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**

  How can we use reduced models to interpret our findings, despite the complexity of plasma turbulence?

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Prélude: Turbulent Transport of Heat and Momentum in Tokamaks

Two Major Questions:

- **Energy Confinement** – How long does injected power stay in the tokamak?
- **Toroidal Rotation** – How can large-scale coherent flows form from turbulence in tokamaks?
  - How is this interrelated with energy confinement?

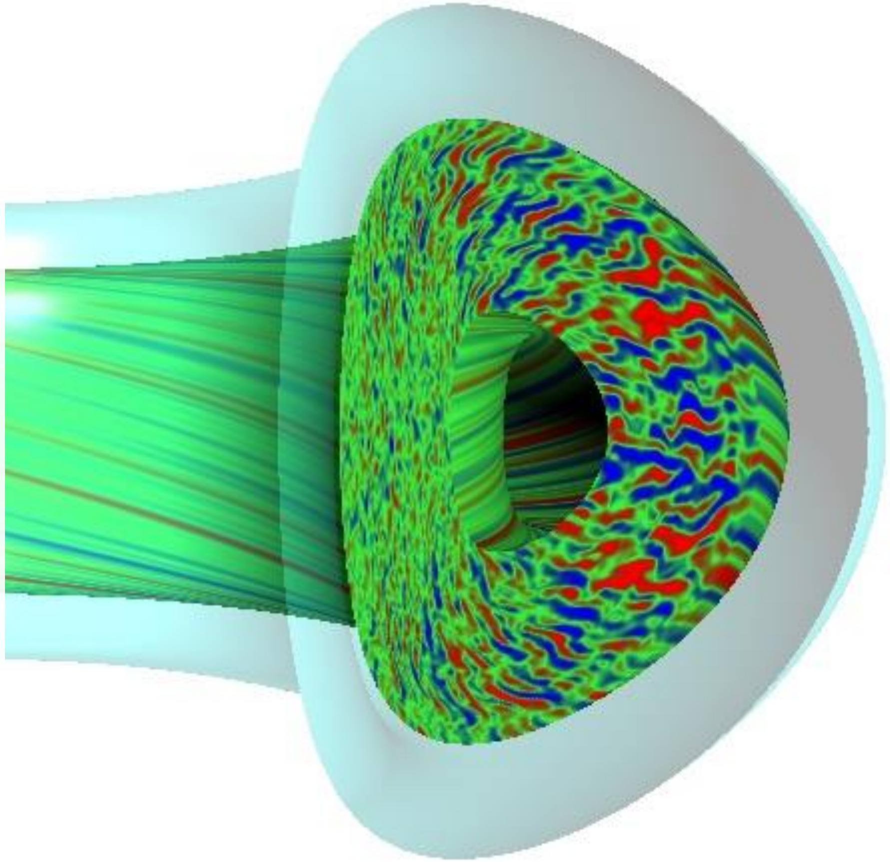


Image from https://w3.pppl.gov/~hammett/viz/viz.html

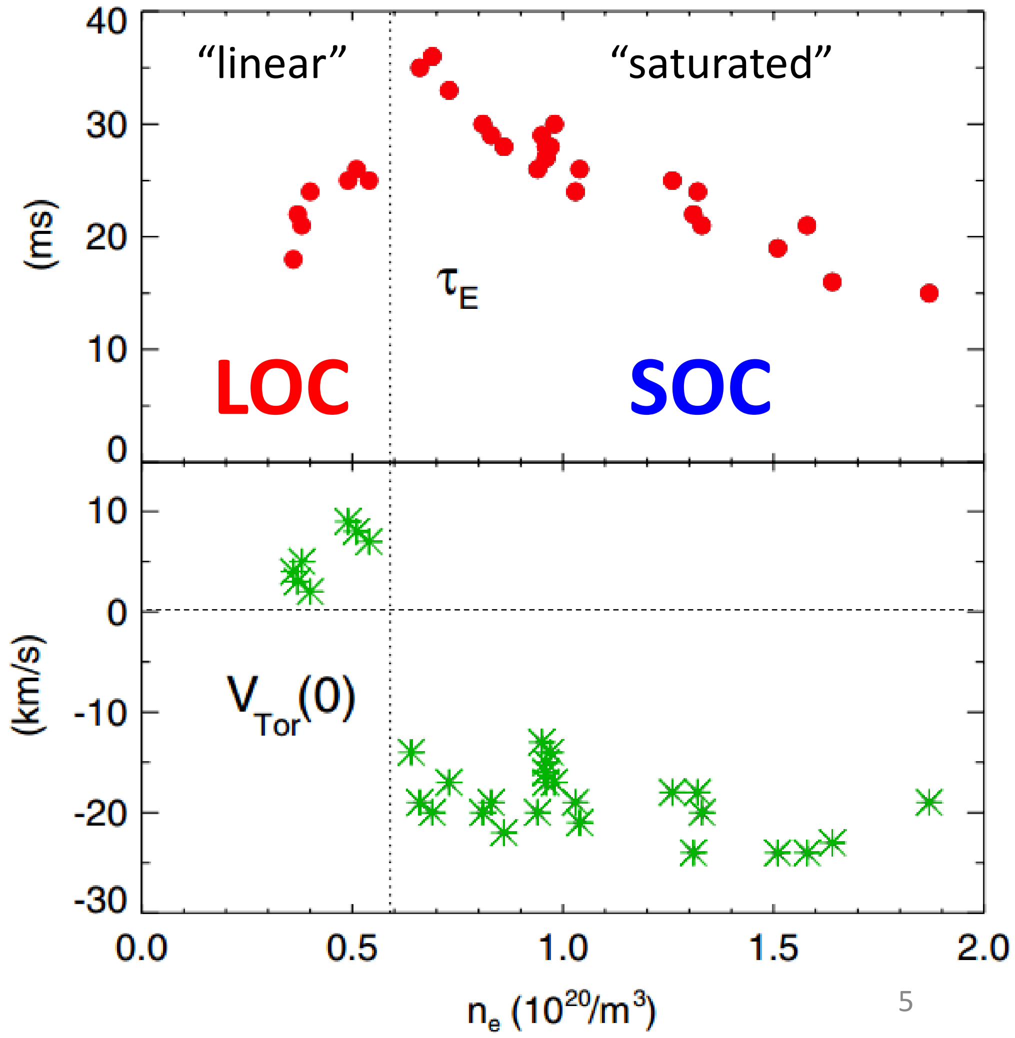
Introduction: A Tale of Two Transitions in Tokamak Turbulence

- **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

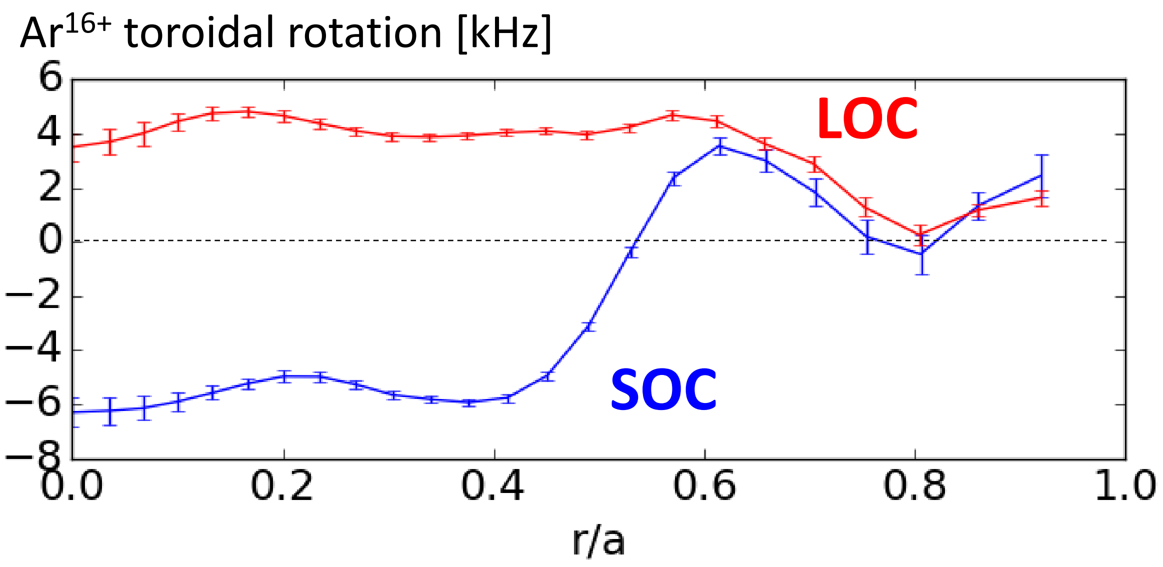
- *How are these two transitions linked? And what can we learn from them to improve our turbulence models?*

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
- 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

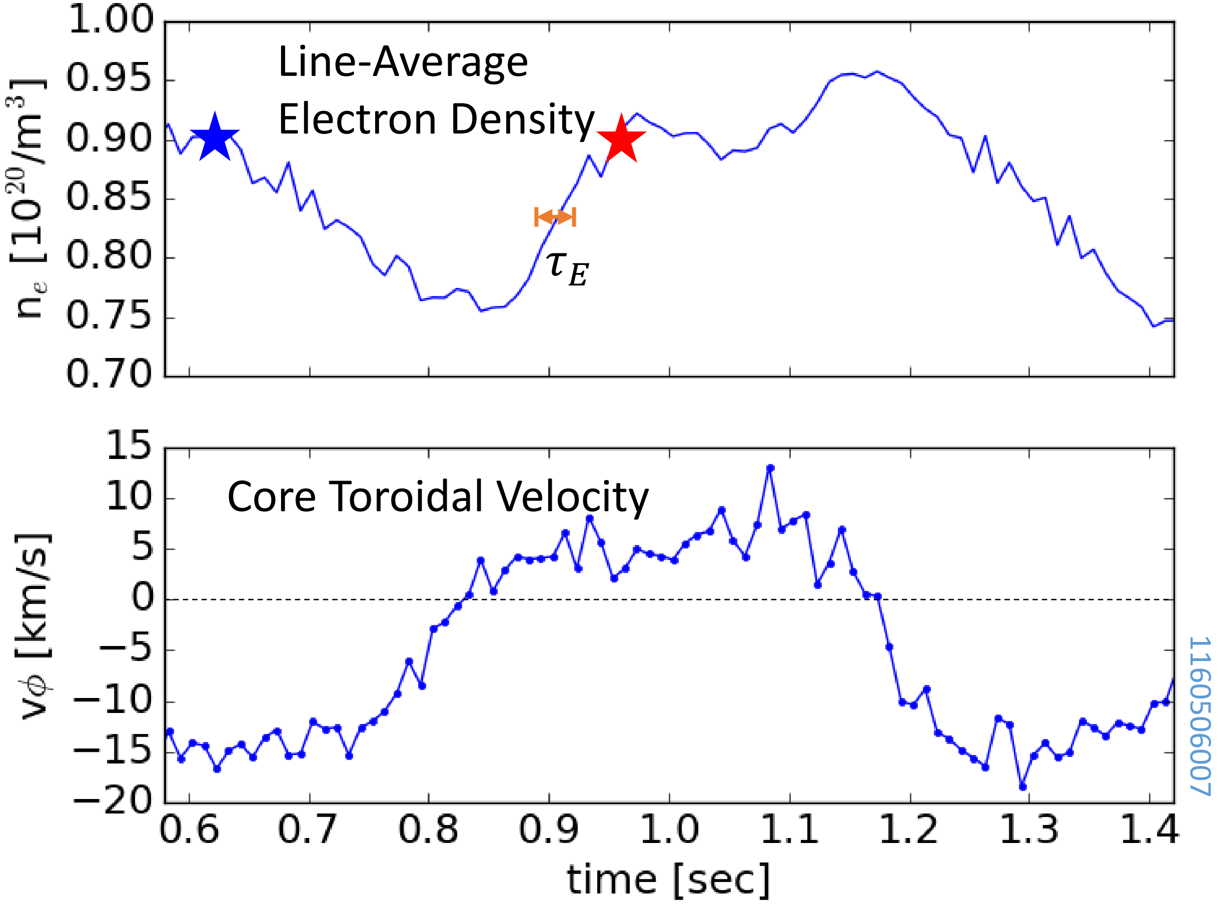


$$\frac{\Pi_{r\phi}}{\langle n \rangle} = -\chi_\phi \langle v_\phi \rangle' + V \langle v_\phi \rangle + \pi^R_{r\phi}$$

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. The physics of the dominant linear instability alone is **not enough** to explain the link between transitions
    2. A **subdominant mode transition** is found through Quasilinear modeling which is consistent with the observed transport



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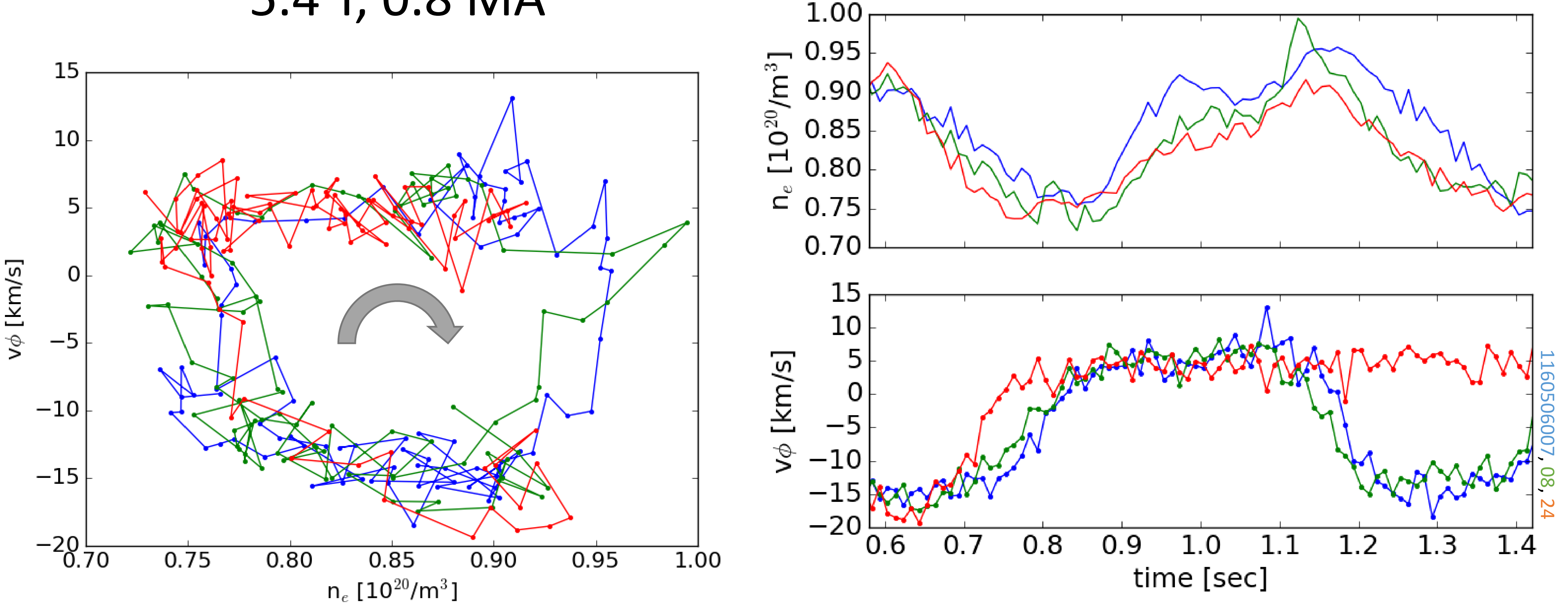
Experiments show hysteresis is a reproducible phenomenon across multiple shots

5.4 T, 0.8 MA



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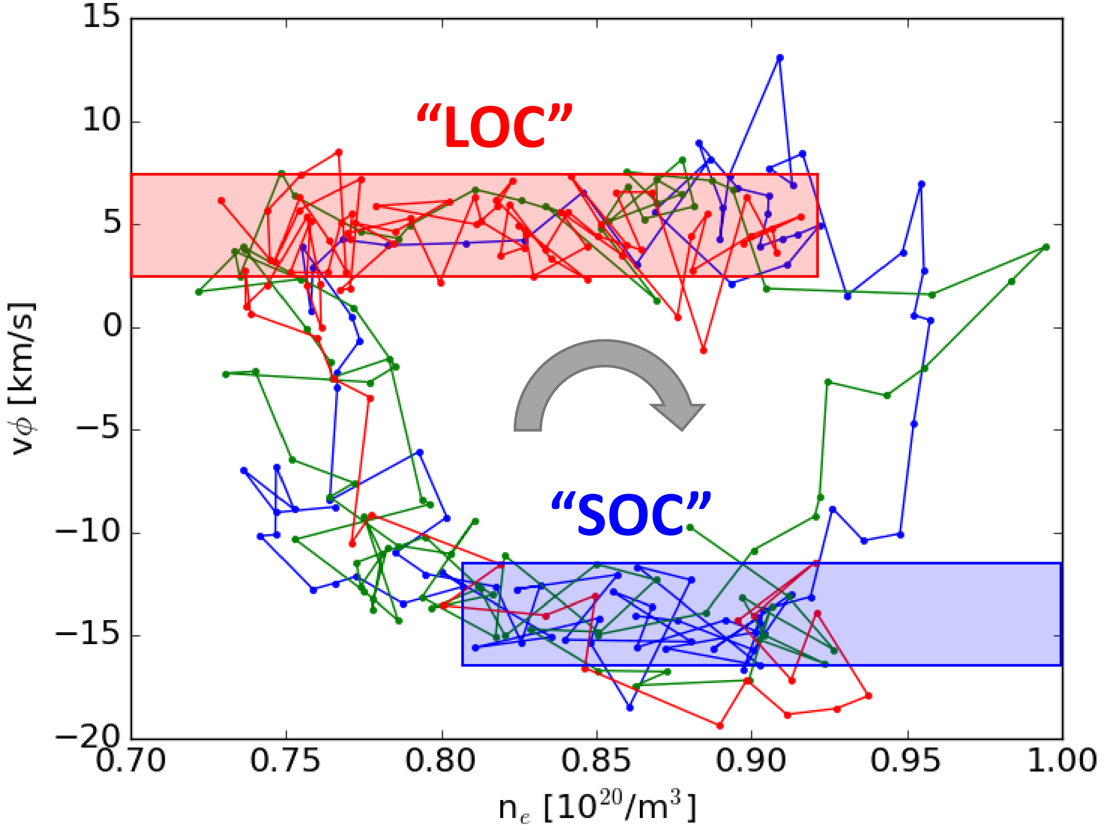
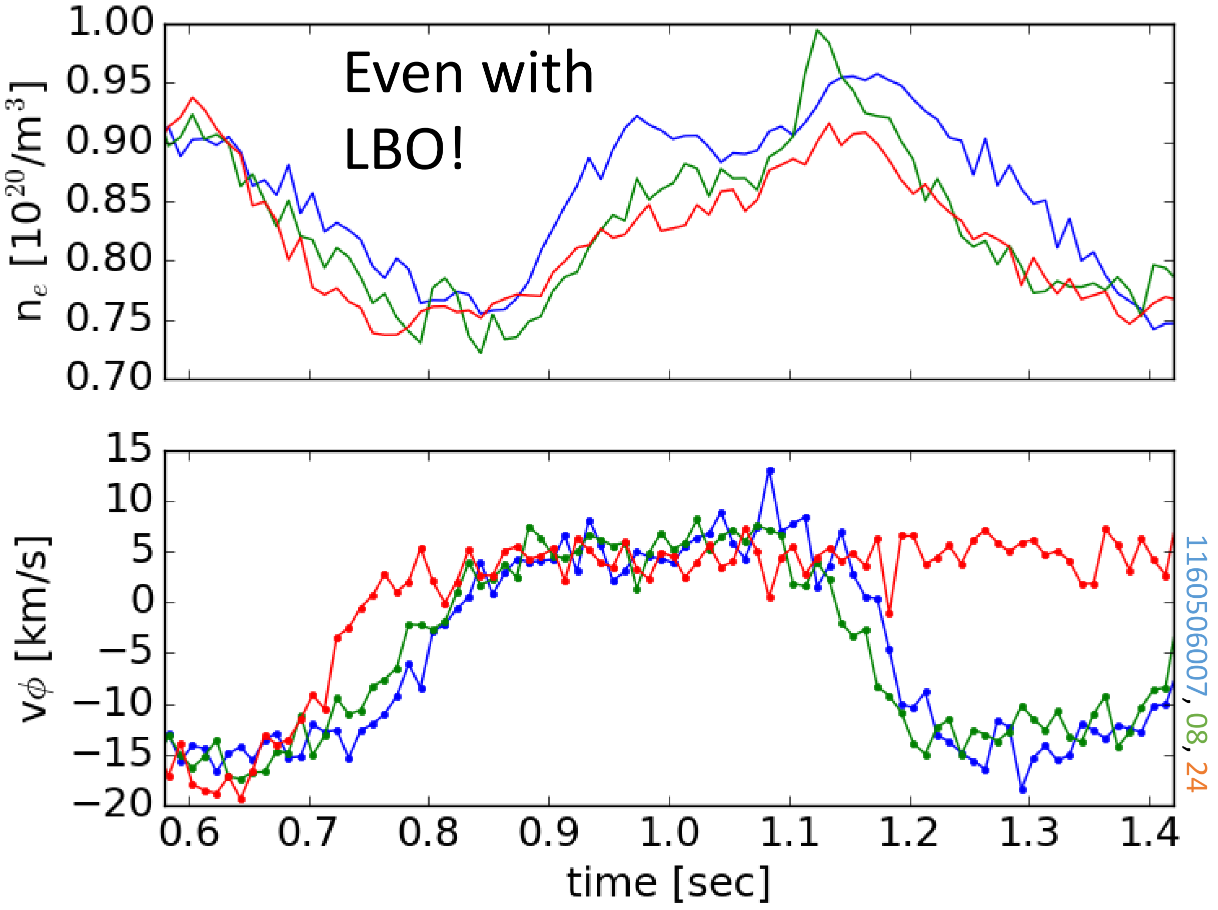
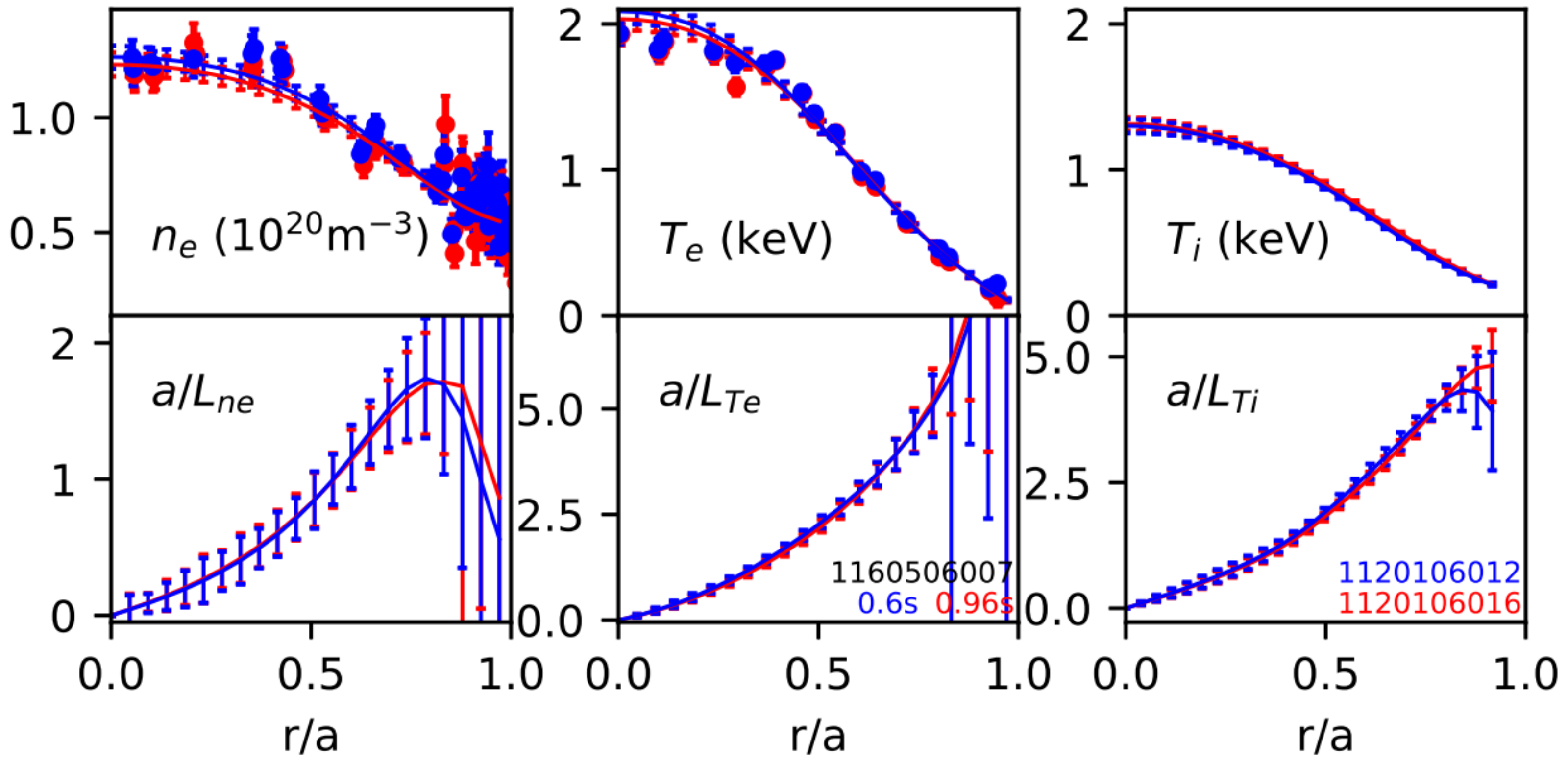




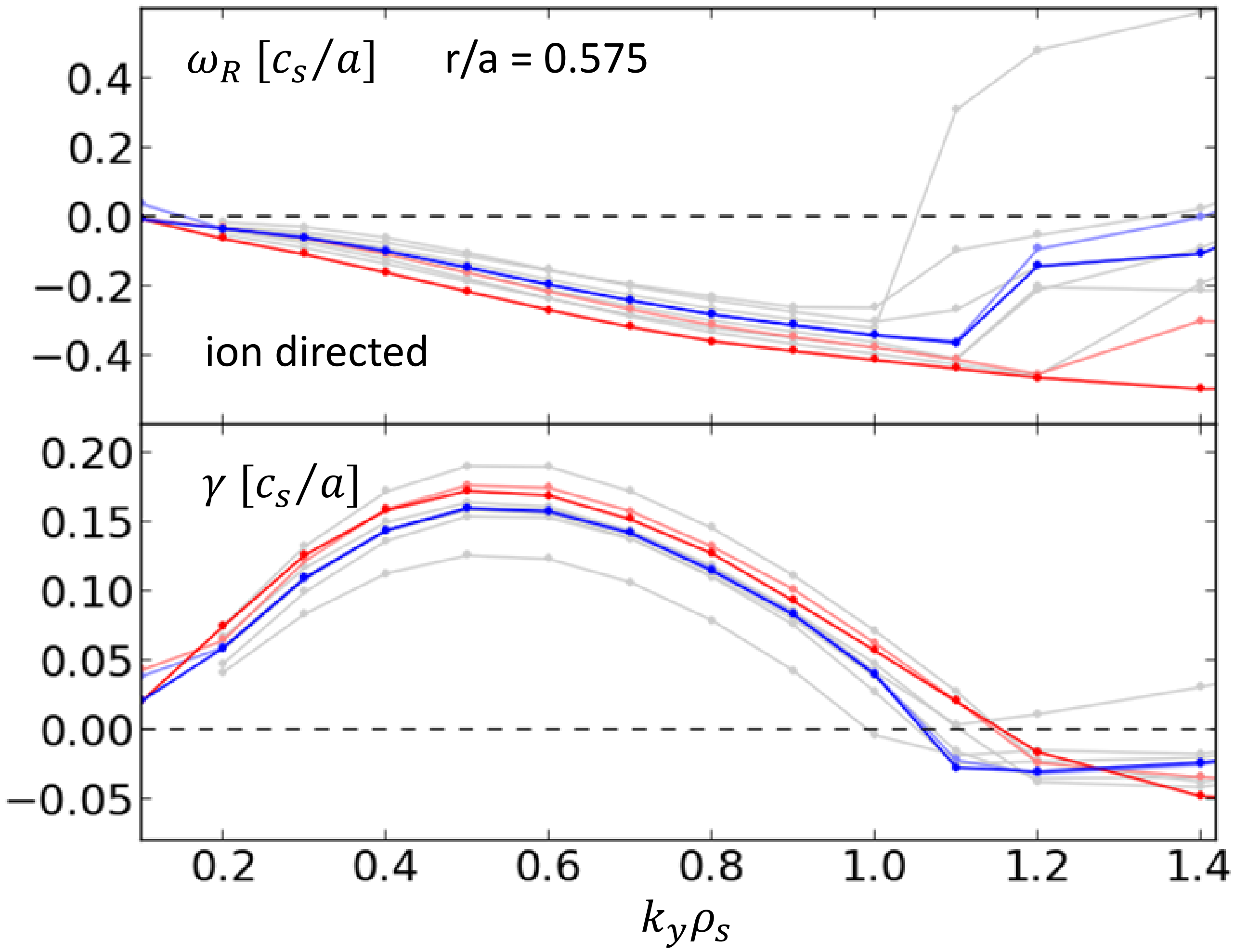
Nearly Indistinguishable Density and Temperature Profiles Can Lead to Different Rotation States

- 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 discharge
    - error rigorously estimated with GPR [Chilenski NF 2017]
  - Ion profiles from different but matched shots.



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 on Alcator C-Mod and AUG plasmas [White PoP 2013, Sung PoP 2016, Erofeev NF 2017]
- Motivates a need to look at **subdominant modes** to understand turbulent state



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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***)

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

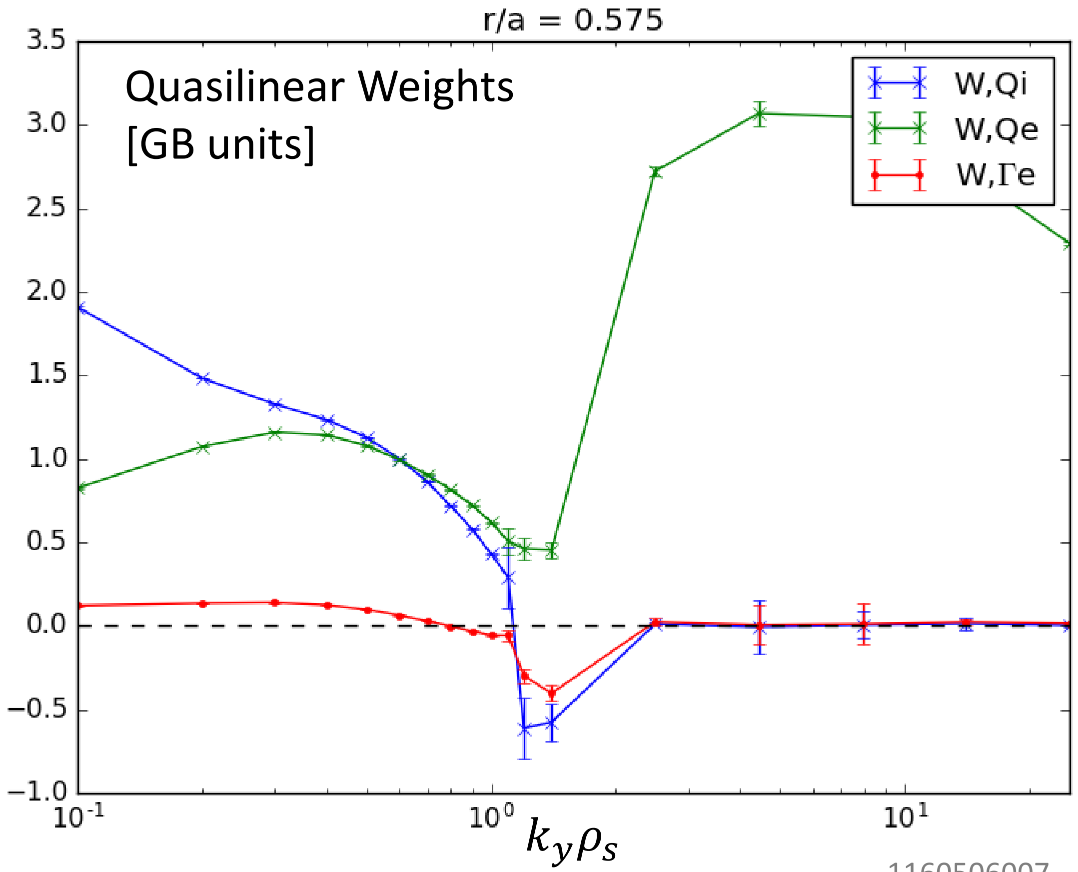
$$Q_{e,\mathrm{turb}} = \sum_k W_{Q_e,k} \left\langle \bar{\phi}_k{}^2 \right\rangle$$

- *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]. *Phase dynamics?*

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



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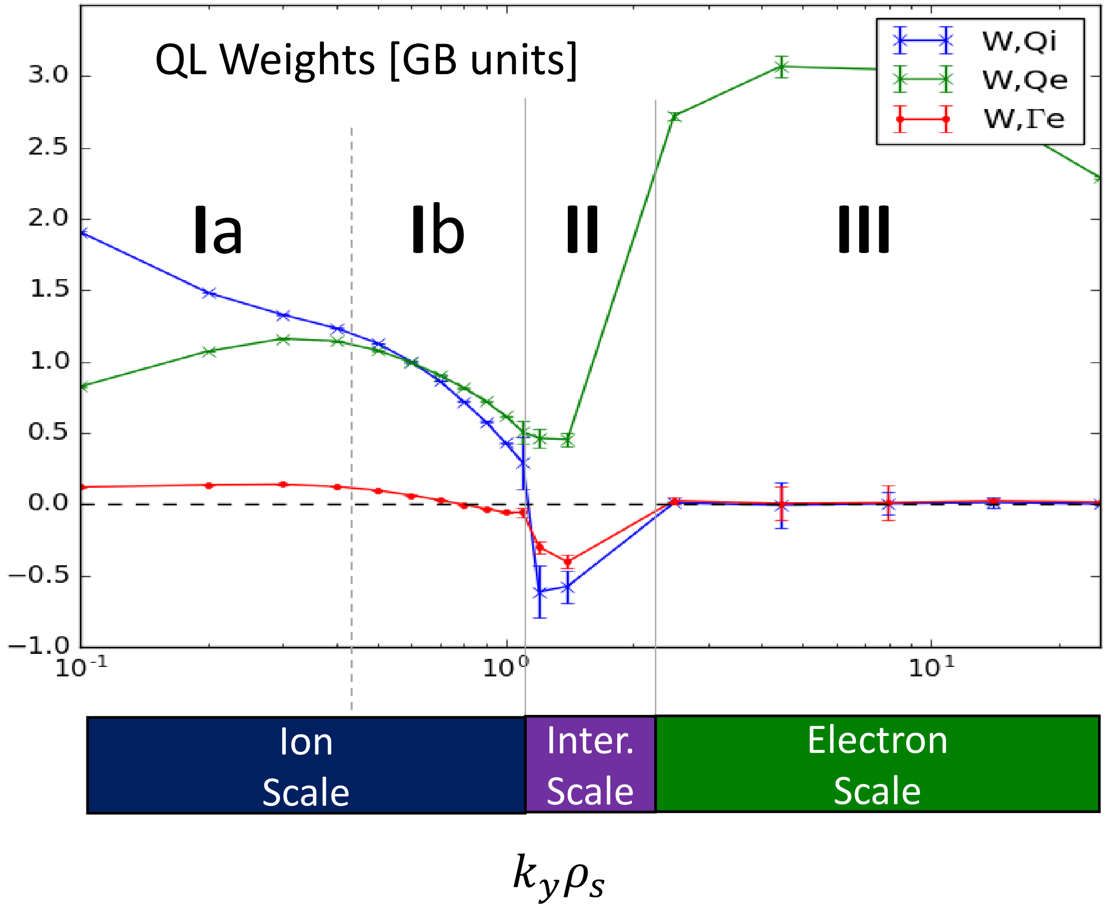
Reduced Family Model Allows Understanding Mixed Mode Picture



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

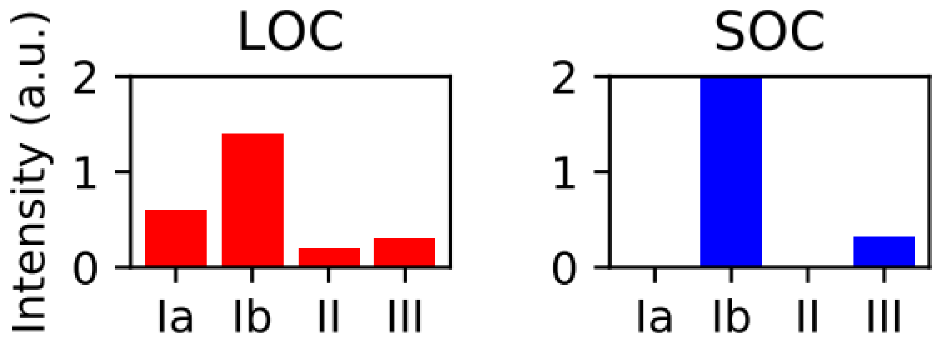
$$\textbf{Flux} = \sum_{\text{families}} \textbf{weight} \cdot \textbf{intensity}$$

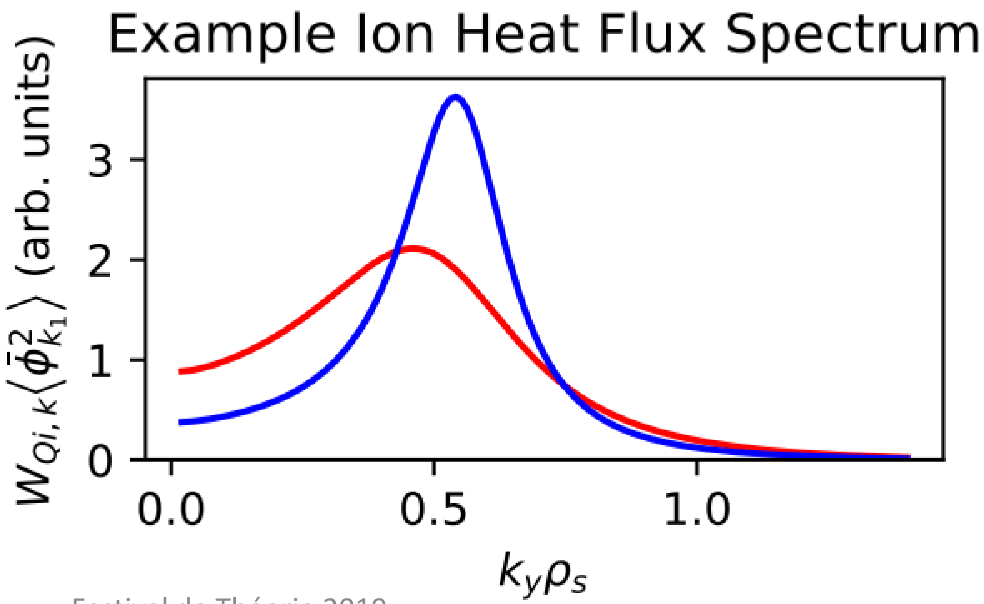
I. ion-scale ion-directed; (a) has net outward particle transport and (b) has roughly balanced transport

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

- 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

Possibilities include…

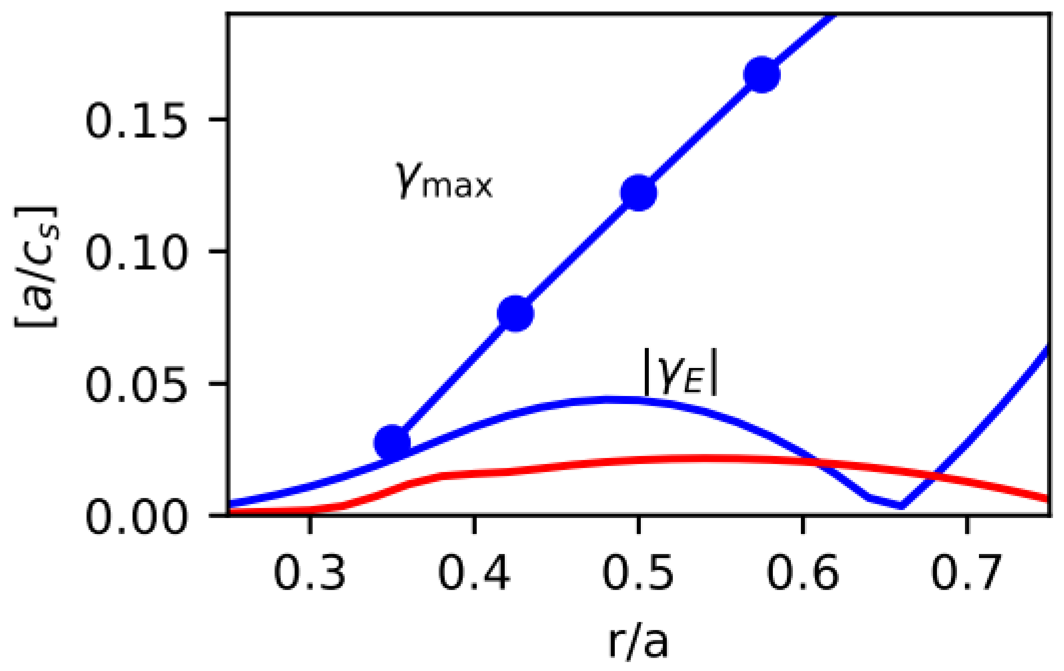
1. We're on a stability boundary, so small profile changes lead to big changes in turbulence
   - Robustness to LBO seems to rule this out
2. Mean rotation profiles contribute to change in turbulence through ExB shearing
   - Next slide will discuss…
3. Change in meso-scale or micro-scale turbulent nonlinear interactions (e.g. staircases, eddy-eddy interaction)
   - How to identify the key physics? Perhaps phase dynamics involved – what happens to the assumption of quasilinear transport?

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



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*: Identify the key physics; look into nonlinear simulation or experimental measurements of fluctuations

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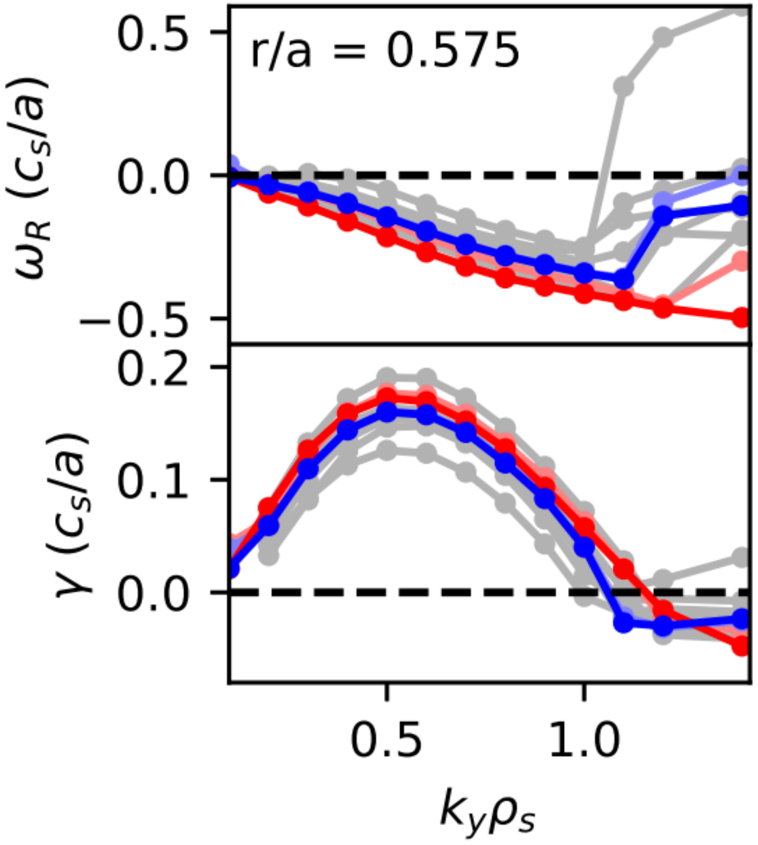
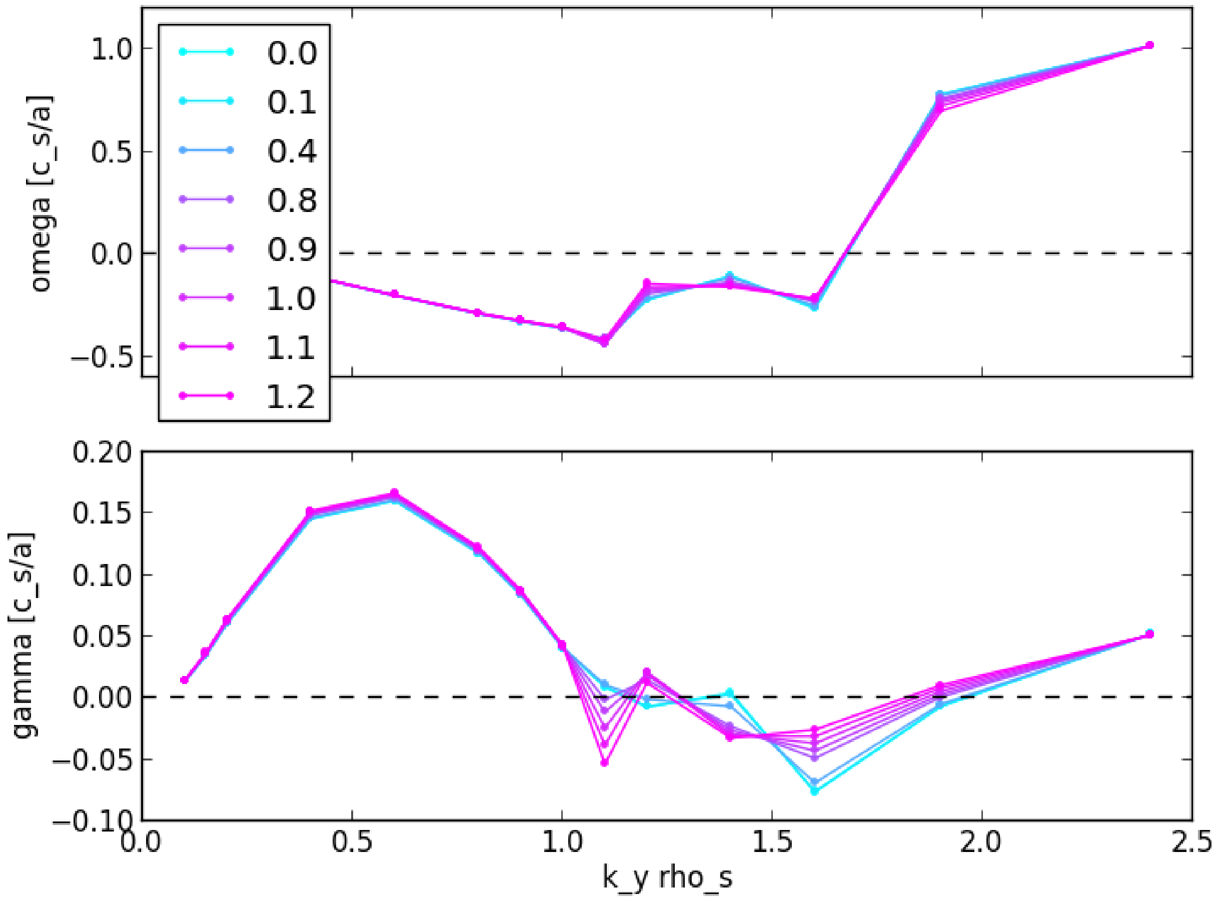
Extra Slides

Density Gradient

- With +20% scan in a/Lne, dominant modes remain ion directed



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

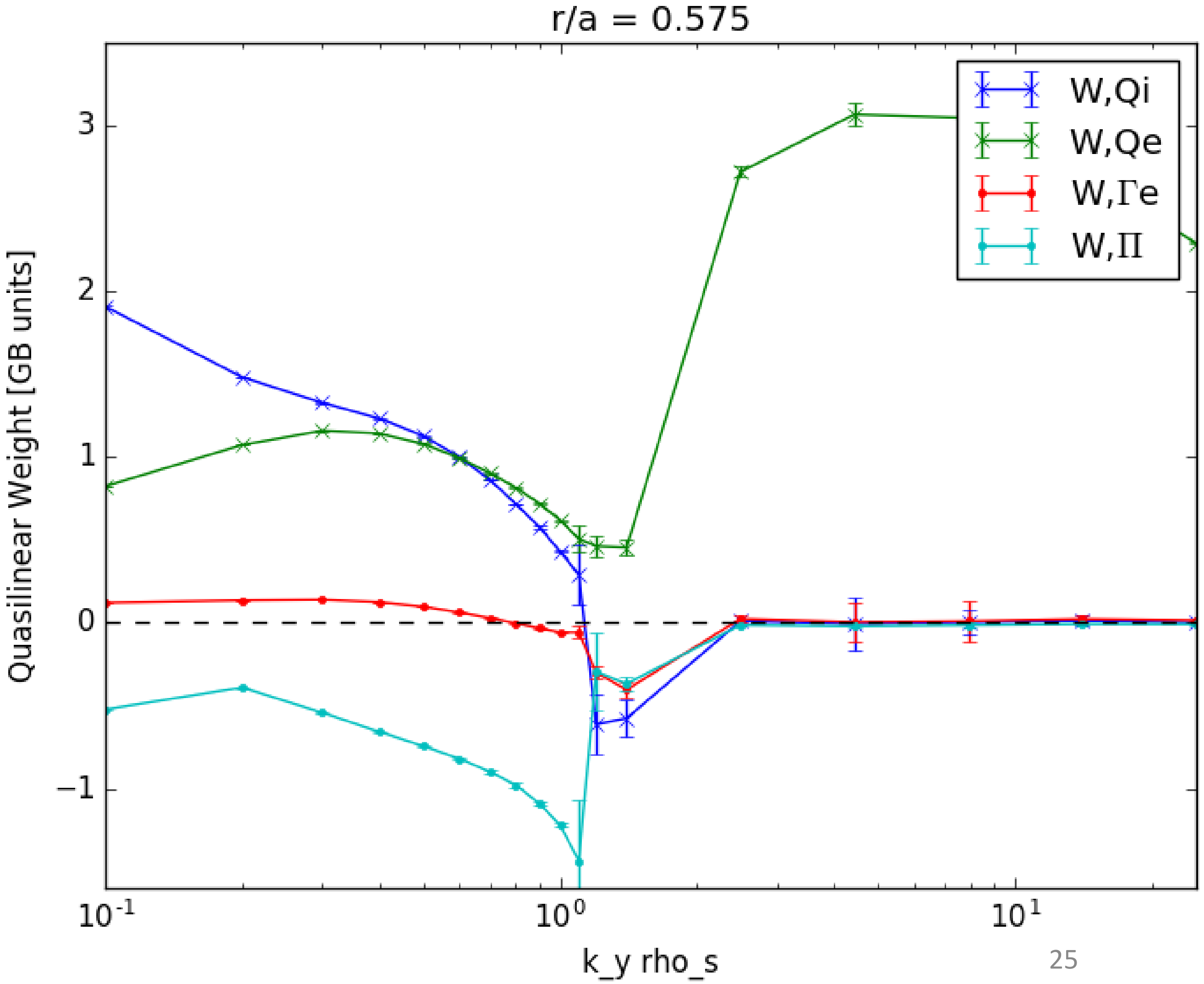


- Performed scans reducing mean ExB and Mach flow shear (color scale on plot to the right)
- Marginal modes with large enough $k_y \rho_s$ strongly affected by flow shear, while ion modes relatively unchanged
- Provides possible mechanism for bifurcation (increasing flow shear -> changed mode population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

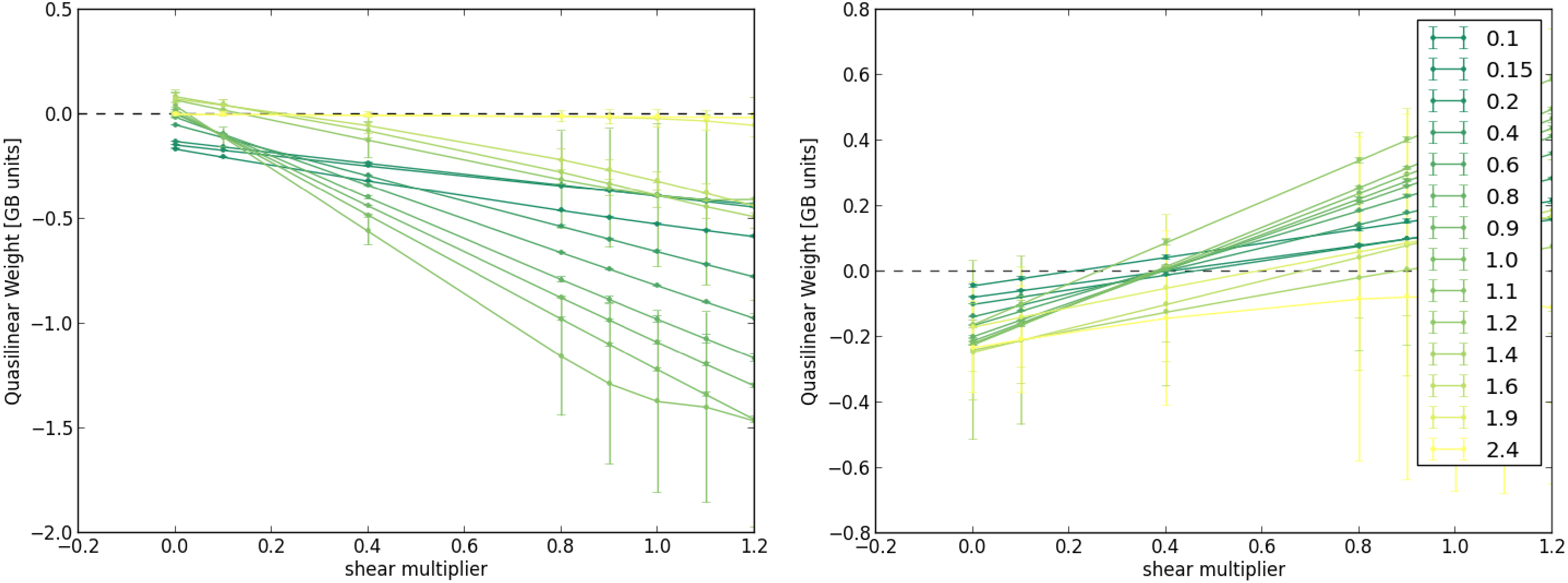
What about momentum?

- 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

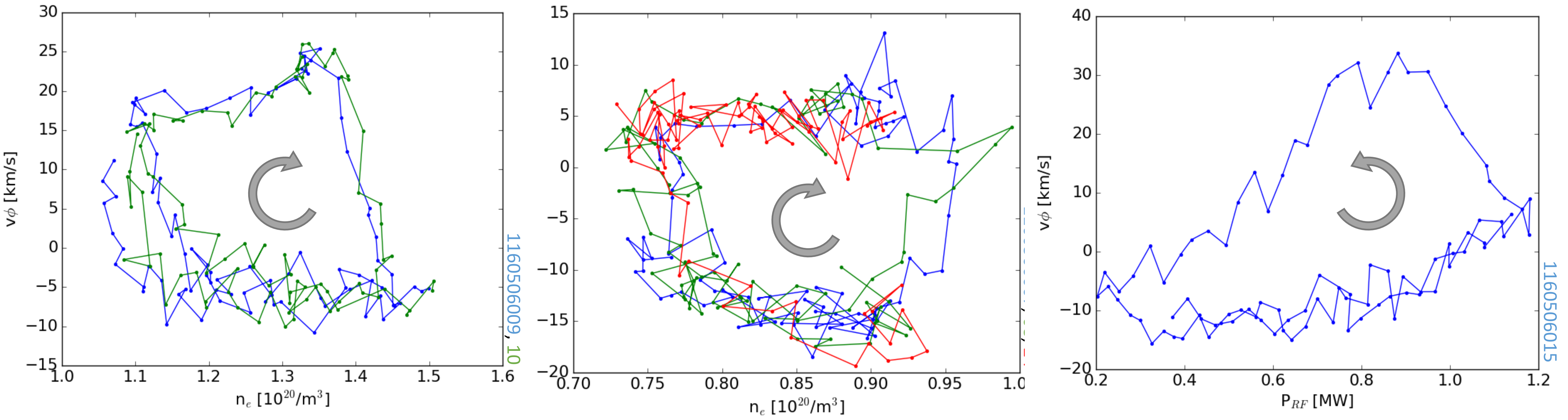


Momentum Transport Predicted is Primarily Diffusive

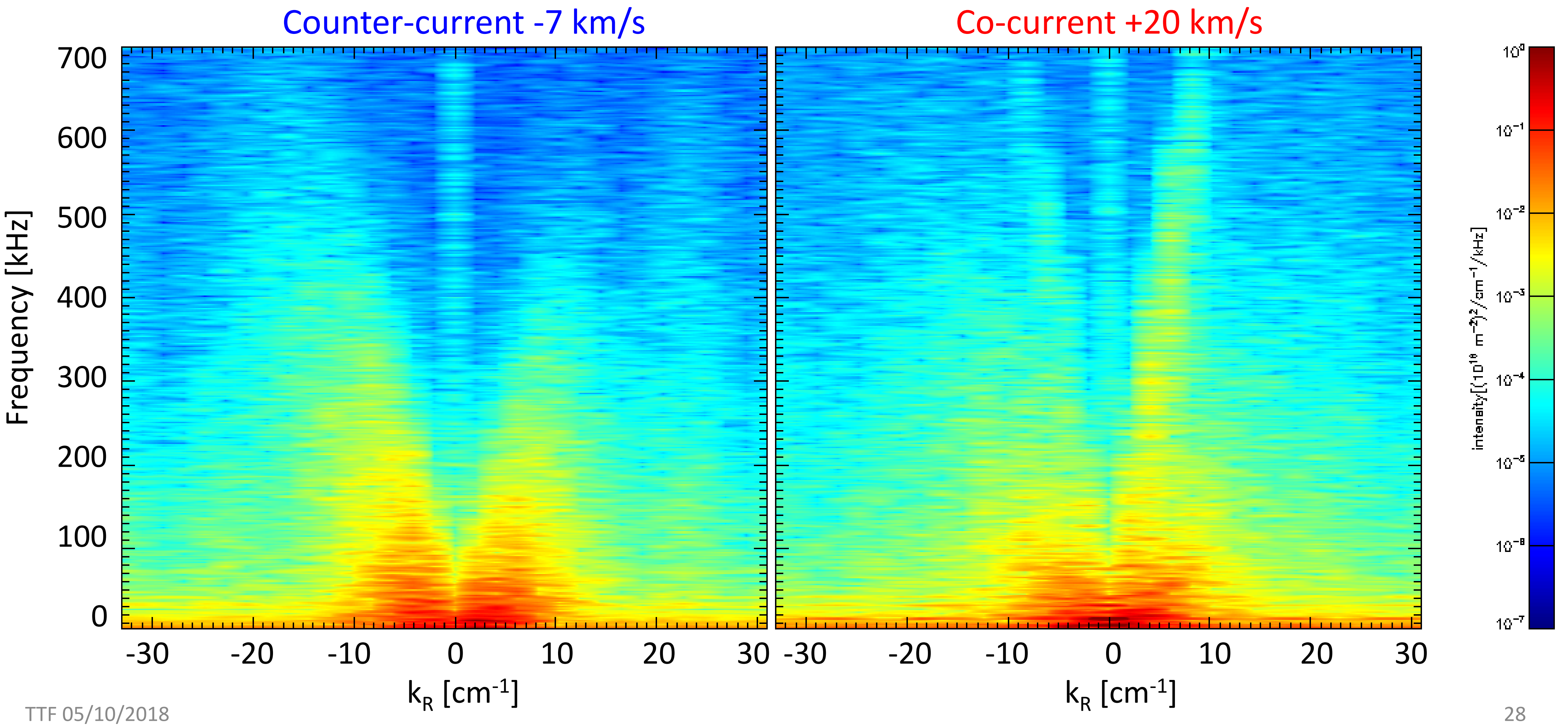


Hysteresis Observed Robustly in Multiple Plasma Conditions

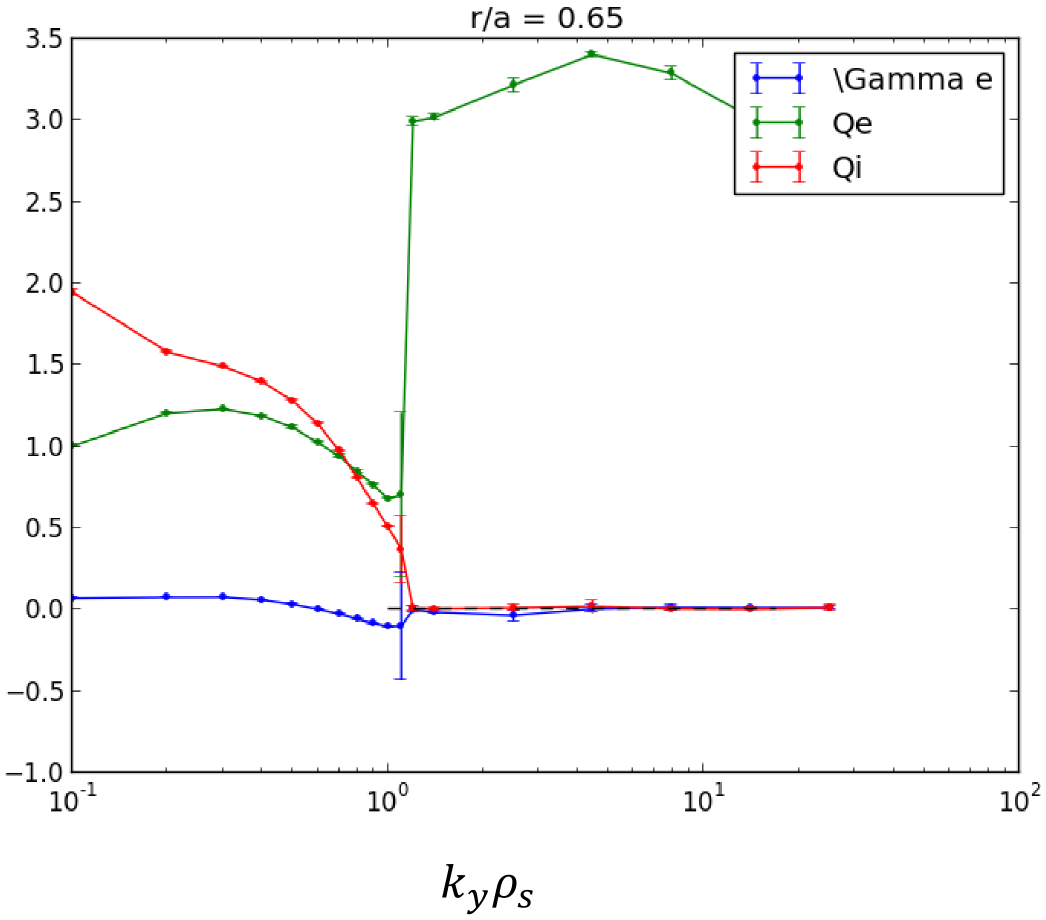
- Hysteresis is observed at multiple currents, and survives perturbation from LBO.
- Low-power ICRF heating ramps also lead to hysteresis, with similar



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



Radial Dependence of Parameters – Global versus Local Transition?



- Electron-direction quasilinear response is different at different radii.
- Turbulence Spreading may be responsible for excitation of marginally stable modes, leading to “global” transition rather than “local” transition
  - Plays well with “population collapse” theory

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)

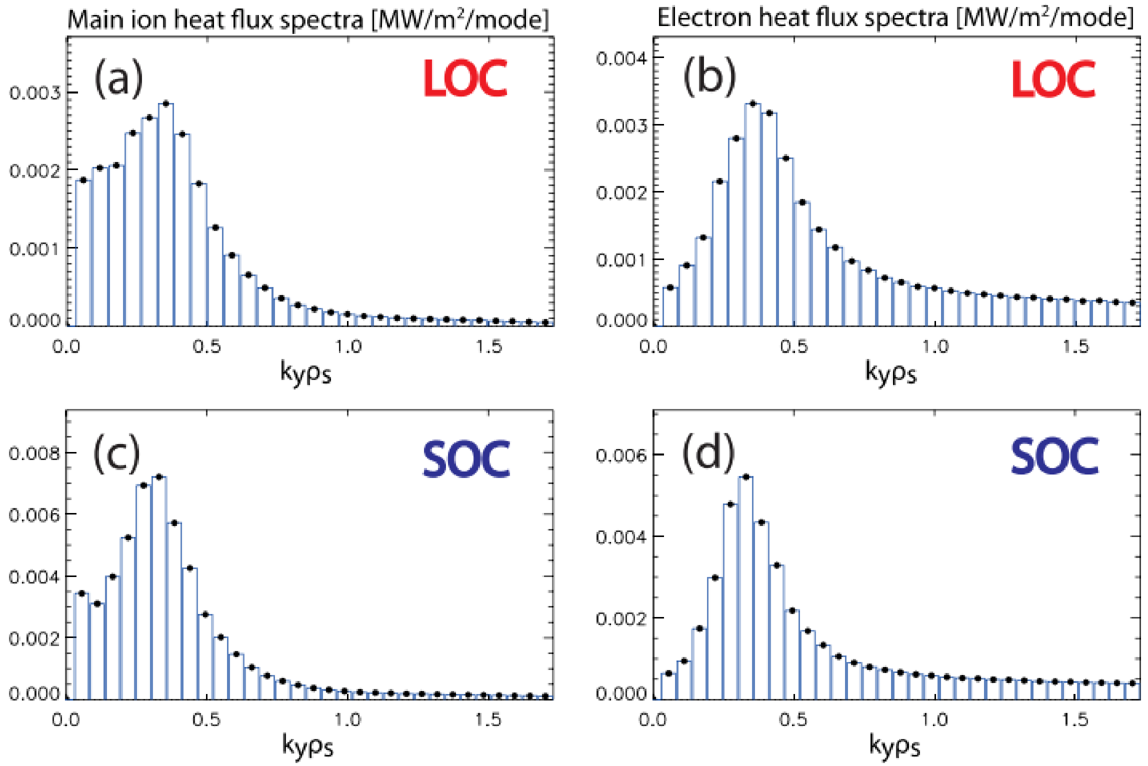
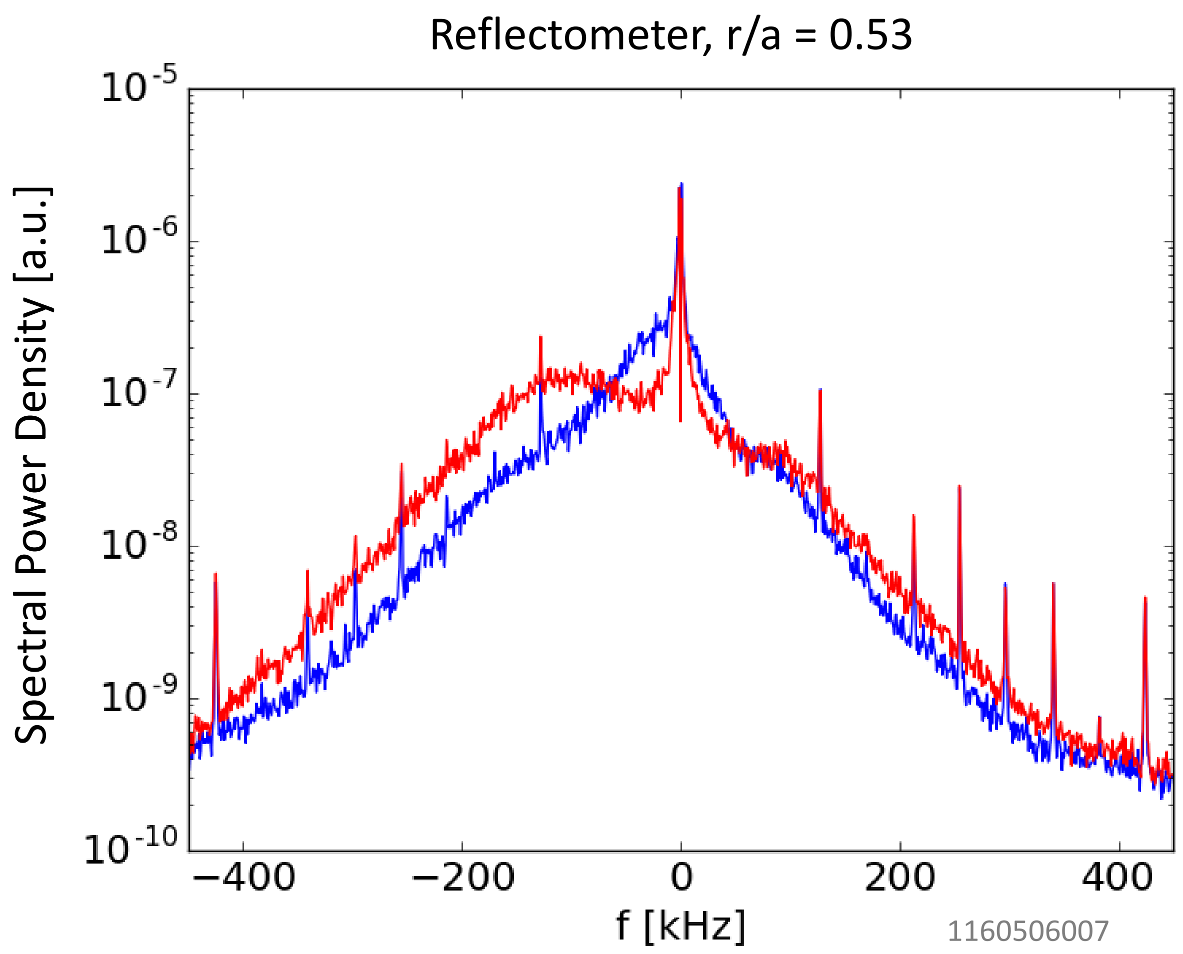


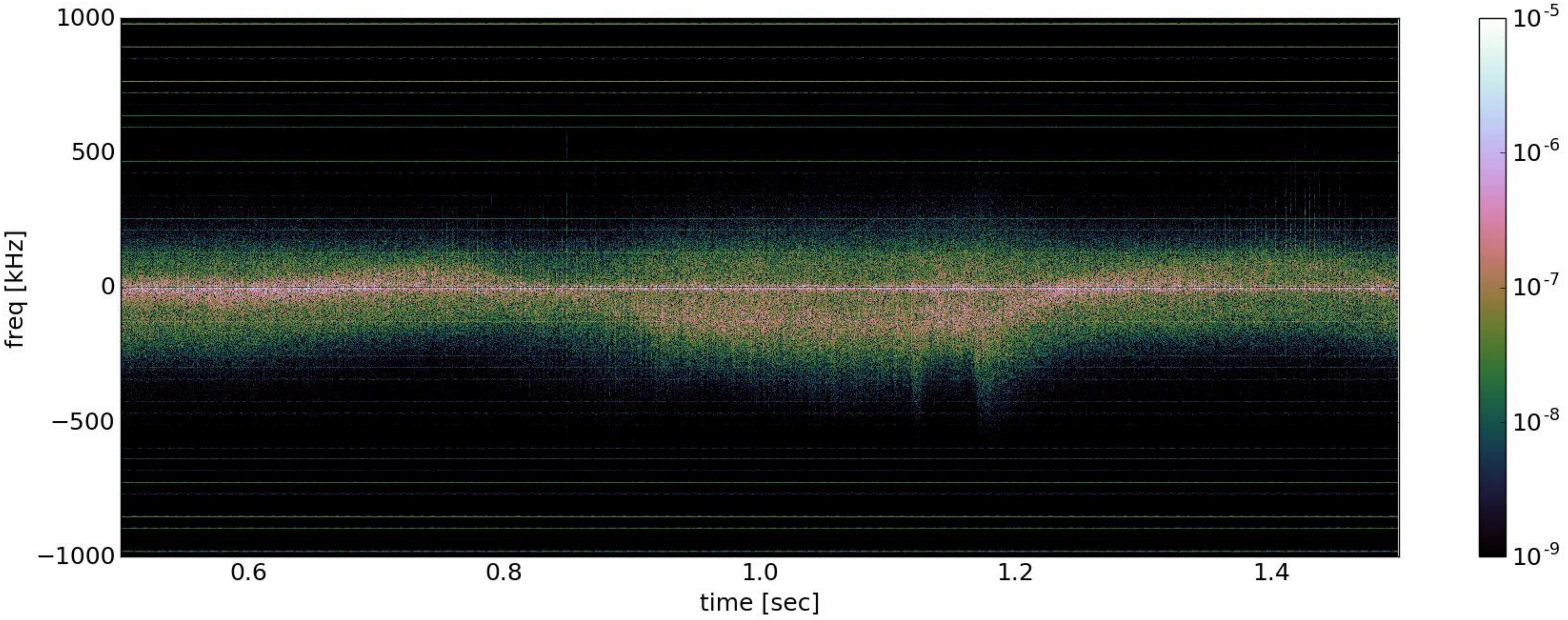
FIG. 14. Time averaged heat flux spectra on $k_y\rho_s$ in the "ion heat flux matched" runs (a) main ion heat flux spectrum in the LOC discharge (shot 1120626023) and (b) electron heat flux spectrum in the LOC discharge (c) main ion heat flux spectrum in the LOC discharge (shot 1120626028) and (d) electron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

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



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)

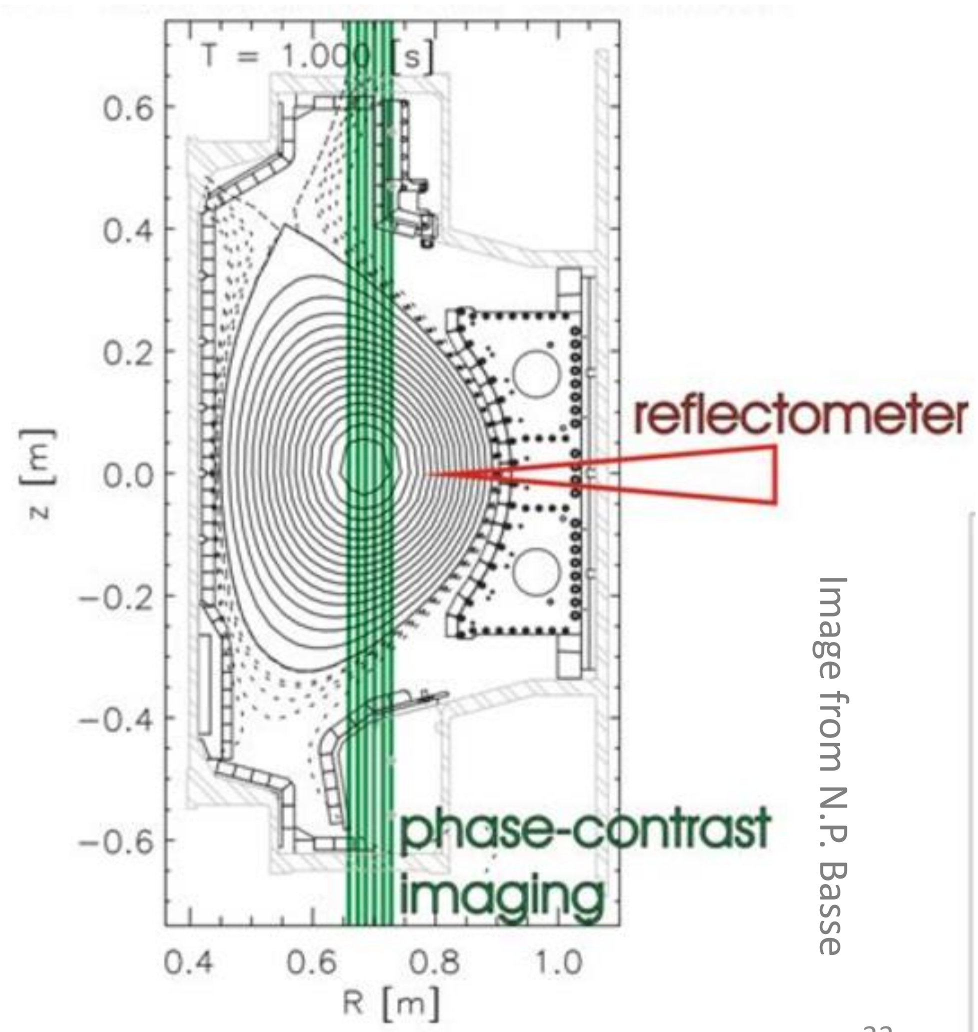


Image from N.P. Basse