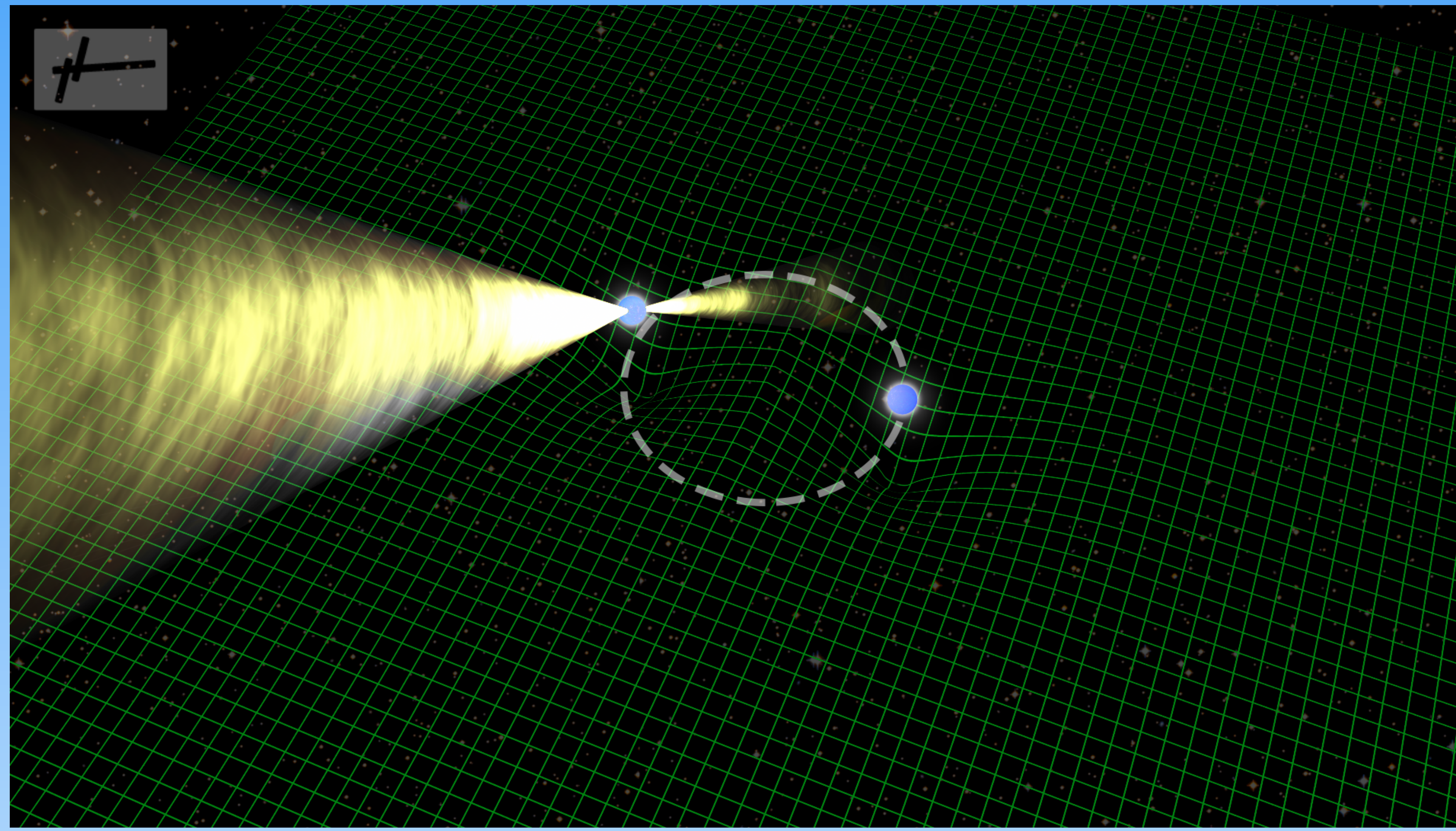

Image made by Joeri van Leeuwen

A New Relativistic Binary System Found by PALFA

Kevin Stovall, NRAO
PALFA Collaboration
+ Paul Demorest, Duncan Lorimar & Nihan Pol

Postdoc Symposium March 19, 2018

NANOGrav

NRAO

Arecibo L-band Feed Array Pulsar Survey
PALFA

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Ziggy Pleunis, McGill
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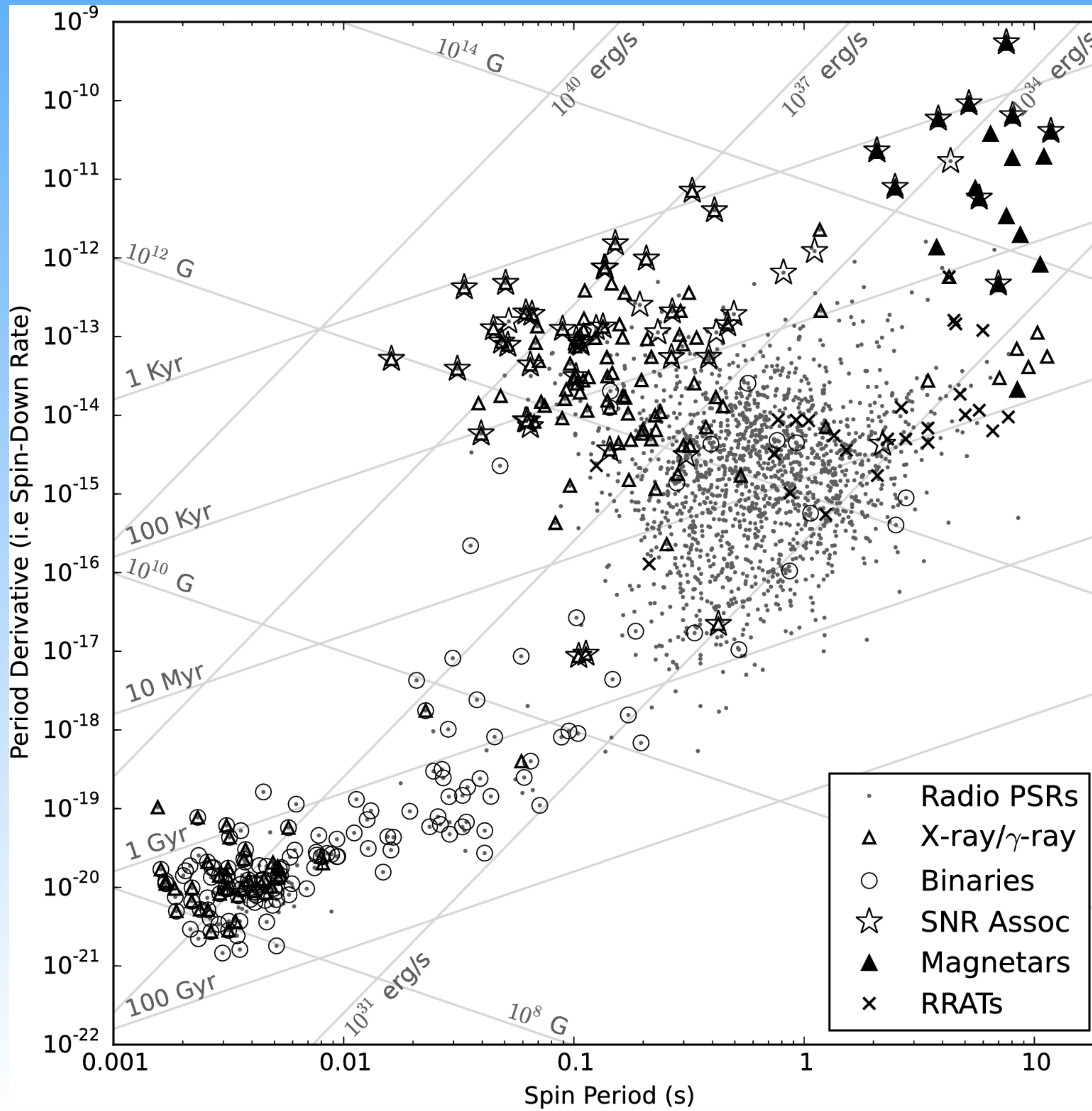
Andrew Seymour, Arecibo
Xavi Siemens, UWM
Ingrid Stairs, UBC
Ben Stappers, Jodrell Bank
Joe Swiggum, UWM
Weiwei Zhu, NAO

Pulsars

- > 2,600 pulsars known
- Mass ~1 - 2 solar masses, 10s of km diameter
- Spin Periods ranging from ~1 millisecond to tens of seconds
- Steep spectrum
- Large magnetic fields



Pulsar Applications

Populations

- Neutron Stars
- Supernovae / Massive Stars
- Binaries
- Millisecond Pulsars (MSPs)

Exotic Systems

- Triple Systems
- Double Pulsar
- Pulsar-BH
- Double Neutron Stars (DNSs)

Clocks

- Time Standard

Study of Medium

- Dispersion
- Scattering/Scintillation
- Faraday rotation

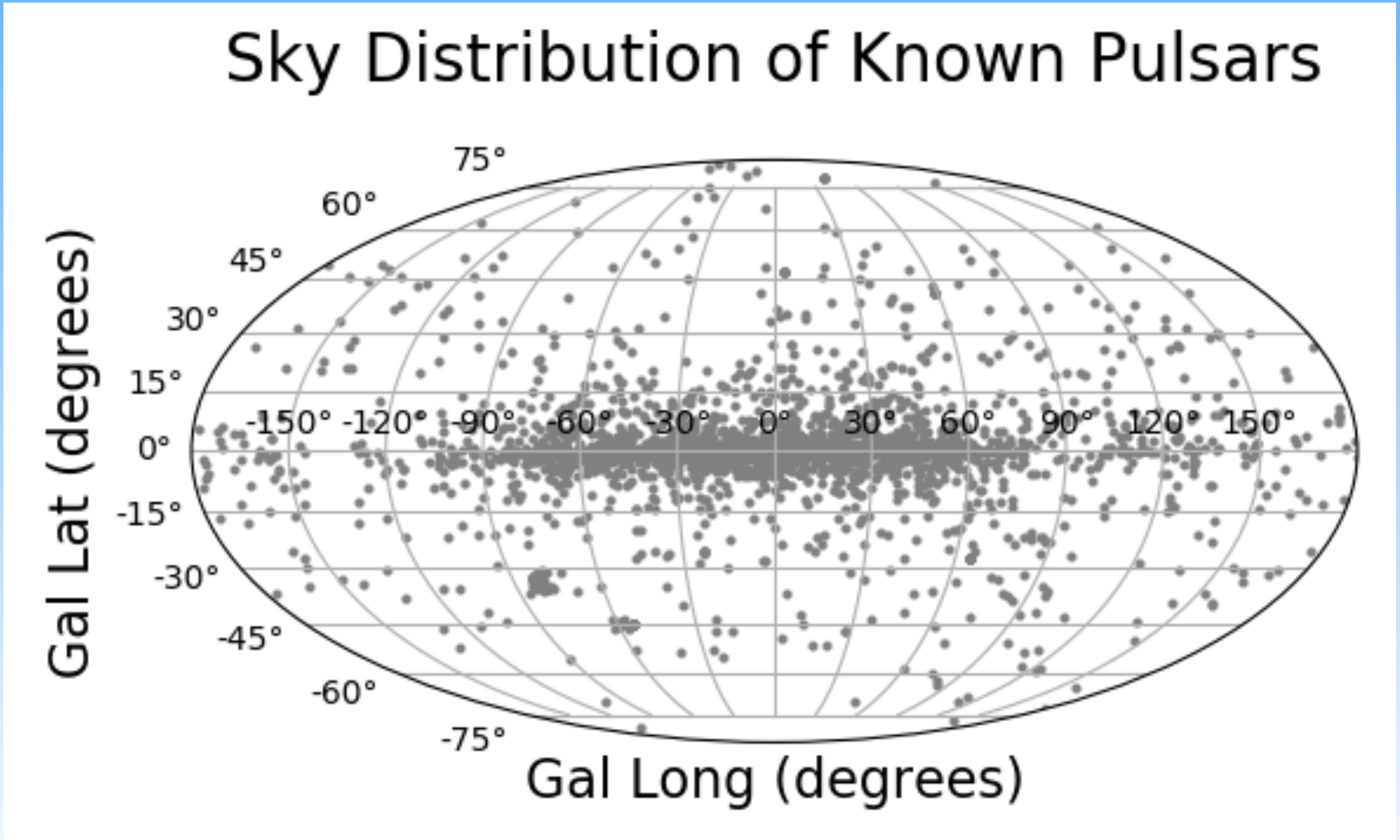
Extreme Environments

- Large B-field
- Neutron Star Interior
- Tight Binary systems
- Fast Spinning

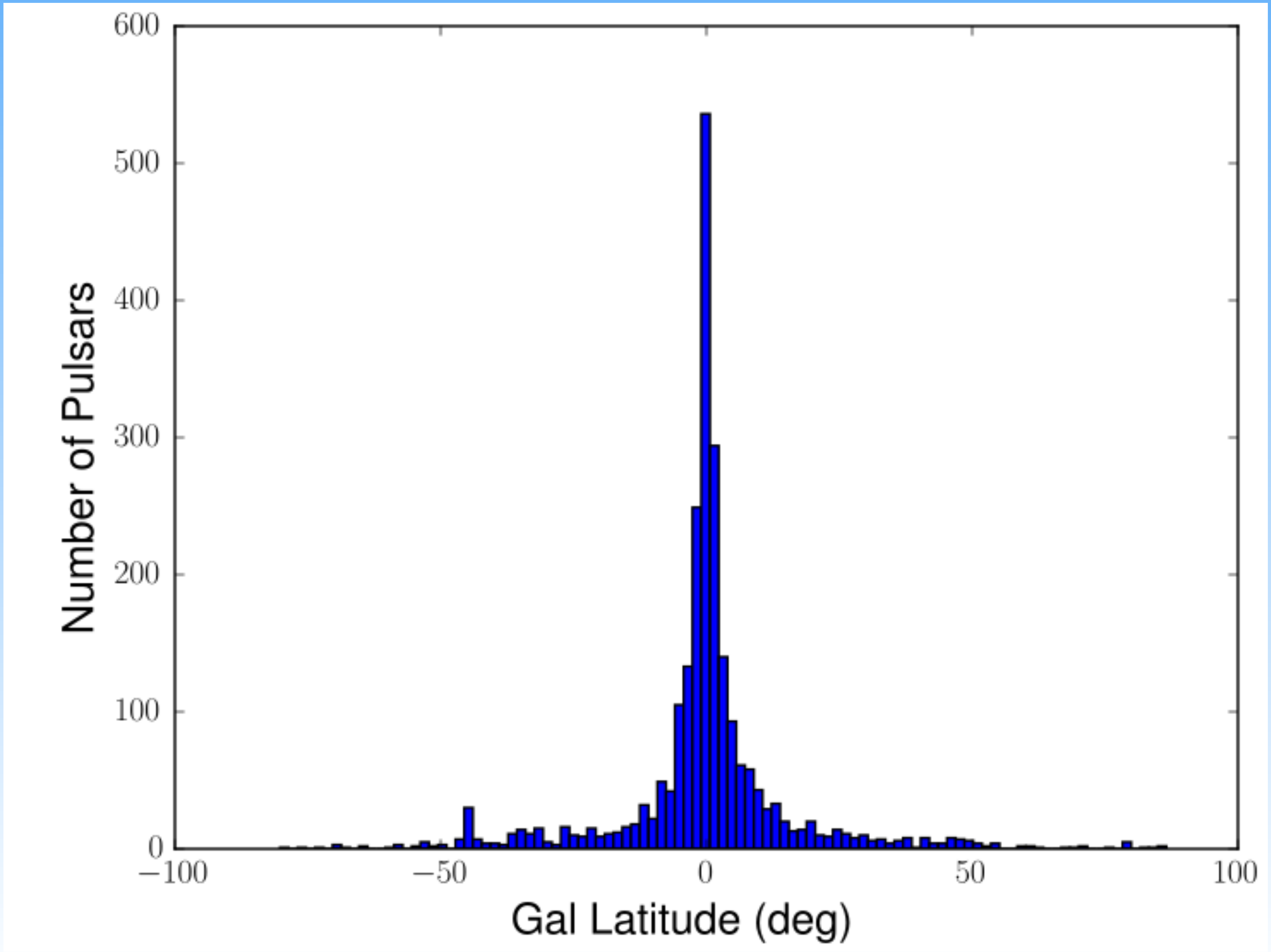
Theories of Gravity

- Tests of GR
- Tests of Alternatives
- Gravitational Waves

Pulsar Spatial Distribution



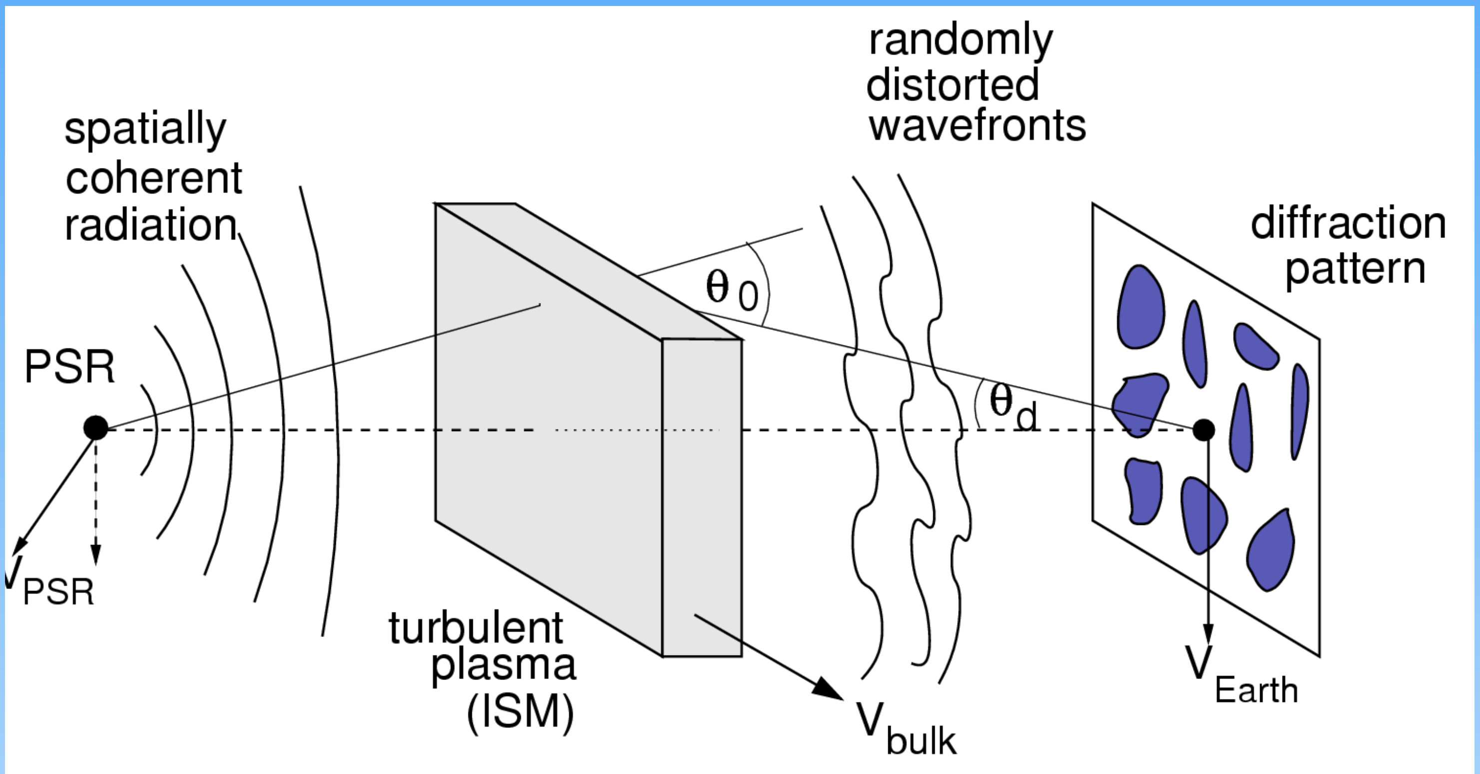
Pulsar Spatial Distribution

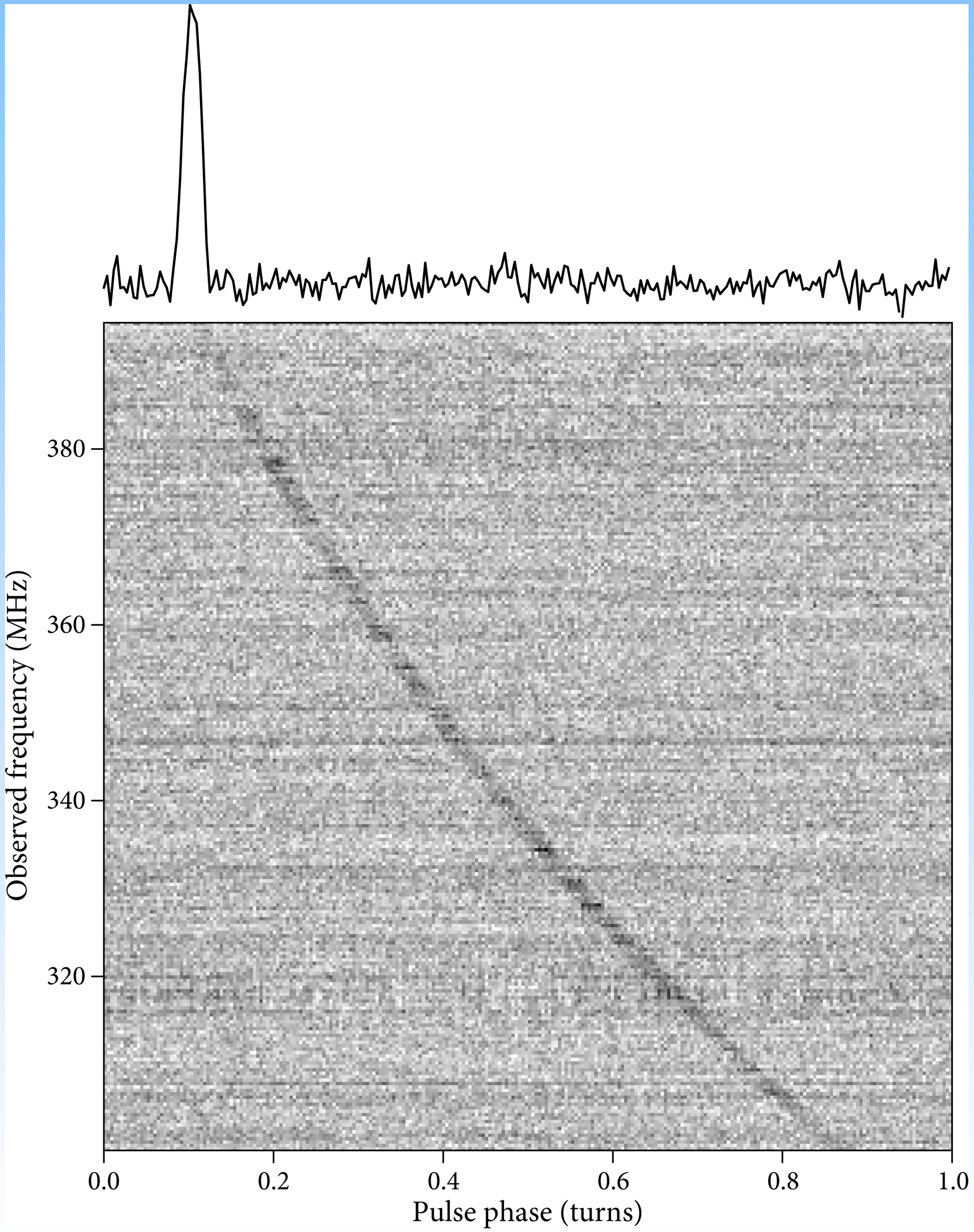


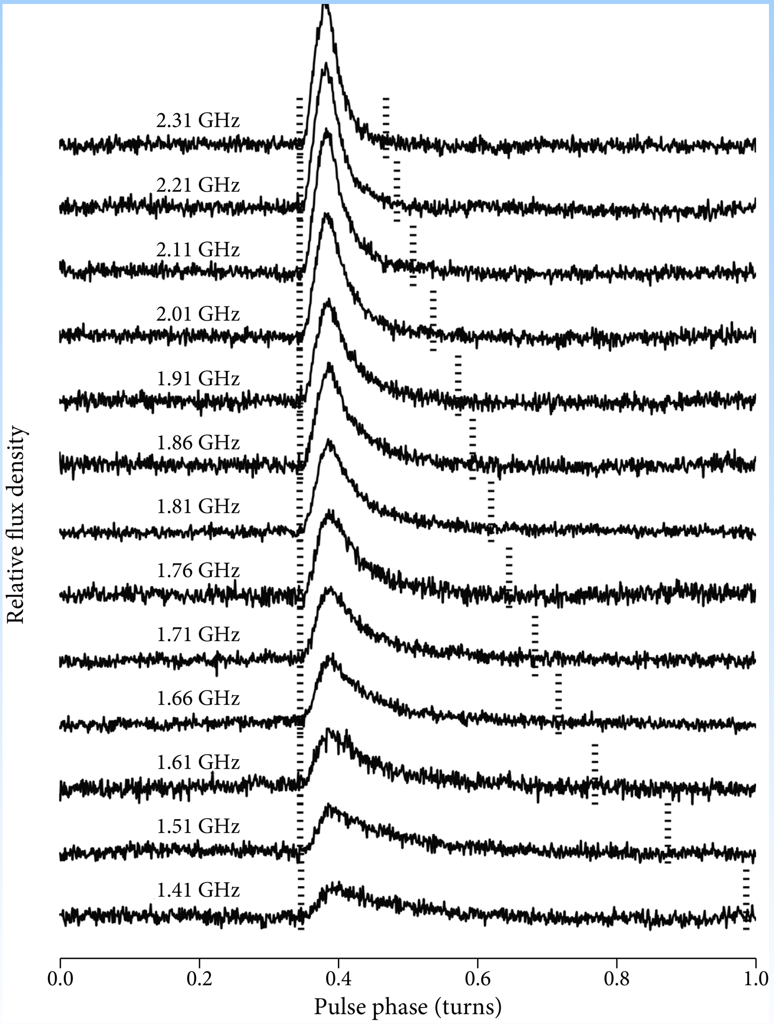
Effects of Interstellar Medium

$$\text{Delay} \propto \text{DM}\,\nu^{-2}$$

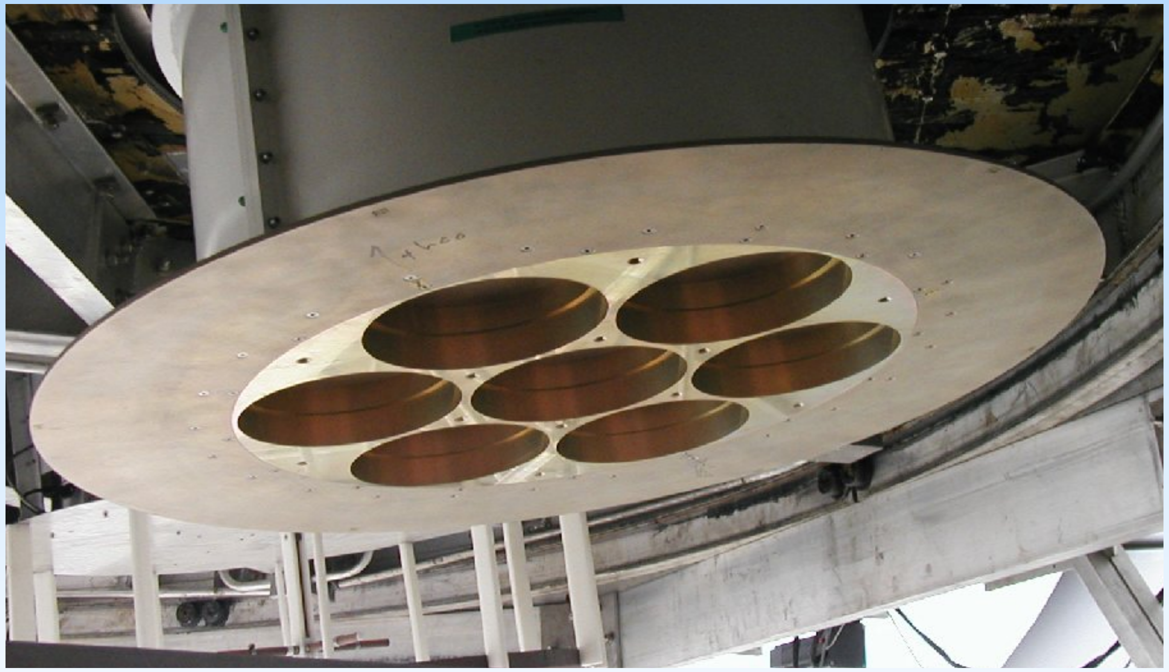
$$\text{DM} = \int_0^d n_e\,dl$$

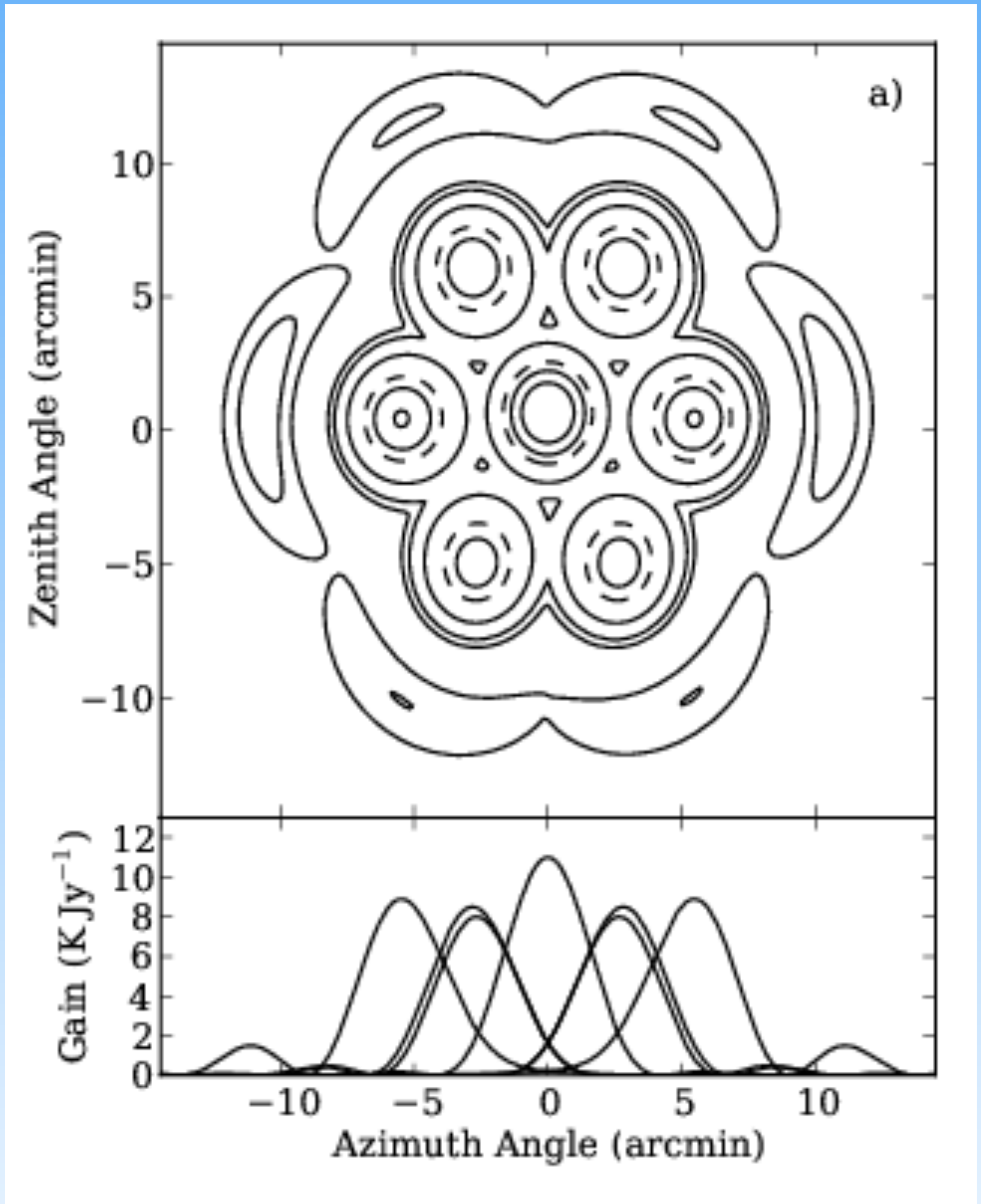




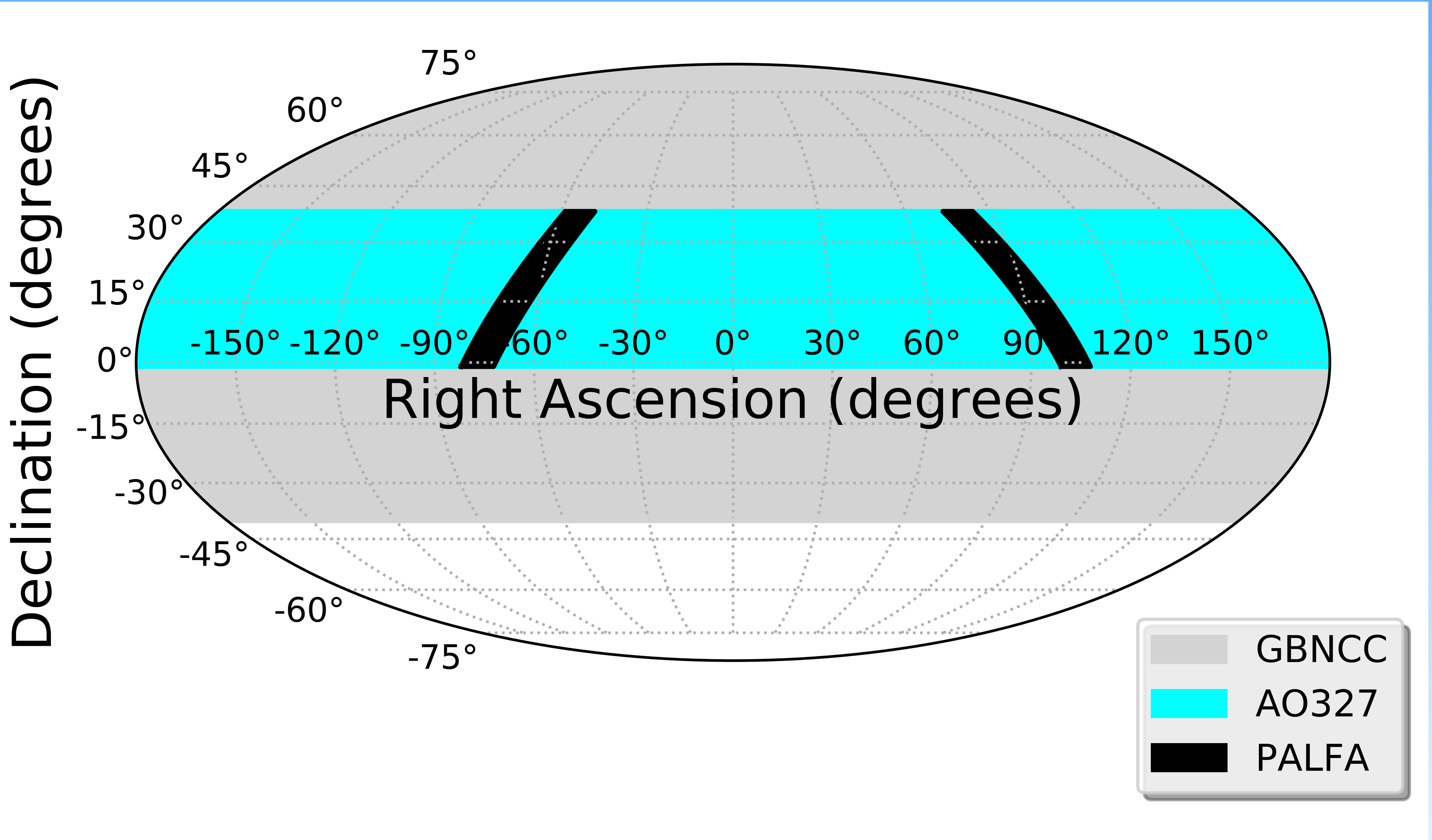


Arecibo L-band Feed Array





PALFA Survey



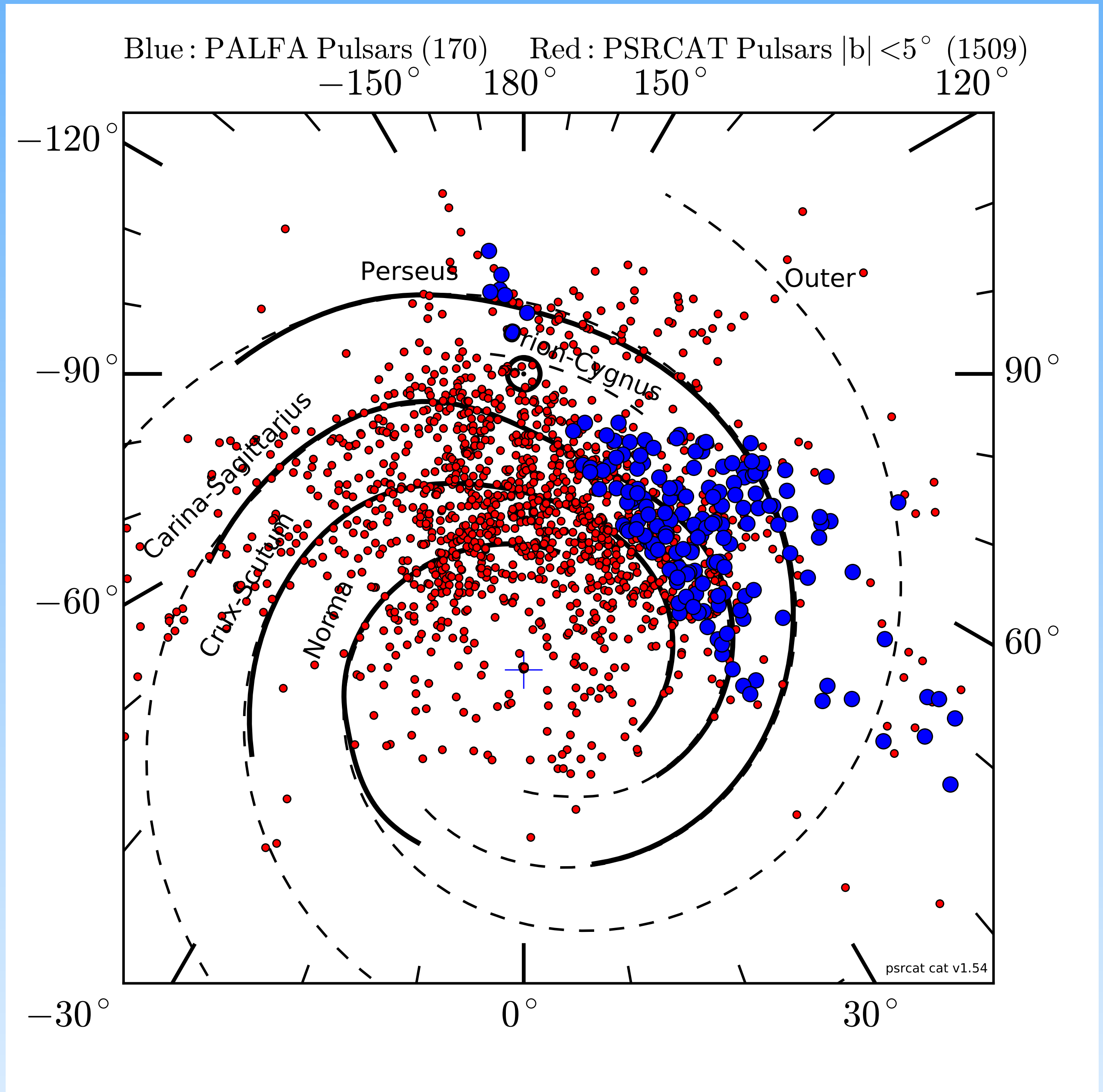
Gal Long: 32 to 77 deg & 168 to 214 deg

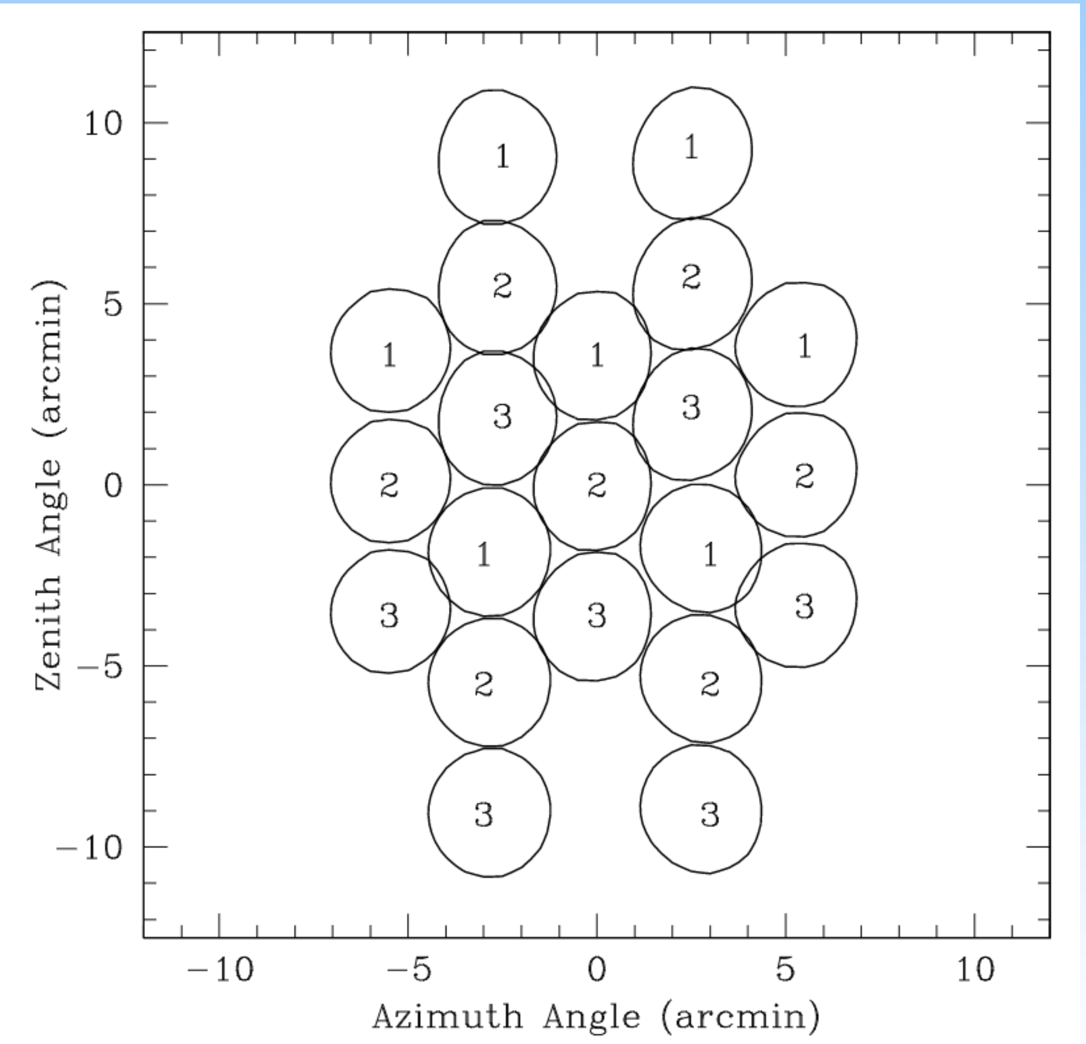
Gal Lat: <=|5|

PALFA

- Uses the 7-beam ALFA system to survey the Galactic plane at L-band (BW~330 MHz)

- Discoveries to date: 179 Pulsars, 22 MSPs, 3 DNSs, 1 Repeating FRB





http://www.naic.edu/~palfa/

Cordes et al. 2006, ApJ, 637, 446

Lazarus et al. 2015, ApJ, 812, 81

PALFA Search

PALFA uses 3 separate search pipelines:

1) PALFA Pipeline - This is the main pipeline and was originally based on other typical pulsar search pipelines, but has had many improvements put in over the years: RFI excision, Single Pulse identification tools, Fast-Folding Algorithm

2) Einstein@Home - Searches use computing time donated by volunteers, does a template-matching search for binary pulsars

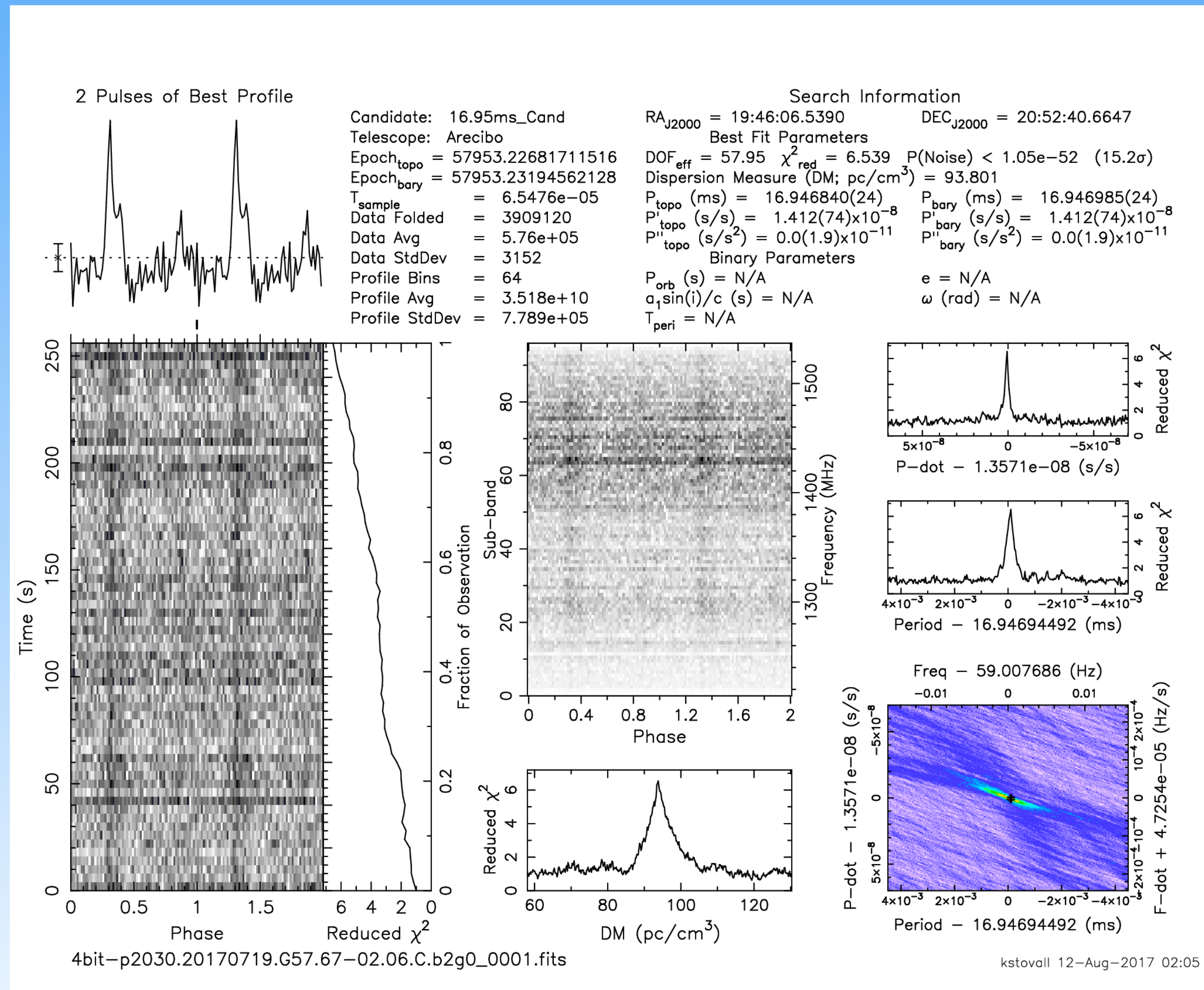
3) "Quicklook" pipeline - Searches the data at Arecibo similar to typical pulsar search pipelines, but data immediately downsampled in time by a factor of 2 and no acceleration search is done to keep search times down.

PALFA Discovery

PSR J1946+2052

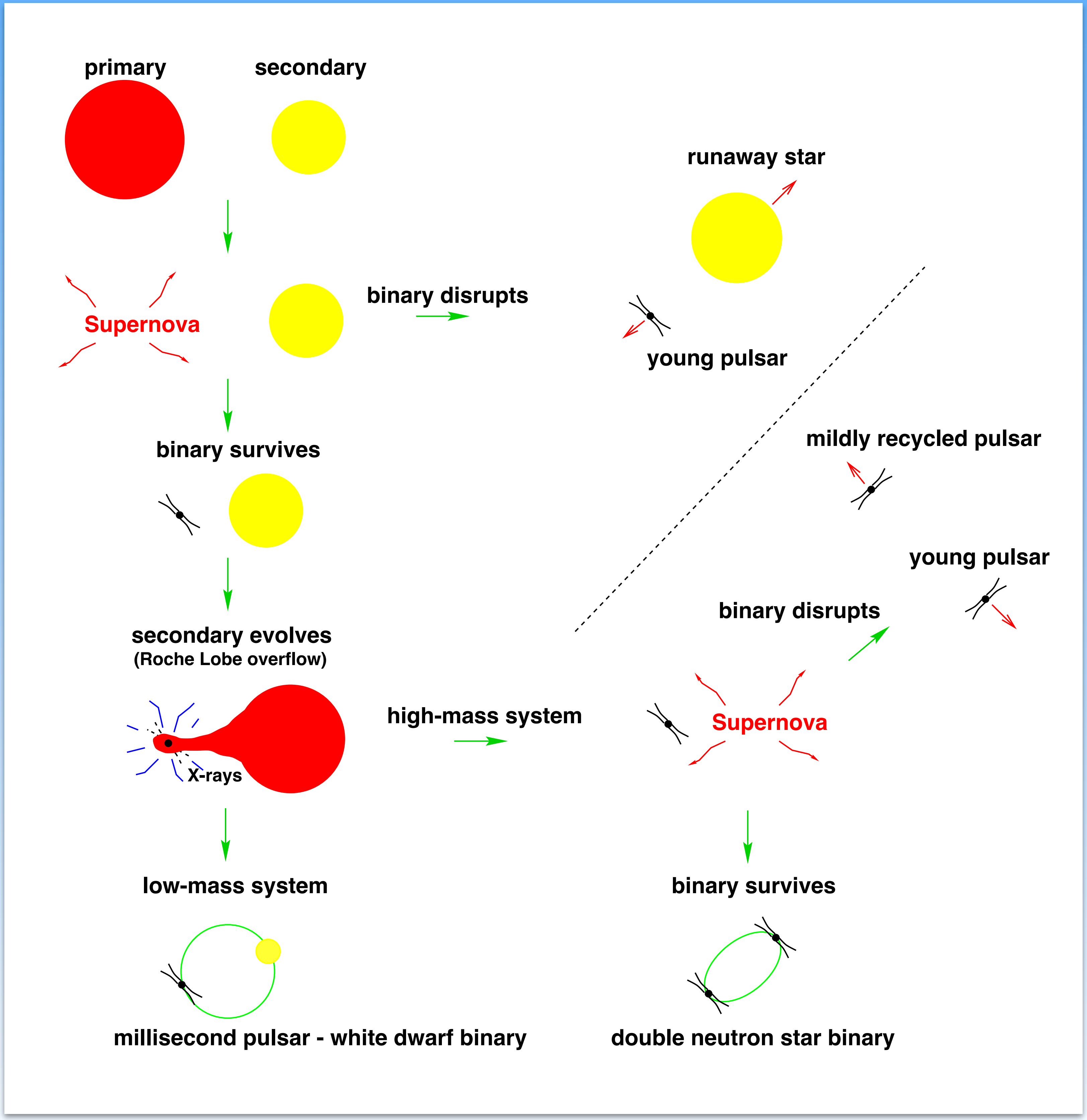
- Discovered in observation from July 19th 2017 in the Quicklook pipeline (identified in early Aug.).

- 17 ms spin period at a DM of 94 pc/cm^3, found to have a large apparent change in period due to orbital motion.



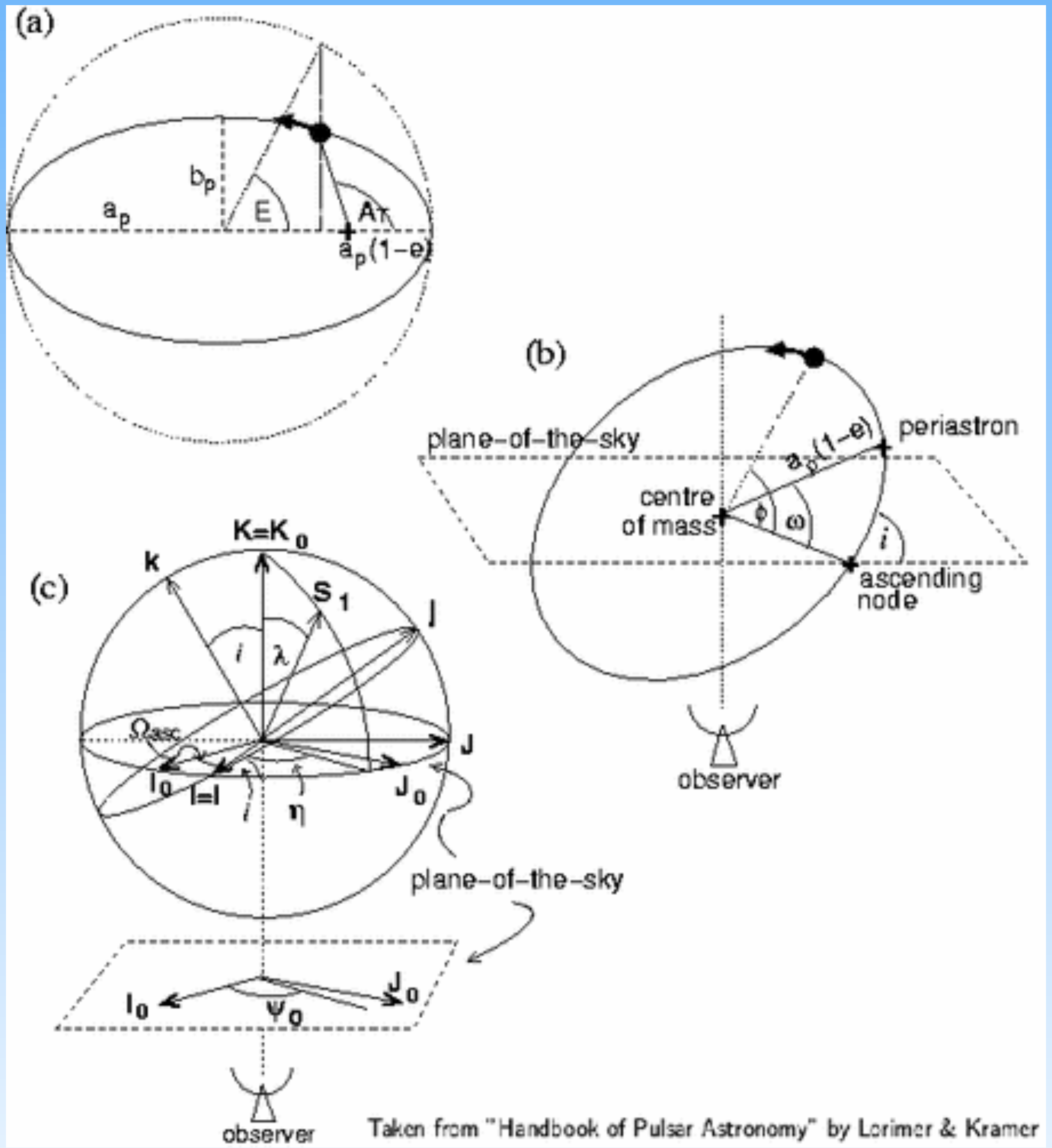
Stovall et al. 2018, ApJL, 854, 22 arxiv:1802.01707

Recycled Pulsars



Lorimer, 2008, LRR, 11

Binary Parameters



Keplerian Binary Parameters

Orbital Period: PB

Projected Semimajor axis: A1

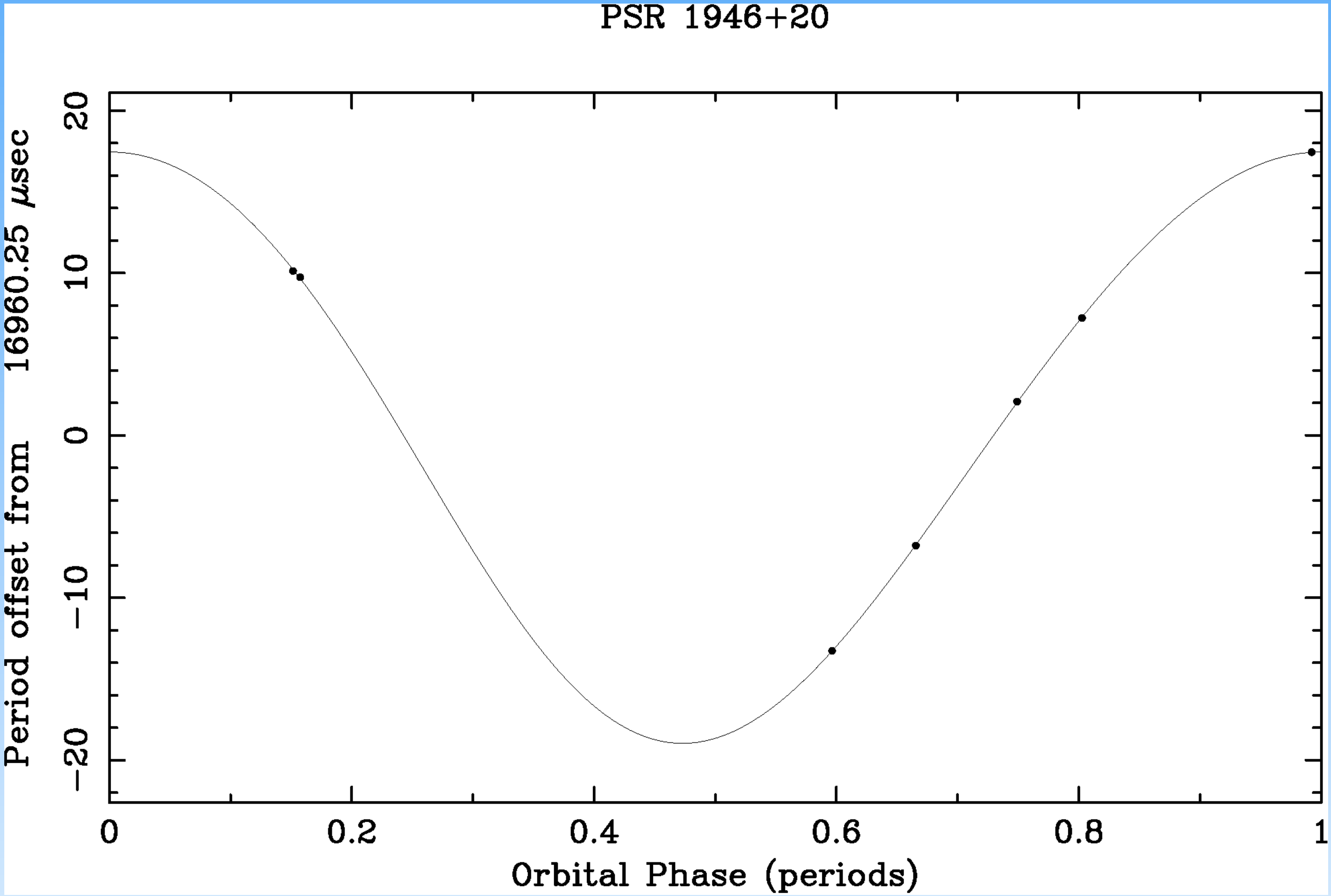
Time of Periastron Passage: T0

Eccentricity: E

Longitude of Periastron: OM

Binary Parameters

P0 0.01696015
A1 1.16246
E 0.061866
T0 57953.21362
PB 0.078487
OM 136.83

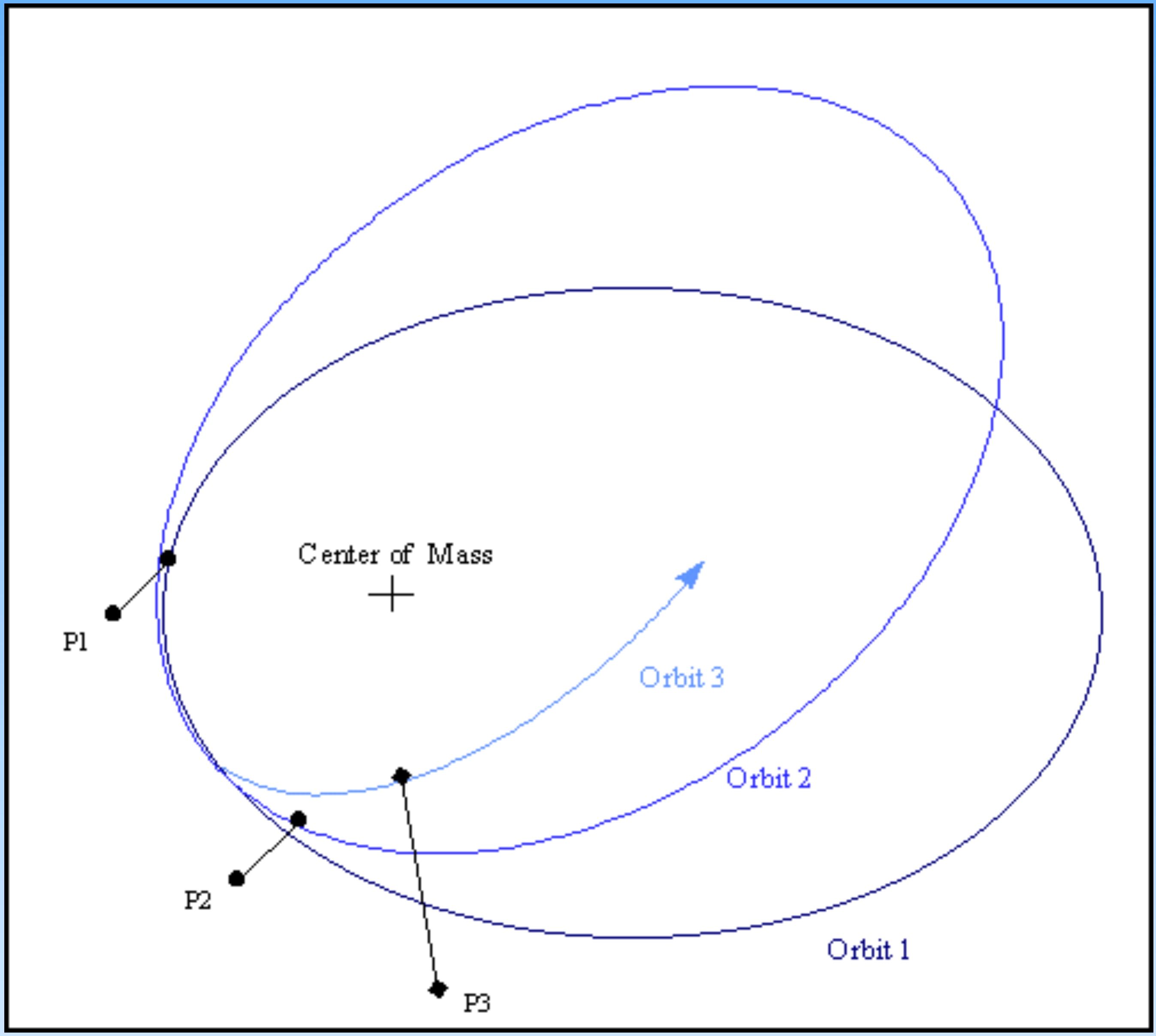


So, the system is in a 1.88 hour (1 hr 53 min), eccentric orbit with a ~1.2 solar mass companion.
-> Double Neutron Star (DNS) system, shortest orbital period of any such system

Binary Parameters

Then we added the advance of periastron to the fit ("omega-dot") and found a significant detection at 25.6 deg/year, the largest omega-dot for any pulsar system. This gives a total system mass of about 2.5, which is small for such systems.

We can also use the parameters to estimate the time to merger, which is 45.5 Myr.



Mercury: 43 arcseconds/century
B1913+16: 4 deg/year
J0737-3039: 17 deg/year

Pulsar Timing

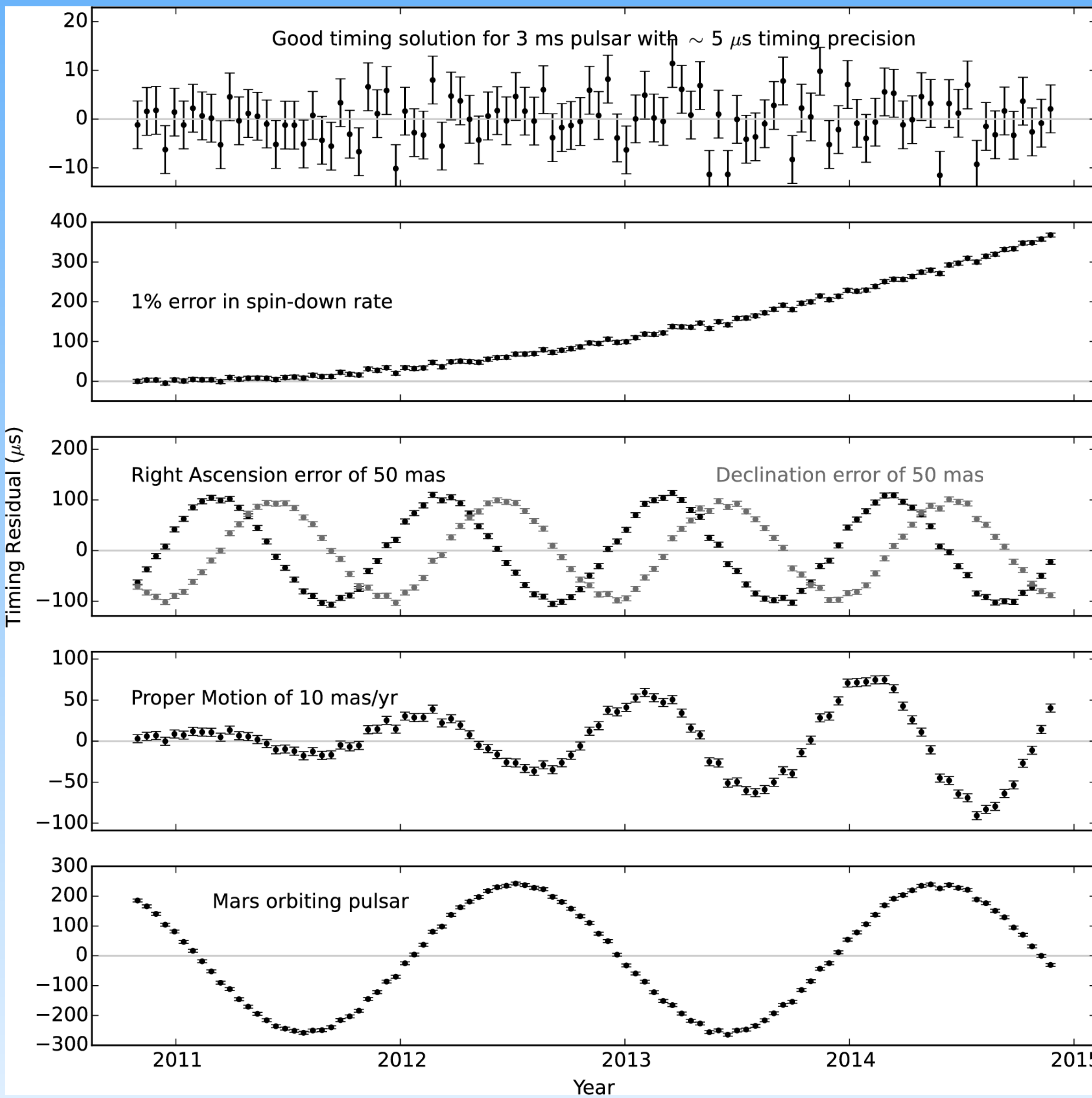


Table 1 | Physical parameters for PSR J1614-2230

Parameter	Value
Ecliptic longitude (λ)	245.78827556(5)°
Ecliptic latitude (β)	−1.256744(2)°
Proper motion in λ	9.79(7) mas yr^{-1}
Proper motion in β	−30(3) mas yr^{-1}
Parallax	0.5(6) mas
Pulsar spin period	3.1508076534271(6) ms
Period derivative	$9.6216(9) \times 10^{-21}$ s s^{-1}
Reference epoch (MJD)	53,600
Dispersion measure*	34.4865 pc cm^{-3}
Orbital period	8.6866194196(2) d
Projected semimajor axis	11.2911975(2) light s
First Laplace parameter (esin ω)	$1.1(3) \times 10^{-7}$
Second Laplace parameter (ecos ω)	$-1.29(3) \times 10^{-6}$
Companion mass	0.500(6)$M_{\odot}$
Sine of inclination angle	0.999894(5)
Epoch of ascending node (MJD)	52,331.1701098(3)
Span of timing data (MJD)	52,469–55,330
Number of TOAs†	2,206 (454, 1,752)
Root mean squared TOA residual	1.1 μs
Right ascension (J2000)	16 h 14 min 36.5051(5) s
Declination (J2000)	−22° 30′ 31.081(7)″
Orbital eccentricity (e)	$1.30(4) \times 10^{-6}$
Inclination angle	89.17(2)°
Pulsar mass	1.97(4)$M_{\odot}$
Dispersion-derived distance‡	1.2 kpc
Parallax distance	>0.9 kpc
Surface magnetic field	1.8×10^{8} G
Characteristic age	5.2 Gyr
Spin-down luminosity	1.2×10^{34} erg s^{-1}

Localizing J1946+2052

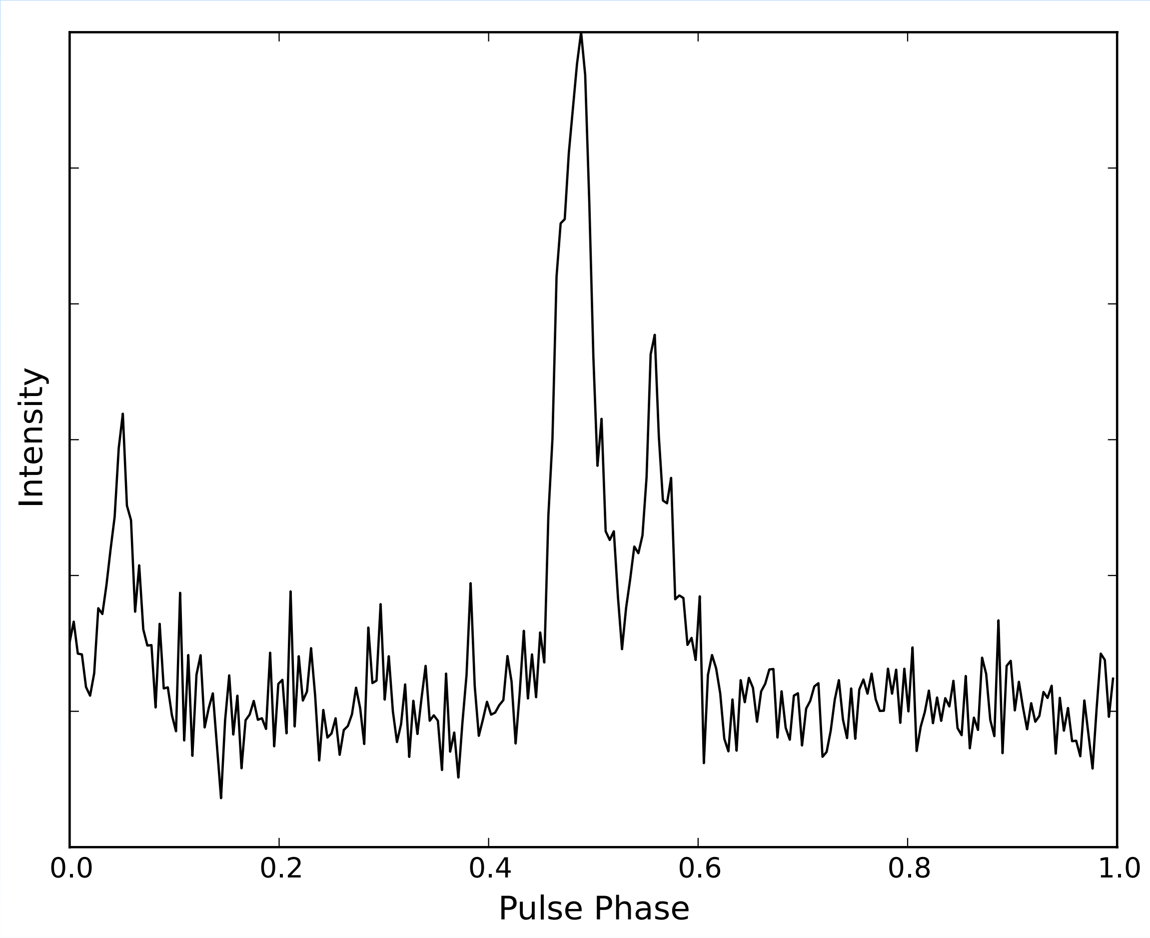
The Jansky Very Large Array (JVLA)

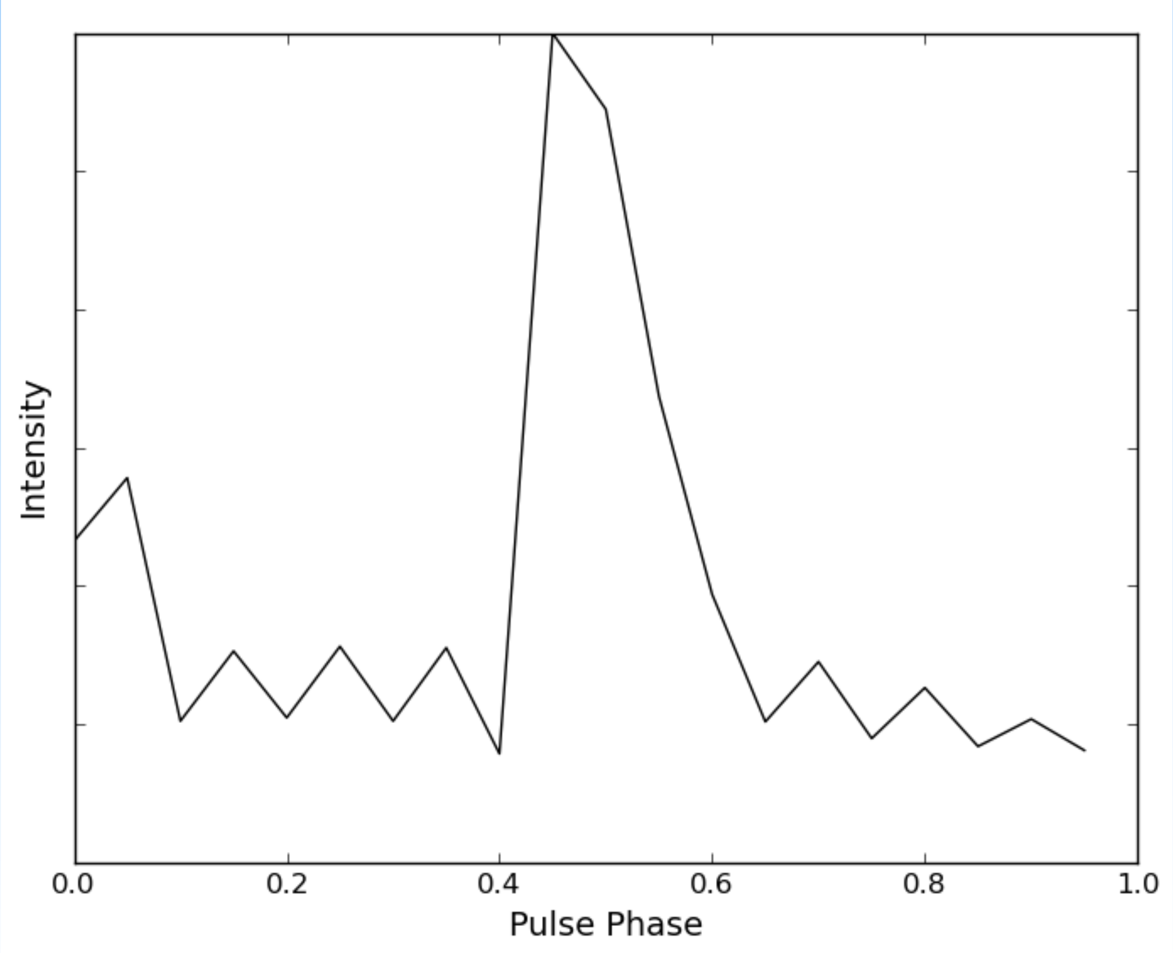
National Radio Astronomy Observatory

Localizing J1946+2052

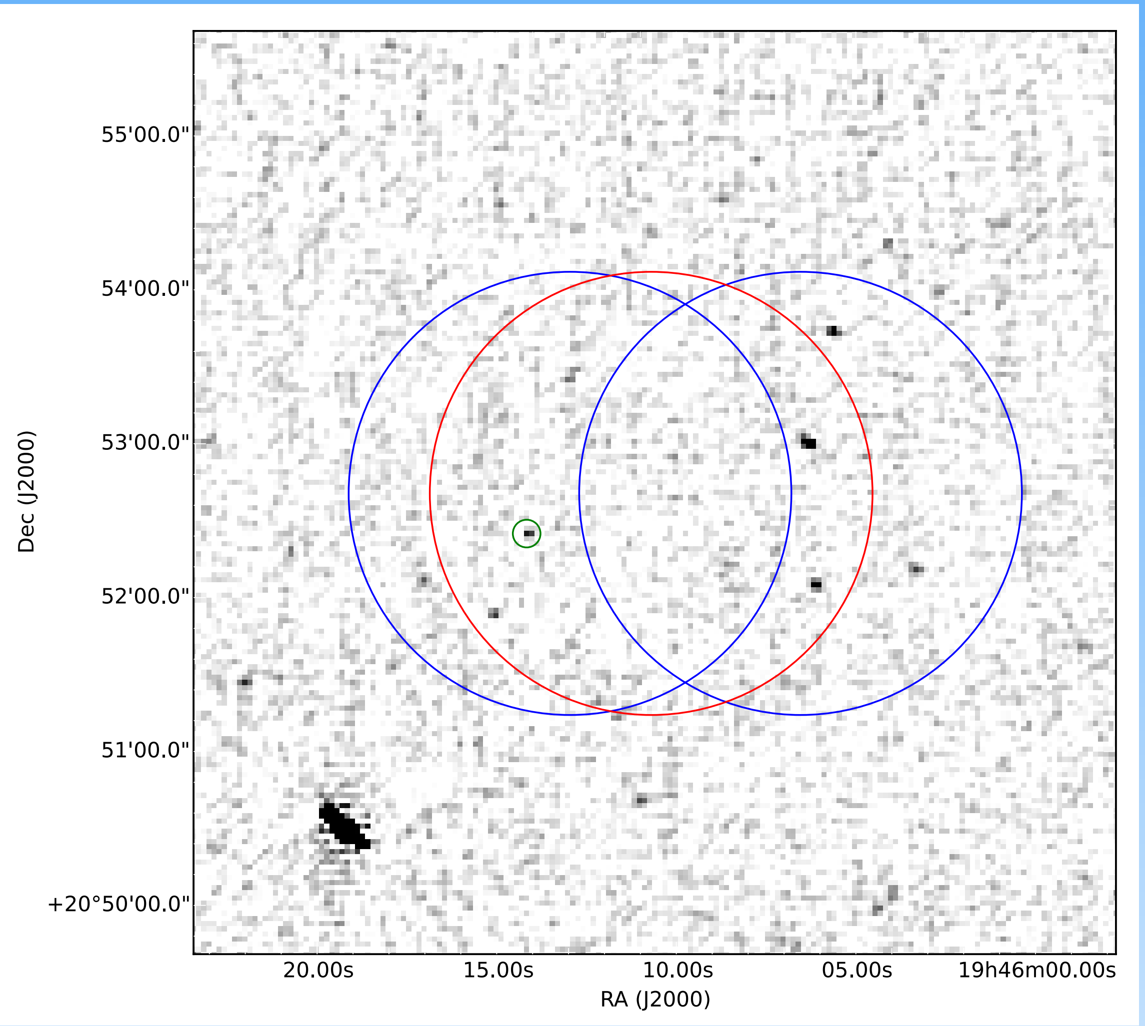
- Initial position uncertainty was ~3.5', some gridding with L-wide resulted in ~2' position.
- Typical pulsar timing results in sub-milliarcsecond positions, but have to wait for ~1 year.

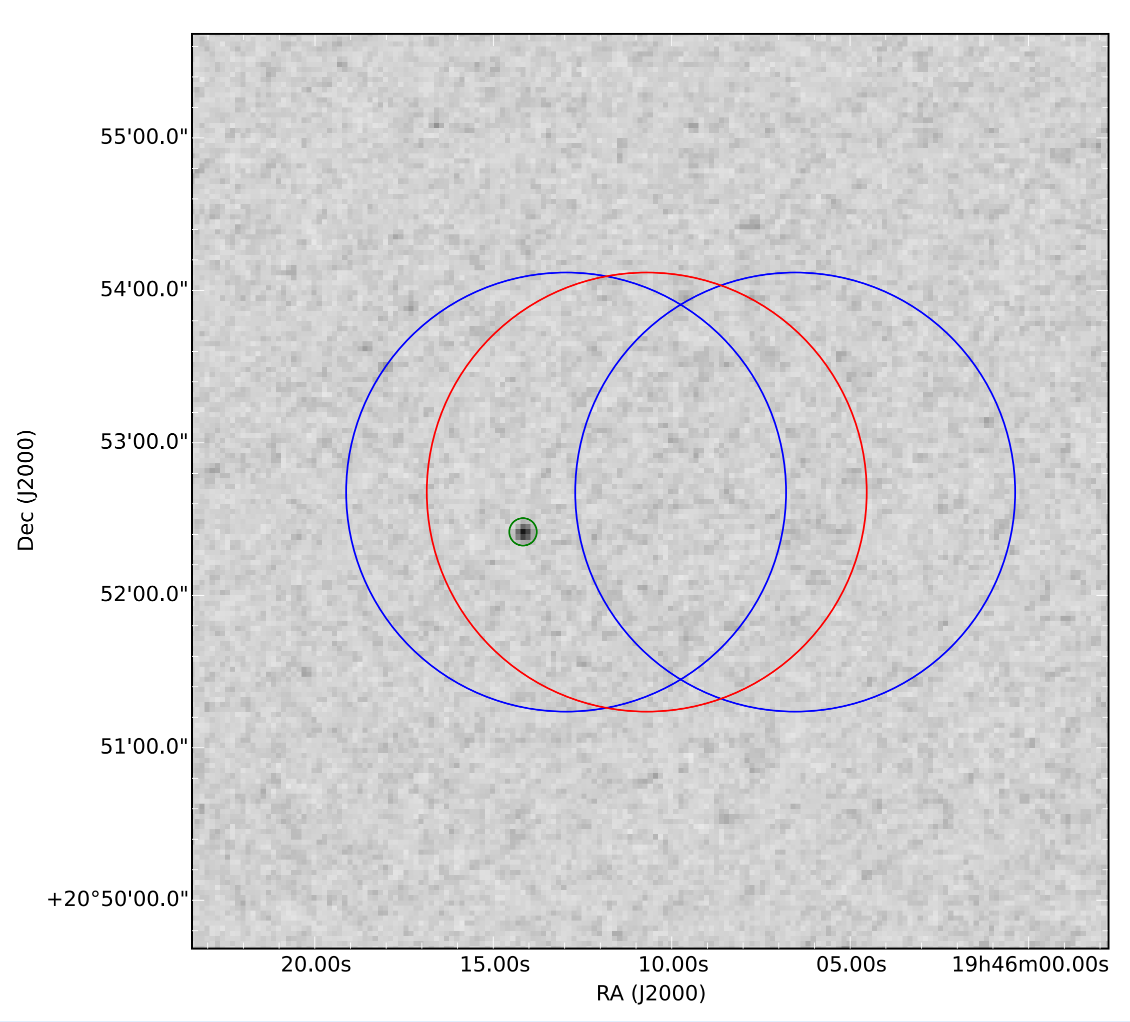
- We can use the VLA to get sub-arcsecond positions by imaging, but we expected the field to be crowded and for PSR J1946+2052 to be weak, so we took data in VLA's "phase-binning" mode.

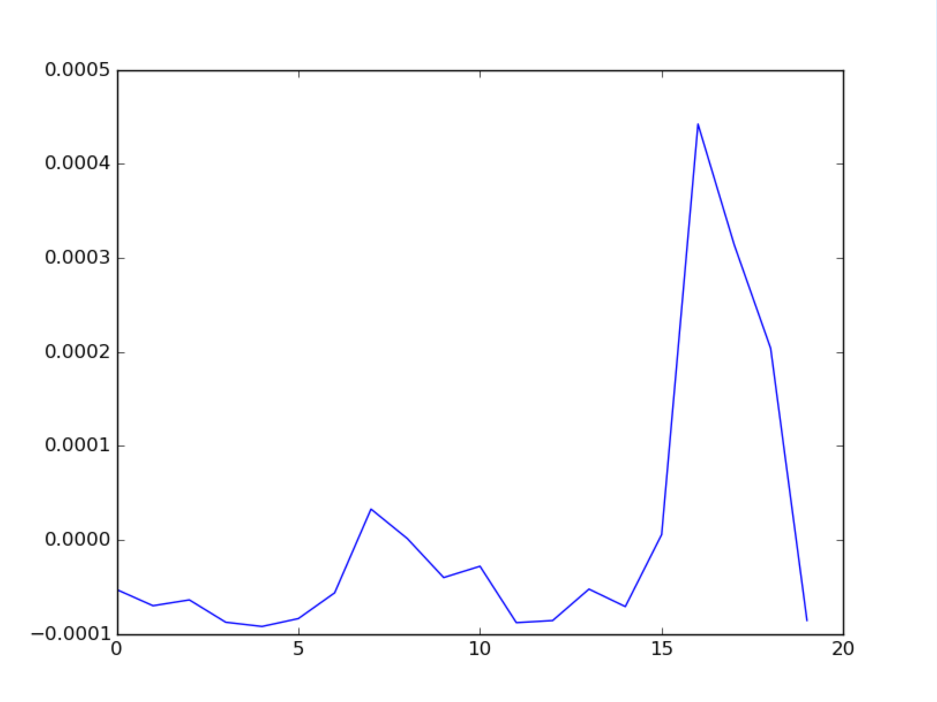




VLA Follow-up of J1946+2052







VLA Phase Binning Mode

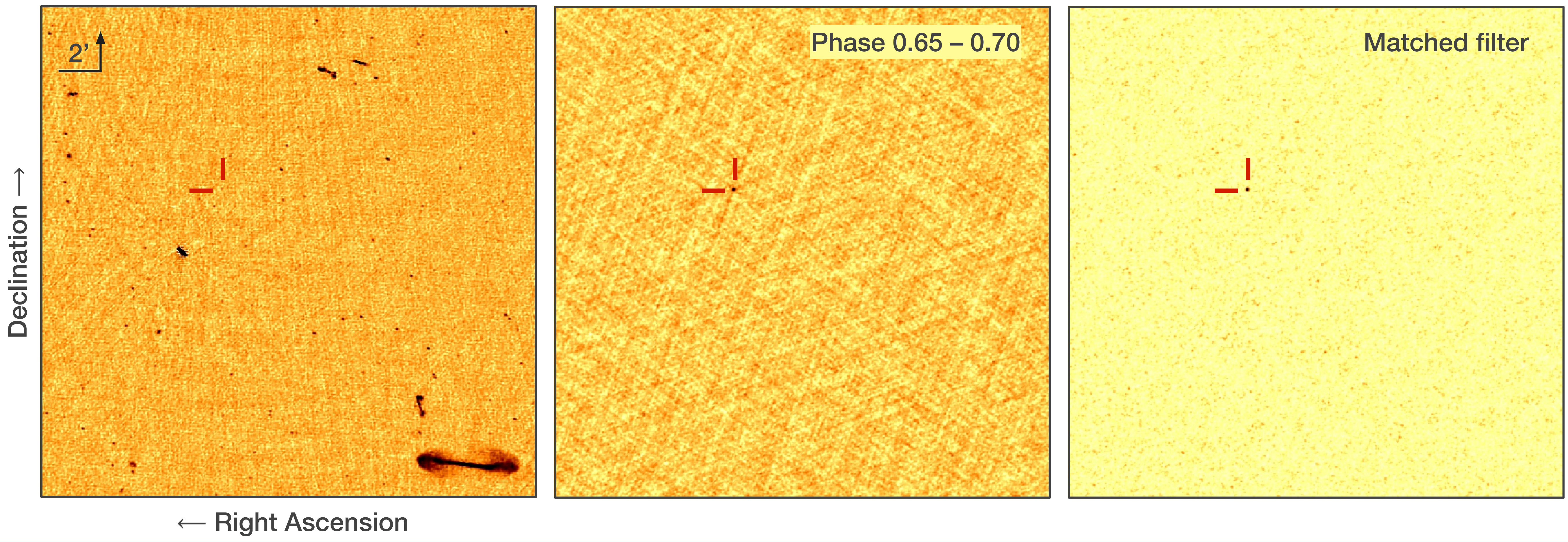


Image created by Shami Chatterjee

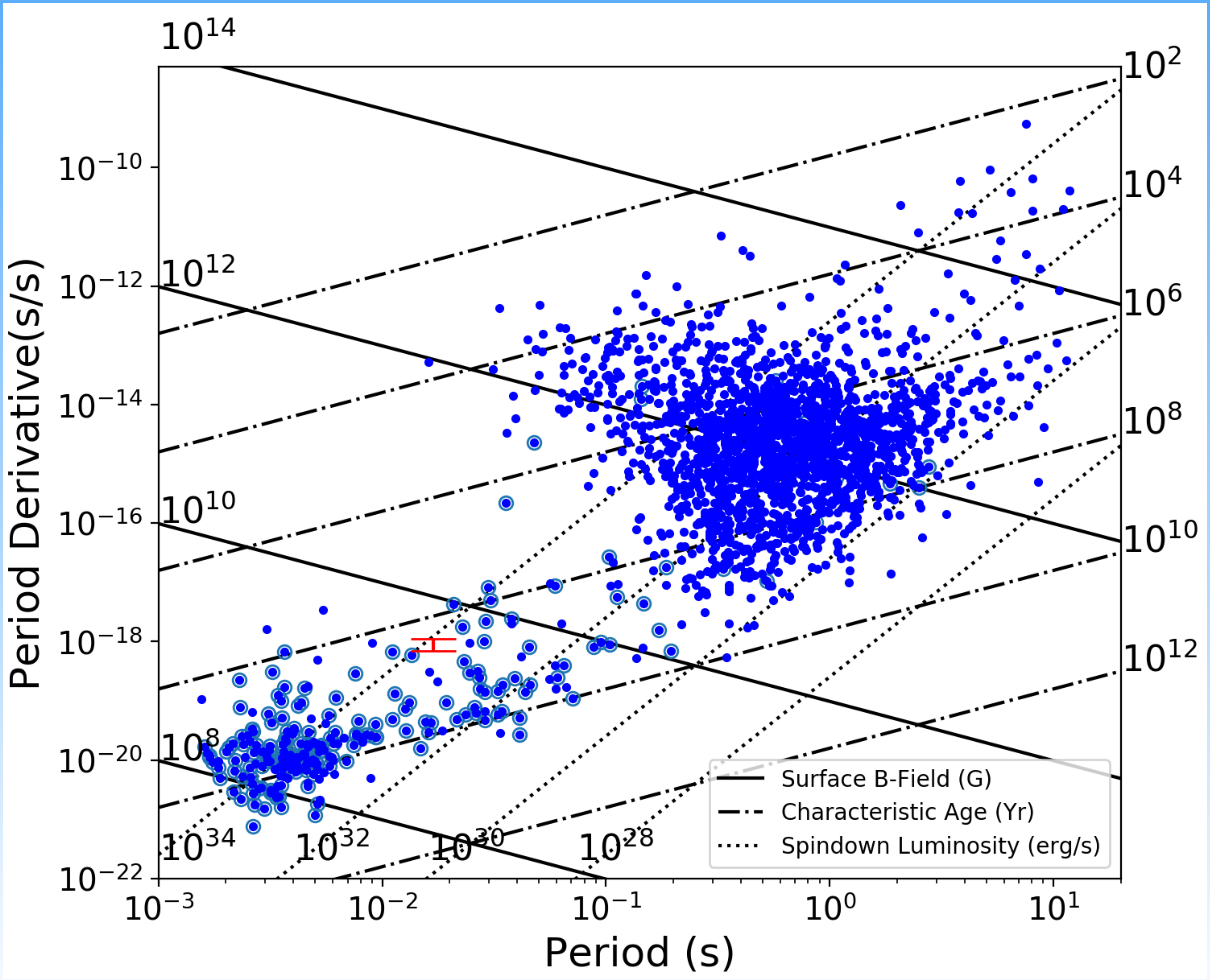
New Position: 19:46:14.130(6) +20:52:24.64(9)

Timing Solution

The VLA position has allowed for us to determine the system has definitely been recycled and to begin looking at optical/IR/X-ray/Gamma-ray data and has improved our data since we can now center the Arecibo Observations on the actual position.

Table 1. Fitted and derived parameters for PSR J1946+2052.

Measured Parameters	
Right ascension, α (J2000.0)	19:46:14.130(6)[a]
Declination, δ (J2000.0)	20:52:24.64(9)[a]
Pulse frequency, ν (s^{-1})	58.9616546404(7)
First derivative of pulse frequency, $\dot{\nu}$ (s^{-2})	$-3.2(6)\times10^{-15}$
Epoch (MJD)	57982.080242
Dispersion measure, DM (pc cm^{-3})	93.965(3)
Epehemeris	DE436
Clock	TT(BIPM)
Binary model	DD
Orbital period, P_b (days)	0.07848804(1)
Projected semimajor axis, x (lt s)	1.154319(5)
Orbital eccentricity, e	0.063848(9)
Epoch of periastron, T_0 (MJD)	57953.212395(8)
Longitude of periastron, ω (degrees)	130.38(3)
Rate of periastron advance, $\dot{\omega}$ (degrees/yr)	25.6(3)
Derived Parameters	
Galactic latitude, l (degrees)	57.66
Galactic longitude, b (degrees)	−1.98
DM-derived distance to pulsar (NE2001), d_{DM} (kpc)	4.2
DM-derived distance to pulsar (YMW16), d_{DM} (kpc)	3.5
Spin period, P (s)	0.0169601753224(2)
Period derivative, $\dot{P}$	$9(2)\times10^{-19}$
Characteristic age, $\tau_c = P/2\dot{P}$ (Myr)	290.0
Surface magnetic field, $B_S = 3.2\times10^{19}\sqrt{P\dot{P}}$ (10^9G)	4.0
Spindown luminosity (10^{32} erg/s)	75
Mass function, f_{mass} ($M_\odot$)	0.268184(12)
Total mass, $M_{\rm Total}$ ($M_\odot$)	2.50(4)



Period Derivative(s/s)
Period (s)
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{14}
10^{12}
10^{10}
10^{8}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{34}
10^{32}
10^{30}
10^{28}
Surface B-Field (G)
Characteristic Age (Yr)
Spindown Luminosity (erg/s)

DNS Systems

Pulsar	P (ms)	Orb Period (days)	E	Distance (kpc)	Merger Time (Myr)	Total Mass (sol mass)
J0453+1559	45.8	4.072	0.113	1.07		2.734(3)
J0737-3039A	22.7	0.102	0.088	1.15	86	2.58708(16)
J0737-3039B	2773.5	"	"	"	"	"
J1411+2551	62.5	2.616	0.170	1.0		**2.54(2)**
J1518+4904	40.9	8.634	0.249	**0.63**		2.7183(7)
B1534+12	37.9	0.421	0.274	1.05	2730	2.678463(8)
J1753-2240	95.1	13.638	0.304	3.46		
J1756-2251	28.5	0.320	0.181	0.73	1660	2.56999(6)
J1757-1854	21.5	0.184	0.605	7.4	76	2.73295(9)
J1811-1736	104.2	18.779	**0.828**	5.93		2.57(10)
J1829+2456	41.0	1.176	0.139	0.74		2.59(2)
J1913+1102	27.3	0.206	0.090	?	480	**2.875(14)**
B1913+16	59.0	0.323	0.617	9.80	301	2.828378(7)
J1930-1852	185.5	45.060	0.399	1.5		2.59(4)
J1946+2052	**17.0**	**0.078**	**0.064**	3.5	**46**	**2.50(4)**

Post-Keplerian Parameters

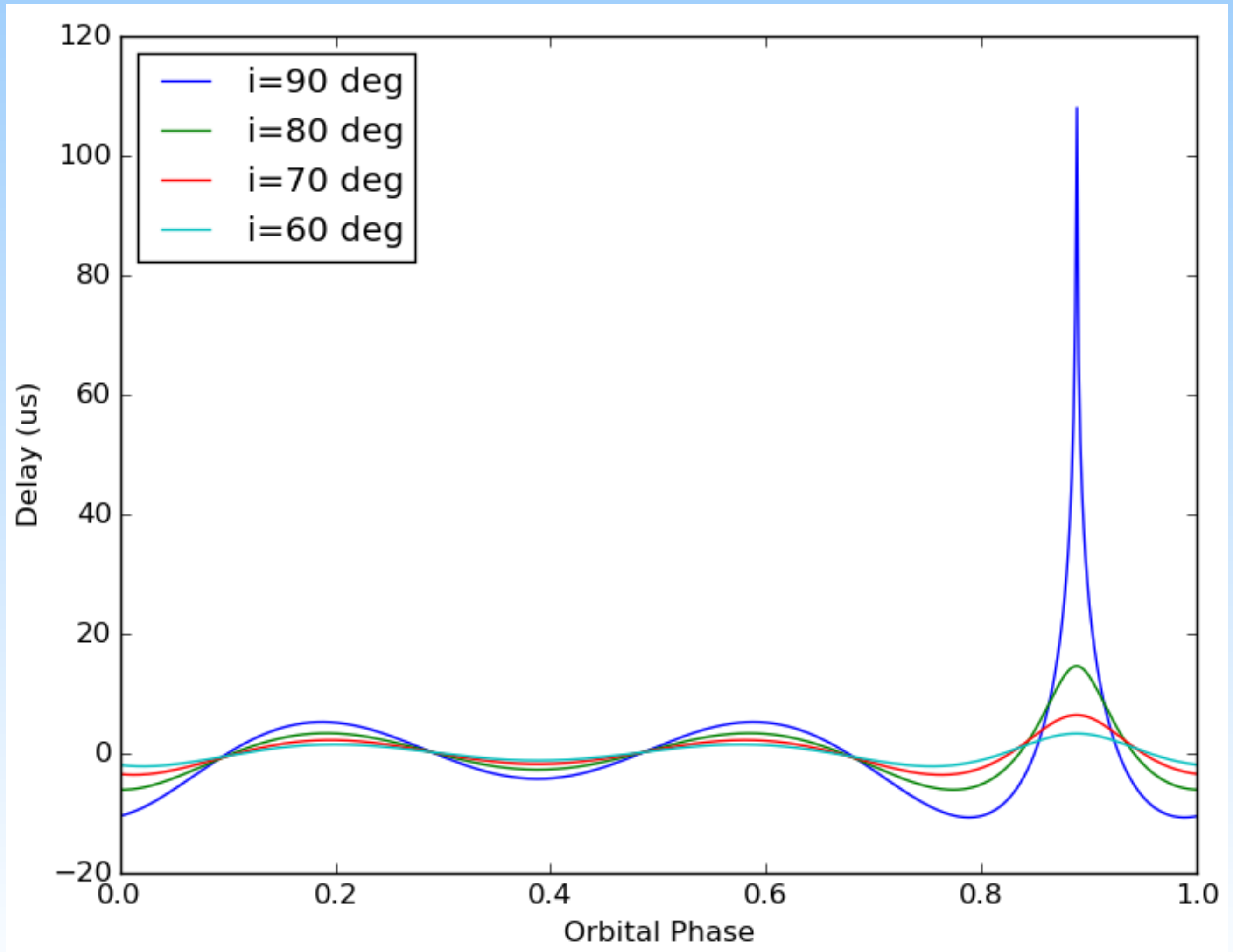
$$\dot{\omega} = 6\pi f_b (2\pi M f_b)^{\frac{2}{3}} (1 - e^2)^{-1}$$

$$\gamma = e(2\pi f_b)^{-1} (2\pi M f_b)^{\frac{2}{3}} \frac{m_2}{M} (1 + \frac{m_2}{M})$$

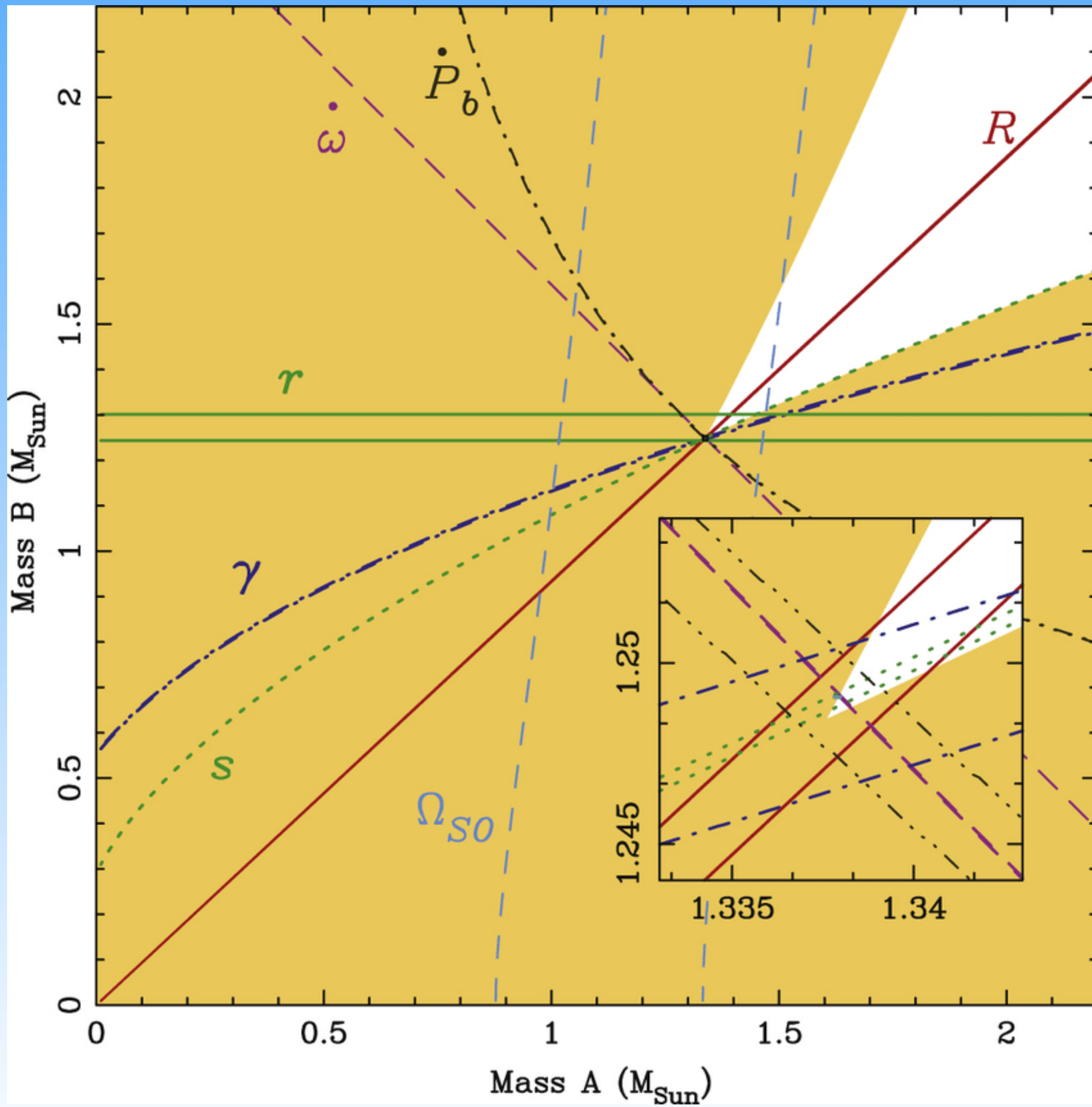
$$\dot{P}_b = -\frac{192\pi}{5} (2\pi \mu f_b)^{\frac{5}{3}} F(e)$$

$$r = m_2$$

$$s = sin(i)$$

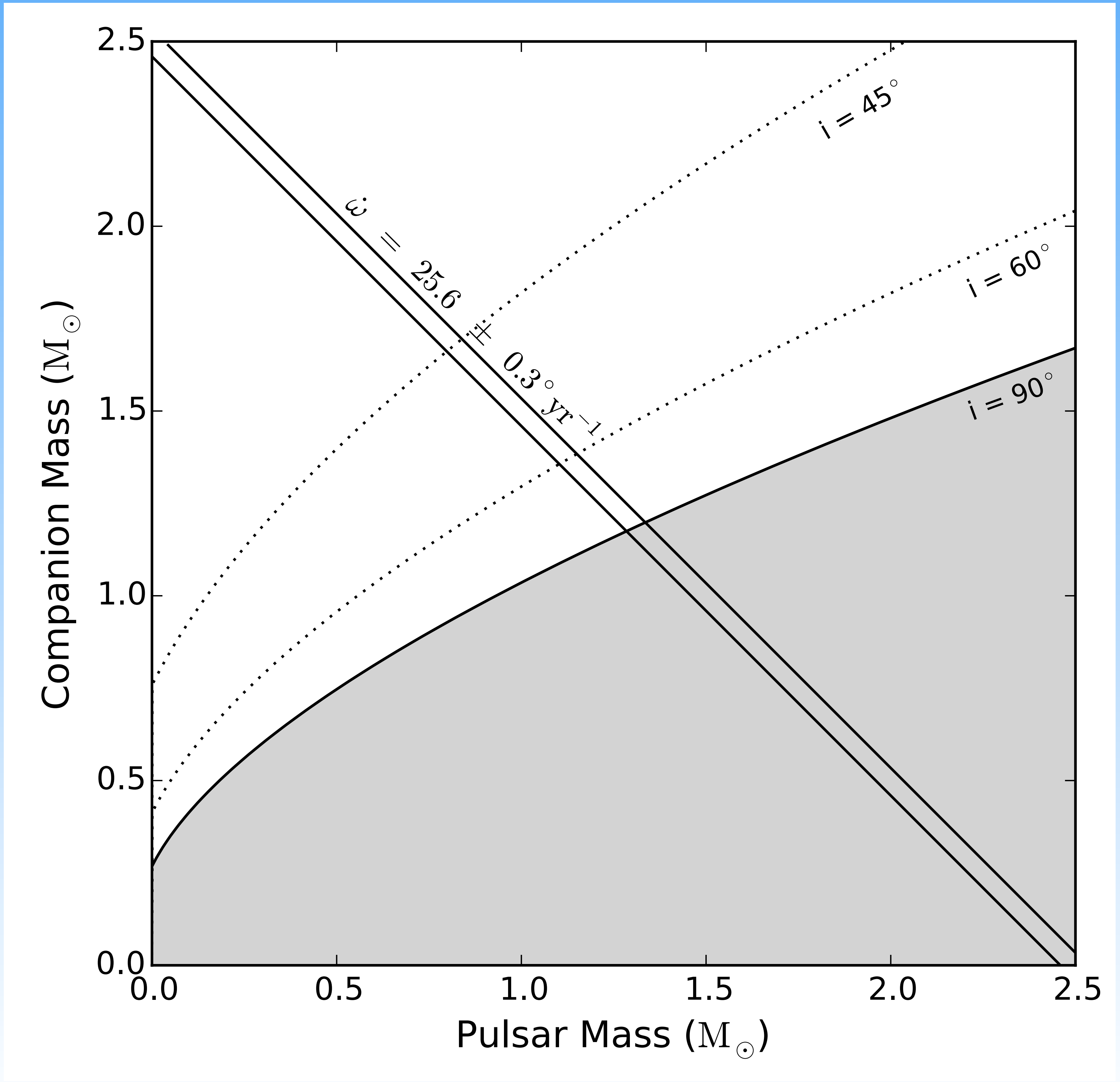


Double Pulsar GR Tests



Kramer et al. 2015

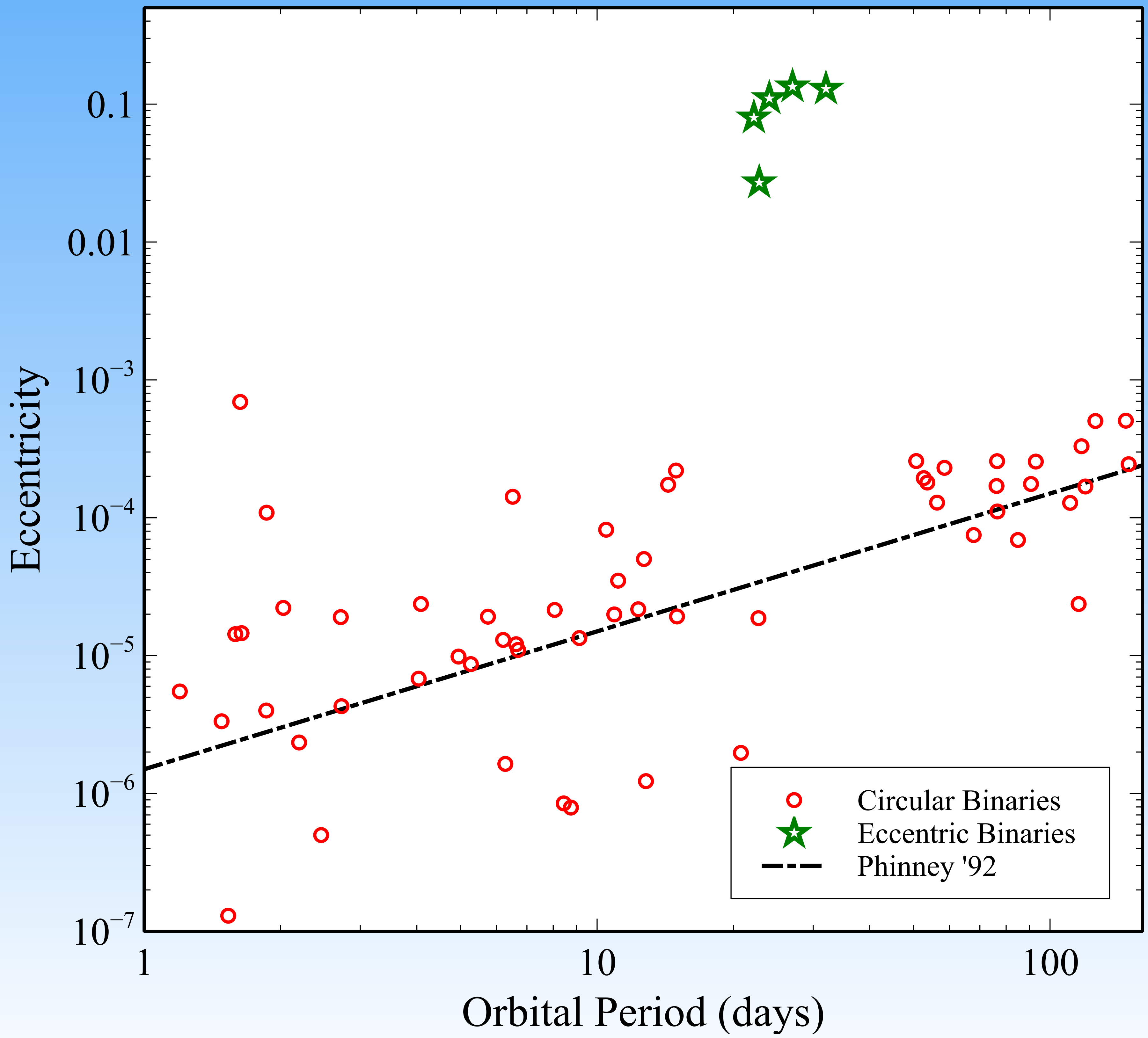
J1946 Component Masses



Summary

- PALFA observations have resulted in the discovery of a relativistic binary with the shortest orbital of any such systems.
- We were able to measure the advance of periastron passage within a few days of follow-up. We expect other relativistic parameters to be measurable in the coming years.
- We used a new VLA mode to image the location of the source and then used new techniques to identify the position of J1946+2052.
- We were able to obtain a publishable timing solution for this source within ~2 months of discovery, compared to ~year for typical pulsar discoveries.

Extra Slide



0.1
0.01
10^−3
10^−4
10^−5
10^−6
10^−7
Eccentricity
1
10
100
Orbital Period (days)
Circular Binaries
Eccentric Binaries
Phinney '92