Plasma Science and Fusion Center

# Turbulence and transport studies in ALCATOR C-Mod using Phase Contrast Imaging (PCI) Diagnostics and Comparison with TRANSP and Nonlinear Global GYRO

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with special thanks to Ron Waltz and Jeff Candy, General Atomics

References:

L. Lin, M. Porkolab,E. M. Edlund, et al, Phys. Plasmas **16**, 012502 (2009);
also, in Plasma Phys. Contr. Fusion **51**, 065006 (2009)

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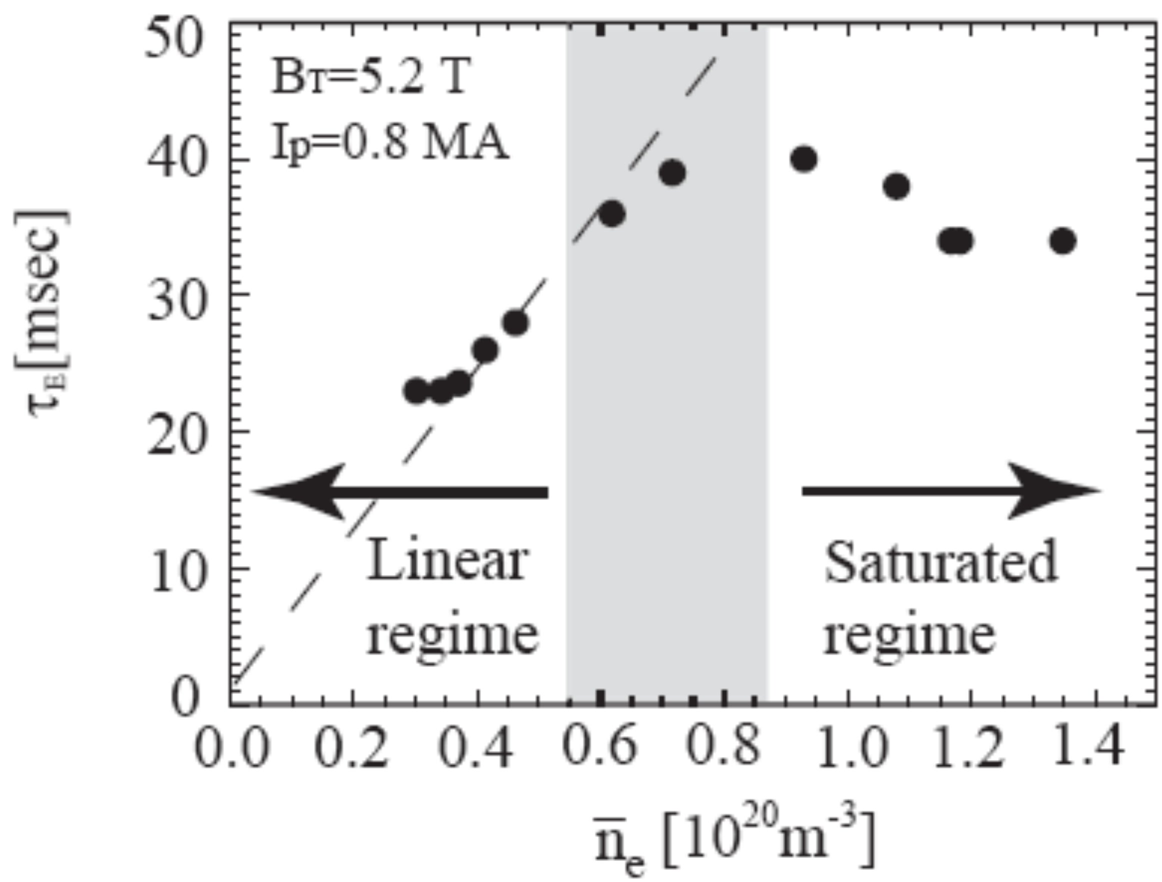
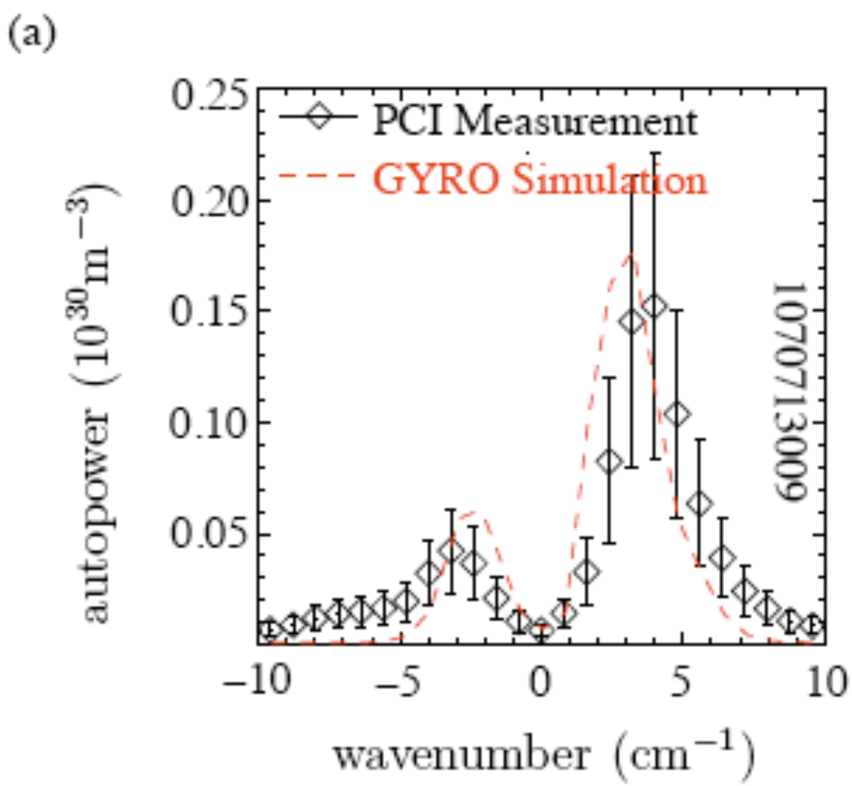
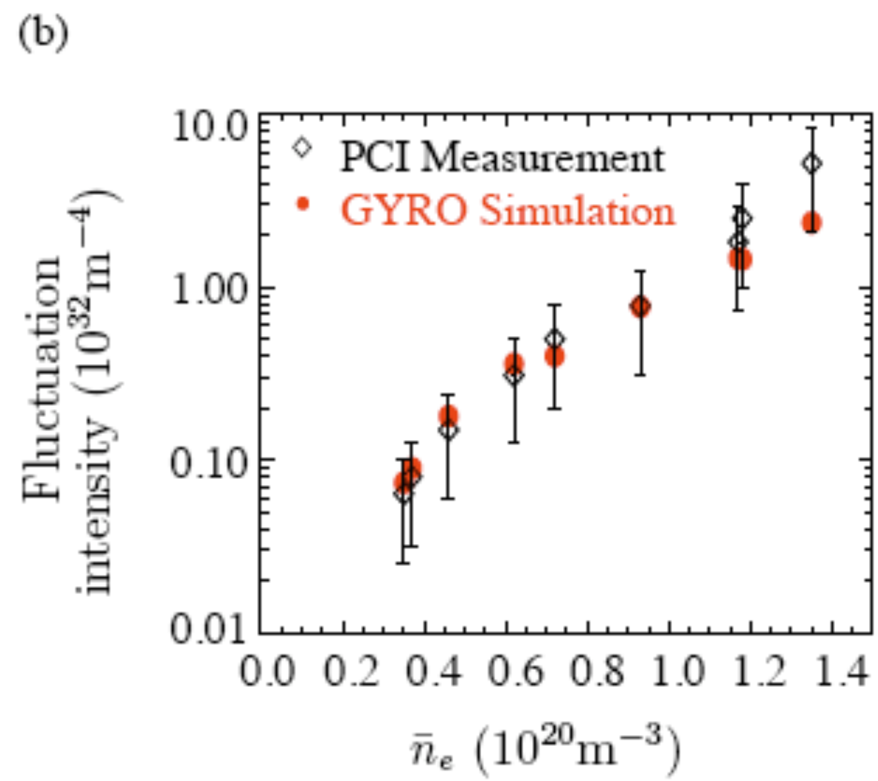
**Well known experimental results from Alcator C (Greenwald, Parker, 1984), as well as other tokamaks up to the present time, indicate that Ohmic confinement follows a linear scaling with density, followed by a saturated confinement regime in L mode; Why ? Gyrokinetics ?**




The results imply that in the linear confinement (neo-Alcator) regime the electron thermal diffusivity should decrease as the density increases.

# Turbulence measurements in Alcator C-Mod plasmas as a function of density show good agreement with the GYRO in ohmic plasmas at frequencies above 80 KHz with phase velocities dominantly in the ion diamagnetic direction



**Turbulence measured with Phase Contrast Imaging (PCI) at high frequencies in H mode plasmas (high densities) shows good agreement with GYRO nonlinear simulations with phase velocities in the ion diamagnetic direction**

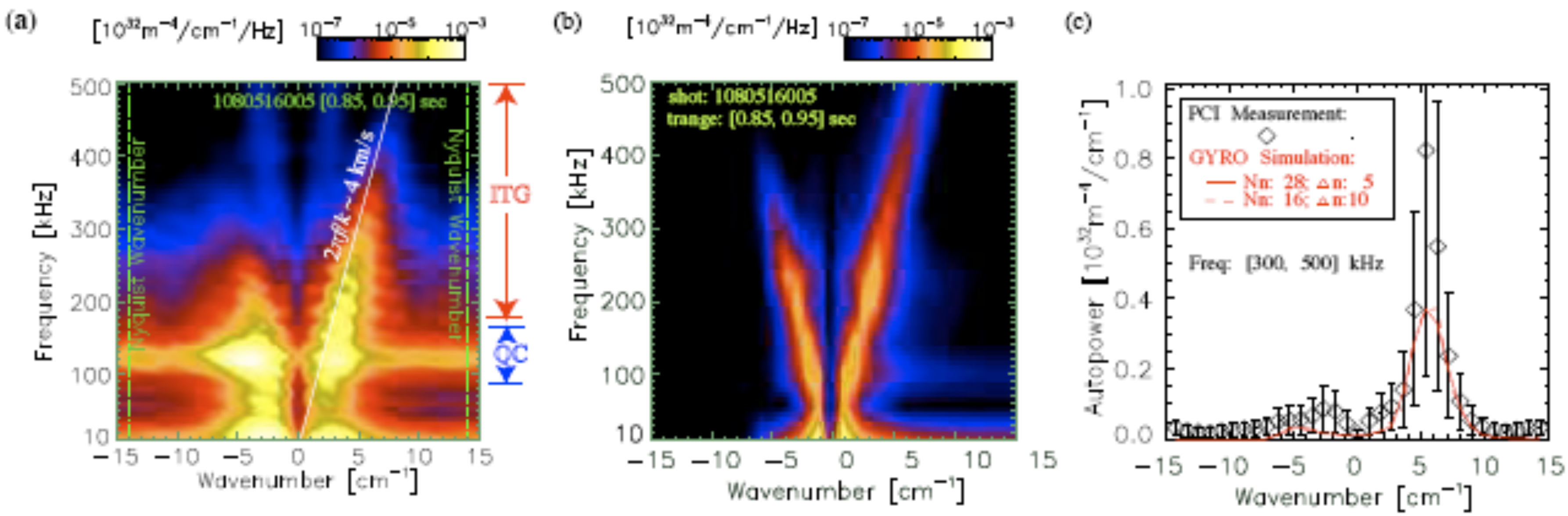


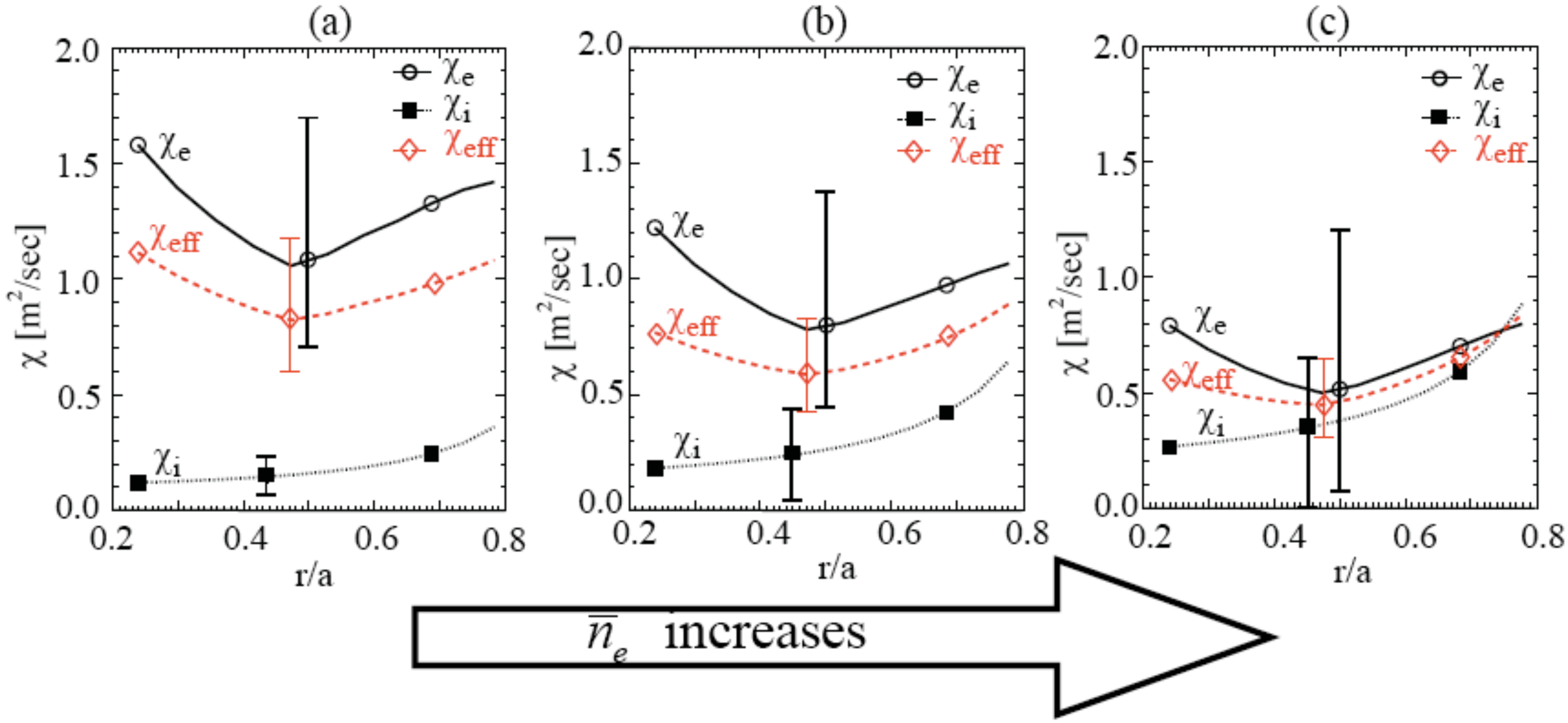

Figure 13: Comparison between C-Mod experimental results and GYRO simulations during H-mode. (a) PCI $S(k, f)$ with mask filter. (b) Synthetic PCI including Doppler shift. (c) Quantitative comparison between spectra integrated over 300–500 kHz.

# In the linear ohmic regime, $\chi_i$ is much smaller than $\chi_e$.

**( Experimental results using TRANSP analysis)**

Alcator C-Mod

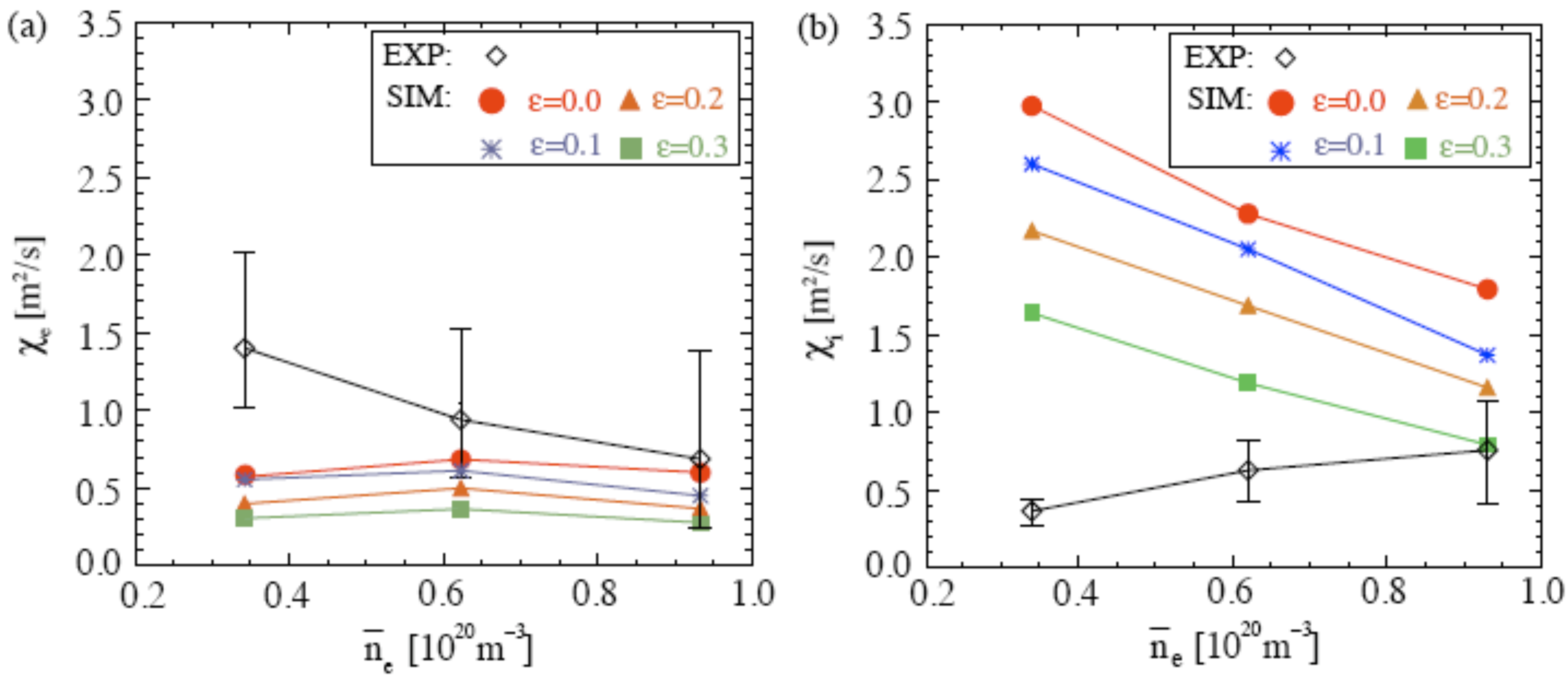
| Linear ohmic | Transition | Saturated ohmic |
| --- | --- | --- |
| $\overline{n}_e = 0.34\times10^{20} m^{-3}$ | $\overline{n}_e = 0.62\times10^{20} m^{-3}$ | $\overline{n}_e = 0.93\times10^{20} m^{-3}$ |




- As $n_e$ increases, $\chi_e$ decreases, but $\chi_i$ increases slowly, $\chi_{eff}$ also decreases.
- In the saturated ohmic regime, $\chi_i$ becomes comparable to $\chi_e$.

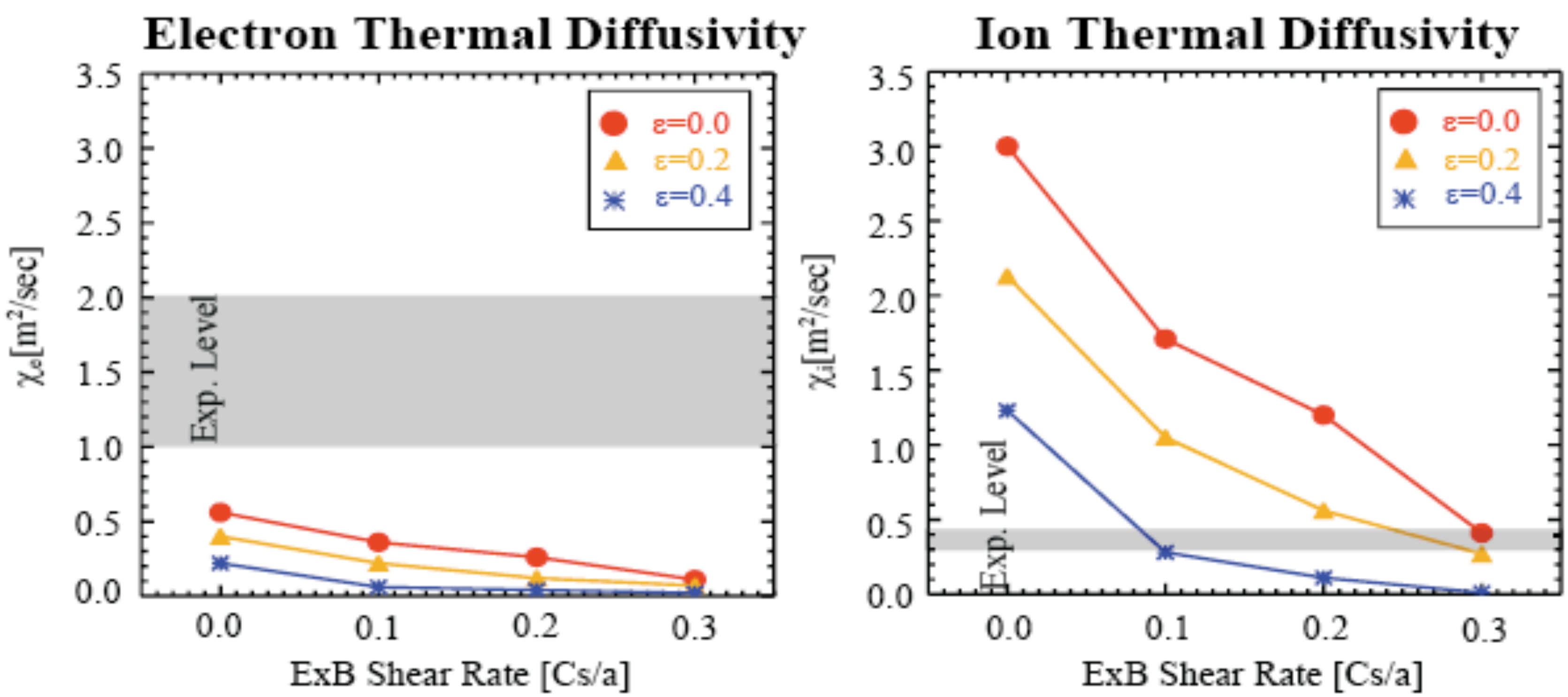
$$\chi_{eff} = \frac{n_e\chi_e\nabla T_e + n_i\chi_i\nabla T_i}{n_e\nabla T_e + n_i\nabla T_i}$$

## Measured transport coefficients at low densities significantly deviate form the GYRO code prediction and cannot be resolved even with variation of density and temperature profiles



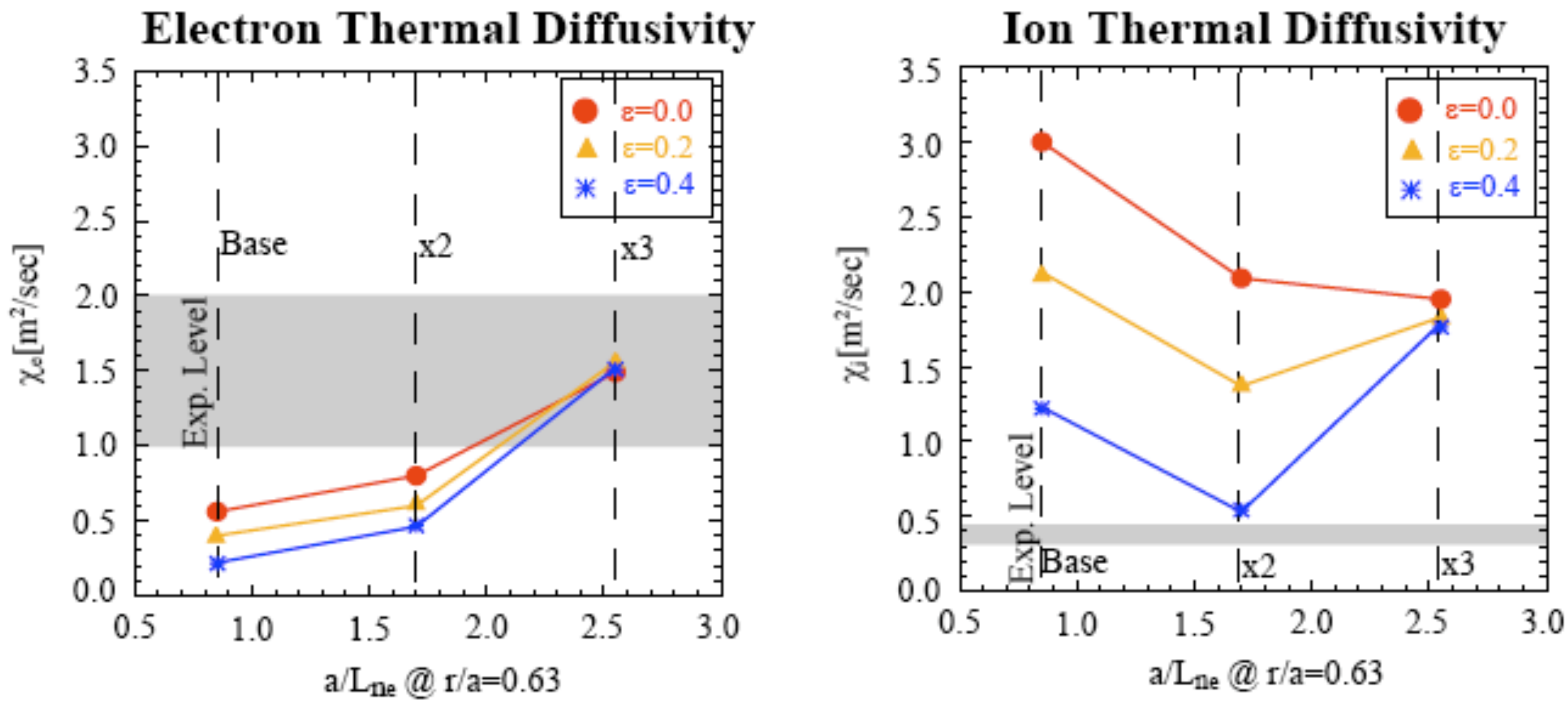

ε is the reduction factor of $a/L_{Ti}$ : $$\left(\frac{a}{T_i}\frac{\partial T_i}{\partial r}\right)_{sim} = (1-\varepsilon)\frac{a}{T_i}\frac{\partial T_i}{\partial r}$$

## The simulated $\chi_i$ can be reduced to the experimental level by further reducing $a/L_{Ti}$ and/or adding E×B shear, but by doing so the simulated $\chi_e$ is further reduced below the experimental level.




- $\varepsilon$ is the reduction factor of $a/L_{Ti}$ : $$\left(\frac{a}{T_i}\frac{\partial T_i}{\partial r}\right)_{\mathrm{sim}} = (1-\varepsilon)\frac{a}{T_i}\frac{\partial T_i}{\partial r}$$

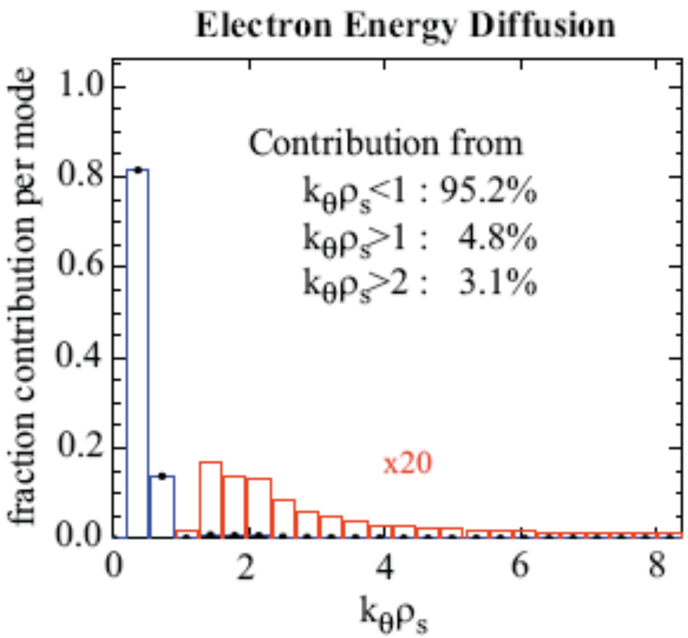
# Significant transport contribution from the TEM turbulence is not likely for the measured temperature and density profiles.




- ε is the reduction factor of a/$L_{Ti}$ : $\left(\frac{a}{T_i}\frac{\partial T_i}{\partial r}\right)_{sim} = (1-\varepsilon)\frac{a}{T_i}\frac{\partial T_i}{\partial r}$
- The simulated $\chi_e$ can only be raised to the experimental level after increasing a/$L_{ne}$ by a factor of two where the TEM turbulence becomes significant.

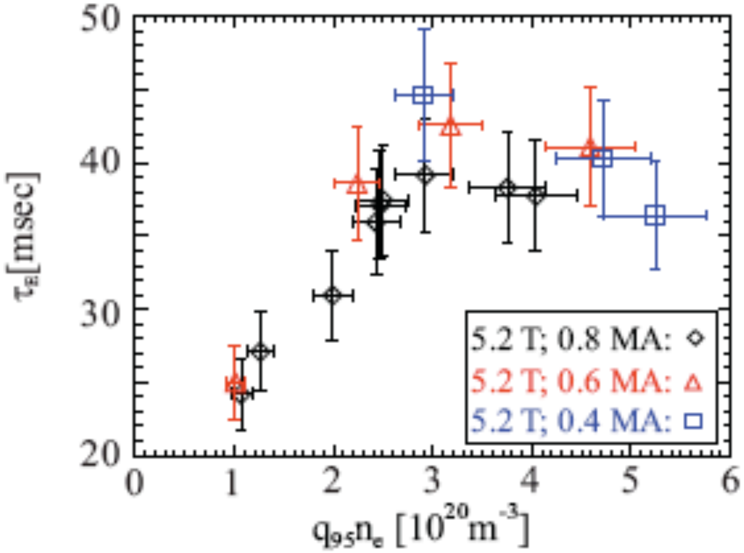
## At the lowest density, inclusion of high-k turbulence in the ETG range $k_\theta \rho_s$=2-8 accounts for less than 5% of total simulated electron transport; it is not known if including even higher values of $k_\theta \rho_s$ would significantly change this result.

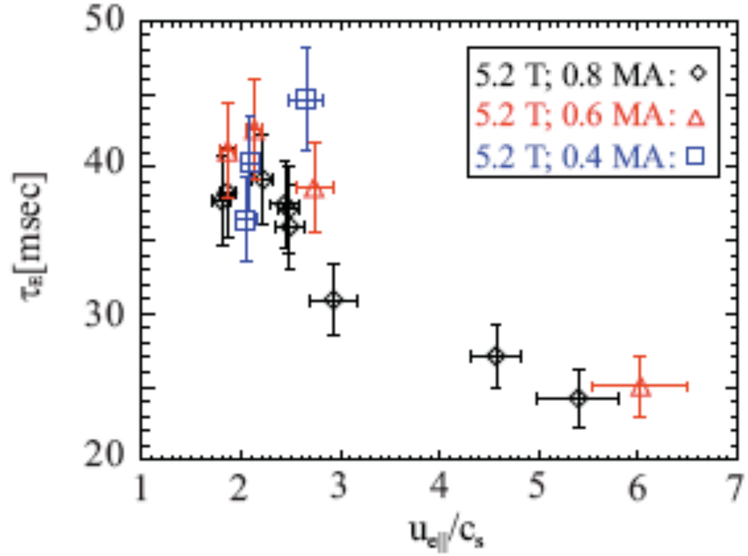
Linear ohmic $\overline{n}_e = 0.35\times 10^{20} m^{-3}$

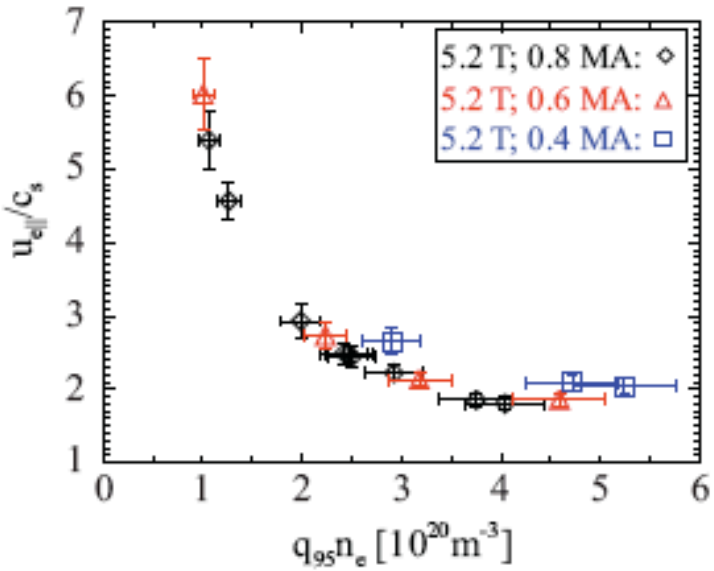



- The short wavelength turbulence in the range of 8.0>$k_\theta \rho_s$>2.0 only can contribute to the electron thermal transport by less 5.0%.
- After adding E×B shear suppression and/or reducing ∇Ti, to match $\chi_i$, the electron transport from high-k turbulence is not significantly affected.
- Measurements to date by PCI indicate very low levels of high-k turbulence, falling into the background noise level.

# As density increases the drift speed decreases to $c_s$ and confinement improves




- **A correlation exists between the energy confinement time and the ohmic drift velocity.**

***Do current driven drift waves play a role ? Theorists say no !***

# Summary of Turbulence and Transport Study

- **The key role played by the ITG turbulence in the saturated ohmic regime has been verified in these studies.**

  - Propagation of turbulence is found to be dominantly in the ion diamagnetic direction.

  - Intensity of the ITG turbulence increases with density, in agreement between simulation and experiments.

  - The absolute fluctuation intensity agrees with simulation within experimental error.

  –Simulated $\chi_{eff}$, $\chi_e$, and $\chi_i$ agree with experiments after reducing $a/L_{Ti}$ within 20%.

- **At the low densities in the linear ohmic regime, where the electron transport dominates ($\chi_e >> \chi_i$), GYRO shows $\chi_i > \chi_e$ .**

  -TEM is unlikely to be important for the measured density and temperature profiles.

  -Electrostatic ETG simulation with $k_\theta \rho_s \leqslant 4$ does not raise $\chi_e$ to the experimental level.

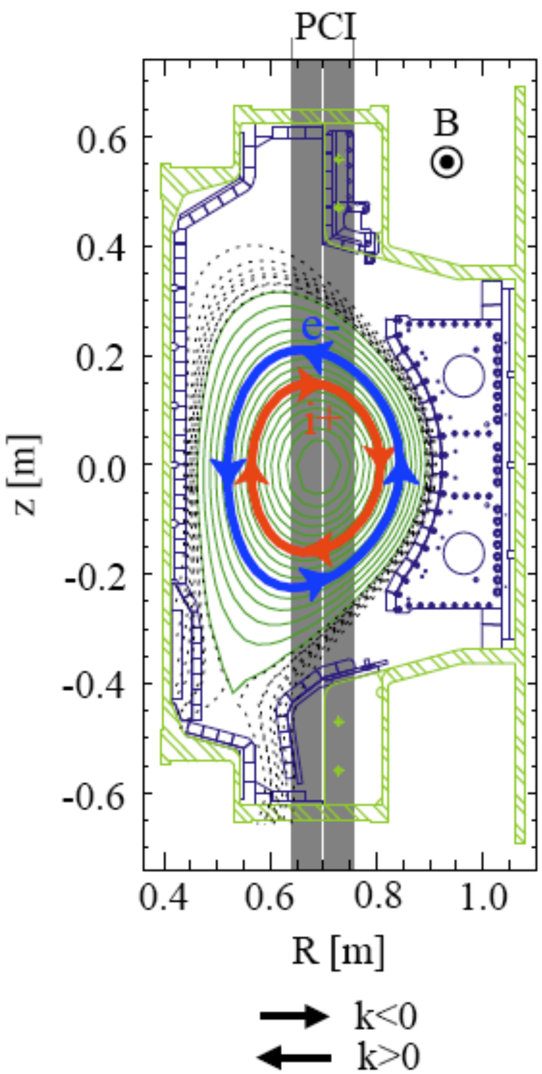
  -GYRO shows that the contributions from the electromagnetic fluctuations are negligible in the low-$\beta$ C-Mod Plasmas.

  -Electron drift velocity ($u_{e\|}/c_s \geqslant 1$) associated with the "ohmic toroidal plasma current" may play an important role.

# SUMMARY

- PHASE CONTRAST IMAGING IS A POWERFUL DIAGNOSTIC TOOL TO MEASURE WAVES, INSTABILITIES AND TURBULENCE IN TOKAMAK PLASMAS
- THE COST IS VERY REASONABLE ( 150-200 K$)
- THE SHORTCOMING OF THE DIAGNOSTIC IS LACK OF GOOD LOCALIZATION ALONG THE LASER BEAM

# Phase Contrast Imaging (PCI) in Alcator C-Mod




- PCI measures density fluctuations along 32 vertical chords.

**Wavenumber Range:**

**$0.5cm^{-1} < |k_R| < 55\ cm^{-1}$**

**Frequency Range:**

**2kHz~5MHz**

- The localization upgrade allows PCI to resolve the direction of propagation of the measured turbulence in ITG and TEM range.

- The improved calibration also allows for the intensity of the observed fluctuations to be determined absolutely.

Alcator C-Mod

# Edge Turbulence on Alcator C-Mod

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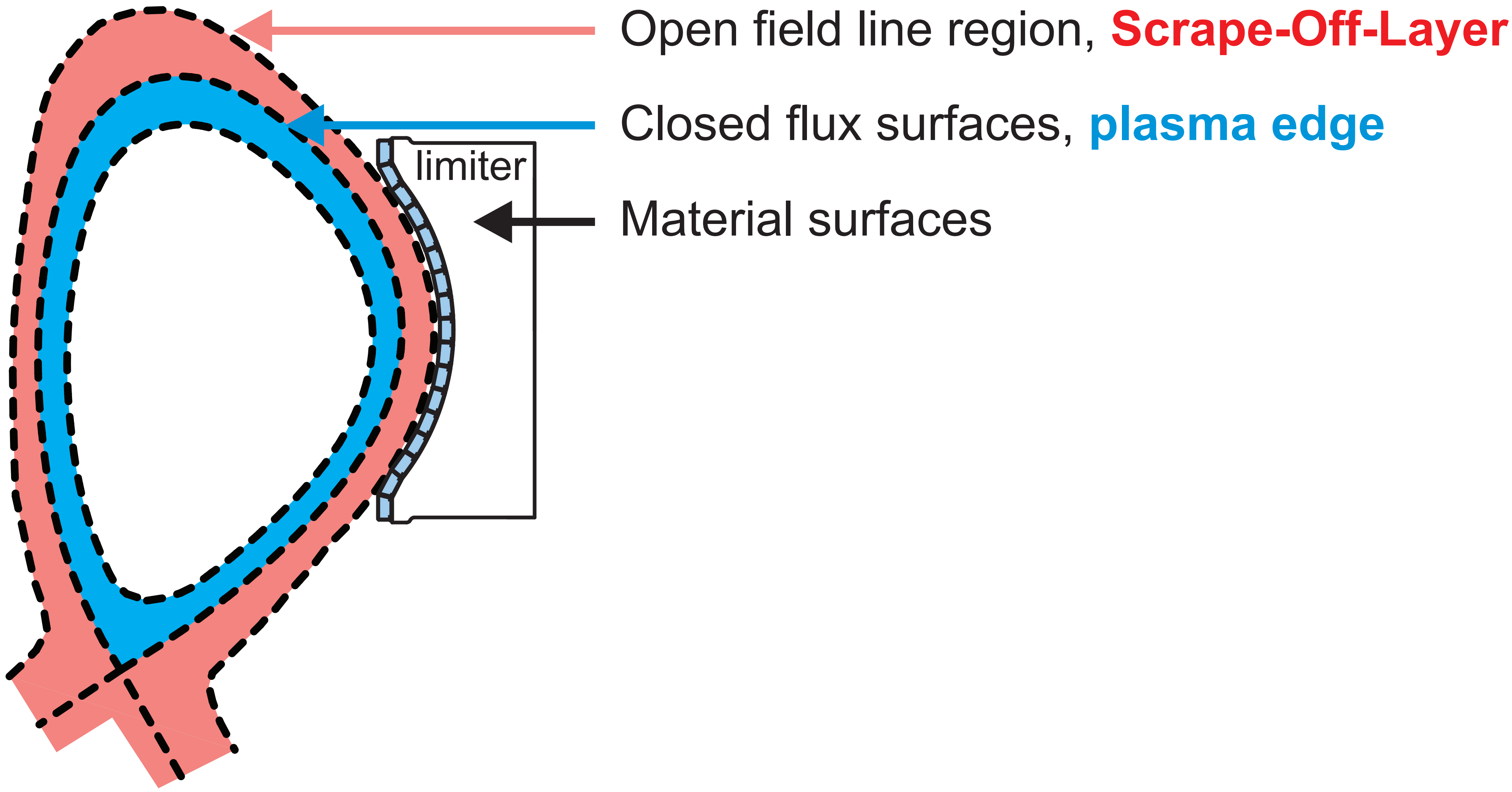
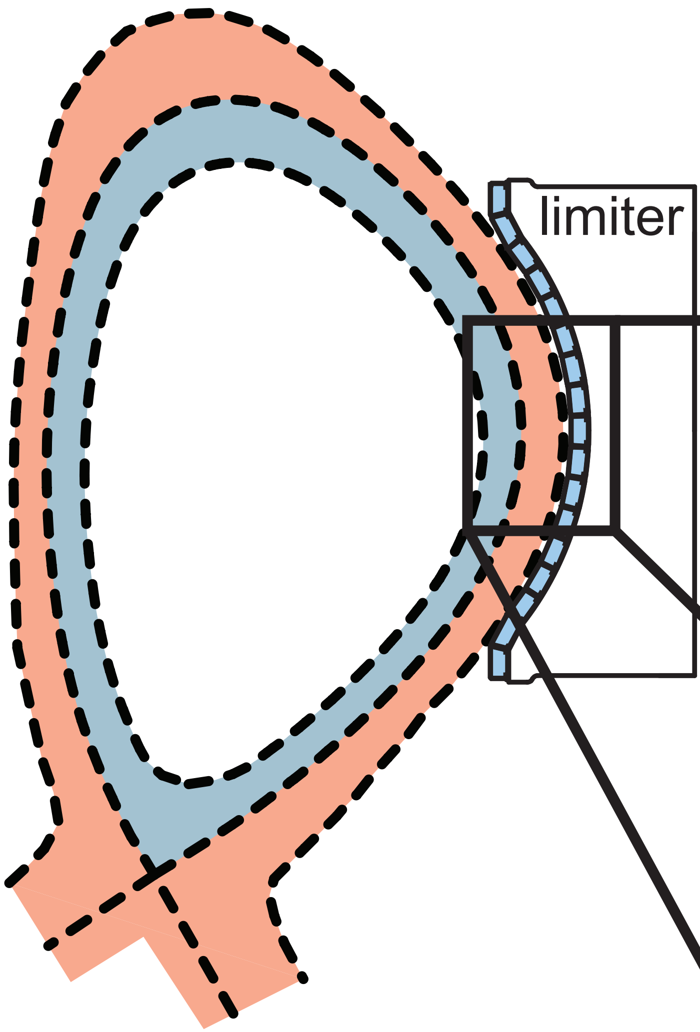
3rd EFTSOMP Dublin, Ireland, 28-29 June 2010

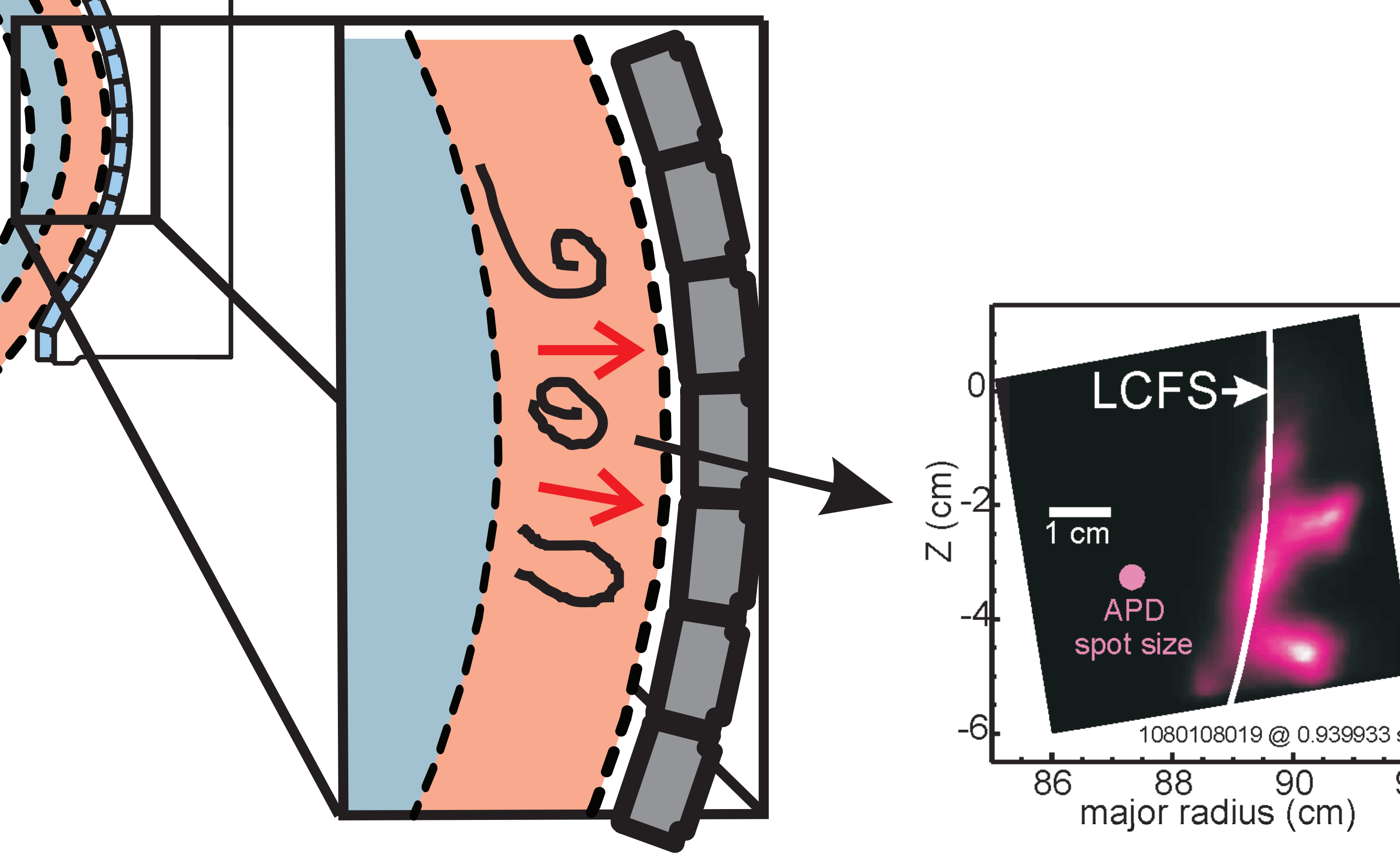
# Background and motivations: Edge-SOL transport schematic



# Background and motivations: Edge-SOL transport schematic

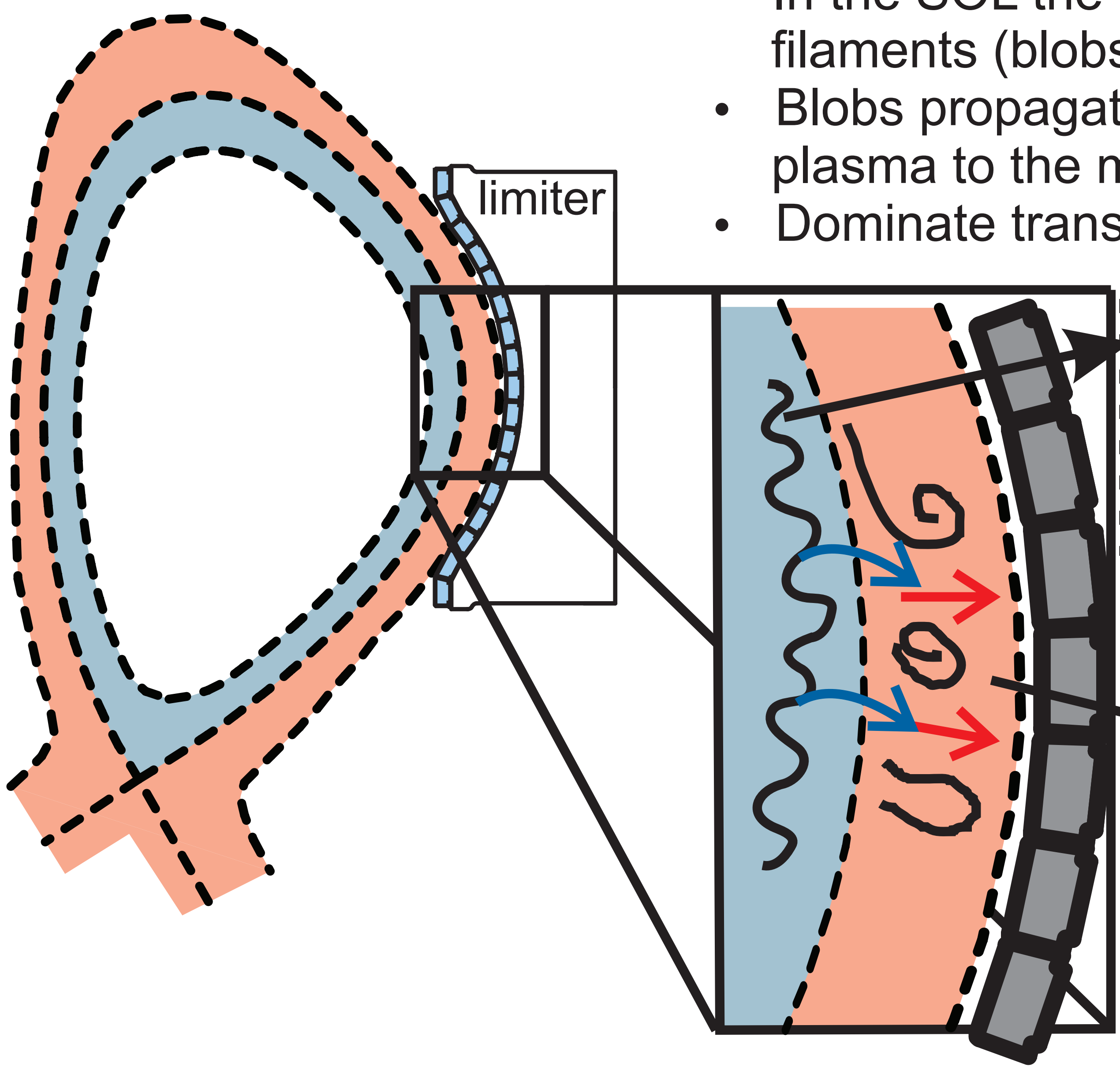
- In the SOL the turbulence is manifested as filaments (blobs)
- Blobs propagate rapidly radially, carrying plasma to the main walls
- Dominate transport



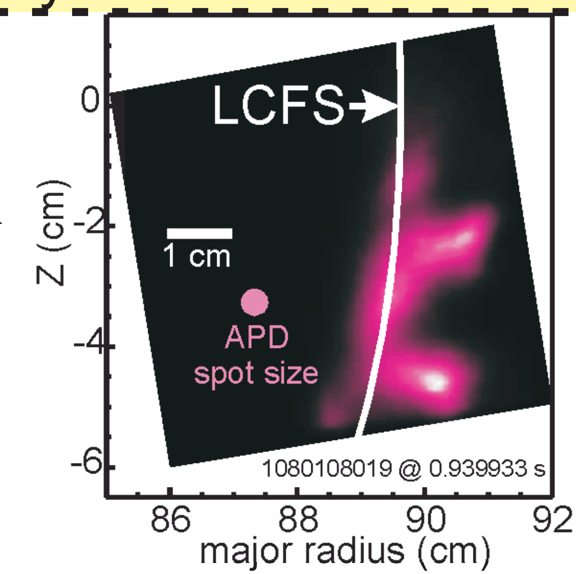



# Background and motivations: Edge-SOL transport schematic

- In the SOL the turbulence is manifested as filaments (blobs)
- Blobs propagate rapidly radially, carrying plasma to the main walls
- Dominate transport through SOL



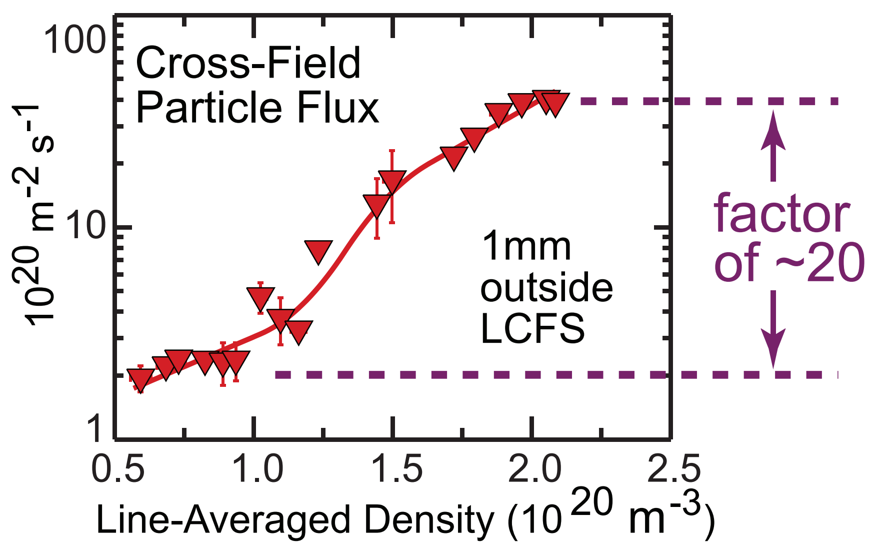

- Source of SOL plasma
- Wavelike edge fluct.
- Why is SOL transport the way it is?

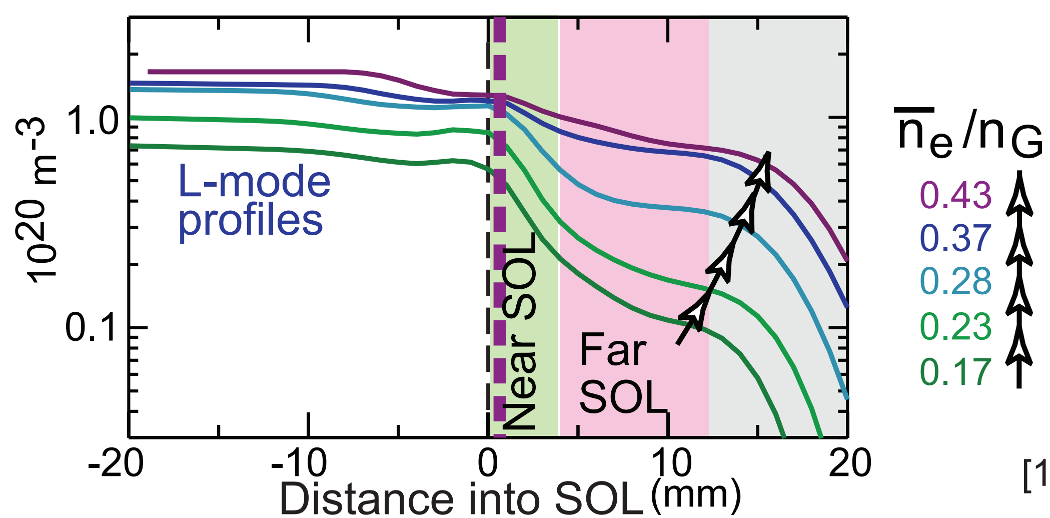


# How does cross-field particle transport work? Observations in **Ohmic L-modes**

## 1) As central density is raised, density profiles flatten in the SOL

## 2) Fluxes across the LCFS increase exponentially with density

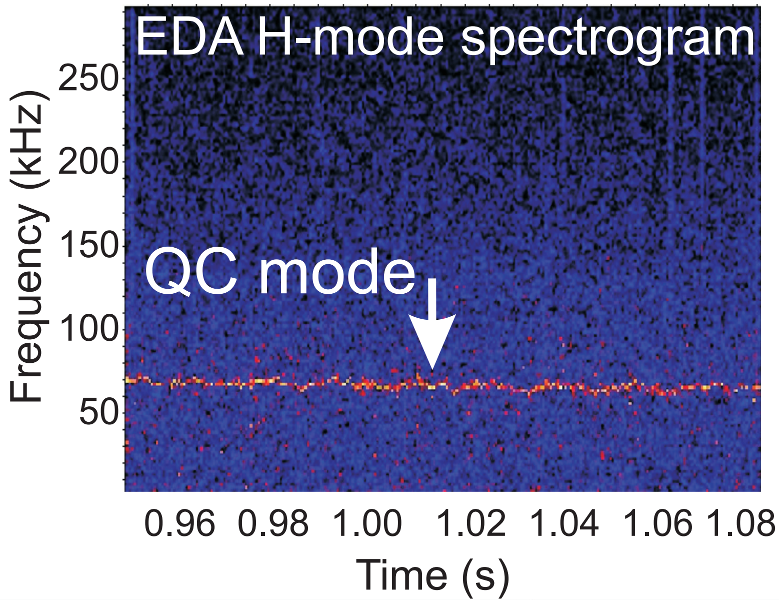


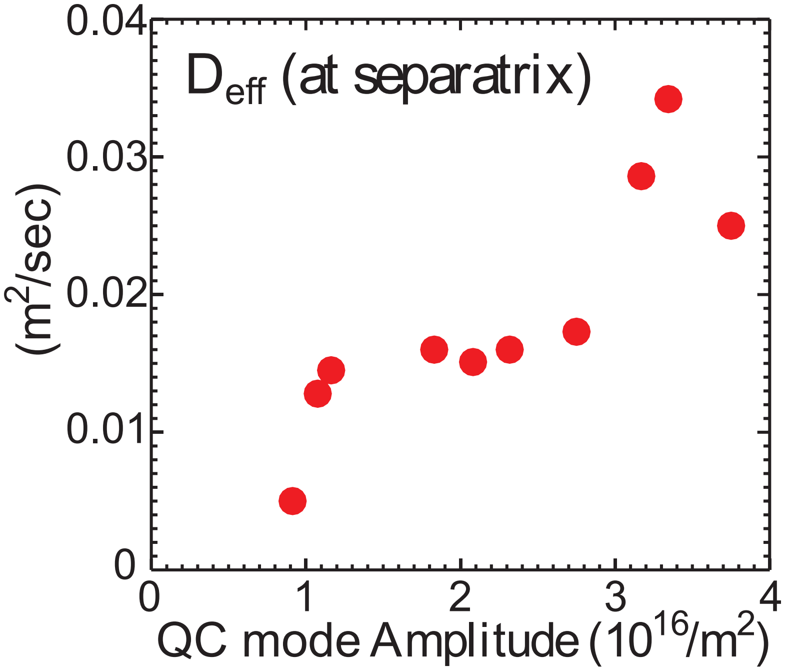




[1]

Search for the underlying cause of this increase of transport as $n_e$ grows.

# Observations: **Enhanced D-Alpha H-mode** QC mode leads to cross-field transport



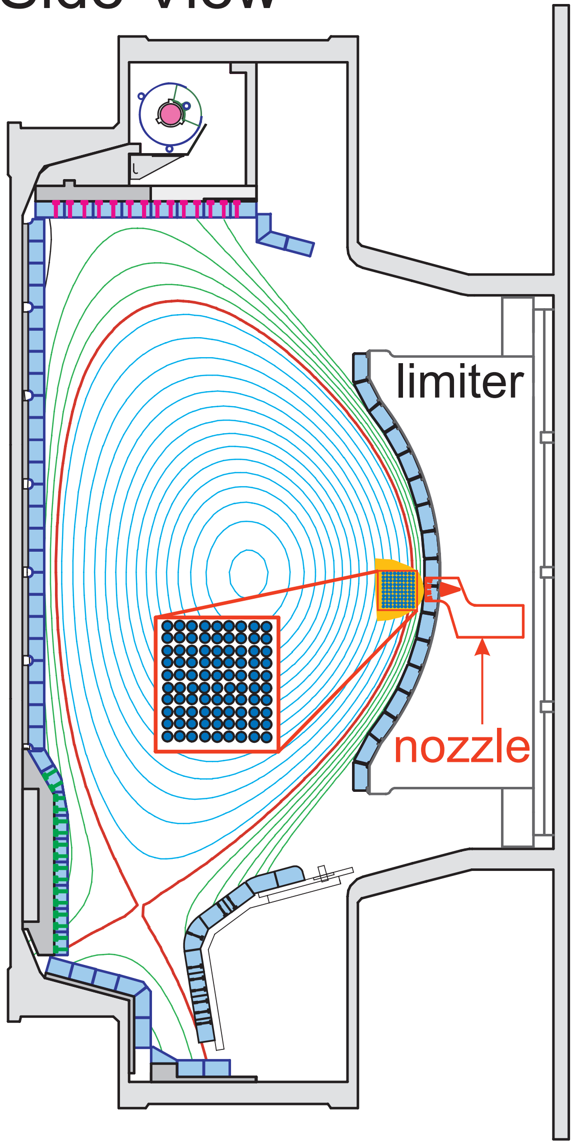

- In EDA H-mode QCM provides edge relaxation instead of large ELM's
- The Quasi-Coherent Mode is an EM edge oscillation
- Frequency range ~ 50-150 kHz
- Propagates in the EDD in lab

$D_{eff}$ not meant to imply diffusive transport:

$$D_{eff} = -\Gamma_{\perp} / \nabla_{\perp} n_e \text{ [2]}$$

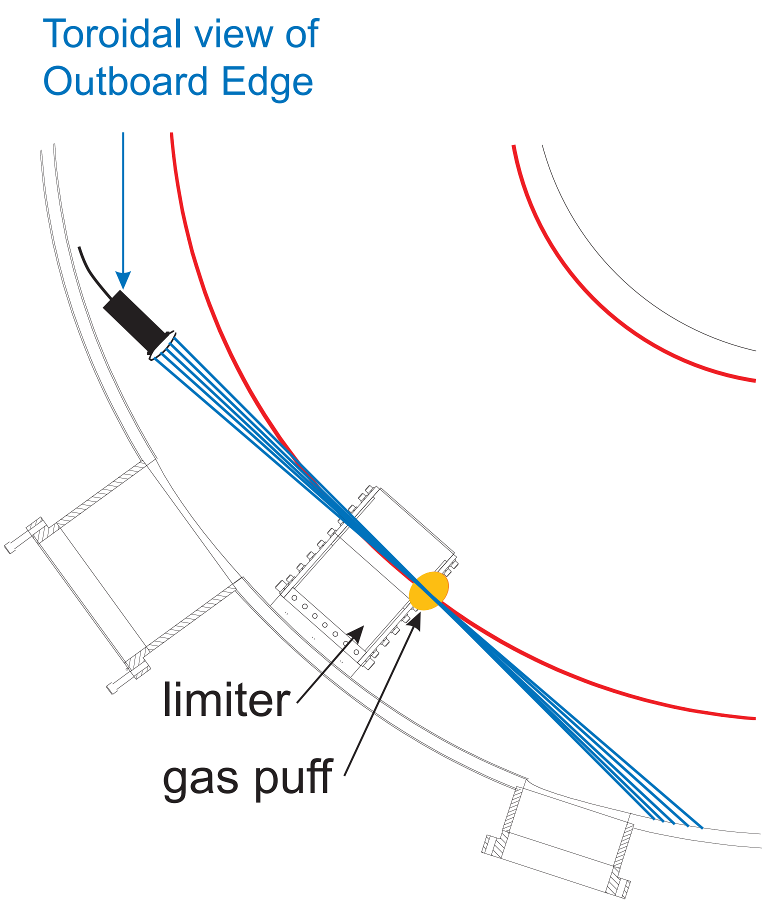
# Experimental setup
# Gas-Puff-Imaging diagnostics

## Side View




- gas puff injects neutral $D_2$, sensitive to $n_e$, $T_e$
- small toroidal extent (~5cm) allows localization
- 90 channels cover ~ 5cm x 5cm
- views coupled to APD arrays, sampled @ 2MHz

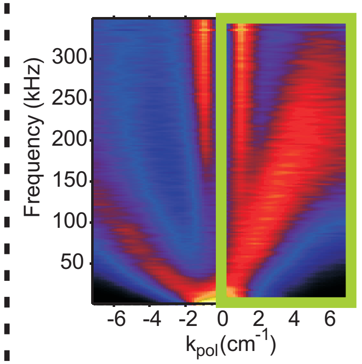
## Top View



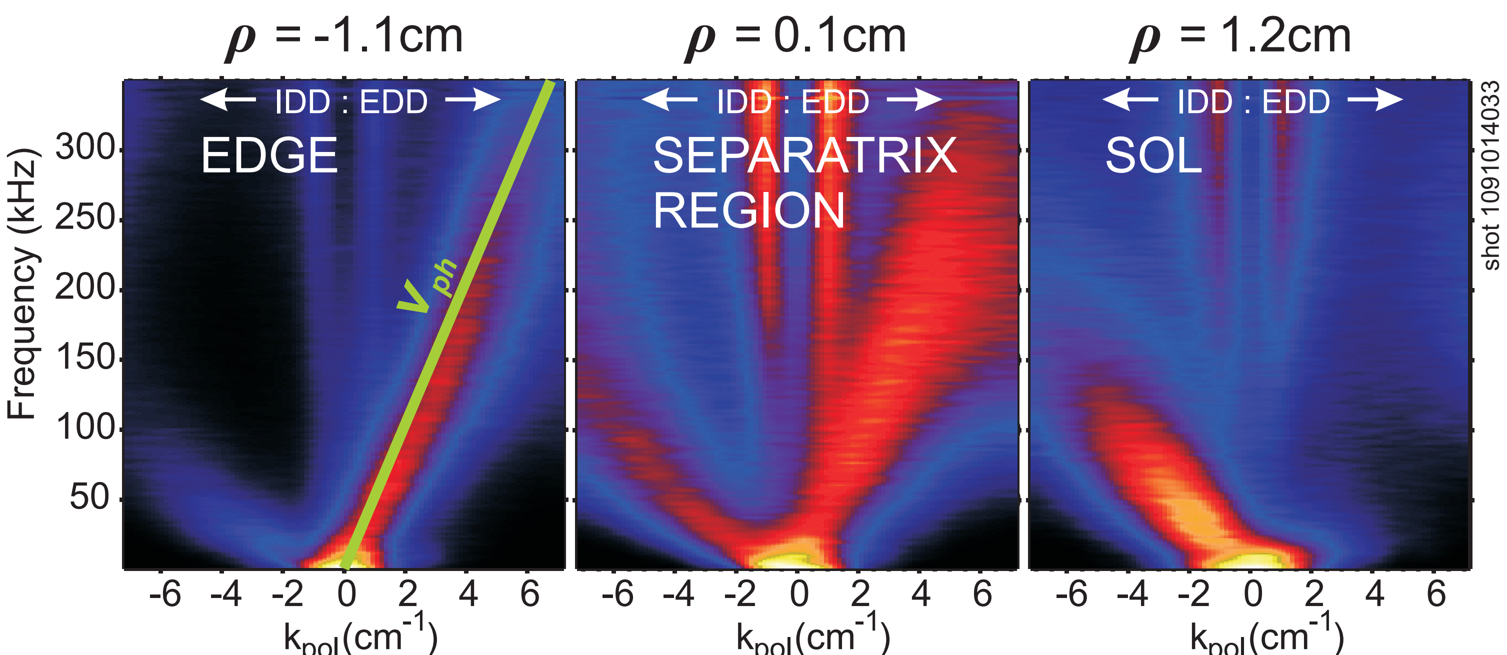
# The edge of Ohmic L-mode plasmas is dominated by EDD while the SOL is dominated by IDD propagating features

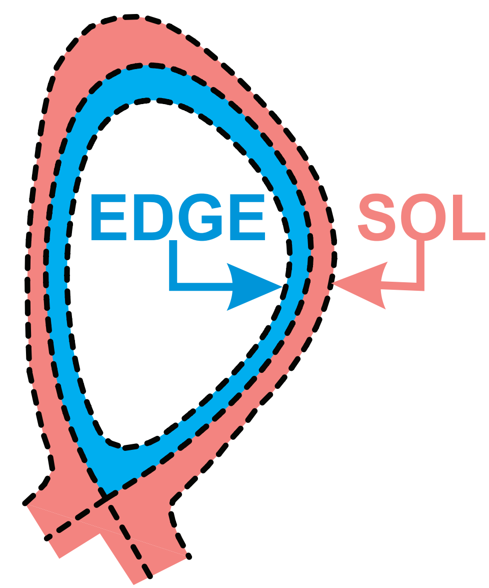
poloidal arrays + time history: $S(k_\theta, \nu)$

- $S(k_\theta|\nu)=S(k_\theta,\nu)/S(\nu)$
- Shows dispersion and dominant frequencies
- Dispersions are found to be very nearly linear:
- $k_\theta(\nu) \longrightarrow v_{ph}=2\pi\nu/k_\theta$

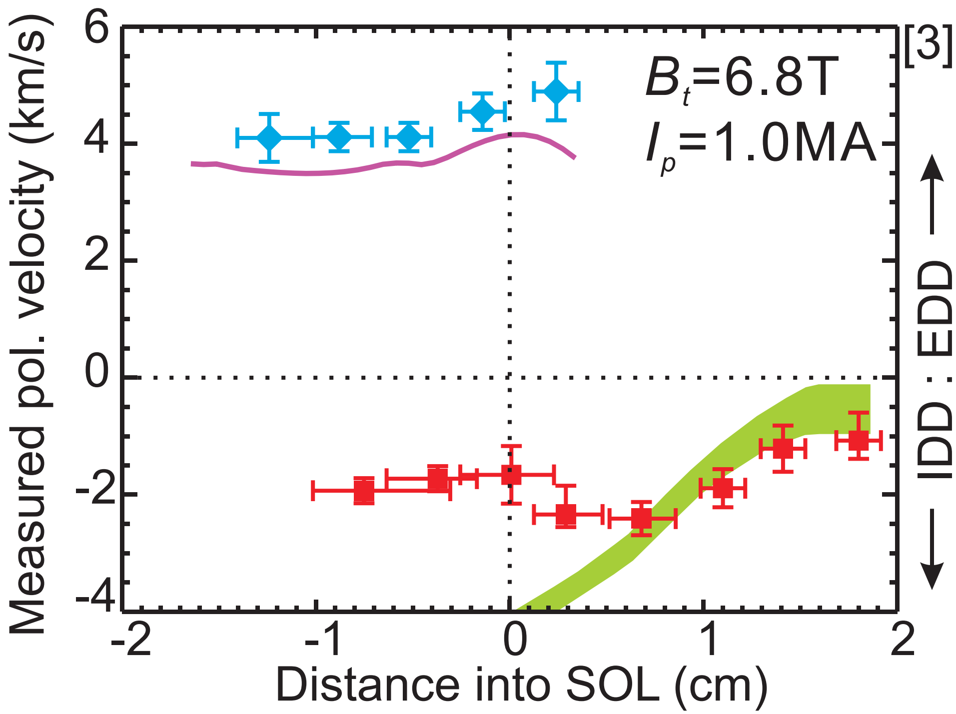



- $S(\nu)=S_{k<0}(\nu)+S_{k>0}(\nu)$
- Shows power spectra
- Characteristic scales can be seen

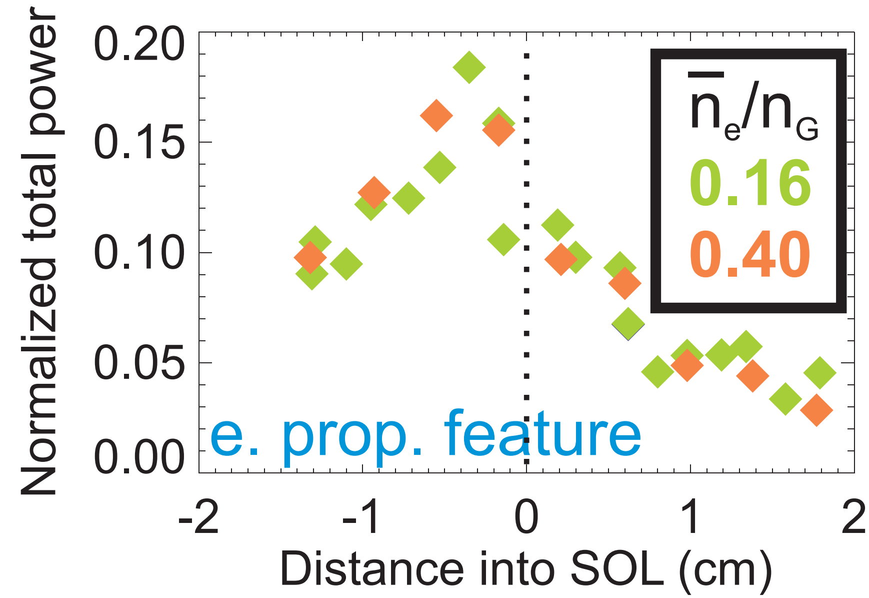


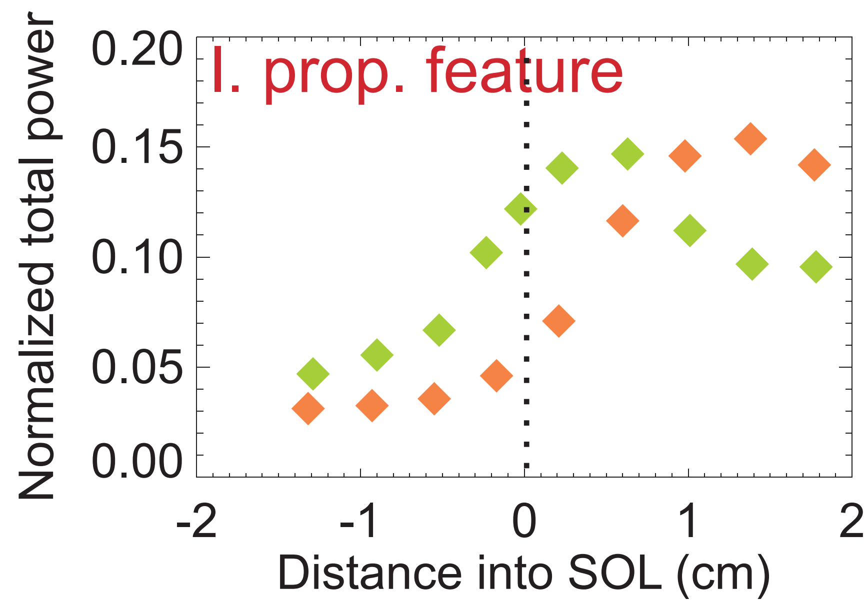



# EDD velocity in edge is close to $\omega_*/k_{pol}$
# far SOL IDD velocity matches ExB (expected for blobs)

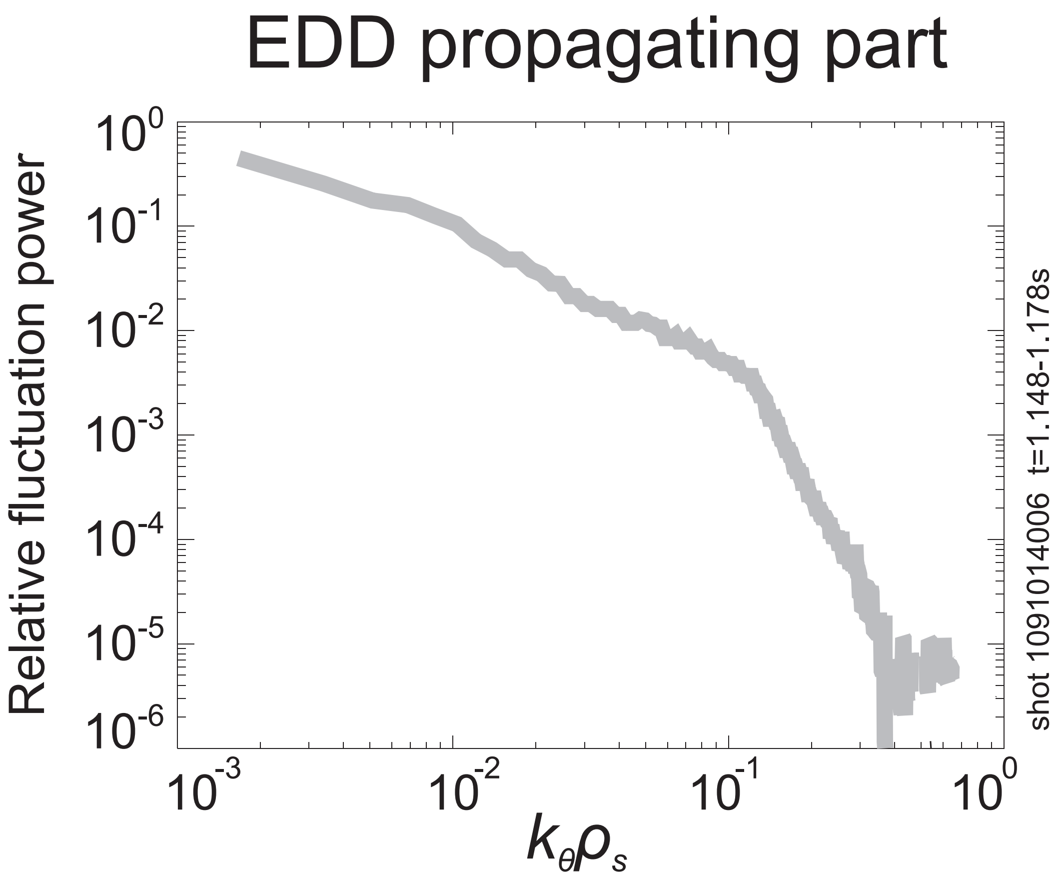



- **EDD propagation in the edge** is close to the **electron diamagnetic flow velocity estimated from TS profile**
- Poloidal velocity in the far SOL where **blobs** are seen matches **ExB velocity estimated from probe measurements**
- Overlap region between the two features

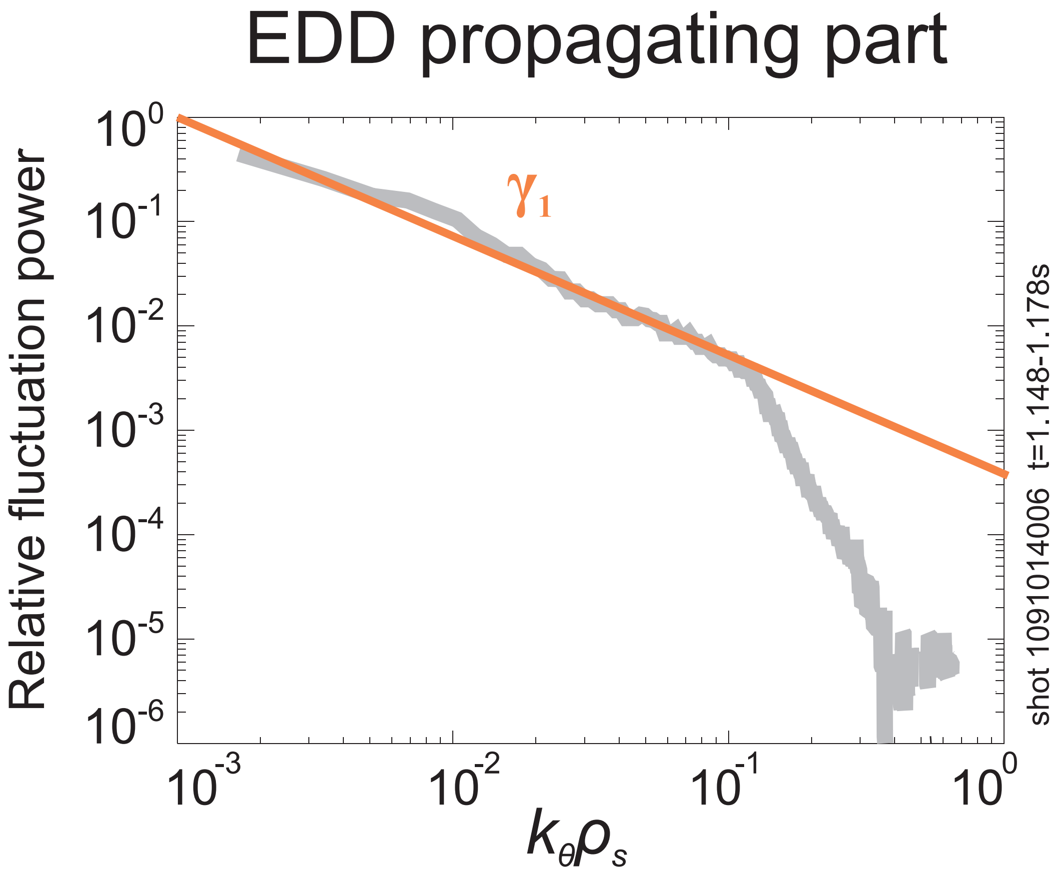


# Wavenumber filtered spectra $S_{k>0}(\nu)$ can yield information on underlying dynamics



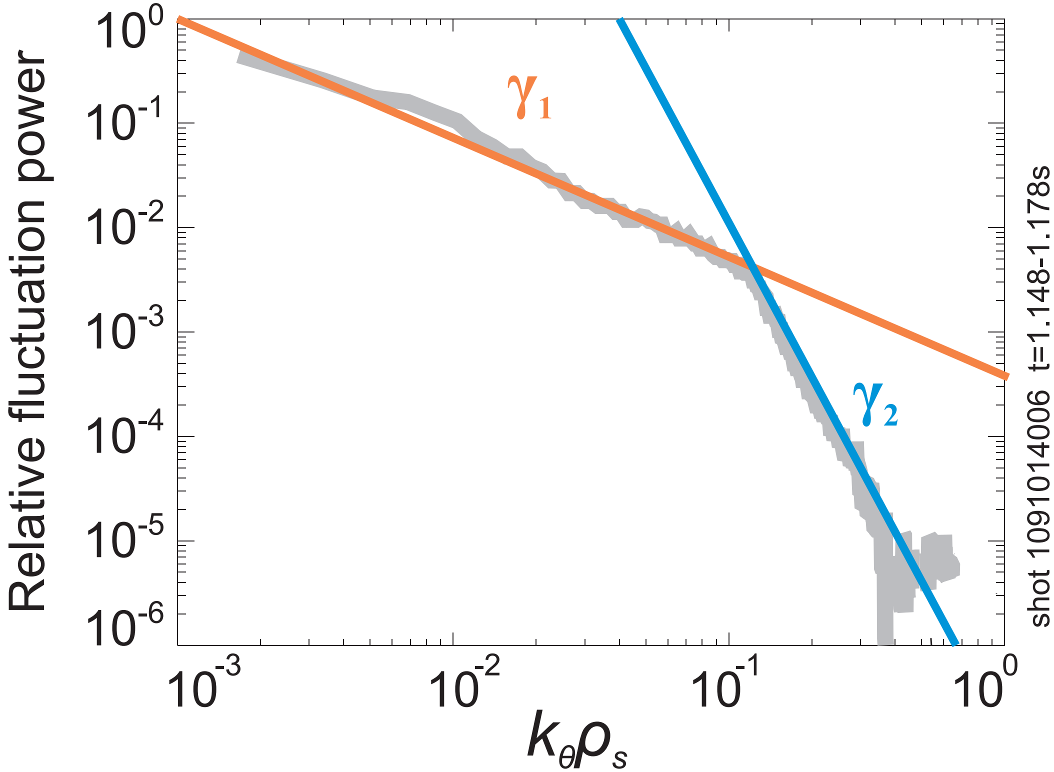
# Wavenumber filtered spectra $S_{k>0}(\nu)$ can yield information on underlying dynamics




- Spectra are often clear power laws
- Spectral indices contain information about the spectral transfer dynamics similar to Kolmogorov cascades

# Wavenumber filtered spectra $S_{k>0}(\nu)$ can yield information on underlying dynamics

## EDD propagating part

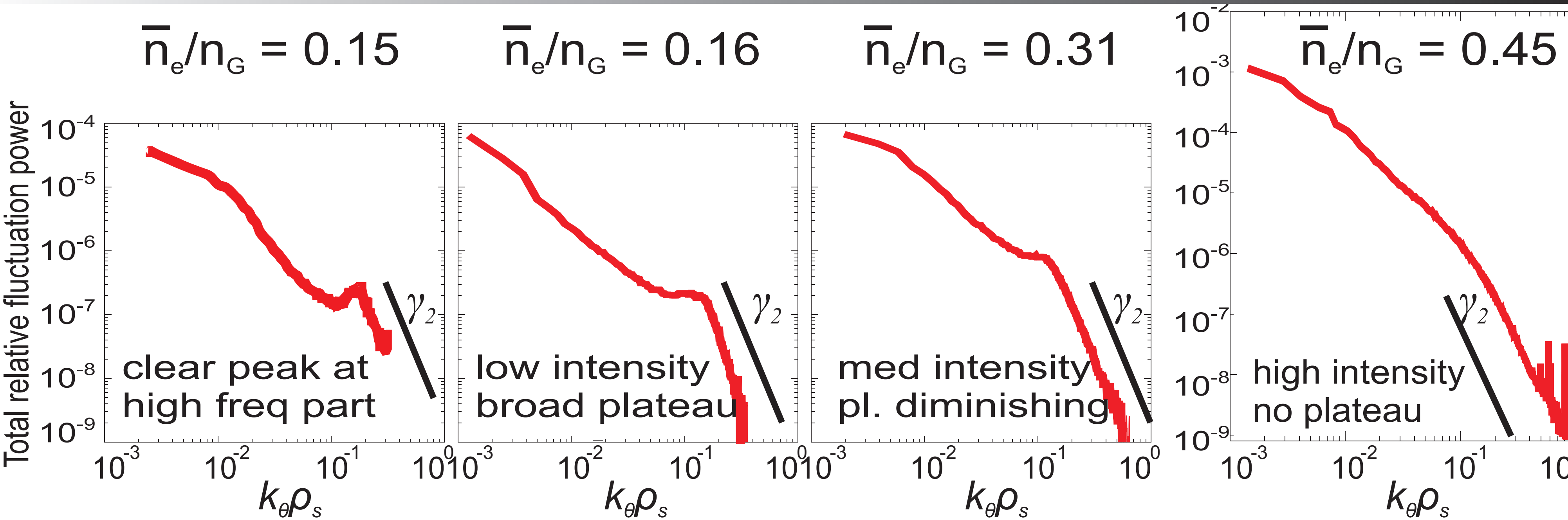



$\gamma_1$ = -1.3±0.40

$\gamma_2$ = -4.6±0.30

- Spectra are often clear power laws
- Spectral indices contain information about the spectral transfer dynamics similar to Kolmogorov cascades
- Break-in-slope $\nu^c$ may indicate:
  - dissipation scale
  - scale of energy input
- In the latter case:
  - $\gamma_1$ indicates "inverse cascade"
  - $\gamma_2$ indicates "forward cascade"

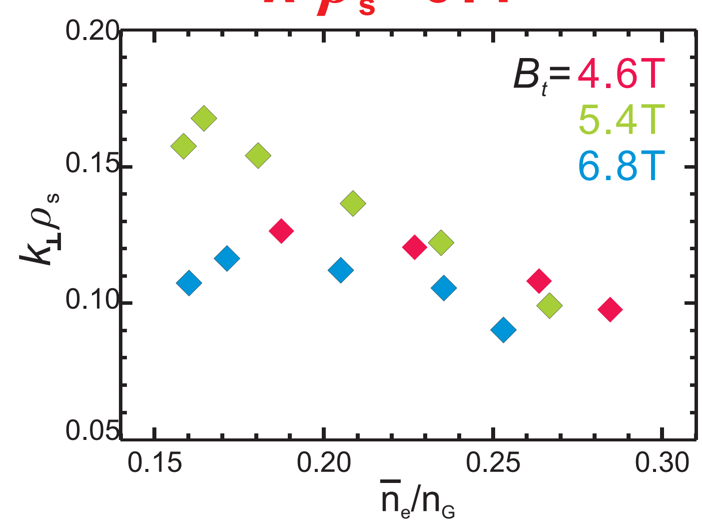
# The total spectral power and the distribution in L-mode show a strong dependence on $\bar{n}_e/n_G$




## $\gamma_2$ = -4.6±0.30

- forward transfer (features breaking up) is reproducible
  - Wakatani-Hasegawa (collisional drift)[4]: (Kolmogorov-Kraichnan 2D) $\gamma = -3$
  - Hasegawa-Mima (theory)[5], Fyfe (sim)[6], Xia (exp)[7]: $\gamma = -6$
  - Chen, Fowler (dimensional)[8]: $\gamma = -5$
  - Chen (exp): $\gamma = -4.6$
- break-in-slope spectral position develops a peak
  hindered inverse dynamics? increased dissipation?

**$k^c \rho_s \sim 0.1$**



# Bispectral analysis: estimation of three-wave interactions and spectral transfer

Bicoherence spectra $b^2(k_1, k_2)$ ? strength of phase coupling

? no information on energy flow, coupling coefficients

Spectral transfer function can be estimated from two separate times:

$$Y_k = L_k X_k + \sum_{k=k_1+k_2} Q_k^{k_1,k_2} X_{k_1} X_{k_2}$$

$$X_k = \phi(k,t) \quad Y_k = \phi(k, t+\tau)$$

$$\phi(k, t+\tau) = (\Gamma_k \tau + 1 - i\theta_k) e^{i\theta_k} \phi(k,t) + \sum_{k=k_1+k_2} \Gamma_k(k_1,k_2) \tau e^{i\theta_k} \phi(k_1,t)\phi(k_2,t)$$

$$\langle Y_k \bar{X}_k \rangle = L_k \langle X_k \bar{X}_k \rangle + \sum_{k=k_1+k_2} Q_k^{k_1,k_2} \langle X_{k_1} X_{k_2} \bar{X}_k \rangle$$

$$\partial_t P_k = 2\Re \Gamma_k P_k + \sum_{k=k_1+k_2} T_k(k_1,k_2)$$

$$\langle Y_k \bar{X}_{k_1} \bar{X}_{k_2} \rangle = L_k \langle X_k \bar{X}_{k_1} \bar{X}_{k_2} \rangle + \sum_{k=k_1'+k_2'} Q_k^{k_1',k_2'} \langle X_{k_1'} X_{k_2'} \bar{X}_{k_1} \bar{X}_{k_2} \rangle$$

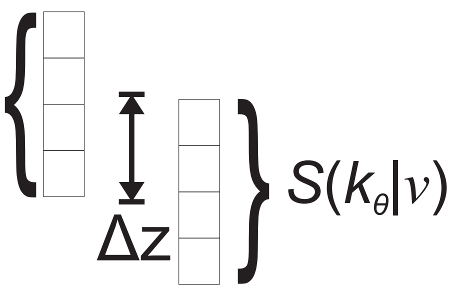
$$L_k \quad Q_k(k_1,k_2) \longrightarrow$$

$$\sum_{k=k_1+k_2} T_k(k_1,k_2) = \Re\left( \sum_{k=k_1+k_2} \Gamma_k(k_1,k_2) \langle X_{k_1} X_{k_2} \bar{X}_k \rangle \right)$$

# Bispectral analysis results:
# energy input at the same scale for H-mode and L-mode
# stronger transfer towards large scales in L-mode

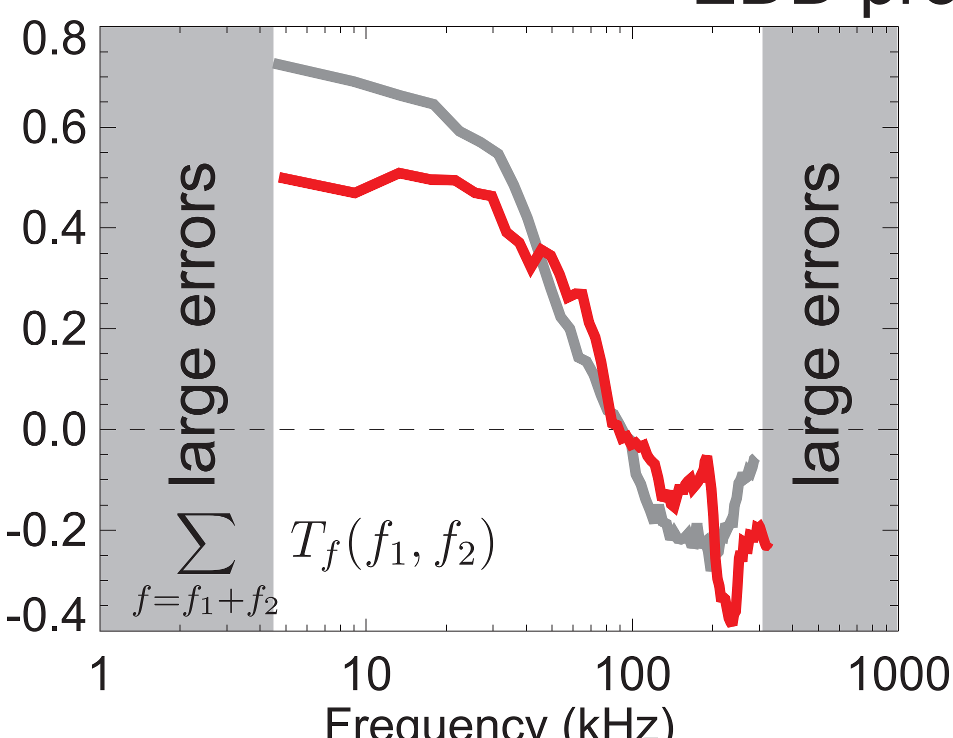
From $S(k_\theta|\nu)$ we can move to spatial separation rather than time using $k_\theta(\nu) \rightarrow v_{ph}=2\pi\nu/k_\theta$, and the appropriate Galilean transformation for the velocities.

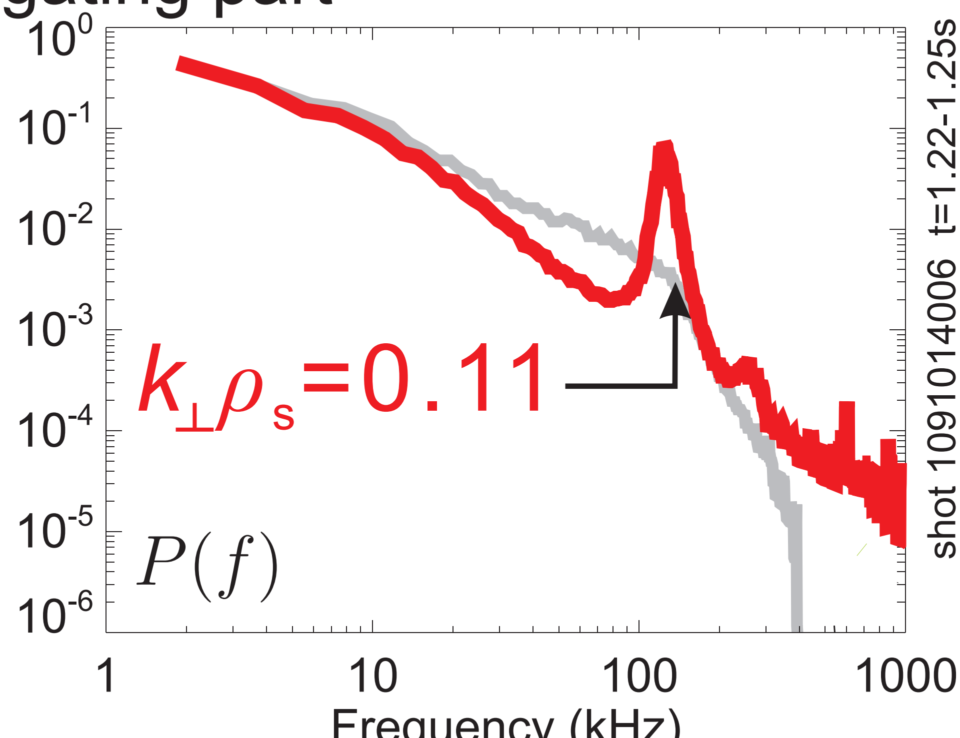
viewing chans



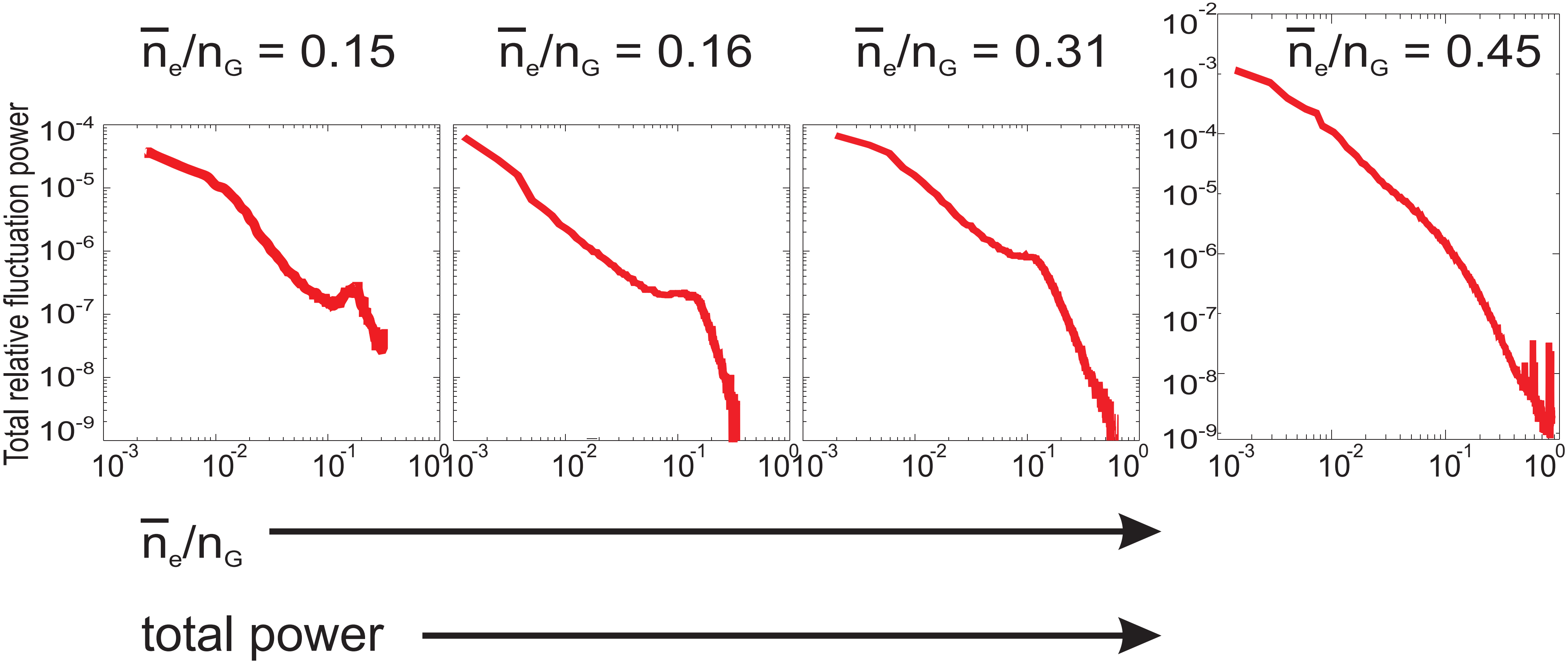

→ time average instead of ensemble average

EDD propagating part



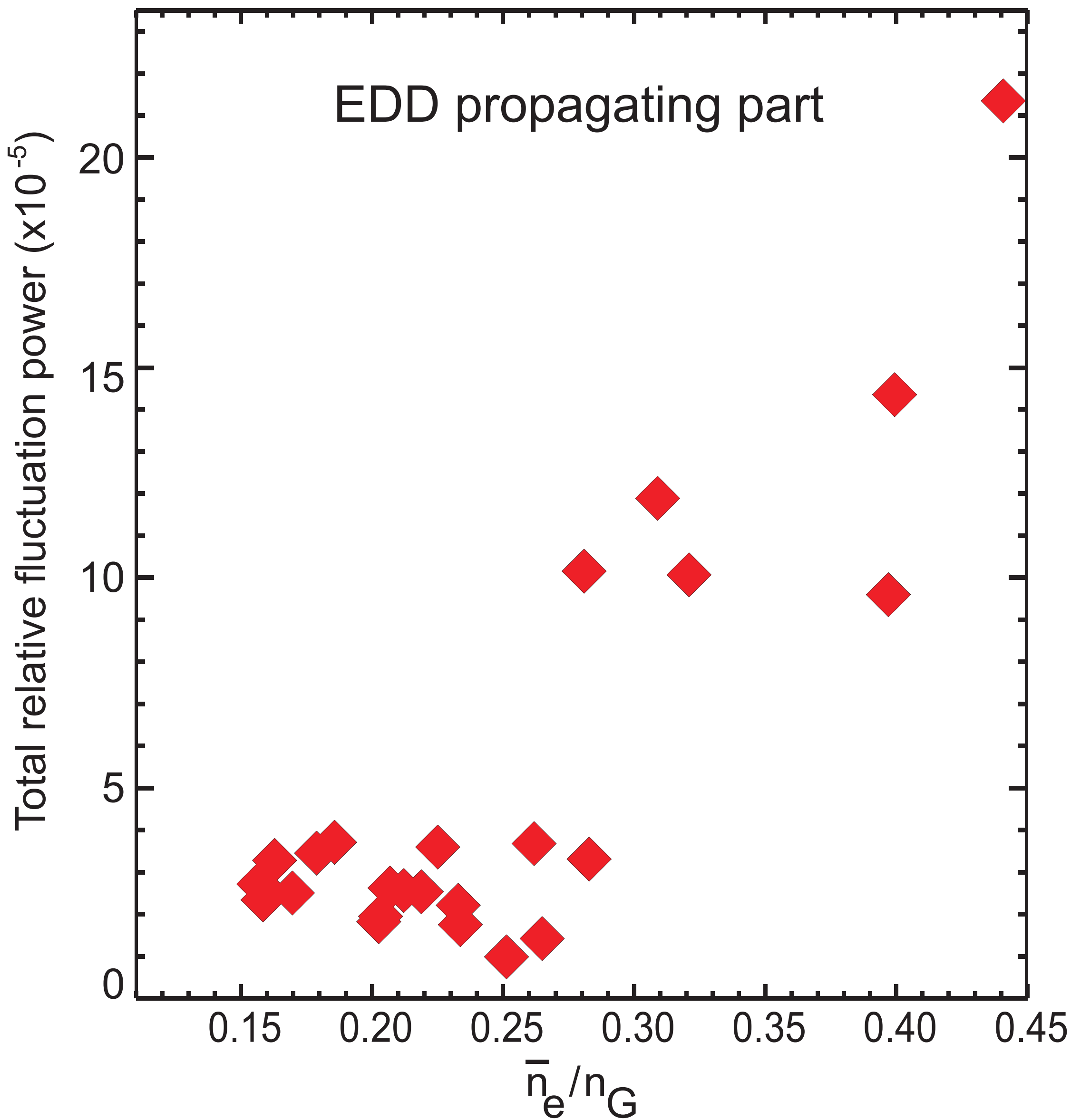



# Total fluctuation power increases with Greenwald fraction

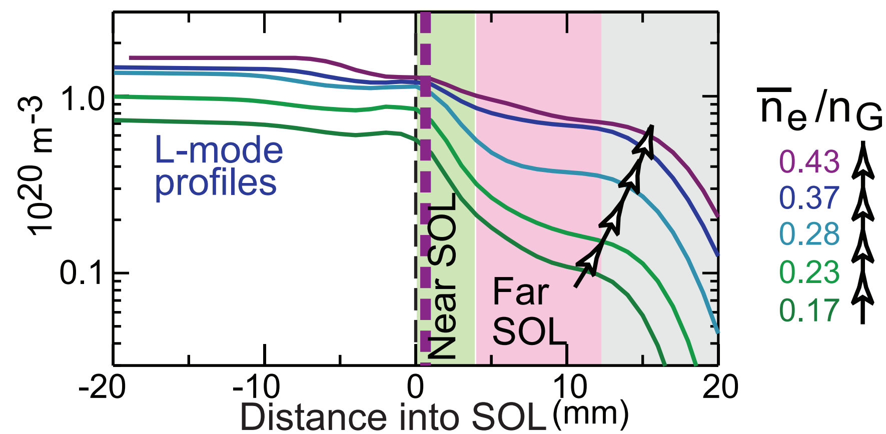


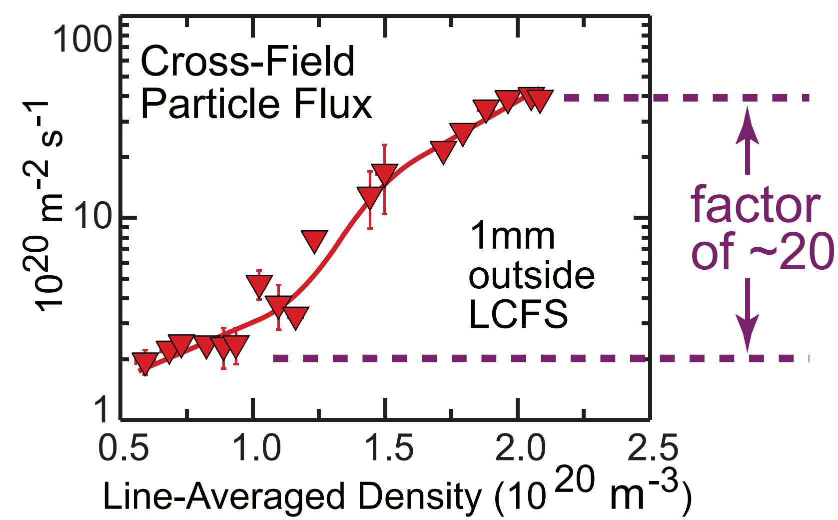
# Evidence that the EDD propagating edge turbulence is a major factor in edge particle transport and may be related to the robust tokamak (Greenwald) density limit

## EDGE REGION




## SOL densities

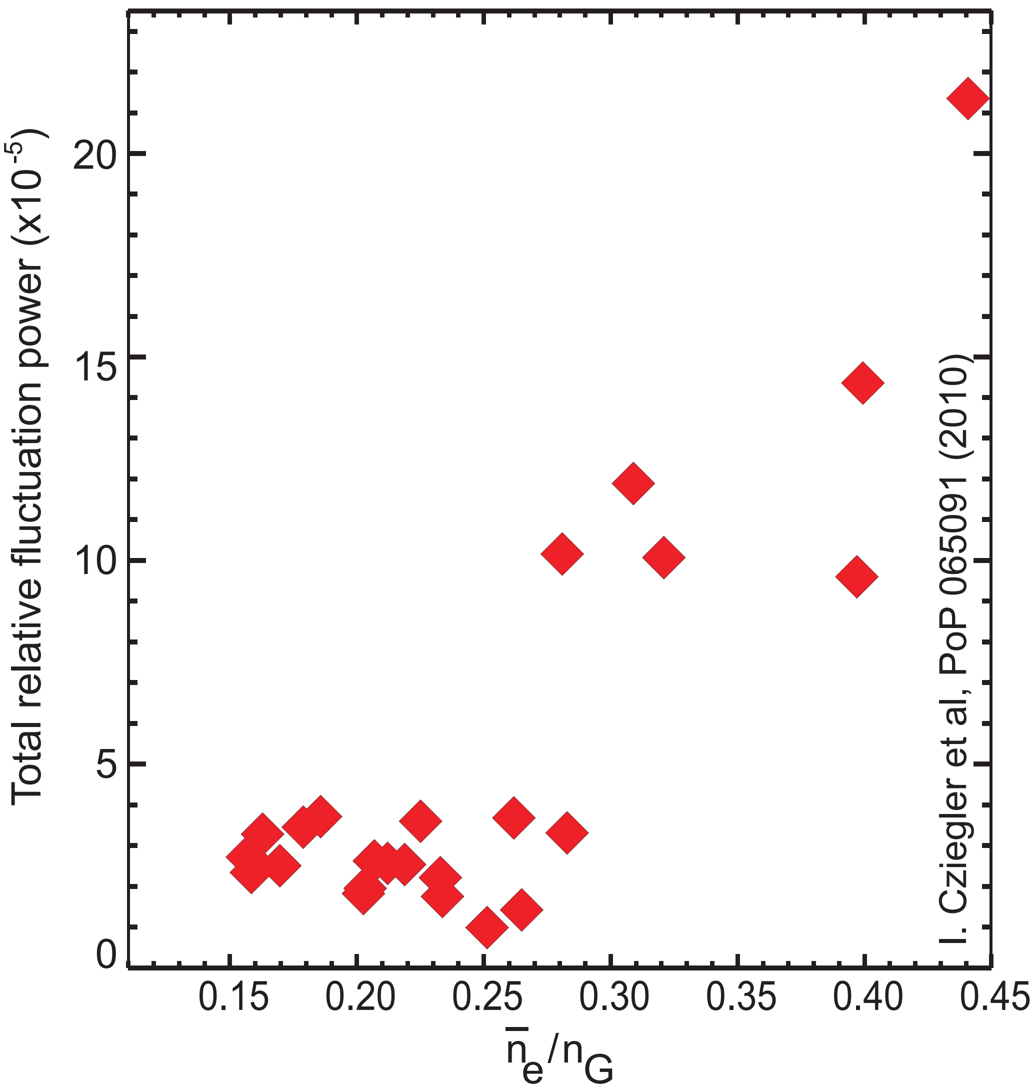


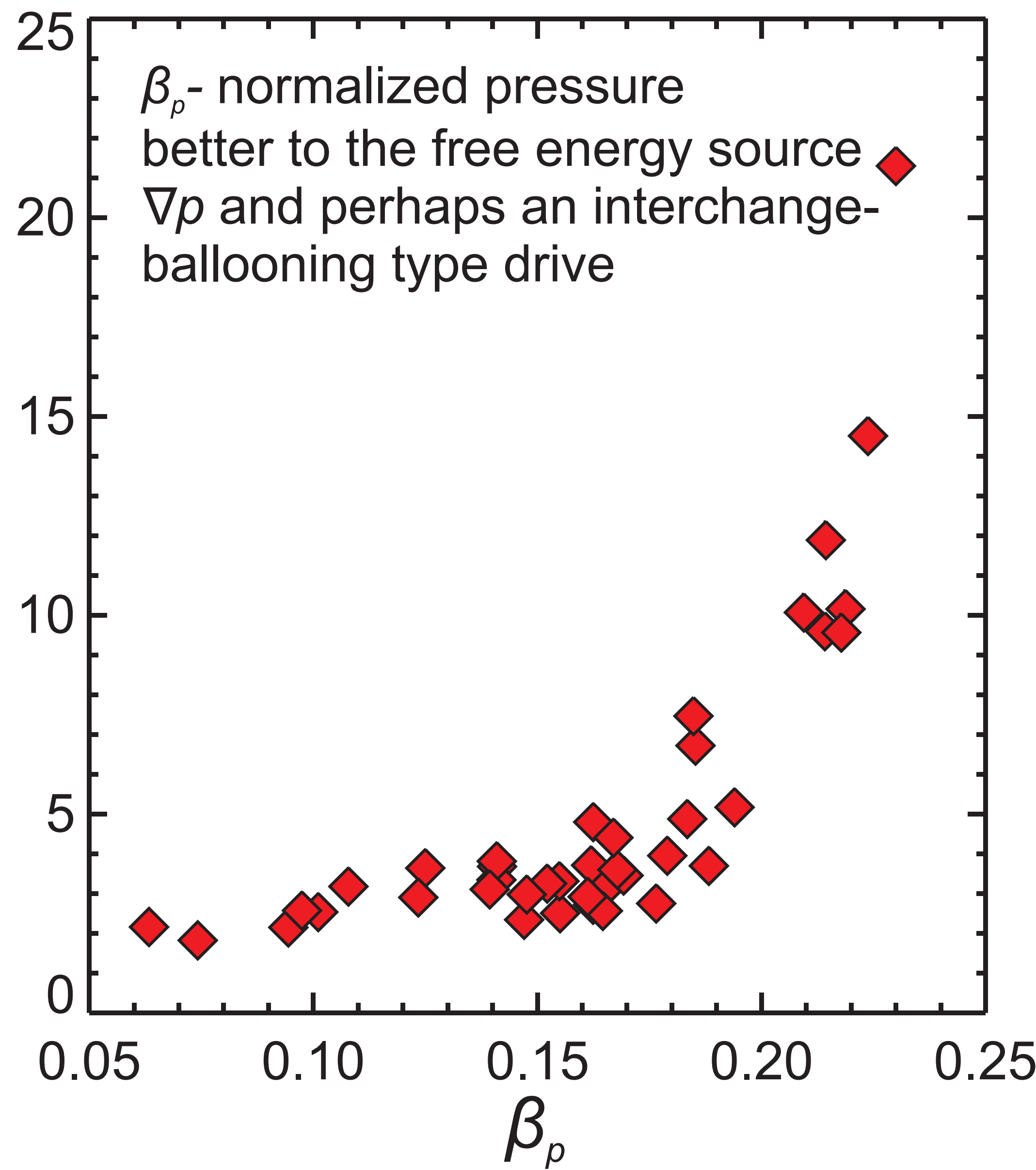



# The physical variable $\beta_p$ seems to parametrize the turbulence more sensitively than the Greenwald fraction

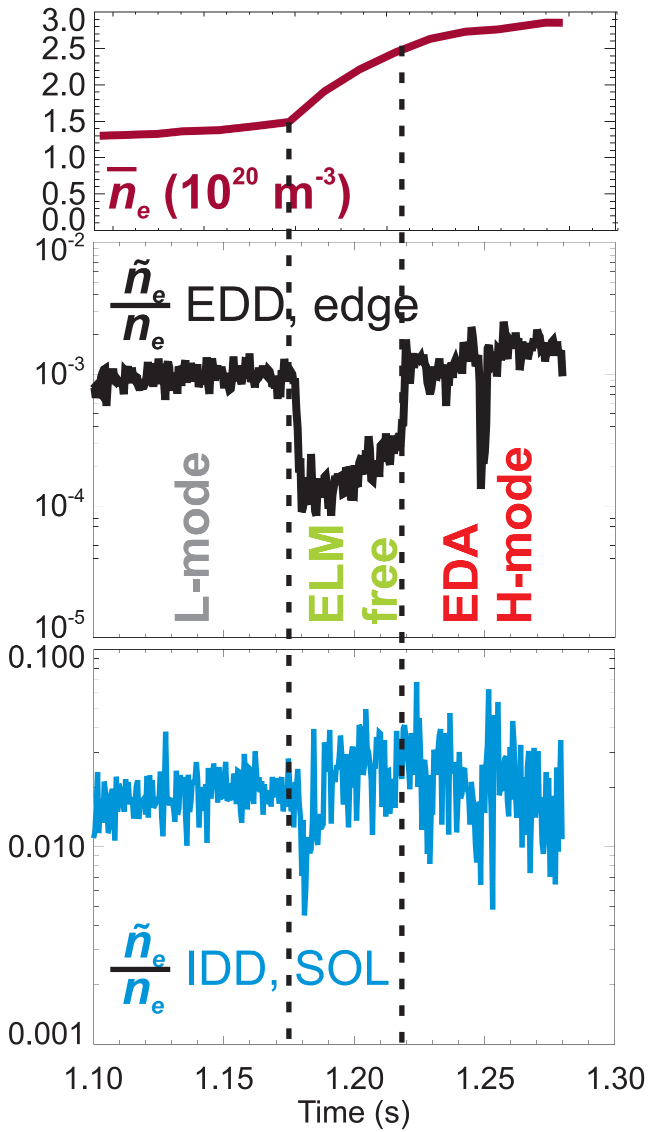
## EDGE REGION

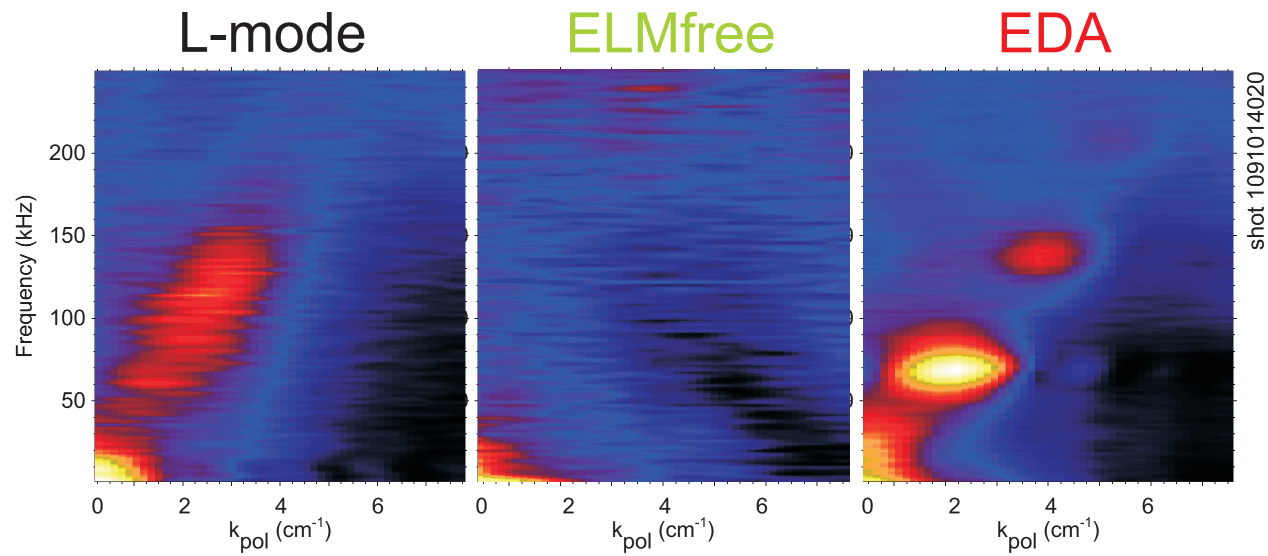
EDD propagating part

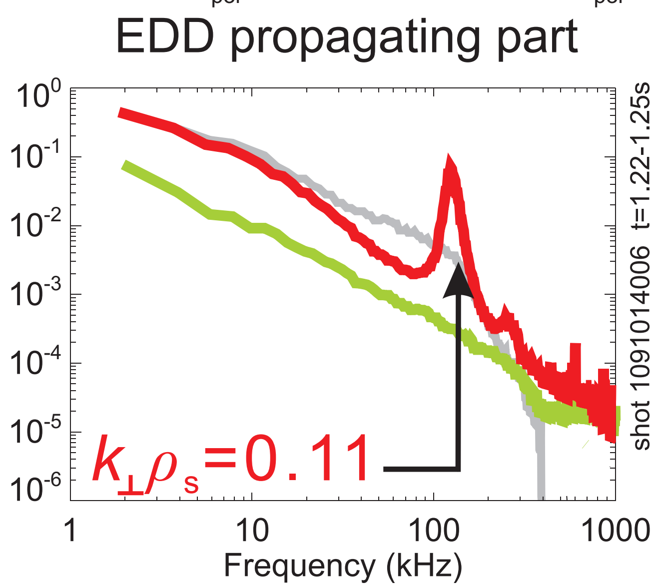


# Significant reduction in EDD turb. power at L-H transition and suggested connection to the QC mode

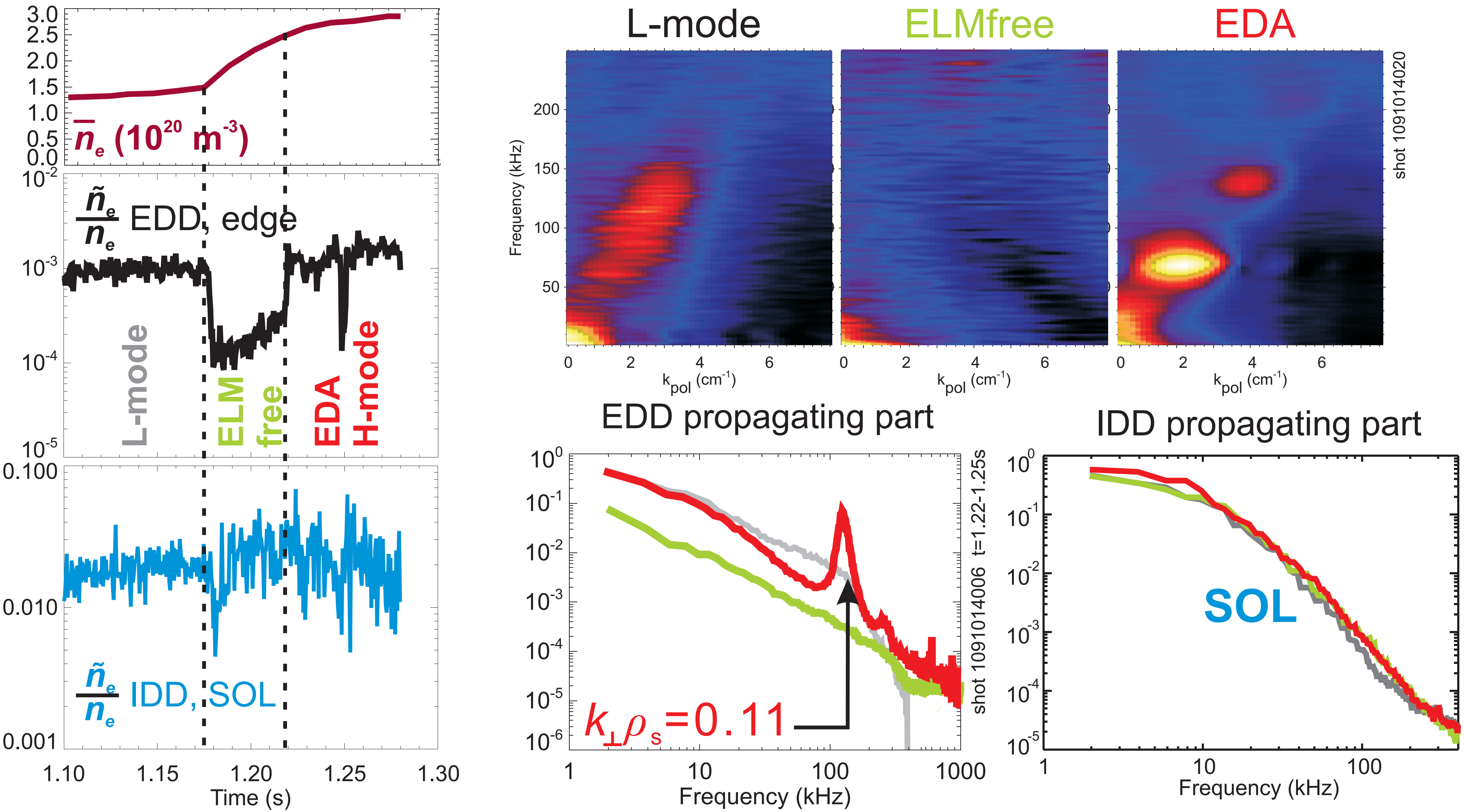



- Edge turbulence drops at L-H transition
- No change in norm. SOL fluct. level
- Further evidence to transport-relevance of EDD edge turbulence
- critical wavenumber is at the same physical scale as QCM

# Fluctuations in the far SOL show no change in character or relative amplitude



# Summary

- Drift-wave-like edge turbulence overlaps with IDD features at the SOL boundary
- Short wavelength spectra $\gamma_2 = -4.6$ quite reproducible but not explained
- Found evidence that the *edge* turbulence may be responsible for cross field particle transport, ie creating blobs
- The energy input scale is $k_\perp \rho_s \sim 0.1$
  and shows likely connection to QCM (resistive ballooning drive)
  through spectral transfer
- Sensitive dependence on $\bar{n}_e/n_G$ (or $\beta_p$ - indication of grad-p source?)
- What theory predicts the right spectra and what consequences does the right model have for transport?

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