Problems and challenges of studying the non-stationary properties of QPPs

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Questions of interest

1. QPPs – what are they?
   New terminology:
   what do we mean under
   non-stationarity

2. Three Zoos:

   - Theory

   - Observations

   - Analysis

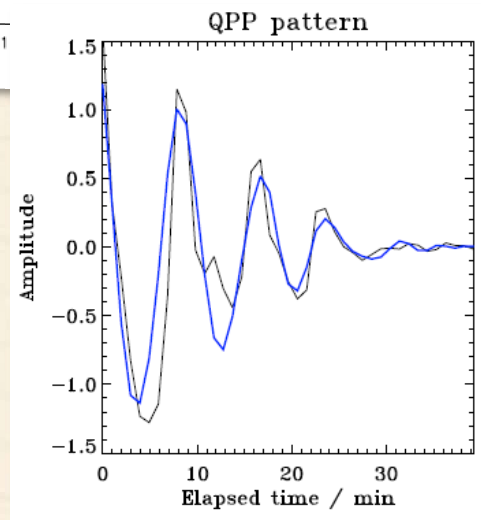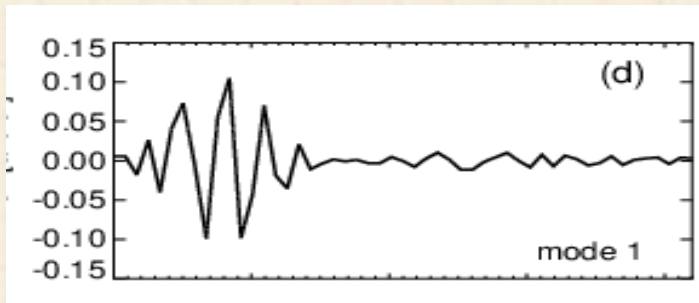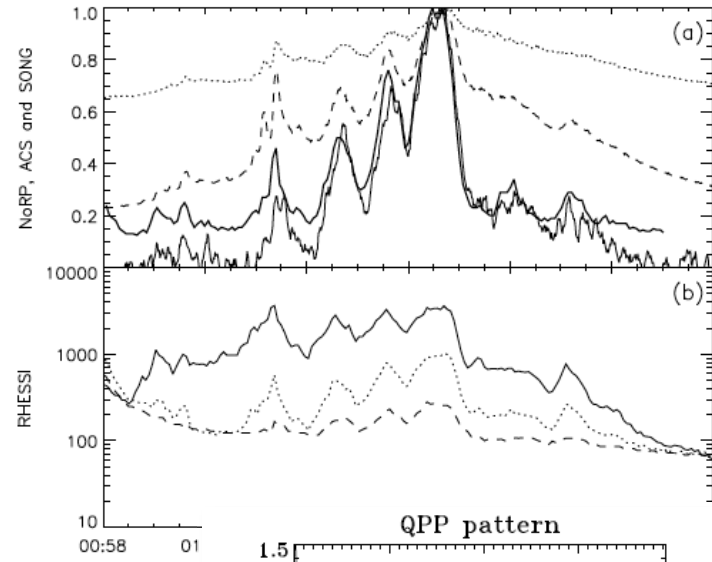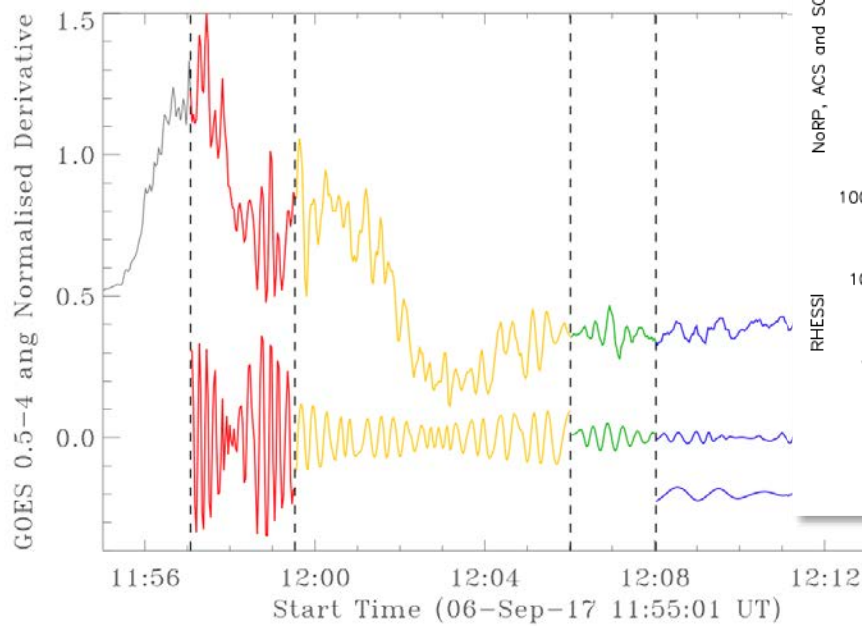3. Case study – two events – two types of non-stationarity

What do we mean by non-stationary properties?

What is the stationary signal, or Periodic Pulsations (PP)?
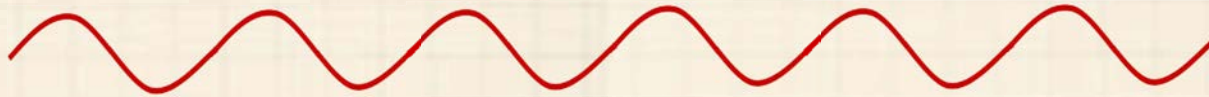
Any deviation from the harmonic shape is called Quasi-Periodic Pulsations (QPPs)

A zoo of deviations from the PP

(Kolotkov et al. 2018ApJ...858L...3K)

(Nakariakov et al. 2010PPCF...52I4009N)

Periods -> characteristic time scales

Types of the non-stationarities

Multiple modes' interference

Natural non-stationarity

Two processes going on consequently or simultaneously

It is associated with a time-dependent physical process

Types of the non-stationarities

Multiple modes' interference

Natural non-stationarity
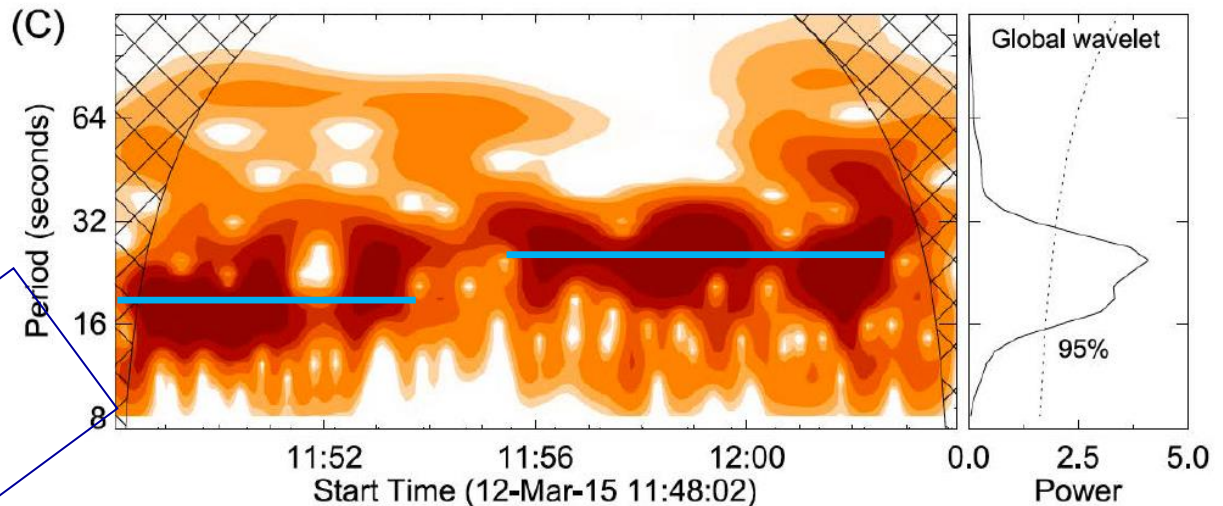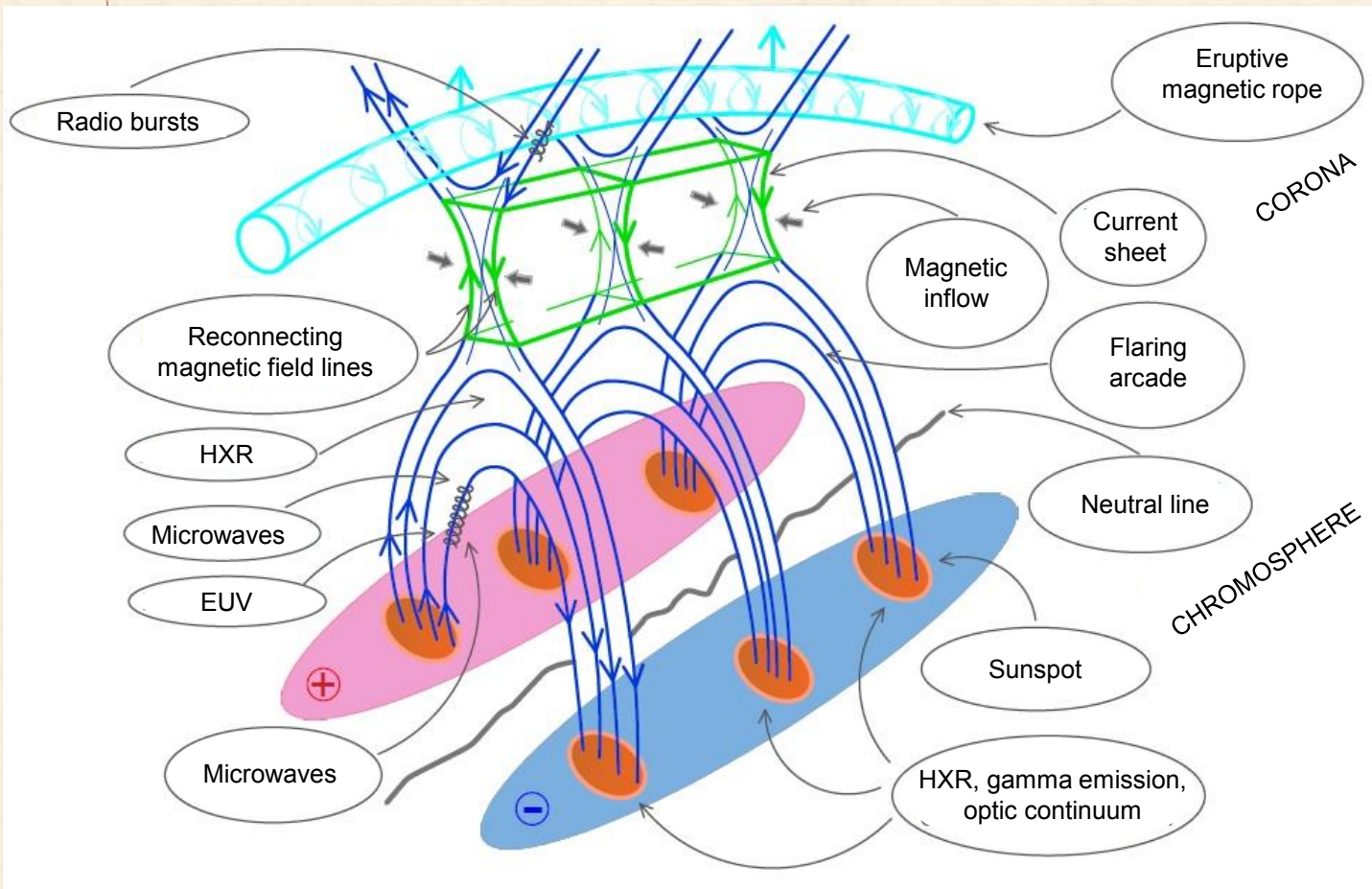
Two processes going on consequently simultaneous

Talk by Hui Tian yesterday

Evolving period

(C)

Global wavelet

Period (seconds)

64

32

16

8

95%

11:52   11:56   12:00
Start Time (12-Mar-15 11:48:02)

0.0   2.5   5.0
Power

- Two dominant periods at 19 s and 27 s
- The 19 s period: likely not the second harmonic, but caused by change of the loop internal condition (*N, B, L*)
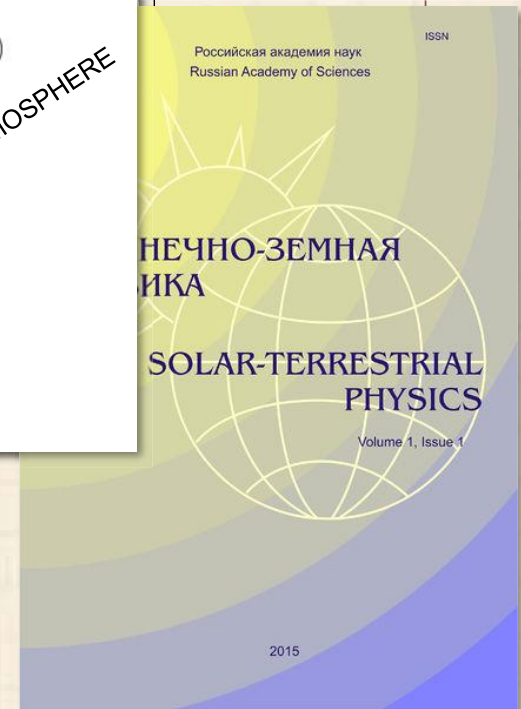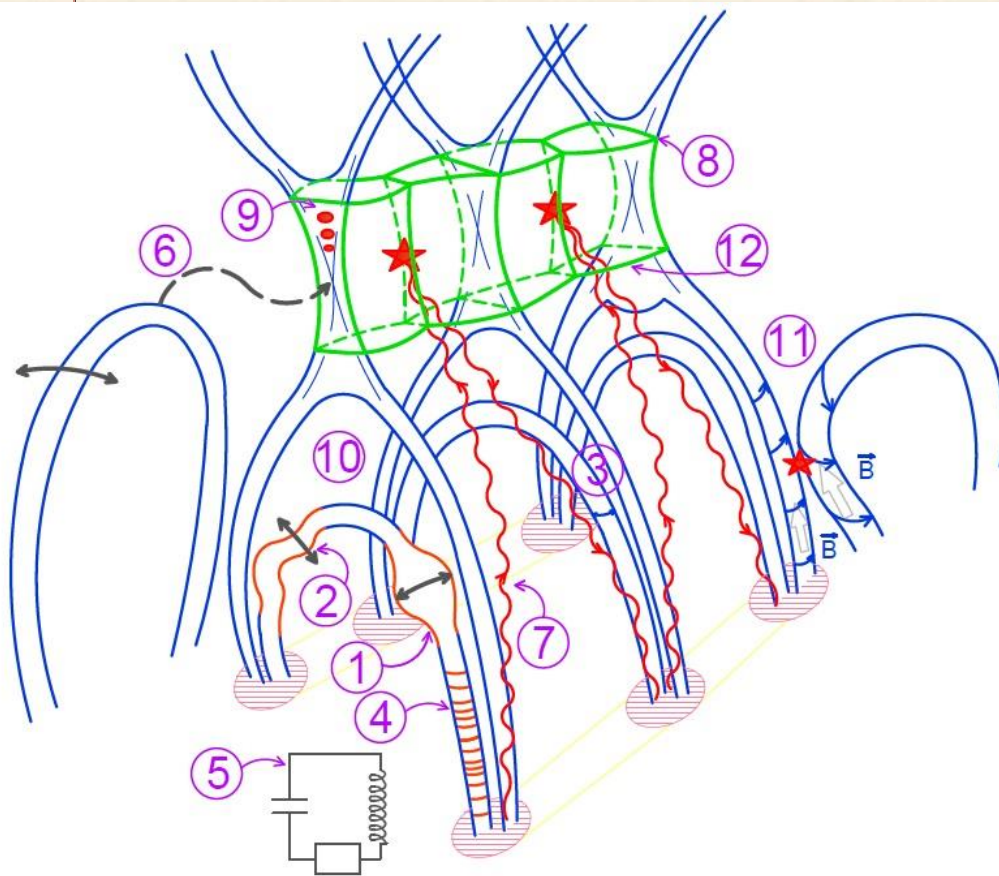
Mechanisms of QPPs

"Quasi-periodic pulsations in solar and
stellar flares"
E.G. Kupriyanova, D.Y. Kolotkov,
V.M. Nakariakov, A.S. Kaufman
STP 2019 (The review is under reviewing)

Mechanisms of QPPs

1 Sausage mode
   Nakariakov et al. (2012)

2 Kink mode

3 Torsion mode

4 Slow magnetoacoustic mode

5 RLC contour
   Zaitsev, Stepanov (2008)

8 Flapping oscillations
   Erkaev et al. (2007)

9 Auto-oscillations
   Murray et al. (2009)
   Nakariakov et al. (2010)

10 Oscillatory thermal instability
   Zavershinskii et al. (2019)

11 Oscillatory two-loop coalescence
   Tajima et al. (1987)
   Kolotkov et al. (2016)

12 Magnetic fork
   Takasao, Shibata (2016)

6 Periodically induced reconnection
   McLaughlin et al. (2011)
7 Nakariakov, Zimovets, 2011

MHD mechanism for non-stationarity

(Zaitsev, Stepanov 1975; Edwin, Roberts 1983; papers of Nakariakov and his team)

Period of the standing MHD wave or of Alfven wave in a loop:

$$P = \frac{2L}{n v_{\mathrm{ph}}}$$

$\begin{cases} L & \text{is loop length} \\ n & \text{is a harmonic number} \\ v_{\mathrm{ph}} & \text{is the phase speed} \end{cases}$

Dispersion equation of the MHD modes – stationary case:

$$\rho_e \left(v_{ph}^2 - v_{Ae}^2\right) \mu_0 \frac{Z'_m \left(\mu_0 a\right)}{Z_m \left(\mu_0 a\right)} + \rho_0 \left(v_{A0}^2 - v_{ph}^2\right) \mu_e \frac{Z'_m \left(\mu_e a\right)}{Z_m \left(\mu_e a\right)} = 0.$$

$\begin{cases} L, & a \\ N_{\mathrm{o}}, B_{\mathrm{o}}, T_{\mathrm{o}} \\ N_{\mathrm{e}}, B_{\mathrm{e}}, T_{\mathrm{e}} \end{cases}$

Parameters in dispersion equation depend on time. Changing of the physical parameters => changing the observables, parameters of QPPs => non-stationarity of the QPPs

What do we mean by non-stationary properties?

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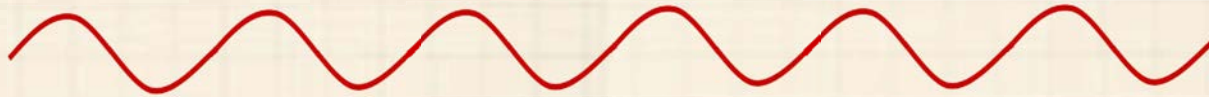
Any deviation from the harmonic shape is called Quasi-Periodic Pulsations (QPPs)

Really ANY deviation?

What is the upper limit of the deviation allowing not to fall to a noise?

Methods of analysis of QPPs: time profiles

➢ Fourier periodogram (of total time series, of the de-trended time series, AFINO code)

➢ Wavelet transform

➢ Empirical mode decomposition (EMD)

➢ Bayesian inference and Markov chains Monte Carlo (talk by Sergey Anfinogentov on Monday)

Significance tests are important !

Methods of analysis of QPPs: time profiles

A blueprint of state-of-the-art techniques for detecting quasi-periodic pulsations in solar and stellar flares

ANNE-MARIE BROOMHALL,[1,2] LAURA A. HAYES,[3] ANDREW R. INGLIS,[4] DMITRII Y. KOLOTKOV,[1] JAMES A. MCLAUGHLIN,[5] TISHTRYA MEHTA,[1] VALERY M. NAKARIAKOV,[1,6] YUTA NOTSU,[7] DAVID J. PASCOE,[8] CHLOE E. PUGH,[1] AND TOM VAN DOORSSELAERE[8]

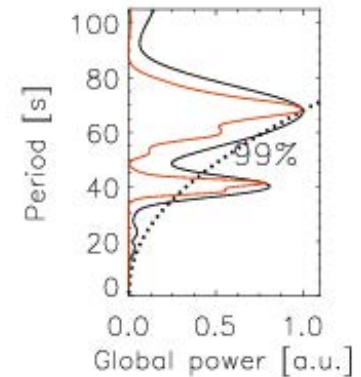8 methods were tested

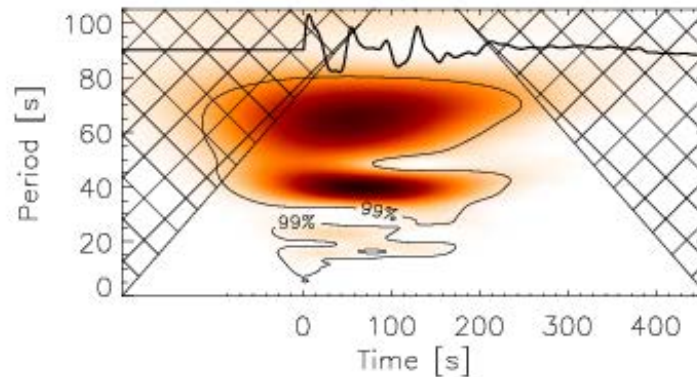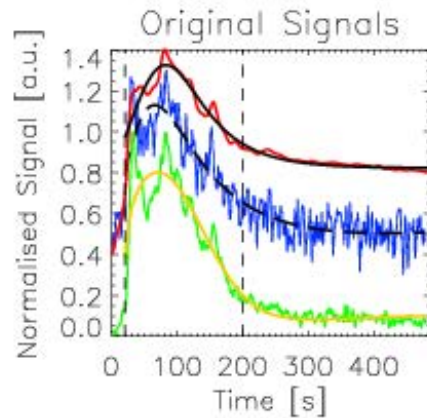**Non-stationarity** is better defined by EMD and MCMC
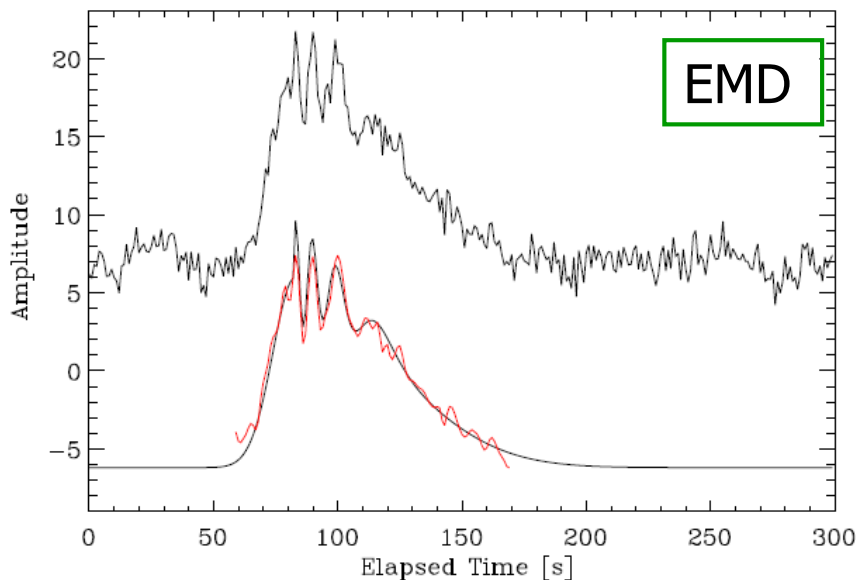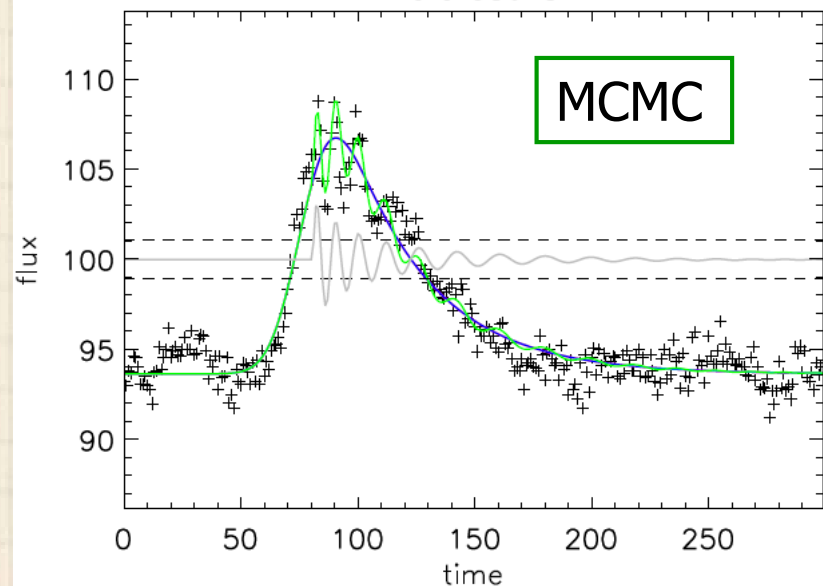
Flare B: 05-Sep-2017 01:30 UT
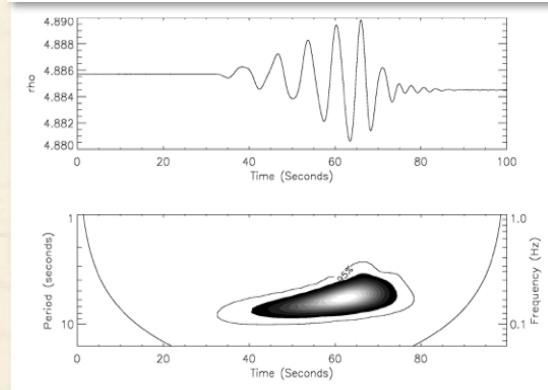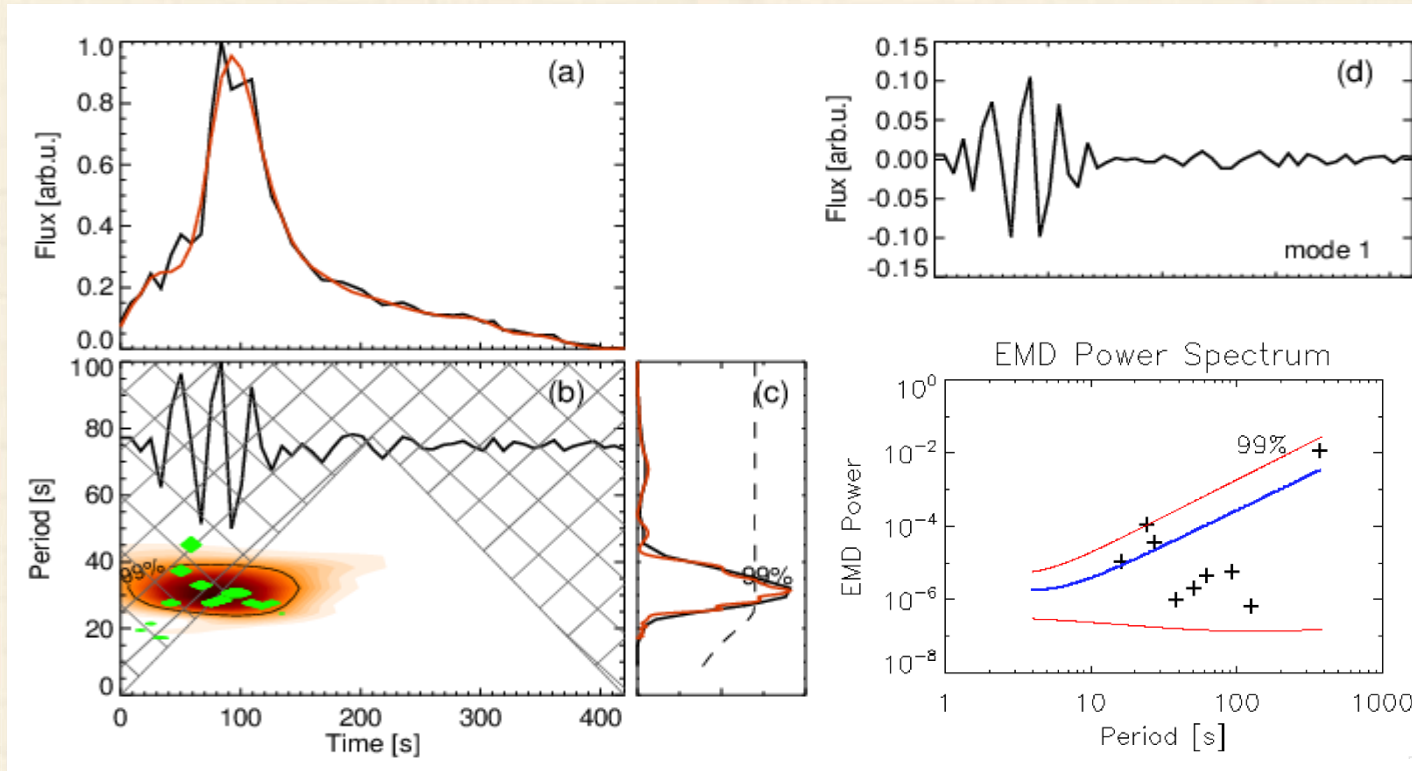## Multi-modal QPPs
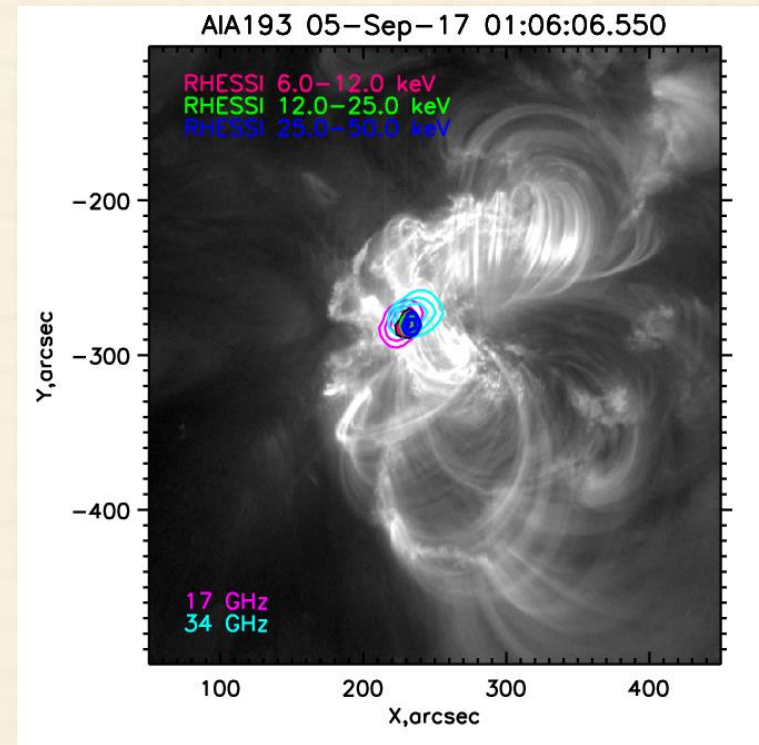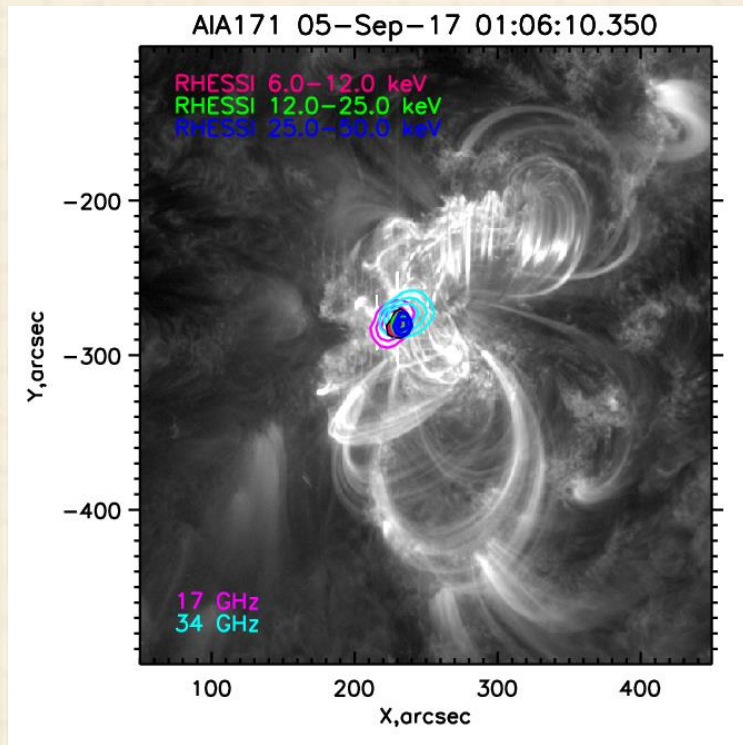
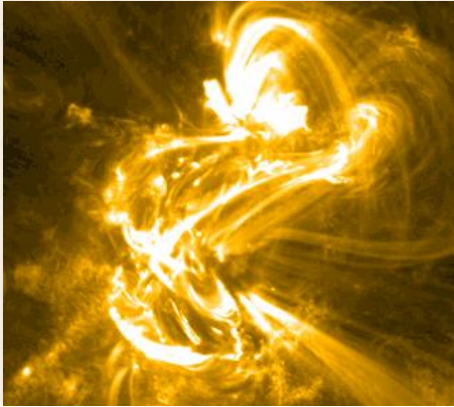# Flare B: 05-Sep-2017 01:30 UT Multi-modal QPPs
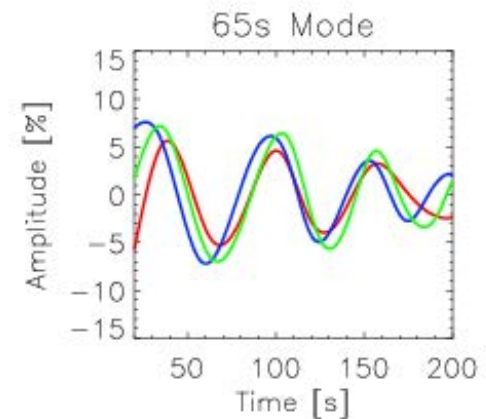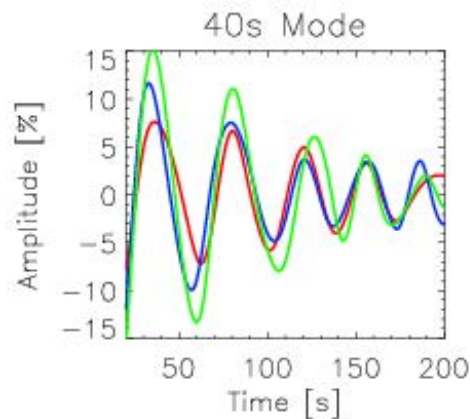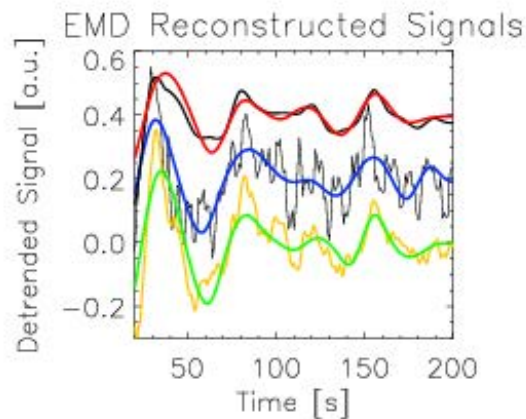
Flare C: 05-Sep-2017 07:06 UT
Natural non-stationarity.

Wavelet spectrum of "crazy tadpoles" (Nakariakov et al. 2004, MNRAS 349, 705).

Flare C: 05-Sep-2017 07:06 UT
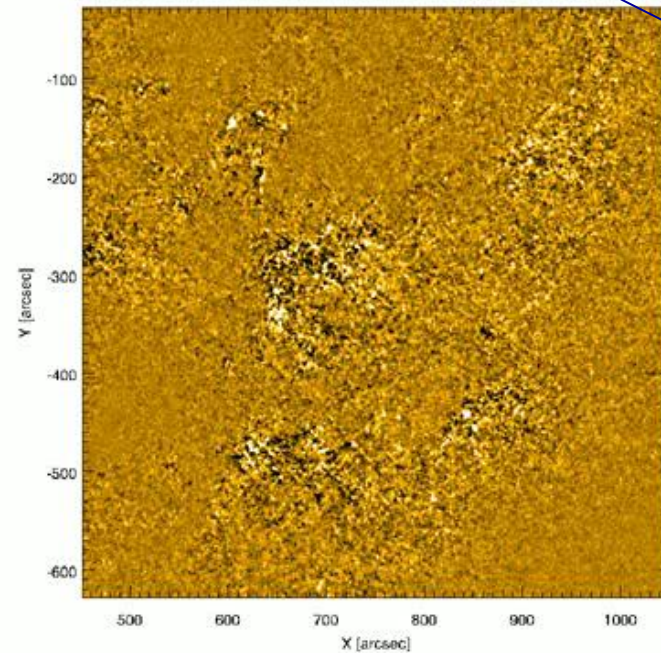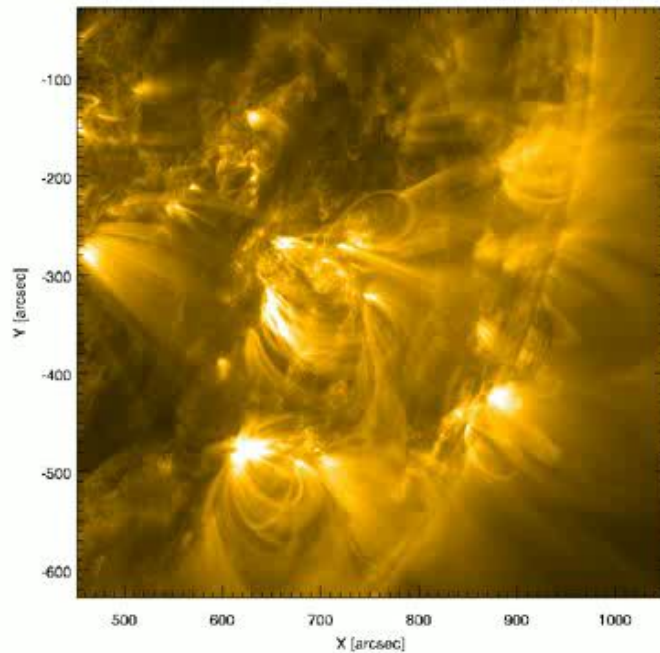# Natural non-stationarity.

Propagating quasi-periodic waves of

EUV intensity in lower corona

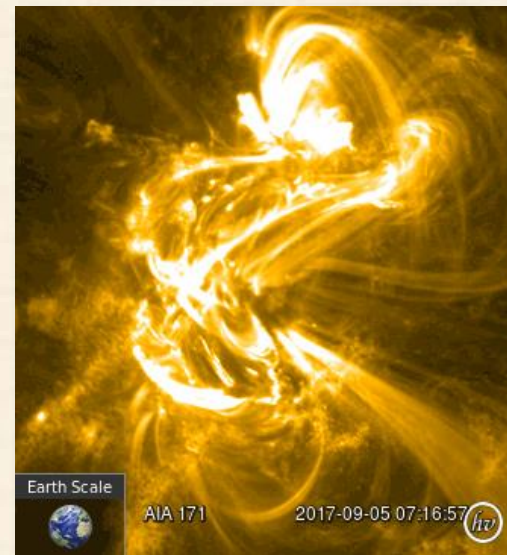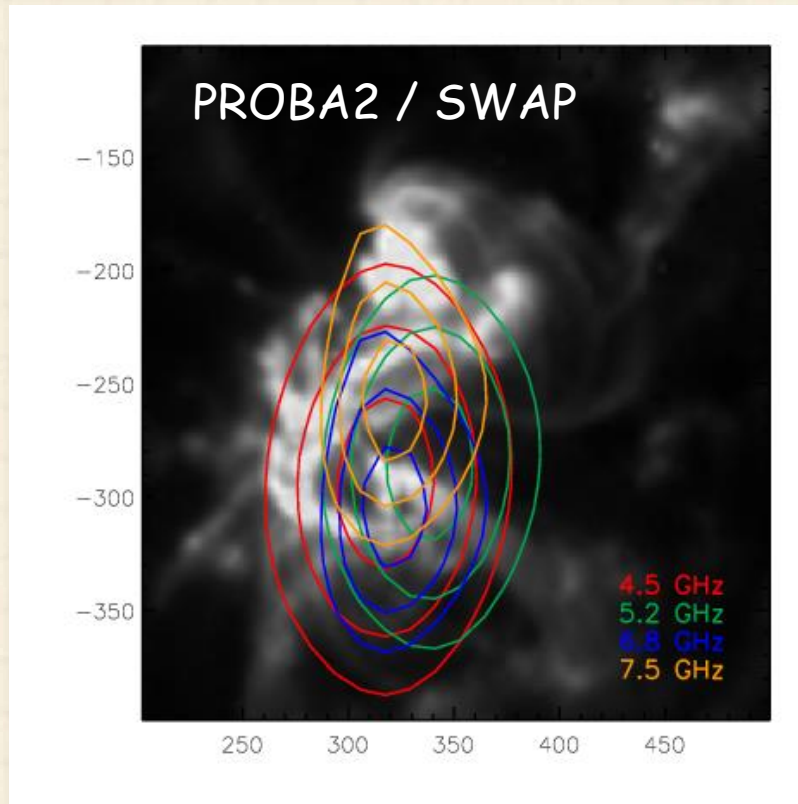Nistico et al. A&A, 2014

Also the talk by Leon Ofman yesterday
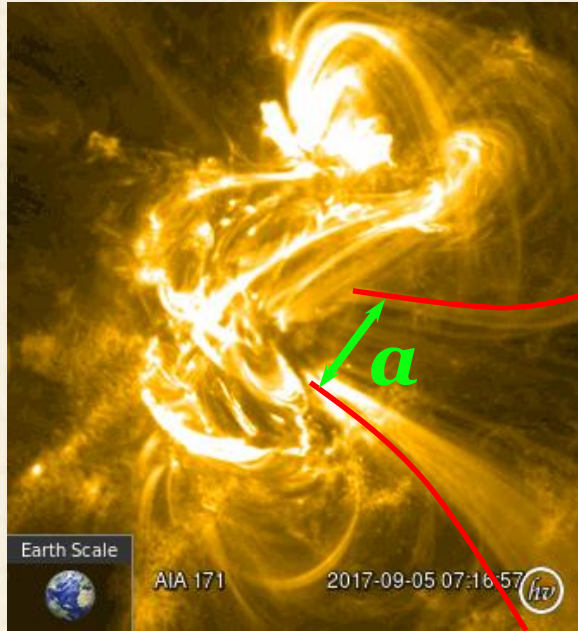

SDO/AIA 171 2013-12-07T07:00:23.34

Flare C: 05-Sep-2017 07:06 UT Natural non-stationarity.

Flare C: 05-Sep-2017 07:06 UT
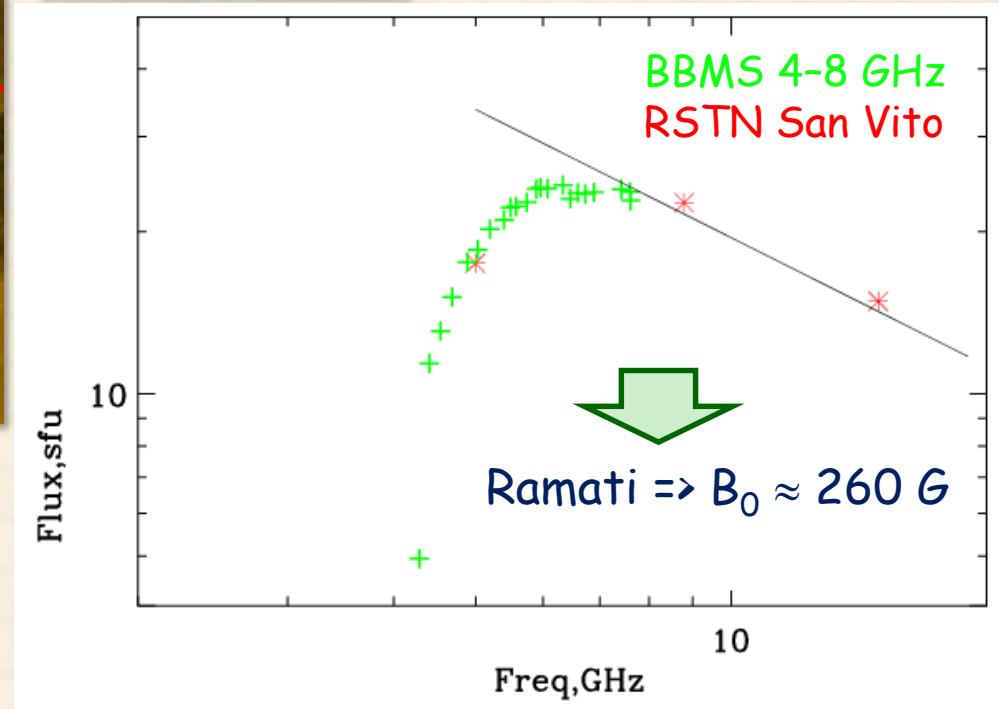## Natural non-stationarity.

$$P_1 \approx \frac{2.62a}{v_A}.$$

Roberts et al. 1983, 1984
Nakariakov et al. 2012

$a \approx 50" \approx 36000\ km$

$P \approx 30\ s$

$v_A \approx 3200\ km/s$

BBMS 4–8 GHz
RSTN San Vito

Ramati => $B_0 \approx 260\ G$

Flux, sfu

Freq, GHz

$B_0 = 260\ G$
$n_0 = 3 * 10^{10}\ cm^{-3}$
$v_A \approx 3300\ km/s$

$B_0 = 260\ G$
$n_0 = 10^{10}\ cm^{-3}$
$v_A \approx 5700\ km/s$

Conclusion

1. The non-stationary properties of QPPs are predicted by theory and they are observed by different instruments.

2. Two types of non-stationarity are introduced:
   1. natural non-stationarity associated with a time-dependent physical process
   2. the one appeared due to a multi-modal structure of QPPs

3. Methodic is under developing to detect and analyze the QPPs with non-stationary properties

4. Two solar flare are analyzed. Evidences are found of relation of the non-stationarity (the period shortening) to the propagating fast MHD mode.