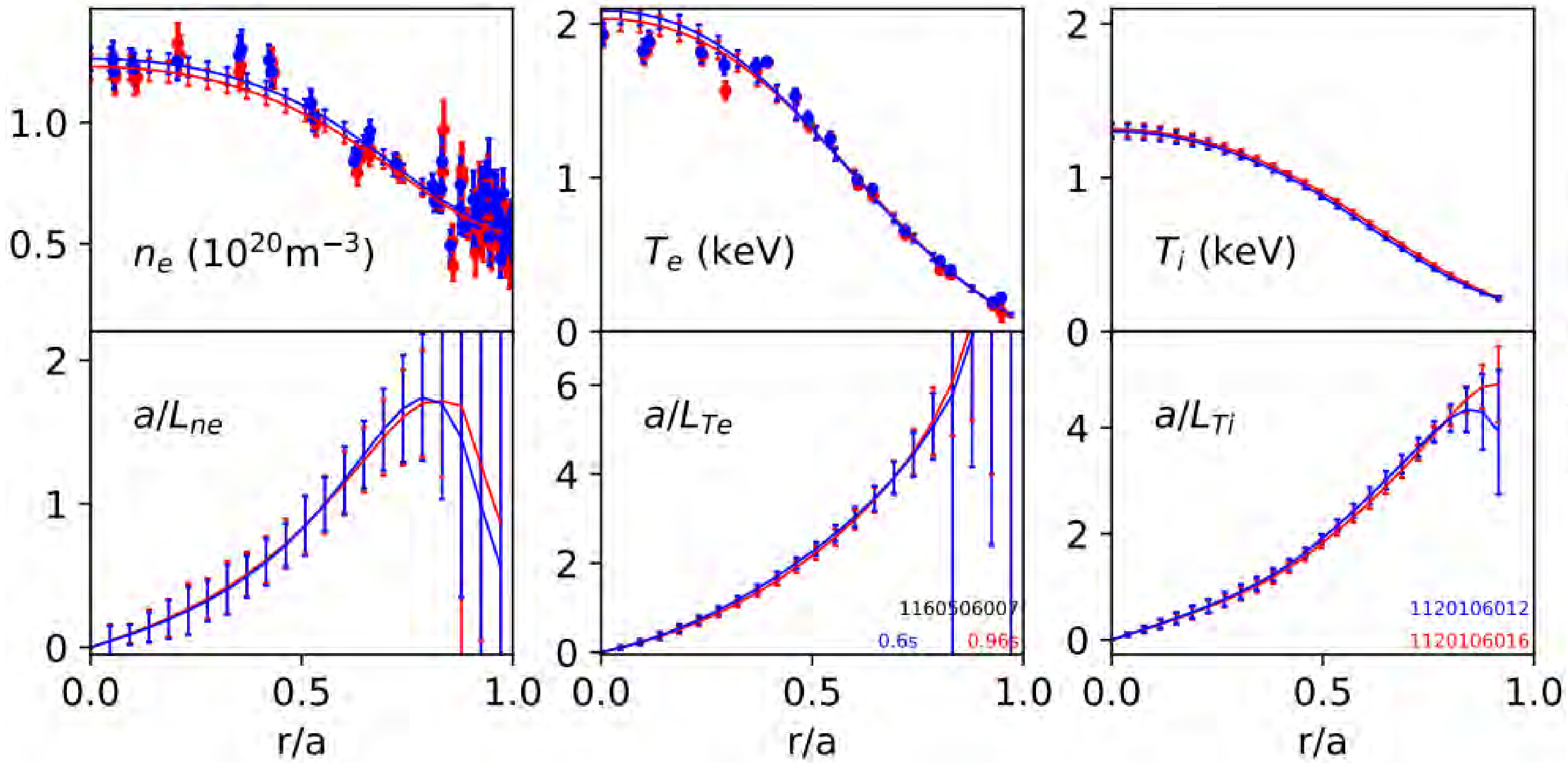
- Hysteresis robust to perturbative LBO
- Well-defined and well-separated rotation states => ***distinct states of turbulence***

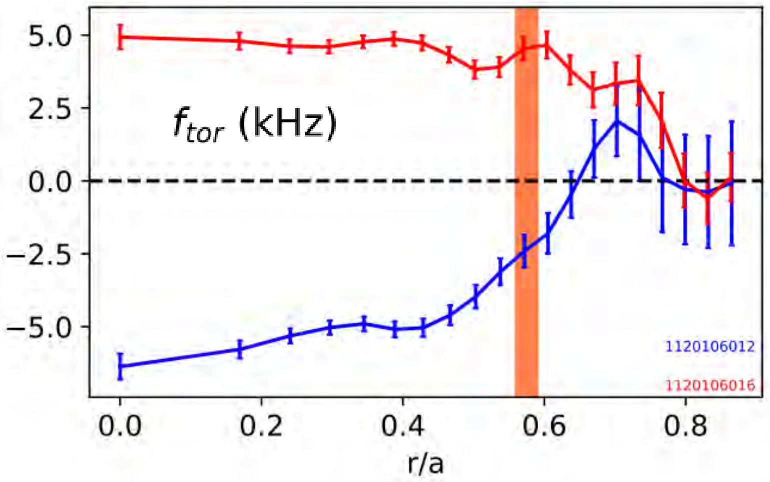


Nearly Indistinguishable Density and Temperature Profiles Can Lead to Different Rotation States

- Profiles are shown here for **LOC** (t=0.96 s) and **SOC** (t=0.6 s)
  - Electron profiles from same discharge (Thomson, GPC-ECE)
    - error rigorously estimated with GPR[1]
  - Ion profiles from different but matched shots (HIREXSR XICS)

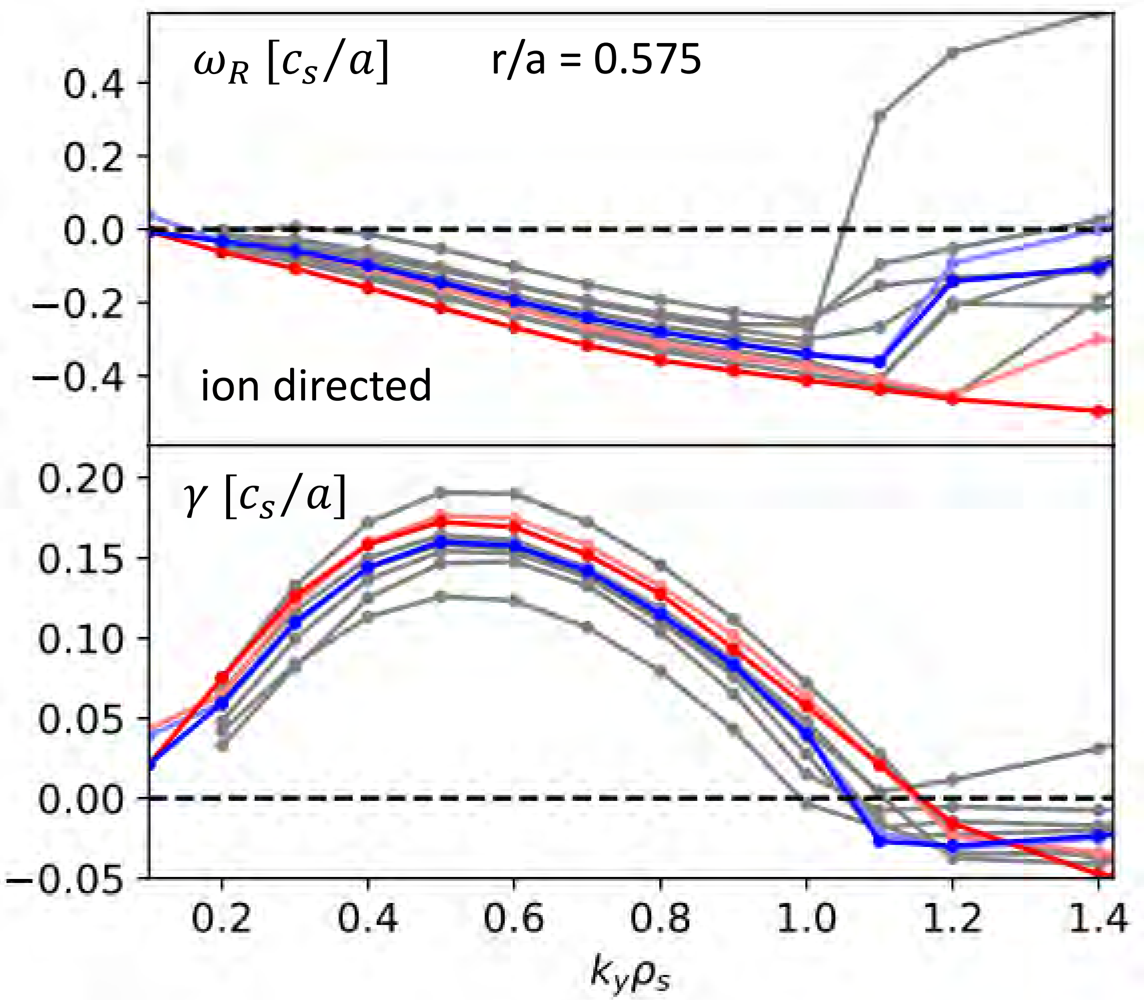
[1]Chilenski NF 2017





Linear Gyrokinetic Simulations Show Mode Stability Unchanged across LOC/SOC Transition

- Linear CGYRO run for multiple times in the same shot in rotation reversal region
  - Matched profiles from **LOC** and **SOC**
  - ±1σ scan from SOC, shown in gray
- Ion-scale instabilities robustly remain ion-directed near transition – ***change in dominant linear instability not sufficient to explain LOC/SOC transition!***
  - Consistent with previous work on Alcator C-Mod and AUG plasmas[1,2,3]
  - Note: <2σ from TEM/ITG boundary
- Motivates a need to look at **subdominant modes** to diagnose turbulent state



[1]White PoP 2013
[2]Sung PoP 2016
[3]Erofeev NF 2017

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Separation of Linear and Nonlinear Physics: Quasilinear Transport Approximation (QLTA)

- In linear mode QLTA (mQLTA), flux is given by the sum over modes of a quasilinear weight (***linear eigenmode structure***) times a mode intensity (***nonlinear saturation***)

$$\mathbf{Flux} = \sum_k \mathbf{weight} \cdot \mathbf{intensity}$$

$$Q_{e,\mathrm{turb}} = \sum_k W_{Q_e,k} \left\langle \bar{\phi}_k{}^2 \right\rangle$$

- *Note on Applicability*: Weights used in mQLTA match weights from fully nonlinear simulation[1]; cross-phases match experiment[2,3]

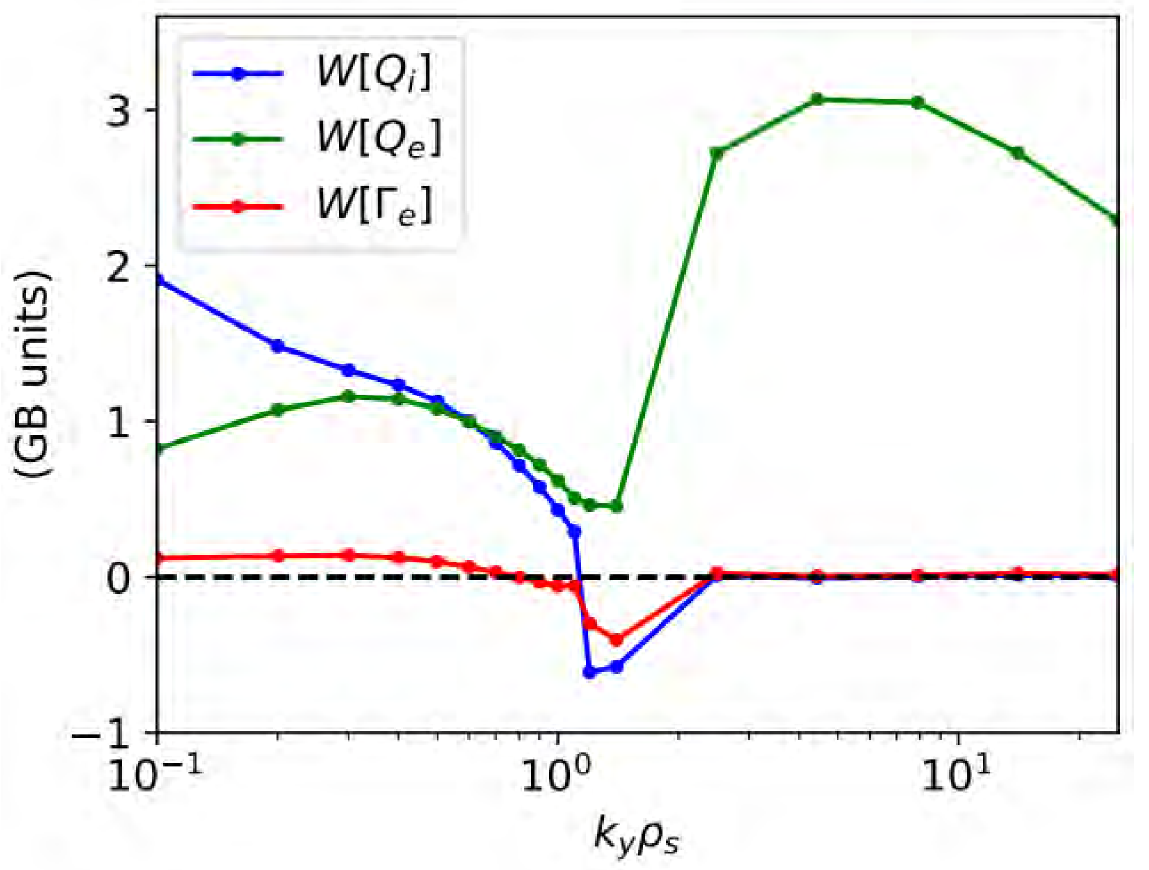
[1]Waltz PoP 2009
[2]White PoP 2010
[3]Freethy PoP 2018

mQLTA: Experimental Fluxes Provide a Constraint on Nonlinear Mode Saturation Levels

$$\textbf{Flux} = \sum_{k} \textbf{weight} \cdot \textbf{intensity}$$

- **Turbulent Fluxes** inferred from power balance (TRANSP - NEO)
- **Quasilinear Weights** from Linear Gyrokinetic Simulation (CGYRO)
  - *Example*: The only non-zero weight on high-k modes is electron heat flux, so they only contribute to electron heat flux
- Can't directly invert equation to solve for mode intensities

Quasilinear Weights, r/a=0.575



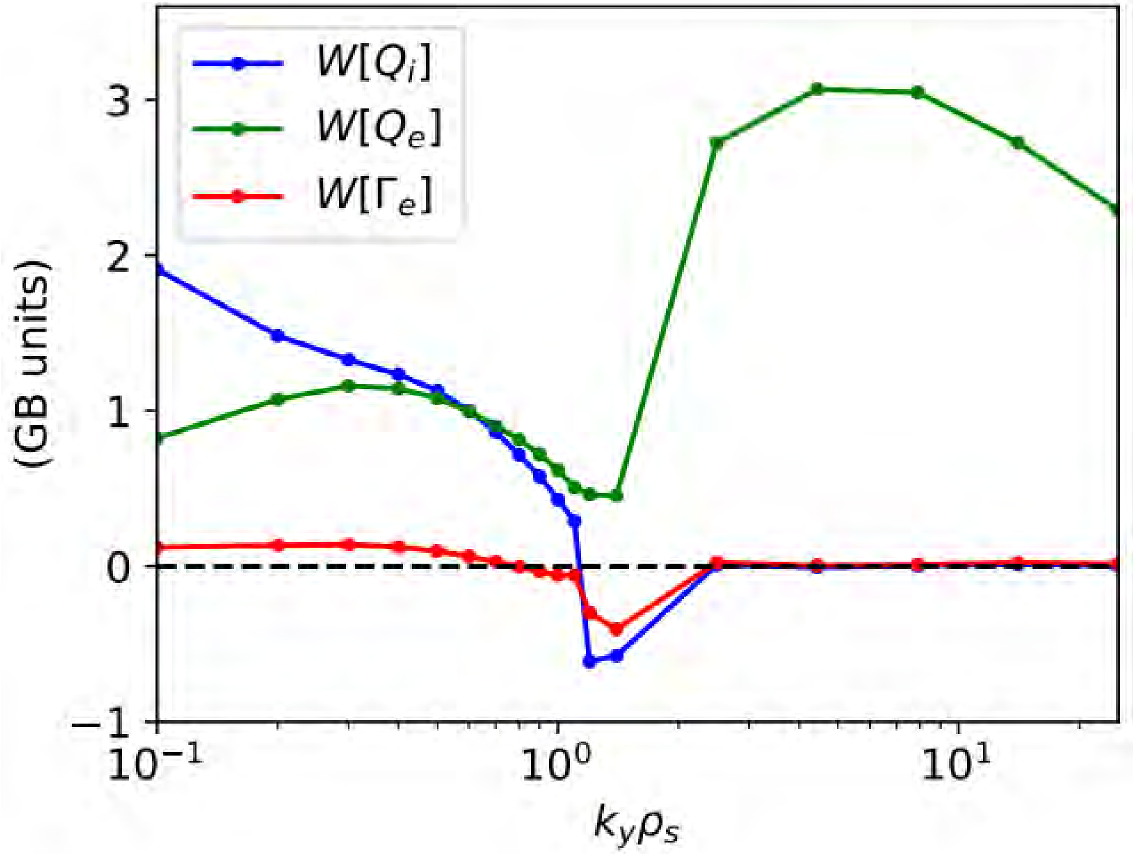
Reduced Family Model Allows Understanding Mixed Mode Picture

- Not interested in detailed shape of spectrum, only general trends
- Construct a reduced model that lumps related modes into 'families':

$$\textbf{Flux} = \sum_{\text{families}} \textbf{weight} \cdot \textbf{intensity}$$

- Greatly reduces the number of unknowns, and allows for the experimental fluxes to be used meaningfully as constraints

Quasilinear Weights, r/a=0.575



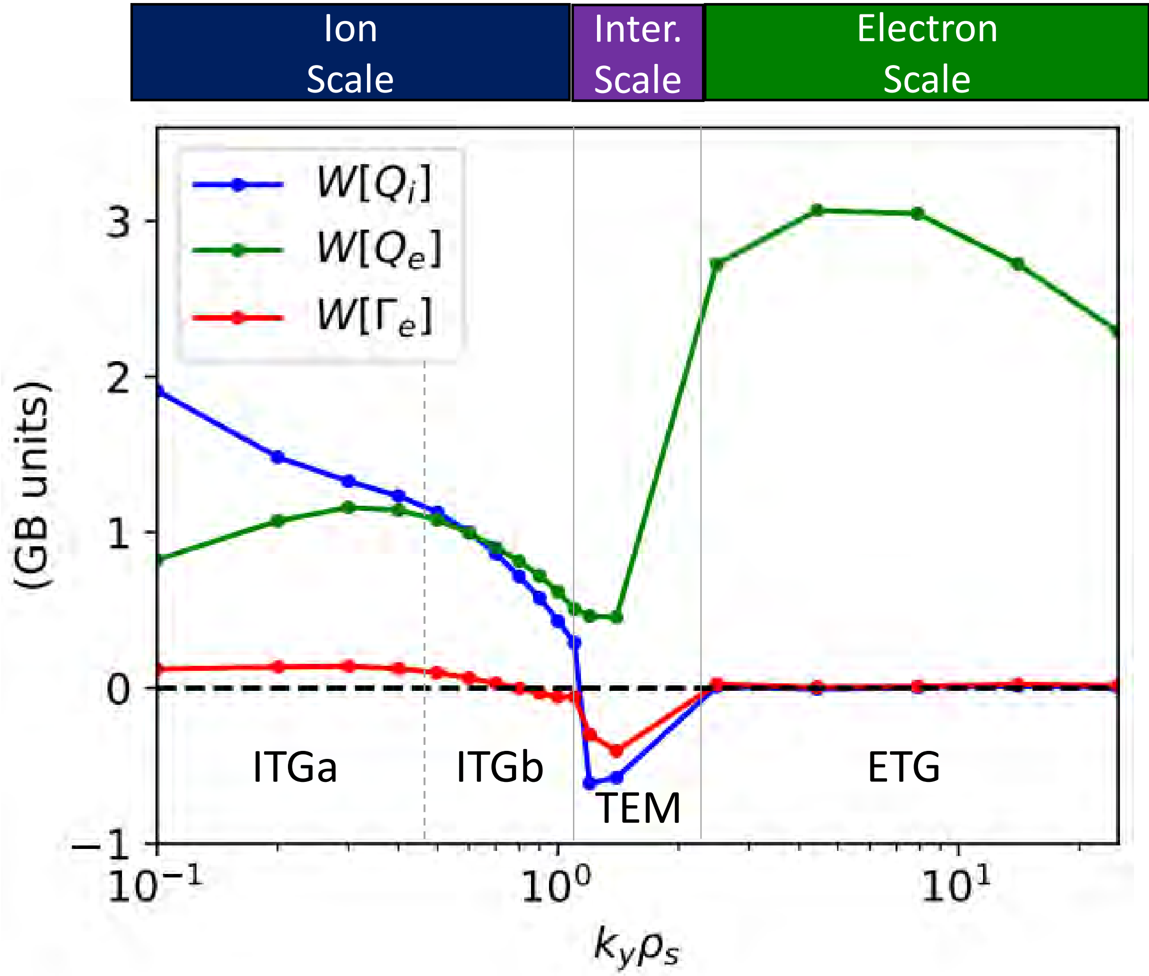
Reduced Family Model Allows Understanding Mixed Mode Picture

$$\textbf{Flux} = \sum_{\text{families}} \textbf{weight} \cdot \textbf{intensity}$$

ITG (a,b) Ion-scale, ion-directed modes; separated into low-k (a) and mid-k (b) based on particle transport:
(a) Net outward particle transport
(b) Roughly balanced particle transport

TEM Intermediate-scale $k_y \rho_s \gtrsim 1$, electron or hybrid-direction modes; marginal modes, with inward particle pinch

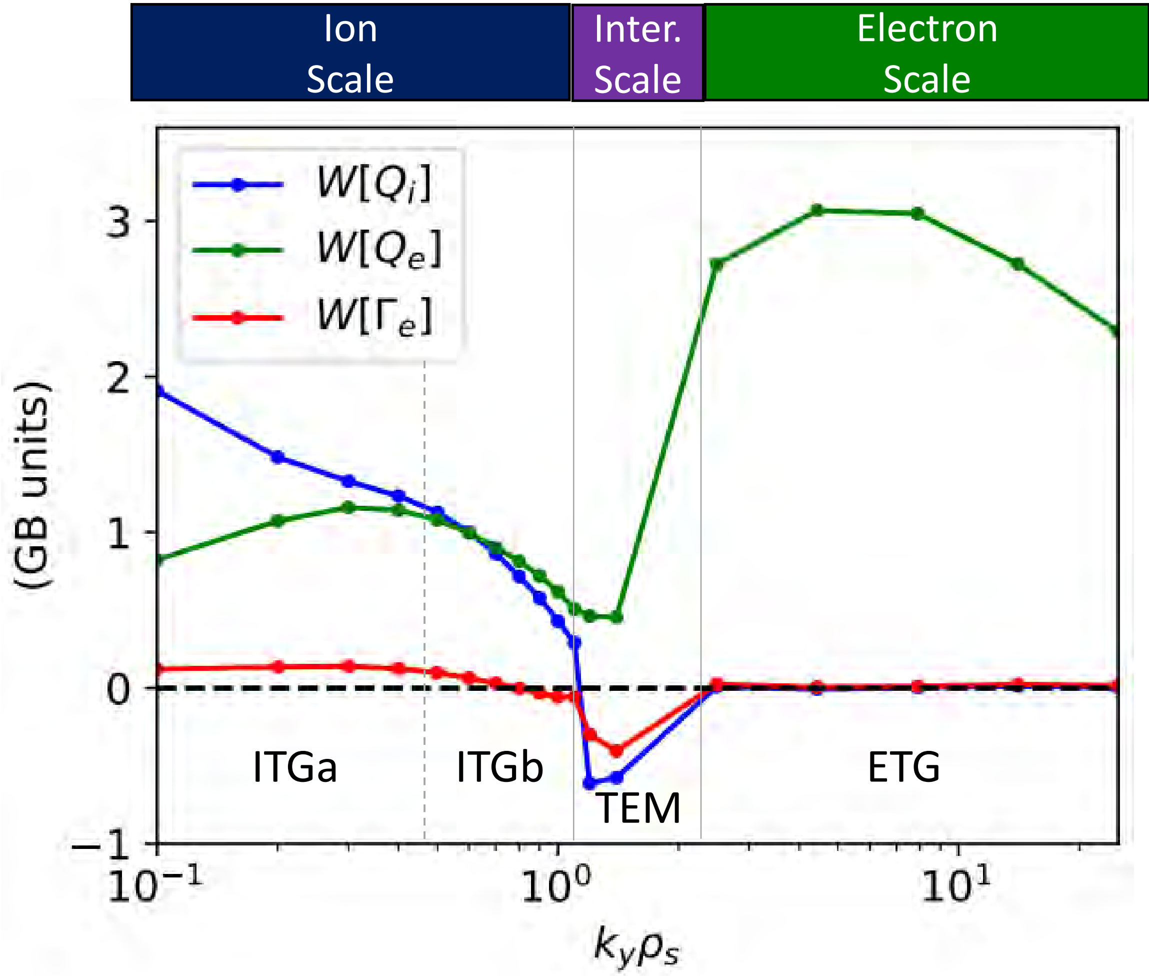
ETG Electron-scale electron-directed modes; exhausts mostly electron heat flux, ions adiabatic



Novel Candidate Subdominant Mode Transition Identified, Consistent with Observed Transport

- No core fueling, so $\Gamma_e = 0$
- To satisfy particle flux constraint:

	LOC-like	SOC-like
Active Mode Families	ITGa,b TEM ETG	ITGb ETG
Particle Flux Balance	ITGa balances TEM	Balance within ITGb



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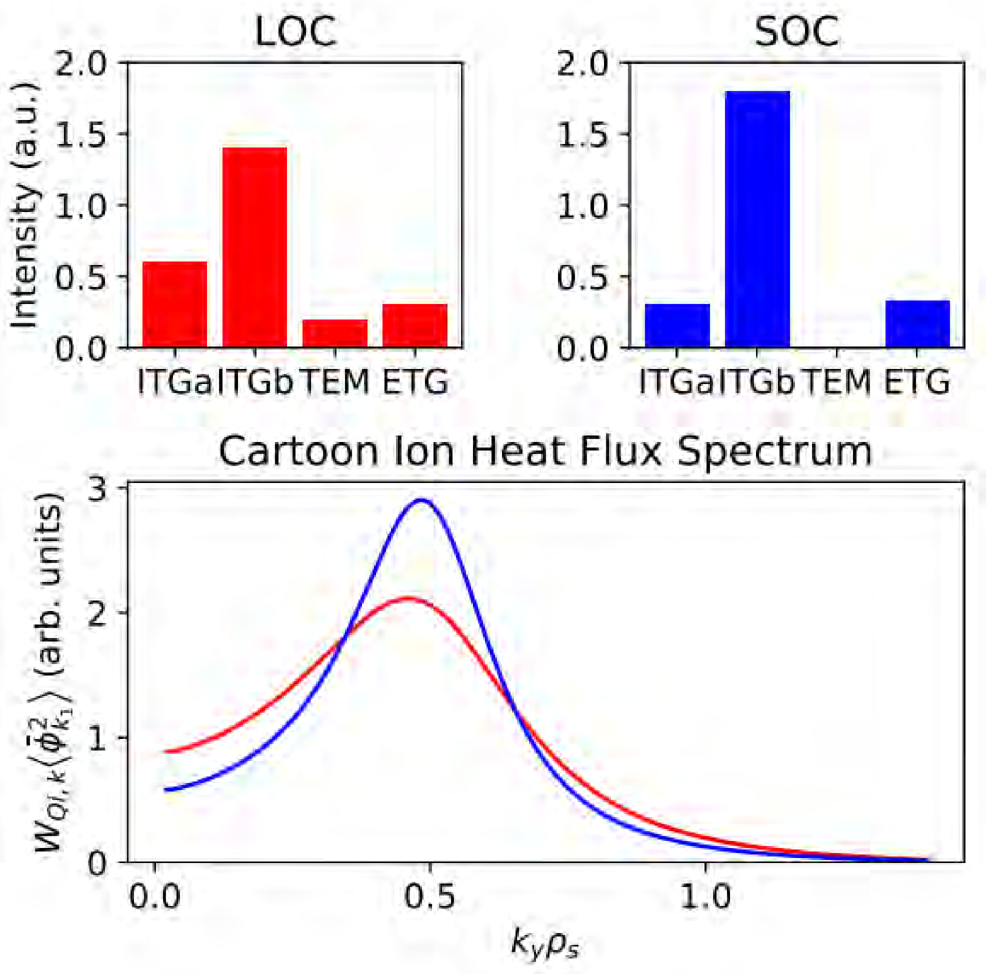

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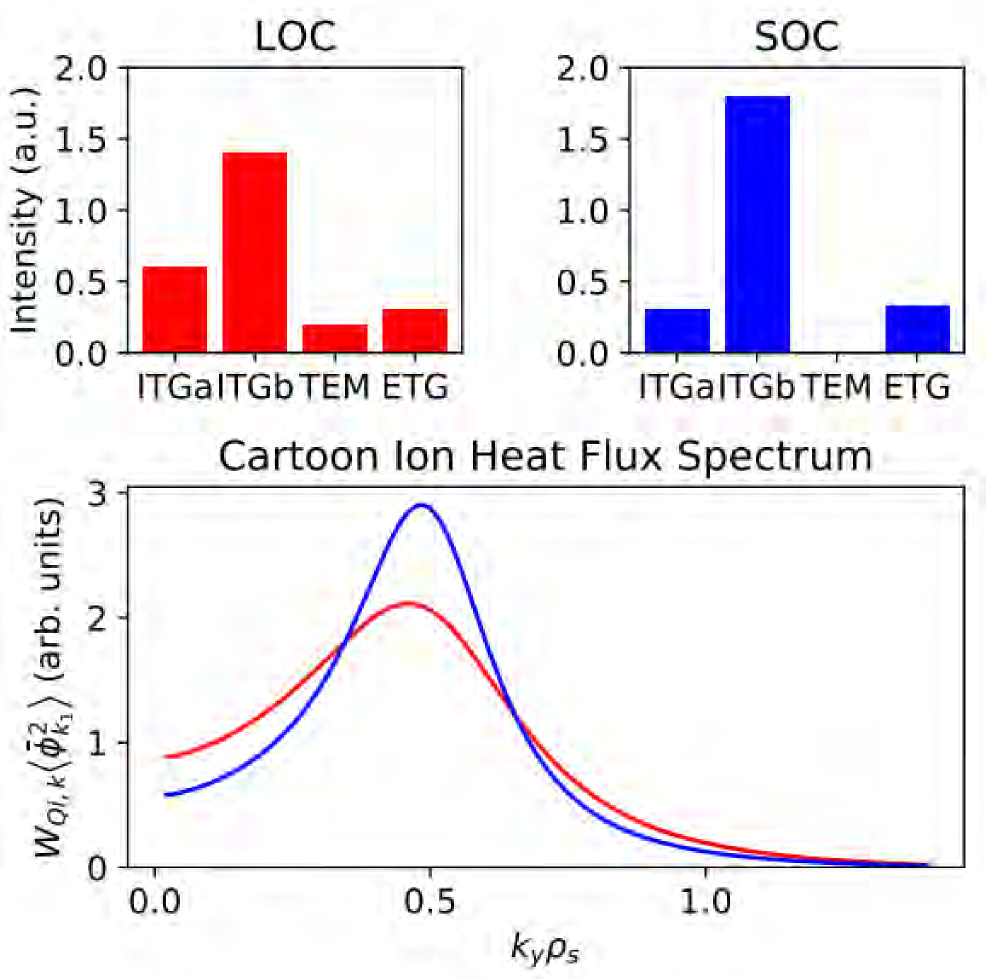
Active Mode Families	ITGa,b TEM ETG	ITGb ETG
Particle Flux Balance	ITGa balances TEM	Balance within ITGb

- Away from transition, continuity implies different transport dependencies

Electron Heat Transport	TEM and ETG	ETG dominates
Torque Balance	TEM and ITG	ITG dominates



Mechanism leading to Transition and Bistability still Unknown

Experimental Constraints on Possibilities:

1. We're on a stability boundary, so small profile changes lead to big changes in turbulence
   - Robustness to perturbative LBO seems to rule this out
2. Mean rotation profiles contribute to change in turbulence through ExB shearing
   - Reminiscent of L-H transition, next slide will discuss…
3. Change in meso-scale or micro-scale turbulent nonlinear interactions (e.g. entering/leaving weak turbulence regime)
   - QL may fail for TEMs[1,2], and shear flows affect cross-phase[3]. How to identify key physics, and what happens to QL estimates?

[1]Xiao PRL 2009

[2]Kosuga PoP 2011

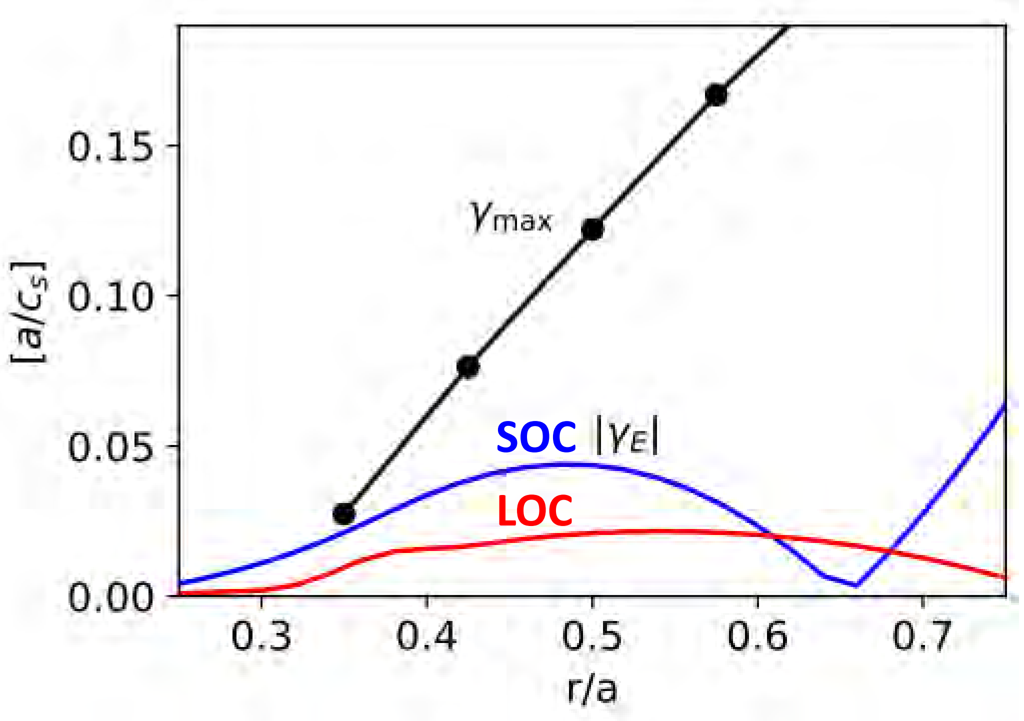
[3]Terry PRL 2001

Change in mean ExB shear across transition possibly non-negligible?

- Mean ExB shearing rate calculated from force balance

$$\gamma_E = \frac{r}{q}\frac{d\omega_0}{dr}$$

- CGYRO scans show shear is not enough to linearly stabilize observed ion modes, but could play a role in saturation of more marginal modes
  - Not conclusive based on linear arguments alone! Need to consider nonlinear interactions[1]
- Possibly amenable to reduced dynamical modelling through predator-prey (similar to L-H[2,3])



[1]Waltz et al PoP 1998

[2]Diamond et al PRL 1994

[3]Kim et al PRL 2003

Summary and Paths Forward

- Experiments show **changes in toroidal rotation** and turbulent residual stress despite **nearly identical density and temperature profiles**
  - A change in dominant linear instability alone is not sufficient to explain the LOC/SOC transition
- Quasilinear modelling identifies a candidate **subdominant ITG/TEM transition** which is consistent with the observed transport
  - Reminiscent of a "population collapse" or quenching of marginal TEM turbulent intensity
- Provides a stepping stone for future inquiry:
  - Hints towards nonlinear physics required to adapt reduced dynamical models
  - Hysteresis experiments in nonlinear global simulation to probe residual stress physics
  - Characterize turbulent fluctuations in hysteresis experiments on other machines

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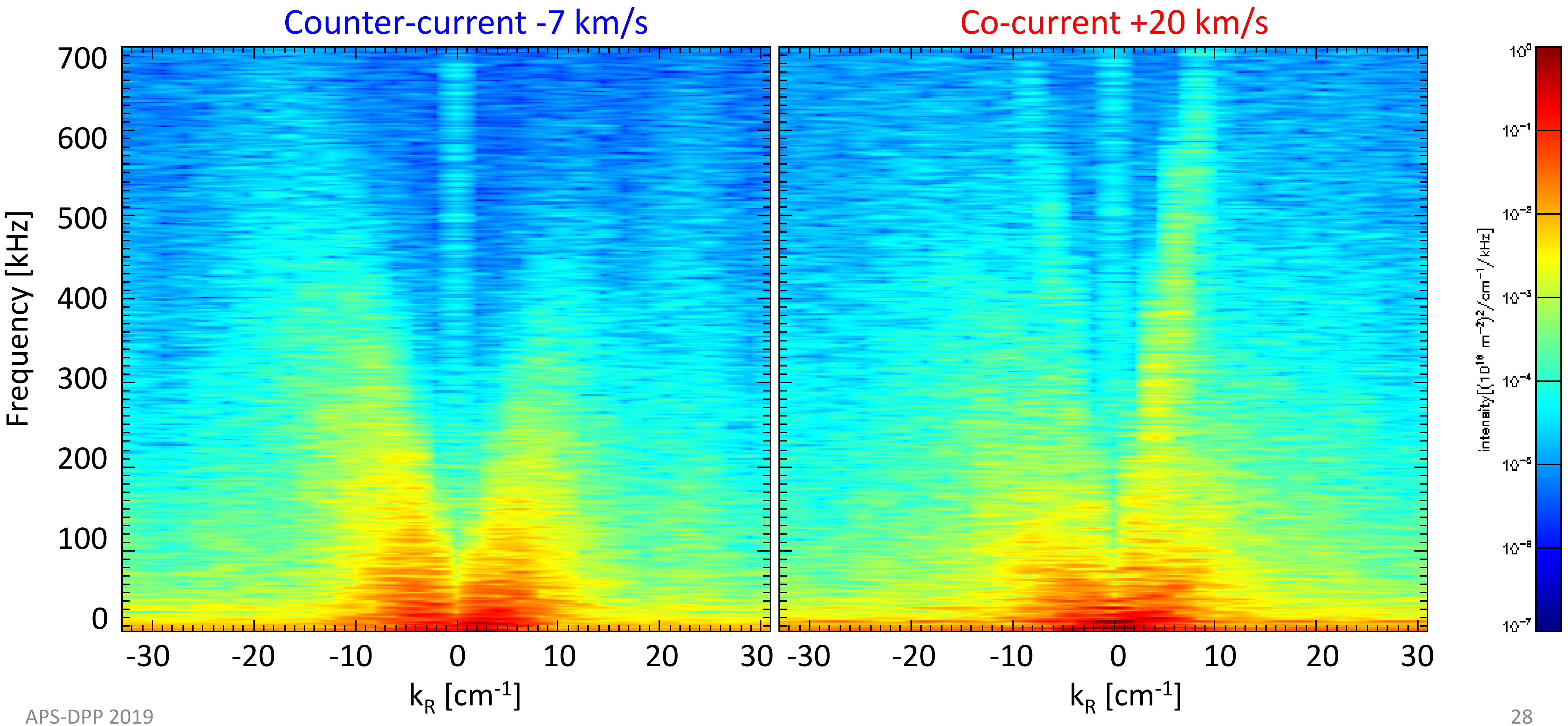
Extra Slides

What Evidence Exists for ITG/TEM Picture of LOC/SOC Transition?

- Modelling Consistent with TEM in deep LOC, ITG in deep SOC
  - Romanelli (analytic w/ mixing length), Erofeev, Grierson (Predictive Transport Modeling w/ TGLF)
  - Rodriguez-Fernandez (role of TEMs vs ITGs in determining cold pulse dynamics)
- Residual Stress physics and Theoretical Suspicions
  - Wang, Grierson (GTS papers), Hornsby (GKW)
  - Camenen, Diamond (wave group velocity in relation with momentum)
- Experimental Signatures
  - JET and Tore Supra Citrin (QC-TEMs go away at LOC/SOC; “TEMs being unstable is not enough”)

1.1 MA Ohmic – **different** toroidal rotation, **same** local profiles, **different** PCI spectra

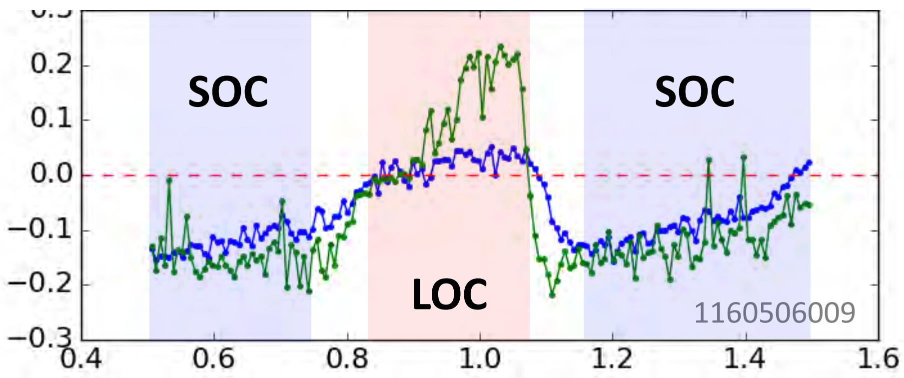


PCI Spectra provide circumstantial evidence of turbulence change in hysteresis experiments

- Circumstantial evidence suggests a sudden change in turbulence, in direction of LOC => SOC, before the reversal finishes
  - Reminder: Bistability robust to perturbative laser blow-off injection

High: 300 kHz < f < 700 kHz
Low: 50 kHz < f < 200 kHz

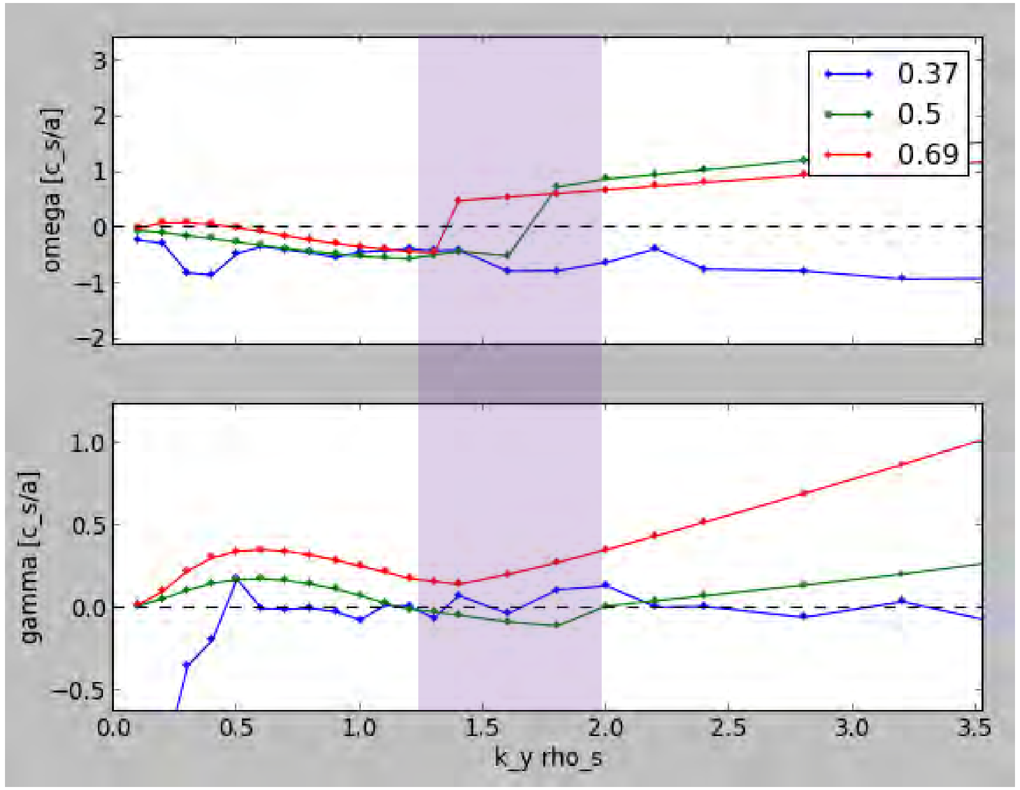
Observed $\pm k_R$ Fluctuation Asymmetry
$(P_{+k_R} - P_{-k_R})/\bar{P}$

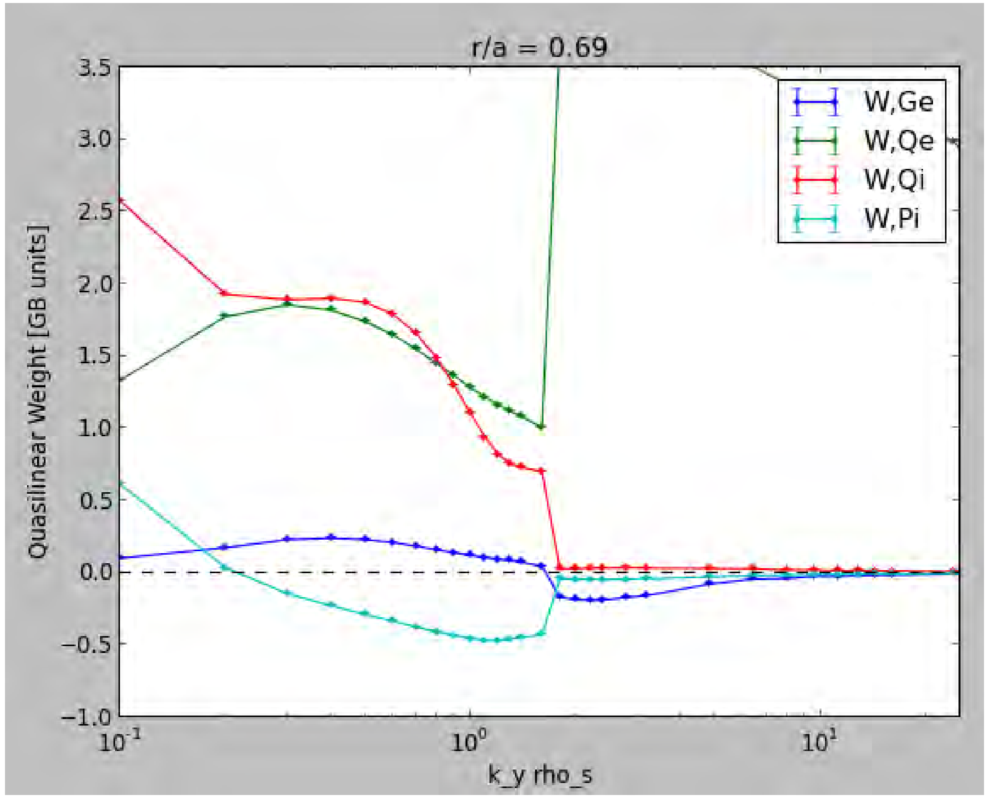


[N.M. Cao TTF 2017]

What Exactly are the intermediate-k Modes?

Appear in the crossover between TEM and ITG branches of dispersion,
when the overlap decreases, almost certainly the remnants of TEM+ITG;
unstable TEM also have inward particle pinch





Nonlinear Heat Flux Spectra Possibly Consistent with mQLTA Prediction

Heat flux spectra at r/a=0.8

042303-14 Sung *et al.* Phys. Plasmas **23**, 042303 (2016)

Peaking factor 1.5

Peaking factor 2

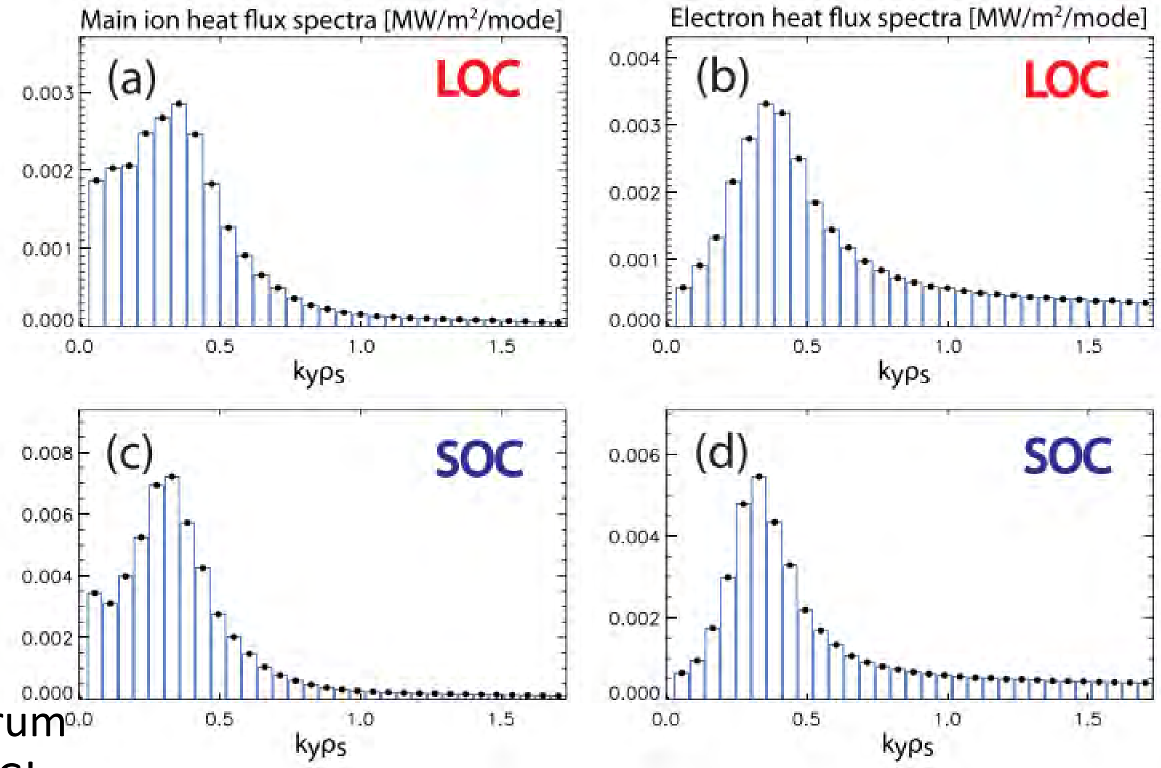


FIG. 14. Time averaged heat flux spectra on $k_y\rho_s$ in the "ion heat flux matched" runs (a) main ion heat flux spectrum in the LOC discharge (shot 1120626023) and (b) electron heat flux spectrum in the LOC discharge (c) main ion heat flux spectrum in the LOC discharge (shot 1120626028) and (d) electron heat flux spectrum in the LOC discharge.

Ion heat flux spectrum more peaked in SOC!

Ways the Quasilinear Approximation Could Fail, and Resulting Physics

Possibilities include…

1. Wave-particle nonlinearity (Kubo number)
   - ITG Kubo # good, TEM Kubo # > 1
2. DW-DW interactions
   - TEM dispersion weak at ion-scales
3. DW-Flow shear interaction (note difference between trapped and passing particle response)
   - Hahm-Burrell Shearing parameter

Calculating Gradients and Uncertainties has "Coastline Paradox" Problem

- Coastline measurement paradox involves the measurement of arclength, which depends on derivative

$$\int ds \approx \sum\sqrt{\Delta x^2 + \Delta y^2}$$

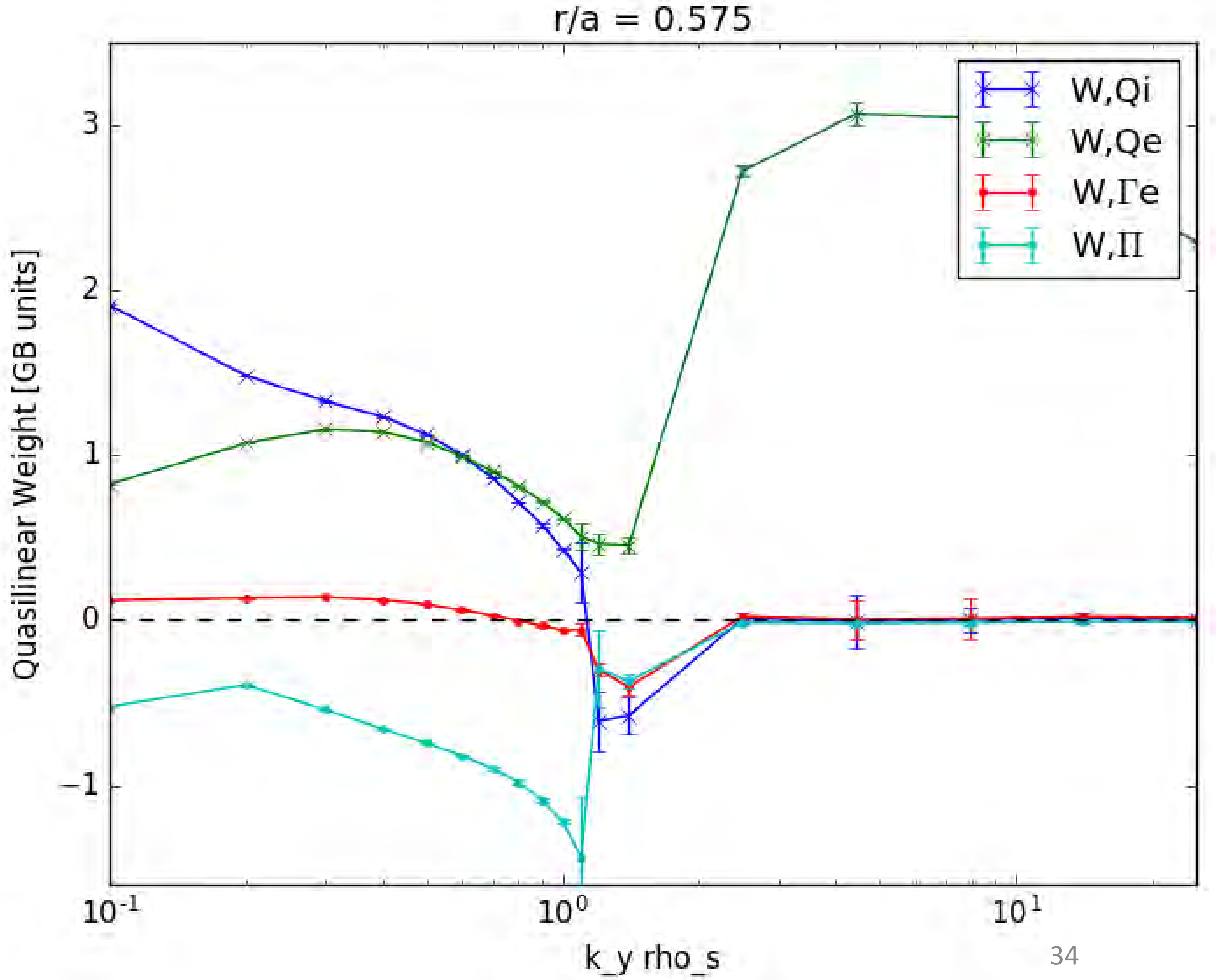
- Problem is ill-posed; answer tends to diverge as length of ruler gets smaller e.g. detail increases as length-scale used to view increases, typically with $\alpha < 0$ [Richardson]

$$L(G) = MG^{\alpha}$$

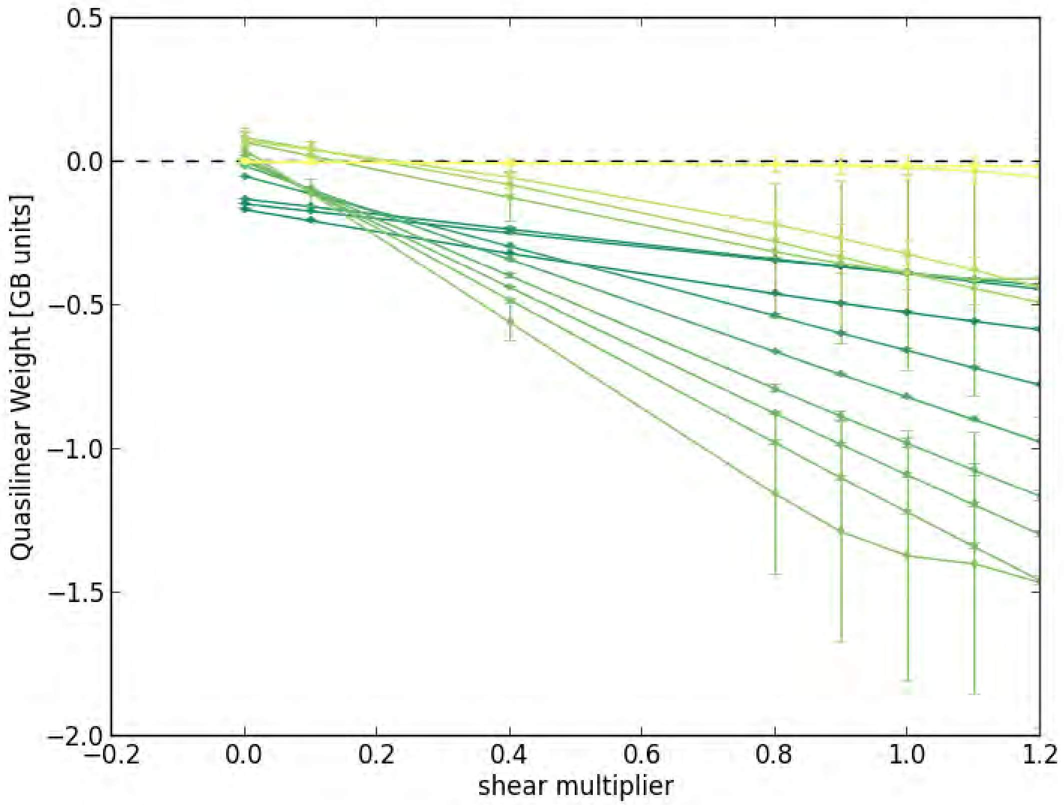
  - Note relationship with anomalous dissipation in turbulence, appearance of singularities in limit of zero dissipation
- This is an issue intrinsic to the derivative operator (related to sensitivity to high frequency components), not a quirk of the measurement! There is no such thing as a gradient measurement without a length scale.
- Importance of different length scales imply different physics

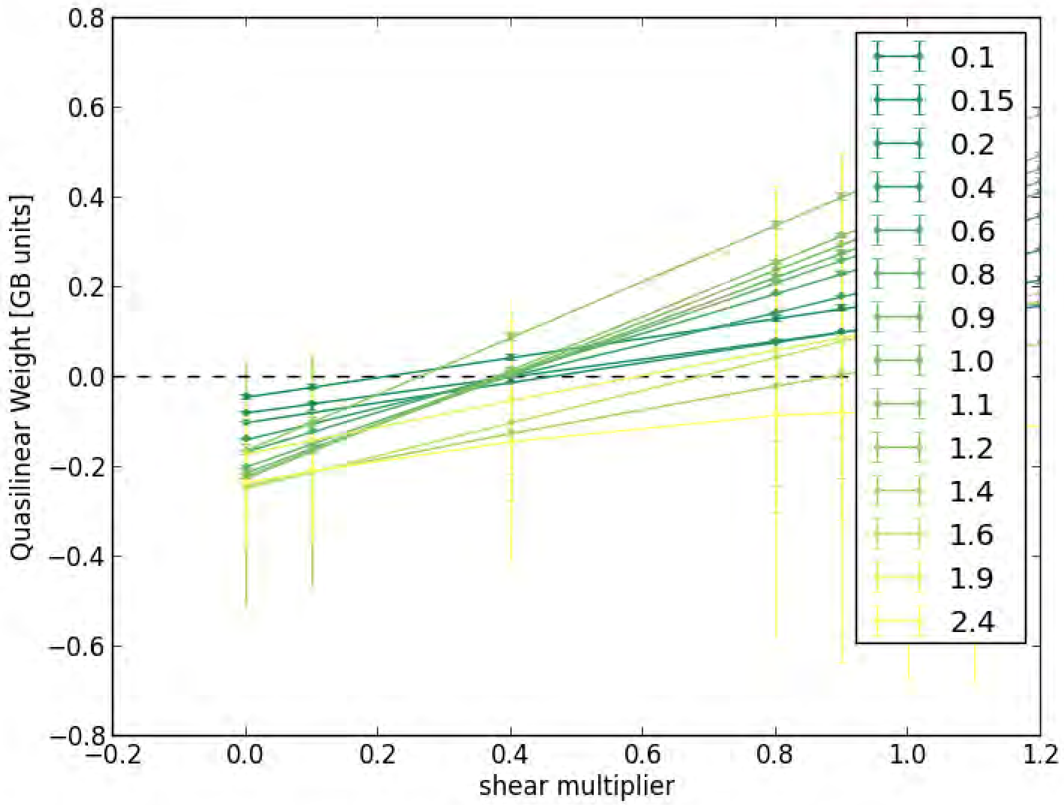
What about momentum?

- Don’t expect many intrinsic stress sources to be captured by local linear runs
- [Grierson PRL 2017] Turbulent momentum diffusion balances with intrinsic stress generation

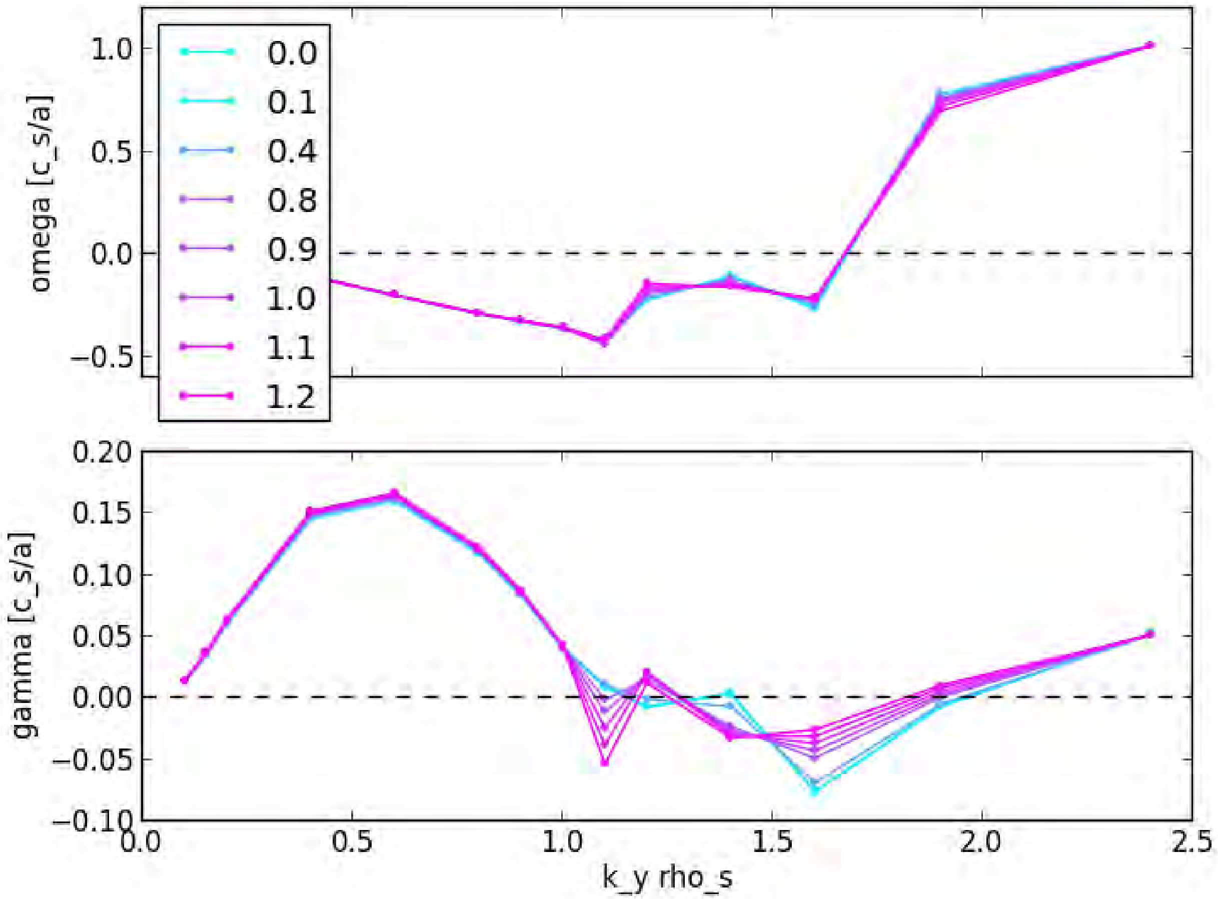


Momentum Transport Predicted is Primarily Diffusive





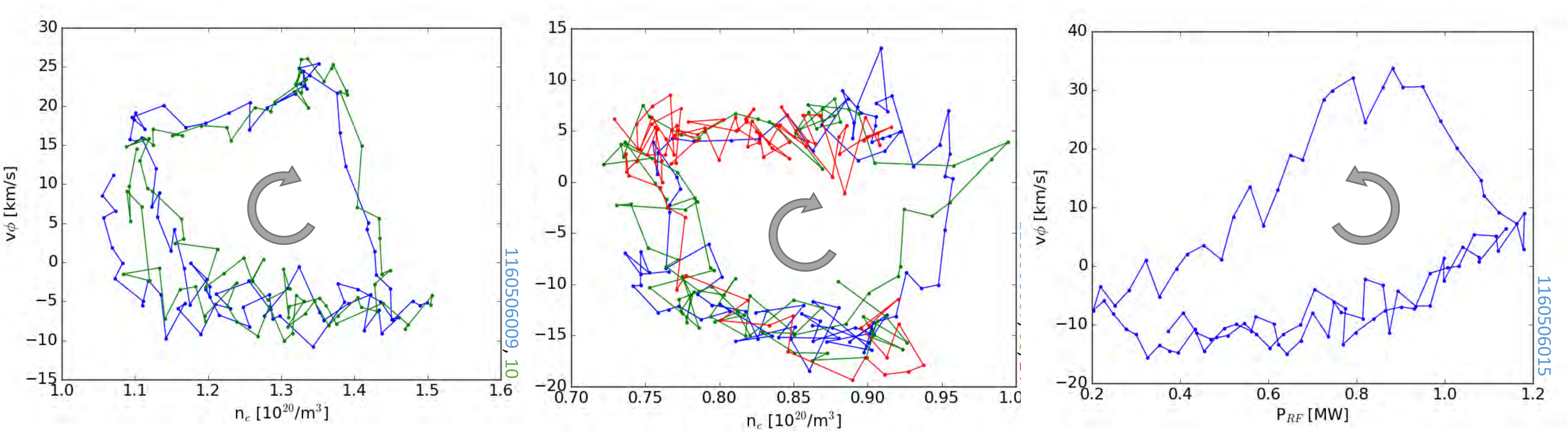
Flow Shear Affects Growth Rates of $k_y \rho_s \sim 1$ Marginal Modes



- Performed scans reducing mean ExB and Mach flow shear (color scale on plot to the right)
- Marginal modes with large enough $k_y \rho_s$ strongly affected by flow shear, while ion modes relatively unchanged
- Provides possible mechanism for bifurcation (increasing flow shear -> changed mode population -> increasing flow shear)

Hysteresis Observed Robustly in Multiple Plasma Conditions

- Hysteresis is observed at multiple currents, and survives perturbation from LBO.
- Low-power ICRF heating ramps also lead to hysteresis, with similar



Fluctuation Measurements Change Despite Nearly Identical Profiles

- Power spectra of complex signal from 88 GHz channel of C-Mod midplane O-Mode reflectometer shown for **LOC** and **SOC**
- Reflectometry is sensitive to density perturbations, $k_\perp$ up to 10 cm^{-1} [Lin PPCF 2001]
- Open question if change in power spectrum actually due to change in turbulence, not just Doppler shift