Observation and Quasilinear Modelling of Rotation Reversal Hysteresis in Alcator C-Mod Plasmas

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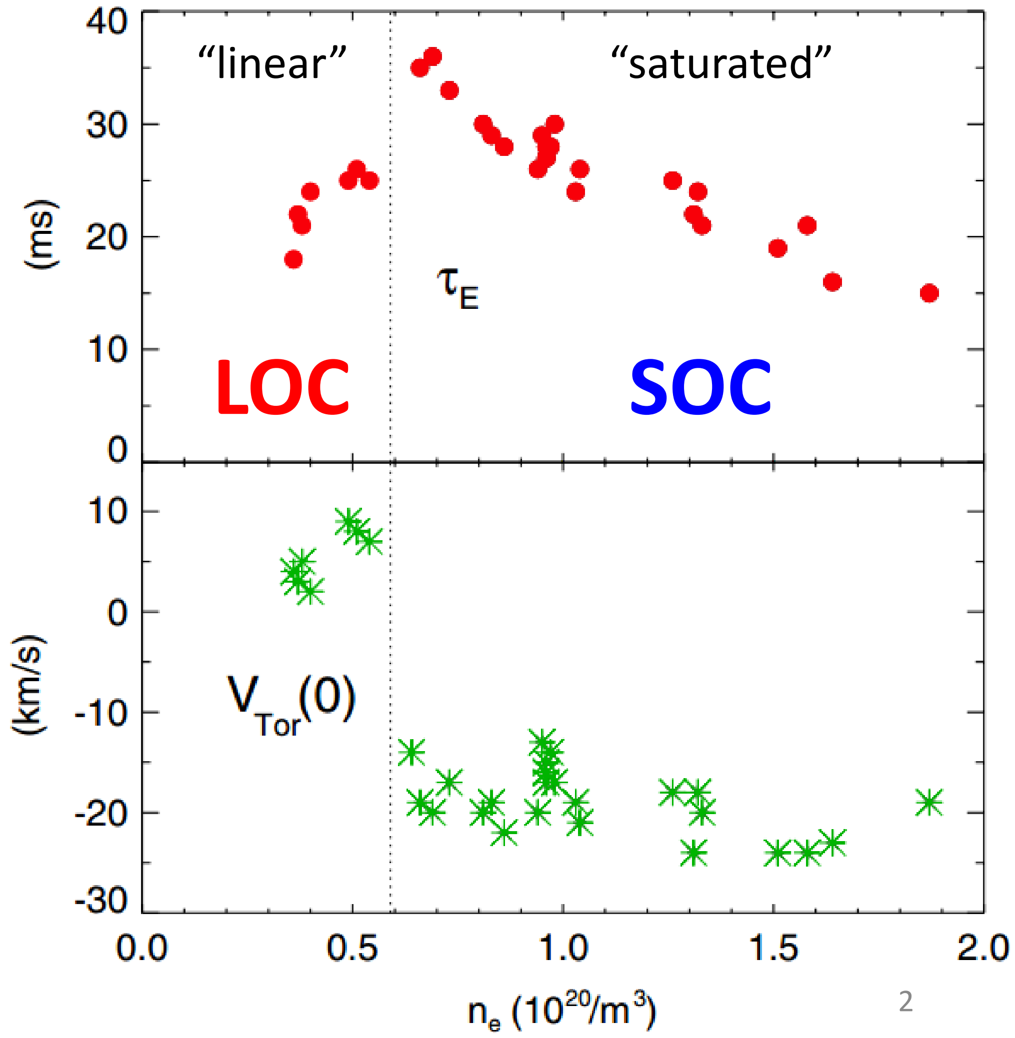
Introduction: A Tale of Two Transitions in Tokamak Turbulence

- **LOC/SOC transition** is a universally observed transition in tokamak confinement time found in L-mode plasmas
- **Intrinsic Rotation Reversal** is a spontaneous change in the toroidal rotation profile in plasmas with no external momentum input
- *How are these two transitions linked? And what can we learn from them to improve our turbulence models?*

Rice NF 2011

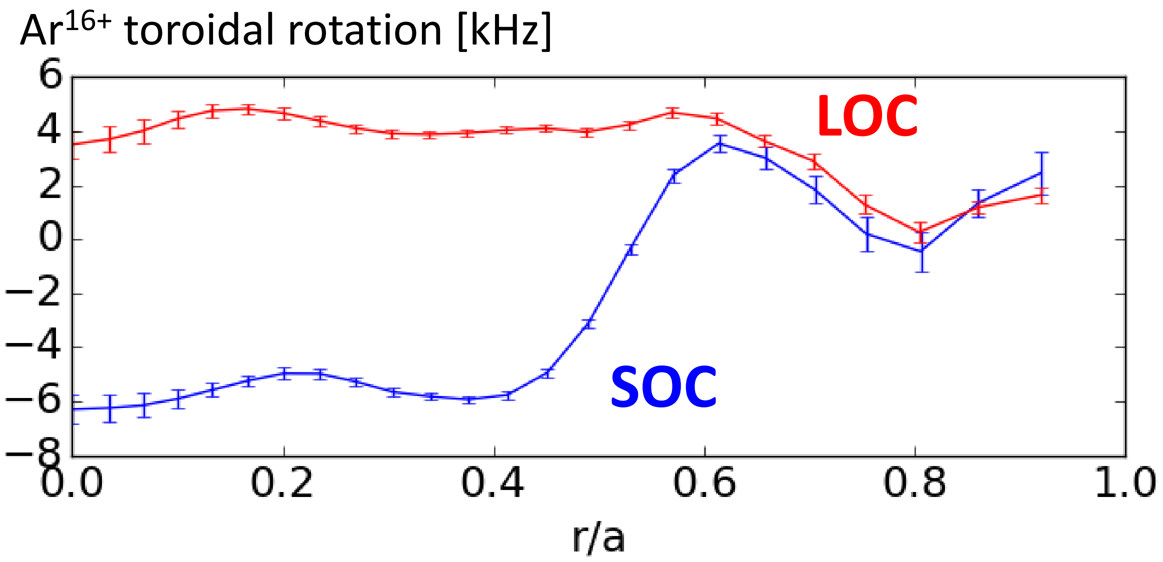


Background: Understanding of Drift Wave Turbulence Necessary to Explain Transitions

- Gyrokinetic drift wave turbulence is responsible for most of the heat and particle transport in tokamaks
  - Linear theory well understood, non-linear theory less so
- Observed rotation profiles require a non-zero residual stress, driven by turbulence [Diamond NF 2013]
- Both thought to be linked to a transition in DW turbulence from **TEM to ITG** [Diamond PoP 2008, Camenen PPCF 2017], but the underlying mechanism is unclear

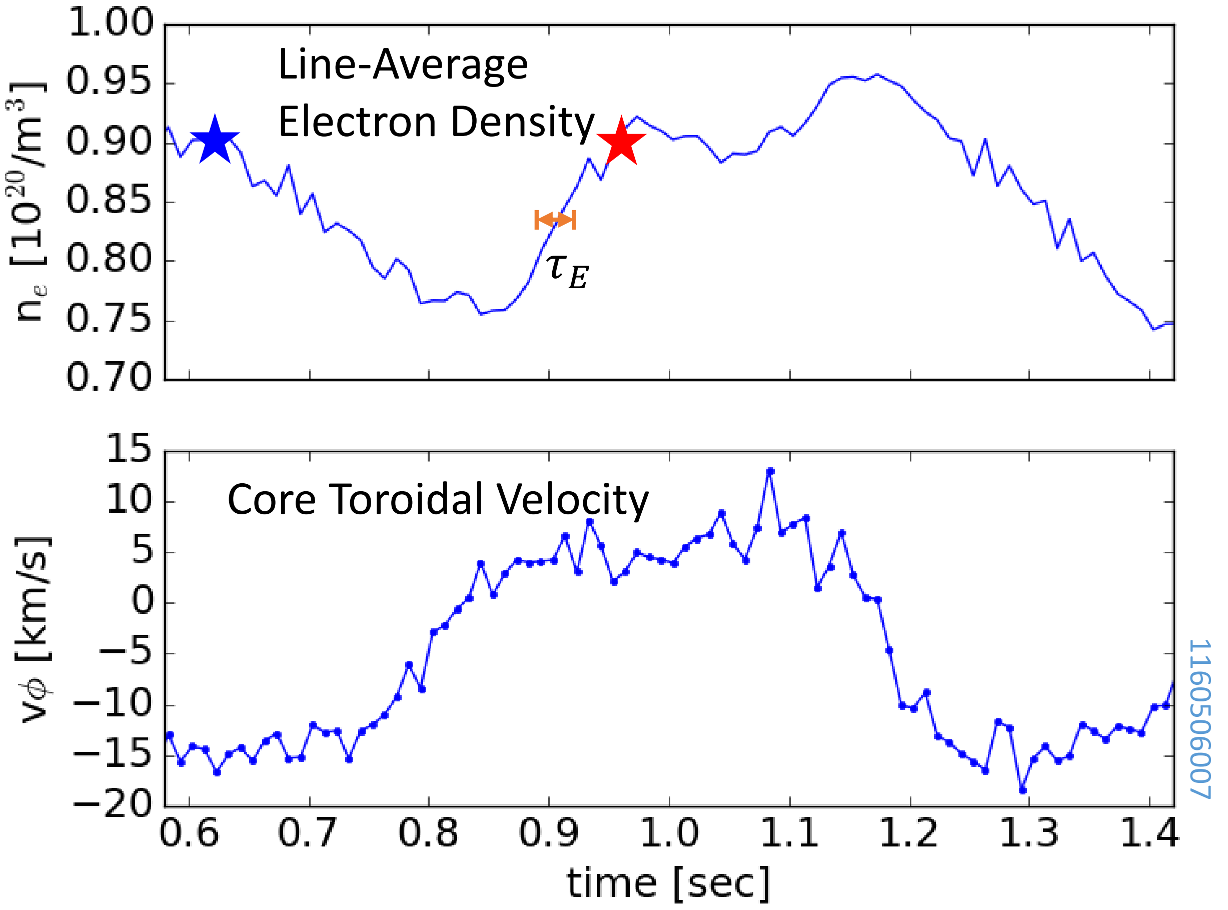
$$\frac{\Pi_{r\phi}}{\langle n \rangle} = -\chi_\phi \langle v_\phi \rangle' + V \langle v_\phi \rangle + \pi^R_{r\phi}$$

momentum flux = diffusion + pinch + residual



Motivation: Hysteresis Experiments Provide Controlled Probe of Turbulent Transition!

- Reversals exhibit **hysteresis,** so the same mean plasma parameters manifest different rotation states
- *This Work*:
    1. Finding the dominant linear instability is **not enough** to understand the whole picture of driven turbulence
    2. Quasilinear modeling identifies a **subdominant mode transition** consistent with the observed transport

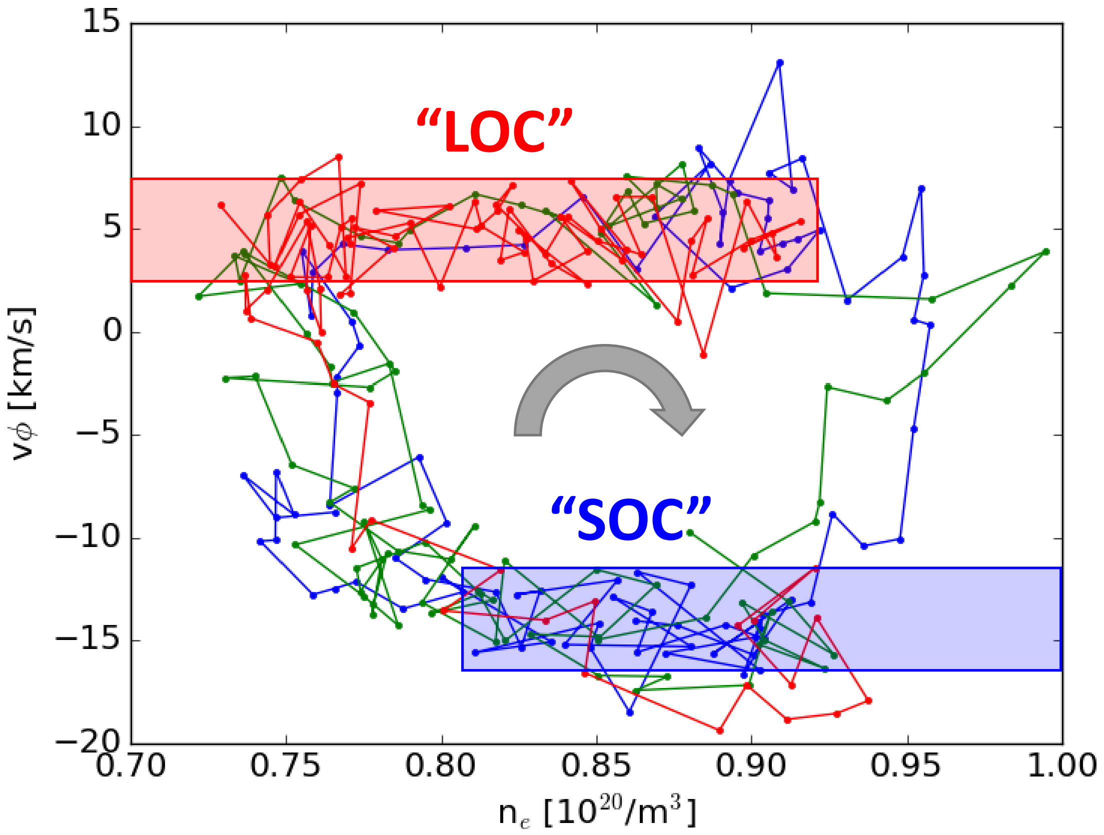


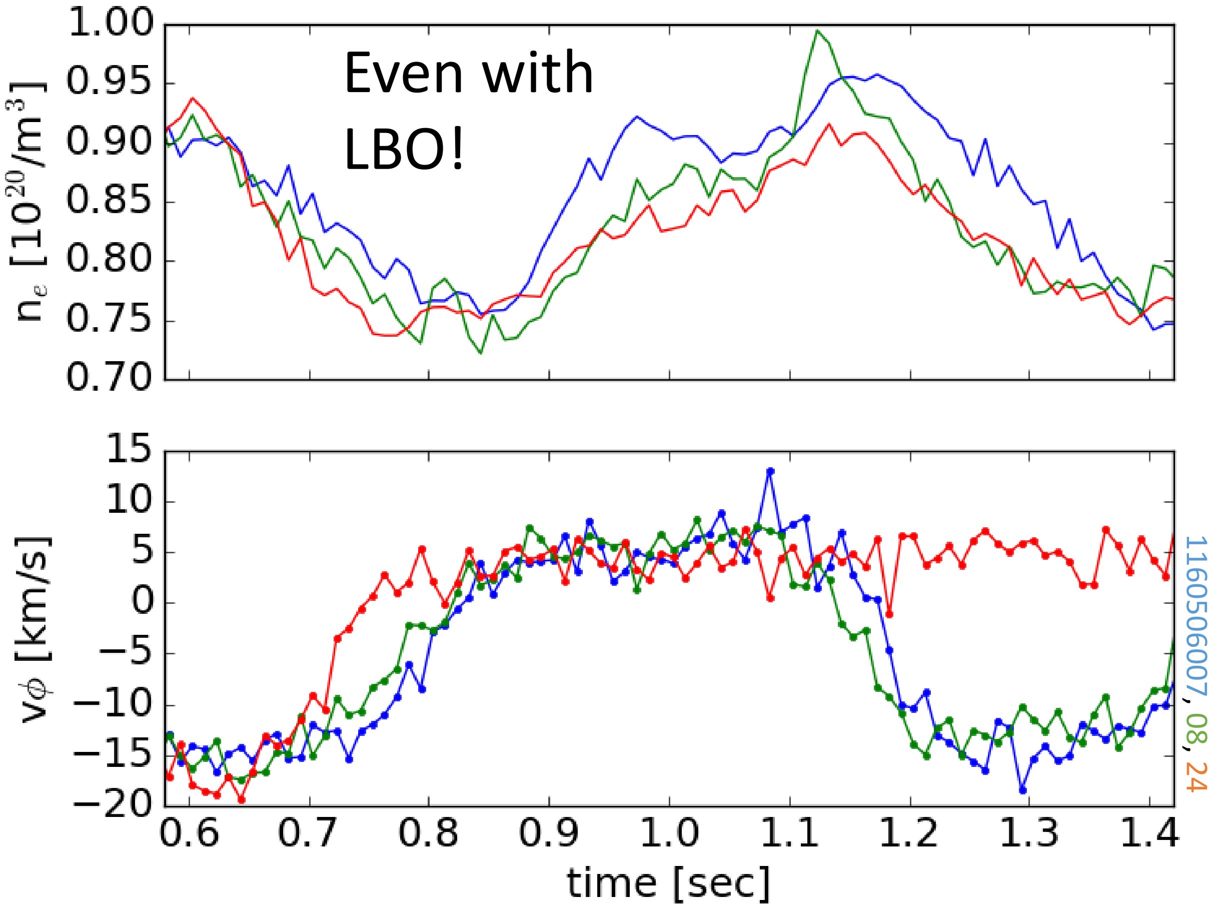
Experimental characterization of Hysteresis

[Section Header]

Experiments show hysteresis is a reproducible phenomenon across multiple shots

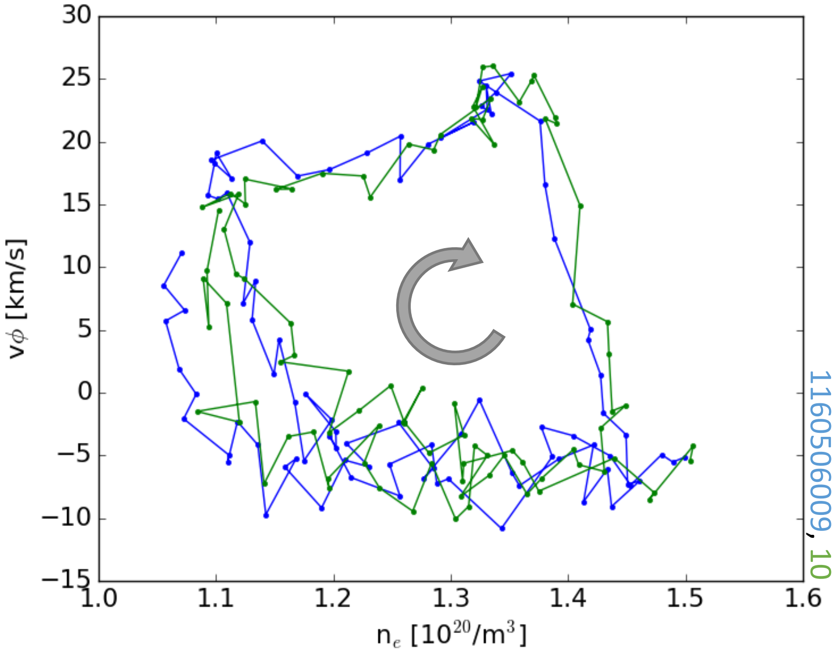
5.4 T, 0.8 MA

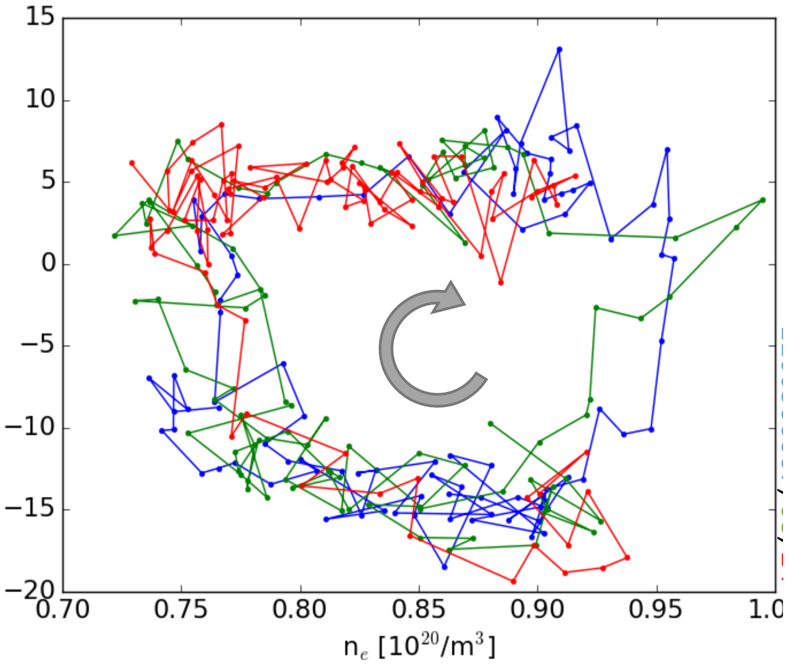


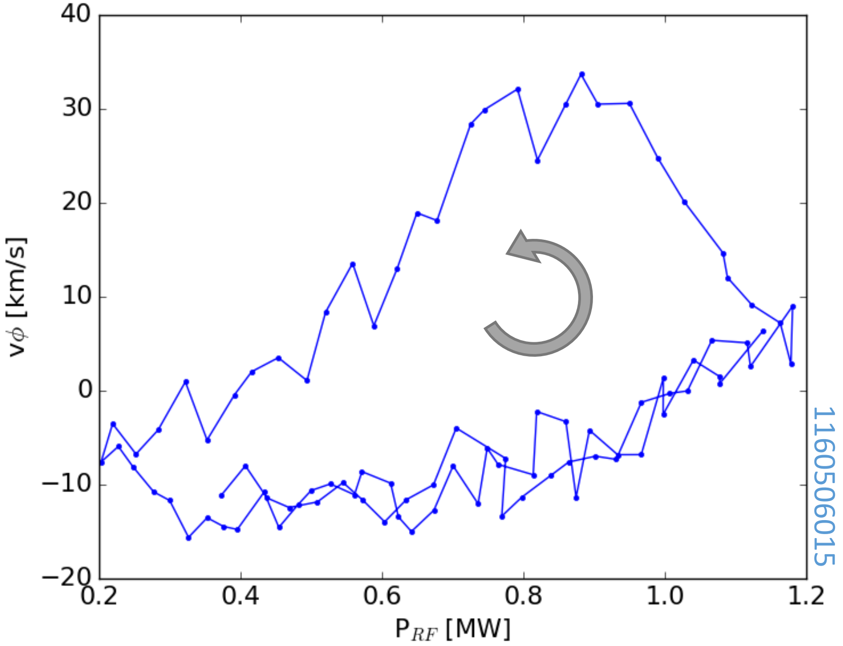


Hysteresis Observed Robustly in Multiple Plasma Conditions

- Under different plasma conditions, transition appears to occur when the normalized collisionality crosses $\nu^* \equiv \frac{\nu_e \epsilon}{\omega_{be}} \approx 0.4$ [Rice NF 2013]
  - Suggests the link with trapped electron modes

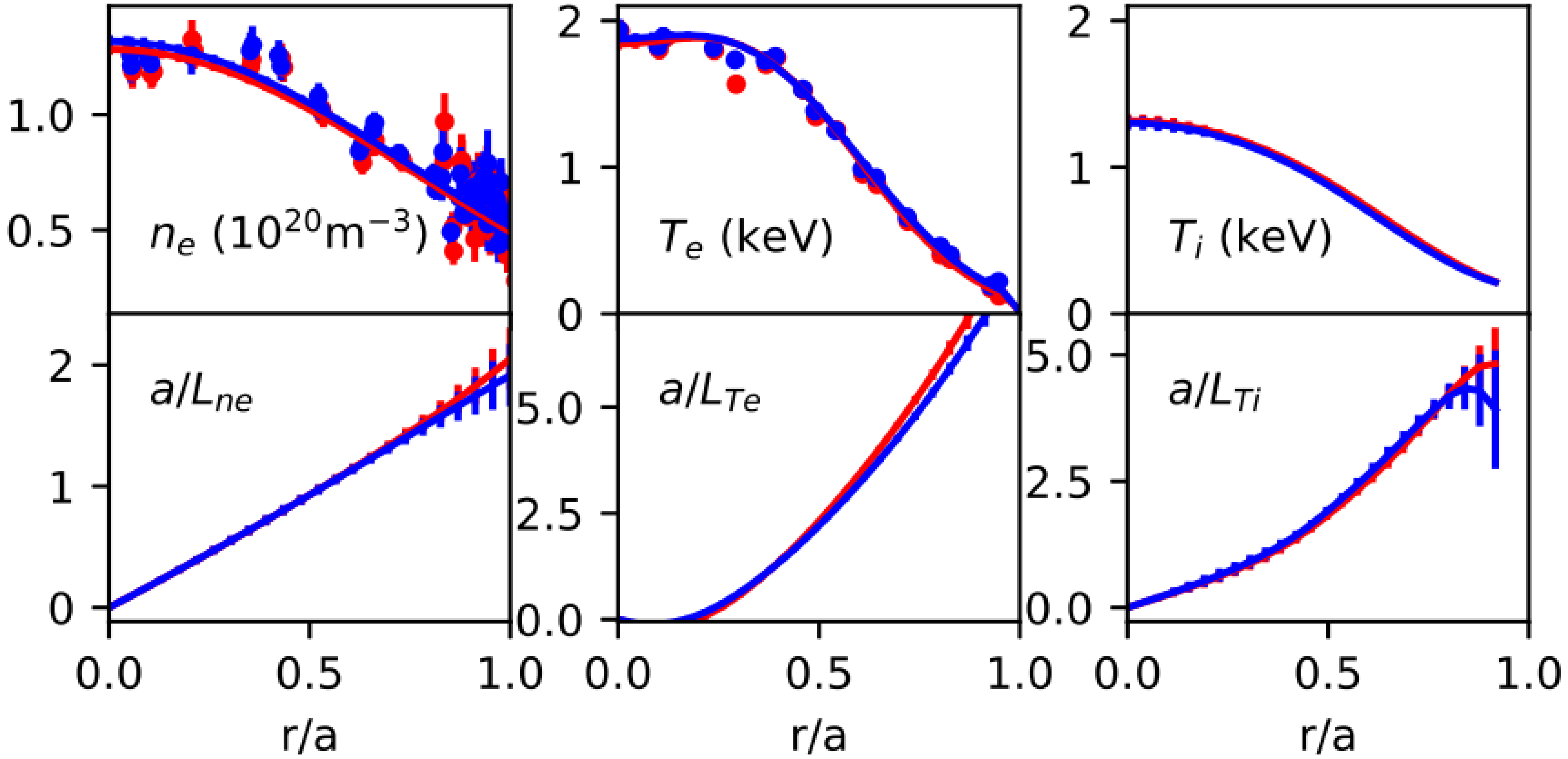






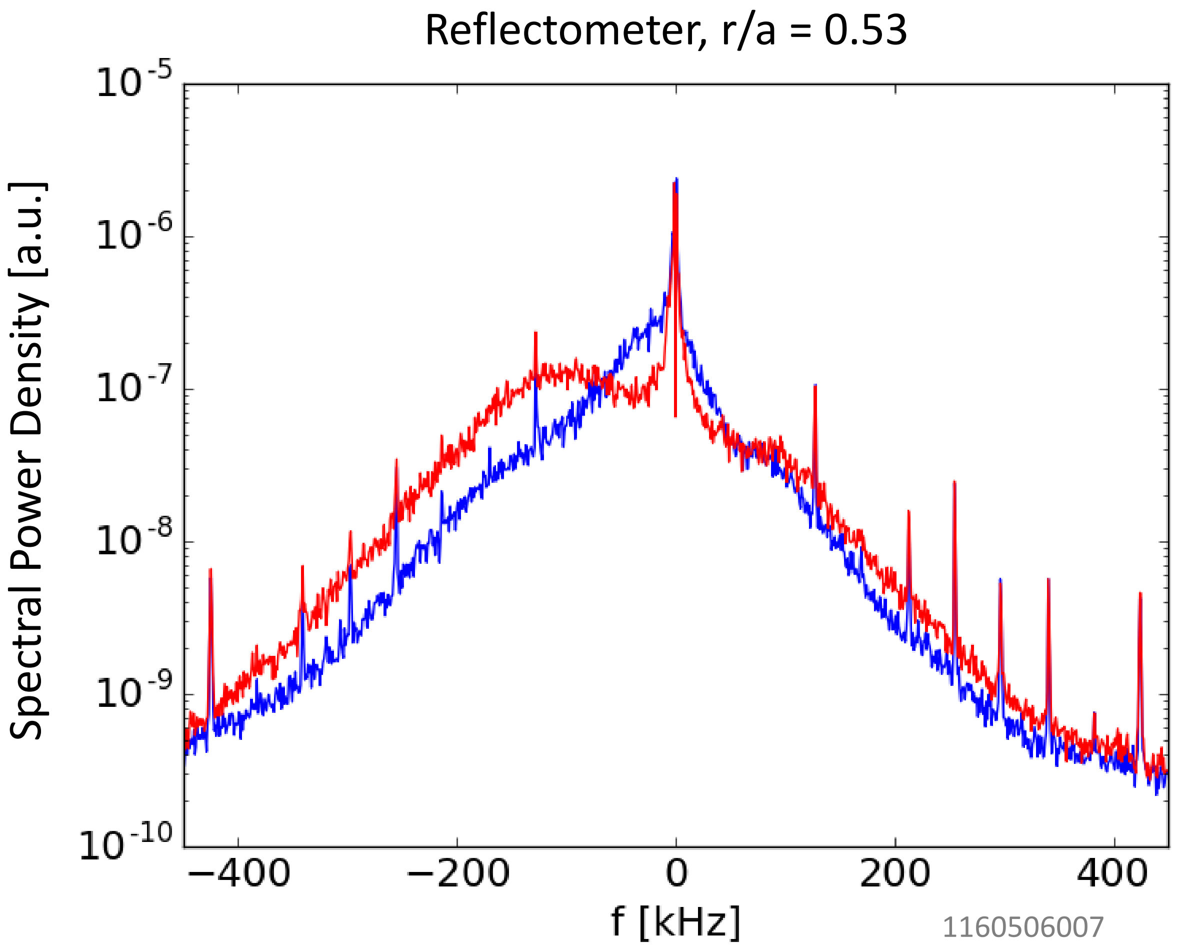
Nearly Indistinguishable Density and Temperature Profiles Can Lead to Different Rotation States

- Profiles are shown here for 5.4 T, 0.8 MA **LOC** (t=0.96 s) and **SOC** (t=0.6 s)
  - Electron profiles from same shot; error rigorously estimated with GPR [Chilenski NF 2017]
  - Ion profiles from different but matched shots.



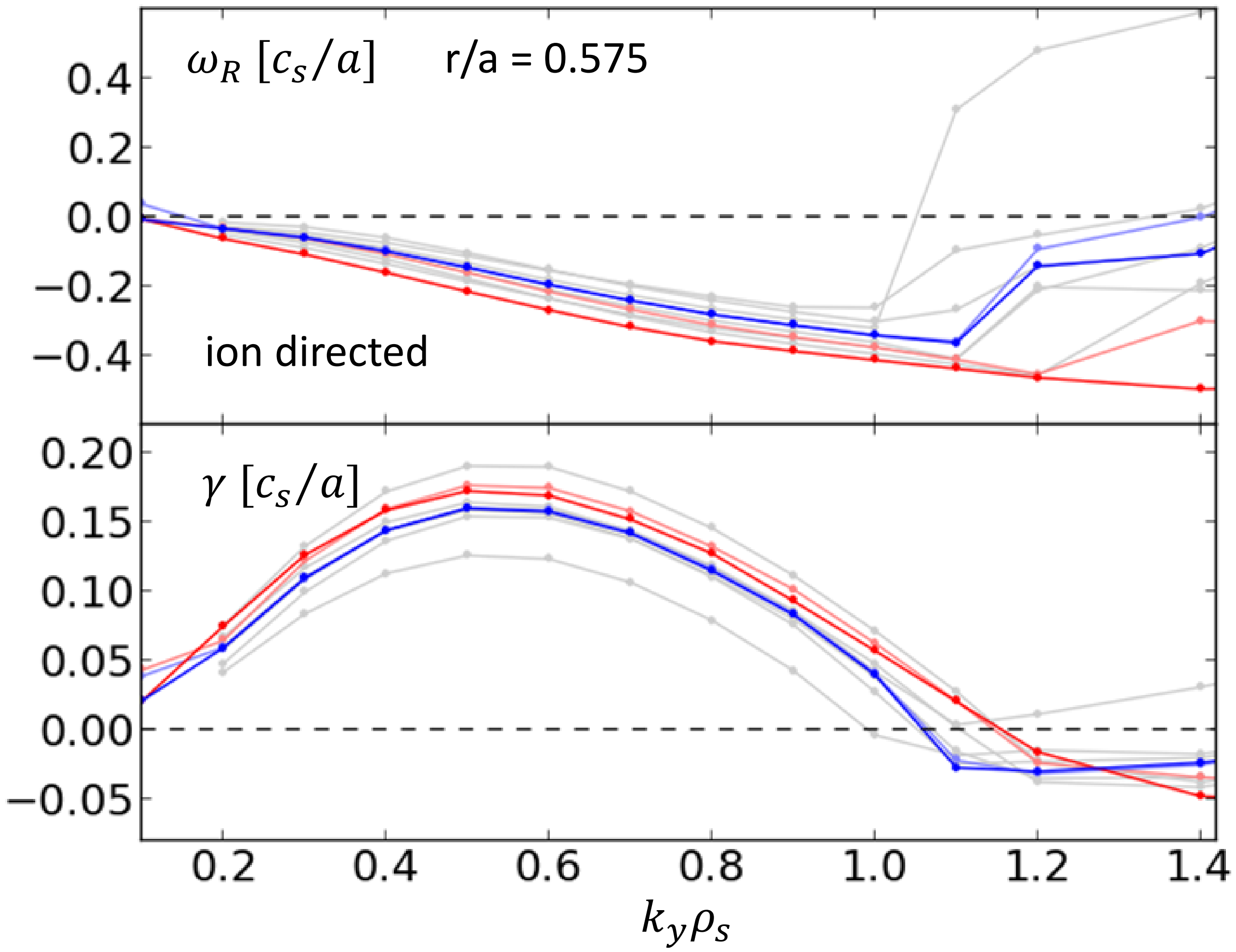
Fluctuation Measurements Change Despite Nearly Identical Profiles

- 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



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**
  - ±10% 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 looking at Alcator C-Mod and AUG plasmas [Sung NF 2013, White PoP 2013, Erofeev NF 2017]
- Motivates a need to look at **subdominant modes** to understand turbulent state



Section Summary

- Different rotation states were observed for nearly identical density and temperature profiles

- Turbulence changes despite unchanged linear growth rates

- How can we begin to analyze this? Need to identify the difference between these matched LOC and SOC states.

Quasilinear Modelling

[Section Header]

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

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

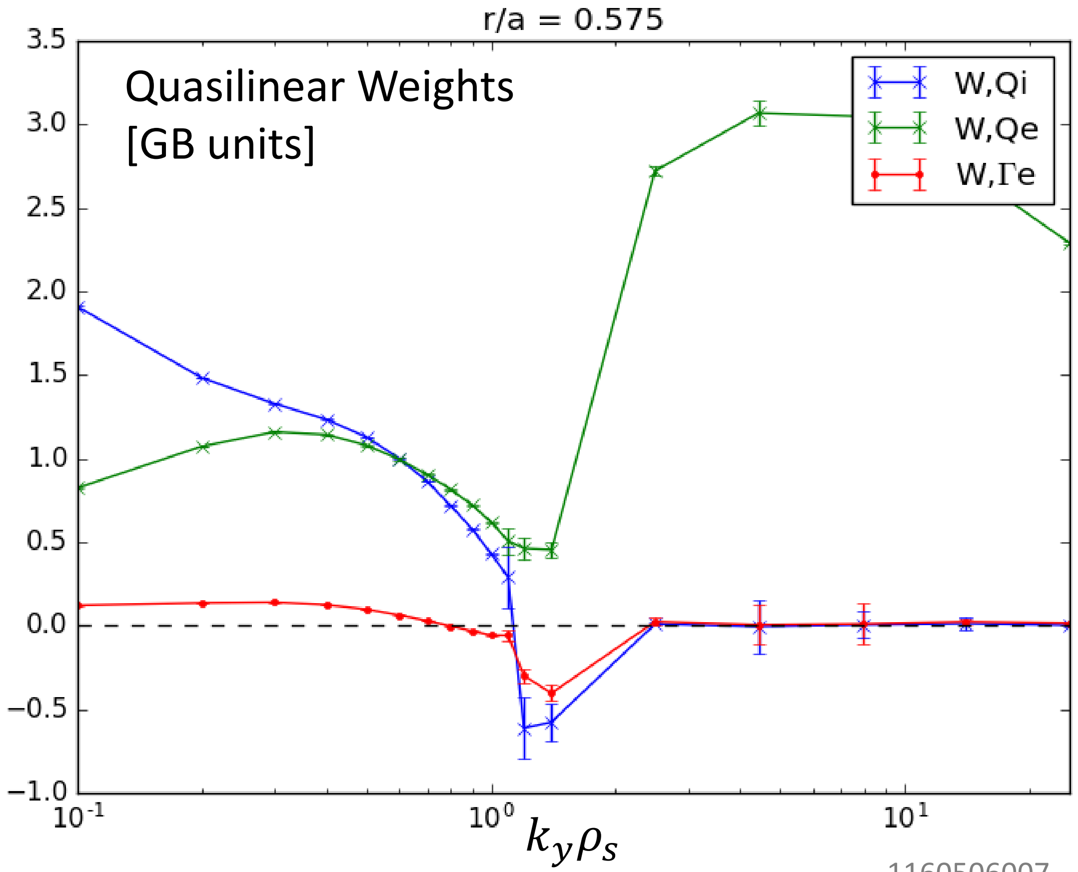
$$\mathbf{Flux} = \sum_k \mathbf{weight} \cdot \mathbf{intensity}$$

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

- *Note on Applicability*: Weights used in mQLTA match weights from fully nonlinear simulation [Waltz PoP 2009]; cross-phases match experiment [White PoP 2010, Freethy PoP 2018]

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

- **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



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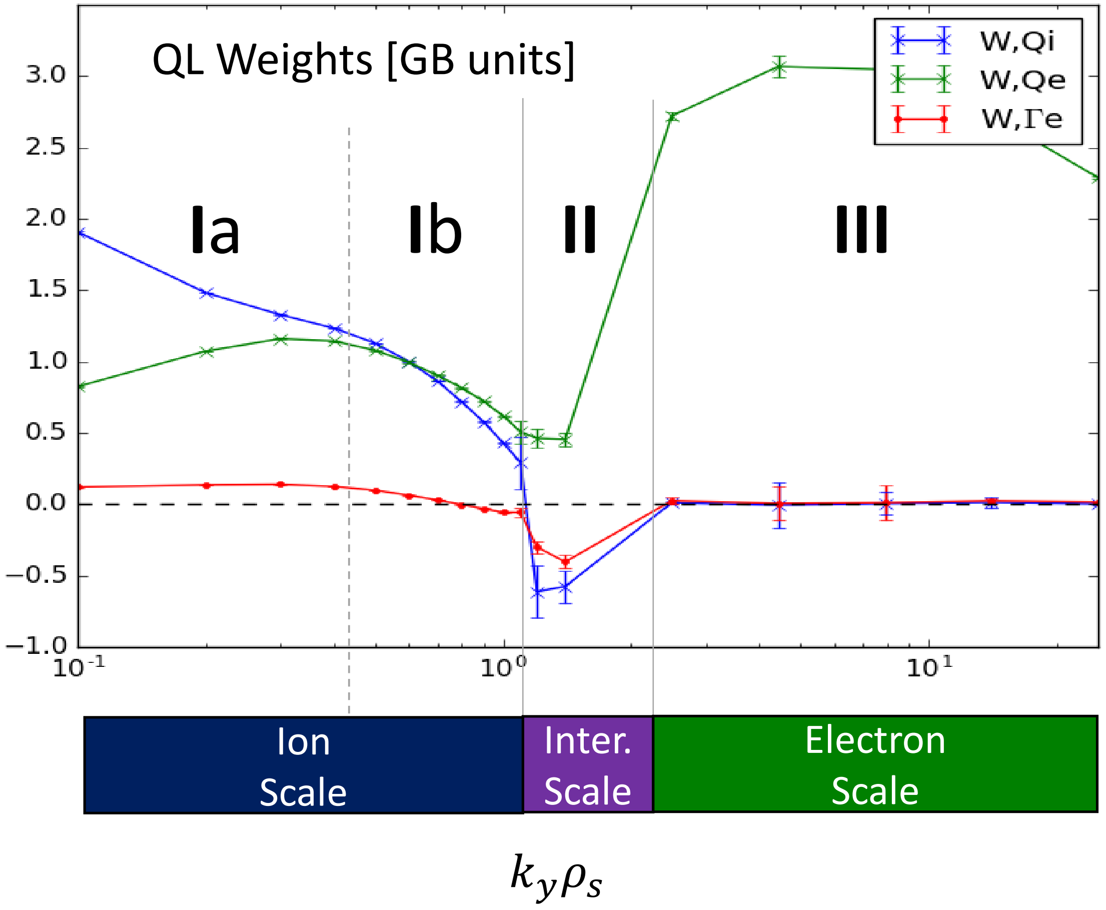
Reduced Family Model Allows Understanding Mixed Mode Picture



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

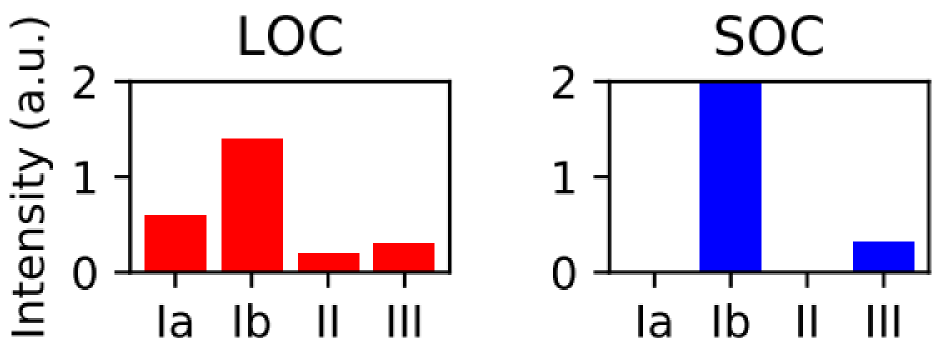
$$\textbf{Flux} = \sum_{\text{families}} \textbf{weight} \cdot \textbf{intensity}$$

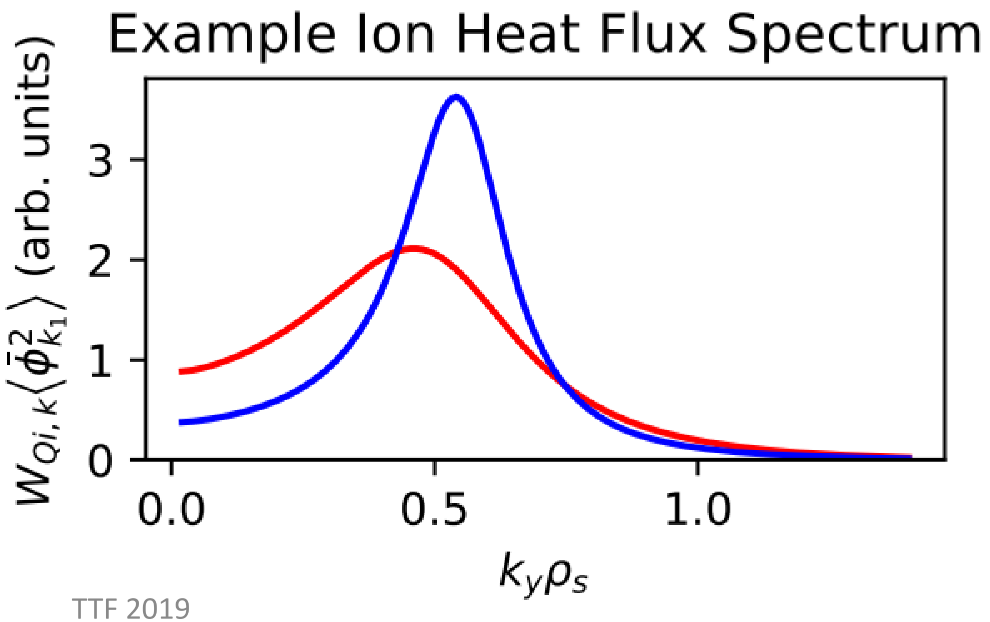
I. ion-scale ion-directed; (a) has net outward particle transport and (b) has roughly balanced transport

II. hybrid mode $k_y\rho_s \gtrsim 1$; strong inward particle pinch

III. electron-scale electron-directed; exhausts mostly Qe

Subdominant Mode Transition Found to be Consistent with Observed Transport





- In order to satisfy particle flux constraint, two solutions exist:

	LOC-like	SOC-like
Active Mode Families	ITG (Ia, Ib) TEM-like (II) ETG (III)	ITG (Ib) ETG (III)
Particle Flux Balance	Ia balances II	Balance within Ib

- Leading to qualitatively 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

Possibilities include…

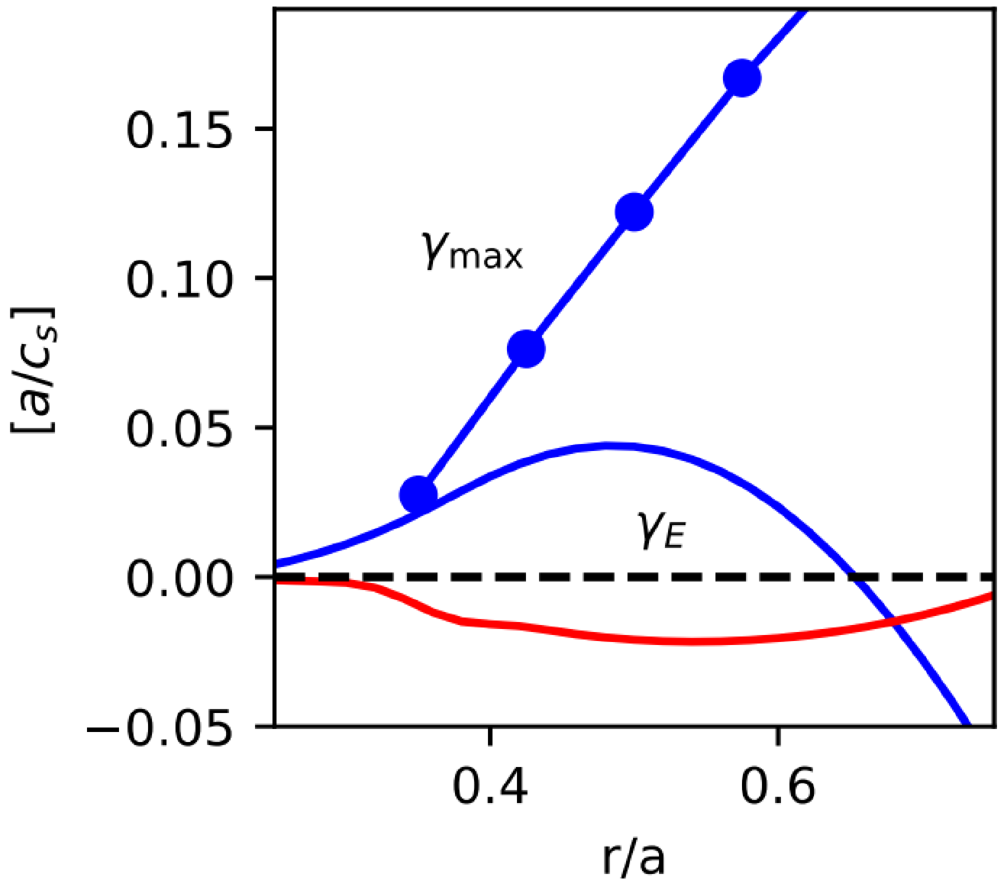
1. We're on a stability boundary, so small profile changes lead to big changes in turbulence
   - But what about LBO?
2. Mean rotation profiles contribute to change in turbulence through ExB shearing
   - (See below)
3. The fluctuation interaction nonlinearity (e.g. DW-ZF or DW-DW) is changing
   - How to identify the key physics?

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 turbulence, but shear could contribute nonlinearly to saturation mechanisms



Conclusions and Future Work

- 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 shows that a **subdominant ITG/TEM transition** is consistent with the observed transport
  - Reminiscent of a “population collapse” or quenching of turbulent TEM-like mode intensity
- *Future work*: Compare predictions against global nonlinear simulation, and identify if changes are consistent with fluctuations measured in experiment

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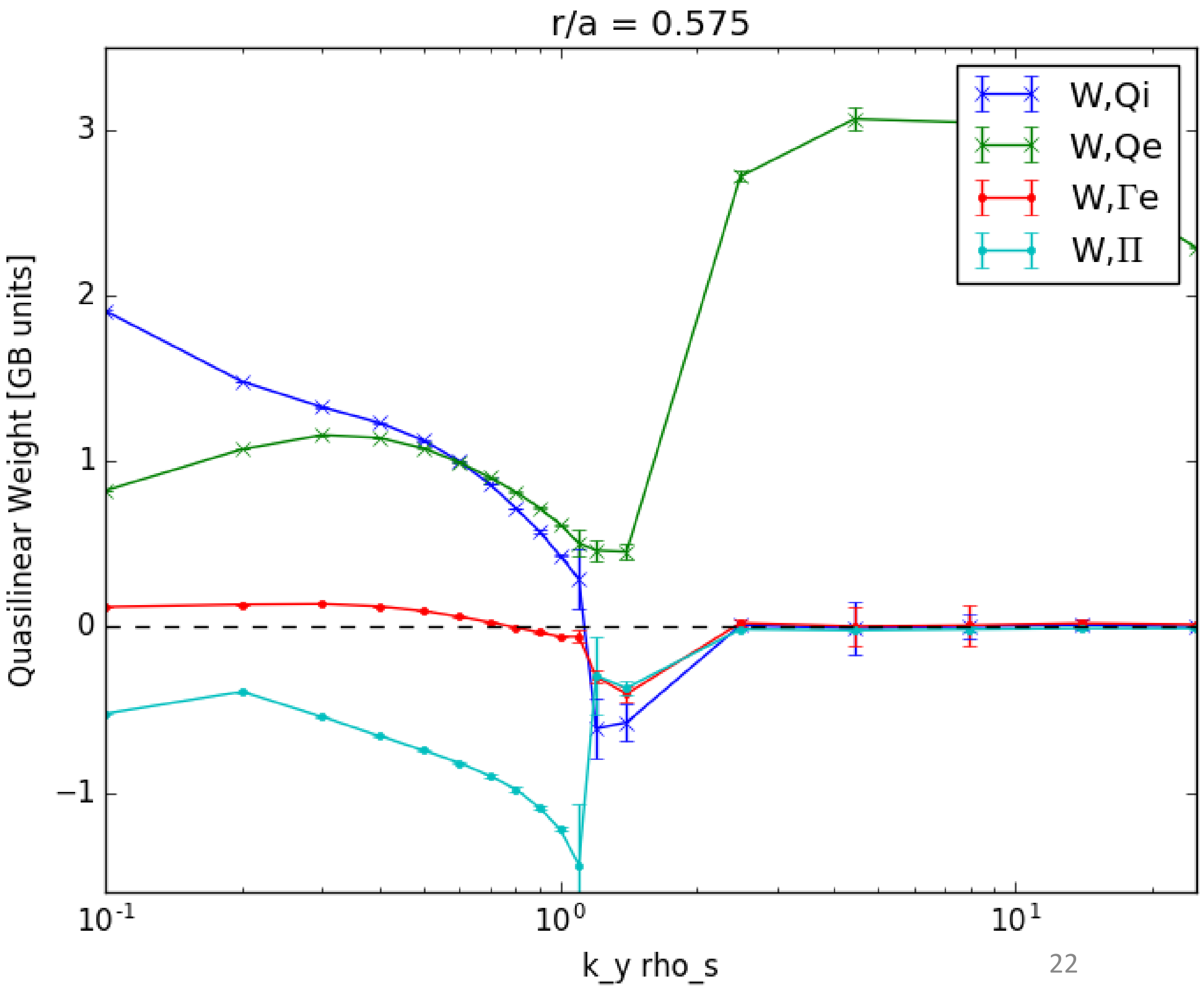
Extra Slides

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



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)

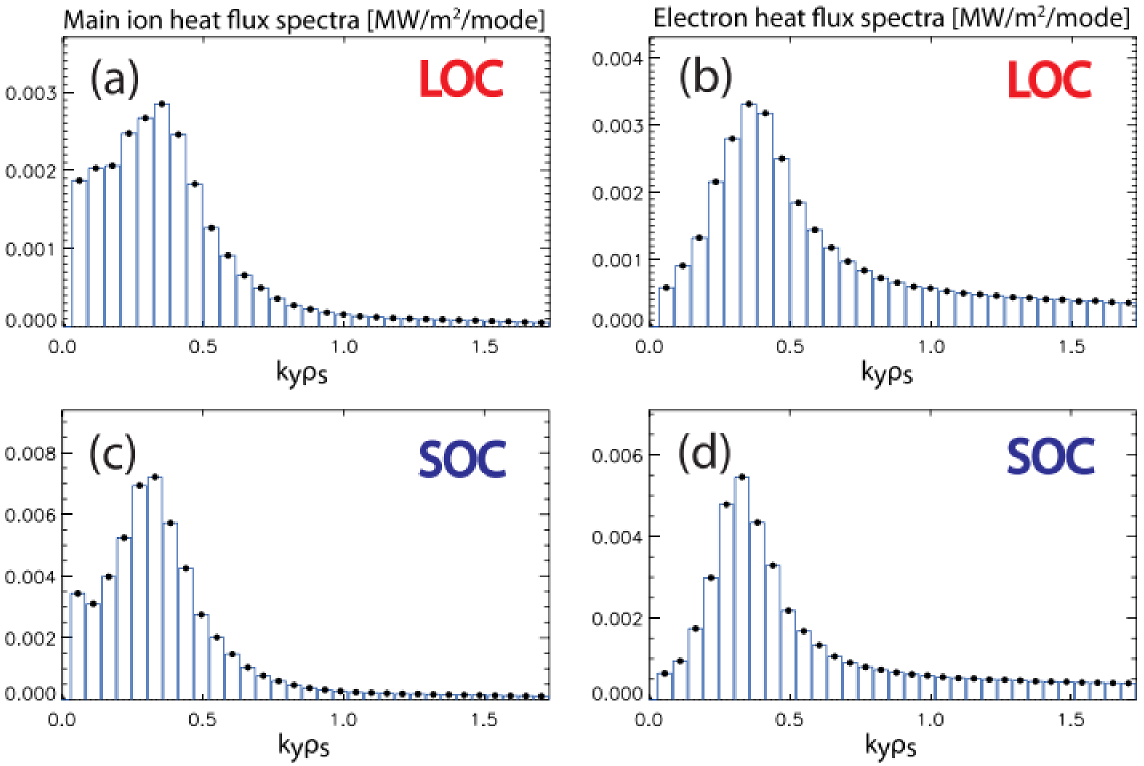
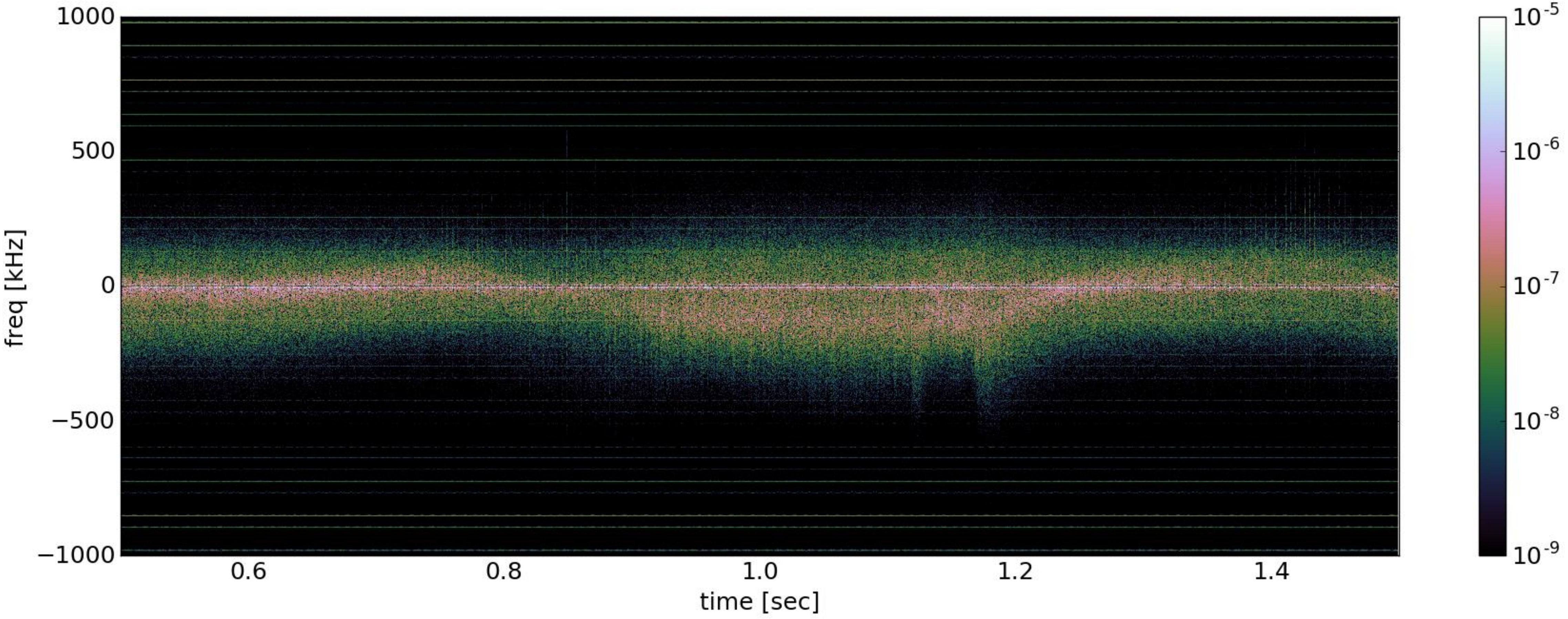


FIG. 14. Time averaged heat flux spectra on $k_y\rho_s$ in the "ion heat flux matched" runs (a) main ion heat flux spectrum in the LOC discharge (shot 1120626023) and (b) electron heat flux spectrum in the LOC discharge (c) main ion heat flux spectrum in the LOC discharge (shot 1120626028) and (d) electron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

0.8 MA Reflectometer power spectra show differences



Reflectometry Provides Local Fluctuation Measurements

- These data are collected from the 87.5 GHz and 88.5 GHz channels of the C-Mod O-Mode baseband reflectometer
- 2D scattering effects (e.g. scattering, diffraction, sidebands) complicate the analysis of the returned signal.
- Can be sensitive to $k_\perp$ up to 10 cm^{-1} (see Lin PPCF 2001)

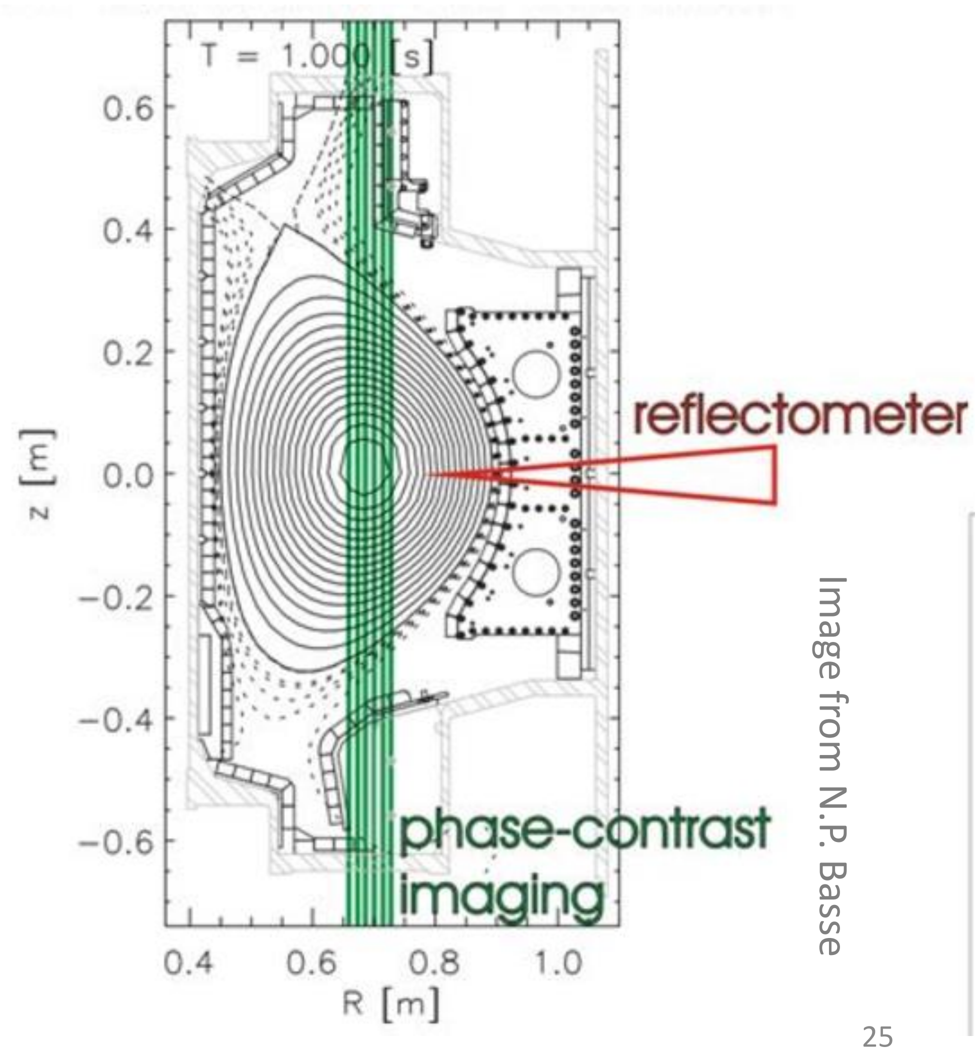


Image from N.P. Basse