Orbits, rotation, flashes, and more variable stuff

AN INTRODUCTION TO X-RAY TIMING USING STINGRAY

Matteo Bachetti

with Daniela Huppenkothen and the Stingray community

X-RAY ANALYSIS

Jul 31st, 2024

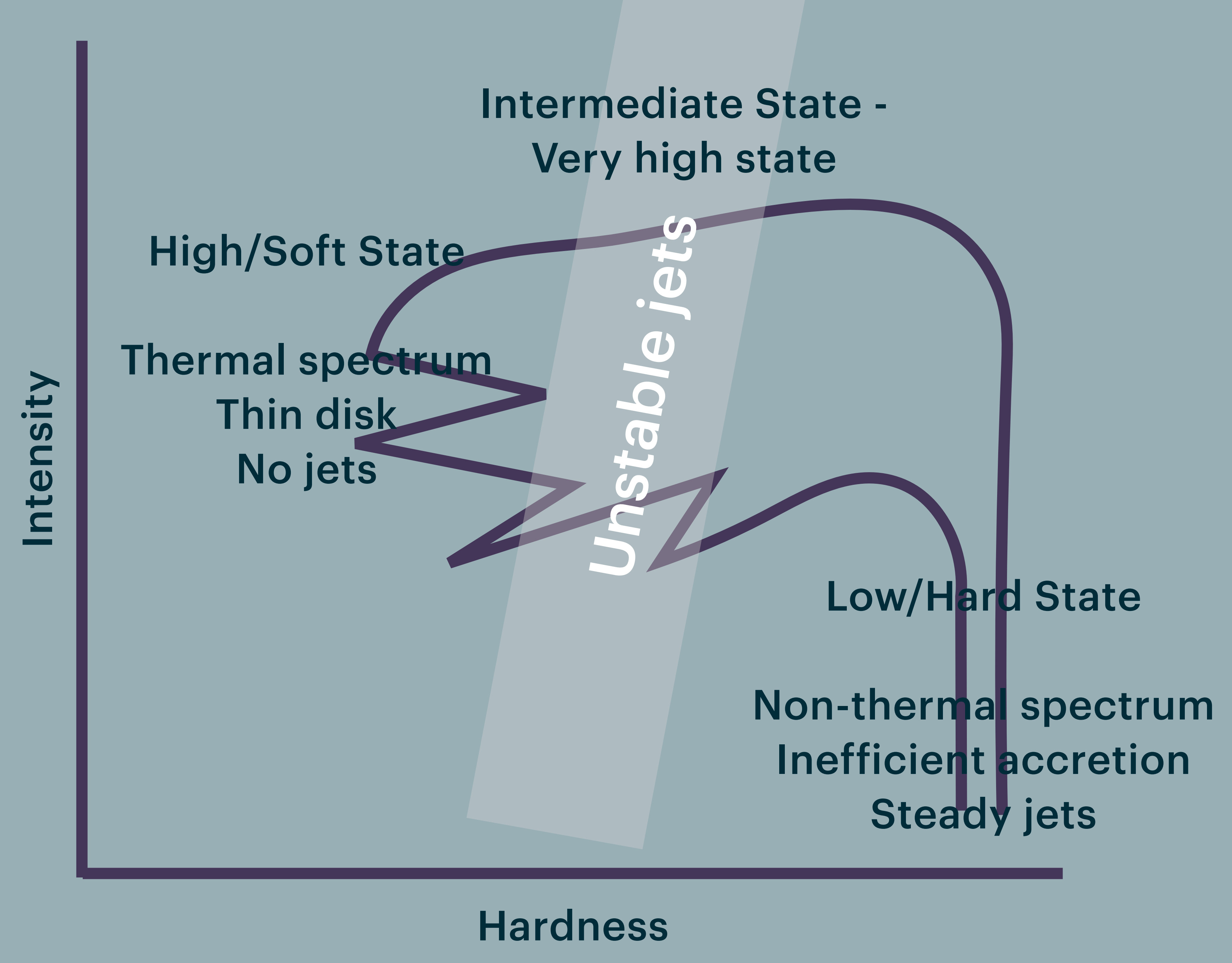
NICER/IXPE WORKSHOP

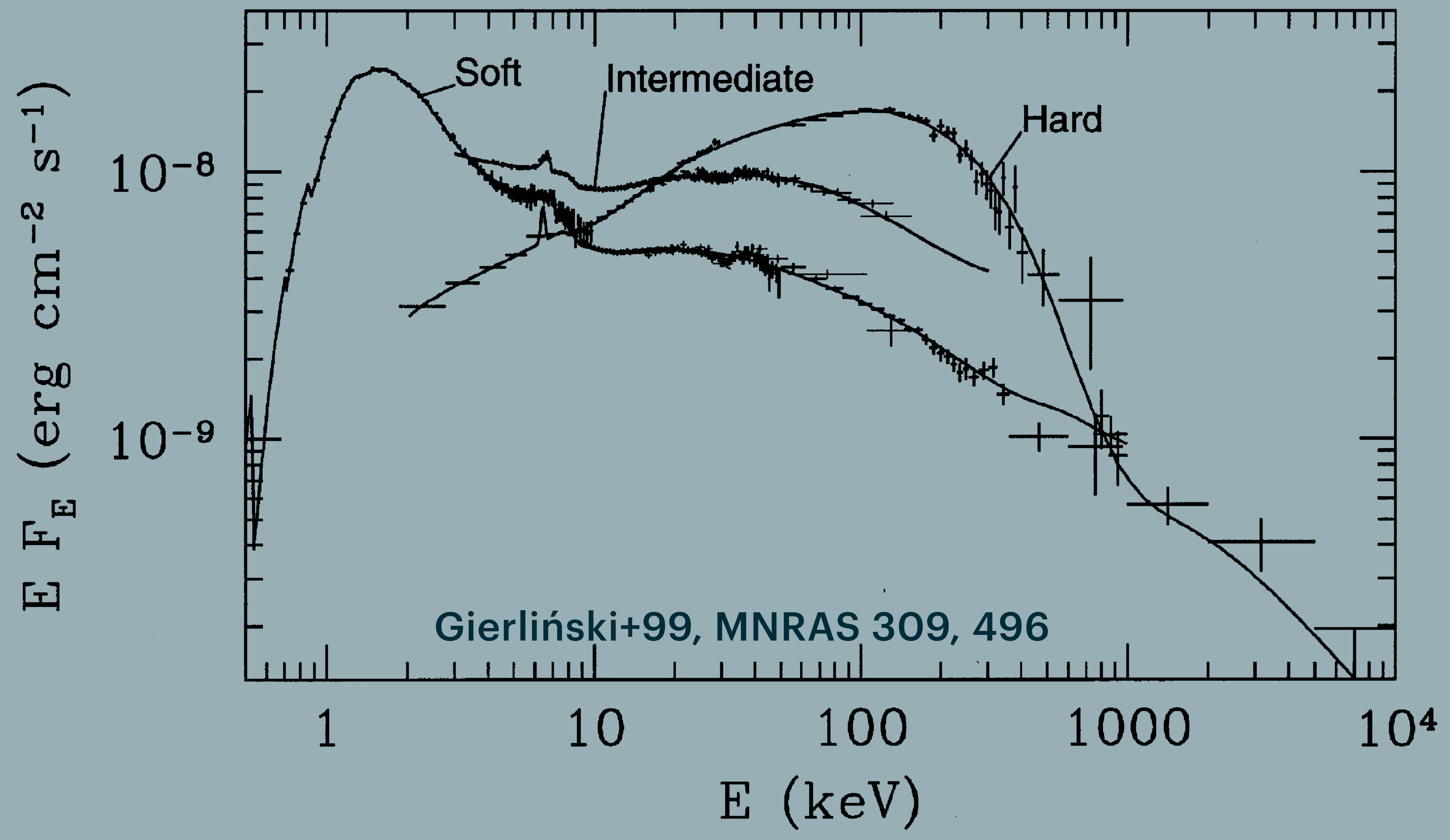
VARIABILITY IN ASTROPHYSICS

- **Deterministic/Periodic:**
  - Orbital motion (Doppler shifts, eclipses, …)
  - Star rotation (pulsars, CVs, …)
  - Star pulsations (i.e. RR Lyrae)
  - …

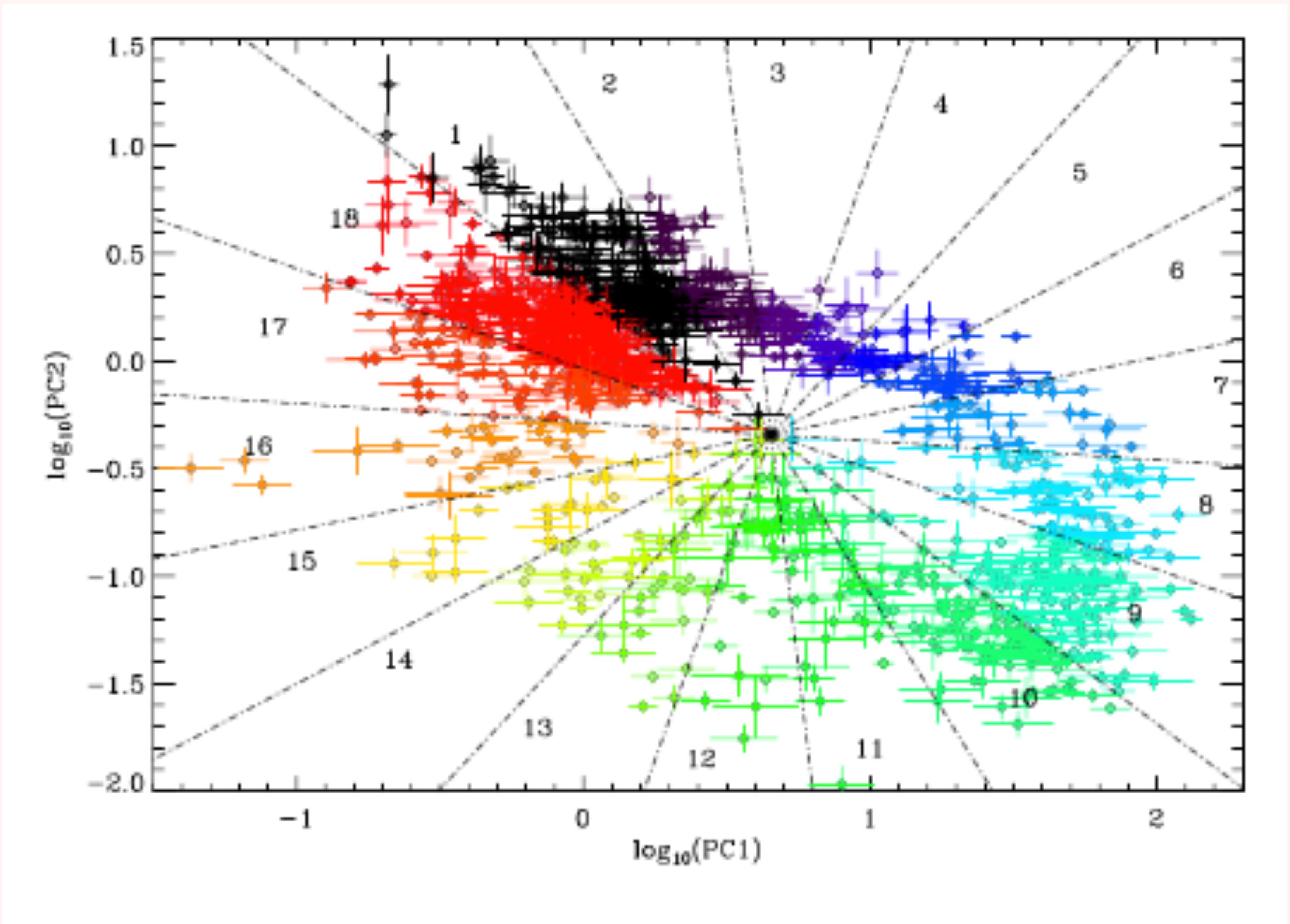
- **Random/Transient/Aperiodic:**
  - Quasi-periodic oscillations (accretion disks?)
  - X-ray/Gamma ray/(fast) radio/optical **bursts**
  - Broadband noise (any randomly variable signal)
  - …

TIMESCALES: MICROSECONDS -> AGE OF THE UNIVERSE

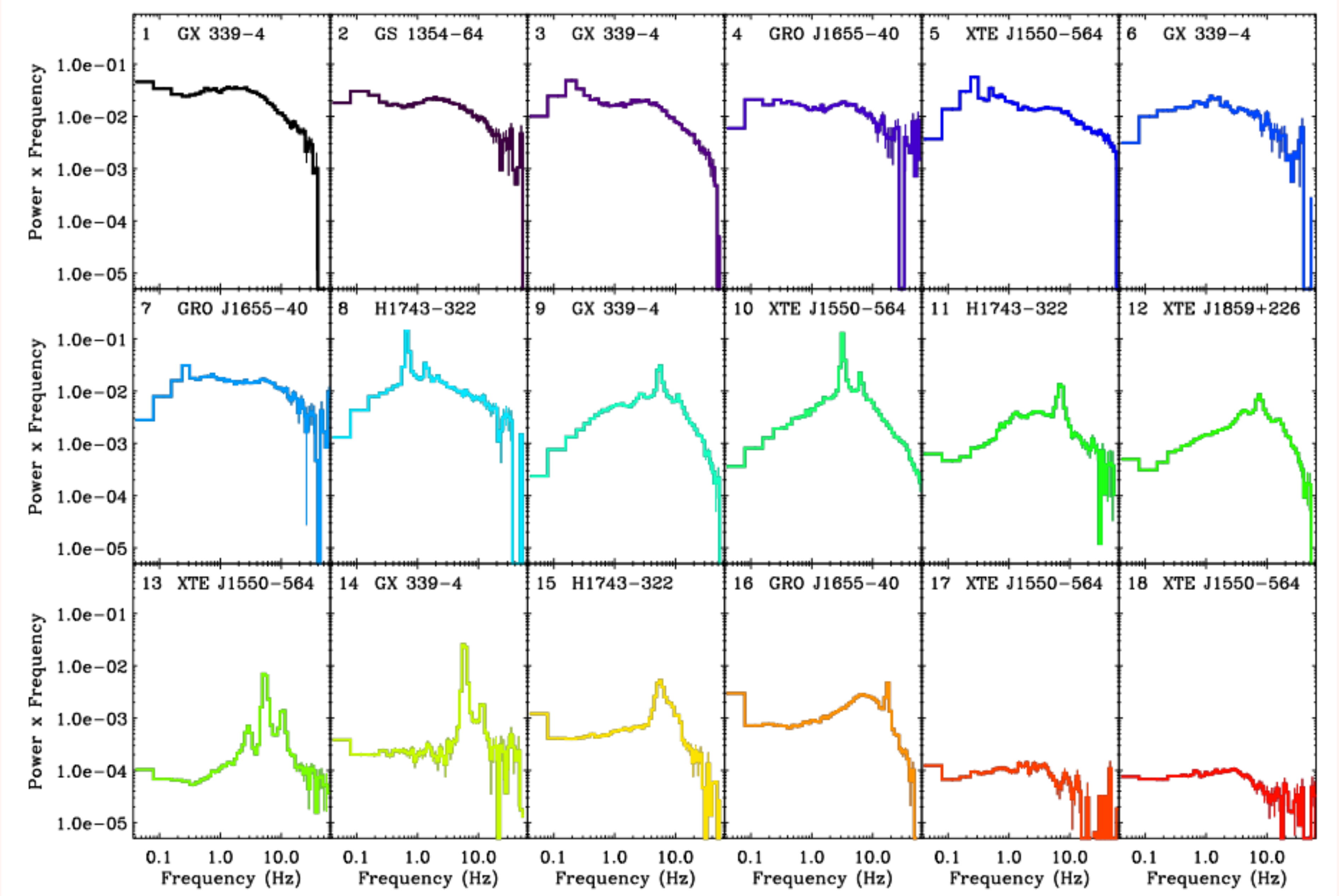




SPECTRA



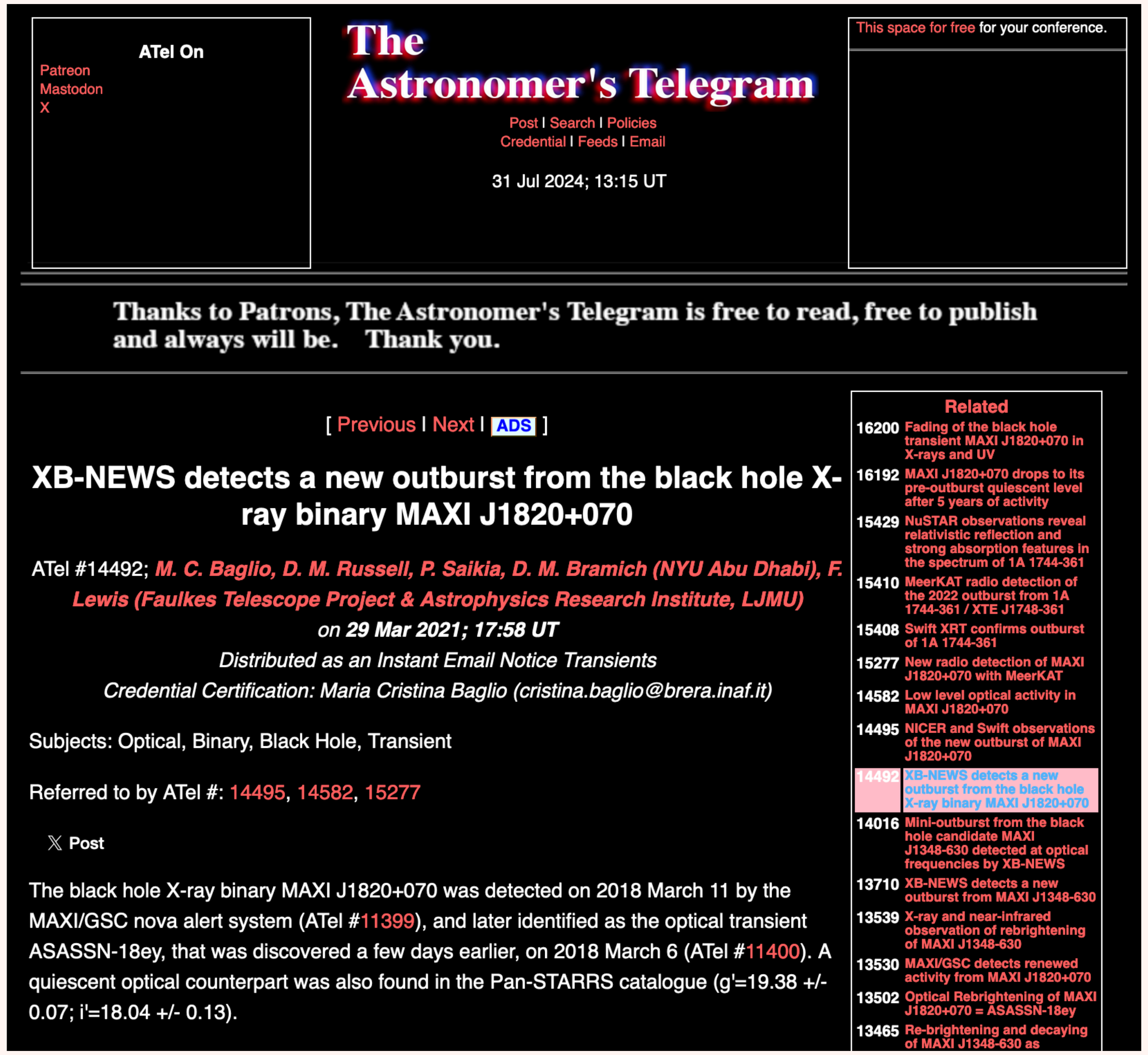
Heil, Uttley, & Klein-Wolt, MNRAS 448, 3339–3347, 2015.



FAST VARIABILITY

DATA EXPLORATION

A new transient!
Quick! Get some data!



ATel On
Patreon
Mastodon
X

The Astronomer's Telegram

Post | Search | Policies
Credential | Feeds | Email

31 Jul 2024; 13:15 UT

This space for free for your conference.

Thanks to Patrons, The Astronomer's Telegram is free to read, free to publish and always will be. Thank you.

[Previous | Next | ADS]

XB-NEWS detects a new outburst from the black hole X-ray binary MAXI J1820+070

ATel #14492; *M. C. Baglio, D. M. Russell, P. Saikia, D. M. Bramich (NYU Abu Dhabi), F. Lewis (Faulkes Telescope Project & Astrophysics Research Institute, LJMU)*
on ***29 Mar 2021; 17:58 UT***
Distributed as an Instant Email Notice Transients
Credential Certification: Maria Cristina Baglio (cristina.baglio@brera.inaf.it)

Subjects: Optical, Binary, Black Hole, Transient

Referred to by ATel #: 14495, 14582, 15277

X Post

The black hole X-ray binary MAXI J1820+070 was detected on 2018 March 11 by the MAXI/GSC nova alert system (ATel #11399), and later identified as the optical transient ASASSN-18ey, that was discovered a few days earlier, on 2018 March 6 (ATel #11400). A quiescent optical counterpart was also found in the Pan-STARRS catalogue (g'=19.38 +/- 0.07; i'=18.04 +/- 0.13).

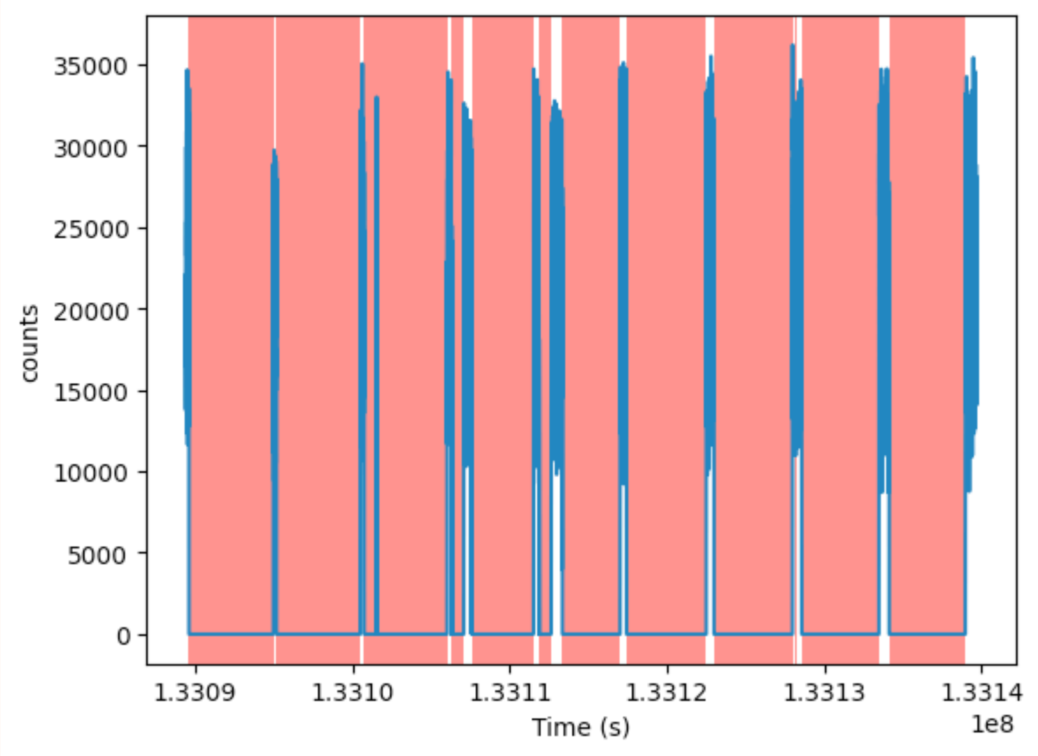
Related

16200	Fading of the black hole transient MAXI J1820+070 in X-rays and UV
16192	MAXI J1820+070 drops to its pre-outburst quiescent level after 5 years of activity
15429	NuSTAR observations reveal relativistic reflection and strong absorption features in the spectrum of 1A 1744-361
15410	MeerKAT radio detection of the 2022 outburst from 1A 1744-361 / XTE J1748-361
15408	Swift XRT confirms outburst of 1A 1744-361
15277	New radio detection of MAXI J1820+070 with MeerKAT
14582	Low level optical activity in MAXI J1820+070
14495	NICER and Swift observations of the new outburst of MAXI J1820+070
14492	XB-NEWS detects a new outburst from the black hole X-ray binary MAXI J1820+070
14016	Mini-outburst from the black hole candidate MAXI J1348-630 detected at optical frequencies by XB-NEWS
13710	XB-NEWS detects a new outburst from MAXI J1348-630
13539	X-ray and near-infrared observation of rebrightening of MAXI J1348-630
13530	MAXI/GSC detects renewed activity from MAXI J1820+070
13502	Optical Rebrightening of MAXI J1820+070 = ASASSN-18ey
13465	Re-brightening and decaying of MAXI J1348-630 as

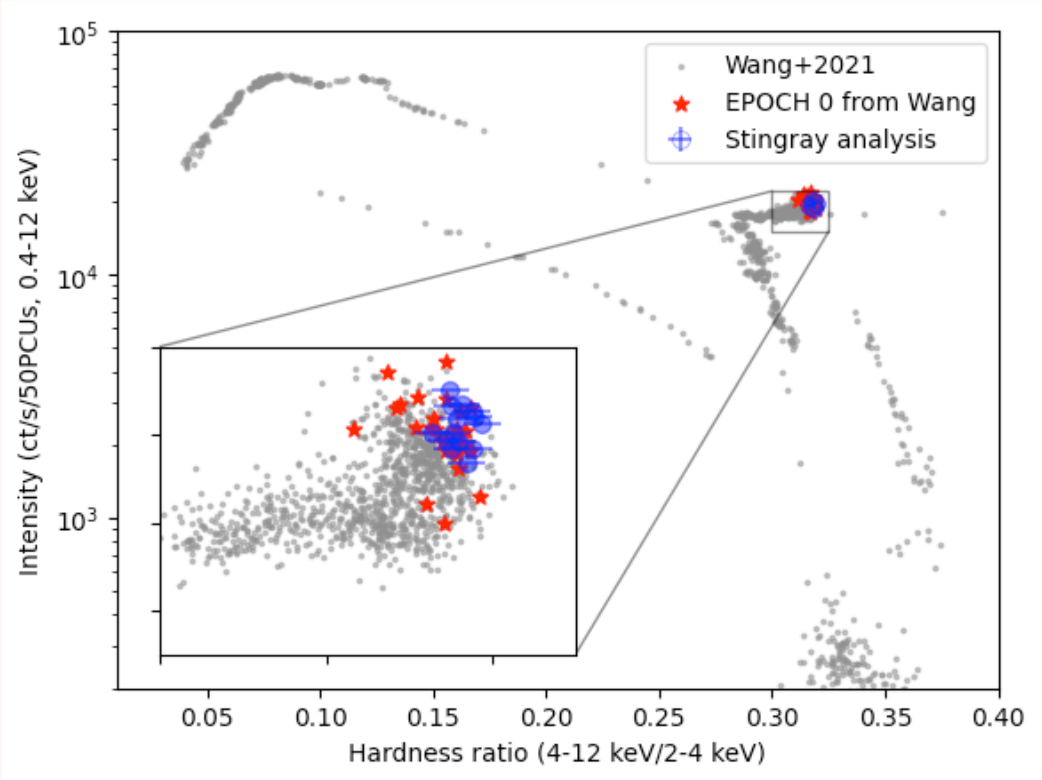
DATA EXPLORATION

A new transient!
Quick! Get some data!

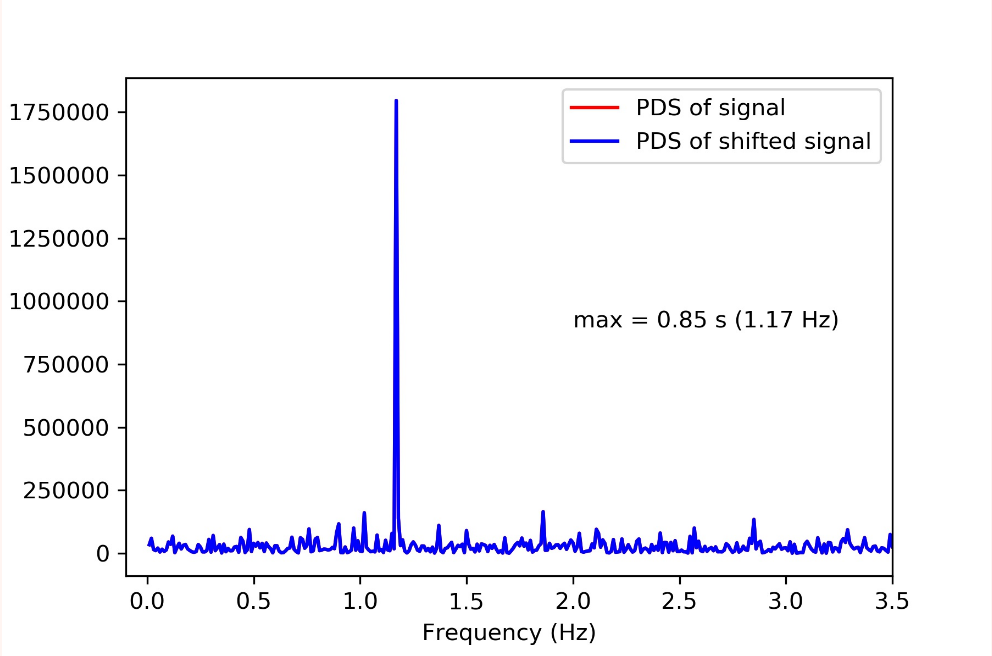
Basic variability characterization



Color-based diagnostics



Pulsation search

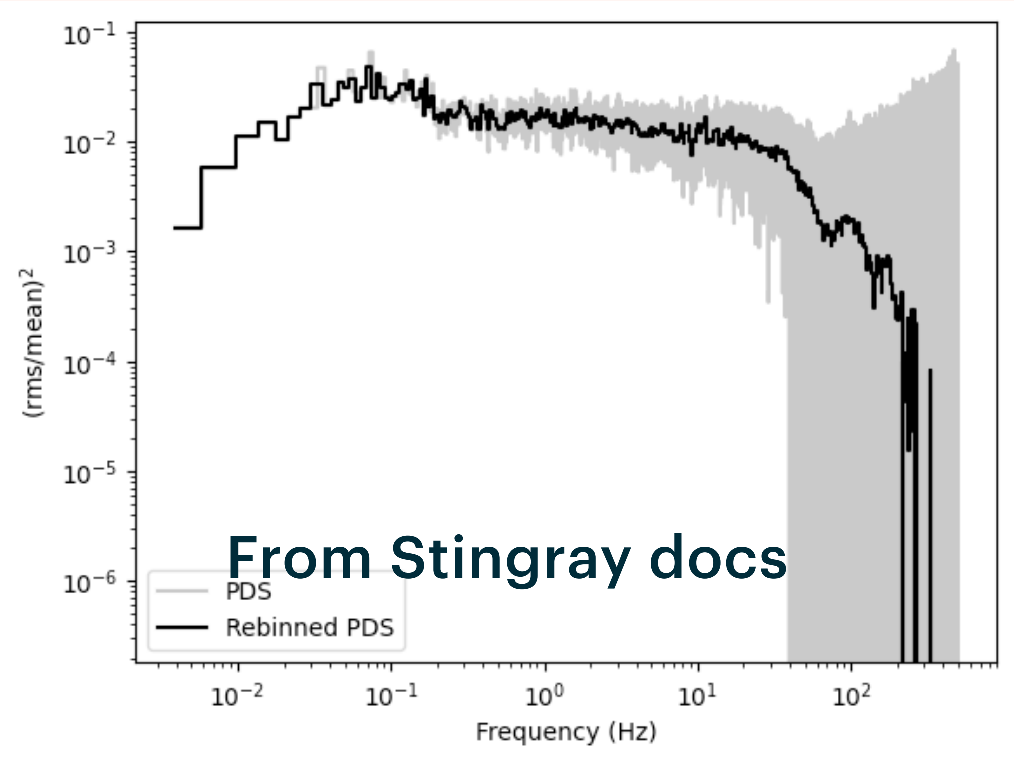


DATA EXPLORATION

A new transient! Quick! Get some data!

Basic variability characterization

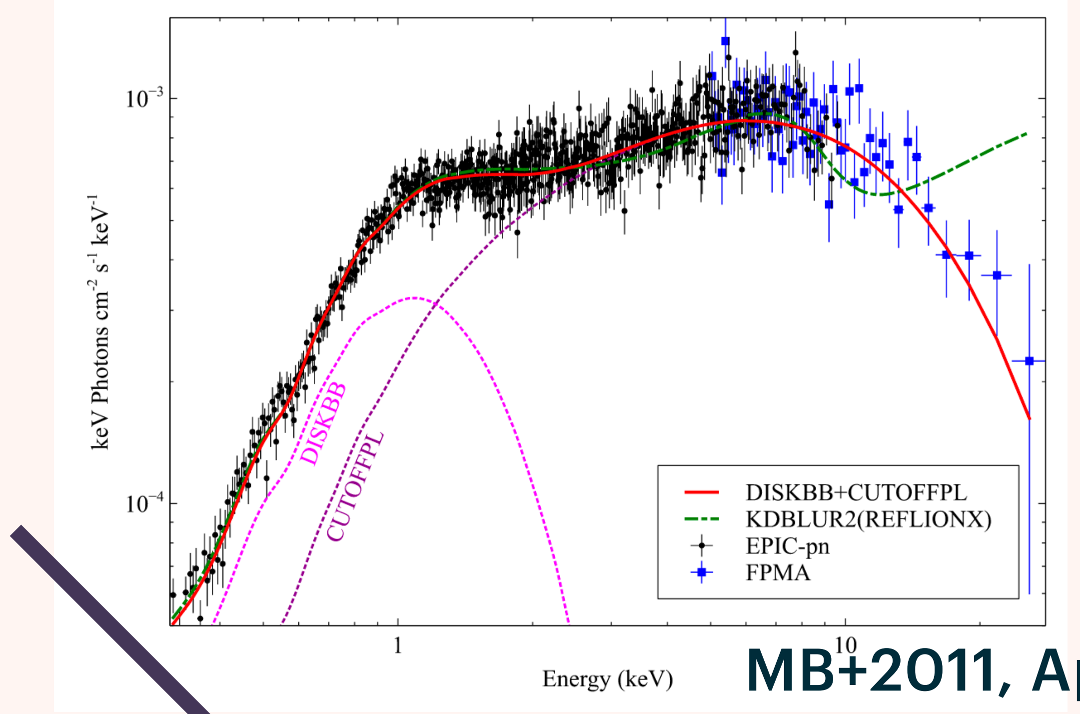
Aperiodic and quasi-periodic properties



From Stingray docs

Color-based diagnostics

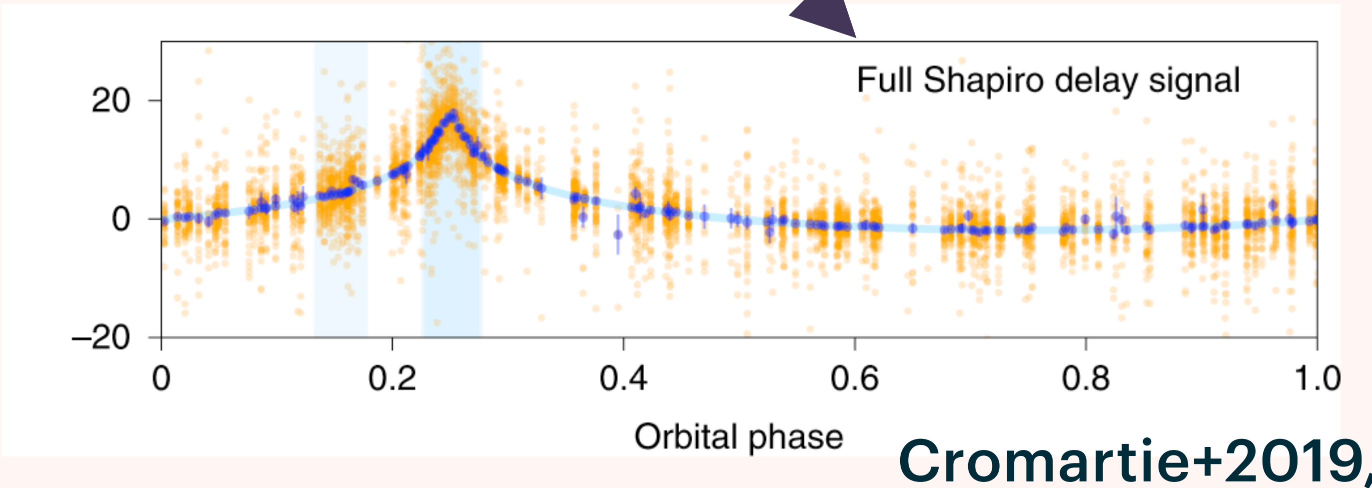
Spectro-polarimetric analysis



MB+2011, ApJ

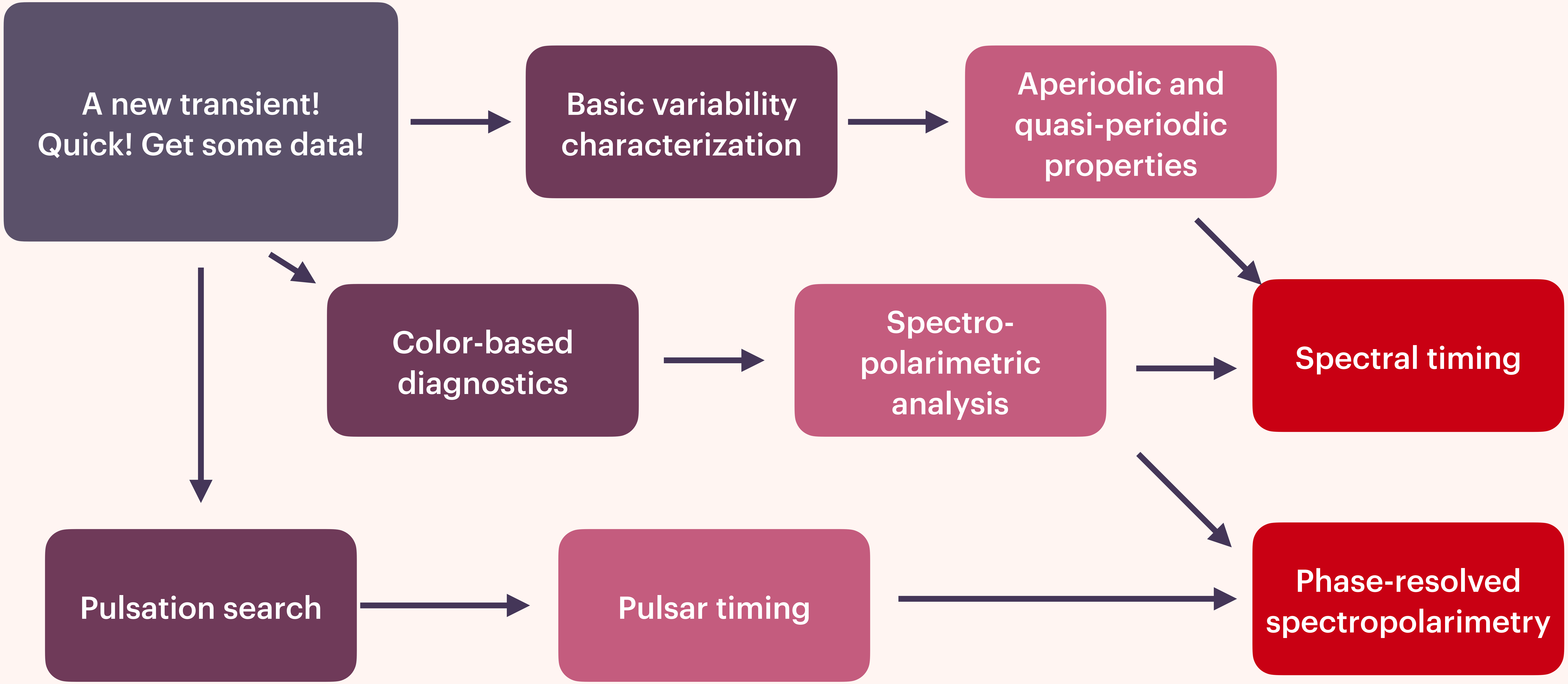
Pulsation search

Pulsar timing

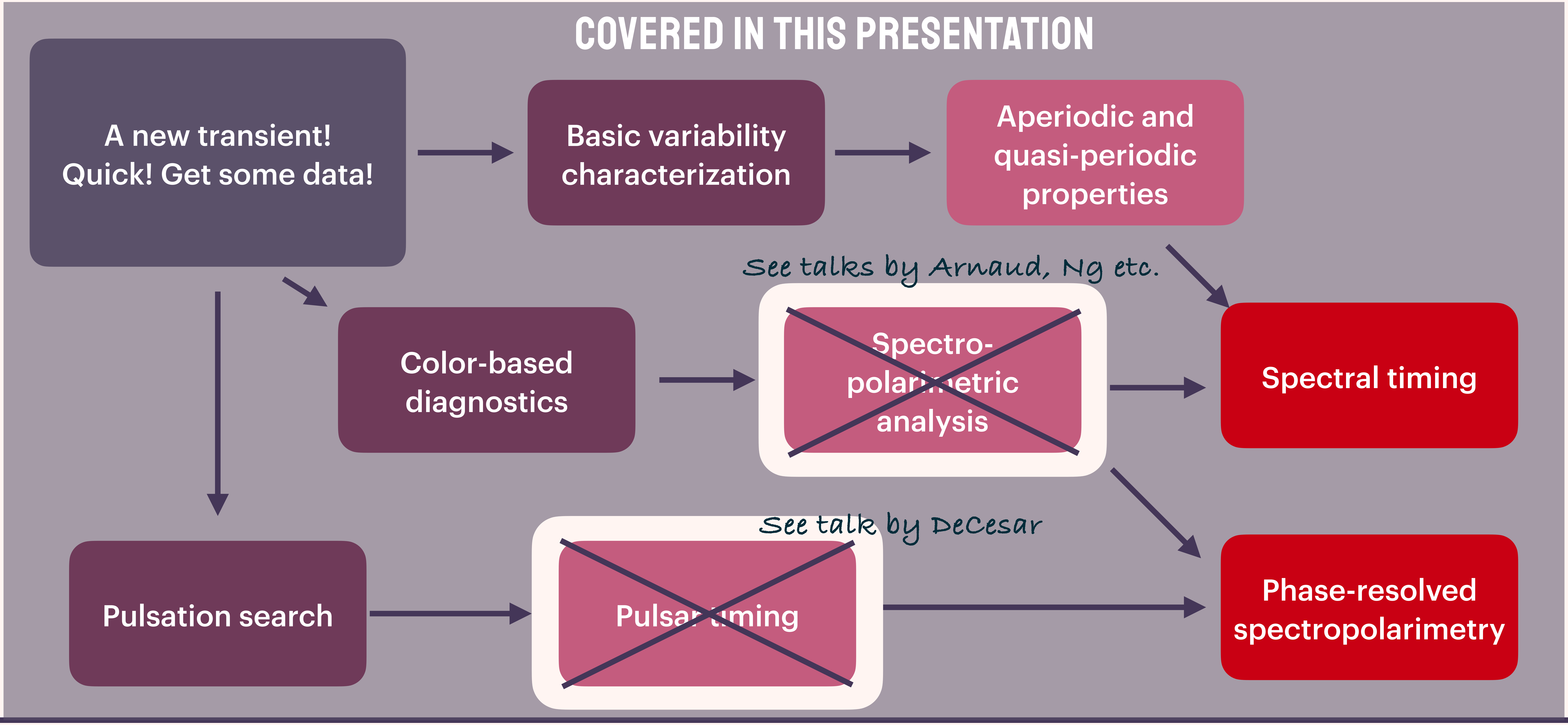


Cromartie+2019, Nat.Ast. 4, 72

DATA EXPLORATION

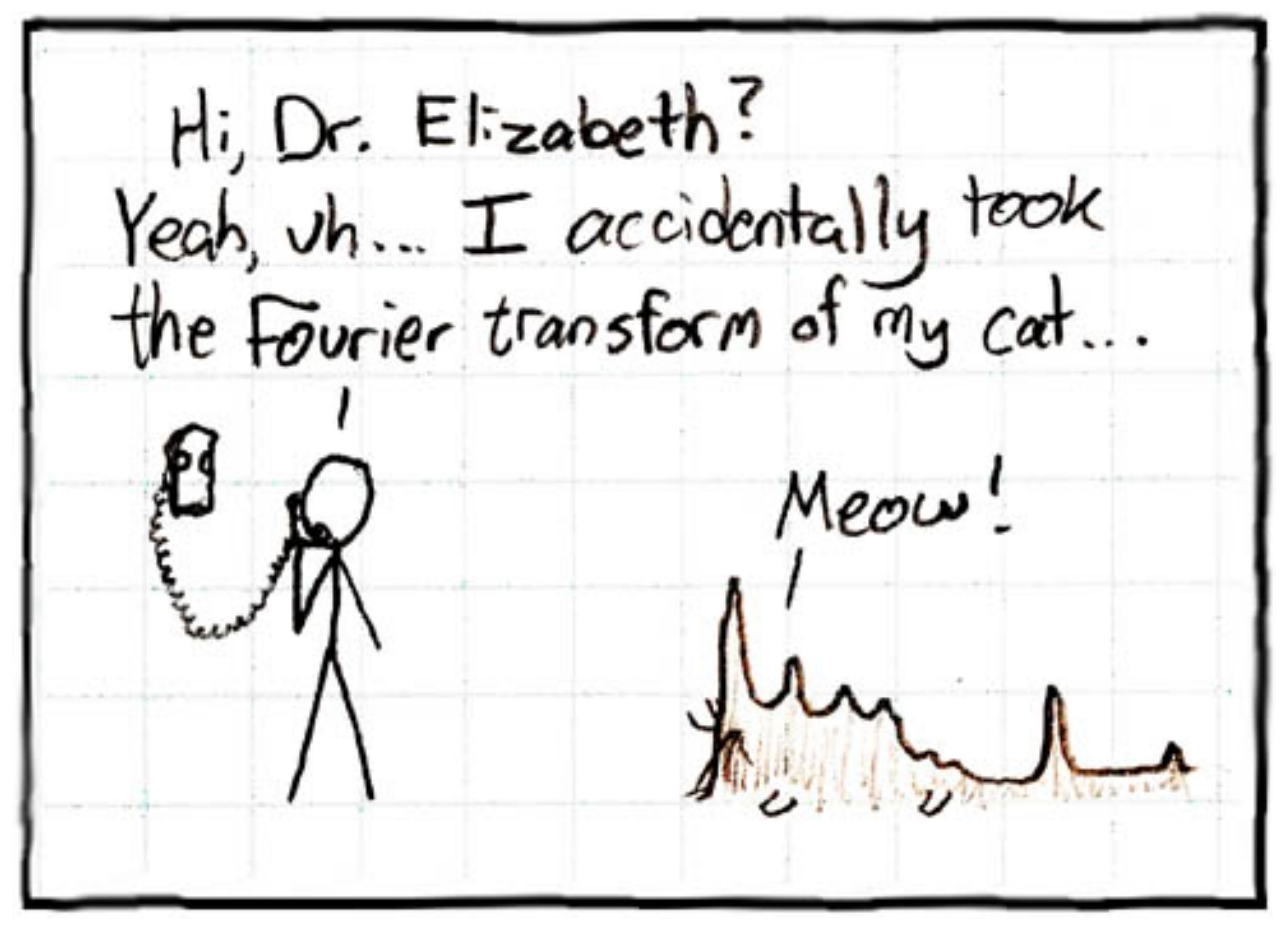


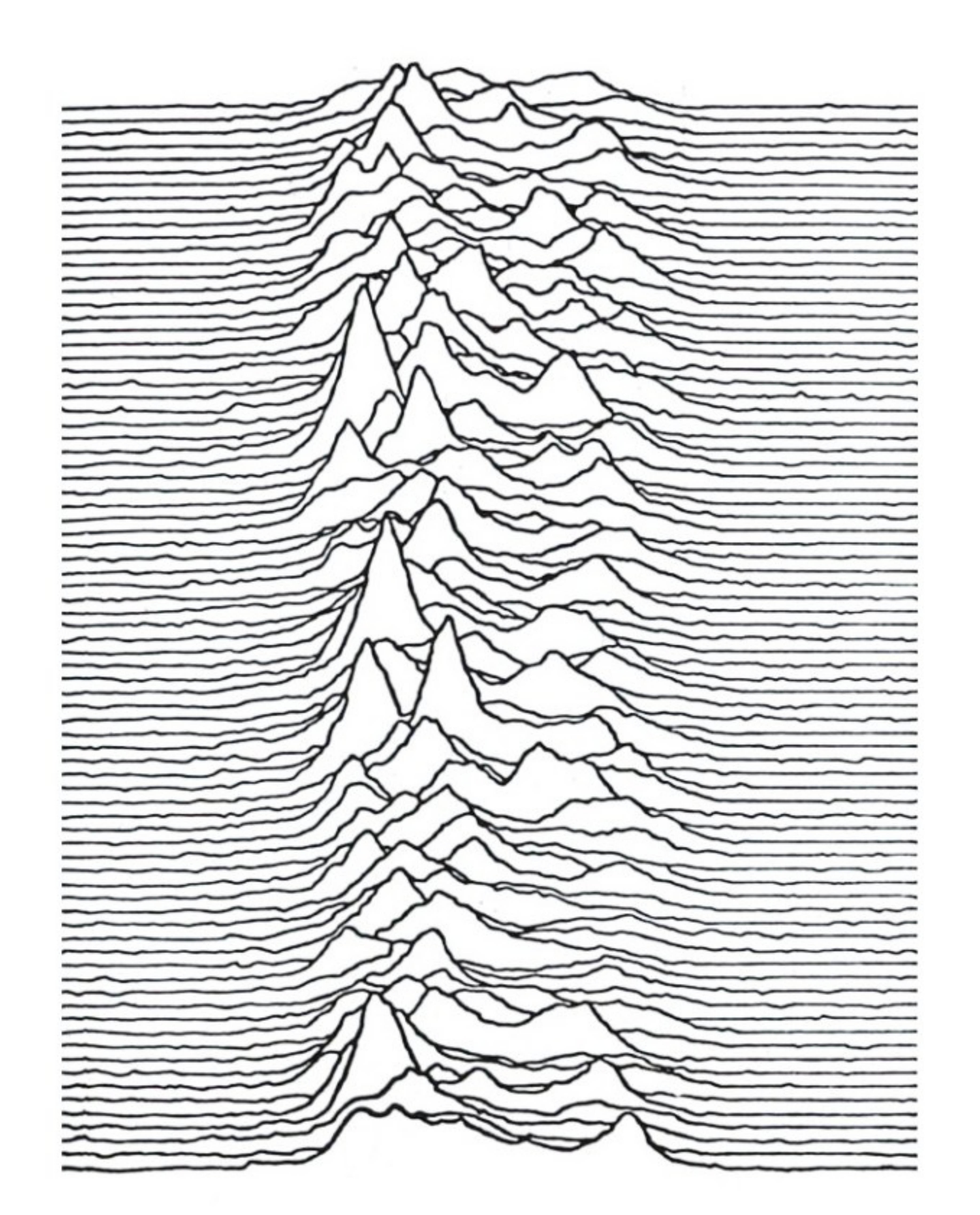
DATA EXPLORATION



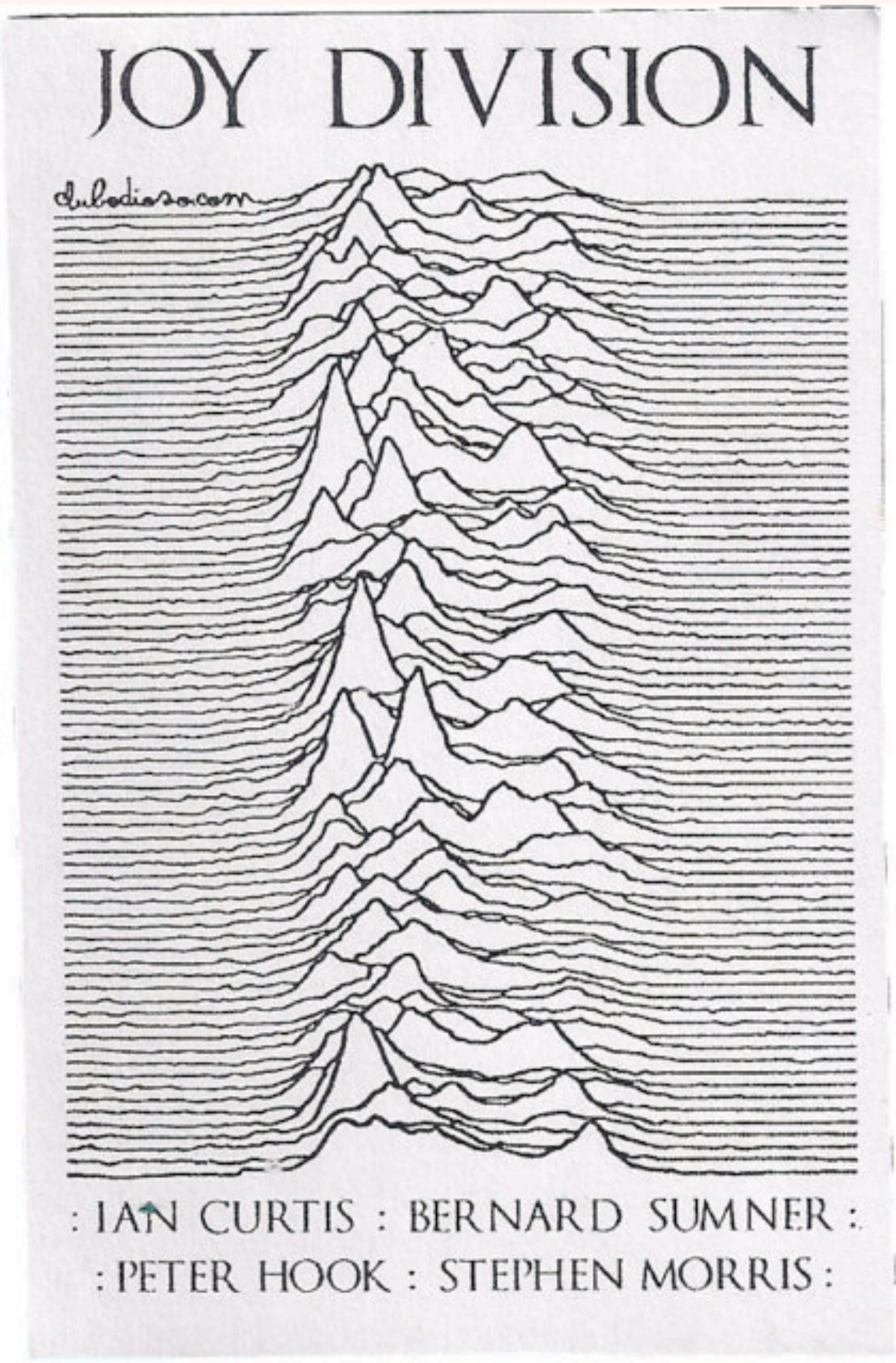
BASE FOURIER METHODS

- Fast Fourier Transform
- Periodogram
- Lomb-Scargle periodogram





CP 1919, the first pulsar



$$\mathcal{F}(\omega) = \int_{-\infty}^{\infty} e^{-i\omega t} f(t)$$

OR, DISCRETELY: $F_k = \sum_{k=0}^{N-1} e^{-2\pi i k n / N} t_n$

FAST FOURIER TRANSFORM-I

- Note that the discrete Fourier transform would be a very slow operation:

  $$F_k = \sum_{n=0}^{N-1} e^{-2\pi i k n/N} t_n \quad k = -N/2, N/2$$

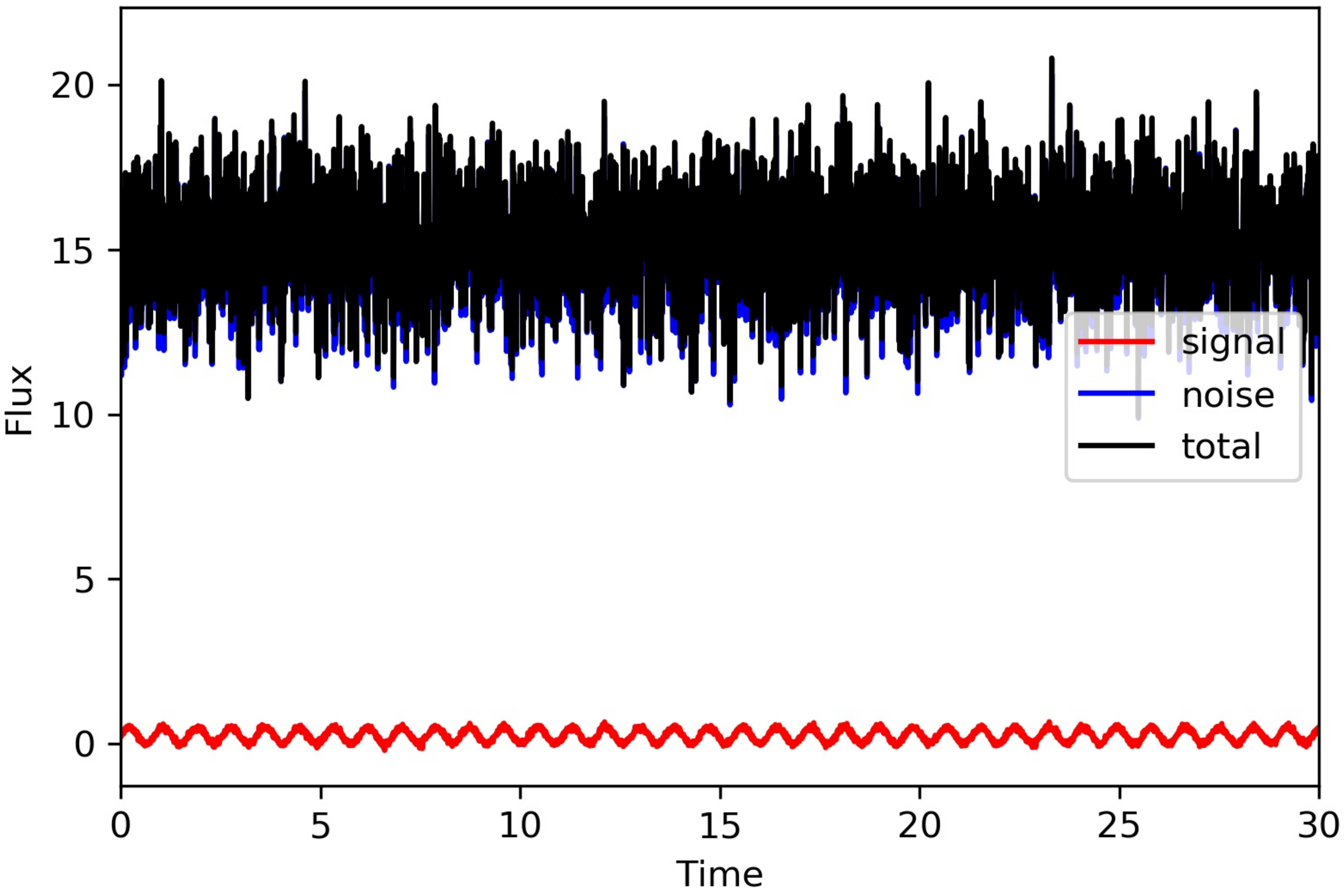
  This formula needs to iterate over the N samples for each of the N frequencies. It is a $O(N^2)$ algorithm.

- The **Fast Fourier Transforms** are a family of algorithms to compute it in O(N *log* N) operations. Beware! Most rely on a power-of-two number of samples in the light curve, and the actual performance is wildly different between implementations. In Python, I recommend **numpy** and **pyfftw**. scipy.fft is much slower.

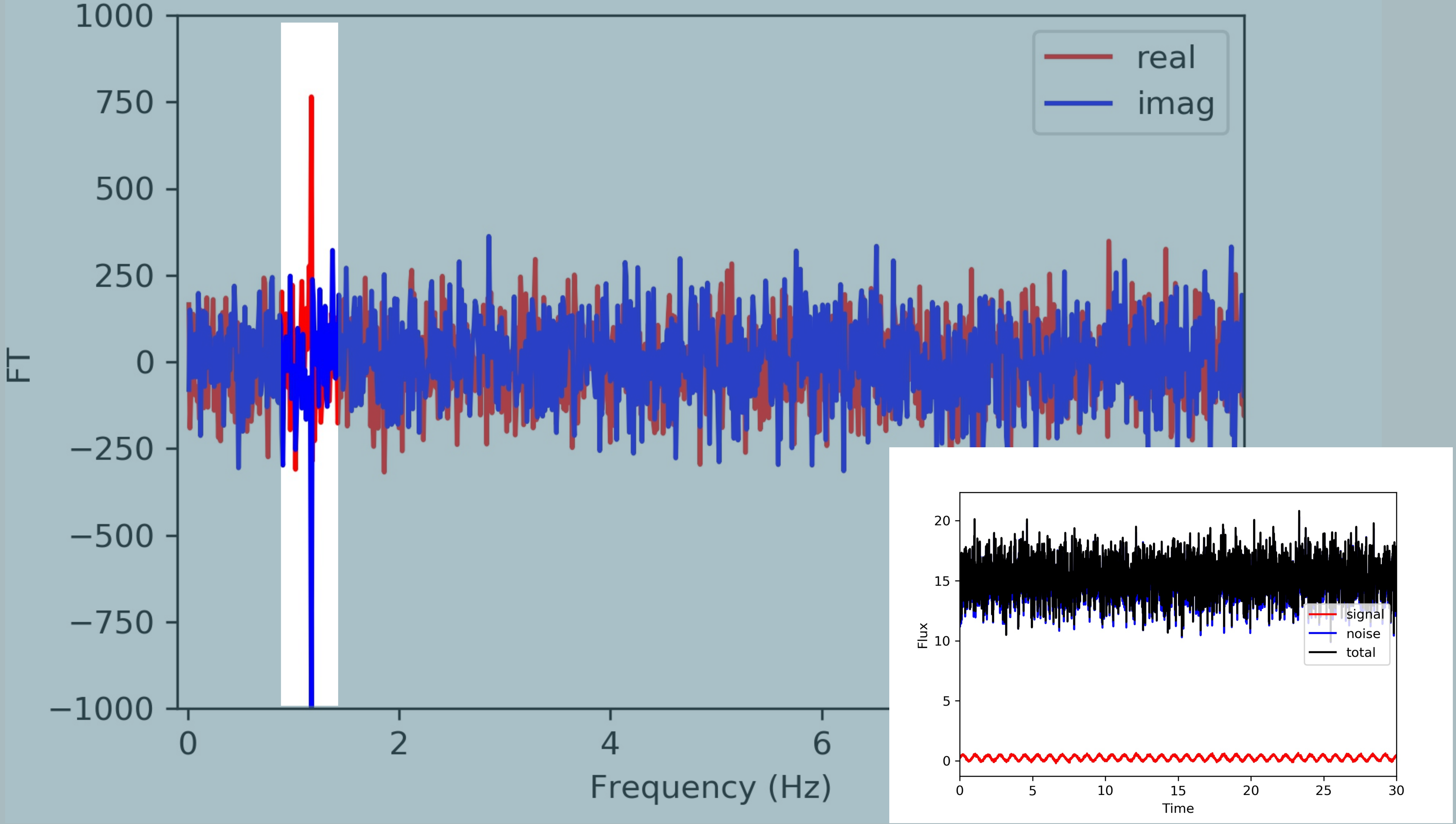
FAST FOURIER TRANSFORM-II

- The **frequency resolution** of the FFT is fixed to
  $$\Delta\nu = \frac{1}{T}$$
  where T is the **duration** of the observation.

- The maximum frequency is the **Nyquist frequency**
  $$\nu_{\mathrm{Nyq}} = \frac{0.5}{\Delta t}$$
  where Δt is the **sampling time**.



Flux
Time
signal
noise
total
0
5
10
15
20
25
30



real
imag
FT
Frequency (Hz)
1000
750
500
250
0
−250
−500
−750
−1000
0
2
4
6
signal
noise
total
Flux
Time
20
15
10
5
0
25
30

Same sinusoid, different phase
real
imag
FT
Frequency (Hz)
1000
750
500
250
0
−250
−500
−750
−1000
0
2
4
6
8
10

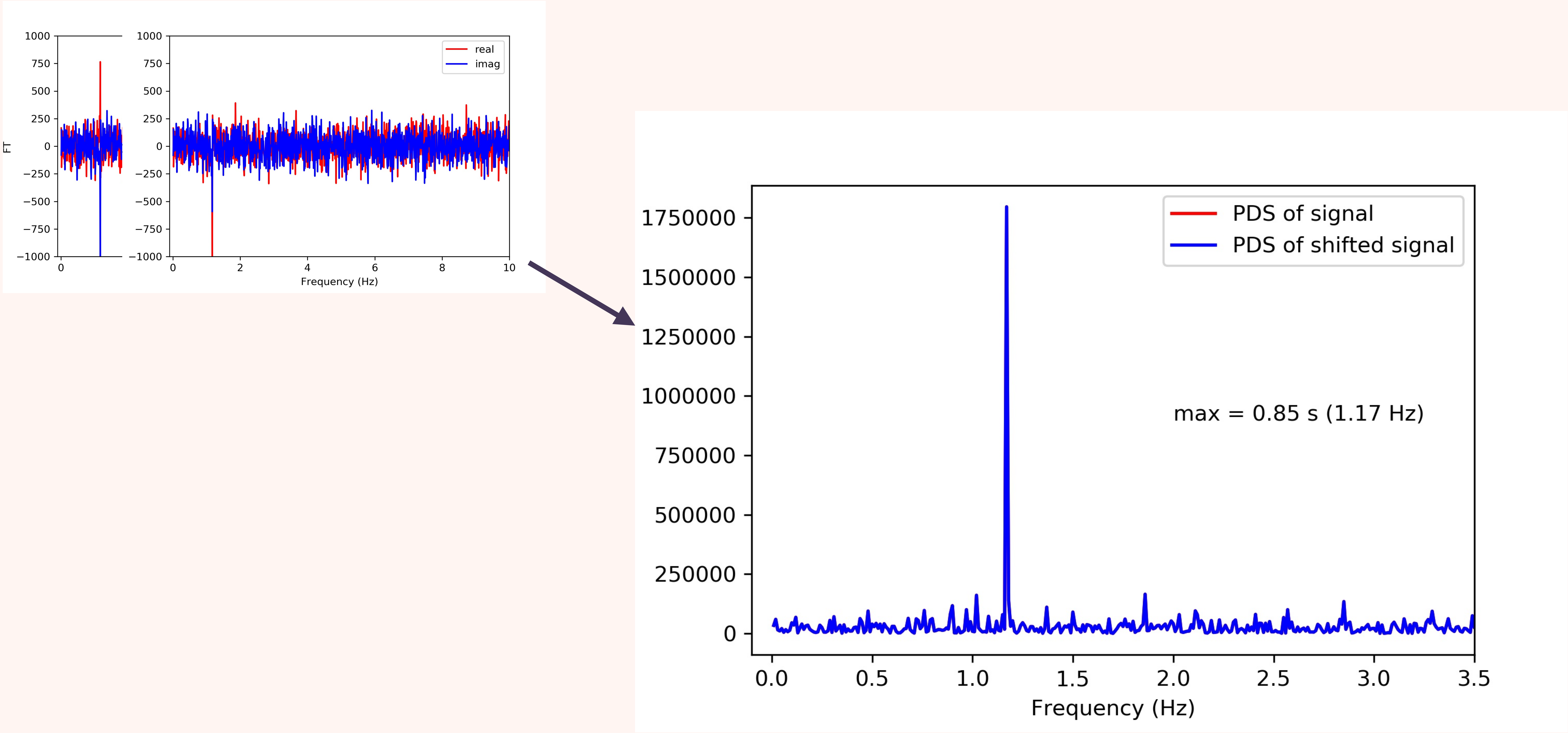
PERIODOGRAM
(POWER DENSITY SPECTRUM)

If our goal is just detecting periodicities, we can take the *squared modulus* of the Fourier transform. This is called **Periodogram**, but most people use the word **Power Density Spectrum** (PDS; a periodogram is actually a single realization of the underlying PDS).

$$\mathscr{P}(\omega) = \mathscr{F}(\omega) \cdot \mathscr{F}^*(\omega)$$

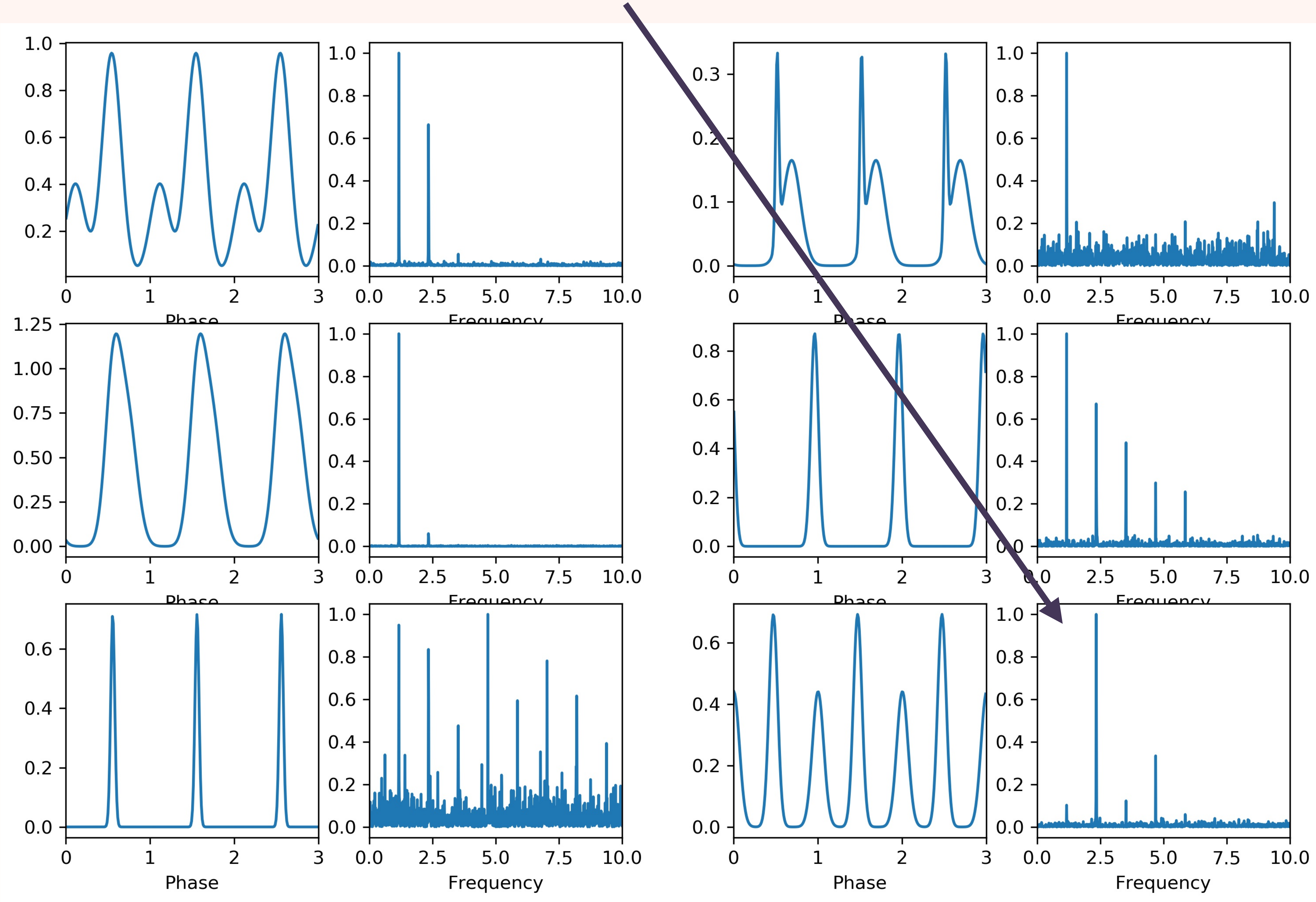
Refer to van der Klis 1989ASIC..262...27V

This function is positive-definite and results in a clear peak at the pulse frequency, with no difference between the original and the shifted signal



The PDS of a generic non-sinusoidal pulse profile will, in general, contain more than one harmonic.

The fundamental is not always predominant



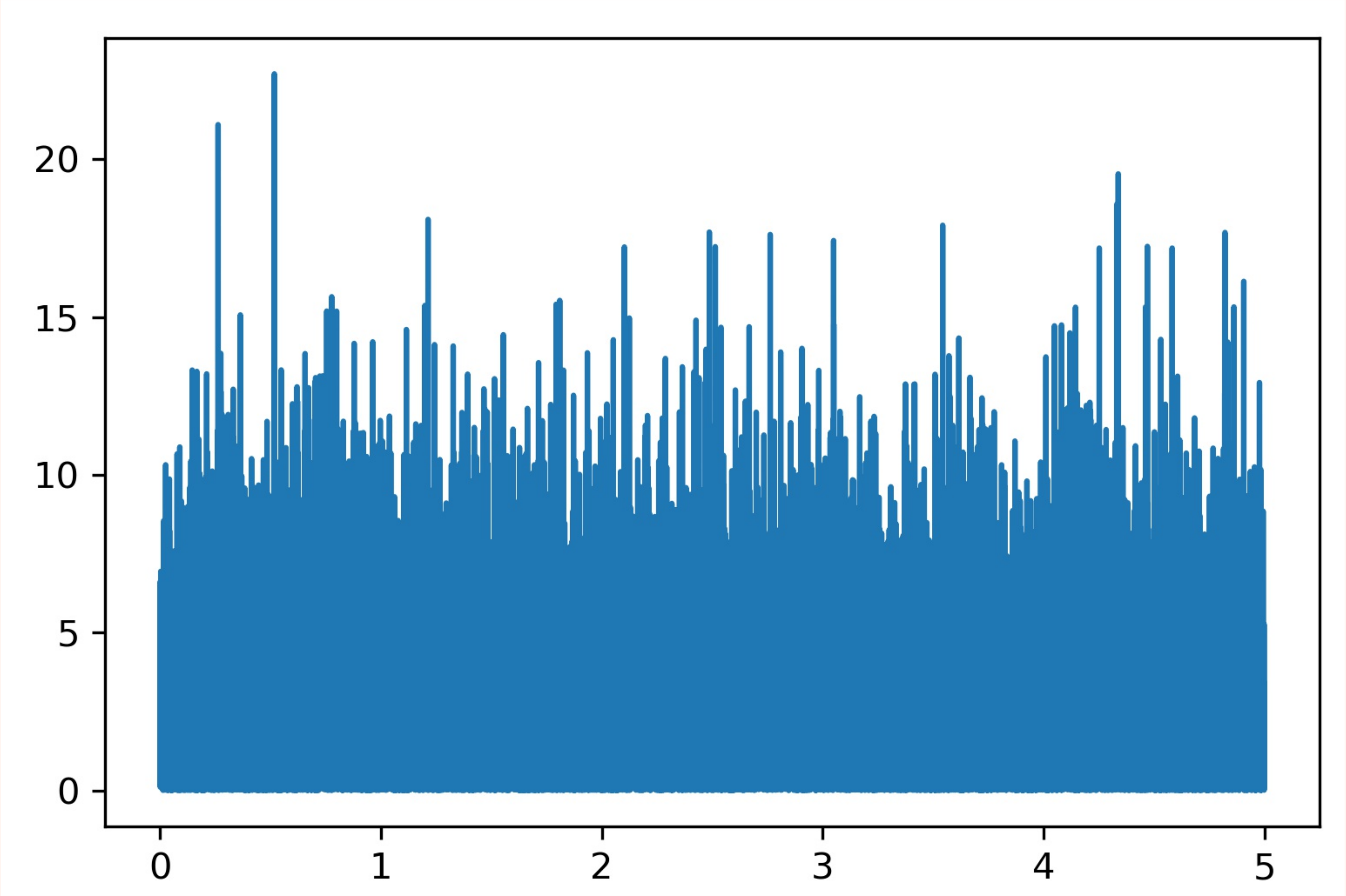
SOME PERIODOGRAM STATISTICS - I

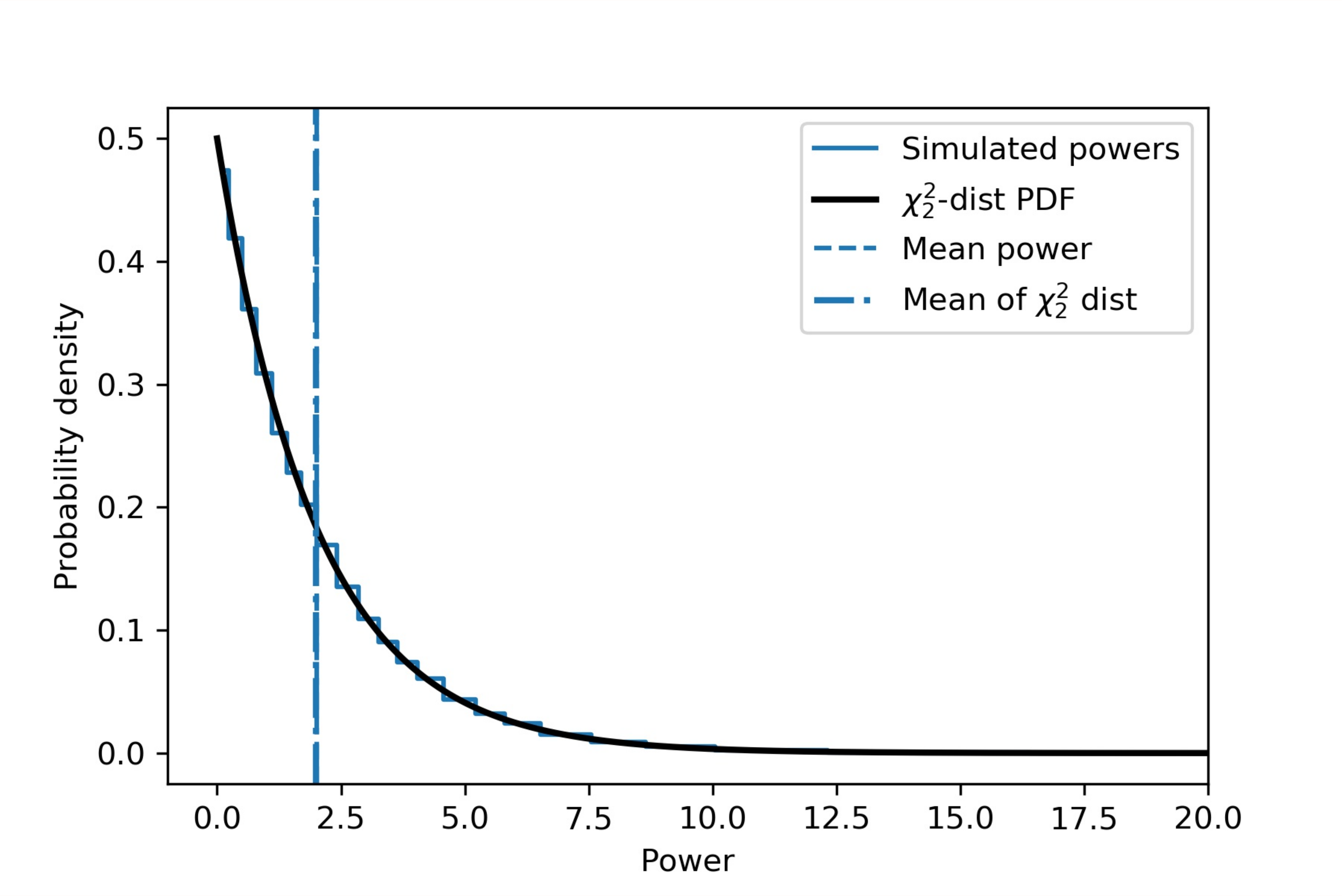
The power density spectrum of uniformly sampled Poissonian data (such as counting experiments) can be conveniently normalized as follows:

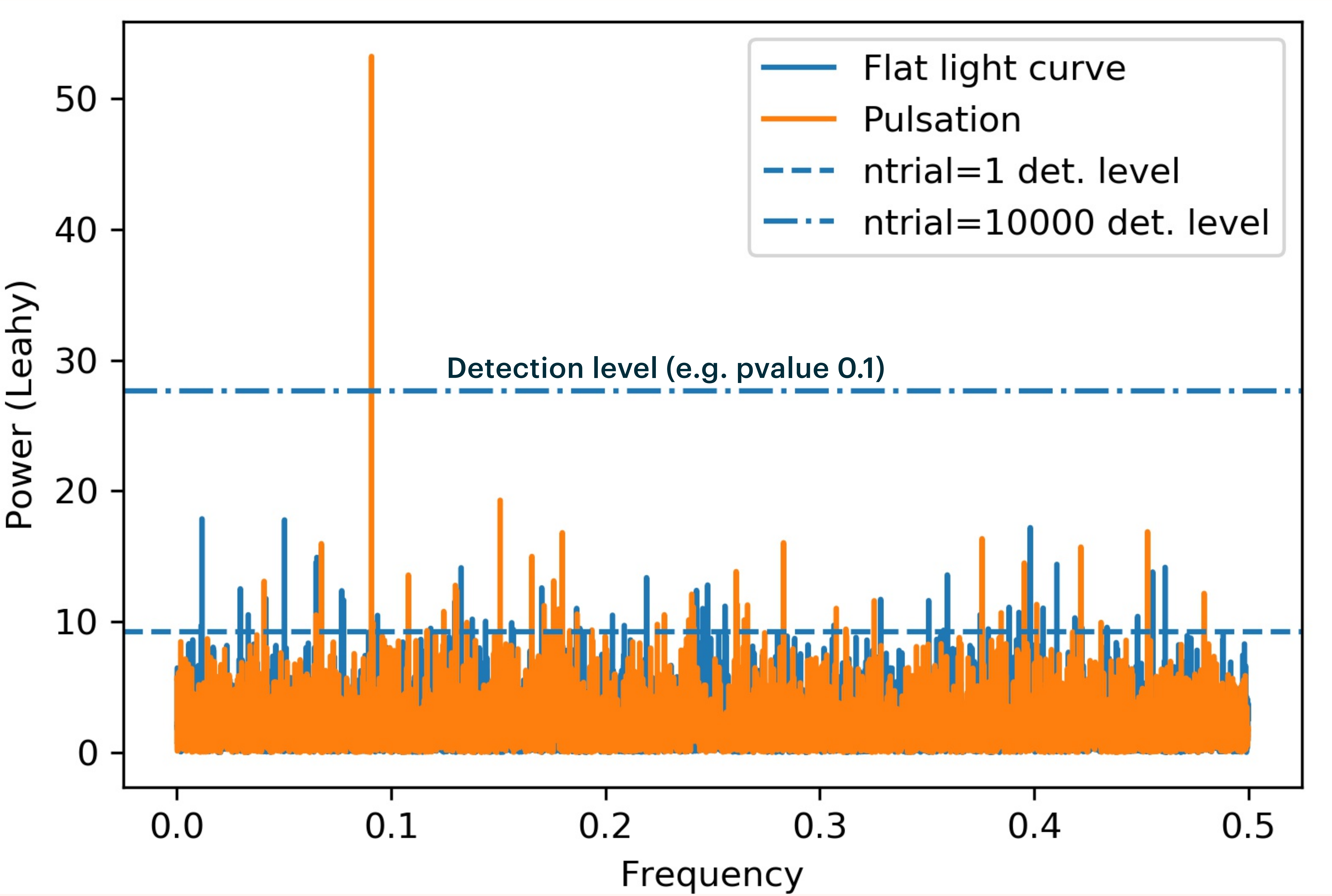
$$P_k = \frac{2}{N_{\mathrm{ph}}} F_k F_k^*$$

where $F_k, k = -N/2, N/2 - 1$ is the Fourier transform of the light curve.

In this particular normalization, the periodogram of white noise is distributed according to a Chi squared statistics with 2 degrees of freedom in the absence of signal (Leahy+83). This is referred to as the Leahy normalization.

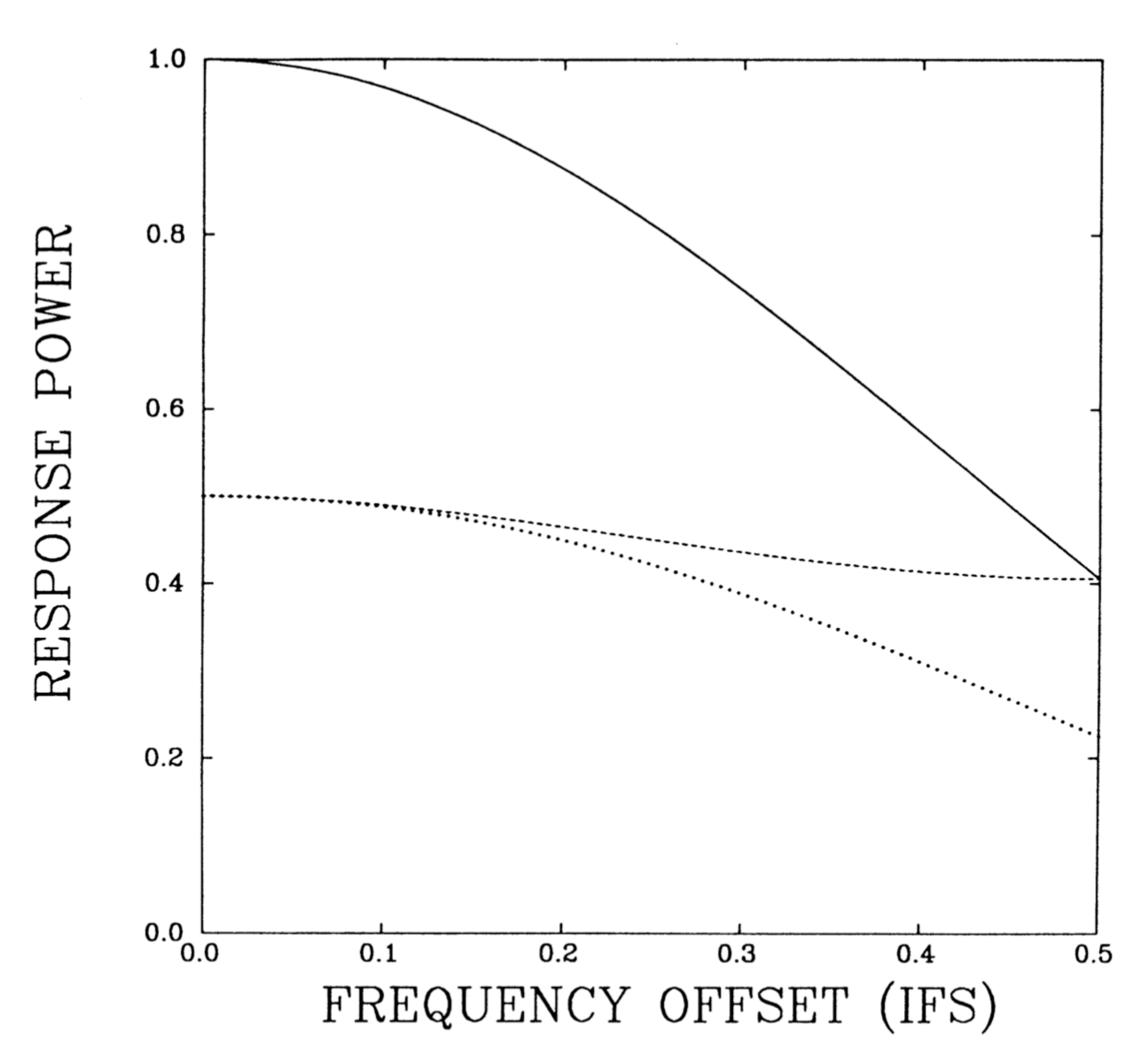





Flat light curve
Pulsation
ntrial=1 det. level
ntrial=10000 det. level
Detection level (e.g. pvalue 0.1)
Power (Leahy)
0
10
20
30
40
50
0.0
0.1
0.2
0.3
0.4
0.5
Frequency

THINGS TO KEEP IN MIND - I

- The sensitivity of the PDS is not uniform throughout the frequency range, and inside the frequency bins.
- A drop of 36% sensitivity if the signal frequency is at the border of the frequency bin
- Use high frequency resolution if possible, and/or set detection levels to account for the sensitivity drop
- Use very high Nyquist frequency!

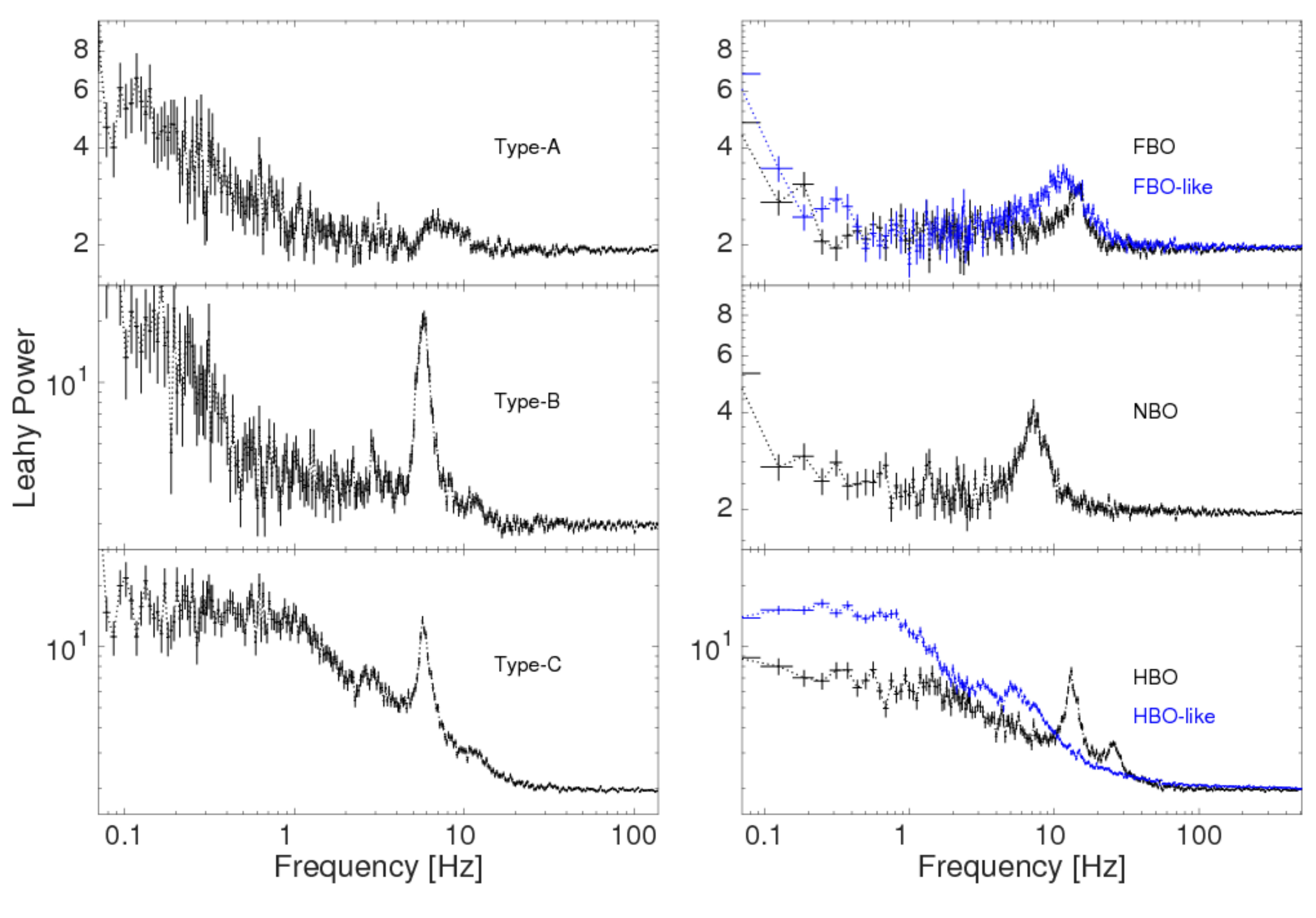


van der Klis '98

THINGS TO KEEP IN MIND - II

- The Periodogram rarely contains purely white noise. Broadband noise components and other distortions of the periodogram can occur, that **alter the detection level**
  - Random source variability (red noise, QPOs, etc):
  - **Dead time** greatly affects the shape of the periodogram
  - Data gaps, e.g. occultation from the Earth, SAA, etc.

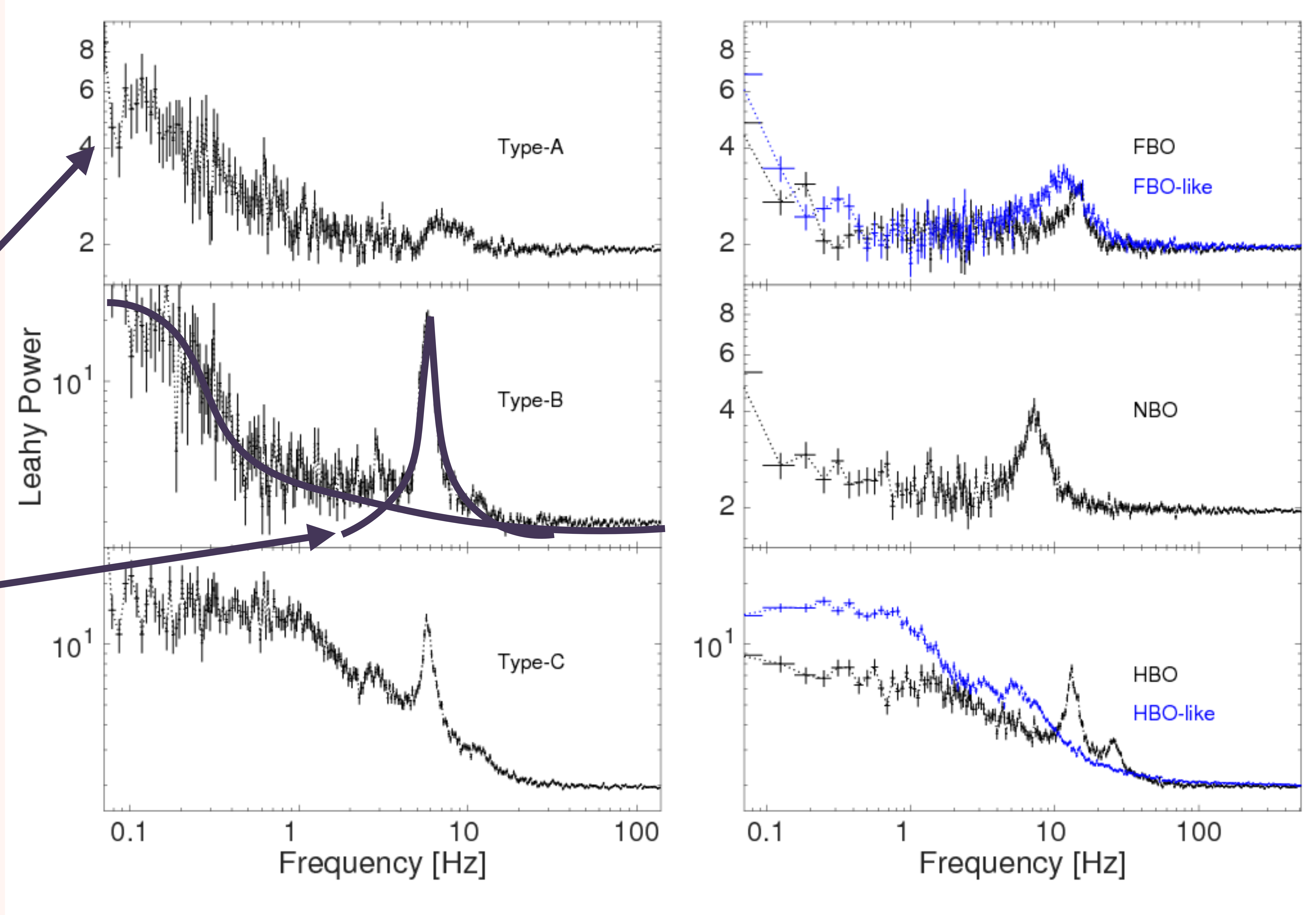
APERIODIC TIMING



Motta et al. 2014

APERIODIC TIMING

- Broadband noise
- Quasi-periodic oscillations (QPOs)



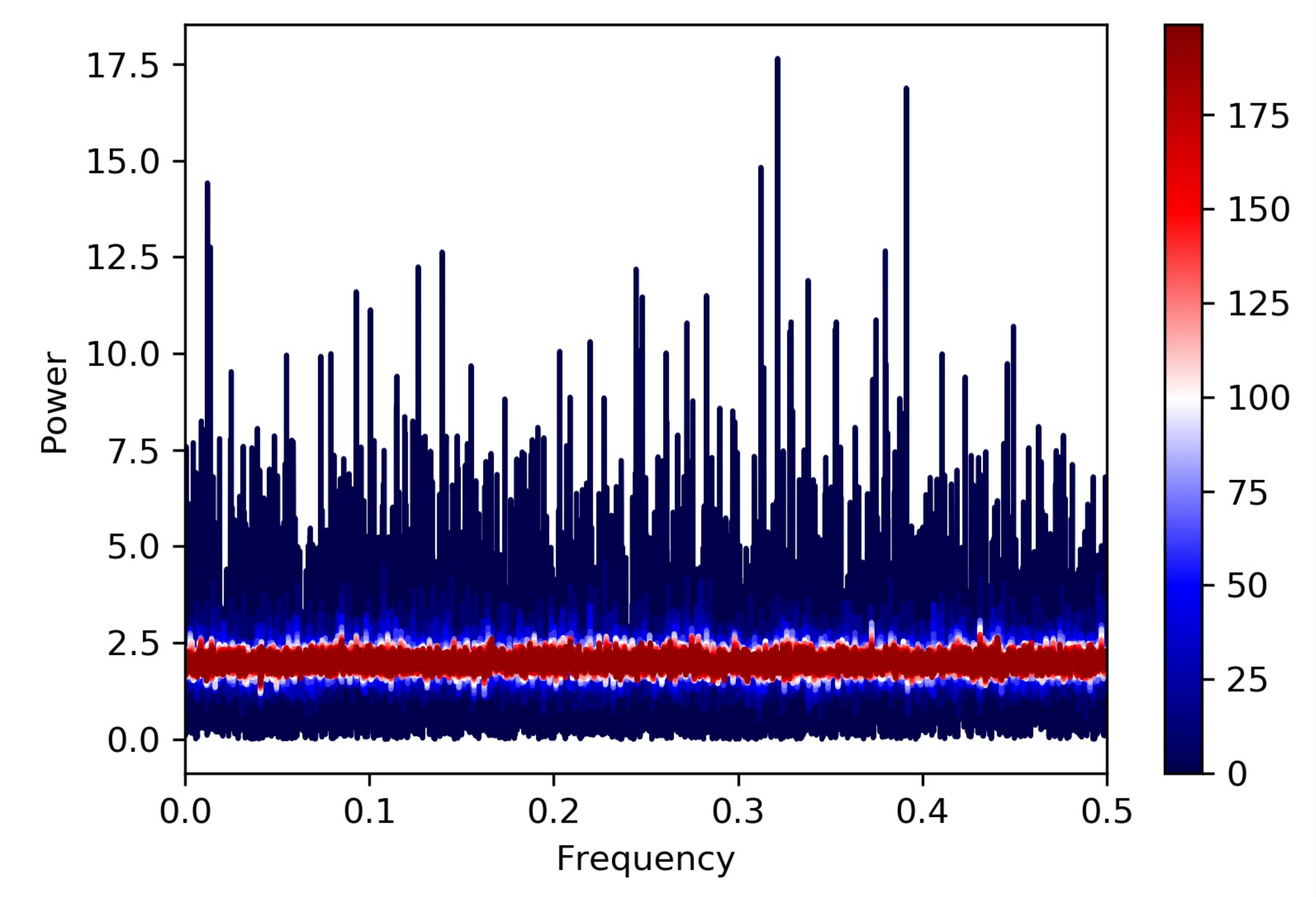
Motta et al. 2014

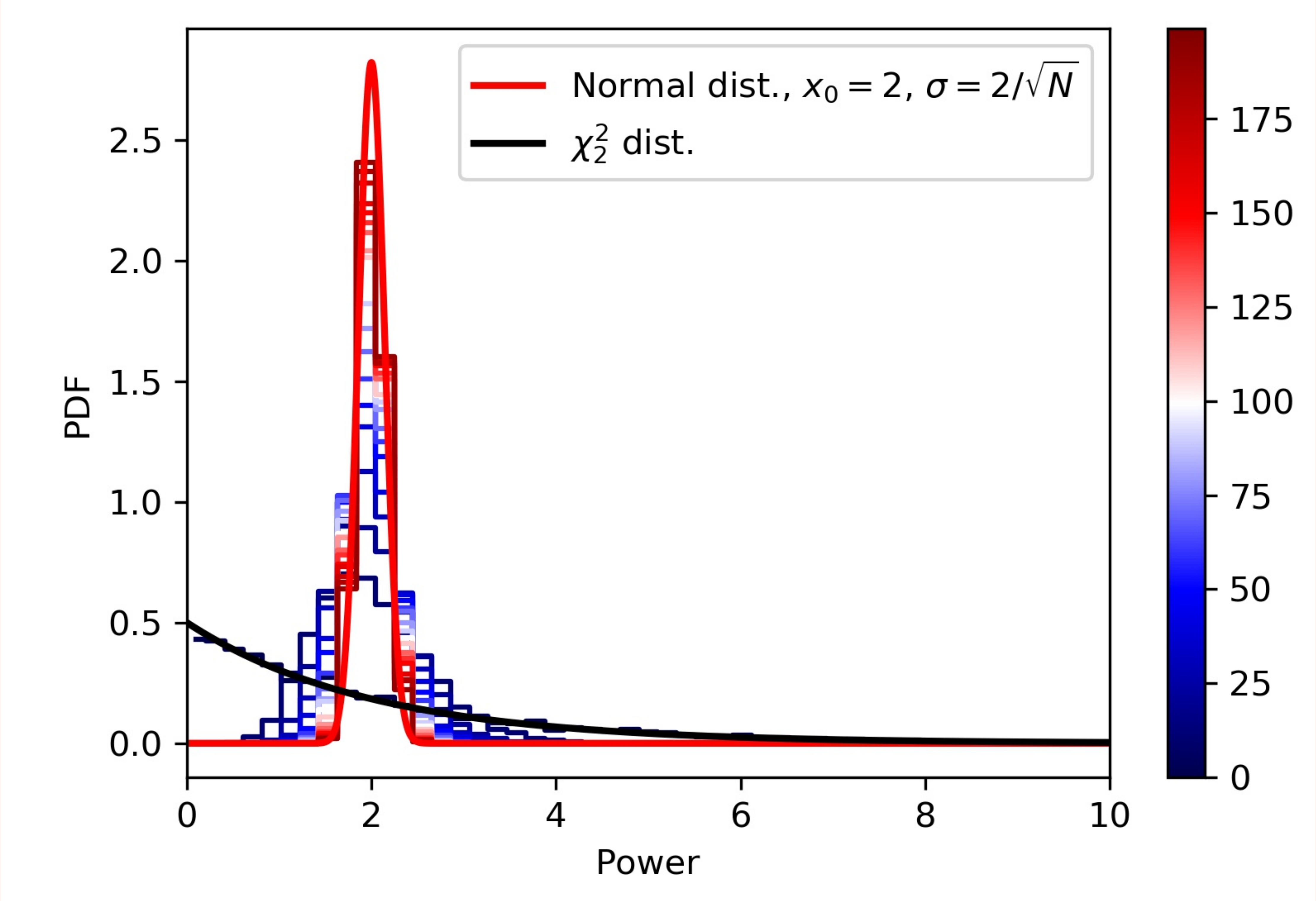
WHAT CAN WE LEARN FROM APERIODIC VARIABILITY?

- Important timescales, e.g.:
  - a QPO at 1 Hz says that the region producing it is < ~1 l-s
  - similarly for a break frequency in the PDS
- Test physical models:
  - Are those QPO corresponding to relativistic oscillations?
  - Is that broadband noise produced by the propagation of instabilities in the disk?

SOME PERIODOGRAM STATISTICS - II

For the central limit theorem, averaging many PDSs (or equivalently, averaging many nearby bins) will lead to normally-distributed white noise powers. Typically: one uses the **Bartlett periodogram**: an average of the periodogram over many intervals of light curve

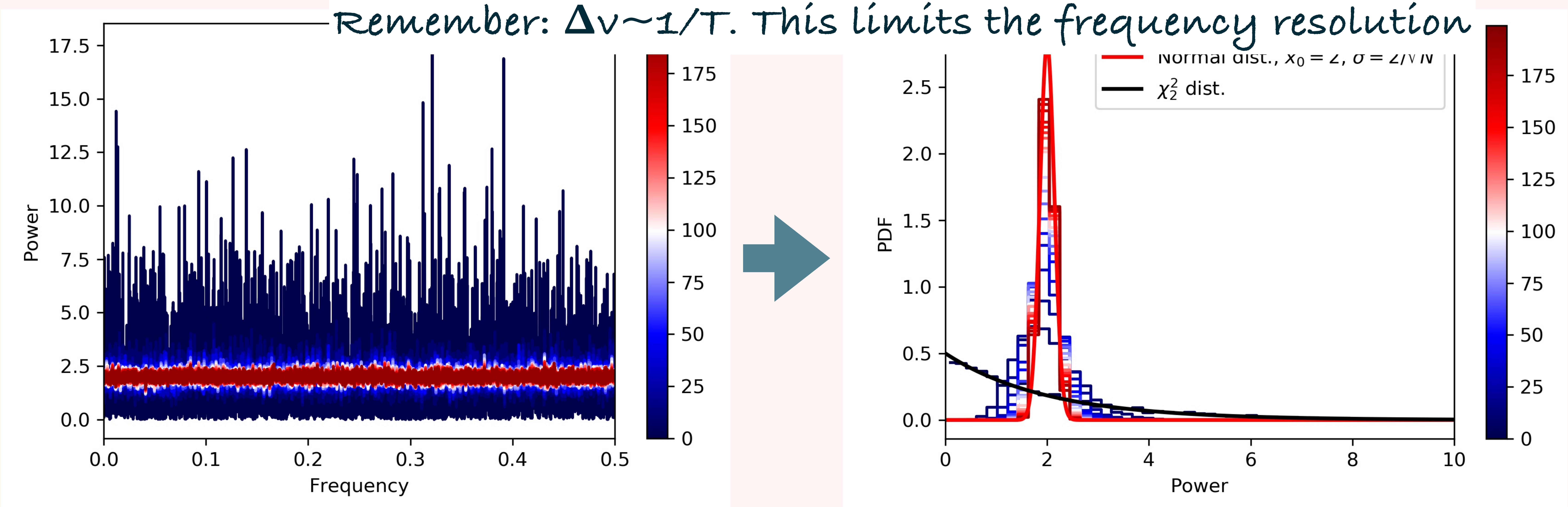




SOME PERIODOGRAM STATISTICS - II

For the central limit theorem, averaging many PDSs (or equivalently, averaging many nearby bins) will lead to normally-distributed white noise powers. Typically: one uses the **Bartlett periodogram**: an average of the periodogram over many intervals of light curve

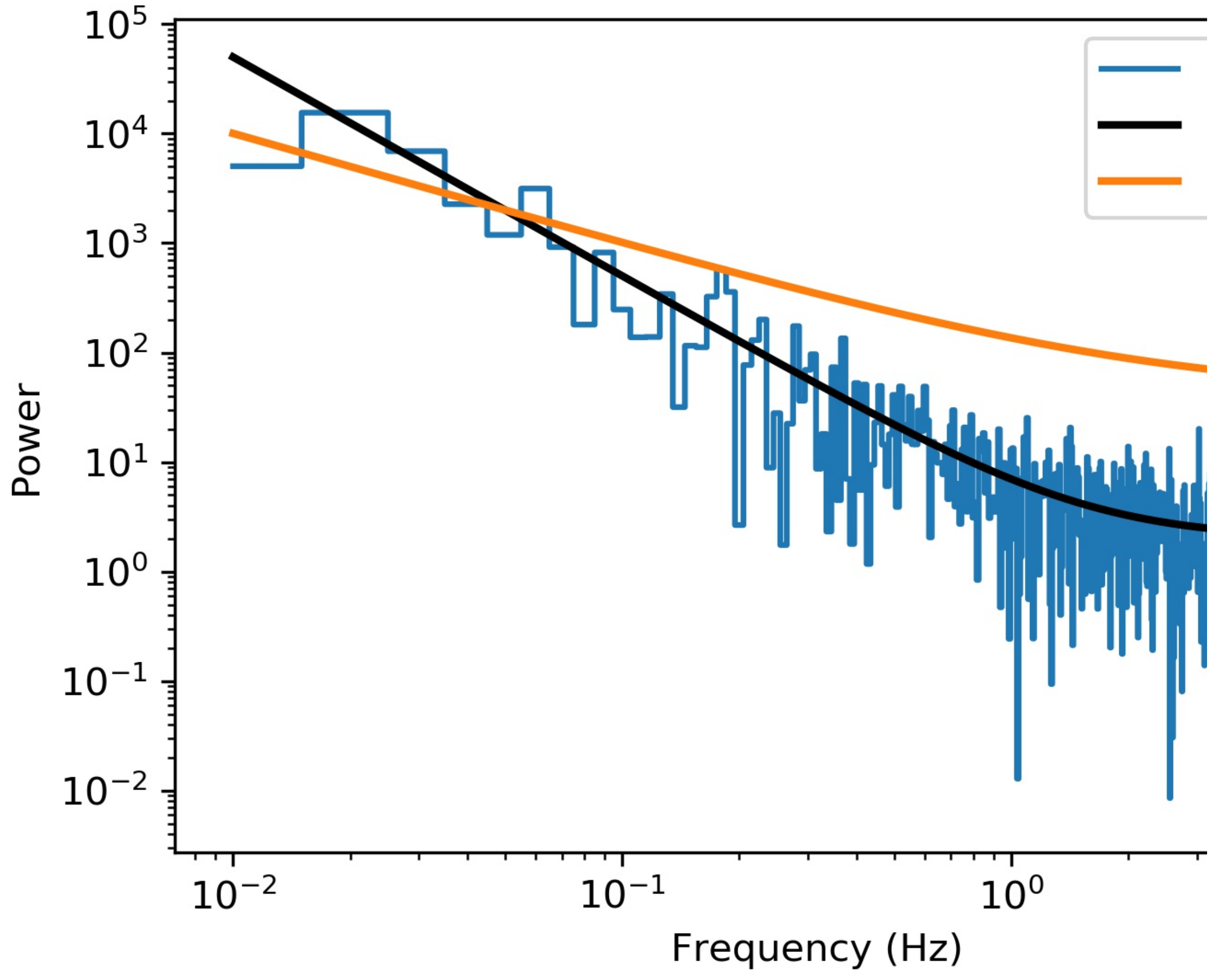
Remember: $\Delta\nu \sim 1/T$. This limits the frequency resolution



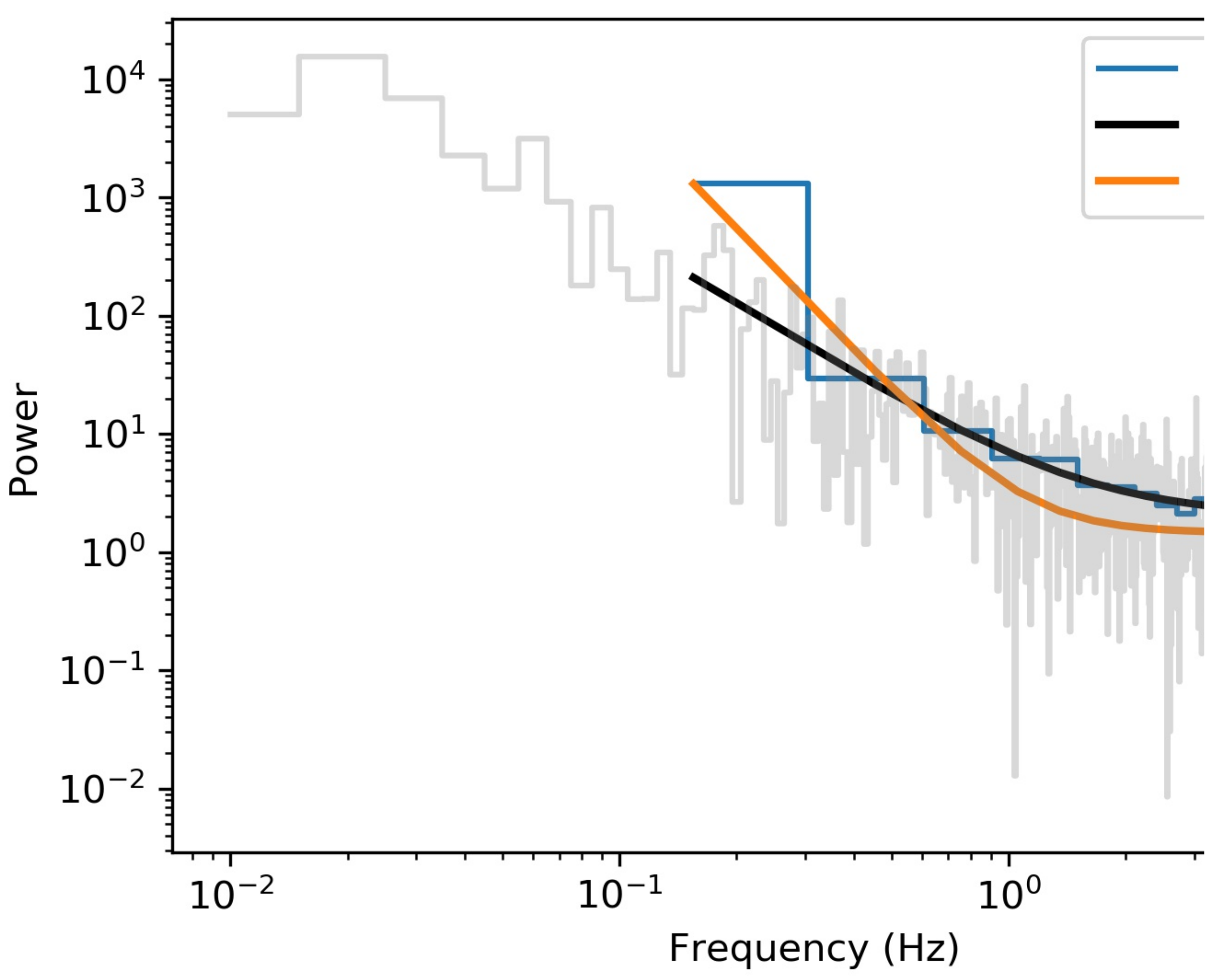
FITTING PERIODOGRAMS

Unless one has averaged >> 30 PDSs, it is recommended **not** to assume Gaussian error bars.
Use maximum likelihood or Bayesian fitting with the correct likelihood instead.

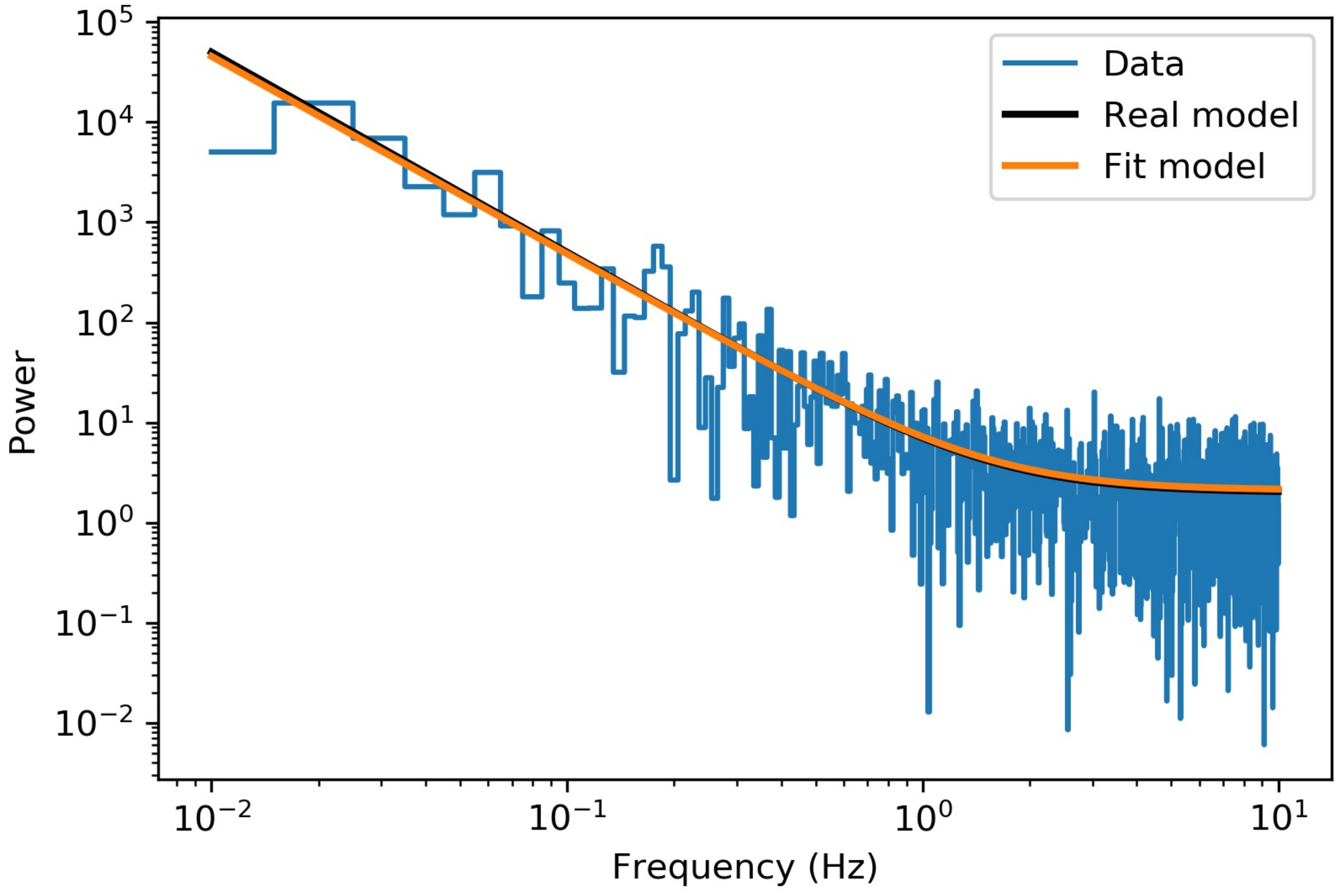
Chisq. fit on original PDS



Chisq. fit on rebinned PDF



Max-Likelihood fit on original PDS



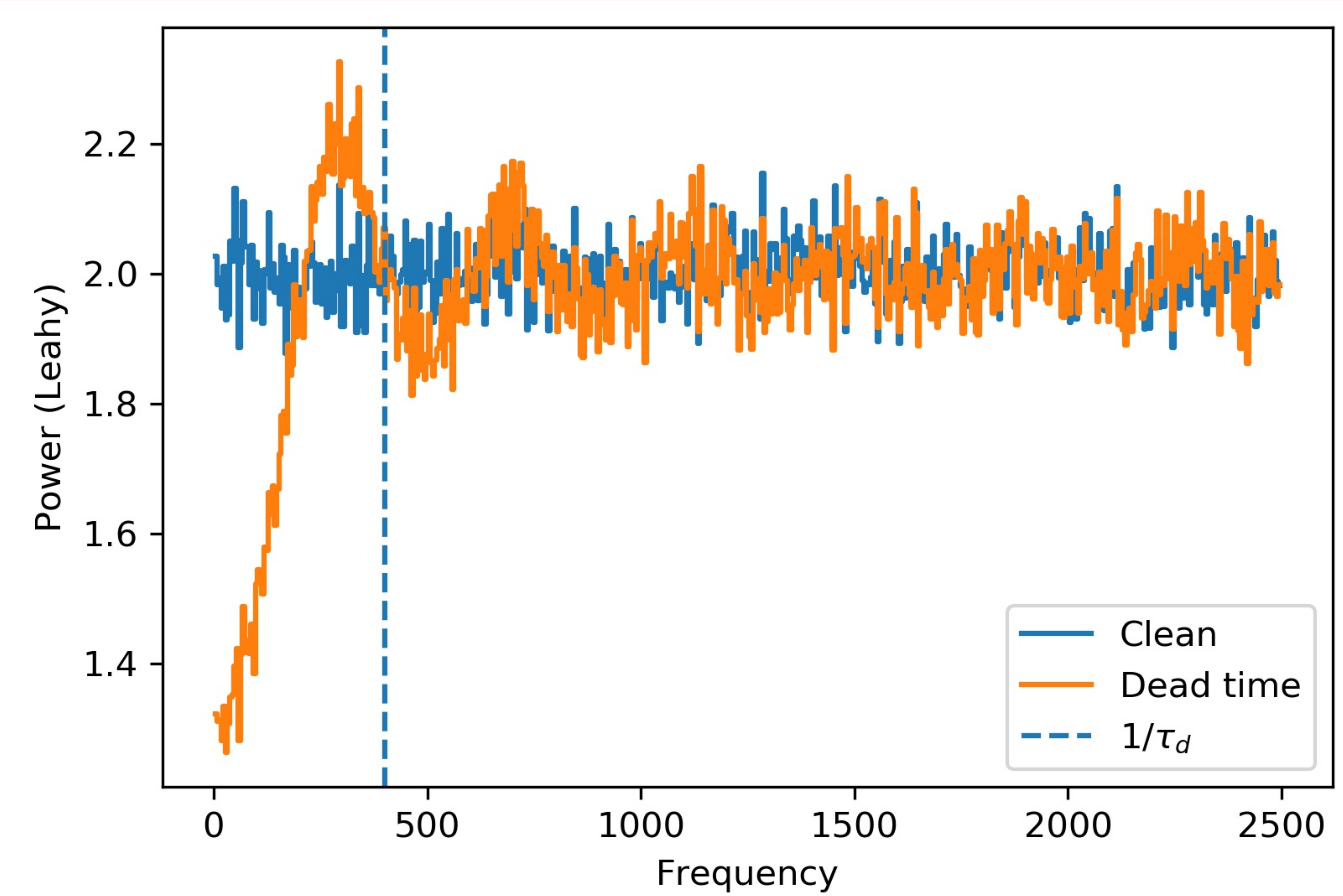
CROSS PRODUCTS

- If we have two light curves from two channels 1 and 2 (e.g. two independent detectors, two energy ranges), and their Fourier transforms are called $\mathscr{F}_1(\omega)$ and $\mathscr{F}_2^*(\omega)$, their **cross spectrum** is defined as
  $\mathscr{C}(\omega) = \mathscr{F}_1(\omega) \cdot \mathscr{F}_2^*(\omega)$
- It is a complex quantity (unless 1 and 2 contain the same signal)
- The real part of the cross spectrum is called **cospectrum**
- The angle is called **phase lag**
- From the cross spectrum, we can calculate the **coherence**, **covariance** and the other cross products

DEAD TIME

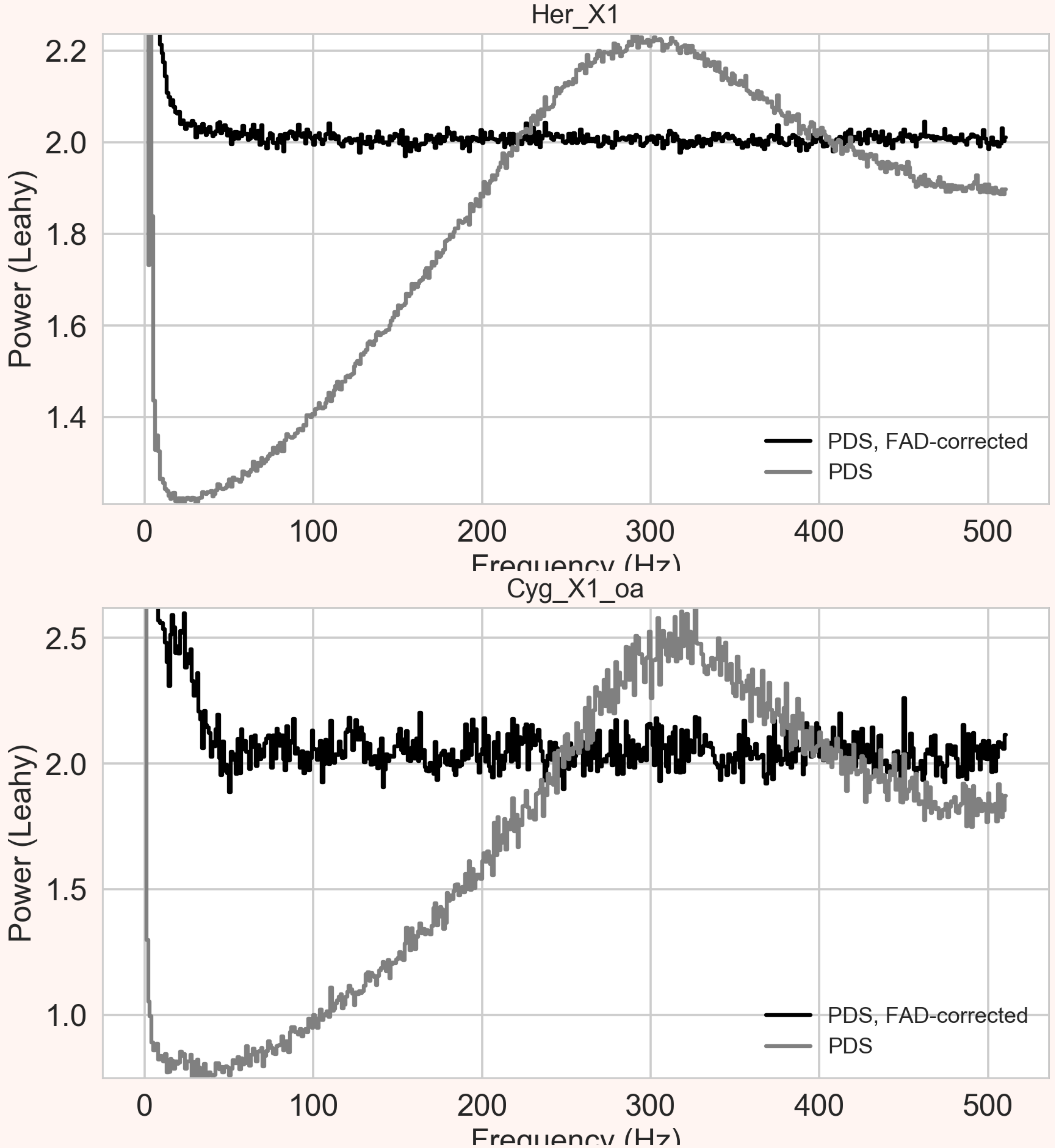
- The presence of dead time alters the frequency response of the signal, especially for bright sources. The shape of the periodogram is then distorted.

- This distortion has two unwanted consequences:
  - It is harder to model the white noise level and hence the aperiodic variability and the detection levels
  - The variability measurements are also wrong (variability is suppressed, differently at different frequencies)

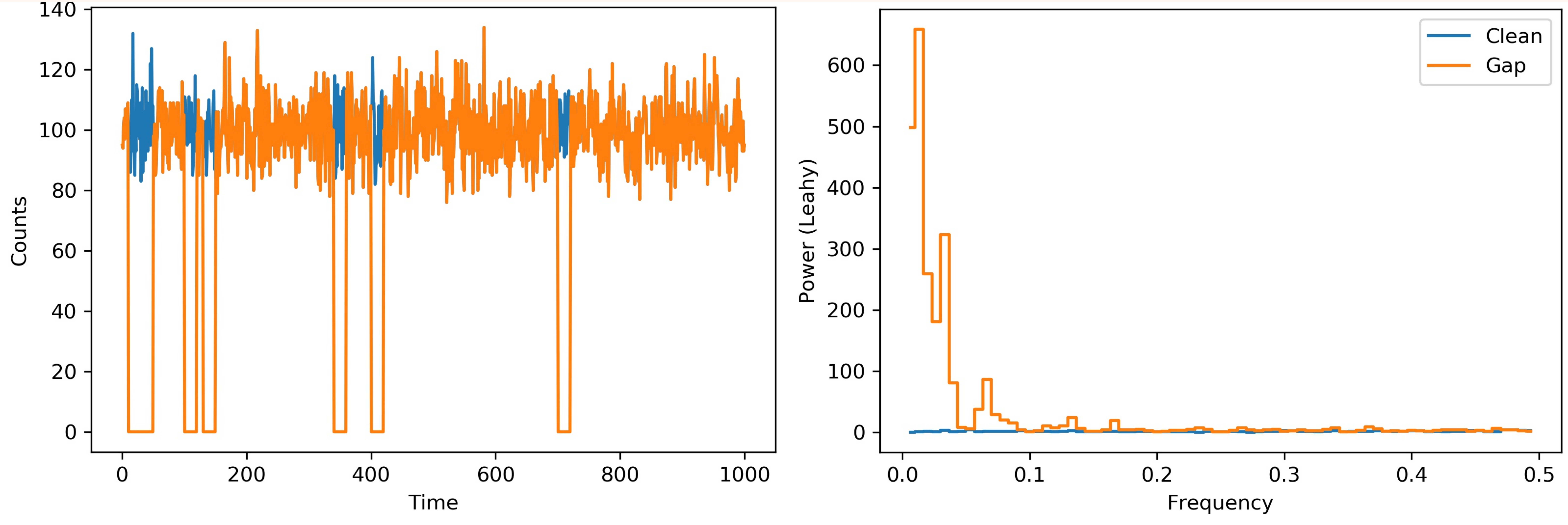


DEAD TIME CORRECTION

- Bachetti & Huppenkothen 2018 describe a way to correct a dead-time distorted PDS using data from multiple, identical instrument (feasible in IXPE!)

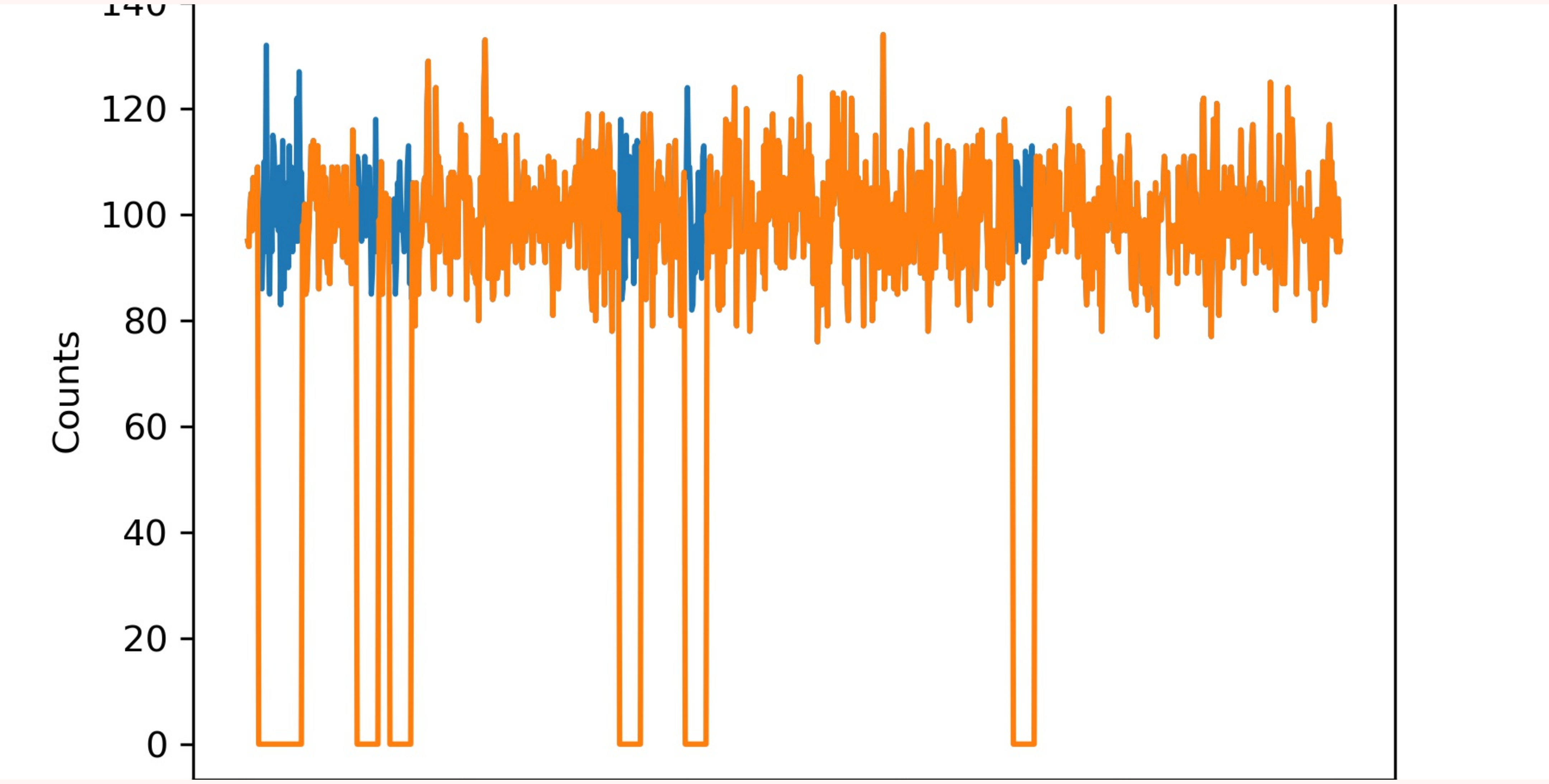


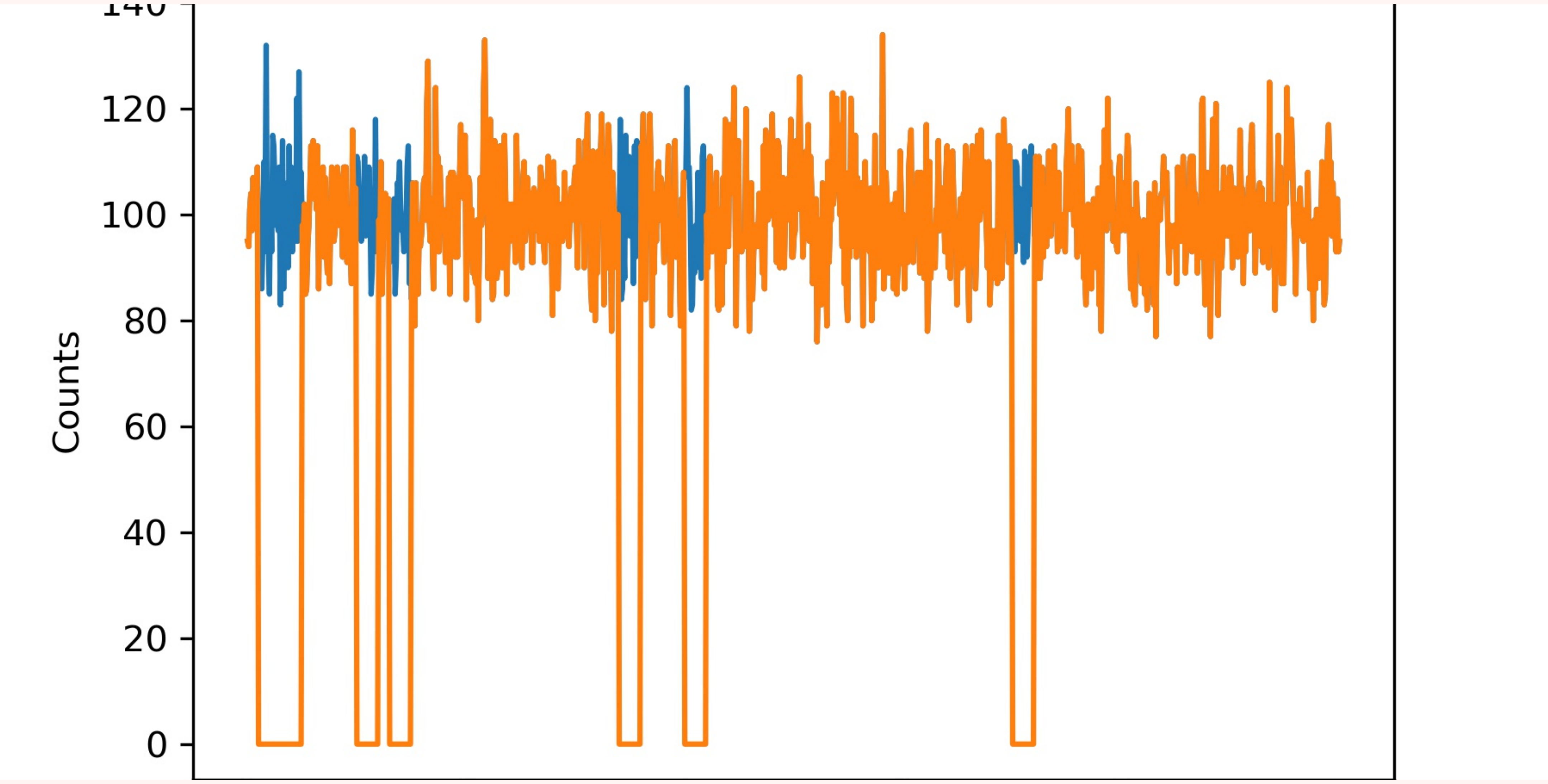
DATA GAPS



Counts
Time
0
200
400
600
800
1000
0
20
40
60
80
100
120
140
Power (Leahy)
Frequency
0.0
0.1
0.2
0.3
0.4
0.5
0
100
200
300
400
500
600
Clean
Gap

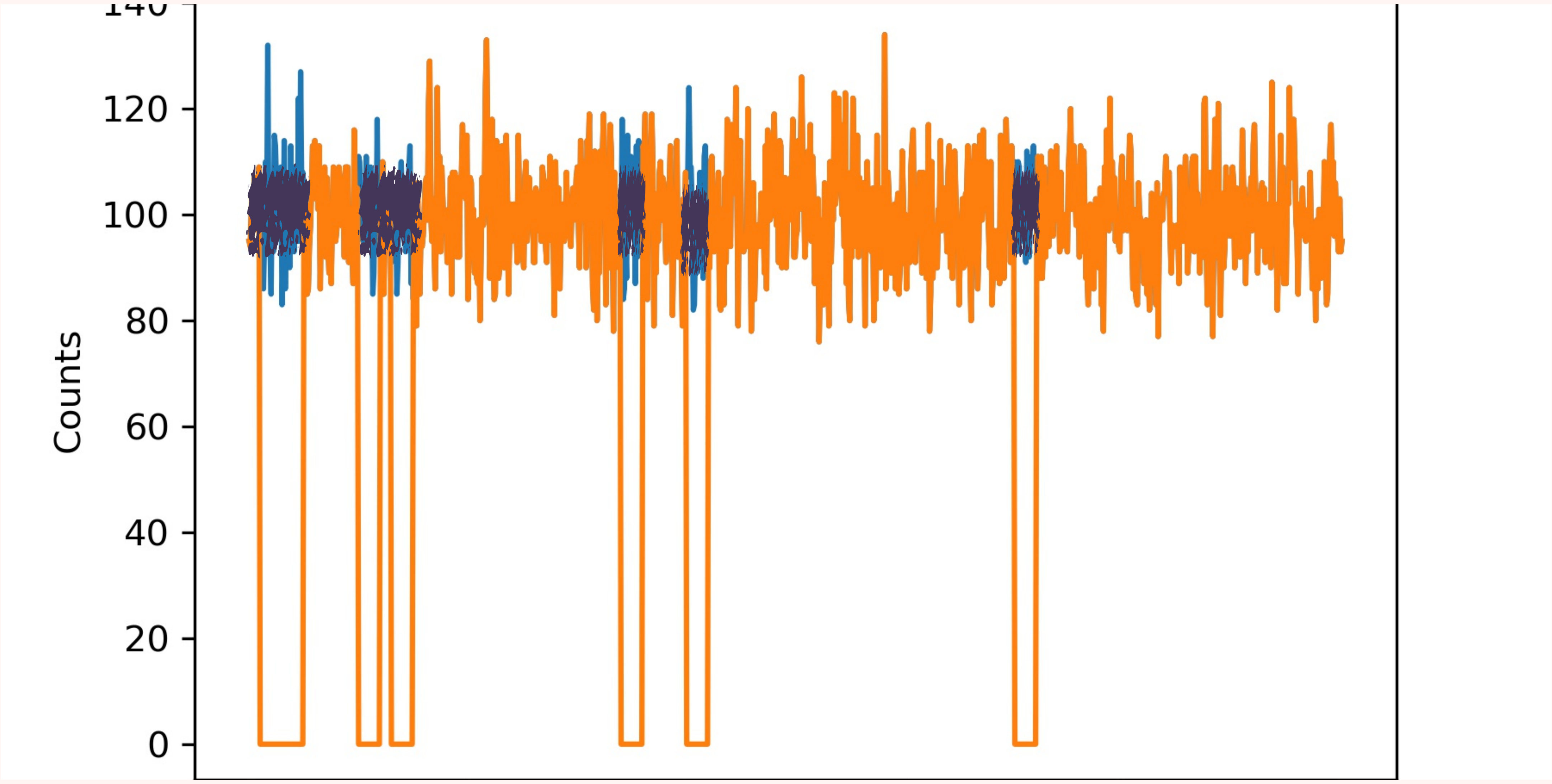
TREATING DATA GAPS

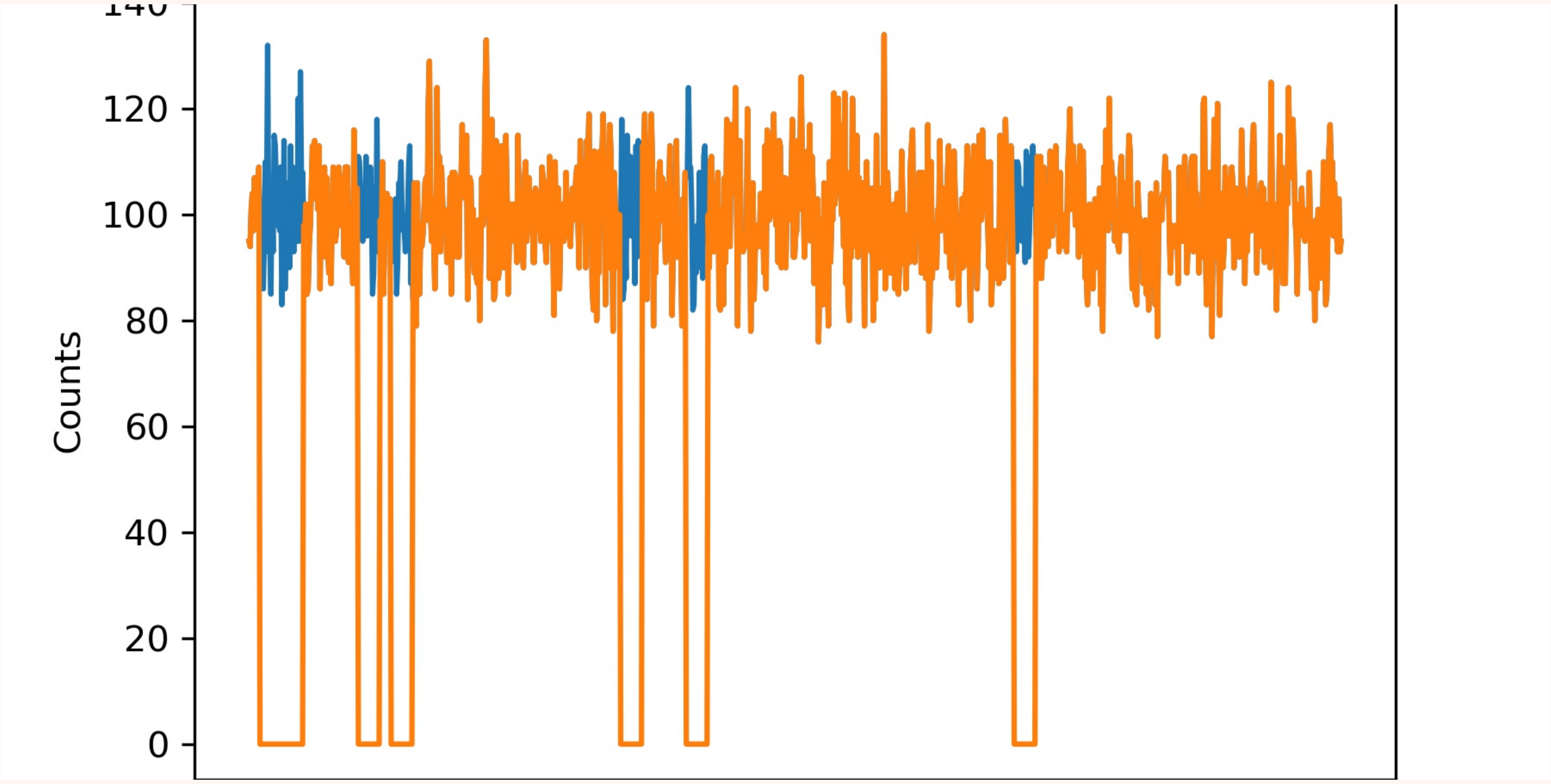




TREATING DATA GAPS

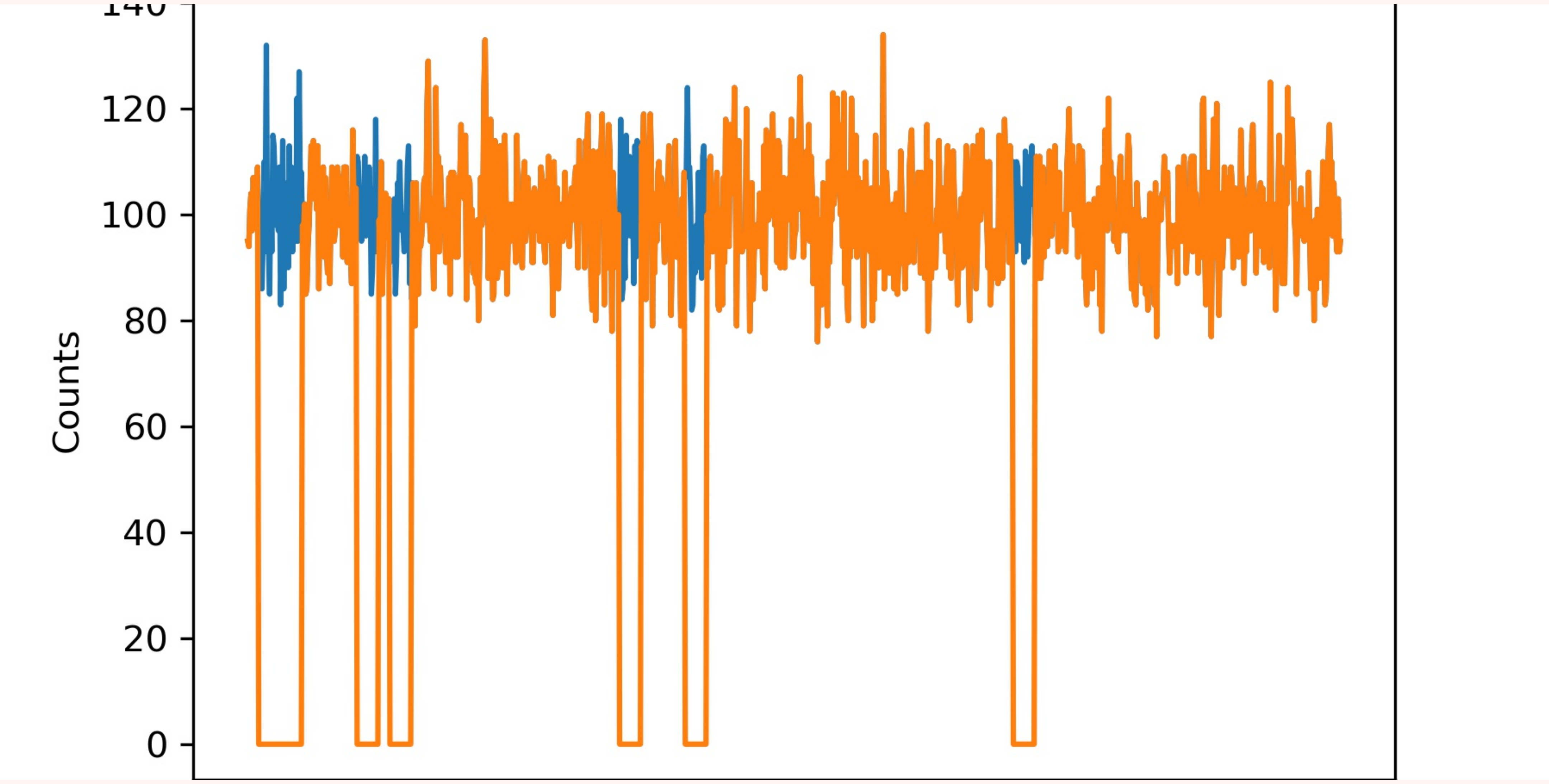
- For pulsation searches: fill gaps

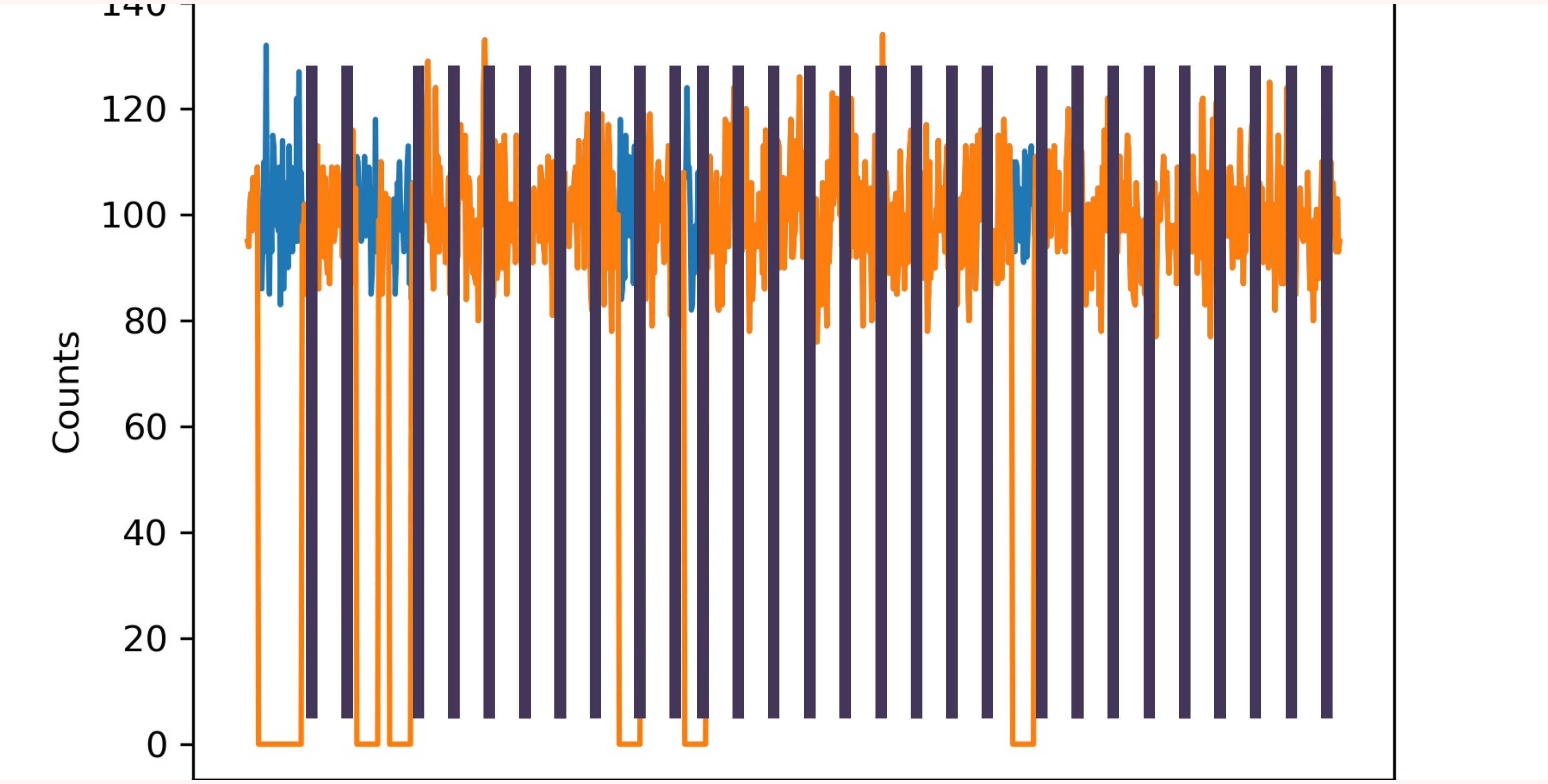




TREATING DATA GAPS

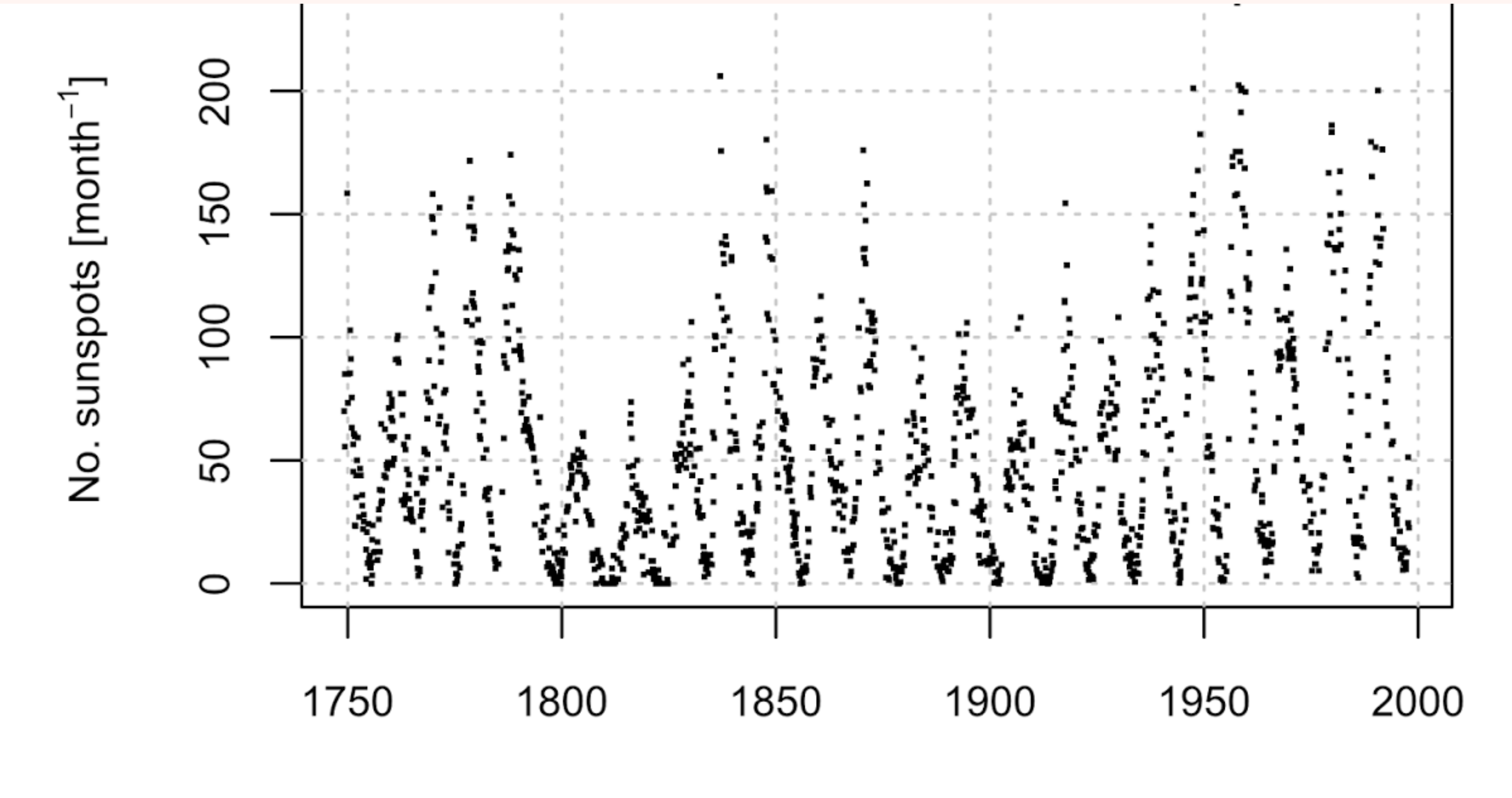
- For pulsation searches: fill gaps
- For aperiodic variability: select data from good time intervals

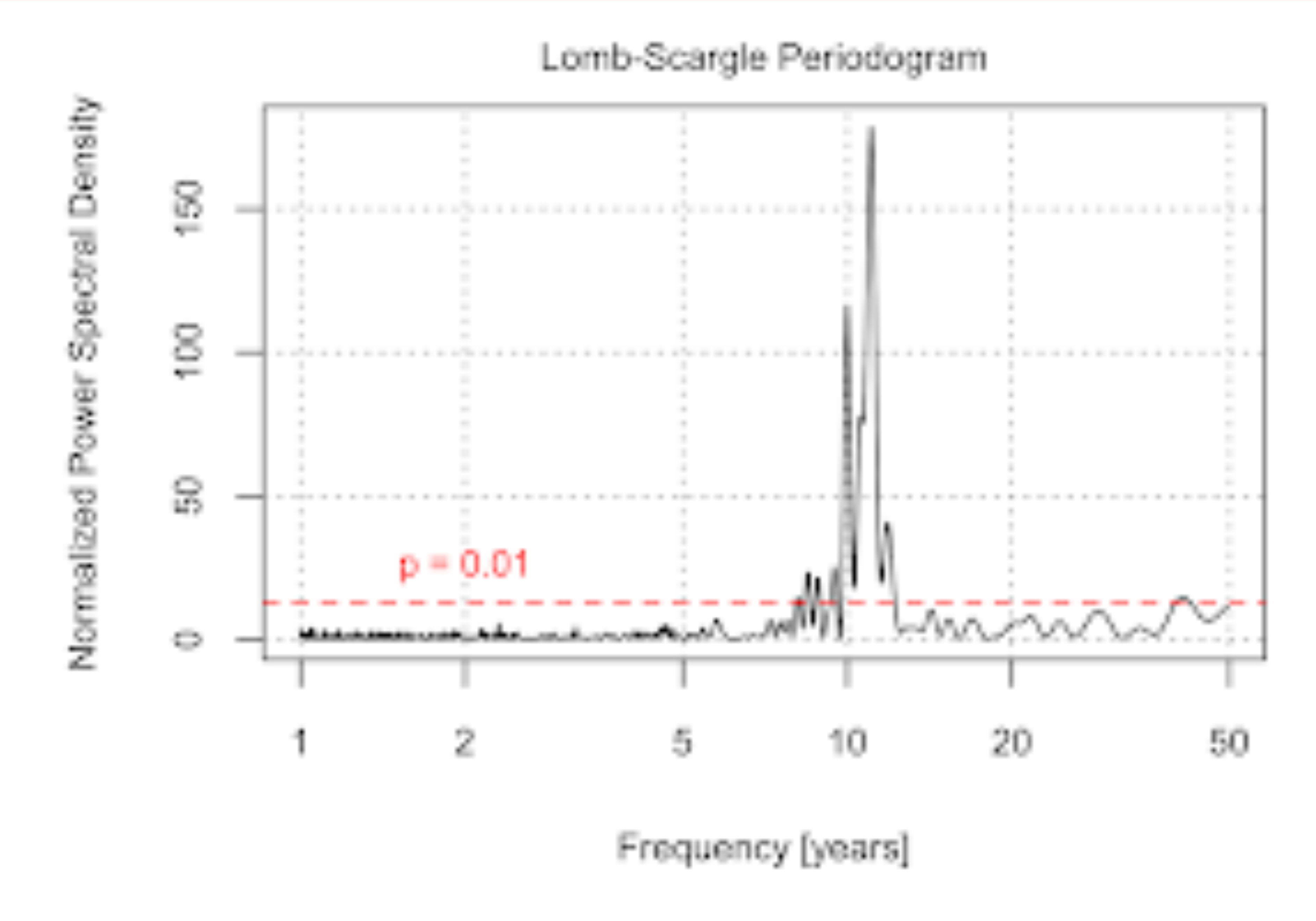




UNEVENLY SAMPLED DATA

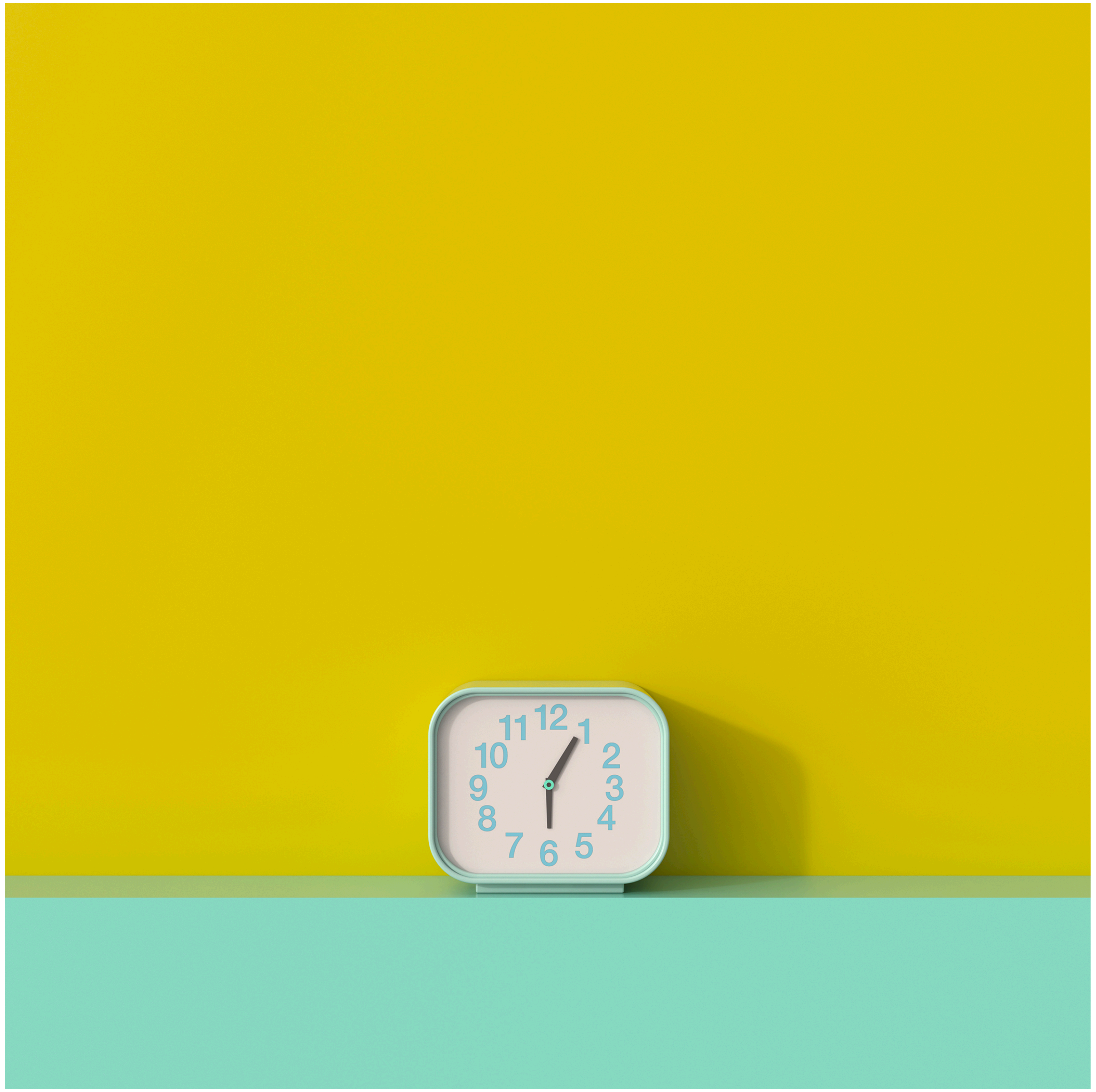
- The **Lomb-Scargle periodogram** is often adequate for the task, with caution. See arXiv:1703.09824 https://jakevdp.github.io/blog/2017/03/30/practical-lomb-scargle/





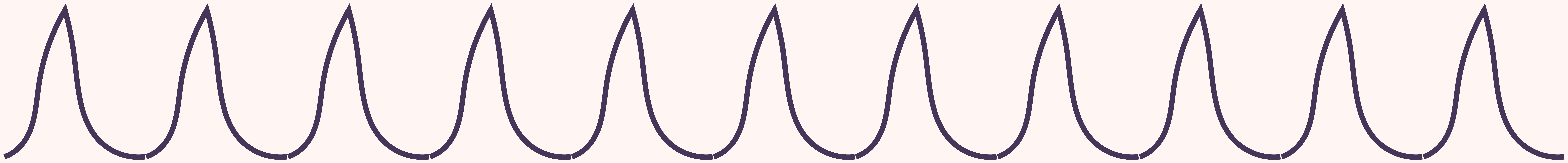
TIME DOMAIN METHODS

- Light curves
- Epoch Folding
- Gaussian processes -> not for today



EPOCH FOLDING

- Epoch folding consists of summing equal, one pulse period-long, chunks of data. If the period is just right, the crests will sum up in phase, gaining signal over noise



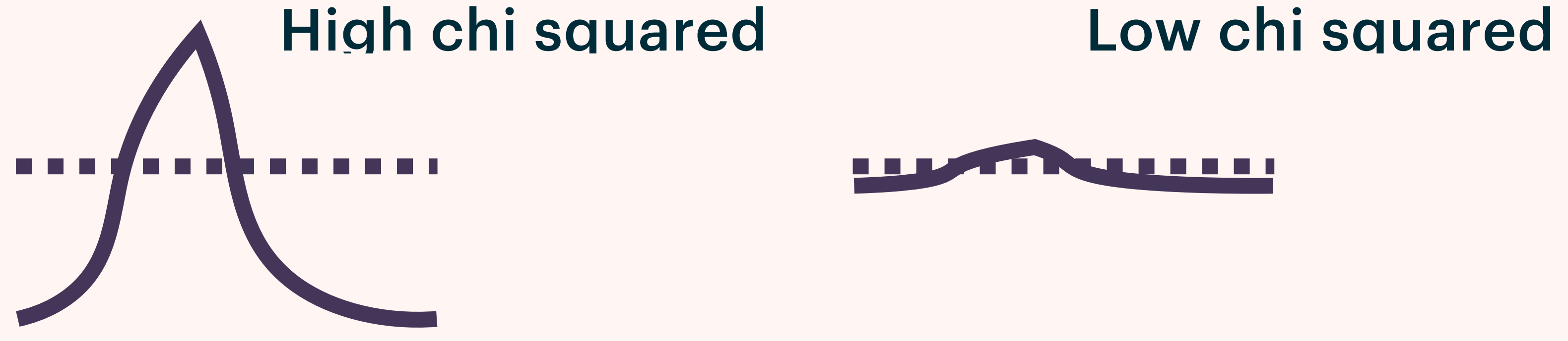
EPOCH FOLDING

- Epoch folding consists of summing equal, one pulse period-long, chunks of data. If the period is just right, the crests will sum up in phase, gaining signal over noise

EF, Z, H SEARCHES

- Now, let's run epoch folding at a number of trial periods around the pulse period. To evaluate how much a given profile "looks pulsar-y", we can use the Chi squared statistics, as follows:

$$\mathcal{S} = \sum_{i=0}^{N} \frac{(p_i - \bar{p})^2}{\sigma_p^2}$$



for each profile obtained for each trial value of the pulse frequency and look for peaks.

EF, Z, H SEARCHES

- The Z search is sensitive to profiles described by sums of *n* sinusoids:

$$Z_n^2 = \frac{2}{N} \sum_{k=1}^{n} \left[\left(\sum_{j=1}^{N} \cos k\phi_j \right)^2 + \left(\sum_{j=1}^{N} \sin k\phi_j \right)^2 \right]$$

In this form, it's run on the phases of N single photons. It can be modified to be run on folded data, as follows:

$$Z_n^2 \approx \frac{2}{\sum_j w_j} \sum_{k=1}^{n} \left[\left(\sum_{j=1}^{m} w_j \cos k\phi_j \right)^2 + \left(\sum_{j=1}^{m} w_j \sin k\phi_j \right)^2 \right]$$

Where the `weight` quantity is the number of photons in a given bin (Huppenkothen+2019):

EF, Z, H SEARCHES

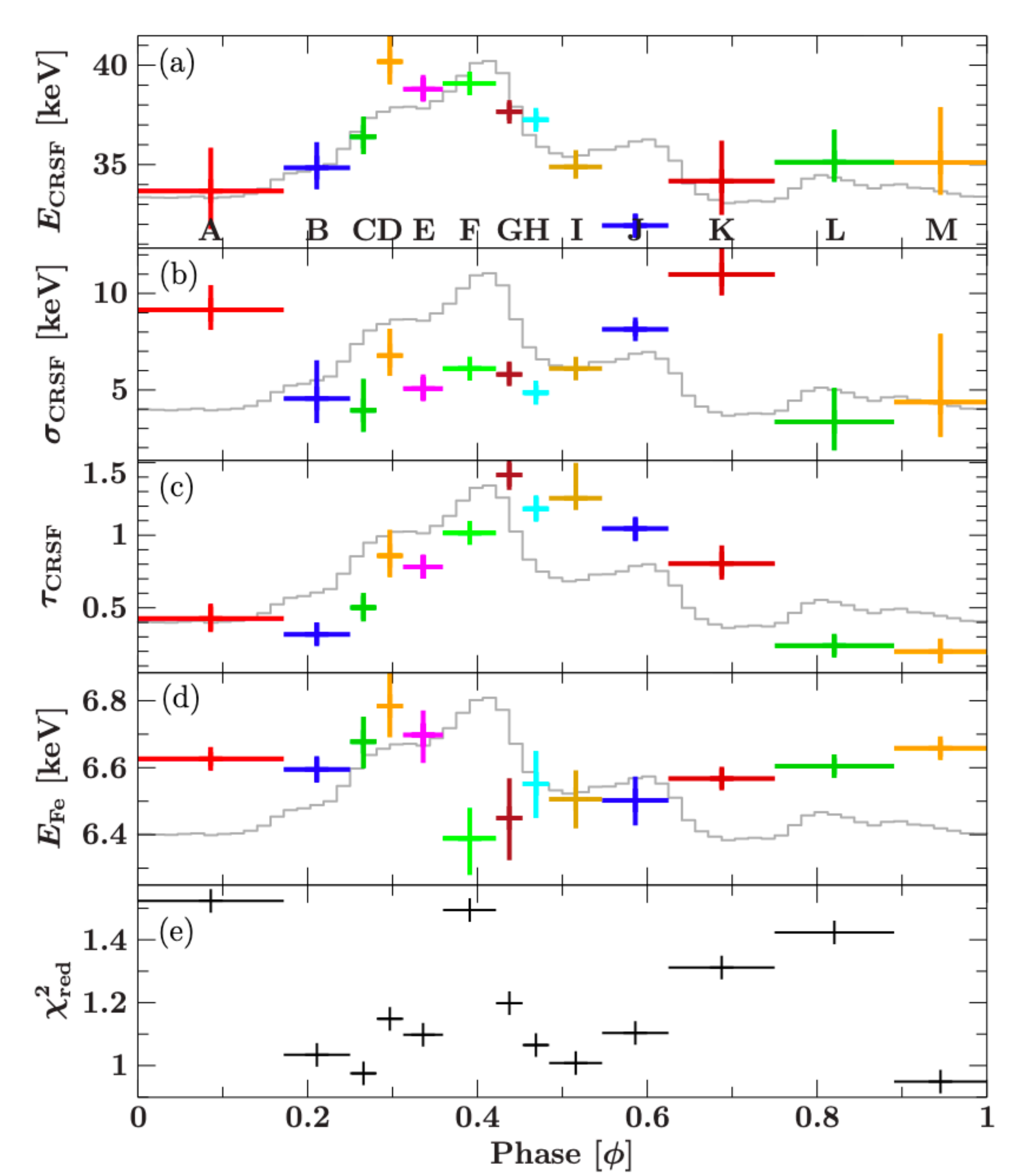
- A “blind” Z search has to look for pulsations composed of many harmonics. We will have to run the search with n=1, 2, …
  Alternatively, we can calculate all Z values corresponding to different *n* in a single pass, and compare them with proper rescaling:

  $$H = \max(Z_M^2 - 4M + 4,\ M = 1,2,..20)$$

  This statistics is the most adequate for searches where the pulse profile can be anywhere between sinusoidal and sharp

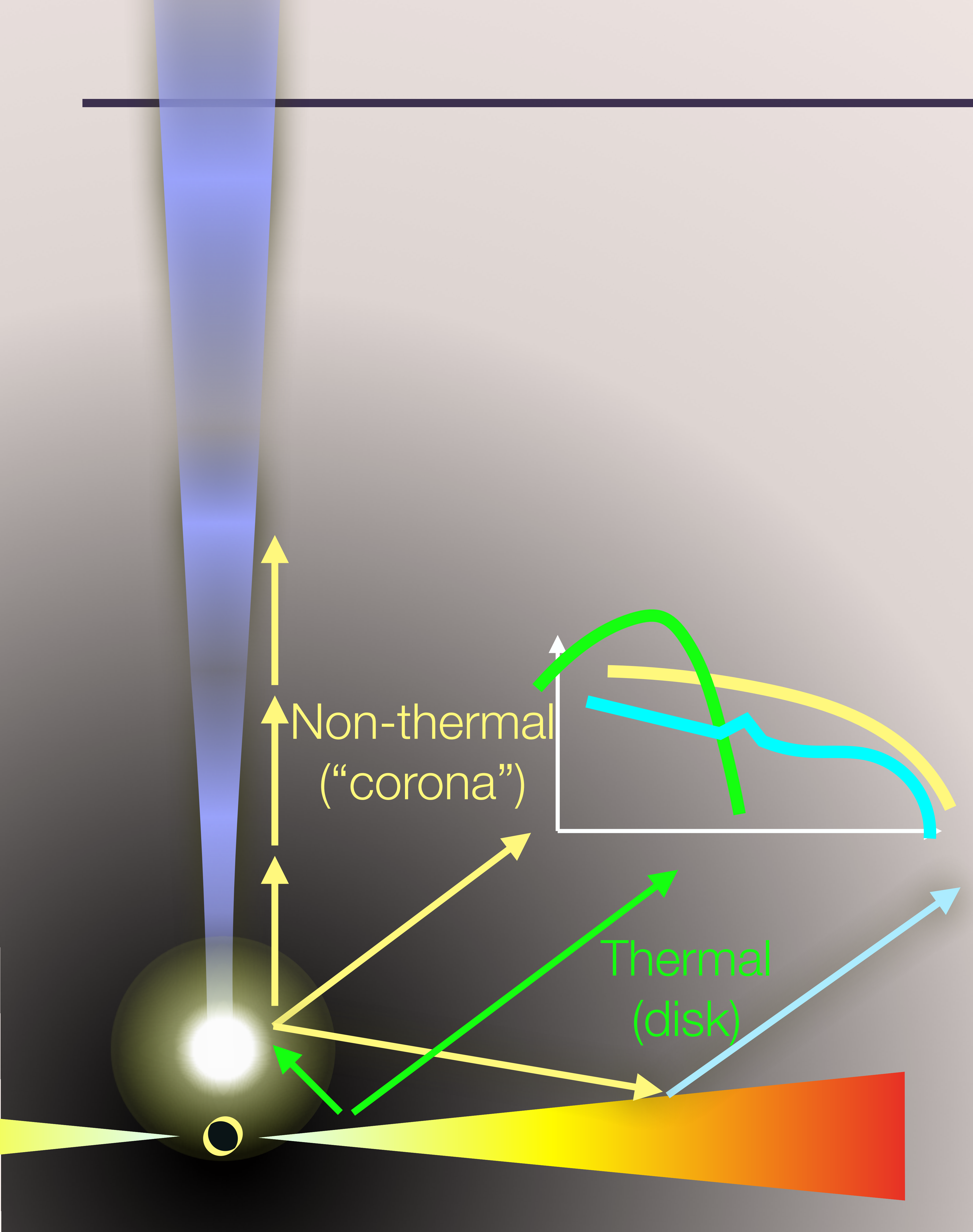
PHASE-RESOLVED SPECTRA

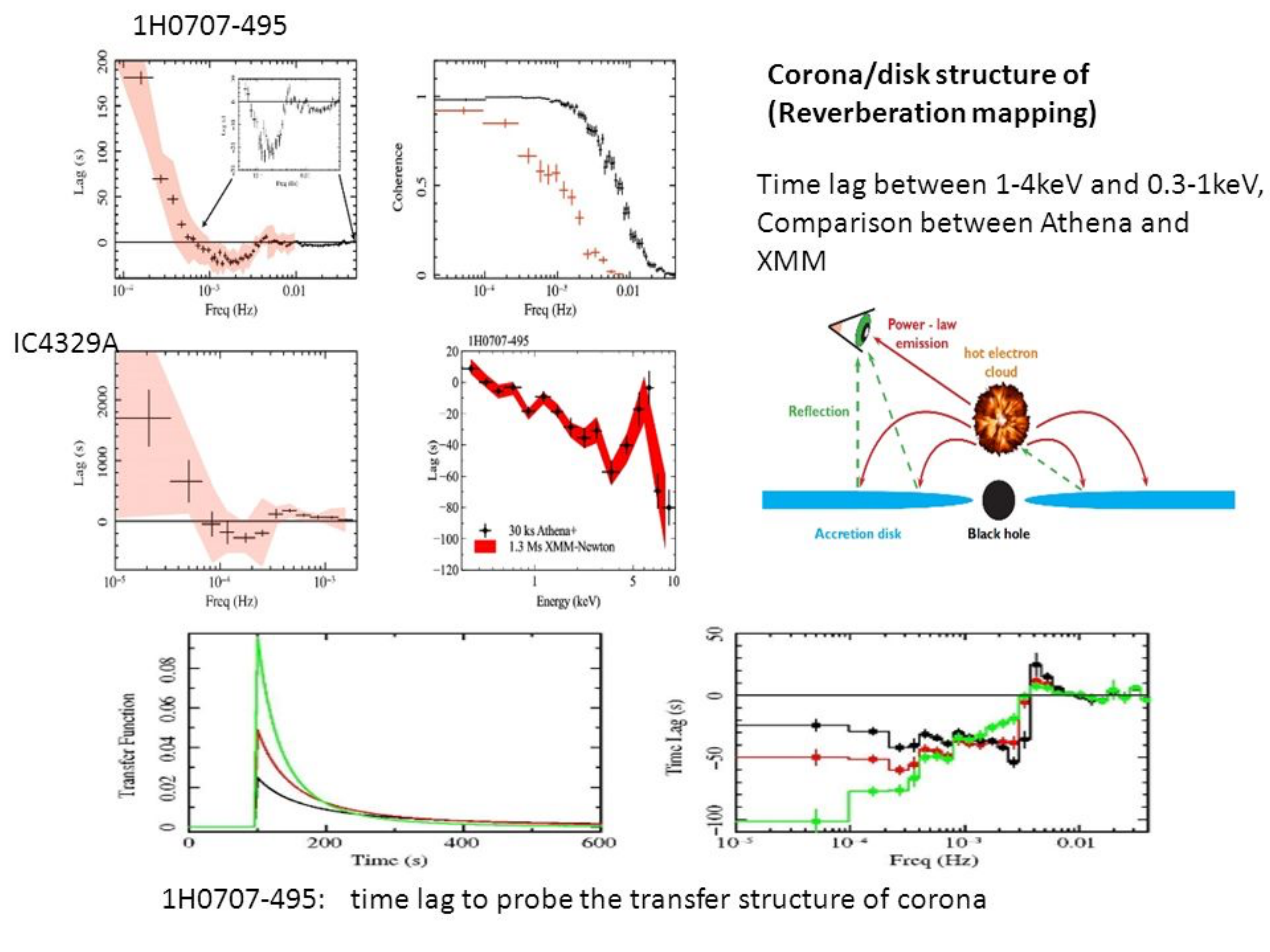
- Select photons from different phases of the pulse profile
- Calculate and fit spectra (or polarization!)



SPECTRAL **TIMING**

- **Lag Energy Spectra**
- **Phase-resolved QPOs**
- **...**


Non-thermal
("corona")
Thermal
(disk)


1H0707-495
Lag (s)
Freq (Hz)
Coherence
Freq (Hz)
Corona/disk structure of
(Reverberation mapping)
Time lag between 1-4keV and 0.3-1keV,
Comparison between Athena and
XMM
Power - law
emission
hot electron
cloud
Reflection
Accretion disk
Black hole
IC4329A
Lag (s)
Freq (Hz)
1H0707-495
Lag (s)
30 ks Athena+
1.3 Ms XMM-Newton
Energy (keV)
Transfer Function
Time (s)
Time Lag (s)
Freq (Hz)
1H0707-495: time lag to probe the transfer structure of corona

astropy-powered
astropy.org

STINGRAY

Astropy-affiliated spectral timing software in Python

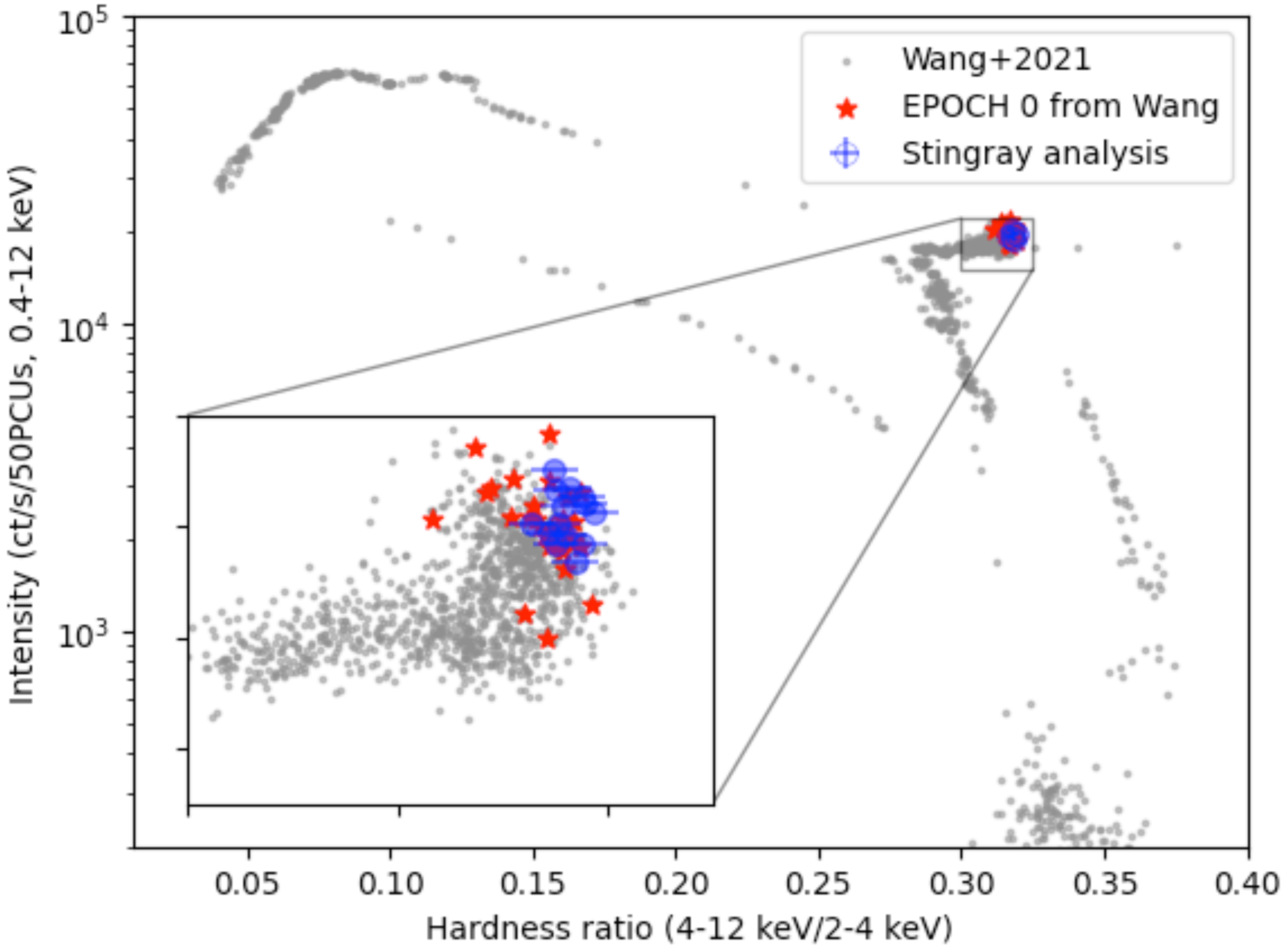
Includes:

- Input data from OGIP FITS files (events, light curves)
- Exploratory timing products, e.g.
  - Light curves
  - Periodograms
  - Colors, Power colors
- Periodogram modeling (Maximum Likelihood, Bayesian)
- Systematics handling, e.g.
  - Good Time Interval (GTI) support
  - Dead time correction and models
- Spectral timing products, e.g.:
  - Cross products, Time lags
  - Covariance, Coherence, RMS, lag spectra
  - Cross-correlation
  - Bispectra, Bicoherence
  - Phase-resolved QPO spectra
- (Accelerated) Pulsar search methods
  - PDS based
  - Epoch folding/Z/H search

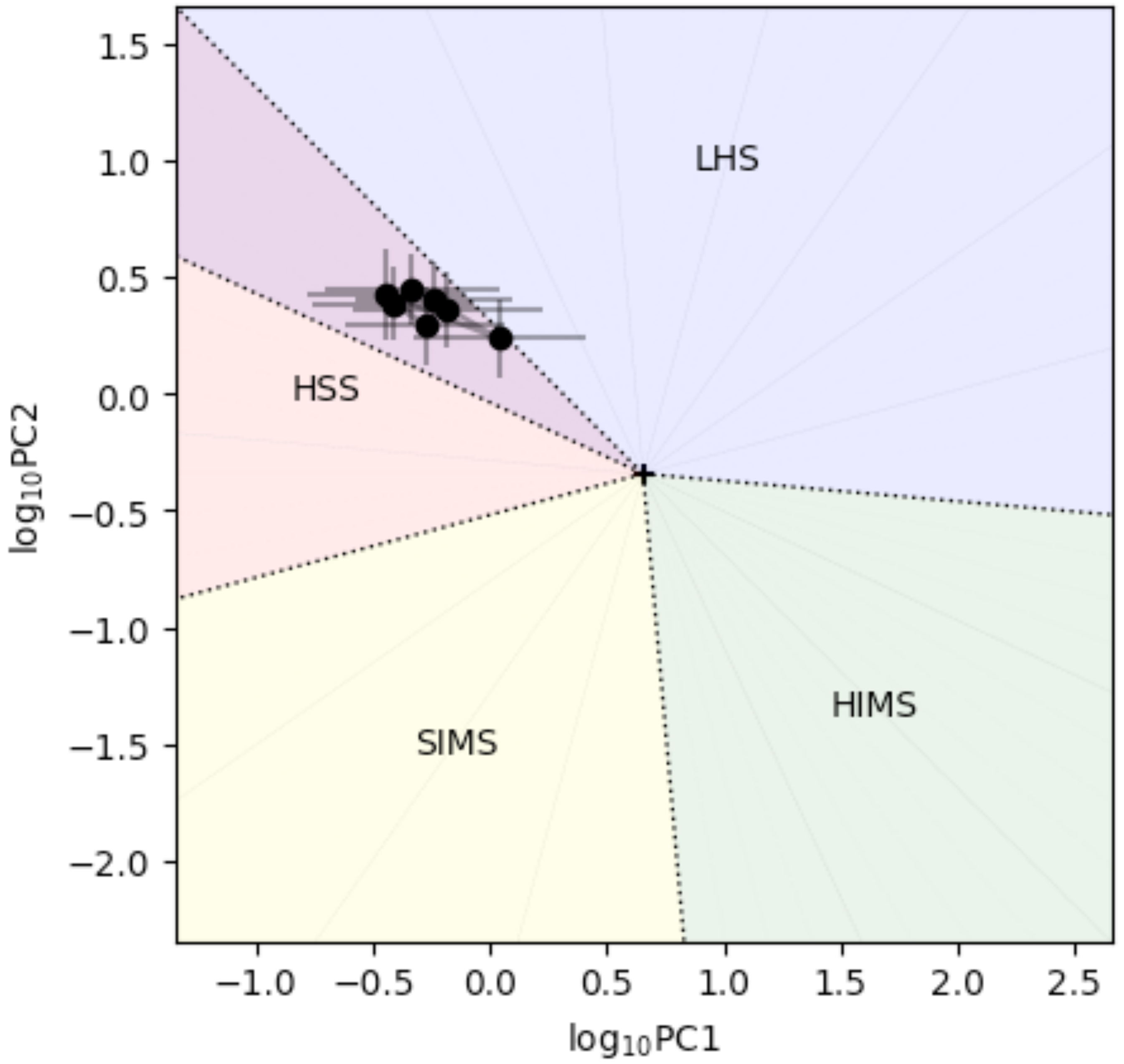
Huppenkothen et al. 2019,ApJ 881, 39

docs.stingray.science/

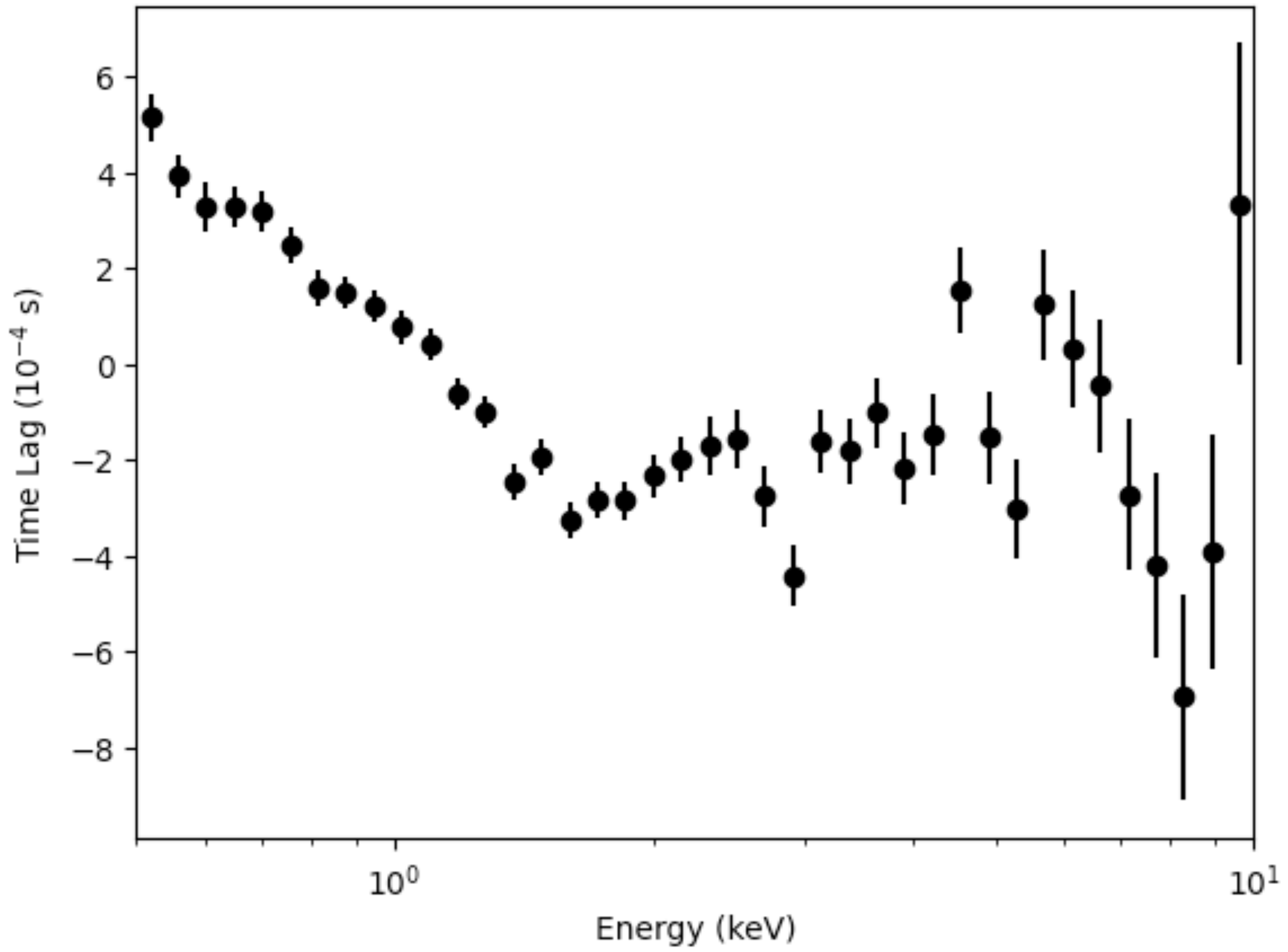
HID, color-color diagrams



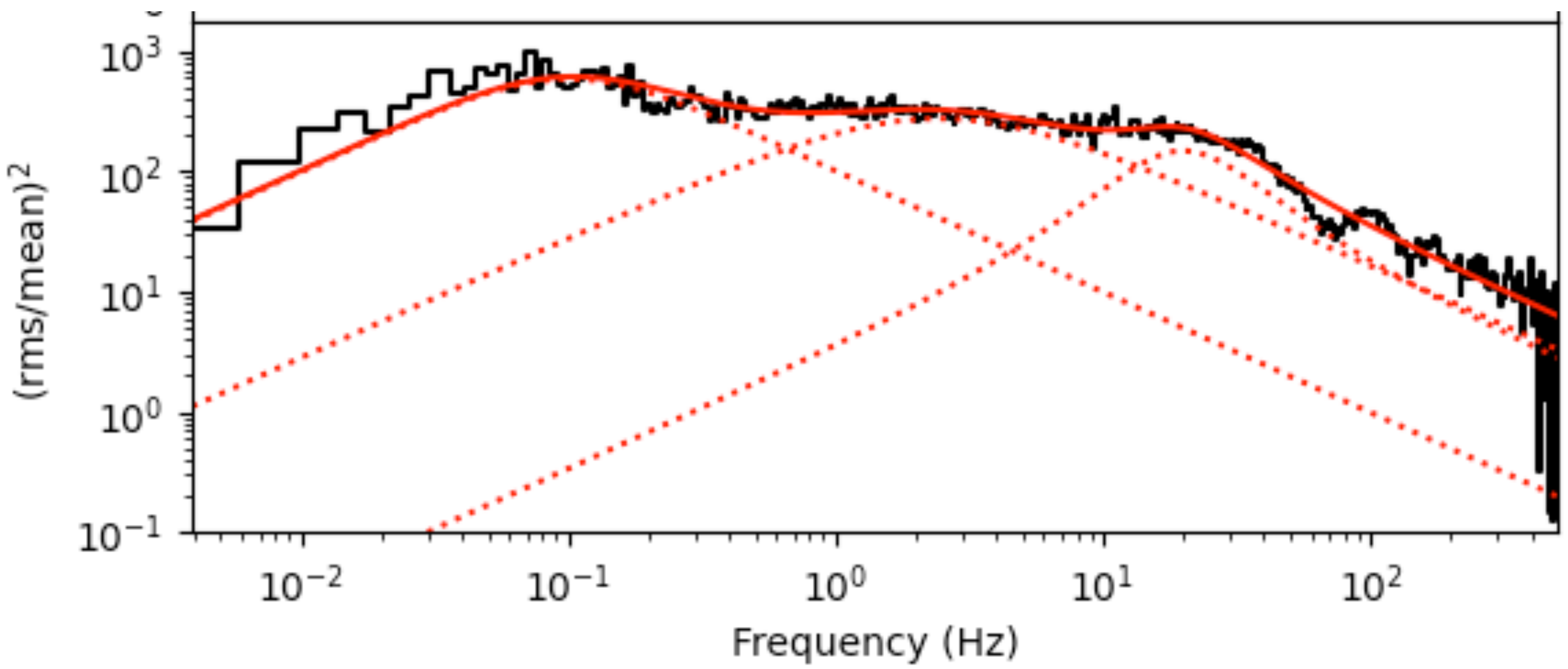
Power colors



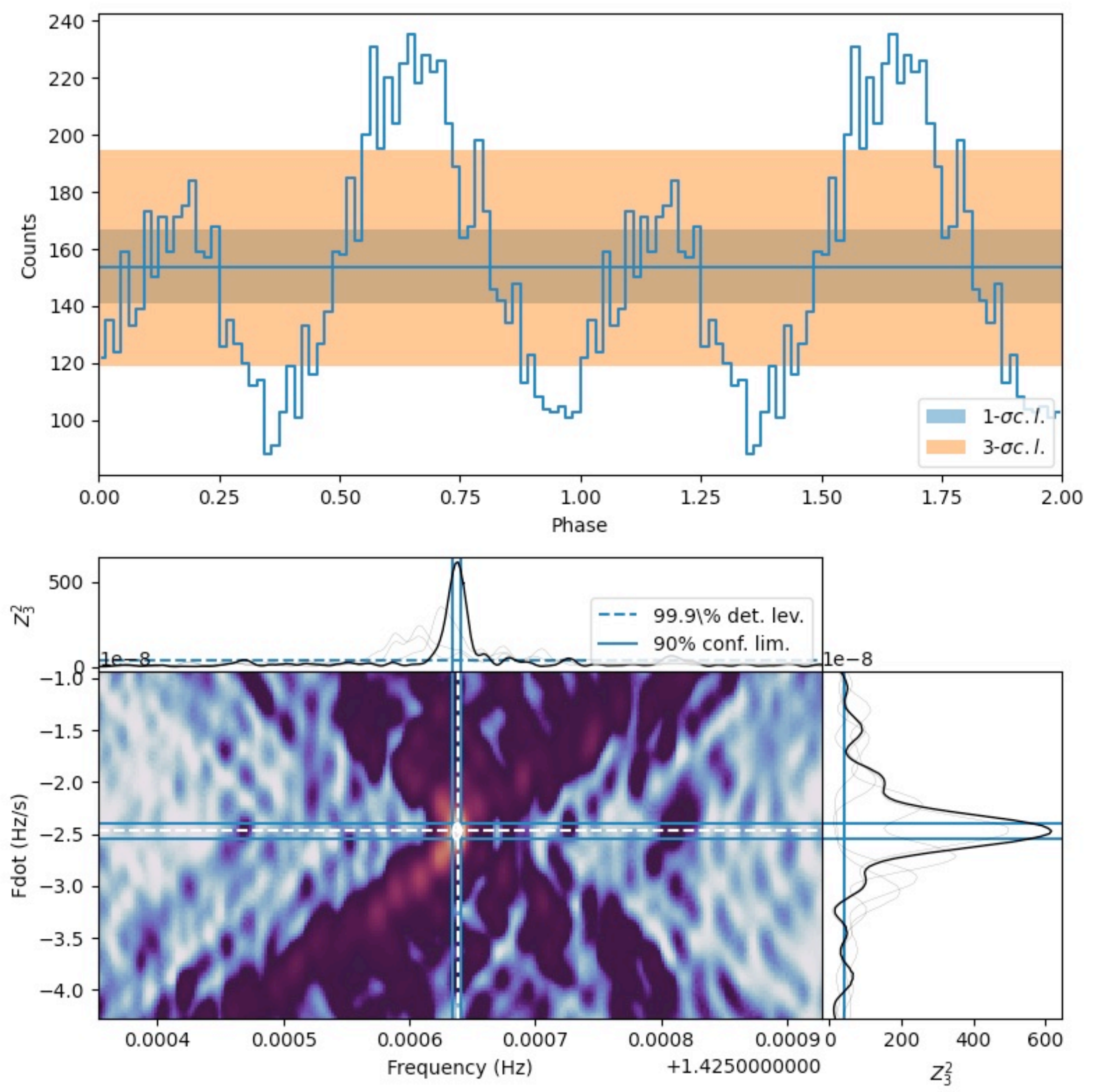
Lag spectra



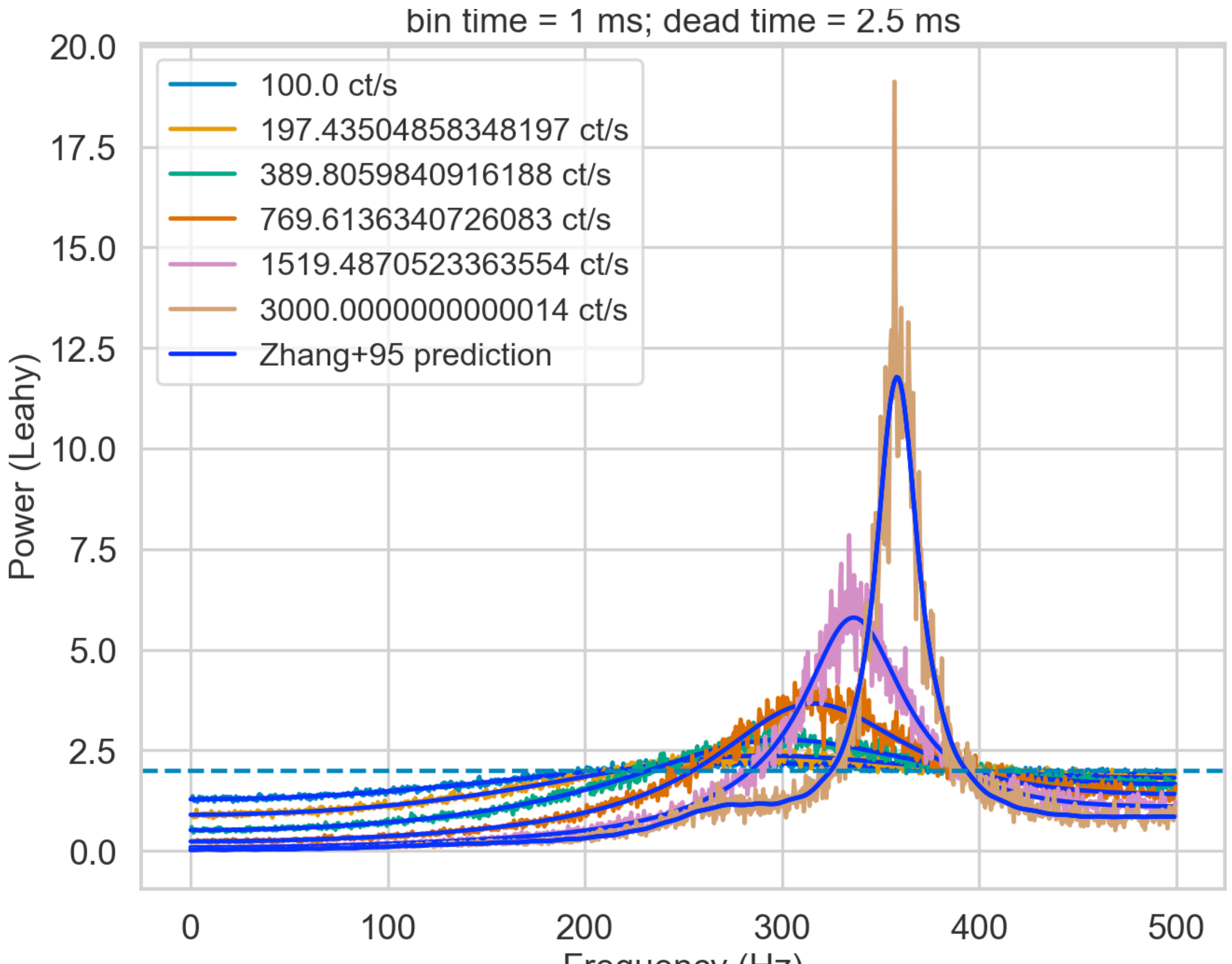
Maximum-likelihood fitting of periodograms



Pulsar searches



Dead time modeling



Luigi Task Status ≡ Task List Dependency Graph Workers Resources Running

ConfirmCandidates__home_mbachett_P_n Show task details

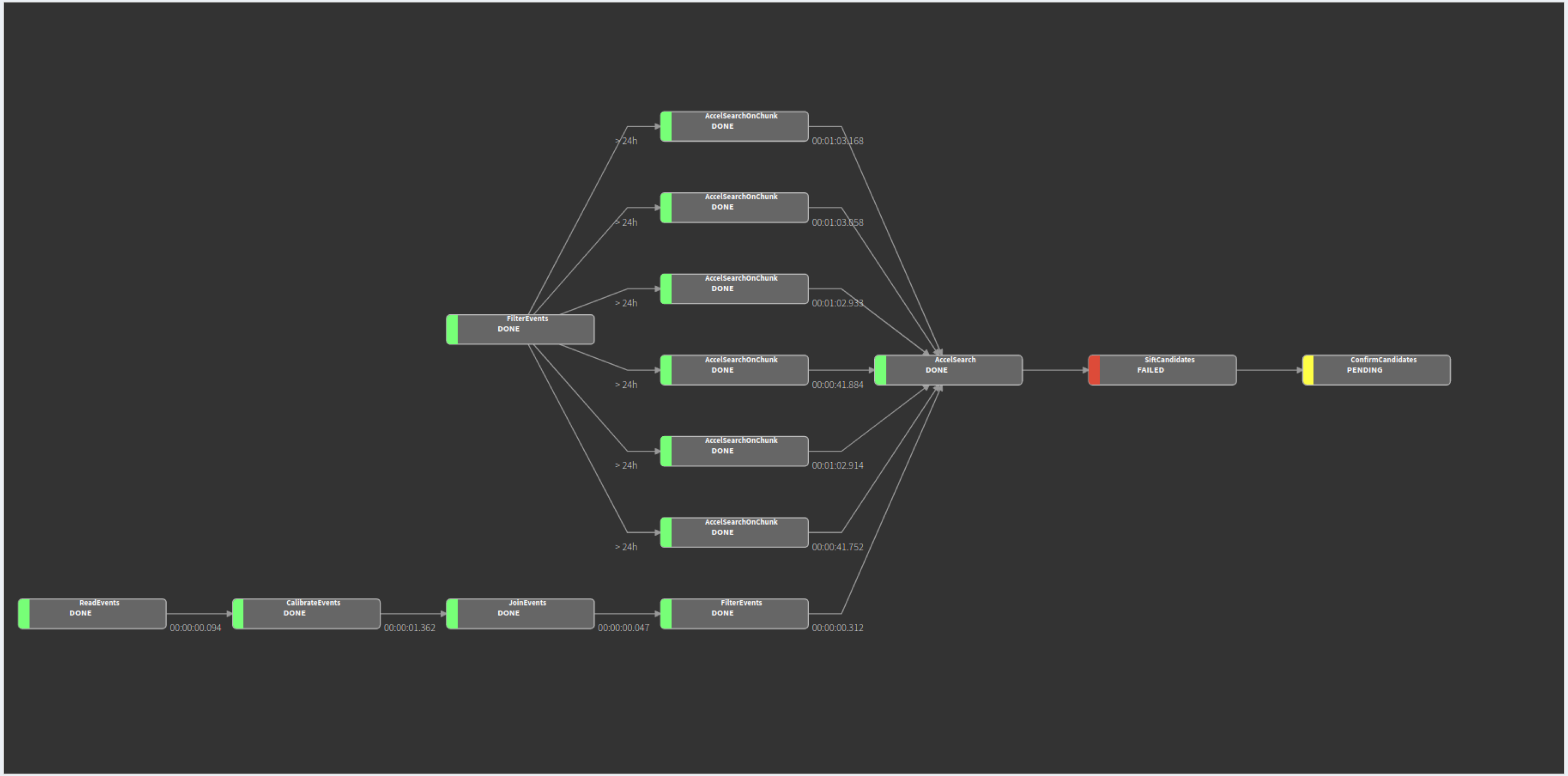
Show Upstream Dependencies

Hide Done

Visualisation Type D3 SVG

ConfirmCandidates(config_file=/home/mbachett/PULSAR/config.yaml, fname=[redacted]l_C_src1.evt, worker_timeout=1500)

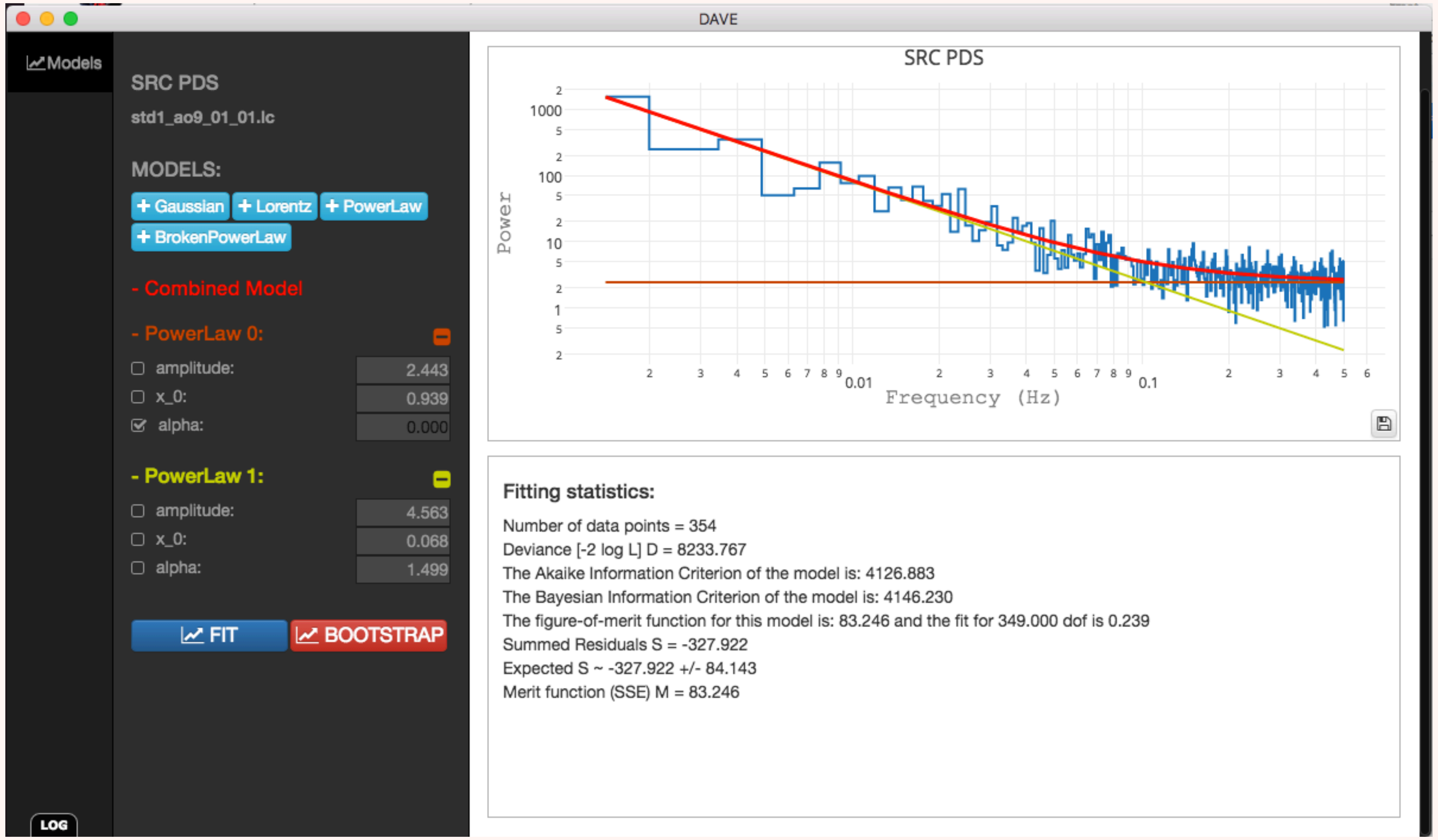
Dependency Graph



local firefox window to open. – lesmana Sep 3 '10 at 6:53

DAVE

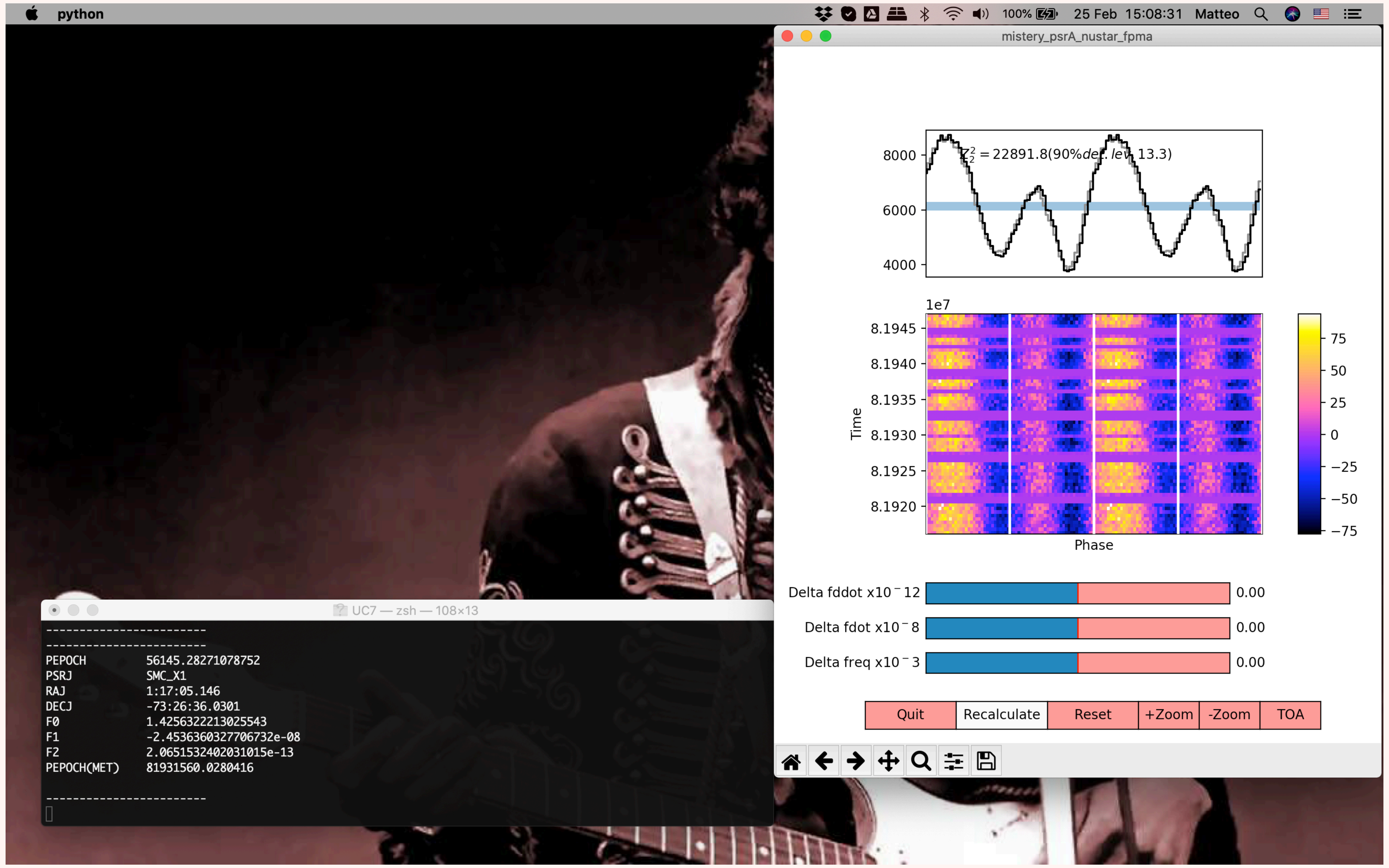
- ESA-funded GUI for Stingray
- Timing exploration made easy
- Stingray functionality made interactive (PDS modeling, pulsar searches, lag spectra, etc.)
- Issues: currently unmaintained



https://github.com/StingraySoftware/dave/

HENDRICS

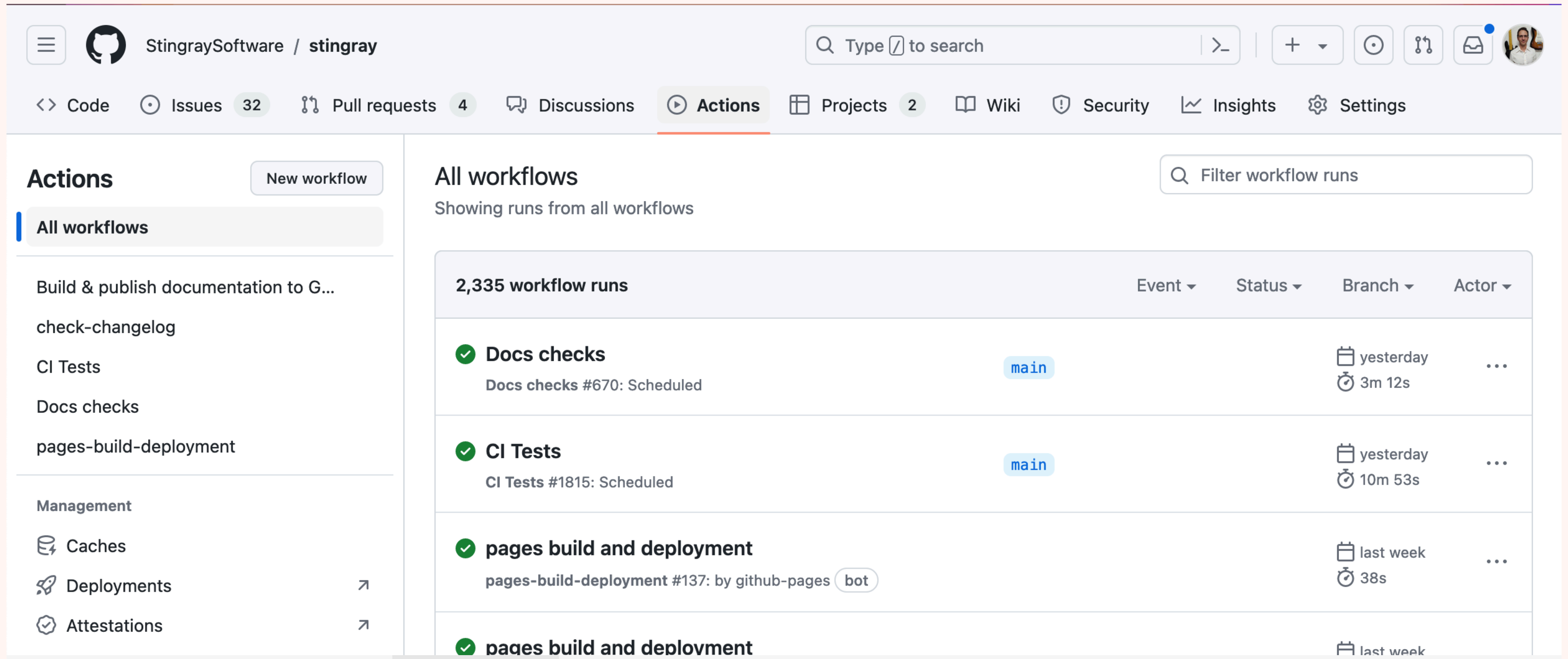
- Command line interface to Stingray
- “Hides” Python API
- Simplifies Batch scripting
- Some interactive functionality (for pulsars)
- Cutting-edge pulsar searches (some not yet available in Stingray)

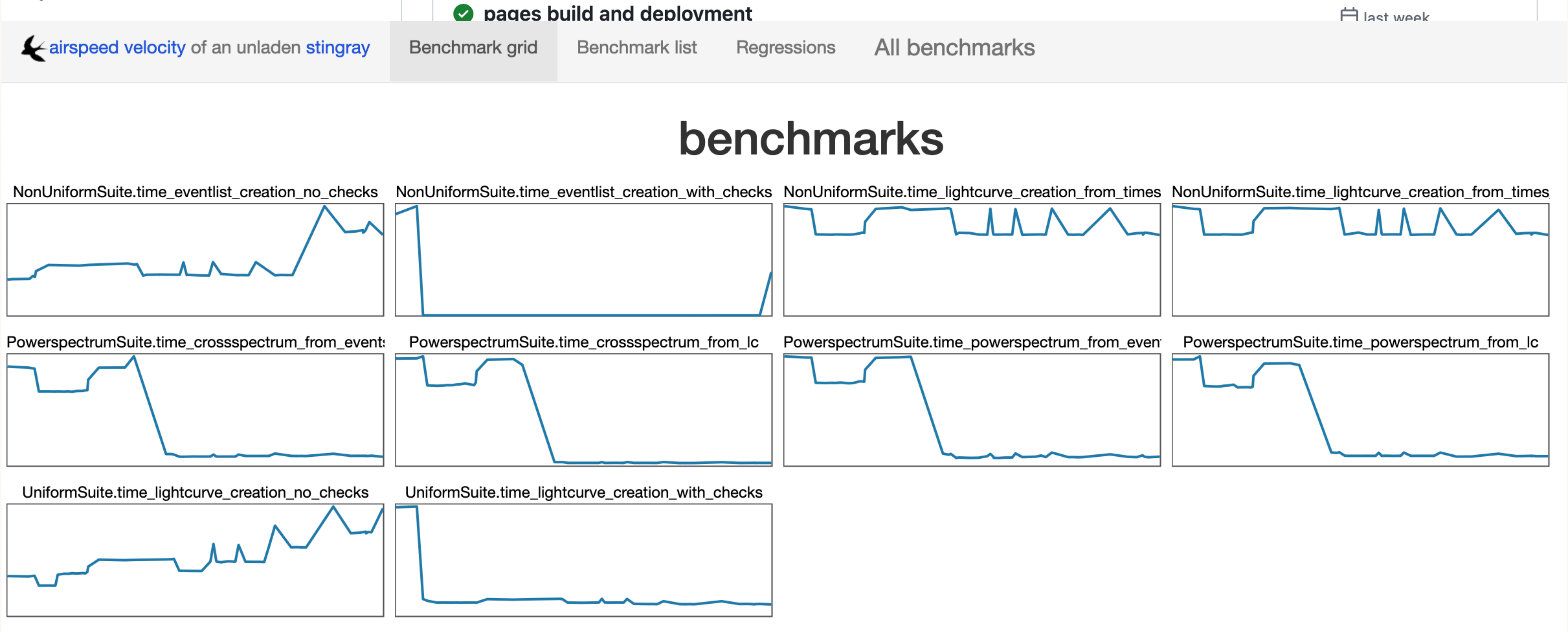


hendrics.stingray.science/

OTHER NOTABLE FEATURES

- **Continuous integration with unit tests and integration tests**
- **Continuous performance tracking through automatic benchmarks**





docs.stingray.science/

OTHER NOTABLE FEATURES

- **Continuous integration with unit tests and integration tests**
- **Continuous performance tracking through automatic benchmarks**
- **Interoperability with Astropy TimeSeries, LightKurve, Pandas, Xarray**
- **Just-In-Time compilation of computation-intensive operations (via Numba)**
- **Large dataset handling (NICER-ready!)**

NumPy

emcee
The MCMC Hammer

astropy-powered
astropy.org

Numba

RECENT DEVELOPMENT

- Performance improvements for large datasets
- Basic "Polarimetric timing" products
- Advanced pulsar search techniques
- Experimental port to Julia (GSOC 22)
- Improved upper limit estimates
- Non-uniformly sampled data (GSOC 23)
- Expansion of supported missions (notably RXTE)

SpecTemPolar!
PRIN INAF 2019

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

ICSC
Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

REPVBBLICA ITALIANA

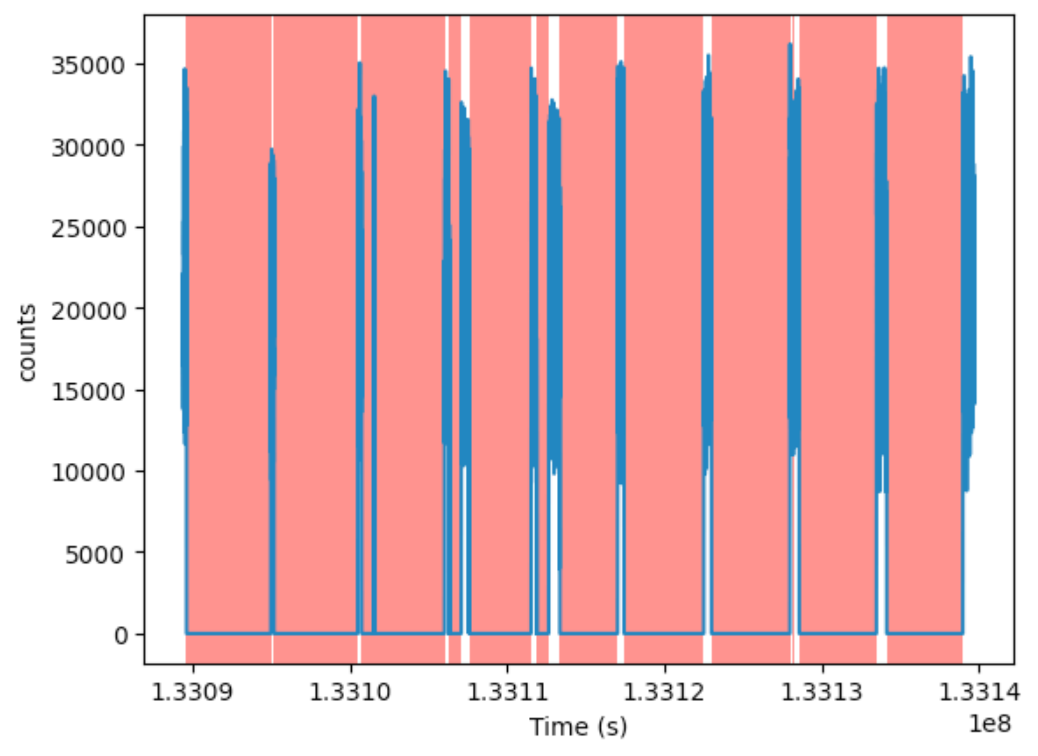
UNIAM
PRIN MIUR 2017

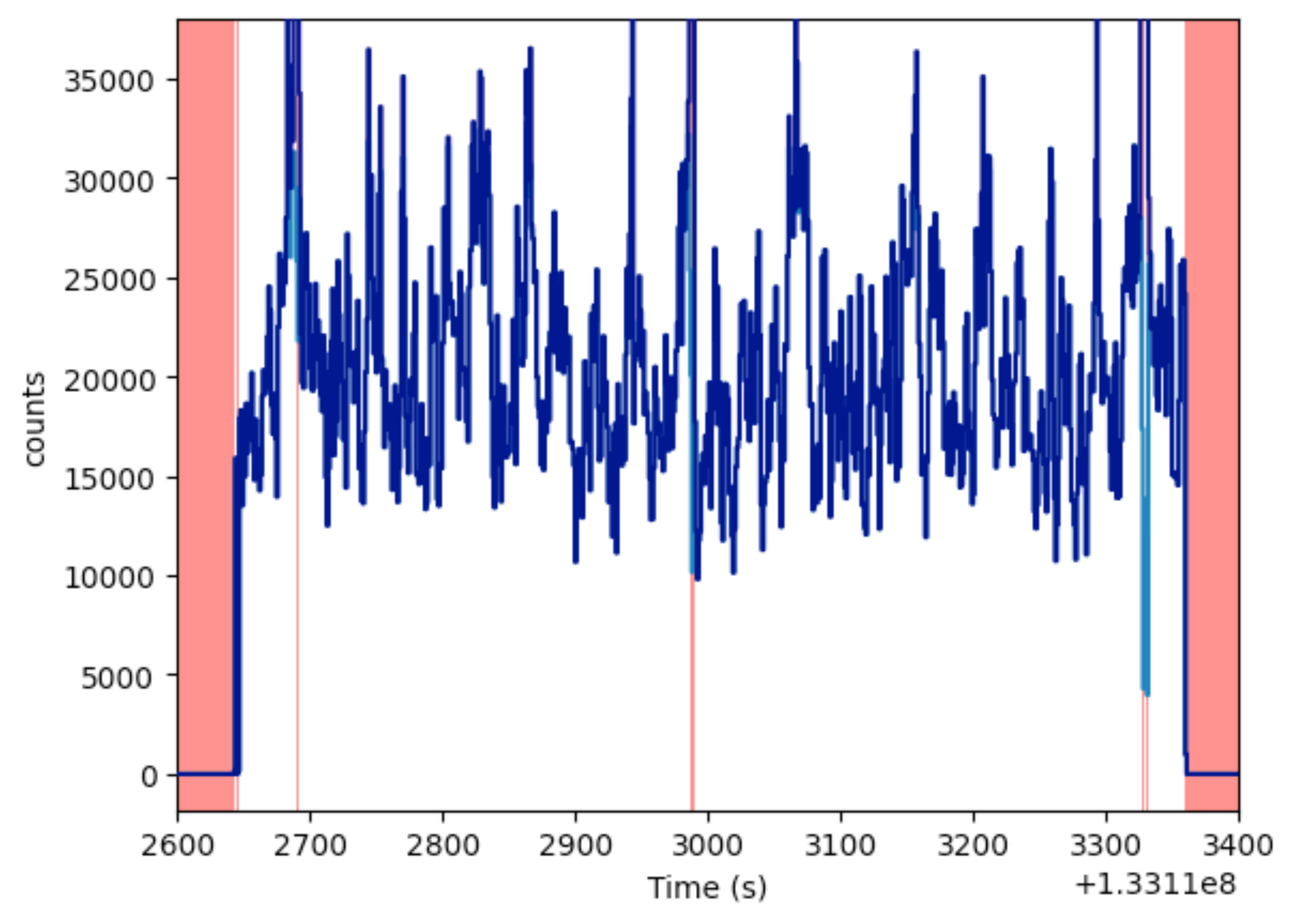
Google Summer of Code
2016-2018, 2020-2024

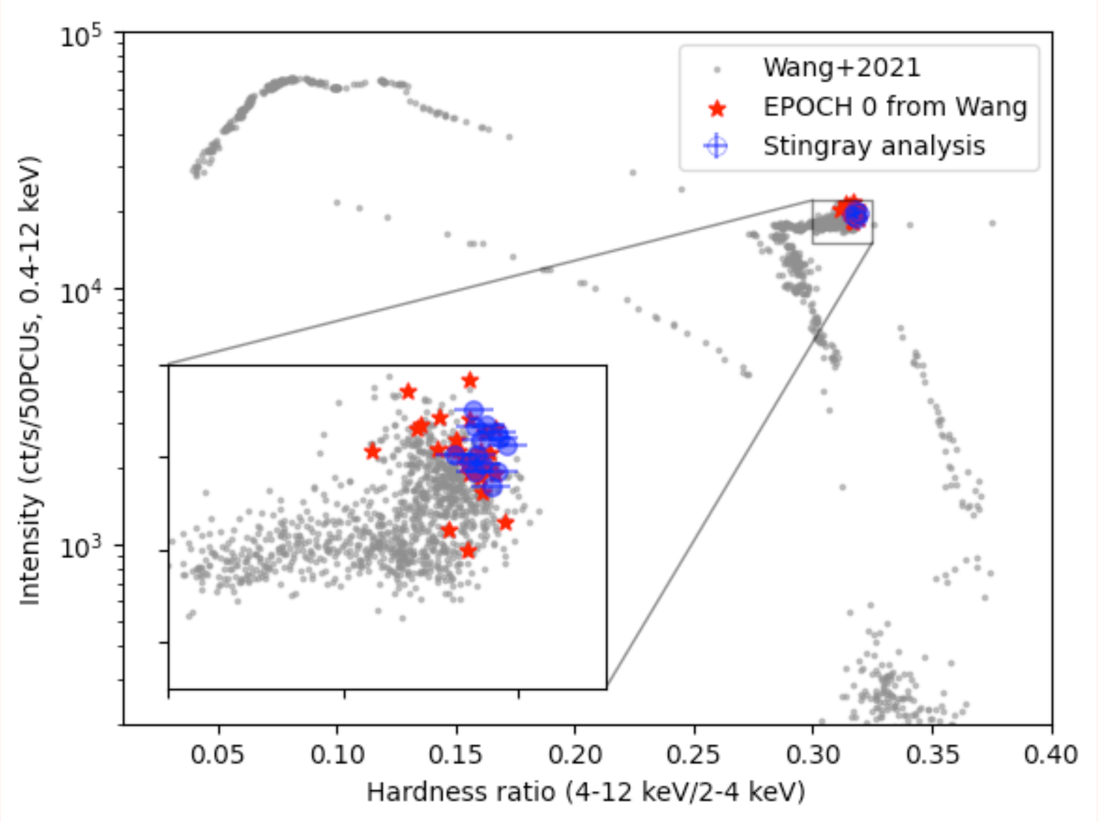

NIKE

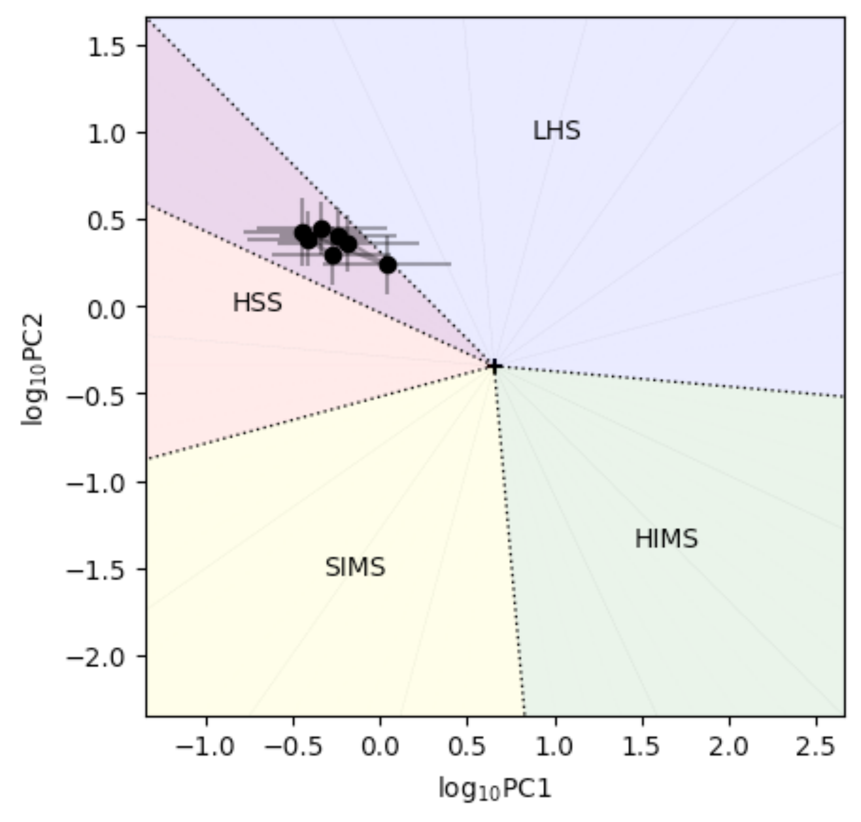
QUICKLOOK - I

- **Plot a light curve**
  - Find problematic intervals (e.g. bkg flares)
  - Check presence of small gaps in light curve
- **Plot colors**
  - How do colors compare to known sources?
  - Is this a known spectral state?
- **If significant variability: plot Power colors!**
  - Similar diagnostics to colors, based on fast variability









https://docs.stingray.science/en/stable/notebooks/Spectral%20Timing/Spectral%20Timing%20Exploration.html

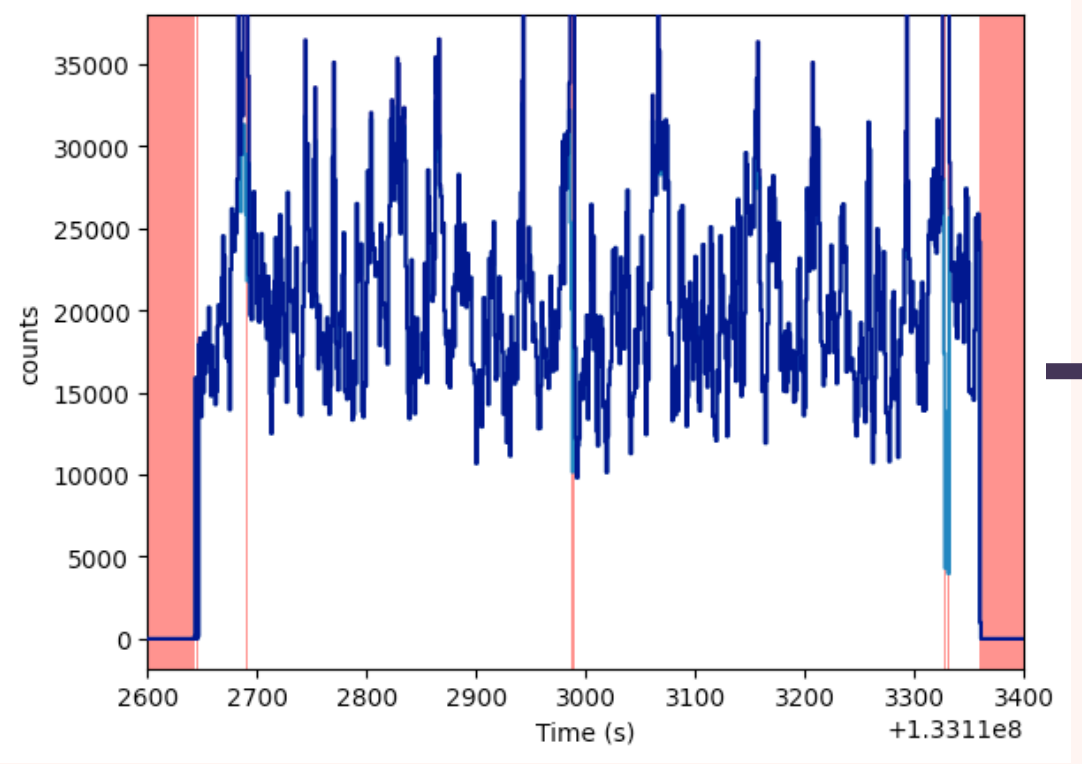
QUICKLOOK - I

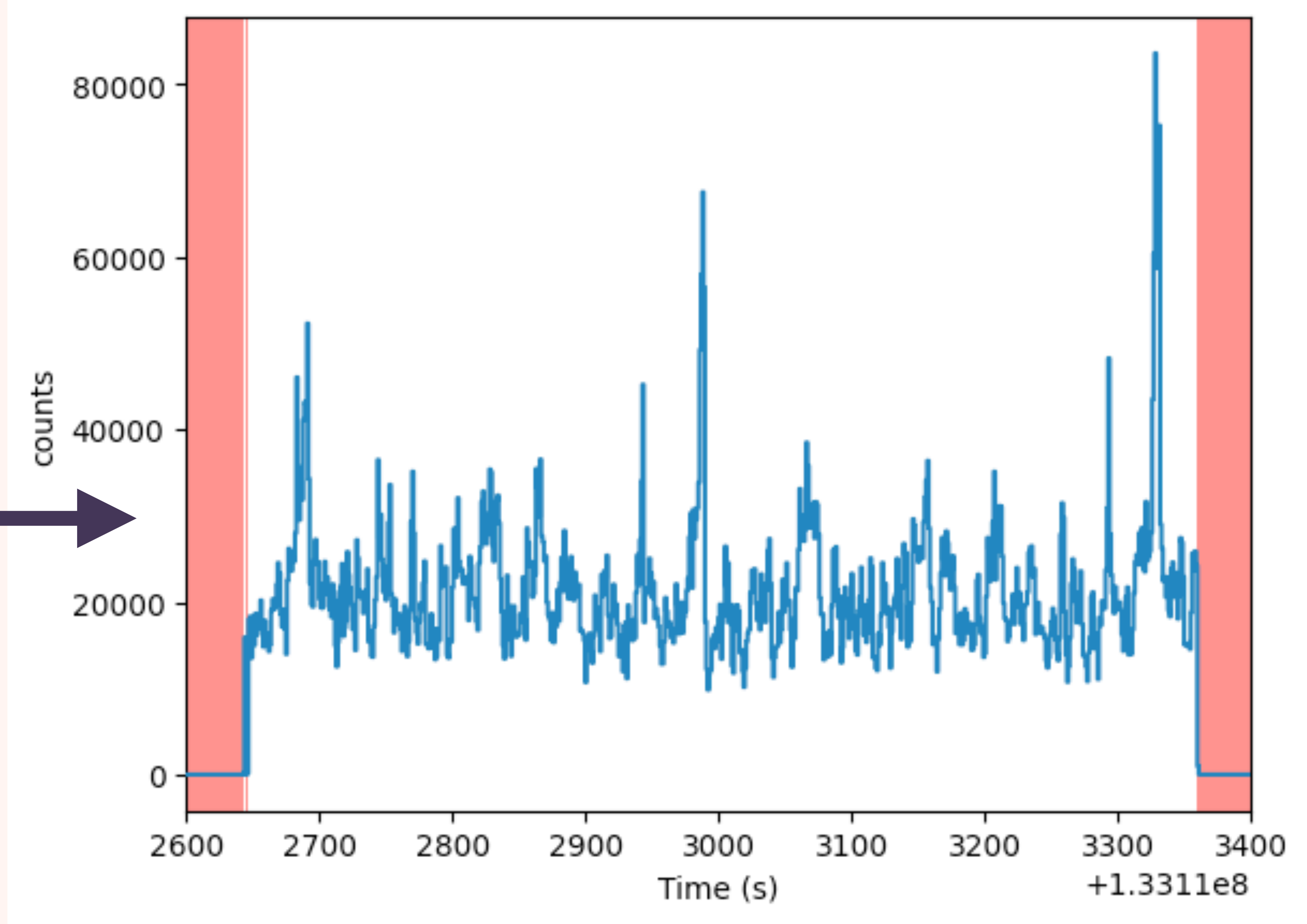
- **Plot a light curve**
  - Find problematic intervals (e.g. bkg flares)
  - Check presence of small gaps in light curve

Filter with data masks!

Fill with random data!

- **Plot colors**
  - How do colors compare to known sources?
  - Is this a known spectral state?
- **If significant variability: plot Power colors!**
  - Similar diagnostics to colors, based on fast variability

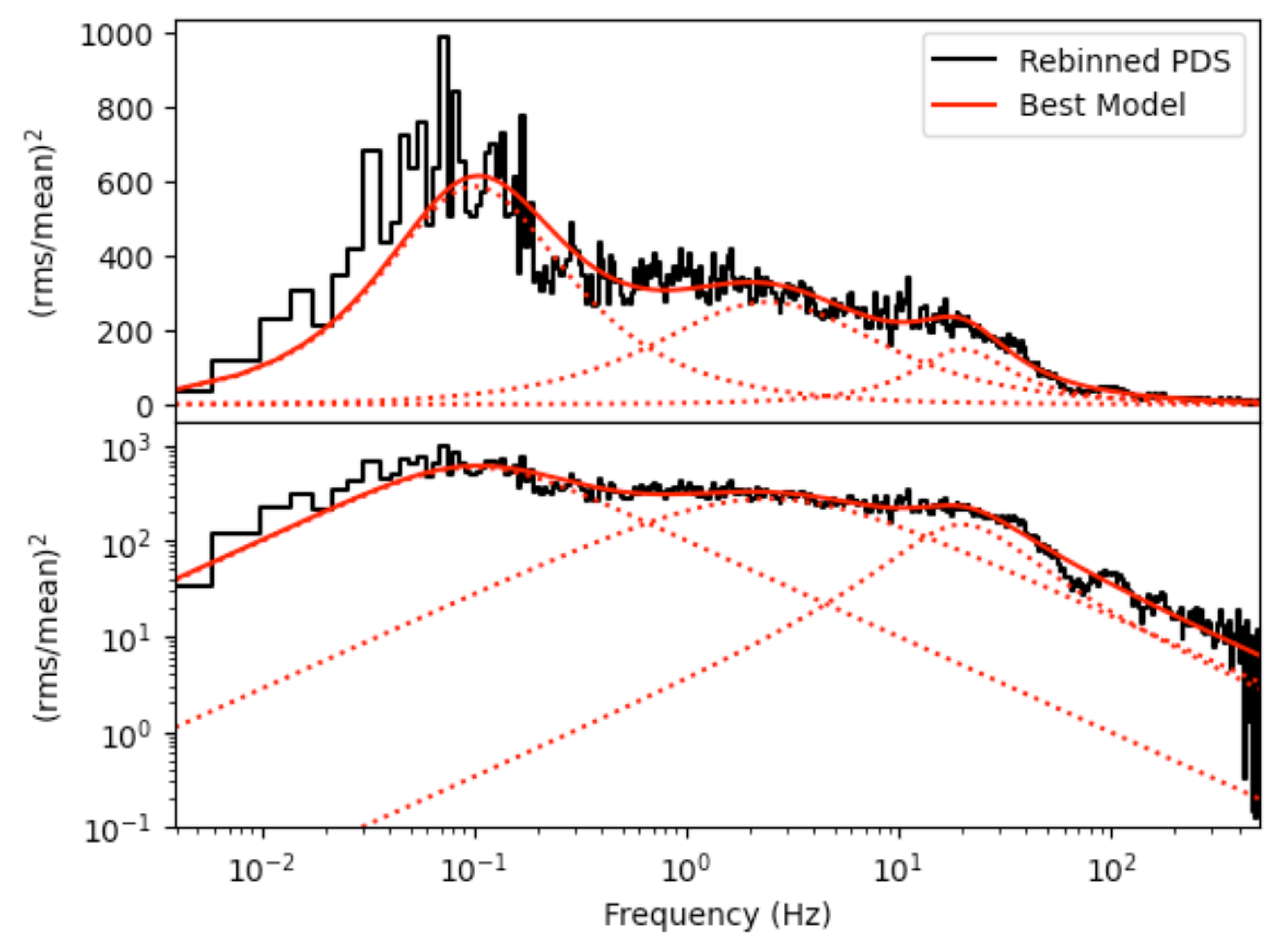


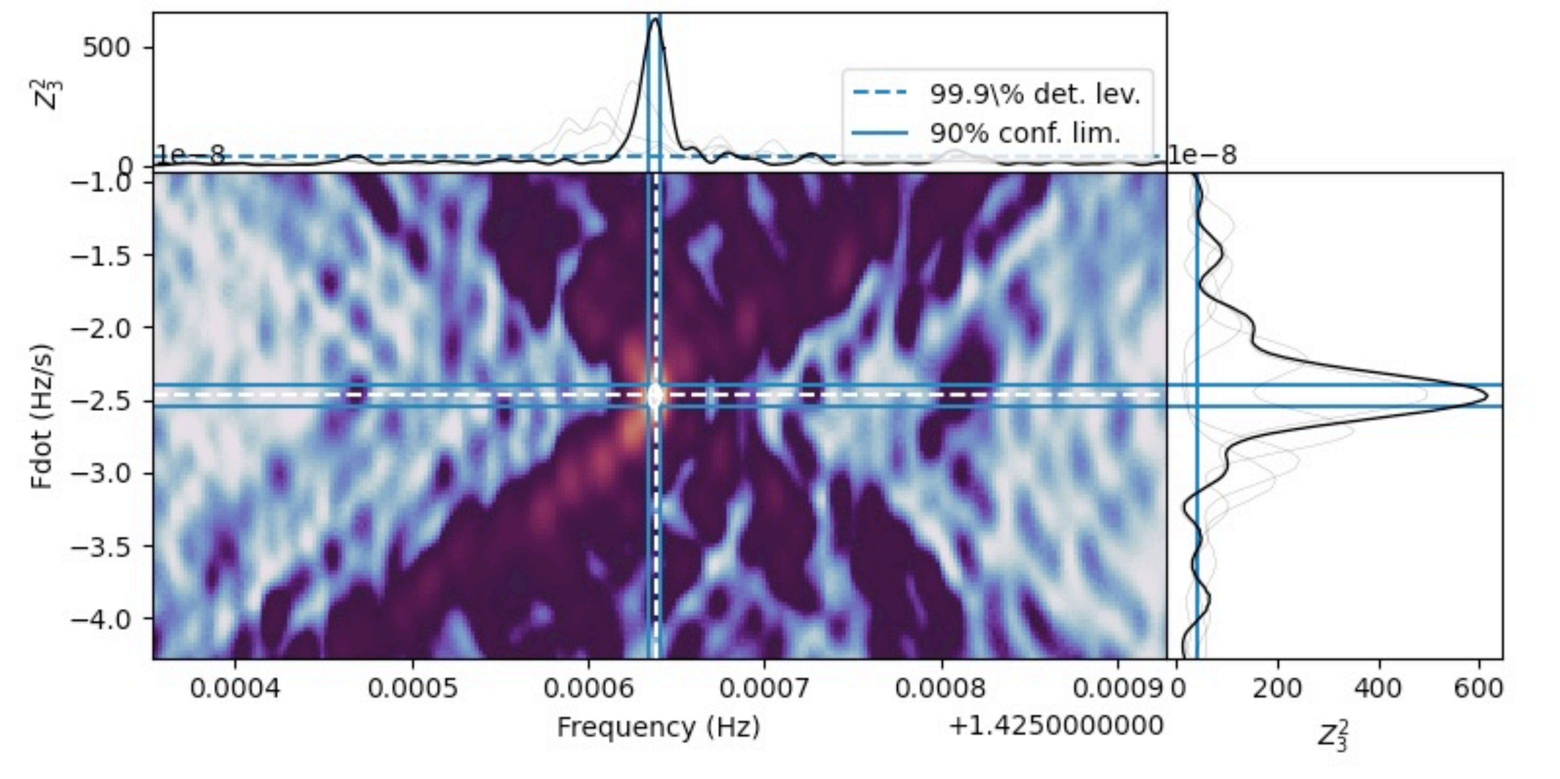


https://docs.stingray.science/en/stable/notebooks/Spectral%20Timing/Spectral%20Timing%20Exploration.html

QUICKLOOK - II

- **Plot a Bartlett periodogram, rebin logarithmically**
  - Is it affected by dead time?
  - Is it dominated by aperiodic variability?
  - Is there a QPO or other periodic phenomena?
  - Fit a model!
- **Search for pulsar candidates:**
  - Search for peaks in a non-rebinned Bartlett periodogram
  - Run accelerated search (à la Ransom+2002)
  - Run accelerated Z search around candidates

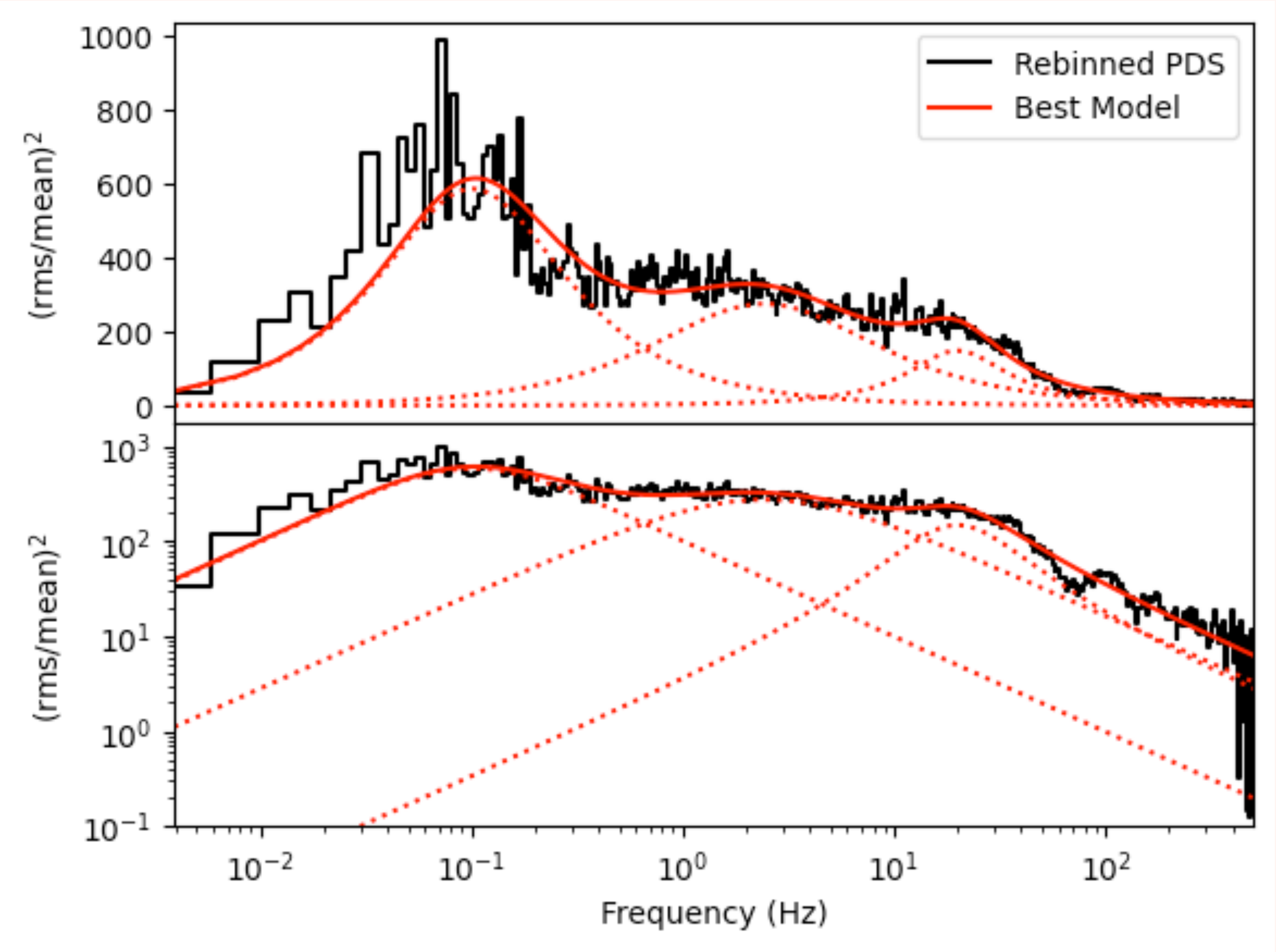




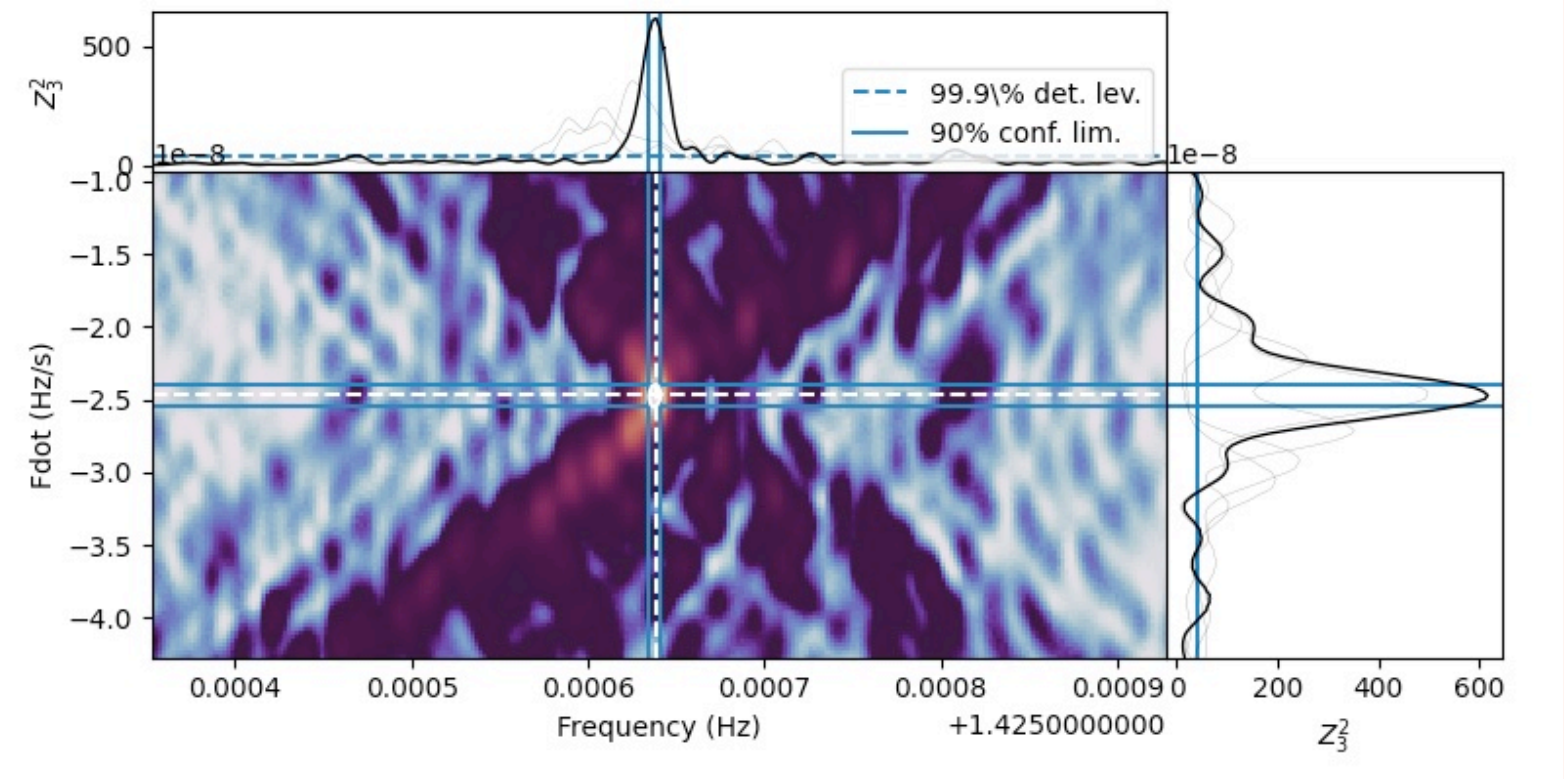
https://docs.stingray.science/en/stable/notebooks/Spectral%20Timing/Spectral%20Timing%20Exploration.html
https://hendrics.stingray.science/en/latest/tutorials/pulsars.html

QUICKLOOK - II

- **Plot a Bartlett periodogram, rebin logarithmically**
  - Is it affected by dead time? *Correct with FAD!*
  - Is it dominated by aperiodic variability?
  - Is there a QPO or other periodic phenomena?
  - Fit a model! *Use stingray.modeling*



- **Search for pulsar candidates:**
  - Search for peaks in a non-rebinned Bartlett periodogram
  - Run accelerated search (à la Ransom+2002) *Use HENDRICS (HENaccelsearch) or PRESTO*
  - Run accelerated Z search around candidates *Use HENDRICS (HENzsearch)*

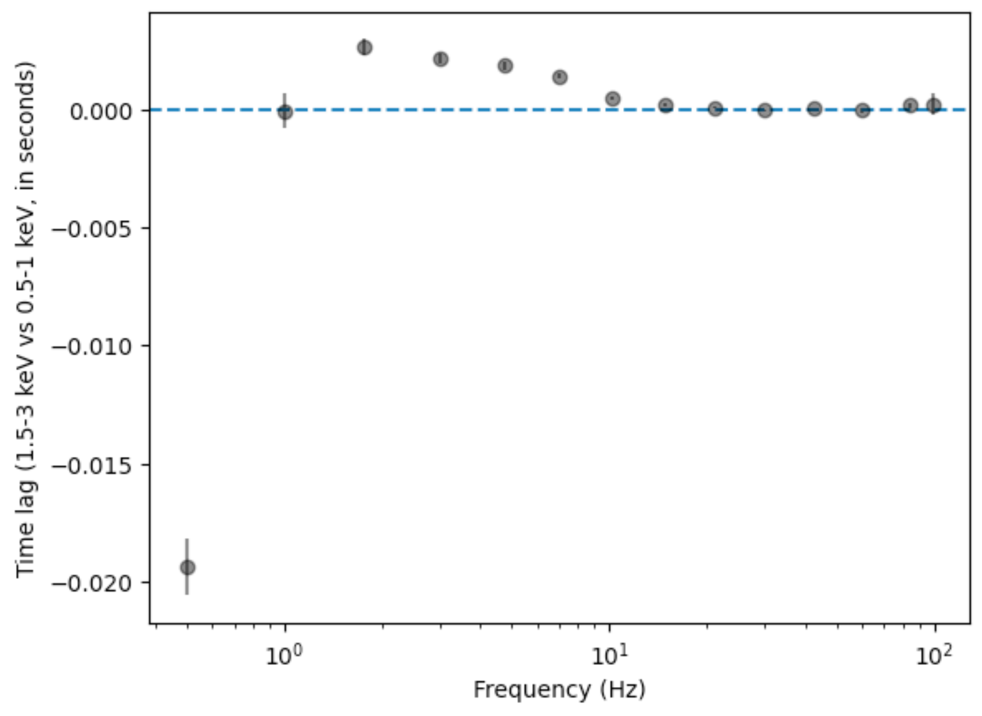


https://docs.stingray.science/en/stable/notebooks/Spectral%20Timing/Spectral%20Timing%20Exploration.html

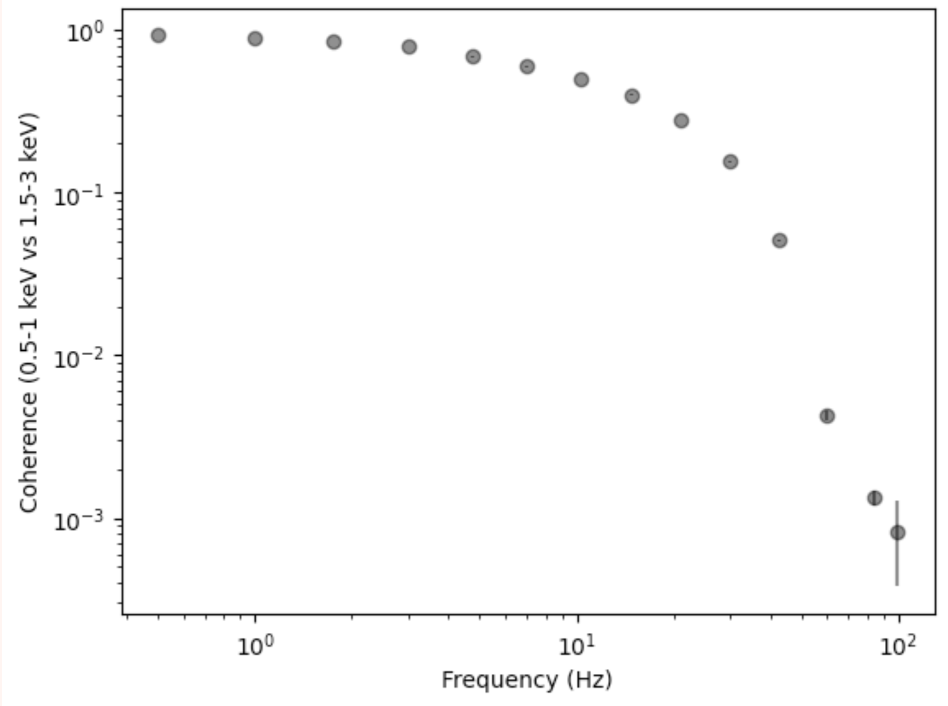
https://hendrics.stingray.science/en/latest/tutorials/pulsars.html

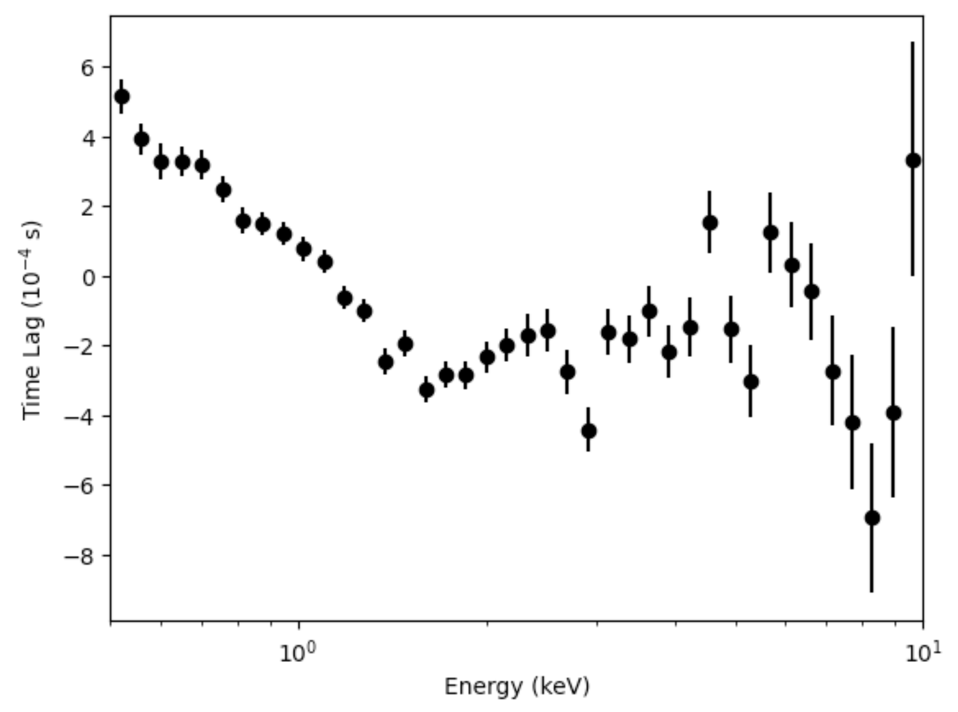
ADVANCED

- **Calculate time lags vs frequency and coherence**
  - Is there evidence for time lags? How do they compare to the literature?
  - Are time lags associated with a feature in the periodogram?
- **Calculate time lags vs energy**
  - Are time lags associated with an energy spectral feature (e.g., the reflection hump or the power law)
- **Calculate covariance spectra**
  - Is *variability* associated with a specific spectral feature?

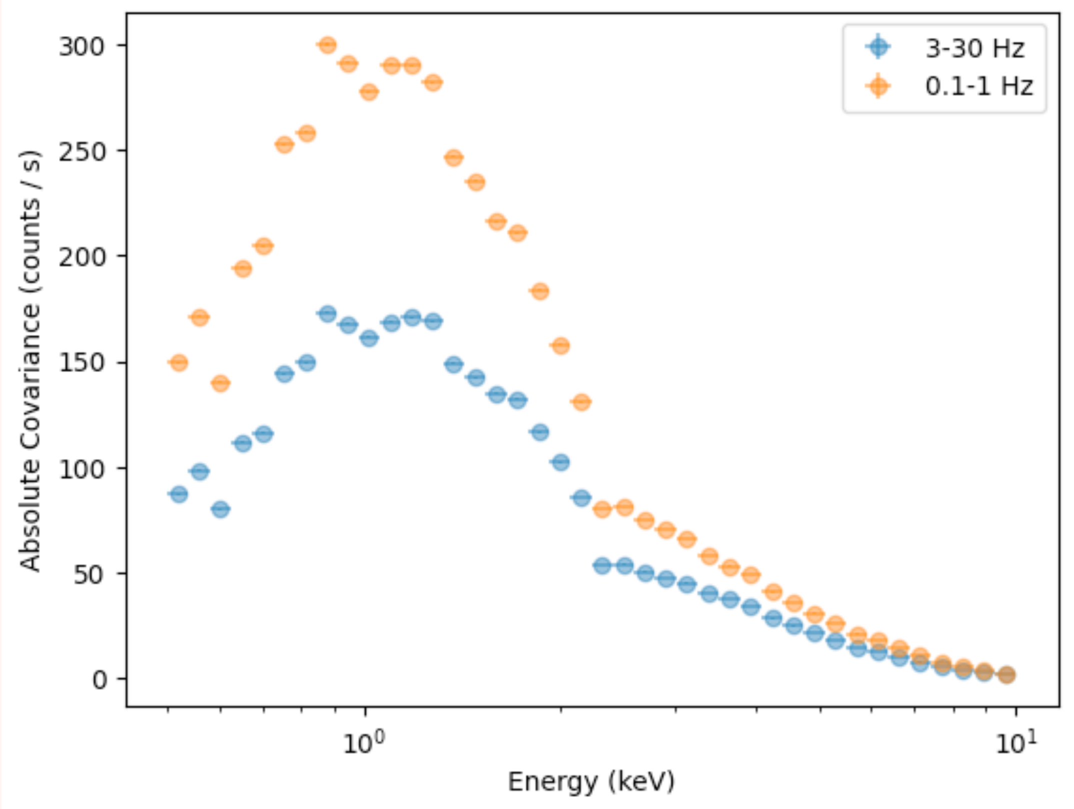


Check the coherence!





Fit in Xspec using responses!



https://docs.stingray.science/en/stable/notebooks/Spectral%20Timing/Spectral%20Timing%20Exploration.html

https://hendrics.stingray.science/en/latest/tutorials/pulsars.html

OUR TUTORIALS

- **Stingray tutorials**
  - https://docs.stingray.science/en/stable/index.html#using-stingray

    Check in particular the Spectral Timing exploration
- **HENDRICS tutorials**
  - https://hendrics.stingray.science/en/latest/tutorials/index.html

    Check in particular pulsar searches!