

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

R. Sabot, Y. Sun, S. Heuraux, G. Verdoolaege, X. Garbet, S. Hacquin, G. Hornung

▶ **To cite this version:**

R. Sabot, Y. Sun, S. Heuraux, G. Verdoolaege, X. Garbet, et al.. Trends Emerging from a Systematic Analysis of a Decade of Fluctuation Reflectometry Measurements on Tore Supra. 14 th International Reflectometry Workshop, May 2019, Lausanne, Switzerland. cea-02288920

HAL Id: cea-02288920
https://cea.hal.science/cea-02288920

Submitted on 16 Sep 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

DE LA RECHERCHE À L'INDUSTRIE

www.cea.fr

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

R. Sabot[1], Y. Sun[1], S. Heuraux[2], G. Verdoolaege[3,5], X. Garbet[1], S. Hacquin[1,4], G. Hornung[3]

& Tore Supra team

[1] *CEA, IRFM, F-13108 Saint Paul Lez Durance, France*

[2] *IJL UMR 7198 CNRS, Université de Lorraine, F-54011 Nancy, France*

[3] *Department of Applied Physics, Ghent University, 9000 Gent, Belgium*

[4] *Eurofusion PMU Culham Science Centre, Culham, OX14 3DB, UK*

[5] *LPP-ERM/KMS, B-1000 Brussels, Belgium*

24/05/2019

Systematic Analysis

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 ?

Outline

I. Introduction

II. Parametrization of fluctuation frequency spectra

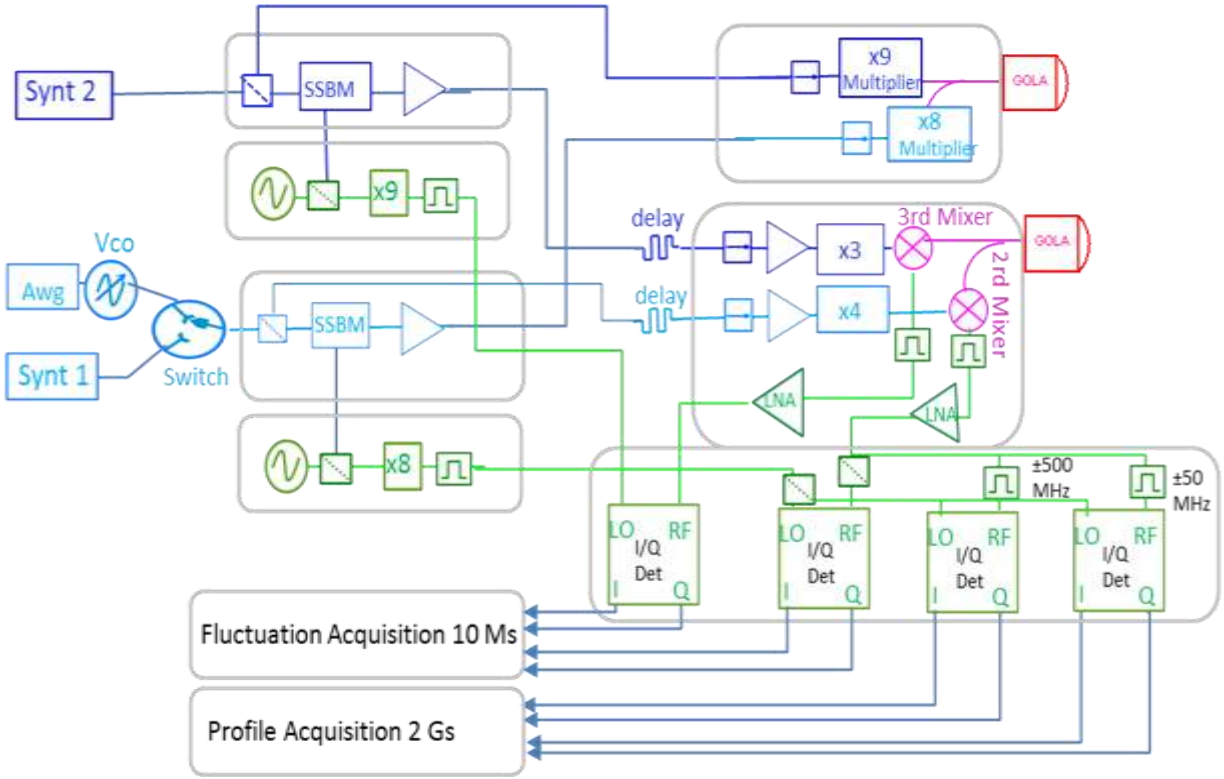
III. Radial profiles of broadband contribution

IV. Collisions and spectrum characteristics

V. Conclusions and perspectives

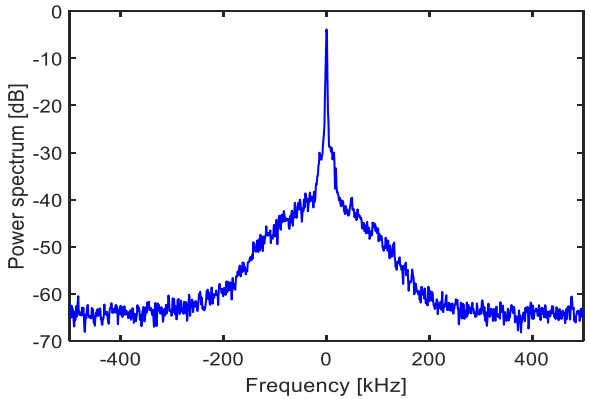
II. Parametrization of fluctuation frequency spectra

A data reduction is required



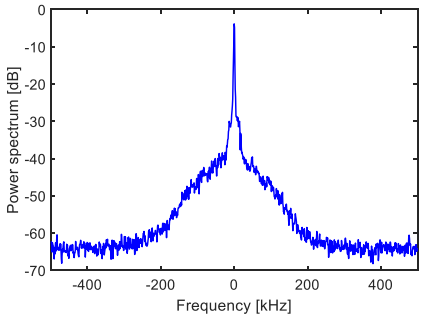
typ: 2*20 steps of 10 ms (40*10 000 complex values)
several times/shot

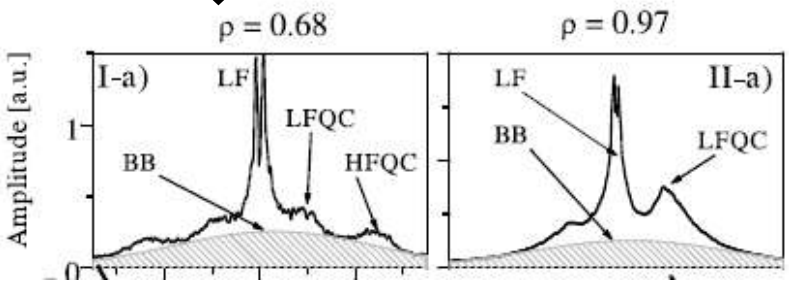
Frequency spectrum
(N_{FFT}~1,000)



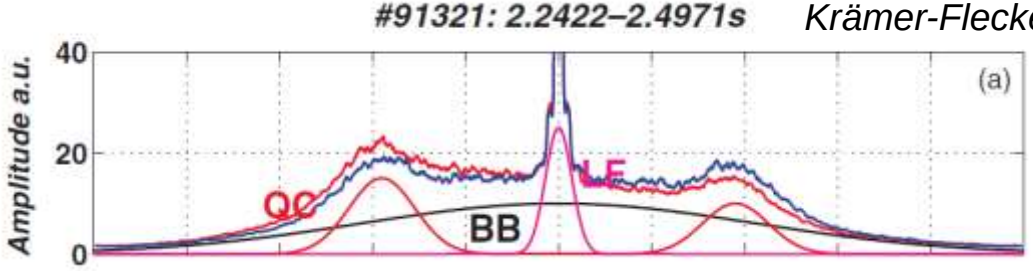
1 step ➔ 1 spectrum
500 to ~ 1000 values (A(f))

A data reduction is required





Vershkov NF 2005



Krämer-Flecken NF 2004

Frequency spectrum (N_{FFT}~1,000)

Decomposition

Few parameters (N_p ~ 10)

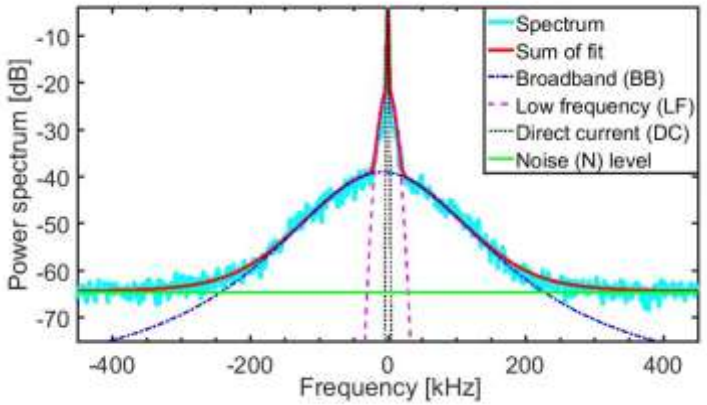
database

Decomposition ➔ 1 spectrum ≅ few components

Parametrization of frequency spectra

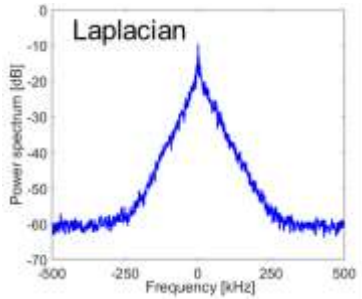
Decomposition

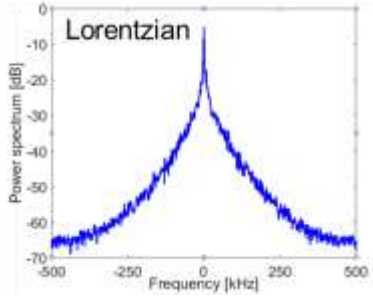
- Noise (N) level ➔ 1 parameter
- Direct current (DC) } 2 Gaussian
- Low-frequency (LF) } 6 parameters
- Broadband (BB) component
- MHD and quasi-coherent (QC) modes not considered yet (narrow ➔ modest contribution)



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





Y. Sun RSI 2018

11 parameters for each spectrum

Constrained optimization

- The spectrum are normalized to the total power:

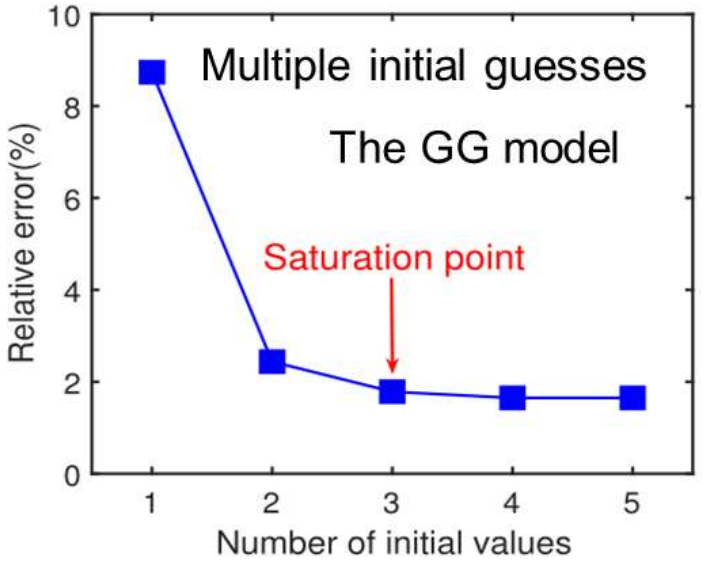
$$1 \approx \frac{\int \mathrm{BB+LF+DC+N\ dF}}{\text{Total power of spectrum}} \approx \frac{\int \mathrm{BB dF}}{\int \mathrm{BB dF}+\int \mathrm{LF dF}} + \frac{\int \mathrm{LF dF}}{\int \mathrm{BB dF}+\int \mathrm{LF dF}} \sim \mathbf{E_{BB}}+\mathbf{E_{LF}}$$

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

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

- Minimization using interior-point algorithm with several initial guess

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



Construction of the database

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

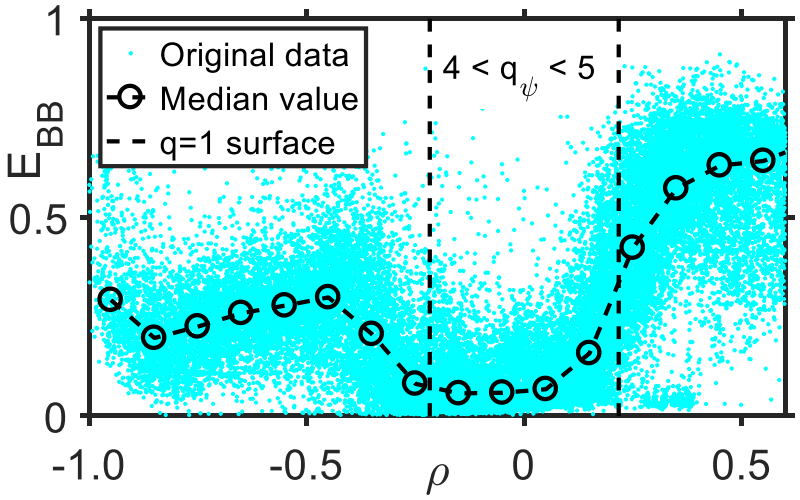
- Global operating parameters: $B_{t,0}, I_p, R, a, q_\psi, N_l$ and more
- Diagnostic characteristics: acquisition parameters, probing frequencies,…
- cutoff positions ρ_c (density profiles from 10 channel interferometry inversion)
- Local plasma parameters (at ρ_c): $n_e, T_e, B_t, L_\epsilon, (\nabla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

Index	ρ	$B_{t,0}$	I_p	q_ψ	n_e	T_e	E_{BB}	W_{BB}	β_{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 the BB contribution



Radial profiles of E_{BB} in Ohmic

- The basin inside q=1 is recovered [1]
- Width of this basin scales with a/q_ψ
- Shift wrt q~1 explained by the ≠ between interferometry & reflectometry n_e profiles

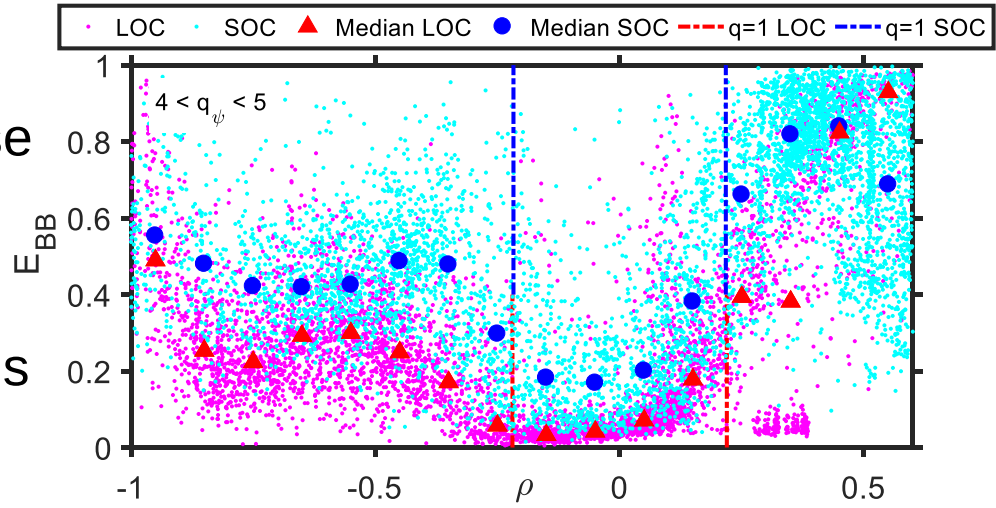
Radial profiles in LOC/SOC

LOC/SOC threshold from the database

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

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

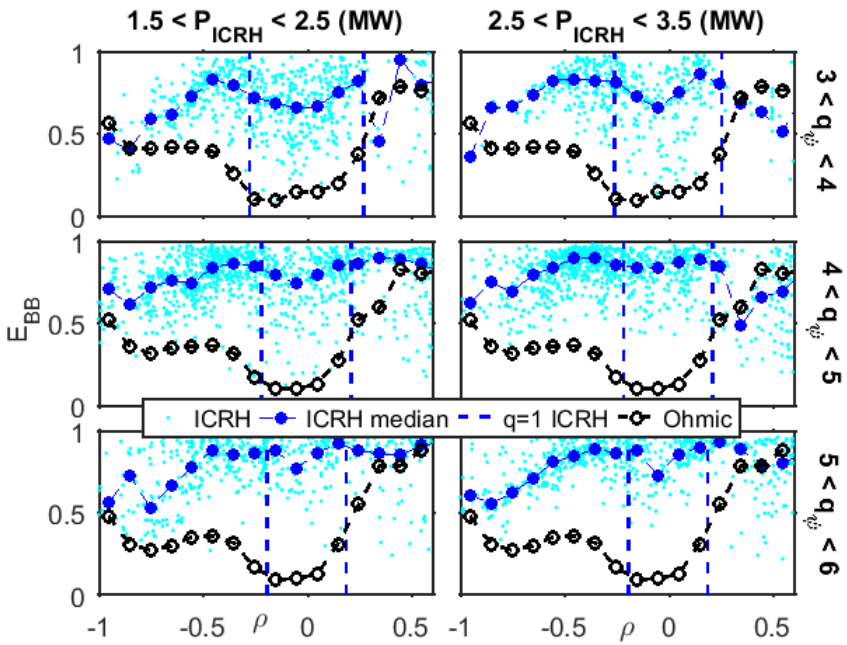
$$E_{BB}{}^{SOC} > E_{BB}{}^{LOC}$$



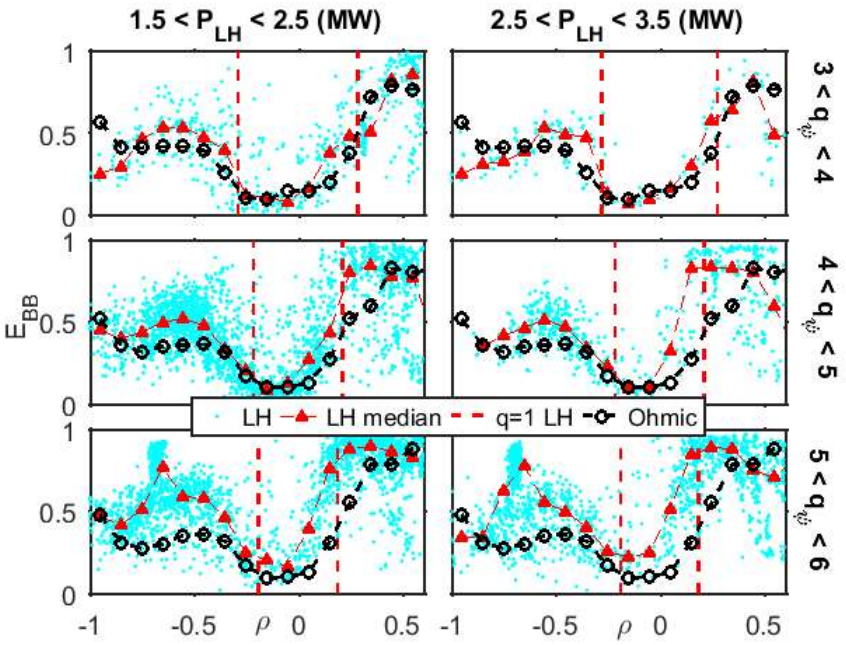
[1] Sirinelli PhD 2006

Radial profiles of E_{BB} with additional heating

Pure ICRH



Pure LH



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

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

Similar confinement times cannot be explain the ≠ BB contribution

IV. Collisions and spectrum characteristics

ν_{eff} seems to control the BB contribution (1/3)

Many parameters tested to explain ICRH vs LH differences

➔ density emerged as a key (E_{BB} ↗ with ne ↗)

➔ but ne threshold depends on P_{add}, q_ψ …

Clearer results obtained with **the effective collisionality**

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

ν_{ei}: electron/ion collision freq. & ω_{De}: curvature drift freq.

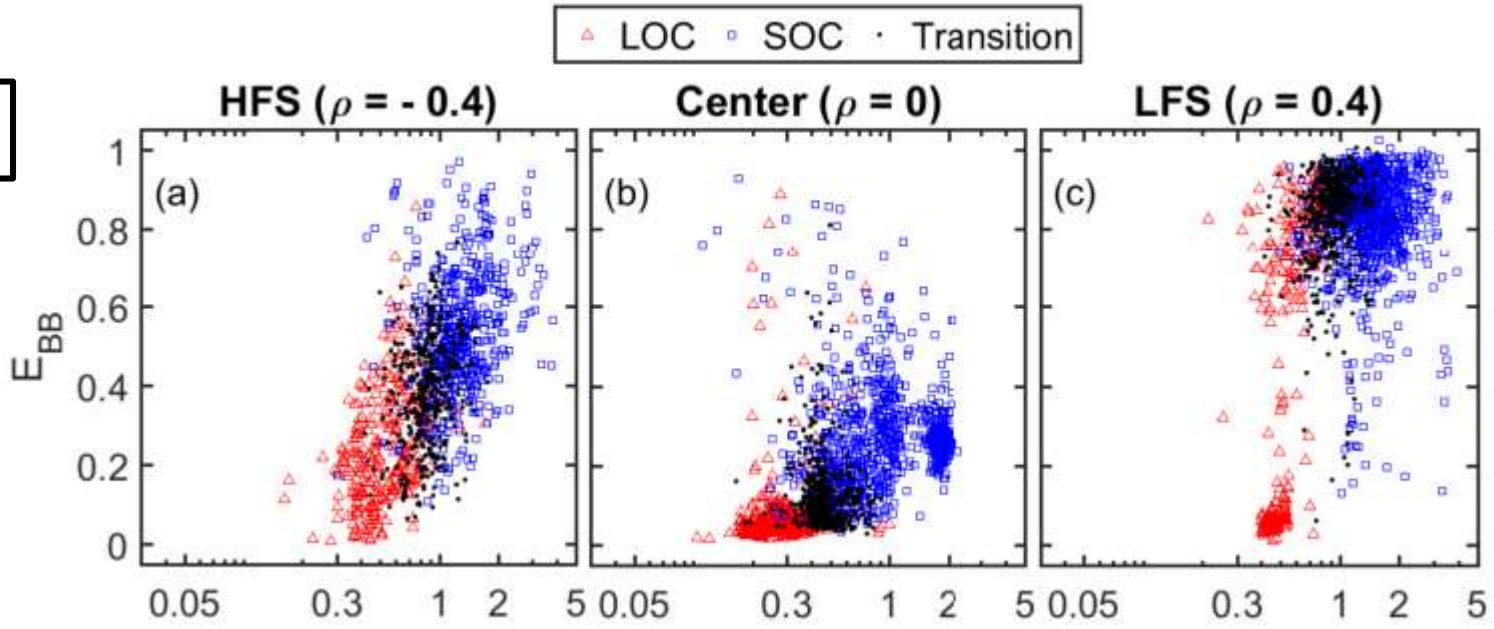
$\boldsymbol{\nu_{eff}}$ can be approximated by [1]

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

[1] C. Angioni *PPCF* 2003

ν_{eff} seems to control the BB contribution (2/3)

Ohmic

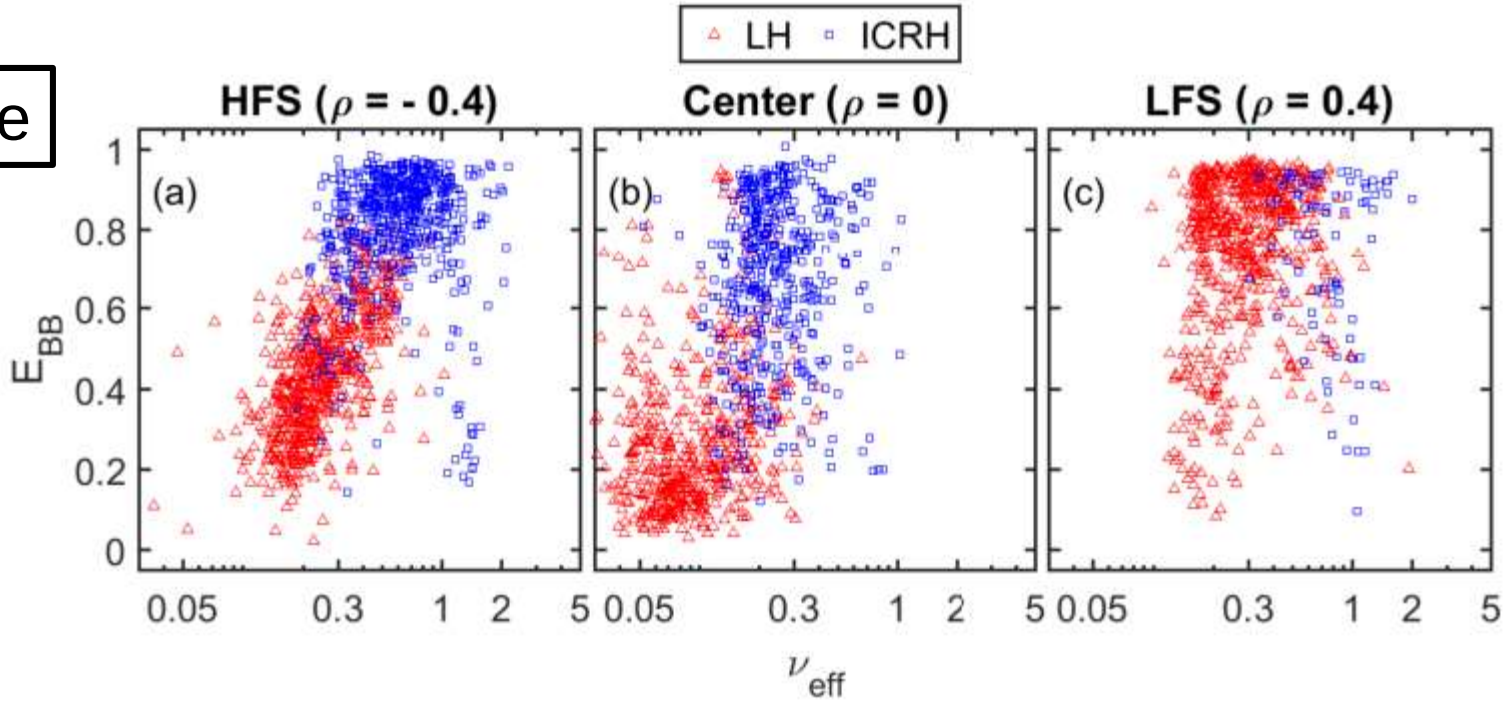


Y. Sun POP 2019

- E_{BB} increases with local ν_{eff}
- LOC/SOC transition (0.9~1.1 $N_{LOC/SOC}$) around $\nu_{eff} \sim 0.5 - 1$
- HFS: increase from low E_{BB} in LOC to E_{BB}~1 in LOC
- Center: low E_{BB} in LOC & transition, up to E_{BB}~0,5 in SOC
- LFS: results less clear due to saturated E_{BB} ~1

ν_{eff} seems to control the BB contribution (33)

L-mode

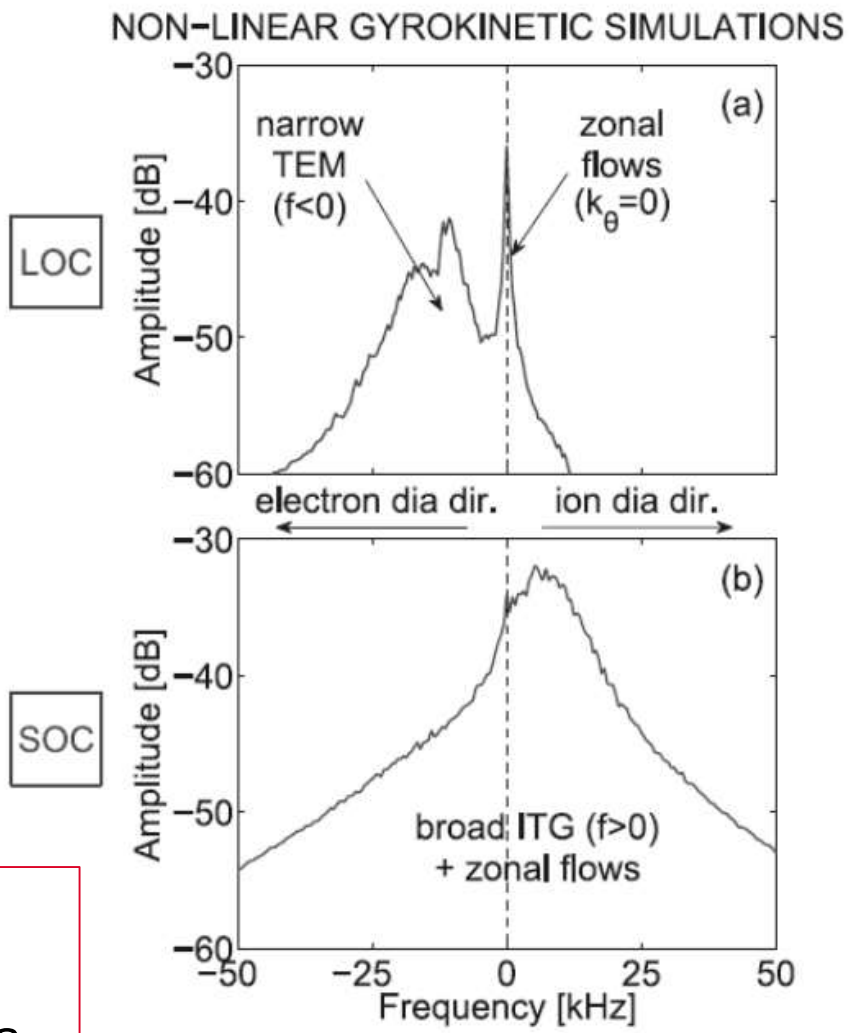


- Similar trends as in Ohmic
- Most LH discharges at **low ν_{eff}** (<0.5)
- most ICRH ones at high ν_{eff} (>0.3) because of higher density for better ICRH coupling

Proposed interpretation for spectrum shape modifications

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 ν_{eff}

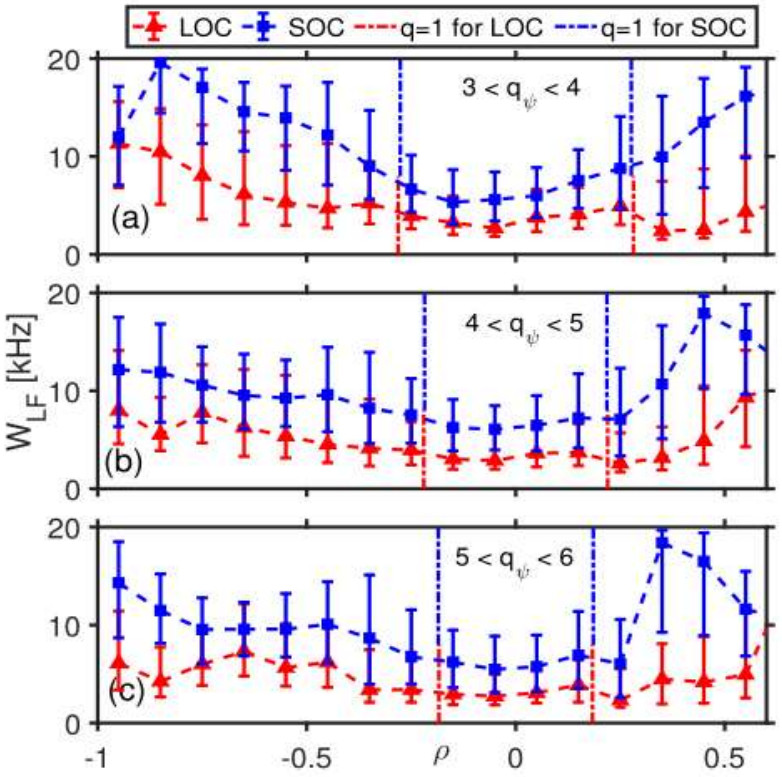
are compatible with the simulation results

[1] Arnichand PPCF 2016

[2] Citrin PPCF 2017

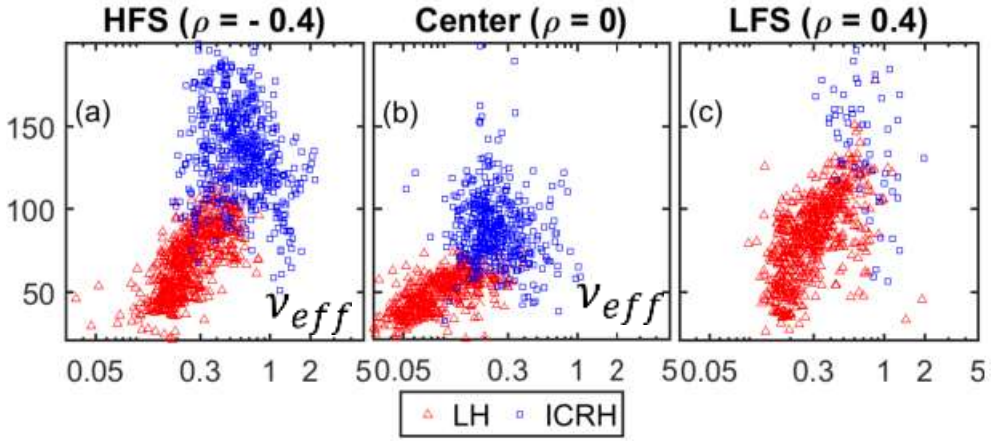
Other parameters supports this interpretation

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



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

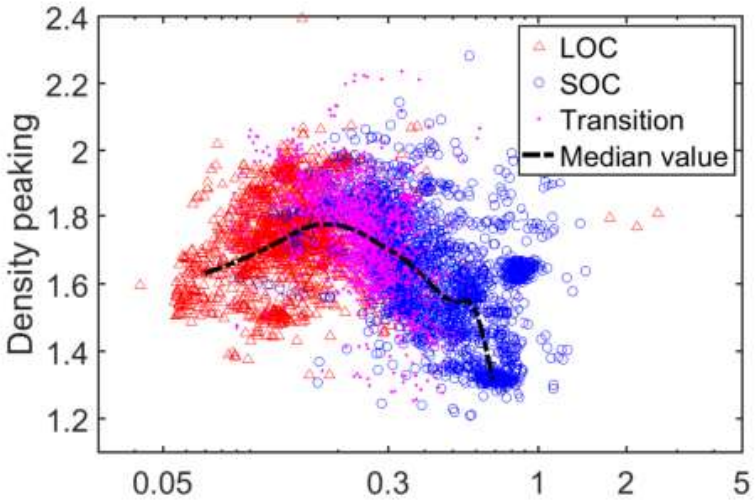
Width of the LF component (W_{LF}) in L-mode



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

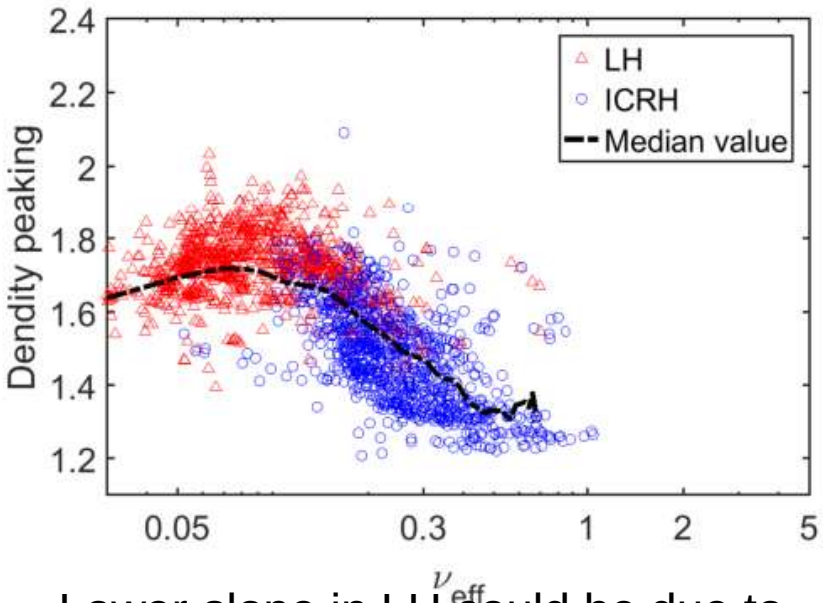
Density Peaking with ν_{eff}

During LOC/SOC transition, TEM stabilization ➔ ↘ n_e peaking [1,2]



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

A similar trend is observed in L-mode



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

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

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

V. Conclusions and perspectives

Conclusions

- Parametrization reduces the ~ 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_ψ & LOC/SOC.
    Its width and position linked to q=1 surface (a/q_ψ)
  - Collisionality ν_{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.

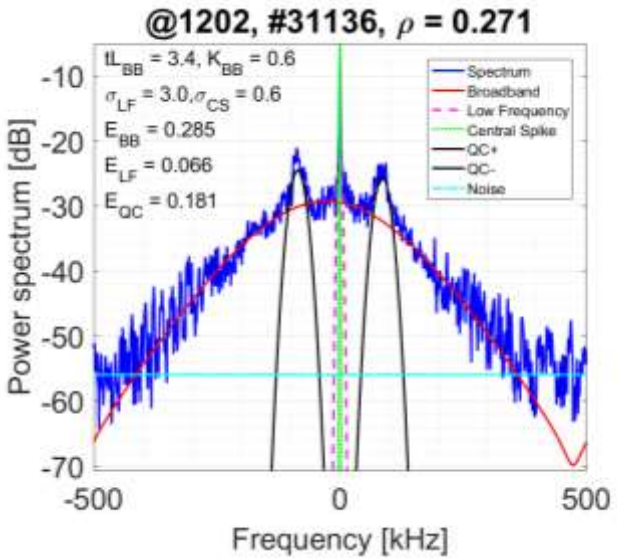
- Gyro-kinetic simulations and full-wave reflectometry simulations are required to confirm this interpretation as well as to dedicated experiments with controlled & well measured parameters.

Perspectives

- 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 ?)



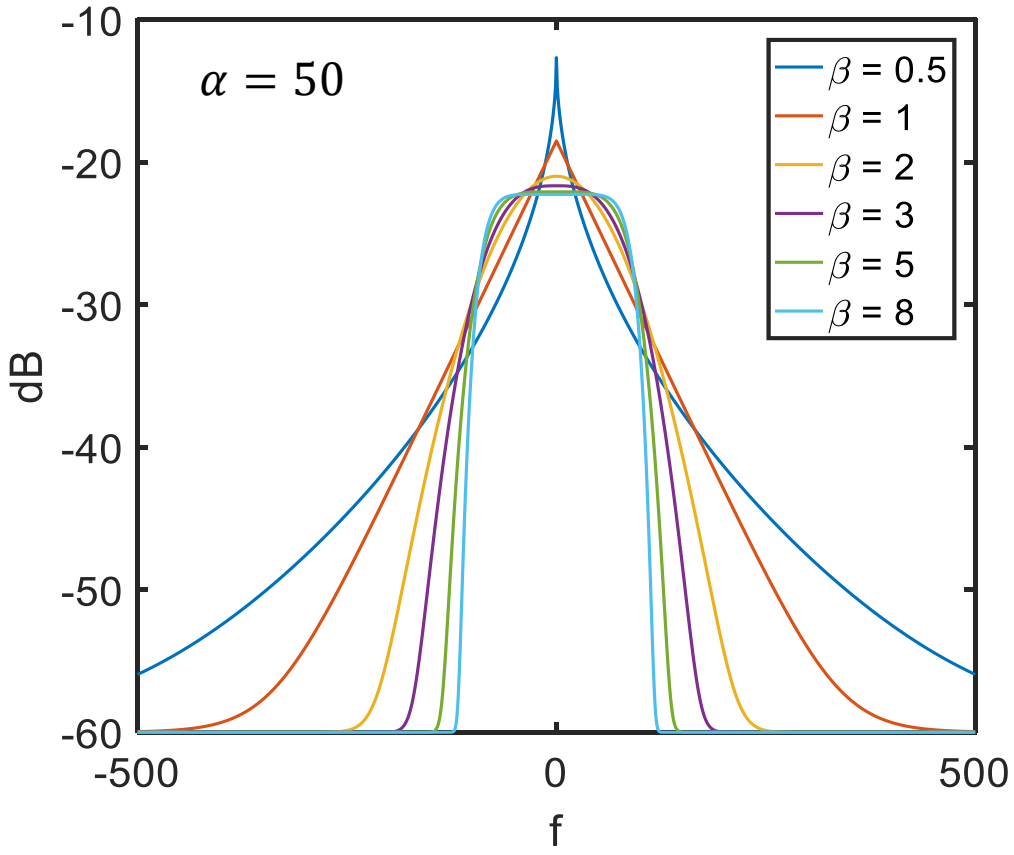
4 parameters added to fit the QC modes
- A_+ & A_- amplitudes
- Position & width

Back up

The GG model

The generalized Gaussian (GG) function:

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



- Direct relation between α and width (std deviation)
- Very peaked at low β

➔ $\beta \leq 0.5$

The Taylor model

Correlation function of a turbulence signal in plasmas (P. Hennequin, EPS 2001):

$$F_{corr}(k,u,\tau) = exp\left[-k^2u^2\tau^2\left(\frac{t}{\tau} - 1 + e^{-t/\tau}\right)\right]$$

$ku\tau \gg 1$ ➔ convective limit

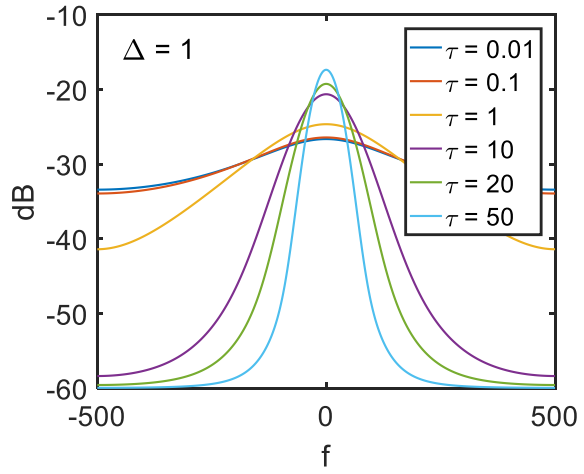
$ku\tau \leq 1$ ➔ diffusive behavior

The Taylor model:

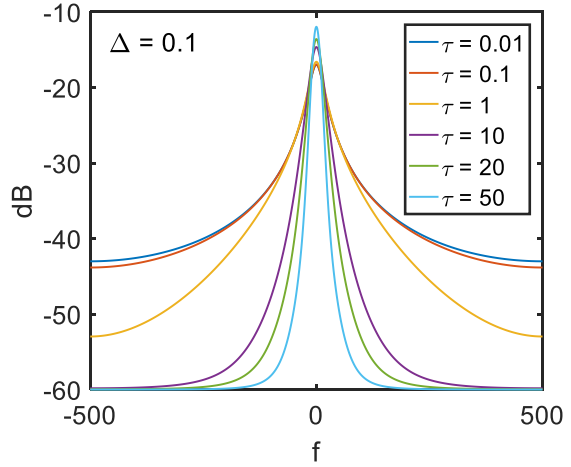
$$C_{\mathrm{BB}}{}^{\mathrm{Taylor}} = A_{BB} \times FFT\left\{F_{corr}(k,\Delta_{BB},\tau_{BB}) \times \exp(\mu_{BB})\right\}$$

$\Delta_{BB} = k^2D, D = u^2\tau$ is the diffusion coefficient & τ_{BB} the correlation time,

Gaussian or Laplacian-like



Lorentzian-like



- 4 parameters (A,μ,Δ,τ)
  but complicated link between Δ_{BB} and τ_{BB} ➔ shape
- Less peaked in f~0 than the GG