Pulsar Sources for SEXTANT

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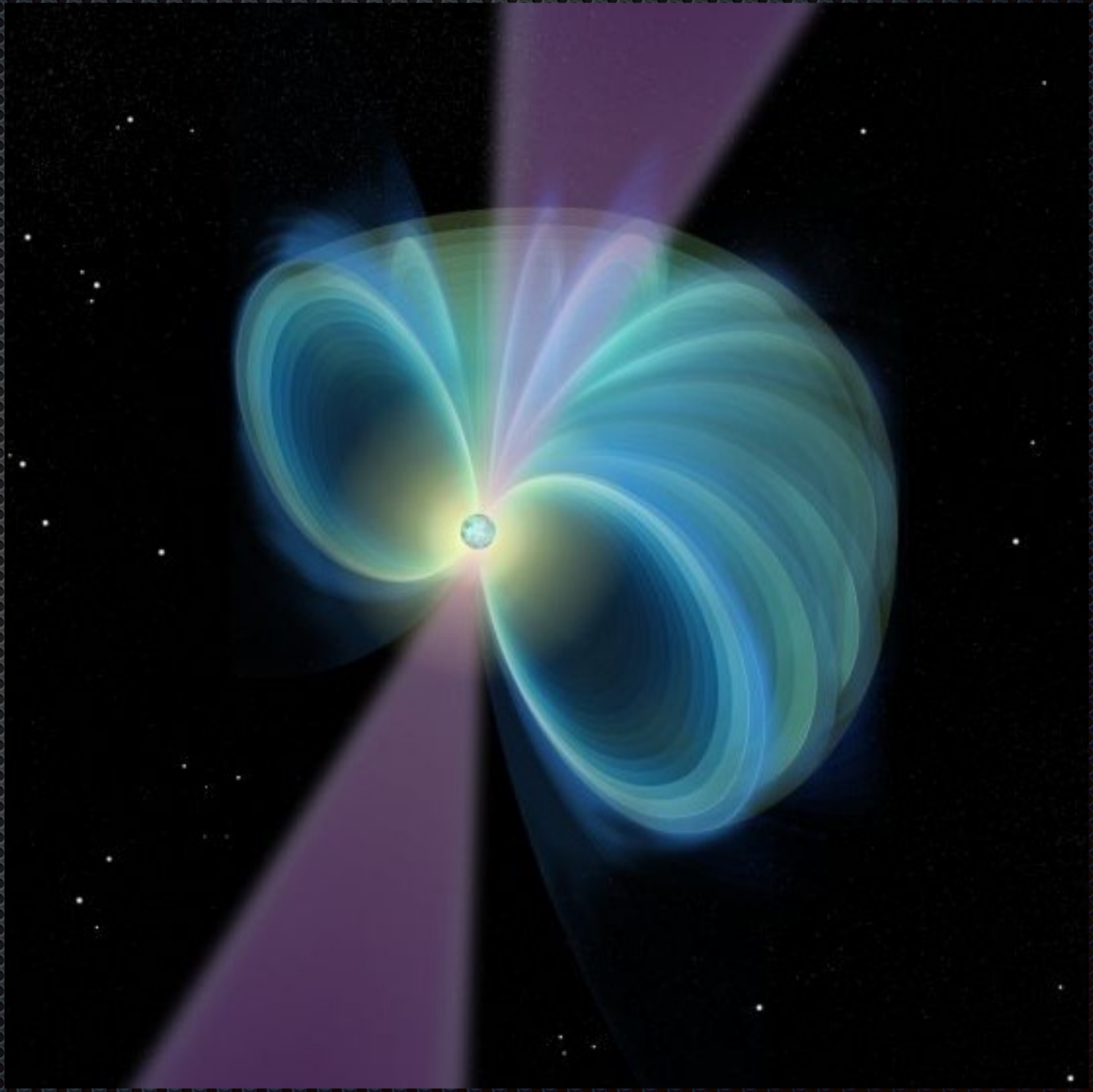
Energy Sources in X-ray Pulsars

- Rotational Kinetic Energy
  - Rotating fields can accelerate and heat particles
  - Energy comes from spindown of star
- Gravitational potential energy
  - Accretion of matter into a deep potential well provides the energy
- Nuclear Burning
  - Requires a surface and high temperature
  - Can be steady or explosive burning
- Magnetic Field Energy
  - Decaying fields in “magnetars” ($B \sim 10^{14}$ G) can provide energy
- Thermal
  - NS/WD are very hot when formed and can have long cooling times

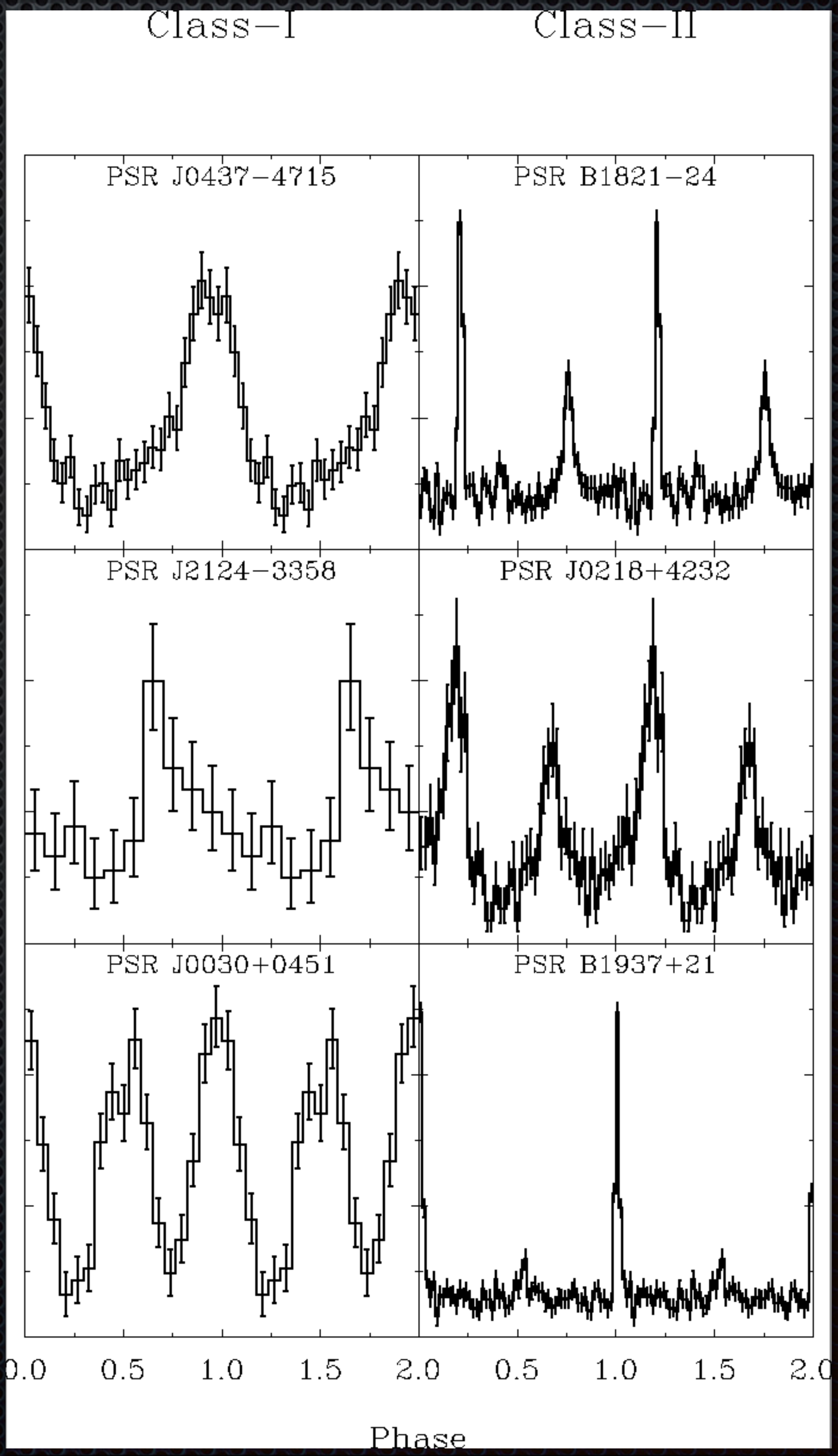
Rotation-Powered Pulsars (Normal)

- Born with periods of ~10 ms, then spin down to ~10 seconds
- Mostly isolated
- Strong magnetic fields (~10^{12} G)
- Timing noise correlated with period derivative

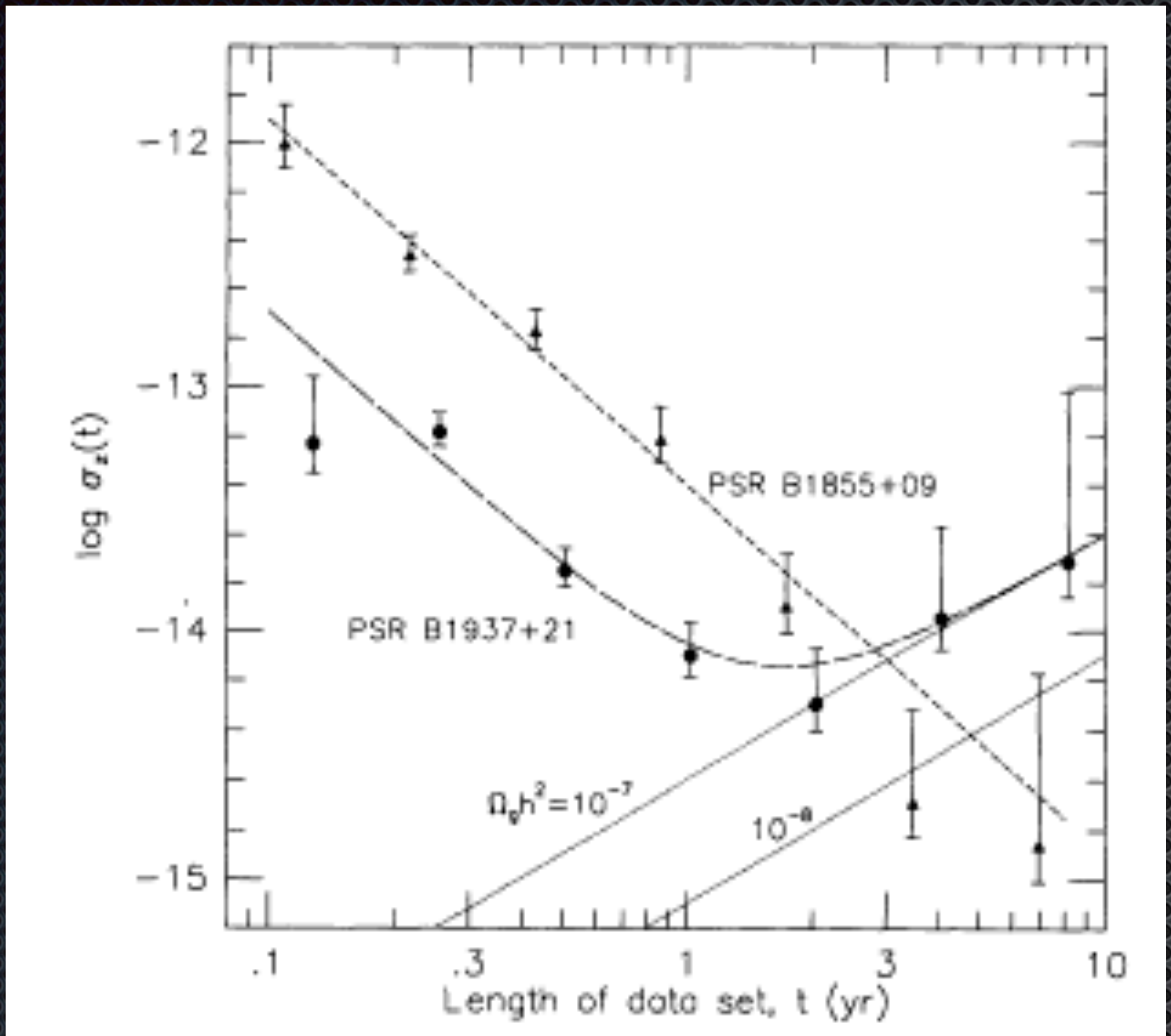


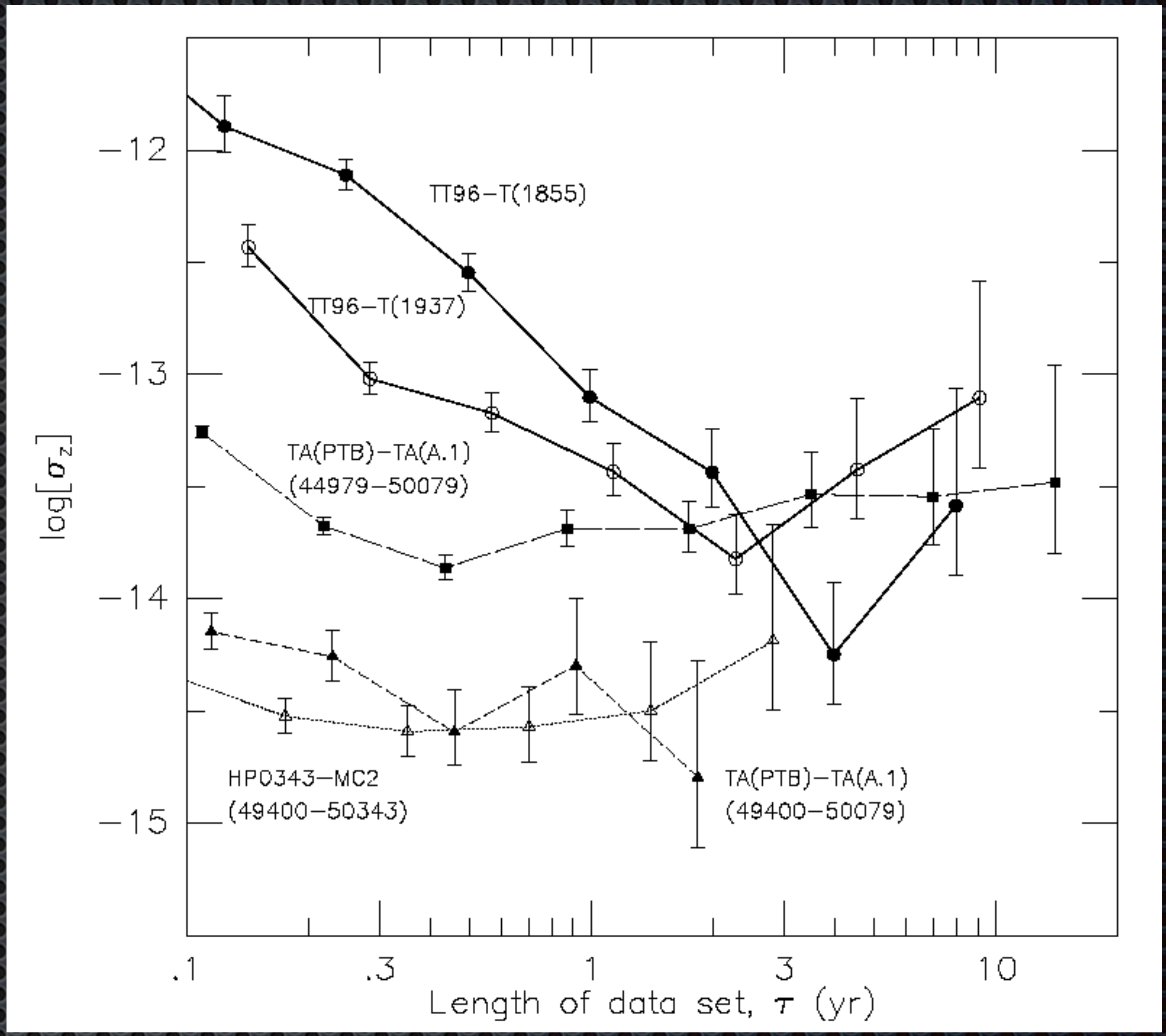
Recycled (Millisecond) Pulsars

- Fast (1.5–16 ms), low B field (10^{8-9} G)
- Very low period derivatives imply lifetimes of Gyr
- Often (>75%) in binary systems
- About a dozen have pulsed X-ray emission detected
- Two spectral classes
  - I: Faint, soft, broad pulses but best intrinsic clocks
  - II: Bright, hard, narrow pulses but exhibit some timing noise and small glitches



Timekeeping — MSPs vs. Atomic Clocks





- Pulsars can provide stable frequency standards
- Variance of millisecond pulsars (most precise astronomical clocks) is comparable to that of atomic clocks

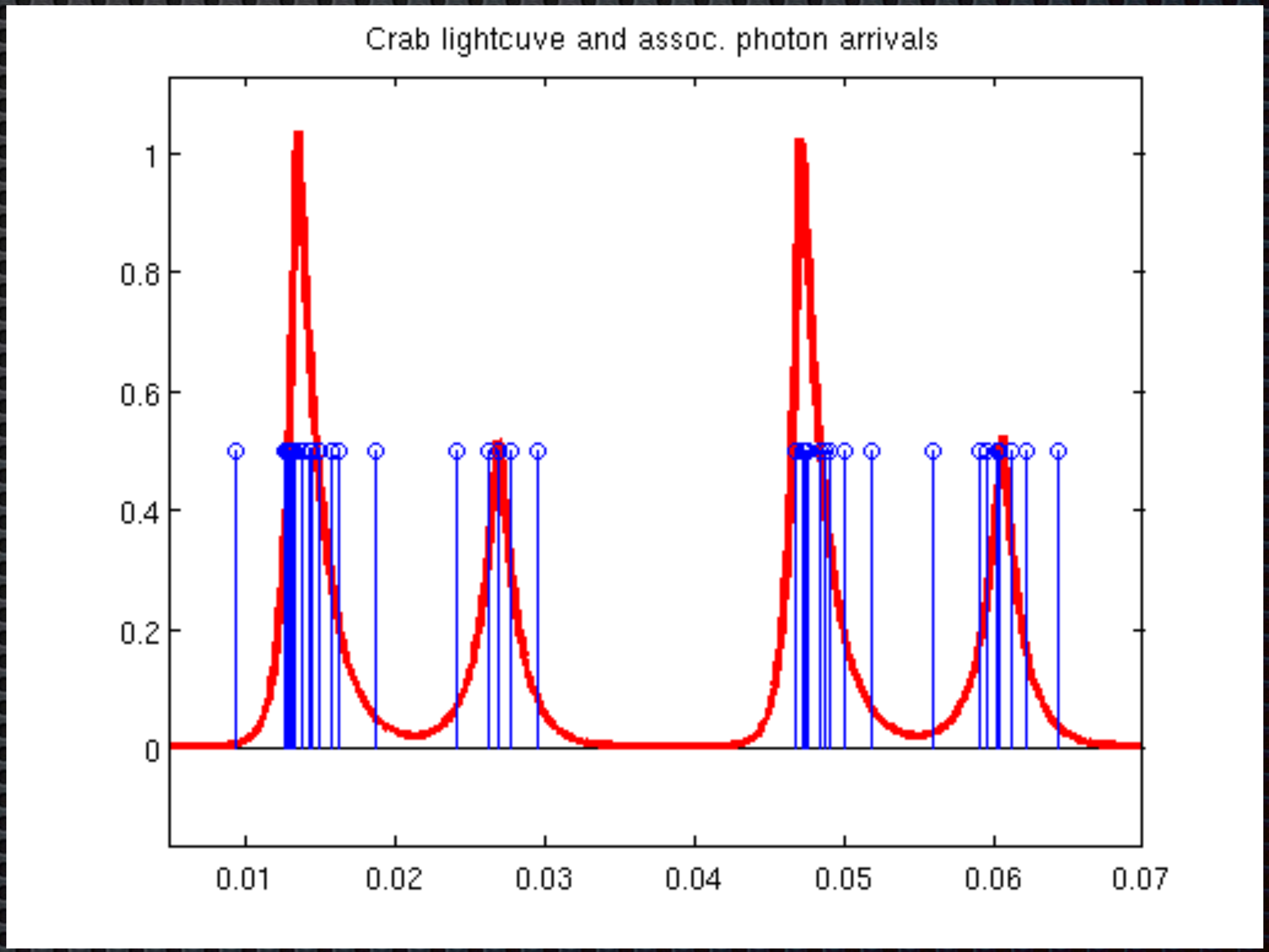
SEXTANT Requirements

- Navigation accuracy requirement is 10 km (33 μs), worst direction
  - Stretch goal is 1 km (3 μs), worst direction
- Integration time limited by ISS orbit period and fidelity of onboard orbit propagator, so planning for 1800 s typical integration time per pulsar
- Ephemeris uploads about once per week
  - Timing models must be good on this timescale, and longer provides more autonomy

Select pulsars that can achieve 300 μs accuracy in reasonable observing time, which essentially means MSPs

Modeling Photon Event Arrival Times

- Variable rate (non-homogeneous) Poisson process
  $$\bar{\lambda}(t) = \lambda(\phi(t)) = \beta + \alpha h(\phi(t))$$
- *h(ϕ)* is the pulsar lightcurve, periodic on [0,1) and normalized to integrate to 1
- α is the mean pulsed flux
- β is the total background rate (from all components)



Pulse Phase Arrival Model

- The phase model at the detector is

$$\phi(t) = \phi_0(t - \tau(t))$$

  - ϕ_0 is the phase evolution at a reference observatory (e.g. SSB or Geocenter)
  - ϕ_0 provided by the standard pulsar timing software Tempo2
    - Extremely high fidelity models
    - Provides convenient piecewise polynomial approximations to the full timing model ϕ_0
  - ***τ(t)*** the prop time of the pulse wavefront moving from the detector to the RefObs at speed ***c***
    - If the RefObs is *close* to the detector (Geocenter)

$$\tau(t) = \frac{\vec{x}(t) \cdot \vec{n}}{c}$$

  - If the RefObs is not so close to the detector (e.g., SSB), the the full delay terms are need (parallax and Solar Shapiro delay terms)
  - SEXTANT's algorithms are based on a Geocentric RefObs but can support SSB RefObs

To compute error in phase model:

$$\begin{aligned}
\phi(t) &= \phi_0\left(t - \frac{\vec{x}(t) \cdot \vec{n}}{c}\right) \\
&= \phi_0\left(t - \frac{\tilde{\vec{x}}(t) \cdot \vec{n}}{c} + \frac{\delta\vec{x}(t) \cdot \vec{n}}{c}\right) \quad (\tilde{\vec{x}}(t) \text{ from filter}) \\
&\simeq \phi_0\left(t - \frac{\tilde{\vec{x}}(t) \cdot \vec{n}}{c}\right) + \dot{\phi}_0\left(t - \frac{\tilde{\vec{x}}(t) \cdot \vec{n}}{c}\right) \frac{\delta\vec{x}(t) \cdot \vec{n}}{c}, \\
&=: \tilde{\phi}(t) + e(t)
\end{aligned}$$

where $\delta\vec{x}(t) = \tilde{\vec{x}}(t) - \vec{x}(t)$

For SEXTANT, we assume

$$e(t) \simeq q + f(t - t_a)$$

(*q* and *f* are constants)

Alternate models are possible but this linear model works well in simulations (with short observation intervals)

Maximum Likelihood Estimation of Errors

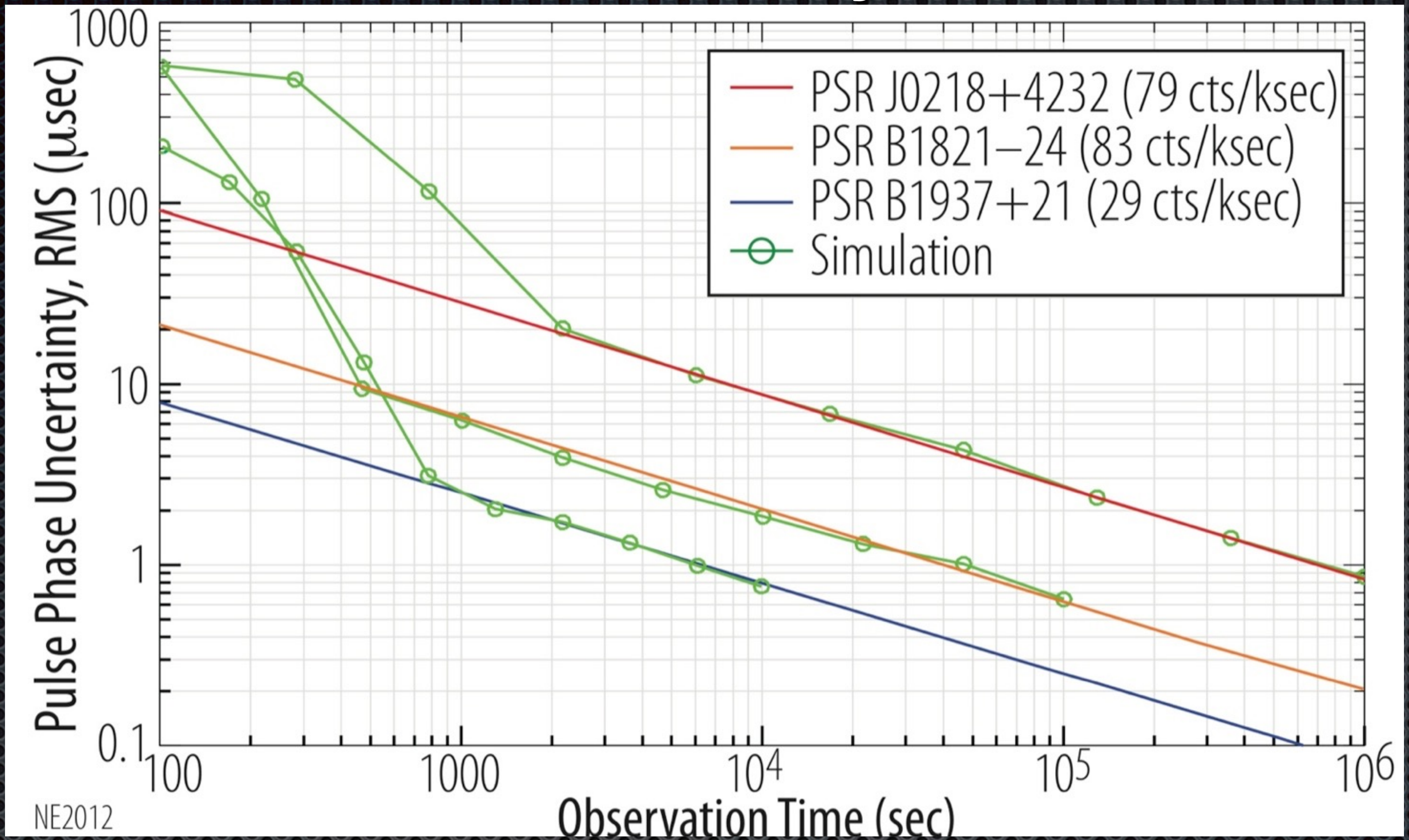
1. Observe arrival times $\{T_k\}_{k=1}^{N}$ during a fixed interval $[t_a, t_b]$.
2. Determine estimates $(\hat{q}, \hat{f})$ of the parameters (q, f) in the model $e(t) = q + f(t - t_a)$ by maximizing the log-likelihood function with $\{T_k\}_{k=1}^{N}$

$$L(\hat{\theta}) = \sum_{k=1}^{N} \log \lambda\Big(\tilde{\phi}(T_k) + q + f(T_k - t_a)\Big) - (\alpha + \beta)(t_b - t_a)$$

   with $\theta = (q, f, \alpha, \beta)$.
3. Form phase and frequency estimates $\hat{\phi}(t) = \tilde{\phi}(t) + \hat{q} + \hat{f}(t - t_a)$ and $\hat{\dot{\phi}}(t) = \dot{\tilde{\phi}}(t) + \hat{f}$, respectively.

Phase and frequency offsets (q,f) fed into GEONS for use in updating the navigation solution

Phase Estimate Accuracy



- The Cramér–Rao lower bound (CRLB) gives limit of achievable accuracy of any estimator with fully specified statistical model.
- We can compute CRLB for NHPP model assuming α, β known
  - For XNAV the CRLB is smallest for short period, for highly peaked pulsars with high SNR
- ML estimators asymptotically (many photons) achieve CRLB
- CRLB useful for
  - performance estimation
  - determining target observation times
- Does not include systematic error effects

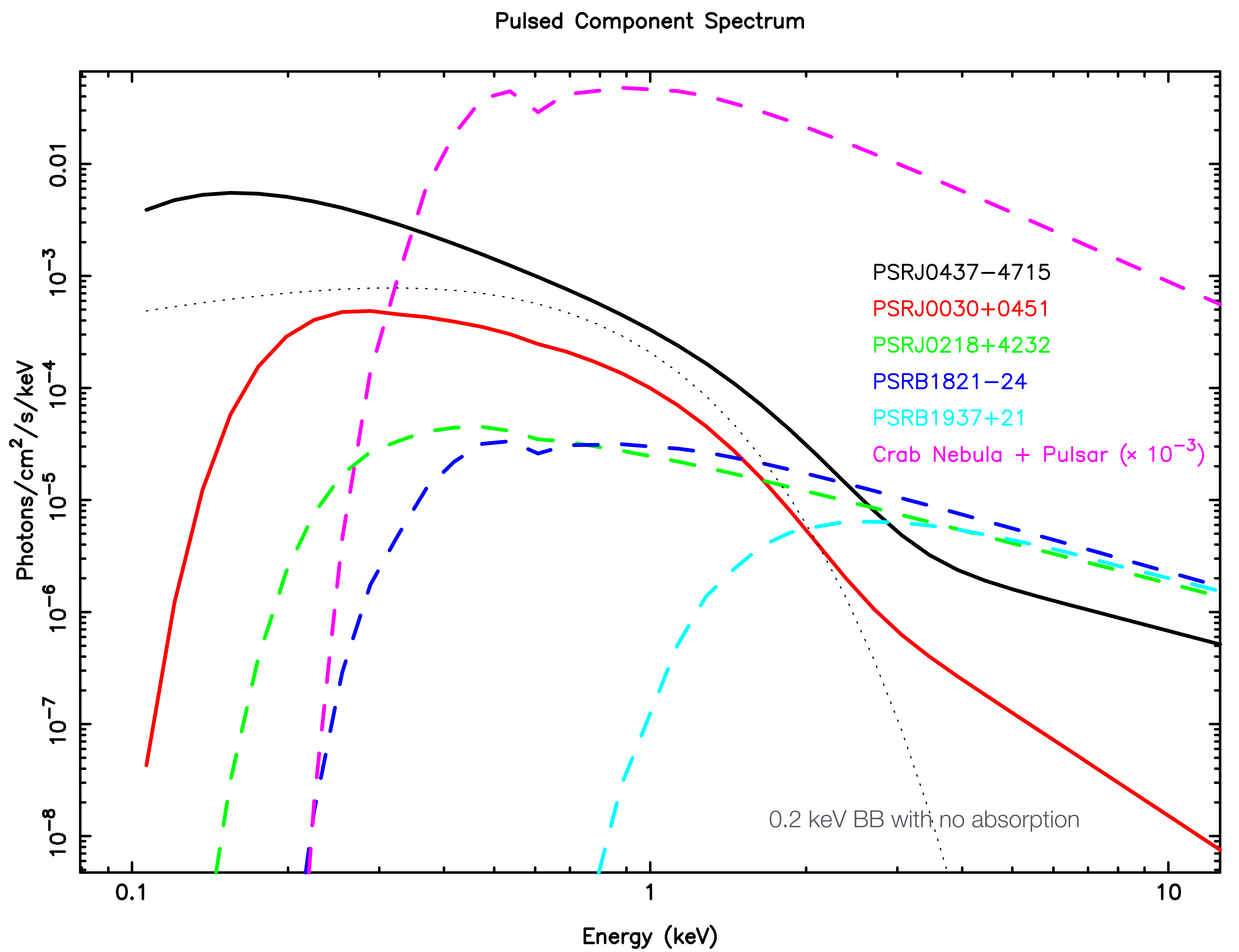
SEXTANT Sources

Name	Period (ms)	Instrument Background Count Rate (cnts/s)	Diffuse X-Ray Count Rate (cnts/s)	Source DC Count Rate (cnts/s)	Total Background Rate (cnts/s)	Source Pulsed Count Rate (cnts/s)	Pulse FWHM	Sigma (μs)
Crab Pulsar	33.0000	0.05	0.15	13,860.00	13860.20	660.000	0.0500	1.5
B1937+21	1.5580	0.05	0.15	0.04	0.24	0.029	0.0186	1.6
B1821-24	3.0540	0.05	0.15	0.02	0.22	0.093	0.0259	1.7
J0218+4232	2.3230	0.05	0.15	0.00	0.20	0.082	0.1120	12.8
J0030+0451	4.8650	0.05	0.15	-	0.20	0.193	0.1500	20.8
J1012+5307	5.2560	0.05	0.15	-	0.20	0.046	0.1000	40.4
J0437-4715	5.7570	0.05	0.15	0.42	0.62	0.283	0.2800	65.0
J2124-3358	4.9310	0.05	0.15	-	0.20	0.074	0.4000	200.4
J0751+1807	3.4790	0.05	0.15	-	0.20	0.025	0.3100	259.2
J1024-0719	5.1620	0.05	0.15	-	0.20	0.015	0.3000	606.1
J2214+3000	3.1192	0.05	0.15	0.06	0.26	0.029	0.3000	216.8

Source Properties Drive Optimal Design

- Source spectra drive energy range
- Source fluxes drive effective area and background rejection
  - MSPs are quite faint

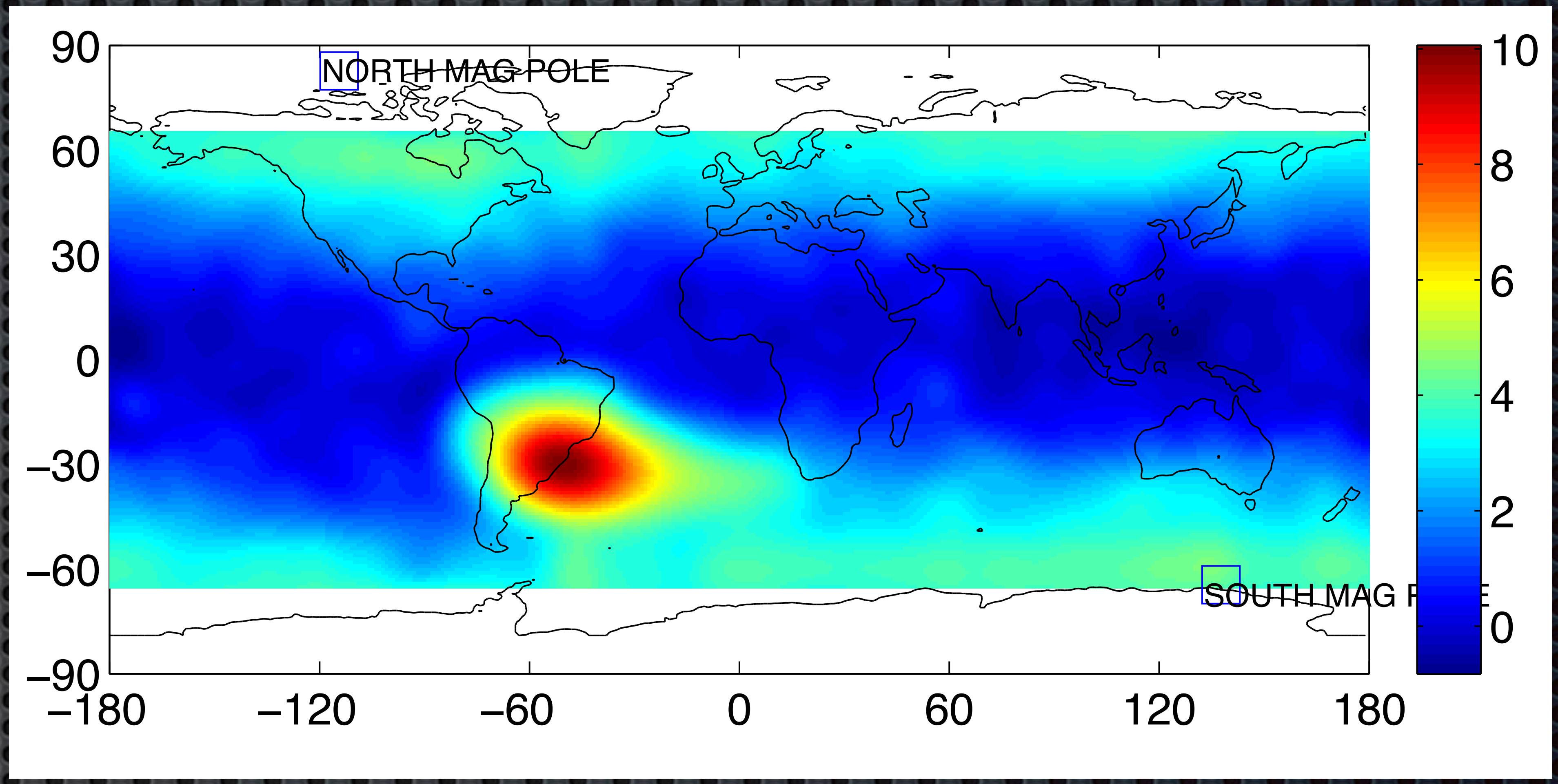
Source Spectra

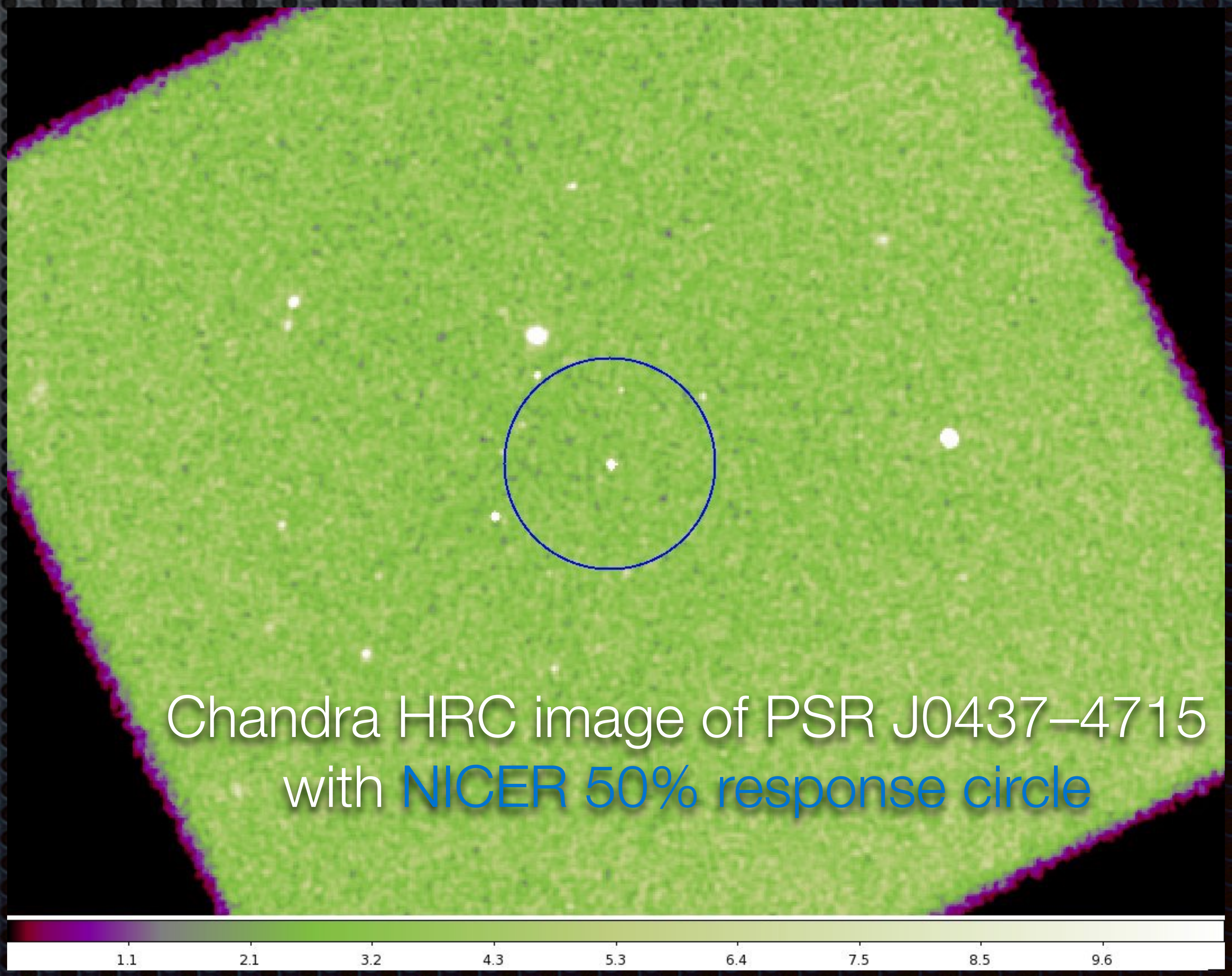


Detectors should be optimized for 0.2–8 keV
Lower limit set by absorption.
Upper end set by the hard sources.

Backgrounds and Mitigation

- Particles and Radiation
  - Concentrating optics to allow for small detector size
  - Shielding
- Diffuse X-ray background
  - Minimize FOV
- Other sources in FOV
  - Minimize FOV, improve stray light performance
- Unpulsed flux from target
  - Optimize energy cuts

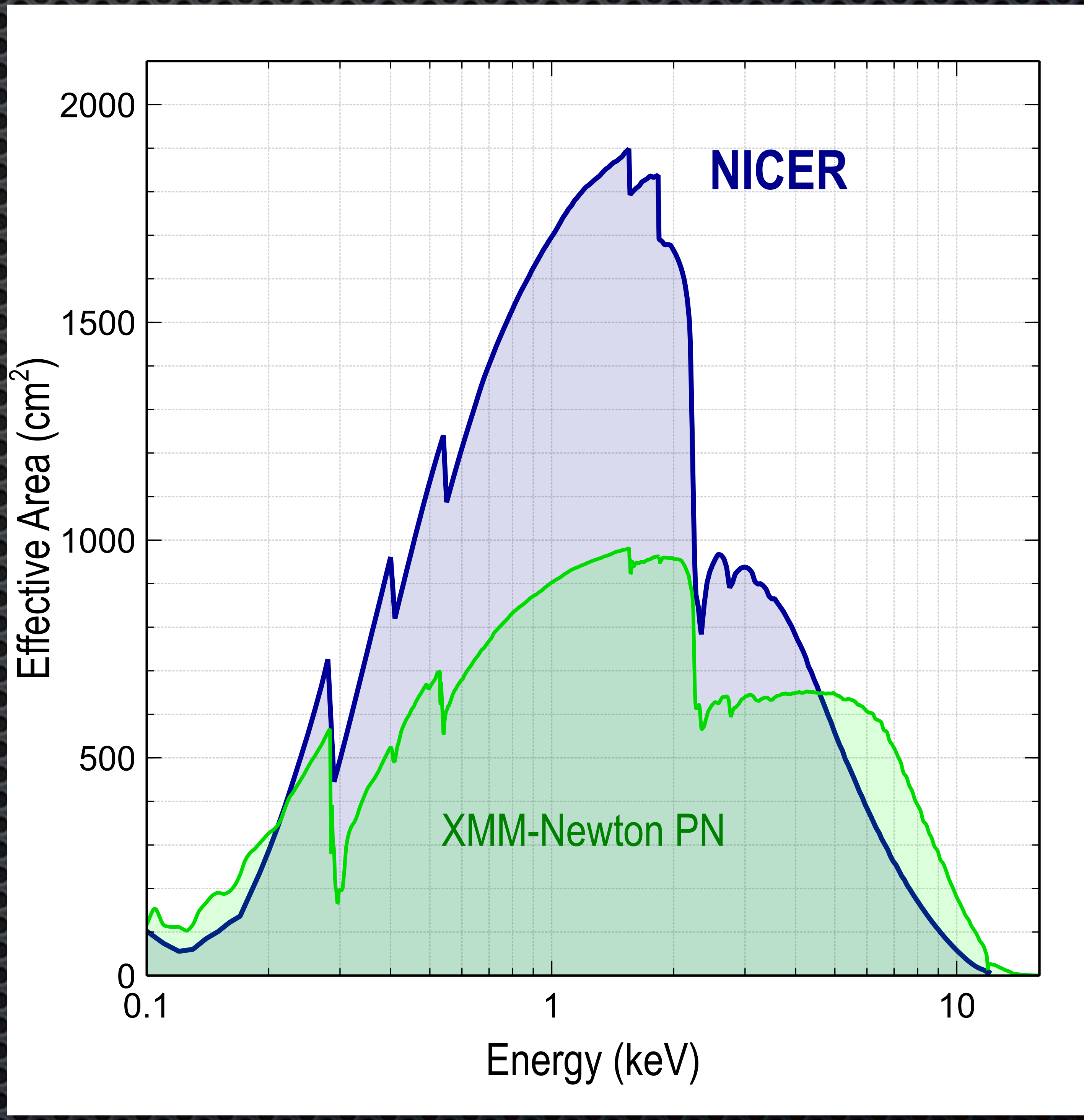




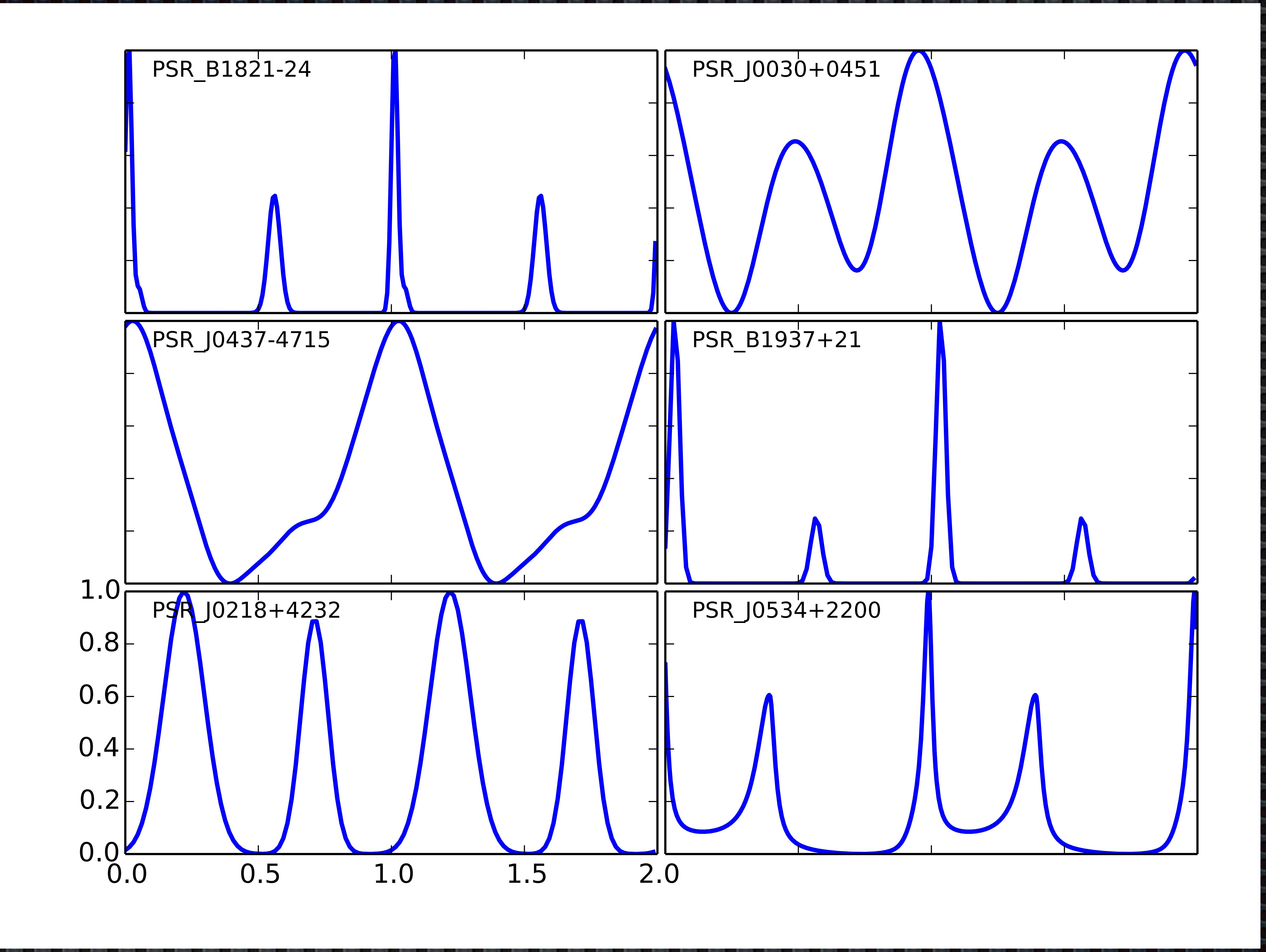
Chandra HRC image of PSR J0437–4715 with NICER 50% response circle

NICER is well optimized for MSP observations

- Concentrating optics provide 6 arcmin FWHM FOV and small detector size
- Large effective area over 0.2–8 keV
- Background rejection from shielding, pulse heights, radial cuts

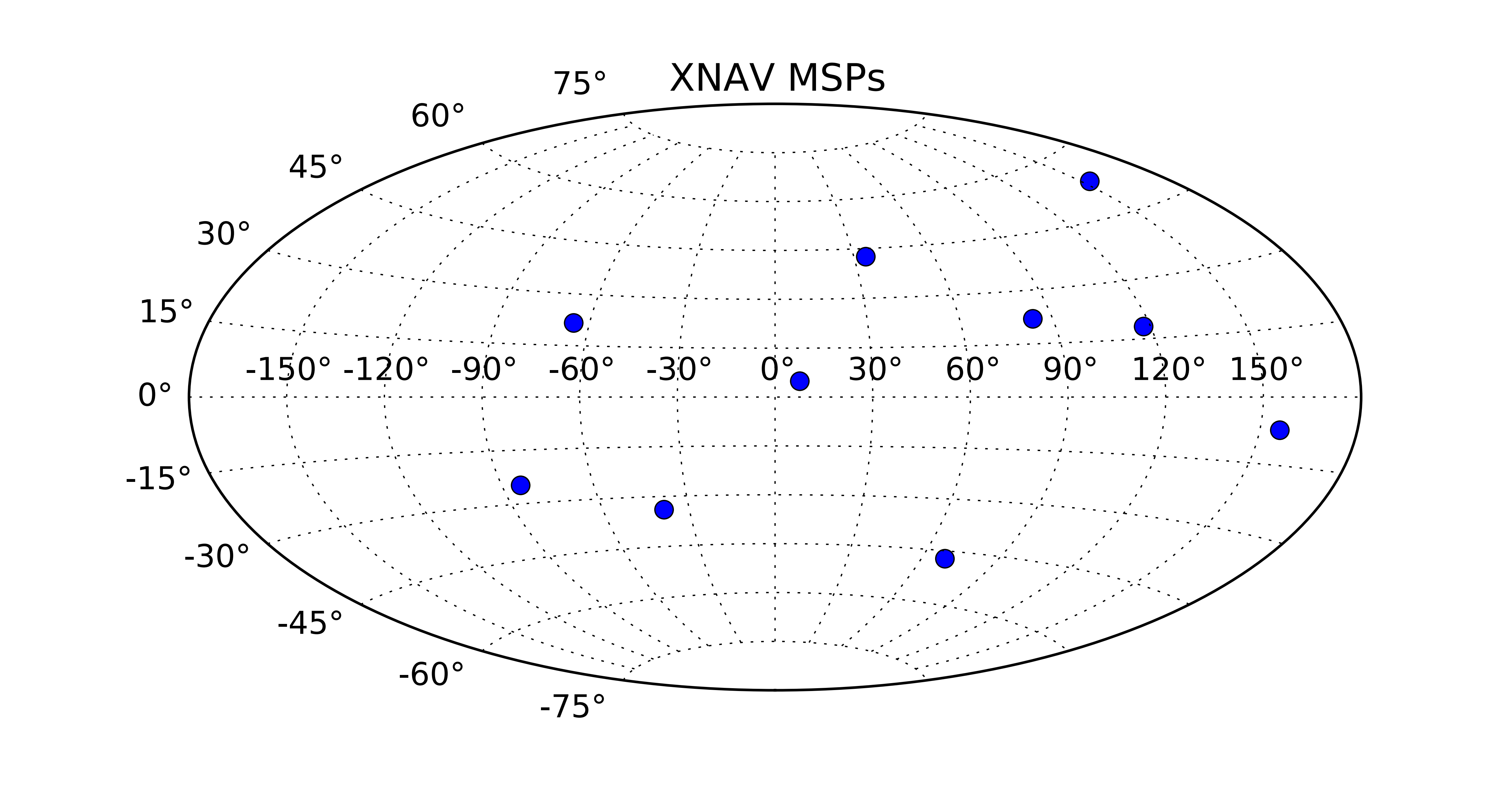


Pulse Profile Templates



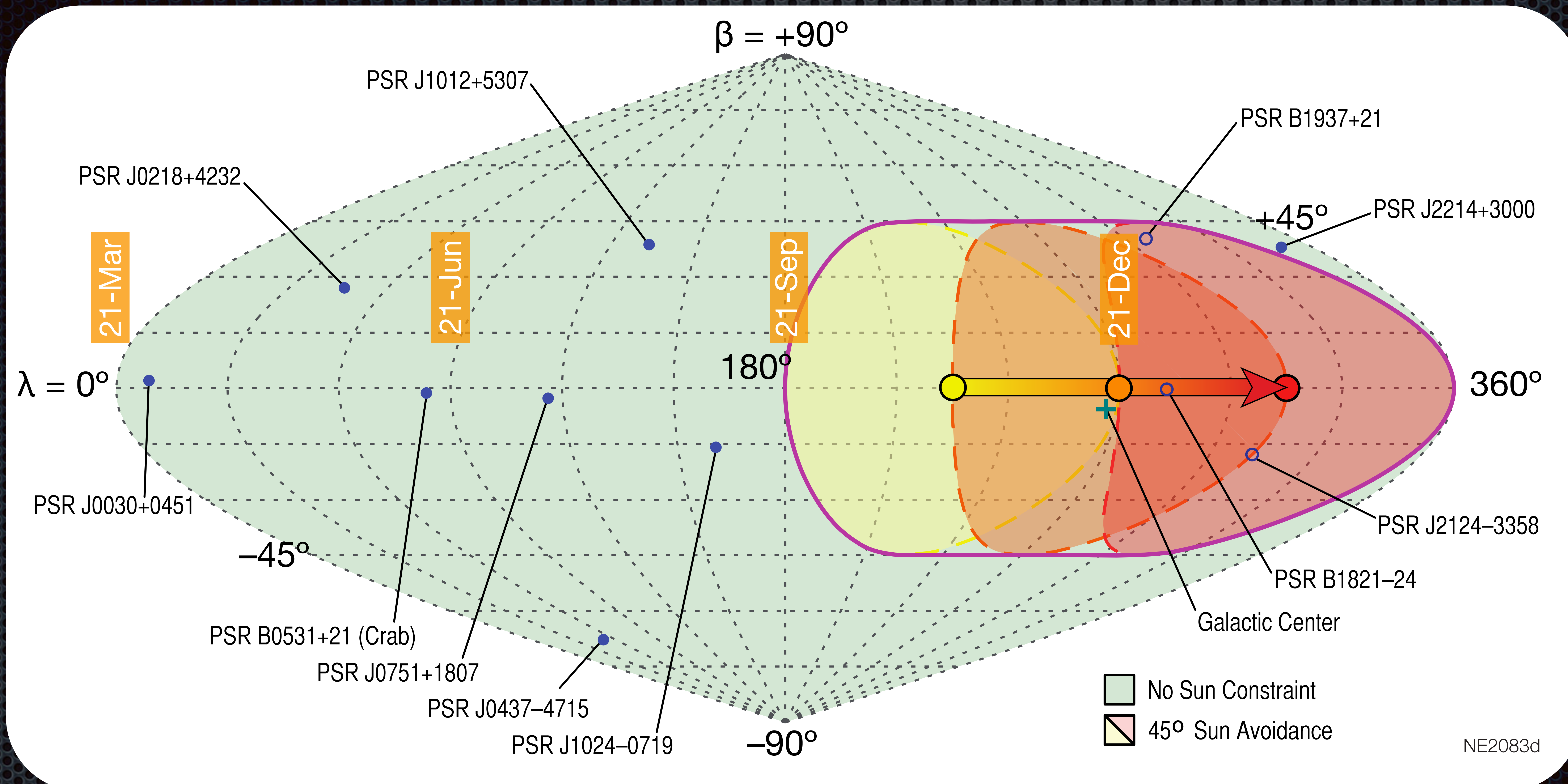
- Templates required to compute phase offsets using MLE
  - Poisson fluctuations removed by using analytic fit to measured template (e.g. multi-gaussian, truncated Fourier series)
  - The hard sources have narrow profiles (Crab, B1821, B1937)
  - Thermal sources are smoother and more sinusoidal

Sky Distribution of SEXTANT Sources



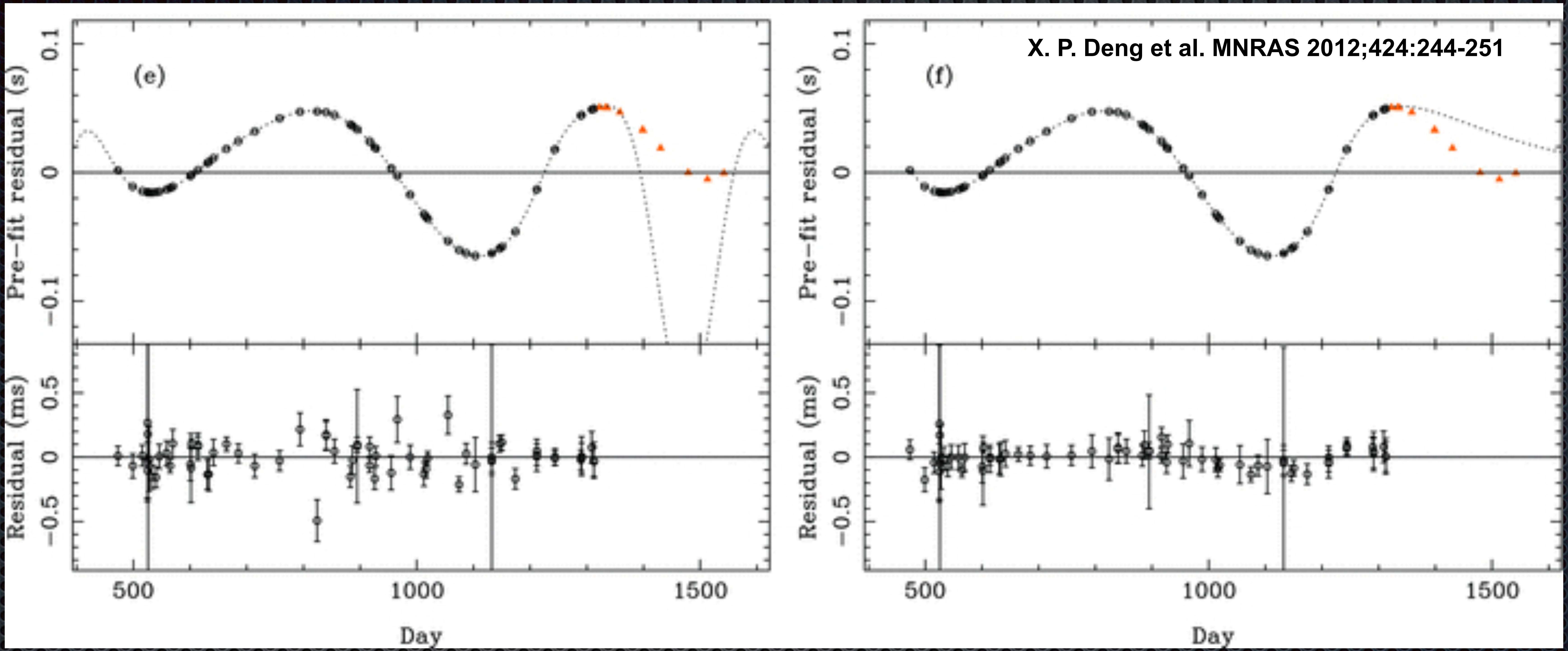
- MSPs are a nearly isotropic population, which results in a good geometry for navigation
- Source visibility constraints limit when each source can be observed
  - Sun and Moon exclusion angles
  - Earth occultation
  - ISS structures

Source Visibility



- Visibility analysis shows 10/20/2016 to 11/03/2016, 02/09/2017 to 02/23/2017, and 08/03/2017 to 08/17/2017 as viable periods for primary SEXTANT experiments.
- B1937+21, J0437-4715, J0218+4232 (Periodic Lunar occultation of B1821-24 and J0534+2200) all visible

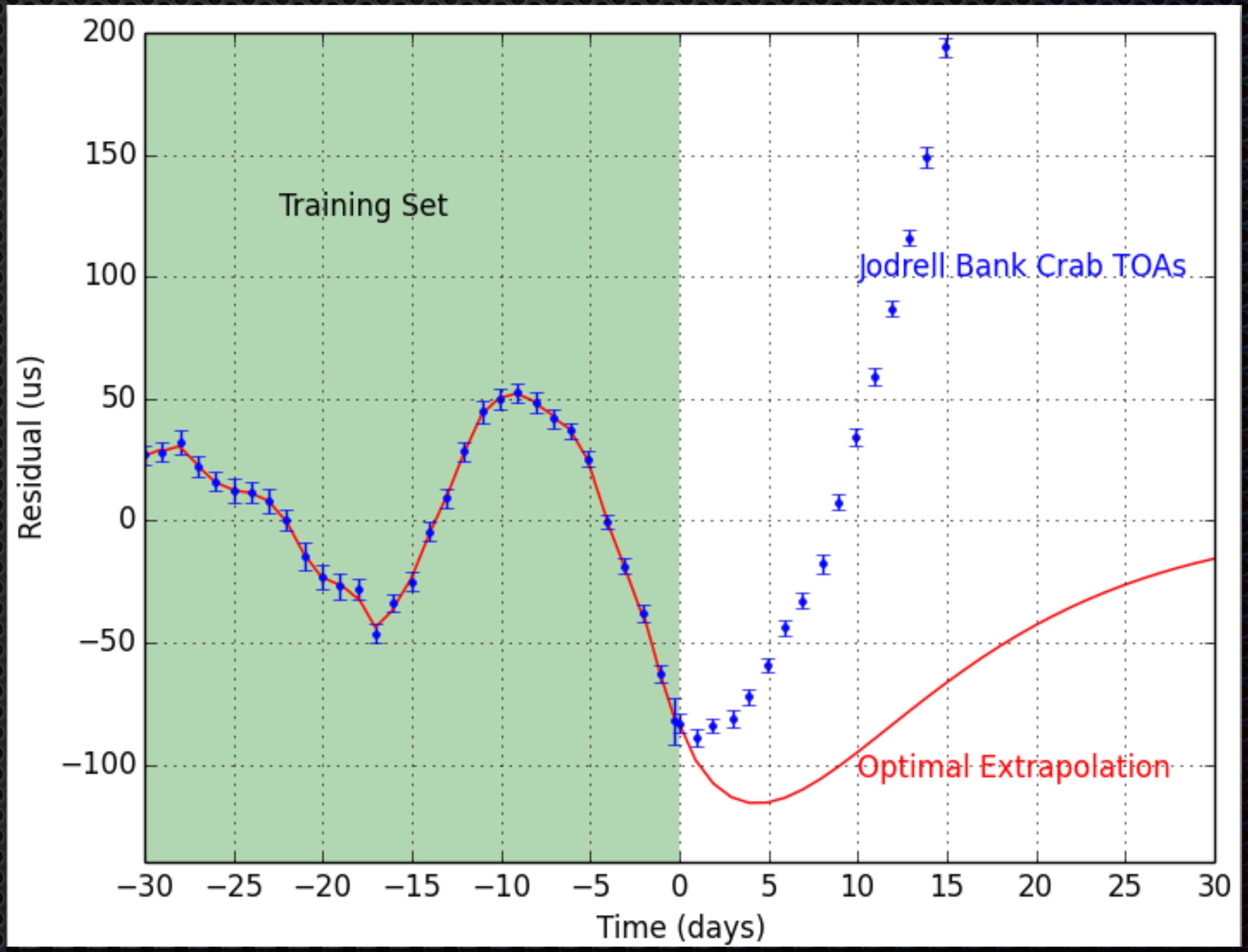
Extrapolating Timing Models



- Care must be taken when extrapolating timing models with significant red (timing) noise.
- High order polynomials and even harmonic sums do not extrapolate well.
- Optimal filter can be constructed from the covariance matrices of the measurement error and the red noise, and is implemented in a Tempo2 plugin.

Crab Is a Special Case

- Pulsed flux is higher than MSPs by 10^4 so integration times can be much shorter
- But, highly unstable rotator so ephemeris updates are required every ~3 days to meet SEXTANT requirements

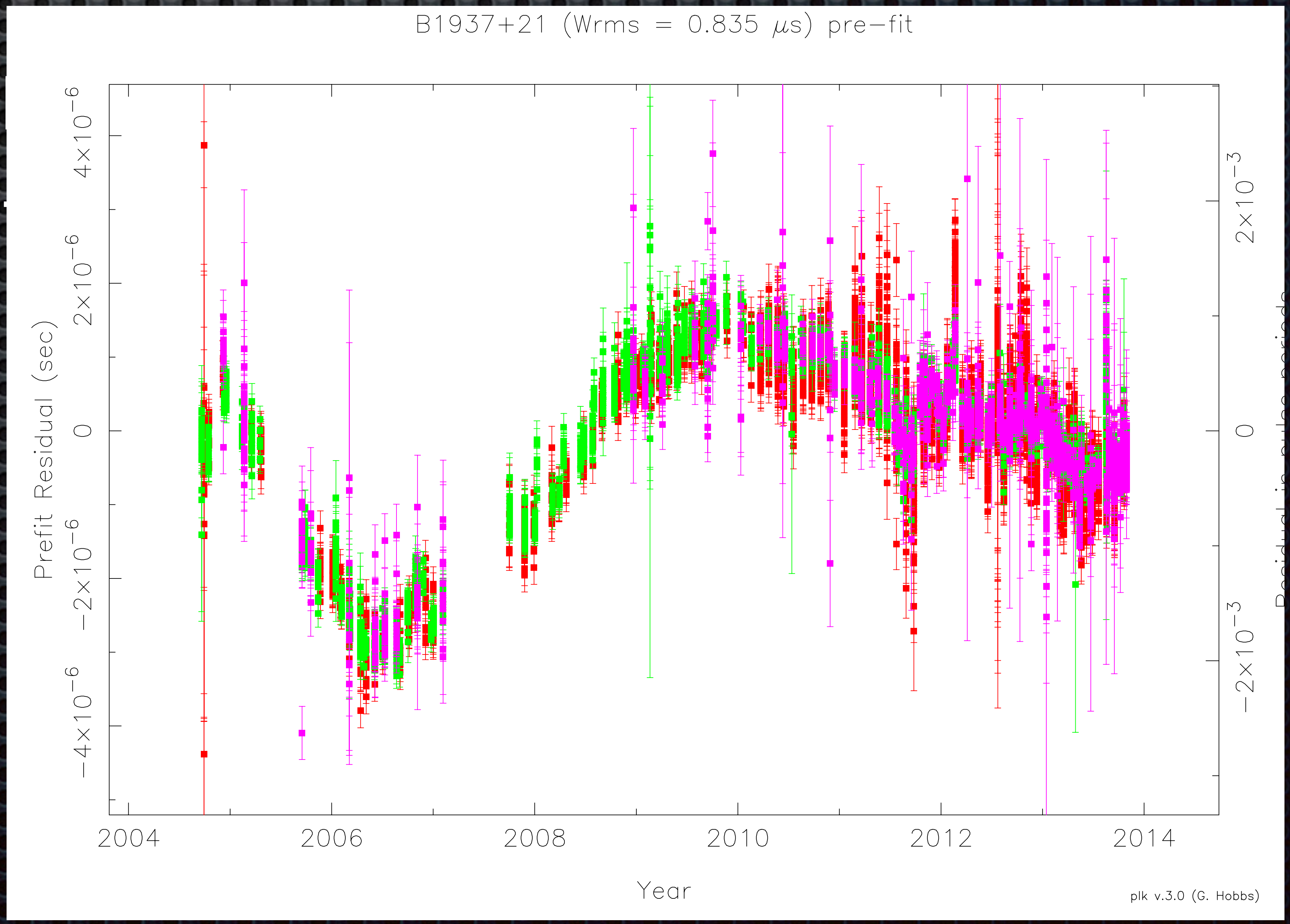


Plan for Ephemeris Updates

- Ground-based radio timing
  - Jodrell Bank observes Crab daily
  - NANOGrav times 4 SEXTANT MSPs
  - PPTA times J0437–4715
  - Nançay has a long-term program on B1821-24
- Using ground-based data requires multifrequency observing to monitor dispersion measure, for extrapolation to infinite frequency
- NICER itself will time them as well. Initial observations will establish definitive template profile and radio-to-X-ray offset

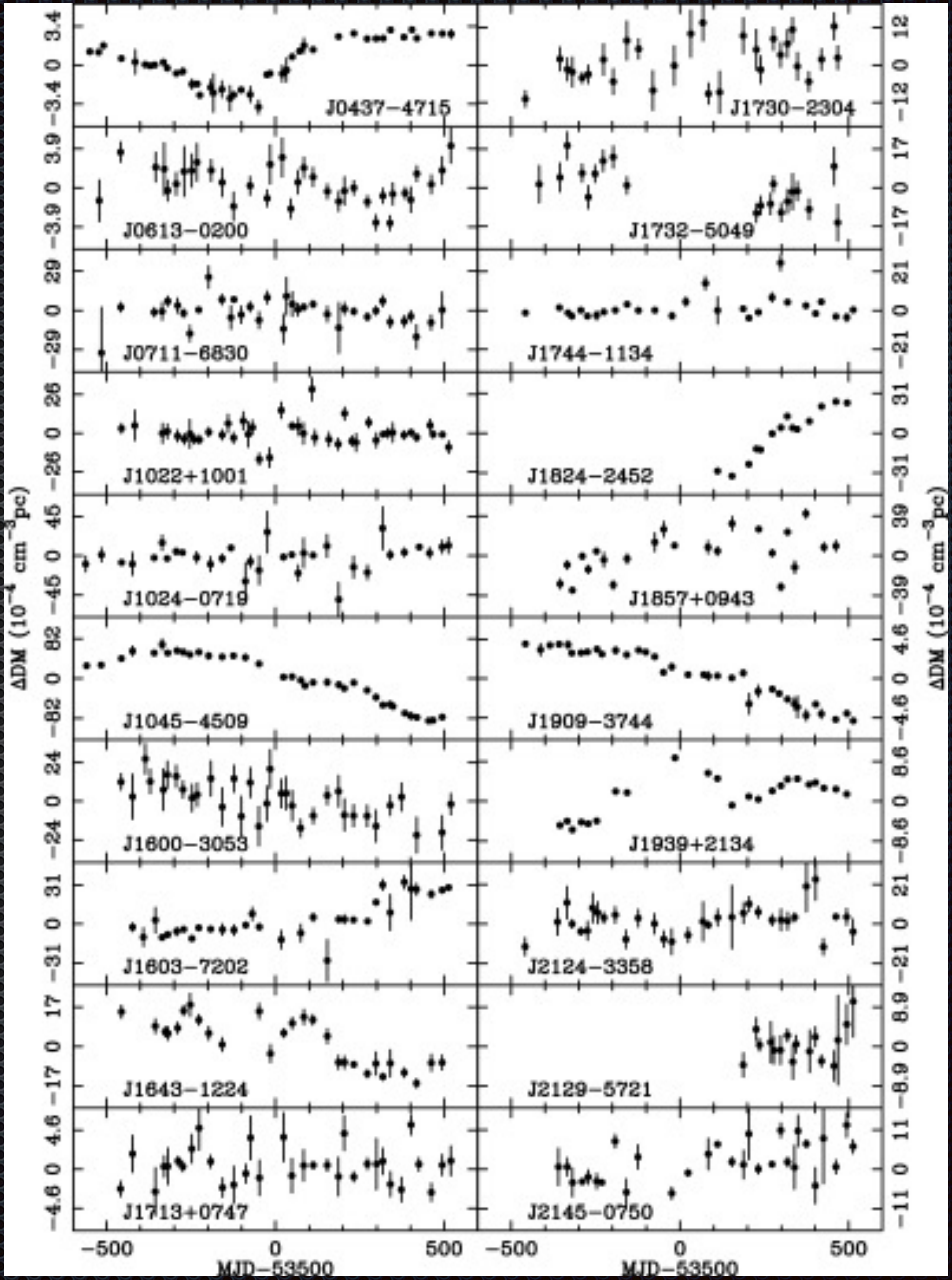
Systematic Errors

- Errors in the timing model predictions translate to location errors that are not reduced by increasing integration time (but can be mitigated by increasing number of sources)
  - Astrometric errors
    - Parameters measured by
      error grows with distance
  - Red noise



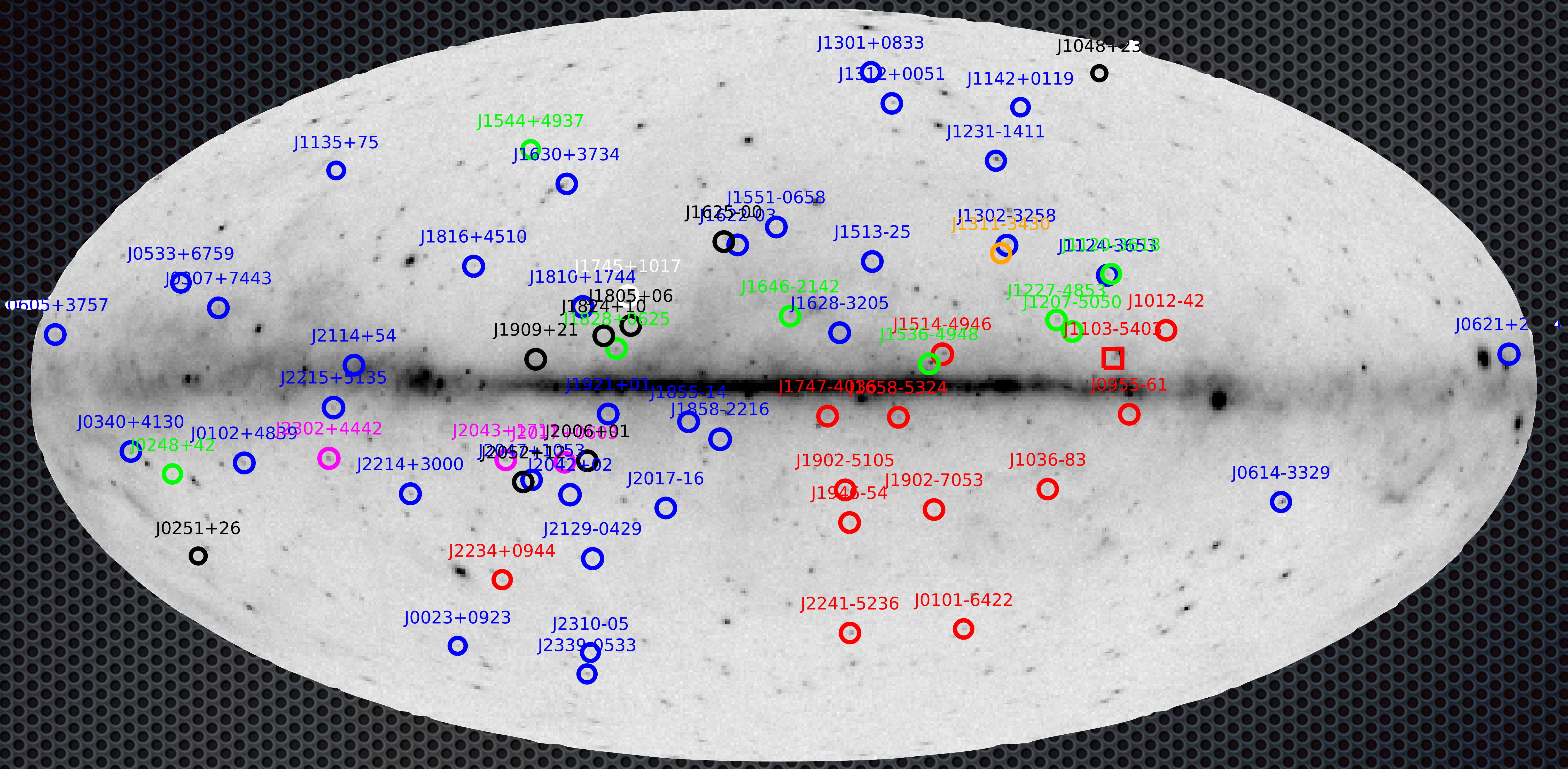
DM Variations

- DM offset of 0.005 produces error of 10 μs in extrapolation from 1400 MHz to X-ray band



X. P. You et al. MNRAS 2007;378:493-506

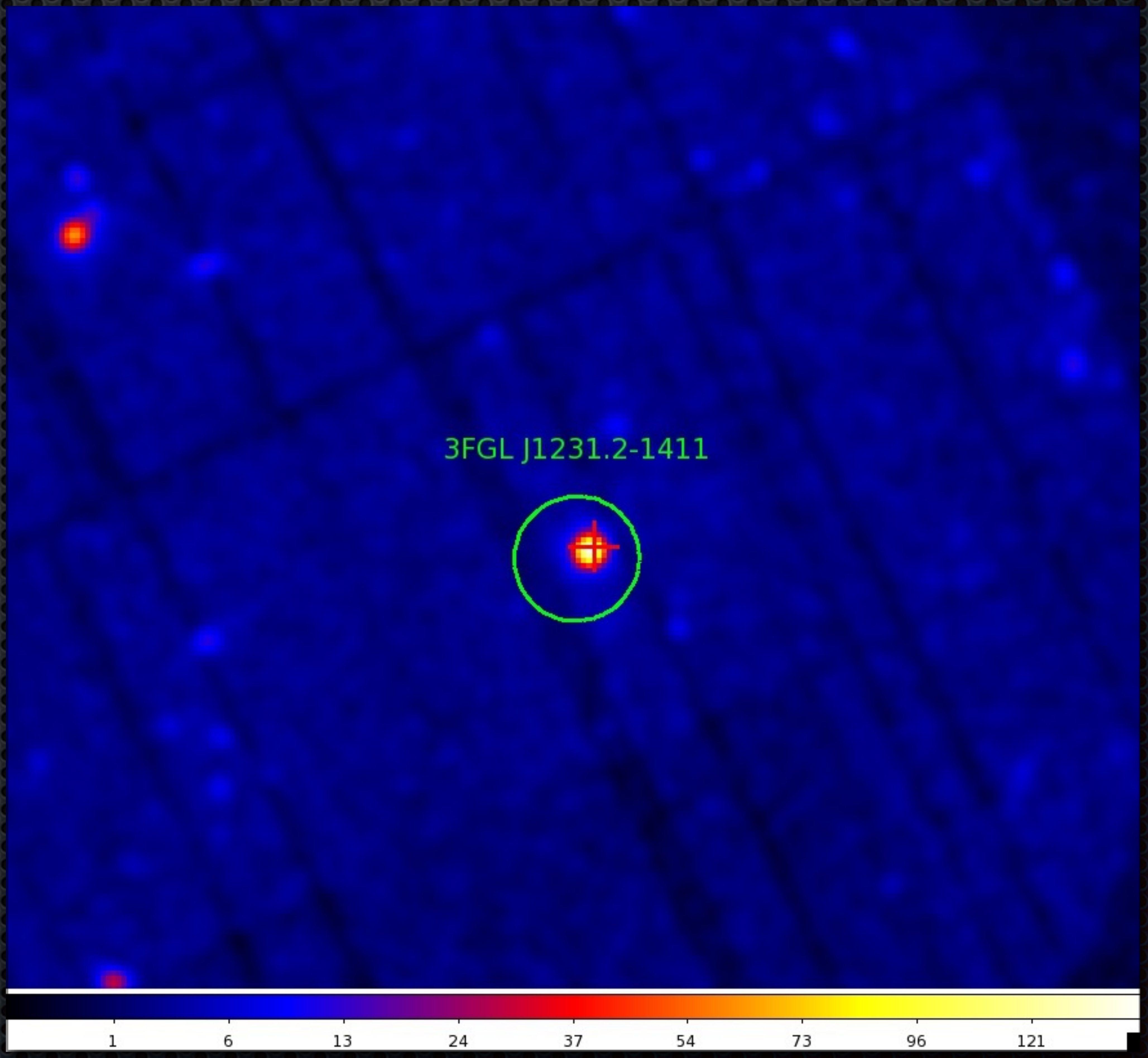
Looking to Expand the Catalog



- Pace of MSP discovery has been very high over past few years
  - Fermi
    - All SEXTANT MSPs are LAT sources, except J1012+5307
    - One LAT source has X-ray pulsations () and J1214 is promising
  - Big surveys: HTRU, GBNCC, AO-drift, PALFA
- NICER will search for X-ray pulsations from several promising candidates and expand the catalog and characterize new candidates for inclusion

Example: PSR J1231-1411

- Fx = 1.2×10^{-13} erg/cm^2/s (0.5-3 keV)
- 0.21 cts/s in NICER, 2nd brightest MSP after J0437-4715
- Need to detect pulsations and characterize pulse profile



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