Unravelling the Physics of Black Holes Using Astronomical Time Series

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ADVANCING DATA-INTENSIVE DISCOVERY IN ALL FIELDS

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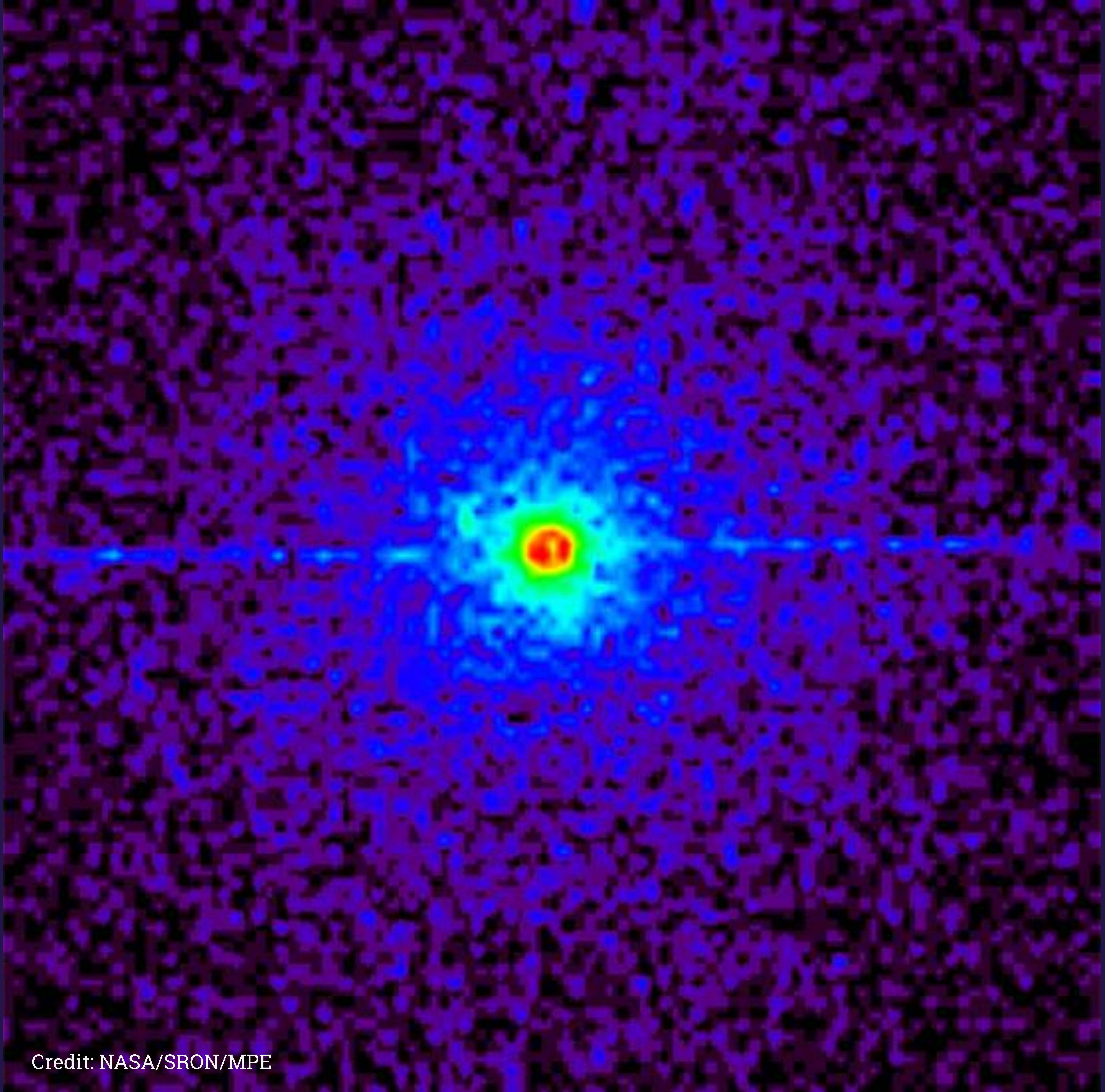
“light curve” = time series


jet
star
black hole
accretion
disk
How do black holes
accrete matter?

Many Open Questions

- What happens to matter in strong gravity?
- What is the shape of the accretion flow close to the black hole?
- How are jets launched and accelerated?
- What is the shape of the accretion disk?
- What precise processes give rise to the emission we see?

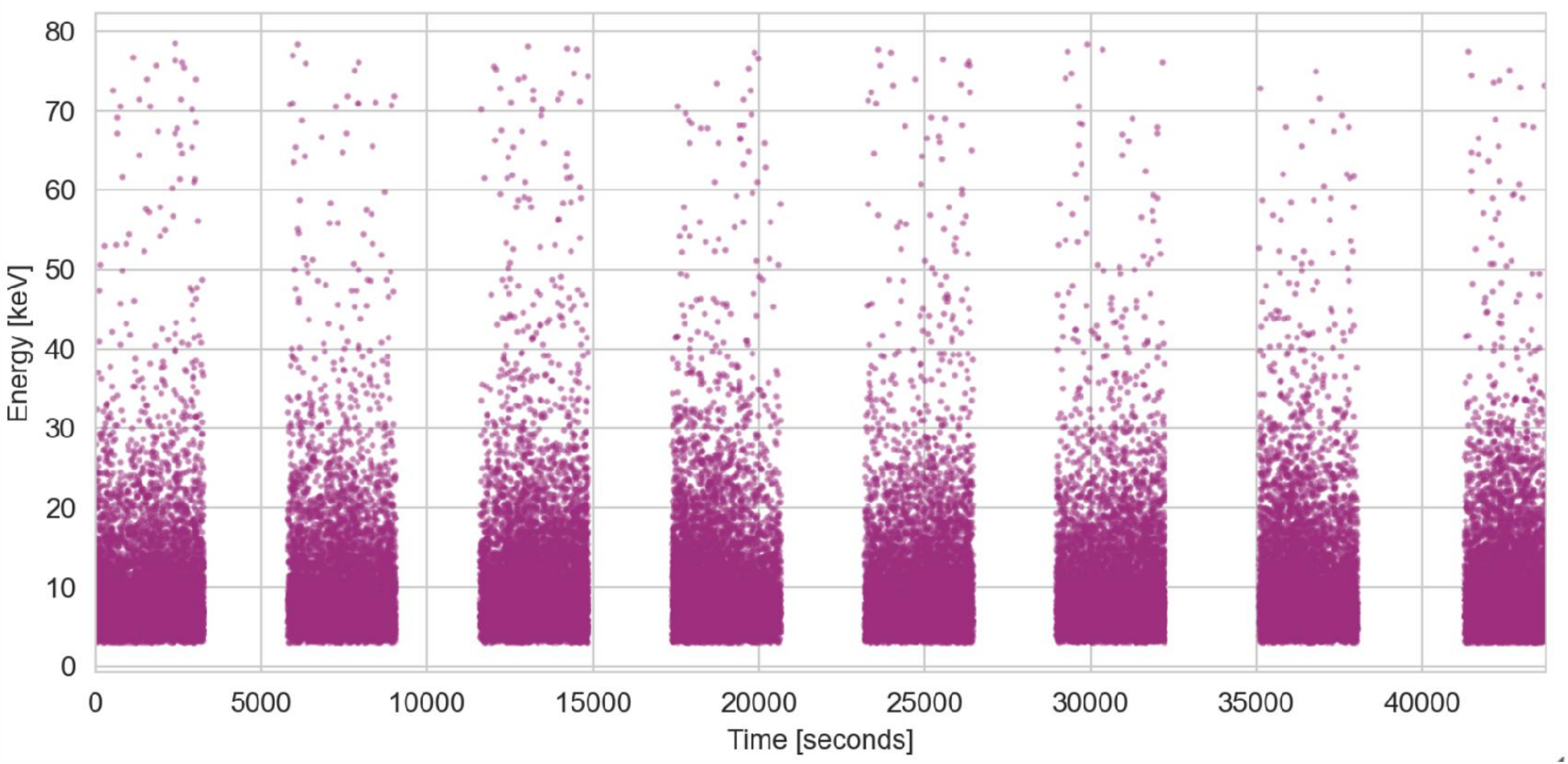
Cygnus X-1



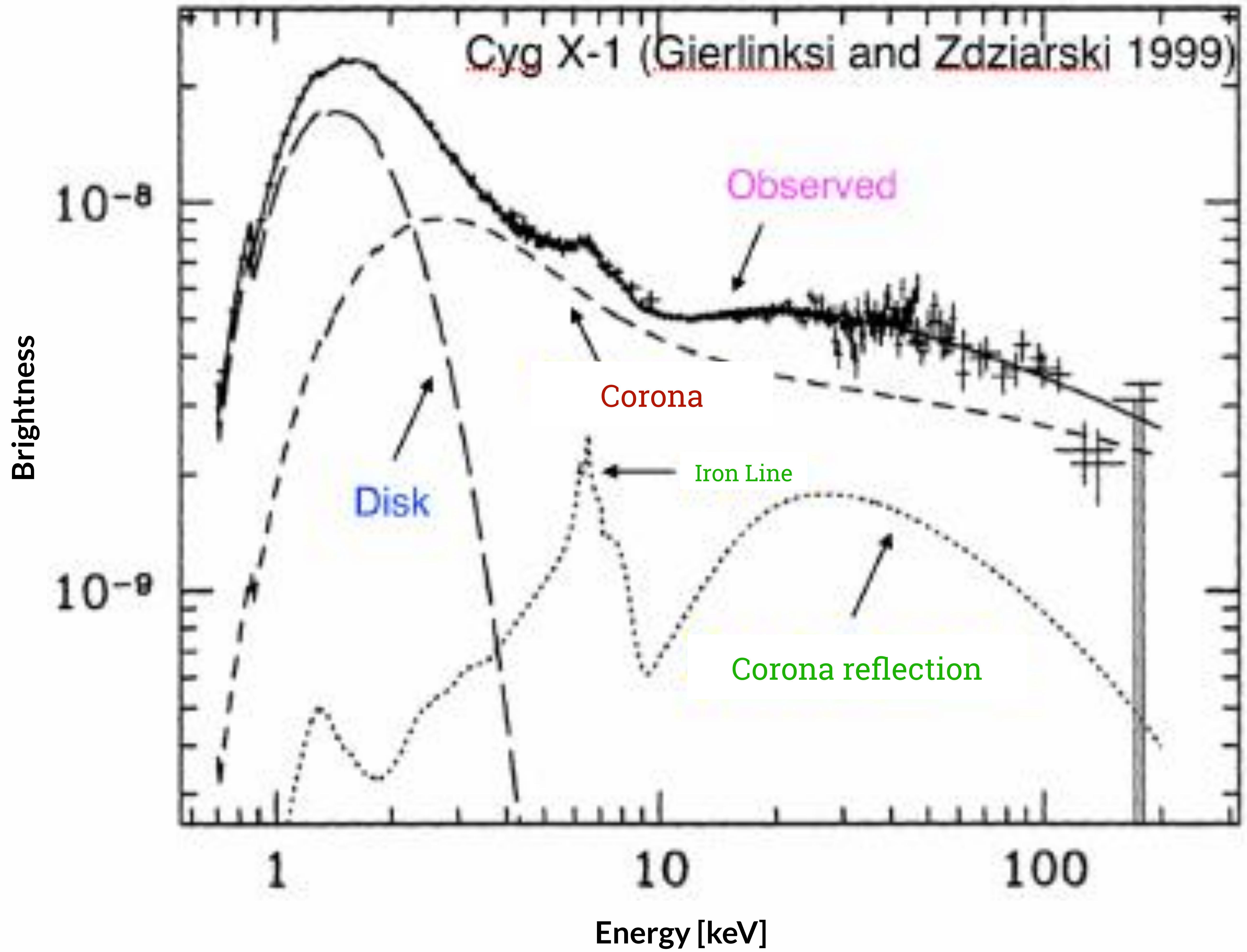
Credit: NASA/SRON/MPE

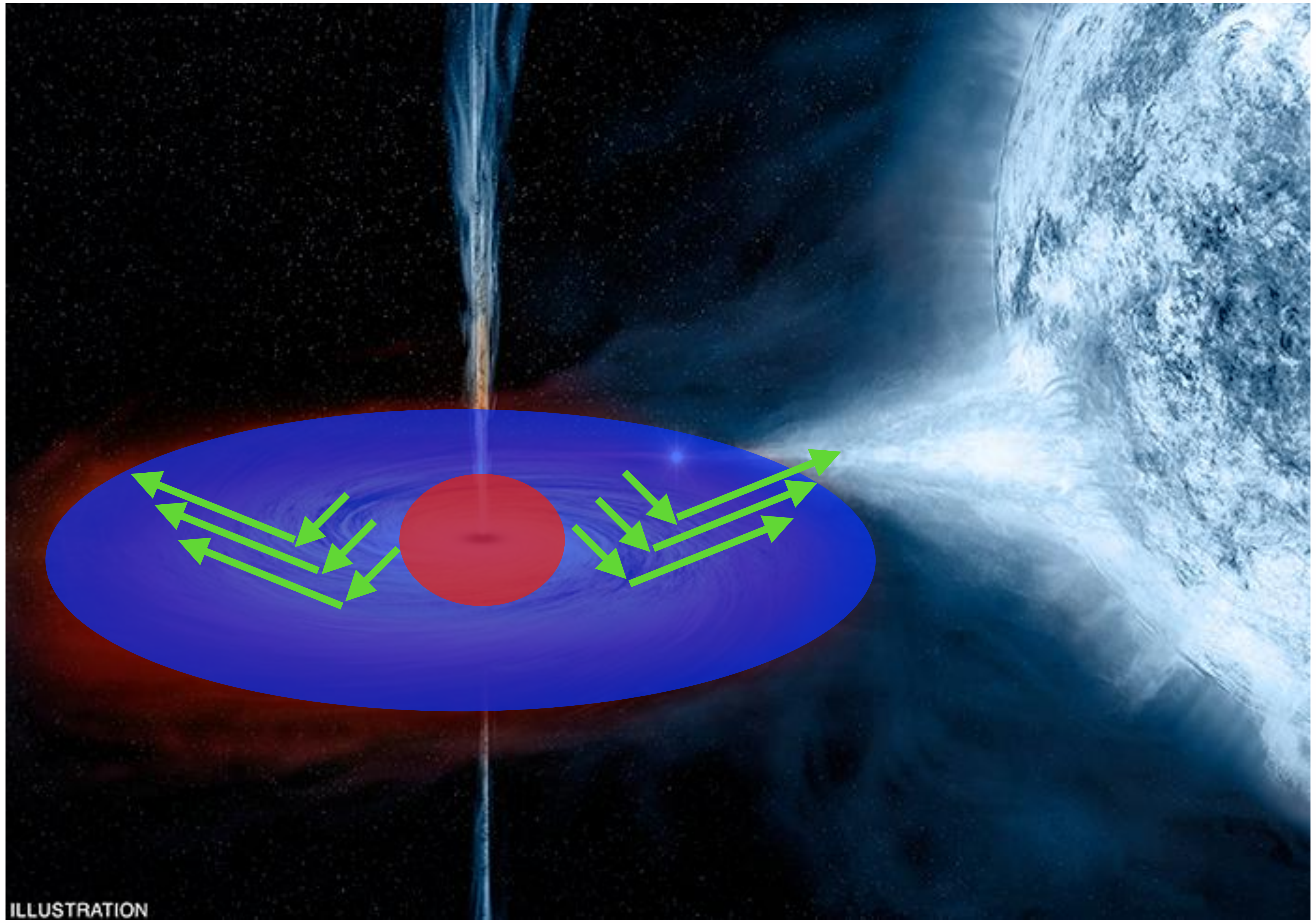
visible light
Atmosphere Opaque to Wavelengths
Radio Window
Atmosphere Opaque to Wavelengths
Optical Window
Atmosphere Opaque to Wavelengths
10^6 (Hertz)
10^9 Hz
10^12 Hz
10^15 Hz
10^18 Hz
10^21 Hz
Radio Waves
Microwaves
Infrared
Ultraviolet
X-rays
Gamma Waves
10^2 (meters)
10^1 m
10^0 m (1 m)
10^-1 m
10^-2 m (1 cm)
10^-3 m
10^-4 m
10^-5 m
10^-6 m (1 µm)
10^-7 m
10^-8 m
10^-9 m
10^-10 m
10^-11 m
10^-12 m
Wavelength = length of a football field
Wavelength = width of a baseball
Wavelength = thickness of paper
Wavelength = width of a water molecule
Wavelength = size of atomic nuclei
AM radio
FM Radio
Cell Phone and Wi-Fi
Microwave Oven
Human bodies radiate heat
Remotes
Visible Light
Sunburn
Medical X-rays
Nuclear Power

Raw Data

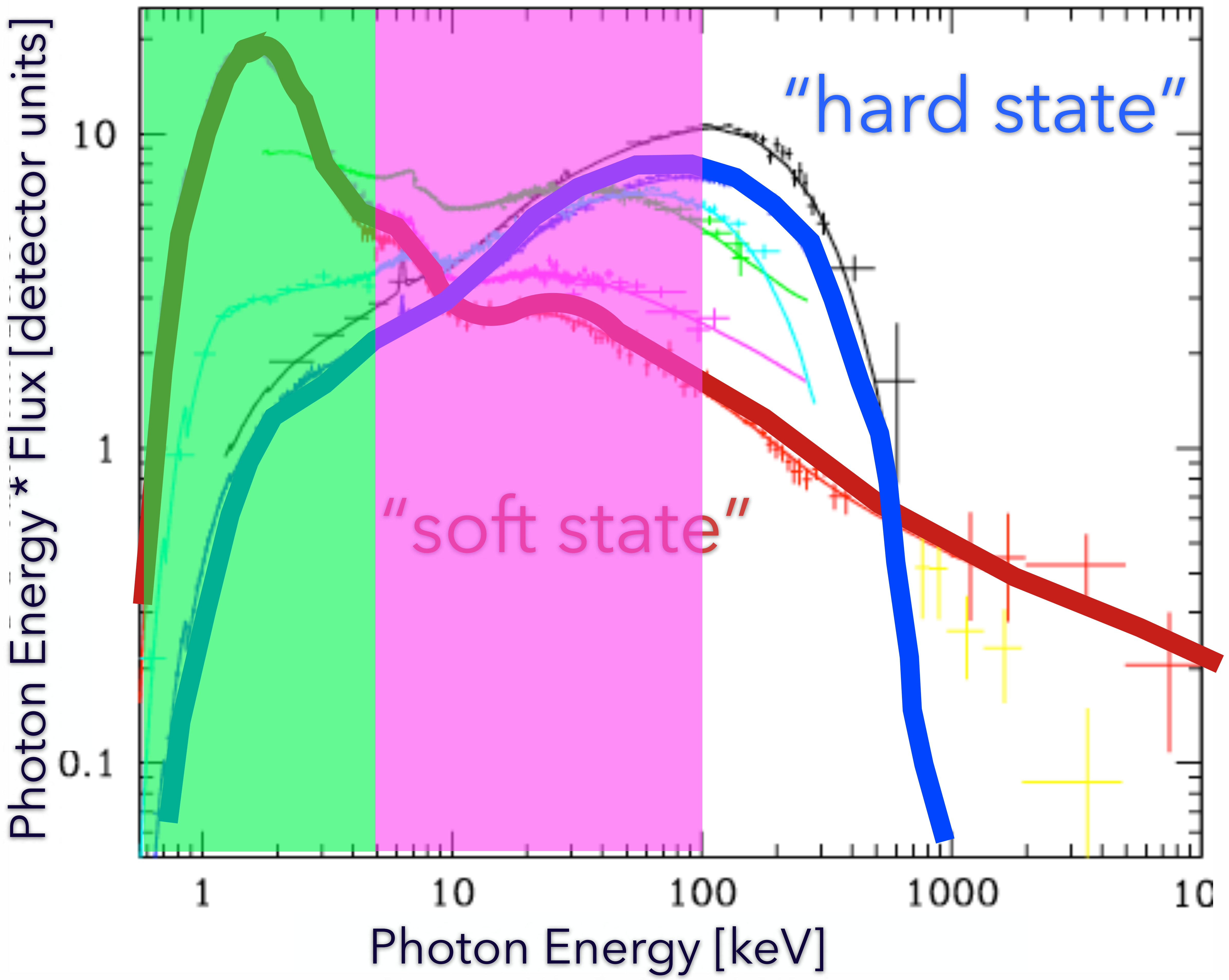


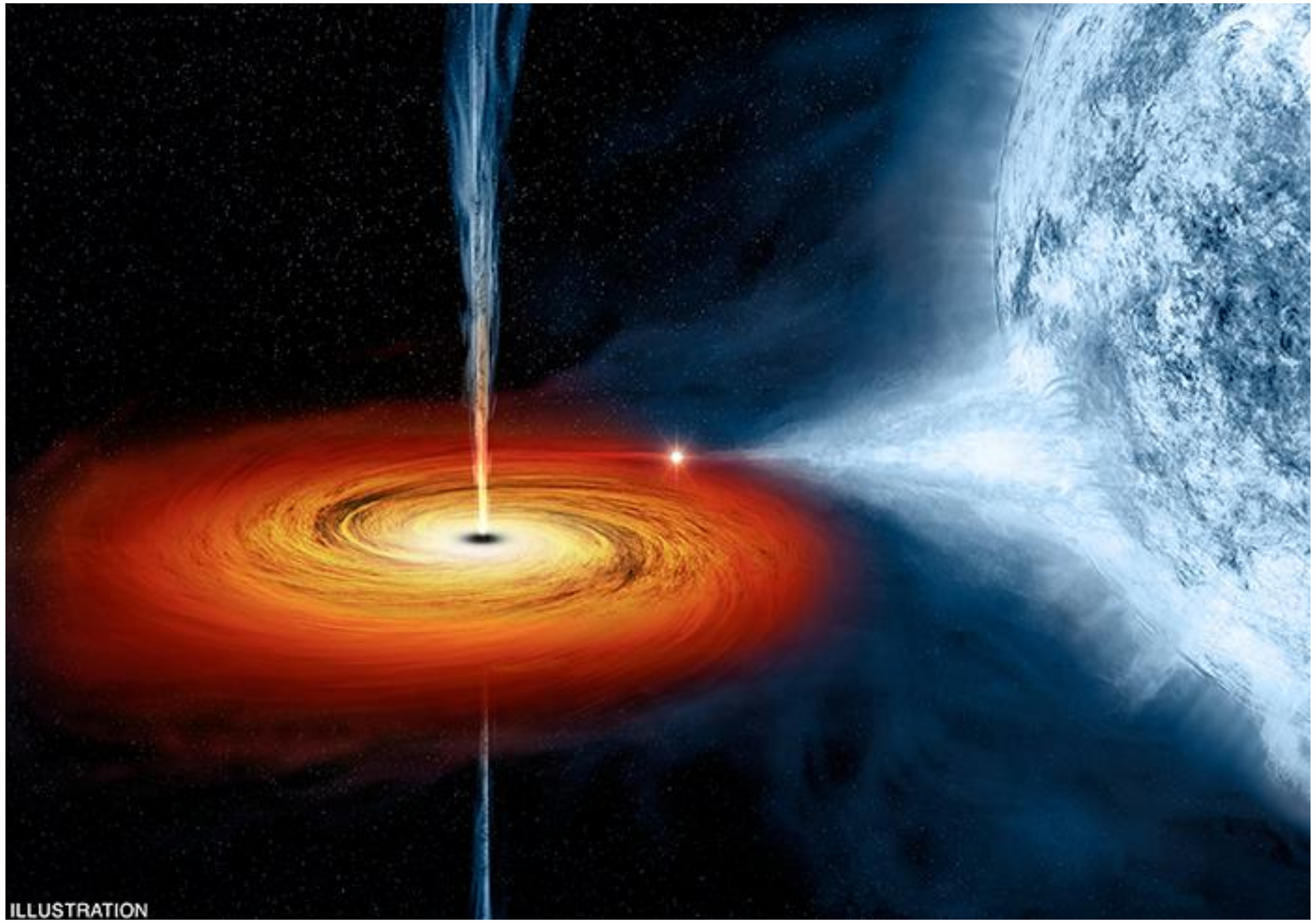
80
70
60
50
40
30
20
10
0
Energy [keV]
0
5000
10000
15000
20000
25000
30000
35000
40000
Time [seconds]


Cyg X-1 (Gierlinksi and Zdziarski 1999)
Observed
Corona
Iron Line
Disk
Corona reflection
10⁻⁸
10⁻⁹
1
10
100
Brightness
Energy [keV]



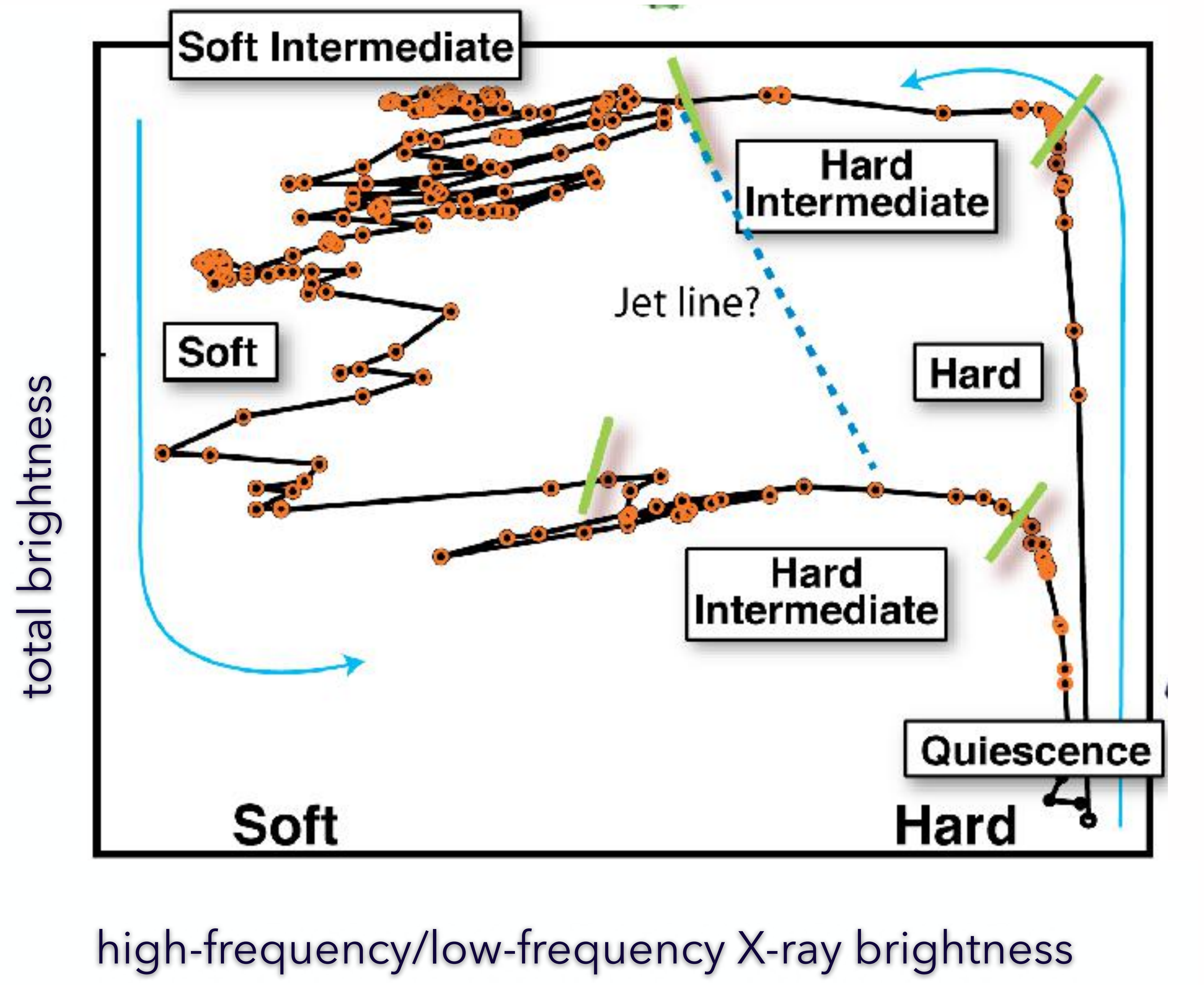
ILLUSTRATION



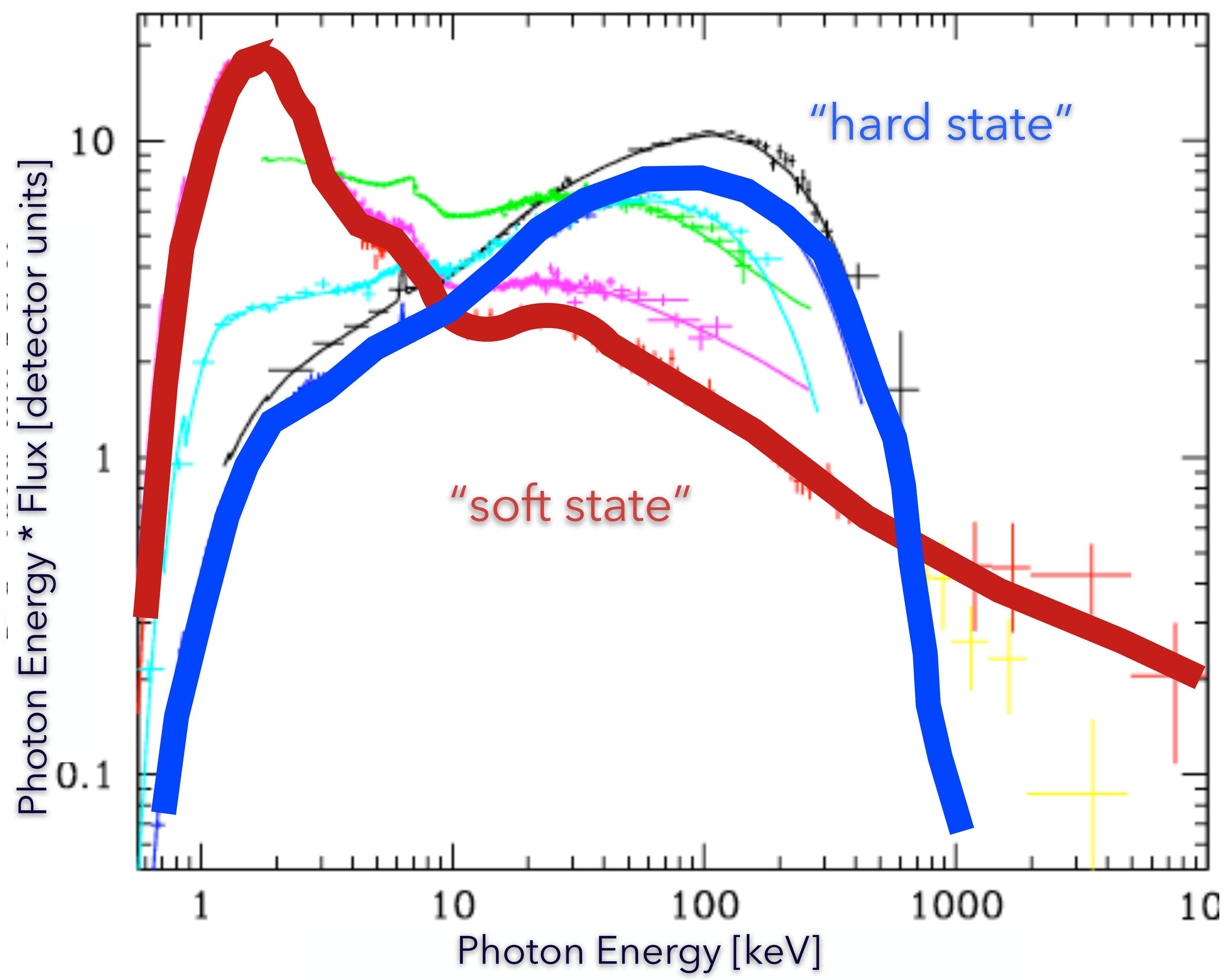


Gierlinski 2008, Maitra et al 2009

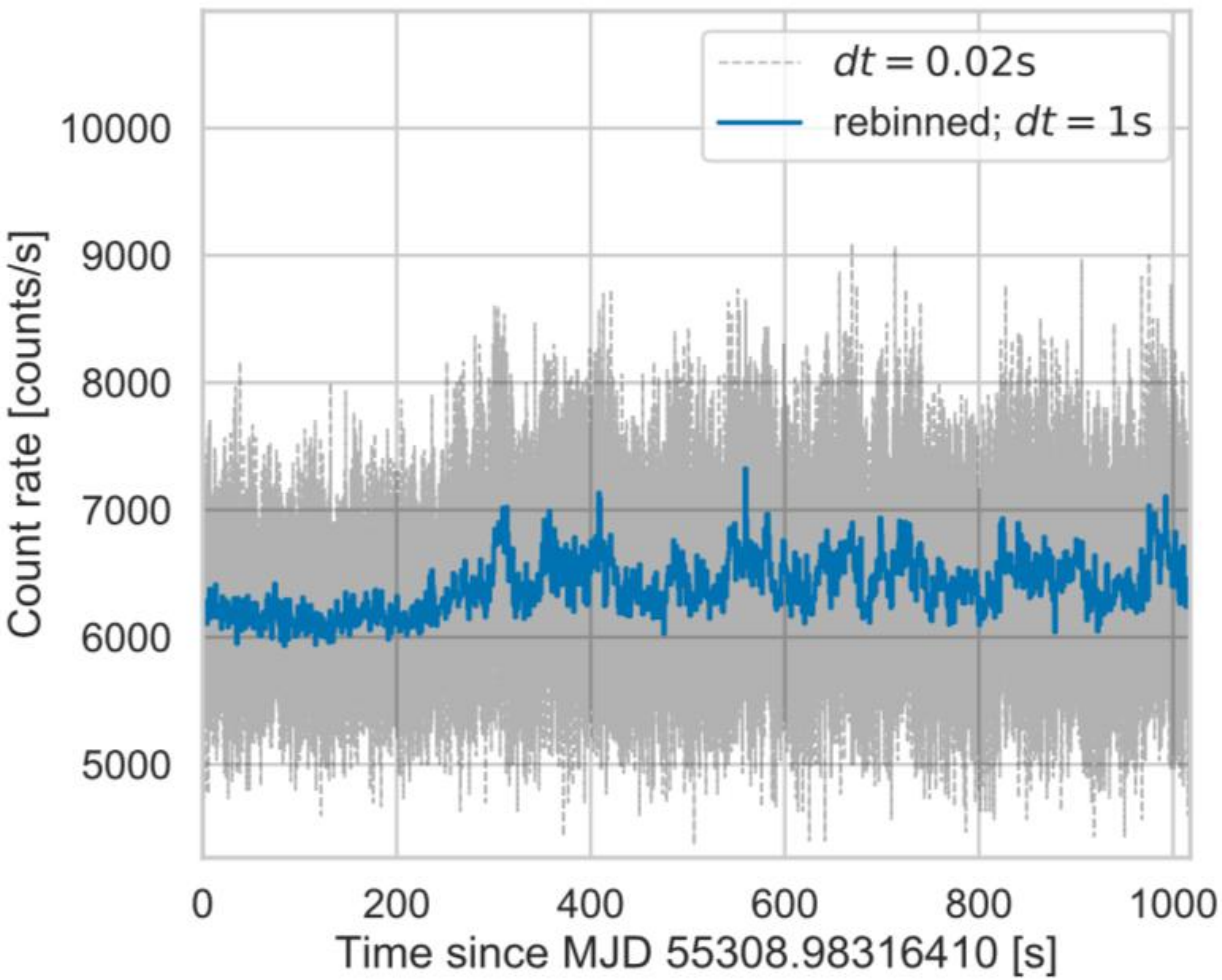
Spectral States



Malzac (2008)



Credit: Sera Markoff



$dt = 0.02$s
rebinned; $dt = 1$s
10000
9000
8000
7000
6000
5000
Count rate [counts/s]
0
200
400
600
800
1000
Time since MJD 55308.98316410 [s]

Fourier Analysis tells us about variability

$$x(t) = \frac{1}{N} \sum_j a_j \cos(\omega_j t - \phi_j) = \frac{1}{N} \sum_j (A_j \cos \omega_j t + B_j \sin \omega_j t) \,.$$

$$a_j = \sum_{k=0}^{N-1} x_k e^{2\pi i j k / N}$$

useful normalization

periodogram:

$$P_j \equiv \boxed{\frac{2}{N_{ph}}} |a_j|^2 \qquad j = 0, \ldots, \frac{N}{2},$$

statistical distribution?

Fourier Analysis tells us about variability

$$x(t) = \frac{1}{N}\sum_j a_j \cos(\omega_j t - \phi_j) = \frac{1}{N}\sum_j (A_j \cos\omega_j t + B_j \sin\omega_j t)\,.$$

assume many data points

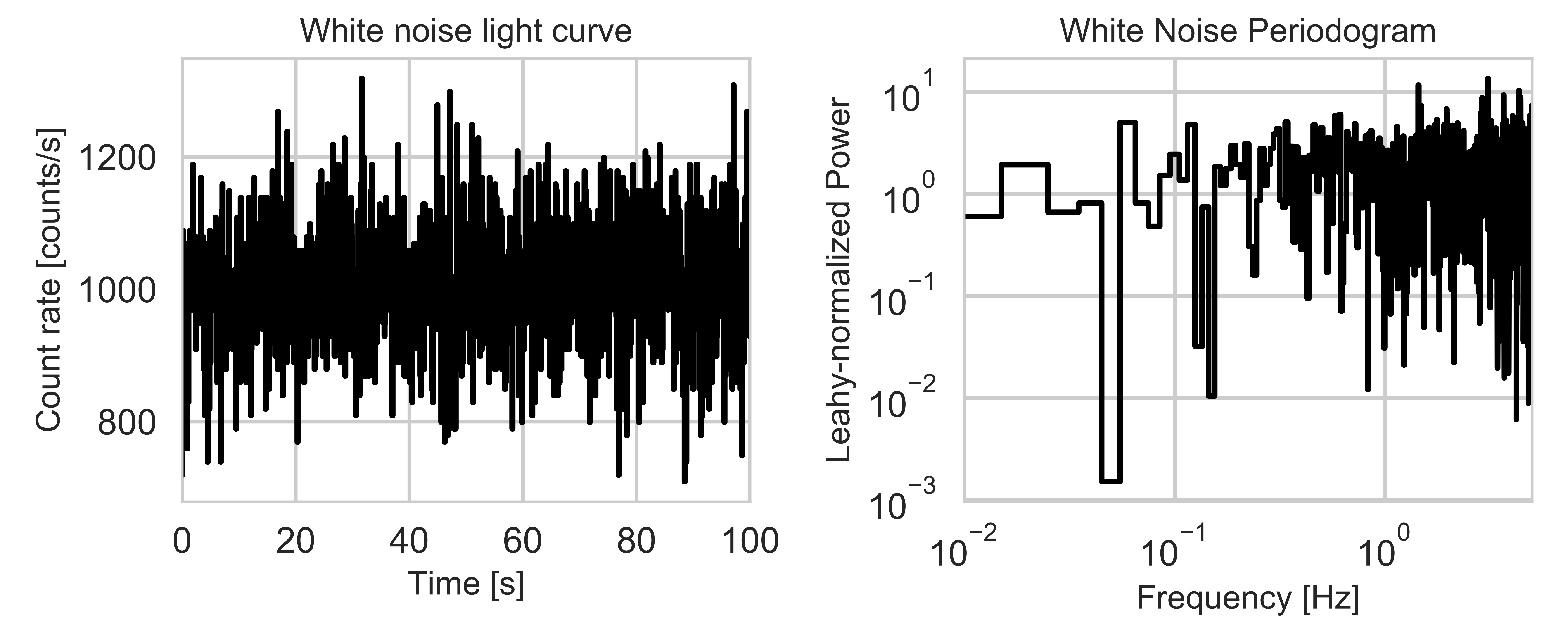
~ Gaussian

$$P_j \equiv \frac{2}{N_{ph}}|a_j|^2 \qquad j = 0, \ldots, \frac{N}{2},$$

$$|a_j|^2 = A^2 + B^2$$

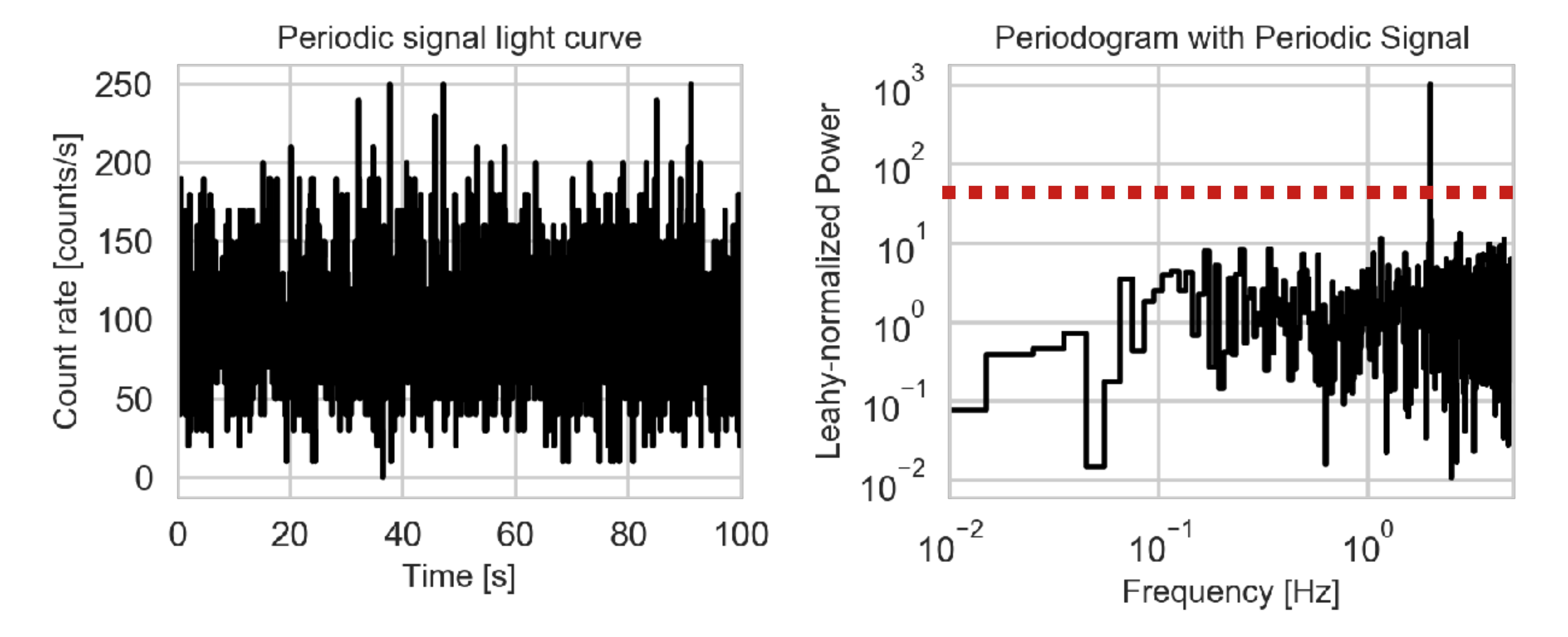
χ^2 with 2 degrees of freedom

Fourier Analysis tells us about variability



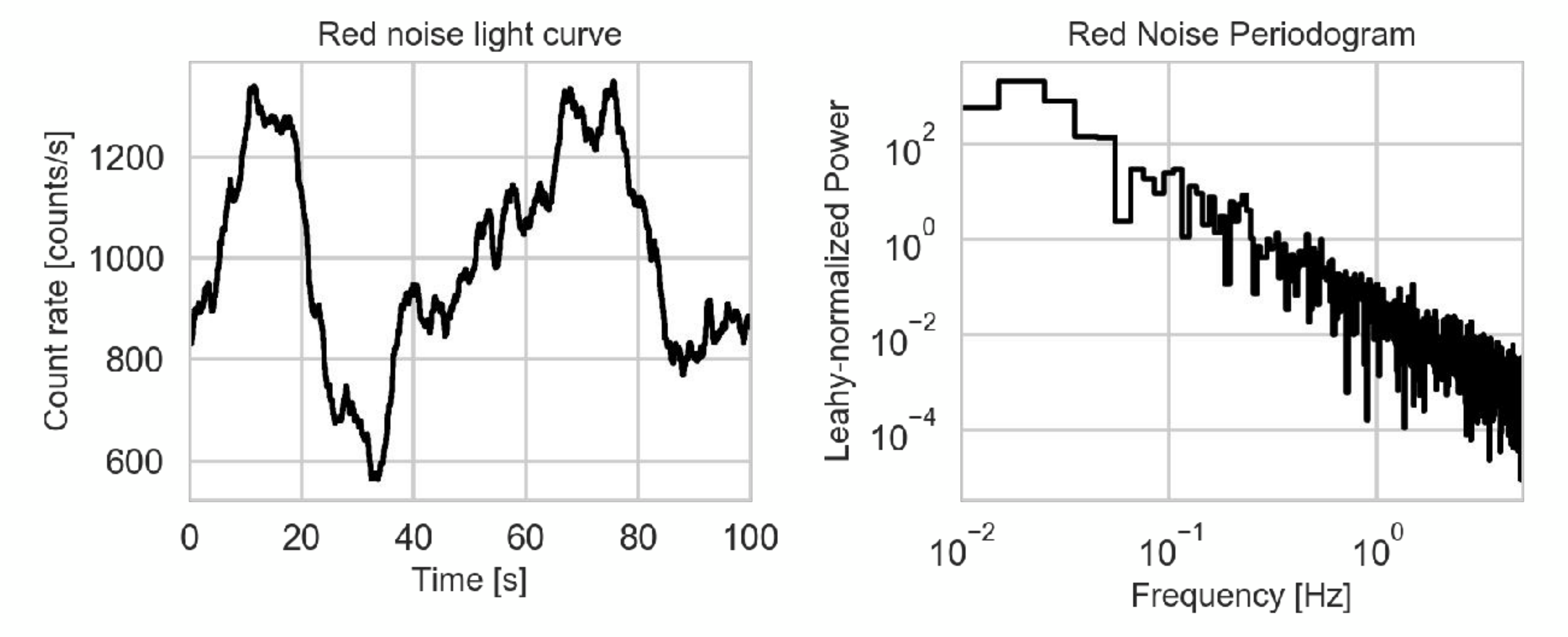
white noise

Fourier Analysis tells us about variability



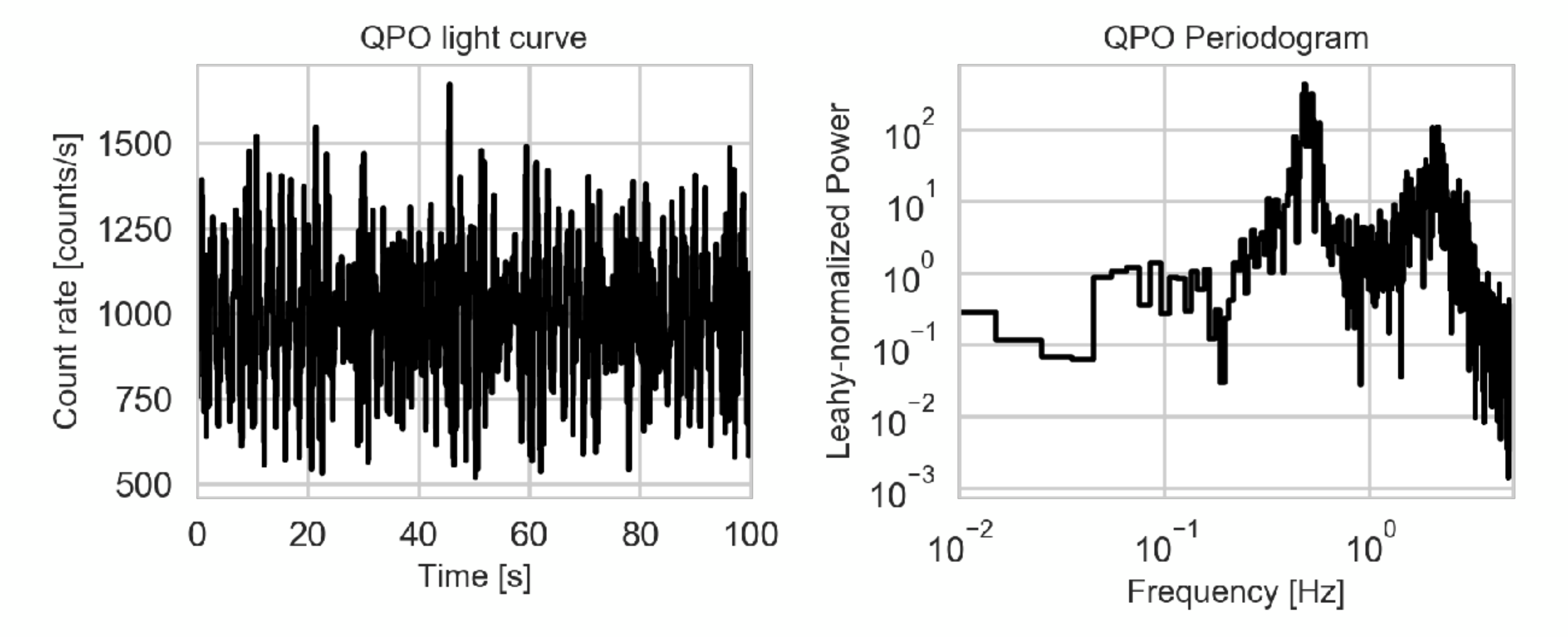
periodic signal

Fourier Analysis tells us about variability

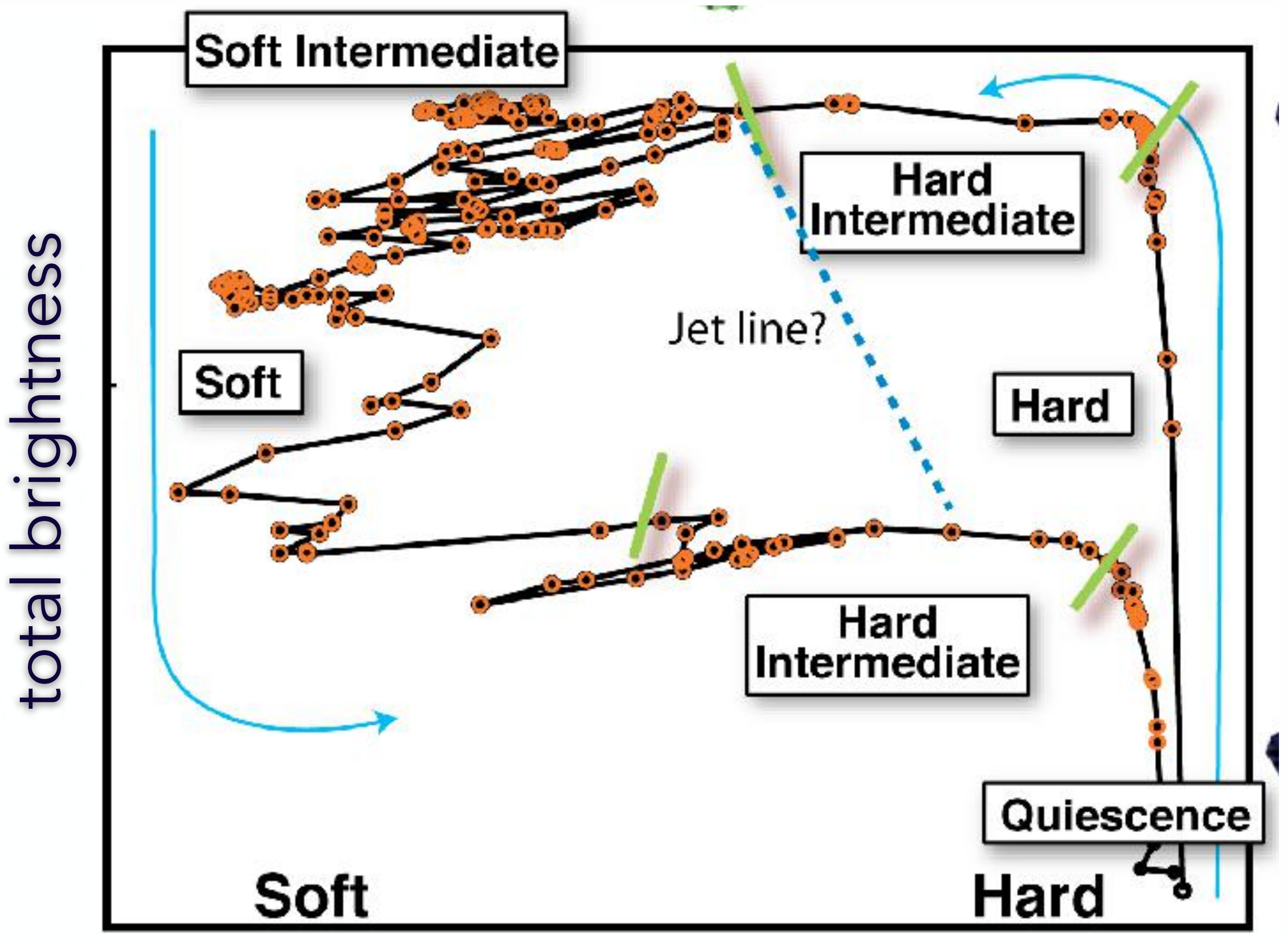


correlated stochastic variability

Fourier Analysis tells us about variability

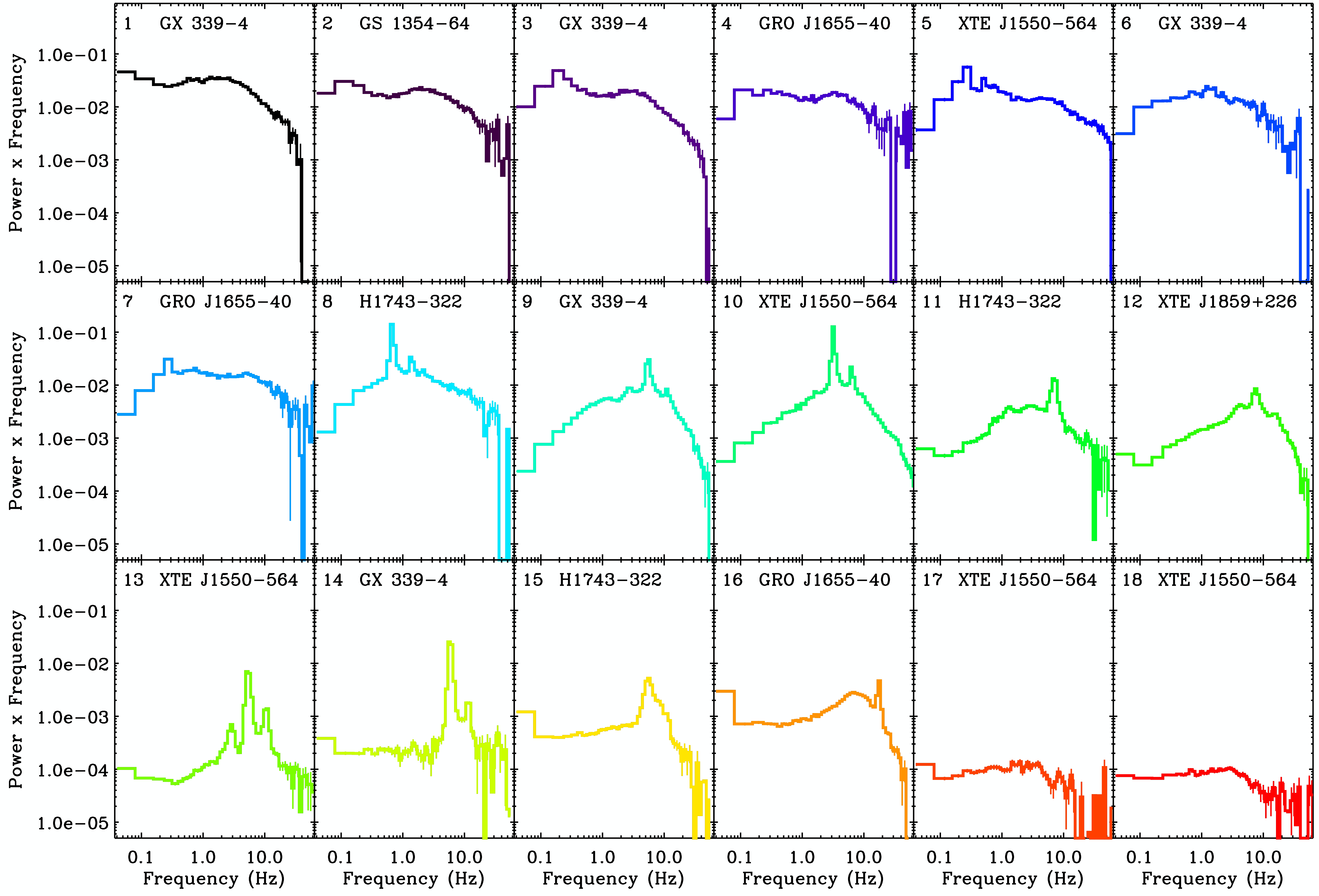


quasi-periodic oscillations

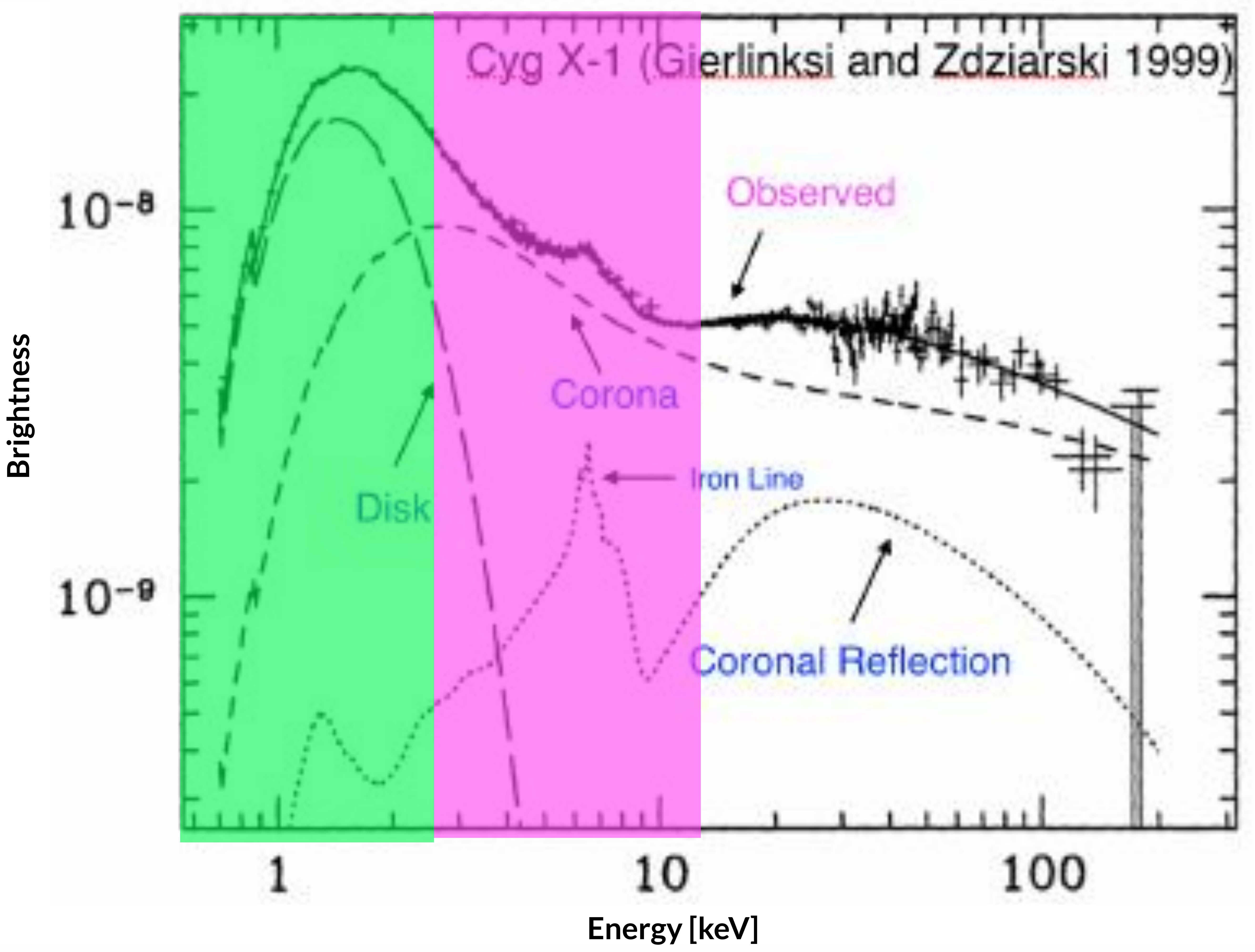


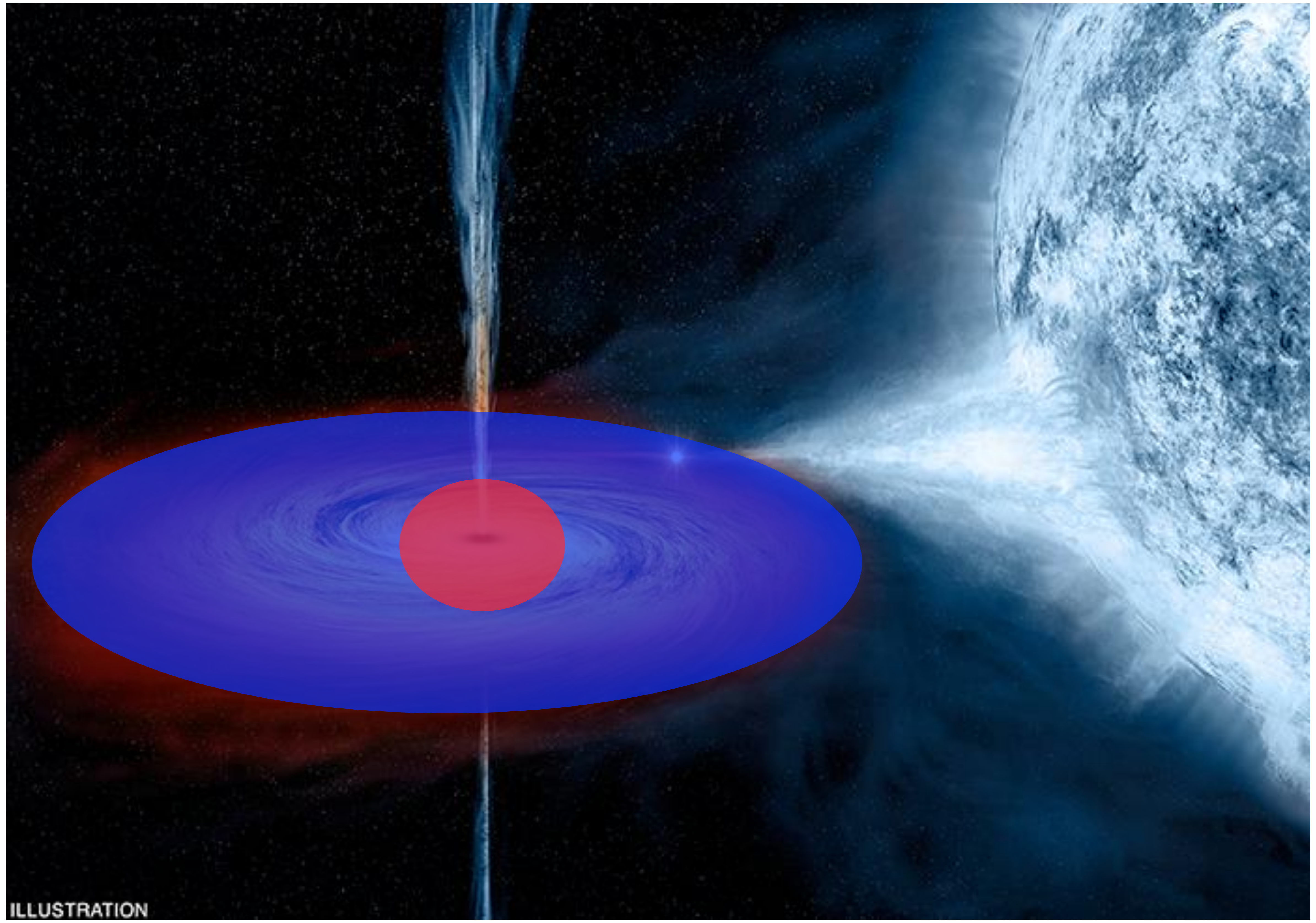
high-frequency/low-frequency X-ray brightness

Heil et al (2014)

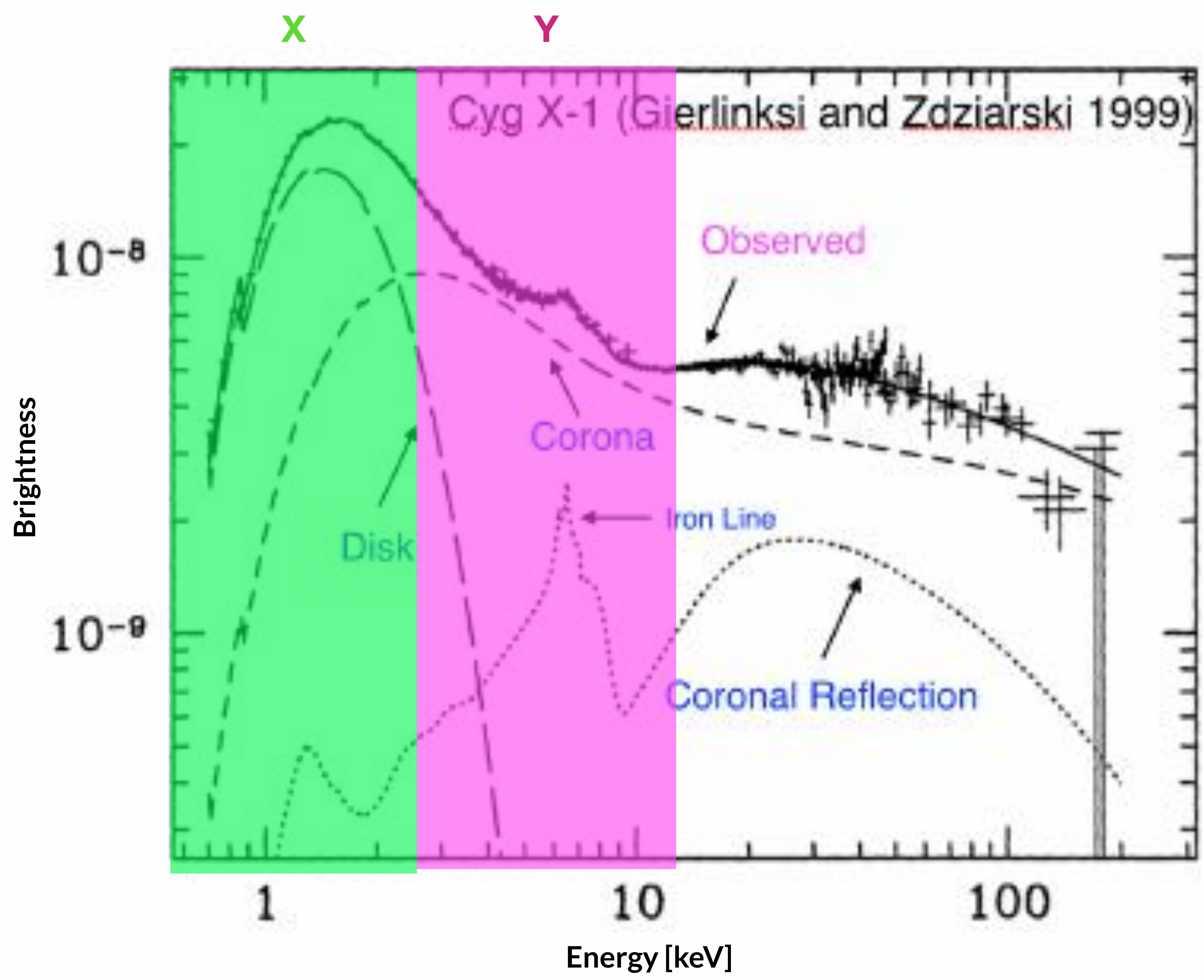


What can we learn about the **geometry** and **physics** of the system from **timing** and **spectral** properties?





Gierlinski 2008, Maitra et al 2009



$$C_{XY} = \mathcal{F}^{\star}_{X}\mathcal{F}_{Y}$$

$$C_{XY,j} = a_{X,j}\exp(-i\theta_j)a_{Y,j}\exp(i(\theta_j + \phi_j))$$

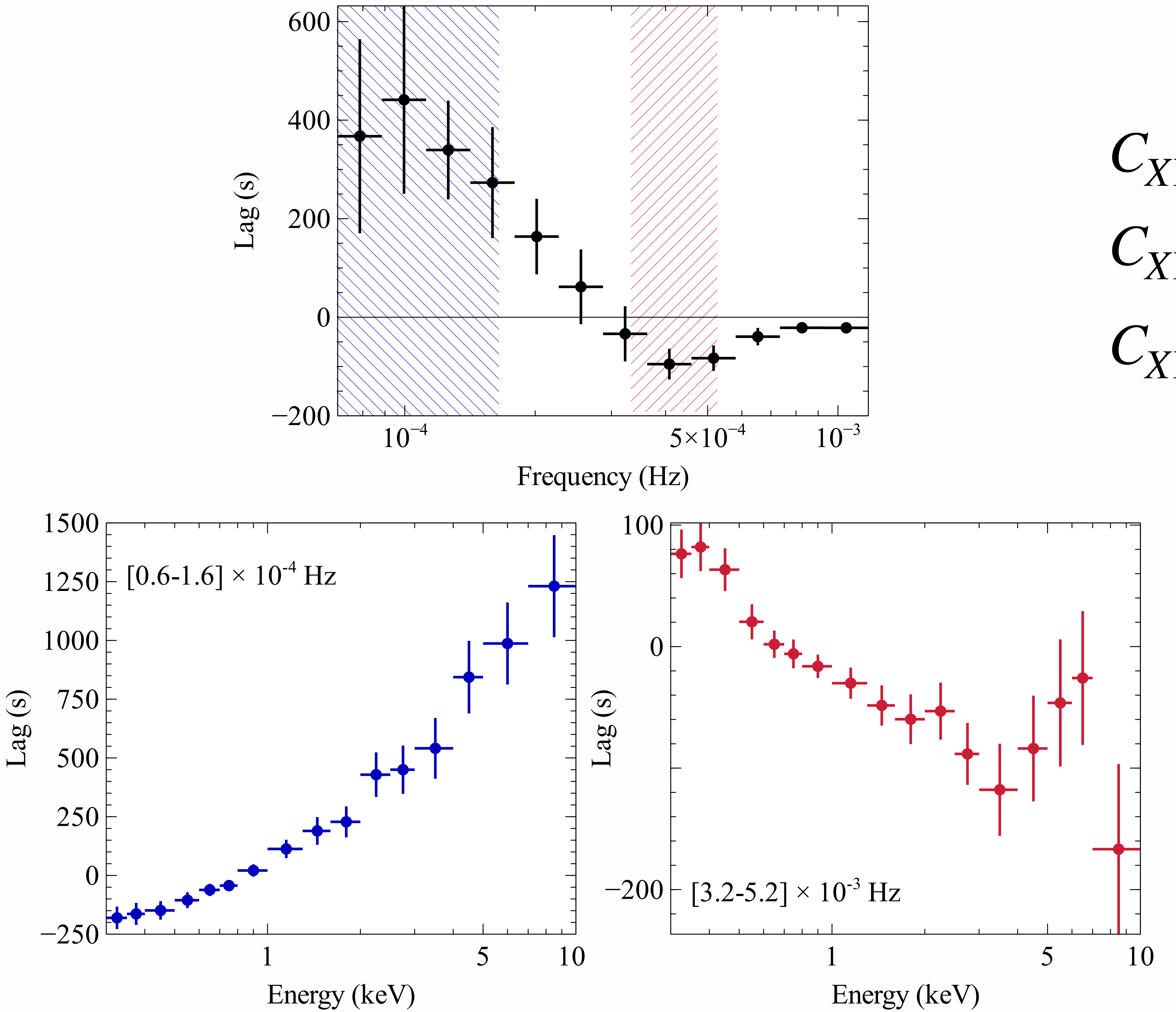
$$C_{XY,j} = a_{X,j}a_{Y,j}\exp(i\phi_j)$$

cospectrum   phase lag

↓

time lag

Gierlinski 2008, Maitra et al 2009



Uttley et al (2014)

$$C_{XY} = \mathscr{F}^{\star}_{X}\mathscr{F}_{Y}$$

$$C_{XY,j} = a_{X,j}\exp(-i\theta_j)a_{Y,j}\exp(i(\theta_j + \phi_j))$$

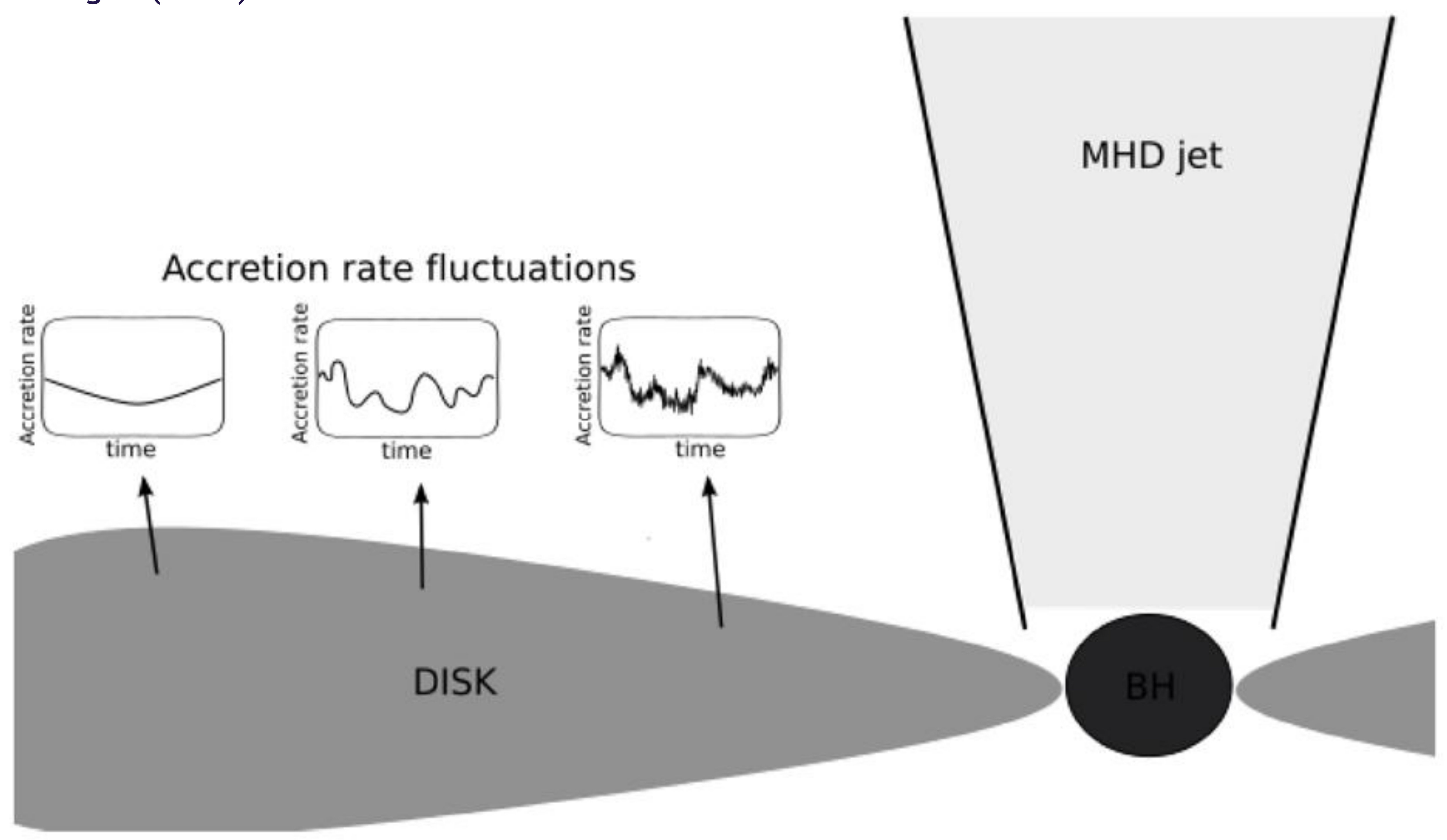
$$C_{XY,j} = a_{X,j}a_{Y,j}\exp(i\phi_j)$$

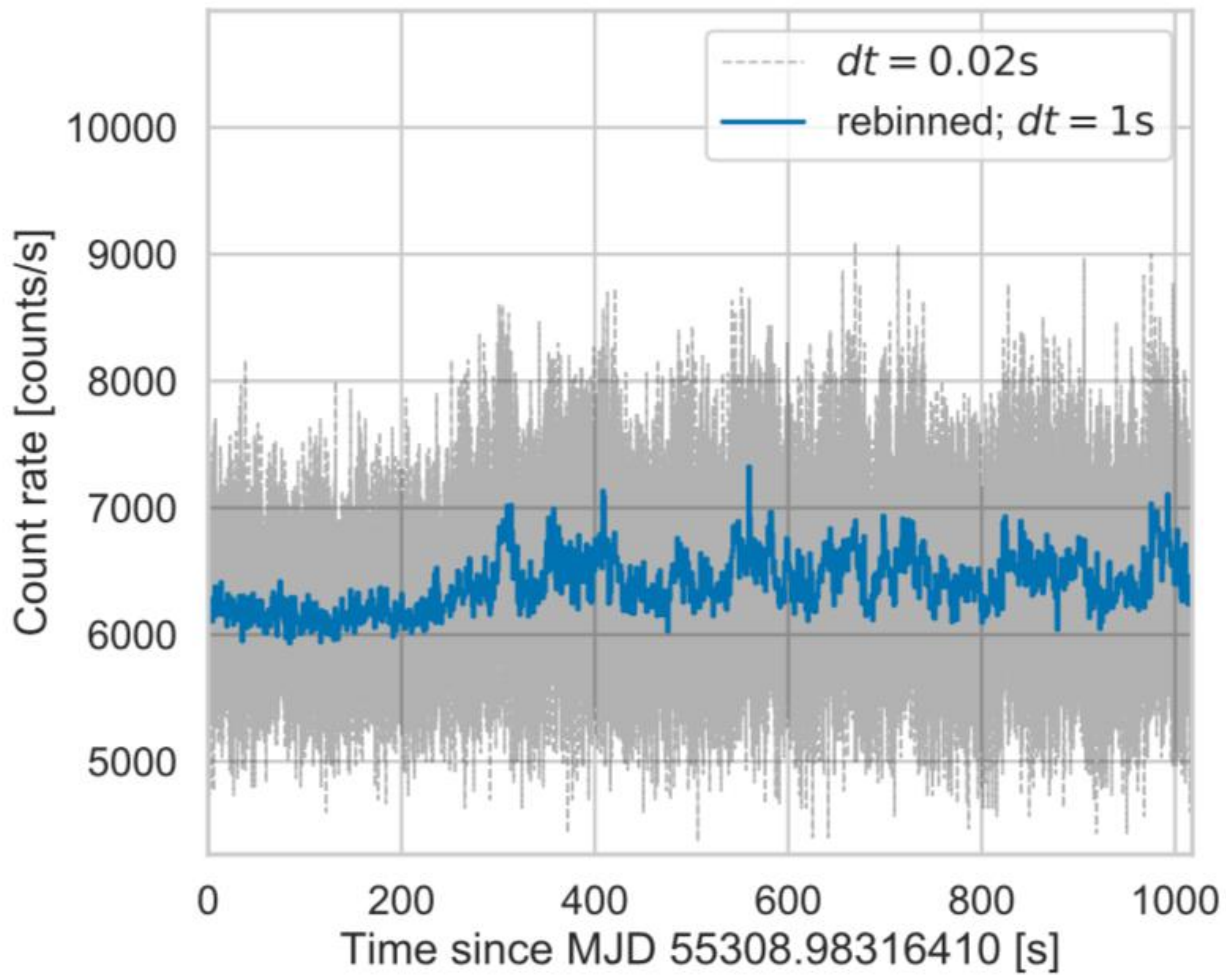
cospectrum phase lag

time lag

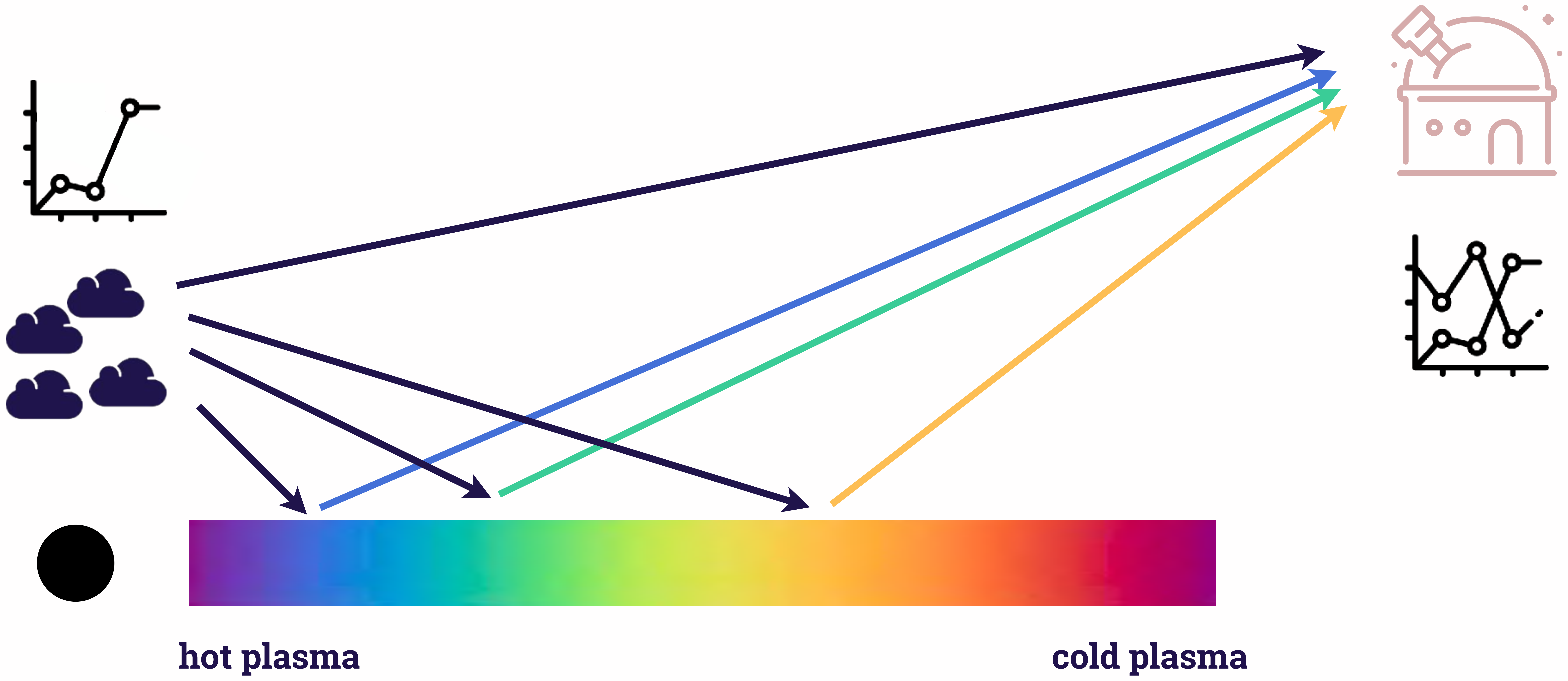
Side note: this is a much bigger black hole

Rieger (2019)



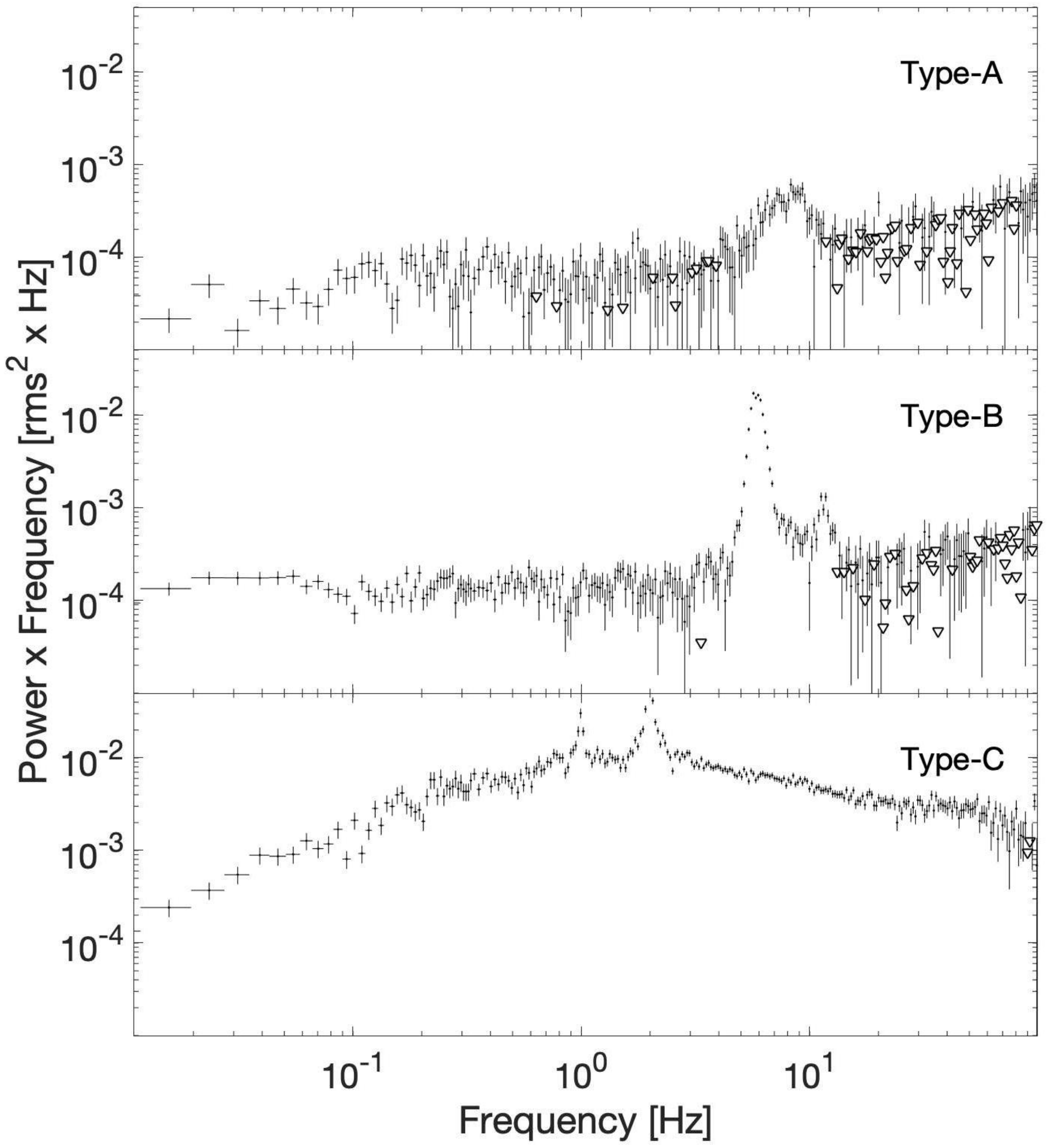


time, wavelength of emission

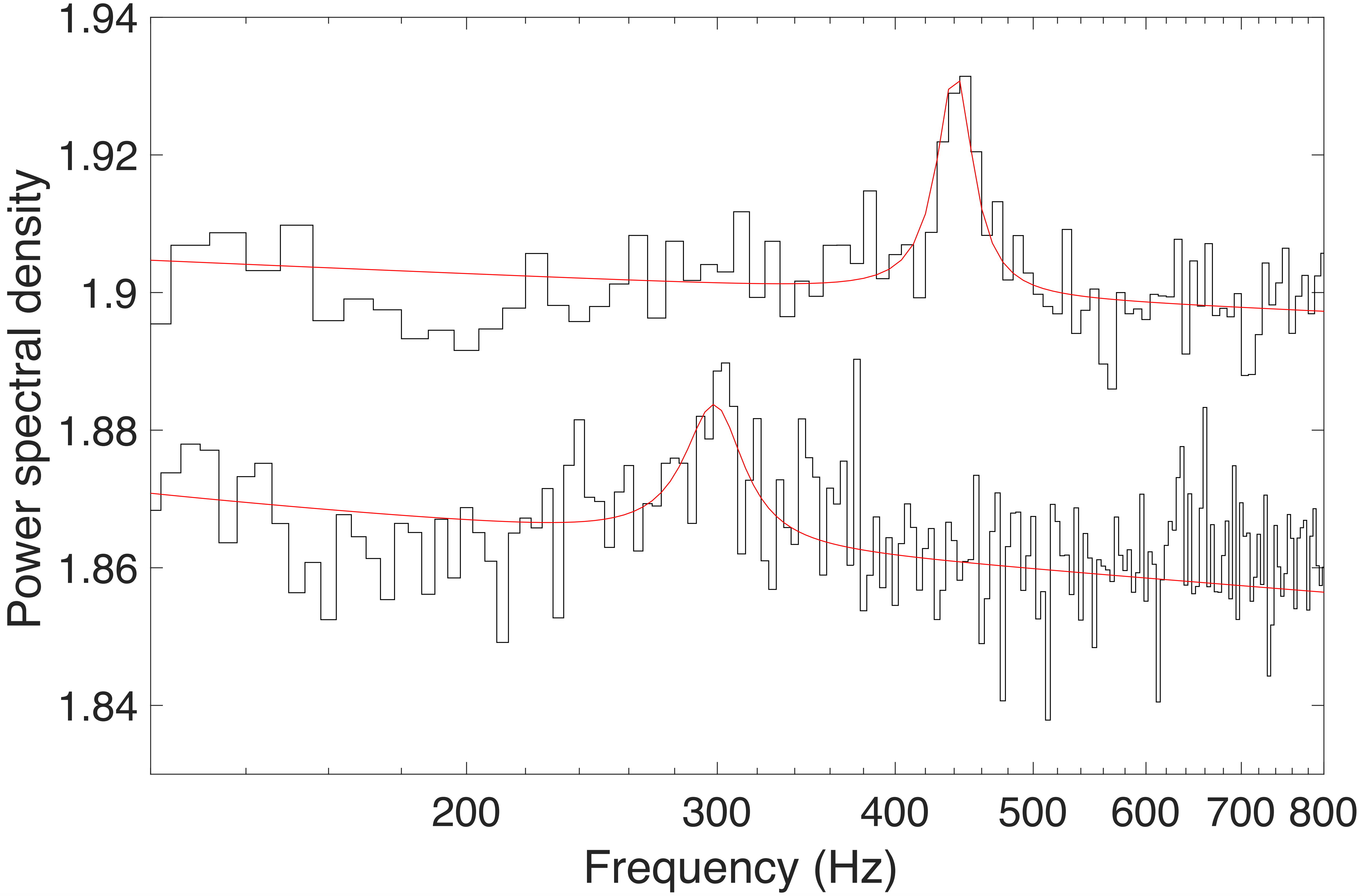

hot plasma
cold plasma

Quasi-Periodic Oscillations

Low-Frequency QPOs



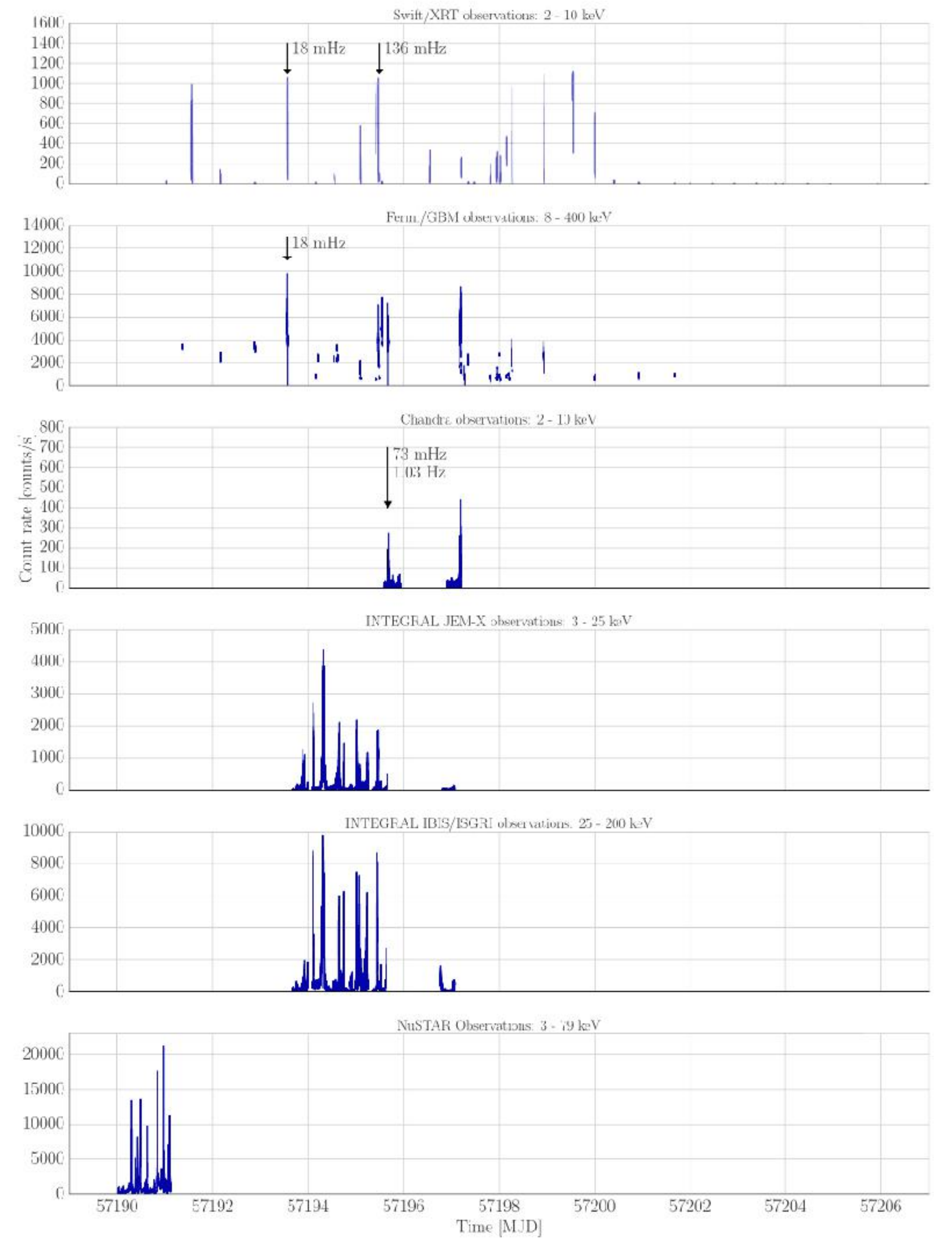
High-Frequency QPOs



Ingram & Motta (2016)


XMM–Newton
NuSTAR
ratio
1.05
1
4
6
8
10
Energy (keV)
1.2
1
0.8
5
10
20
50
Energy (keV)
Credit: NASA

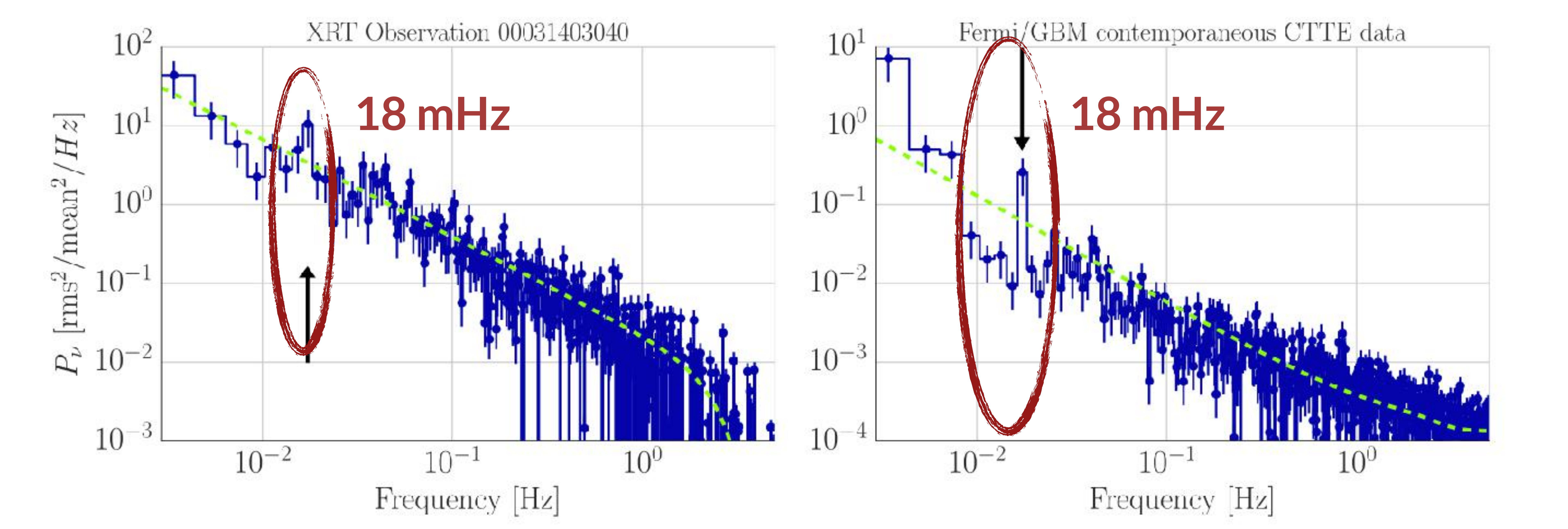
V404 Cygni



Huppenkothen et al, 2017

V404 Cygni

Huppenkothen et al, 2017

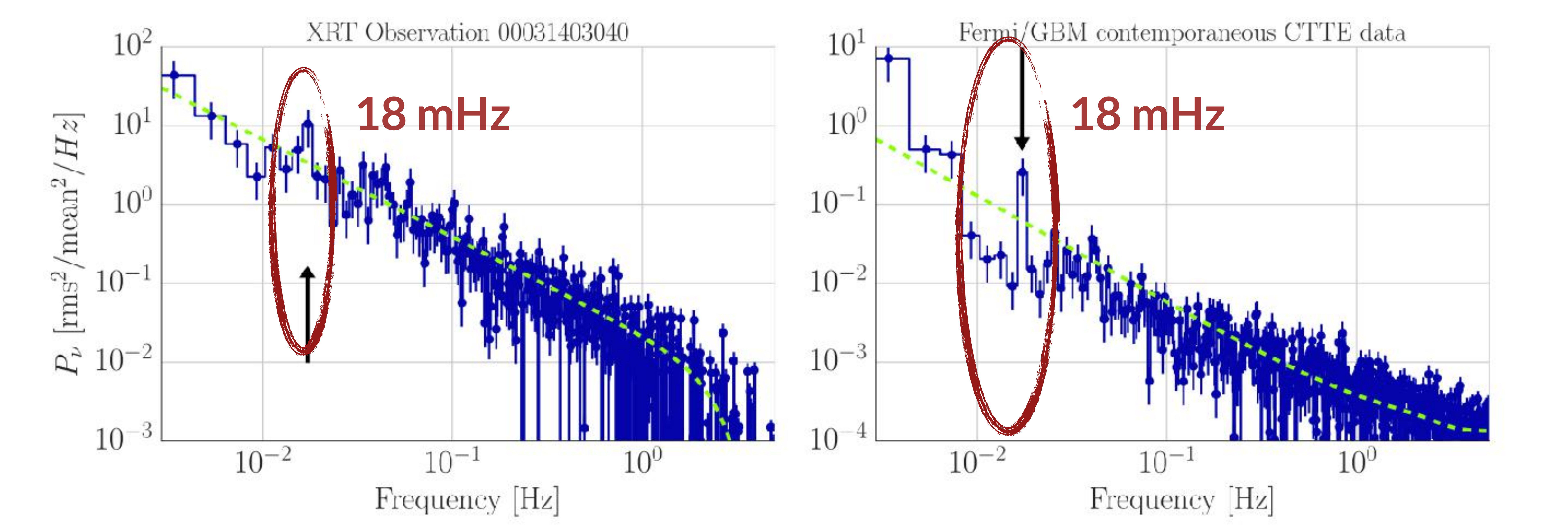


short-lived QPO* with a frequency ~10 times lower than expected

*quasi-periodic oscillation

V404 Cygni

Huppenkothen et al, 2017



possibly signature of **jet precession** or a **warped outer accretion disk**

Stingray

The Next Generation Spectral-Timing Software

- 3 lead developers/maintainers (Huppenkothen, Bachetti, Stevens)
- ~10 contributors
- 5 completed Google Summer of Code Projects
- astropy-affiliated project
- provides functionality for HENDRICS and DAVE

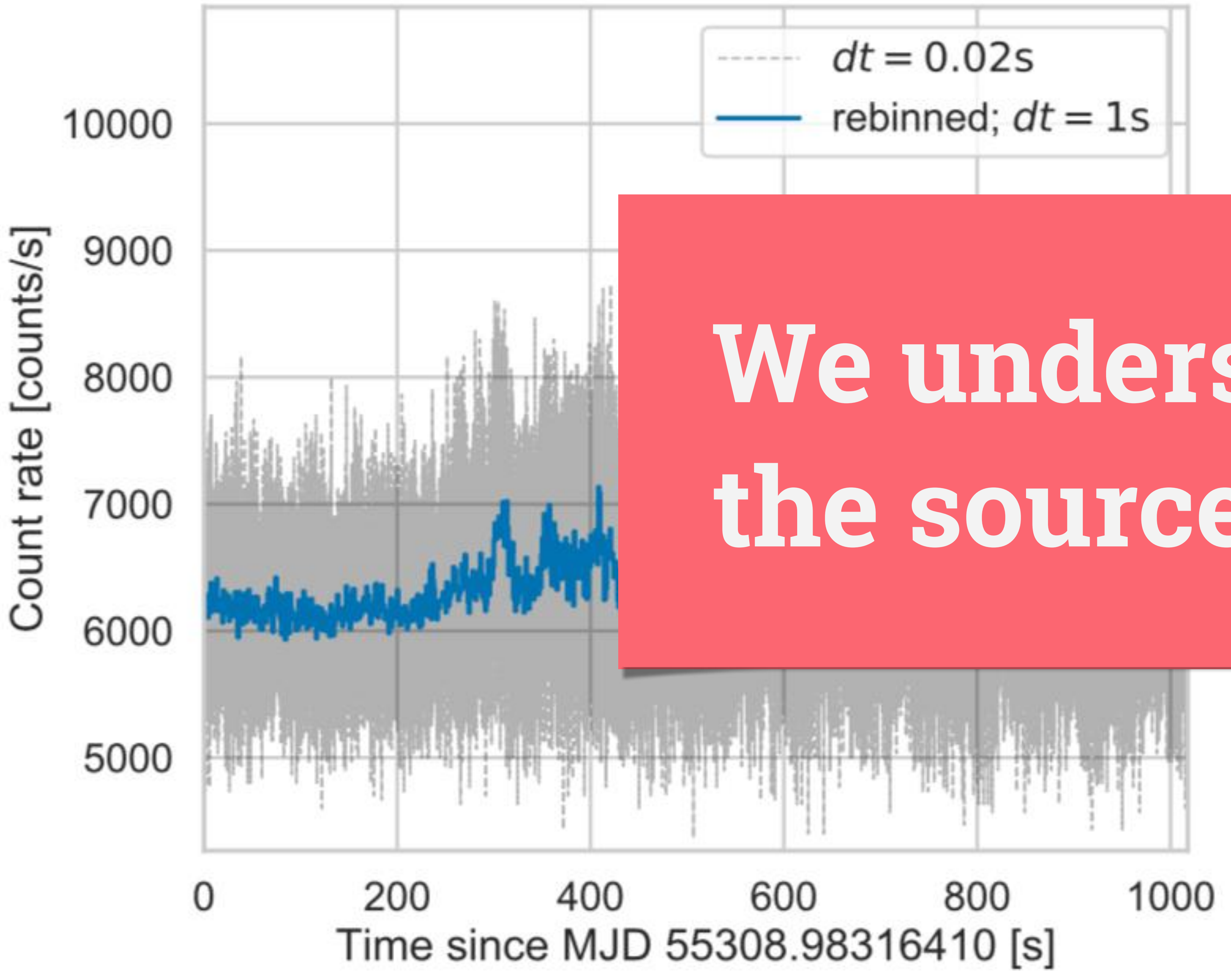
https://stingray.science

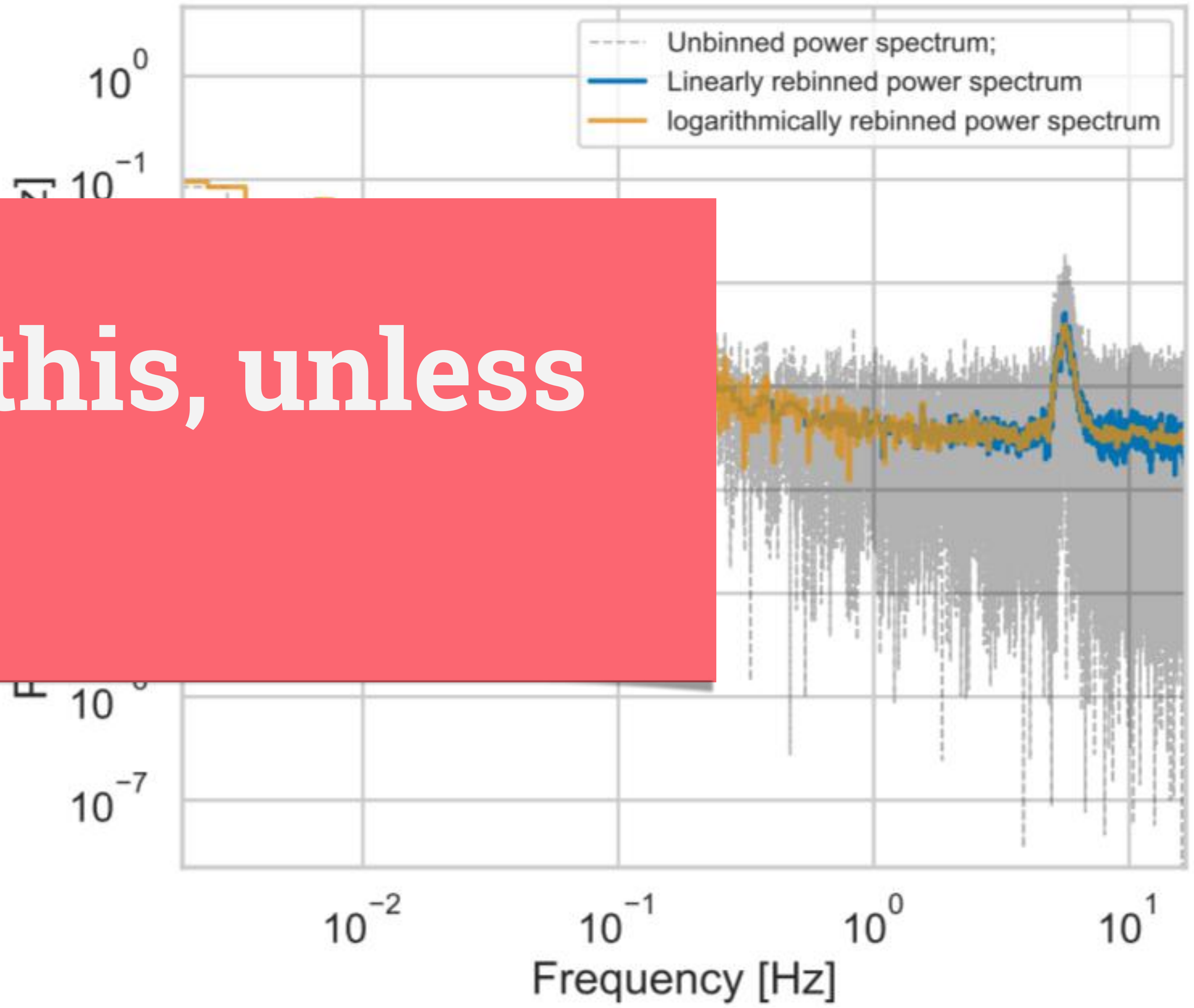
Huppenkothen et al (2019)

Modelling Detector Effects in X-ray Telescopes

Variability: GX 339-4

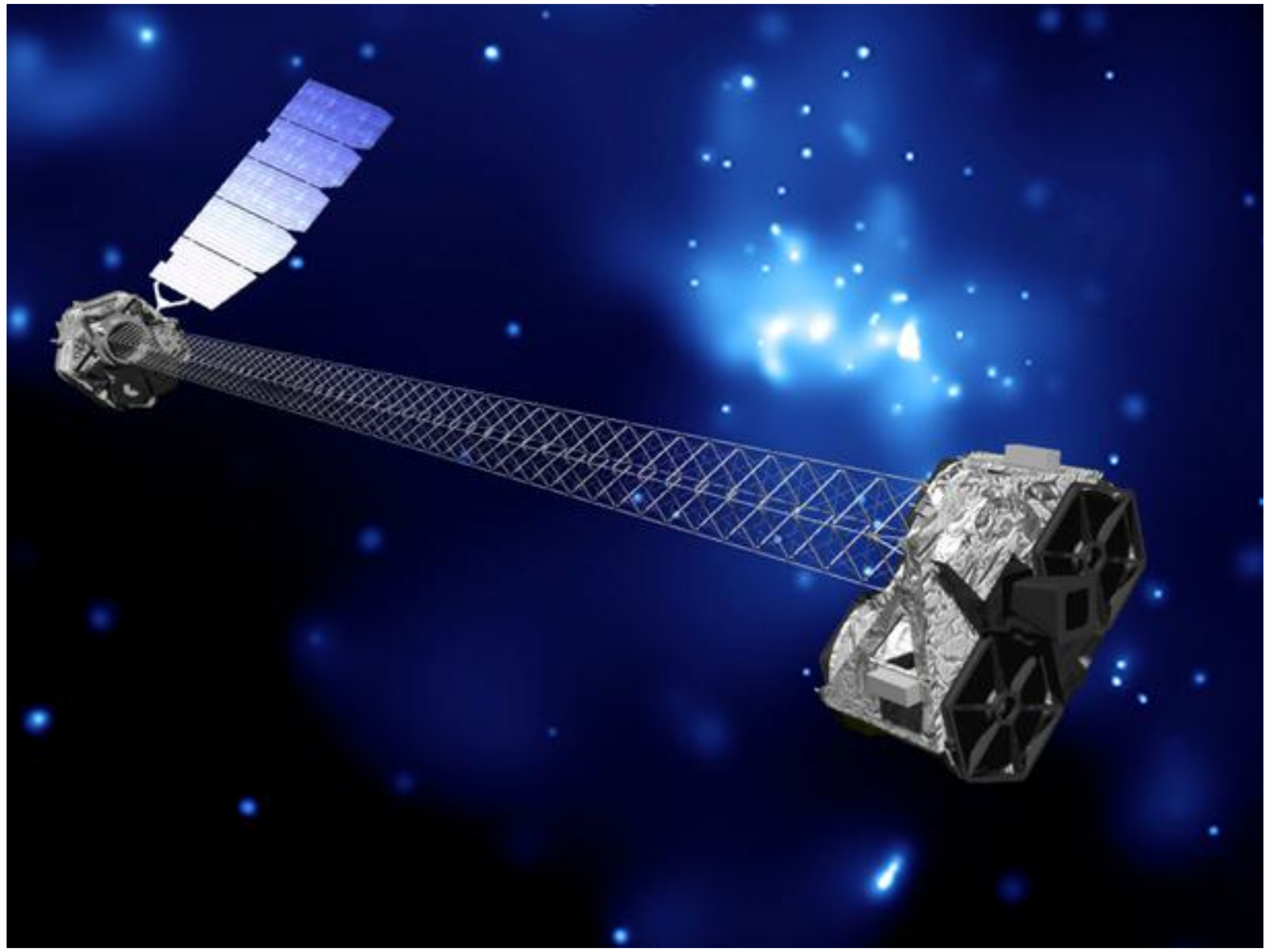
Yamaoka et al (2010);
Huppenkothen et al. (2019)



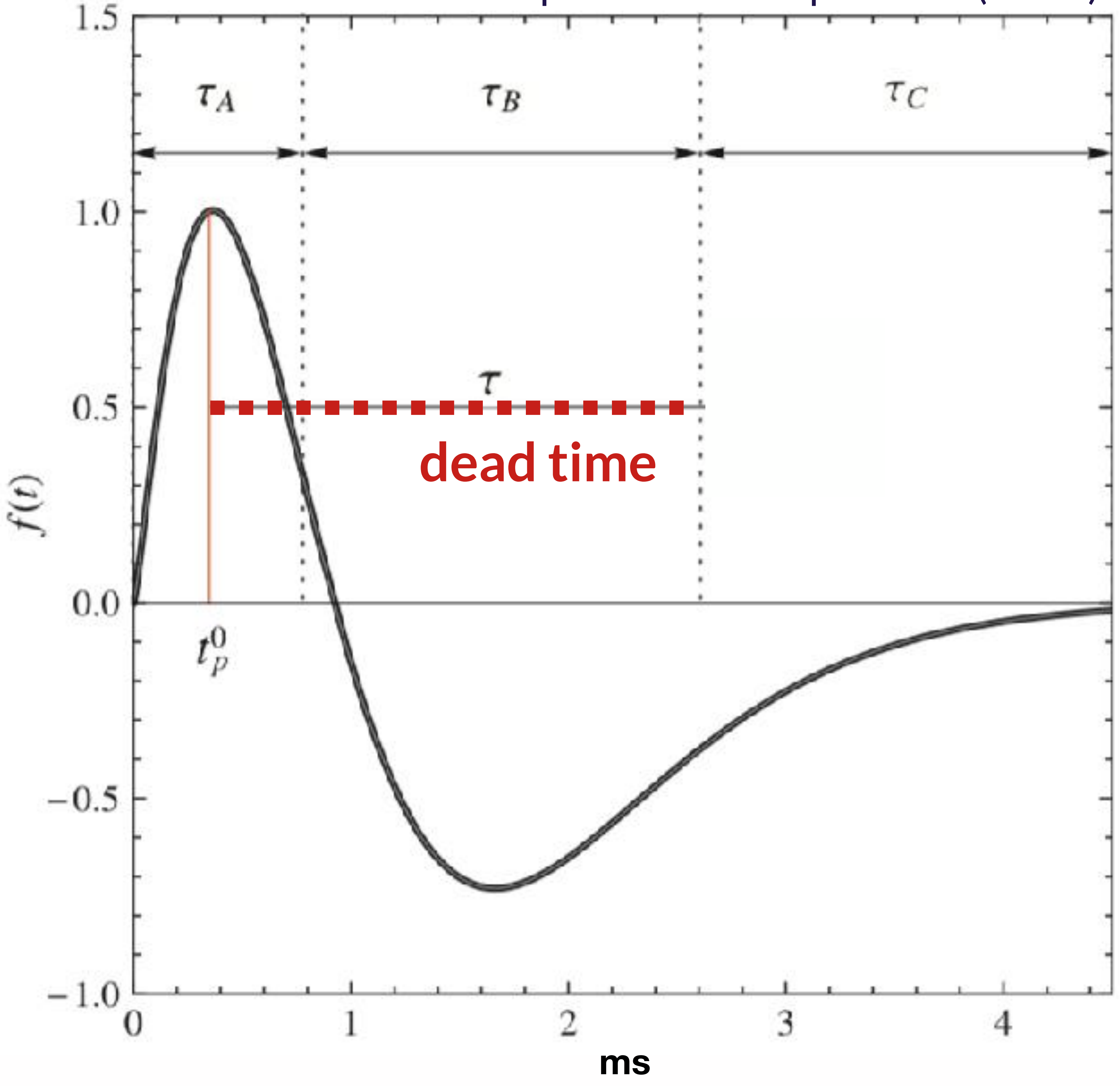


We understand how to do this, unless the sources is very bright

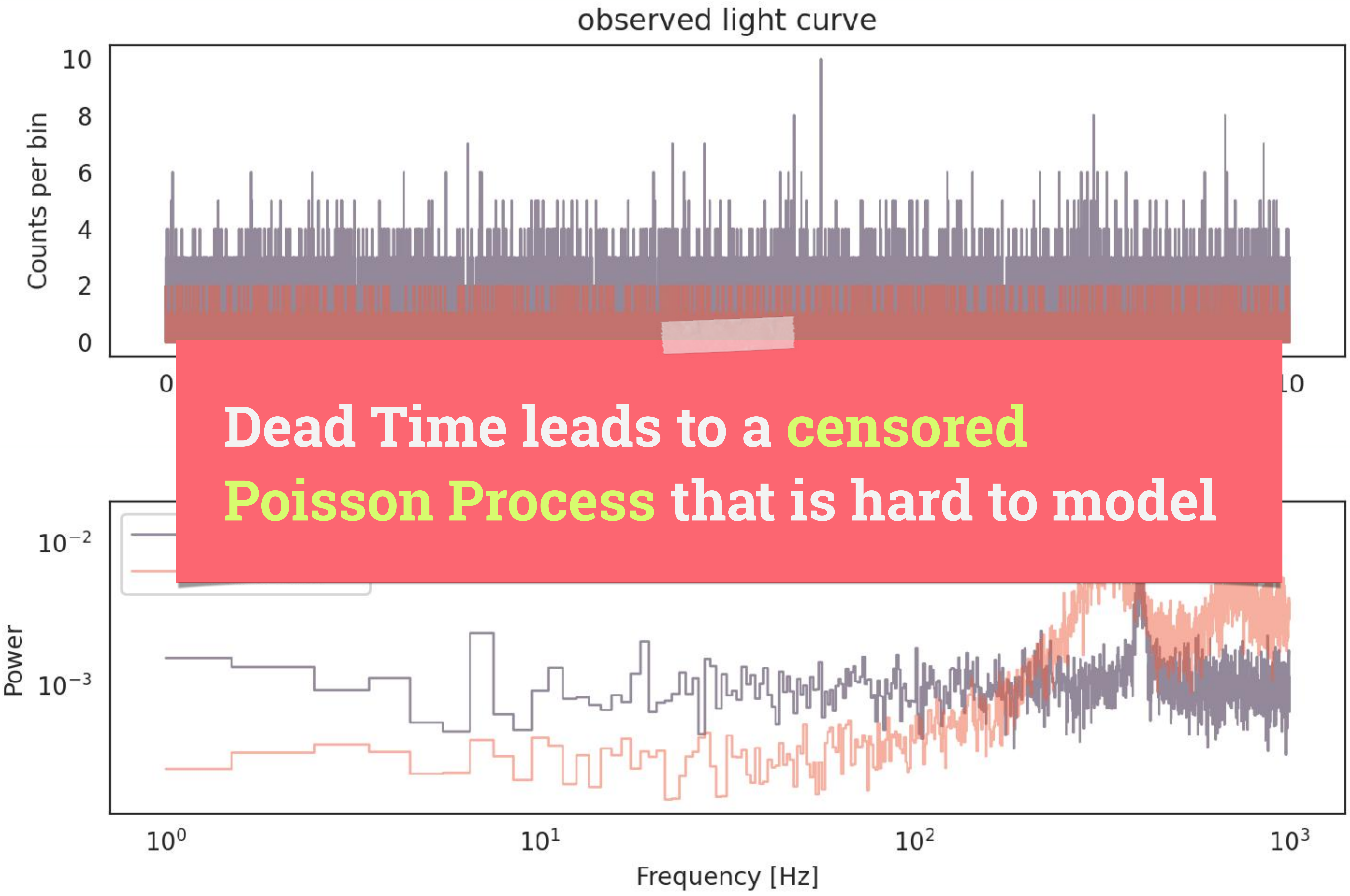
NuSTAR



Adapted from Chaplin et al (2012)



Credit: NuSTAR Observatory Guide



Dead Time leads to a censored Poisson Process that is hard to model

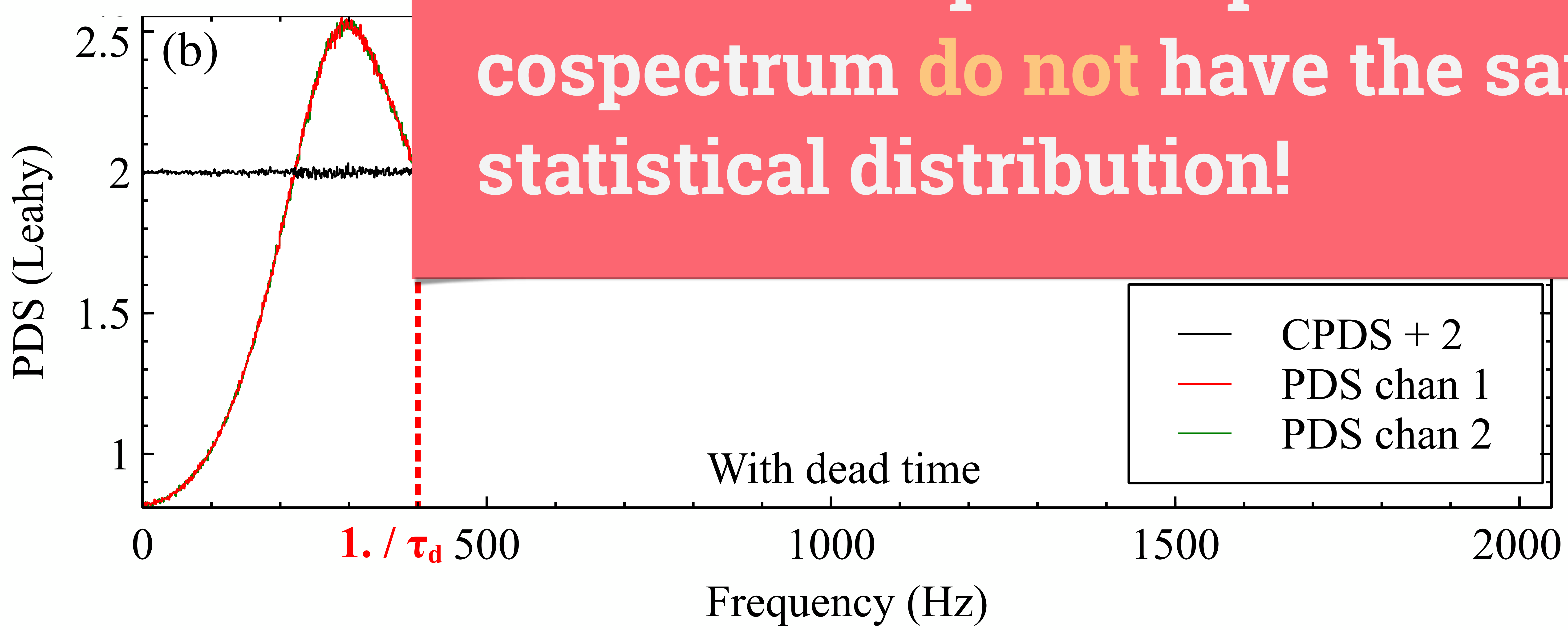
Huppenkothen & Bachetti (submitted)

Problem 1: Searching for periodic signals against a constant background

Dead Time

$$C_{XY} = \mathcal{F}_X^\star \mathcal{F}_Y$$

$$C_{XY,j} = \underbrace{a_{X,j}a_{Y,j}}_{\text{cospectrum}}\underbrace{\exp(i\phi)}_{\text{phase lag}}$$



Caution! The power spectrum and the cospectrum **do not** have the same statistical distribution!

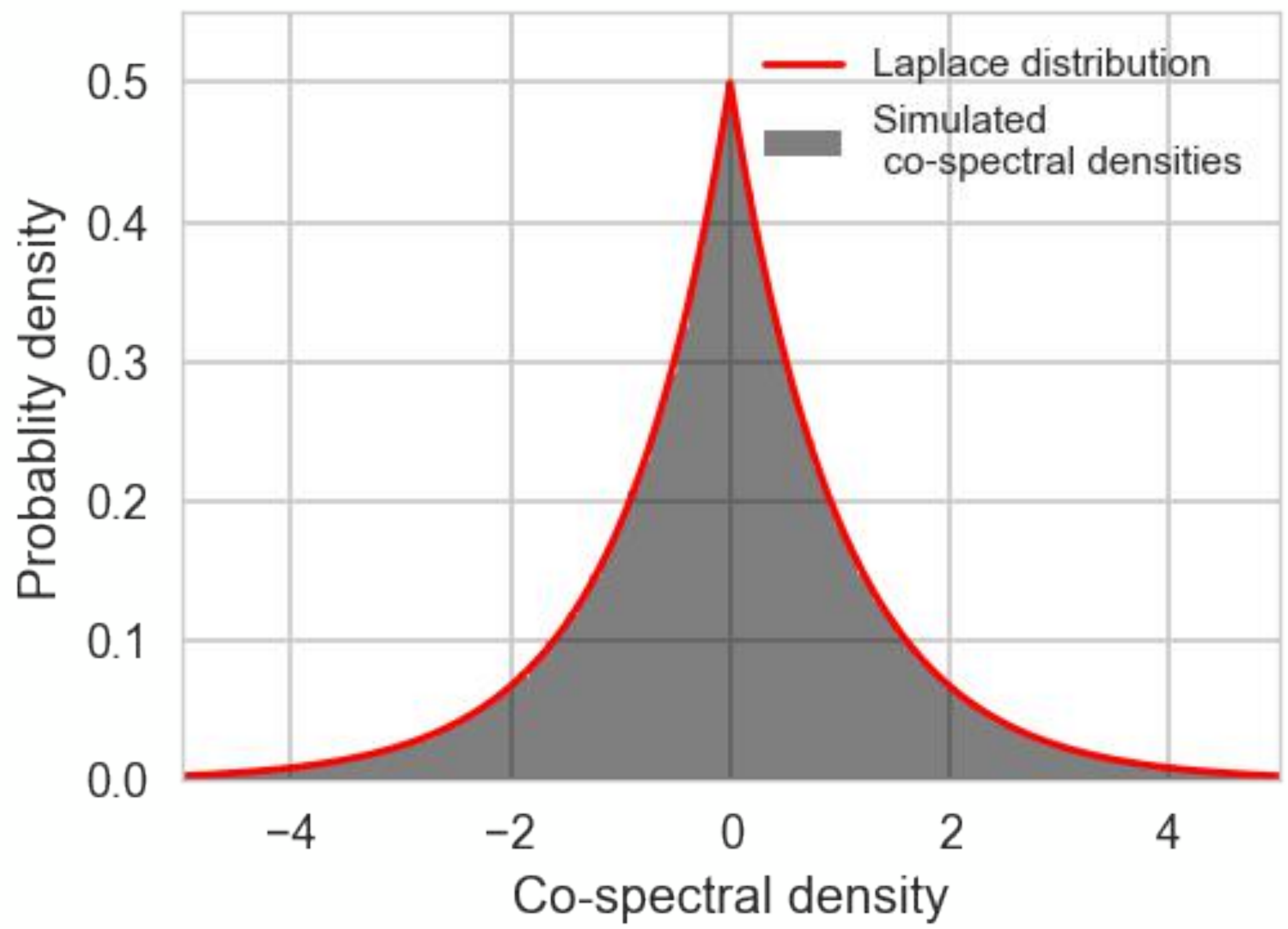
iodogram of a
nstant light
ve, with dead
time

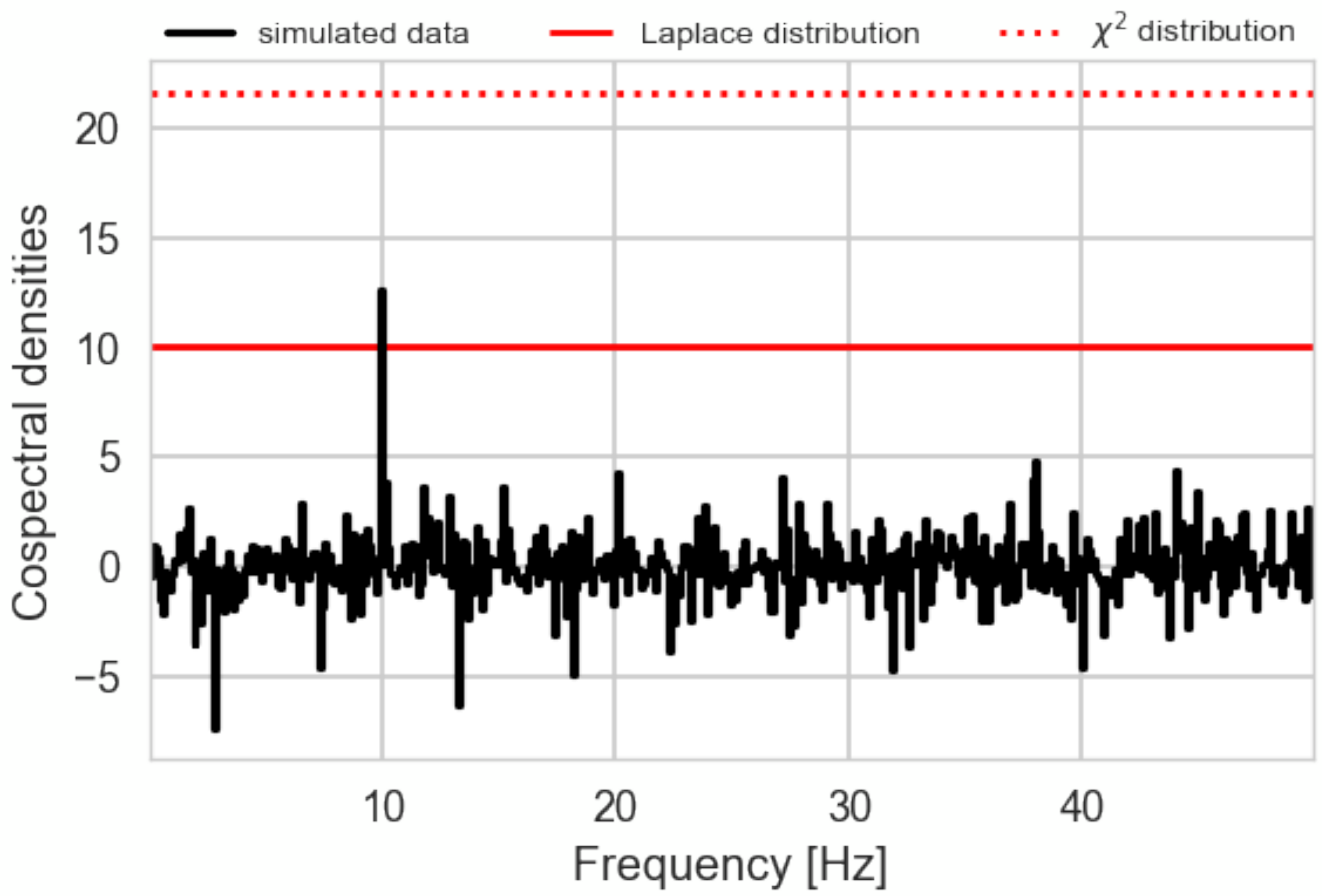
cospectrum of a constant light curve with dead time

Bachetti et al (2015)

Dead Time

Huppenkothen & Bachetti (2018)



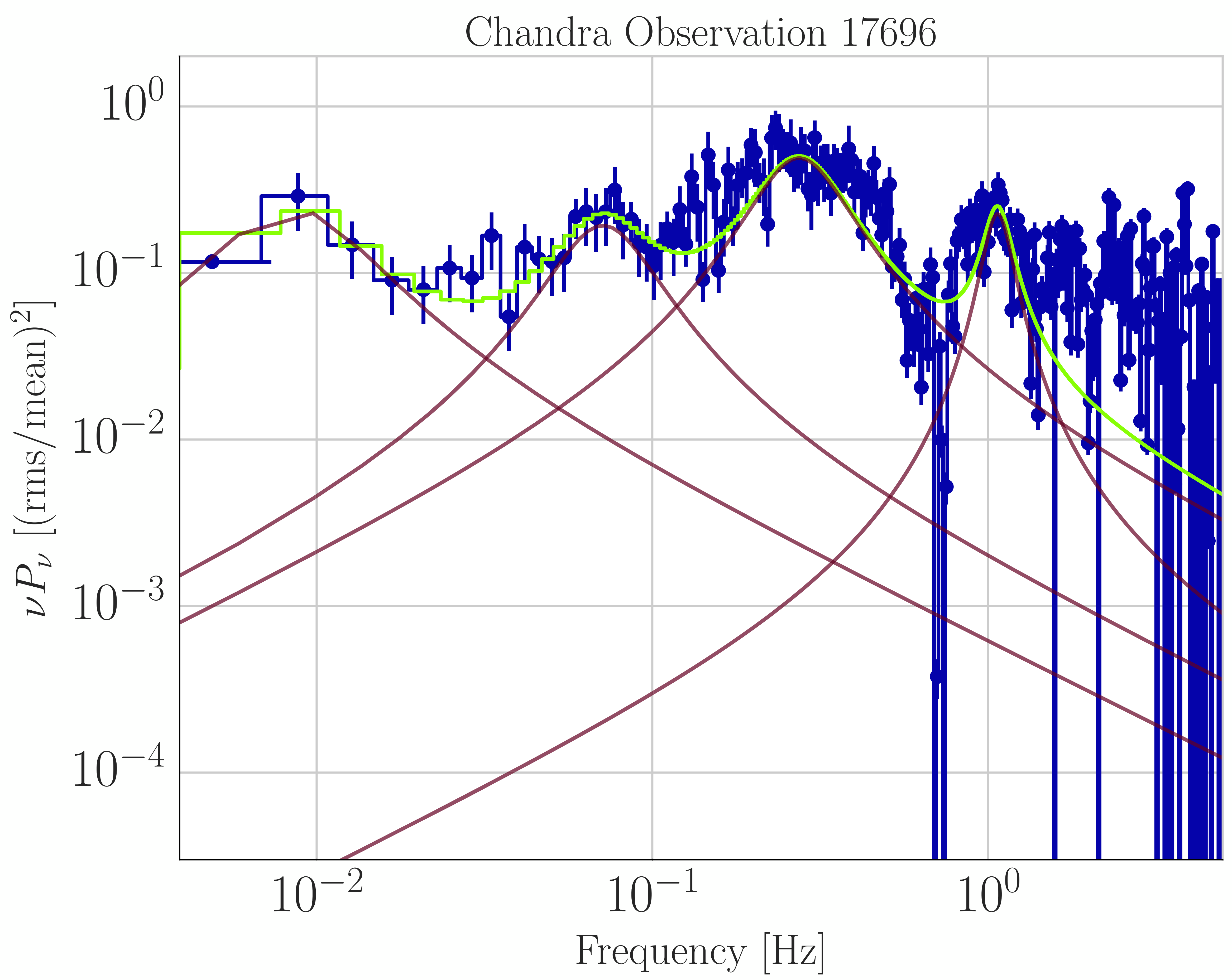


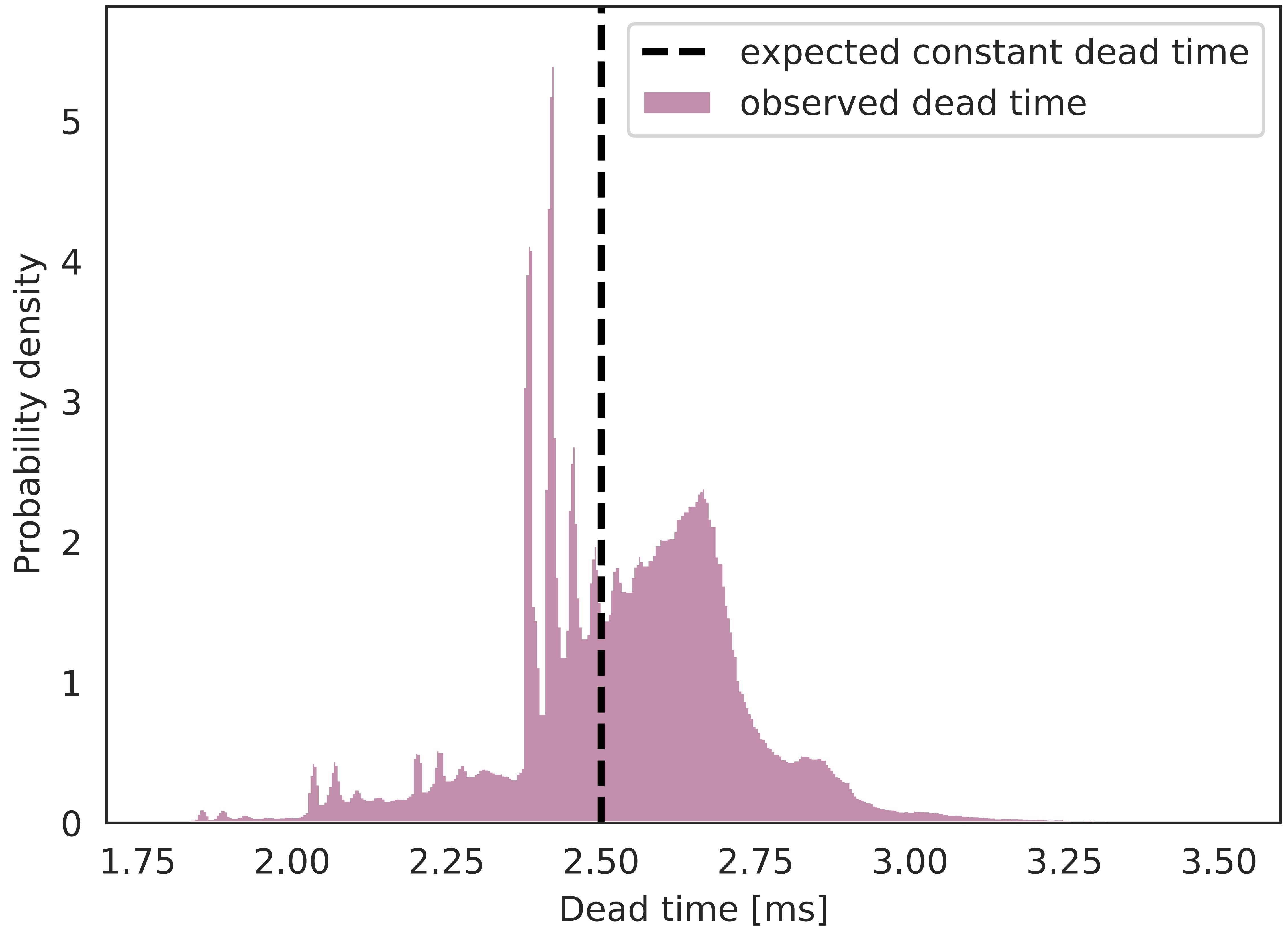
$$p(C_j|0,\sigma_x\sigma_y) = \frac{1}{\sigma_x\sigma_y}\exp\left(-\frac{|C_j|}{\sigma_x\sigma_y}\right)$$

The co-spectral powers are well-described by a Laplace distribution

Problem 2: Modelling Stochastic Variability in Periodograms

X-ray Sources Are Variable

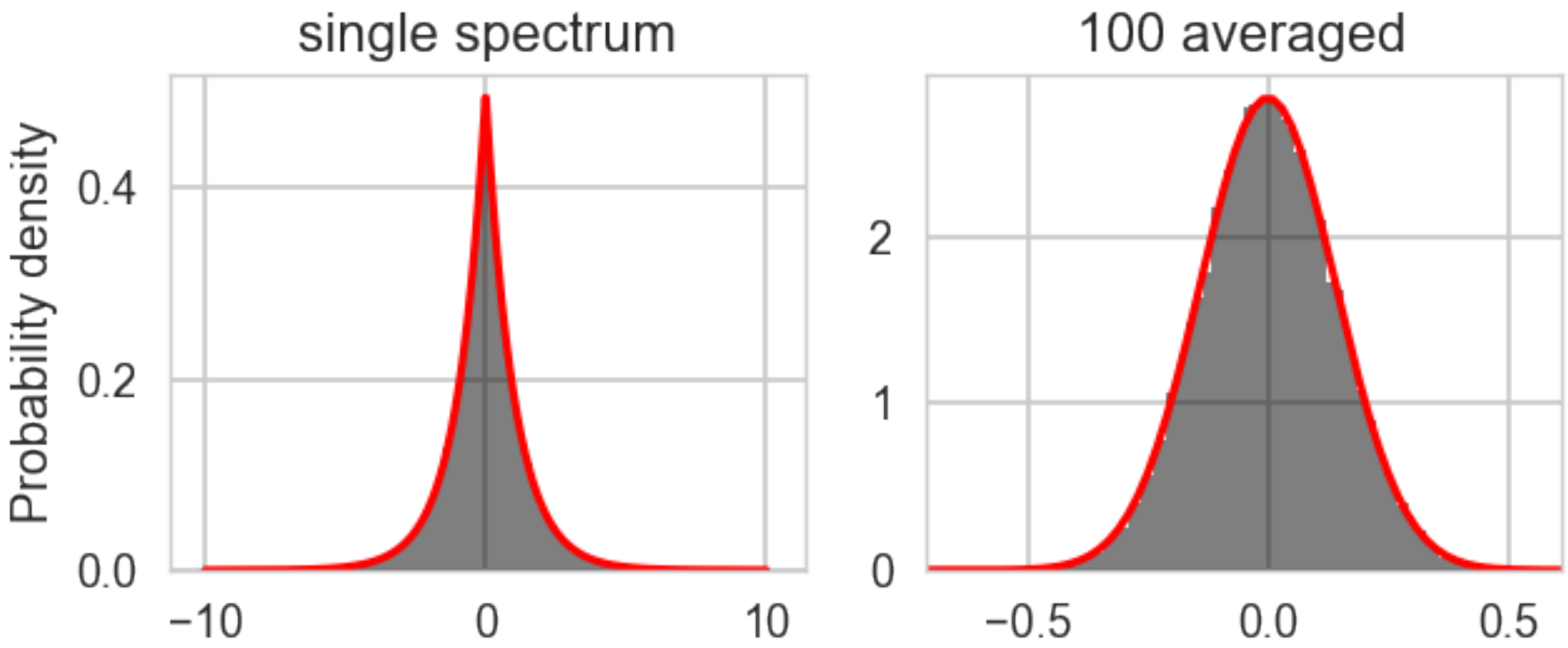




... and so is dead time

Huppenkothen et al (2017)

Option 1: Average >40 periodograms together + assume Gaussian statistics



Huppenkothen & Bachetti (2019)

What if I can’t add together periodograms?

simulator

~~likelihood~~

prior

posterior

$$P(\theta \mid x) = \frac{\cancel{P(x \mid \theta)}\,P(\theta)}{P(x)}$$

marginal likelihood

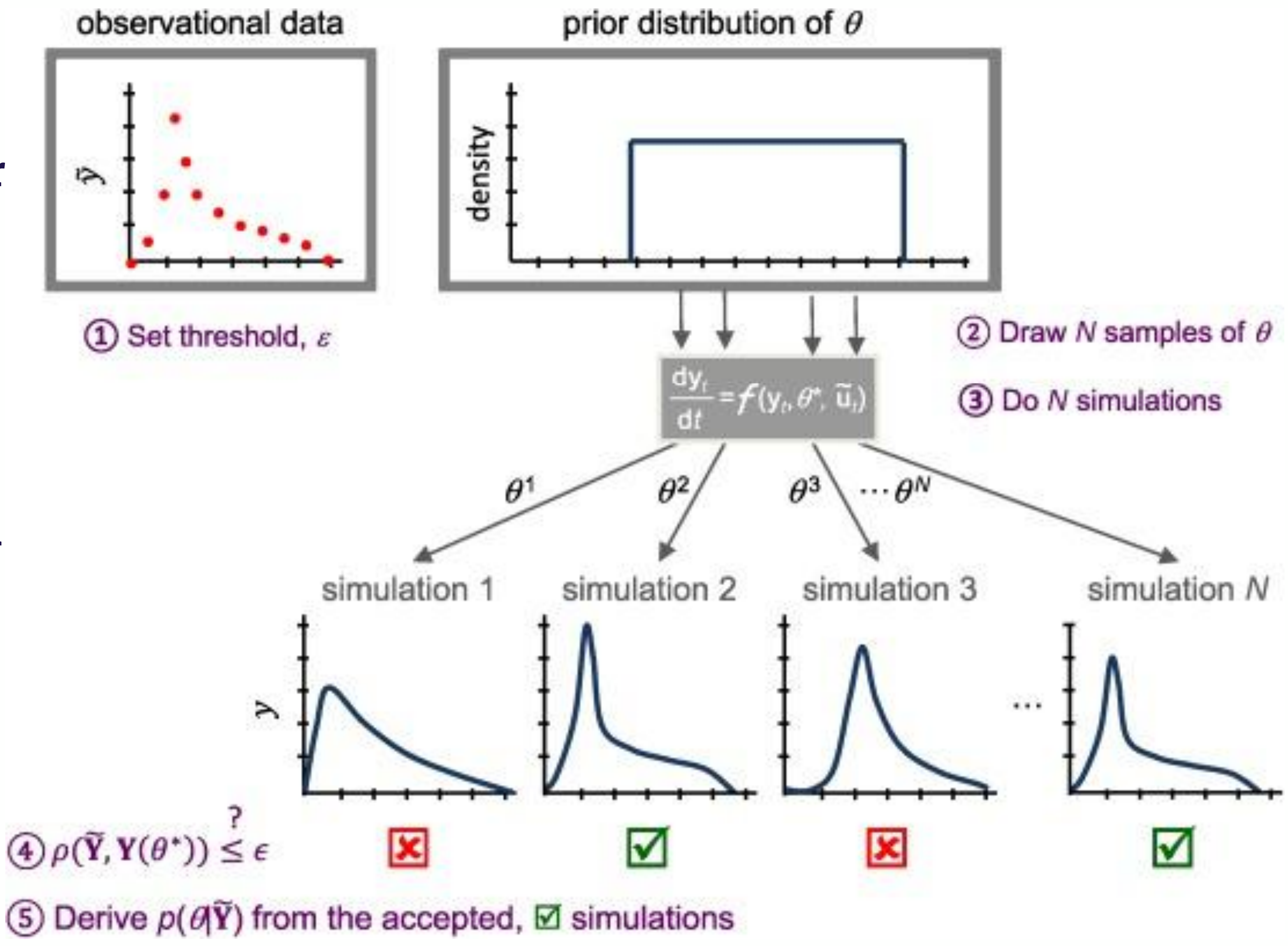
Approximate Bayesian Computation
Likelihood-Free Inference
Simulation-Based Inference

Step 1: draw parameters from prior

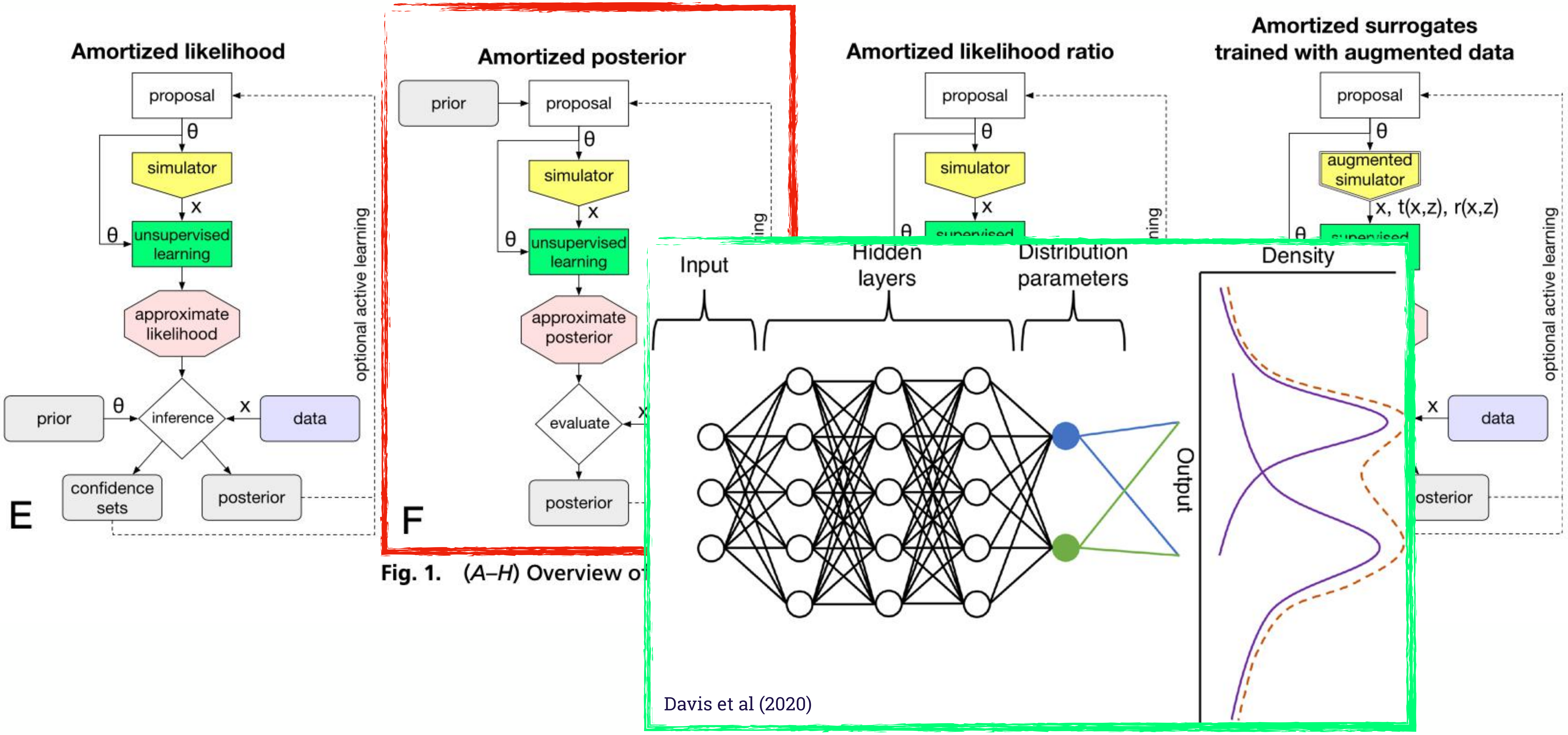
Step 2: simulate data sets

Step 3: **compare** simulated to observed data

Step 4: keep parameters that produce simulations **similar** to the data

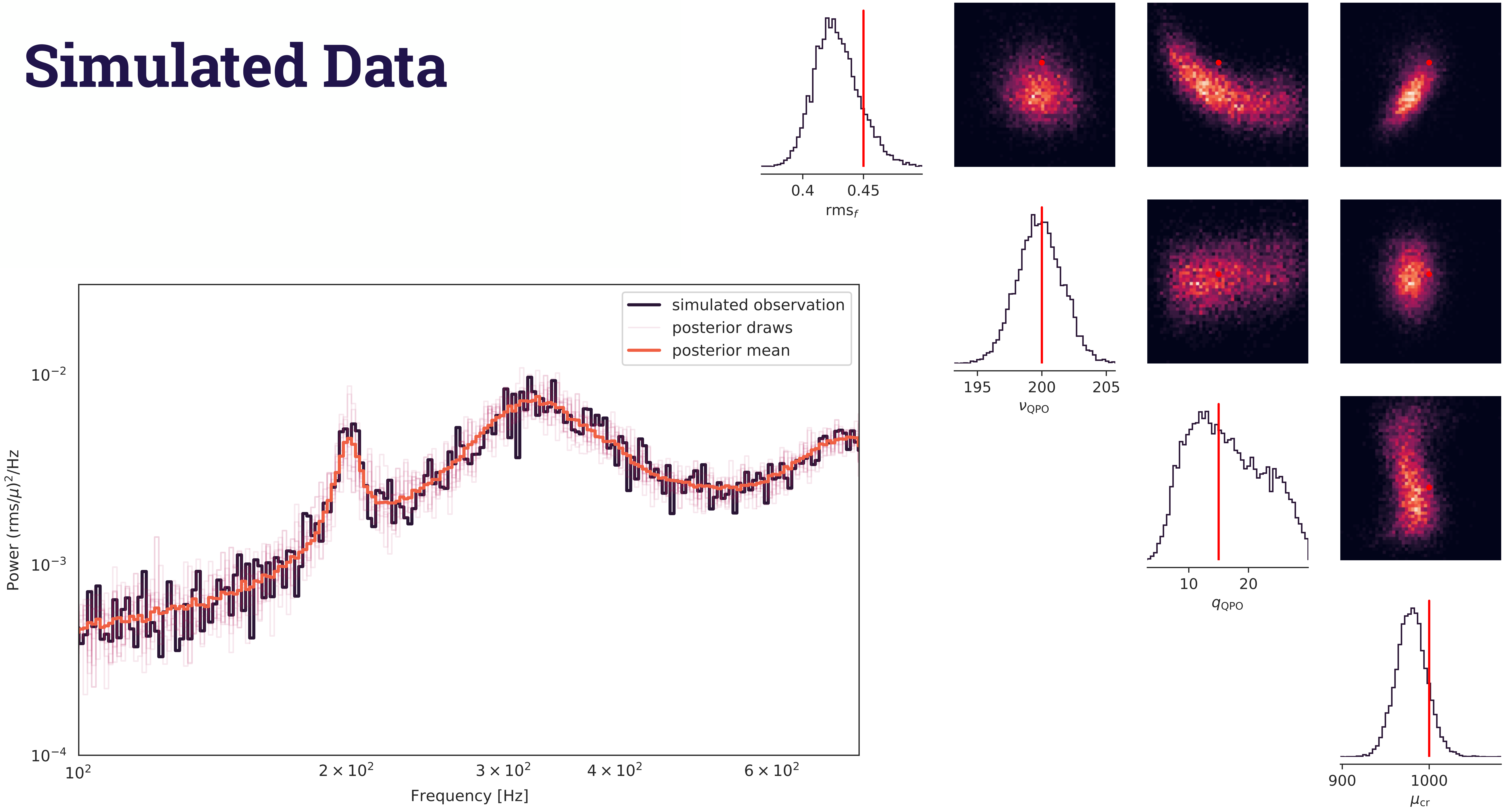


Sadegh + Vrugt, 2014, see also: Brehmer et al (2018a, 2018b), Cranmer et al (2020)



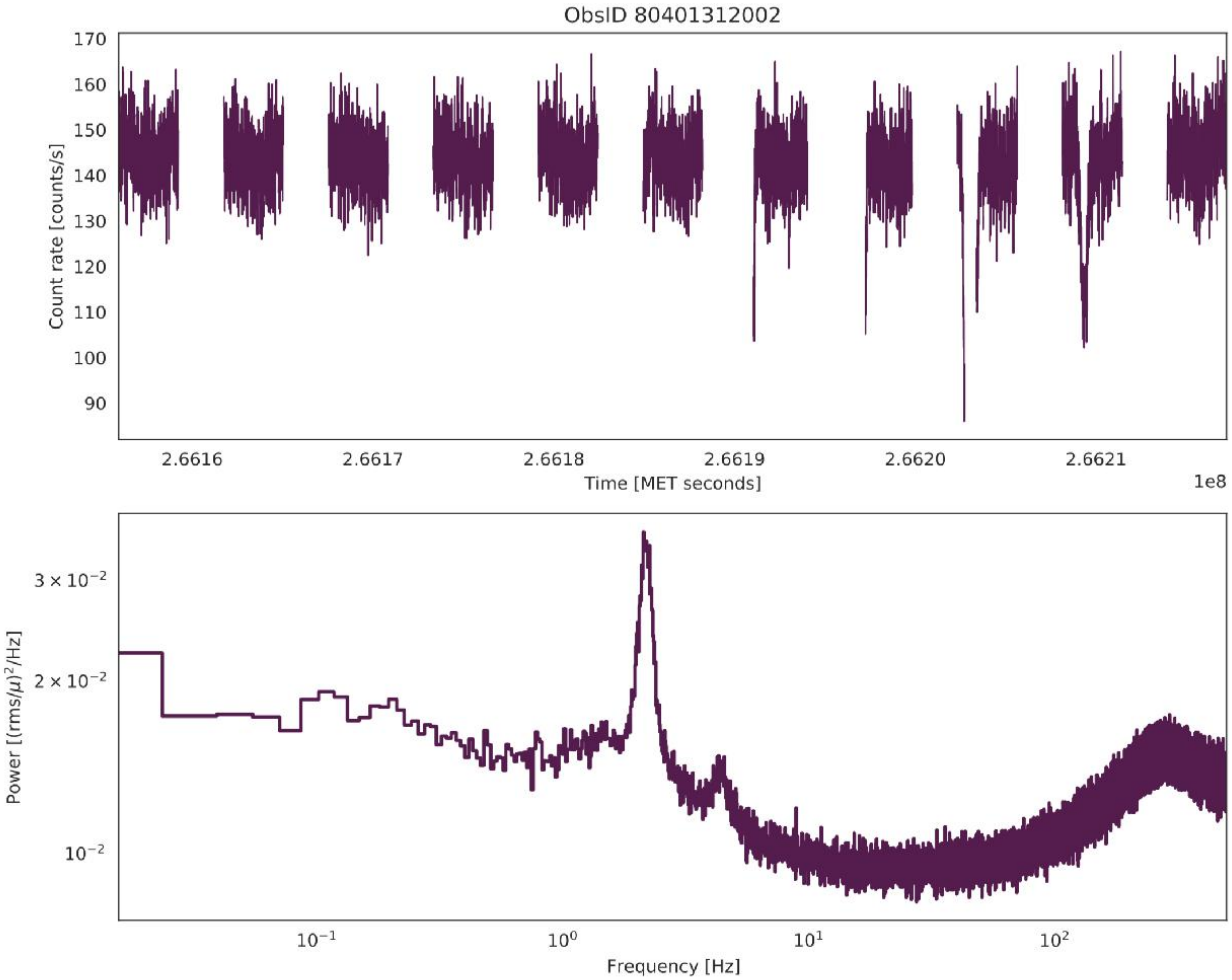
Cranmer et al (2020)

Simulated Data

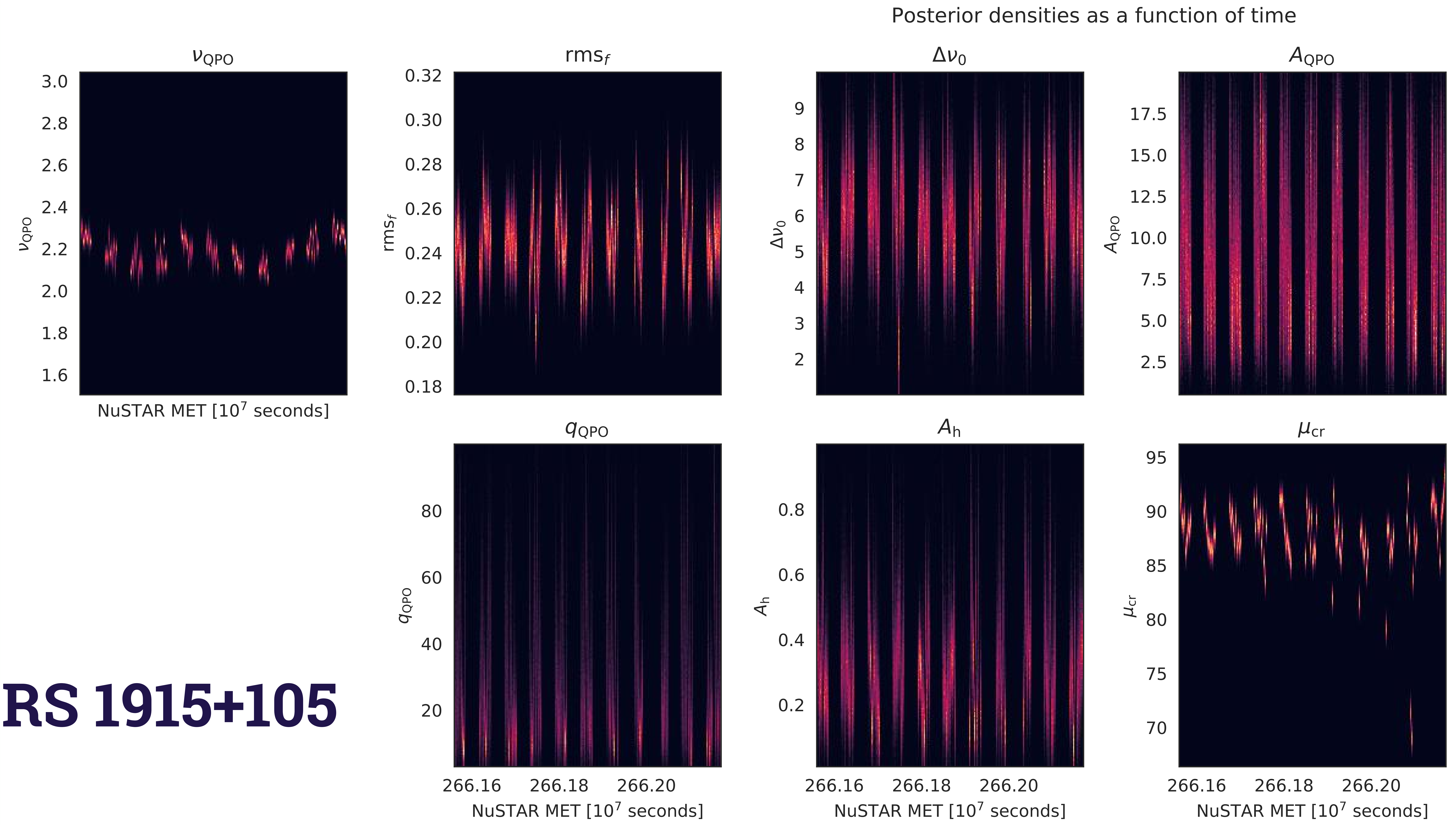


Huppenkothen & Bachetti (submitted)

GRS 1915+105



Huppenkothen & Bachetti (submitted)

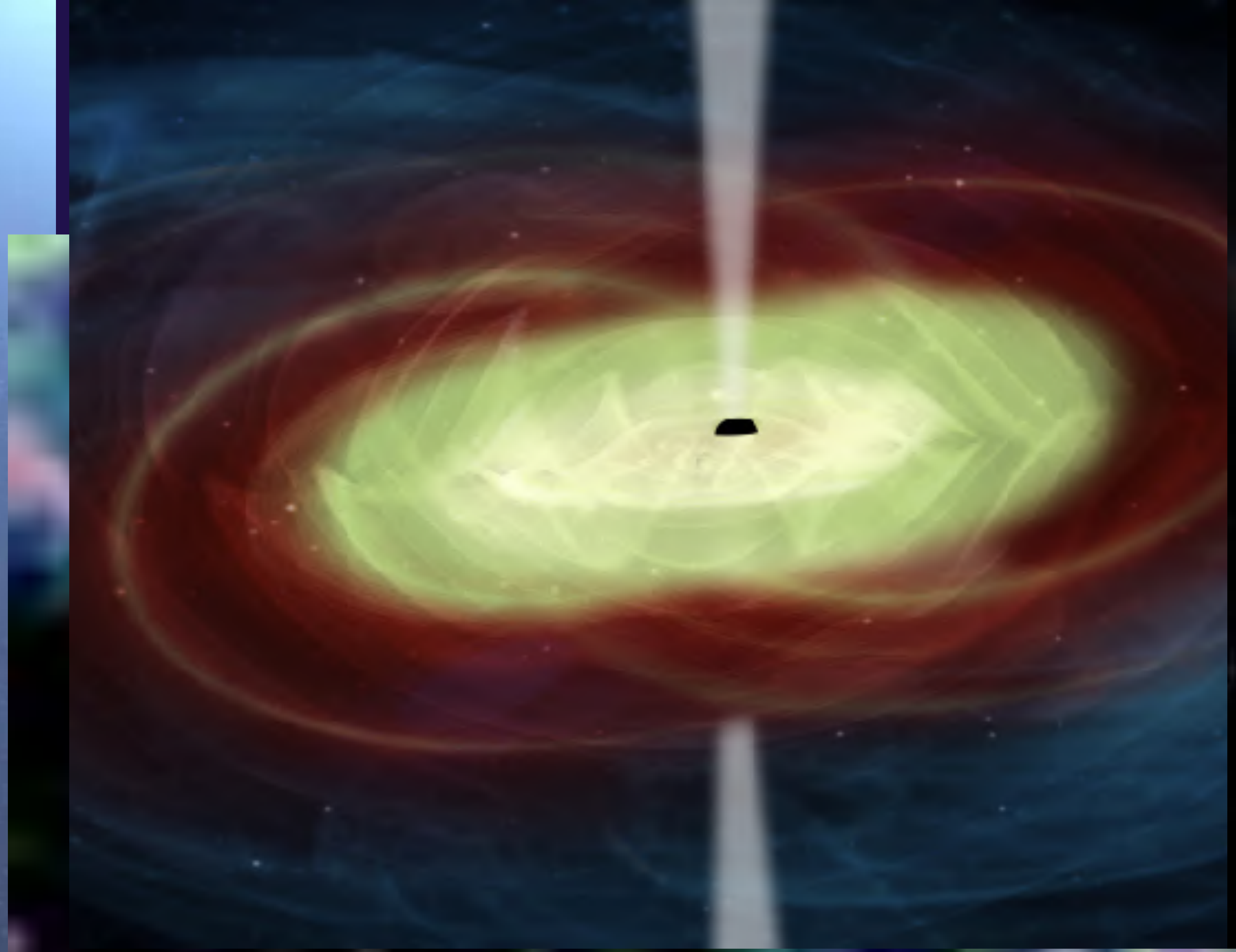


GRS 1915+105

Huppenkothen & Bachetti (submitted)

Future Work

- Hierarchical (simulation-based) inference!
- Uneven sampling
- A more comprehensive description of the raw (time, energy) data
- Additional data dimensions (e.g. polarimetry)


THE ATHENA
MISSION




eXTP
enhanced X-ray Timing and Polarimetry Mission

Conclusions

- Accreting black holes produce complex X-ray emission that carry a wealth of information about the physics of the system
- Unravelling the physics of black holes requires understanding the subtle relationships between temporal and spectral properties
- Statistical challenges arise in uneven sampling, gaps and the response of the detector to bright sources
- In the future, we need better statistical methods and software integration to tackle many of these challenges

Thank you!