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# Trends Emerging from a Systematic Analysis of a Decade of Fluctuation Reflectometry Measurements on Tore Supra

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24/05/2019

Transport is dominated by turbulent instabilities. Many progresses, but turbulence remains an issue.

A **Data-driven discovery** approach could be effective to extract new information:

- 1) The complexity of the problem is great
- 2) Parameters controlling turbulence are numerous & of different types

From 2002 (core reflectometer installation) to 2011 (Tore Supra's last plasma) **350 000 measurements** at fixed frequency were performed over **6000 discharges**.

Could we extract ***new observations*** from this big database ?

## **I. Introduction**

## **II. Parametrization of fluctuation frequency spectra**

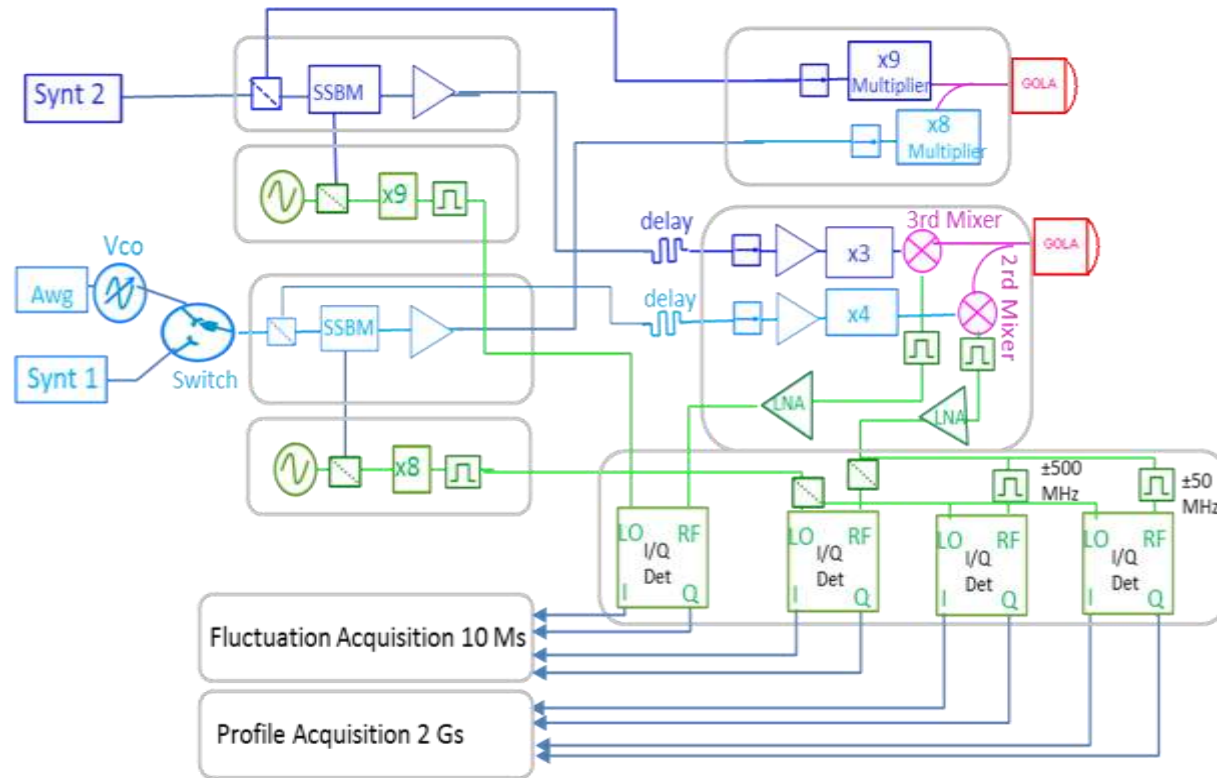
## **III. Radial profiles of broadband contribution**

## **IV. Collisions and spectrum characteristics**

## **V. Conclusions and perspectives**

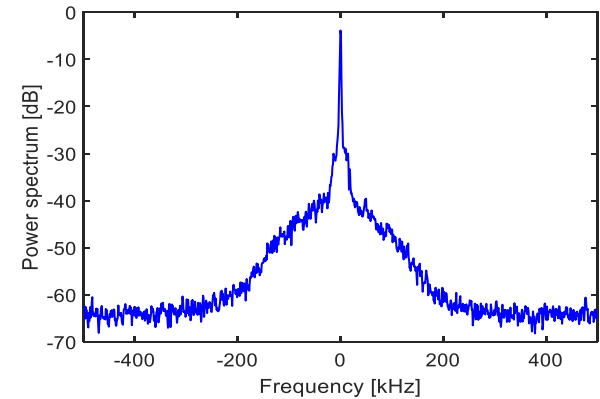
## **II. Parametrization of fluctuation frequency spectra**

# A data reduction is required



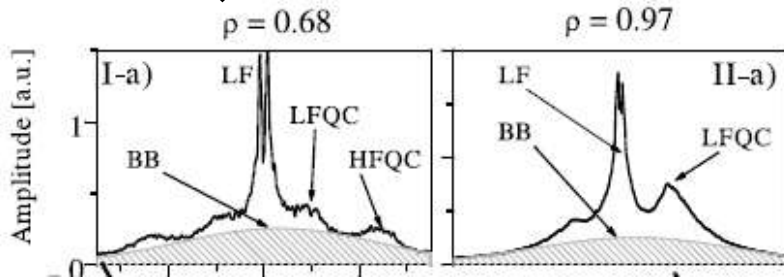
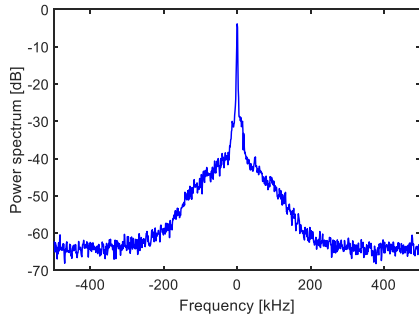
typ: 2\*20 steps of 10 ms (40\*10 000 complex values)  
several times/shot

Frequency spectrum  
( $N_{FFT} \sim 1,000$ )



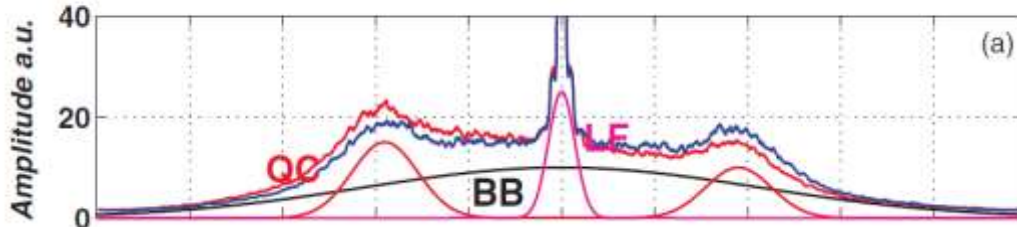
1 step → 1 spectrum  
500 to ~ 1000 values (A(f))

# A data reduction is required



*Vershkov NF 2005*

*#91321: 2.2422–2.4971s Krämer-Flecken NF 2004*



Decomposition → 1 spectrum  $\cong$  few components

Frequency spectrum  
( $N_{FFT} \sim 1,000$ )



Decomposition



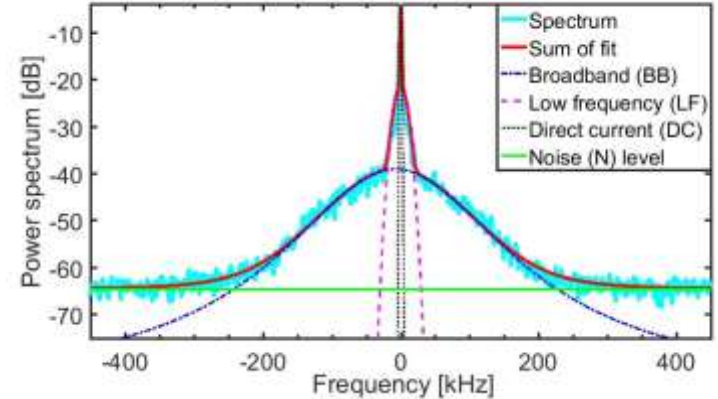
Few parameters  
( $N_p \sim 10$ )



database

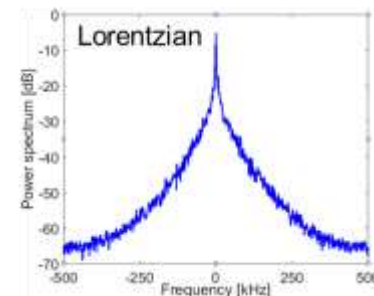
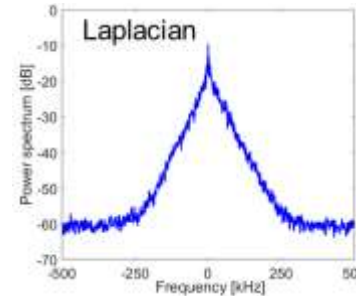
## Decomposition

- ❑ Noise (N) level → 1 parameter
- ❑ Direct current (DC) } 2 Gaussian
- ❑ Low-frequency (LF) } 6 parameters
- ❑ Broadband (BB) component
- ❑ MHD and quasi-coherent (QC) modes not considered yet (narrow → modest contribution)



## 4 parameters needed to fit the BB ≠ shapes

- ❑ Voigt function (Sun IRW13)
- ❑ Generalized Gaussian  $Ae^{\left(\frac{x-\mu}{\sigma}\right)^\beta}$
- ❑ FFT of Taylor function [Hennequin EPS99] complex link btw param & shape





- The spectrum are normalized to the total power:

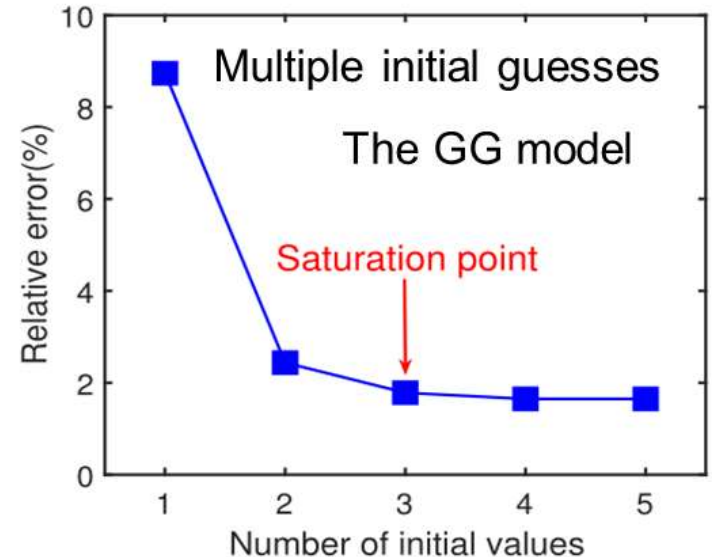
$$1 \approx \frac{\int \text{BB+LF+DC+N } dF}{\text{Total power of spectrum}} \approx \frac{\int \text{BBdF}}{\int \text{BBdF} + \int \text{LFdF}} + \frac{\int \text{LFdF}}{\int \text{BBdF} + \int \text{LFdF}} \sim E_{\text{BB}} + E_{\text{LF}}$$

- Cost function is done in linear (LF) and logarithmic (shape) scales

$$F_{\text{cost}} = (1 - w) \times \frac{|\lg(S_{\text{fit}}) - \lg(S)|^2}{\int [\lg(S)]^2 df} + w \times |S_{\text{fit}} - S|^2 \quad \text{with } w = 0.5$$

- Minimization using interior-point algorithm with several initial guess

- ✓ The GG model
  - ➔  $N_{iv} = 3$
- ✓ The Taylor model
  - ➔  $N_{iv} = 5$



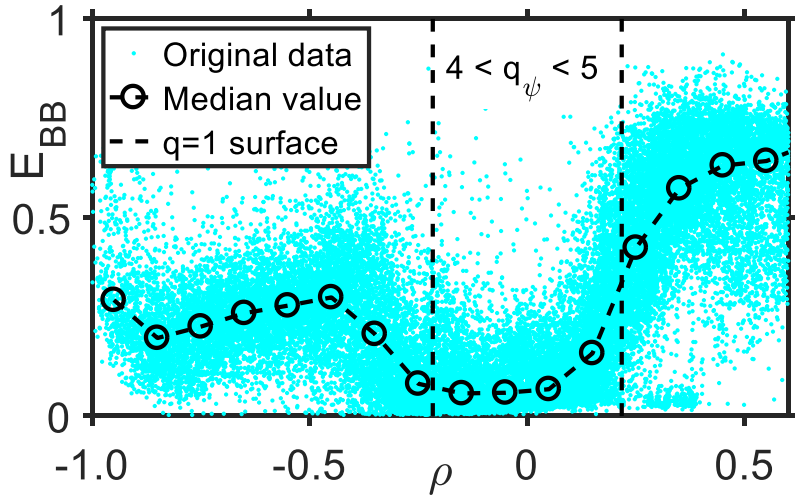
350,000 spectra from 6,000 discharges with Ohmic, LH, ICRH and few ECRH

- Global operating parameters:  $B_{t,0}, I_p, R, a, q_\psi, N_l$  and more
- Diagnostic characteristics: acquisition parameters, probing frequencies, ...
- cutoff positions  $\rho_c$  (density profiles from 10 channel interferometry inversion)
- Local plasma parameters (at  $\rho_c$ ):  $n_e, T_e, B_t, L_\epsilon, (\nabla T_e, \nabla n_e), \dots$
- Turbulence properties: 11 parameters from the parametrization model.

Index	$\rho$	$B_{t,0}$	$I_p$	$q_\psi$	$n_e$	$T_e$	$E_{BB}$	$W_{BB}$	$\beta_{BB}$	...
1	0.65	3.86	1.0	3.64	3.5	2	0.1	50	...	...
2	0.54	3.46	1.0	3.63	4.0	3	0.5	100	...	...
...	...	...	...	...	...	...	...	...	...	...

- For physics studies, “bad” data are excluded: low S/N, strong BB Doppler,  $r/a > 0.6$  (ripple → strong Doppler)

### **III. Radial profiles of broadband contribution**



## Radial profiles of $E_{BB}$ in Ohmic

- The basin inside  $q=1$  is recovered [1]
- Width of this basin scales with  $a/q_\psi$
- Shift wrt  $q \sim 1$  explained by the  $\neq$  between interferometry & reflectometry  $n_e$  profiles

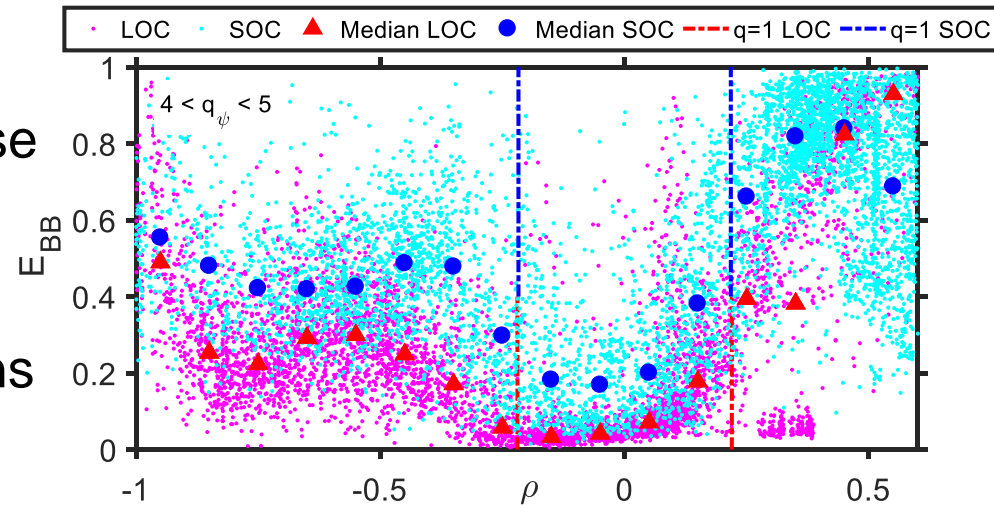
## Radial profiles in LOC/SOC

LOC/SOC threshold from the database

$$N_{LOC/SOC} \approx 2.6 \times I_p \text{ (MA)}$$

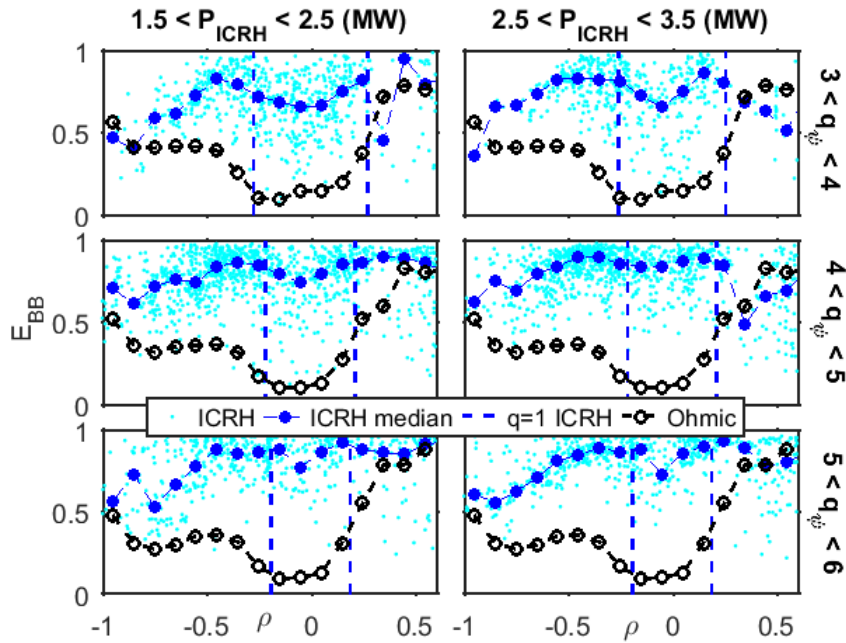
- Basin observed in LOC & SOC
- In the basin, but also at all positions

$$E_{BB}^{SOC} > E_{BB}^{LOC}$$



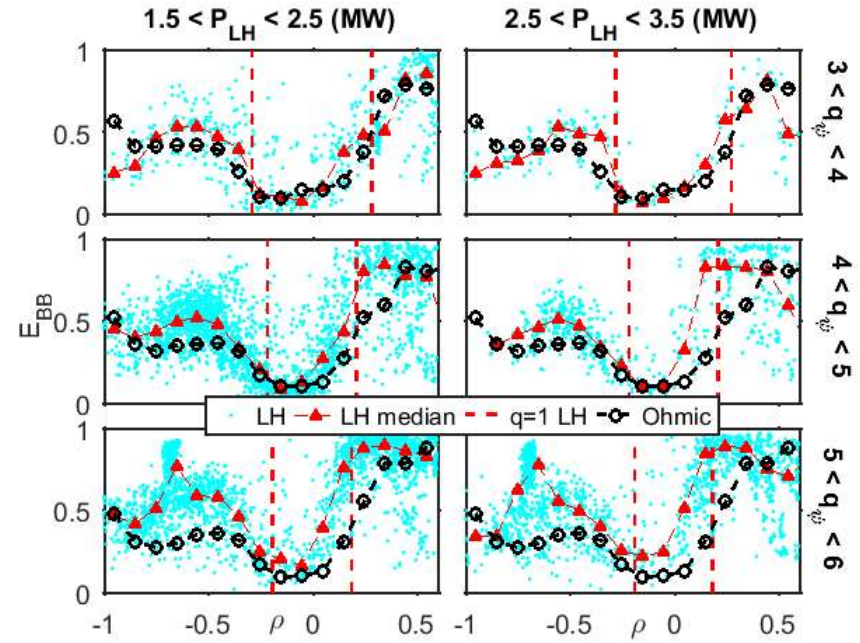
[1] Sirinelli PhD 2006

## Pure ICRH



High  $E_{BB}$  ( $>0.5$ ) even at low  $P_{ICRH}$   
 The basin disappears at high  $P_{ICRH}$

## Pure LH



$E_{BB}$  slightly above Ohmic  
 Basin remains even at high  $P_{LH}$

Similar confinement times cannot explain the  $\neq$  BB contribution

## **IV. Collisions and spectrum characteristics**

Many parameters tested to explain ICRH vs LH differences

→ density emerged as a key ( $E_{\text{BB}} \nearrow$  with  $n_e \nearrow$ )

→ but  $n_e$  threshold depends on  $P_{\text{add}}, q_\psi \dots$

Clearer results obtained with **the effective collisionality**

$$\nu_{\text{eff}} = \nu_{ei} / \omega_{De}$$

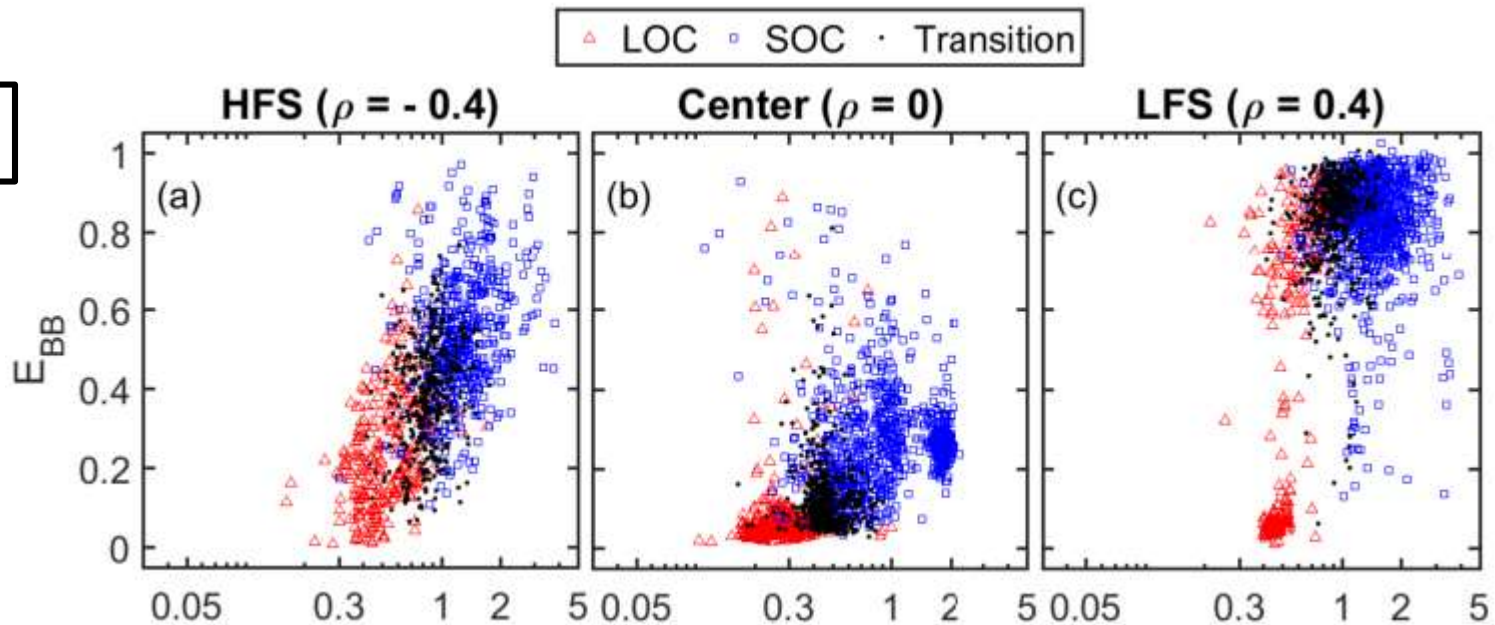
$\nu_{ei}$ : electron/ion collision freq. &  $\omega_{De}$ : curvature drift freq.

$\nu_{\text{eff}}$  can be approximated by [1]

$$\nu_{\text{eff}} \sim 0.1 R Z_{\text{eff}} n_e T_e^{-2} \quad (n_e \text{ in } 10^{19} \text{ m}^{-3}, T_e \text{ in keV})$$

[1] C. Angioni *PPCF* 2003

Ohmic

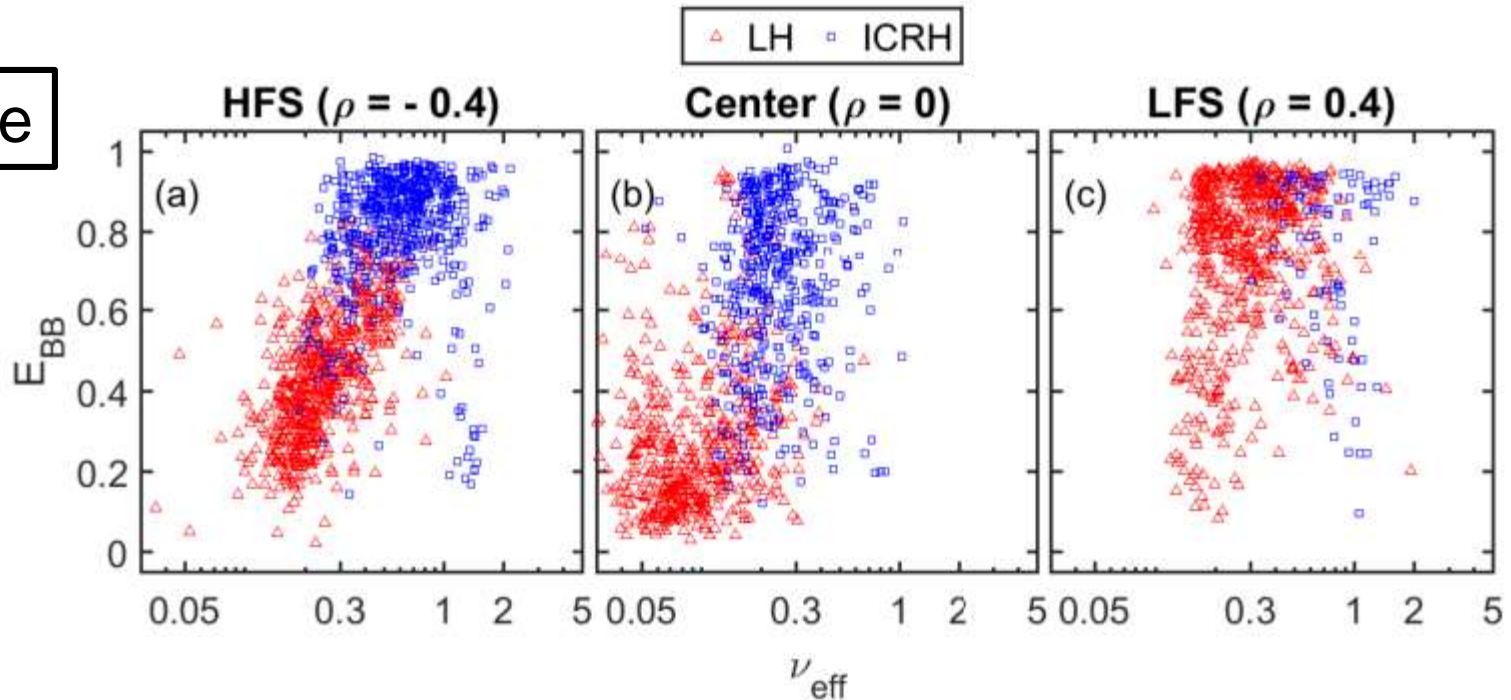


Y. Sun POP 2019

- $E_{BB}$  increases with local  $v_{\text{eff}}$
- LOC/SOC transition ( $0.9 \sim 1.1 N_{LOC/SOC}$ ) around  $v_{\text{eff}} \sim 0.5 - 1$
- HFS: increase from low  $E_{BB}$  in LOC to  $E_{BB} \sim 1$  in SOC
- Center: low  $E_{BB}$  in LOC & transition, up to  $E_{BB} \sim 0.5$  in SOC
- LFS: results less clear due to saturated  $E_{BB} \sim 1$



L-mode



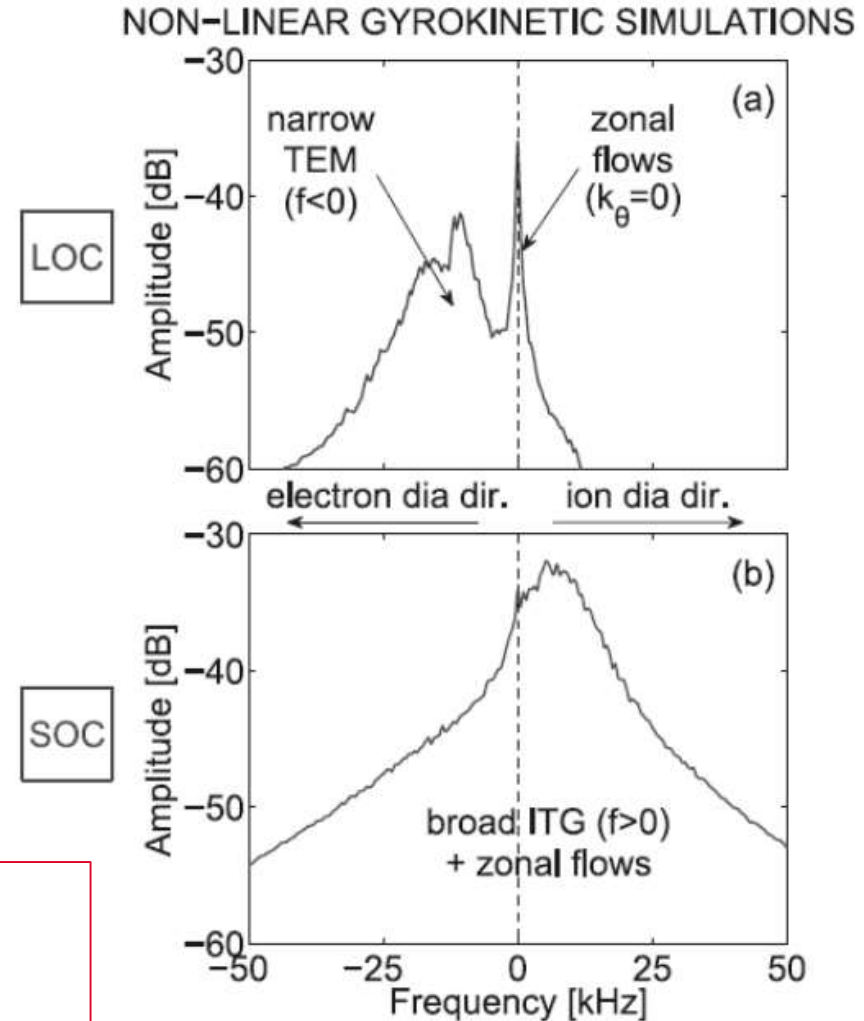
- Similar trends as in Ohmic
- Most LH discharges at **low**  $\nu_{\text{eff}}$  ( $<0.5$ )
- most ICRH ones at high  $\nu_{\text{eff}}$  ( $>0.3$ ) because of higher density for better ICRH coupling

GENE simulations [1,2] performed for a Tore Supra Ohmic ne scan showed

- BB component narrower in LOC(TEM) than in SOC(ITG)
- in TEM, the spectra exhibits a narrow LF component (ZF)
- In ITG, this LF component is integrated in the BB component.

The trends of spectrum modifications:

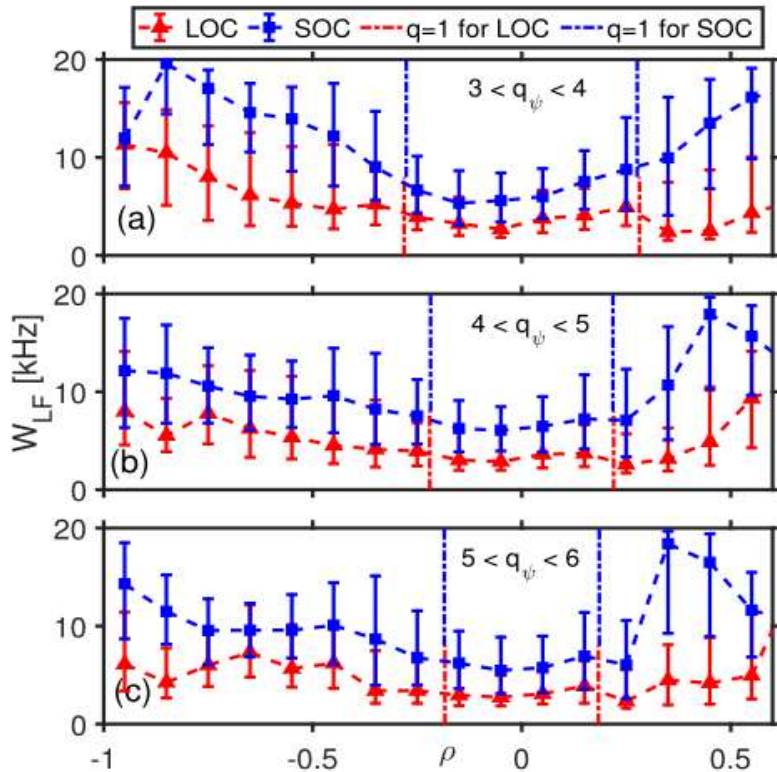
$E_{BB} \nearrow$  &  $E_{LF} \searrow$  with increasing  $\nu_{eff}$   
are compatible with the simulation results



[1] Arnichand PPCF 2016

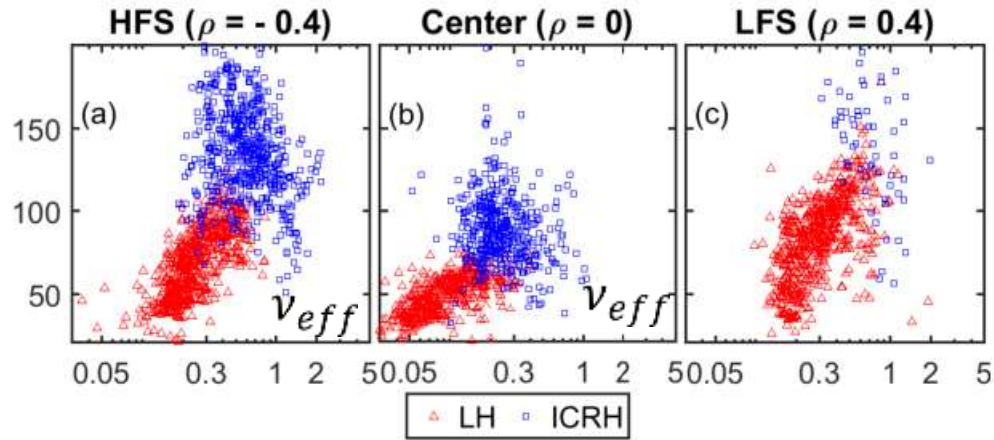
[2] Citrin PPCF 2017

Width of the LF component ( $W_{LF}$ )  
in Ohmic



The LF width is low in LOC and  
much higher in SOC

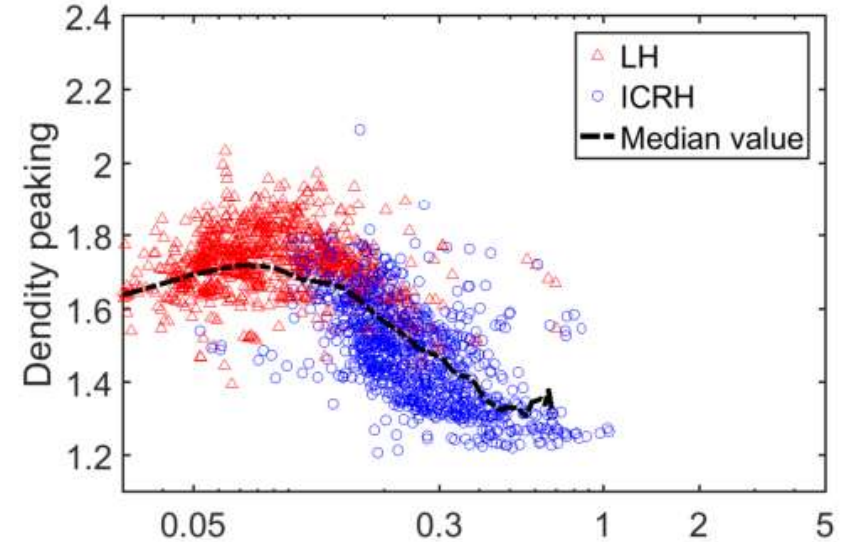
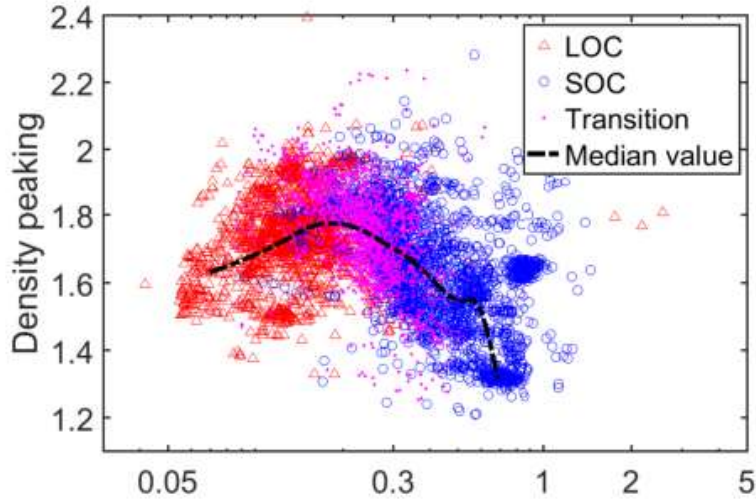
Width of the LF component ( $W_{LF}$ )  
in L-mode



The BB width increase with  $\nu_{eff}$   
- regular trend in LH plasmas  
- wider and large dispersion in ICRH

During LOC/SOC transition, TEM stabilization  $\rightarrow$   $\searrow$   $n_e$  peaking [1,2]

A similar trend is observed in L-mode



This trend is recovered. Peaking is maximum in the intermediate regime.

Lower slope in LH could be due to lower  $E_{//}$  (Ware pinch  $\searrow$ )

TEM stabilization  $\rightarrow$  inversion of the thermodifusion pinch from inward (TEM) to outward (ITG)  $\rightarrow$  lower peaking

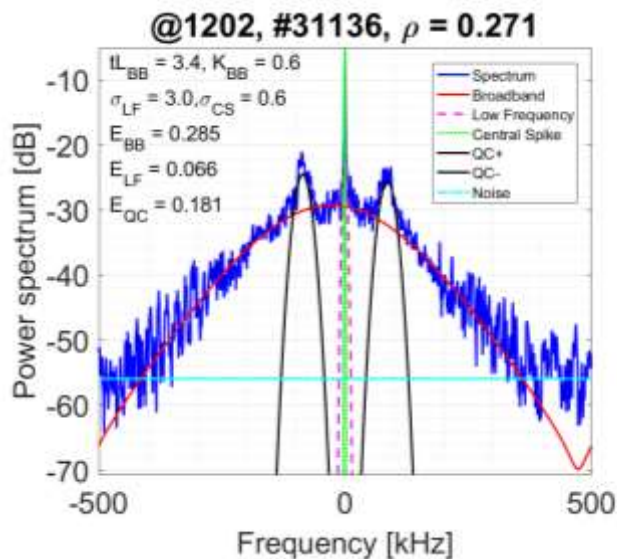
[1] C. Angioni PPCF 2003  
[2] C Bourdelle, PPCF 2005

## **V. Conclusions and perspectives**

- Parametrization reduces the  $\sim 10000$  values of a fluctuation (fixed freq) reflectometry measurement to handful (11) parameters
  - ➔ database of 6000 Tore Supra discharges (350,000 spectra)
  
- Trends and patterns have emerged
  - Basin inside  $q=1$  extended to all  $q_{\psi}$  & LOC/SOC.  
Its width and position linked to  $q=1$  surface ( $a/q_{\psi}$ )
  - Collisionality  $\nu_{\text{eff}}$  seems to control the spectrum shape.
  - Modification of the instability regime was proposed to explain the impact of collisions. This interpretation is supported by other spectrum parameters and the analysis of the density peaking.
  
- Gyro-kinetic simulations and full-wave reflectometry simulations are required to confirm this interpretation as well as to dedicated experiments with controlled & well measured parameters.



- A similar database will be built fore core reflectometer data on WEST. How the elements will compare to Tore Supra ?
- Outliers in the database: some are understood (hardware failure), others need to be investigated
- New parameters could be added to fit other components (quasi-coherent (QC) modes), but criteria should be implement to avoid over-fitting (pattern recognition, NN ?)



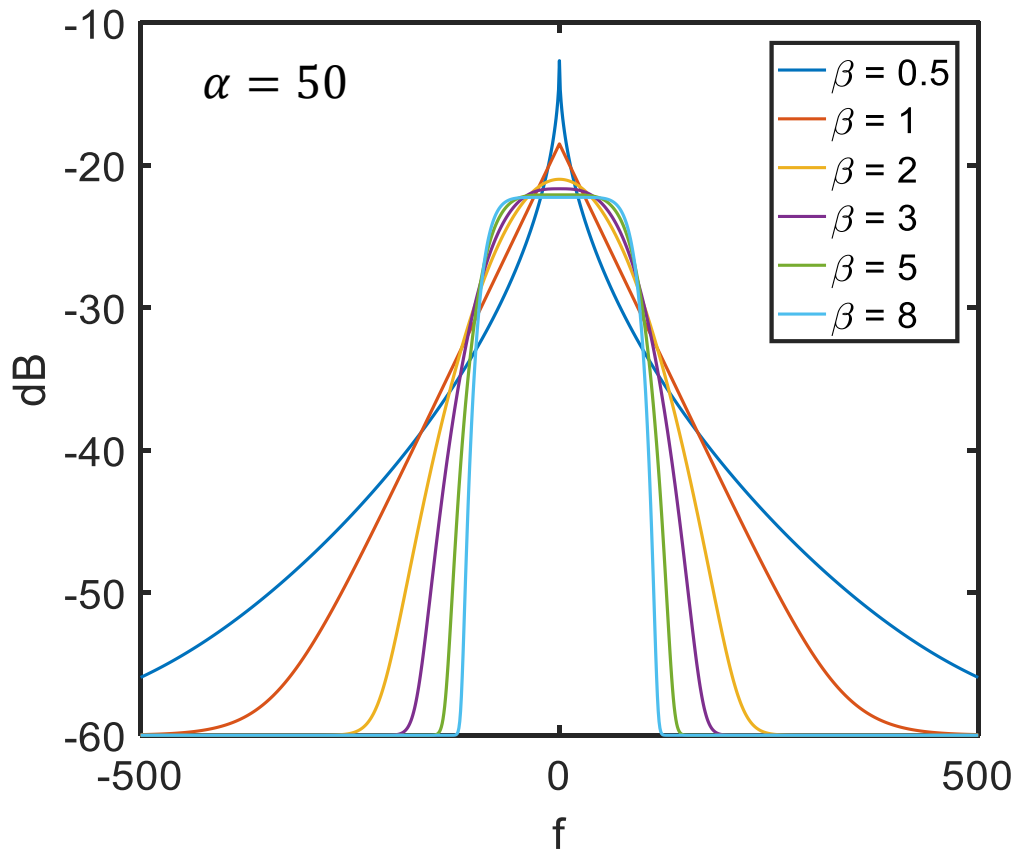
- 4 parameters added to fit the QC modes
- $A_+$  &  $A_-$  amplitudes
  - Position & width

**Back up**



The generalized Gaussian (GG) function:

$$C_{BB}^{GG} = A_{BB} \exp \left[ - \left( \frac{|f - \mu_{BB}|}{\alpha_{BB}} \right)^{\beta_{BB}} \right]$$



- Direct relation between  $\alpha$  and width (std deviation)
- Very peaked at low  $\beta$
- ➔  $\beta \leq 0.5$

