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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]

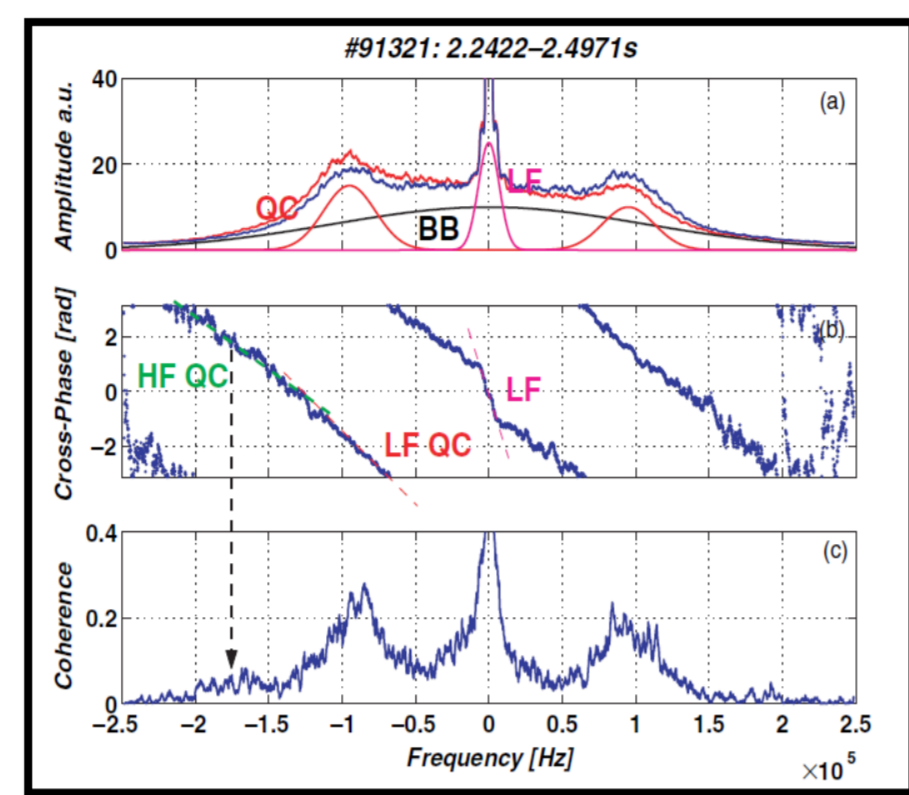
Both rely on the decomposition of the frequency spectrum in components.

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) coherence spectra for an Ohmic plasma [Krämer-Flecken04]

Turbulence in LOC and SOC regimes

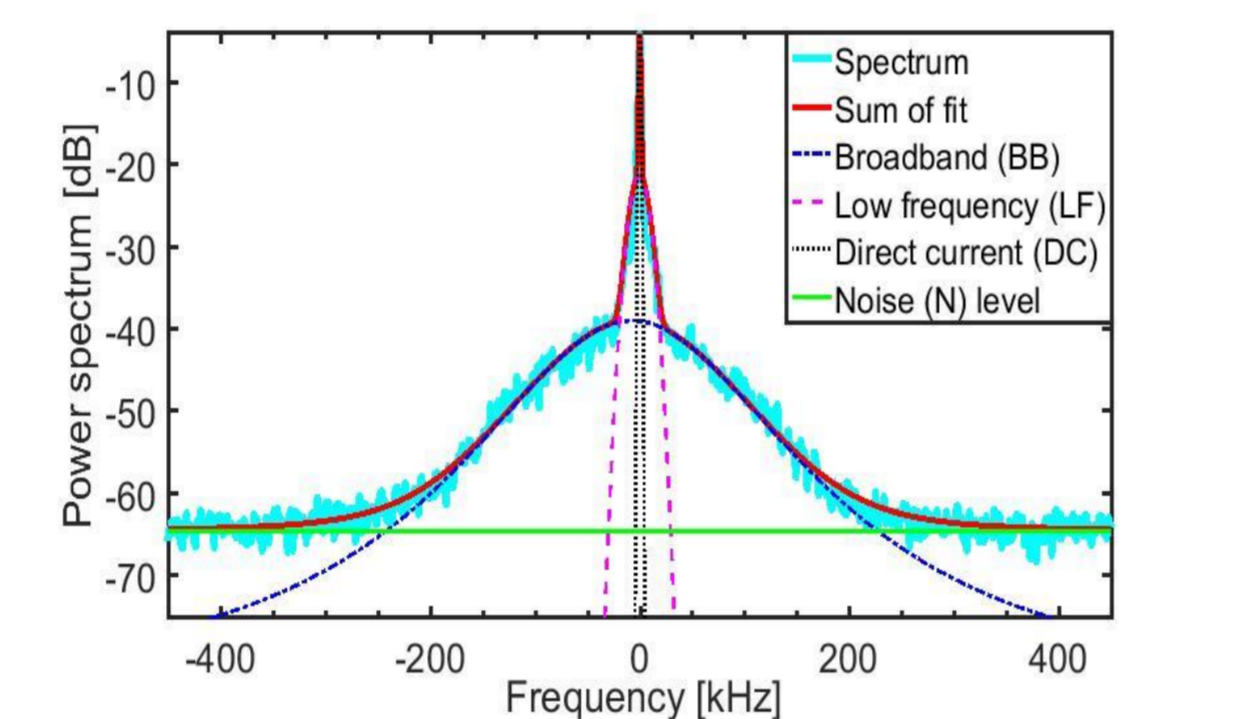
Parametrization method

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

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

Assumptions:

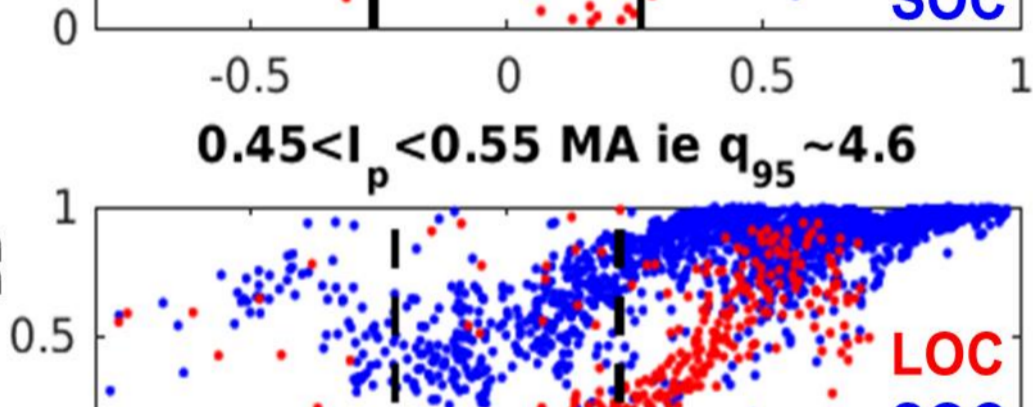
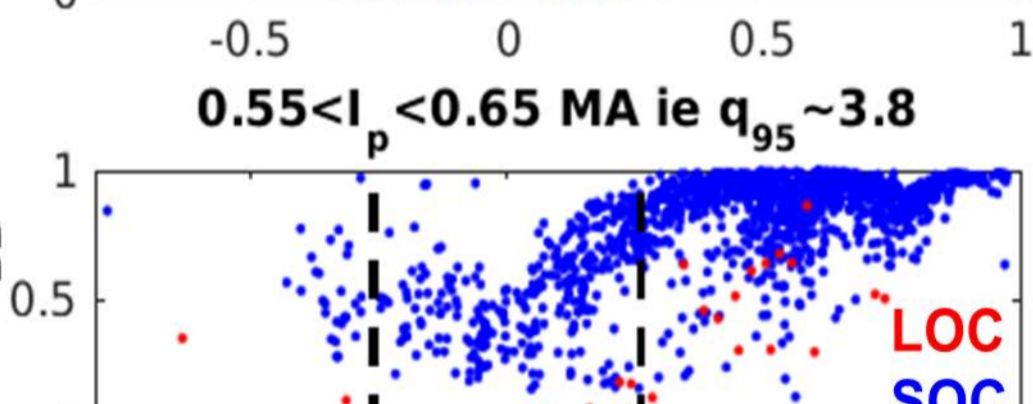
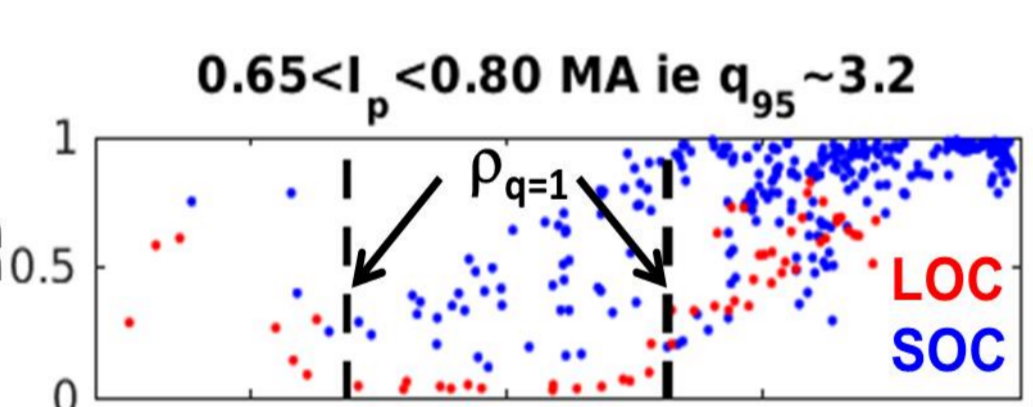
- ad-hoc separation of components
- Narrow modes like quasi-coherent modes neglected
- Stationarity during the measurement (frequency spectrum)



Frequency spectrum and fitting components [Sun18]

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

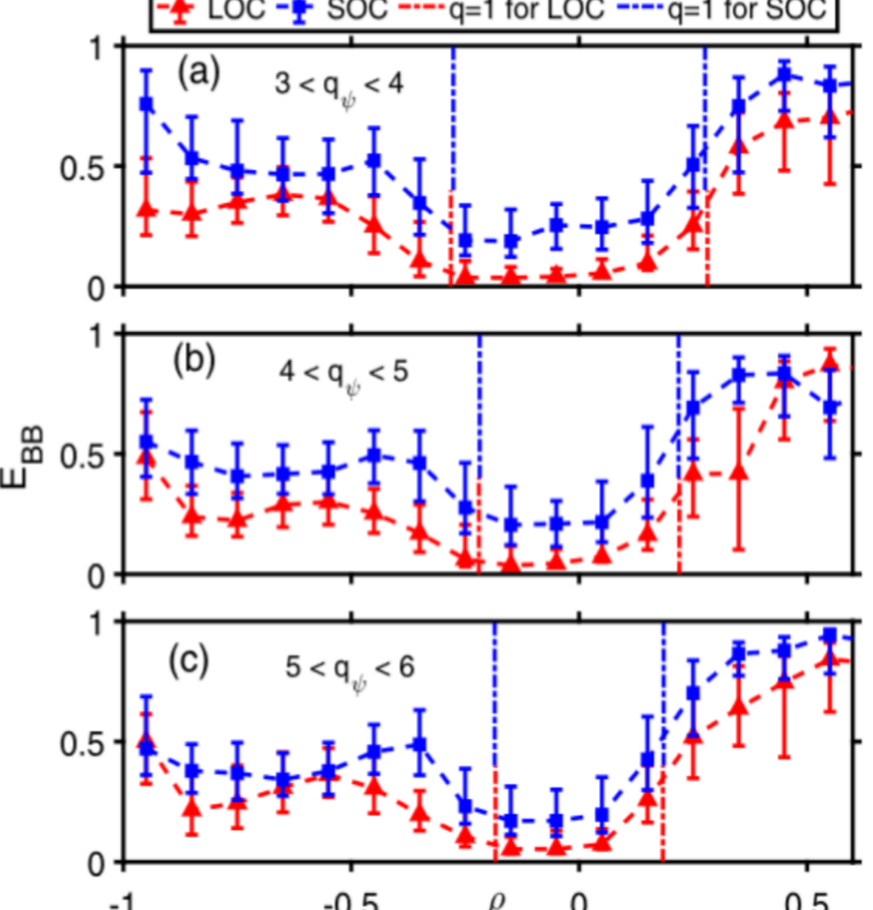
LOC-SOC critical density n_e^{crit}

• 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, Sun19

E_{BB} in SOC > in LOC over the whole cross section for all q_{ρ}
 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

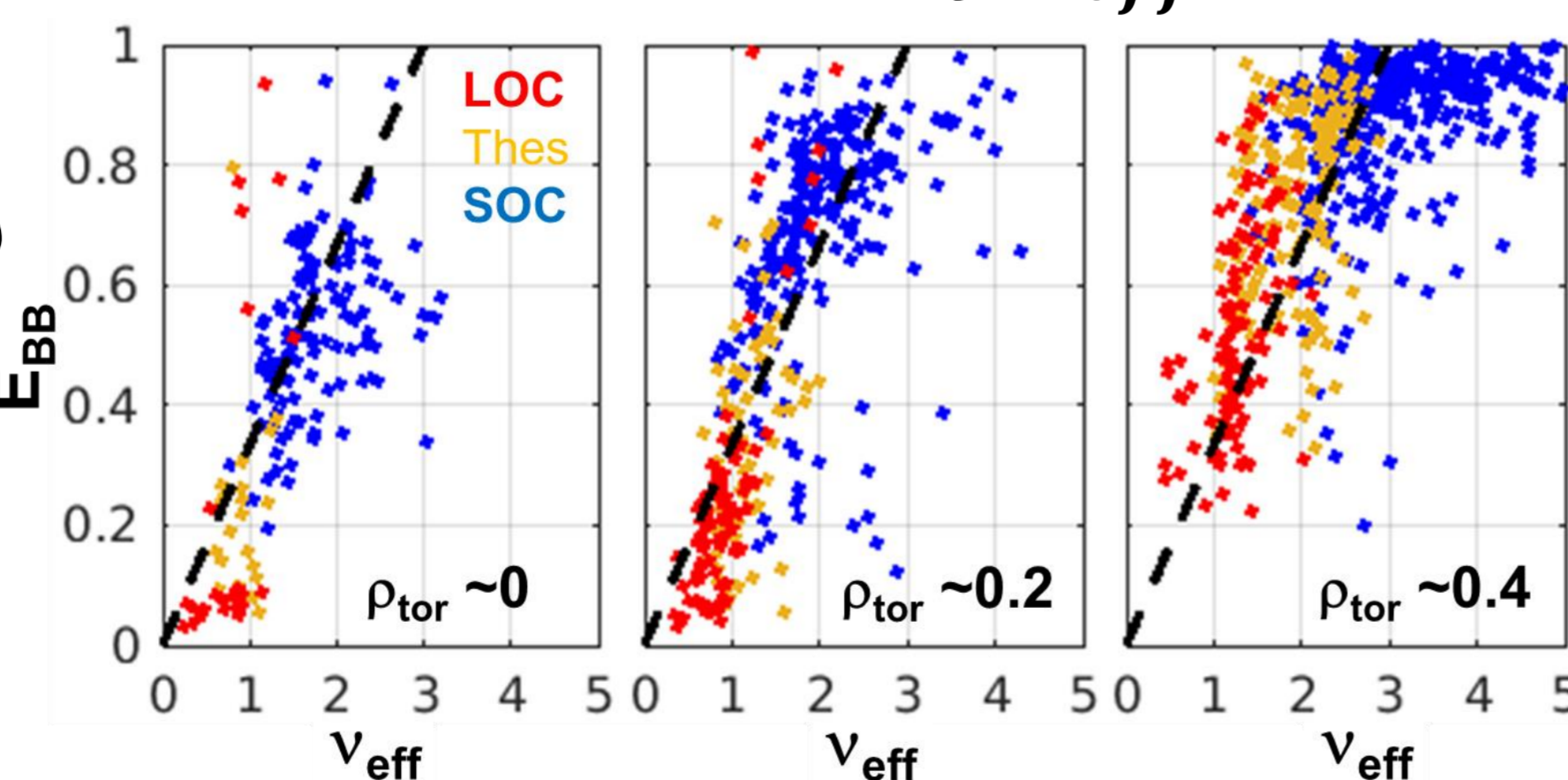
BB contribution with the effective collisionality ν_{eff}

Similar linear evolution inside & outside $q=1$

$$E_{BB} \sim \frac{1}{3} \nu_{eff} (\nu_{eff} \sim 1.1 R Z_{eff} n_e T_e^{-2} \text{ [Angioni03]})$$

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

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



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

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Quasi-coherent modes

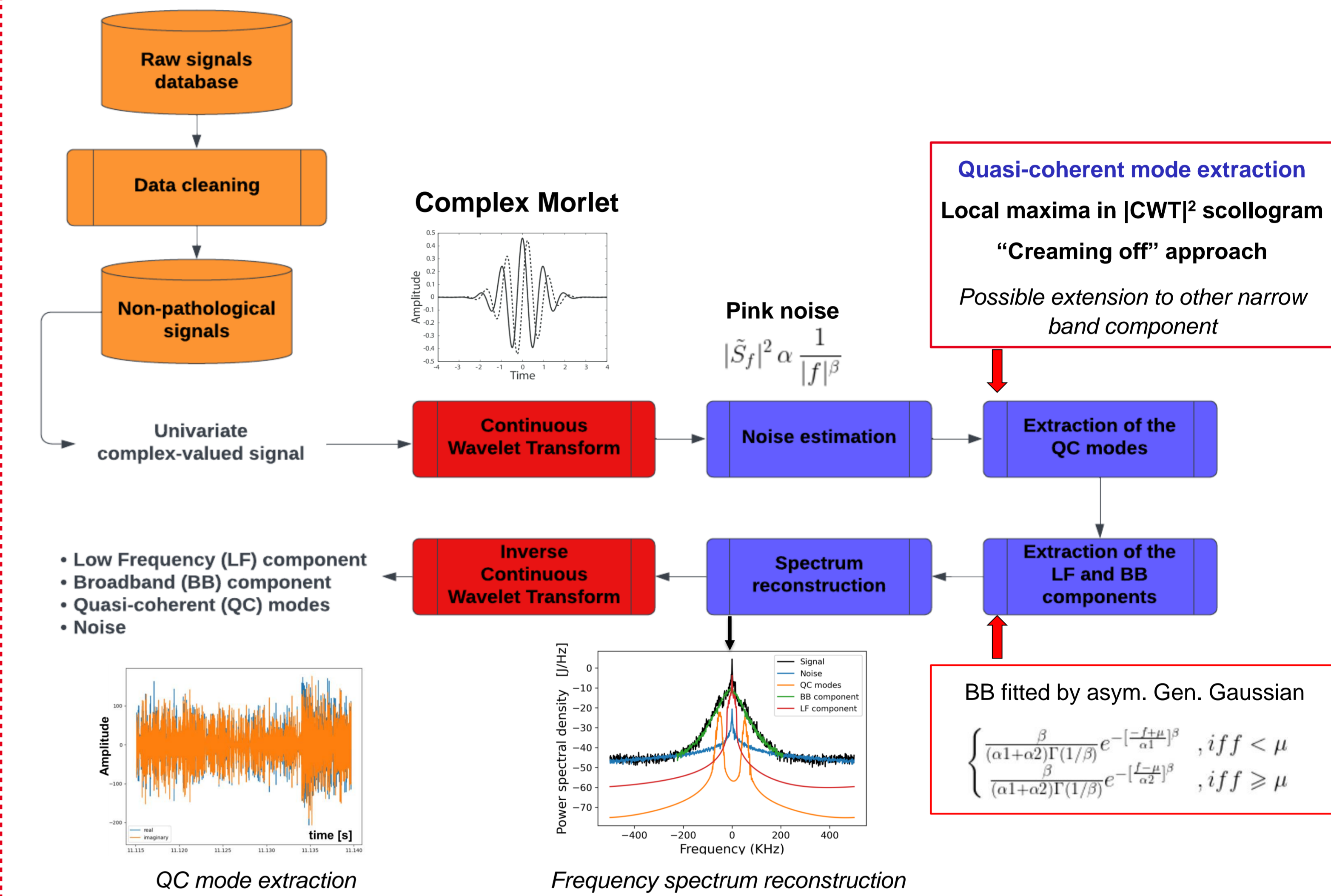
Experiment analysis of several devices and gyrokinetic simulations showed the QC mode are associated to TEM (Trapped Electron Mode) dominated regimes like LOC [Arnichand 14, Hacquin 16, Citrin 17].

Components extraction method

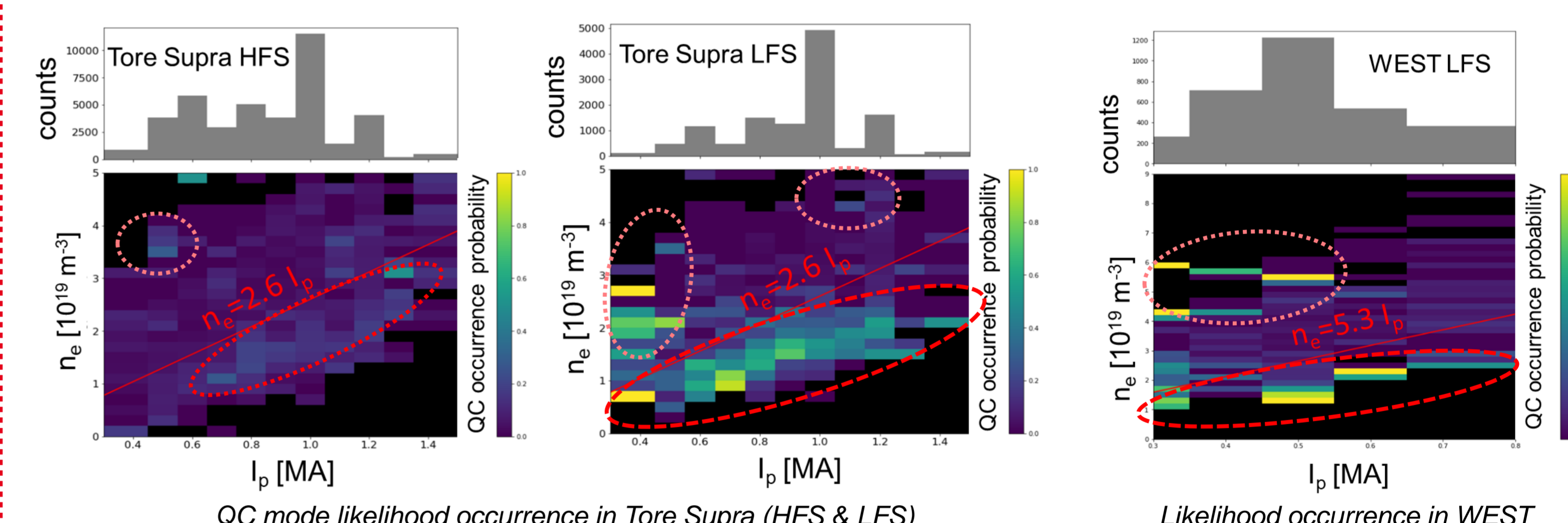
The method born out of the necessity to remove the limitation of the parametrization method:

- 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

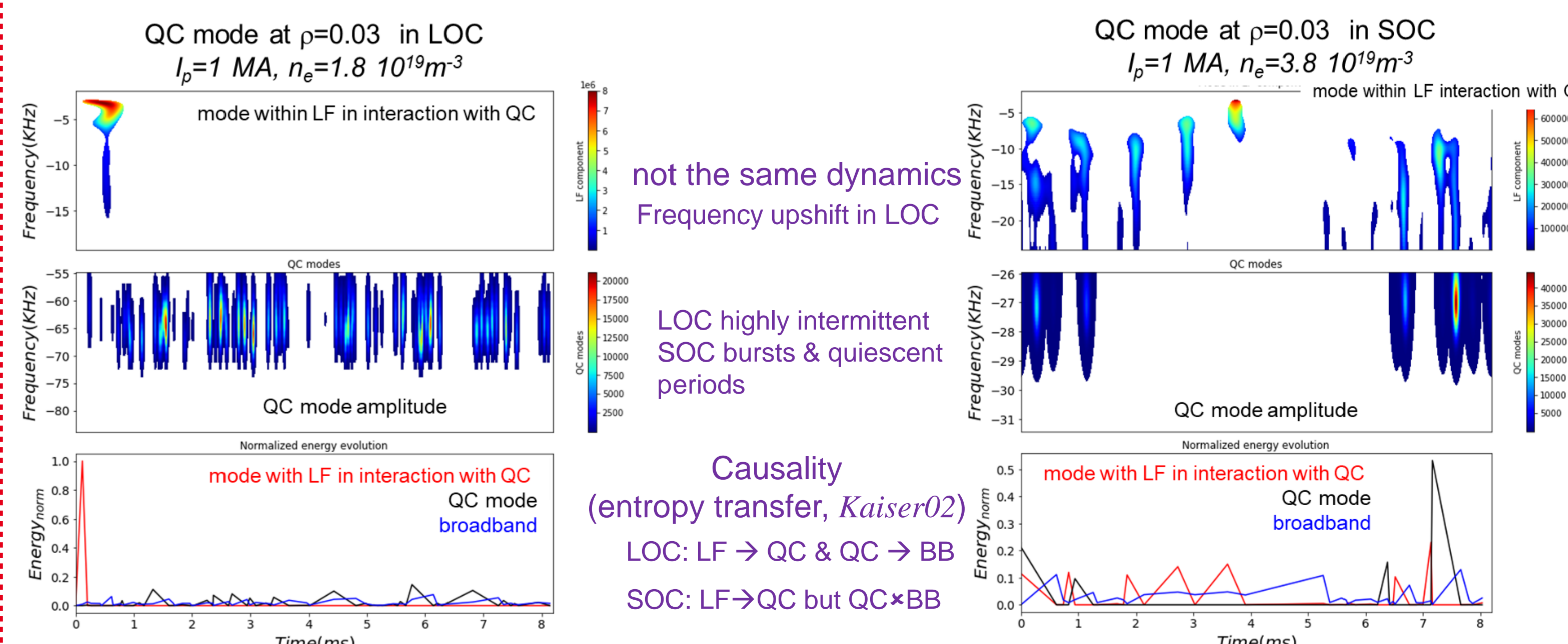


Likelihood occurrence of quasi-coherent modes



- 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 SOC
- ✓ 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