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Roland Sabot, Luigui Salazar, Stéphane Heuraux, A. Krämer-Flecken, Alberto Gallo, et al.. Systematic analysis of turbulence: component extraction of the density fluctuations and study of their dynamics for different regimes. 29th IAEA Fusion Energy Conference (FEC 2023), Oct 2023, Londres, United Kingdom. cea-04566218

**HAL Id: cea-04566218**

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Submitted on 2 May 2024

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# SYSTEMATIC ANALYSIS OF TURBULENCE: COMPONENT EXTRACTION OF THE DENSITY FLUCTUATIONS AND STUDY OF THEIR DYNAMICS FOR DIFFERENT REGIMES

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## Introduction

**Data driven approach:** database digging for systematic analysis of experiments → trend, universality

Two approaches to reduce the dimensionality of density fluctuation measurements → database

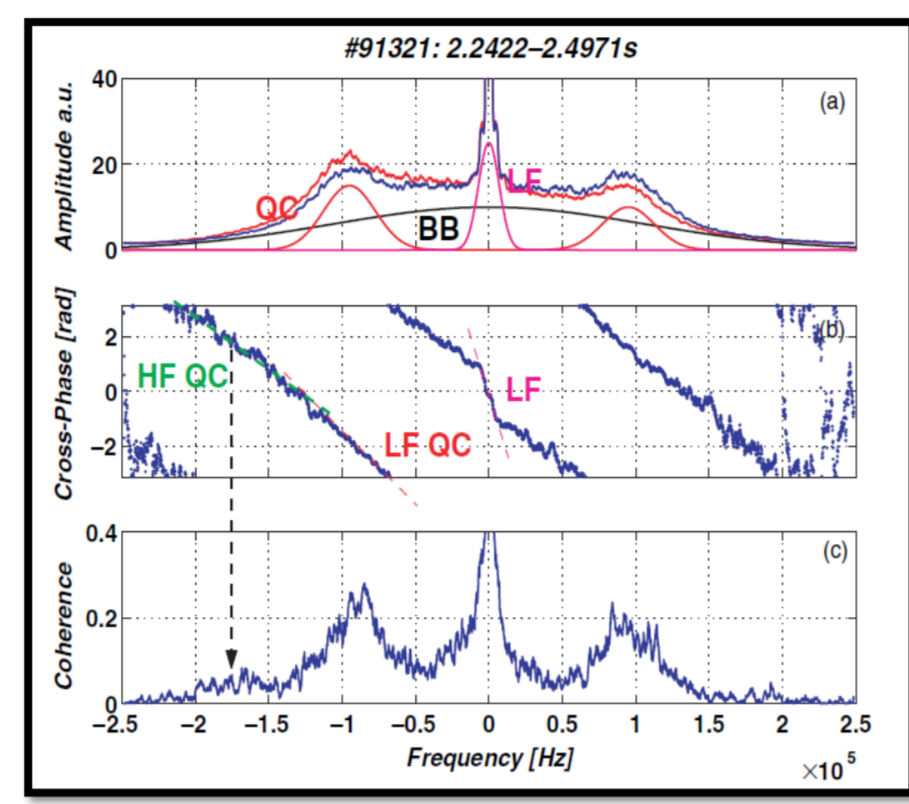
- **Parametrization:** the reflectometry frequency spectrum is reduced 3 components [Sun 18 & 19]
- **Component extraction** by combining signal processing with machine learning [Salazar 22 & 23]

Both rely on the decomposition of the frequency spectrum in components.

## Reflectometry spectrum components

Using correlation reflectometry, the frequency spectrum was shown to be the superposition of several components [Vershkov04, A. Krämer-Flecken05]:

- **Low Frequency (LF) components**
- **quasi coherent modes (LFQC & HFQC)**
- **broadband component (BB)**
- Noise level
- + MHD modes



(a) Amplitude, (b) cross-phase and (c) coherency spectra for an Ohmic plasma [Krämer-Flecken04]

## Turbulence in LOC and SOC regimes

### Parametrization method

The frequency spectrum is fitted by **3 components**:

- narrow ( $\pm 1$  kHz) wavecarrier (DC): Gaussian
- low frequency ( $\pm 10$  kHz) fluctuations (LF): Gaussian
- The BB is fitted by the Taylor function (Hennequin99) or generalized Gaussian: 4 parameters
- + noise level = 11 parameters

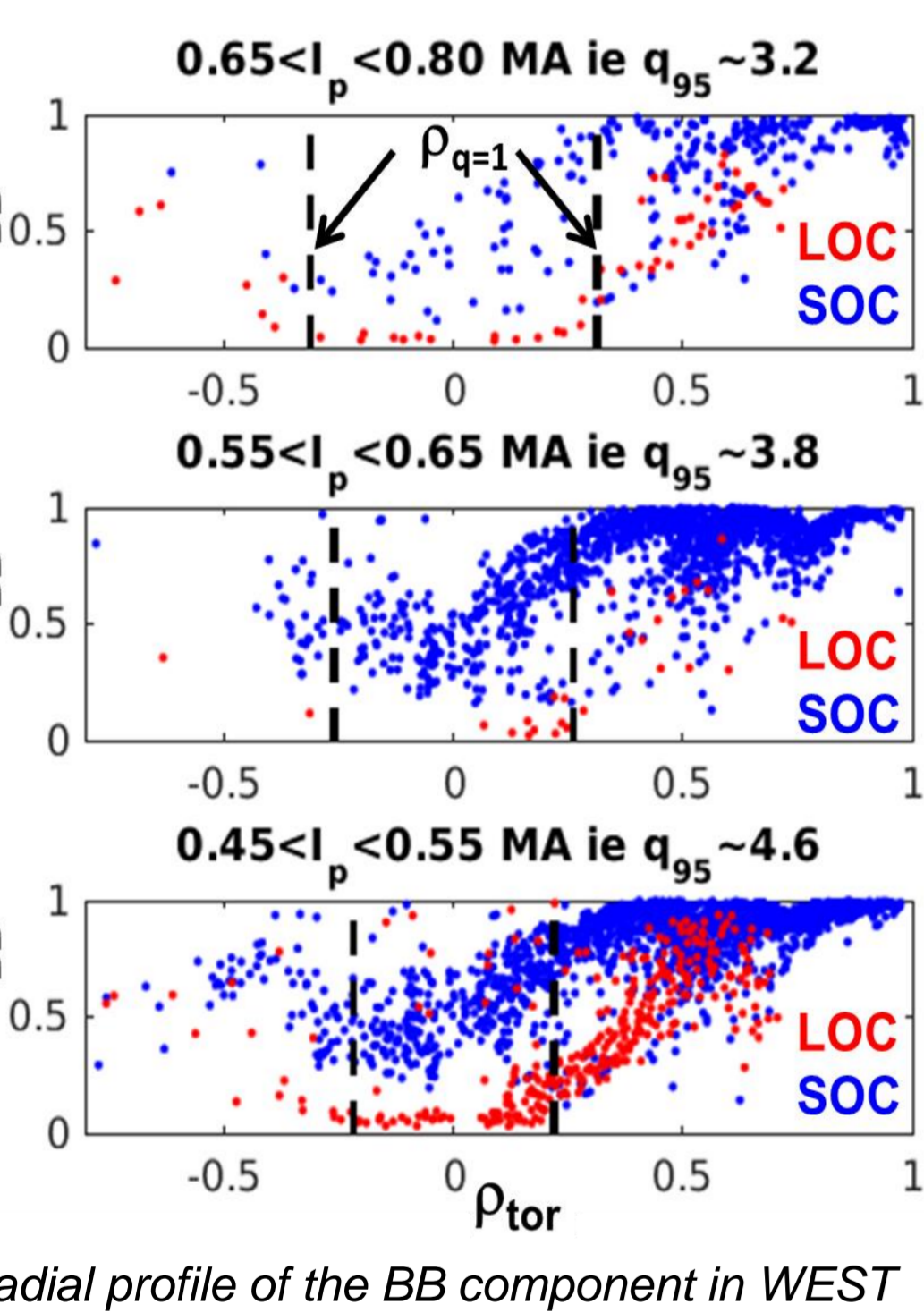
#### Assumptions:

- ad-hoc separation of components
- Narrow modes like quasi-coherent modes neglected
- Stationarity during the measurement (frequency spectrum)

**Tore Supra Database:** 300 000 spectra from 6000 discharges } Core X-mode reflectometer [Sabot06]

**WEST Database:** 75 000 spectra from 800 discharges }

## Radial evolution of the BB contribution in Ohmic regimes



radial profile of the BB component in WEST

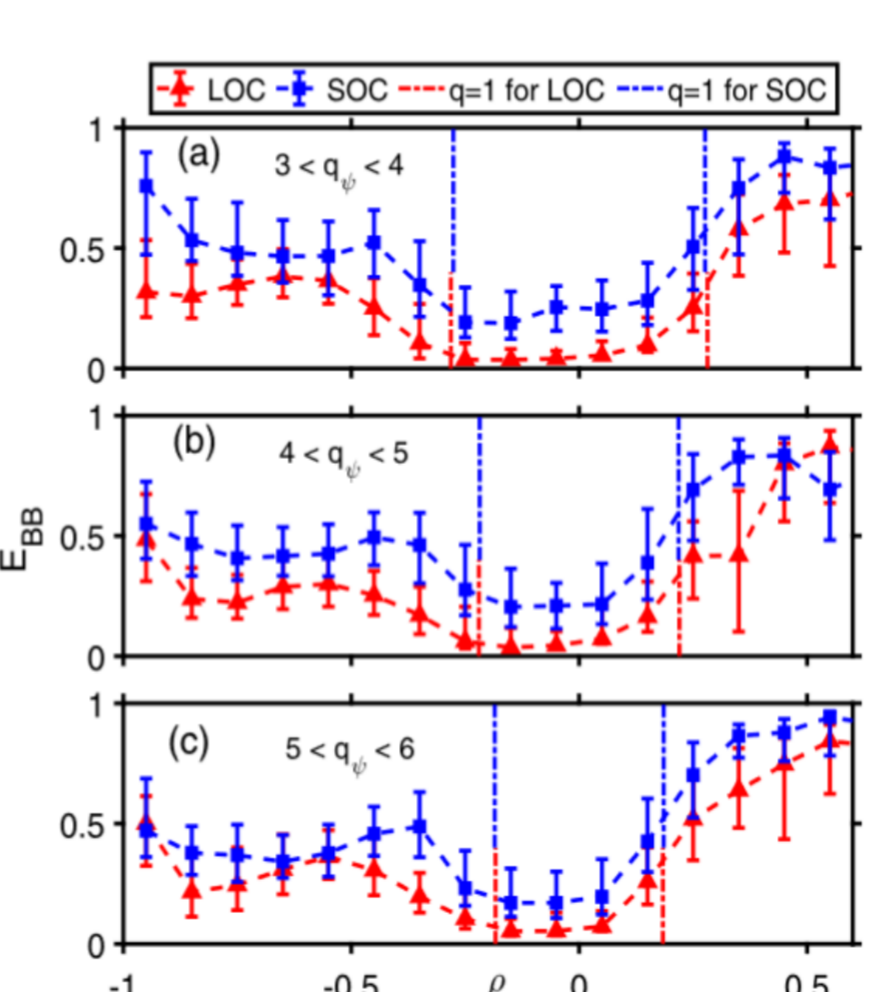
### LOC-SOC critical density $n_e^{crit}$

• WEST:  $n_e^{crit} = 5.3 I_p$  (from Ostuni22 reduced database)

• Tore Supra:  $n_e = 2.6 I_p$  [Sun 19]

#### LOC-SOC discrimination

- LOC:  $n_e < 0.9 n_e^{crit}$
- SOC:  $n_e > 1.1 n_e^{crit}$
- Threshold  $0.9 n_e^{crit} < n_e < 1.1 n_e^{crit}$



BB component in Tore Supra, Sun 19

$E_{BB}$  in SOC > in LOC over the whole cross section for all  $q_{\rho}$   
 $E_{BB}$  very low inside  $q=1$  in LOC, shallower basin in SOC in WEST  
 Beyond  $q=1$  on LFS in SOC, most spectrum energy is in the BB

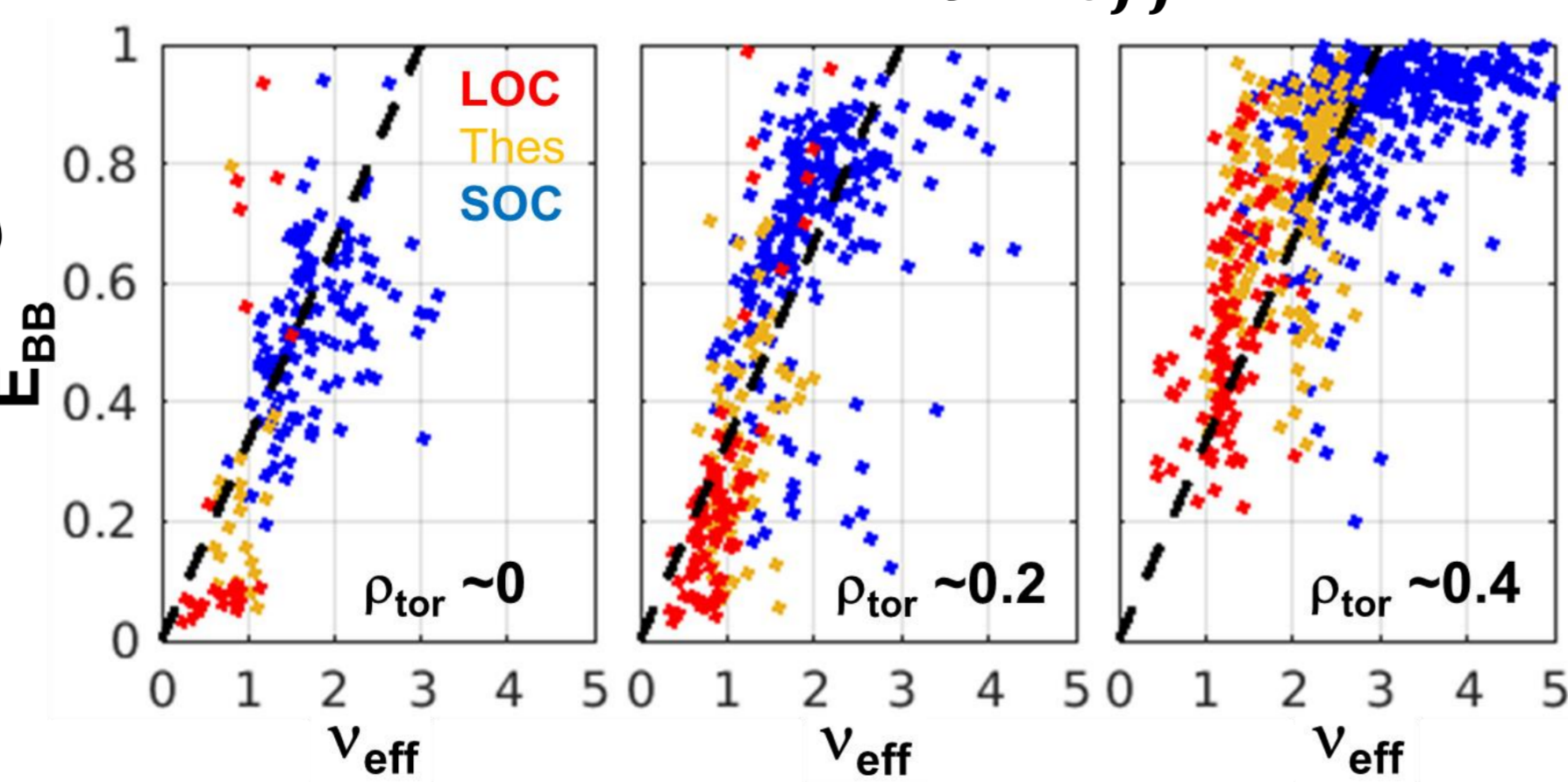
## BB contribution with the effective collisionality $\nu_{eff}$

Similar linear evolution inside & outside  $q=1$

$$E_{BB} \sim \frac{1}{3} \nu_{eff} (\nu_{eff} \sim 1.2 R \nu_{eff} n_e T_e^{-2} \text{ [Angioni03]})$$

while  $\langle E_{BB} \rangle$  increases with  $\rho$

- $\rho \sim 0 \rightarrow \langle E_{BB}^{LOC} \rangle \sim 0.1$  ( $E_{BB}^{Thres} \sim 0.2$ )
- $\rho \sim 0.2 \rightarrow \langle E_{BB}^{LOC} \rangle \sim 0.2$  ( $E_{BB}^{Thres} \sim 0.4$ )
- $\rho \sim 0.4 \rightarrow \langle E_{BB}^{LOC} \rangle \sim 0.6$  ( $E_{BB}^{Thres} \sim 0.7$ )



$E_{BB}$  values for  $\nu_{eff} \sim 1$  similar across the plasma core whereas  $\langle E_{BB}^{Thres} \rangle$  increases with  $\rho$   
**LOC-SOC transition is global phenomena but turbulence depends on local parameters**

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## Quasi-coherent modes

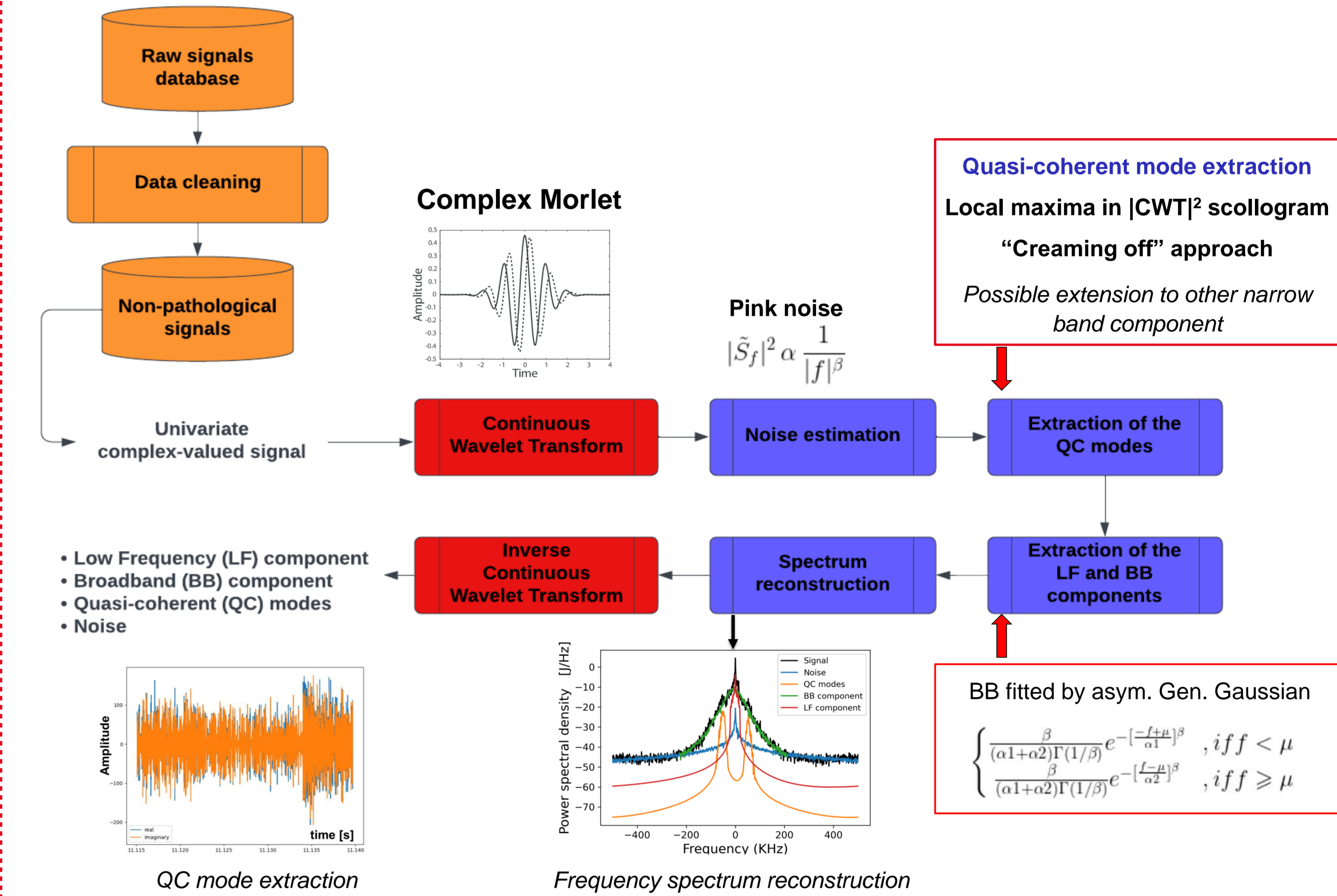
Experiment analysis of several devices and gyrokinetic simulations showed the QC mode are associated to TEM (Trapped Electron Mode) dominated regimes like LOC [Arnichand 14, Hacquin 16, Citrin 17].

## Components extraction method

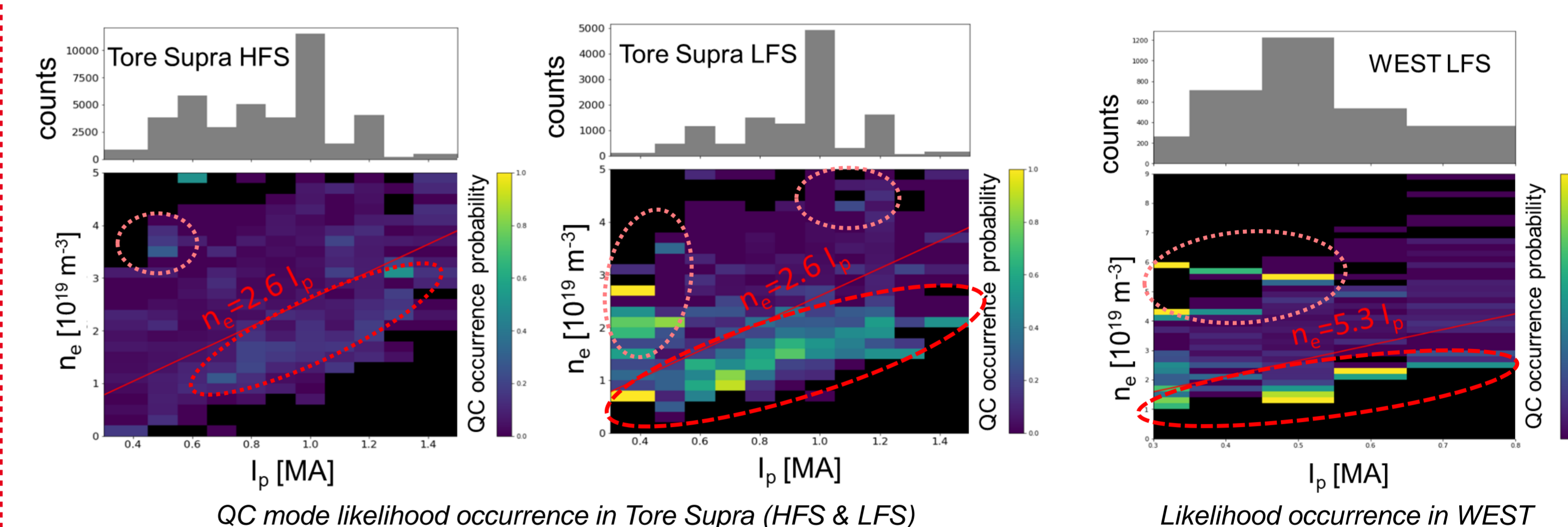
The method born out of the necessity to remove the limitation of the parametrization method:

- Shift from ad-hoc component separation to automatic identification
- Enabling the extraction of neglected components as the QC modes
- Transition from averaged spectrum to instantaneous quantities

Advanced Signal Processing & Machine Learning

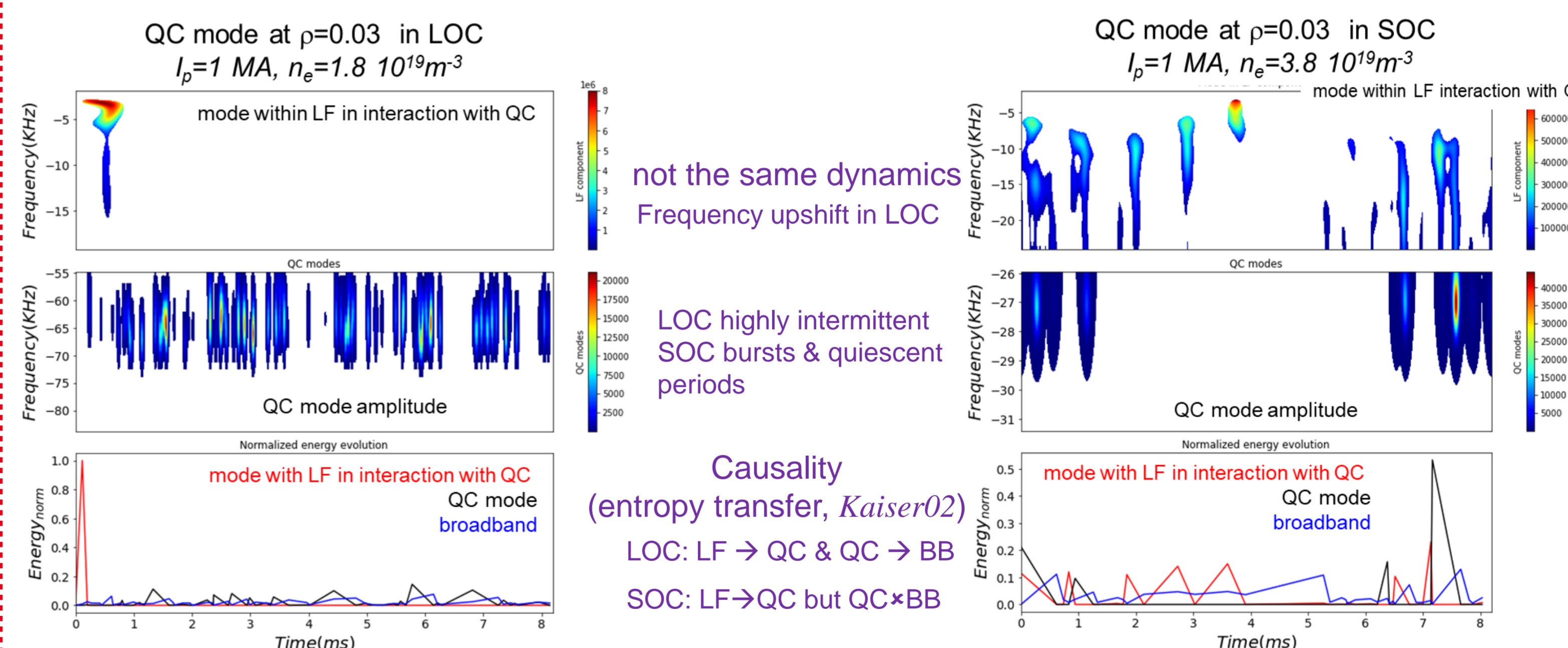


## Likelihood occurrence of quasi-coherent modes



- QC overwhelmingly observed on the LFS below LOC-SOC threshold
- 2 clusters in SOC regime on LFS: at low current & moderate density & high current, high density
- Occurrence likelihood on HFS low in LOC and SOC regimes

## Interactions between QC modes and other modes



Multi-machines, multi-magnetic configurations (Tore Supra, WEST, Textor, W7X) studies have consistently demonstrated the common occurrence of LF component bursts preceding QC generation [Salazar23, Krämer-Flecken23]

## Main results :

- ✓ Profile evolution of the BB contribution in LOC and LOC
- ✓ BB turbulence more dependent on local parameters than global Ohmic confinement regime
- ✓ Expected cluster QC mode below the LOC-SOC threshold confirm the link with LOC and TEM
- ✓ Time-dependent methods have revealed evidence of transient energy exchange
- ✓ Observation of energy exchange among components has provided evidence of causal links among them
- ✓ Different properties of LOC QC modes (intermittency, energy transfer) require further investigations