(Quasi) Periodic Signals in Regularly Sampled Data

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Image: NASA/JPL-Caltech

Outline

- Evenly-spaced time series
- Recap: Fourier transforms, power spectra
- Wavelets, Hilbert-Huang transform
- Dynamical power spectrum
- Signals from:
  - Stellar-mass black holes
  - Neutron stars
  - Regular stars
  - Active galactic nuclei (super-massive black holes)
- Cross-spectral analysis techniques ("spectral-timing")
- Stingray: open-source analysis software

Evenly-spaced time series

- Signal period << observation length
- In X-rays and gamma-rays, we count photons. It's very possible to have zero counts -- "sparse" light curves are common
    - Instead of saving light curves with lots of zeroes, we use event lists
    - Analysis *dt* might be milliseconds, but detector *dt* can be microseconds or nanoseconds!
- In optical etc., bright-enough sources mean you detect flux above background in every time bin (e.g., every 30 seconds)

Fourier transforms

- Observed light curves can vary on timescales from microseconds to years
- Shorter (< 1 minute) variability: Fourier analysis!
  - Study time domain **f** in the frequency domain $\hat{\mathbf{f}}$
  - Break down light curve into sine waves, take amplitude of sines at each frequency

Image: L. Barbosa via wikiMedia

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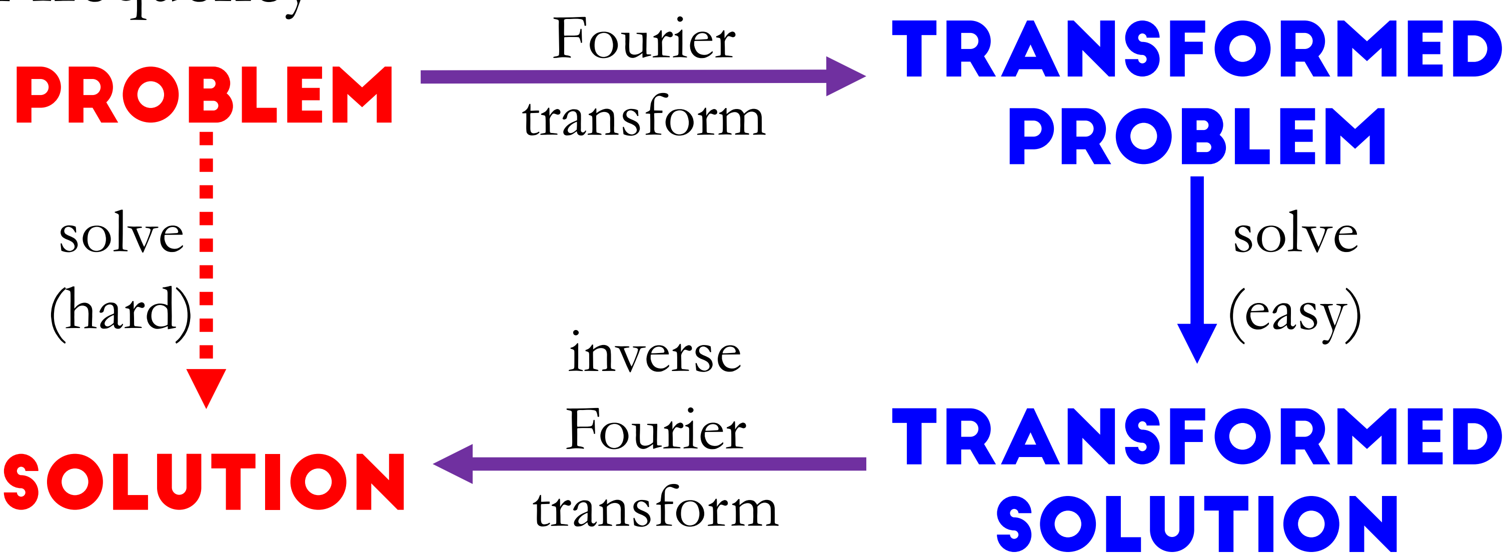


Applying Fourier transforms to data

Time domain

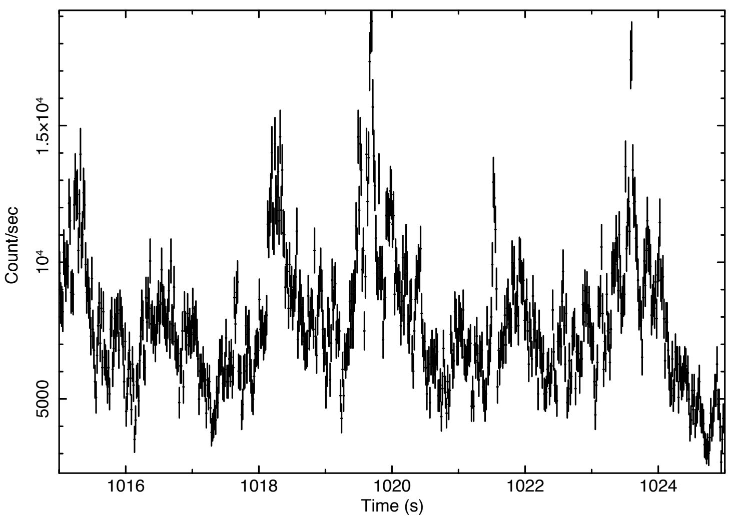
Light curve

$x(t) \rightarrow X(\nu)$

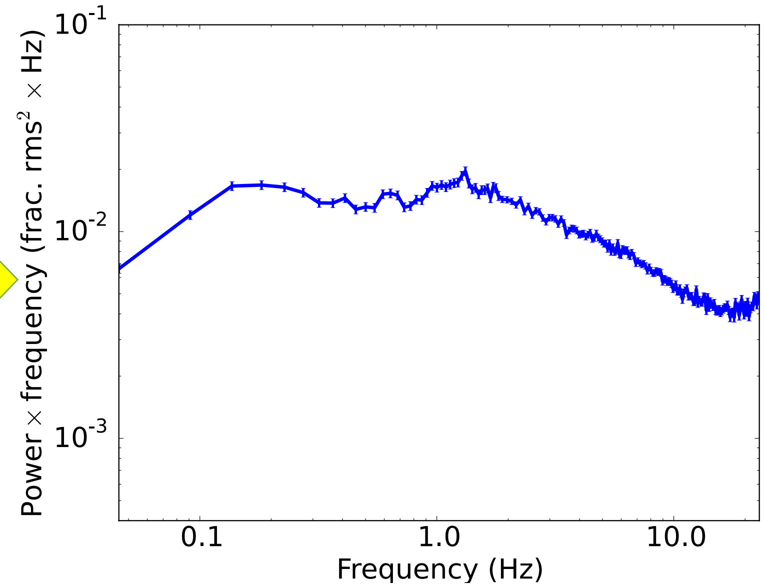
$P(\nu) = X(\nu)X^*(\nu)$
$= |X(\nu)|^2$

Frequency/Fourier domain

Power density spectrum



FOURIER TRANSFORM^2



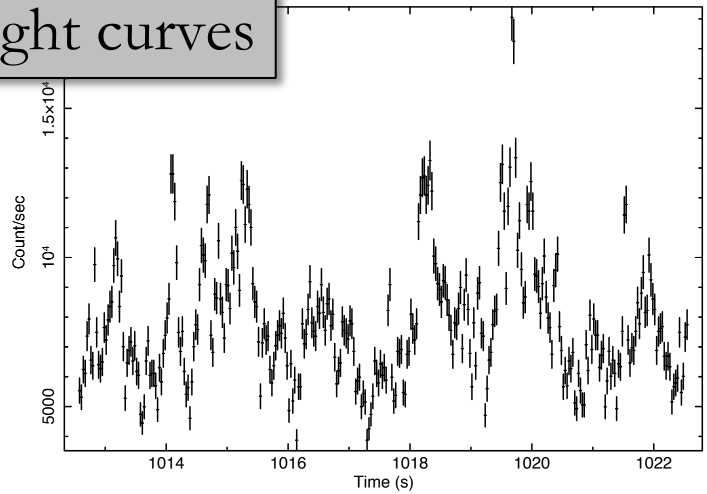
Light curve broken into equal-length chunks,
take power spectrum of each chunk,
average those together

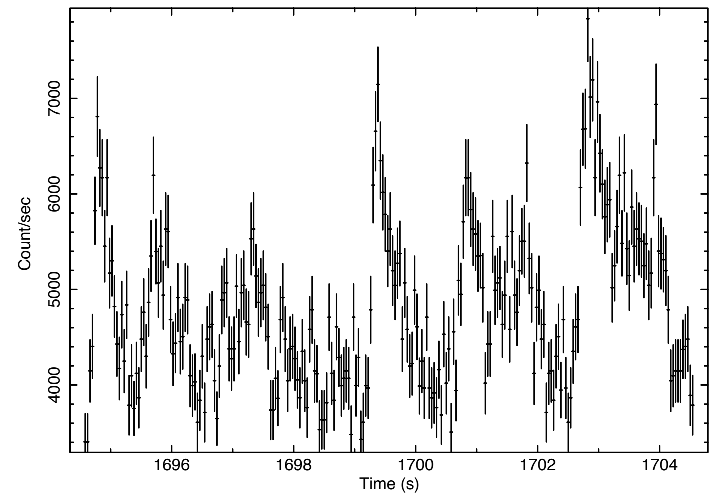
X-ray variability: Hard to see by eye

Noise: Cygnus X-1

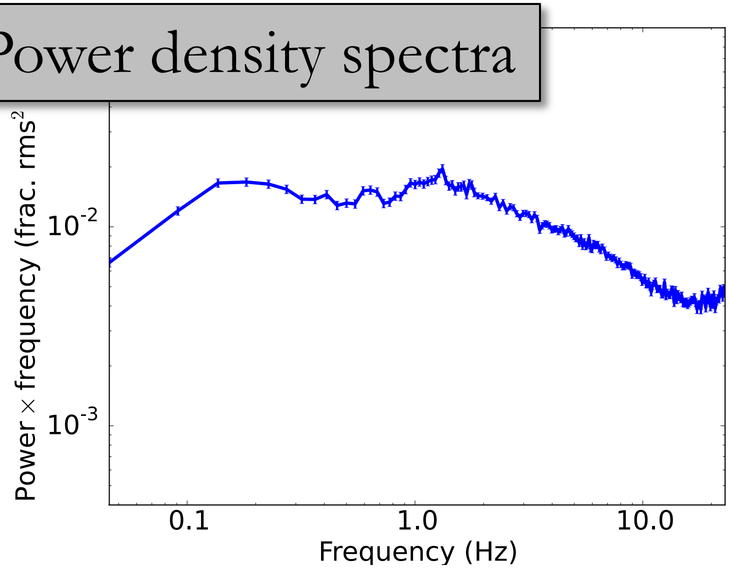
Signal: GRS 1915+105

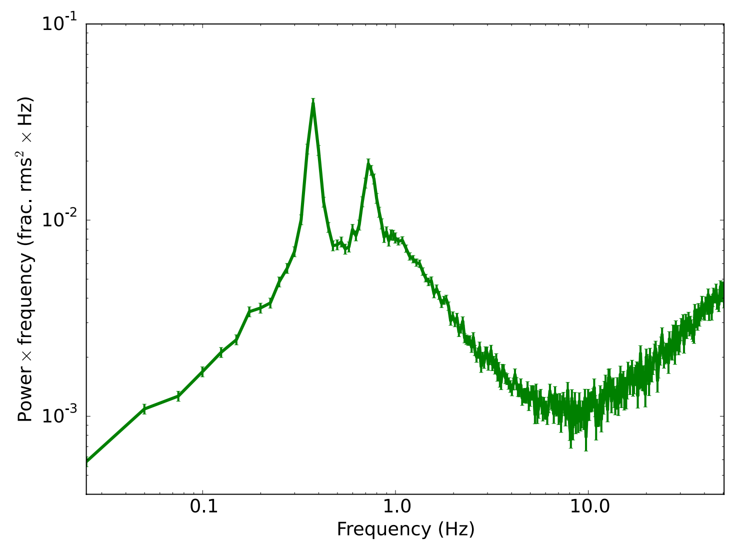
Light curves





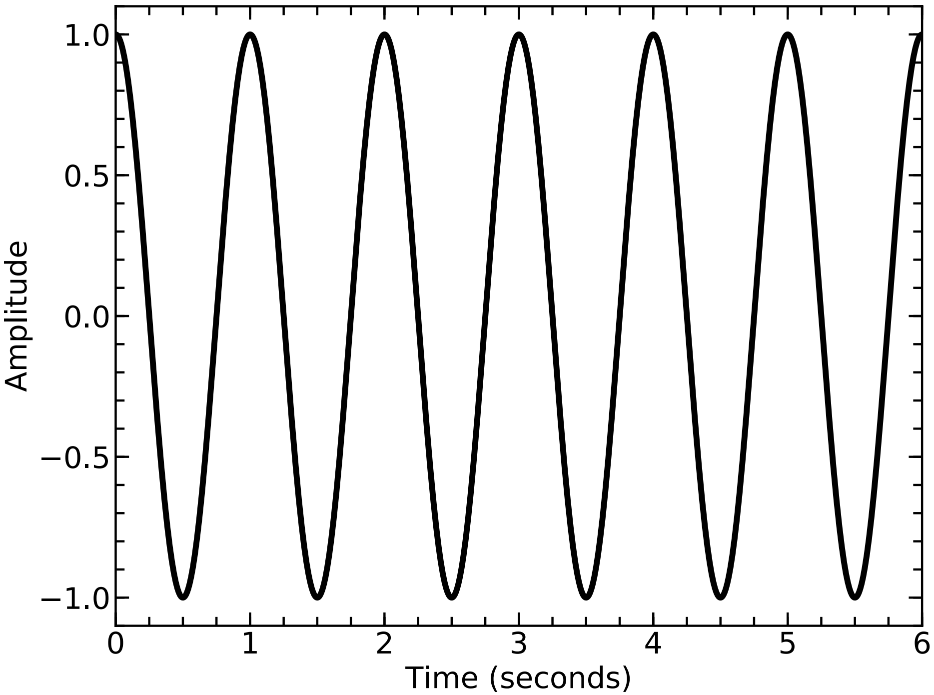
Power density spectra

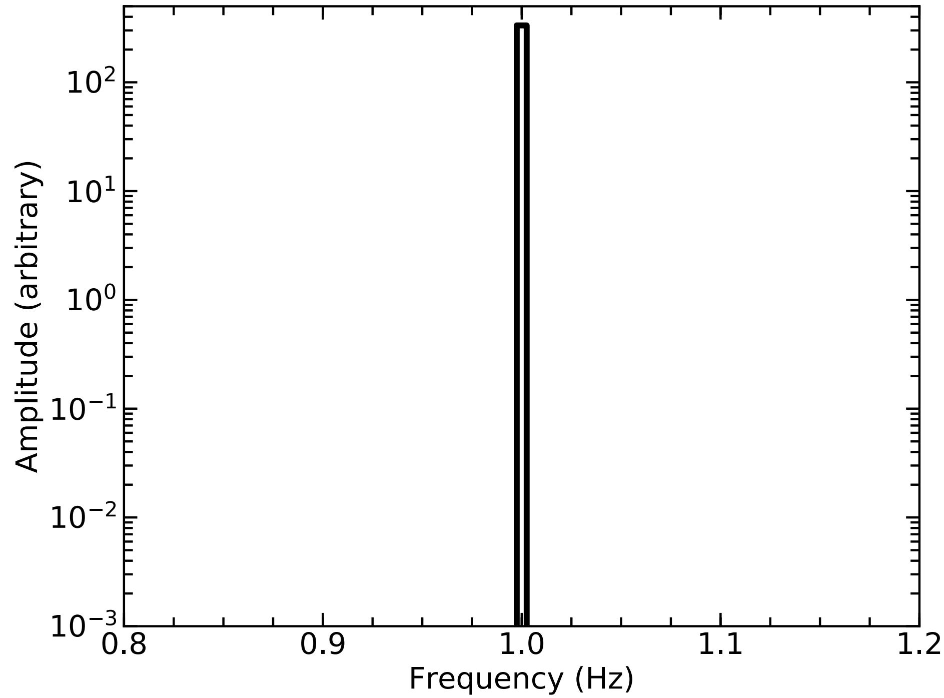




QPOs → Damped harmonic oscillators

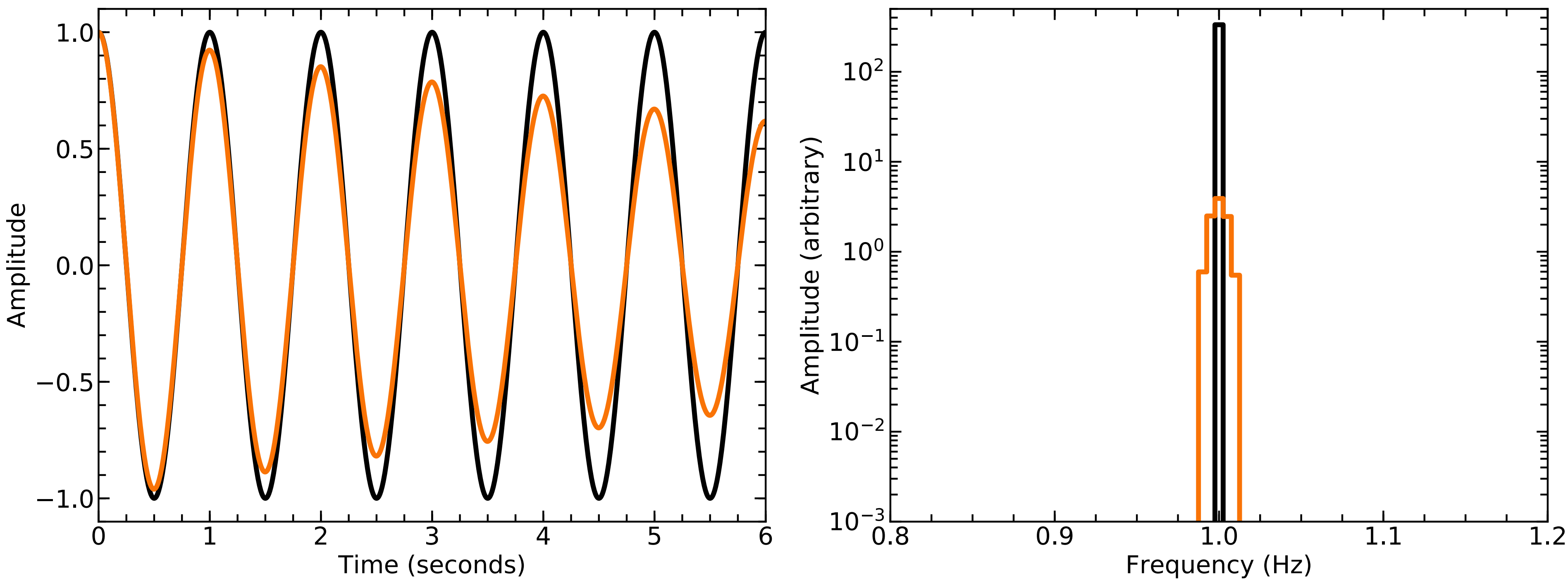
$y = \cos(\omega t)$





QPOs → Damped harmonic oscillators

$$y = \cos(\omega t) \times e^{-bt}$$



b=0

b=0.08

QPOs → Damped harmonic oscillators

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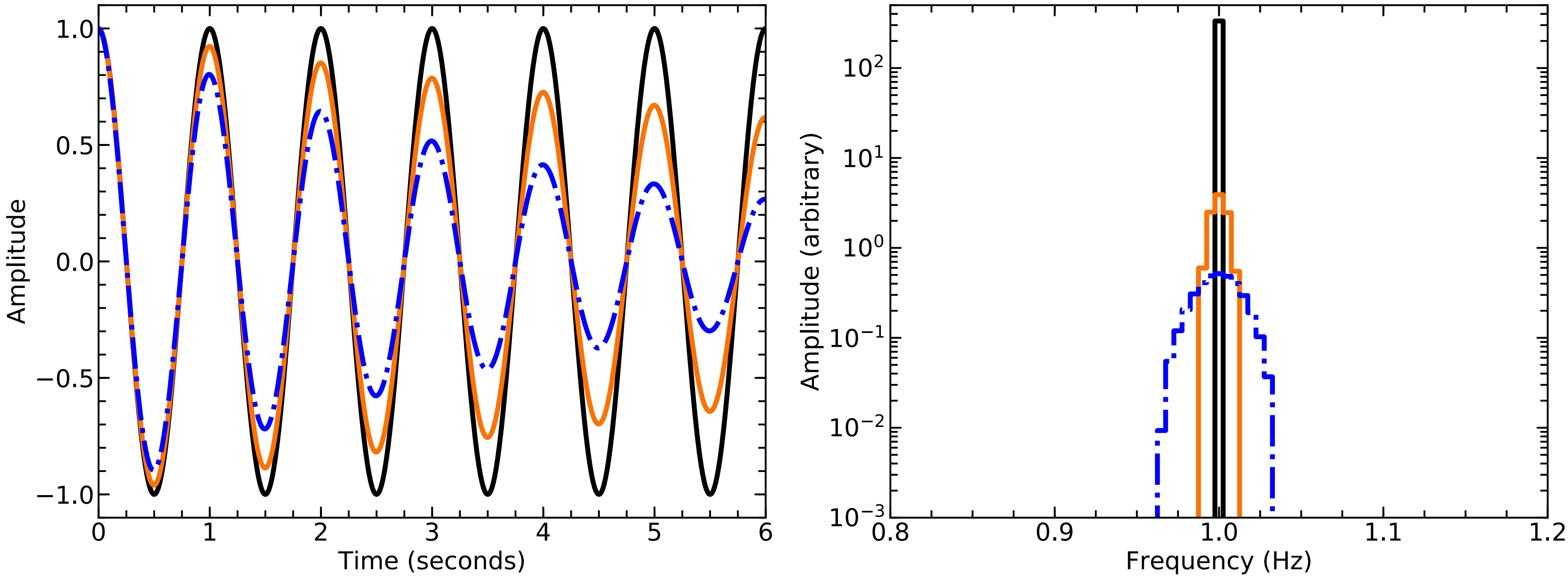

b=0

b=0.08

b=0.22

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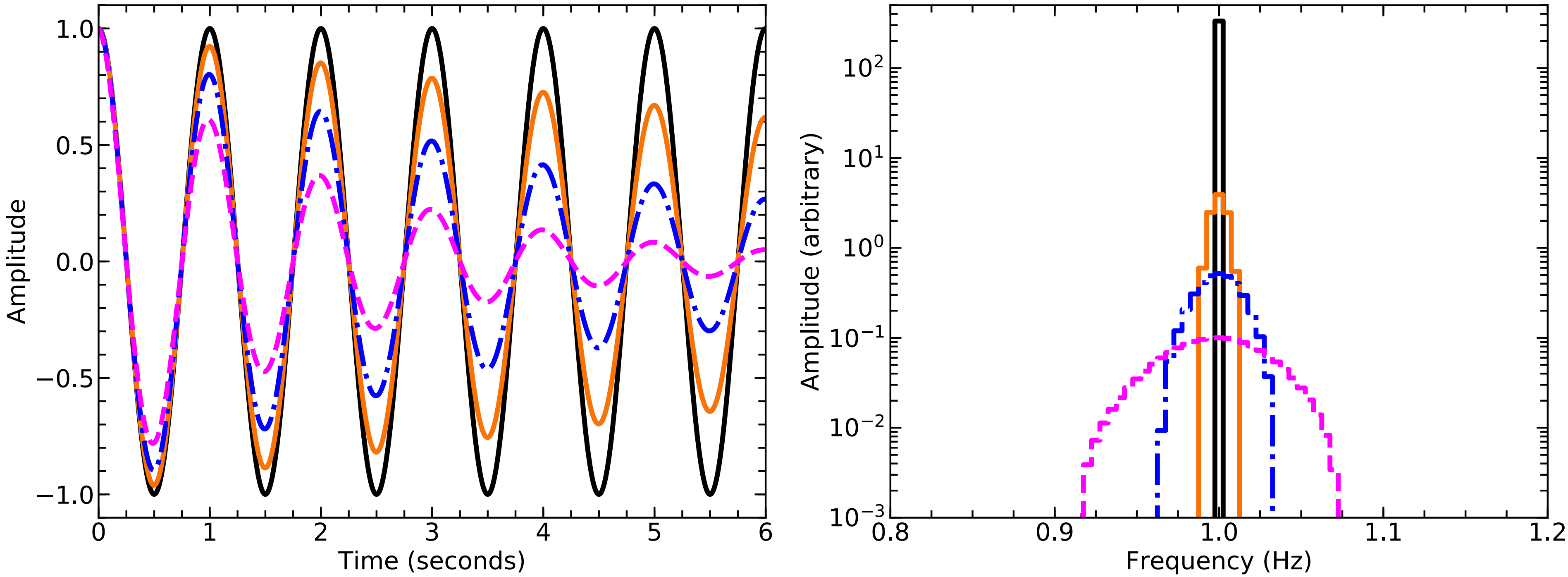


b=0 b=0.5

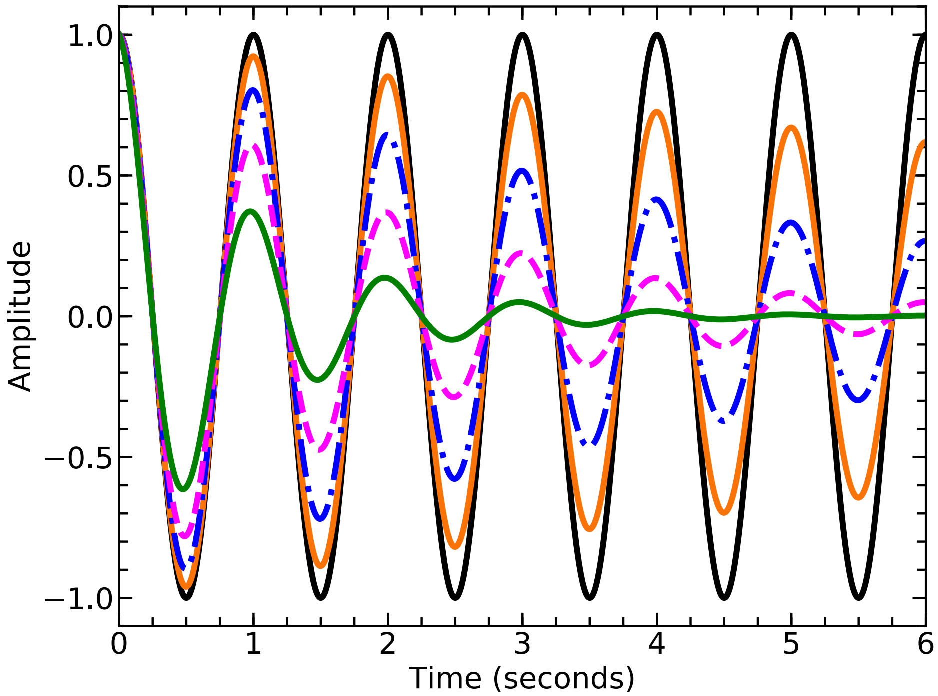
b=0.08

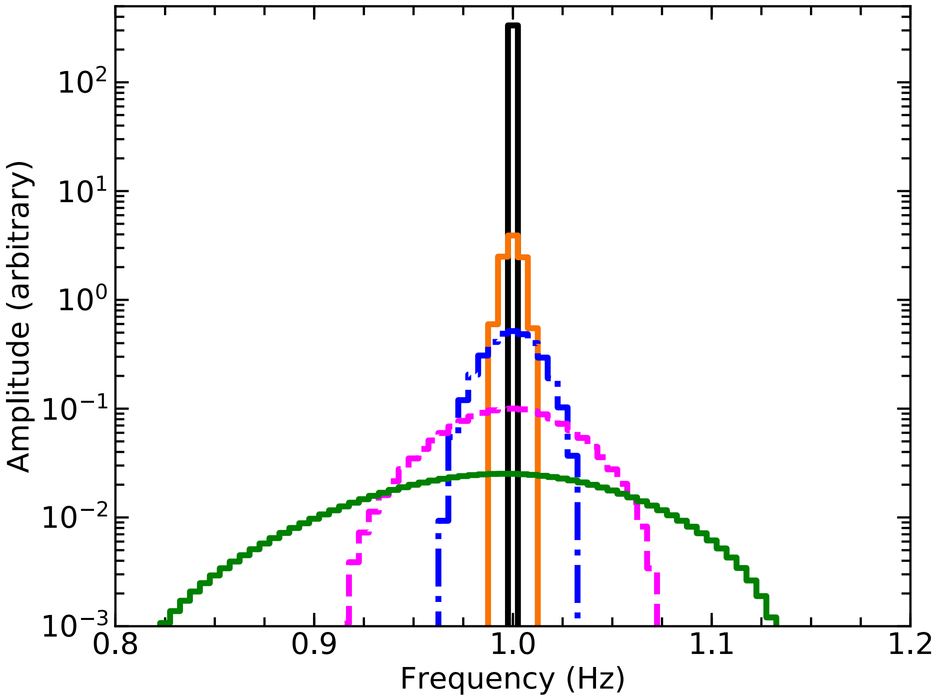
b=0.22

QPOs → Damped harmonic oscillators

$$y = \cos(\omega t) \times e^{-bt}$$

The stronger the damping, the wider the peak





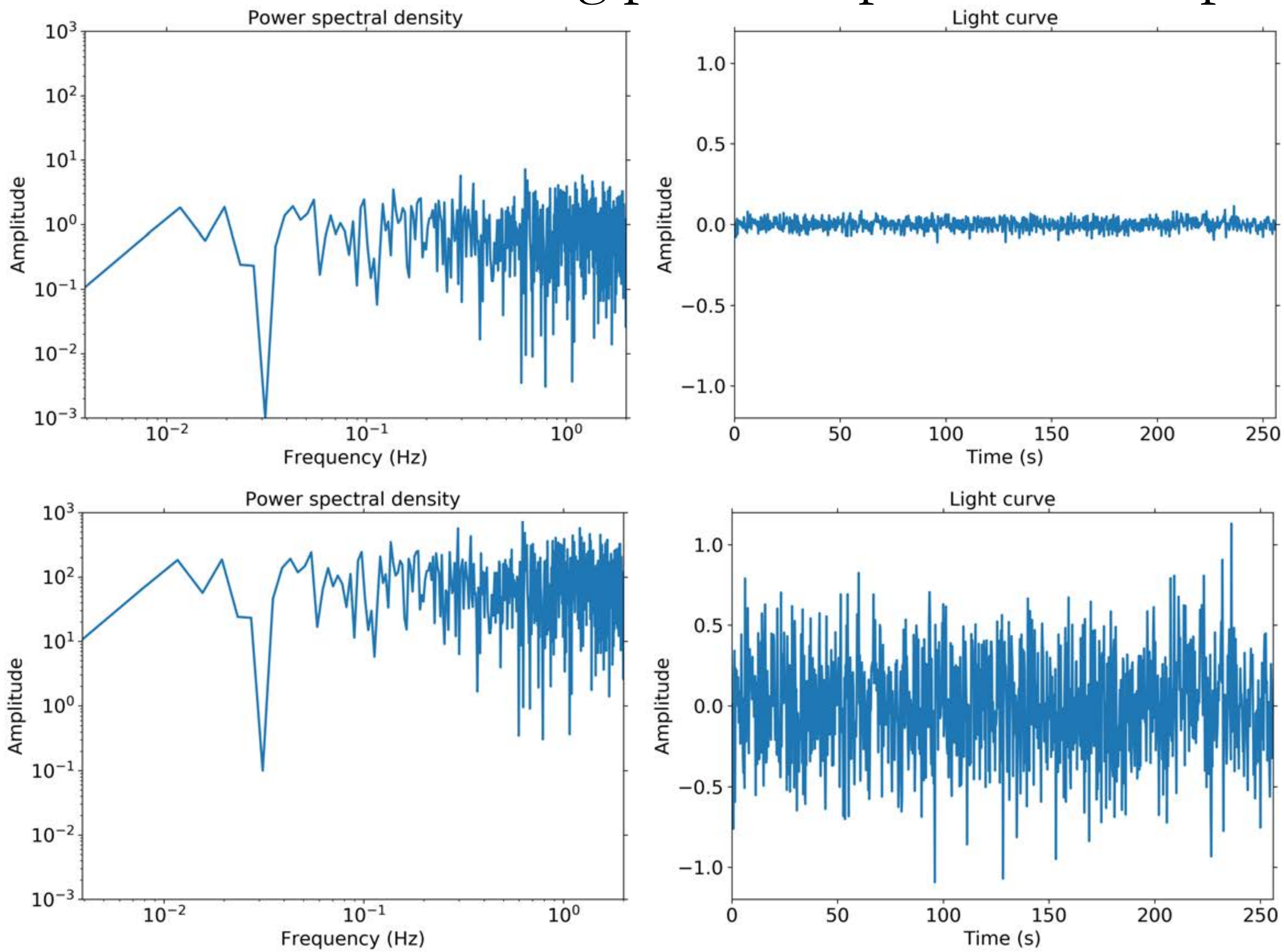
b=0 b=0.5

b=0.08 b=1.0

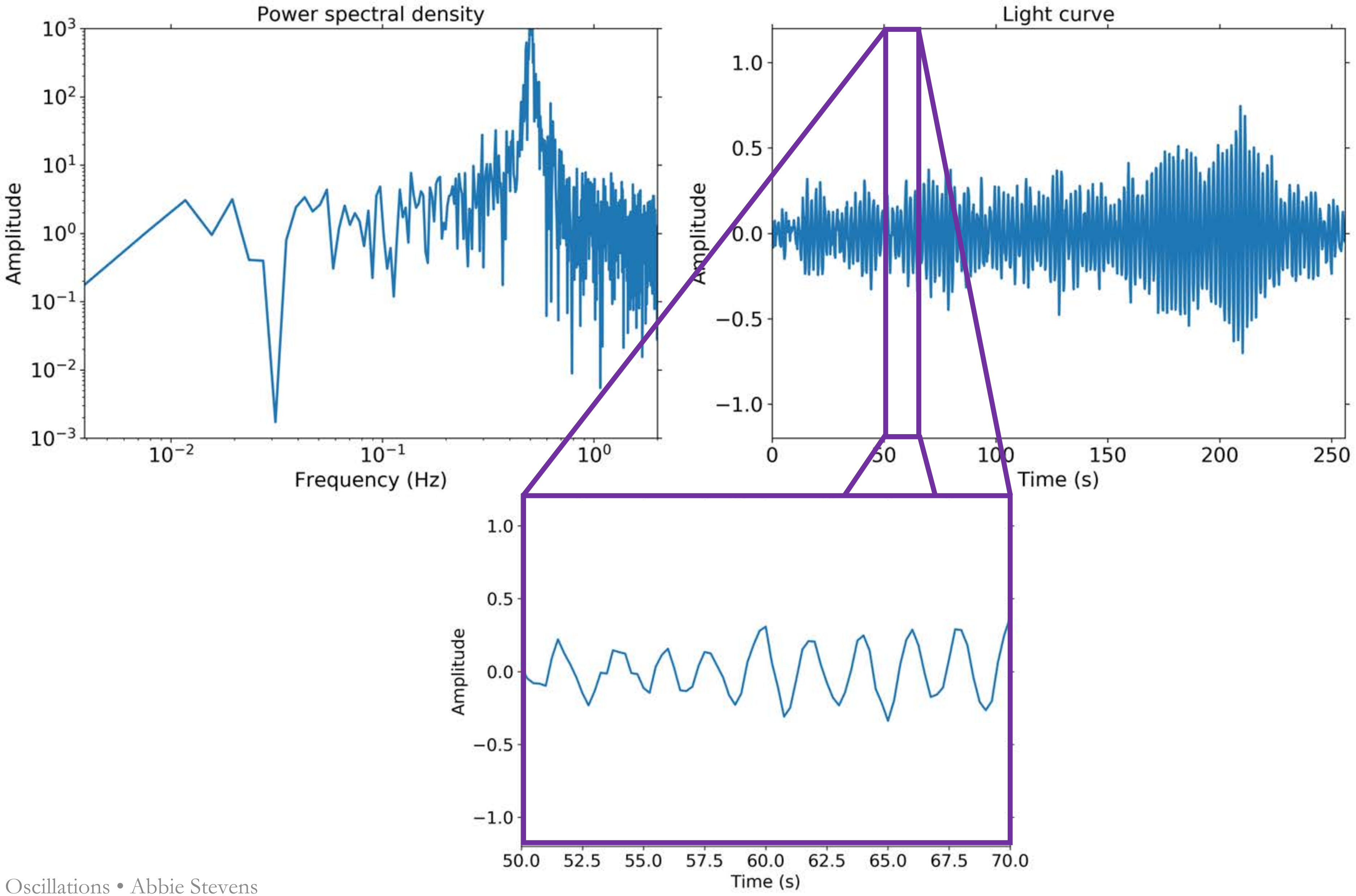
b=0.22

Poisson noise ("white noise")

Poisson noise from counting photons; power-law slope=0

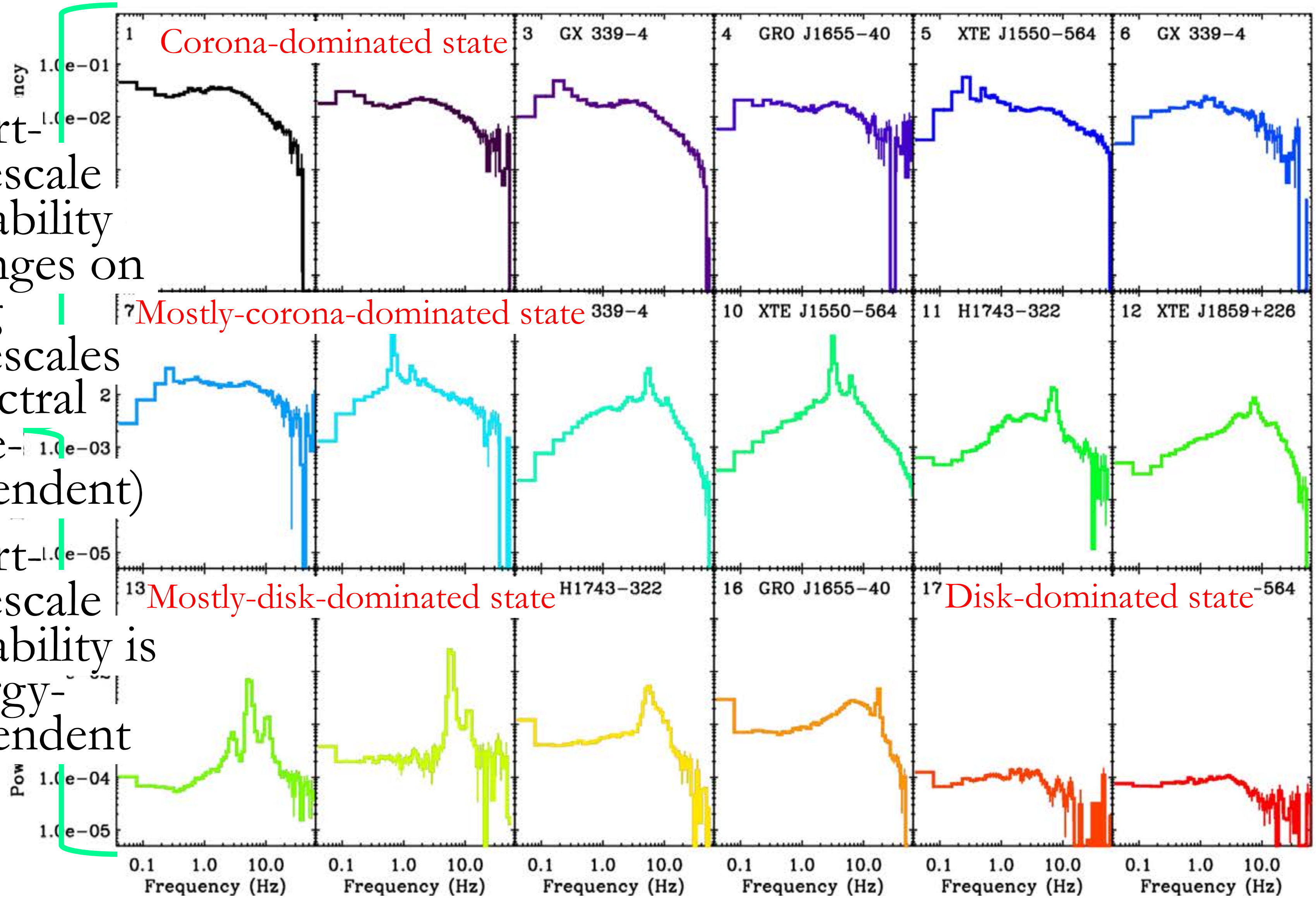


Poisson noise + Lorentzian QPO



Power spectral density (periodograms)

- Short-timescale variability changes on long timescales (spectral state-dependent)
- Short-timescale variability is energy-dependent



If you want to read more, see the power colours paper by Heil+15a

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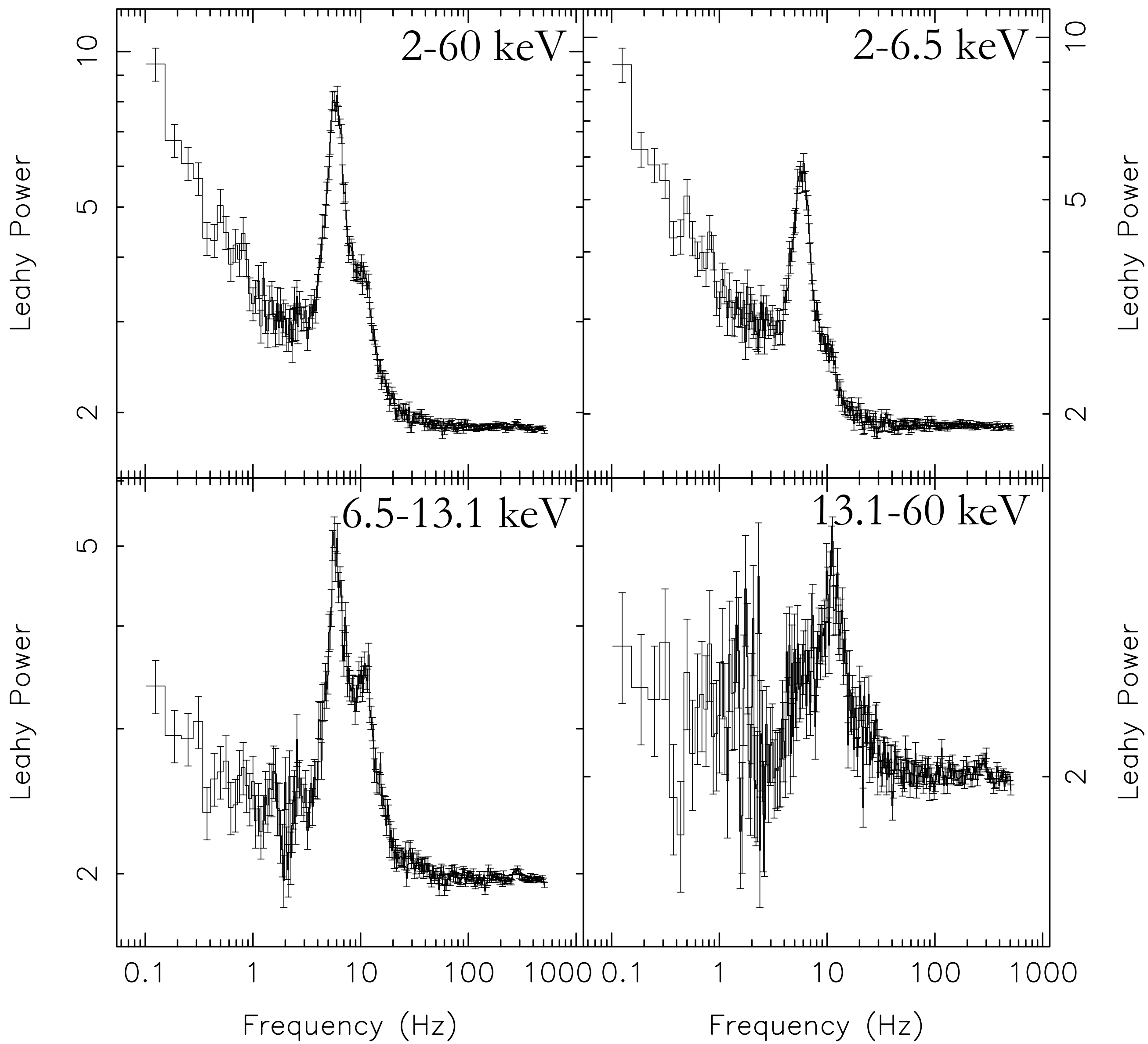
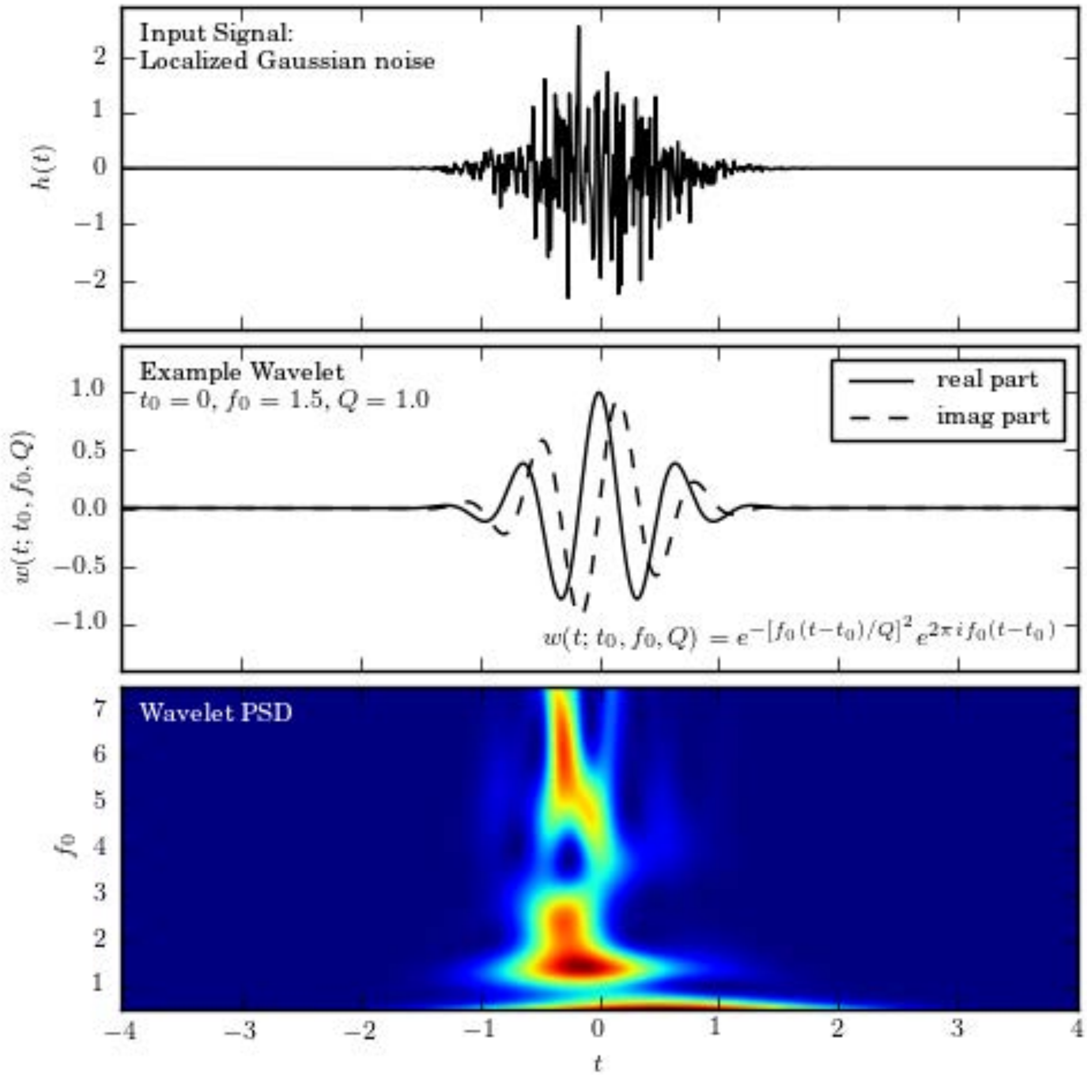


Homan+01

Wavelets are a thing

- Fourier products (like power spectra) don't have an intrinsic way to tell time resolution (i.e., when in the light curve the signal is present)
- Wavelets represent a signal in the time domain as well as the frequency domain



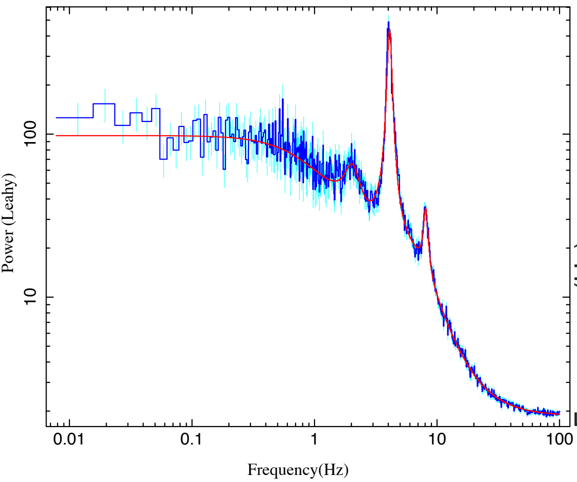
Resource: "A really friendly guide to wavelets", C. Valens, 1999

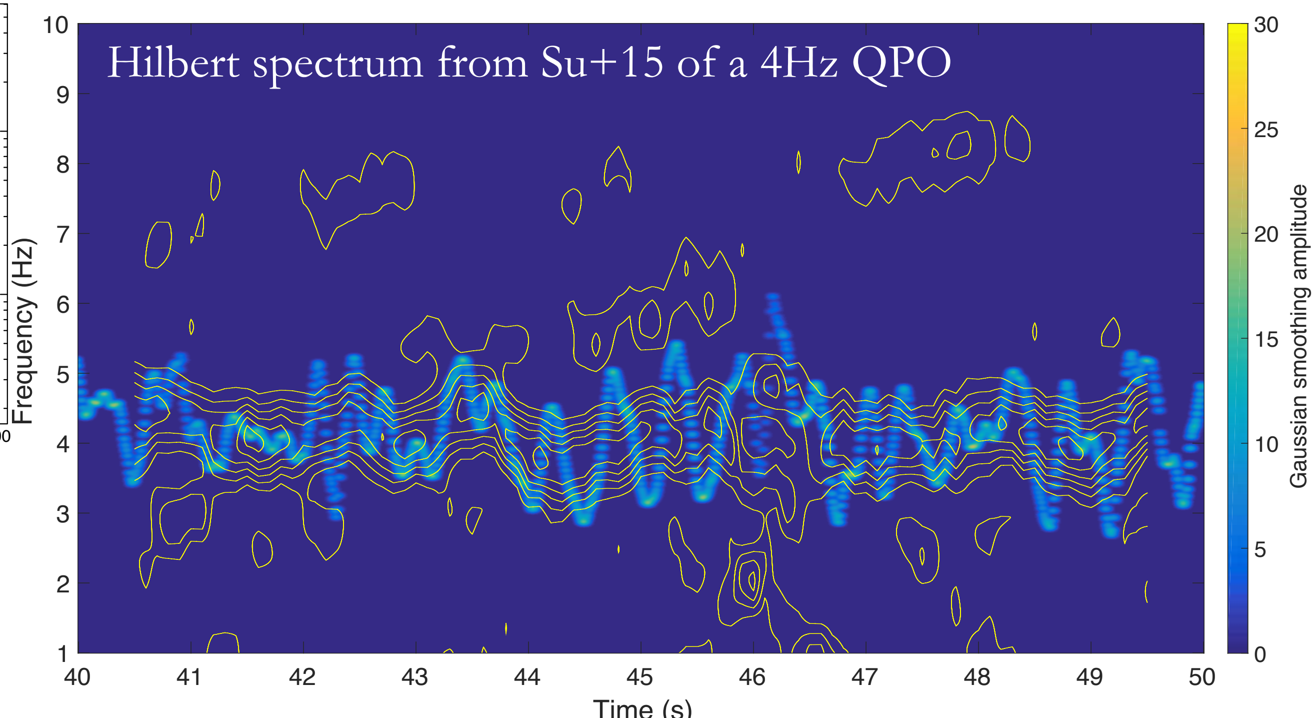
Wavelets aren't great though

- Averaged power density spectra (~50+ segments) follow a chi-squared distribution with 2 degrees of freedom, about the underlying true power spectrum
  - Errors are statistically well-defined and well-understood (and easy to compute!)
- Wavelets do not follow such a well-defined and well-known distribution
- No clear way to assess statistical significance of a signal (which is one of the things we often want to do)

Hilbert-Huang transform

- Frequency-domain product designed for data that are non-stationary and non-linear
- Like an instantaneous Fourier transform → gives (some) time localization!
- Error from standard deviation of (1000+) simulations

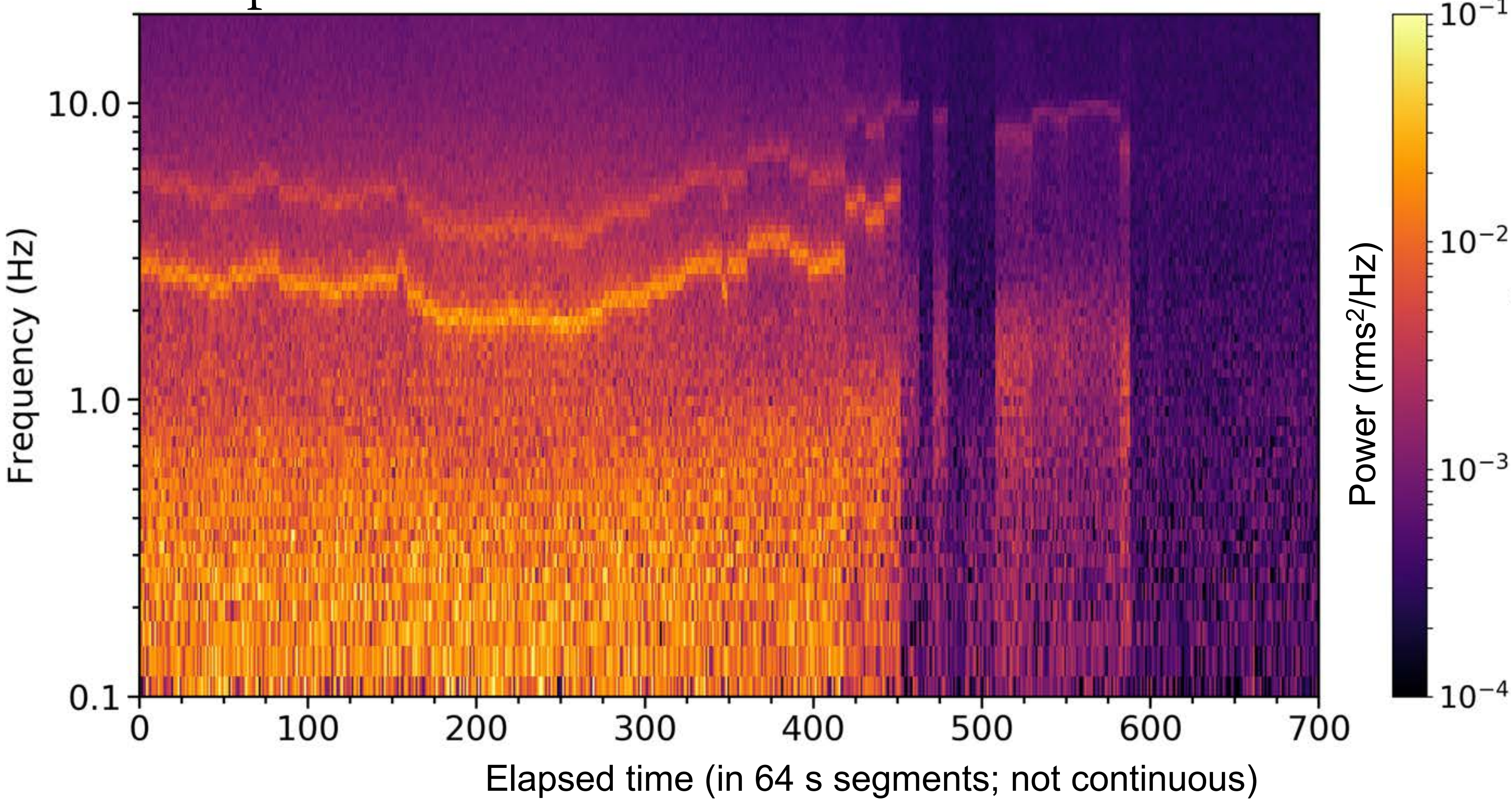




See Su+15 & refs therein for application to black hole data

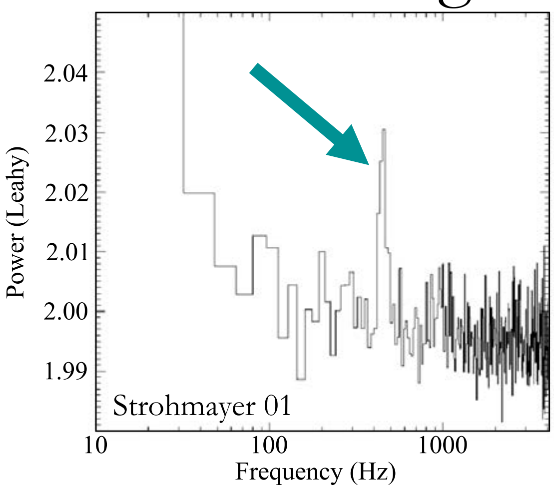
Dynamical power spectrum

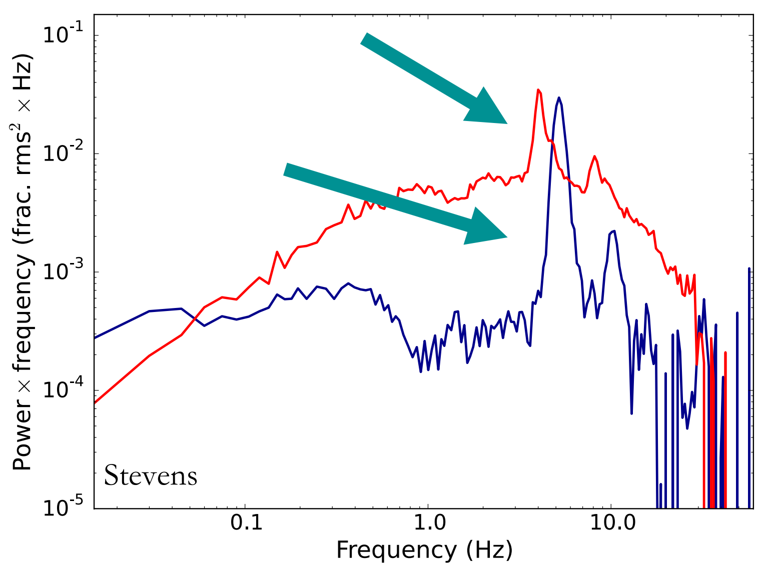
- Evolution of power spectrum in time
- Instead of averaging the segments together, plot them in a colormap

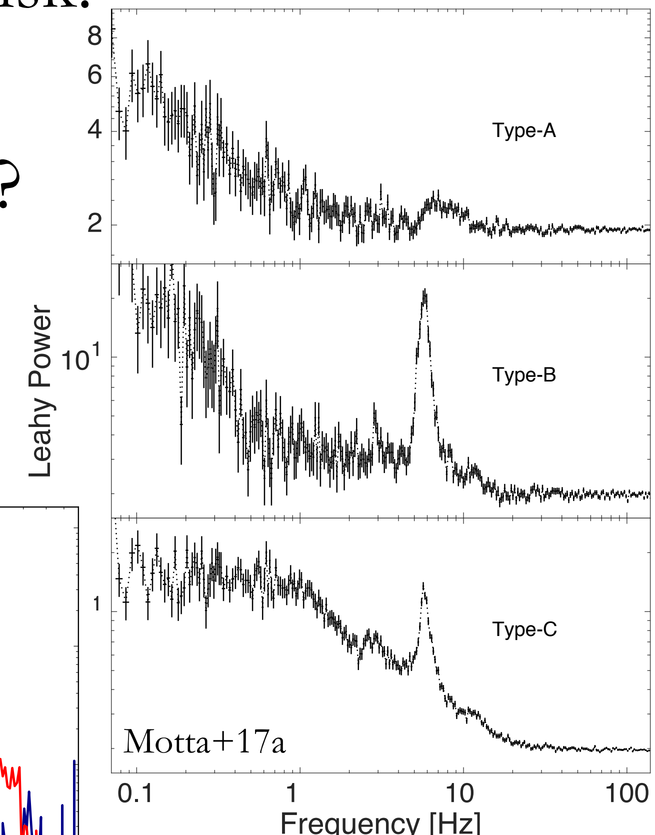


QPOs in black holes and neutron stars

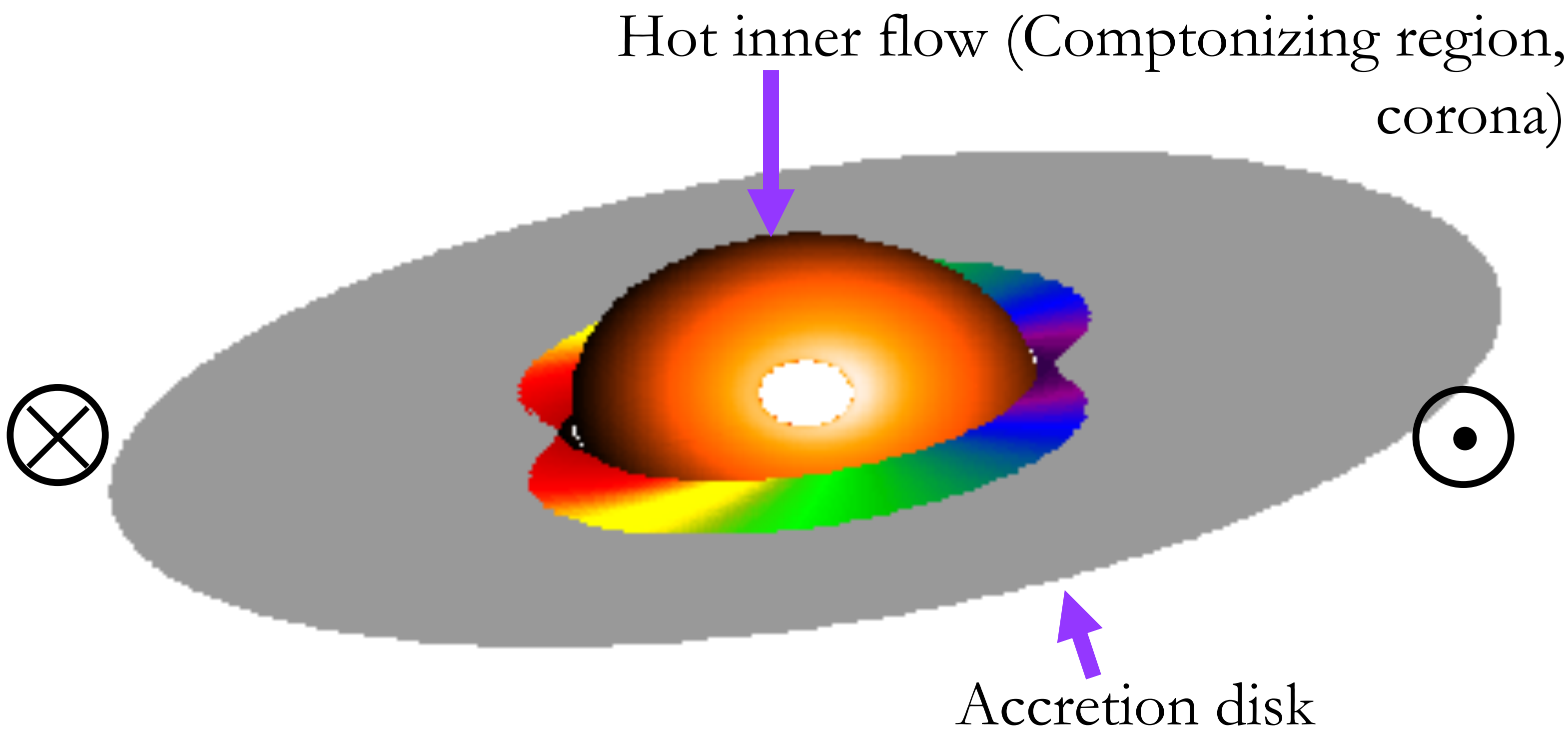
- High-frequency: 100's Hz
  - Hot Keplerian blobs in inner disk?
- Low-frequency: ~0.01-10's Hz
  - Precession of corona/hot flow? Magnetic warps in disk?







Low-freq QPOs: Lense-Thirring precession?



Disk color pattern: Doppler shifting and boosting of emission

Stella+Vietri '98; Fragile+Anninos '05; Schnittman, Homan+Miller '06; Ingram+09; Ingram+van der Klis '15; Fragile+16; Ingram+16a,b; Liska+18

See also: Accretion-Ejection Instability papers by Varniere et al.

Accreting neutron stars

Persistent pulsations from accreting millisecond X-ray pulsars

Transient burst oscillations from thermonuclear (Type 1) X-ray bursts

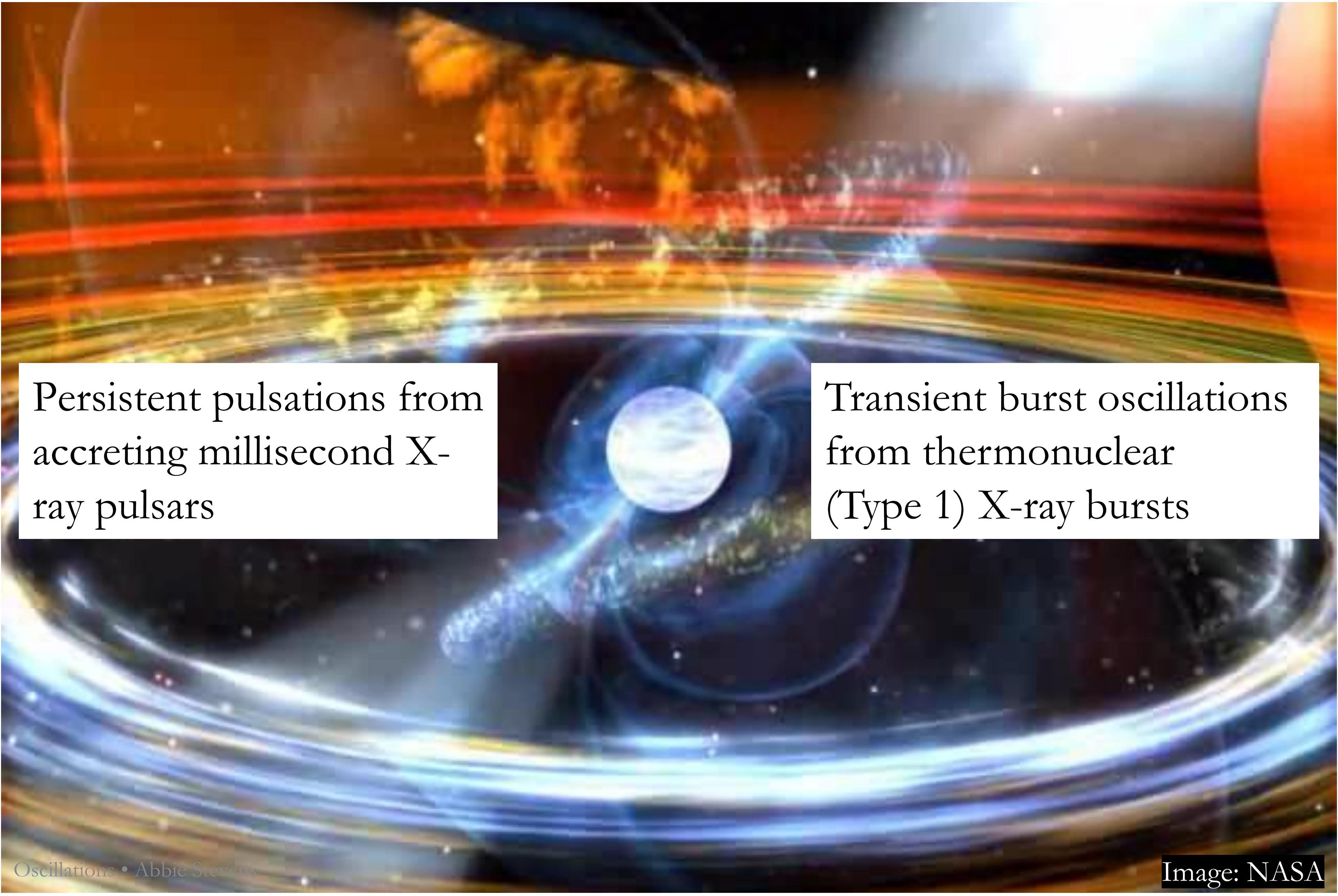
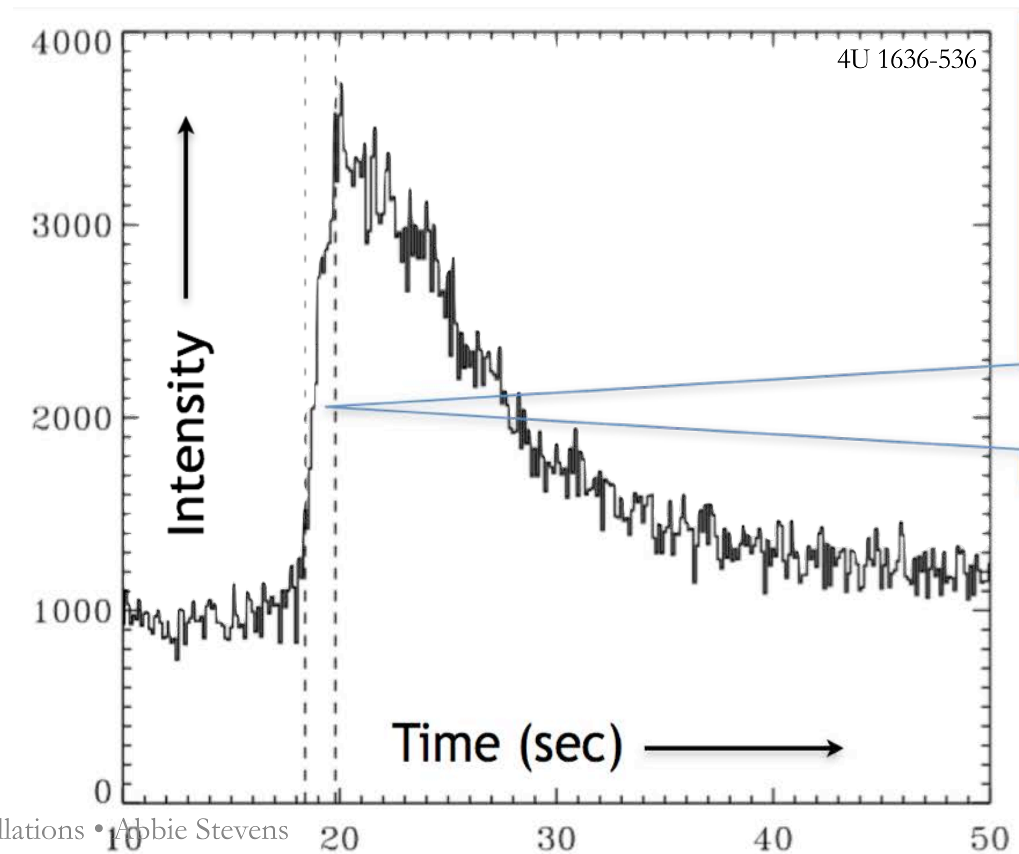
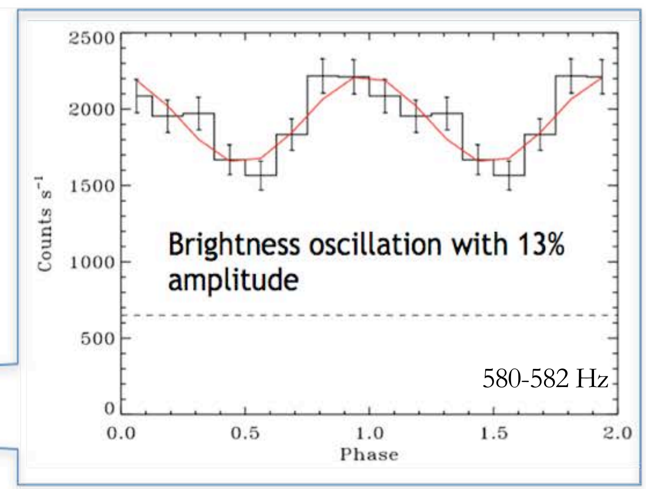


Image: NASA

Thermonuclear X-ray bursts

- Accreting material builds up on surface → nuclear burning
- Spectral evidence of coronal reprocessing of persistent emission or disk reprocessing of burst emission (Keek+18a)
- X-ray emission is coming from NS surface





Discovered by Strohmayer+96 with *RXTE*

Reviews: Galloway+08, Watts12, Bilous+Watts (arxiv:1812.10684)

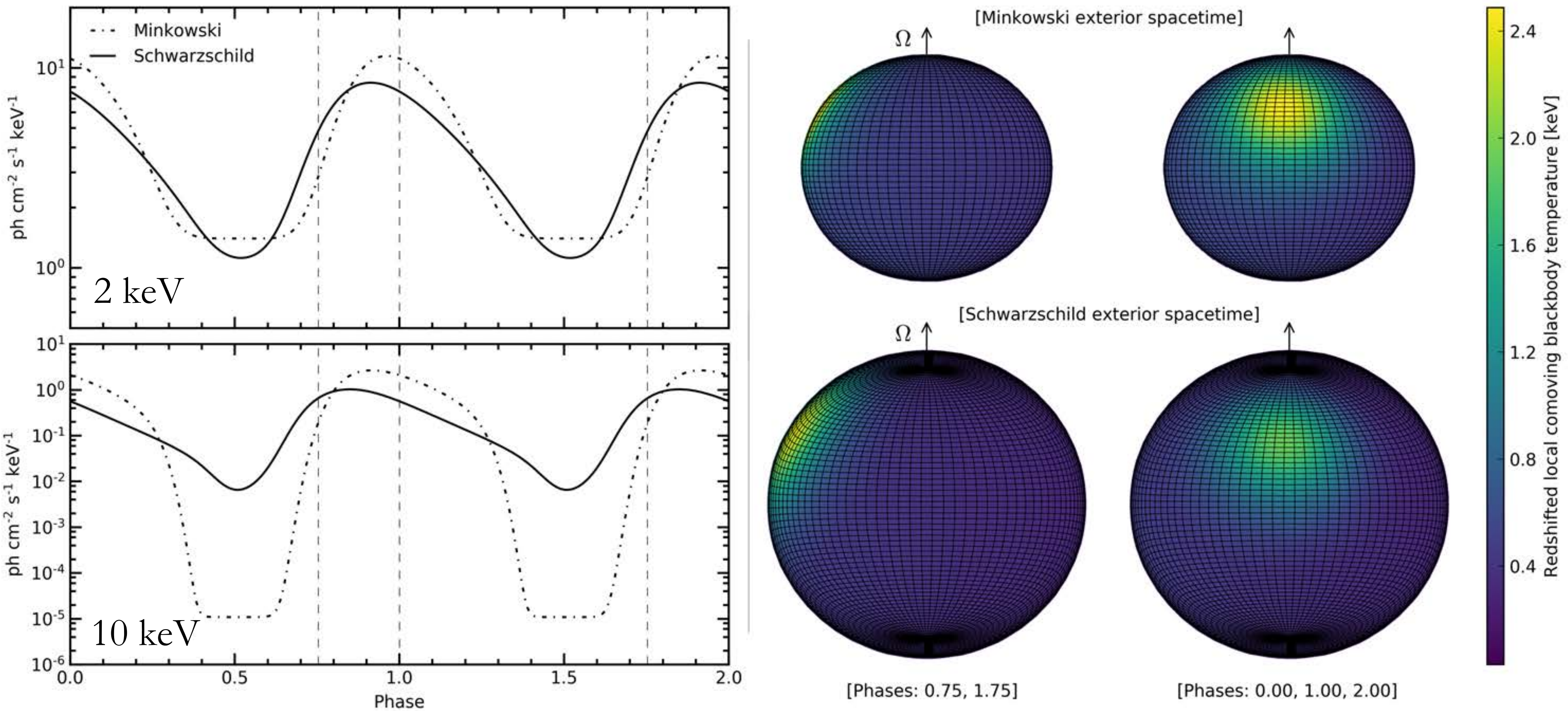
See MINBAR catalog by Galloway

Neutron stars and relativity

Slide thanks to
Anna Watts

- Lightbending: able to see ~3/4 of NS surface
- Typically, hotspot is visible for entire rotation

Watts et al. 2019,
arXiv:1812.04021



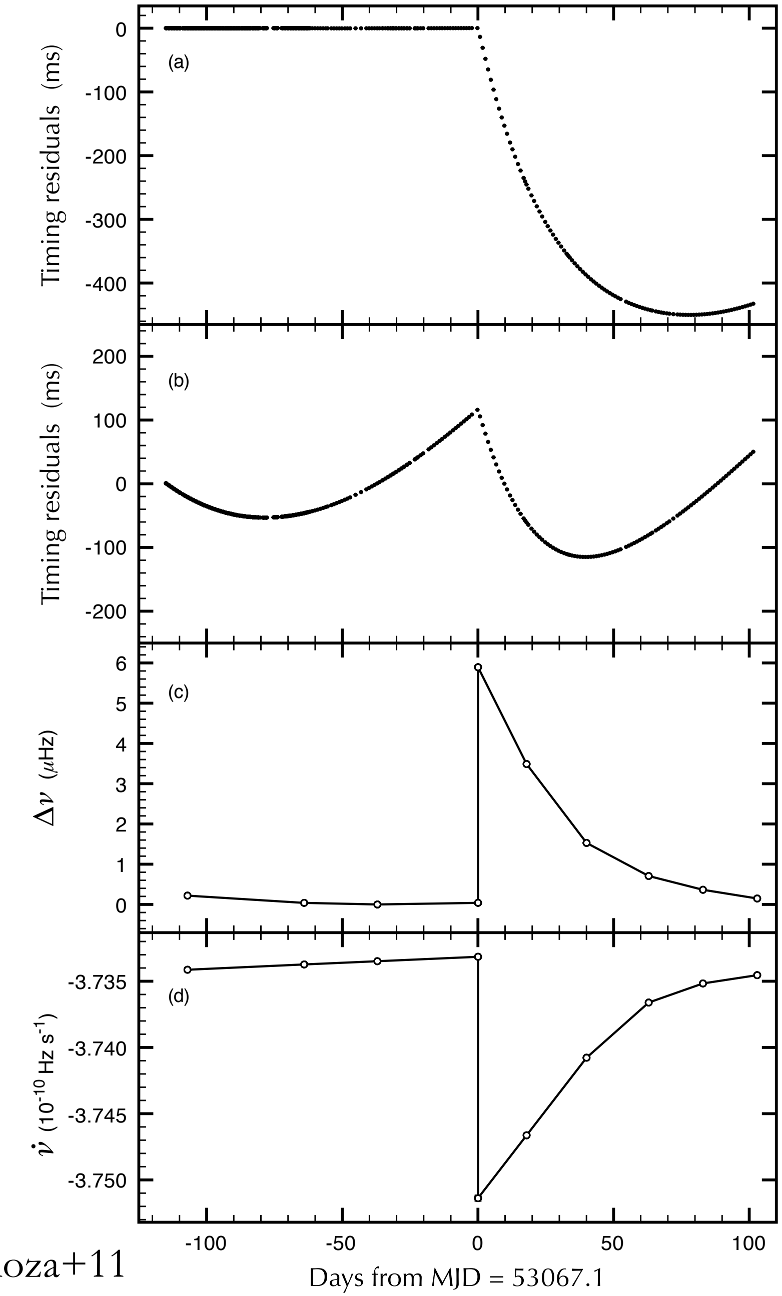
Mass 1.8 $M_{\odot}$, Equatorial radius 14 km, Spin 600 Hz

For papers on relativistic ray-tracing around rapidly rotating neutron stars, see references in Watts+16

Pulsations in neutron stars

- Spin-down: decreasing spin frequency (e.g., losing rotational energy to the environment)
- Spin-up: increasing spin frequency (e.g., accreting material and thus increasing angular momentum)
- Glitch: sudden change in spin frequency (due to superfluid NS core?)

- Seen in residuals of frequency or pulse timing



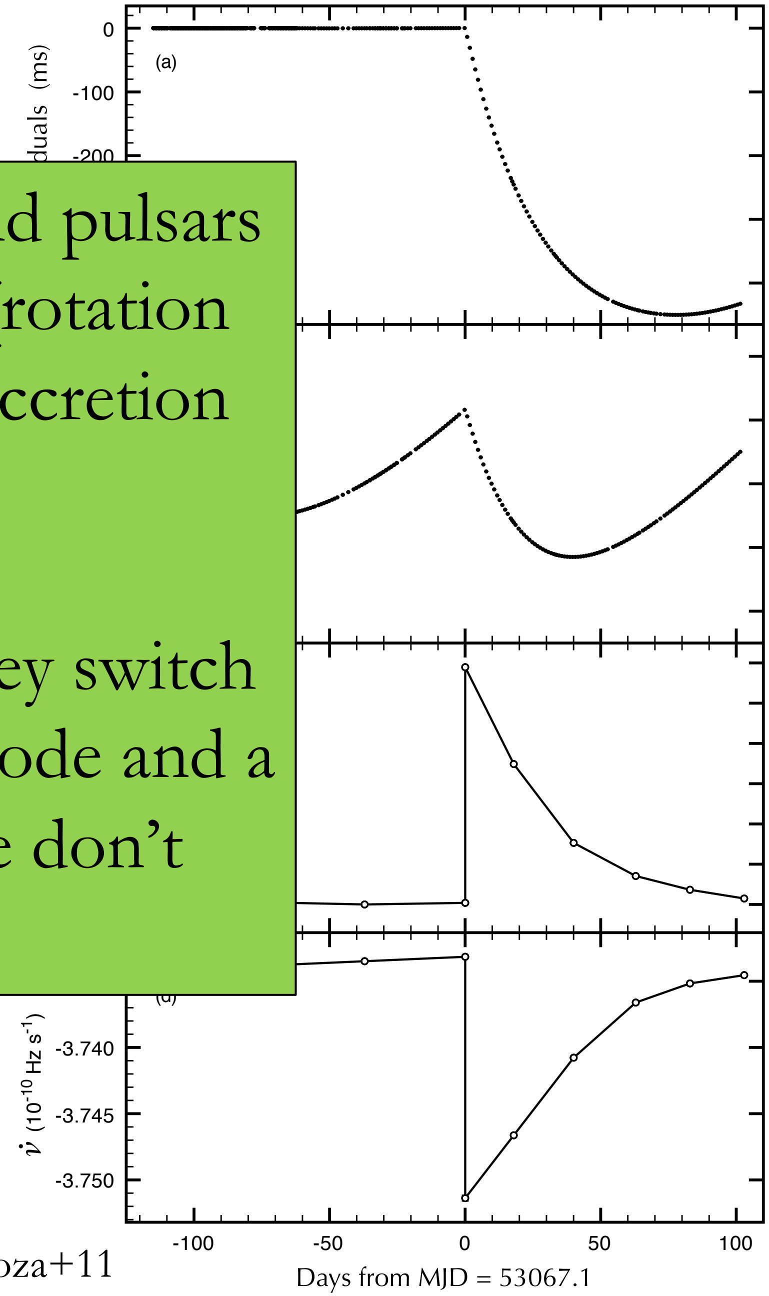
Espinoza+11

Pulsations in neutron stars

- Spin-down: decreasing spin frequency (e... energy to th...
- Spin-up: inc... (e.g., accreti... increasing a...
- Glitch: sudd... frequency (c... core?)
- Seen in residuals of frequency or pulse timing

Transitional millisecond pulsars switch between radio (rotation powered) and X-ray (accretion powered) pulsations.

In their X-ray state, they switch between a high-flux mode and a low-flux mode, and we don't know how or why.



Espinoza+11

Stellar pulsations

- Cepheid variables, RR Lyrae stars, Delta Scuti variables, Blahzko effect (long-period modulation of the periodicity)
- Period-luminosity relation makes them standard candles used as "cosmic distance ladder"
- Slow enough (periods > hours) that time-domain photometry is often used

M15 - Globular Cluster with RR-Lyrae Stars

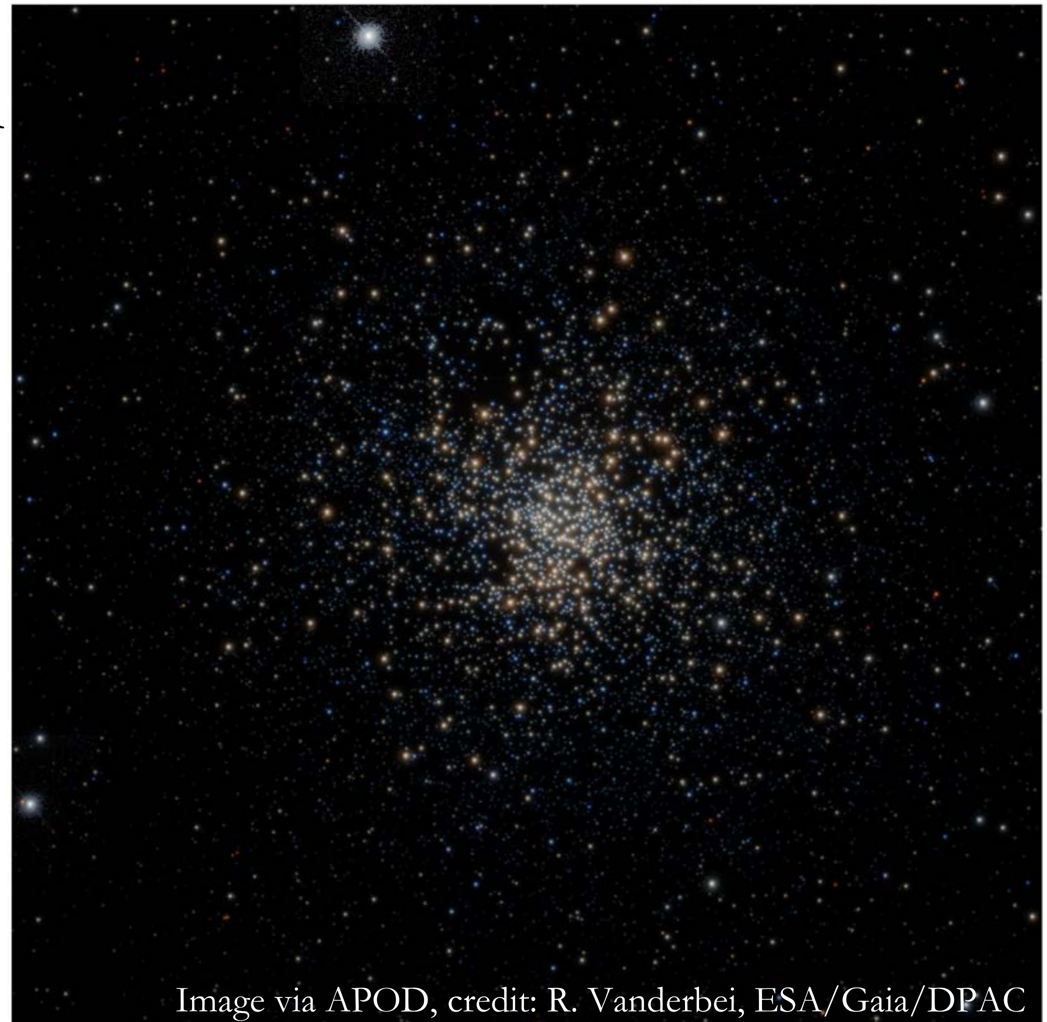
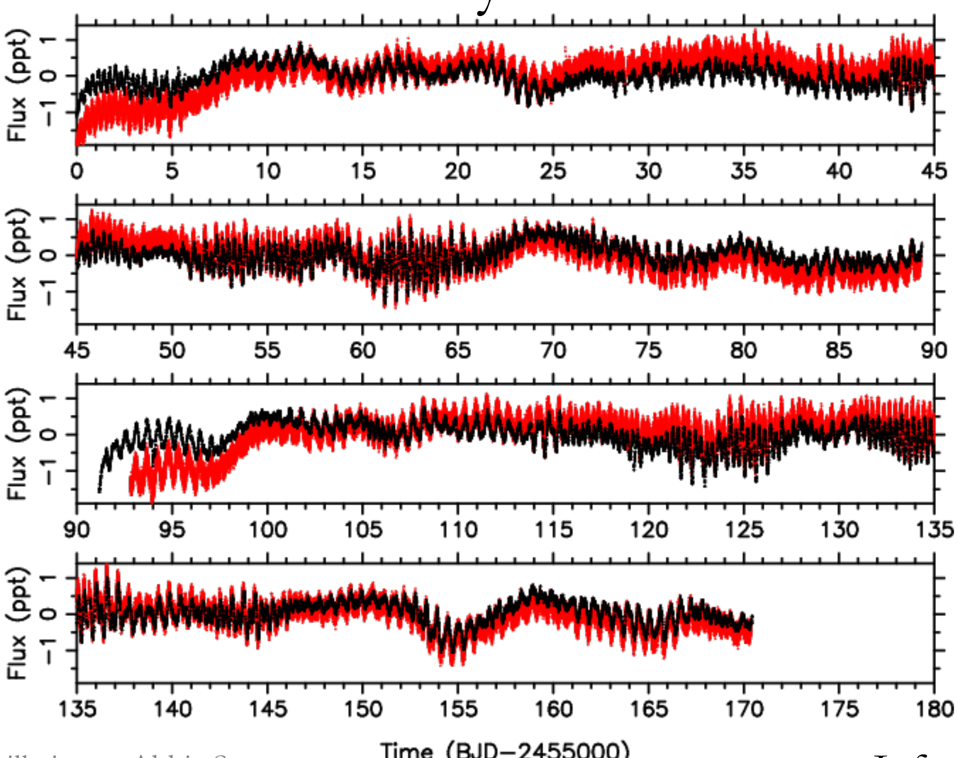
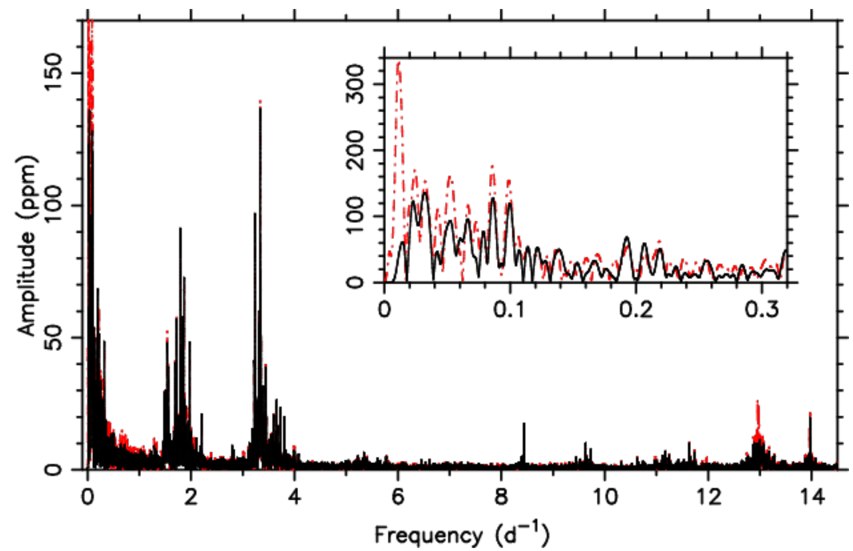


Image via APOD, credit: R. Vanderbei, ESA/Gaia/DPAC

Asteroseismology ("starquakes")

- Understanding the internal structure of stars using their brightness oscillations
- Convective zone excites oscillations
- Fourier analysis of light curves: often see many harmonics





Aerts+19

Info thanks to online slides by T. Bedding and refs therein

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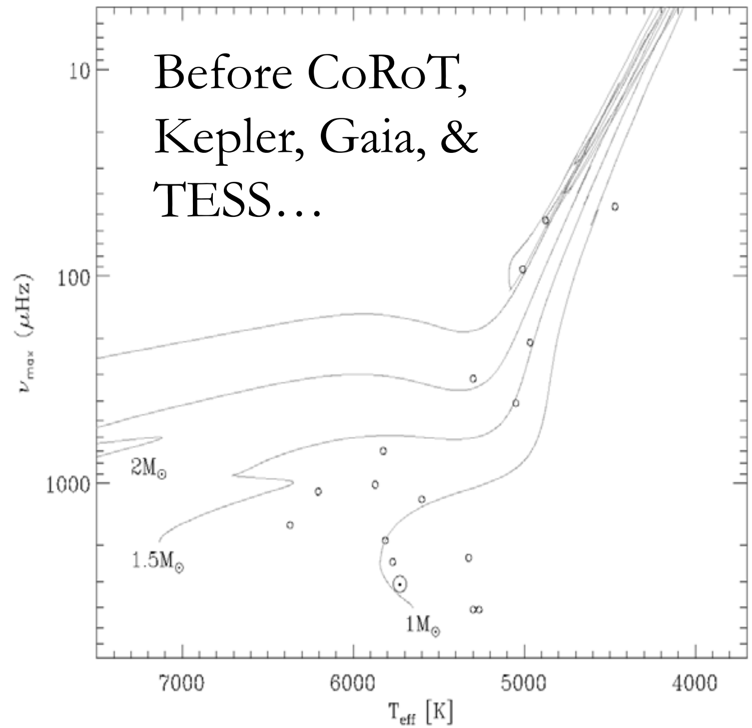
- Sound speed of gas → density
- With frequencies and spectral temperature, can derive mass, radius, size of core and thus stellar age, etc.



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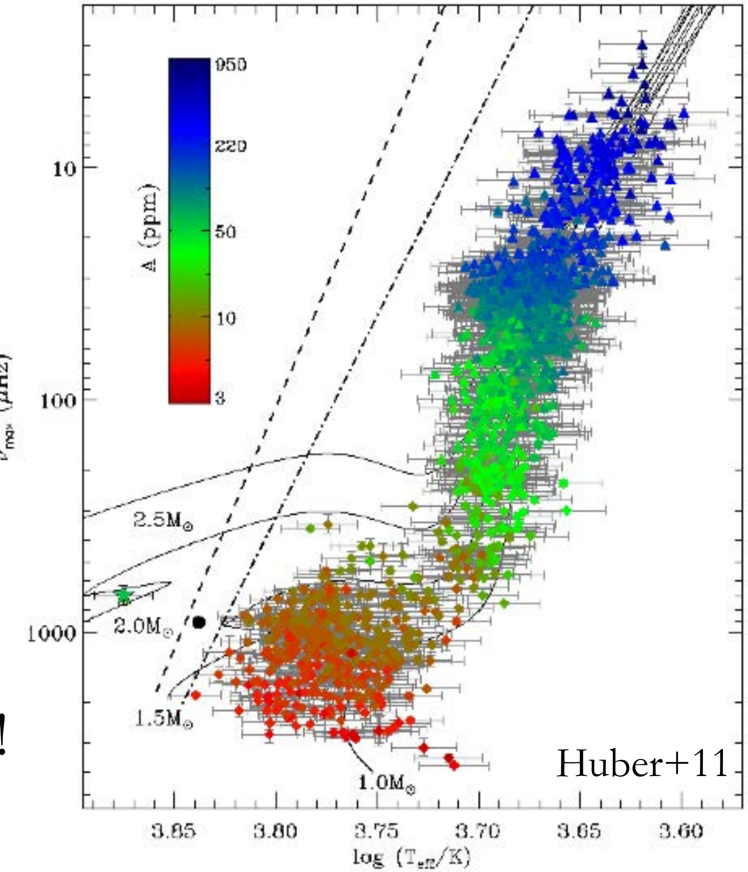


Huber+11

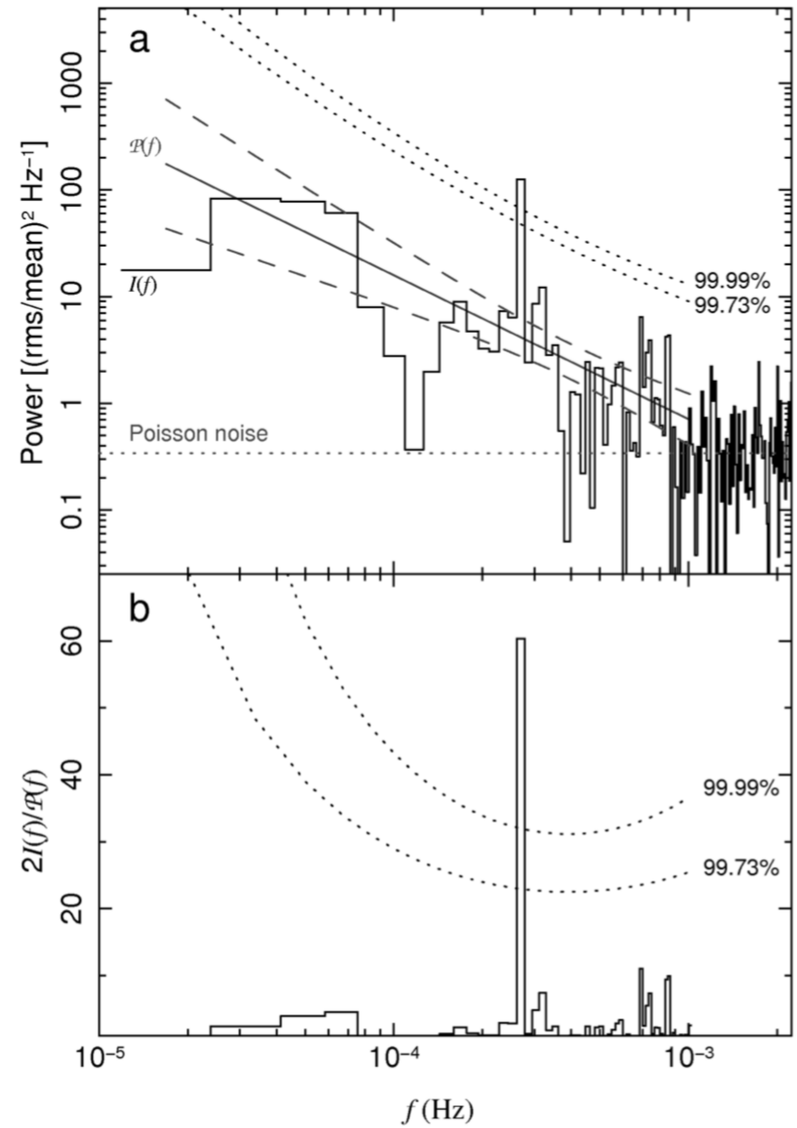
This doesn't even have Gaia or TESS!

Info thanks to online slides by T. Bedding and refs therein

QPOs in active galactic nuclei (AGN)

Gierlinski+08
Alston+14

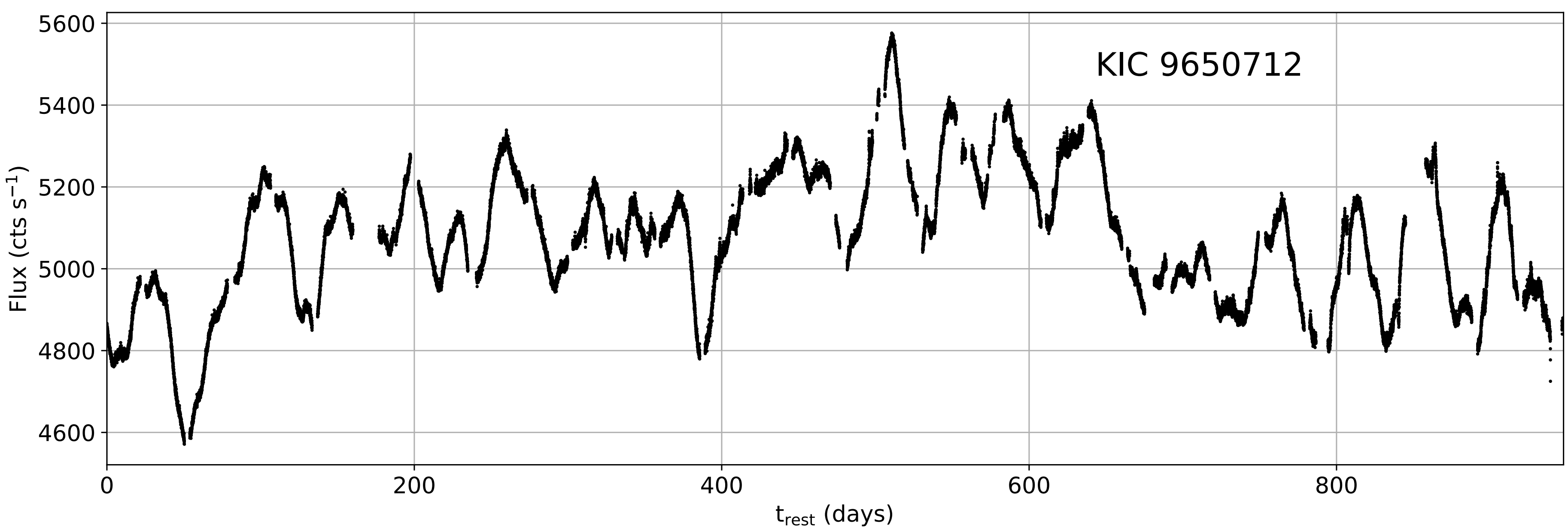
- ~1 hr "periodicity", 91ks observation
- RE J1034+396 is a narrow-line Seyfert 1 AGN
- Saw 16 'cycles' (periods) in one uninterrupted observation!
- Evenly-sampled time bins
- Signal attributed to high-freq. QPO
  - If at innermost stable circular orbit, $M_{BH} \sim 7 \times 10^6 - 1 \times 10^7 \, M_\odot$



QPOs in active galactic nuclei (AGN)

- 44 day low-freq. QPO in KIC 9650712
- NLS1 in original Kepler field
- 30 minute cadence over 3.5 years: ~30 cycles
- Tested periodicity via simulations (Uttley+02) and Lomb-Scargle periodogram

Smith+18b

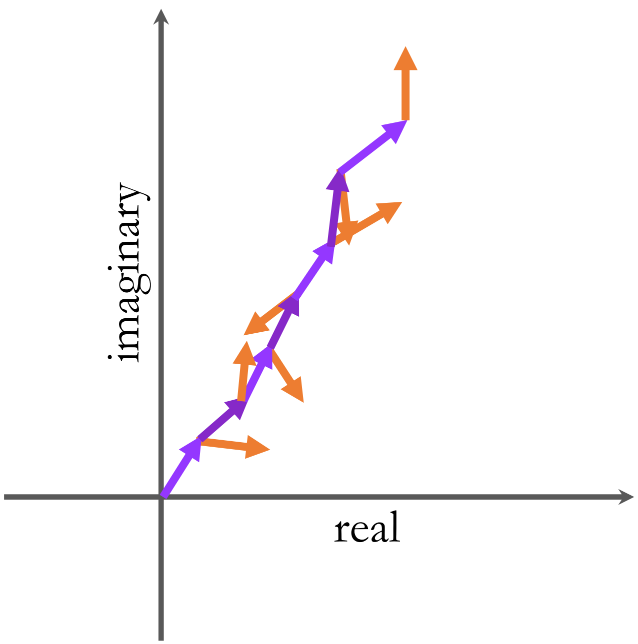


Cross spectra

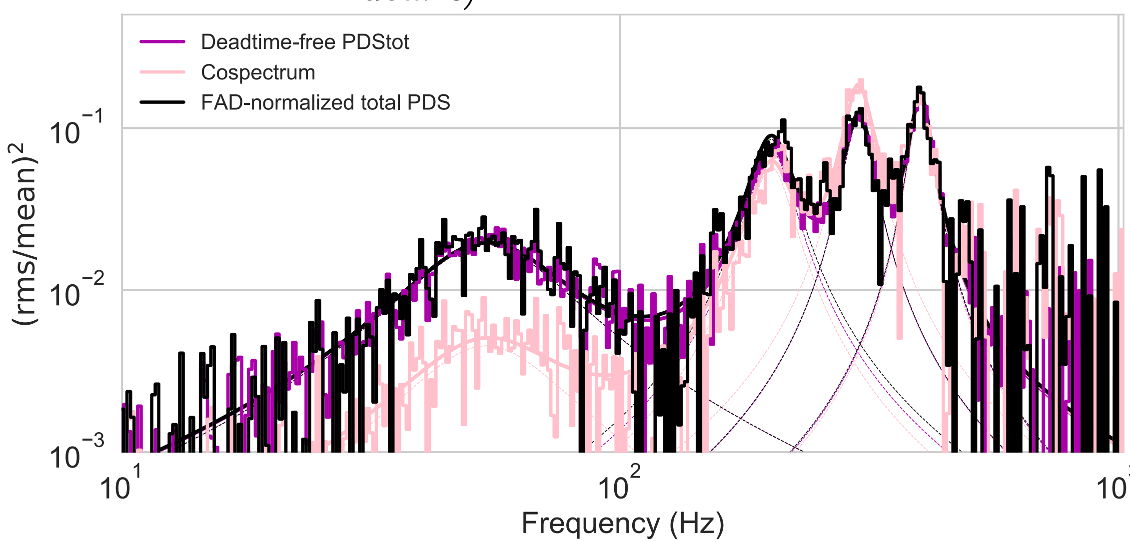
$x(t) \rightarrow X(\nu)$ for many narrow energy bands
$y(t) \rightarrow Y(\nu)$ for a broad-energy reference band

$C_{XY}(\nu) = X(\nu)Y^*(\nu)$

Average segments together: signal adds, noise cancels



Cospectrum: real part of the cross spectrum (see Bachetti+15, Bachetti+Huppenkothen 18 and Huppenkothen+Bachetti 18 for statistical details)

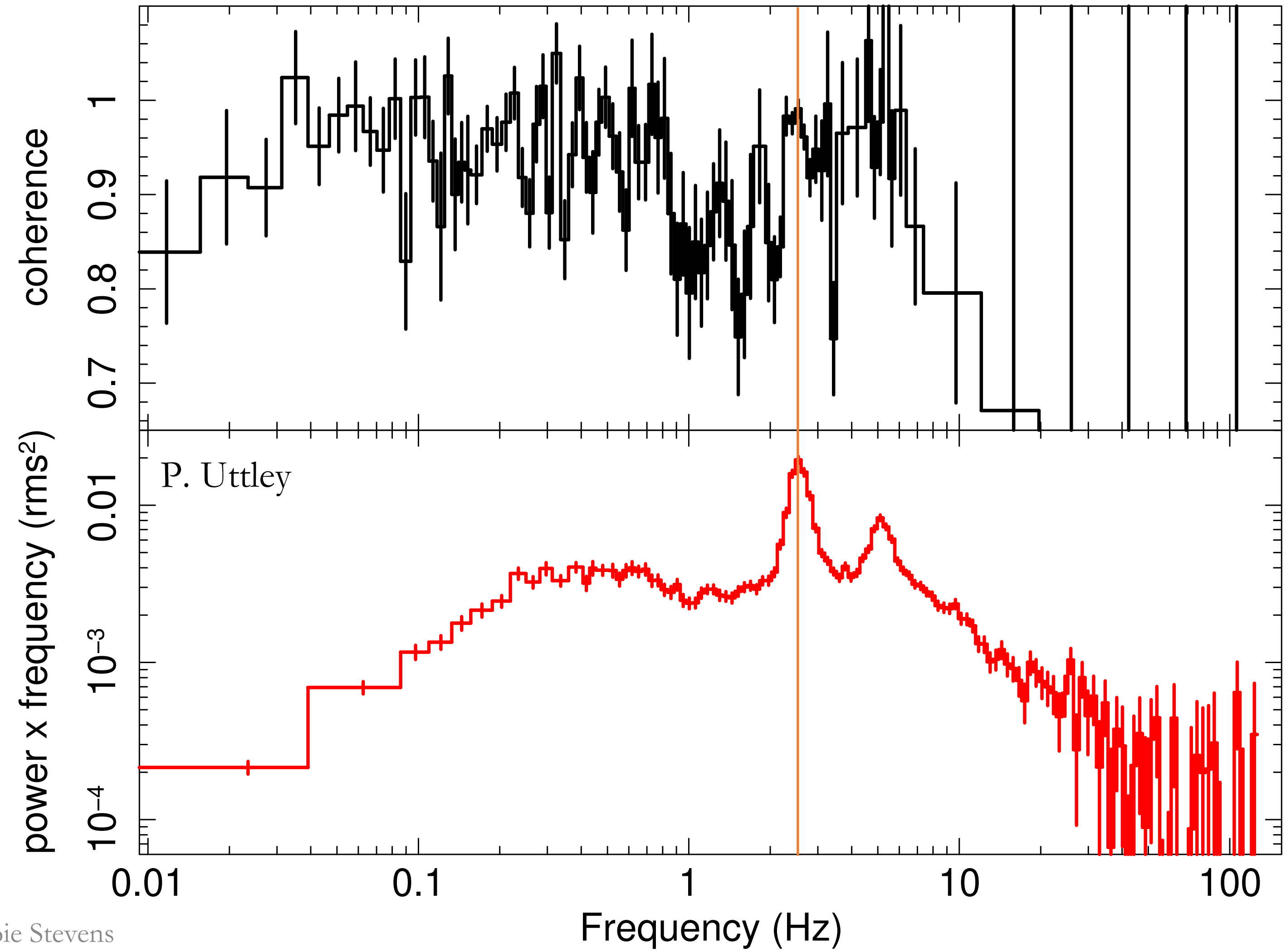


Also used: amplitude of the cross spectrum
Note: for $X(\nu)=Y(\nu)$,
cospectrum=cross amplitude= power spectrum

Coherence

Fraction of the variance in light curve that can be predicted by a linear transformation (like amplitude modulation)

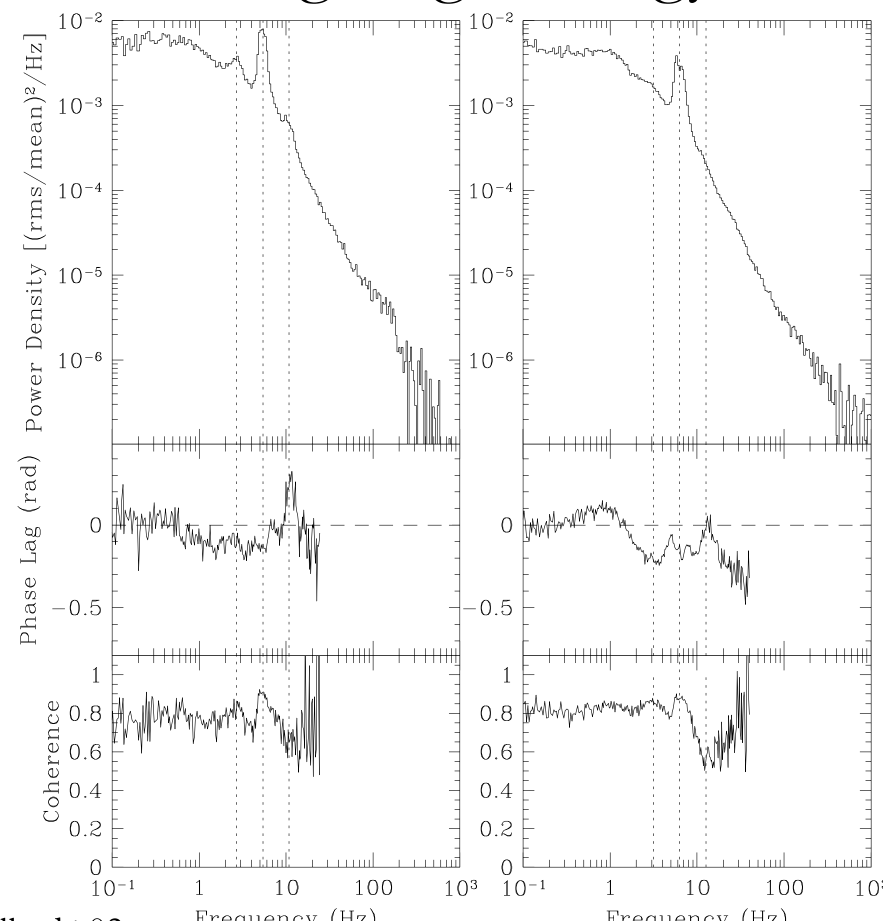
Vaughan+ Nowak97



Lag-frequency spectra

Cross-spectral phase lags between two light curves in different energy bands at Fourier frequencies

- Negative → low-energy light curve lags high-energy light curve



Remillard+02

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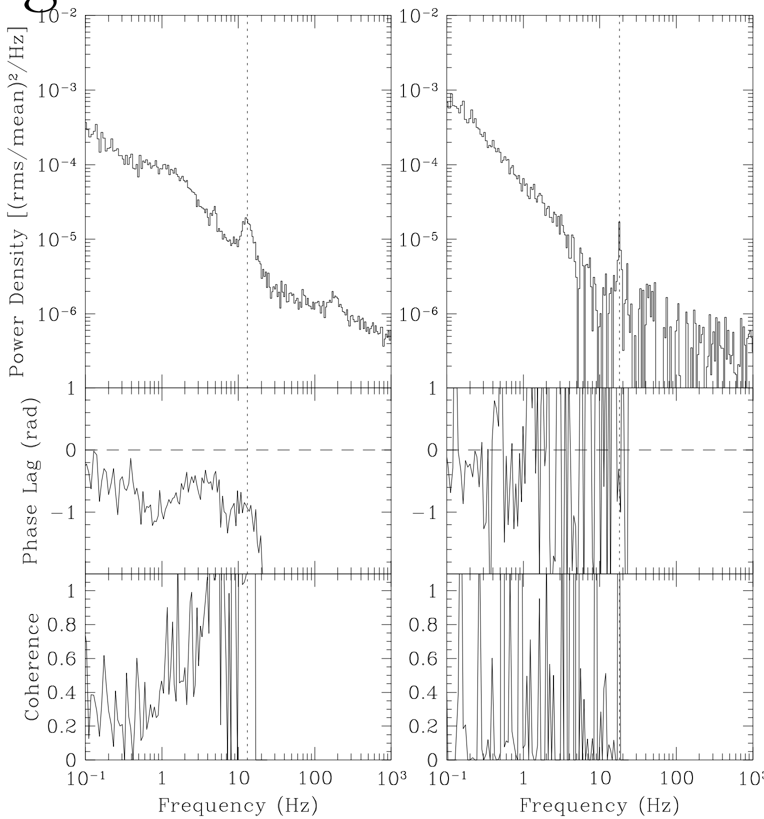

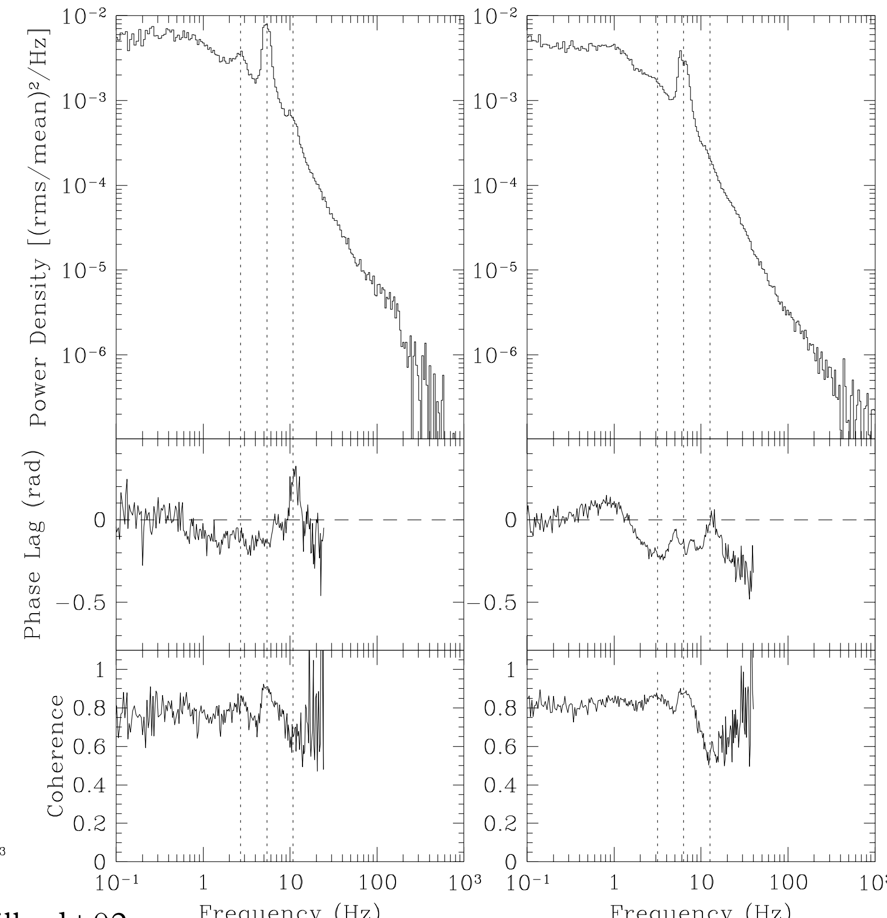

Remillard+02

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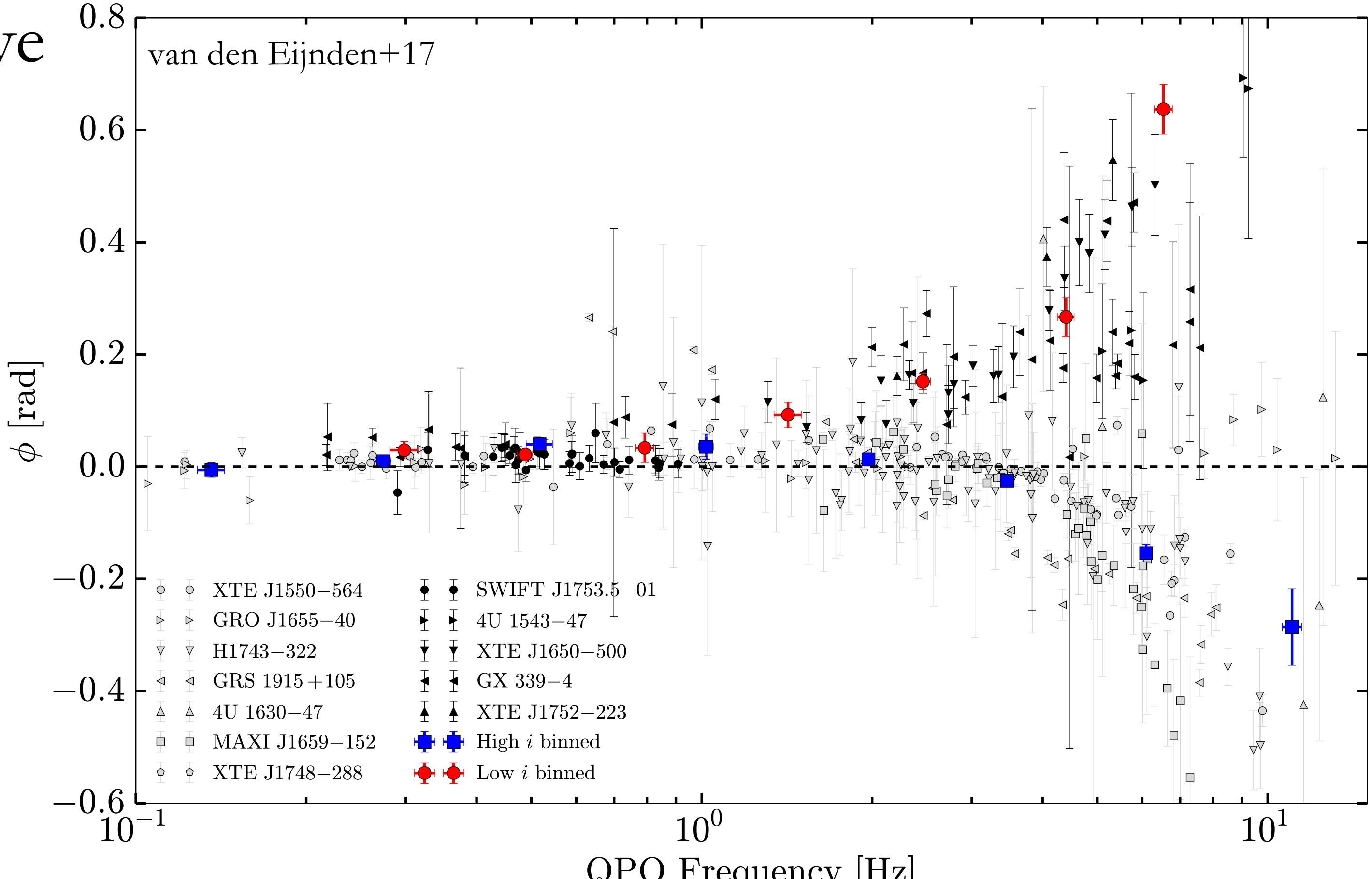
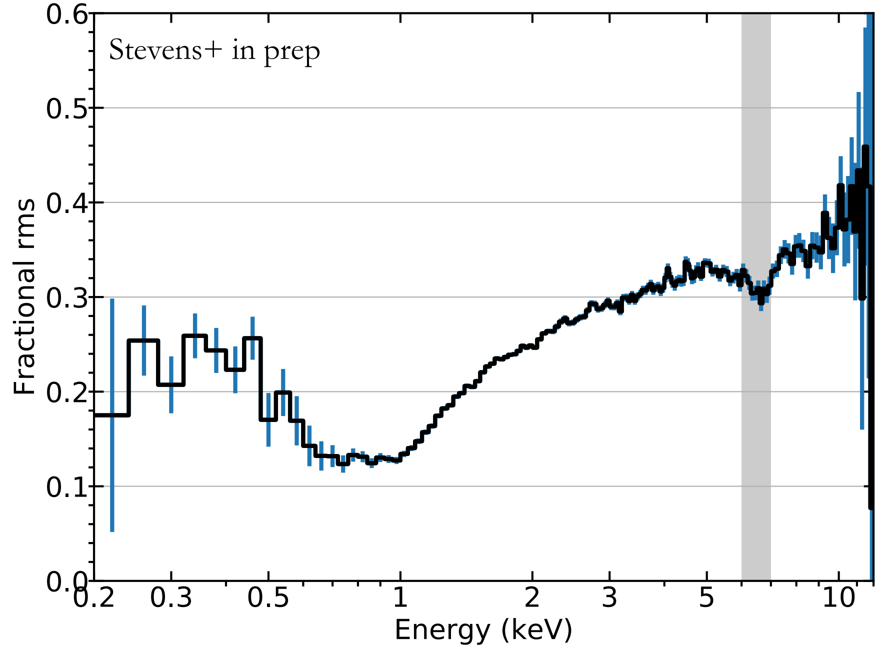
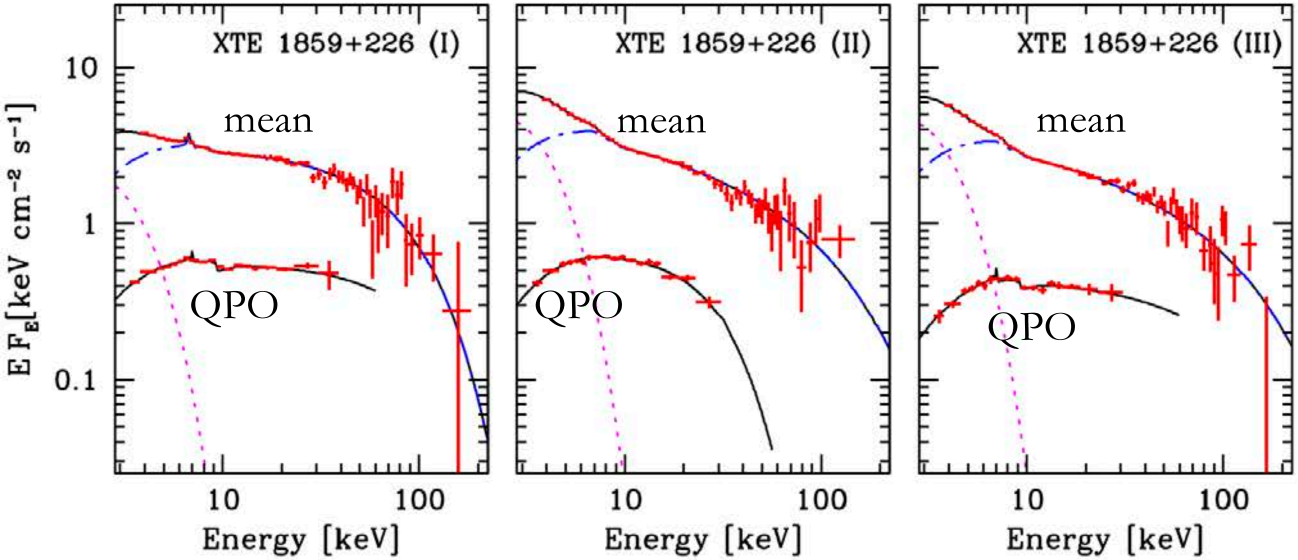


Fourier-resolved spectroscopy

- Rms spectra: fractional variance of a light curve in narrow energy bands (Revnivtsev+99)
- Covariance spectra: fractional variance of a light curve with respect to a reference band (Wilkinson+Uttley 09)



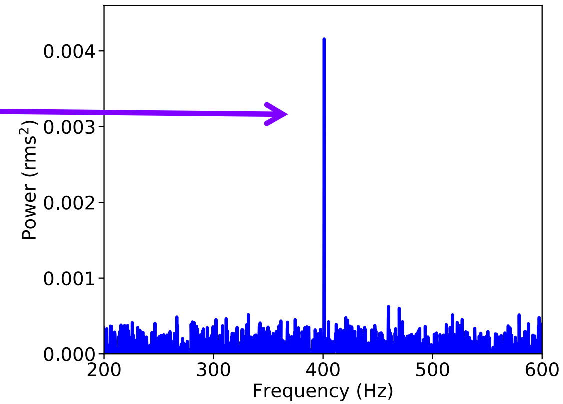


Sobolewska+Życki 06

Phase-resolved spectroscopy

<u>Periodic signals:</u>

- fold light curve at pulse period, stack signal in time domain
- need to know ephemeris of source

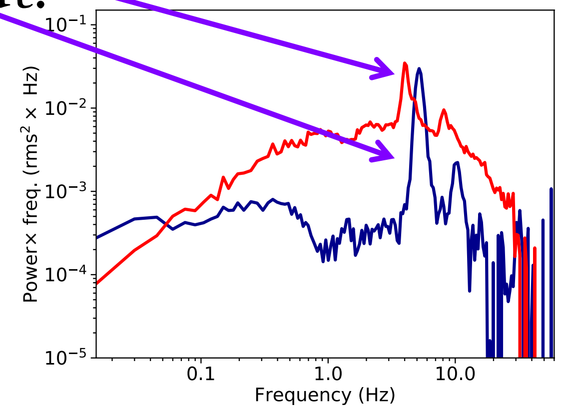


<u>Quasi-periodic signals:</u>

- not coherent enough to fold light curve
- in time domain, signal would smear out!

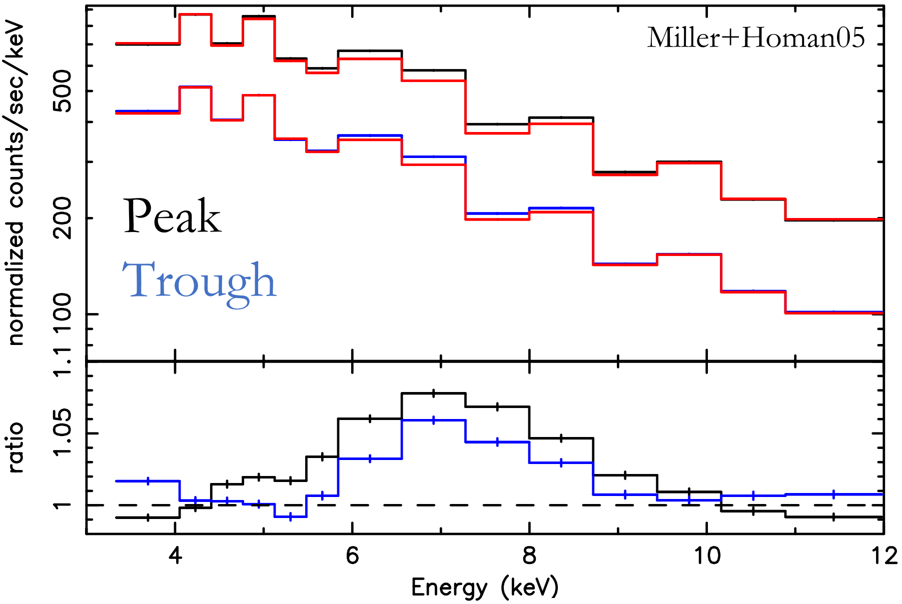
➔ average together signals in *<u>frequency</u>* domain

- ephemeris not needed

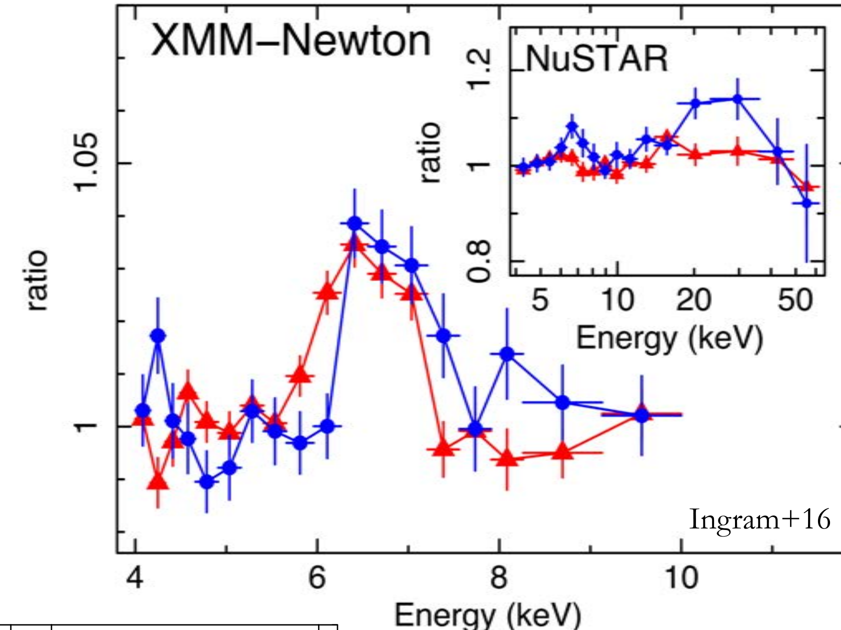


See Miller+Homan 05; Ingram+ van der Klis 15; Stevens+Uttley 16

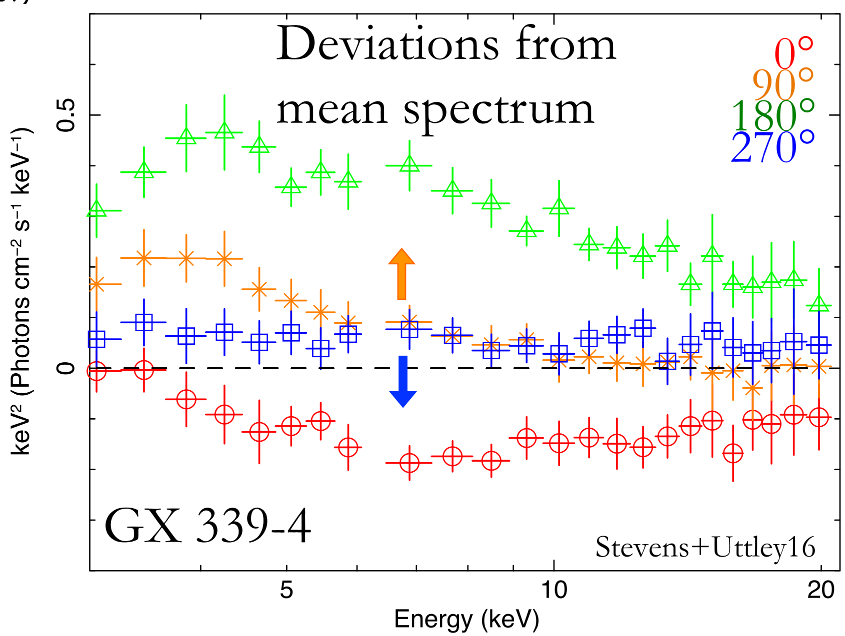
Phase-resolved QPO spectroscopy



GRS 1915+105

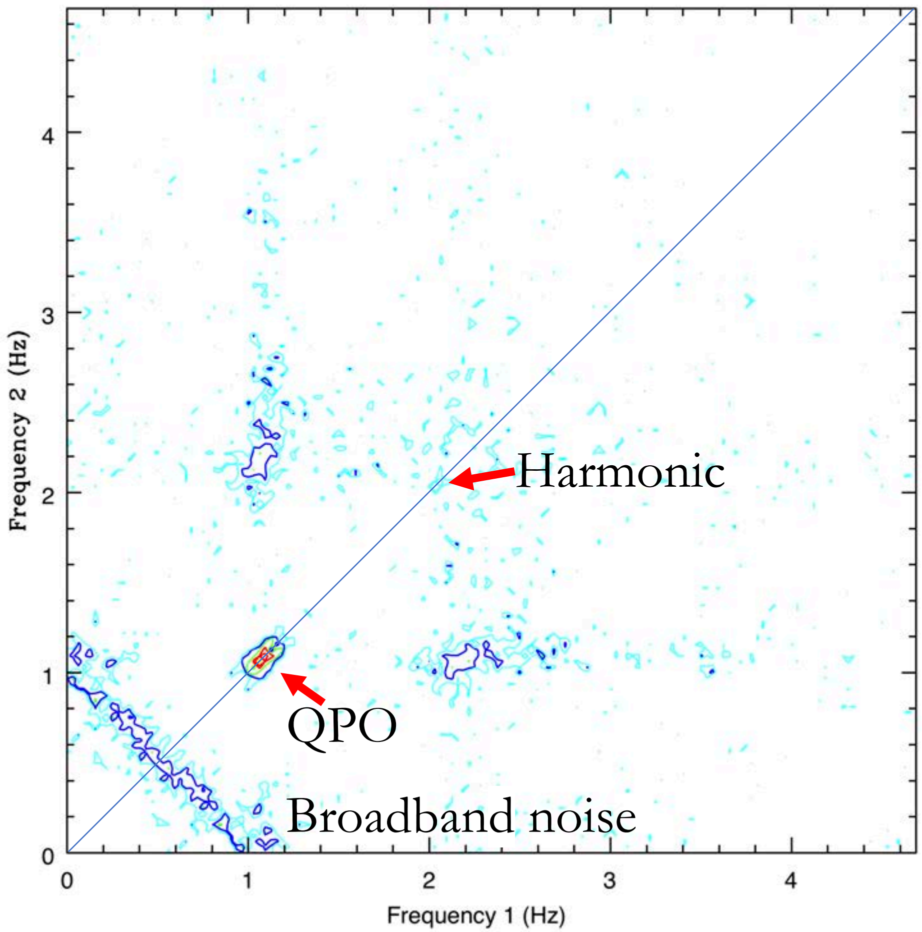


H 1743-322



Bispectrum (& biphase, bicoherence)

- Nonlinear (e.g., multiplicative) interactions between variability components (e.g., broadband noise and QPO)
  (see e.g. papers by T. Maccarone et al., S. Scaringi et al.)



The bispectrum is defined for a frequency pair ν_i and ν_j as:

$$B(\nu_i, \nu_j) = F(\nu_i)\, F(\nu_j)\, F^*(\nu_{i+j})$$

Resource: "An Introduction to the Bispectrum", T. Wolinsky

Stingray: spectral-timing software

- Open-source, community-driven and -developed, python, Astropy-affiliated package
- Stingray: Python library of analysis tools
- HENDRICS: shell scripting interface
- DAVE: graphical user interface
- Tutorials in Jupyter(/iPython) notebooks
- github.com/StingraySoftware

- Leads: D. Huppenkothen, M. Bachetti, A.L. Stevens, S. Migliari, P. Balm
- Google Summer of Code students: S. Sharma ('18); O. Hammad and H. Rashid ('17); U. Khan, H. Mishra, and D. Sodhi ('16)
- Other major contributors: E. Martinez Ribeiro, R. Valles

→ **Now published: Huppenkothen et al. 2019, ApJ, in press!**

Google Summer of Code

Stingray: spectral-timing software

- Library of time series analysis methods
  - Power spectra, cross spectra, bispectra
  - Lag-frequency & lag-energy spectra
  - Rms & covariance spectra
  - Coherence, cross-correlation
  - Handles GTIs, pulsar & QPO searches
  - Phase-resolved spectroscopy of QPOs
- Simulator, modeling
- Well-tested on X-ray timing data (RXTE, NuSTAR, XMM, some NICER); also used by a few people for radio timing

Summary and resources

- There are many types of periodic and quasi-periodic signals in evenly-spaced time-domain astronomy data
  - Compact object quasi-periodic oscillations (QPOs)
  - Pulsars and burst oscillations
  - Stellar pulsations and asteroseismology
- In-depth Fourier technique review: Uttley+2014
  - Power spectra, cross spectra
  - Coherence
  - Phase lags
  - Frequency- and phase-resolved spectroscopy
  - Bispectra
- StingraySoftware.github.io

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