Statistical Properties of Electrostatic Fluctuations and Turbulent Cross-Field Fluxes in DIII-D SOL

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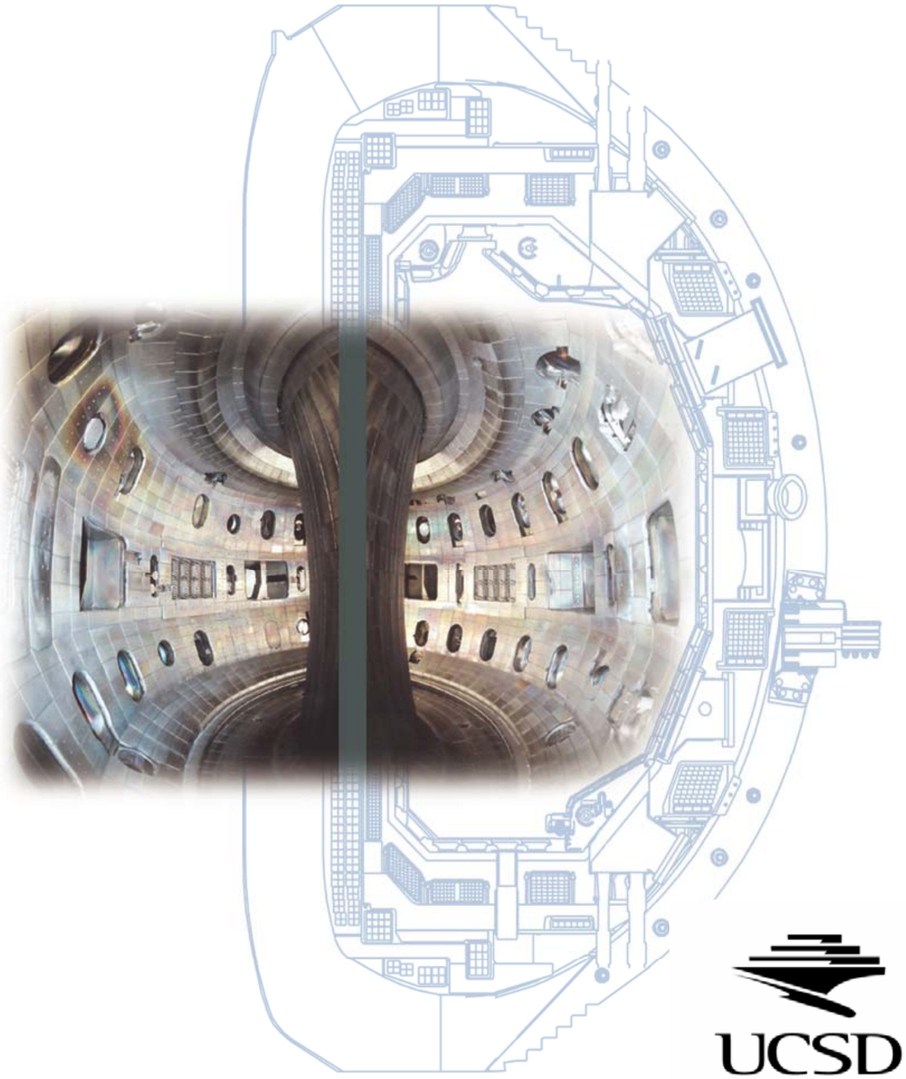

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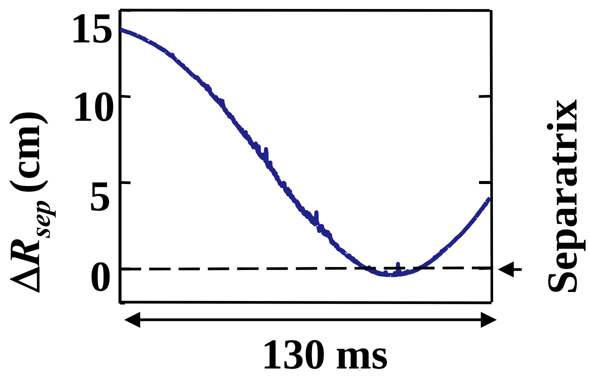
Abstract

Fluctuations of the local plasma density, electron temperature, and floating potential are measured in the scrape-off-layer (SOL) of the DIII-D tokamak by a fast reciprocating probe array. Fluctuation-induced cross-field fluxes of particles and heat are derived from the measurements. Density and temperature fluctuations and fluxes in the SOL are strongly intermittent in time and space. Probability distribution functions (PDFs) of the fluxes are skewed in the outwards direction and have more large transport events than could be expected for Gaussian statistics. Long data records (>250,000 usable points) obtained recently with the probe array kept at a fixed radial position in the SOL allowed us to study statistics of the waiting times between the transport events. We present a comparison of the quiet time statistics of the turbulent fluxes in the DIII-D SOL with those expected from the Self Organized Criticality (SOC) paradigm.

Mid-plane reciprocating probe array

- The in-and-out plunge time is about 0.2 s
- The plunge length is about 15 cm
- On time scale < 1 ms probe can be considered stationary
- Spatial resolution: ~ 2 mm
- Temporal resolution: 1 μs (I_{sat} and V_f)

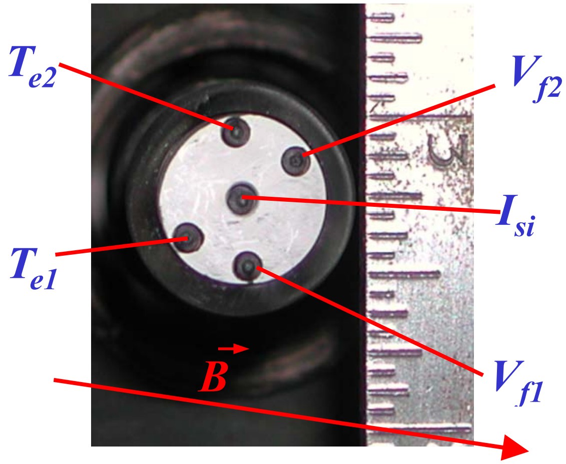
Position trace of a probe plunge



Fast T_e measurement - 10 μs resolution

- Measured parameters: I_{sat} T_e V_f
- Derived parameters: n_e V_p E_θ $\Gamma_\perp$ $Q_\perp$

Probe head layout



Time-resolved turbulent fluxes

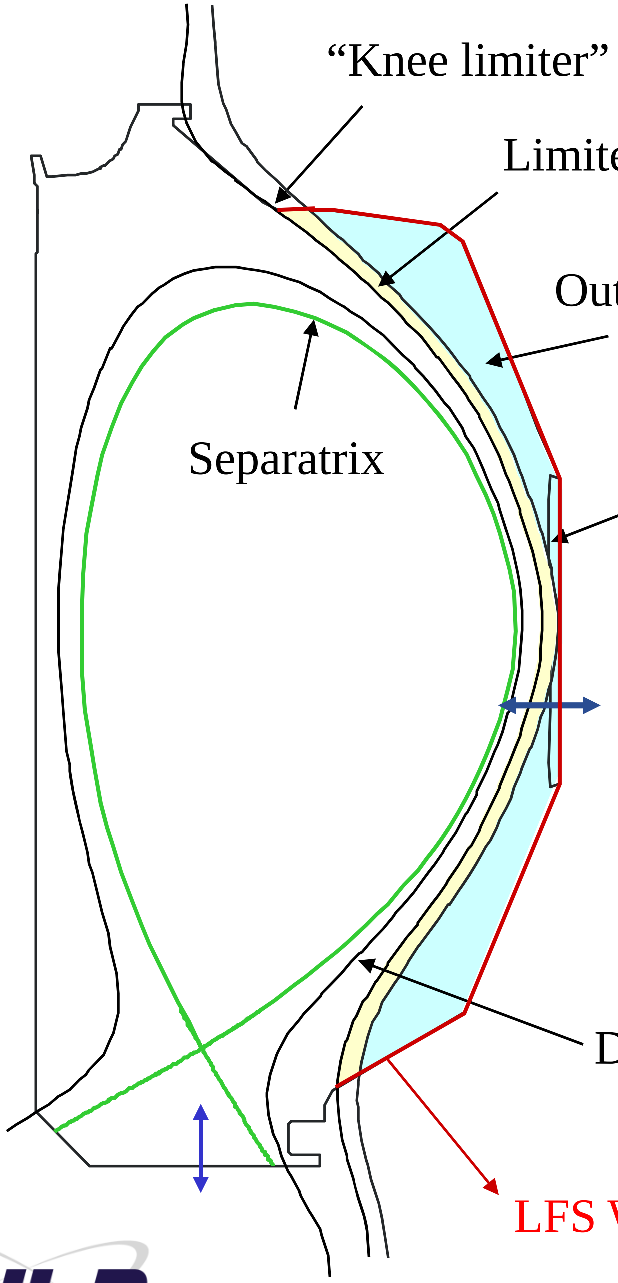
Turbulent particle flux: $$\Gamma_r^{ES} = \frac{1}{B_\varphi} n_e \tilde{E}_\theta$$

Turbulent heat flux: $$Q_r^{ES} = \frac{3}{2B_\varphi} n_e k T_e \tilde{E}_\theta$$

where $\tilde{E}_\theta \equiv E_\theta - \langle E_\theta \rangle$

- Minimum resolved values: I_{sat} ~ 1 mA, n_e ~ 10^{11} cm^{-3}, T_e ~ 3 eV

Structure of the low field side SOL



“Knee limiter”

Limiter SOL (LSOL)

Outer Wall Shadow (OWS)

Separatrix

Bumper Limiter (BL)

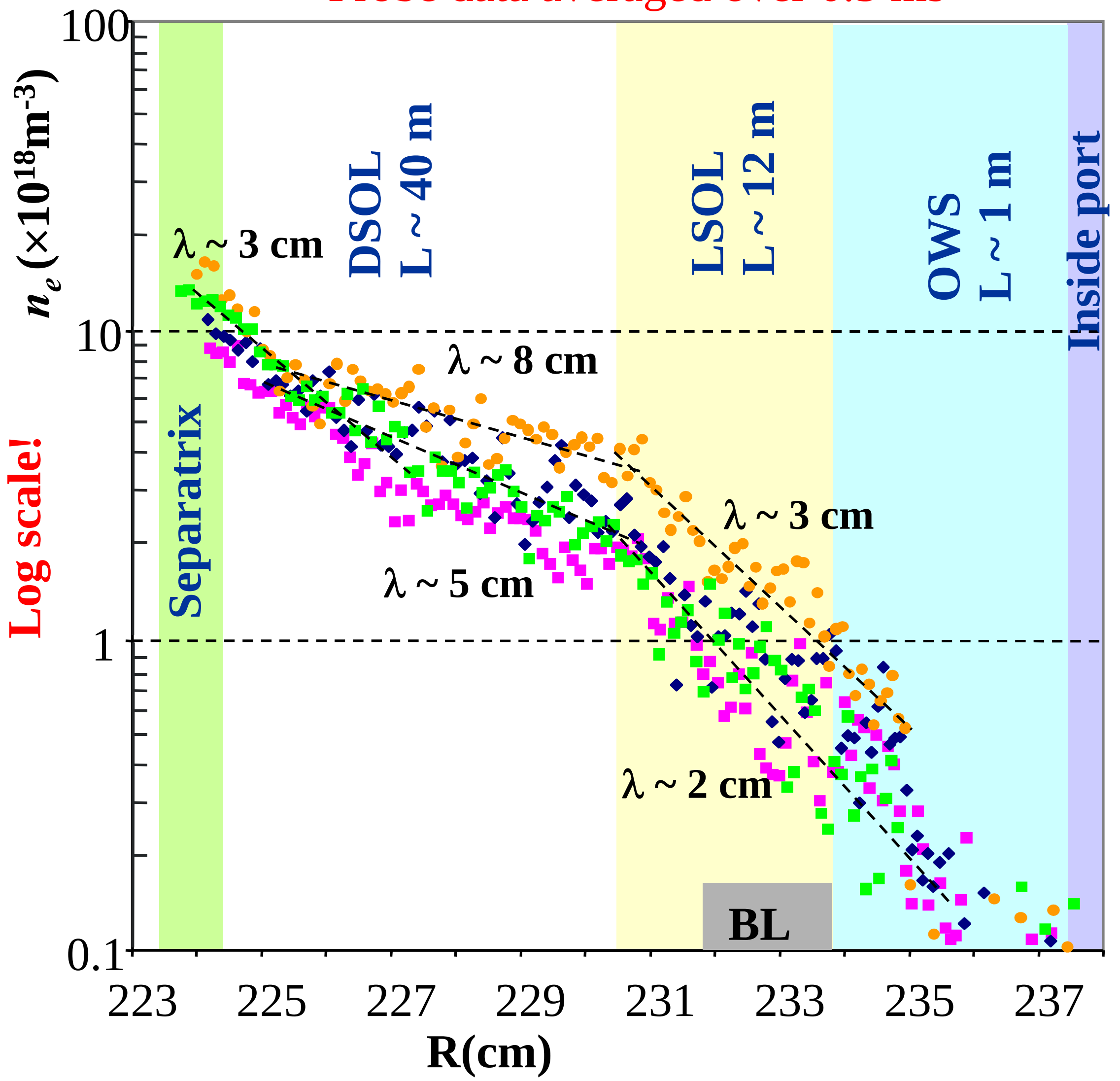
Mid-plane reciprocating probe array

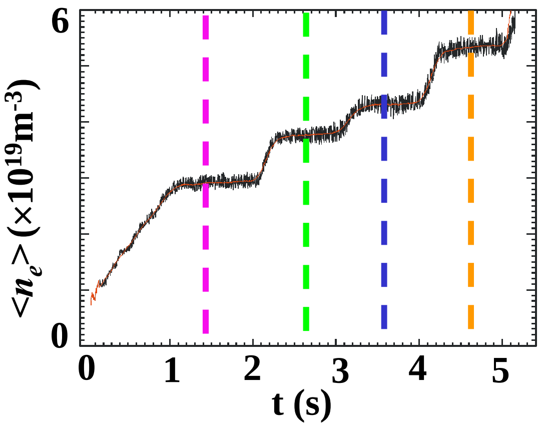
Divertor SOL(DSOL)

LFS Wall

SOL density in L-mode increases with the average discharge density

Probe data averaged over 0.5 ms





LSN L-mode

B_T = 2 T, I_p = 1 MA

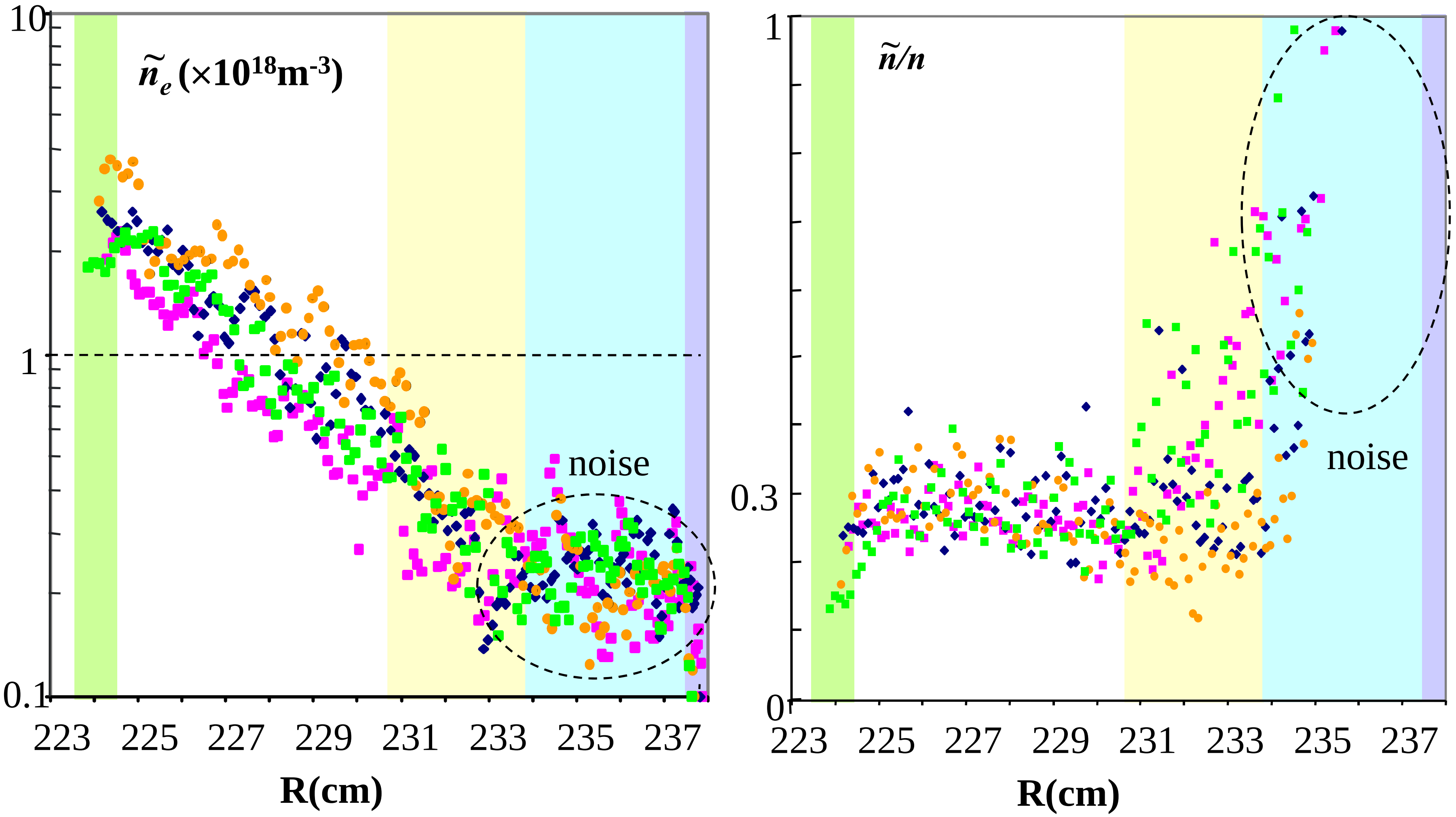
q_{95} ~ 3.8

- ■ f_{Gw} ~ 0.27
- ■ f_{Gw} ~ 0.35
- ◆ f_{Gw} ~ 0.4
- ● f_{Gw} ~ 0.5

$$f_{GW} = \langle n_e \rangle / n_{GW} = \frac{\langle n_e \rangle \left(10^{20}\,\mathrm{m}^{-3}\right)}{I_p(\mathrm{MA}) * \pi \left(a(\mathrm{m})\right)^2}$$

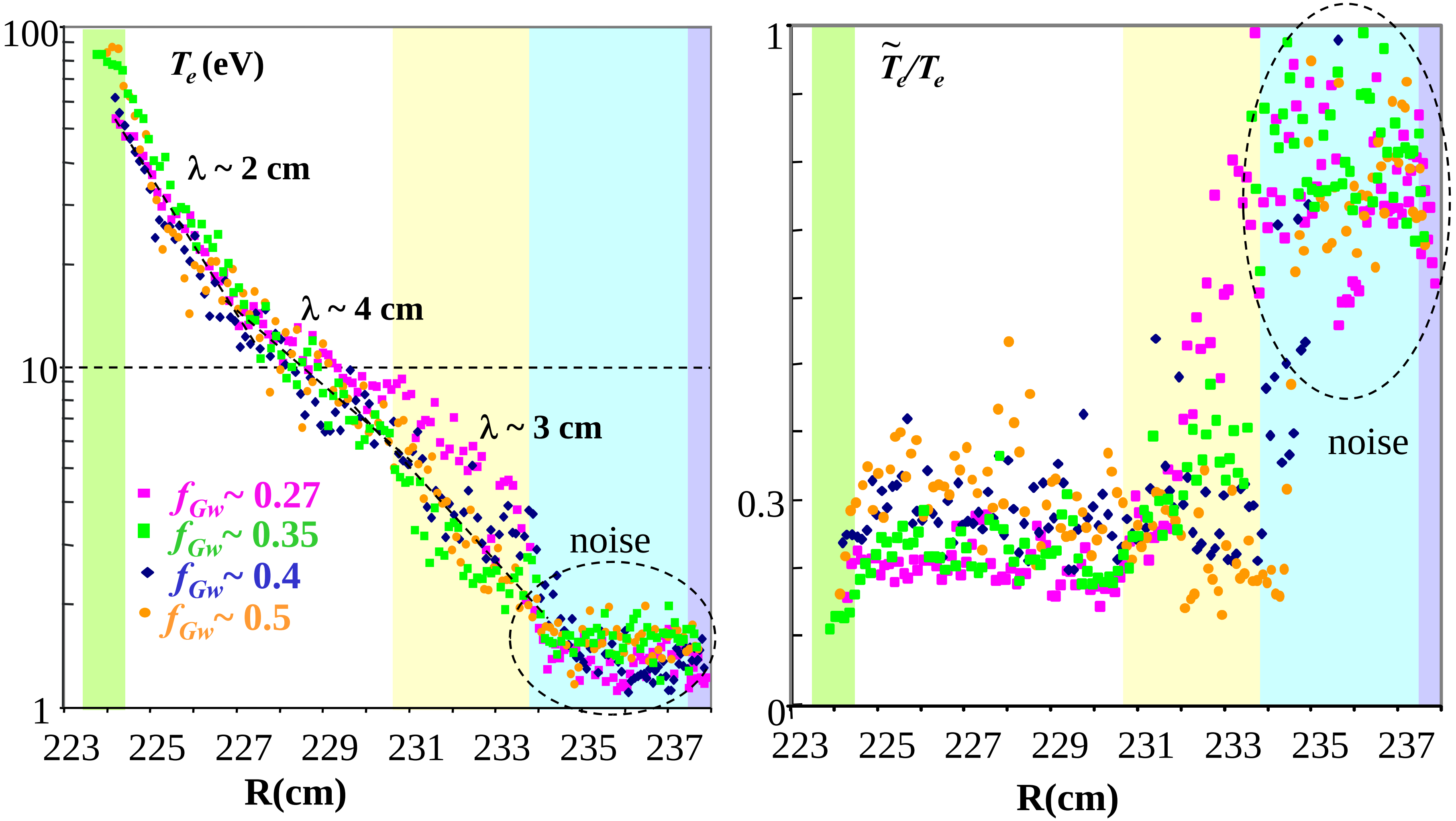
Profiles show a clear break when entering the LSOL region

n_e fluctuation levels increase with discharge density



- Absolute fluctuation levels increase with density
- Relative fluctuation levels are flat and do not change with average density
- Relative fluctuation levels are higher in WSOL

Average T_e does not change with density, fluctuations increase



- SOL temperature decays faster than density
- Relative T_e fluctuation levels increase slightly with density

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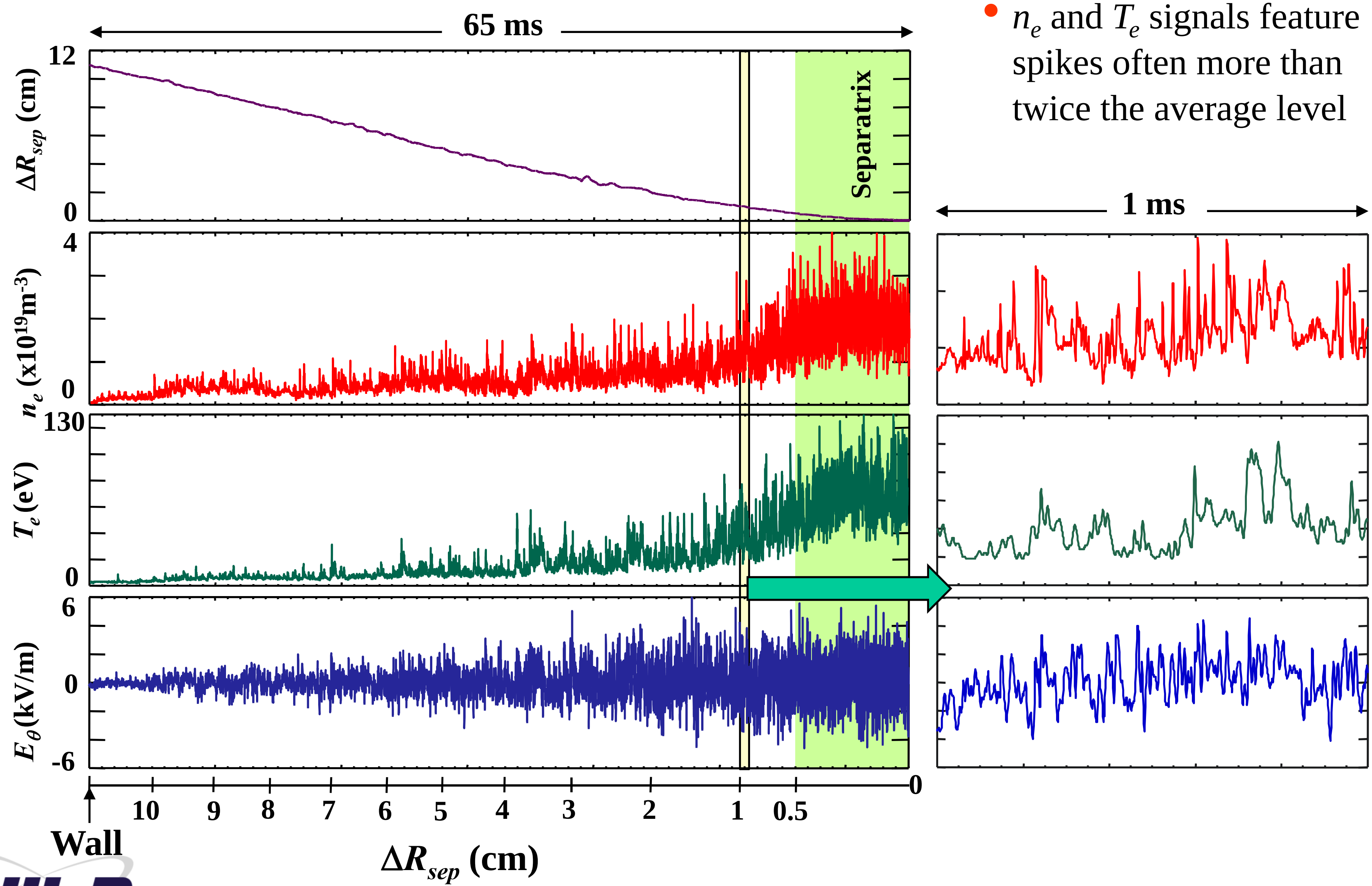
Probe signals in L-mode feature intermittent bursts

Shot# 105524: LSN, $B_t = 2$ T, $\langle n_e \rangle \approx 6\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.5$



- n_e and T_e signals feature spikes often more than twice the average level

Signal characterization by statistical moments

$$\text{Mean} = \overline{X} = \frac{1}{N}\sum_{j=0}^{N-1} X_{j-N/2}$$

Mean value,
SMOOTH in IDL

$$\text{Variance} = \sigma^2 = \frac{1}{N}\sum_{j=0}^{N-1}\left(X_{j-N/2} - \overline{X}\right)^2$$

Square of RMS
amplitude

$$\text{Skewness} = S = \frac{1}{N}\sum_{j=0}^{N-1}\left(\frac{X_{j-N/2} - \overline{X}}{\sigma}\right)^3$$

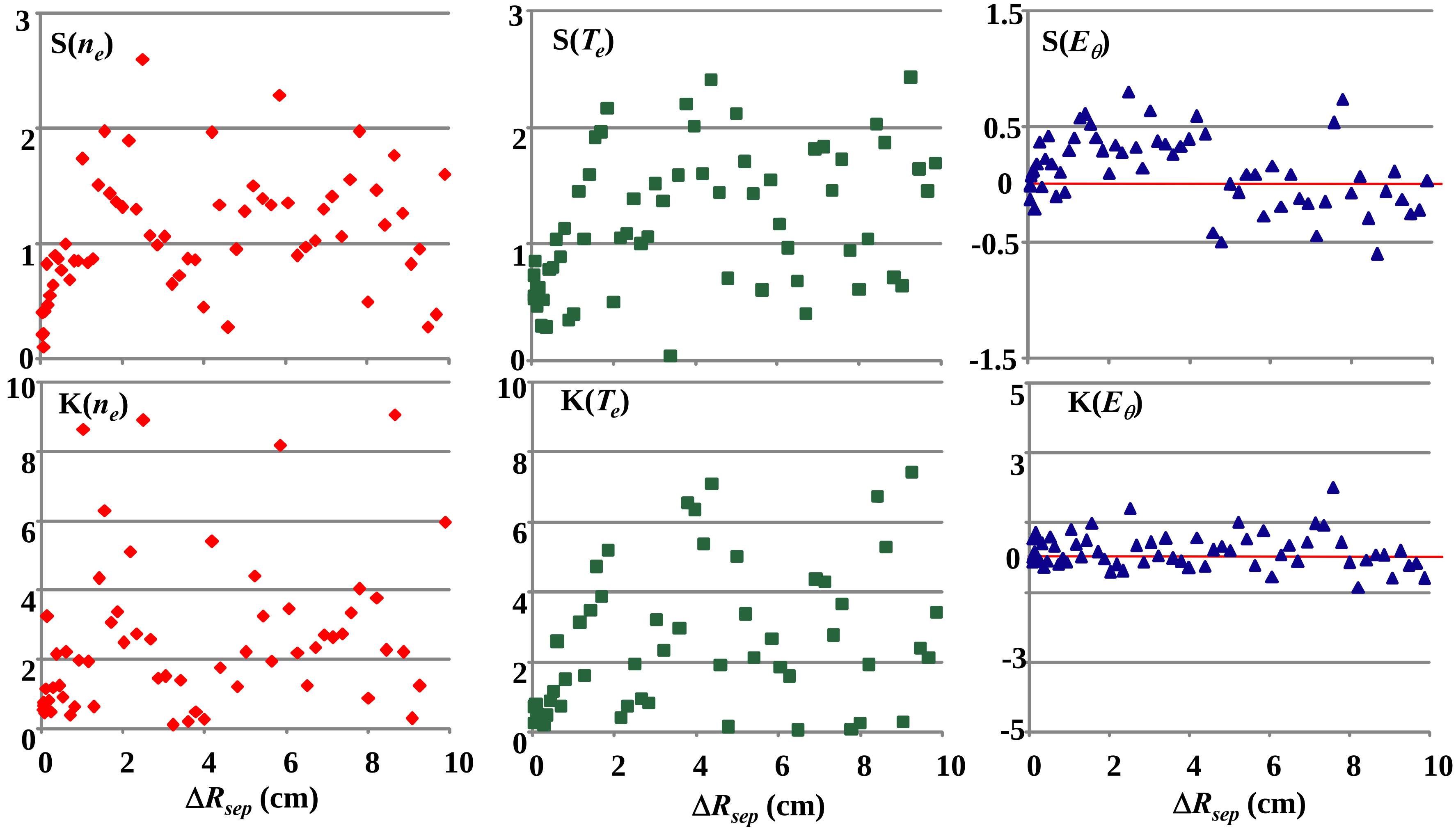
Measure of asymmetry
of the PDF;
for Gaussian PDF $S = 0$

$$\text{Kurtosis} = K = \frac{1}{N}\sum_{j=0}^{N-1}\left(\frac{X_{j-N/2} - \overline{X}}{\sigma}\right)^4$$

Measure of flatness of
the PDF;
for Gaussian PDF $K = 3$

- All the above moments can be calculated in any point i of an array using N adjacent points from $i-N/2$ to $i+N/2$
- This characterization is convenient when there is not enough data points to construct a good quality PDF

Density and temperature fluctuations are strongly non-Gaussian



- n_e and T_e fluctuations get closer to Gaussian near the separatrix
- E_θ fluctuations are near-Gaussian through most of SOL

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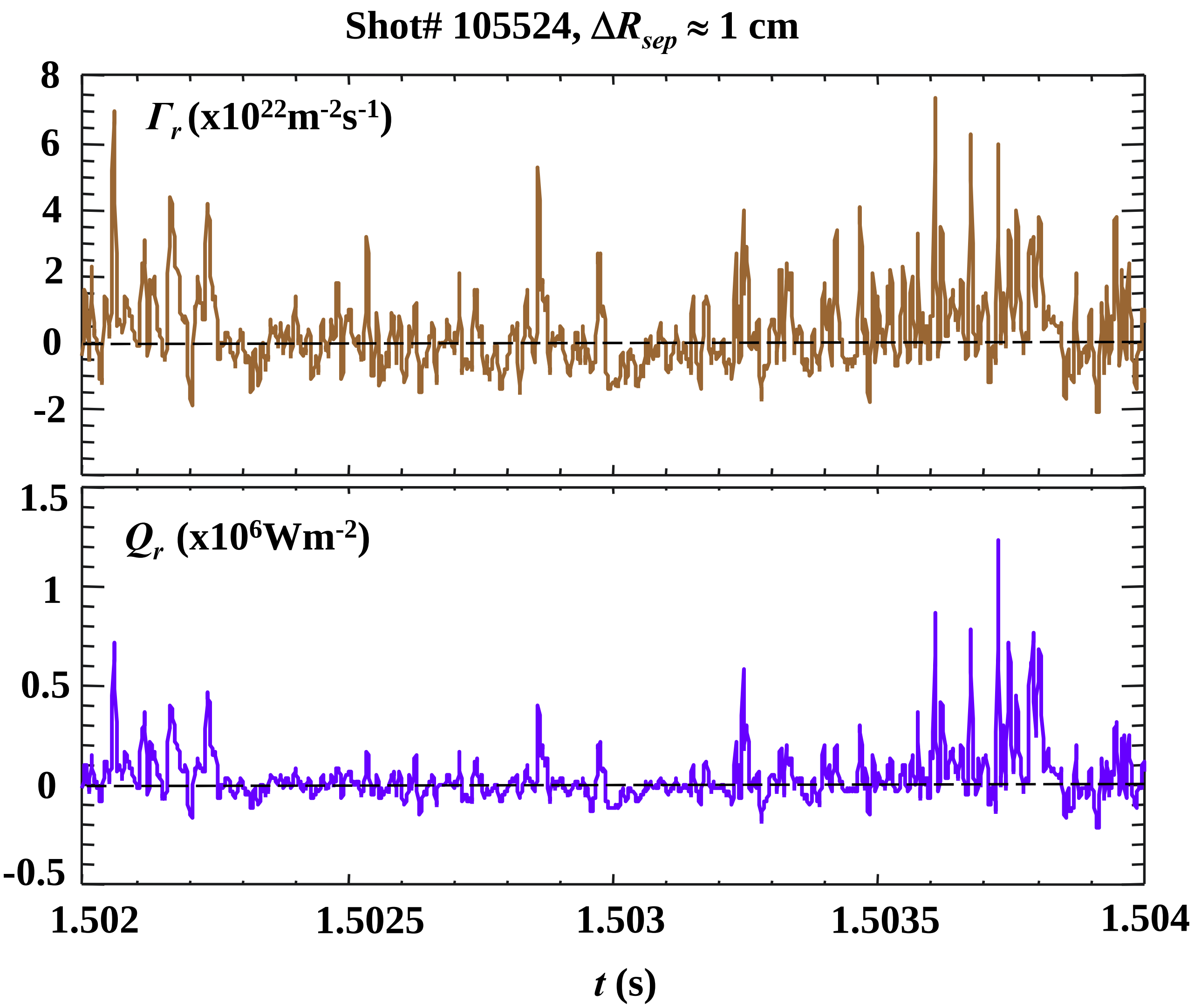
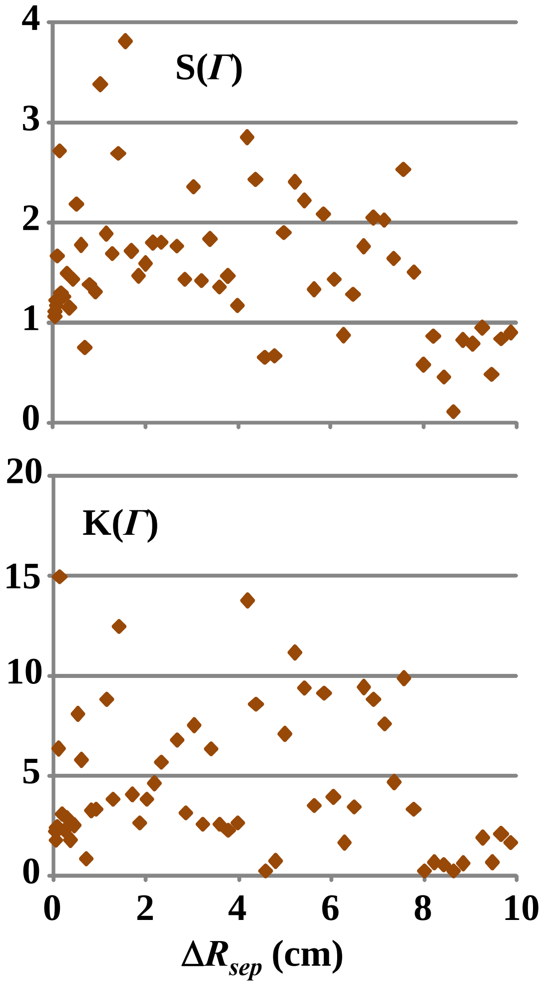
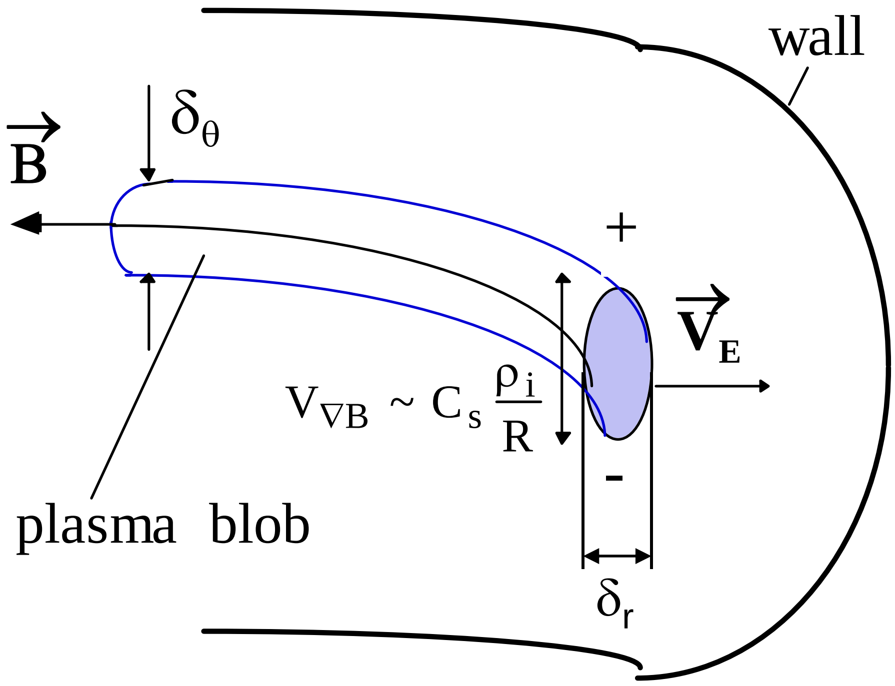
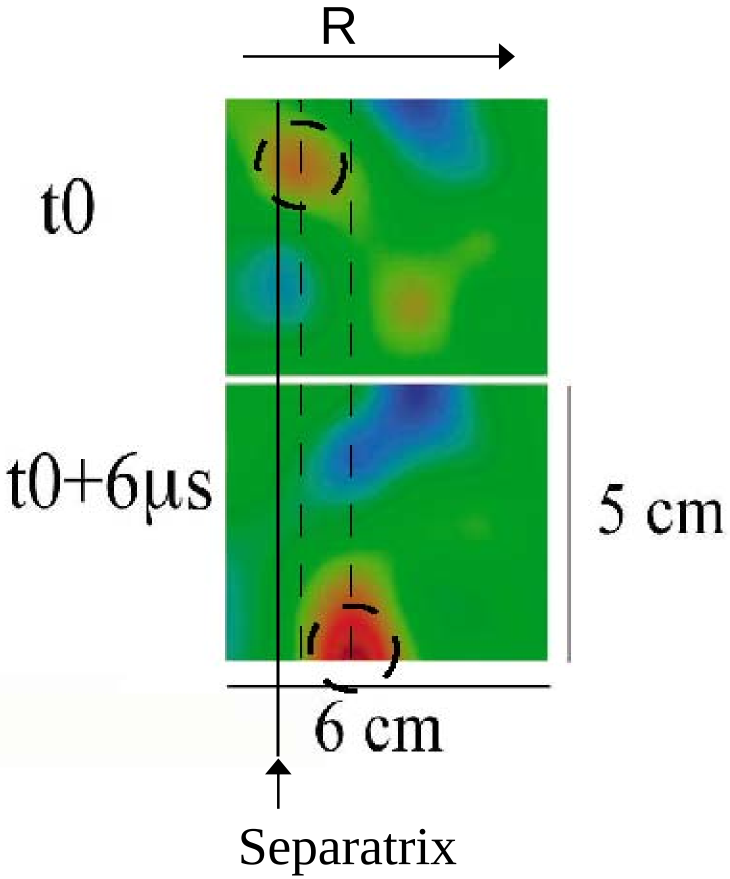
Turbulent particle and heat fluxes are strongly intermittent


Shot# 105524, $\Delta R_{sep} \approx 1$ cm



Flux bursts are caused by radially propagating plasma blobs





S. Krasheninnikov
Phys. Lett. A 283 **(**2001), 368

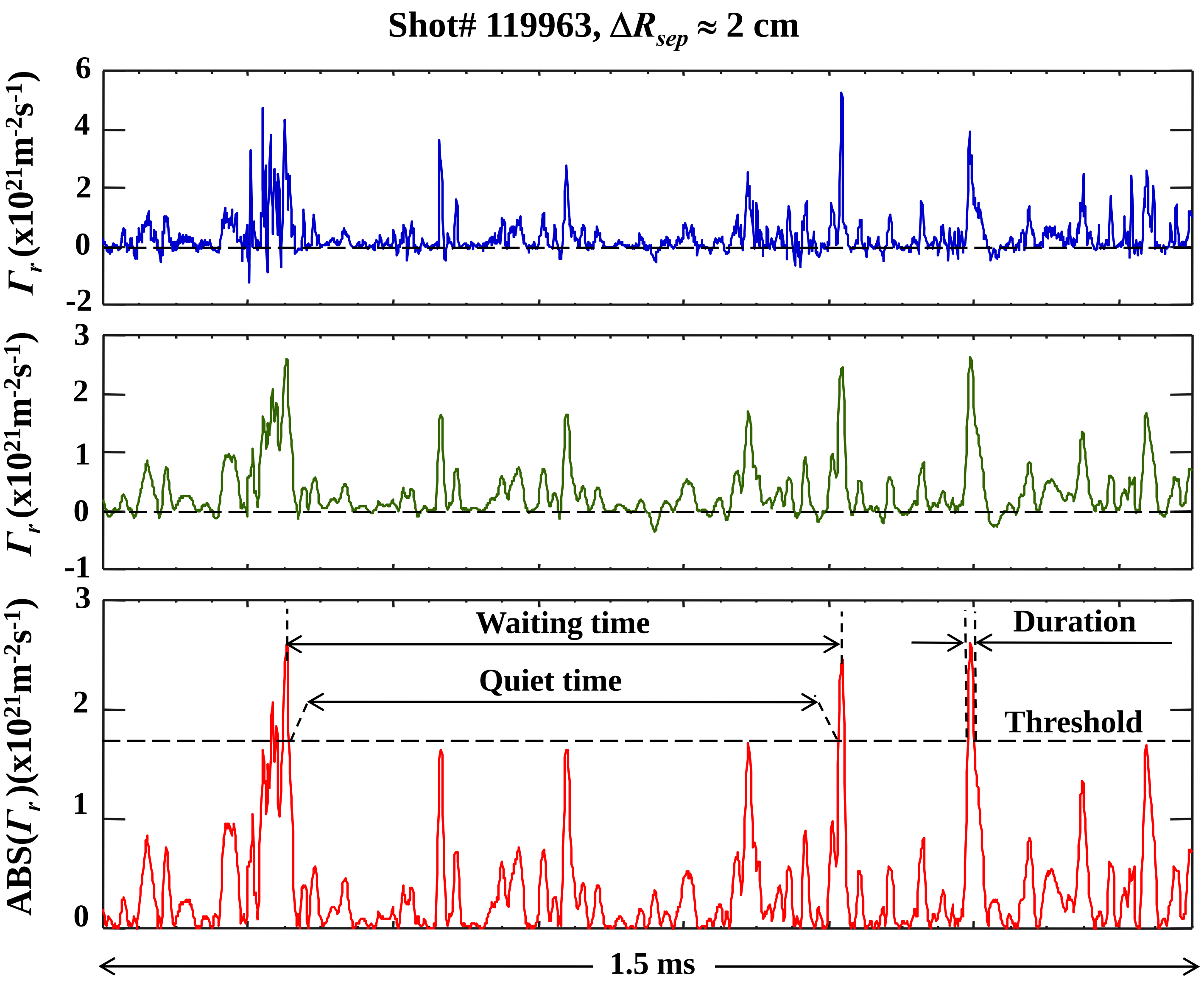
DIII-D BES data courtesy of G. McKee

- Existence of blobs is also confirmed by Gas Puff Imaging measurements in Alcator C-Mod and NSTX and passive fast camera imaging in DIII-D

Can blobs be related to SOC-like phenomena?

- Self-organized criticality (SOC) generally appears in externally driven systems in which a large disparity exists between the time scales associated with the external drive and the system response
- **SOC-like quiet time statistics were observed for turbulent fluxes just inside the separatrix in JET, W7-AX and TJ-II [R. Sanchez et al., *Phys. Rev. Lett.* 90 (2003) 185005]**
- Signals obtained with plunging probe inside of the separatrix in DIII-D don't have enough data points to perform quite time statistics analysis
- Blobs are though to be formed just inside the separatrix by some plasma instability, most likely resistive interchange [O.E. Garcia et al., Plasma Phys. Cont. Fusion 48 (2006) L1]
- Since blobs propagate through the SOL ballistically, quite time statistics of the blobs in near SOL (1-2 cm outside of the separatrix) may reflect properties of the driving instability
- **Long data records (>250,000 usable points) obtained recently with the probe array kept at a fixed radial position in the SOL allowed us to apply the analysis technique developed by Sanchez et al. to SOL fluxes in DIII-D**

Time statistics definitions



Raw particle flux

Flux smoothed over 8 points

Absolute value of smoothed flux

Following Fig. 1 from [R. Sanchez et al., *Phys. Rev. Lett.* 90 (2003) 185005]

Characterization of quite time statistics with survival functions

After [R. Sanchez et al., *Phys. Rev. Lett.* 90 (2003) 185005]

- If the number of data points is scarce, survival functions can be used instead of PDFs
- The survival function $S^q(s)$ of a quantity q gives the probability that q exceeds s
- From the experimental data, $S^q(s)$ is constructed by sorting all recorded values of q in decreasing order $T \equiv \{q_j , j = 1, 2, . . . , N\}$; then a rank number is assigned to each distinct value in T, q^*_k, by using $r_k = r_{k-1} + n_k$, where n_k is the number of appearances of q^*_k and $r_0 = 0$
- The survival function is then given by $S^q(q^*_k) = r_k / r_N$
- Survival function is related to the PDF by $p_q(s) = - dS^q(s)/ds$
- Survival function carries the same information as PDF, exhibiting exponential or power-law behavior only if the PDF does.
- To construct survival functions flux signals are conditioned:
  - ✓ Signals are smoothed over 8 points to eliminate faster local fluctuations
  - ✓ Varying event duration thresholds are applied to the flux signals

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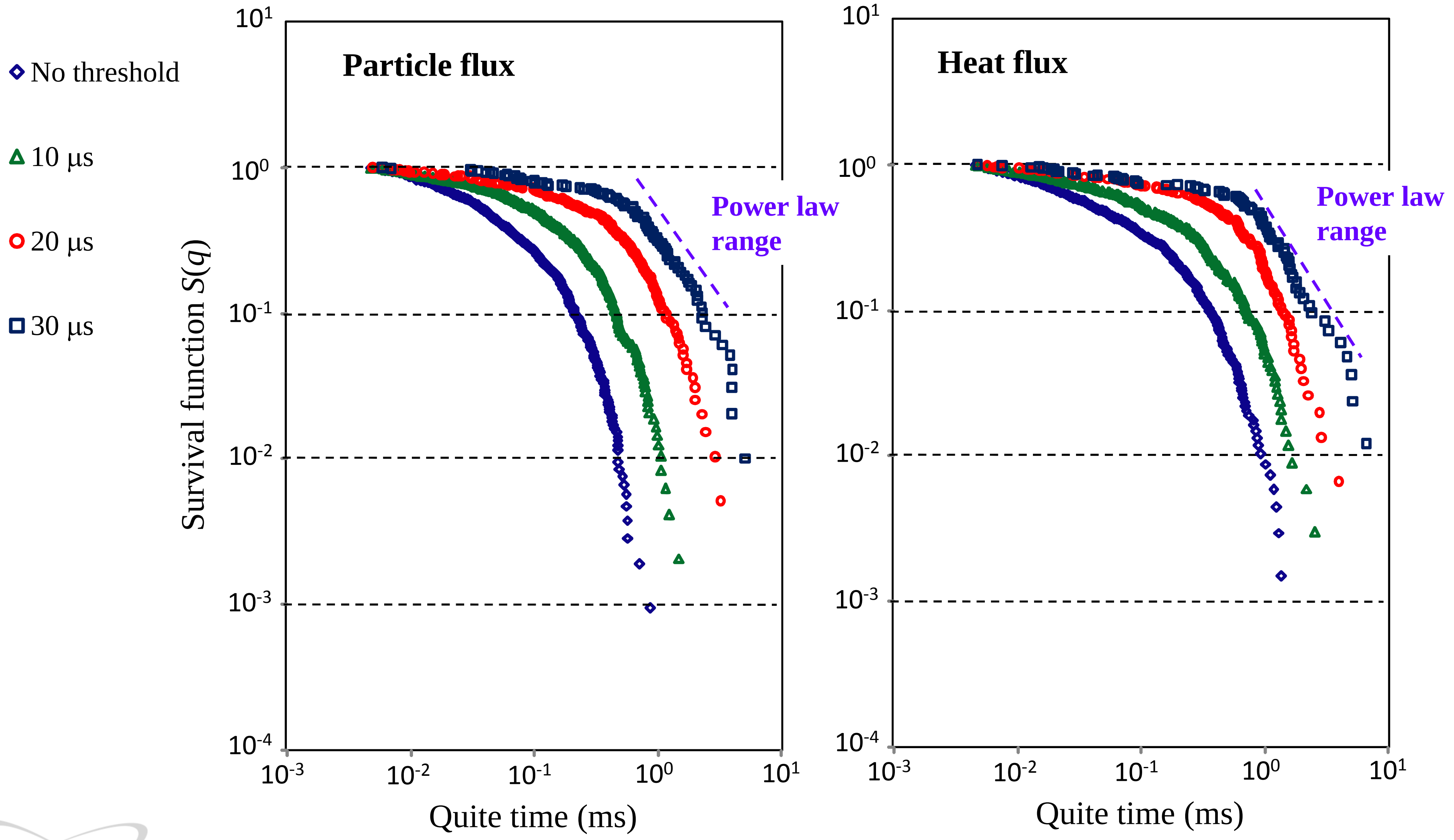
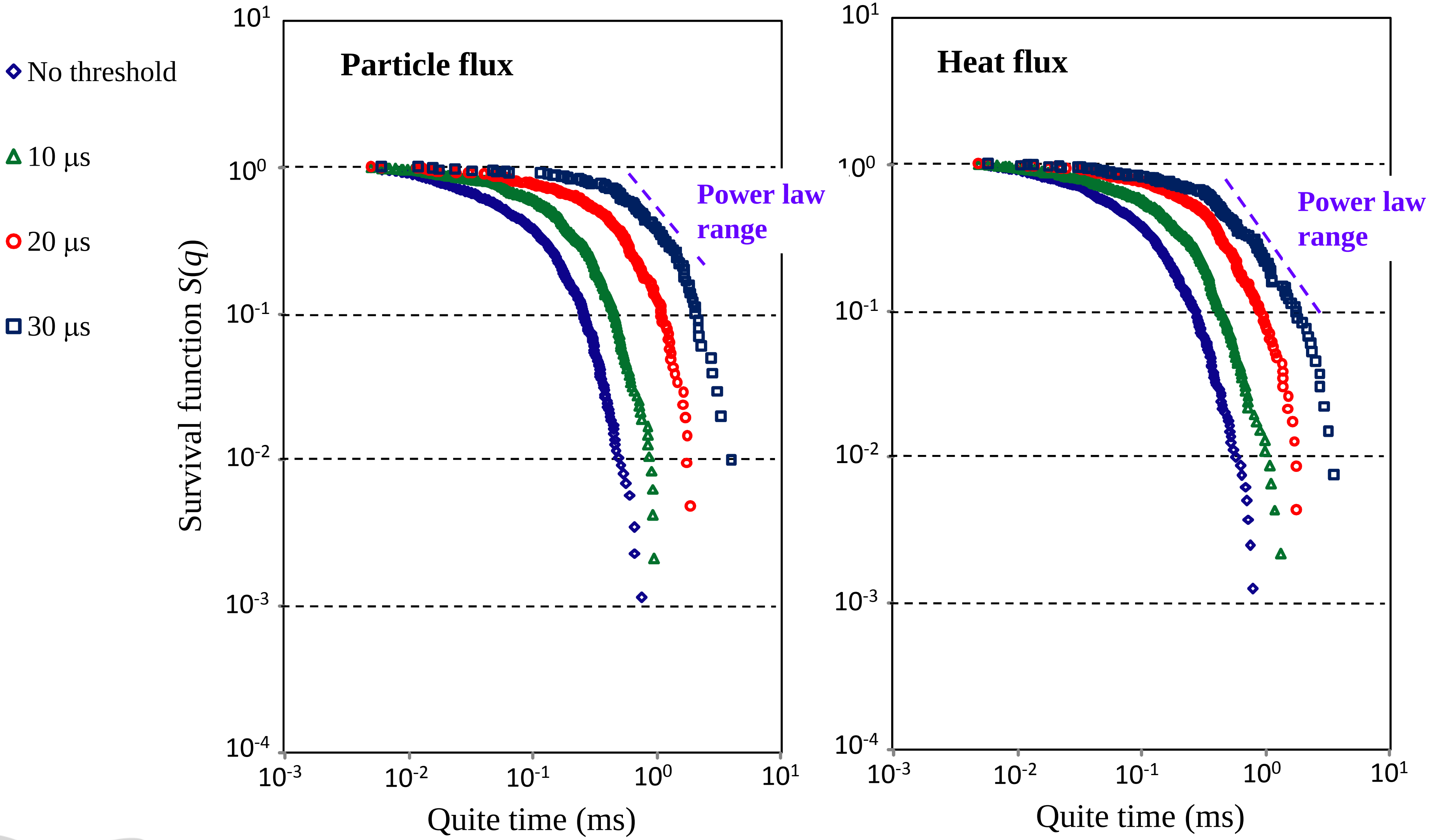
Power law range emerges when only bursts with duration of > 20 μs are considered

High density LSN L-mode, shot # 120710, $\langle n_e \rangle \approx 4.6\times10^{19}$ m^{-3}, $f_{Gw}\sim 0.43$, $\Delta R_{sep} \approx 2.5$ cm



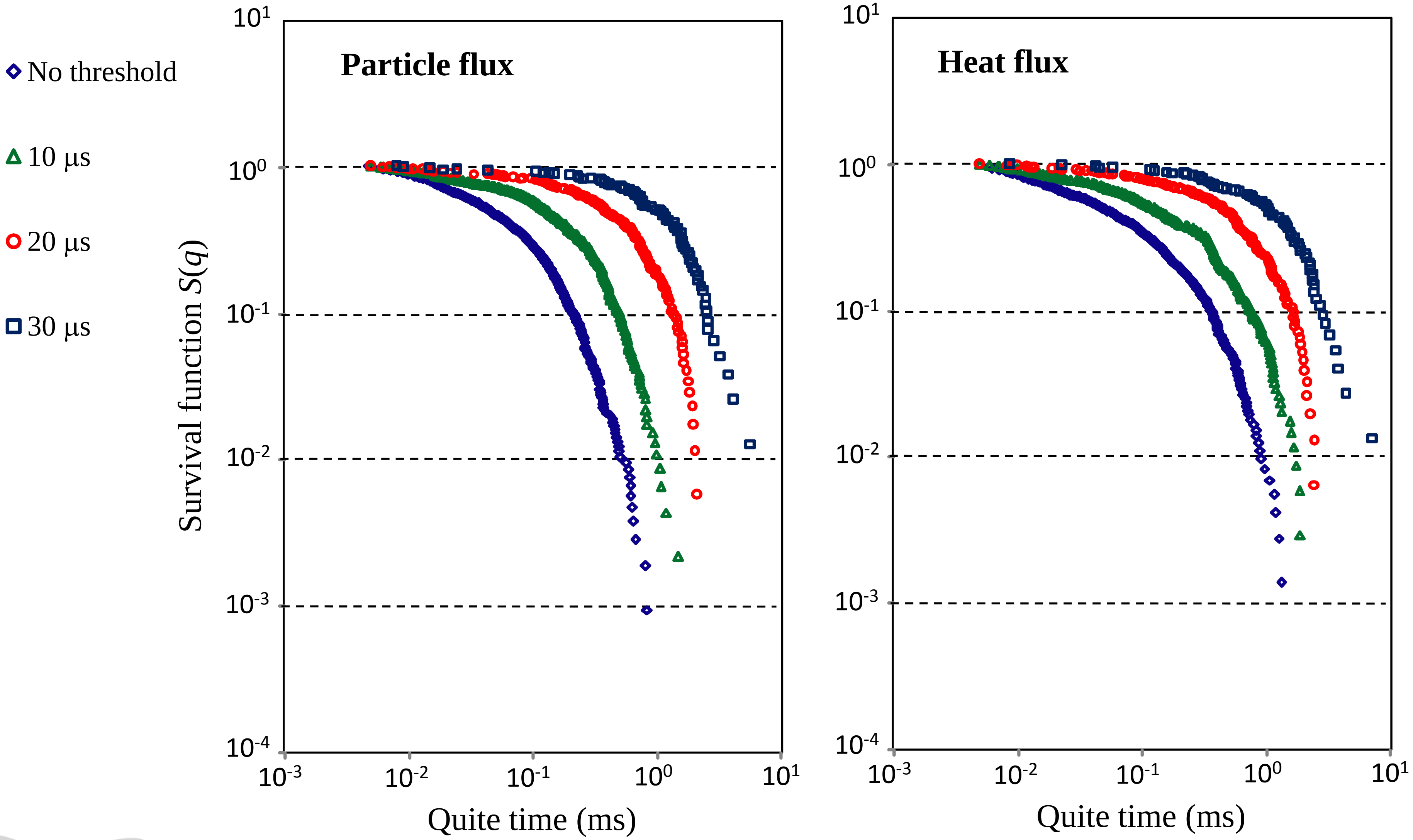
Power law range is observed in both high and low density L-mode discharges ...

Lower density LSN L-mode, Shot# 125281, $\langle n_e \rangle \approx 2.6\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.24$, $\Delta R_{sep} \approx 2.3$ cm



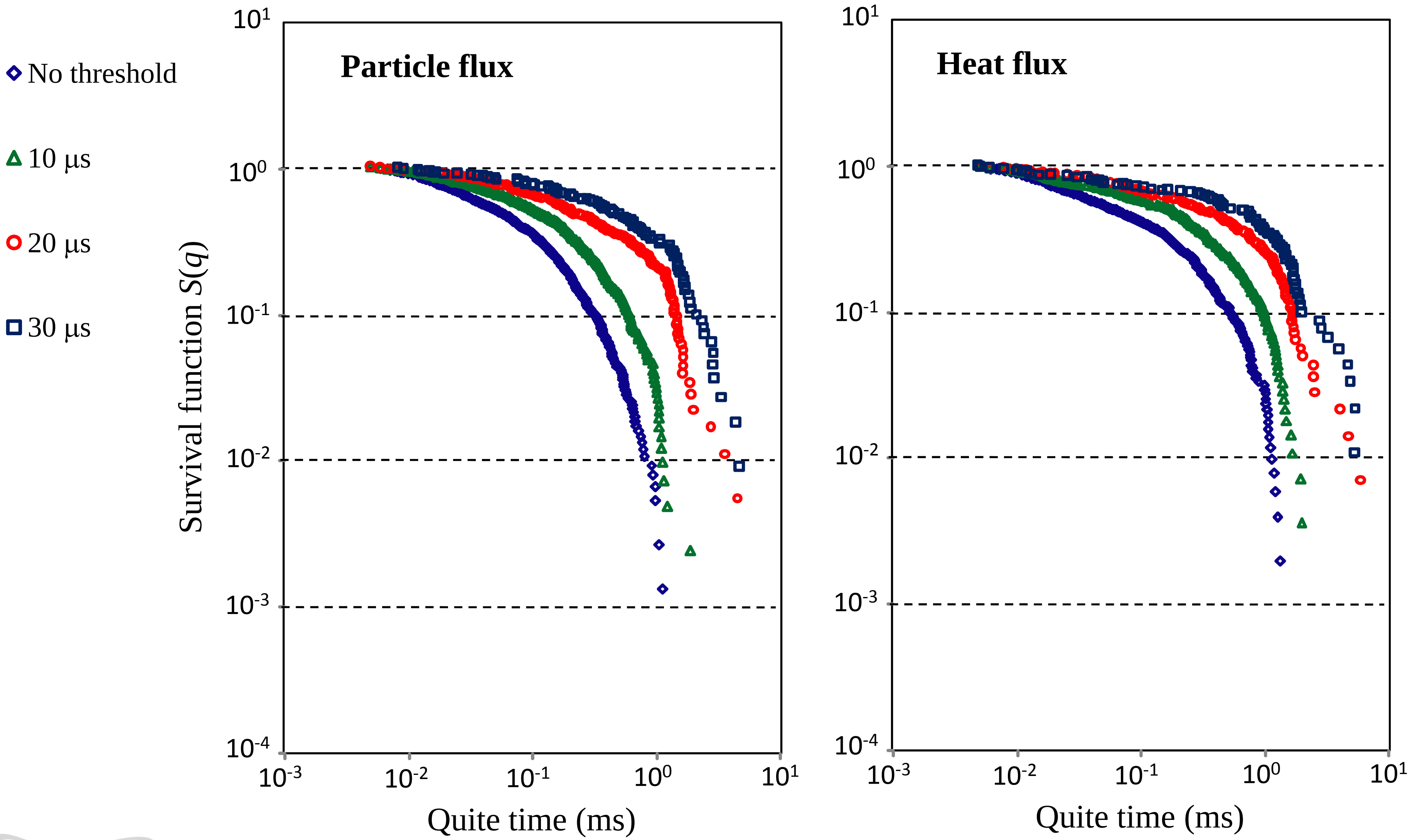
… though it’s not always clearly pronounced …

High density LSN L-mode, Shot# 119963, $\langle n_e \rangle \approx 4.6\times10^{19}\ \mathrm{m}^{-3}$, $f_{Gw} \sim 0.43$, $\Delta R_{sep} \approx 2$ cm



… particularly in far SOL

High density LSN L-mode, shot # 119960, $\langle n_e \rangle \approx 4.6\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.43$, $\Delta R_{sep} \approx 5$ cm



Summary

- SOL fluctuation levels in DIII-D L-mode SOL increase with the average discharge density
- Density and temperature fluctuations and fluxes in the SOL are strongly intermittent in time and space.
- Intermittent flux bursts are caused by radially propagating plasma blobs whose existence is proved by optical imaging
- Quite time statistics of the near SOL particle and heat fluxes show some indication of self-similar behavior
- Further analysis is needed
- **This is work in progress, your comments and suggestions for future work are most welcome!**