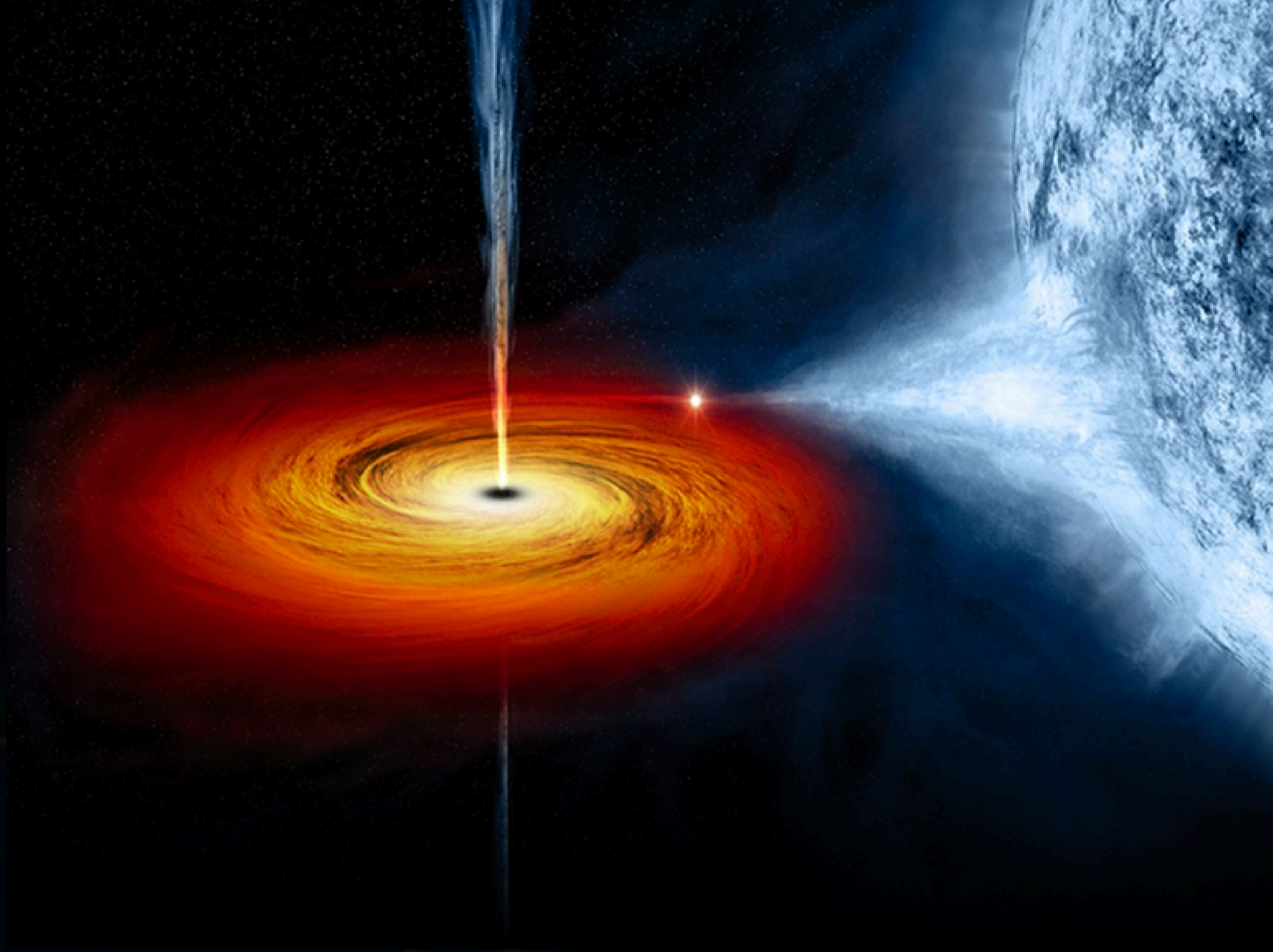
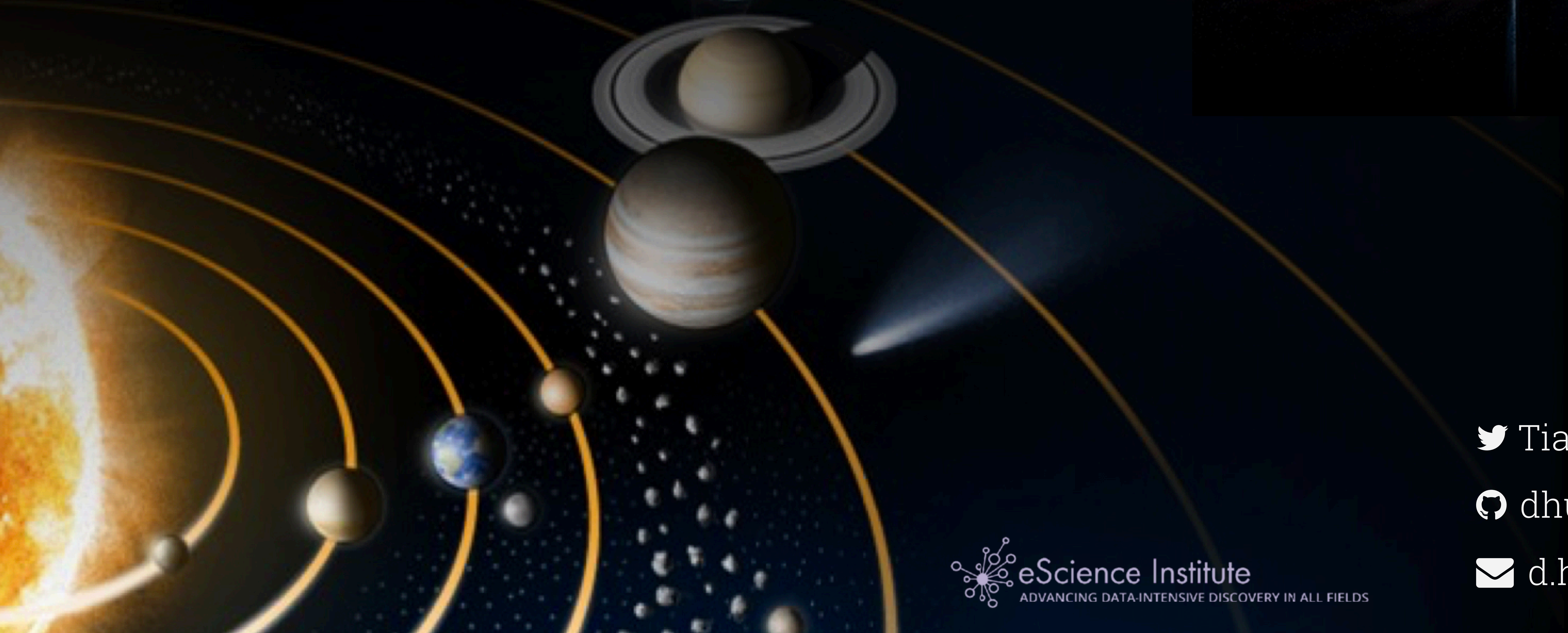
Period Detection with Stingray

Daniela Huppenkothen

SRON Netherlands Institute for Space Research
eScience Institute, University of Washington





eScience Institute
ADVANCING DATA-INTENSIVE DISCOVERY IN ALL FIELDS

Tiana_Athriel

dhuppenkothen

d.huppenkothen@sron.nl

These materials:

https://github.com/tloredo/AAS237-TimeSeries

Documentation:

https://stingray.readthedocs.io/en/latest/index.html

Tutorials:

https://github.com/stingraysoftware/notebooks

Iconic 60s Theme Song:

https://youtu.be/sgkk-MMif-4?t=50

Terminology:

“energy” = photon energy (i.e. photon wavelength)

“frequency” = Fourier (temporal) frequency

Terminology*:

“periodogram” = an observed random realization of a stochastic process

“power spectrum” = the underlying physical process that generated the observation

*except in Stingray

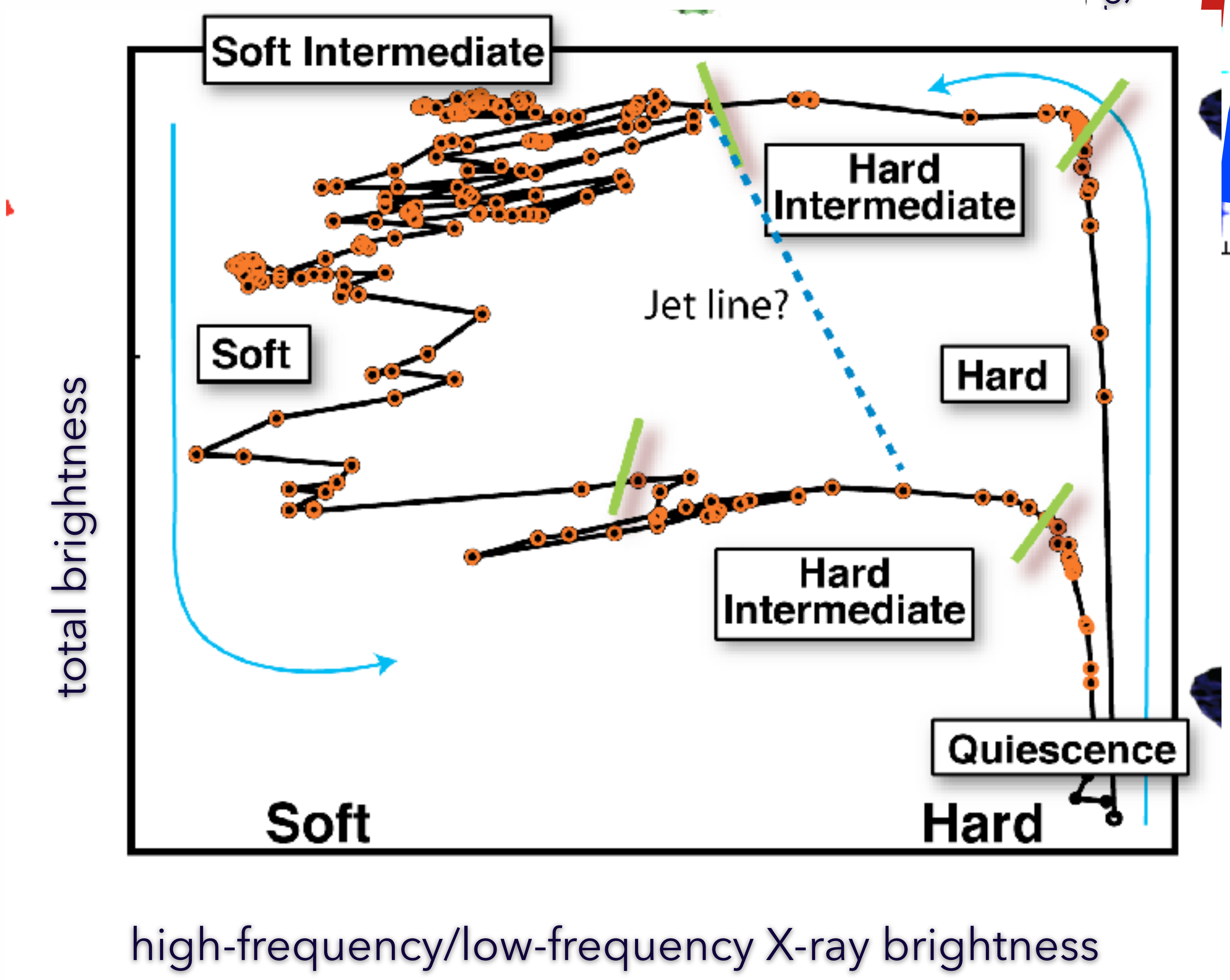
Some Scientific Examples

How do black holes accrete matter?

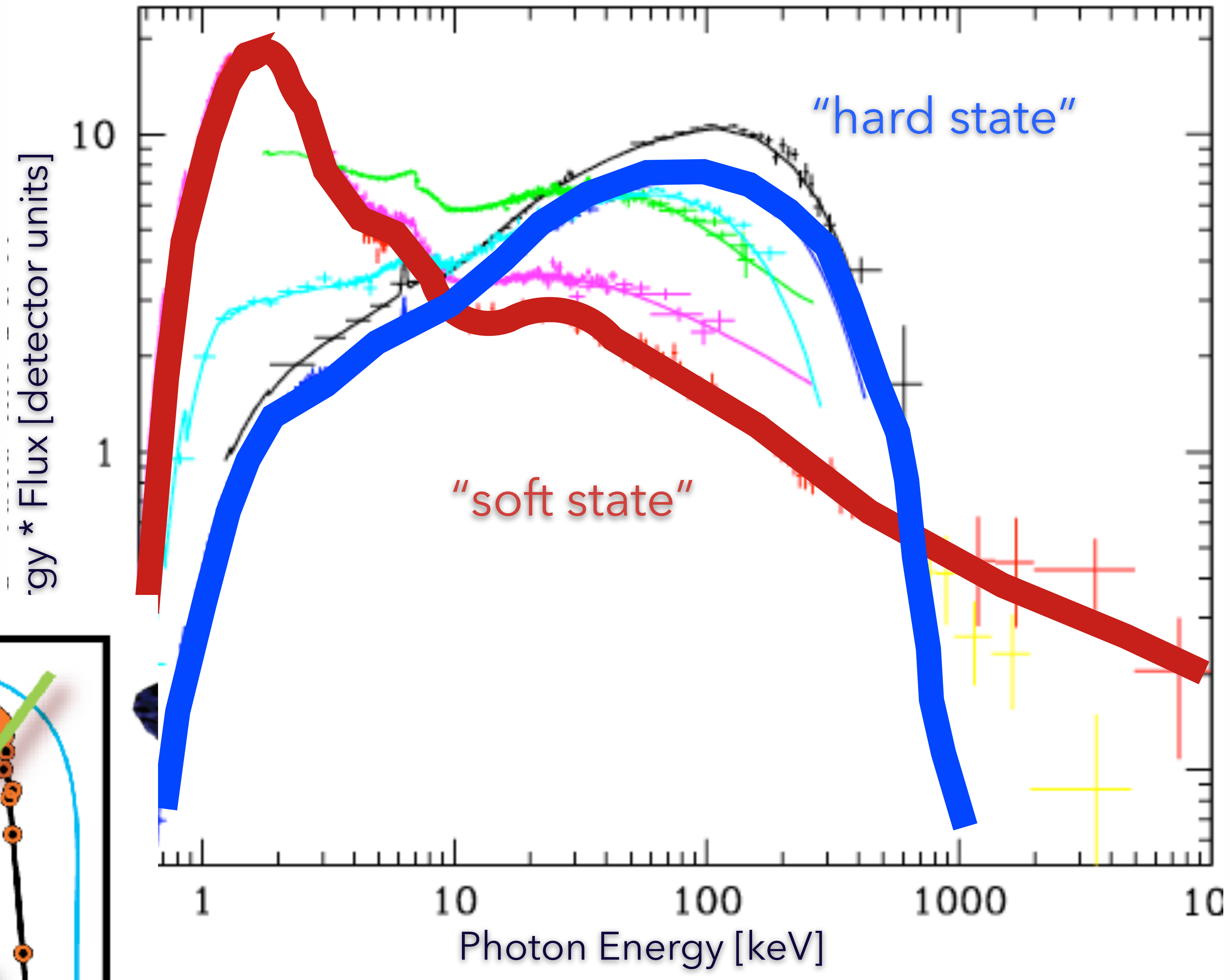

jet physics +
particle acceleration
stellar winds
General
Relativity
plasma physics +
magnetic fields

Spectral States

Credit: Sera Markoff

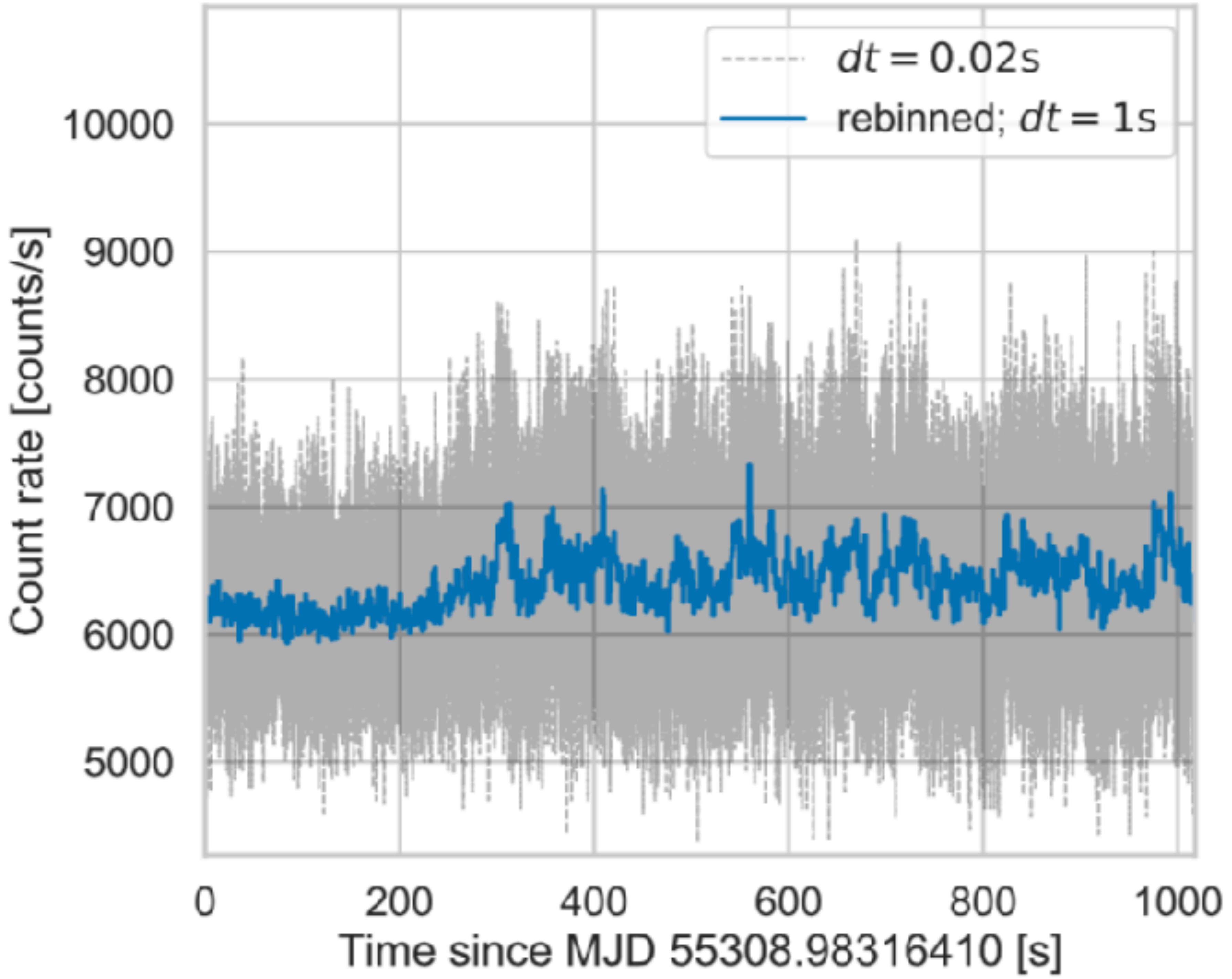


Malzac 2008



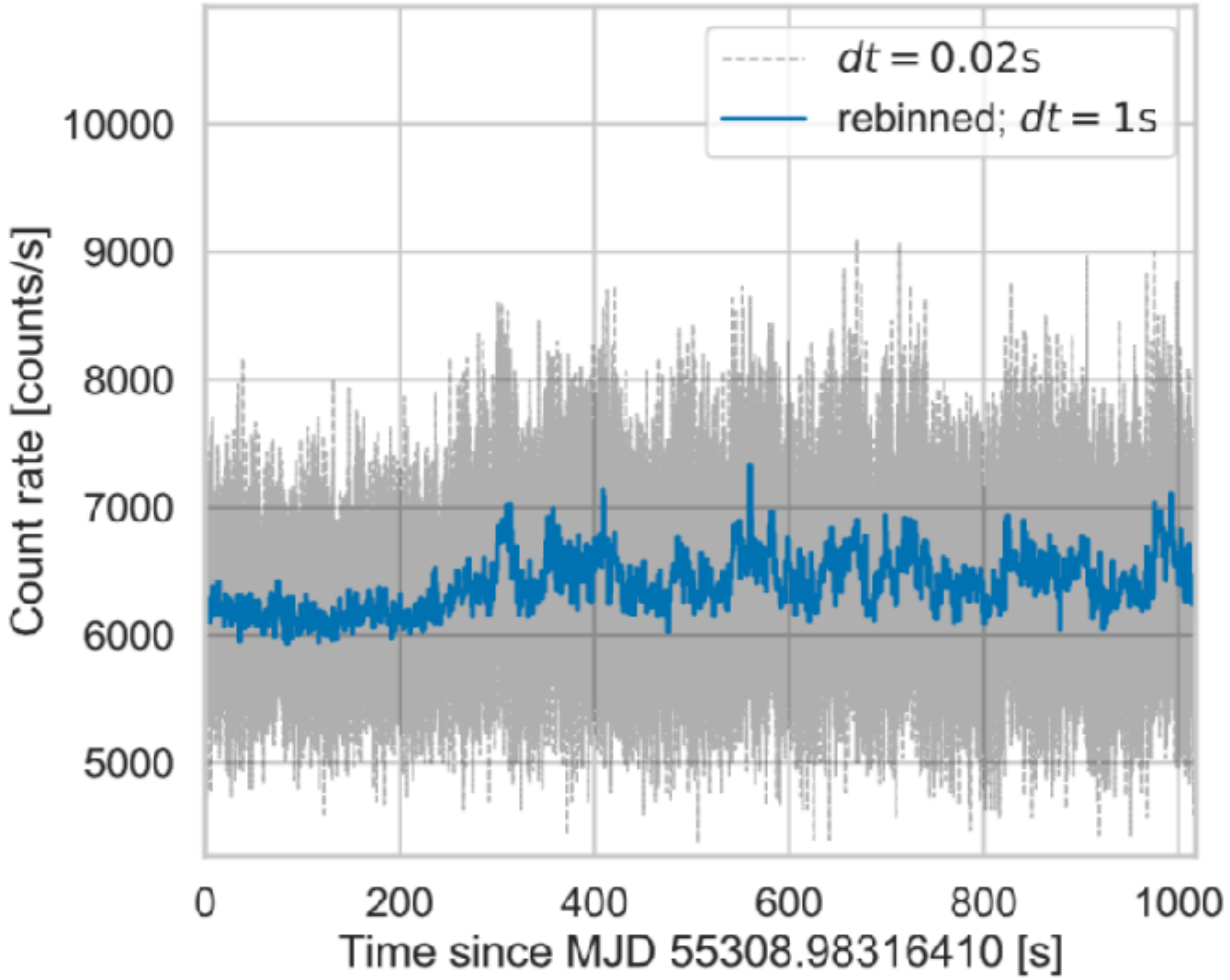
Variability: GX 339-4

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



Variability: GX 339-4

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

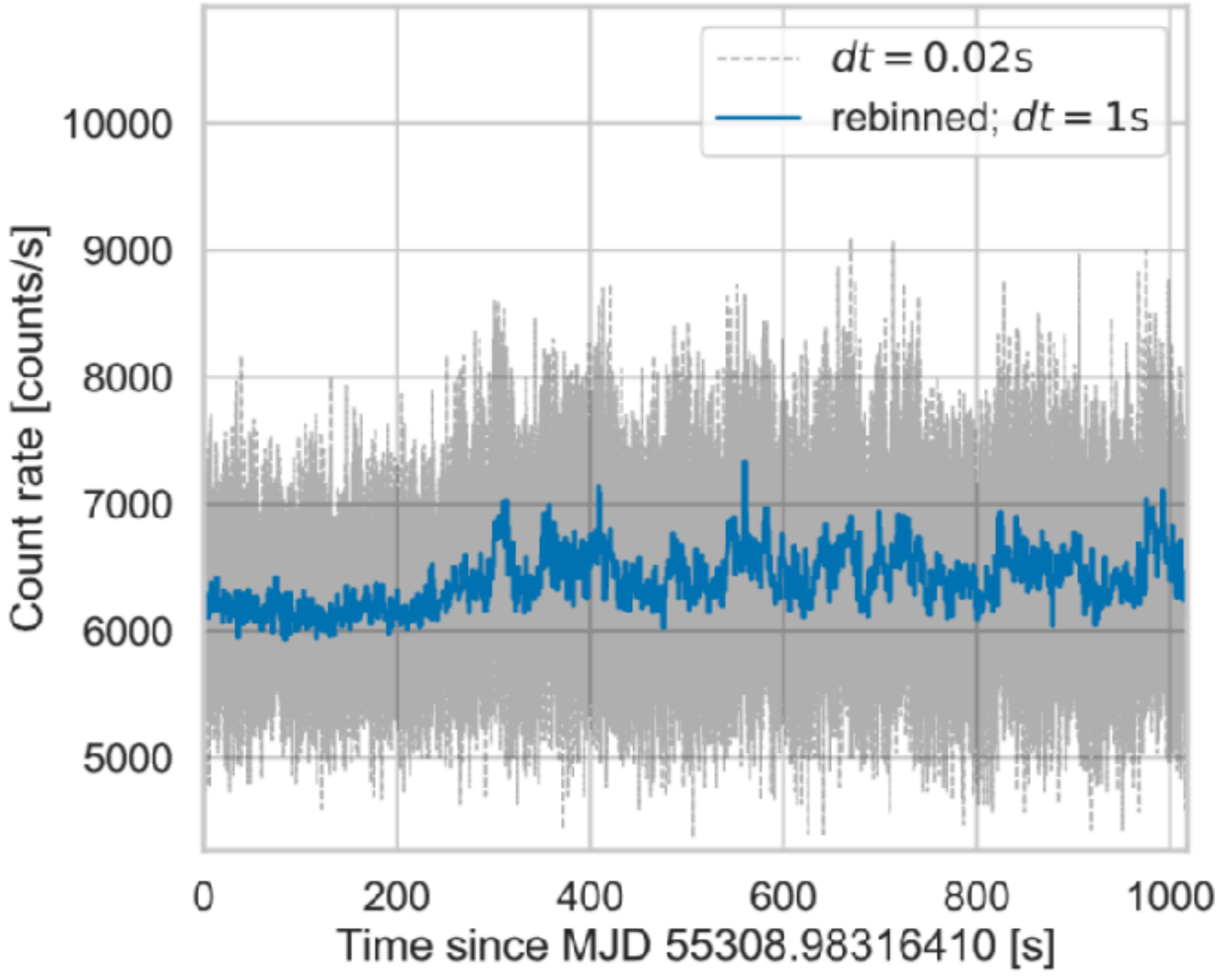


Fast Fourier

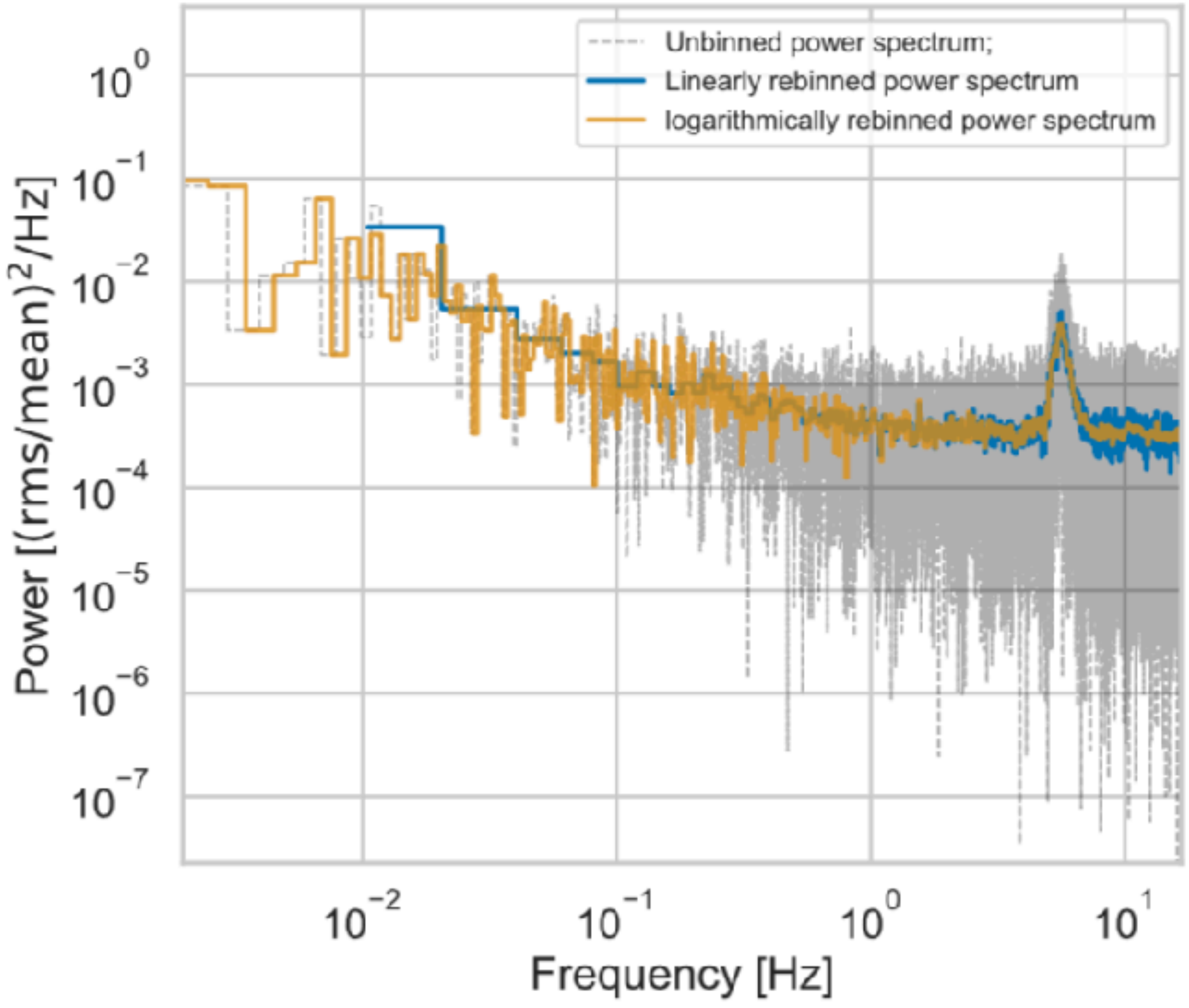
Transform

Variability: GX 339-4

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

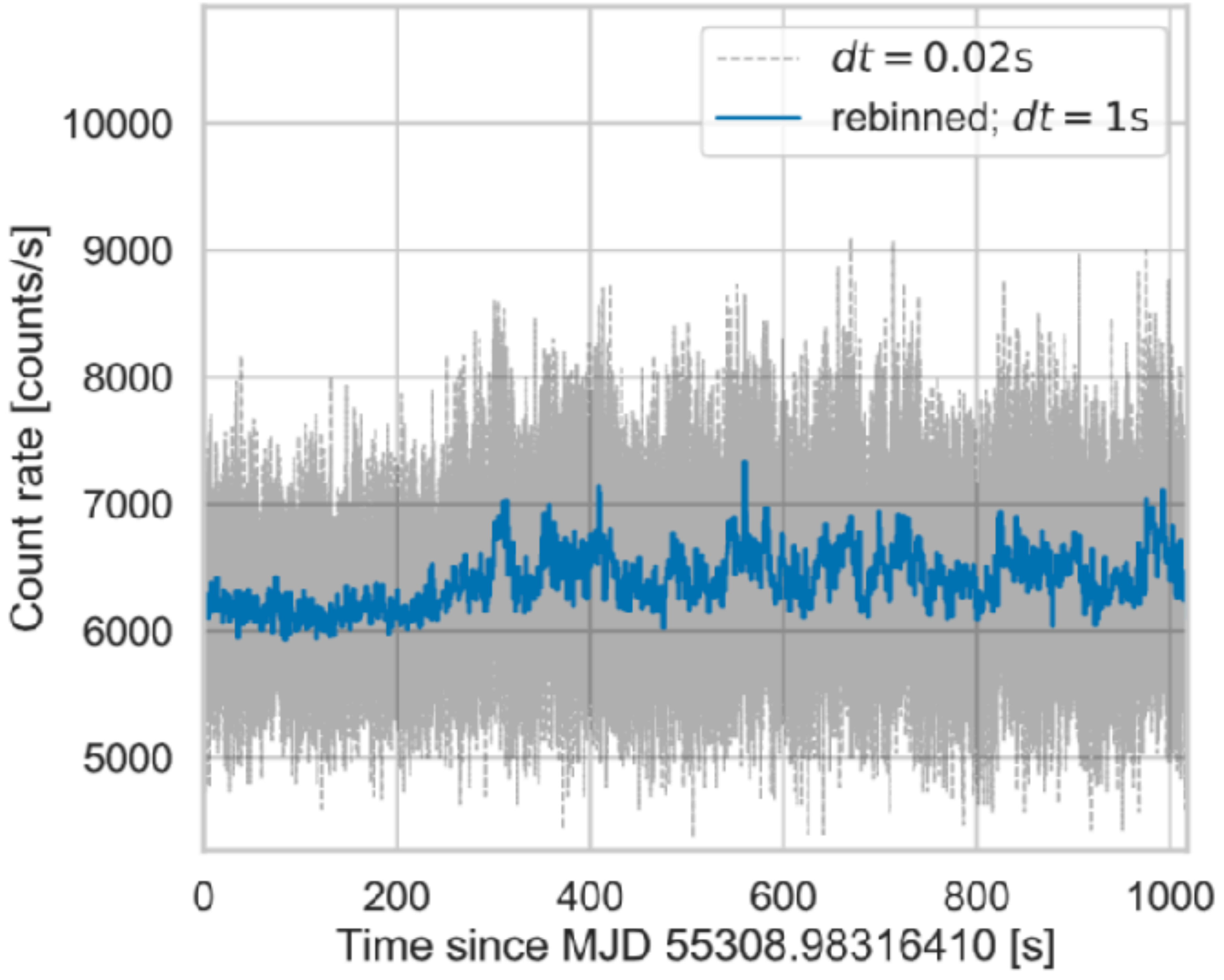


Fast Fourier Transform

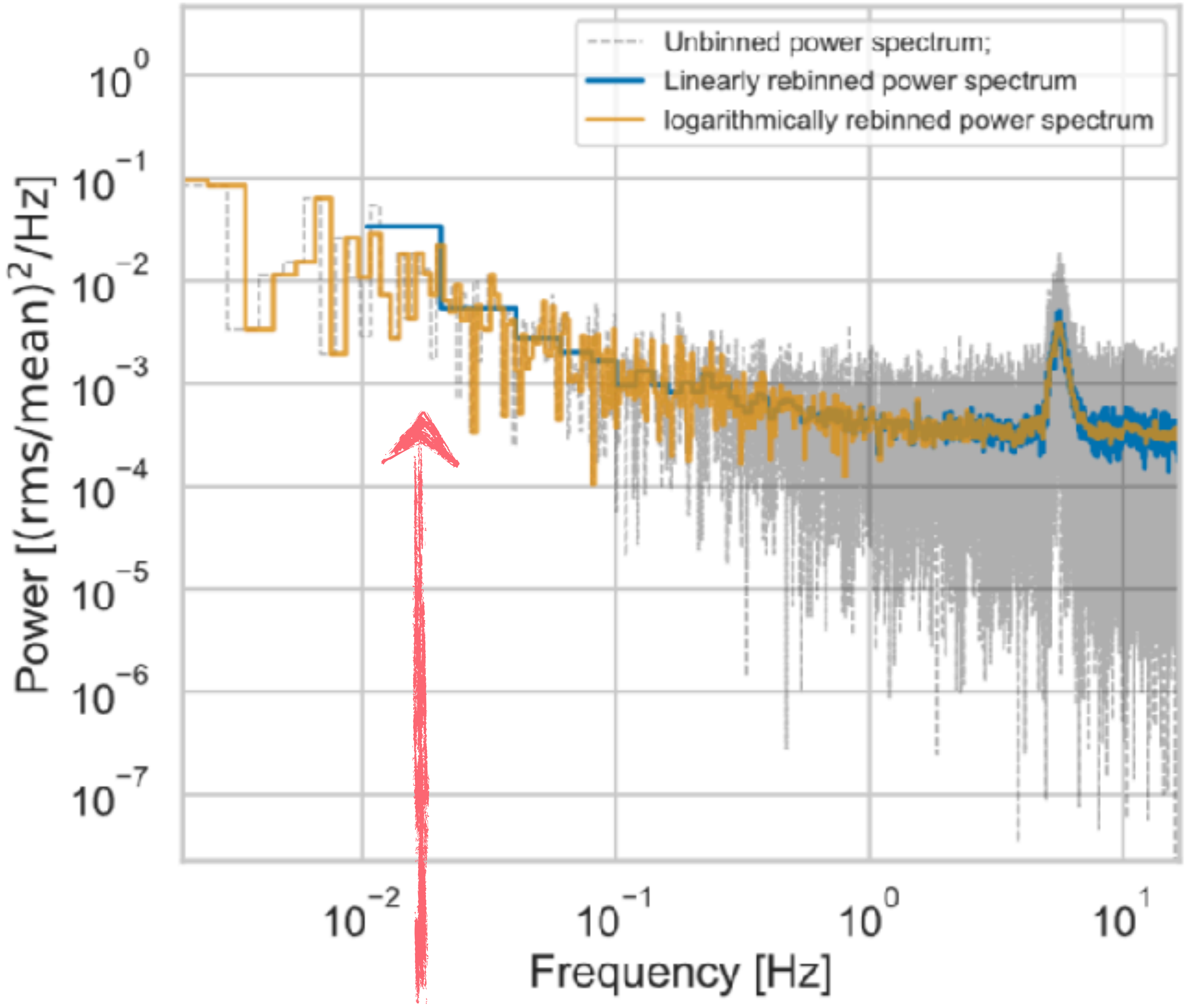


Variability: GX 339-4

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



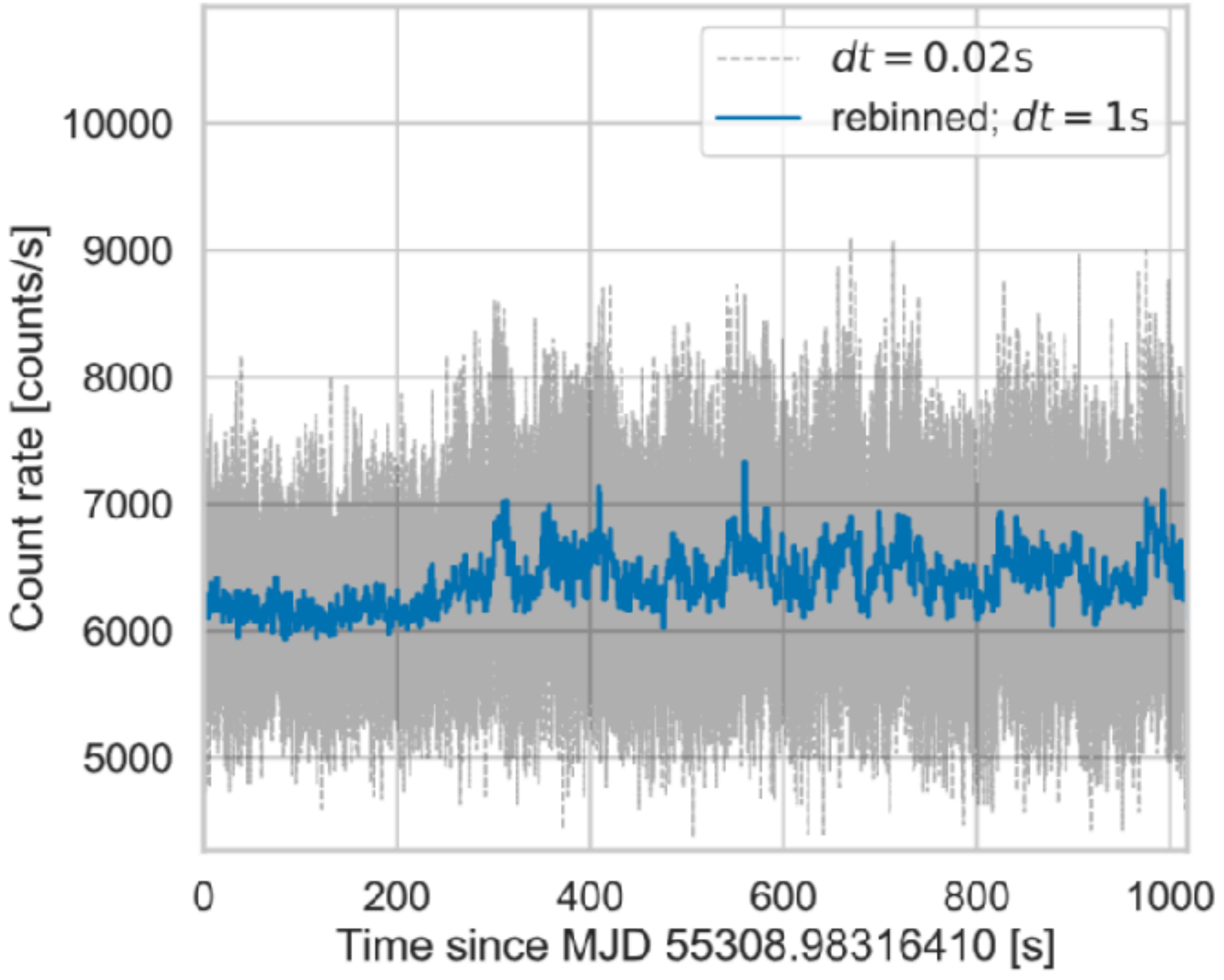
Fast Fourier Transform



stochastic variability (red noise)

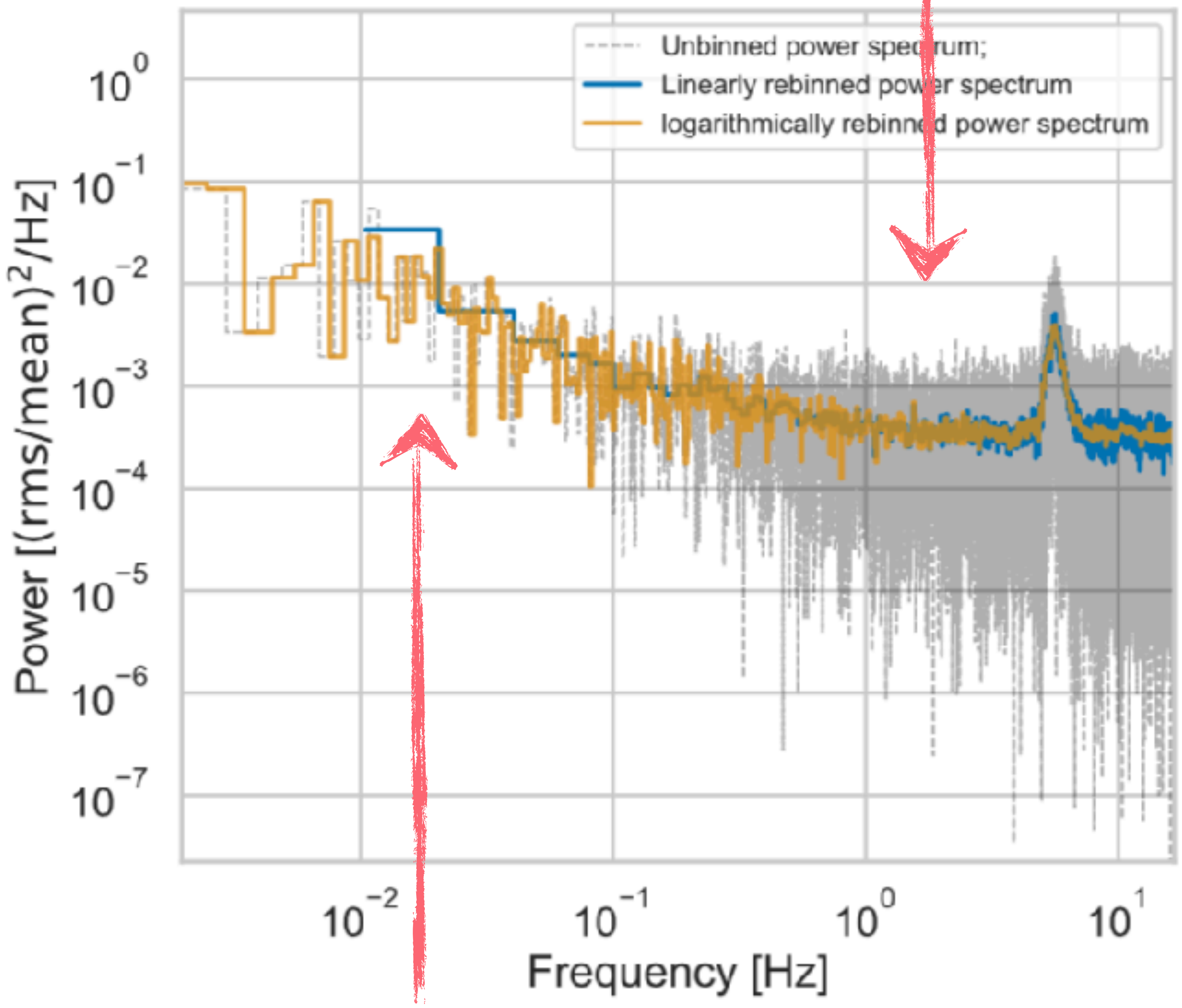
Variability: GX 339-4

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



Fast Fourier Transform

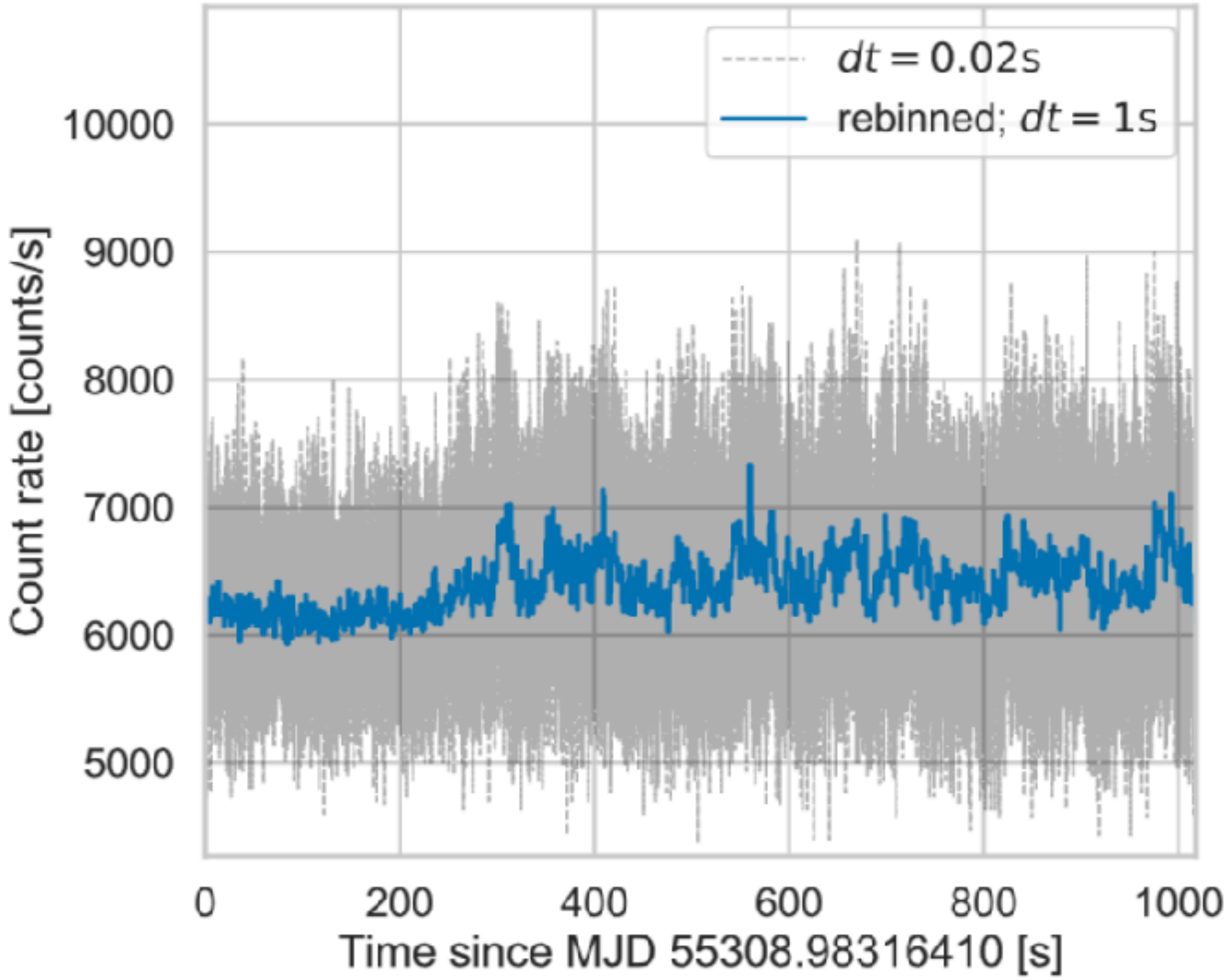
white noise



stochastic variability (red noise)

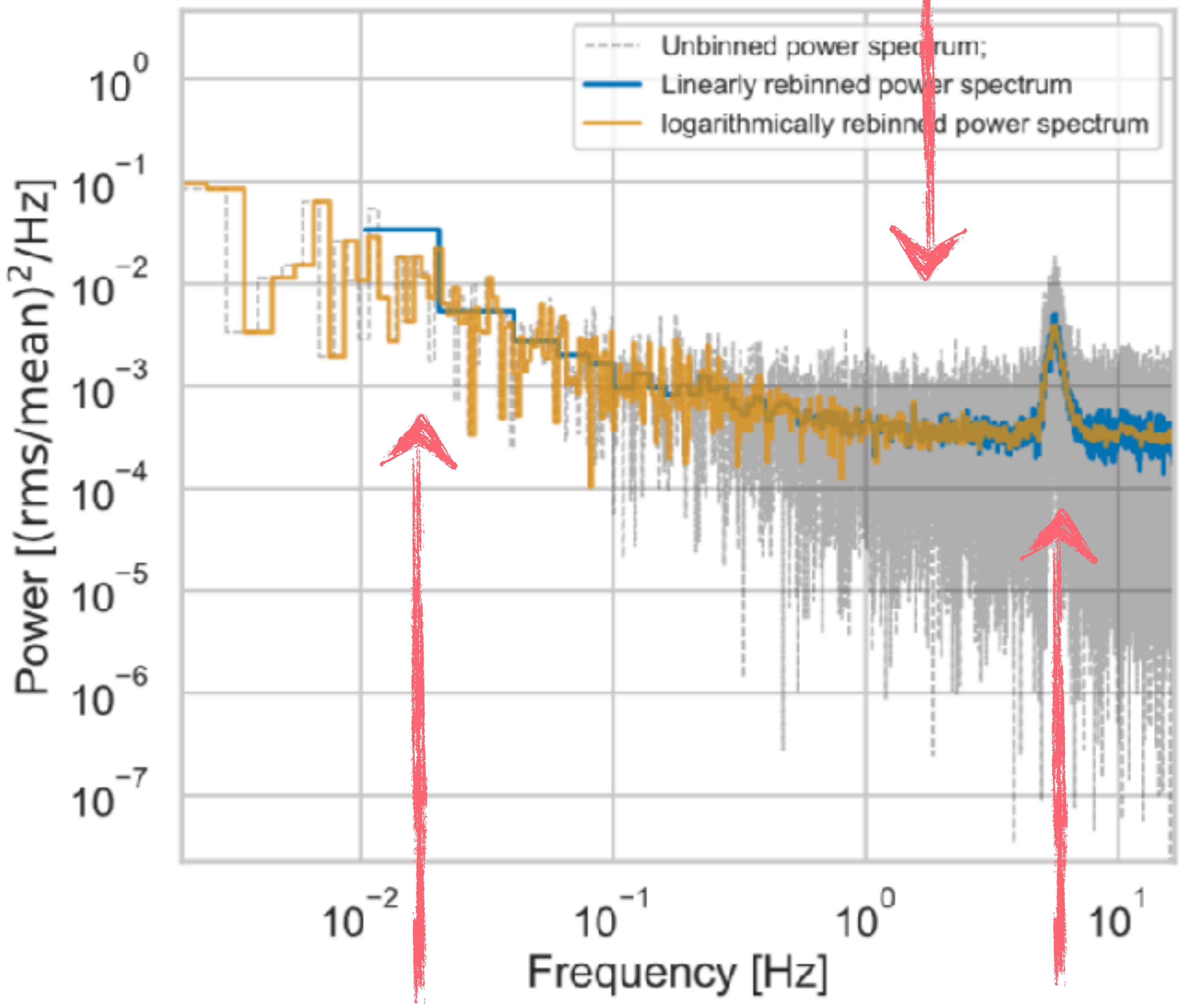
Variability: GX 339-4

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



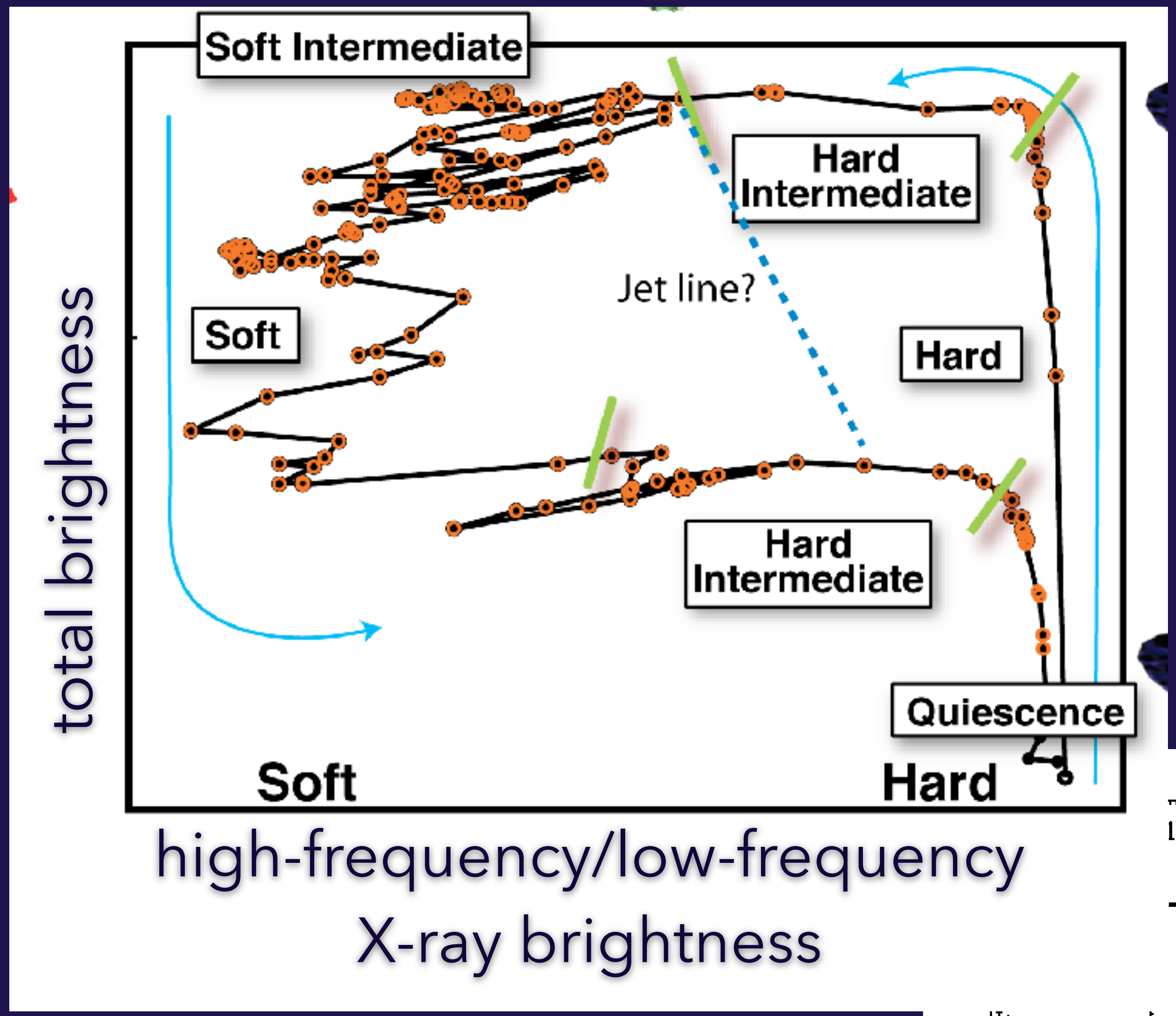
Fast Fourier Transform

white noise

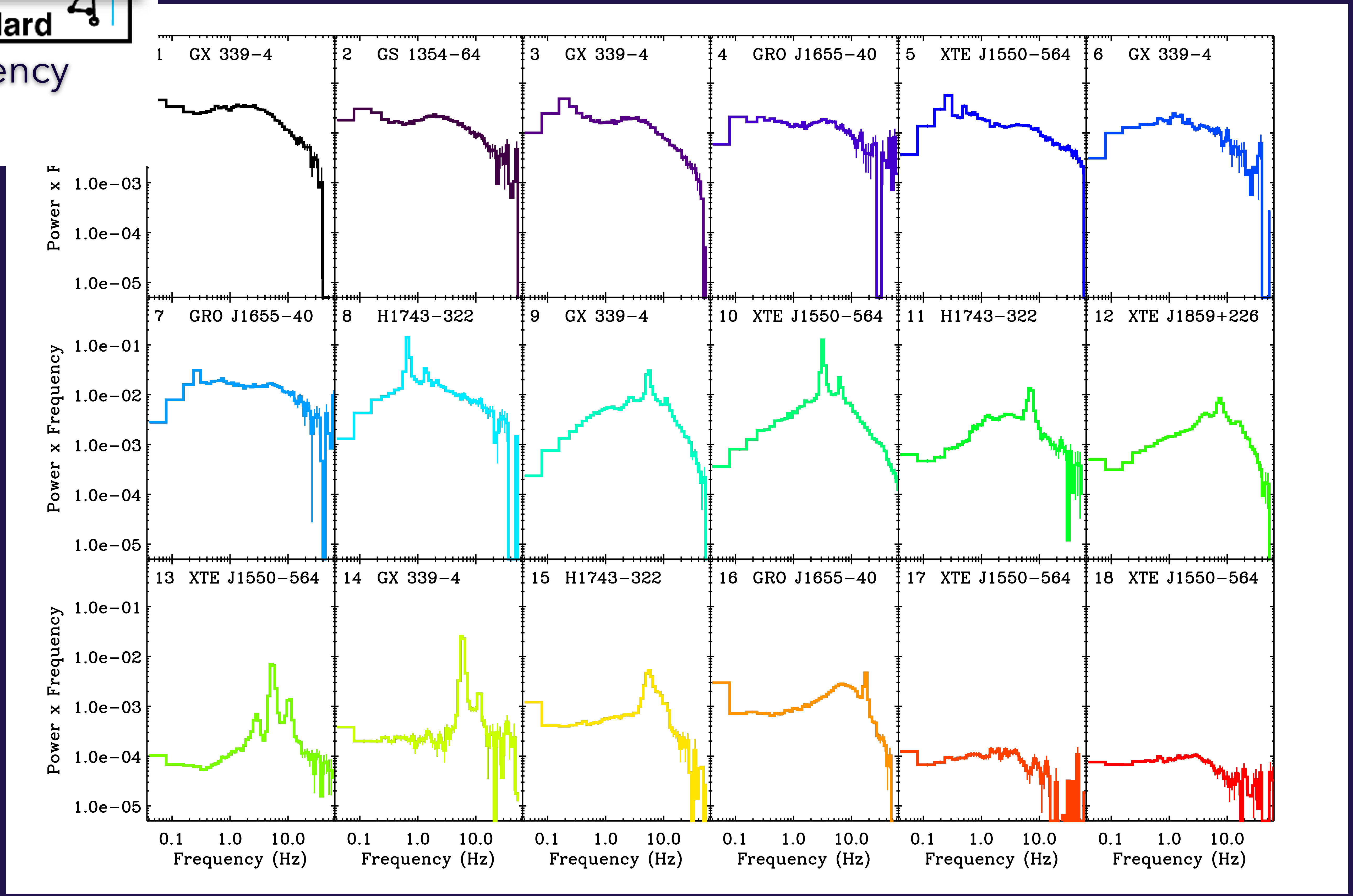


stochastic variability (red noise)

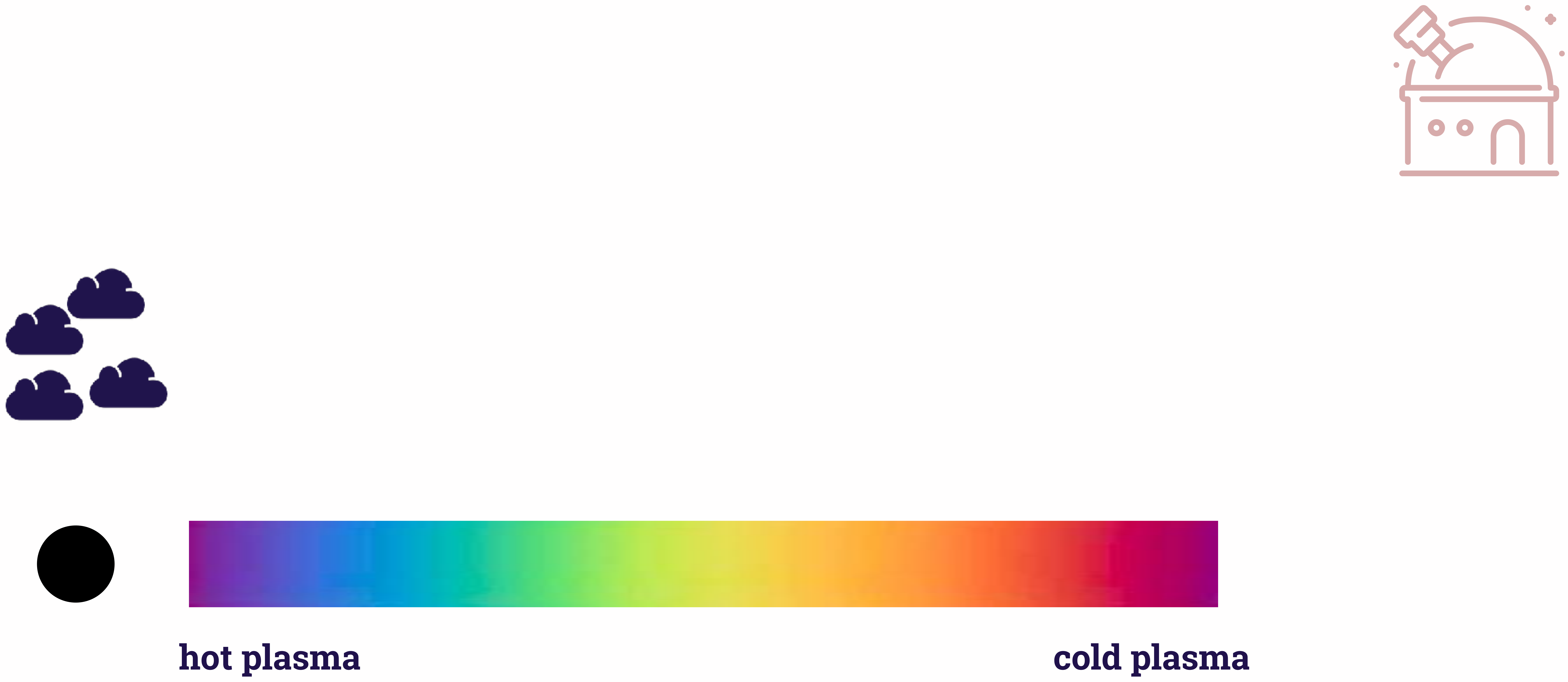
quasi-periodic oscillation (QPO)



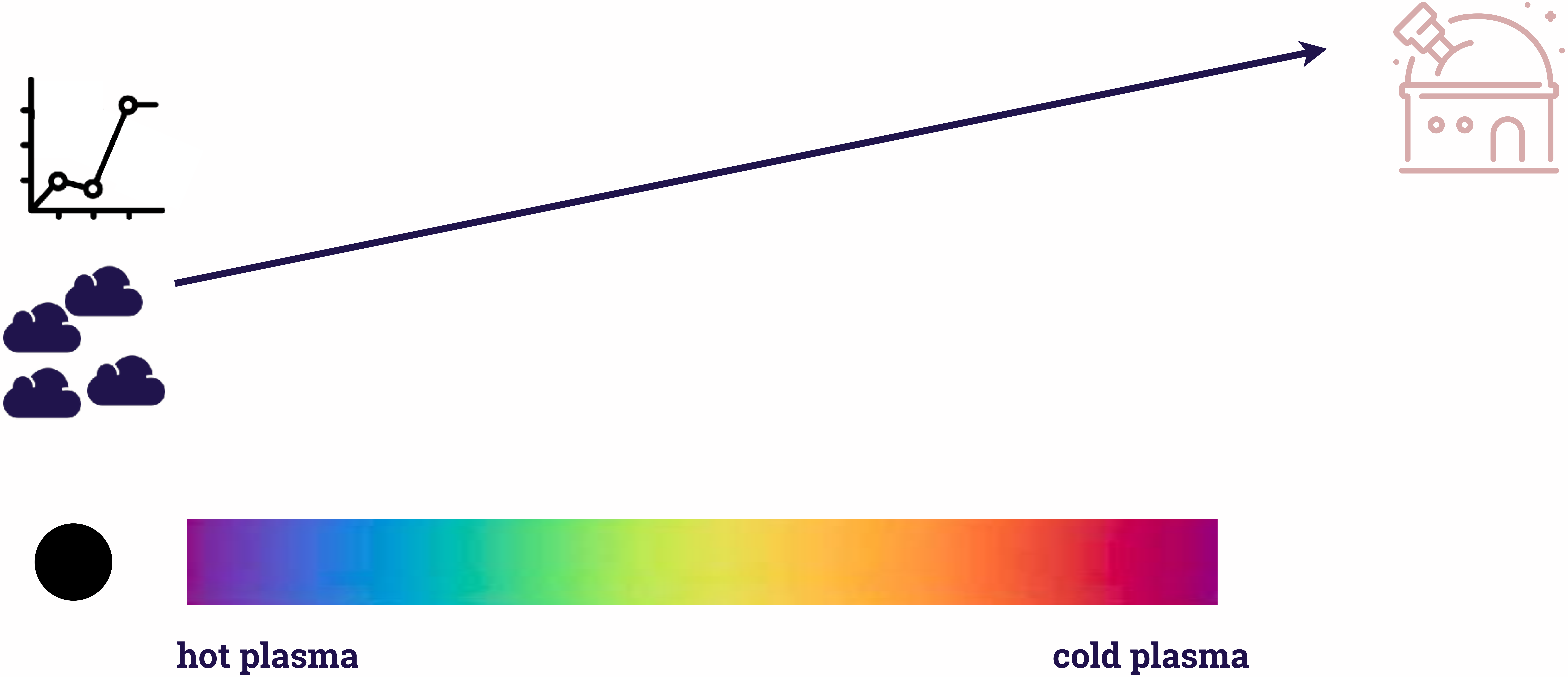
Credit: Sera Markoff

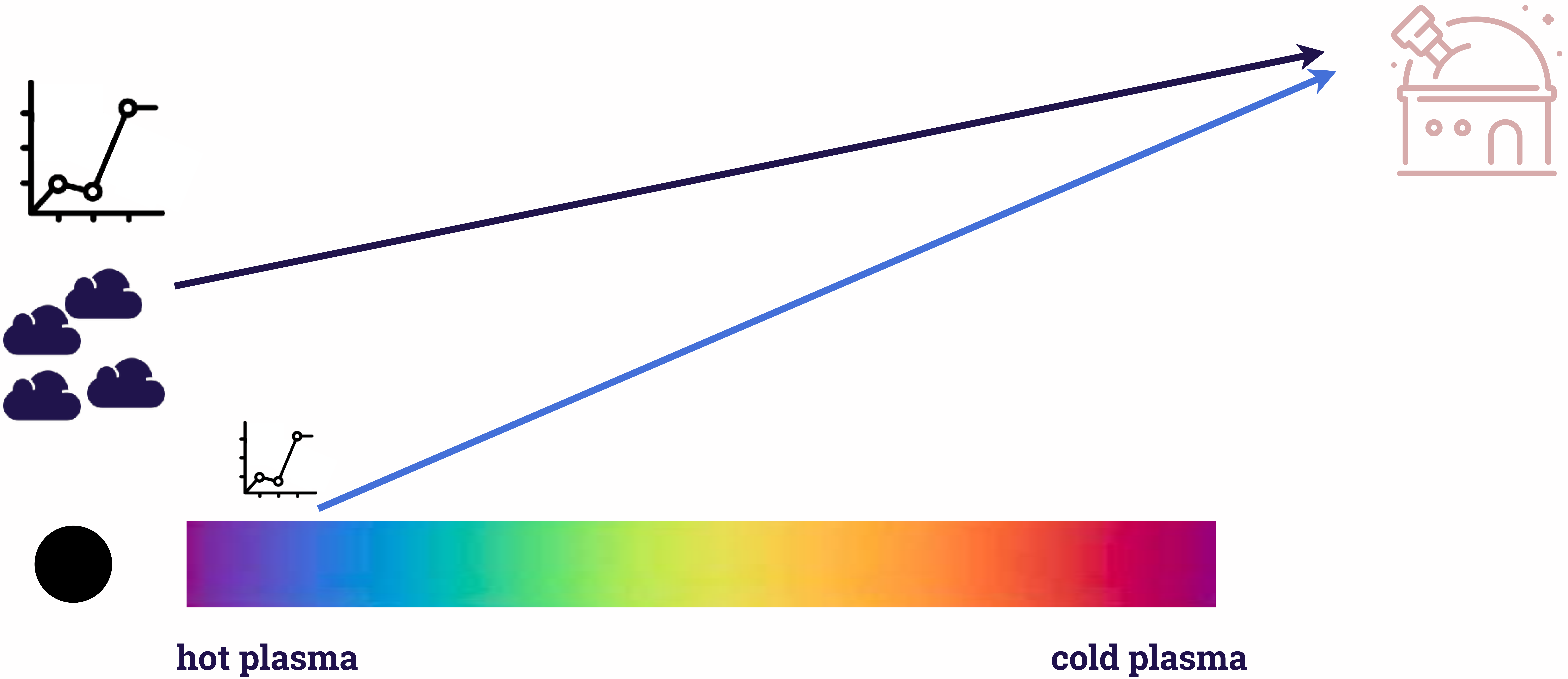


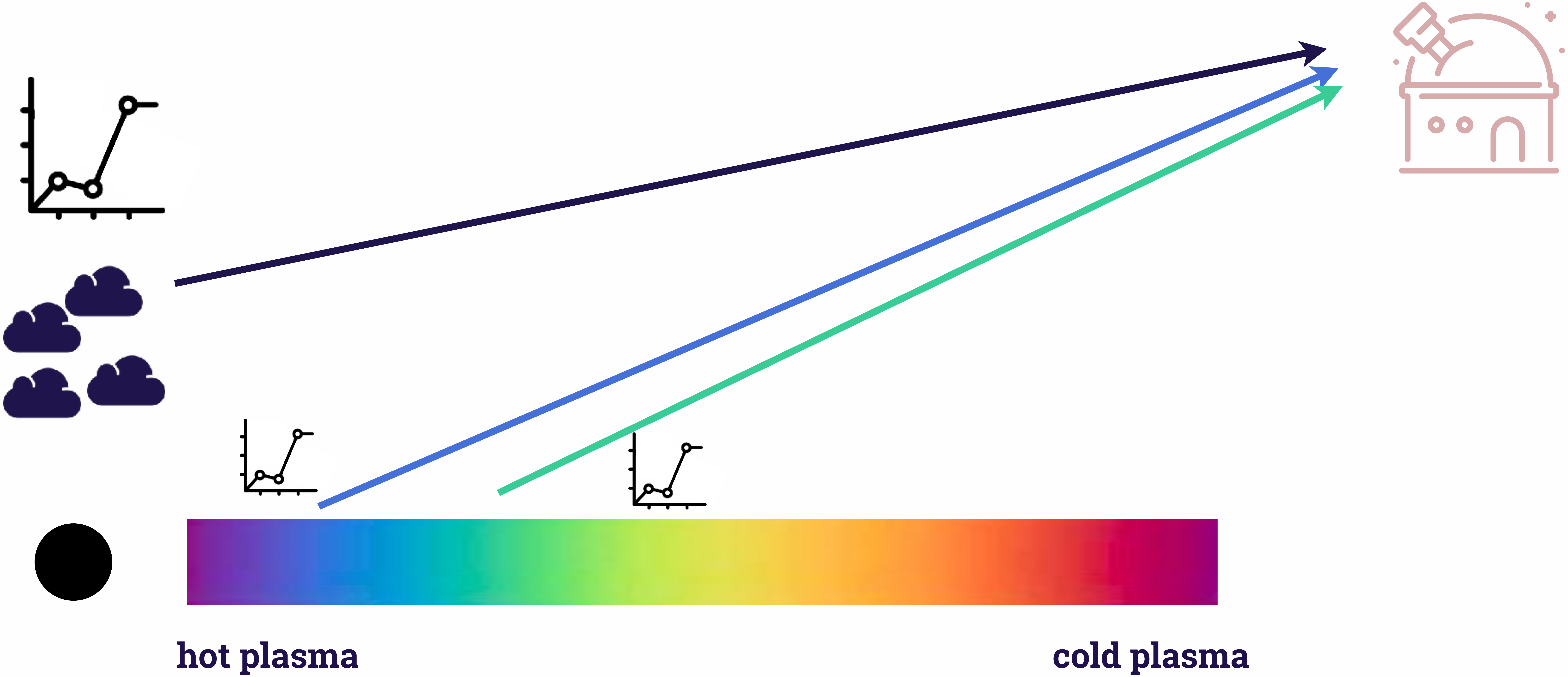
Heil et al 2014

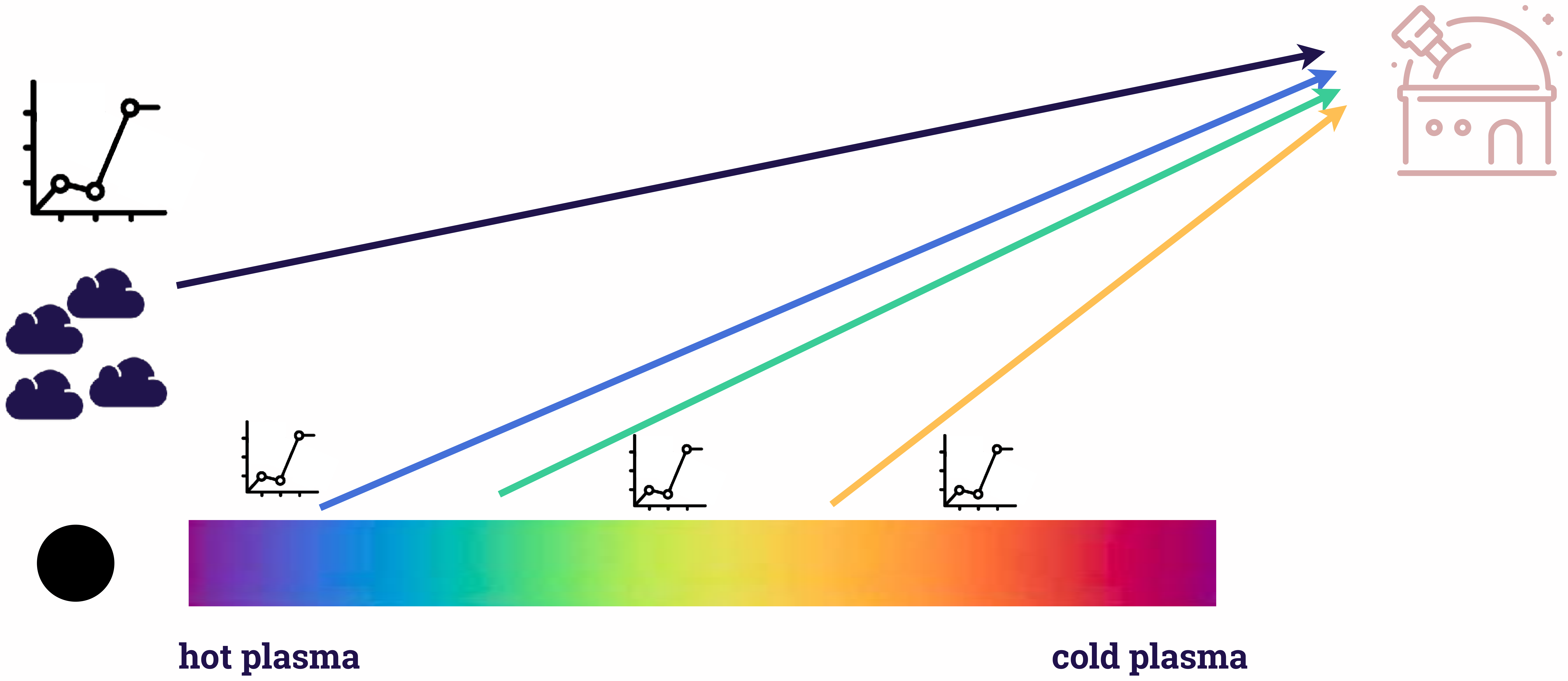

hot plasma
cold plasma

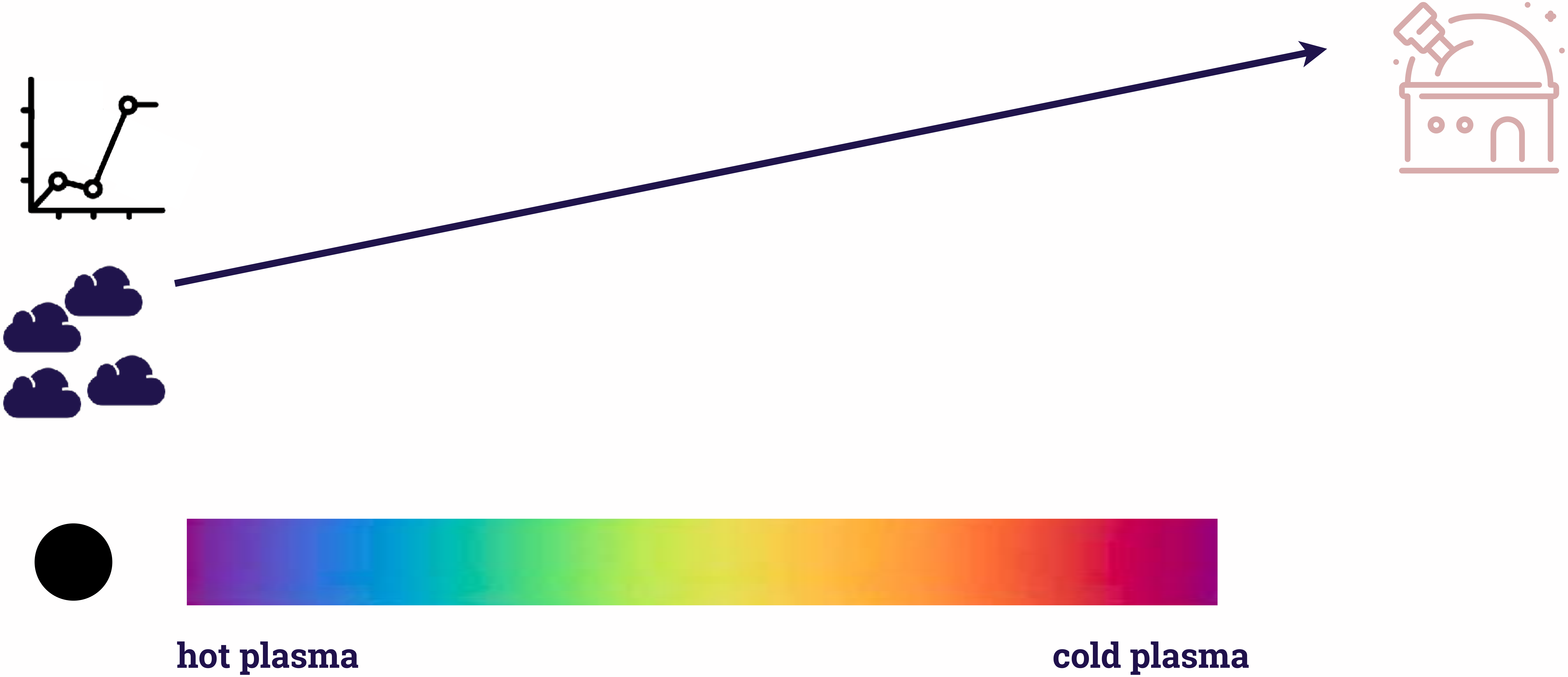
hot plasma **cold plasma**

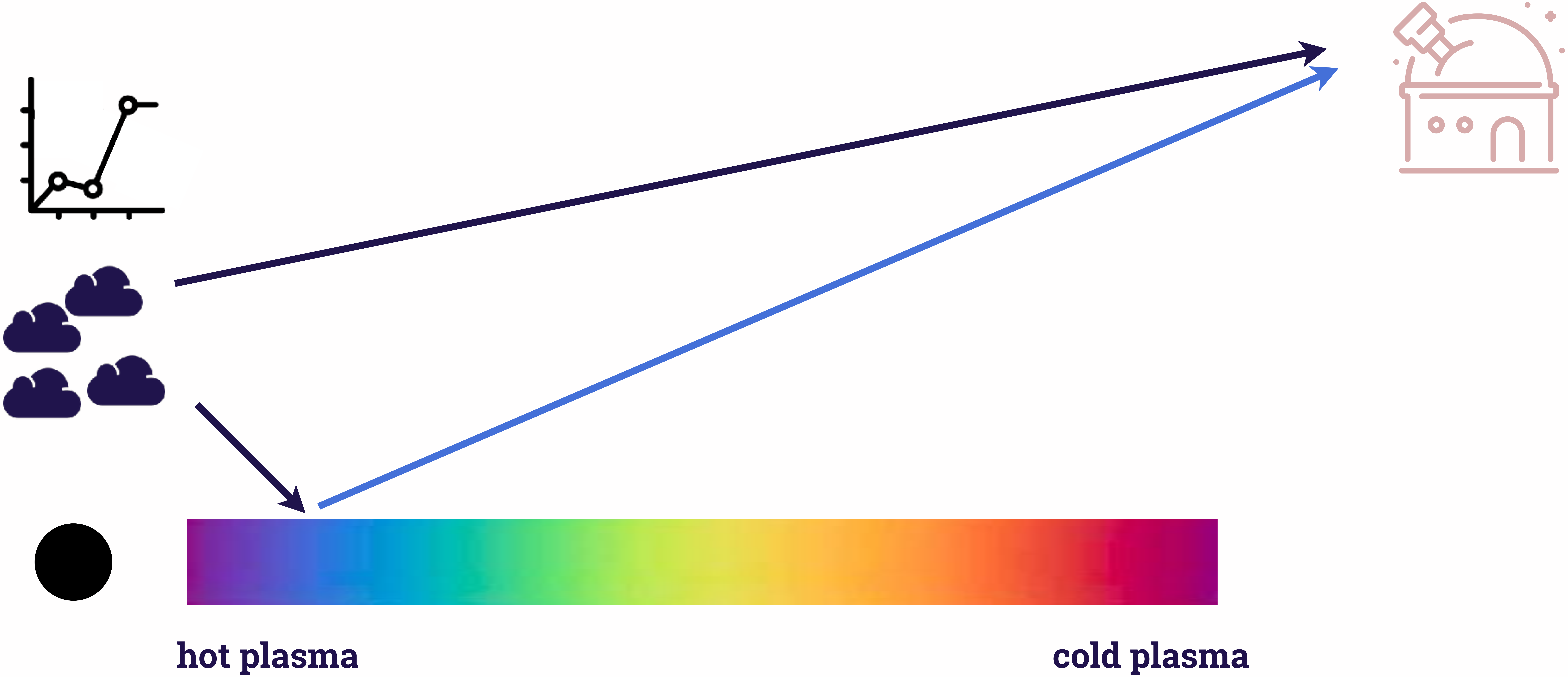

hot plasma
cold plasma

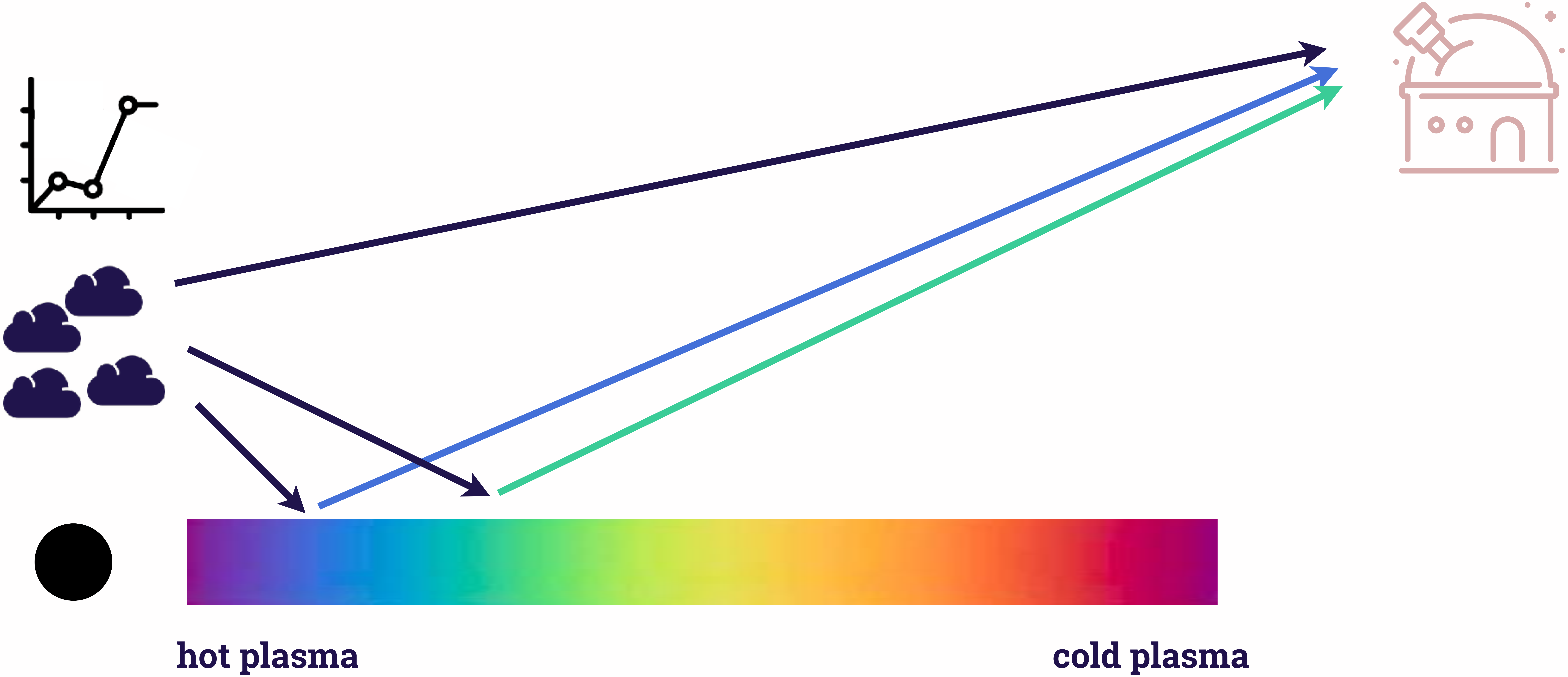

hot plasma
cold plasma

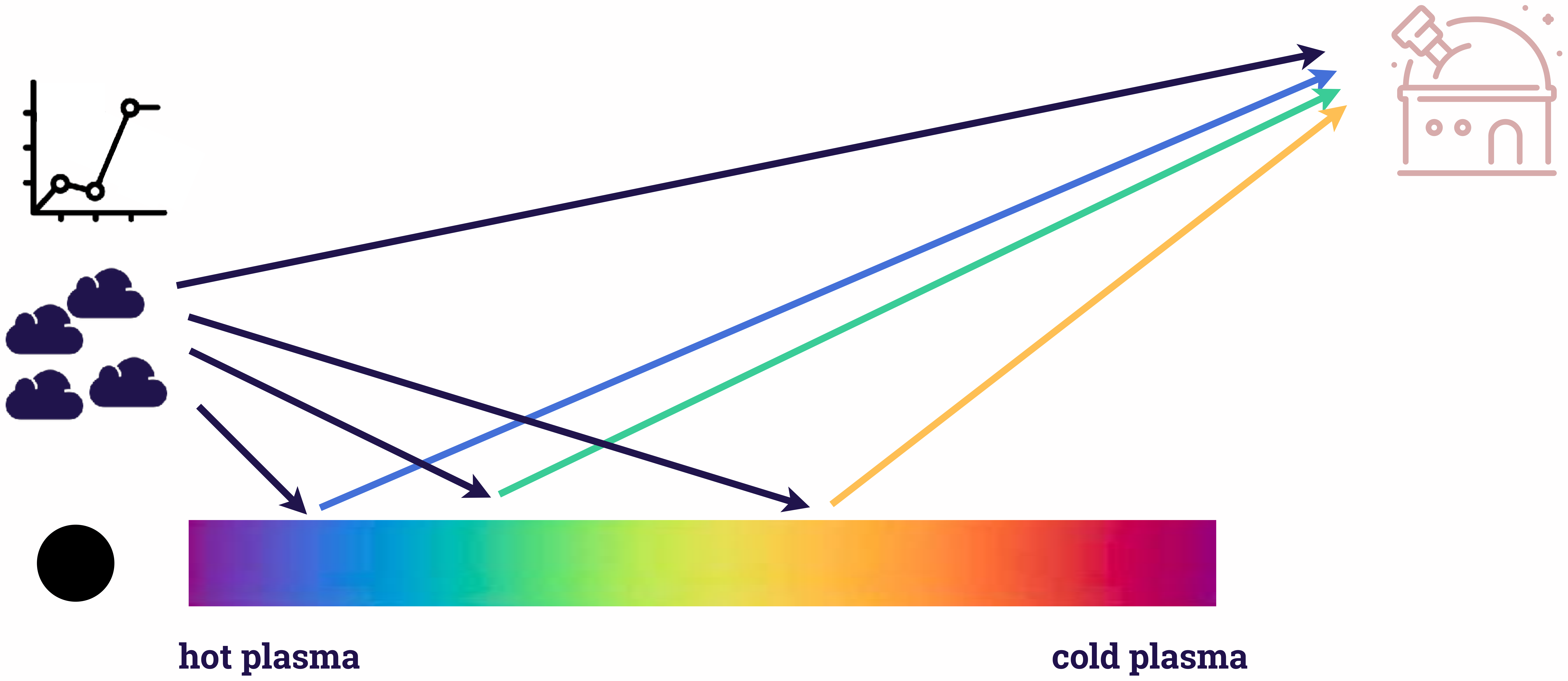

hot plasma
cold plasma

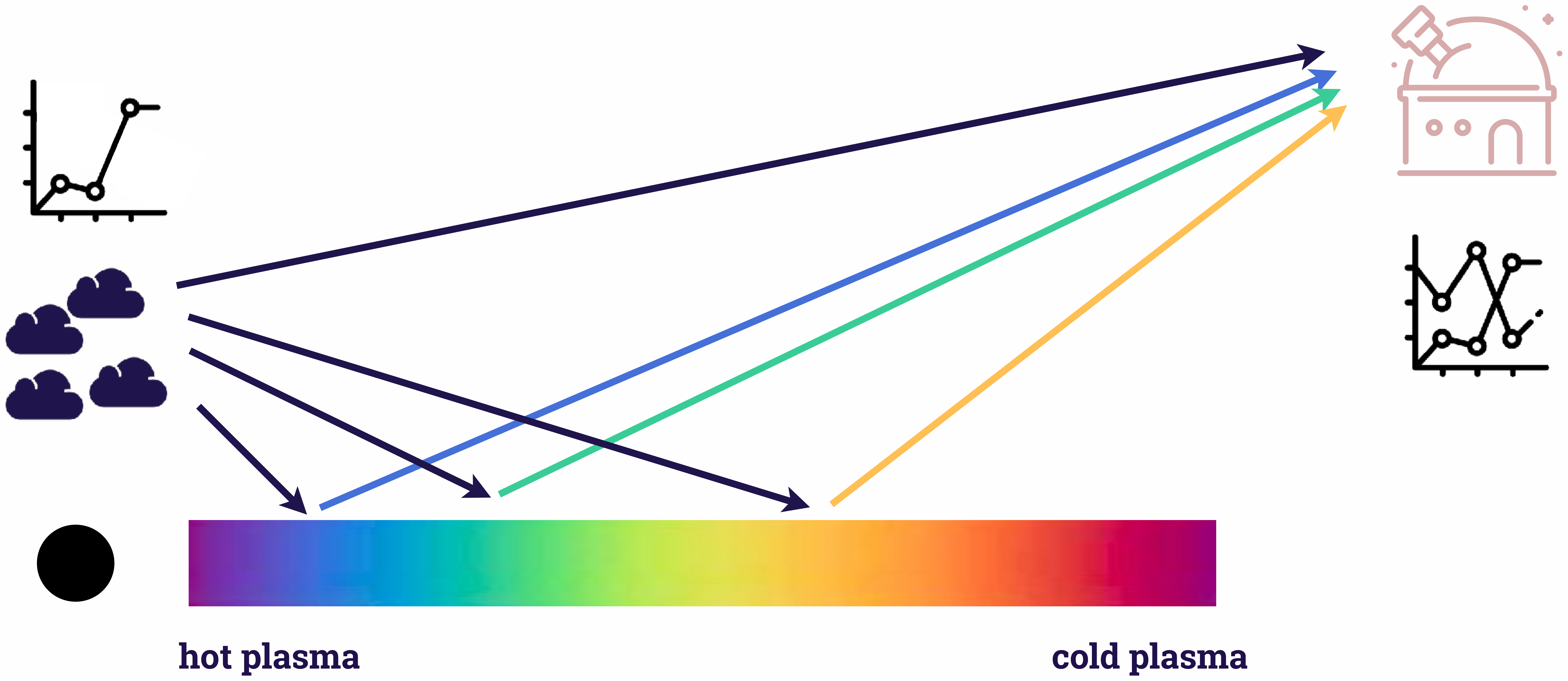

hot plasma
cold plasma

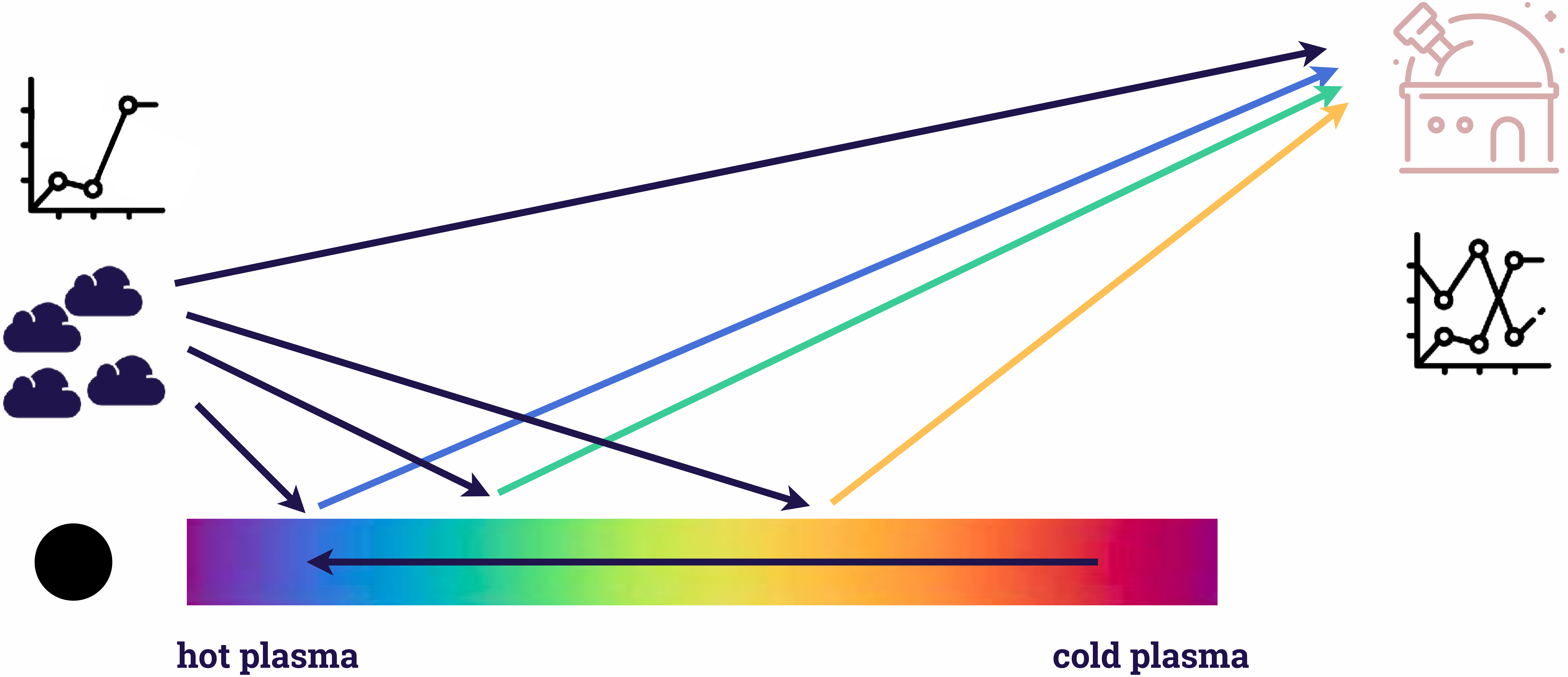

hot plasma
cold plasma


hot plasma
cold plasma


hot plasma
cold plasma


hot plasma
cold plasma


hot plasma
cold plasma


hot plasma
cold plasma

How can we use variability and energy to uncover the underlying physical processes?

Fourier Transforms

$$a_j = \sum_{k=0}^{N-1} x_k e^{2\pi ijk/N} \qquad j = -\frac{N}{2}, \ldots, \frac{N}{2} - 1$$

Complex Fourier Amplitude

$$x_k = \frac{1}{N} \sum_{j=-N/2}^{N/2-1} a_j e^{-2\pi ijk/N} \qquad k = 0, \ldots, N-1.$$

Frequency step: $\delta\nu = 1/T$,

Nyquist frequency: $\nu_{N/2} = \frac{1}{2}N/T$.

For a tutorial, see van der Klis (1989)

Fourier Transforms

$$a_j = \sum_{k=0}^{N-1} x_k e^{2\pi ijk/N} \qquad j = -\frac{N}{2}, \ldots, \frac{N}{2} - 1$$

Complex Fourier Amplitude

$$x_k = \frac{1}{N} \sum_{j=-N/2}^{N/2-1} a_j e^{-2\pi ijk/N} \qquad k = 0, \ldots, N-1.$$

Frequency step: $\delta\nu = 1/T$,

Nyquist frequency: $\nu_{N/2} = \frac{1}{2}N/T$.

Earlier in the workshop …

For a tutorial, see van der Klis (1989)

Fourier Transforms

$$\sum_{k=0}^{N-1} |x_k|^2 = \frac{1}{N} \sum_{j=-N/2}^{N/2-1} |a_j|^2.$$

$$\mathrm{Var}(x_k) = \frac{1}{N} \sum_{\substack{j=-N/2 \\ j\neq 0}}^{N/2-1} |a_j|^2.$$

Parseval's Theorem

For a tutorial, see van der Klis (1989)

Fourier Transforms

Leahy normalization: $$P_j \equiv \frac{2}{N_{ph}} |a_j|^2 \qquad j = 0, \ldots, \frac{N}{2},$$ use for period searches

Fractional RMS normalization: $$P_j = \frac{2T|a_j|^2}{N^2 \mu^2}$$

use for characterizing quasi-periodic signals

Absolute RMS normalization: $$P_j = \frac{2|a_j|^2}{T}$$

For a tutorial, see van der Klis (1989)

The Cross Spectrum

$$\boxed{\mathcal{F}_x(j)\mathcal{F}_y^*(j) = \frac{1}{2}\{(A_{xj}A_{yj} + B_{xj}B_{yj}) + i(A_{xj}B_{yj} - A_{yj}B_{xj})\}}$$

$$C_{XY,j} = \underbrace{C_{x,j}C_{y,j}}_{\text{amplitude}} \exp[i\underbrace{\phi_j}_{\text{phase}}]$$

(same in complex polar coordinates)

Note: be aware of your denominator for the rms normalization!

$$P_j = \frac{2T|C_{X,j}C_{Y,j}|^2}{N^2\langle x\rangle\langle y\rangle}$$

The Cross Spectrum

$$\mathcal{F}_x(j)\mathcal{F}_y^*(j) = \frac{1}{2}\{(A_{xj}A_{yj} + B_{xj}B_{yj}) + i(A_{xj}B_{yj} - A_{yj}B_{xj})\}$$

In practice, you should almost always average across frequencies/segments!

$C_{XY,j} = C$ ... **ar coordinates)**

ampl

Note: be aware of your denominator for the rms normalization!

$$P_j = \frac{2T|C_{X,j}C_{Y,j}|^2}{N^2\langle x\rangle\langle y\rangle}$$

What do I mean by "different light curves":

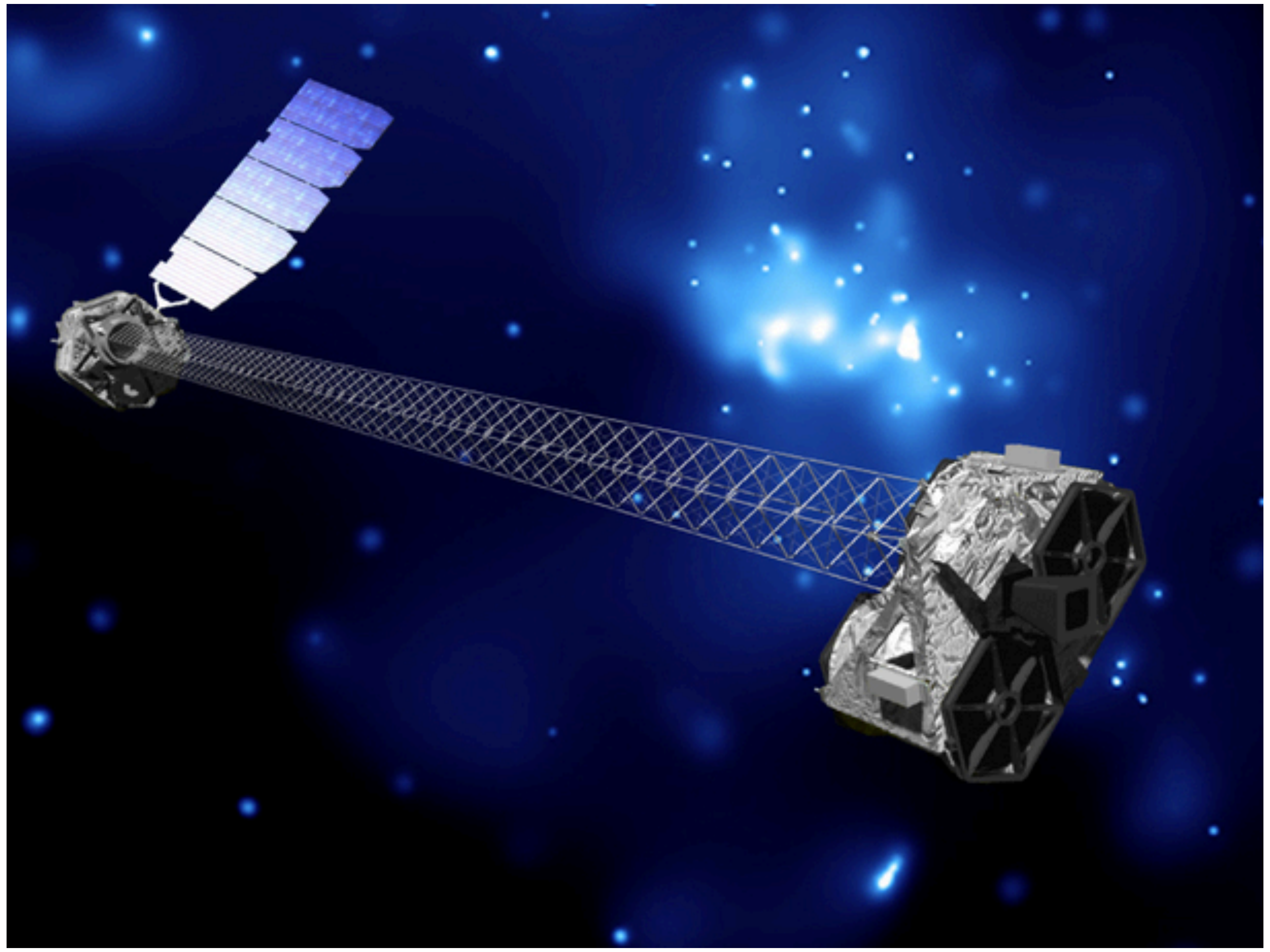
- same energy range; independent, but identical detectors
- different energy ranges, same detector

The Cospectrum

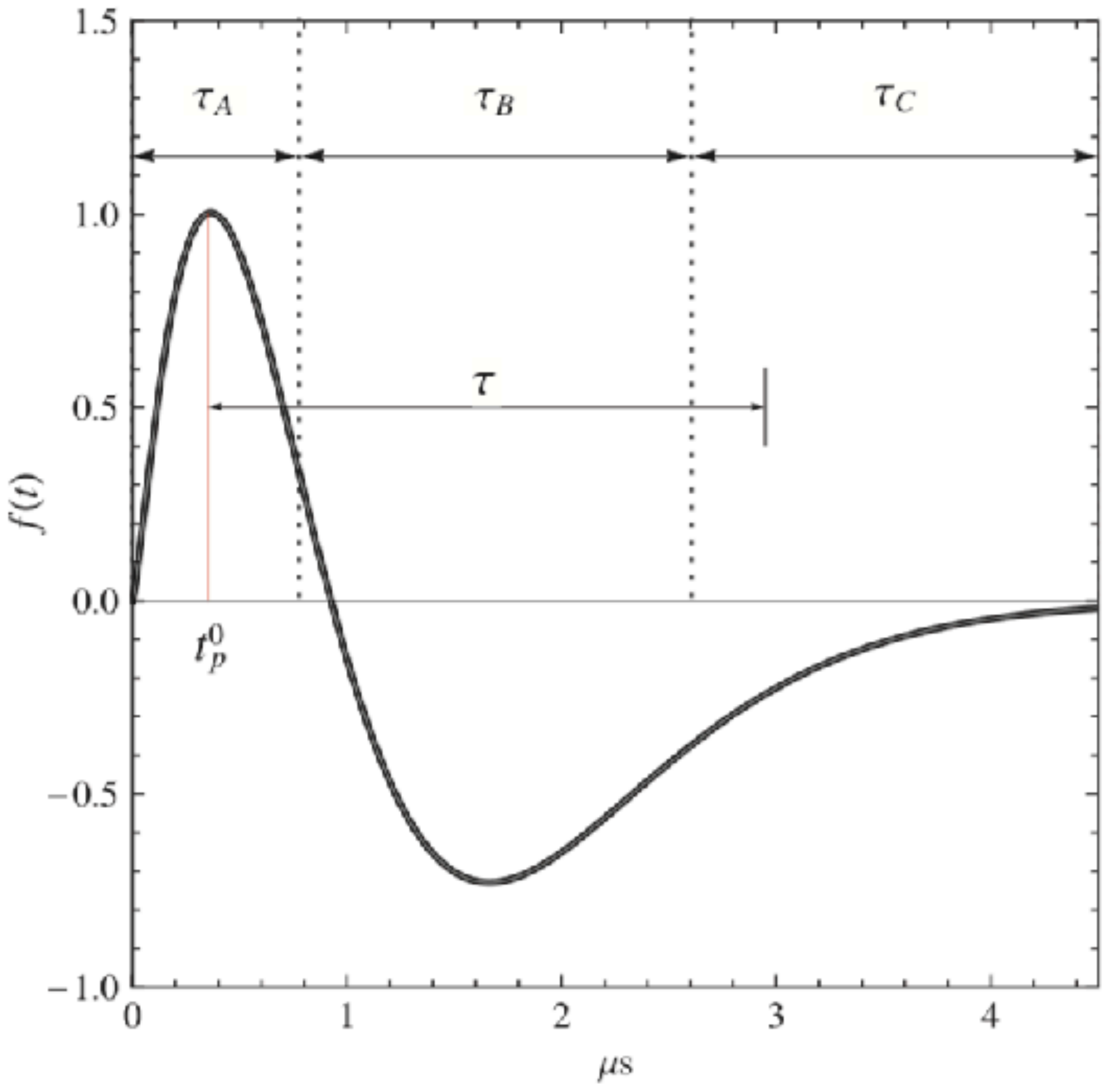
$$C_j = \frac{1}{2}(A_{xj}A_{yj} + B_{xj}B_{yj})\,.$$

Be careful: interpretation of time lags for phases close to π or -π can be difficult due to phase wrapping:

NuSTAR

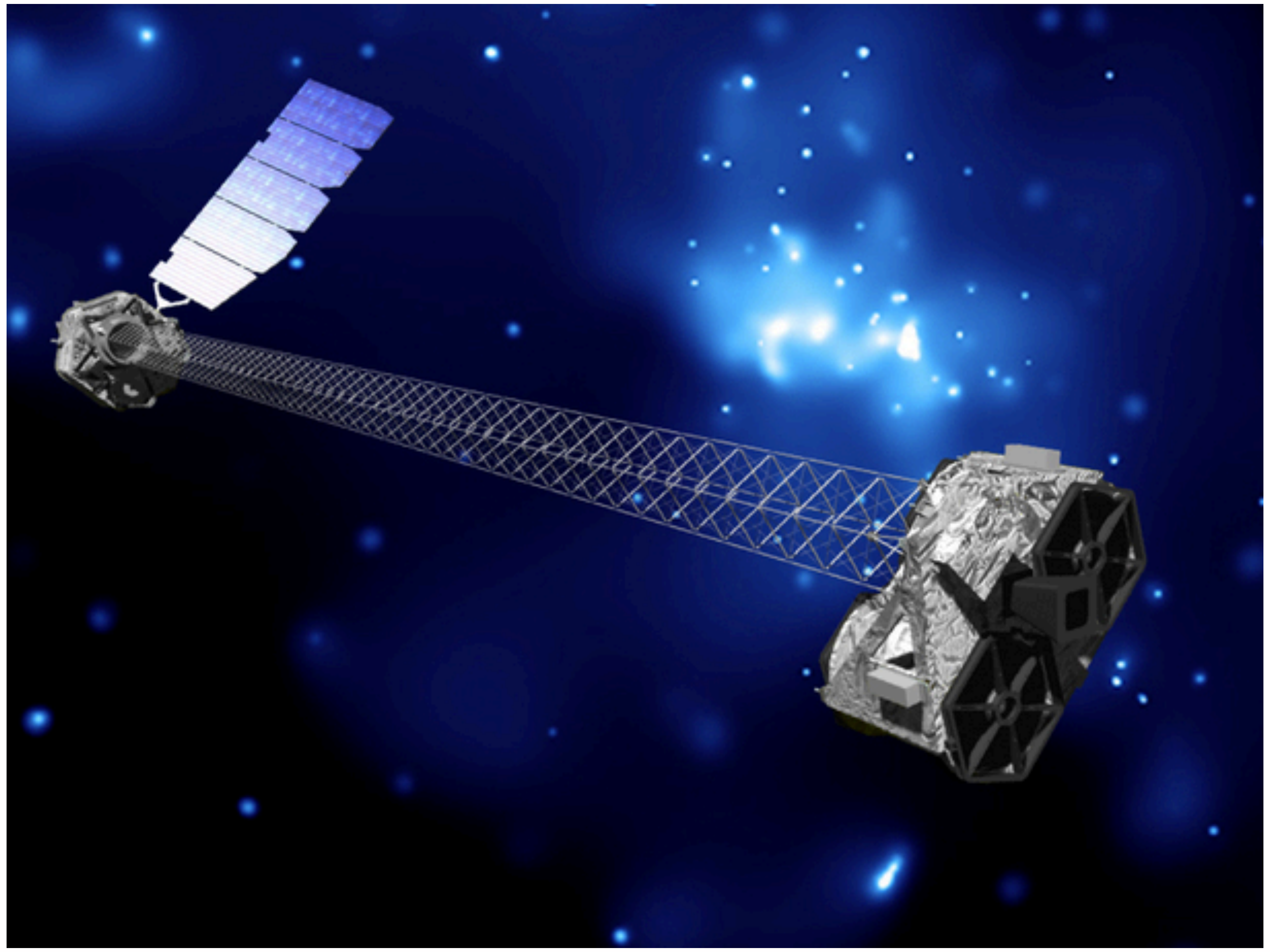


Chaplin et al (2012)

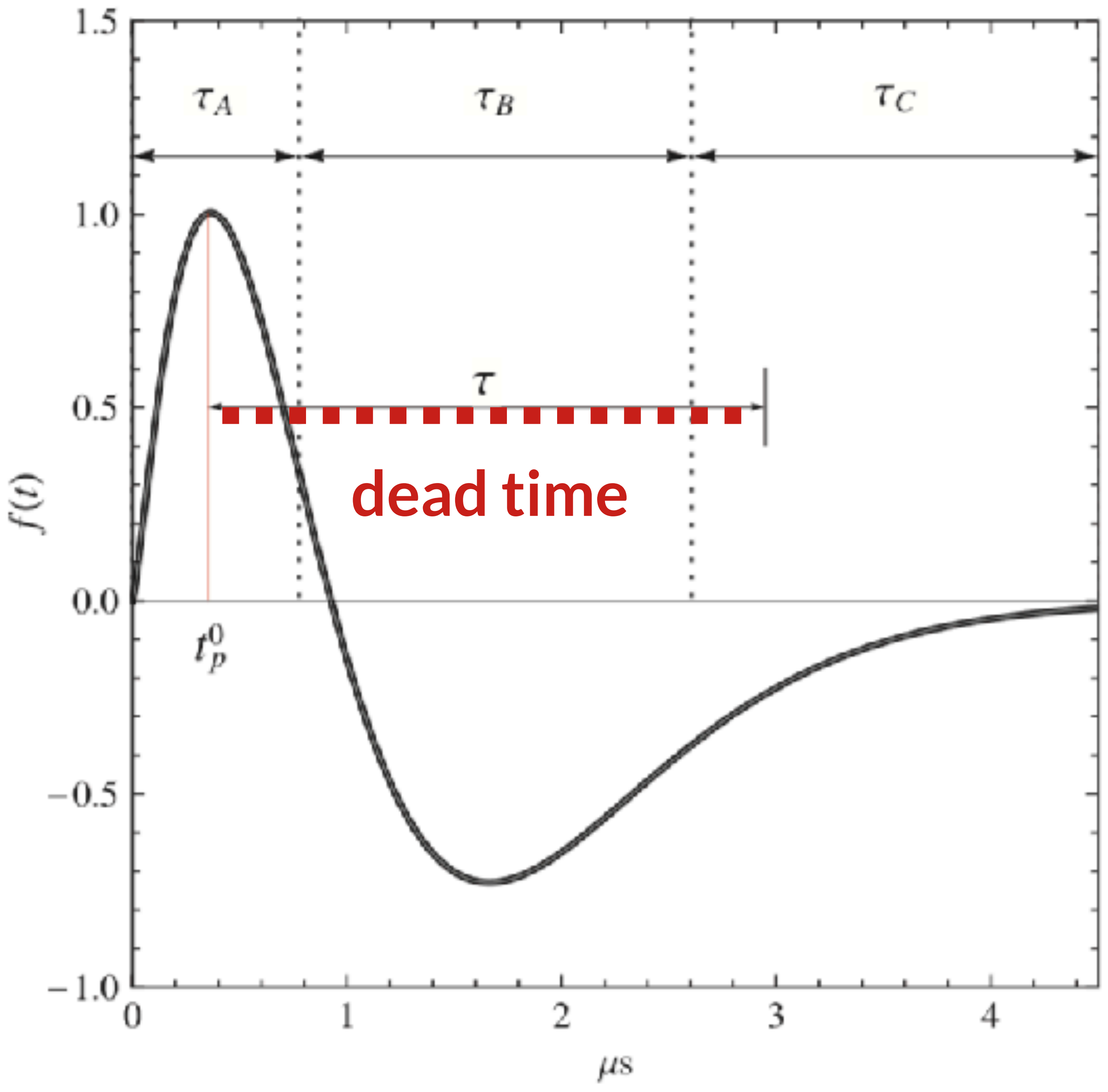


Credit: NuSTAR Observatory Guide

NuSTAR



Chaplin et al (2012)

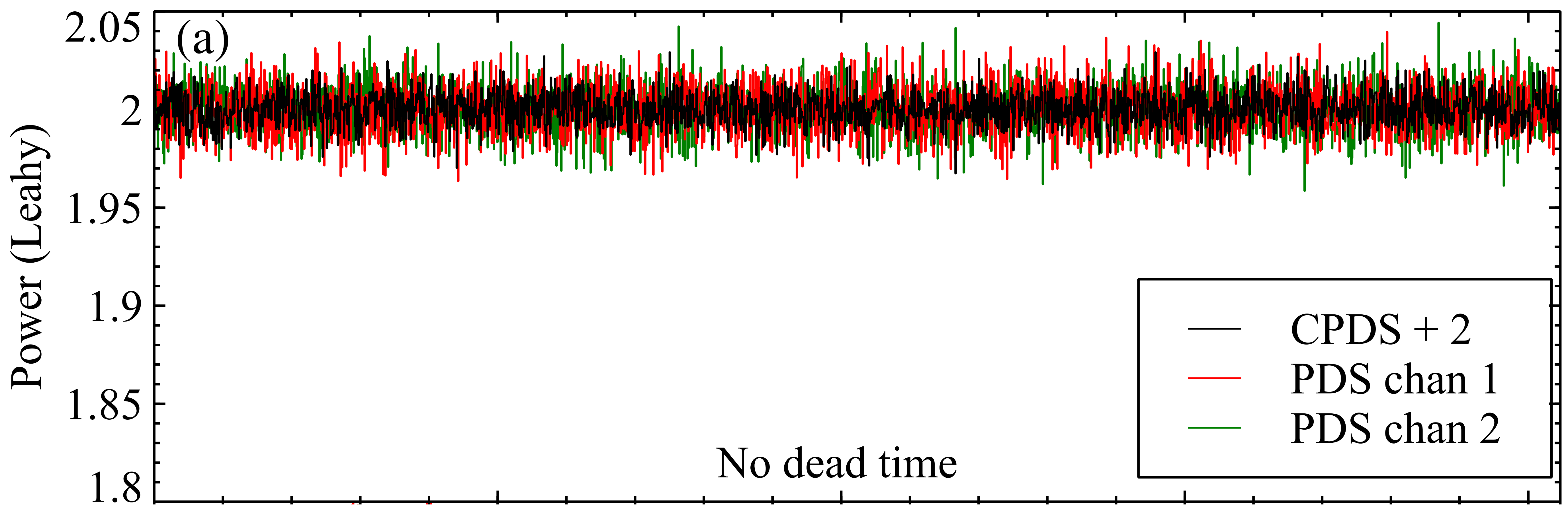


Credit: NuSTAR Observatory Guide

Dead Time

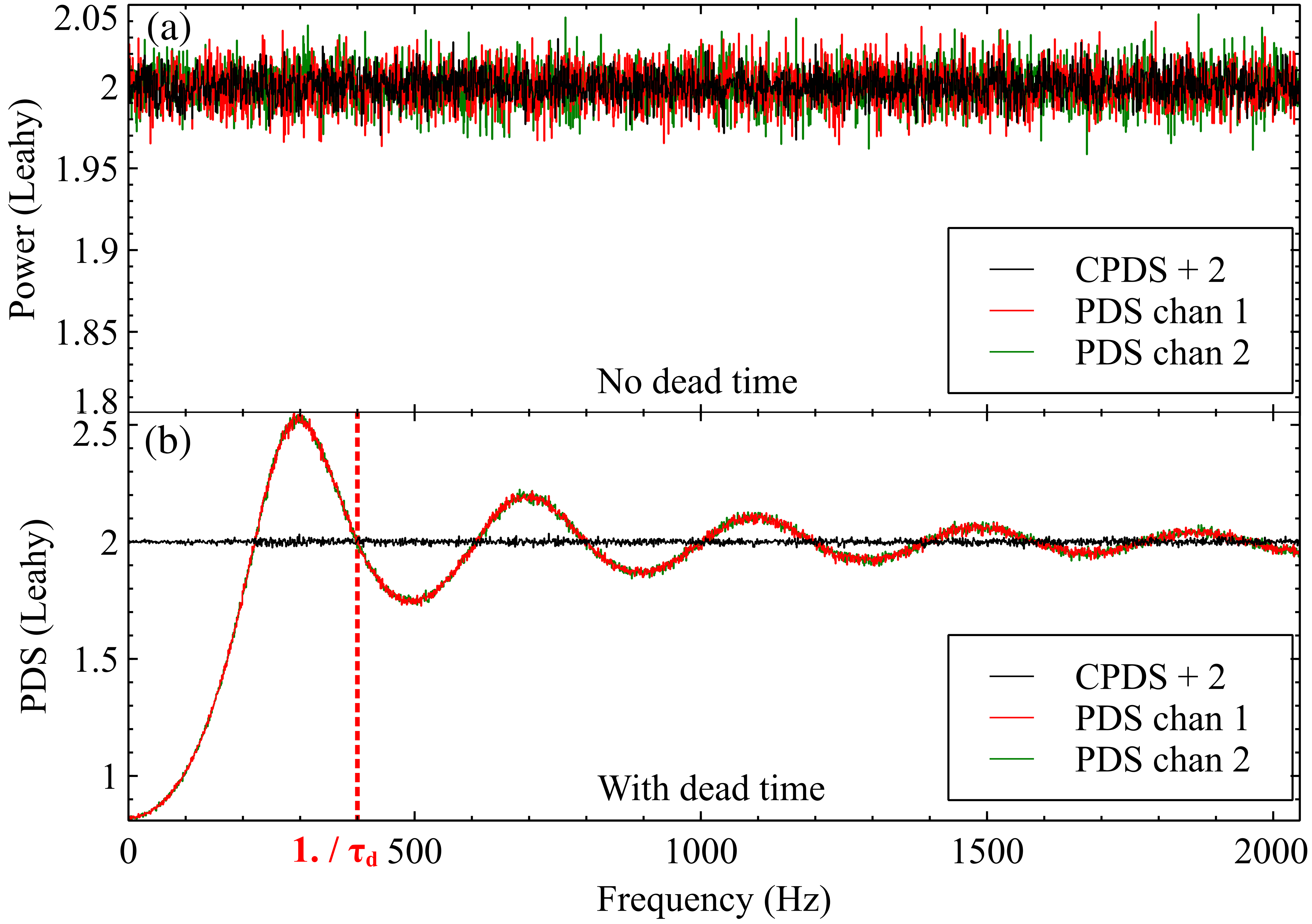
Bachetti et al (2015), Huppenkothen & Bachetti (2018), Bachetti & Huppenkothen (2018)

Dead Time



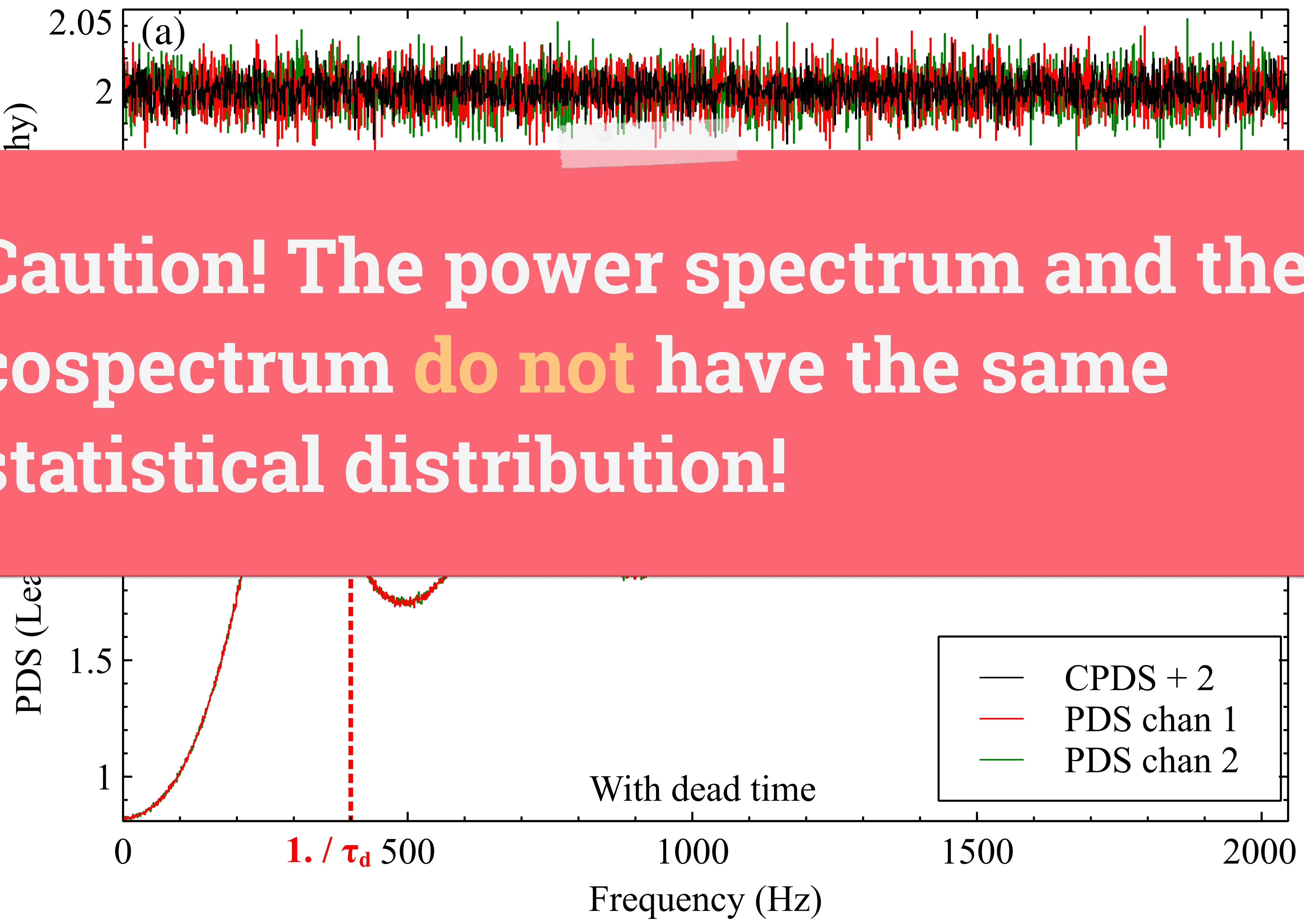
Bachetti et al (2015), Huppenkothen & Bachetti (2018), Bachetti & Huppenkothen (2018)

Dead Time



Bachetti et al (2015), Huppenkothen & Bachetti (2018), Bachetti & Huppenkothen (2018)

Dead Time



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

Bachetti et al (2015), Huppenkothen & Bachetti (2018), Bachetti & Huppenkothen (2018)

The Time Lag

$$\boxed{\tau_j = \frac{\phi_j}{2\pi\nu_j}}$$

Be careful: interpretation of time lags for phases close to π or $-\pi$ can be difficult due to phase wrapping.

The Coherence

$$\gamma^2(\nu_j) = \frac{|\bar{C}_{XY}(\nu_j)|^2 - n^2}{\bar{P}_X(\nu_j)\bar{P}_Y(\nu_j)}$$

where

$$n^2 = \frac{(\bar{P}_X(\nu_j) - P_{X,\mathrm{noise}})P_{Y,\mathrm{noise}} + (\bar{P}_Y(\nu_j) - P_{Y,\mathrm{noise}})P_{X,\mathrm{noise}} + P_{X,\mathrm{noise}}P_{Y,\mathrm{noise}}}{KM}$$

normalization term to account for the contribution of Poisson noise to the cross spectrum term

Interpretation

fraction of variance in both light curves that can be predicted via a linear transformation between them

Interpretation

fraction of variance in both light curves that can be predicted via a linear transformation between them

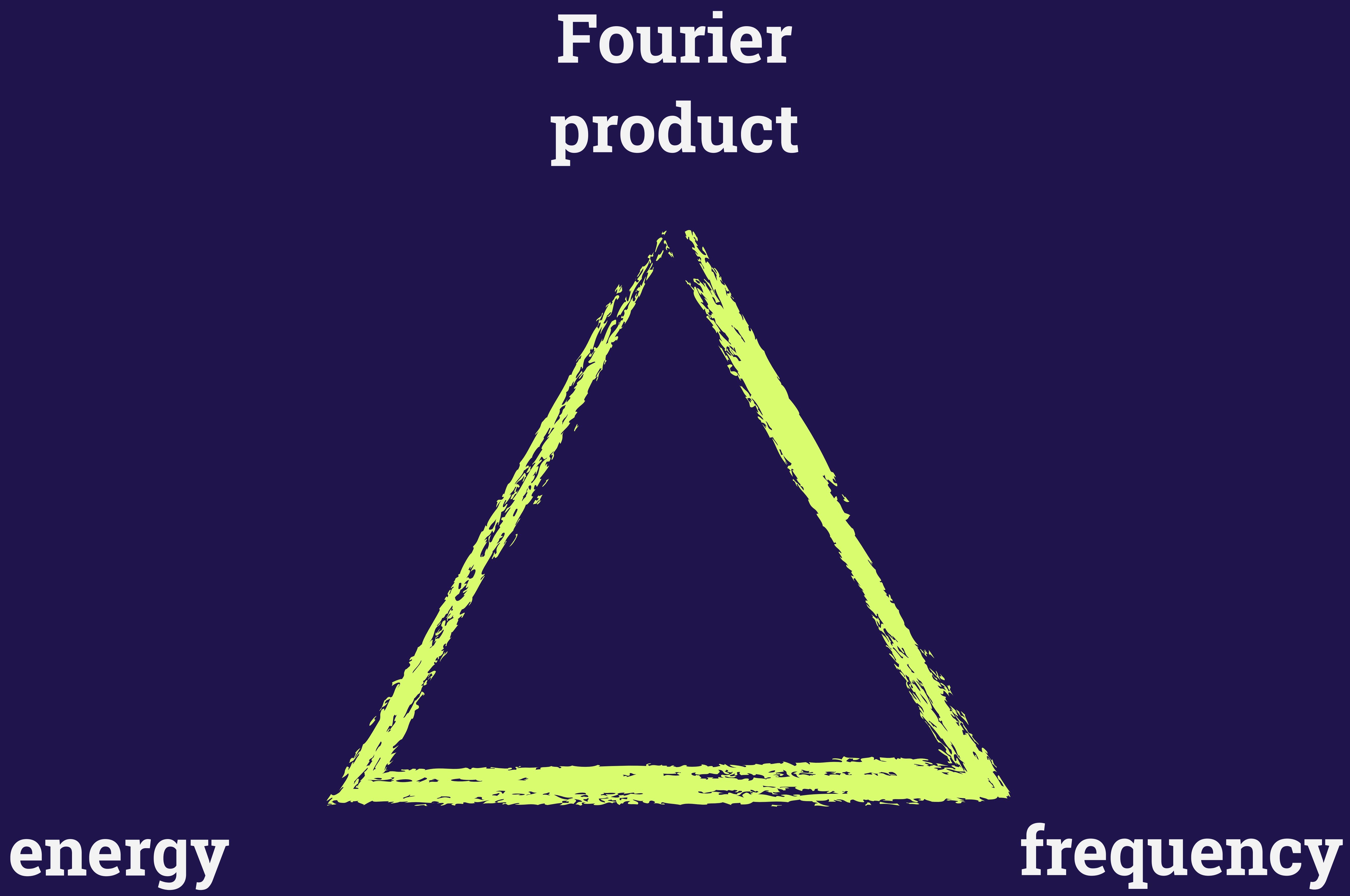
indication of scatter on the cross spectrum vector caused by incoherent components

Error of the Phase Lag

$$\Delta\phi(\nu_j) = \sqrt{\frac{1 - \gamma^2(\nu_j)}{2\gamma^2(\nu_j)KM}}$$

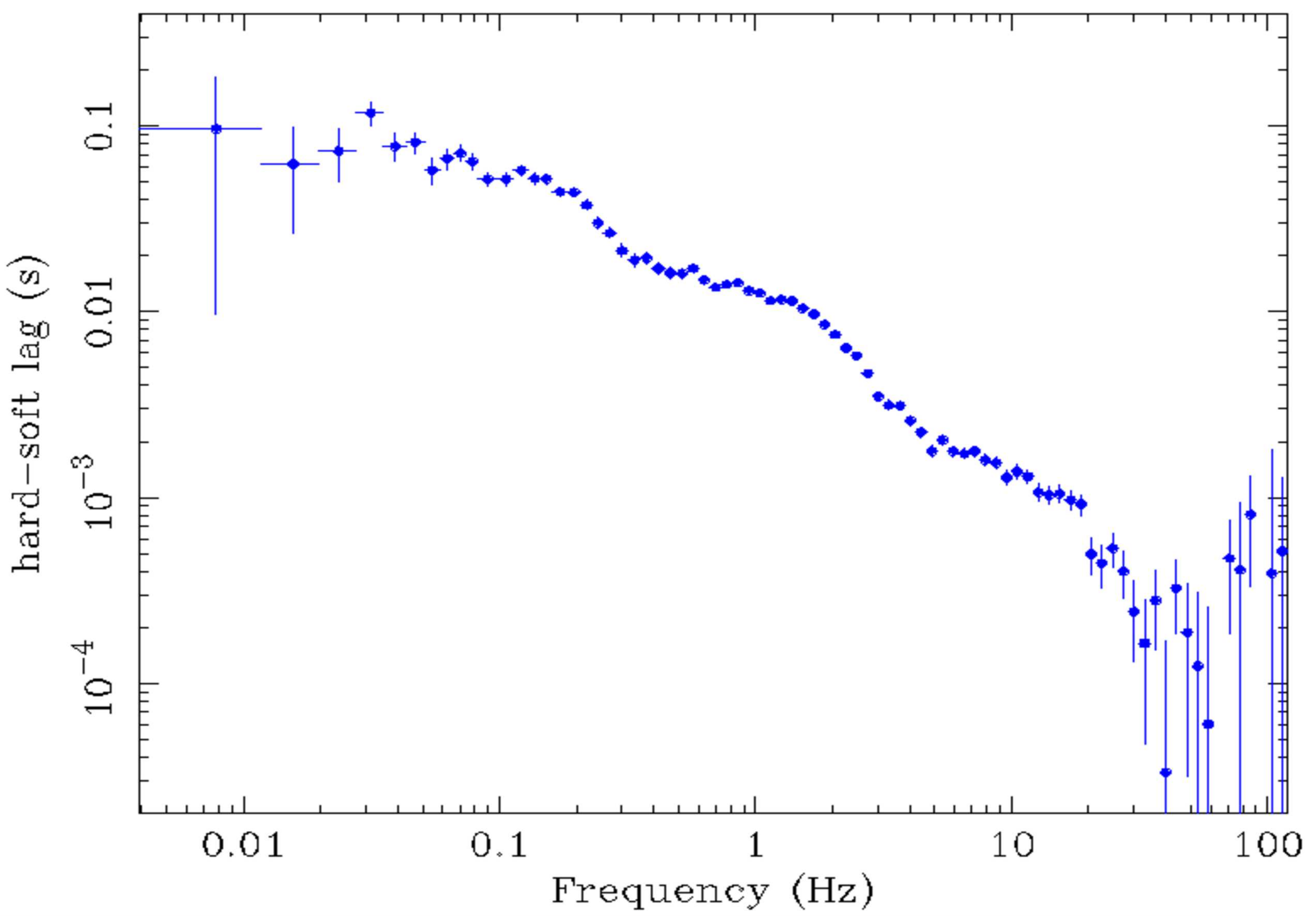
Caution: uses raw coherence (Poisson noise not subtracted from periodograms)

Practical Applications

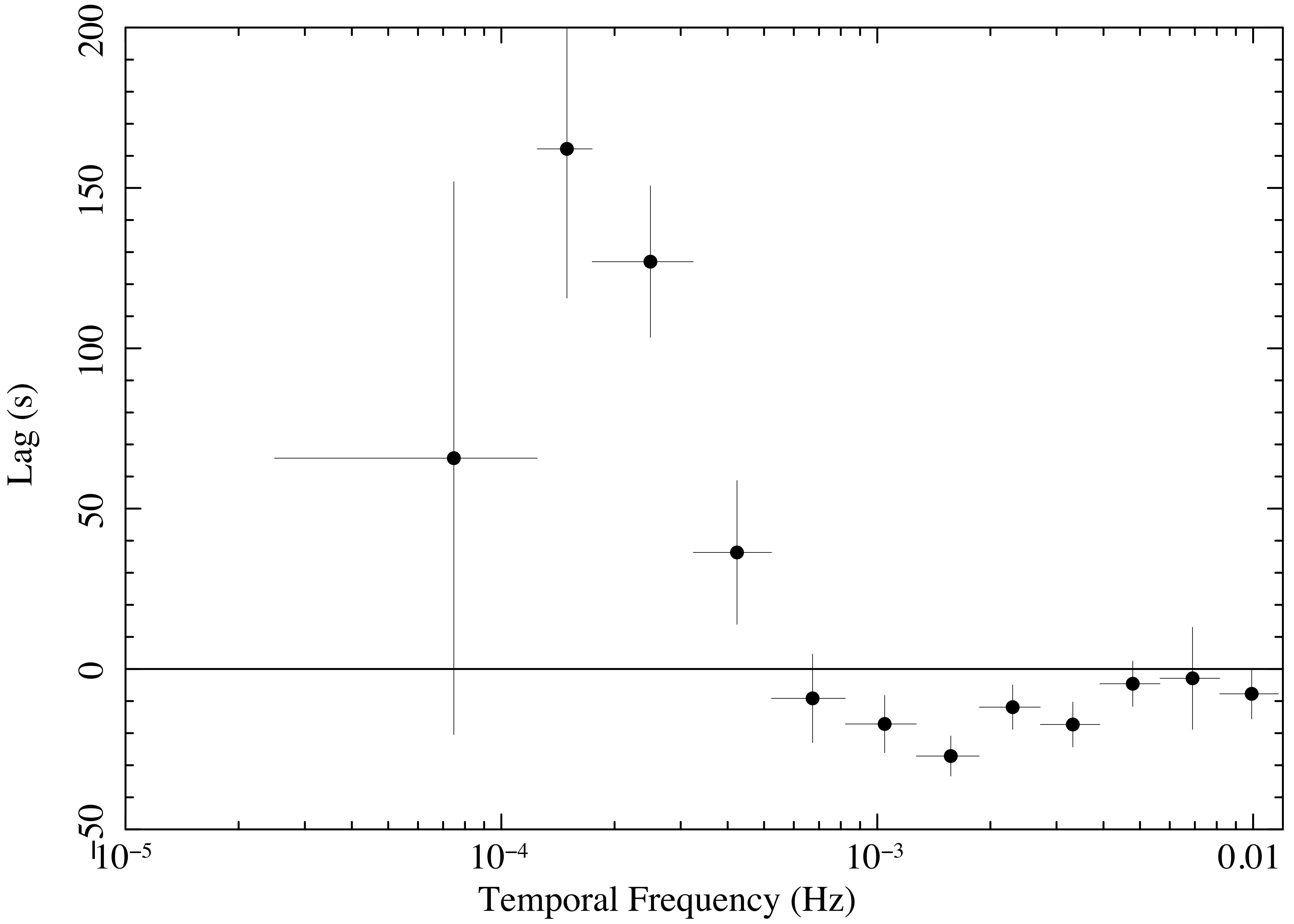


Lag-Frequency Spectrum

Cygnus X-1: Nowak, 2000

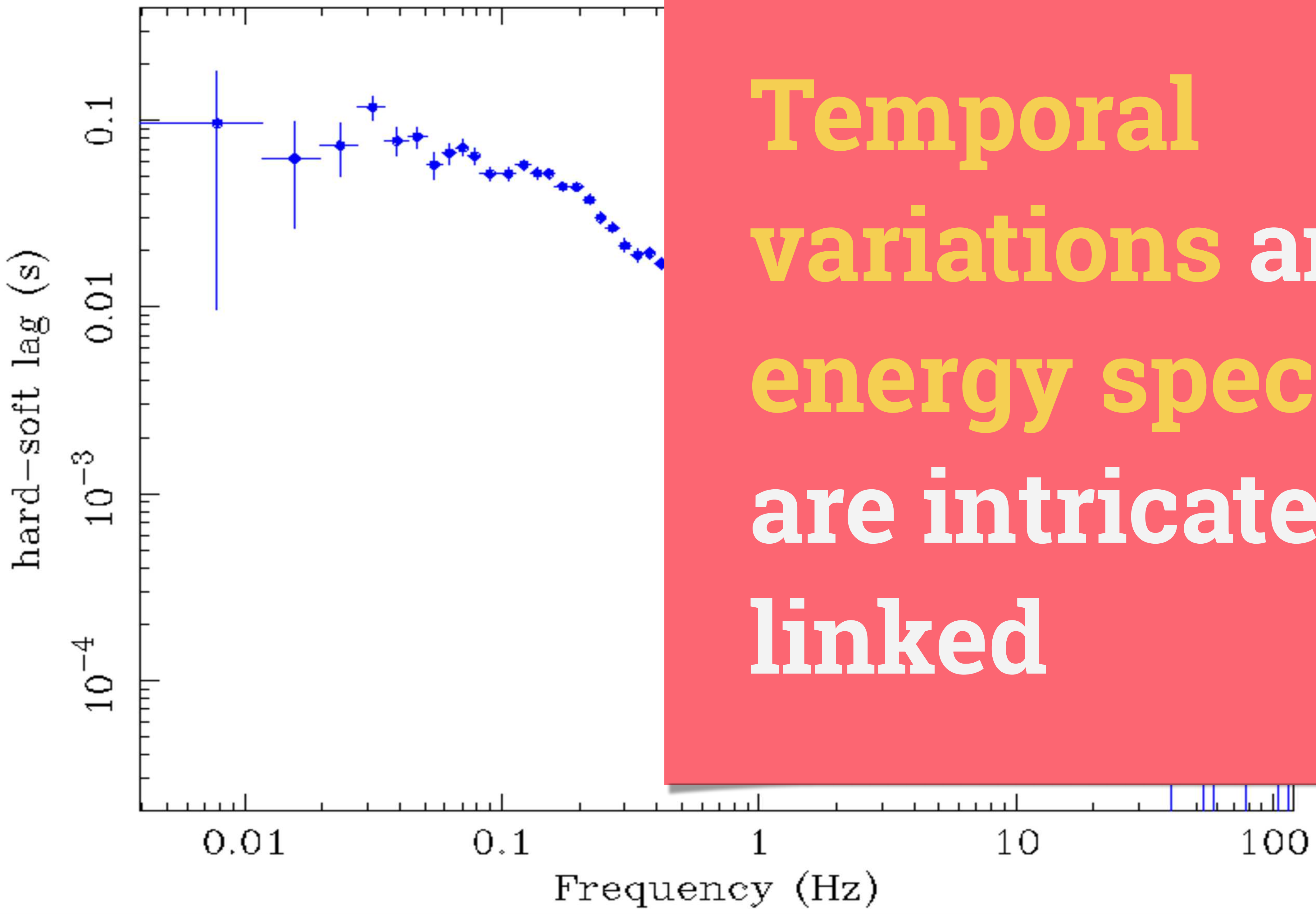


1H0707-495: Uttley et al, 2014



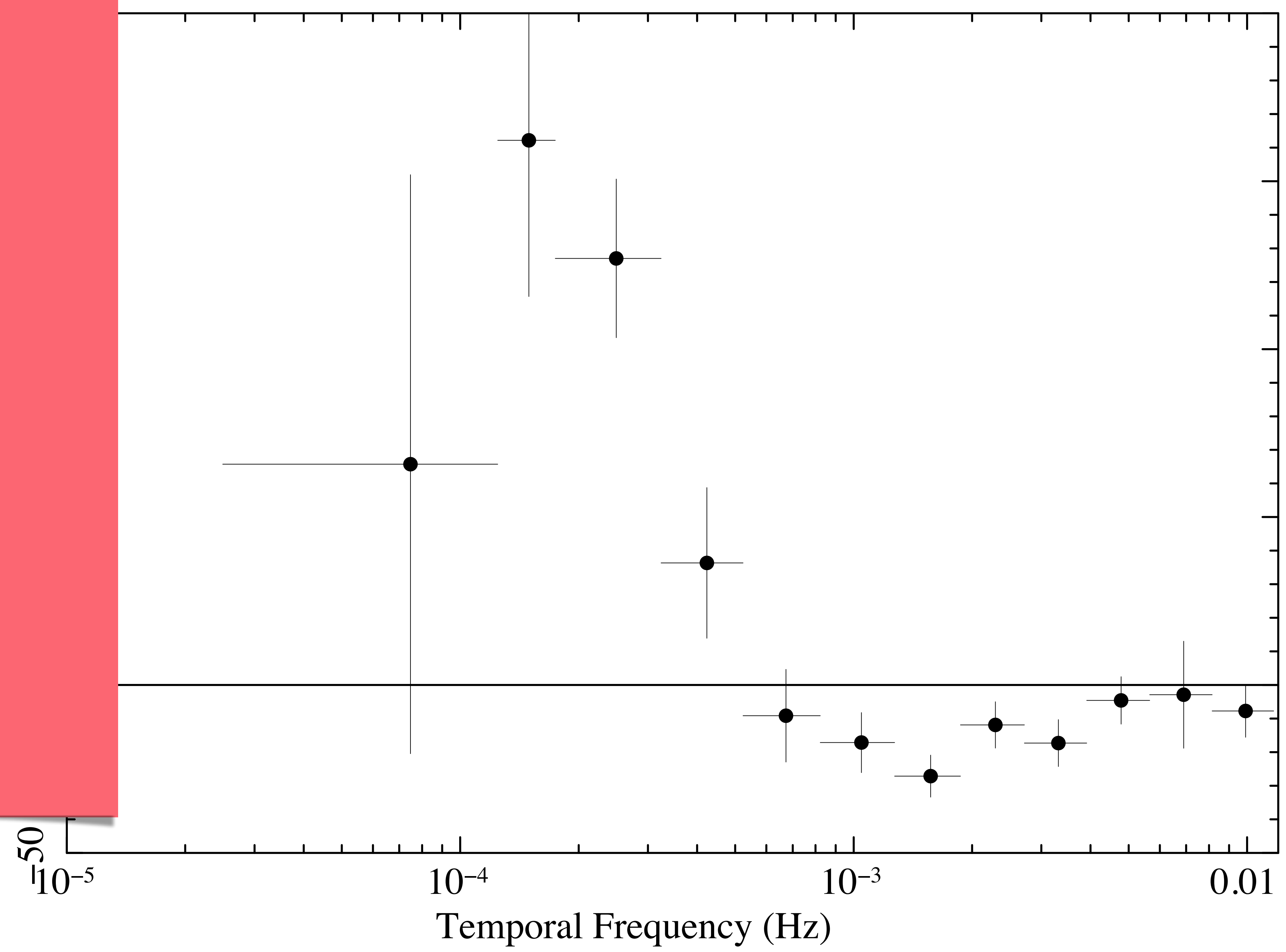
Lag-Frequency Spectrum

Cygnus X-1: Nowak, 2000

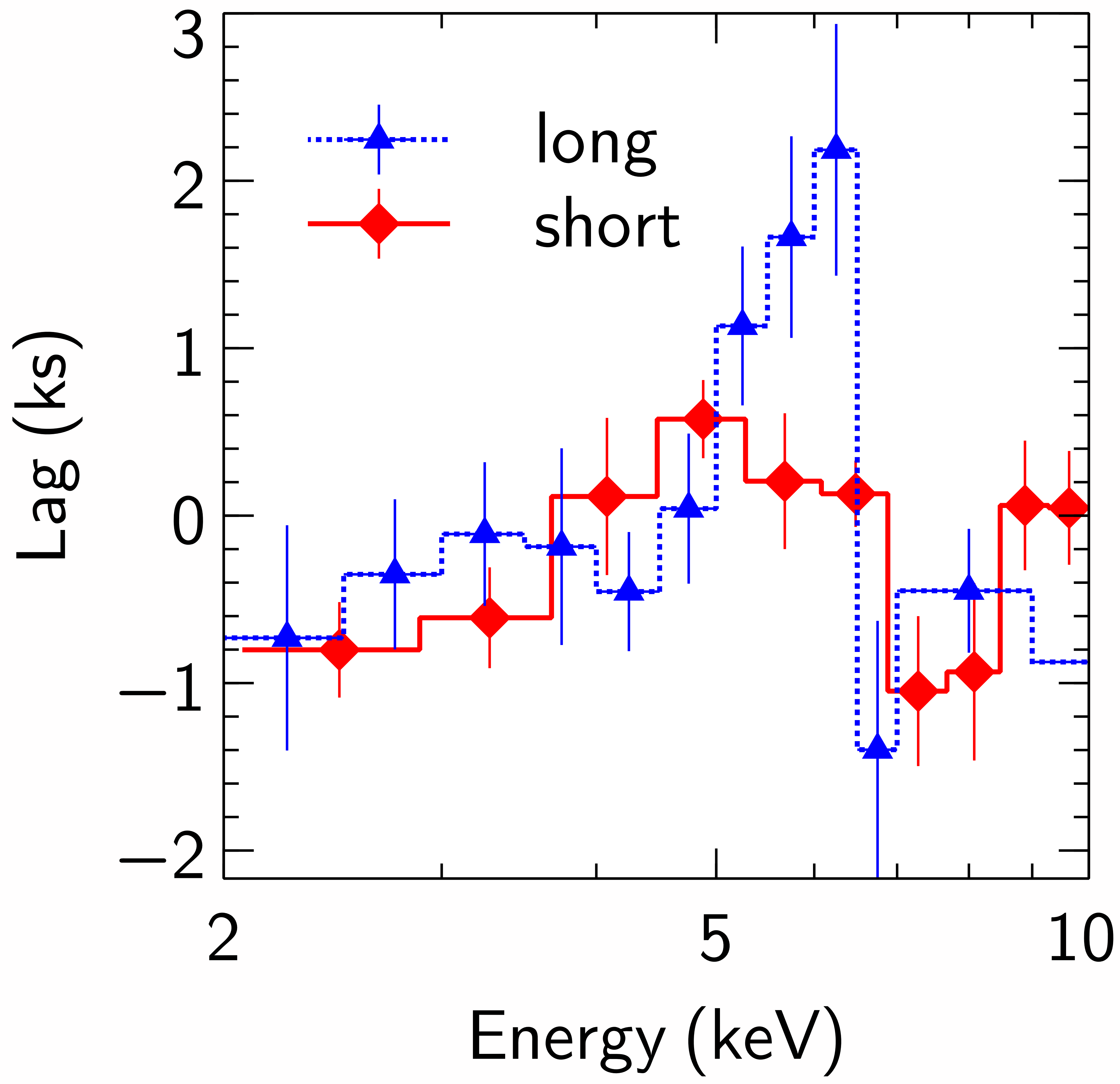


Temporal variations and energy spectra are intricately linked

1H0707-495: Uttley et al, 2014



Lag-Energy Spectrum



Let’s do this ourselves!