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# Suppressed Ion-Scale Turbulence and Critical Density Gradient in the C-2 Field-Reversed Configuration


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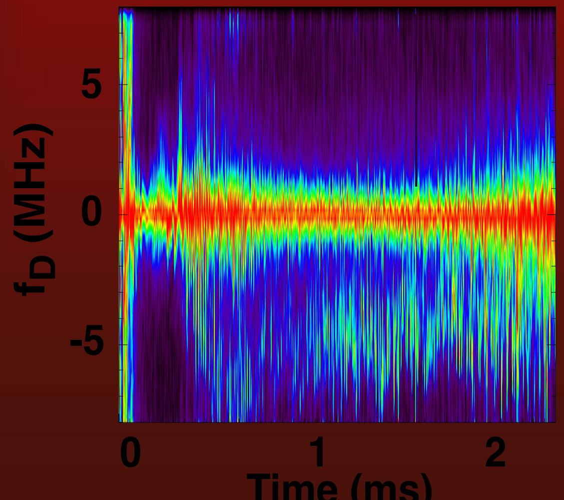
and the TAE Team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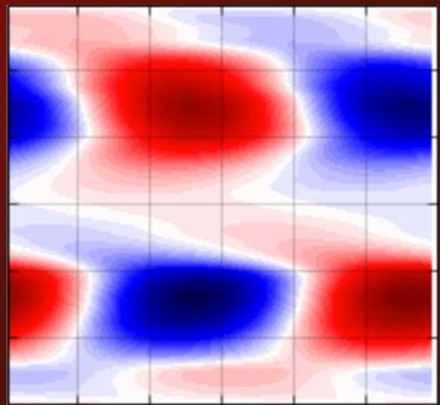
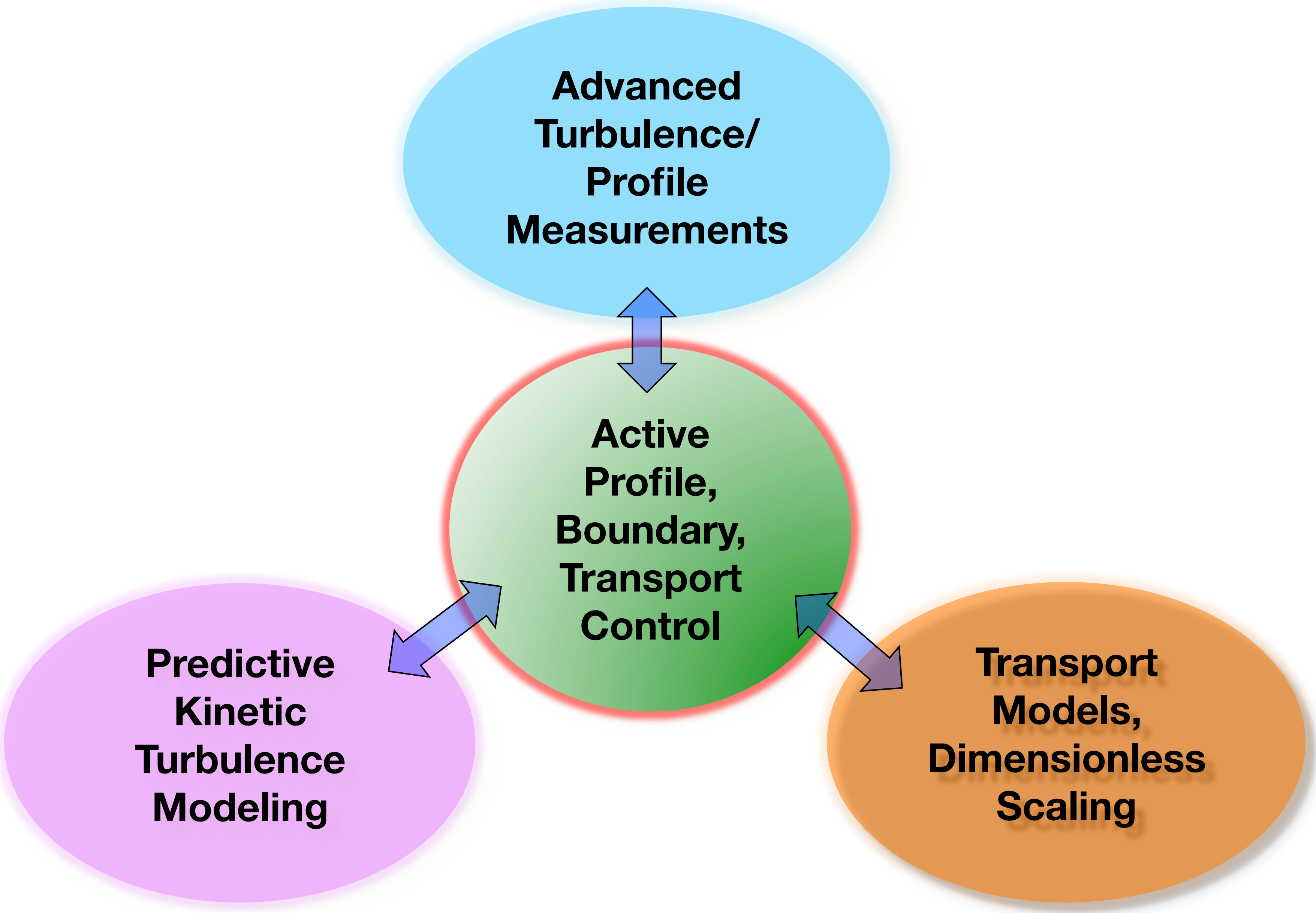


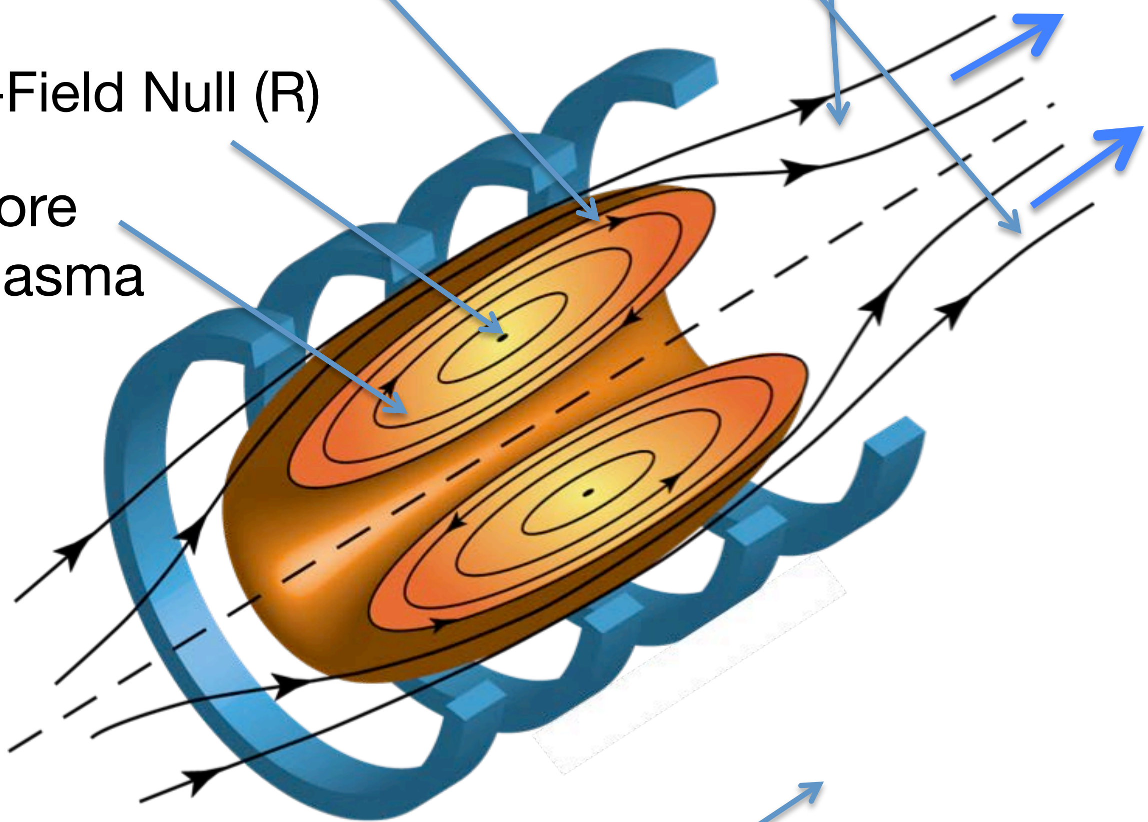
# Goal of FRC Turbulence/Transport Studies: Active Profile, Boundary, and Transport Control



# Outline

- Introduction
- Experimental fluctuation/turbulence studies in the C-2 FRC
- Gyrokinetic Modeling: FRC core and boundary fluctuations
- Critical gradients, core/SOL transition and barrier effects
- Summary

# FRC Geometry / C-2 Parameters




## Typical C-2 Parameters

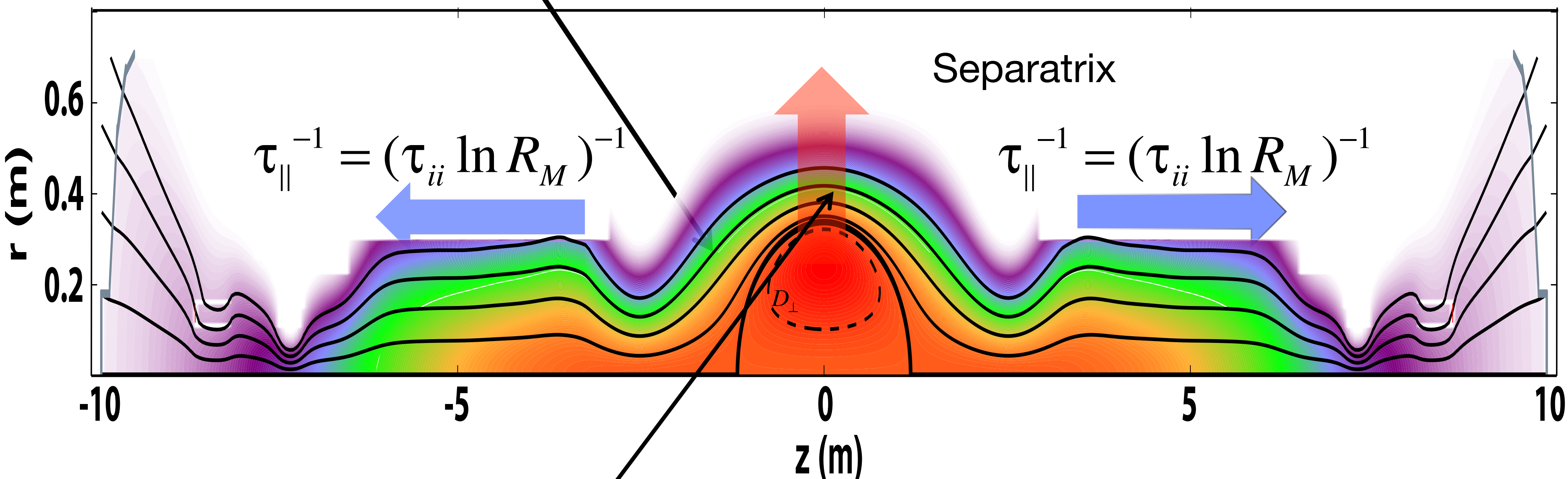
| | FRC Core | SOL |
|---|---|---|
| Density ($10^{19}$ $m^{-3}$) | 2-4 | 0.5-2 |
| $T_i$ (eV) | 600-1000 | ≤250 |
| $T_e$ (eV) | ≤ 150 | 30-80 |
| $B_e$ (Gauss) | | ≤ 1200 |
| Sep. Radius (cm) | 35-45 | |
| Neutral Beam Power | ≤ 4 MW | |

# FRC Radial and Parallel Transport

Scrape-off layer (SOL):
Radial and parallel
Transport (along z)

From continuity (particle conservation:)

$$\nabla_{\parallel}(n\mathbf{v}_i) = -\nabla_{\perp}(n\mathbf{v}_i) \longrightarrow \tau_{\parallel} = \tau_{\perp}$$




Radial transport:

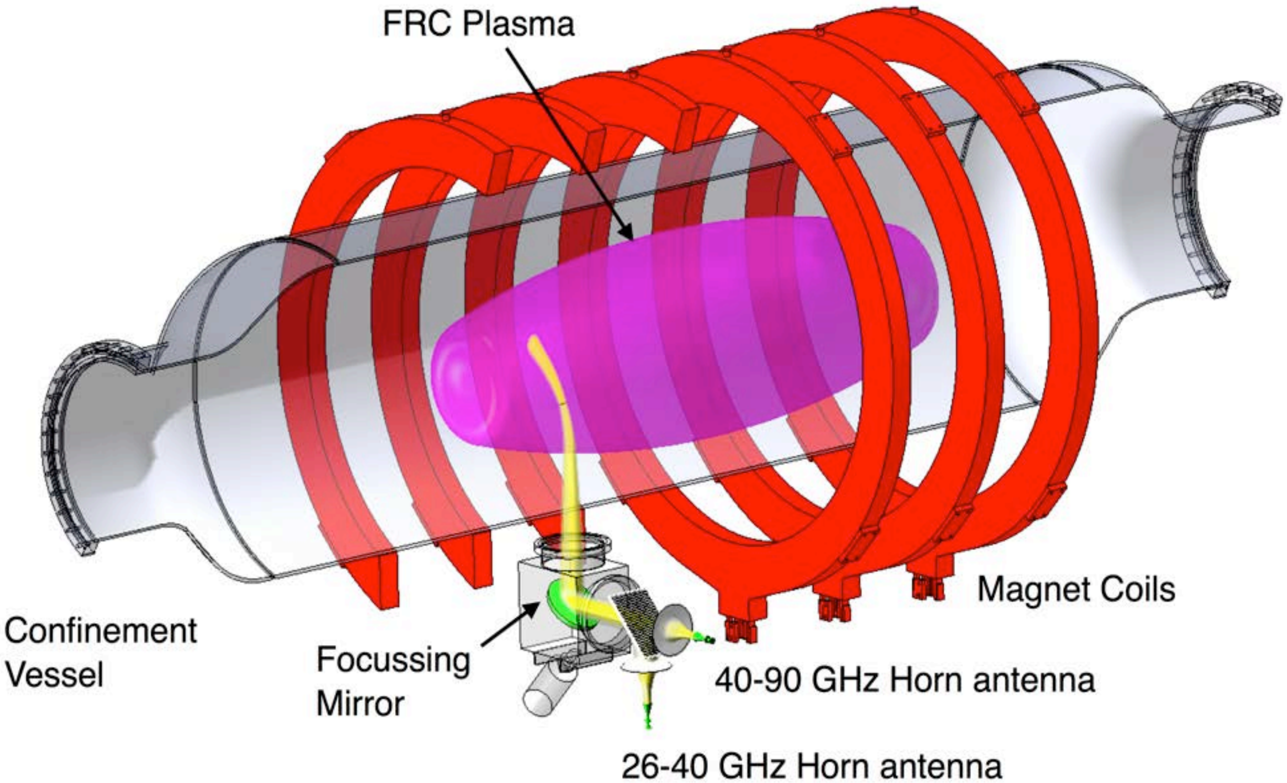
$$\tau_{\perp}^{-1} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD_r \frac{1}{n}\frac{\partial n}{\partial r}\right)$$

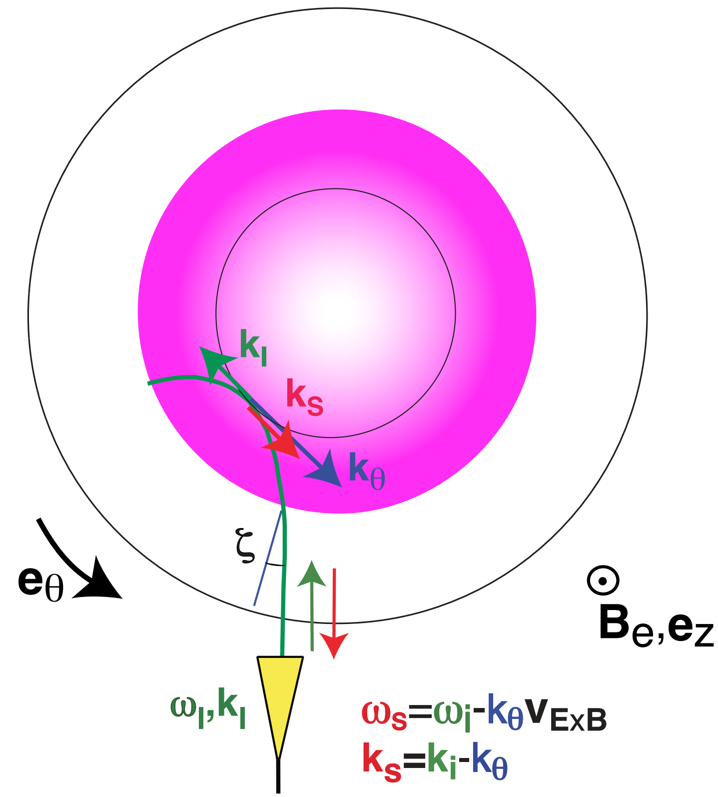
Radial Gradient scale length :

$$L_{n\perp} = \sqrt{D_{\perp}\tau_{ii} \ln R_M}$$

If $D_{\perp}$ depends on $L_{n\perp}$, parallel and perpendicular transport are coupled

# Schematic and Principle of Doppler Backscattering Diagnostic (DBS)



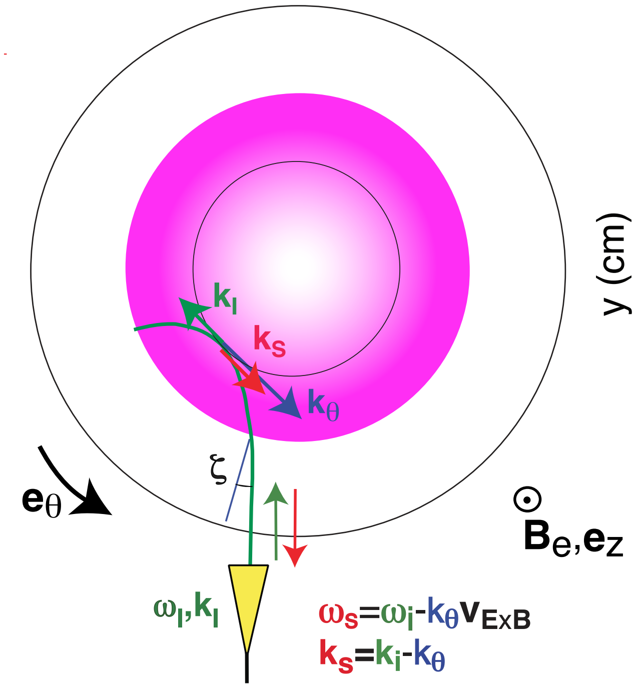

**ñ/n: local density fluctuation level ñ(r)/n(r) vs. $k_\theta$**

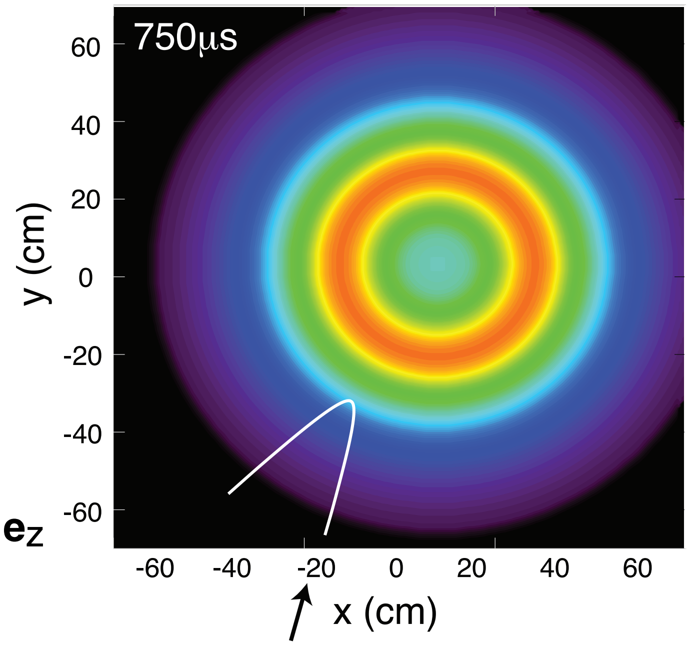
**- here $k_\theta \sim$ 0.5-12 $cm^{-1}$ ($k_\theta \rho_s \sim$1-40)**

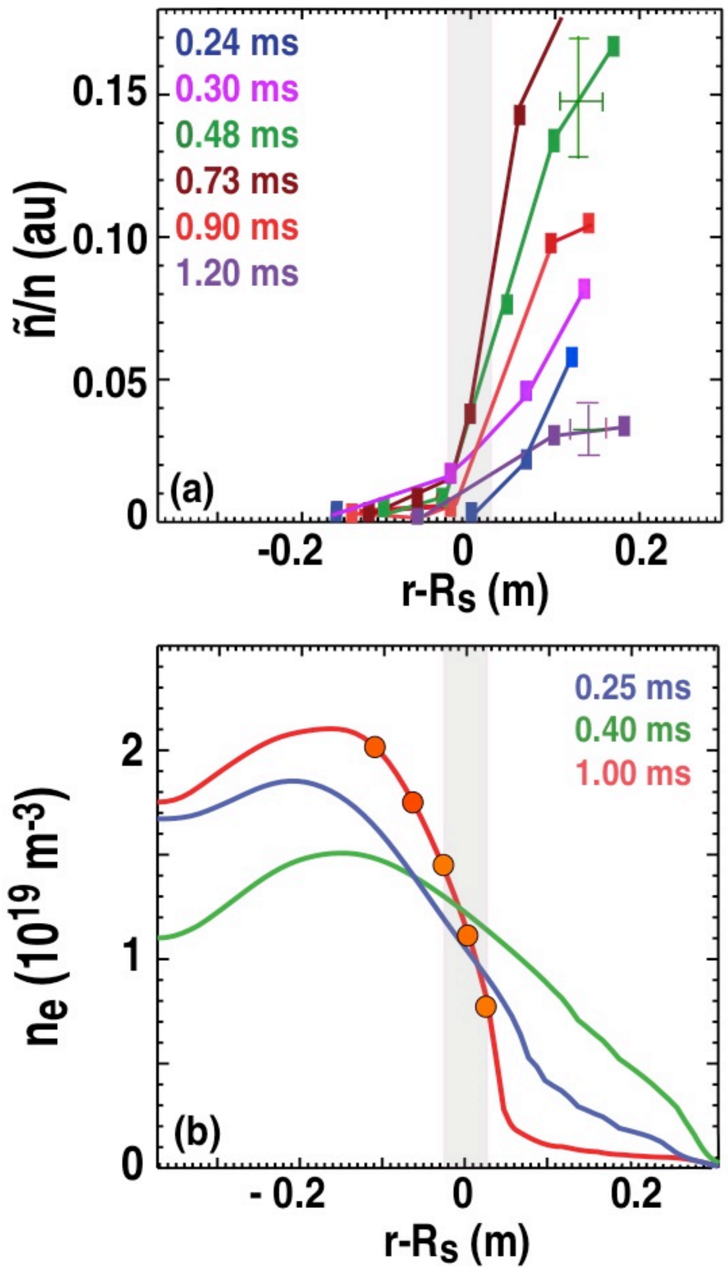
**ExB velocity from Doppler shift of back-scattered signal:** $\omega_{Doppler} = v_{turb} k_\theta \sim v_{ExB} k_\theta$

→ $v_{ExB} \sim \omega_{Doppler} / 2k_i$

# Radial Density Profile and DBS Probing Radii

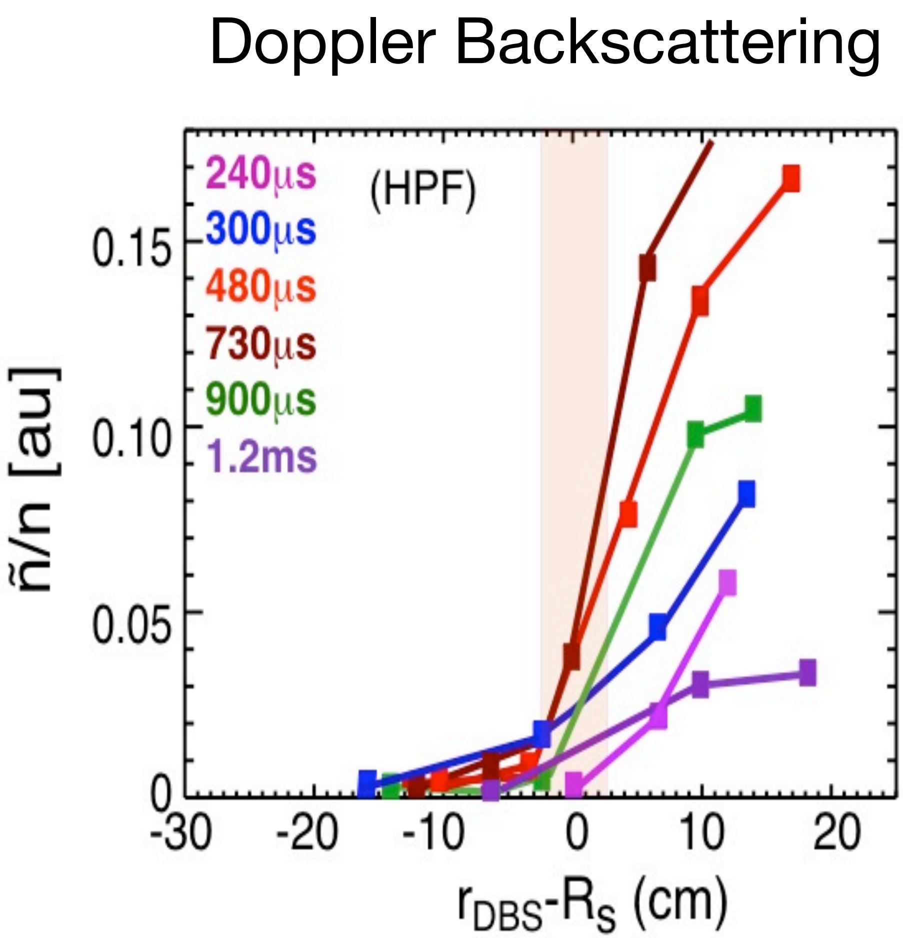


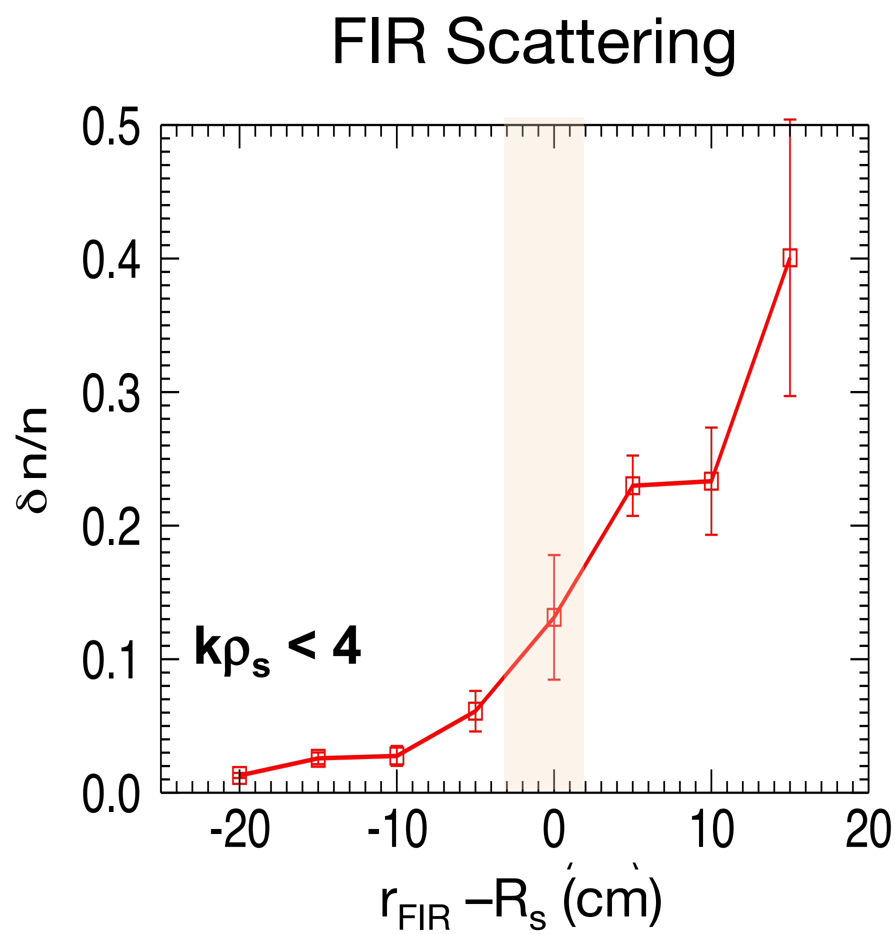




- **DBS: 6 remote-tunable channels (co-linear beams), probing the FRC core (outside field null) and the SOL**
- **Beam path calculated via GENRAY ray/beam tracing, based on reconstructed ($CO_2$) density profiles**

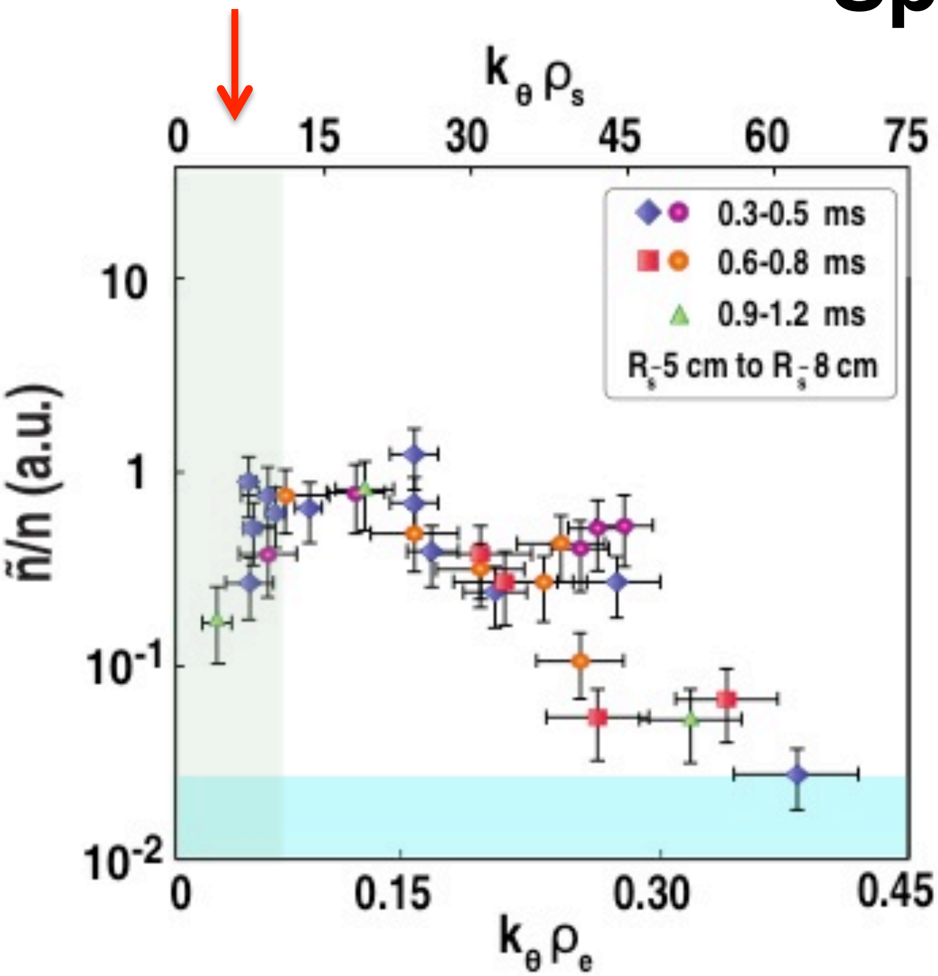
# Density Fluctuations Peak Outside Separatrix Very Low Fluctuations in FRC Core

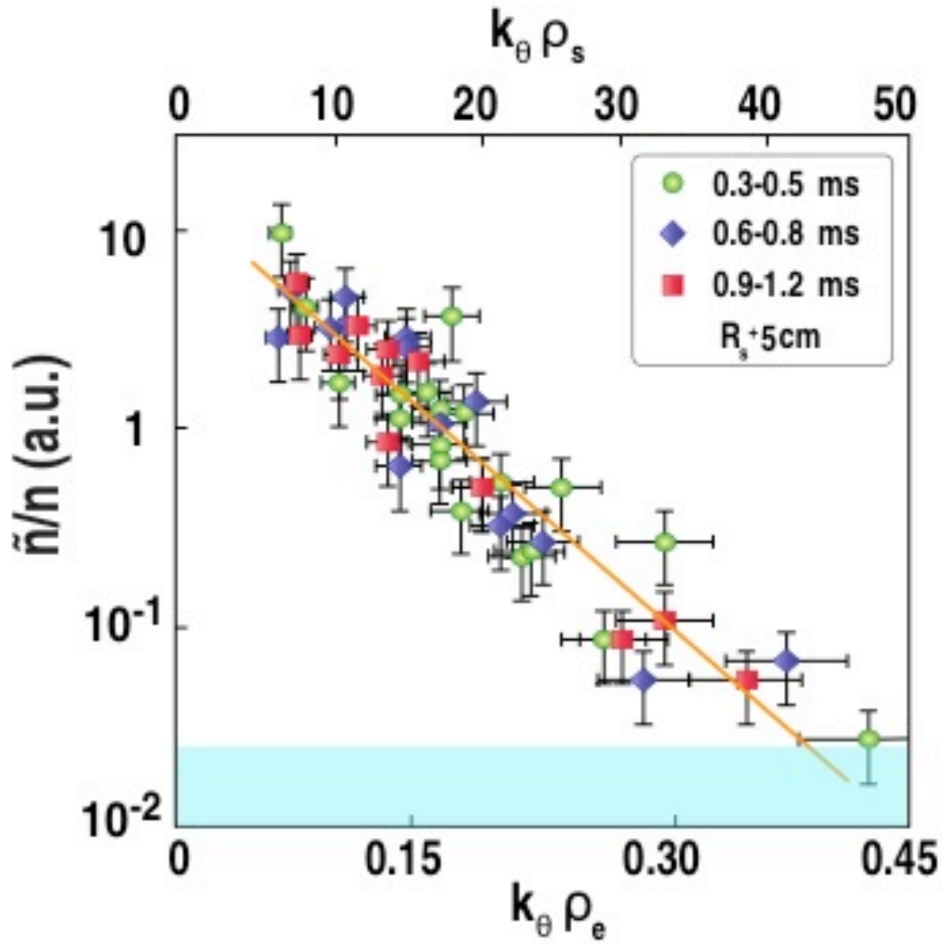



- Fluctuation levels peak outside the separatrix
- Very low fluctuation levels in the FRC core

# FRC Core Plasma: Unique Inverted Wavenumber Spectrum




- **FRC Core: Decreased Fluctuations; Inverted Spectrum at low $k\rho_s$**
- **Spectrum extends to $k\rho_e > 0.3$: Only unstable electron modes!**
- **SOL: Ion and electron-scale modes**
- **Broad exponential spectrum: $(\tilde{n}/n)^2 \sim \exp(-0.32\, k_\theta\rho_s)$**

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# GTC (Gyrokinetic Toroidal Code) Simulations

**First-principles, integrated microturbulence simulations; adapted for FRC geometry (Boozer coordinates): Useful for predictive modeling and reduced transport models**

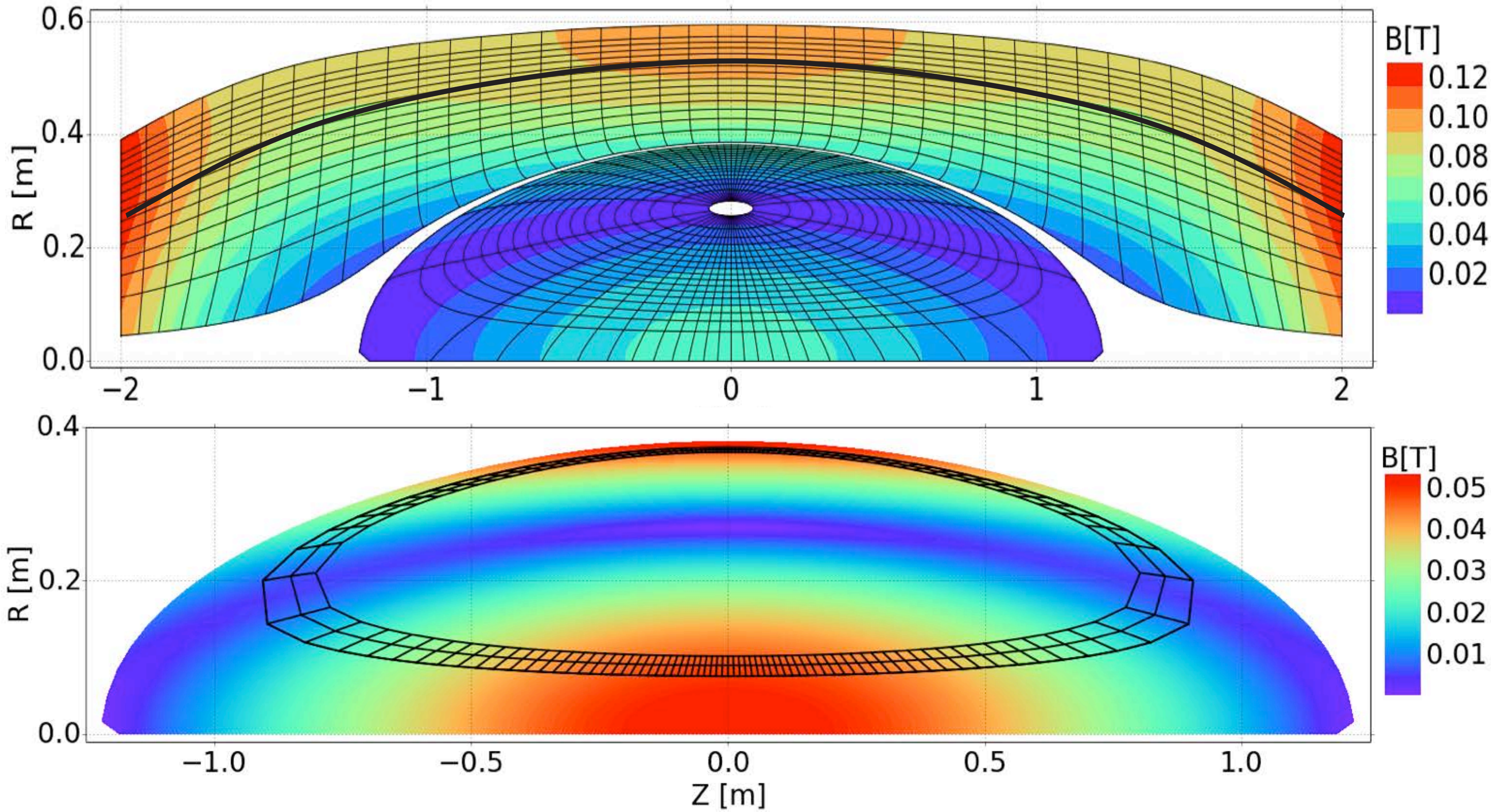
Input: Experimental (measured) or calculated FRC equilibria

Gyrokinetic or kinetic ions, kinetic electrons
Local/global simulations, electromagnetic effects
Fokker-Planck-collisions

Presented here: Results from linear, electrostatic flux-tube simulations, separate calculations for the FRC core and SOL

Future work: Coupled SOL/core, kinetic ions, nonlinear runs

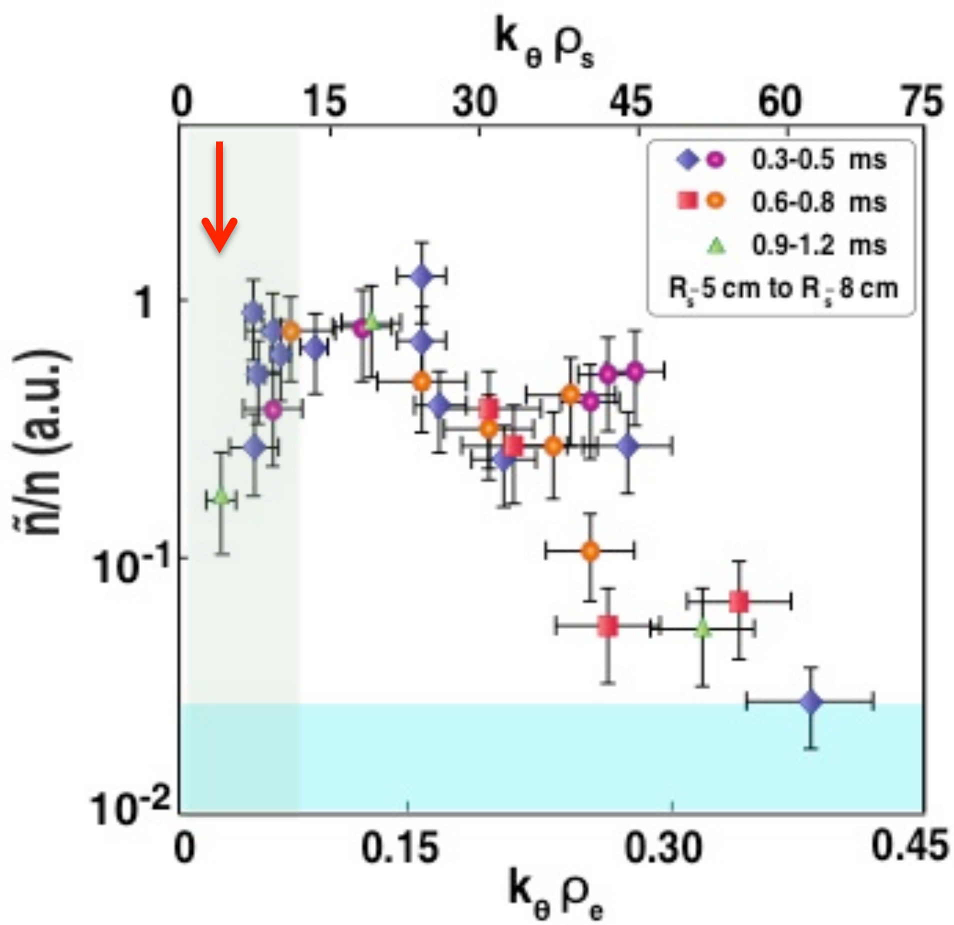
# Simulation Geometry, Parameters



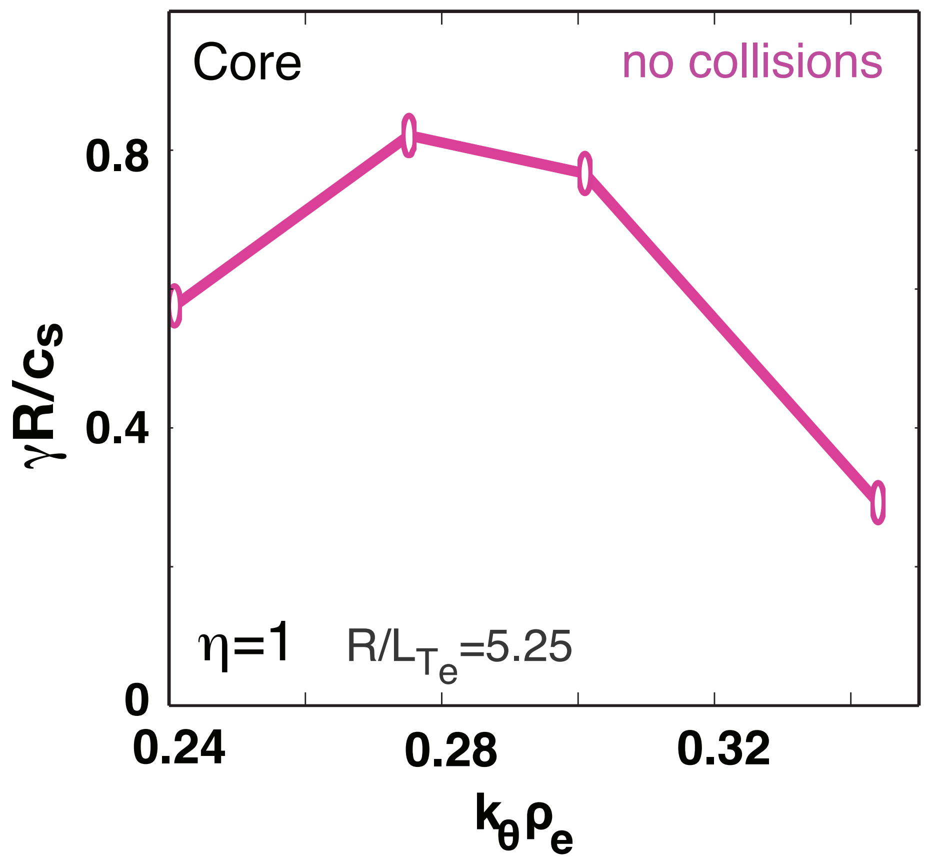

**Core and SOL local simulation: Realistic C-2 Equilibrium**
**Periodic boundary conditions in z and θ**
**Gyrokinetic ions (D) and electrons, $\nu_{e,i}^{*}=\nu/\nu_{transit}$ <<1**

# FRC-Core: Ion Modes Suppressed via FLR Effects, only Electron Modes Unstable

**Measured Saturated Spectrum**




**Calculated Linear Growth Rate from GTC**

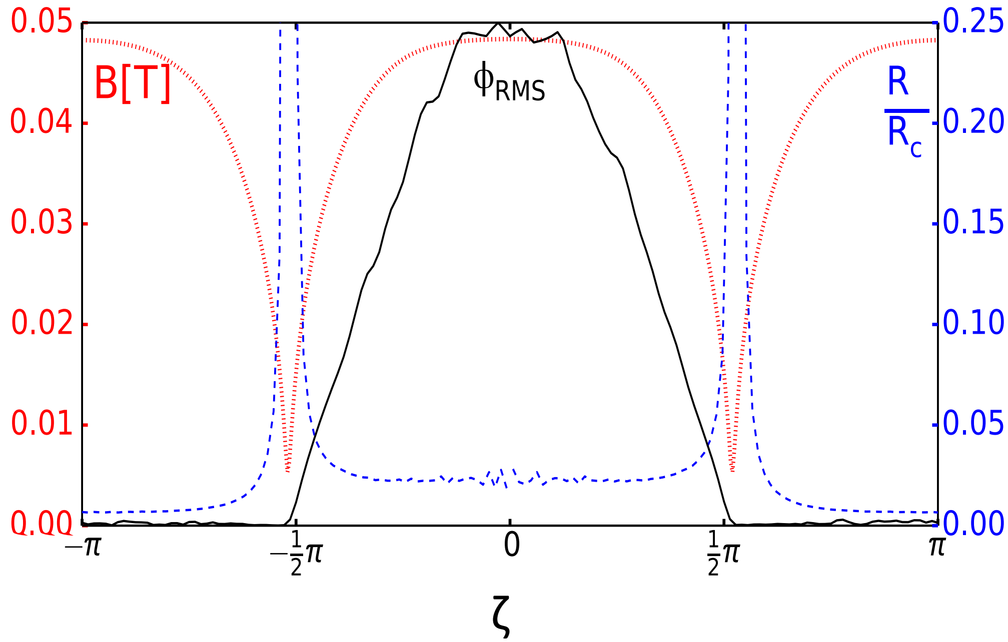



- **Spectrum extends to $k_\theta \rho_e > 0.3$: matches linearly unstable k-range**
  **Dominant electron modes; ion modes weak/absent due to FLR* effects:**

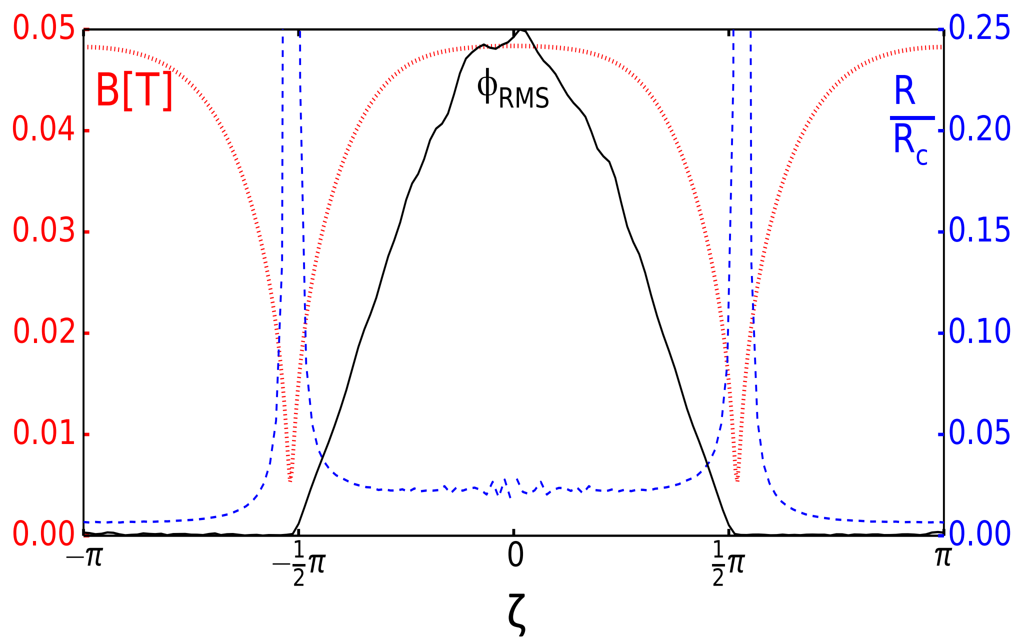
***Rosenbluth, Krall and Rostoker, NF Suppl. pt1, 143 (1962)**

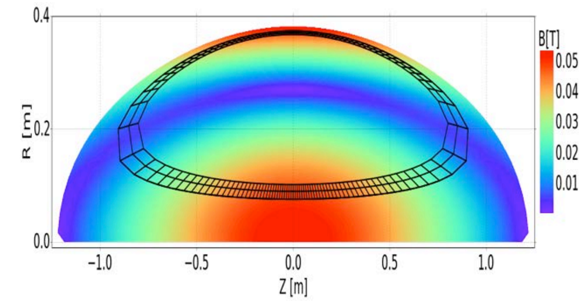
# Ballooning Structure with/without Collisions

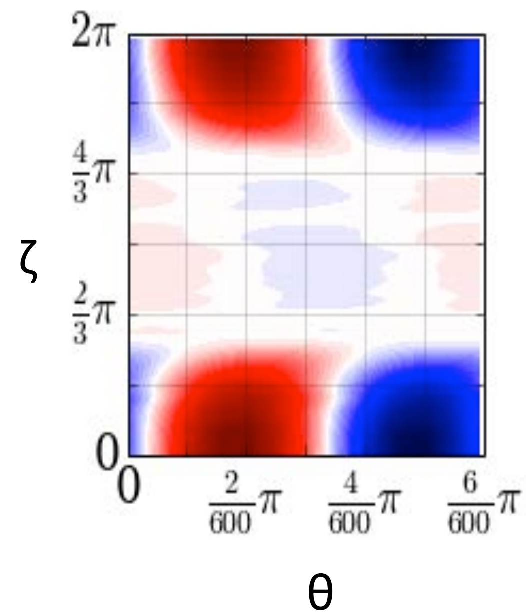
**collisionless**
(ballooning)



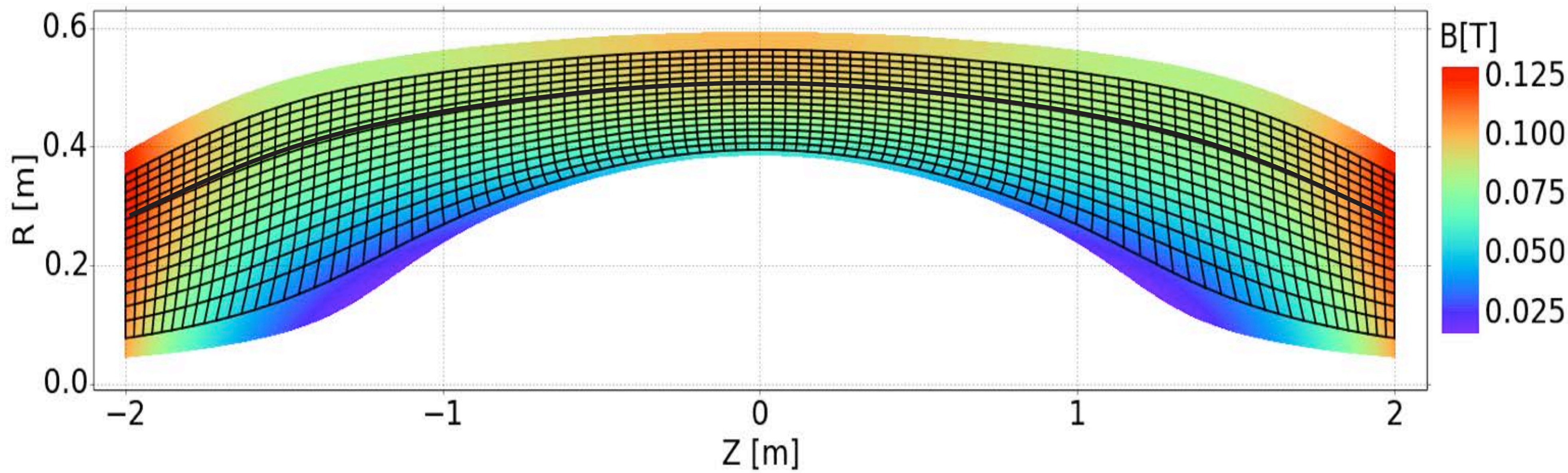

**with collisions**
(ballooning, virtually no change in mode structure)

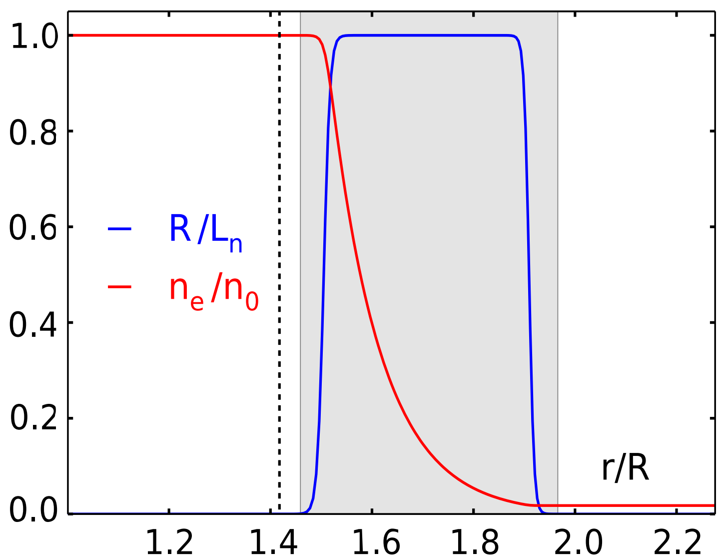


# Local Gyrokinetic SOL Simulations




SOL

**Gyrokinetic D Ions**
**Drift-kinetic electrons**
**$T_i$ = 5$T_e$, $Z_{eff}$ =1.5**
**Fokker-Planck Collisions**

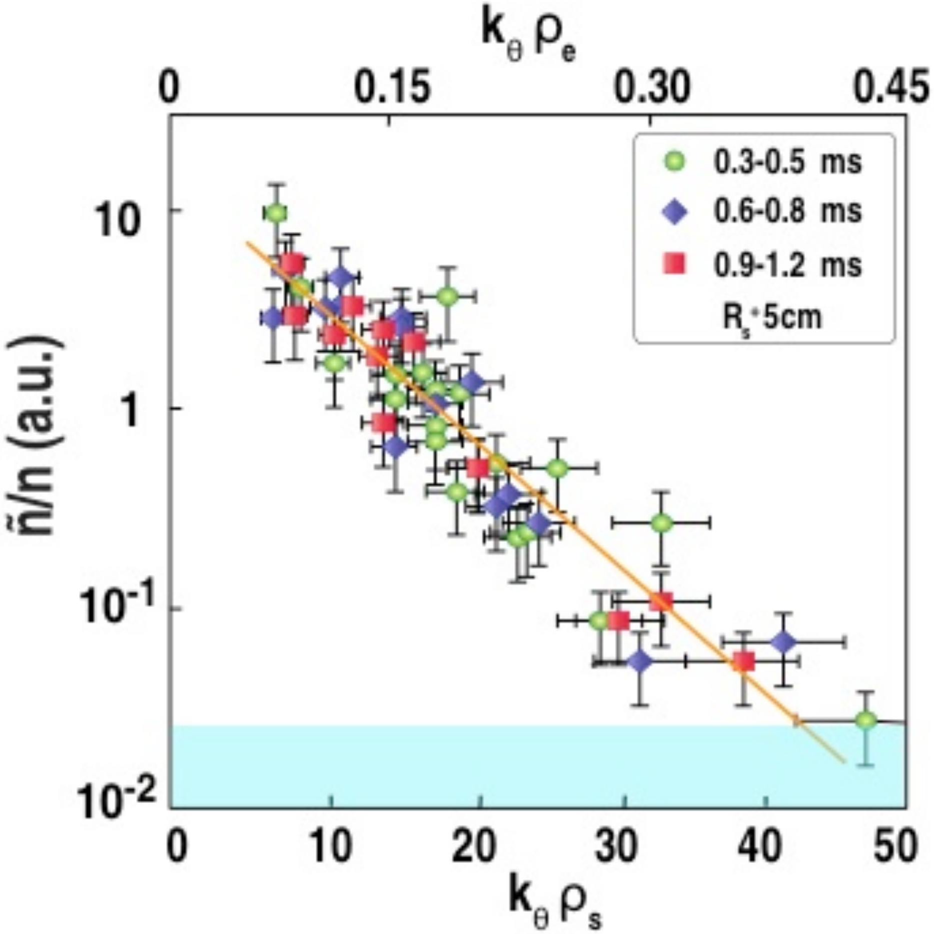
Flux-tube, local simulation at $r/R_s$=1.2; periodic boundary in z

| | i-i | e-i | e-e |
|---|---|---|---|
| $\nu_*$ | 0.0058 | 0.172 | 0.082 |

$\Rightarrow \nu_{*e\text{-}e} = \nu_{e\text{-}e}/(v_{th\text{-}e}/L)$
(moderate electron collisionality )

# SOL: Exponential Wavenumber Spectrum; Unstable Ion Modes

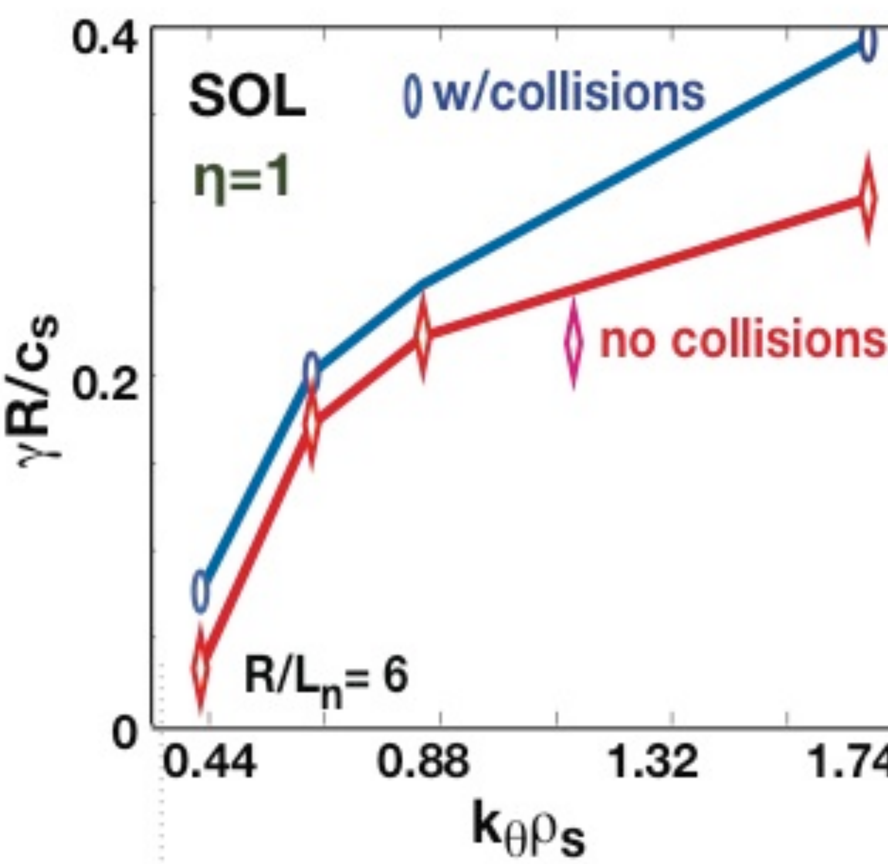
### Measured Saturated Spectrum




$\rho_s=[(kT_e+kT_i)/m_i]^{1/2}/\omega_{ci}$

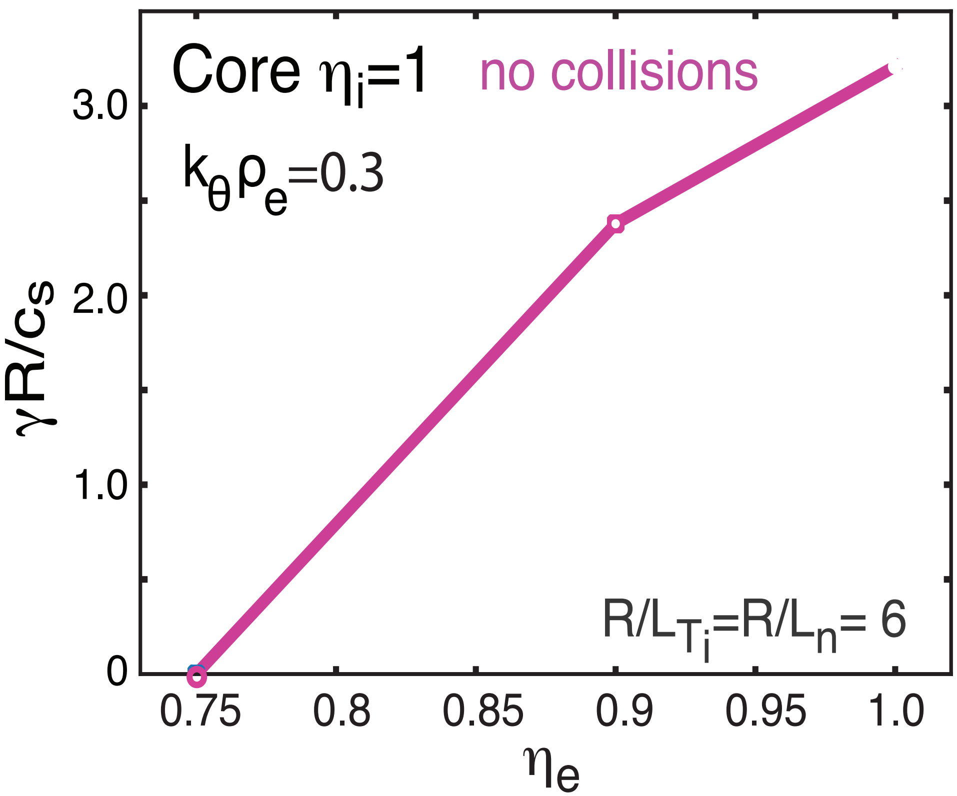
#29587-29610,
#29750-29802

### Calculated Linear Growth Rate from GTC (w/collisions)



# Driving Gradients Differ in FRC Core and SOL

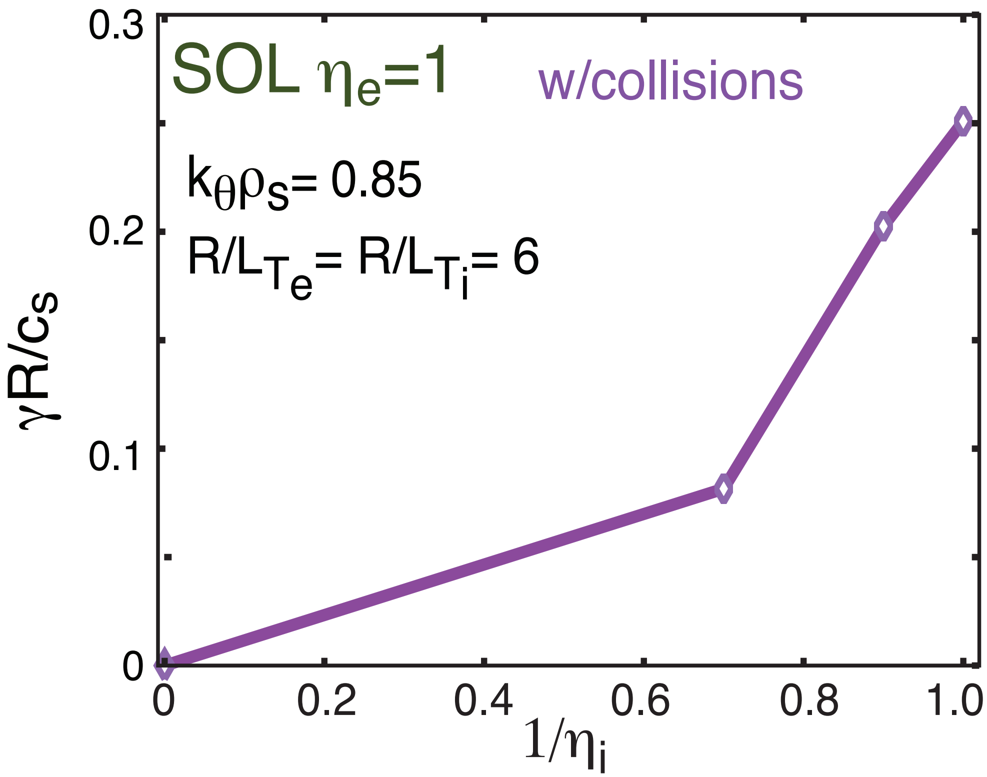
Core Modes are Driven by $\nabla T_e$




No instability below $\eta_e$ <0.75

Electron drift/Interchange Core modes driven by $\nabla T_e$ and curvature

SOL Modes are Driven by $\nabla n$




Instability to $1/\eta_i$ =0

Density gradient-driven SOL ion drift modes

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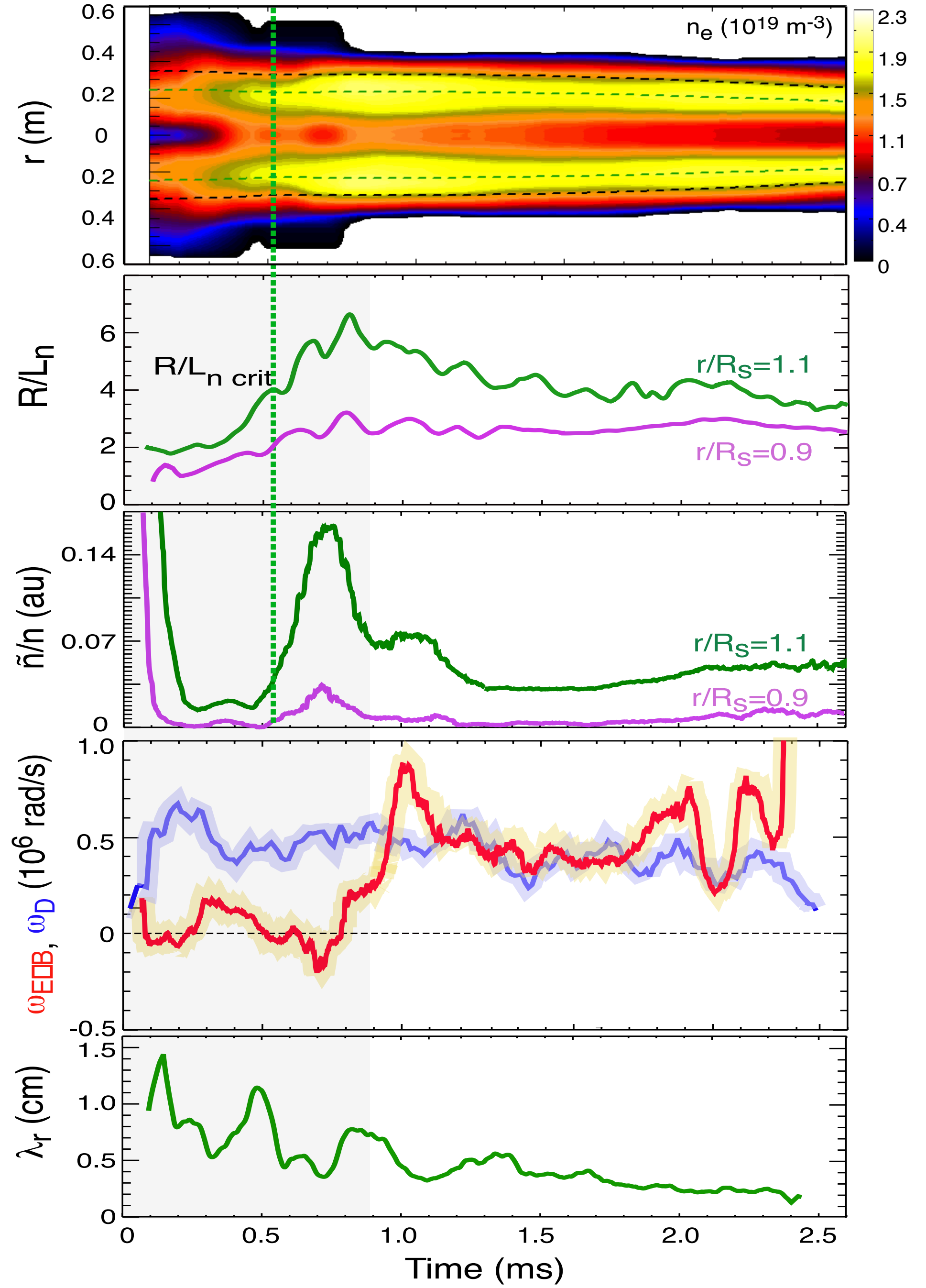
# E×B Shear Increases the SOL Critical Gradient

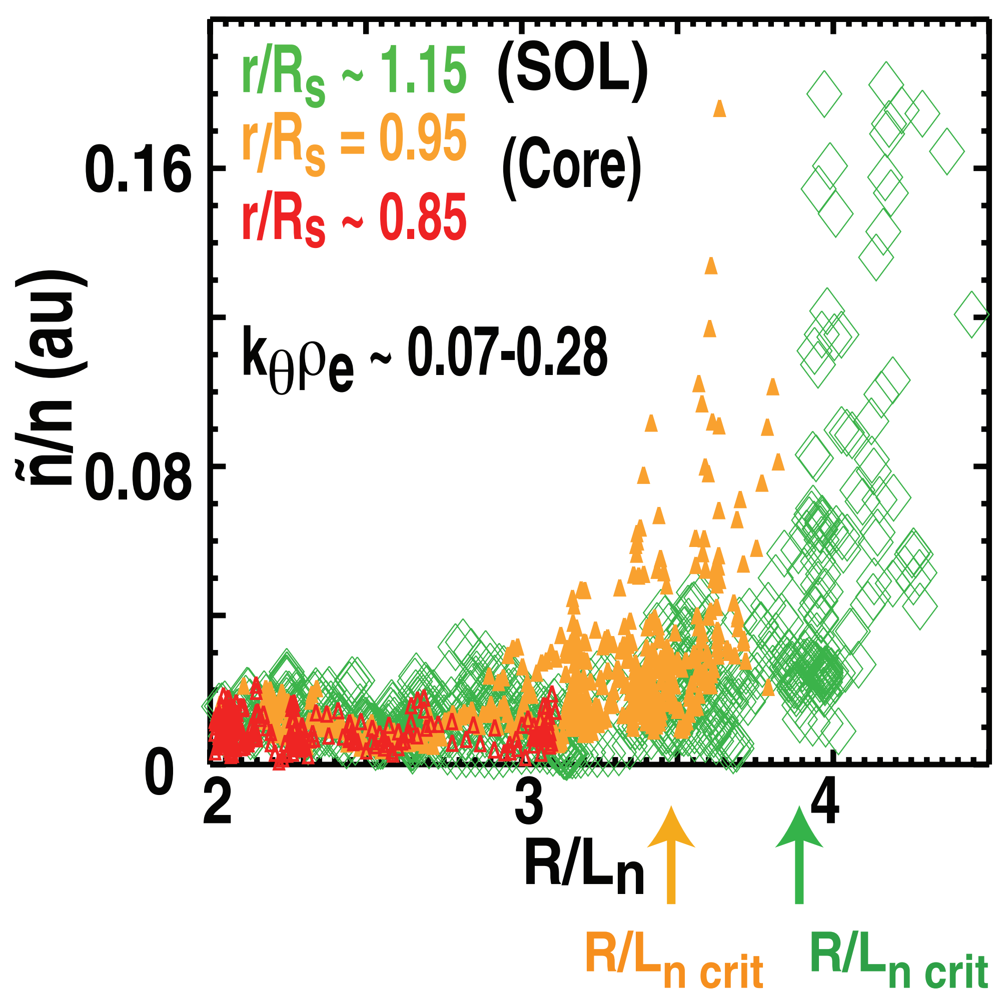
**Density profile time history**

- **Radial density gradient increases after ~0.5 ms (SOL is depleted)**
- **SOL fluctuation increase once critical density gradient is exceeded**
- **Fluctuation decrease once ExB shearing rate increases exceeds the turbulence decorrelation rate:**
  $\omega_{E\times B} > \Delta\omega_D$ **(Biglari, Diamond, Terry, Phys. Fluids B1,1989)**
- **The radial correlation length decreases with increasing ExB shear**

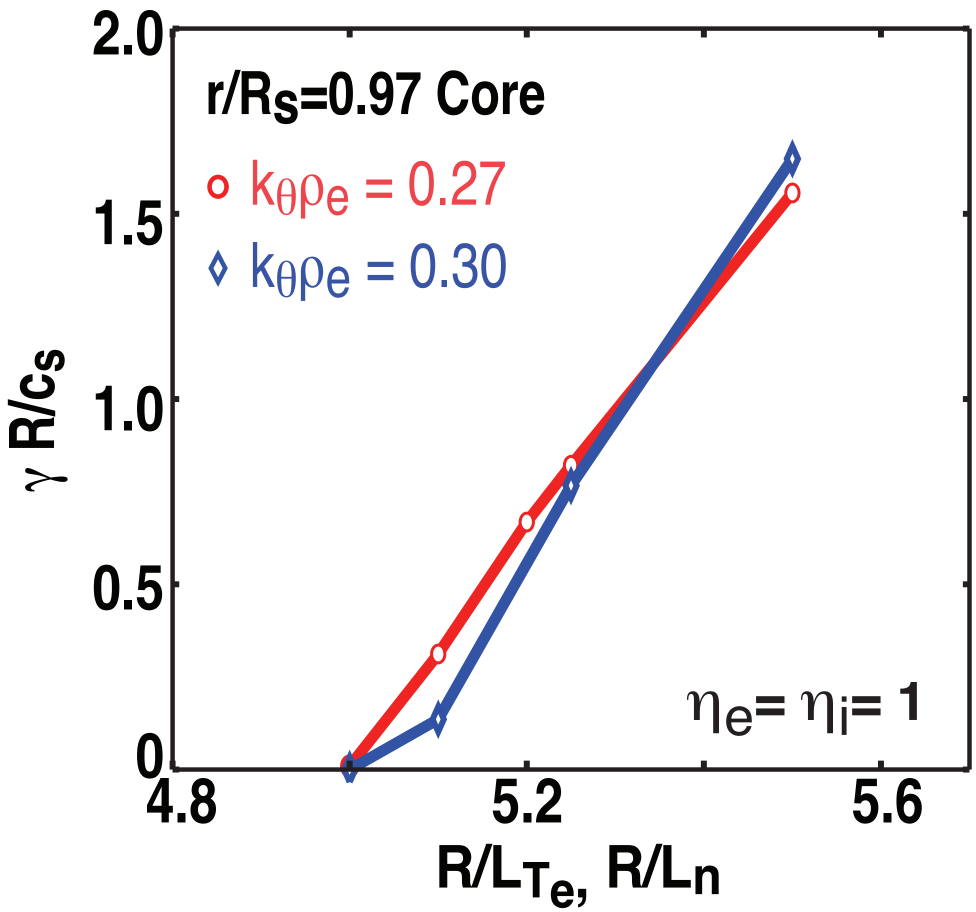


# Measured Critical Gradient and Calculated Core Linear Threshold from GTC

Measured $R/L_{n\ crit}$
(FRC core/SOL)

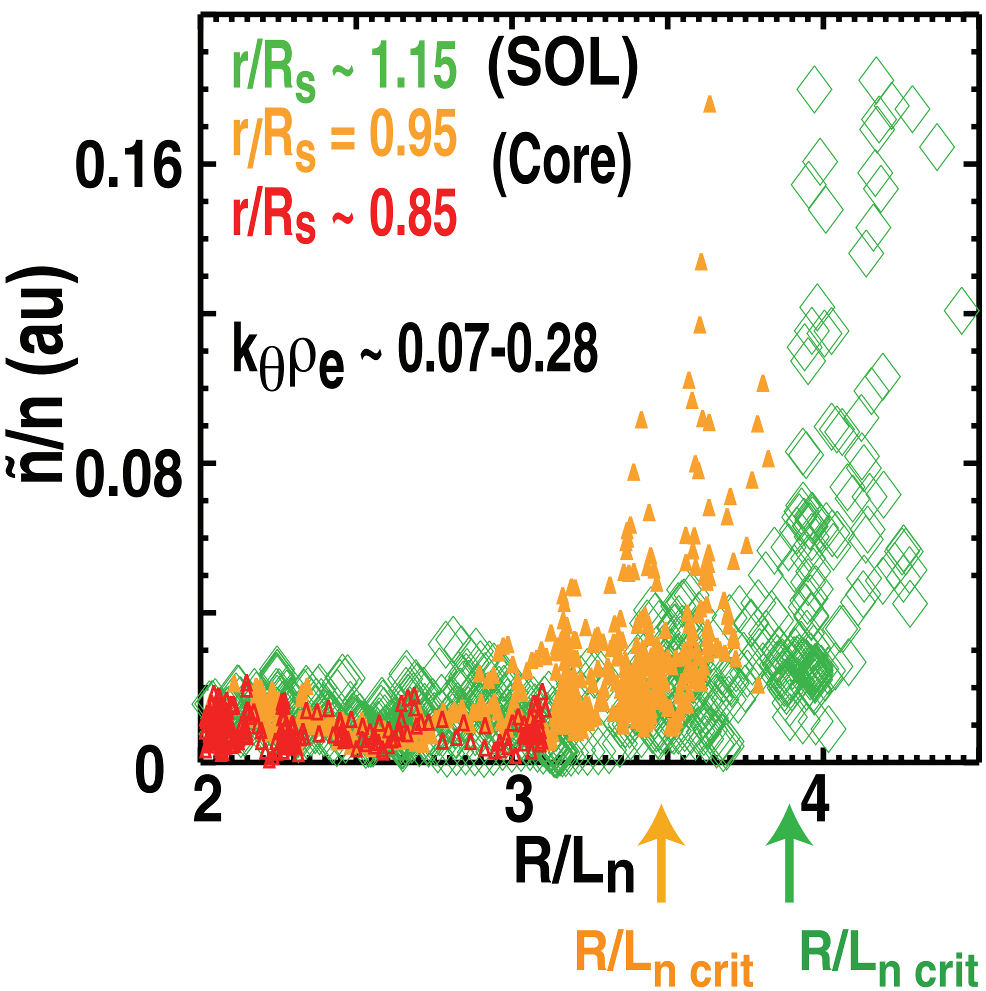



FRC core growth rate vs. $R/L_{Te}$ from linear GTC simulation

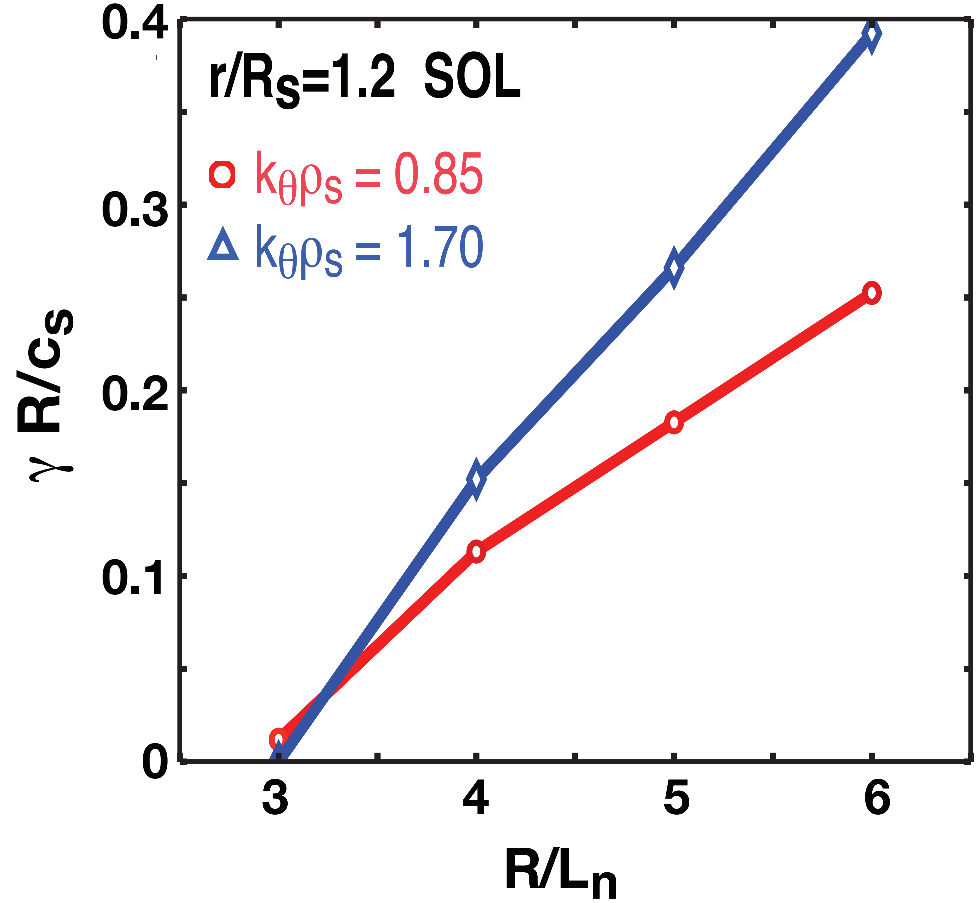


# Measured SOL Critical Density Gradient Similar to Predicted Linear Instability Threshold

**Measured R/ $L_{n\ crit}$ (FRC core/SOL)**




**FRC core growth rate vs. R/$L_n$ from linear GTC simulation**



# Core-SOL Coupling: Evidence for Radial Transport Barrier

- **Radial turbulence correlation length $\lambda_r \leq \rho_i$**
- **No evidence of sustained extended radial structures or streamers**

**$\lambda_r$ reduced just outside $R_s$: Evidence of radial transport barrier.**

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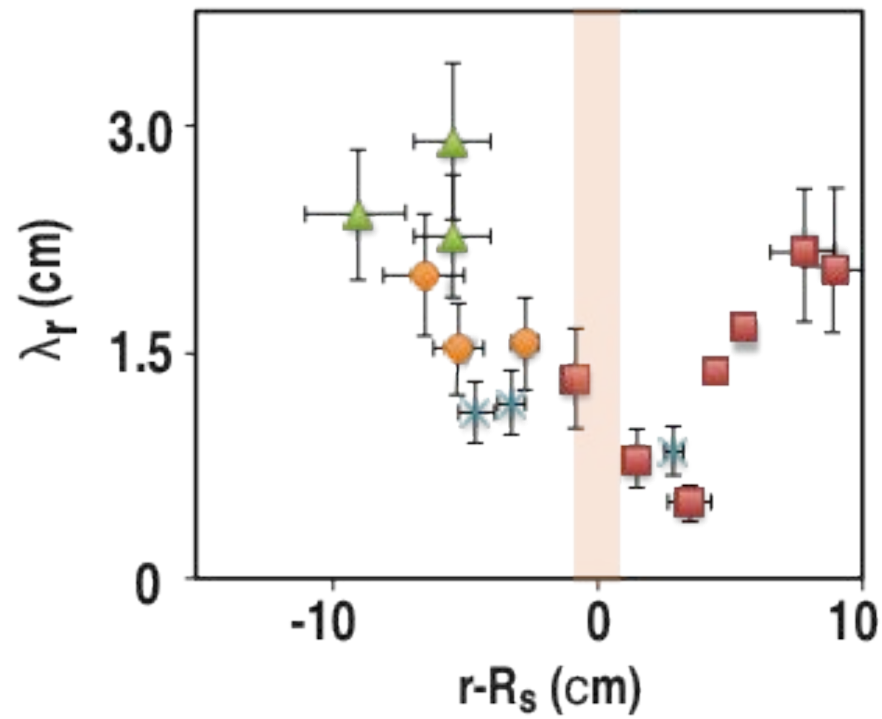
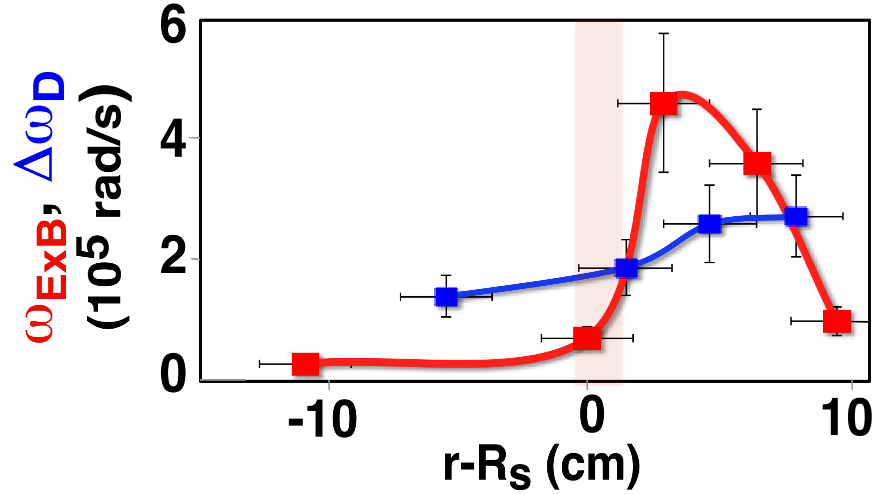



- **Shear decorrelation just outside the separatrix:**

$\omega_{E\times B} > \Delta\omega_D$ (Biglari, Diamond, Terry, Phys. Fluids B1,1989)



# Summary

- **C-2 FRC core: Ion modes stable due to FLR effect; only electron modes unstable (driven by electron temperature gradient and curvature)**
- **Moderate, larger-scale ion-mode SOL turbulence observed/predicted; driven by the radial density gradient.**
- **Strong evidence of radial transport barrier in the SOL. No experimental evidence of sustained large-scale radial structures/streamers (radial correlation length $\lambda_r < \rho_i$)**
- **Observed critical SOL density gradient compares well with predicted linear instability threshold; compatible with required reactor SOL width**

# Thank you for your attention!

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