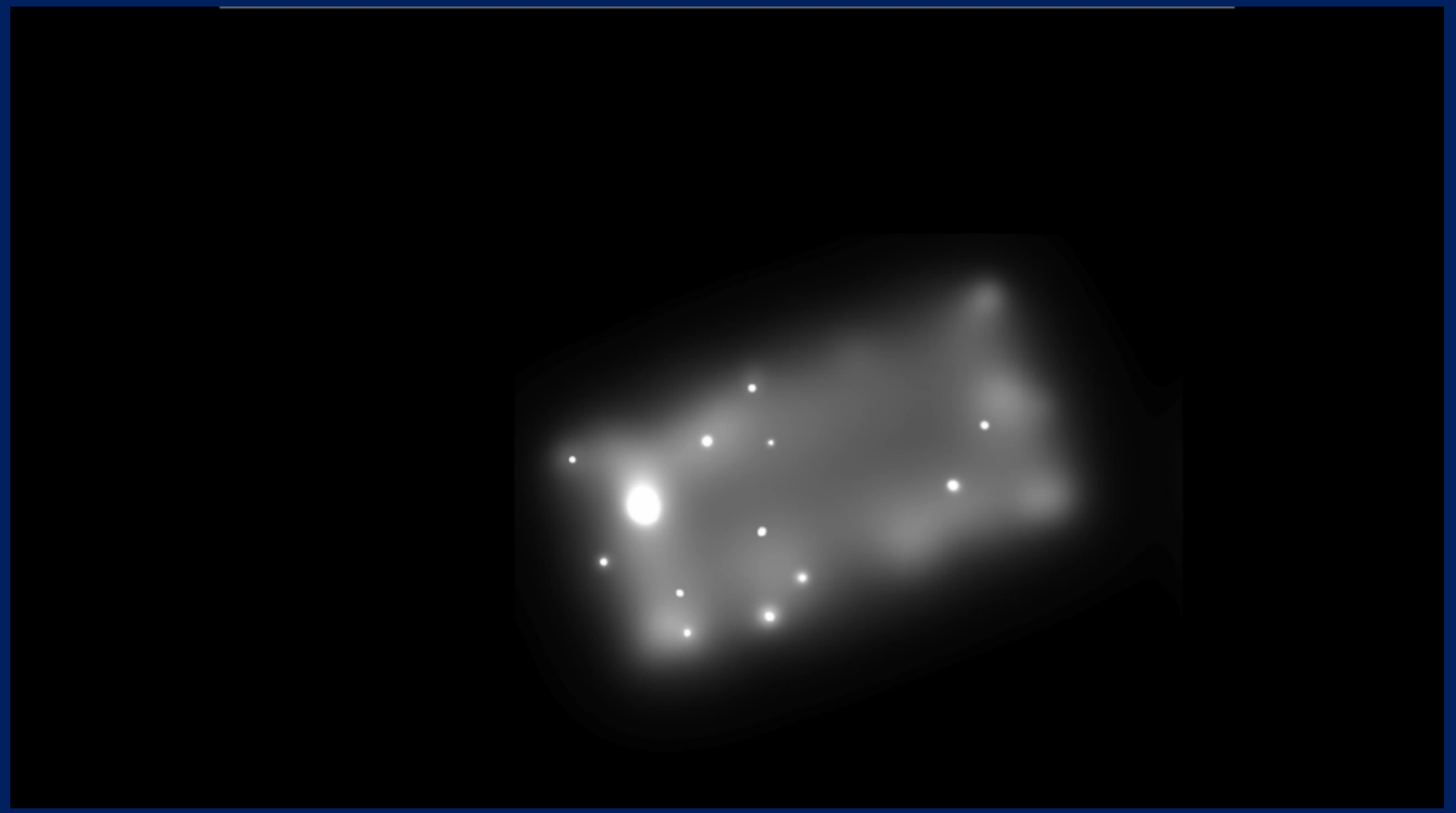
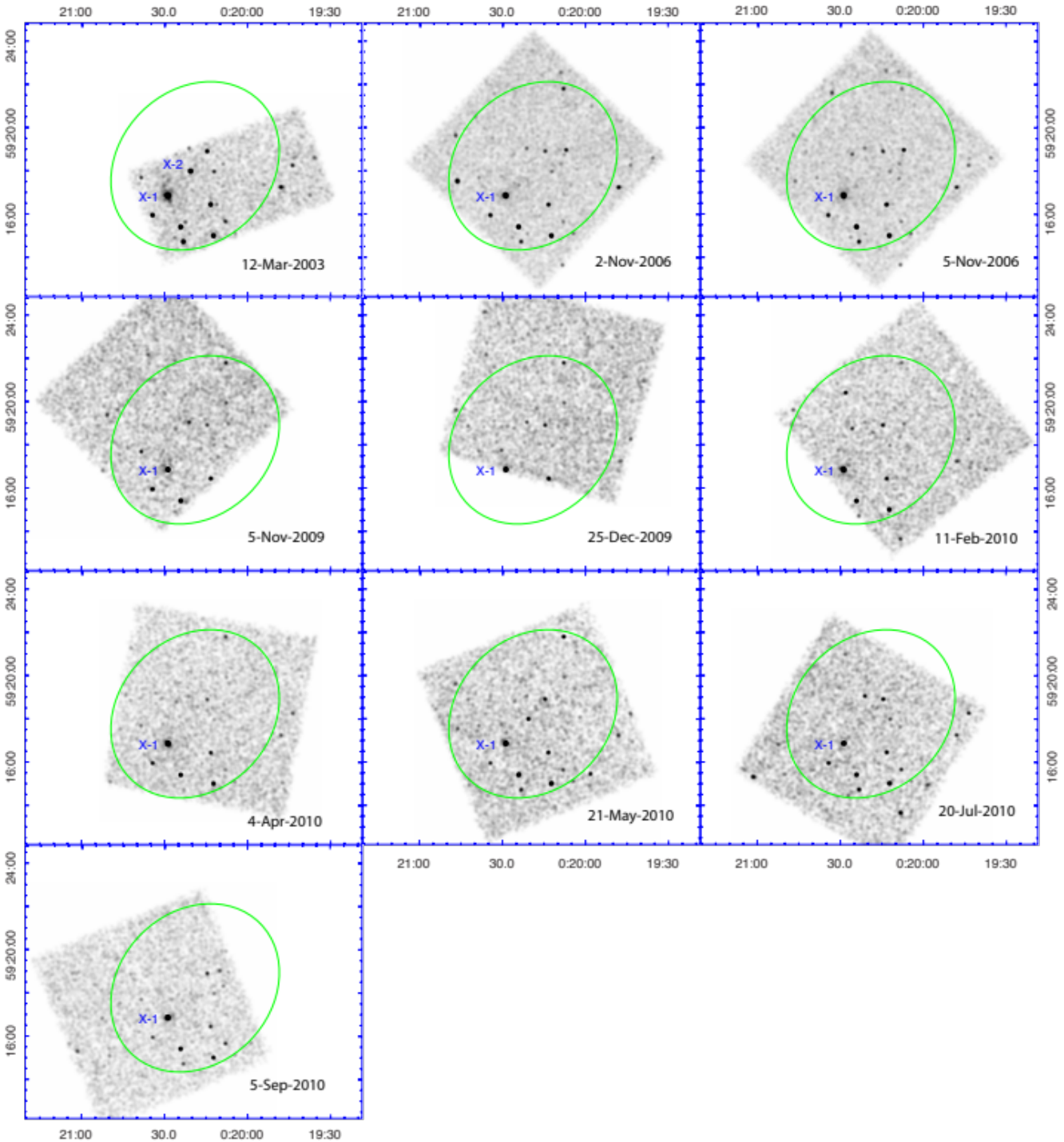
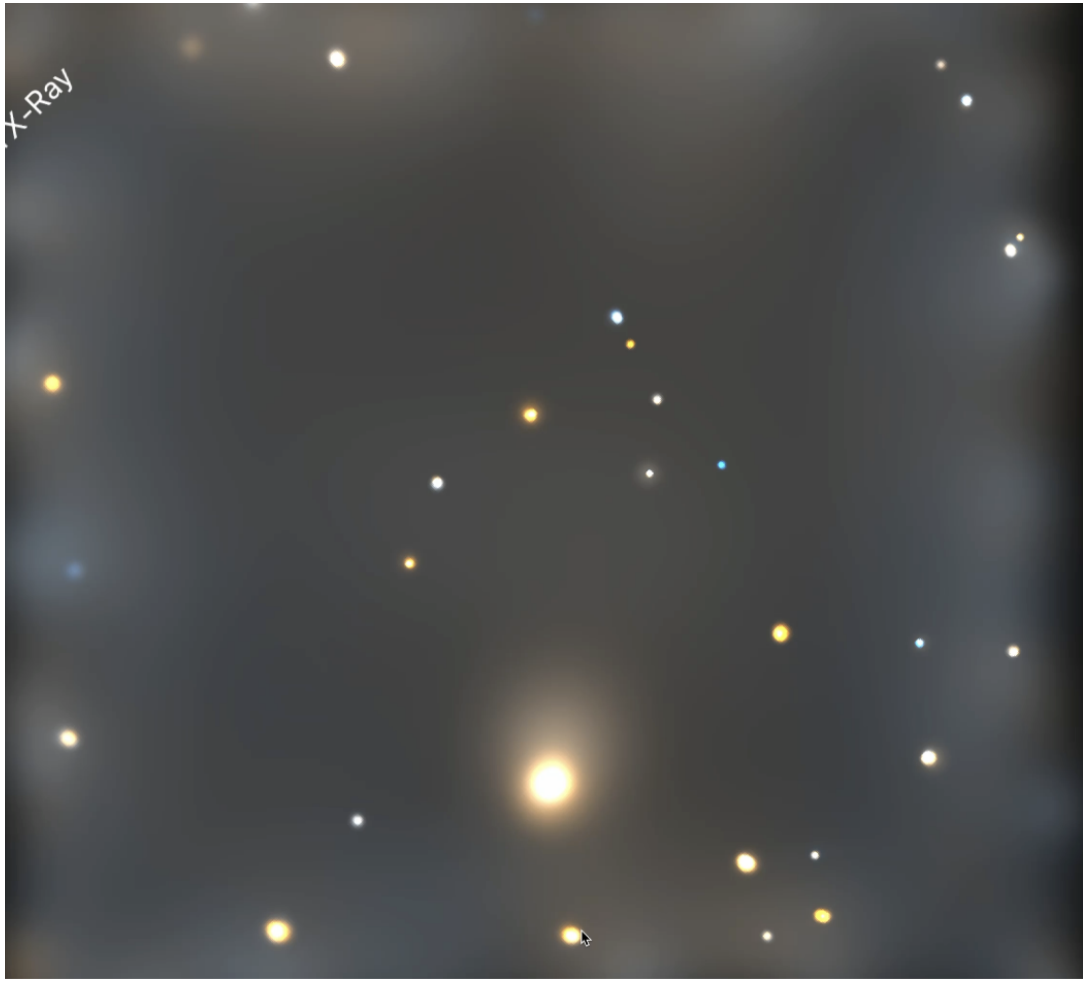


Astronomical Timing Analysis

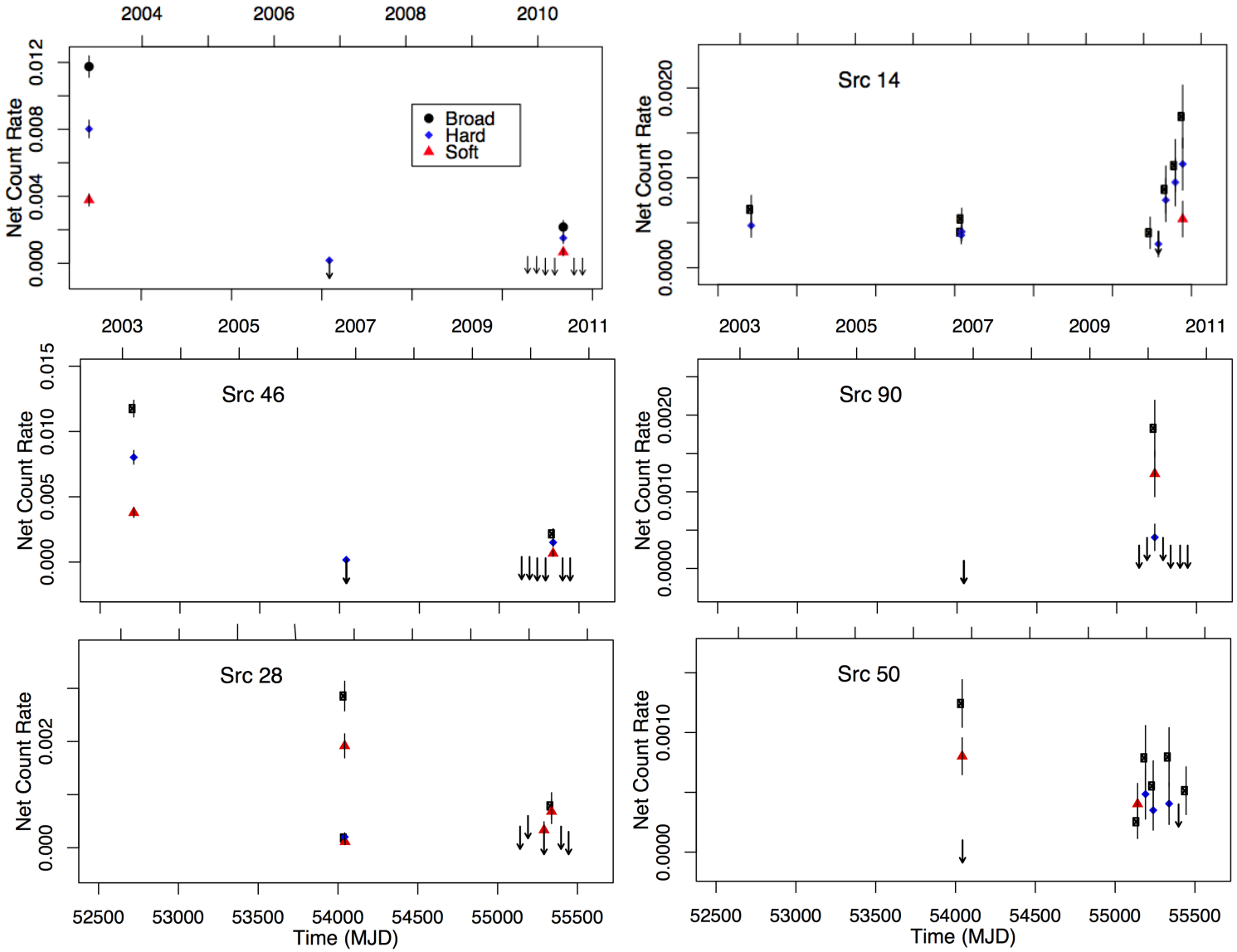
Silas Laycock, UMass Lowell

Variability Survey: IC 10





Sample of variable X-ray lightcurves in IC 10



This talk is about going beyond “simply” measuring brightness in a series of observations.

Is my source Variable ?

Time Systems
Barycenter Correction

Multi-observatory and multi-wavelength

Periodograms

FFT
Uneven Sampling
Gaps
Lomb-Scargle Periodogram

Periodic Signals – e.g. Pulsars
Phase Folding
QPOs
Red Noise

Lightcurve optimization

Binning
Kernel Density Estimators
Bayesian Blocks

Cross-Correlation -> Time Lags

How do we know if a Source Light-curve shows constant or variable flux?

Look at the Data

Appearance of a Lightcurve can depend strongly on time binning

Statistical Tests!

Do the flux values exceed the error bars?

Does not work on Low count regime

Nor at high time resolution

Is the distribution of event arrival times larger than would be expected based on Poisson statistics?

K-S Test

Bayesian Blocks

Gregory-Loredo

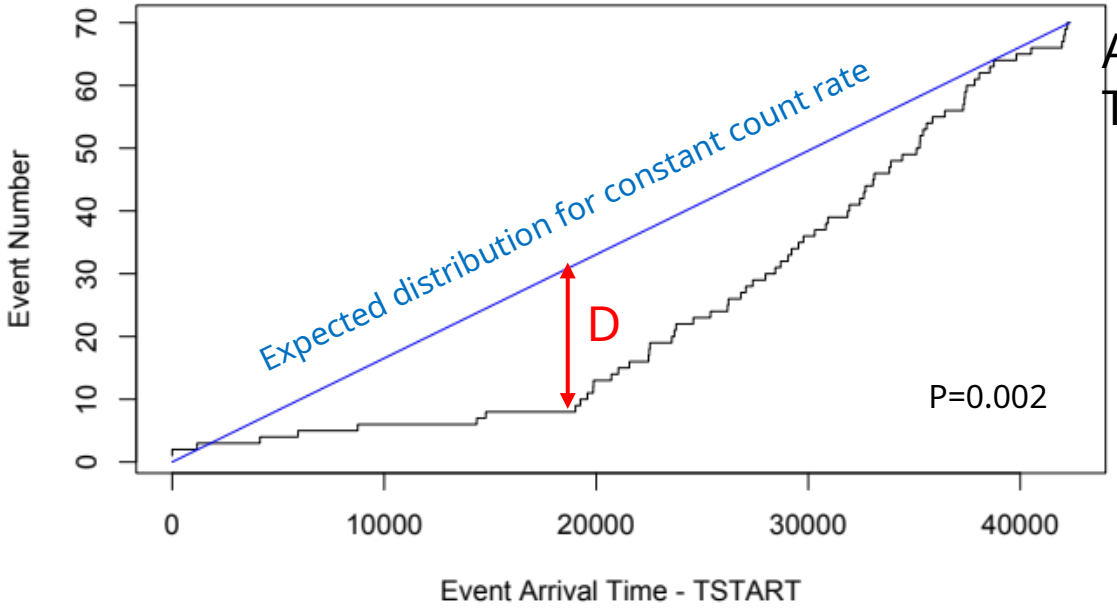
Periodograms

FFT and related approaches

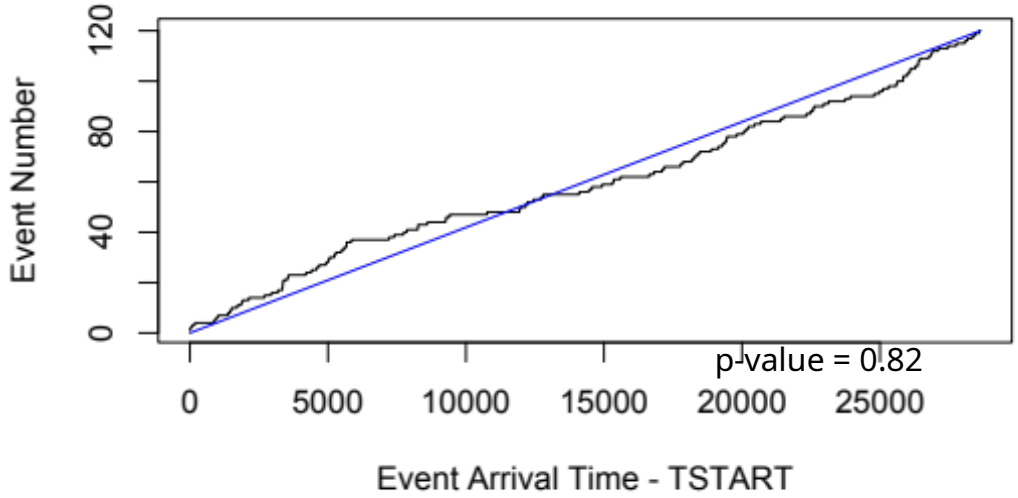
Epoch Folding and related

Is my source Variable? Kolmogorov-Smirnov (K-S) Test

Example: A 70 count Chandra source in a 40 ksec observation



Algorithms exist in R, Python, etc. to compute
The probability of the null hypothesis. i.e. the p value



Feigelson & Babu say we should replace KS with the similar Anderson Darling Test

Example 2: A 120 count Chandra source in a 28 ksec observation

Chat GPT says: To test whether **arrival times** are consistent with a **constant rate Poisson process**, you're essentially testing if the **inter-arrival times** are **exponentially distributed**.
Use the one-sided K-S test against the exponential distribution:

Chandra Source Catalog 2.0 contains KS and several related Statistics, already computed …

This page is for the CSC 2.0 release. Please see the CSC home page for the latest release.

Chandra Source Catalog Source Variability

Source variability within an observation is assessed by three methods: (1) the Kolmogorov-Smirnov (K-S) test, (2) the Kuiper's test, and (3) computation of the Gregory-Loredo variability probability, all based on the source region counts. Intra-observation source variability within any contributing observations to a master source entry is assessed according to the highest level of variability seen within any single contributing observation. Inter-observation source variability between any contributing observations to a master source entry is assessed by application of a χ^2 hypothesis test applied to the source region photon fluxes observed in the contributing observations.

Gregory-Loredo Variability Probability

var_prob

The probability that the source region count rate lightcurve is the result of multiple, uniformly sampled time bins, each with different rates, as opposed to the result of a single, uniform rate time bin. This probability is based upon the odd ratios (for describing the lightcurve with two or more bins of potentially different rates) calculated from a Gregory-Loredo analysis of the arrival times of the events within the source region. Corrections to the event rate are applied accounting for good time intervals and for the source region dithering across regions of variable exposure (e.g., chip edges) during the observation. Probability values are calculated for each science energy band.

Kolmogorov-Smirnov (K-S) Test Probability

ks_prob

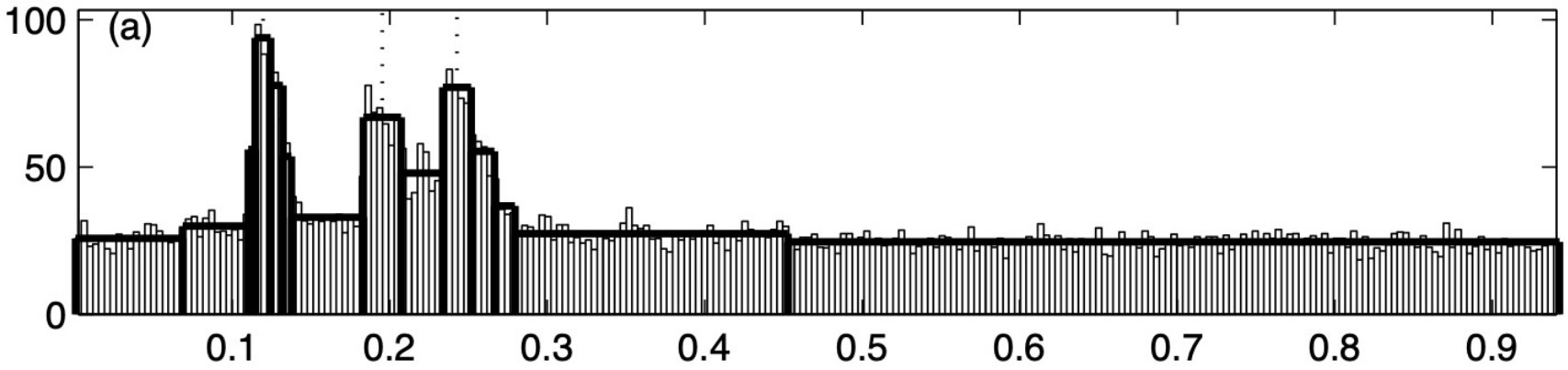
The probability that the arrival times of the events within the source region are inconsistent with a constant source count rate throughout the observation. High values of this quantity imply that the source is not consistent with a constant rate, and that the source is likely variable. The probability is computed by means of a hypothesis rejection test from a one-sample K-S test applied to the unbinned event data, with corrections applied for good time intervals and for the source region dithering across regions of variable exposure (e.g., chip edges) during the observation. Probability values are calculated for each science energy band. Note that this variability diagnostic does not treat the source and background separately.

Kuiper's Test Probability

kp_prob

The probability that the arrival times of the events within the source region are inconsistent with a constant source count rate throughout the observation. High values of this quantity imply that the source is not consistent with a constant rate, and that the source is likely variable. The probability is computed by means of a hypothesis rejection test from a one-sample Kuiper's test applied to the unbinned event data, with corrections applied for good time intervals and for the source region dithering across regions of variable exposure (e.g., chip edges) during the observation. Probability values are calculated for each science energy band. Note that this variability diagnostic does not treat the source and background separately.

Bayesian Blocks



Scargle, J., D., 1998, ApJ, 504, 405

A method for **Segmenting** the data (can also be used for images and higher dimensional data)

Data are divided into **blocks** within which the count rate is **consistent** with being **constant**

Original application: CGRO – BATSE – Gamma ray burst monitoring

Types of Astronomical Source **Variability**

Periodic

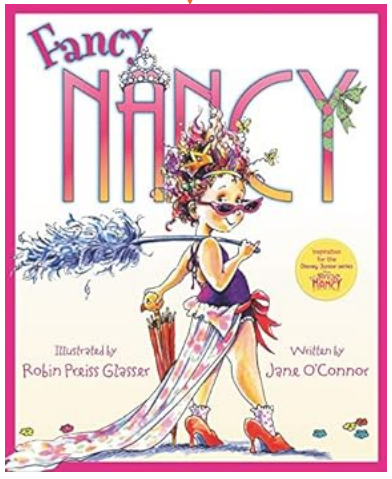
- Rotation
  - Pulsars
- Orbits
  - X-ray Binaries
  - Active binaries
- Magnetic Gating
  - X-ray bursters?
- Pulsation
  - ?

Quasi - Periodic

- QPOs
  - X-ray Binaries
  - AGNs
  - (Accretion Disks)

Aperiodic

- Isolated Events
  - Bursts
  - Flares
- Stochastic
  - Random variability across a range of timescales
  - BHs
    - AGN
    - XRBs
    - (Accretion Disks)
- "Secular"
  - Fancy for slow changes due to some more or less unknown reason





Time Systems

Astronomers need to line up
different dates and from diff
the Time.

- Local Time
- UTC
- Sidereal Time
- Terrestrial Time
- **Julian Date** (Days since Mon, Jan 1st, 4713 BC)

  MJD, TJD .....

Spacecraft time (Mission Elapsed time)
For Chandra and XMM = Seconds since 1998.0, UTC

Can be easily converted into JD

or many Astrophysical purposes, an extra step is needed....

NASA | GSFC | Sciences and Exploration
HEASARC
High Energy Astrophysics Science Archive Research Center

About | Sitemap | Help Desk | Archive Your Data

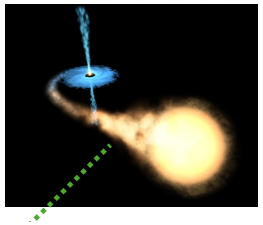
HEASARC | Observatories | Archive | Calibration | Software | Web Tools | User Support

xTime - A Date/Time Conversion Utility HELP

Calendar Time Formats	Input Time [UTC]	Output Time [UTC]
ISO 8601 date (yyyy-MM-dd hh:mm:ss)		2025-05-23 15:30:00
Calendar date (yyyyMondd at hh:mm:ss)		2025May23 at 15:30:00.000 UTC
Year and day number (yyyy:ddd:hh:mm:ss)		2025:143:15:30:00.000 UTC
Julian Date (ddddddd.ddd...)		2460819.14583333
Modified Julian Date (ddddd.ddd...)		60818.64583333
Mission-Specific Time Formats	**Input Time [MET]**	**Output Time [MET]**
Fermi seconds since 2001.0 UTC (decimal)		769707005.000
Fermi mission week (integer)		886
INTEGRAL Julian Date days since 2000.0 TT (decimal)		9274.64663407407
LIGO/GPS seconds since 1980-01-06 UTC (decimal)		1432049418.000
NICER/Hitomi seconds since 2014.0 UTC (decimal)[1]		359479802.000
NuSTAR seconds since 2010.0 UTC (decimal)		485710203.000
RXTE seconds since 1994.0 UTC (decimal)[2]		990631809.000
RXTE seconds since 1994.0 UTC (hexadecimal)		0x3b0bd781
Suzaku/MAXI seconds since 2000.0 UTC (decimal)		801329405.000
Swift seconds since 2001.0 UTC (decimal)[2]		769707000.000
XMM/Chandra seconds since 1998.0 TT (decimal)		864401469.184
XRISM seconds since 2019.0 UTC (decimal)		201713400.000

RXTE clock corrections for this time are not available.
Swift clock correction for this time is not available.
Suzaku clock correction for this time is not available.
XMM/Chandra clock corrections are not available.
NuSTAR clock corrections are not available.
INTEGRAL clock corrections are not available.
XRISM clock corrections are not available.

Time Systems



Problem: The Earth is moving in space and so the distance to any given astronomical source varies periodically with time.

Solution:
Re-compute time at the Solar Sys

n...

:29

Example 1

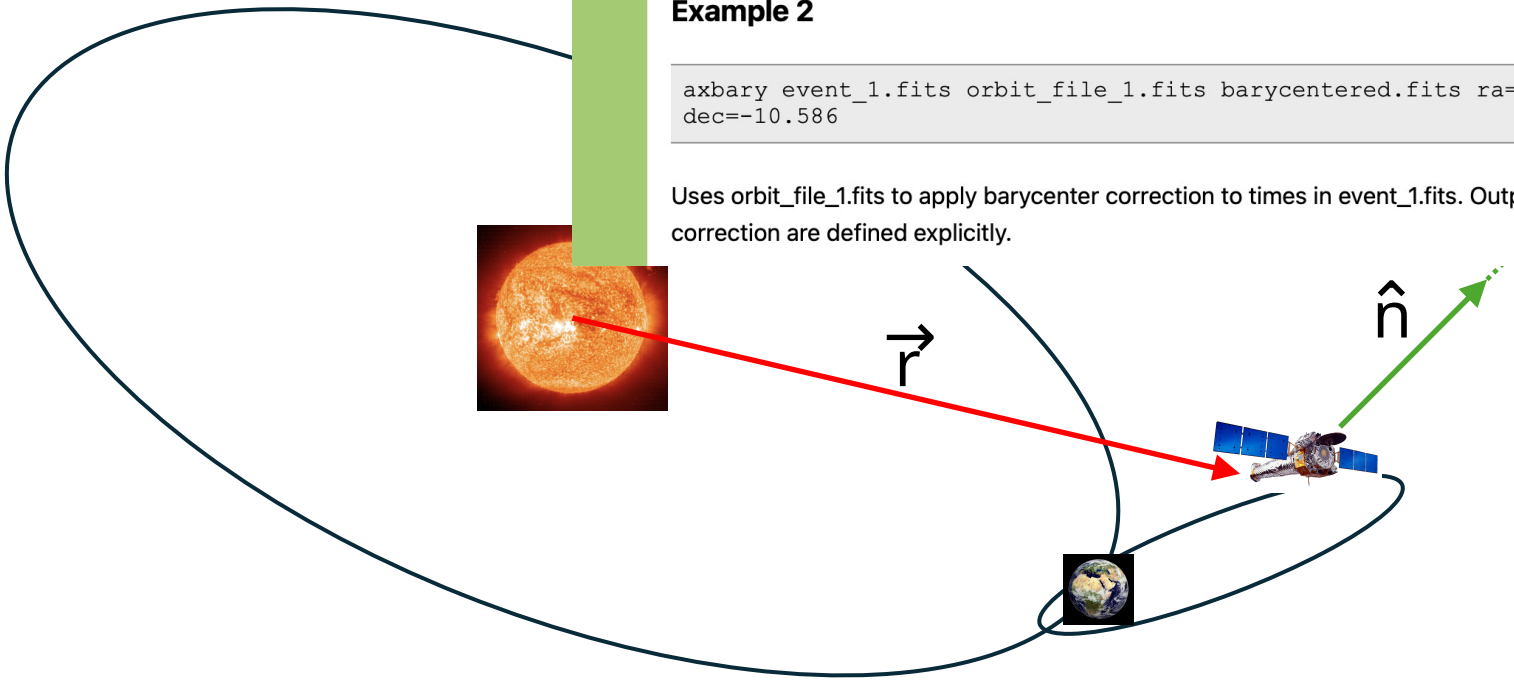
```
axbary event.fits orbit.fits corrected.fits
```

Applies barycenter correction to times in event.fits, using orbit.fits as orbit ephemeris file, and writing output in corrected.fits. RA_NOM and DEC_NOM will be used for the reference position.

Example 2

```
axbary event_1.fits orbit_file_1.fits barycentered.fits ra=278.132
dec=-10.586
```

Uses orbit_file_1.fits to apply barycenter correction to times in event_1.fits. Output is written to barycentered.fits. The RA and DEC for the correction are defined explicitly.



Heliocentric Julian Date

$$HJD = JD + \frac{\vec{r} \cdot \hat{n}}{c}$$

Up to $\pm$ 8 min (approx.)

Ciao: axbary

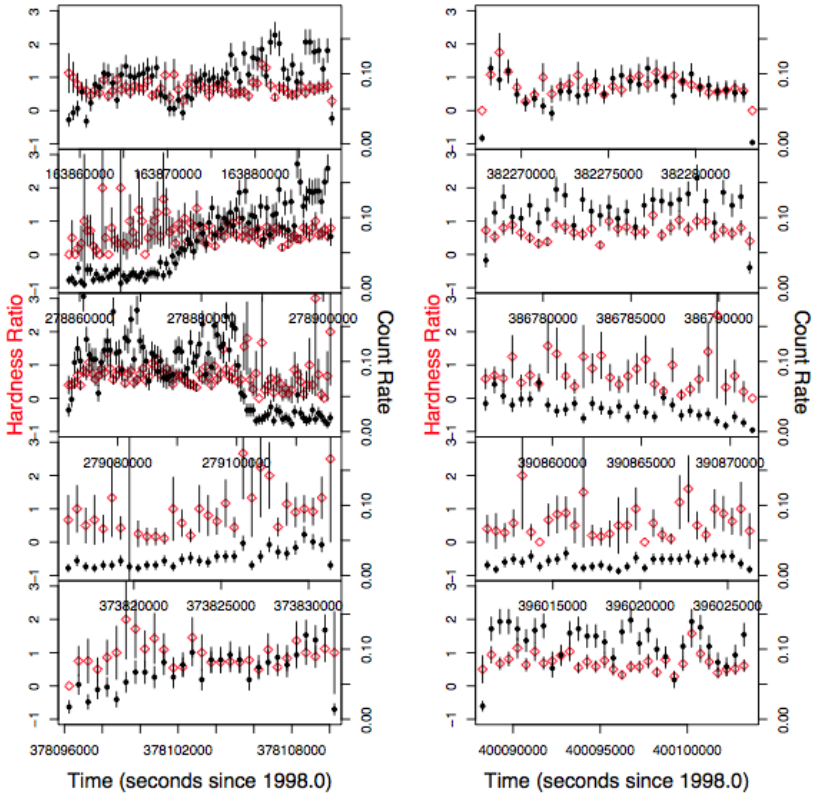
$$HJD = JD - \frac{r}{c} \cdot [\sin(\delta) \cdot \sin(\delta_\odot) + \cos(\delta) \cdot \cos(\delta_\odot) \cdot \cos(\alpha - \alpha_\odot)]$$

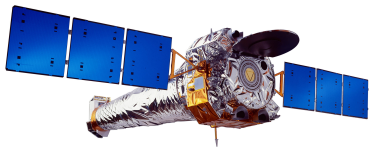
Phase Connecting Multi-observatory Data over Long Time Spans

Example:

...it was possible to phase connect them all

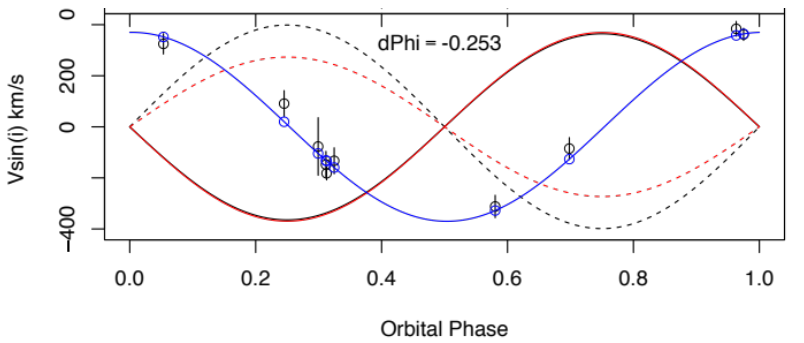
Using lots of separate observations (2002 – 2022)
of the black hole high mass X-ray binary IC 10 X-1...



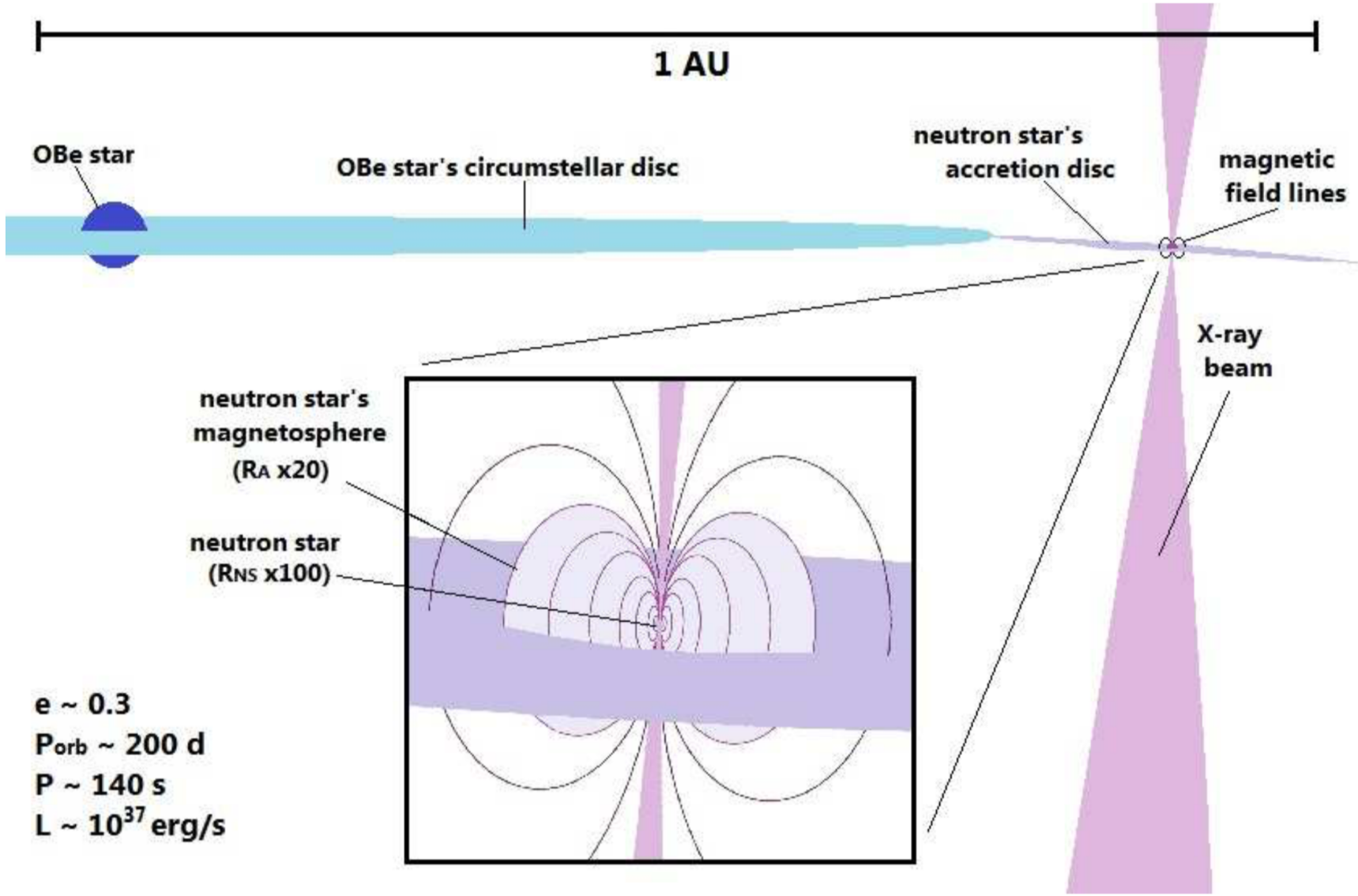








And align the X-rays with Keck and Gemini radial velocity measurements collected over years


1 AU
OBe star
OBe star's circumstellar disc
neutron star's
accretion disc
magnetic
field lines
X-ray
beam
neutron star's
magnetosphere
(RA x20)
neutron star
(RNS x100)
e ~ 0.3
Porb ~ 200 d
P ~ 140 s
L ~ 10^37 erg/s

Pulsars: The Lighthouses of the Universe



Nicholas Sorabella UMass Lowell

Fourier Analysis, some background to help interpret what we see in the Periodogram

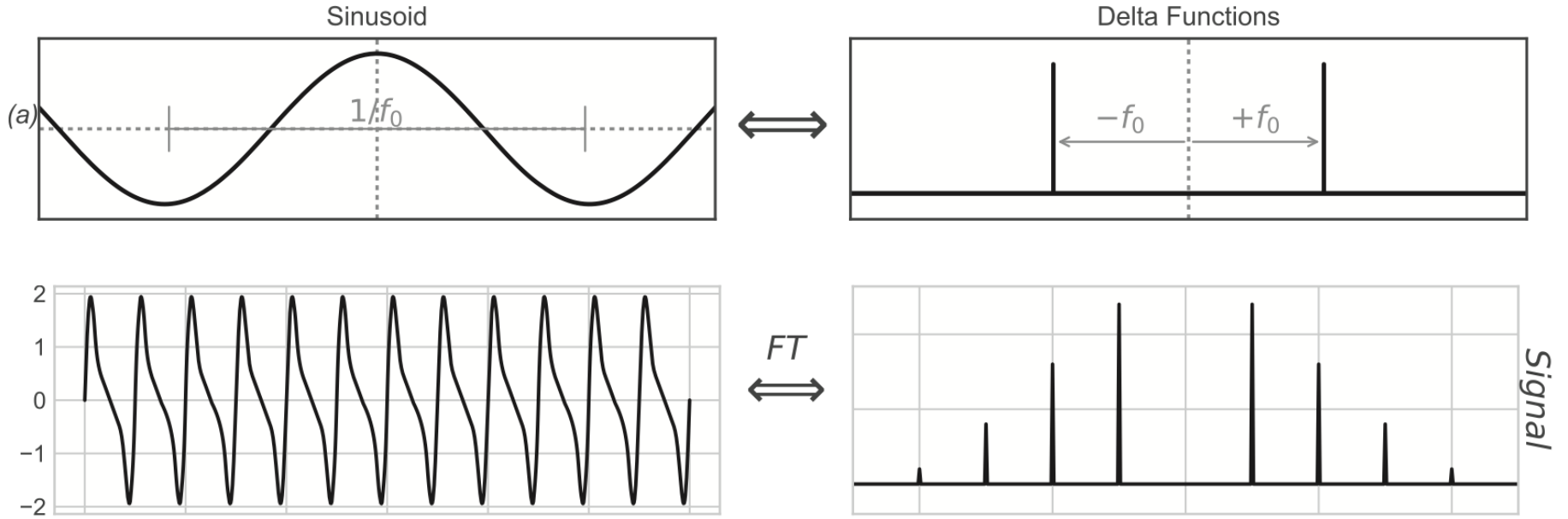
$$s_N(x) = a_0 + \sum_{n=1}^{N} \left(a_n \cos\left(2\pi \frac{n}{P} x\right) + b_n \sin\left(2\pi \frac{n}{P} x\right) \right)$$ (Fourier's theorem)

$$s_N(x) = \sum_{n=-N}^{N} c_n \, e^{i2\pi \frac{n}{P} x}$$

$$c_n = \frac{1}{P} \int_0^P s(x) \, e^{-i2\pi \frac{n}{P} x} \, dx.$$

Fourier Transform is a procedure that finds the Frequency domain representation of the function

$$\widehat{f}(\xi) = \int_{-\infty}^{\infty} f(x) \, e^{-i2\pi\xi x} \, dx$$



Beware Spurious Periods in Periodograms!

1. Valid Frequency range of the data:

Just because your code spits out 1/L to 1/dt doesn't mean you can use it all.
Consider requiring at least 4 cycles of the period
Ignore the periodogram at periods below 2 dt (the Nyquist limit)

2. Instrumental periods:

Chandra's Dither Motion (707s, 1000s)
ACIS readout interval: default 3.2s, but *not always*.

3. Cross-Contamination by nearby sources

4. Scheduling constraints that may be periodic

Spacecraft orbital period
Lunar orbital period
SAA Passage
Earth Year

} Window Function

5. Aliasing

Real Data have an additional ingredient: Observing Cadence

Sampling or Cadence, to astronomers **Window Function** (to Mathematicians)

If a signal g(t) is sampled at a series of times W(t), the observed signal g_{obs} will simply be the product of the signal with the sensitivity as a function of time.

$$g_{\rm obs}(t) = g(t)W(t),$$

The Fourier Transform of the o

$\mathcal{F}\{f \cdot g\} = \mathcal{F}\{f\} * \mathcal{F}\{g\}$. (Beca

$$\mathcal{F}\{g_{\rm obs}\} = \mathcal{F}\{g\} * \mathcal{F}\{W\}.$$

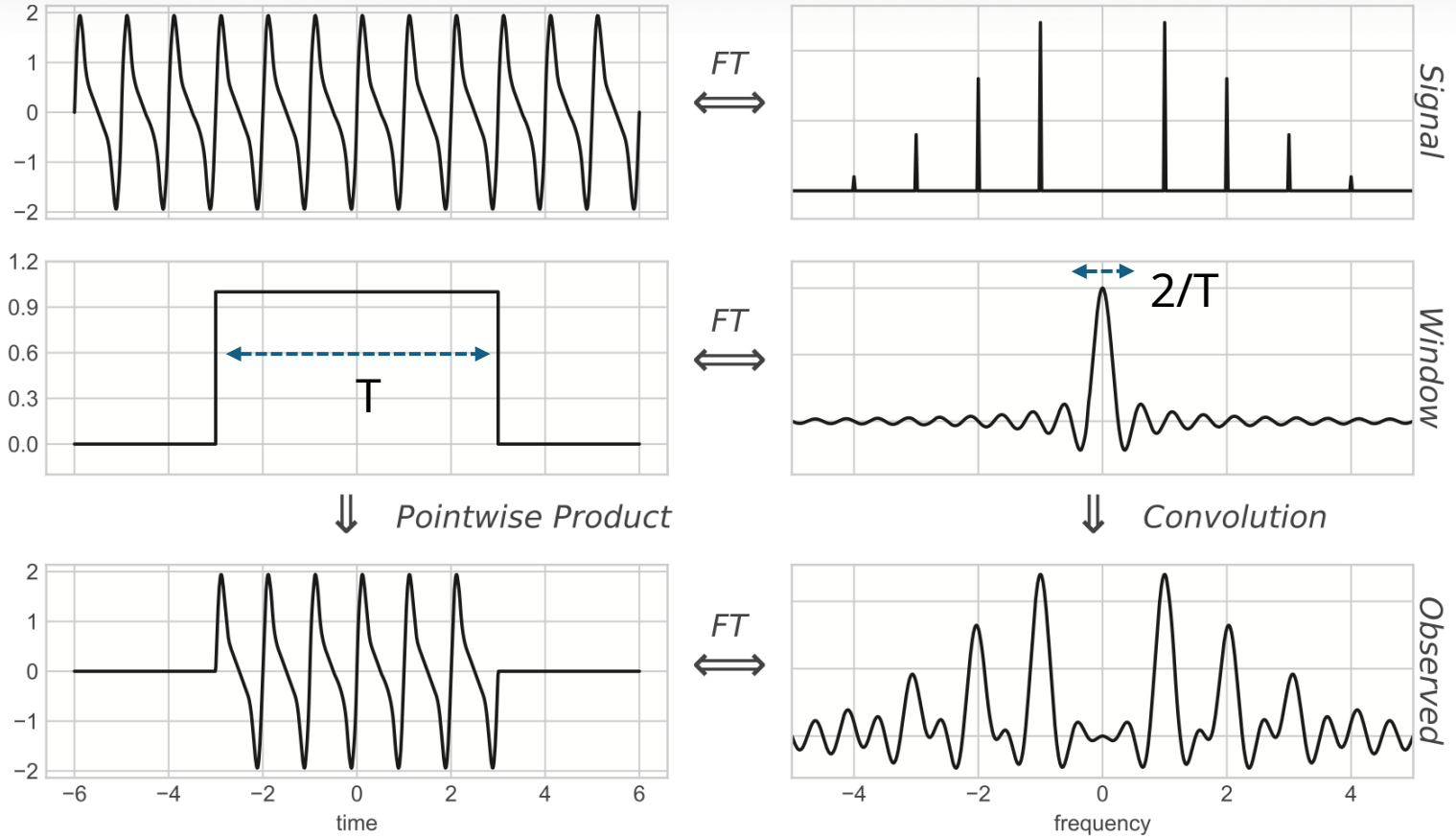


Figure 6. Visualization of the effect on the Fourier transform of a rectangular observing window (i.e., a continuous signal observed in its entirety within a finite range of time). The function used here is $g(t) = 1.2\sin(2\pi t) + 0.8\sin(4\pi t) + 0.4\sin(6\pi t) + 0.1\sin(8\pi t)$. The observed Fourier transform is a convolution of the true transform (here a series of Delta functions indicating the component frequencies) and the window transform (here a narrow sinc function).

This is another version of the "fundamental equation of astronomy"

Sparse Sampling

Irregular Sparse sampling

Dense irregular sparse sampling

Signal

Sampling

Data

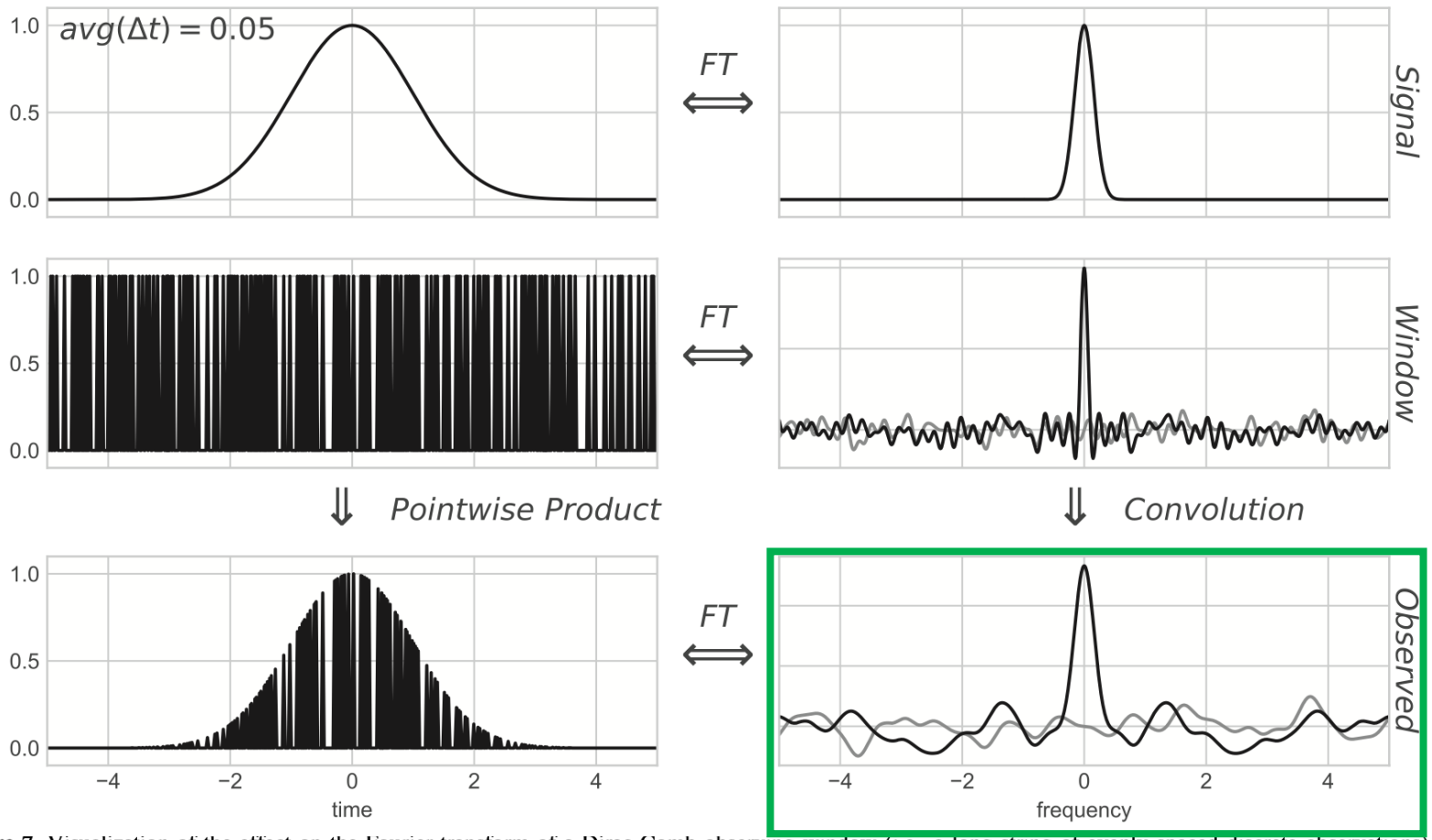


Figure 7. Visualization of the effect on the Fourier transform of a Dirac Comb observing window (i.e., a long string of evenly spaced discrete observations). The observed Fourier transform is a convolution of the true transform (here a localized Gaussian) and the window transform (here another Dirac comb).

Aliasing
Improves with more samples

VanderPlas, J., 2018, The Astrophysical Journal Supplement Series, 236:16 (28pp)

Lomb-Scargle Periodogram

Fourier analysis for unevenly sampled data

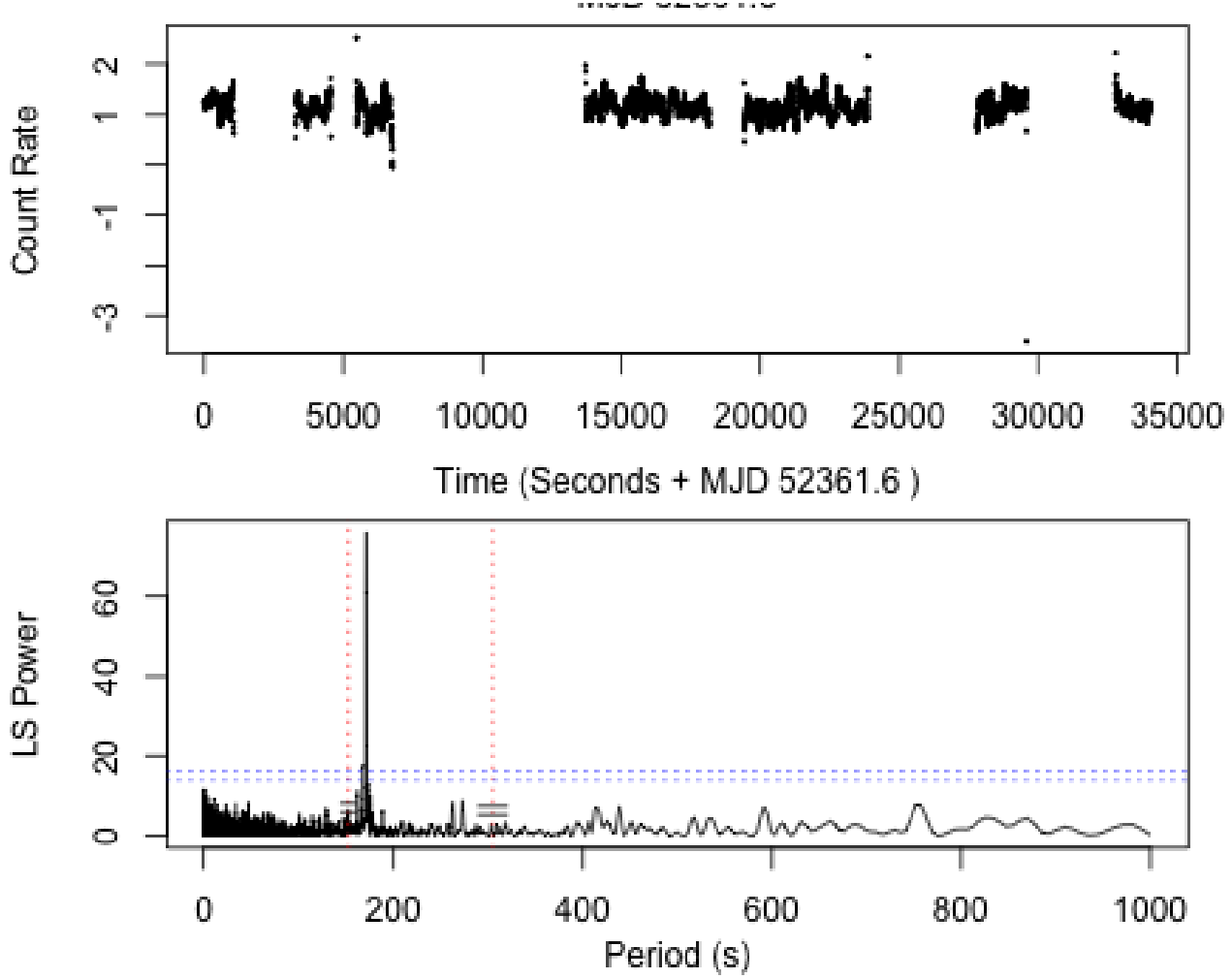
Specifically formulated to solve the problem of doing FFT on Astronomical observations

Chandra data can be extracted into an evenly sampled light-curve but can contain gaps due to GTI structur

You can choose whether to:

take FFT of the contiguous sections, or

use Lomb-Scargle on the whole lightcurv



Confidence Intervals

$$\mathrm{Sig}(\%) = 100(1 - e^{-Z})^{M}$$

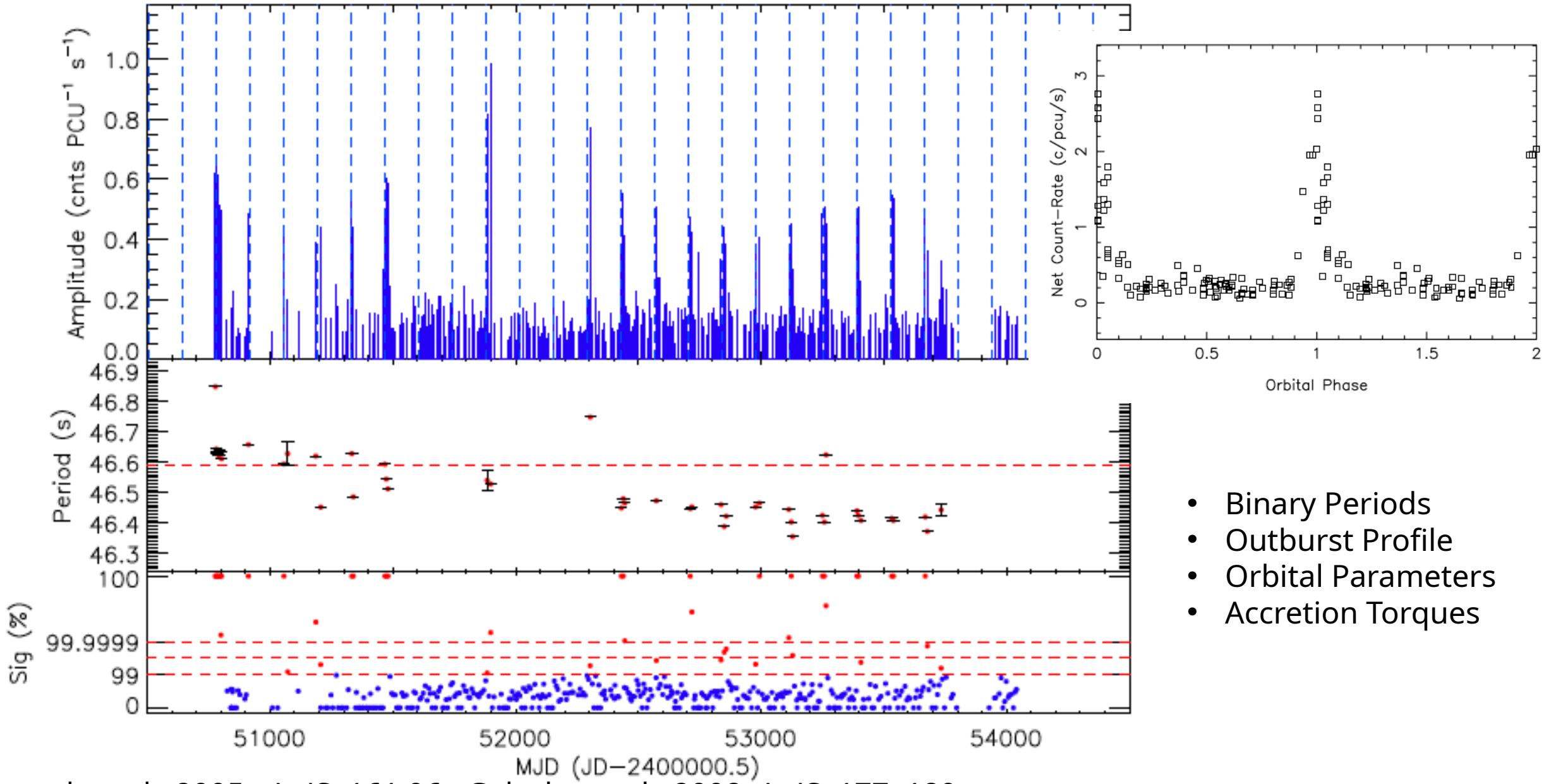
Inferred Pulse Amplitude

$$A = 4\sqrt{\frac{P_{\mathrm{LS}}\sigma_n^2}{N}} \qquad A_{\mathrm{tot}} = \sqrt{\sum_i A_i^2}$$

Period Uncertainty

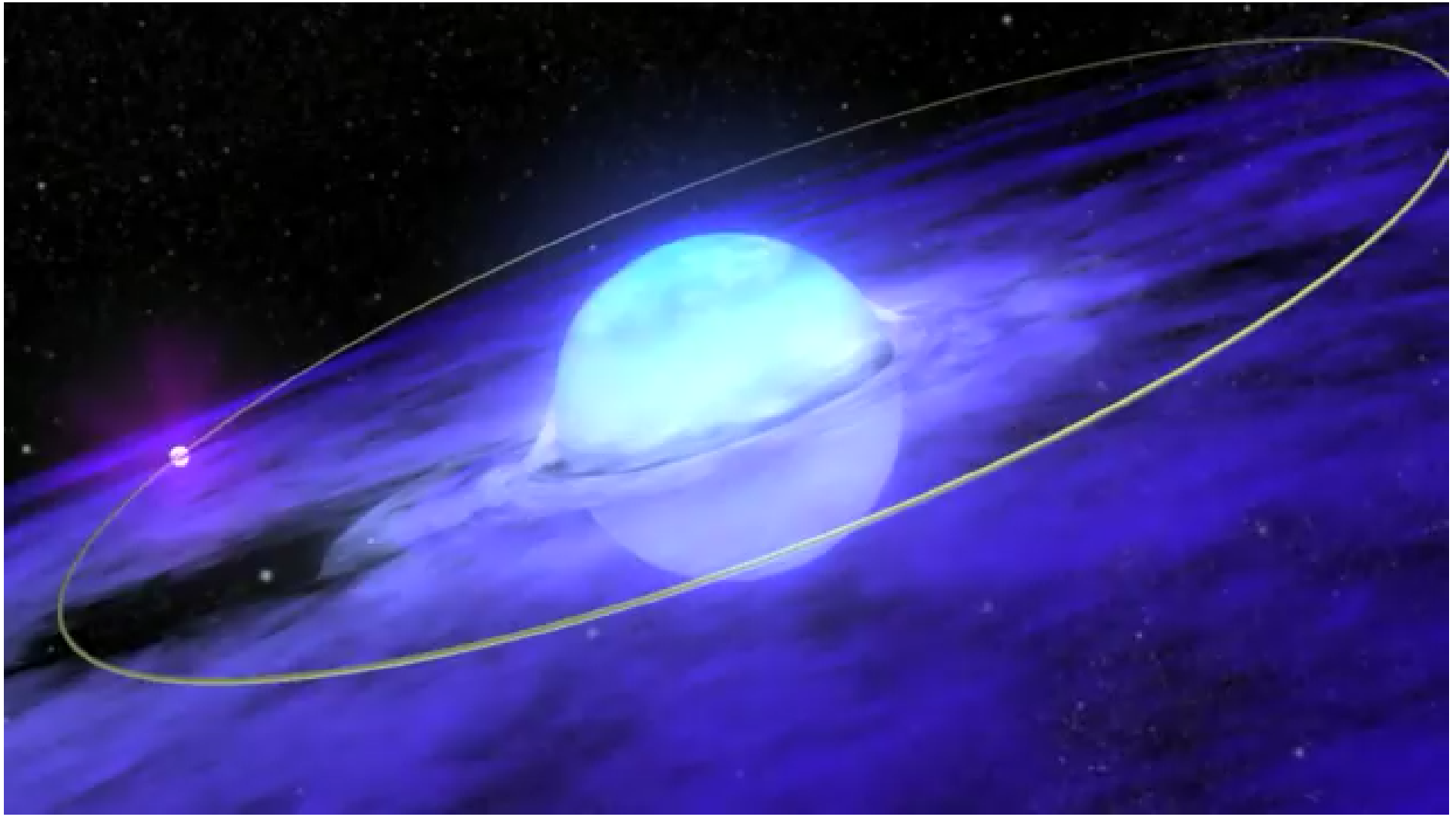
$$dP = \frac{3}{4}\left(\frac{P^2\sigma_n}{\sqrt{N}\tau A}\right)$$

Following the Outburst and Spin Period History of a Pulsar

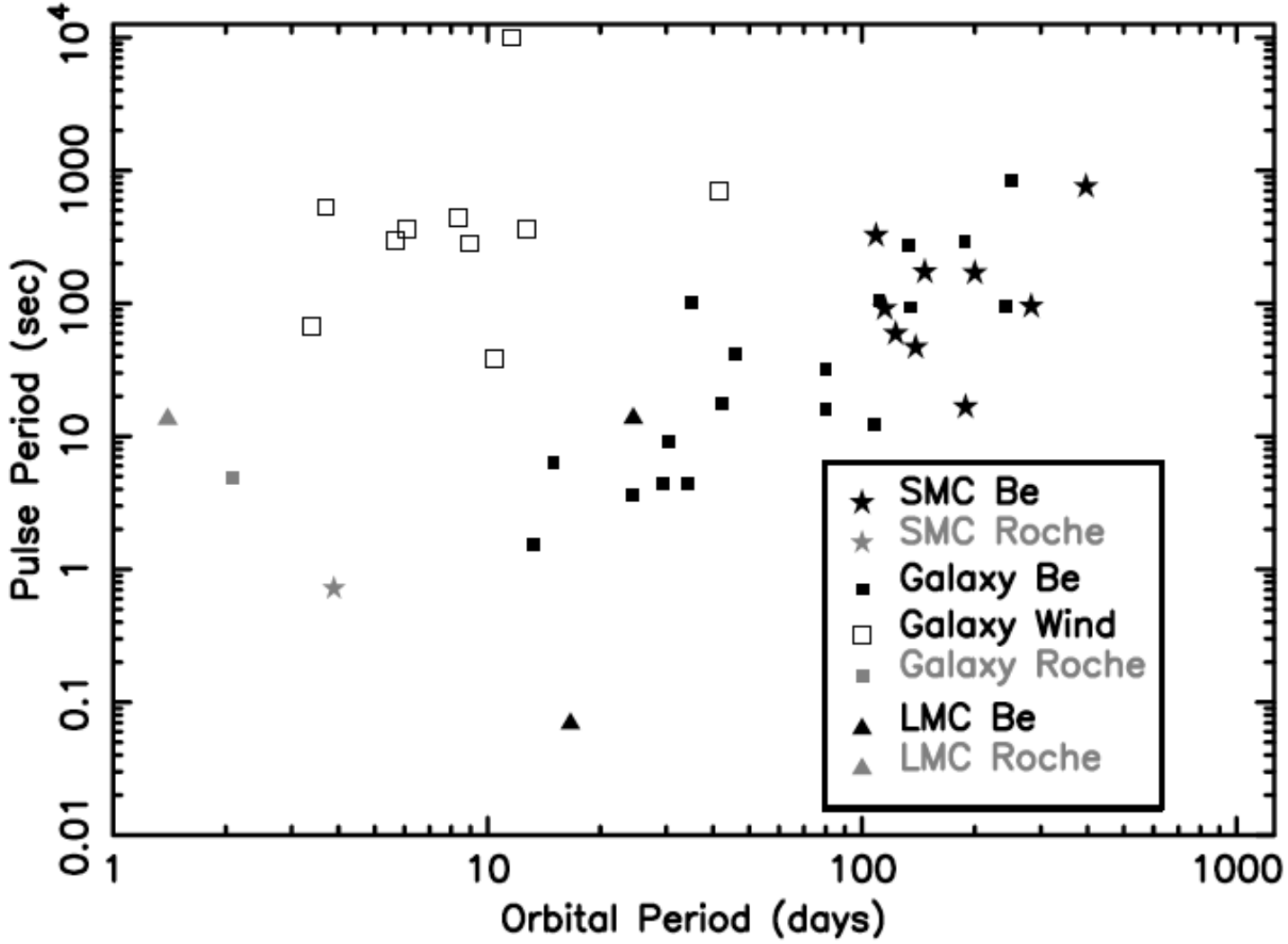


- Binary Periods
- Outburst Profile
- Orbital Parameters
- Accretion Torques

Laycock et al., 2005., ApJS, 161,96 , Galache et al., 2008, ApJS, 177, 189

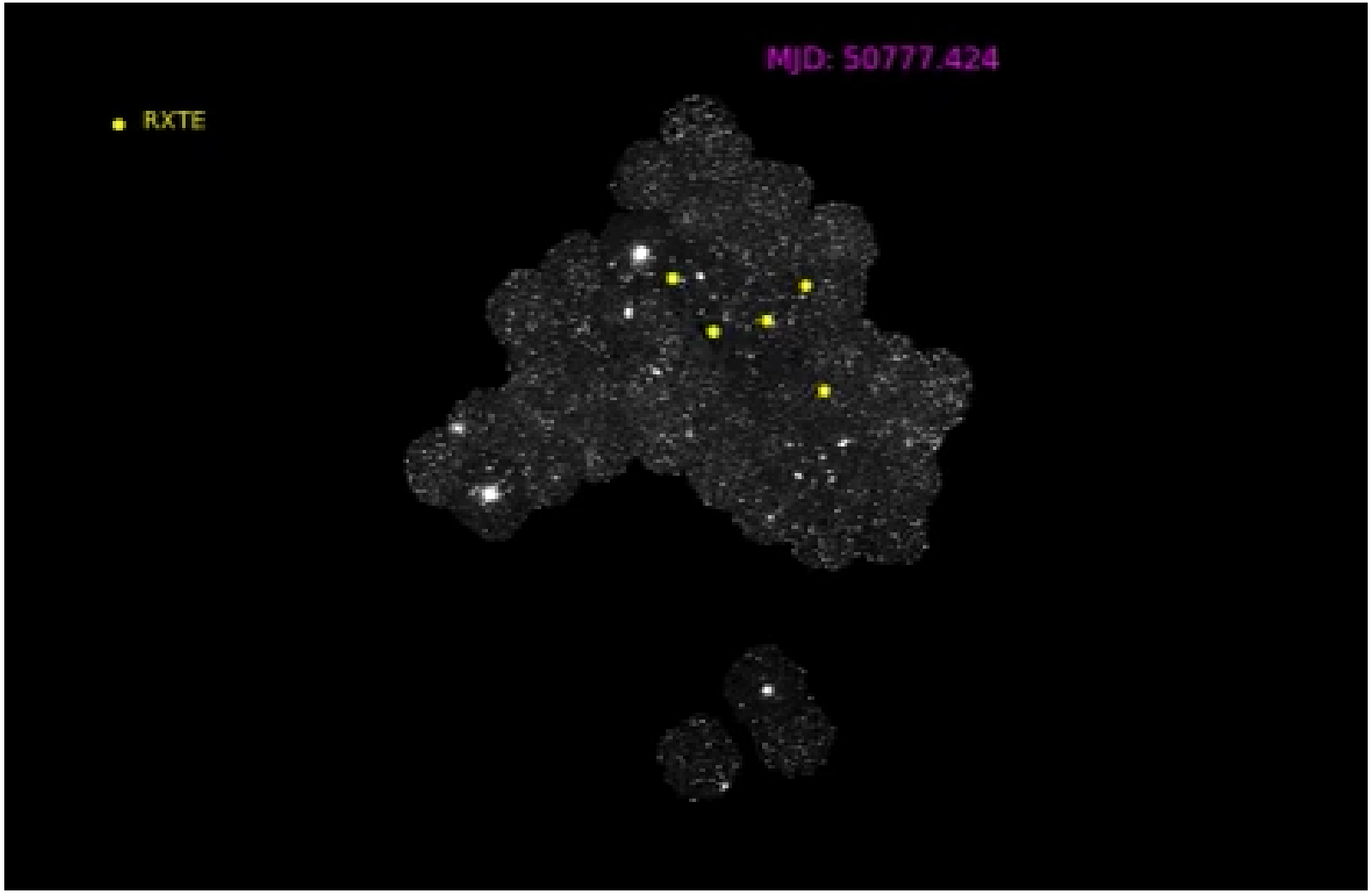


Spin-Orbit Equilibrium - Corbet Diagram



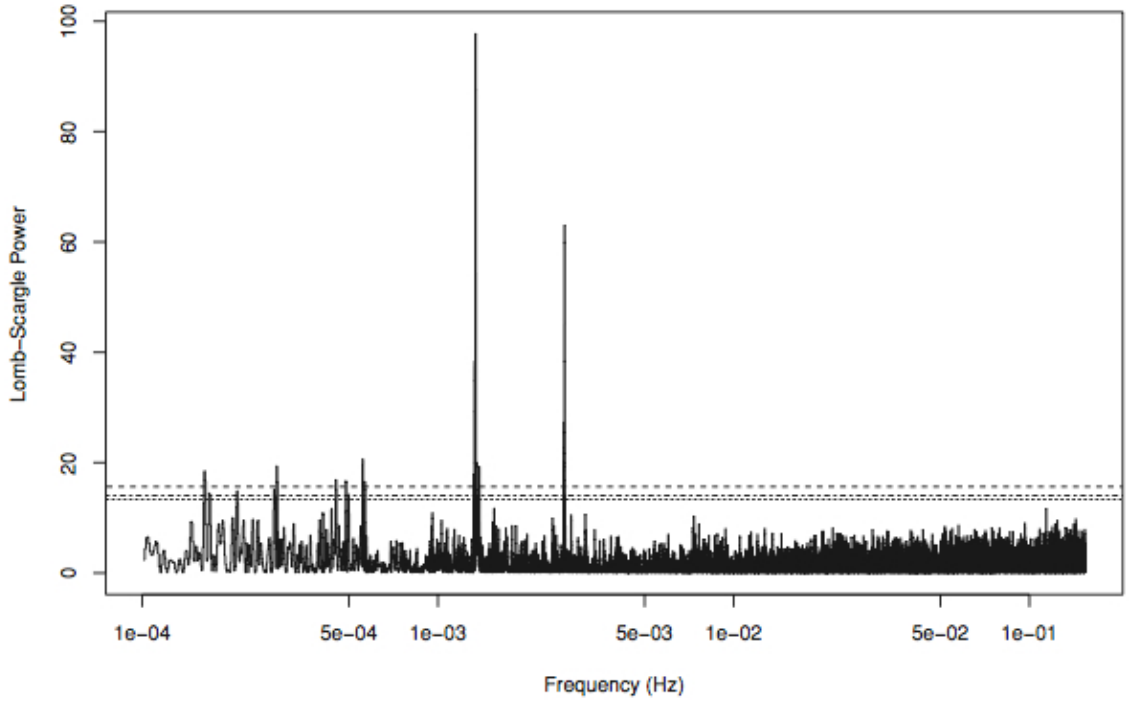
Laycock et al. 2005

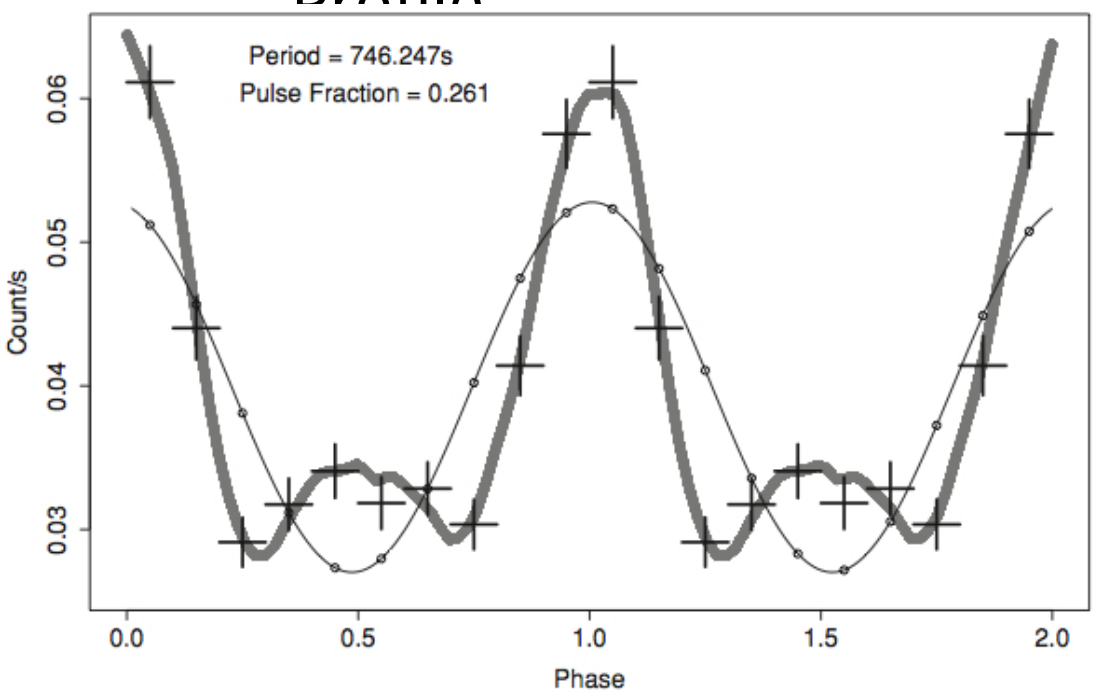
X-ray Pulsars in The Small Magellanic Cloud, as monitored by 5 Observatories, MJD 50777 - 58791



A. Roy, UMass Lowell J. Yang, S. Bhattacharya, S. Laycock

Power (Frequency) Spectrum → Pulse Profile





1. **Decide on the Period, P**

   Significance: 99%, 95%.... ?

   Harmonics

2. **Transform time to Phase**

$$\phi_i = frac\left\{\frac{t_i - T_0}{P}\right\}$$

$$\phi_i = \left\{\frac{t_i - T_0}{P}\right\} - \mathrm{INT}\left\{\frac{t_i - T_0}{P}\right\}$$

3. **Construct Phase Distribution: AKA the Pulse Profile**

   Bin – choices ?

   KDE?

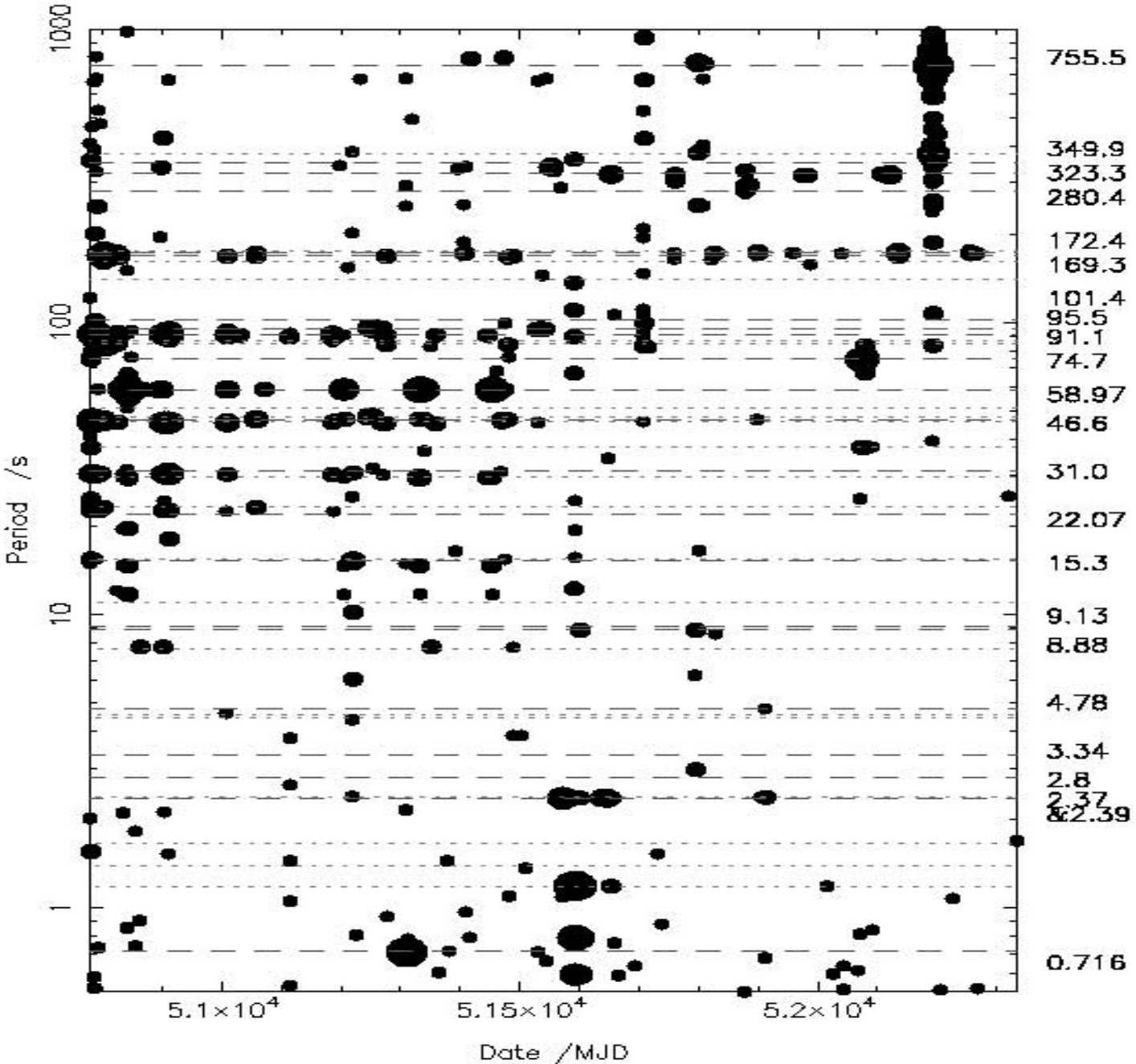
   Smooth?

   Fit a Model?

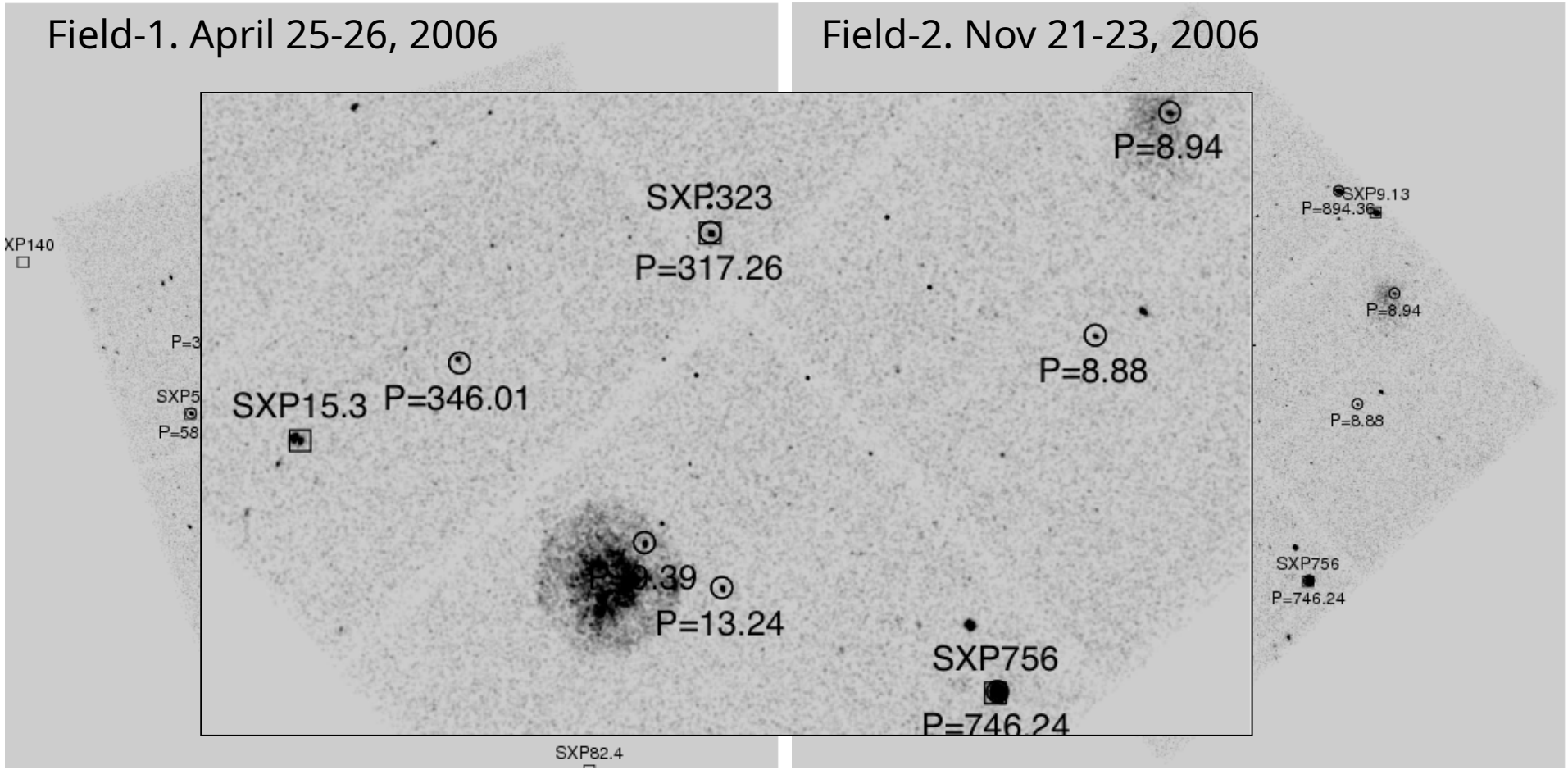
41 X-ray pulsars monitored for ~ a decade

Dot size represents spectral power. All detections >90% significance are plotted.

Dashed lines = pulse periods, dotted lines=harmonics

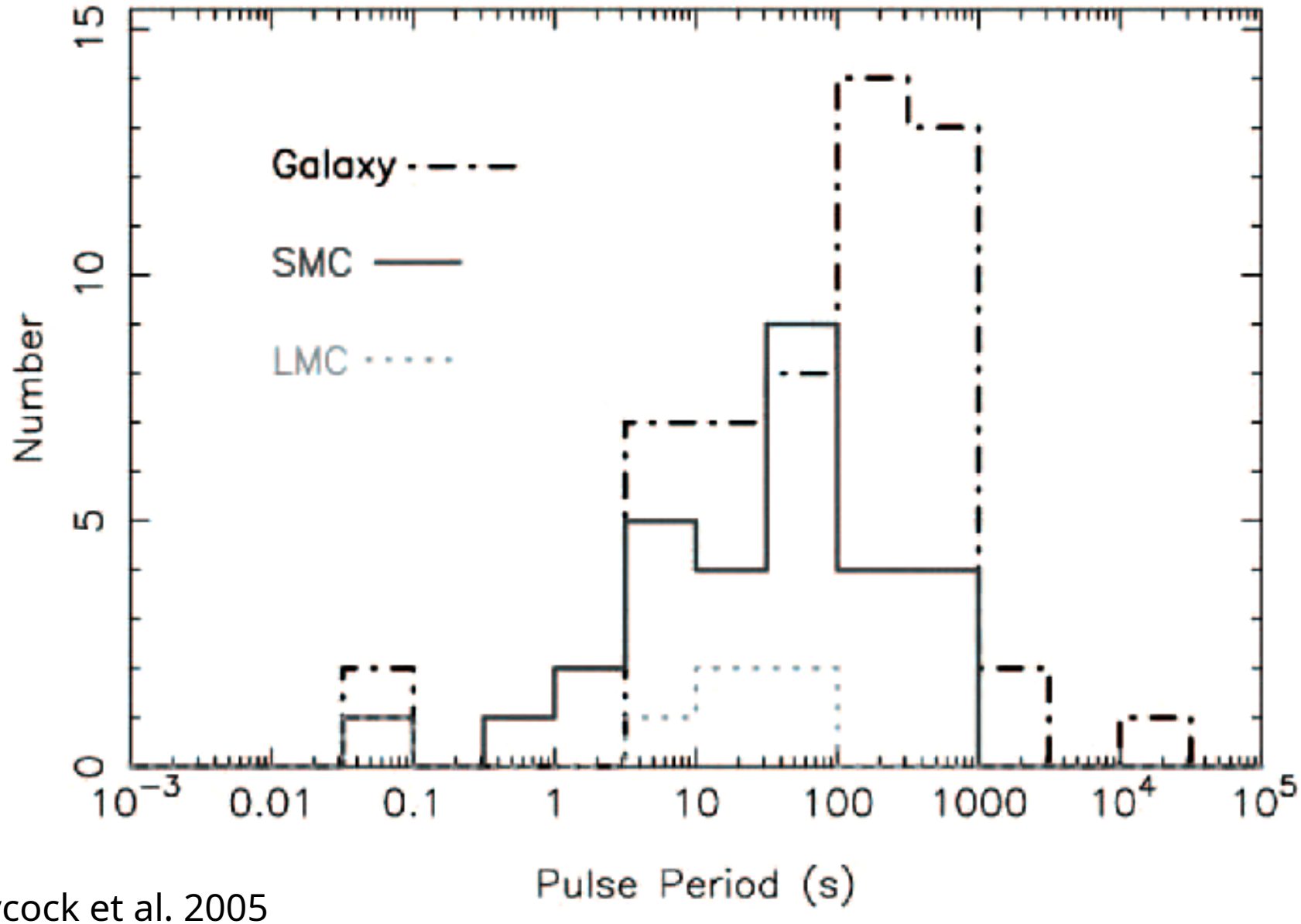


Chandra ACIS-I 100 ksec

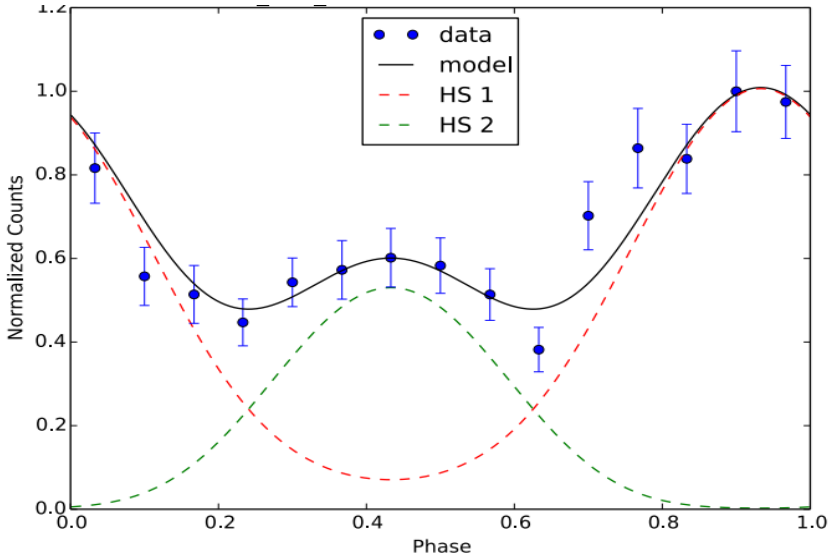


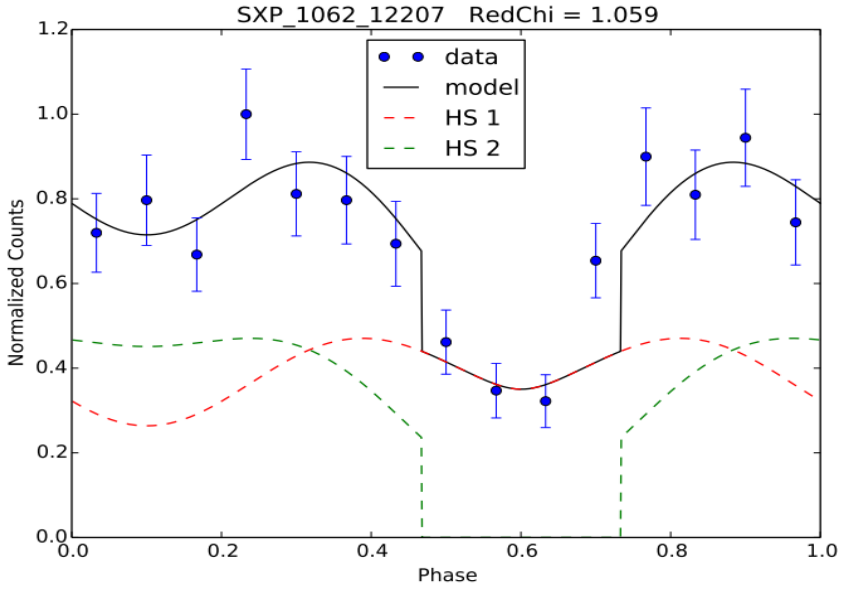
- 394 point-sources, 2 supernova remnants

Distribution of Pulse Periods

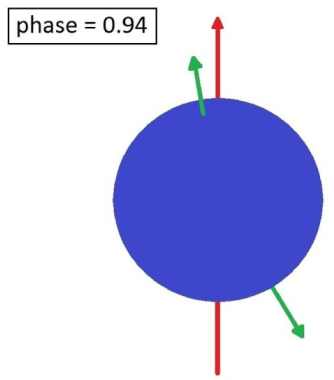


Laycock et al. 2005

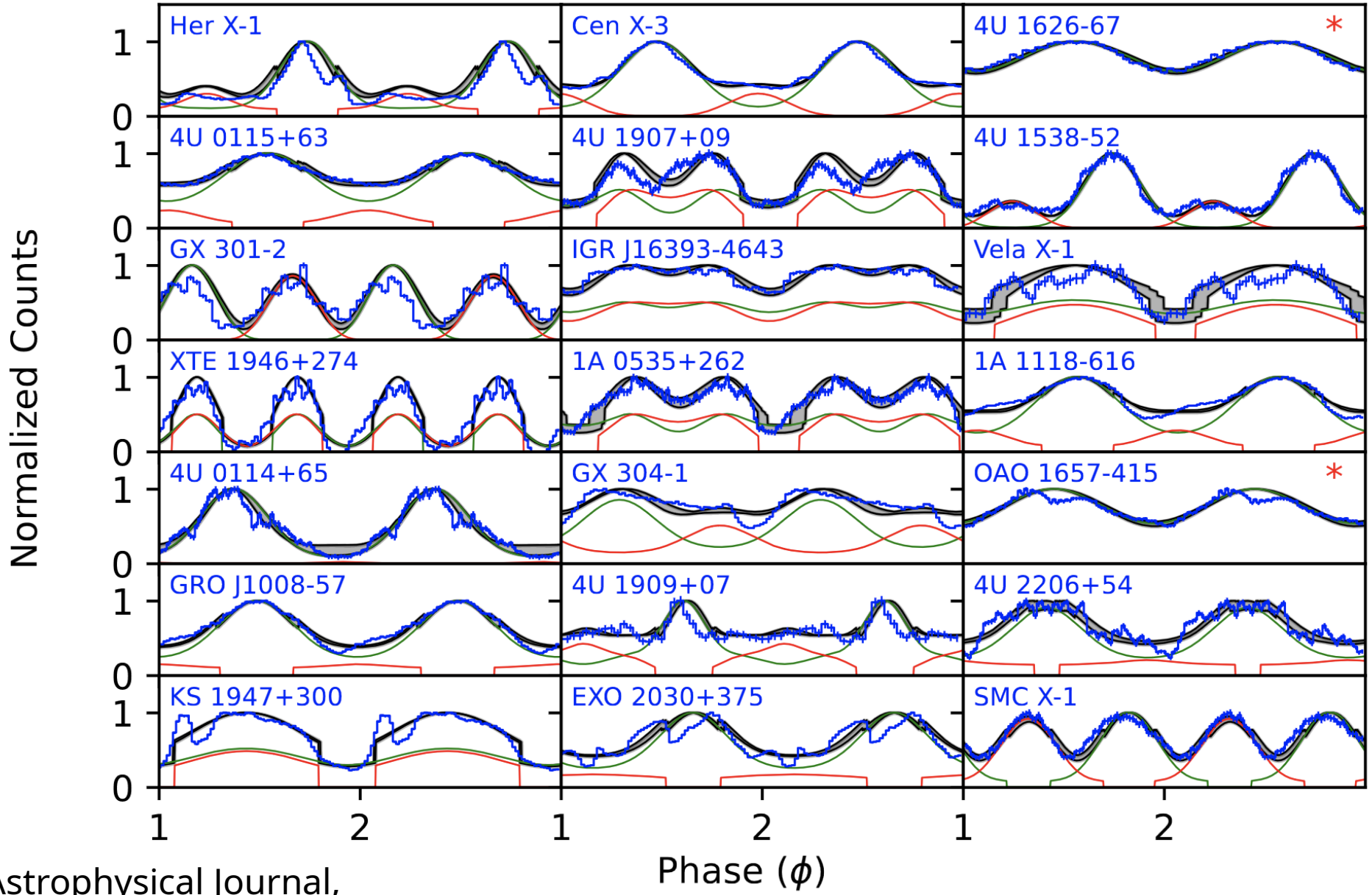




Polestar fits to a XMM-Newton pulse-profiles illustrating some differences between pencil-beam (left) and fan-beam (right) dominated morphology. The fan-beam component reproduces the abrupt drop in flux as the more distant hotspot crosses the terminator. Cappallo et al., (2017).

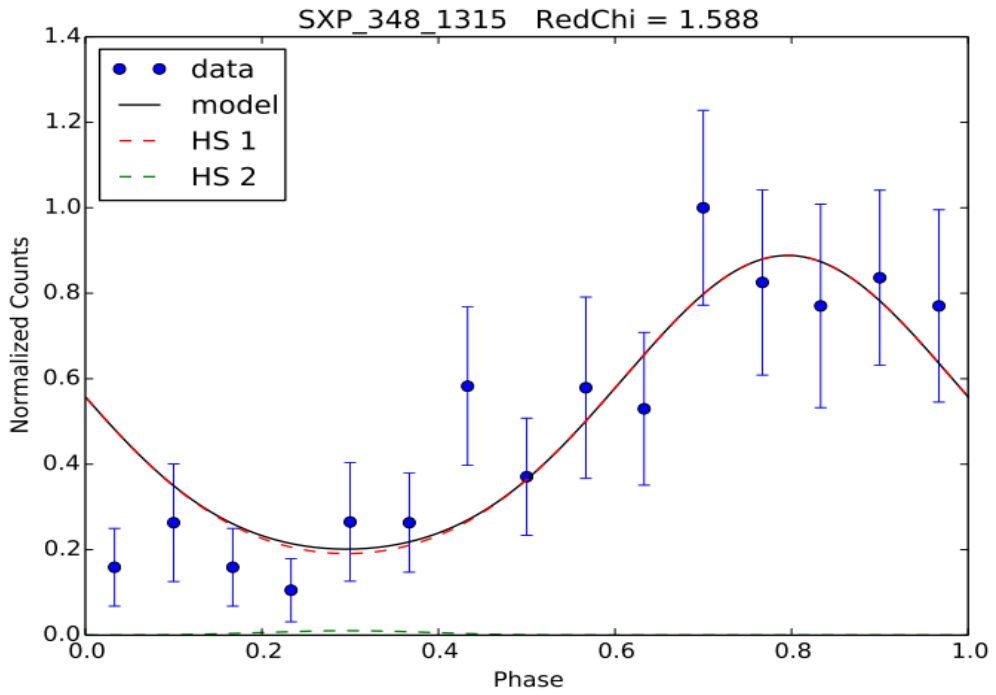


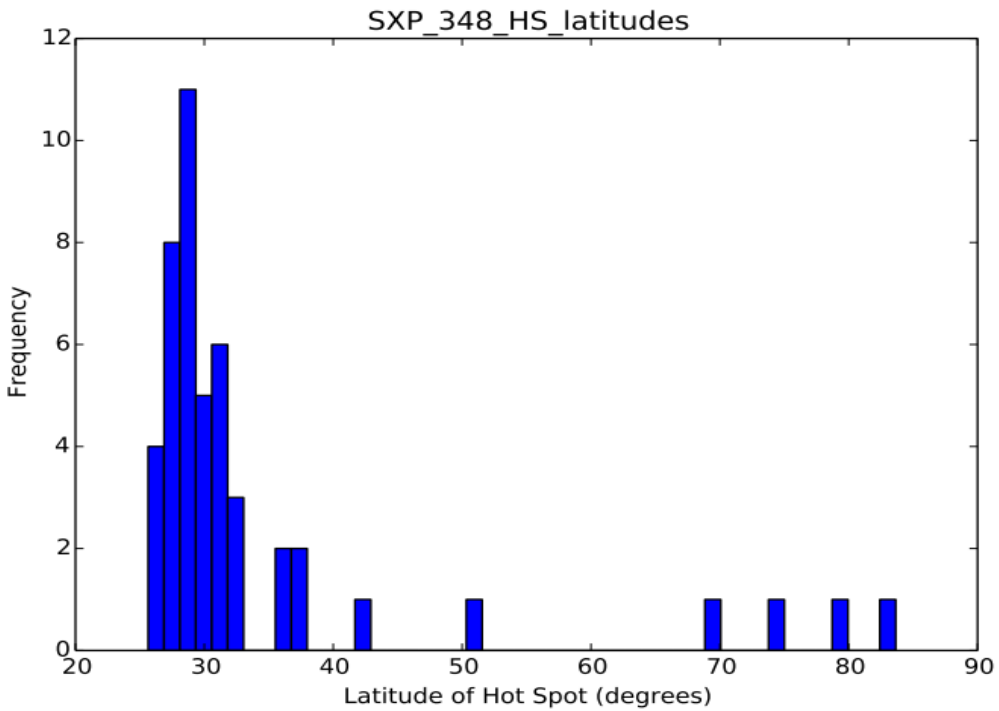
X-rav Pulsar Pules Profiles



Laycock+ 2025, Astrophysical Journal,

Statistical experiments with pulsar populations

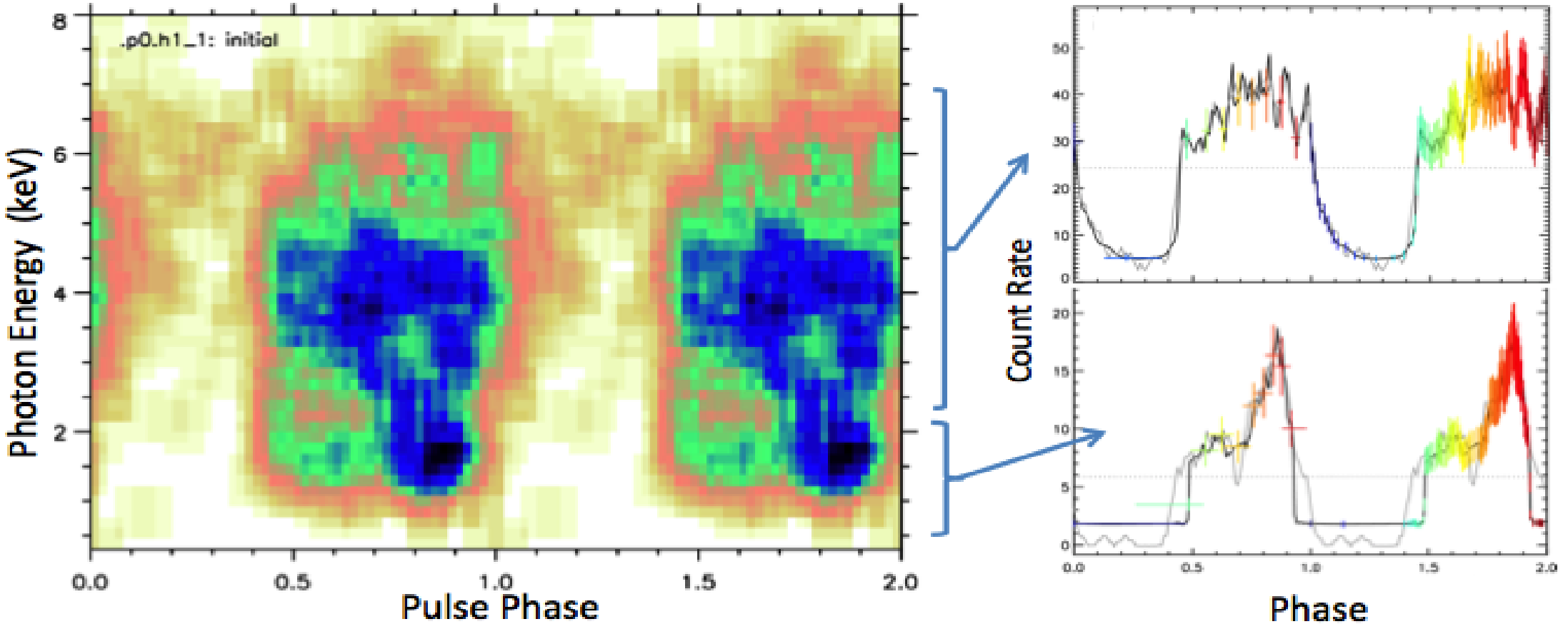




Fitting all library pulse profiles obtained for **the same pulsar** we assemble the histograms of each model parameter. Shown at right is the histogram for magnetic dipole offset angle. A certain value is strongly preferred during most observations, suggesting that we are measuring this fundamental parameter.

Cappallo + 2019, ApJ,

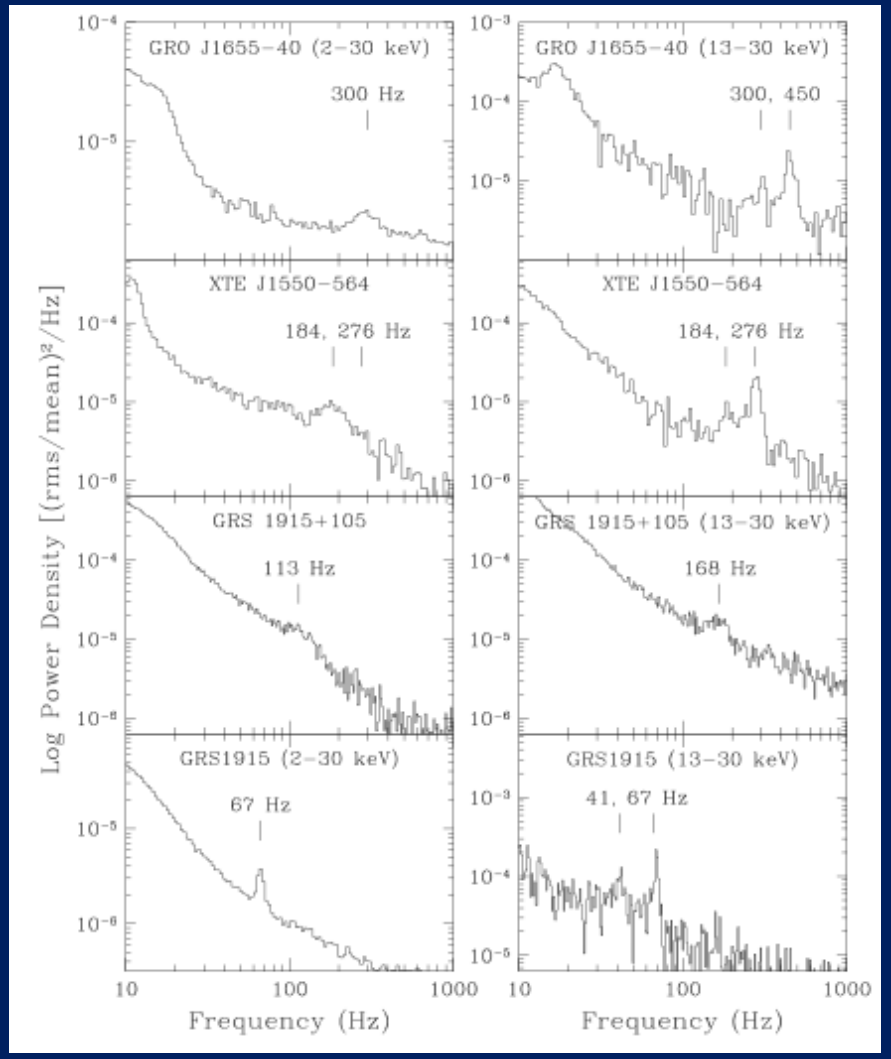
Time Domain Astrophysics



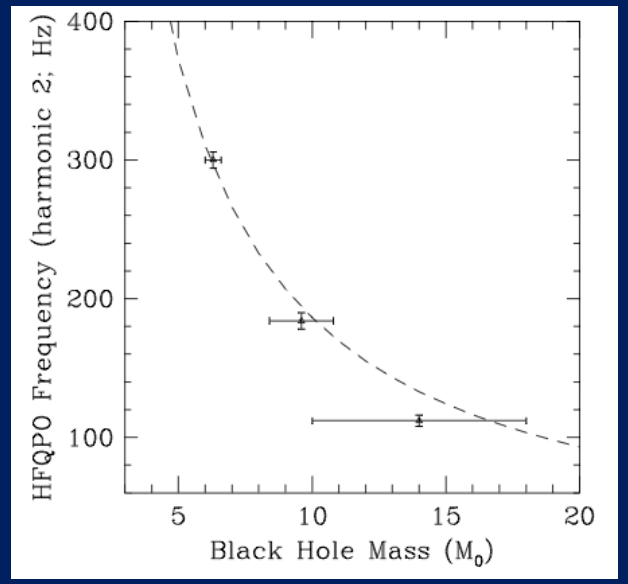
Chandra ACIS Event file for an SXP in a 100 ksec ACIS observation.

Represented as a **Phase-Energy-Intensity map**. We see a broad plateau-like component above 3 keV, while a sharp feature (sharp in both phase and energy) is seen centered around 1.5 keV (Hong+ 2016, ApJ, 826, 8)

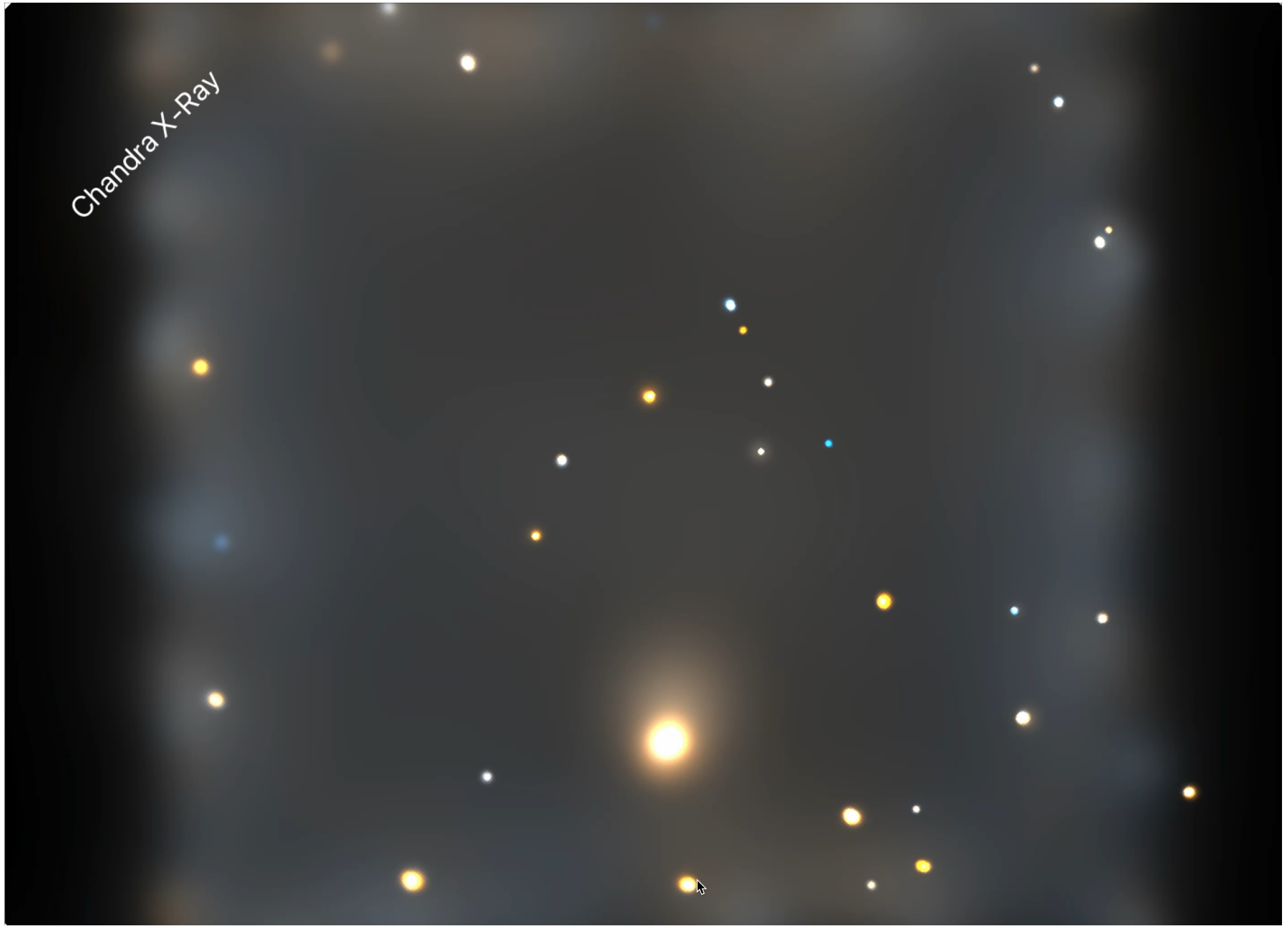
Black Hole Noise. – Aperiodic Variability



- A fascinating correlation exists between the shape of the “noise spectrum” and the mass of the black hole.
- The relation holds over many orders of magnitude, from stellar-mass BHs all the way up to Active Galactic nuclei of many millions of solar masses.
- The more massive the BH, the more the noise shifts to lower frequencies



Multi-band Correlated Variability, with Time lags


Chandra X-Ray