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Signatures of inner-engine dynamics in GRBs as revealed by singular spectrum analysis

G. Greco (U. of Urbino; INFN-Firenze, Italy),
D. Konkdrashov, M. Ciszak, M. Ghil, F. Marino, A. Ortolan, C. Guidorzi, M. Branchesi

The image is a collage of various scientific findings and results, all pinned to a background of a star-filled galaxy. The findings include:

- Prompt's Morphology
- Prompt's Power Density Spectra
- Signal Hidden in Colored Noise
- Monte Carlo SSA
- Signal to Noise Separation! Build your Null-hypothesis!!!
- Extraneous GRB921002C signatures generation
- GRB921002C - a GRB model
- Parameters GRB-system model
- your noise, its volume counting
- Example BATSE GRB 920503 Monte Carlo SSA
- MC-SSA in single Channel
- Results
- Doublet mode in GRB 921002C jet precession?
- Cham!
- too short GRB three series

A large red megaphone icon is positioned on the right side, pointing towards a yellow sticky note that contains the word "Conclusion". Below the megaphone, there is a list of bullet points summarizing the findings:

- We propose a new data analysis methodology, MC-SSA, that succeeds in extracting inner-engine properties from the GRB prompt emission, where standard analyses do not.
- The deterministic components extracted by our analysis support the black-hole-disk-system model.
- The GRB engine reveals its presence through its precessional signature and it can potentially act as a GW source, observable by future low-frequency GW detectors.

merci!

Gamma-Ray Bursts in the Multi-messenger Era- Paris, 16-19 June 2014

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Signatures of inner-engine dynamics in GRBs as revealed by singular spectrum analysis

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The image shows a collection of scientific posters pinned to a dark, star-filled background, likely representing a galaxy or nebula. The posters cover topics such as:

- Prompt's Morphology
- Prompt's Power Density Spectra
- Signal Hidden in Colored Noise
- Monte Carlo SSA
- Signal to Noise Separation: Build your Null-hypothesis!!
- Example BATSE GRB 920403 Monte Carlo SSA
- MC-SSA in Single Channels
- Results
- One GRB made an evidence of jet precessions?
- Chandrasekhar GRB time series

A red pushpin is visible on the right side, pointing towards a large yellow sticky note labeled "Conclusion". The "Conclusion" note contains the following text:

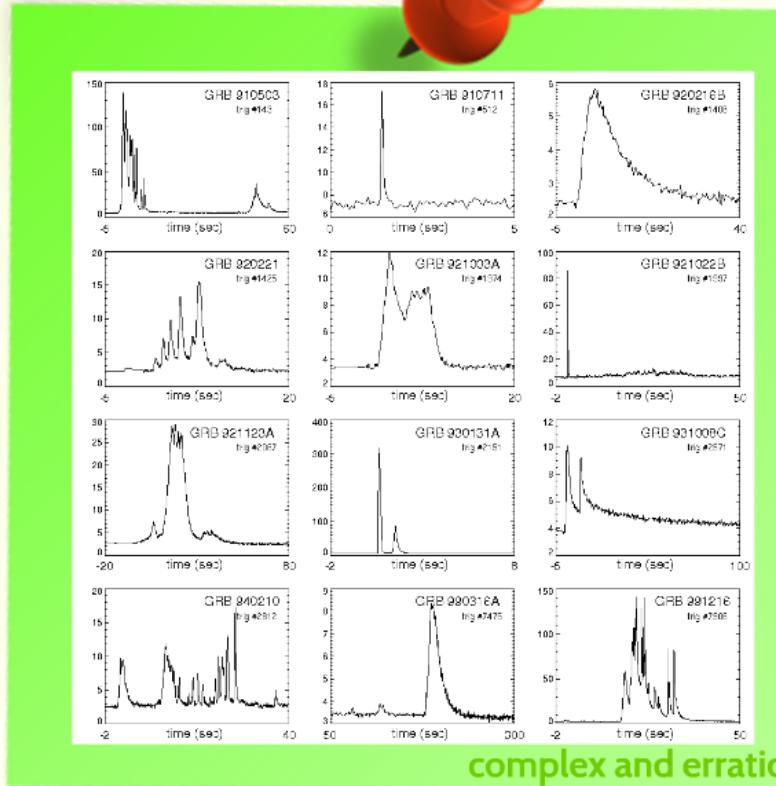
- We propose a new data analysis methodology, MC-SSA, that succeeds in extracting inner-engine properties from the GRB prompt emission, where standard analyses do not.
- The deterministic components extracted by our analysis support the black-hole-disk-system model.
- The GRB engine reveals its presence through its precessional signature and it can potentially act as a GW source, observable by future low-frequency GW detectors.

At the bottom right of the note, the word "merci!" is written.

Gamma-Ray Bursts in the Multi-messenger Era- Paris, 16-19 June 2014

Prompt's Morphology

The prompt gamma-ray emissions from GRBs exhibit a vast range of extremely complex temporal.



The analysis of such variability is crucial to understand the physical mechanisms driving the internal engine

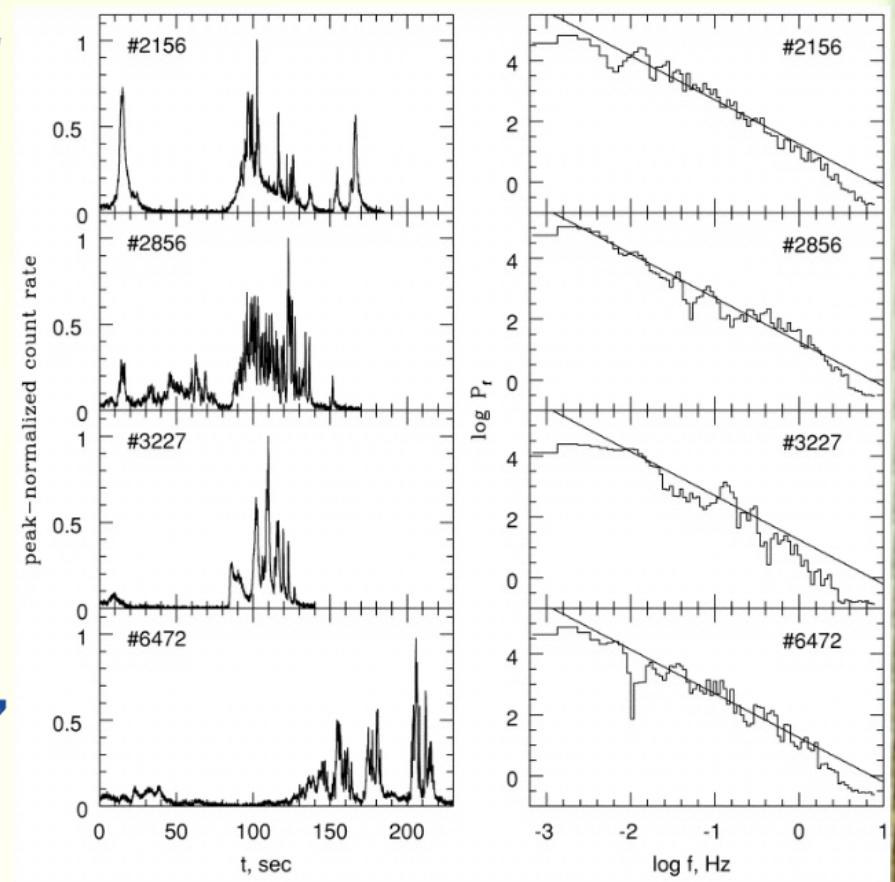
"When you have seen one GRB, you have seen one GRB"

pulse decomp.
Quilligan et al 99; McBreen
04)
pulse-fitting (Norris et al.
96; Lee et al. 00; Hakkila et
al. 14; Kocevski et al. 03)
variability (Ramirez-Ruiz &
Merloni 01; Greco 09)
.....to mention a few

Prompt's Power Density Spectra

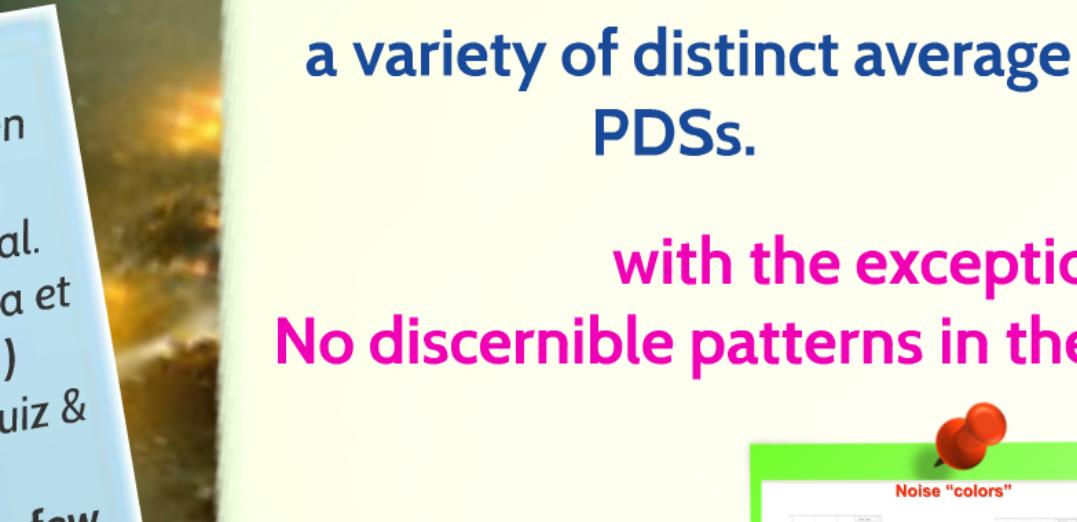
GRBs have an average power density spectrum (PDS) that behaves at large frequencies f like a power-law $1/f^\alpha$, where $\alpha = 5/3$.

While this power-law index appears to be compatible with a Kolmogorov spectrum, individual GRBs still exhibit a variety of distinct average PDSs.

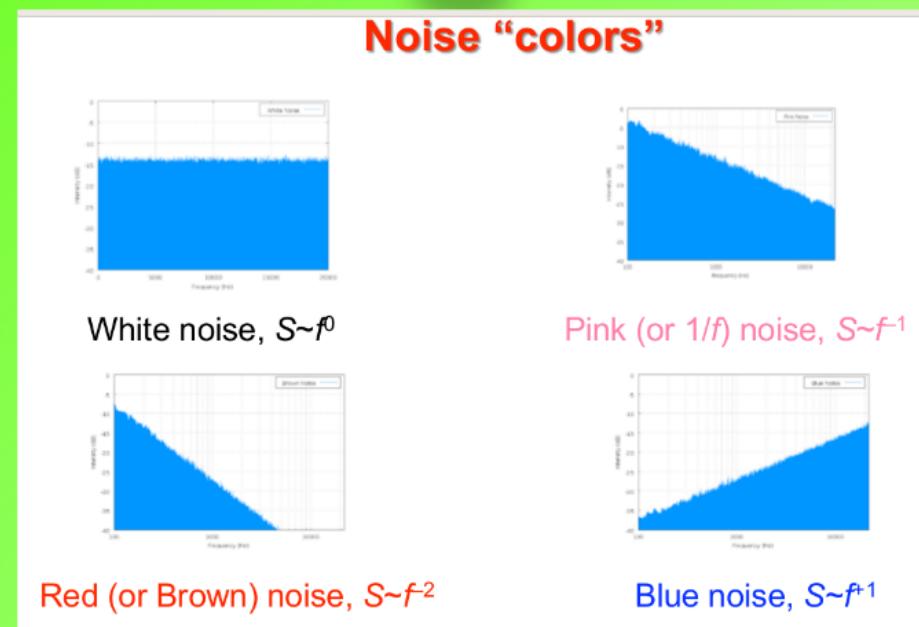


Beloborodov et al., 1999

with the exception of a few cases
No discernible patterns in the time-frequency domain.



patterns in the time-frequency



Colored noise: processes in which power declines monotonically with increasing frequency.

To identify irregular deterministic dynamics in experimental data is extremely challenging, in particular, when the time-series is corrupted by random process with colored power spectral density - like GRBs.

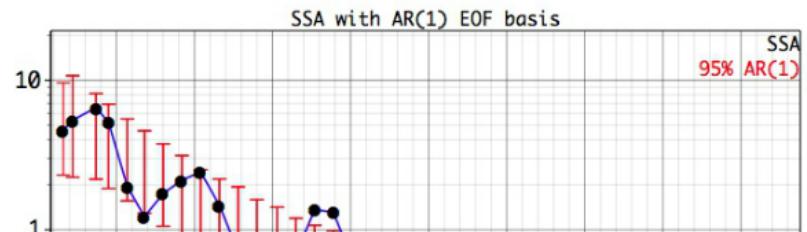
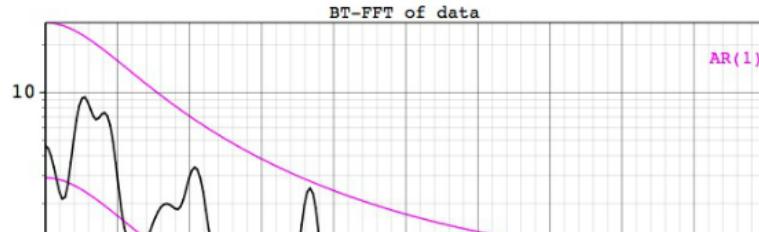
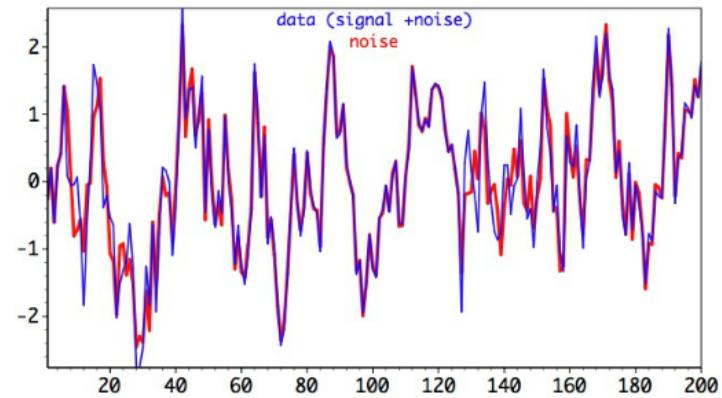
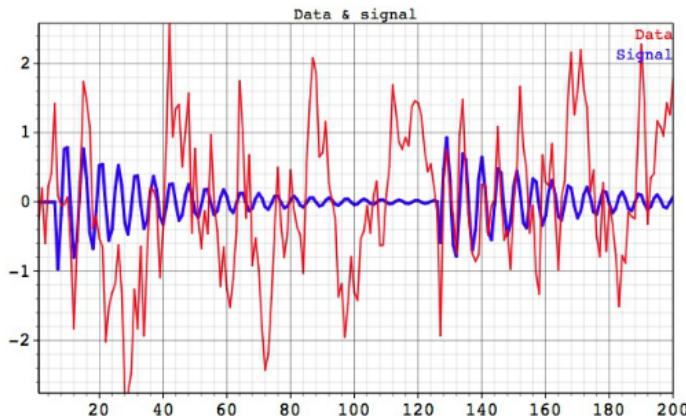
Signal Hidden in Colored Noise

This synthetic test series consists of randomly-generated damped oscillations bursts superimposed on large amplitude AR(1) noise.

The period of the oscillations is 5.5 units, which corresponds to the frequency $f=0.181$ Hz.

The red line is the noise, while the blue is the oscillatory signal.

noise + signal
against noise component only.

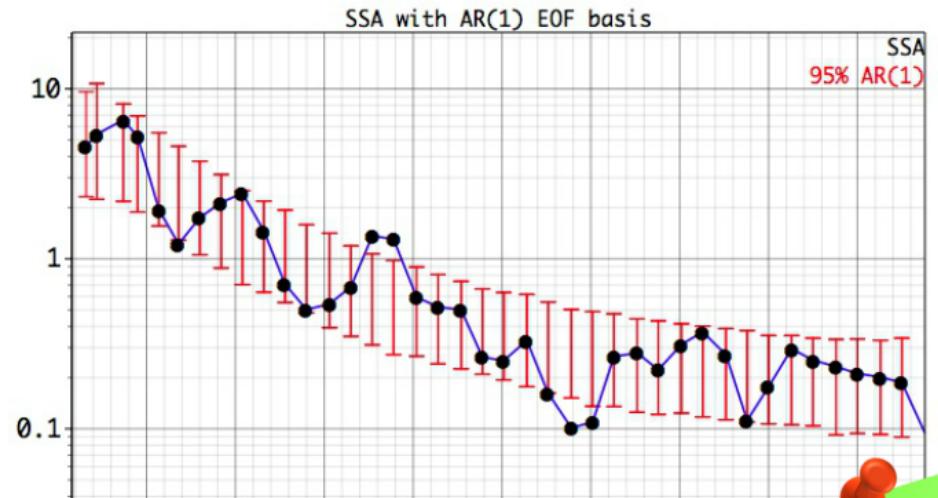
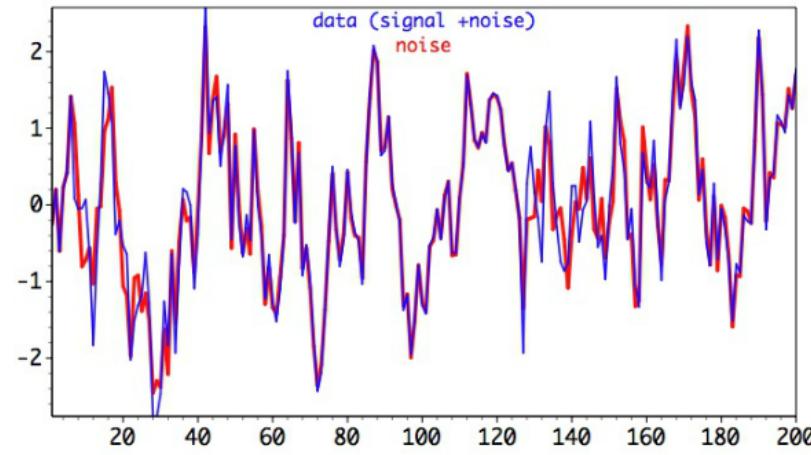
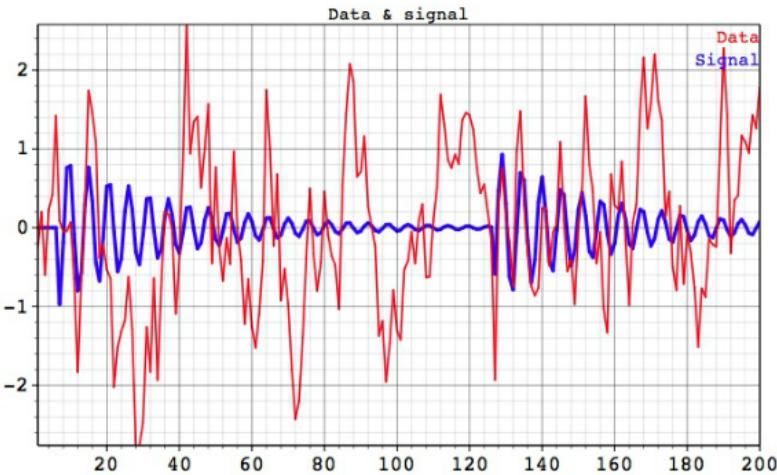


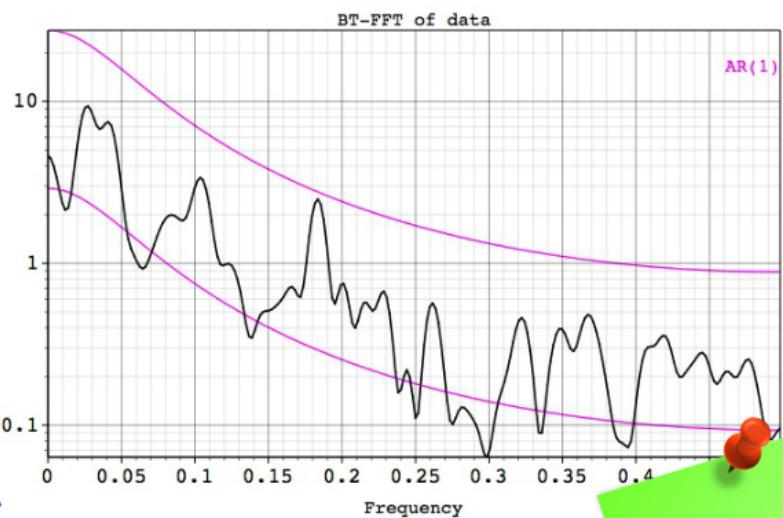
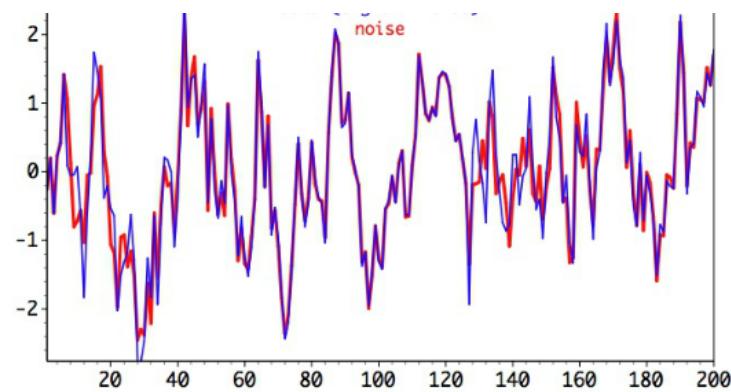
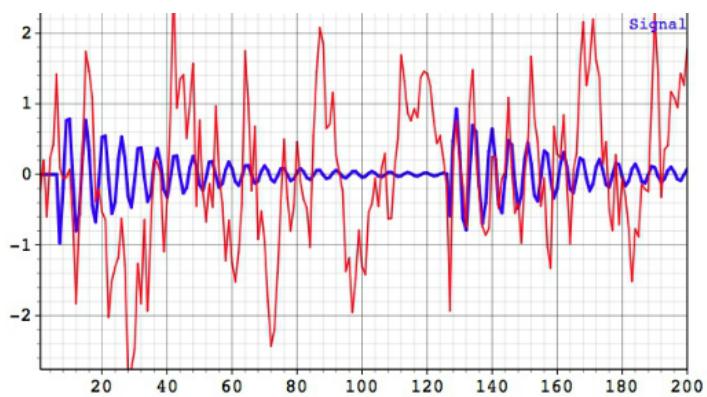
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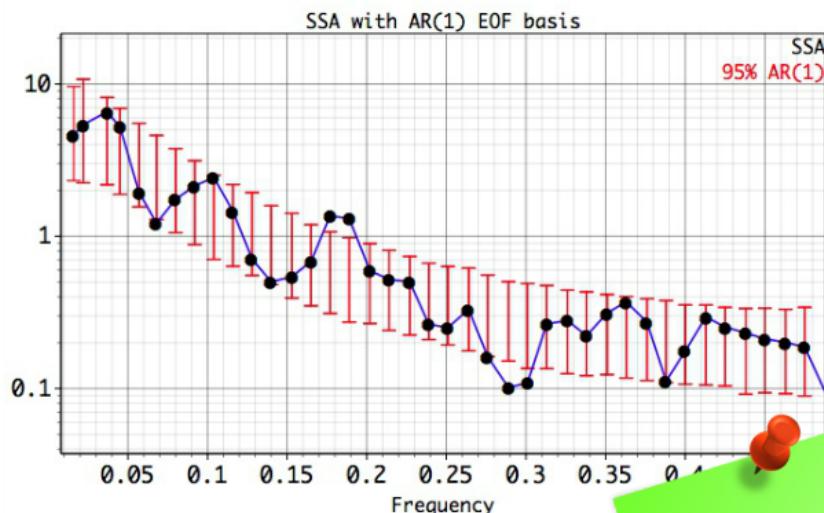
noise + signal
against noise component only.





<http://www.spectraworks.com/>

Results from
Blackmat-Tukey FFT
do not show any
significant peaks!



MC-SSA confirms that
there is significantly
elevated variance at
0.18 Hz!

**formulation of the problem: to detect irregular deterministic signal (if there are)
in colored noise**

Monte Carlo SSA

- SSA is an effective, data-adaptive and non-parametric method for the decomposition of a time series into a well-defined set of independent and interpretable components (non-linear trend, anharmonic, amplitude-modulated oscillations, and a proper noise-model).
- In this context, the Monte Carlo approach to signal to-noise separation introduced by Allen & Smith has become known as Monte Carlo SSA (MC-SSA) .

Given a time series $\{x(t), t = 1, \dots, N\}$ of length N , we build an M -dimensional phase space by using M lagged copies of x .

$$\mathbf{X} = \begin{pmatrix} x(1) & x(2) & \dots & x(M) \\ x(2) & x(3) & \dots & x(M+1) \\ \vdots & \vdots & \dots & \vdots \\ x(N-M+1) & x(N-M+2) & \dots & x(N) \end{pmatrix}$$

from \mathbf{X} , we estimate the covariance matrix

$$\mathbf{C} = \mathbf{X}'\mathbf{X}/N$$

$x(t)$ is shifted of a constant value called window length M

Due to finite-size effects for small N , \mathbf{C} may deviate from symmetry; thus, we use the more accurate Toeplitz approach

$$c_{ij} = \frac{1}{N - |i-j|} \sum_{t=1}^{N-|i-j|} x(t)x(t + |i-j|)$$

the symmetric covariance matrix is diagonalized $\Lambda = \mathbf{E}^T \mathbf{C} \mathbf{E}$

Allen, M. R. & Smith, L. A.
J. Climate. 9, 3373-3404
(1996).

Vautard, R., Yiou, P. & Ghil,
Physica D. 58, 95-126 (1992).
Ghil, M. et al. Rev. Geophys.
40, 1-41 (2002).

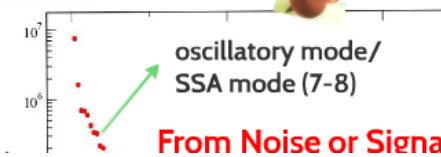
By projecting the time series $x(t)$ onto each of the M eigenvectors \mathbf{E}_k , we get the M principal components (PCs),

$$a_k(t) = \sum_{j=1}^M x(t+j-1)\mathbf{E}_k(j) \quad 1 \leq t \leq N - M + 1.$$

The PCs are the projections of x onto the new basis; in this case, the window width is M .

Oscillatory modes

In order to identify periodic or quasi-periodic behavior in the original signal, we select the eigenvalues at times form a pair, with their variances being nearly equal, while the corresponding eigenvectors have the same period and are in phase quadrature.



Given a time series $\{x(t), t = 1, \dots, N\}$ of length N , we build an M -dimensional phase space by using M lagged copies of x .

$$X = \begin{pmatrix} x(1) & x(2) & \dots & x(M) \\ x(2) & x(3) & \dots & x(M+1) \\ \vdots & \vdots & \dots & \vdots \\ x(N-M+1) & x(N-M+2) & \dots & x(N) \end{pmatrix}$$

x(t) is shifted of a constant value called window length M

from X , we estimate the covariance matrix

$$C = X'X/N$$

Covariance Window

Due to finite-size effects for small N , C may deviate from symmetry; thus, we use the more accurate Toeplitz approach

$$c_{ij} = \frac{1}{N - |i - j|} \sum_{t=1}^{N - |i - j|} x(t)x(t + |i - j|)$$

the symmetric covariance matrix is diagonalized $\Lambda = E^T C E$

to yield a diagonal matrix Λ of eigenvalues λ_k and an orthogonal matrix E . They represent the new M -dimensional basis and λ_k describes the variance of X in the direction of $E k$.

since the eigendecomposition is a similarity transformation of C , the variance of the original time series $x(t)$ is preserved in the eigenvalues, which now lie along the main diagonal of Λ

By projecting the time series $x(t)$ onto each of the M eigenvectors \mathbf{E}_k , we get the M principal components (PCs),

$$a_k(t) = \sum_{j=1}^M x(t+j-1)\mathbf{E}_k(j) \quad 1 \leq t \leq N - M + 1.$$

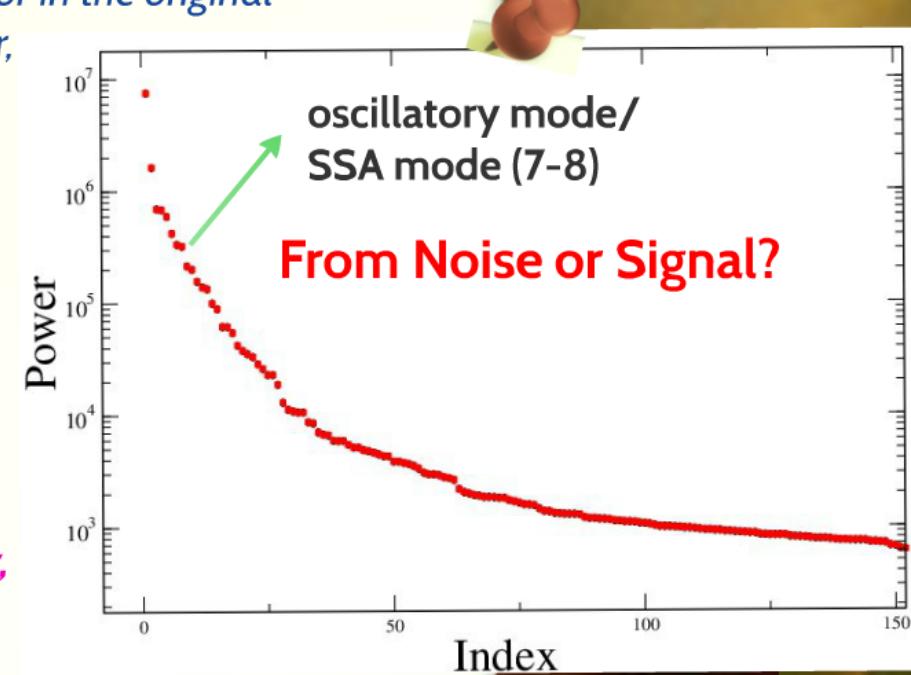
The PCs are the projections of x onto the new basis; in this case, the window width is M .

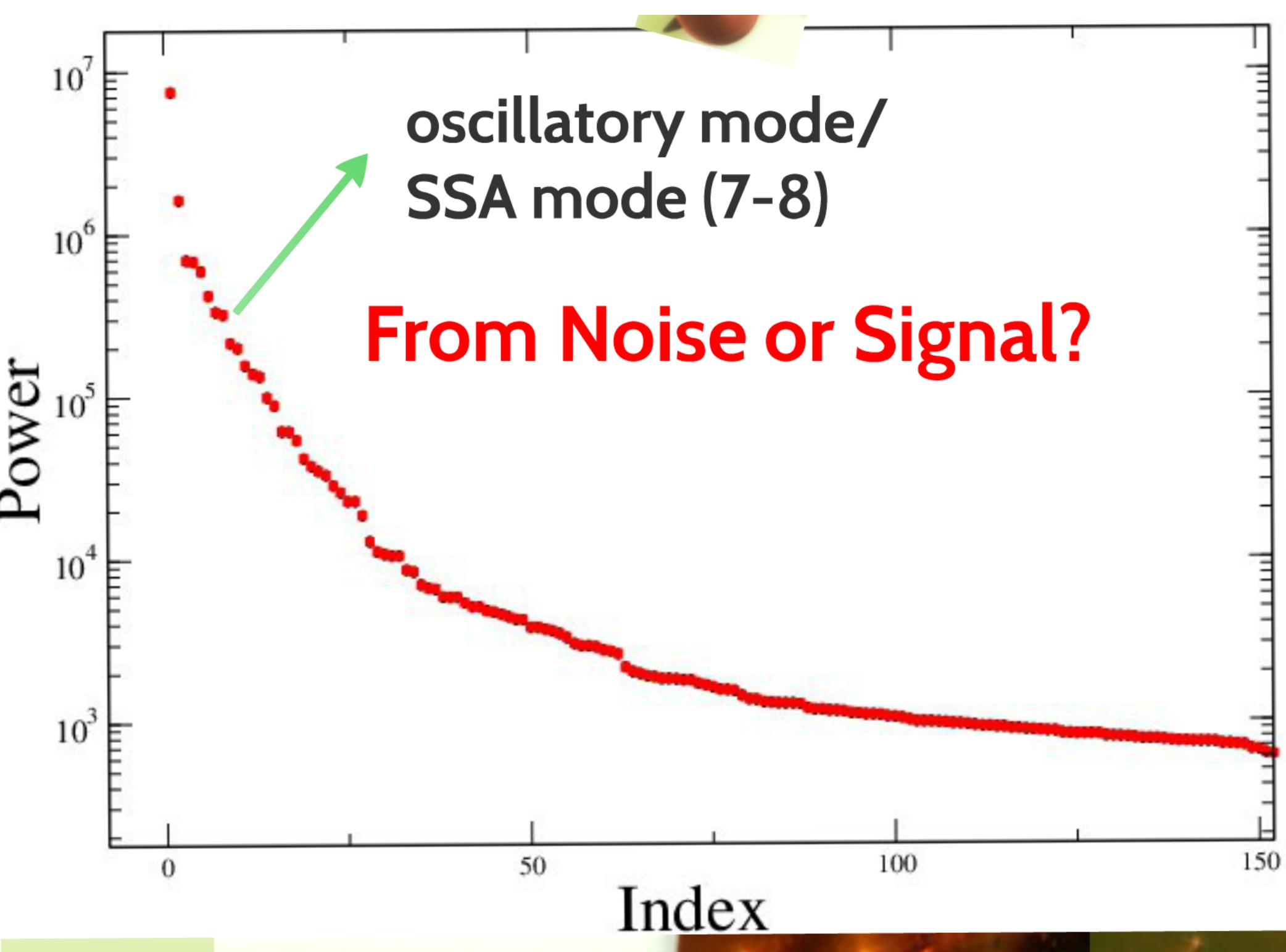
Oscillatory modes

In order to identify periodic or quasi-periodic behavior in the original signal, we select the eigenvalues at times form a pair, with their variances being nearly equal, while the corresponding eigenvectors have the same period and are in phase quadrature.

These so-called “oscillatory-modes” are the analog of sine-and-cosine pairs in Fourier analysis and adaptively capture the oscillations present in the system.

- a pair can efficiently represent even a nonlinear, anharmonic oscillation.





Signal to Noise Separation: *Build your Null-hypothesis!!!*

- choose a "suitable" noise GRB model

$$\text{AR(1): } X_t = \gamma(x_{t-1} - \mu_0) + \alpha z_t + \mu_0 ;$$

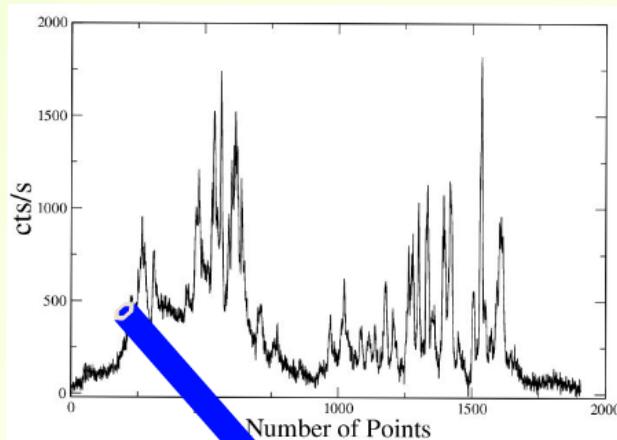
gaussian-distributed white-noise process its mean

the AR(1) coefficients γ and α are estimated from the time-series under consideration by using a maximum-likelihood criterion.

- A set of S surrogate time series is generated from S replicas of the process AR(1).
 - Subsequently, these surrogates are corrupted by Poisson noise to mimic the effect of the CCD shot noise

The time series surrogates are used "to draw" the MC-SSA error bars

Example: BATSE GRB 920513 surrogates generation



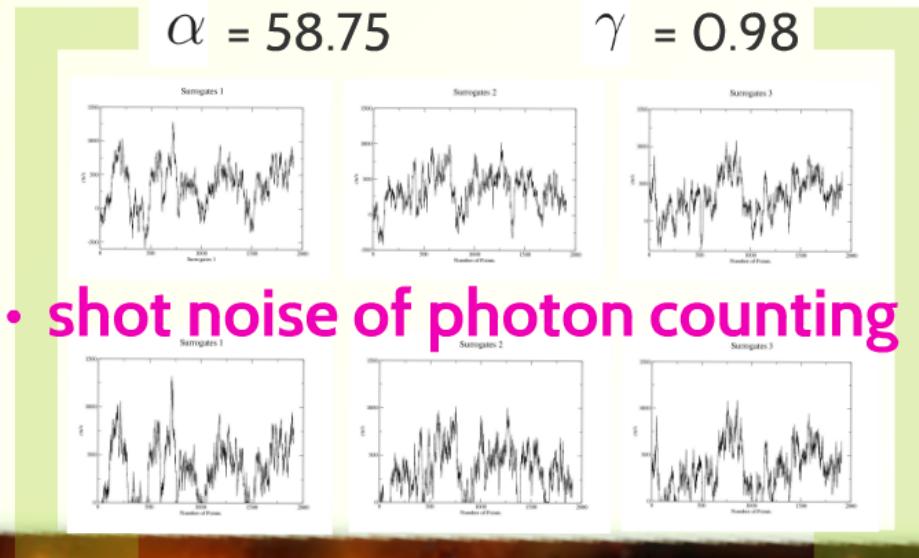
- Number of points = 1907
- time resolution = 64 ms
- background subtracted
- Ch. (1 : 3) 20 - 300 keV



• Parameters AR(1)-noise model

$$\alpha = 58.75$$

$$\gamma = 0.98$$

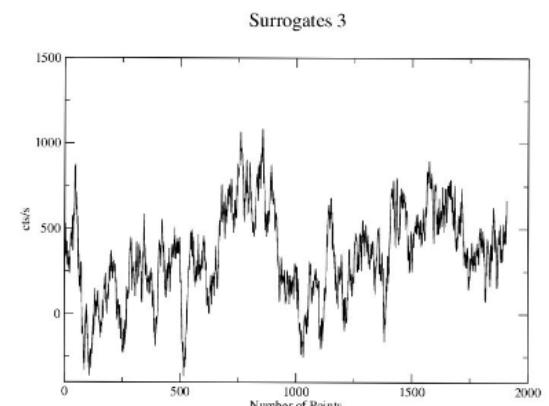
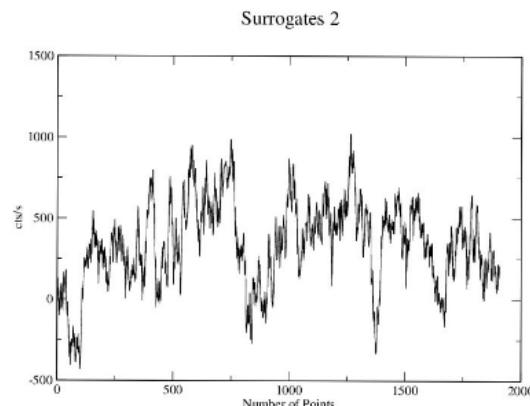
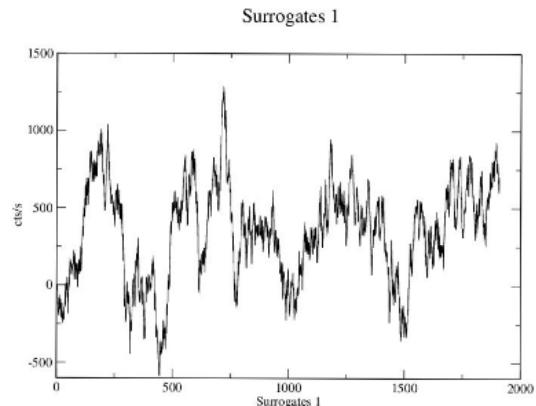


• shot noise of photon counting

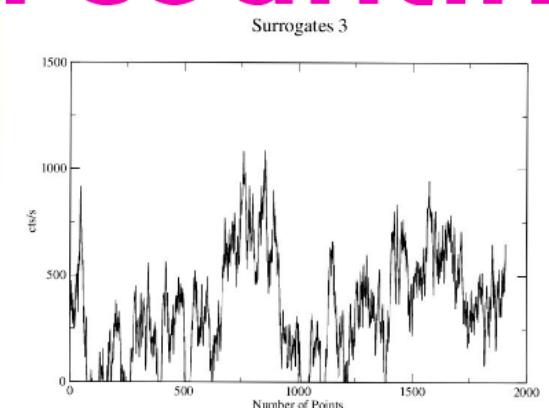
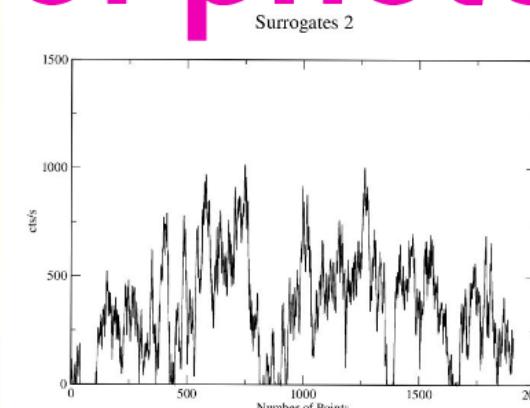
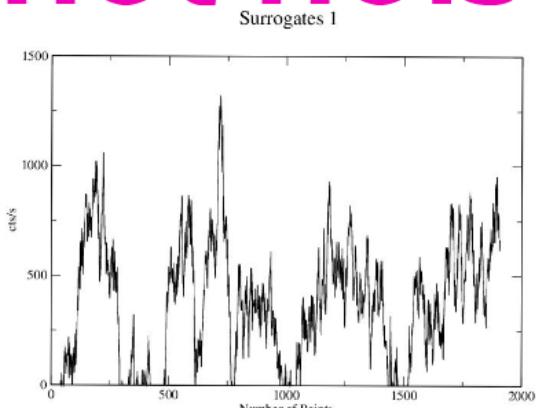
The time series surrogates used "to draw" the MC-SSA error bars

$$\alpha = 58.75$$

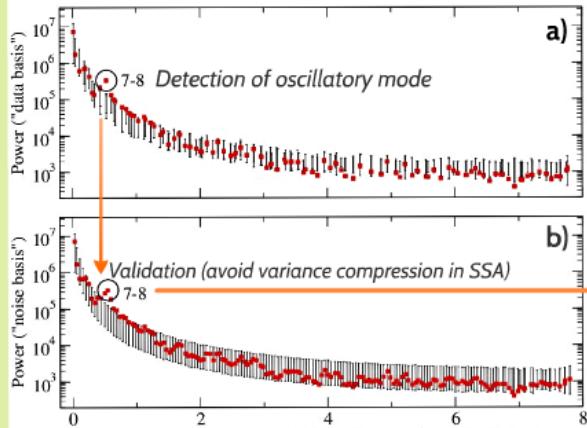
$$\gamma = 0.98$$



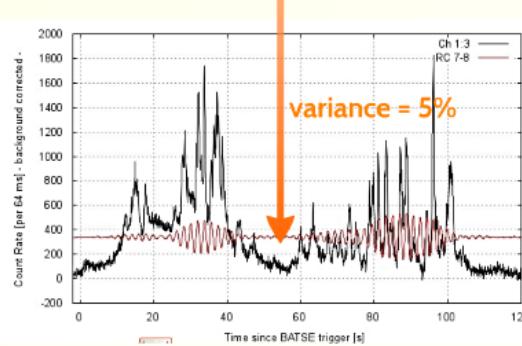
• shot noise of photon counting



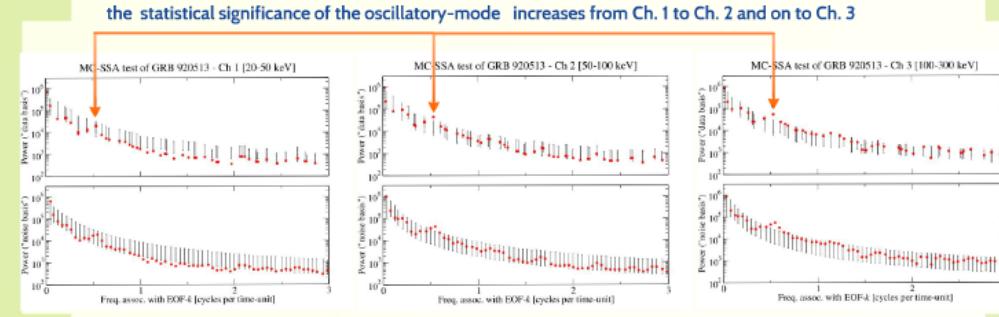
Example: BATSE GRB 920513 Monte Carlo SSA



Reconstruction



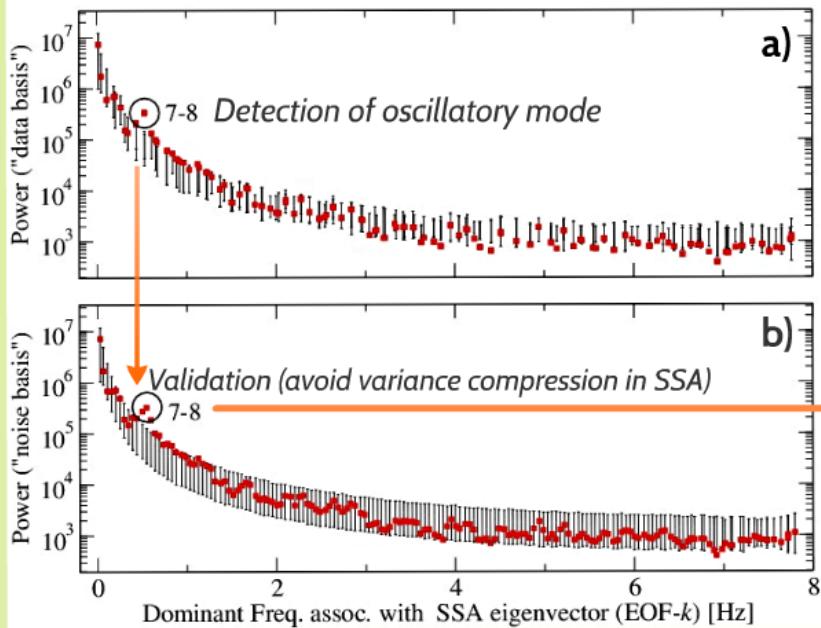
MC-SSA in single Channels



This result could explain the empirical observation that the same GRB pulse appears to be narrower and spikier at higher energies (Norris et al., 1996)

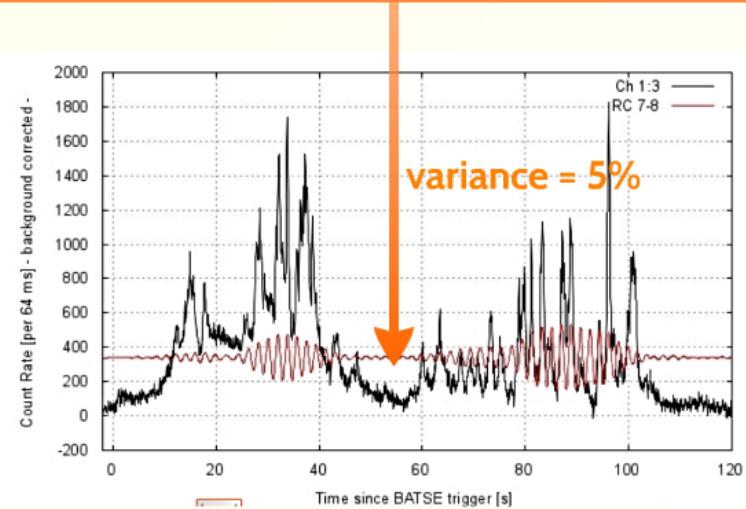
Example: BATSE GRB 920513

Monte Carlo SSA



MC-SSA test of the prompt emission from GRB 920513

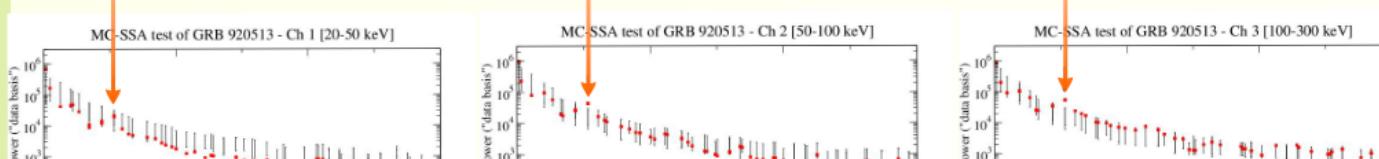
Reconstruction



time- domain reconstruction of the oscillatory mode corresponding to the eigenvalue pair 7-8.

MC-SSA in single Channels

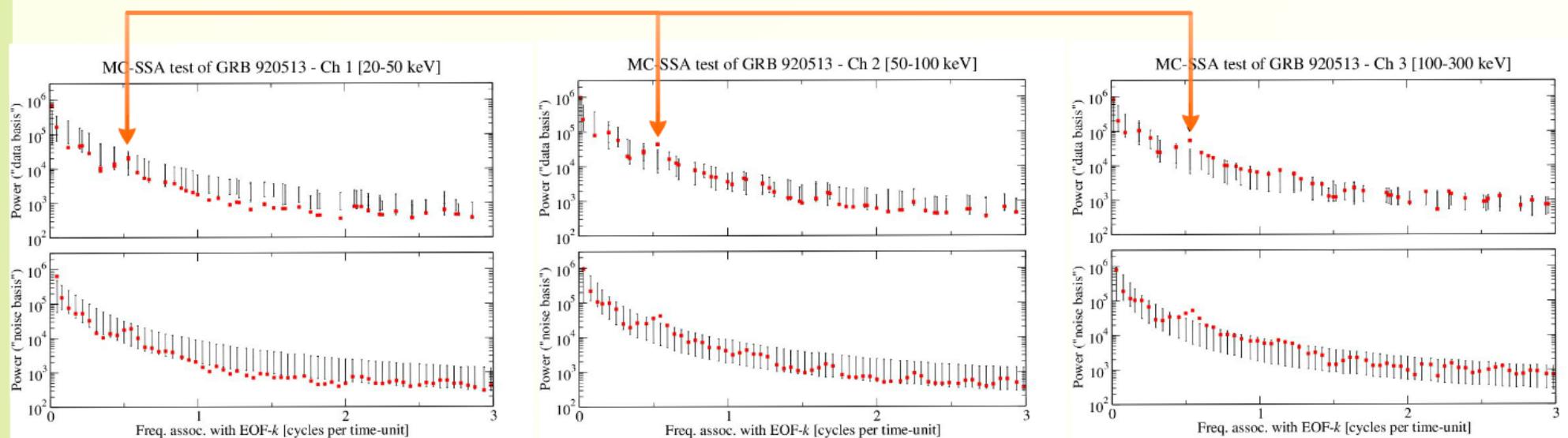
the statistical significance of the oscillatory-mode increases from Ch. 1 to Ch. 2 and on to Ch. 3



This result could explain empirical observation

MC-SSA in single Channels

the statistical significance of the oscillatory-mode increases from Ch. 1 to Ch. 2 and on to Ch. 3



the confidence level is 99.9%



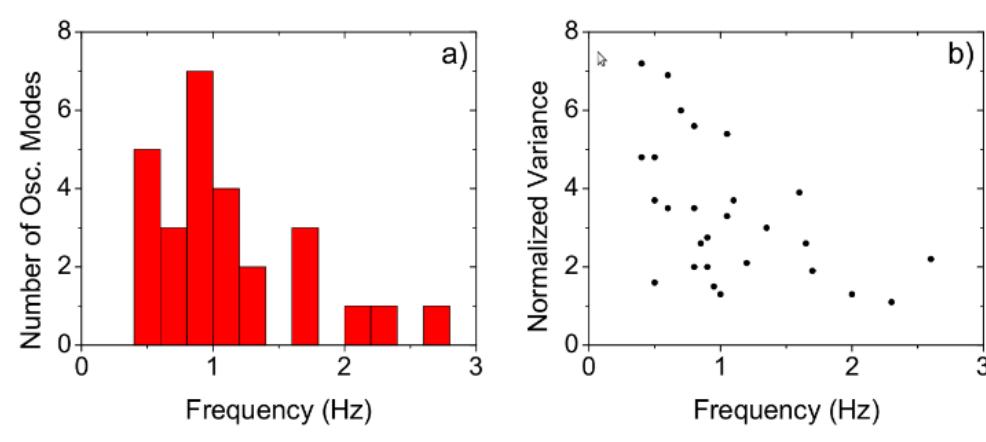
This result could explain the empirical observation that the same GRB pulse appears to be narrower and spikier at higher energies (Norris et al., 1996)

Results

We applied the MC-SSA analysis to a BATSE sample of **70** bright and multistructured GRBs light-curves.

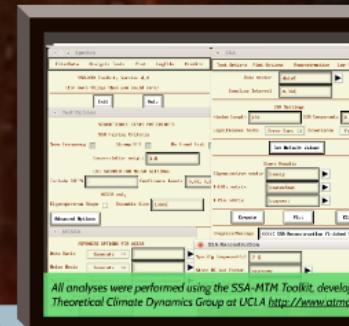
in **20** GRBs -----> H_0 is rejected

in **50** GRBs -----> H_0 is accepted



a) *Histogram of the dominant frequencies associated with the detected oscillatory modes in the selected GRB sample.*

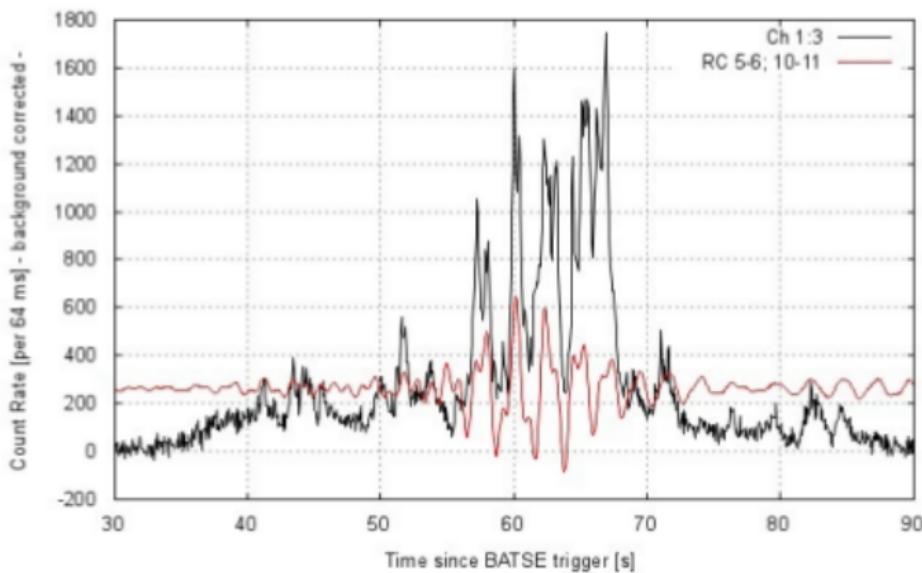
b) *Plot of the normalized variances vs the dominant frequencies.*



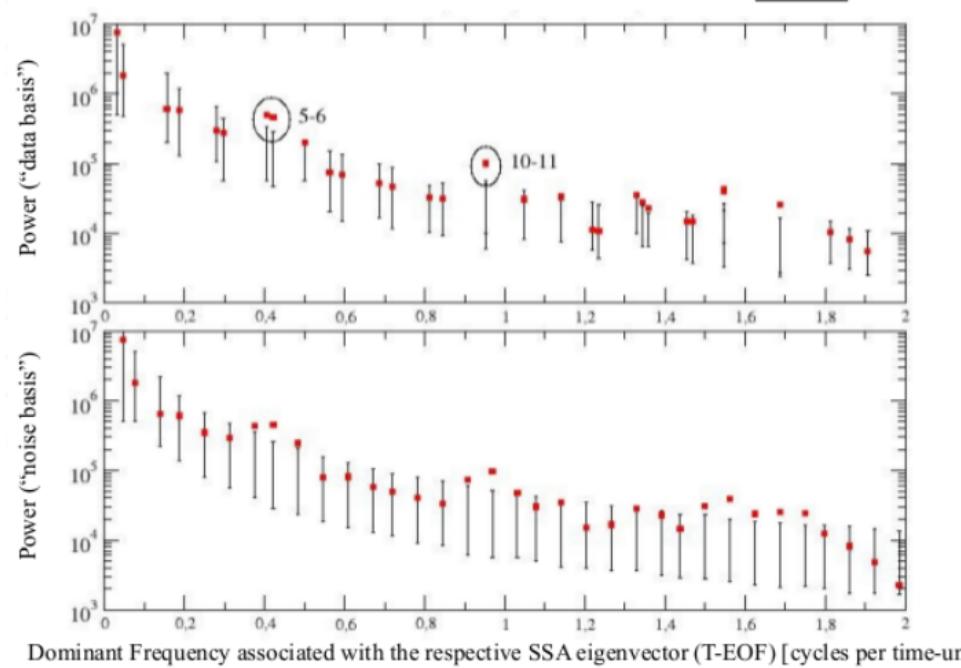
Oscillatory Modes

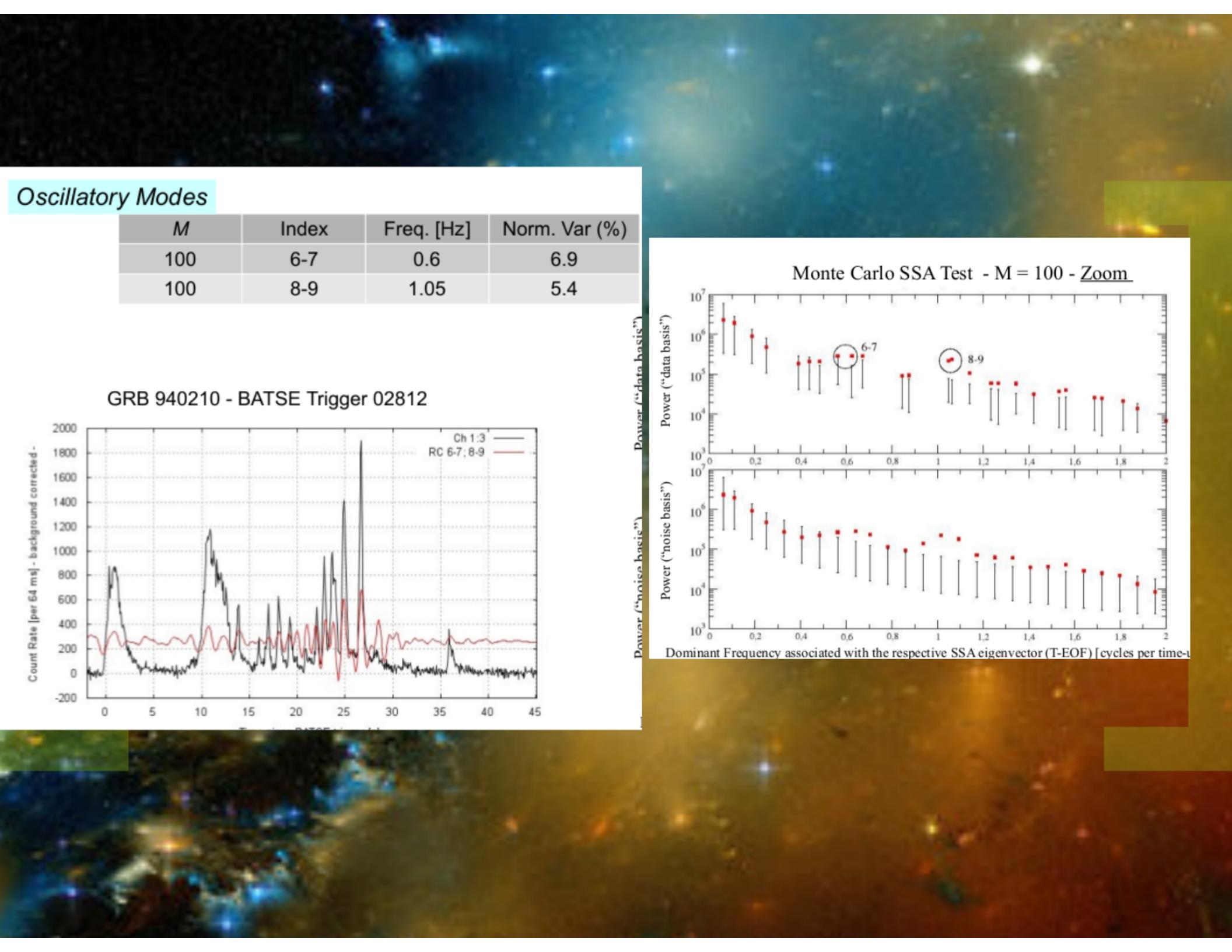
| M | Index | Freq. [Hz] | Norm. Var (%) |
|-----|-------|------------|---------------|
| 130 | 5-6 | 0.4 | 7.2 |
| 130 | 10-11 | 0.95 | 1.5 |

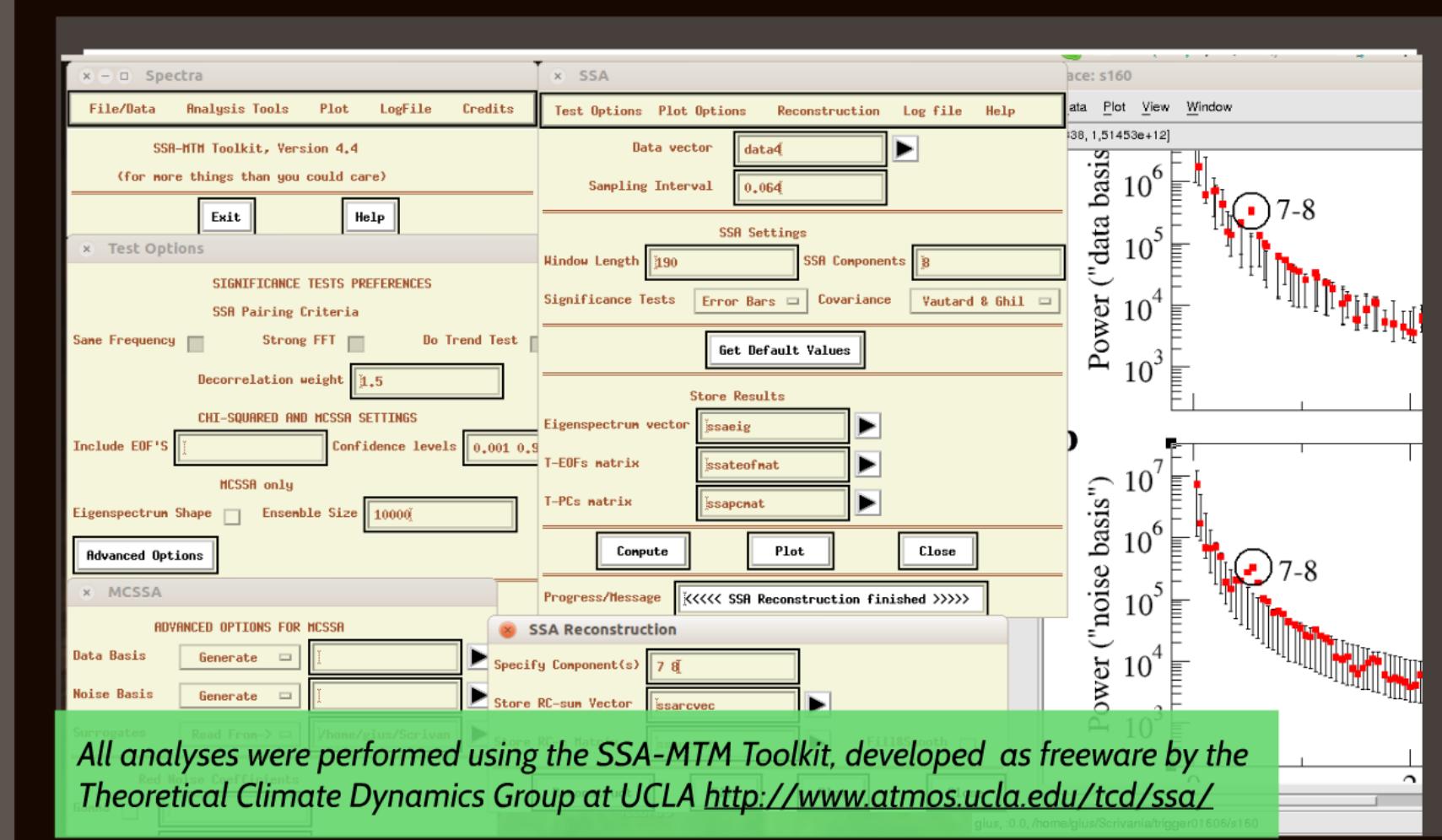
GRB 930720A - BATSE Trigger 02450



Monte Carlo SSA Test - M = 130 - Zoom

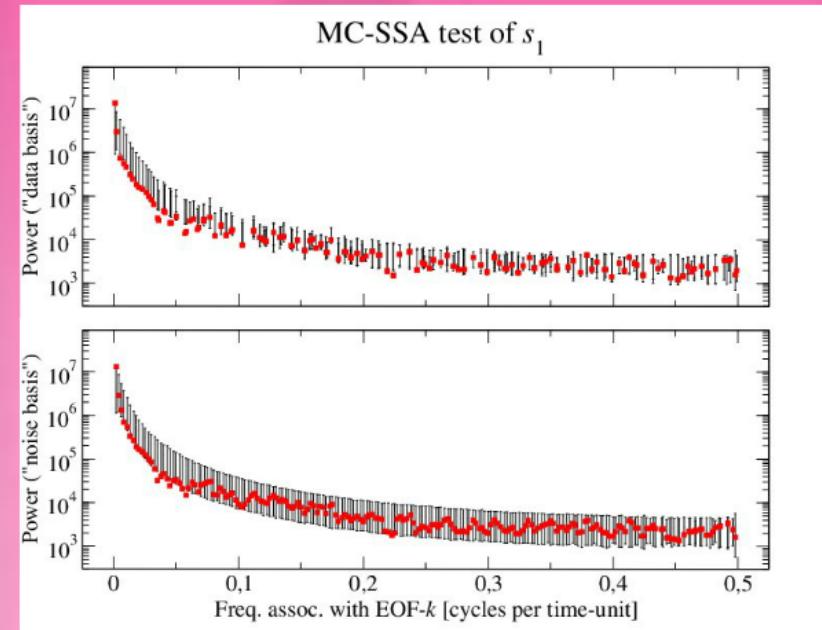
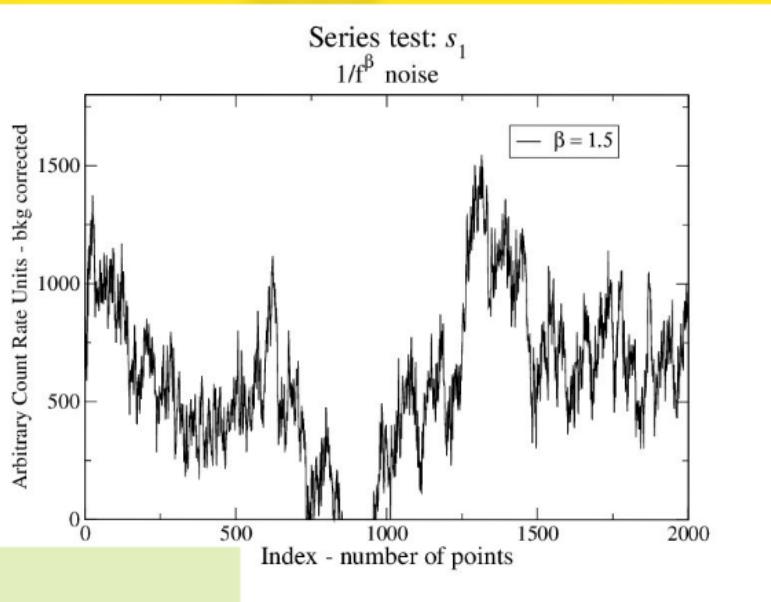


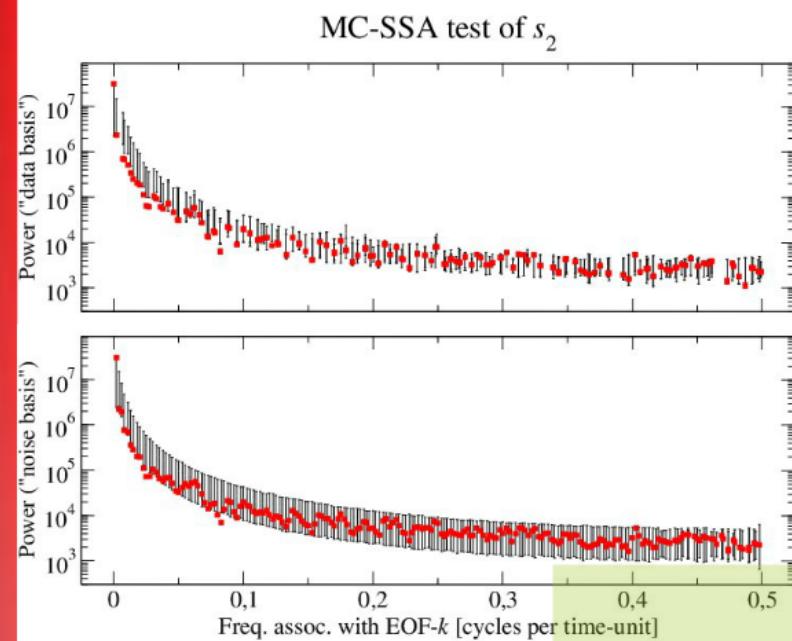
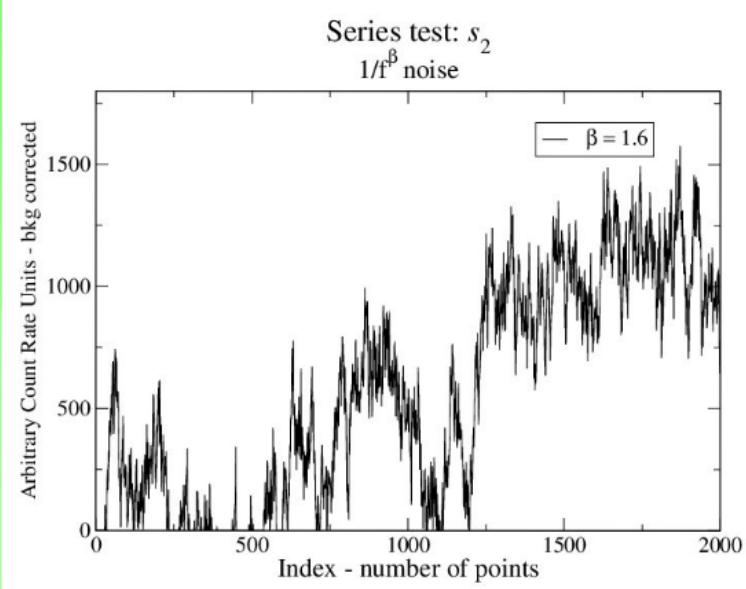




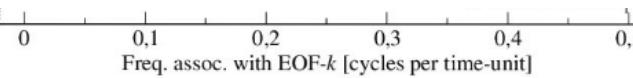
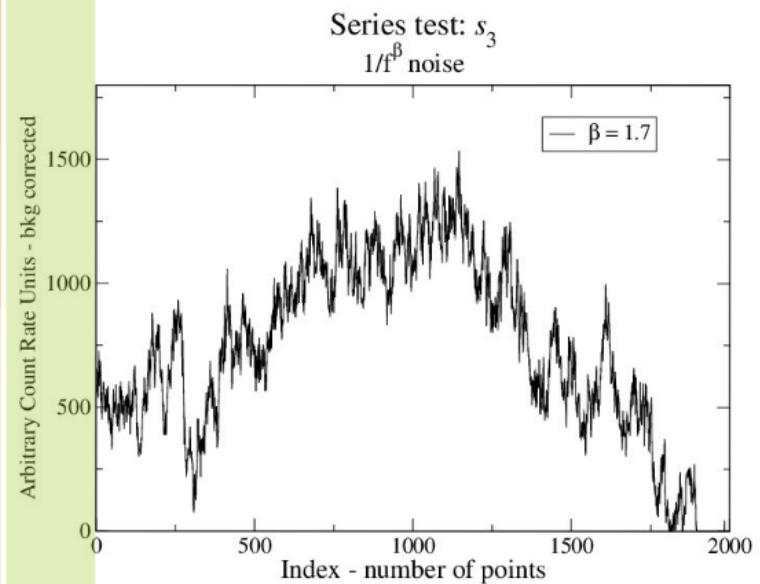
Series Test: Colored Noise + Poisson Noise + Threshold SNR



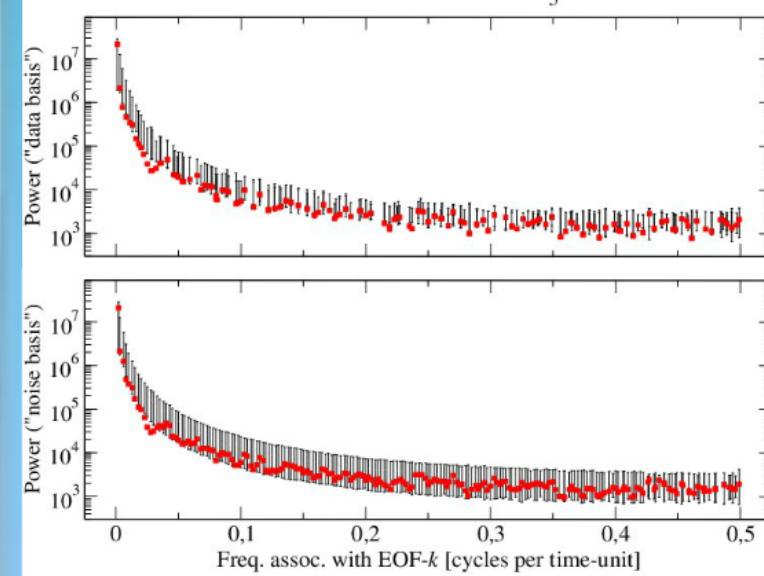


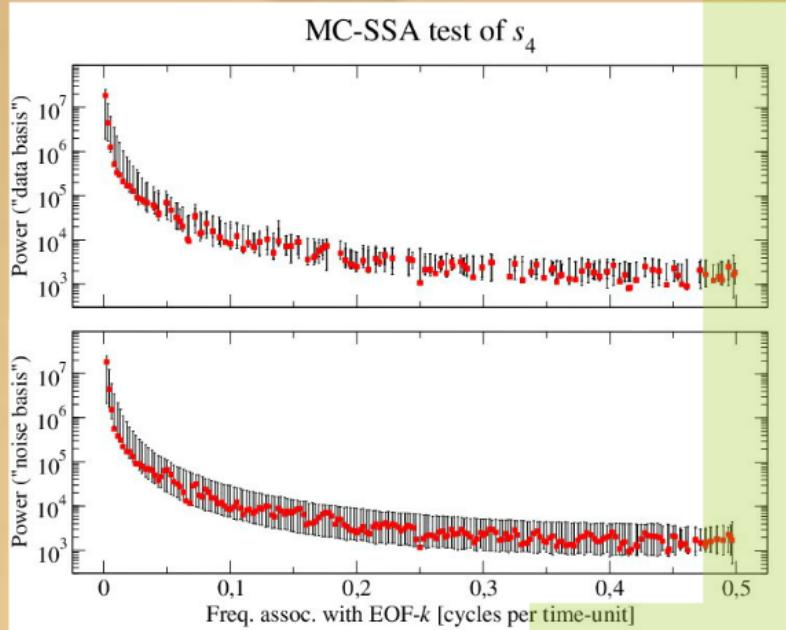
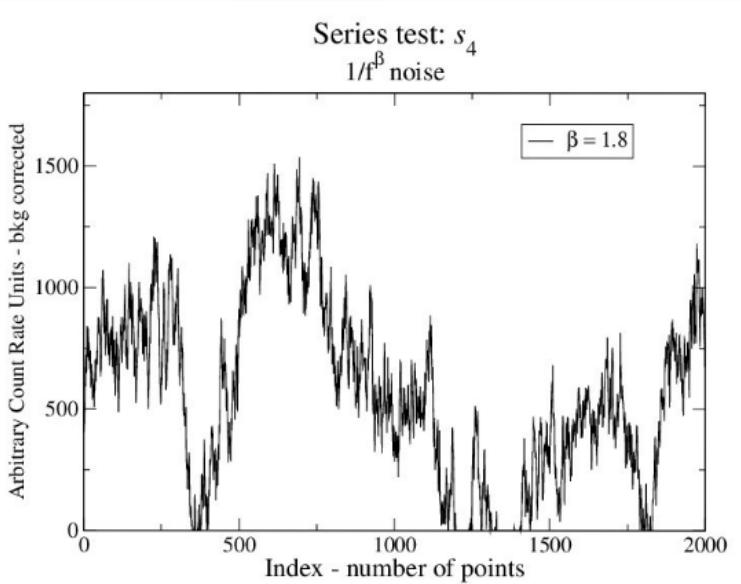


Index - number of points



MC-SSA test of s_3





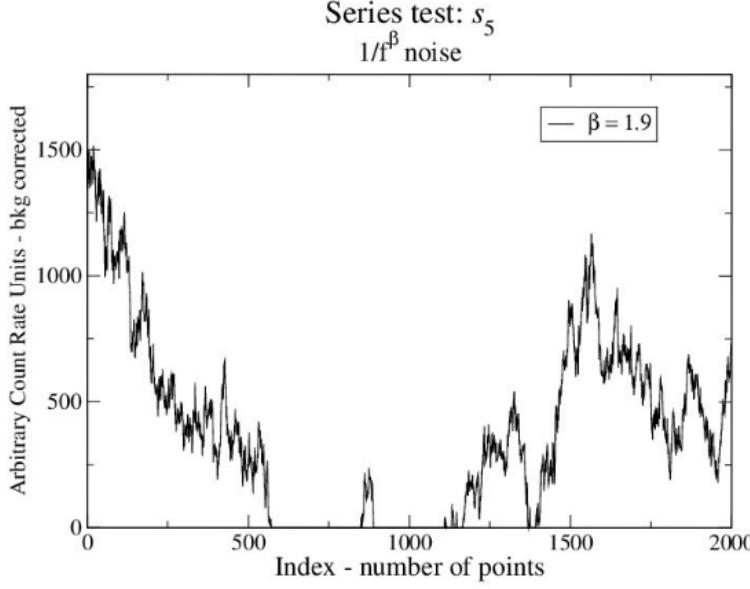
Series test: s_6

MC-SSA test of s_6

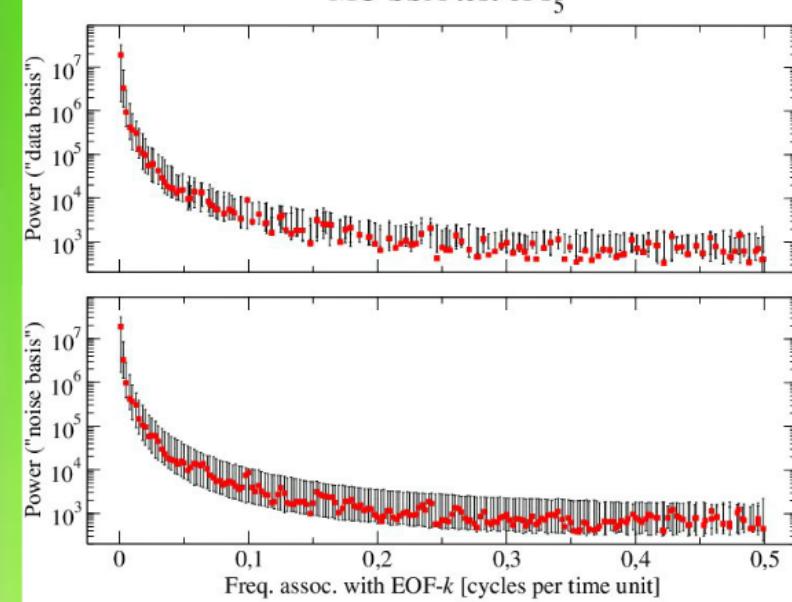
Index - number of points

0 0,1 0,2 0,3 0,4 0,5
Freq. assoc. with EOF- k [cycles per time-unit]

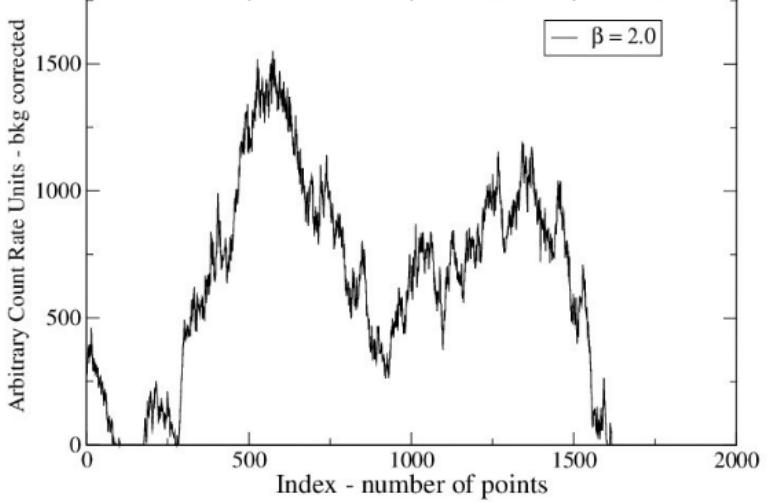
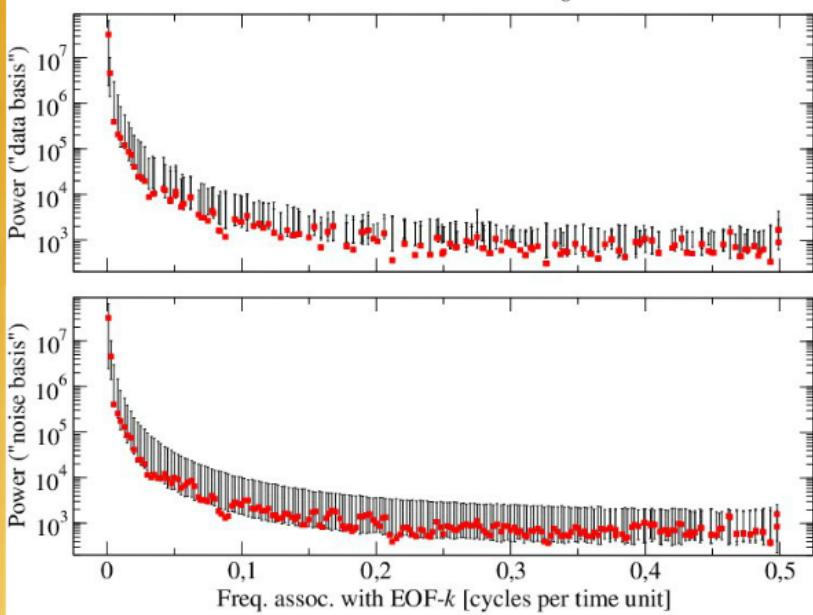
Series test: s_5
 $1/f^\beta$ noise

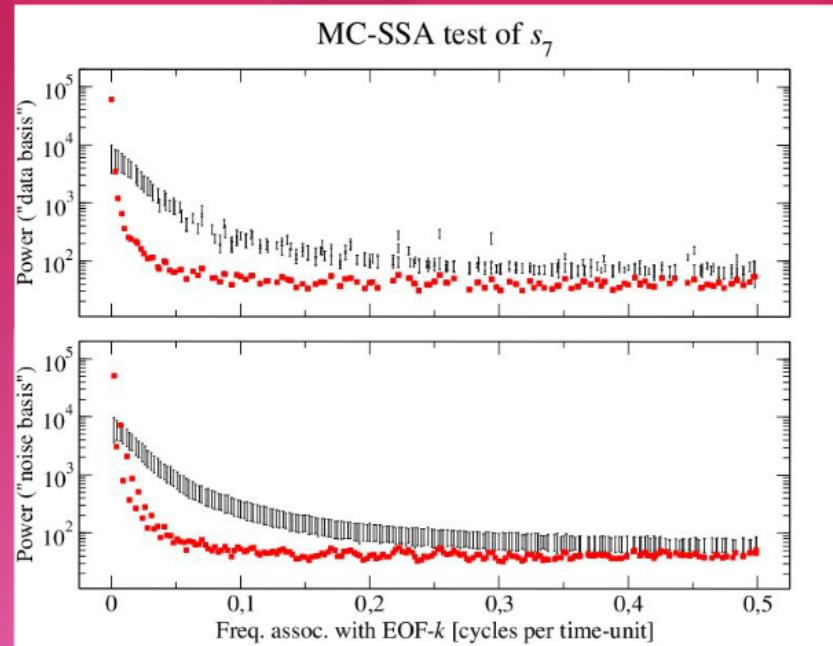
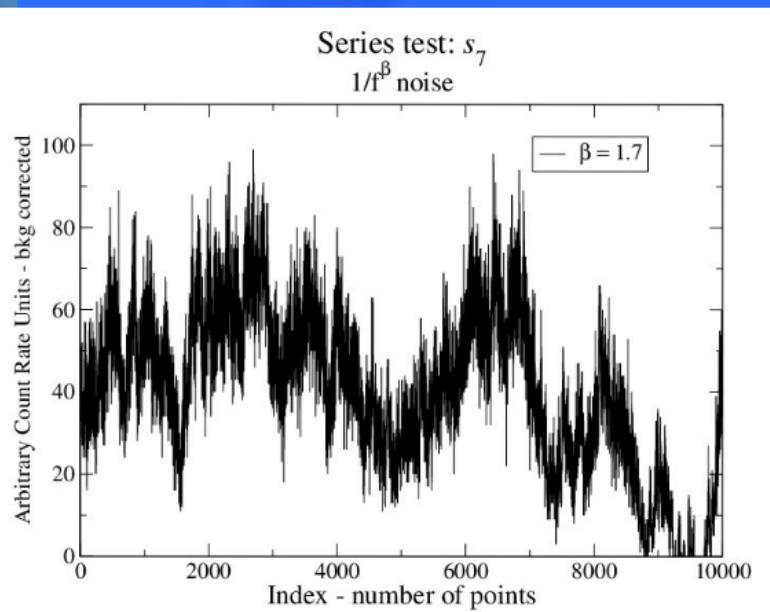
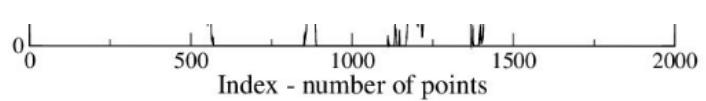


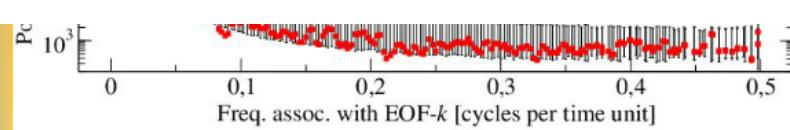
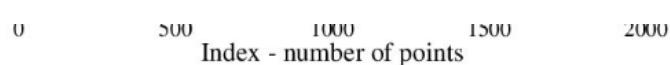
MC-SSA test of s_5



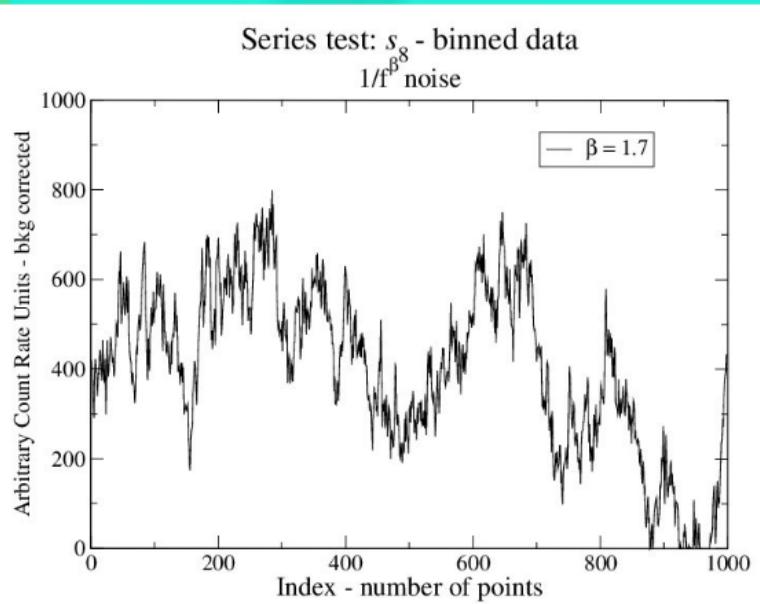
Series test: s_6
 $1/f^\beta$ noise

MC-SSA test of s_6 

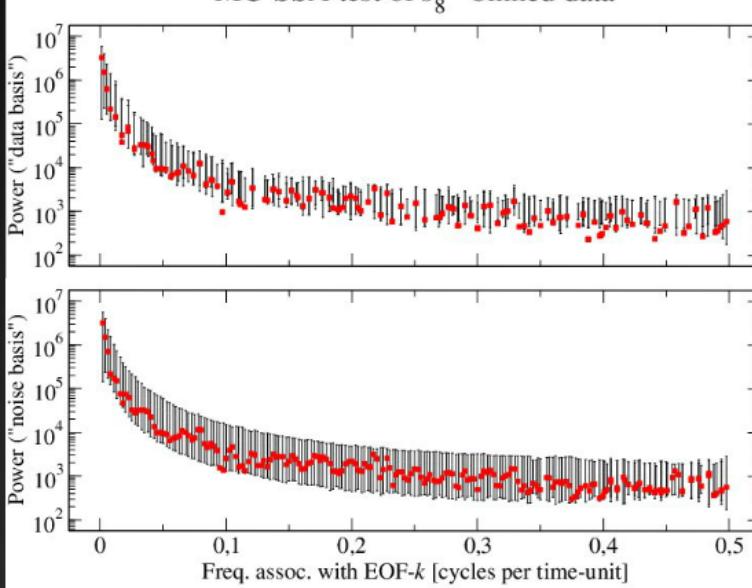




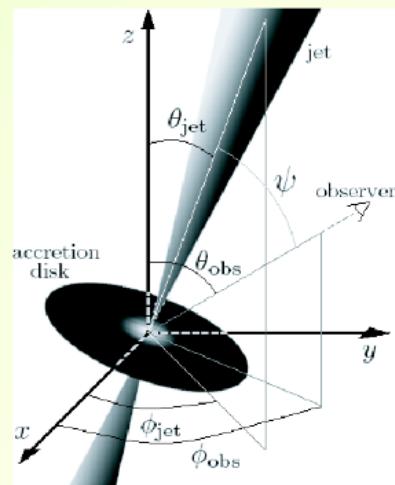
Series test: s_8 - binned data
 $1/f^\beta$ noise



MC-SSA test of s_8 - binned data



Oscillatory mode as evidence of jet-precession?



Several theoretical models agree about the possibility that most of the explosion energy is collimated into an ultra-relativistic jet.

In these scenarios, a precession of the jet could reasonably occur, leading to the formation of microstructures.

Reynoso et al., 06

Portegies Zwart, S. F., Lee, C.-H. & Lee, H. K. Explaining light curves of gamma-ray bursts with a precessing jet. *Astron. Astrophys. Suppl. Ser.* 138, 503-504 (1999).

Portegies Zwart, S. F. & Totani, T. Precessing jets interacting with interstellar material as the origin for the light curves of gamma-ray bursts. *Mon. Not. R. Astron. Soc.* 328, 951-957 (2001).

Reynoso, M. M., Romero, G. E. & Sampayo, O. A. Precession of neutrino-cooled accretion disks in gamma-ray burst engines. *Astron. Astrophys.* 454, 11-16 (2006).

Lei, W. H., Wang, D. X., Gong, B. P. & Huang, C. Y. A model of the light curves of gamma-ray bursts. *Astron. Astrophys.* 468, 563-569 (2007).

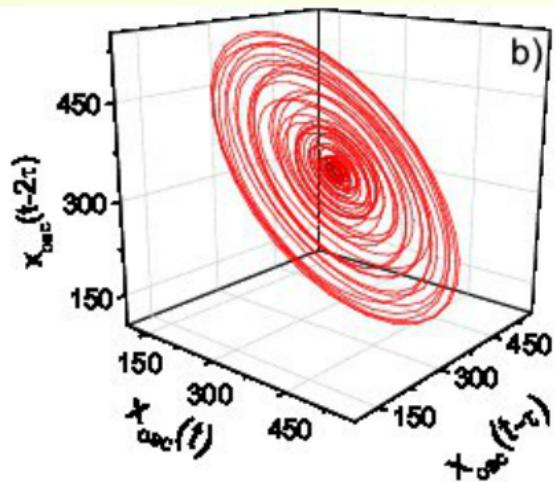
Liu, T. et al. Jet precession driven by neutrino-cooled disk for gamma-ray bursts. *Astron. Astrophys.* 516, A16 (2010).

several models are expected to act as a source of gravitational waves

----- work in progress -----

Chaos?

too short GRB time series



"skeleton" attractor of deterministic component discovered in GRB

Lyapunov exponent= ?



Chaos theory studies the behavior of dynamical systems that are highly sensitive to initial conditions, an effect which is popularly referred to as the *butterfly effect*

Does the Flap of a Butterfly's Wings in Brazil set off a Tornado in Texas ?
Edward Lorenz, American Association for the Advancement of Science in Washington, D.C.

Conclusion

- We propose a new data analysis methodology, MC-SSA, that succeeds in extracting inner-engine properties from the GRB prompt emission, where standard analyses do not.
- The deterministic components extracted by our analysis support the black-hole-disk-system model.
- The GRB engine reveals its presence through its precessional signature and it can potentially act as a GW source, observable by future low-frequency GW detectors.

merci!