The gamma-ray millisecond pulsar deathline, revisited

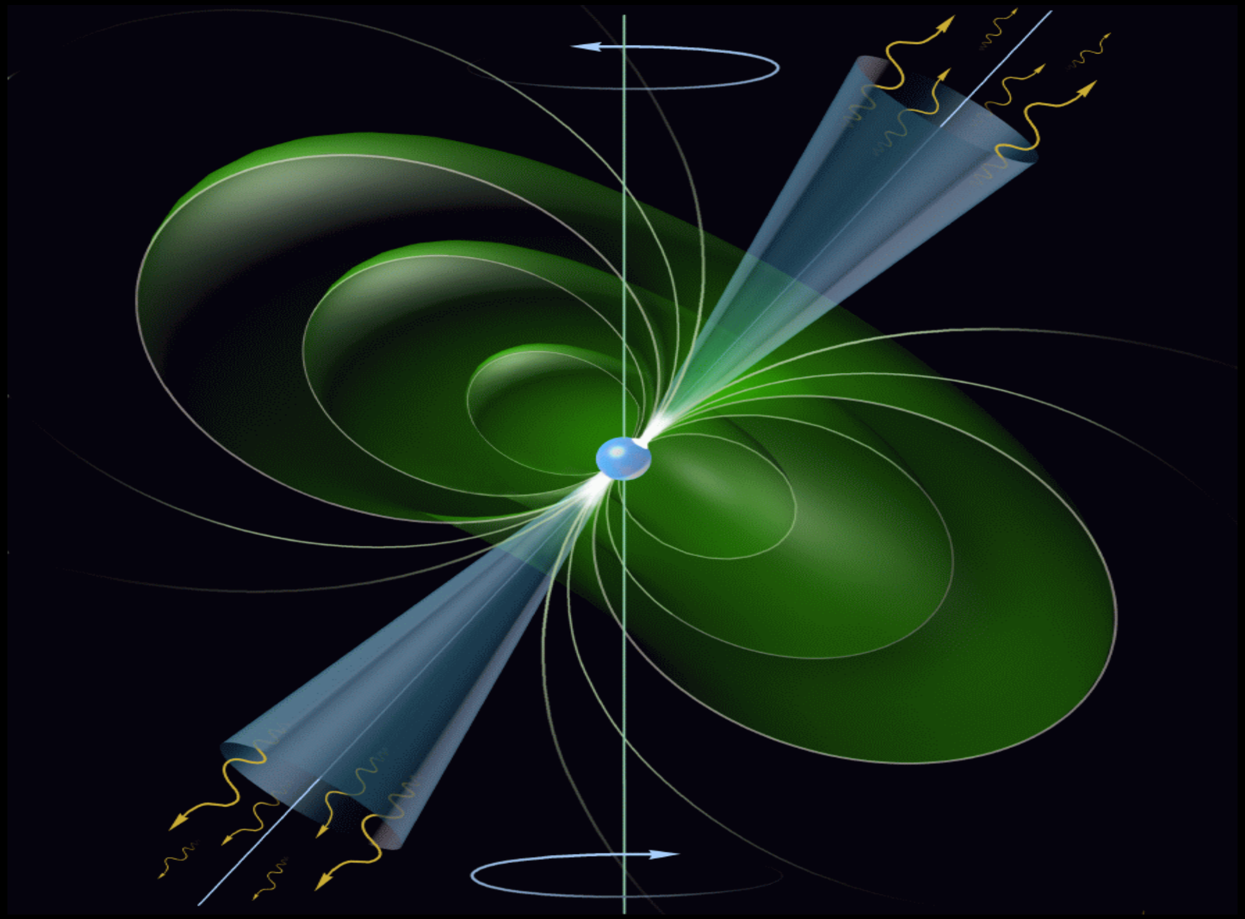
Lucas Guillemot, David A. Smith, Hélène Laffon, Ismaël Cognard, Gilles Theureau, on behalf of many

MODE-SNR-PWN Workshop

Meudon, 19 May 2016

LPC2E
OSUC Observatoire des Sciences de l'Univers en région Centre
UNIVERSITE D'ORLEANS
Station de Radioastronomie de Nançay

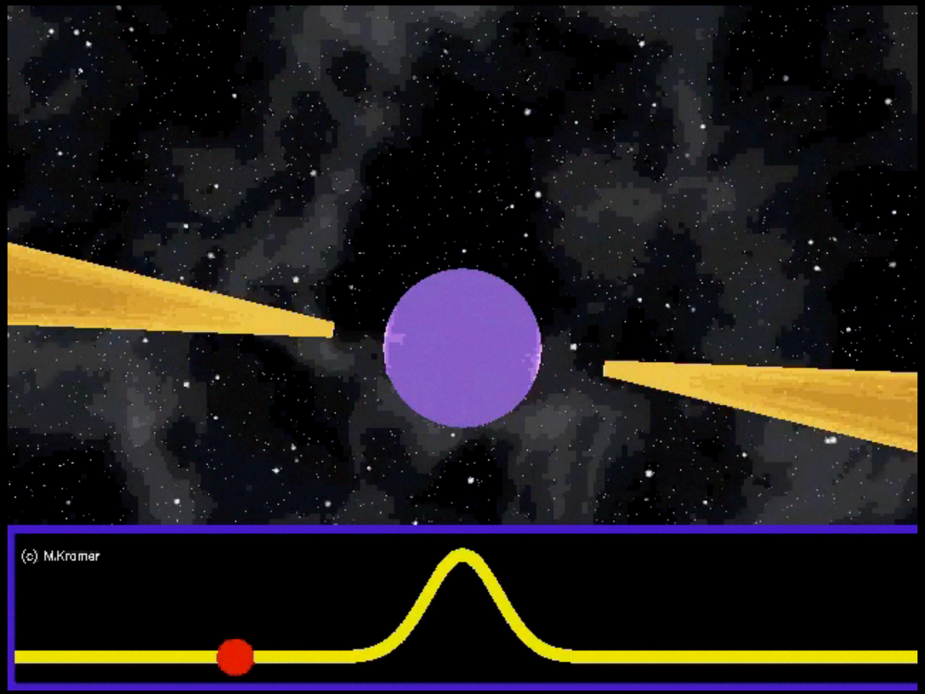
Pulsars



Pulsars are rapidly rotating highly magnetized neutron stars, born in supernova explosions of massive stars.

Masses: 1.2 - 2 $M_\odot$, Radii ~ 13 km.

Emission (radio, optical, X-ray, gamma rays…) produced in beams around the star.



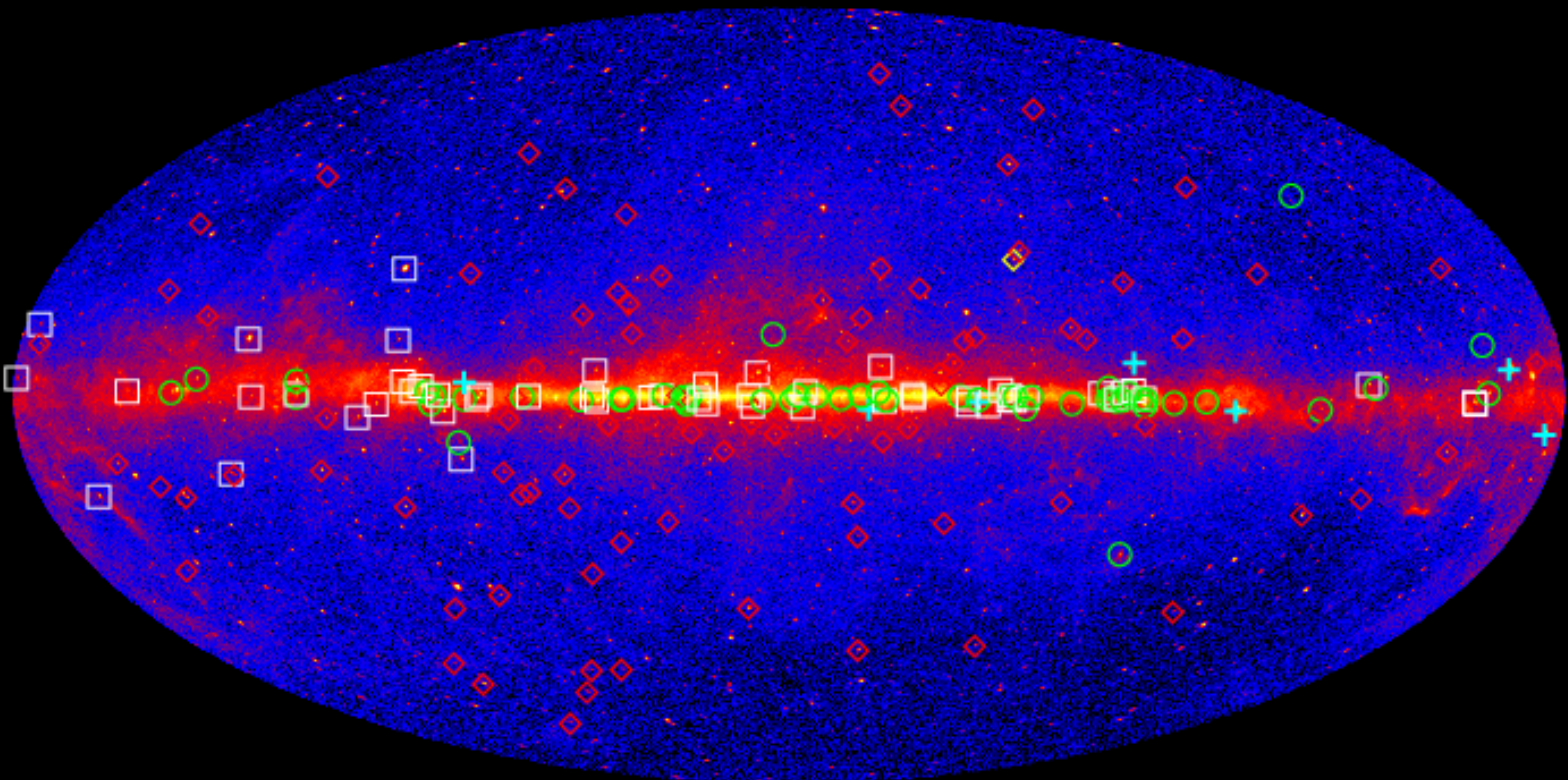
Pulsars are cosmic lighthouses!

Extreme objects:

- Luminosities up to 10^4 $L_\odot$
- Surface temperature ~ 10^6 K
- Surface gravity ~ 10^{11} Earth's
- Surface magnetic fields: 10^8 - 10^{15} G

LAT pulsars as of May 2016

Public list of LAT-detected pulsars available at: https://confluence.slac.stanford.edu/x/5JI6Bg



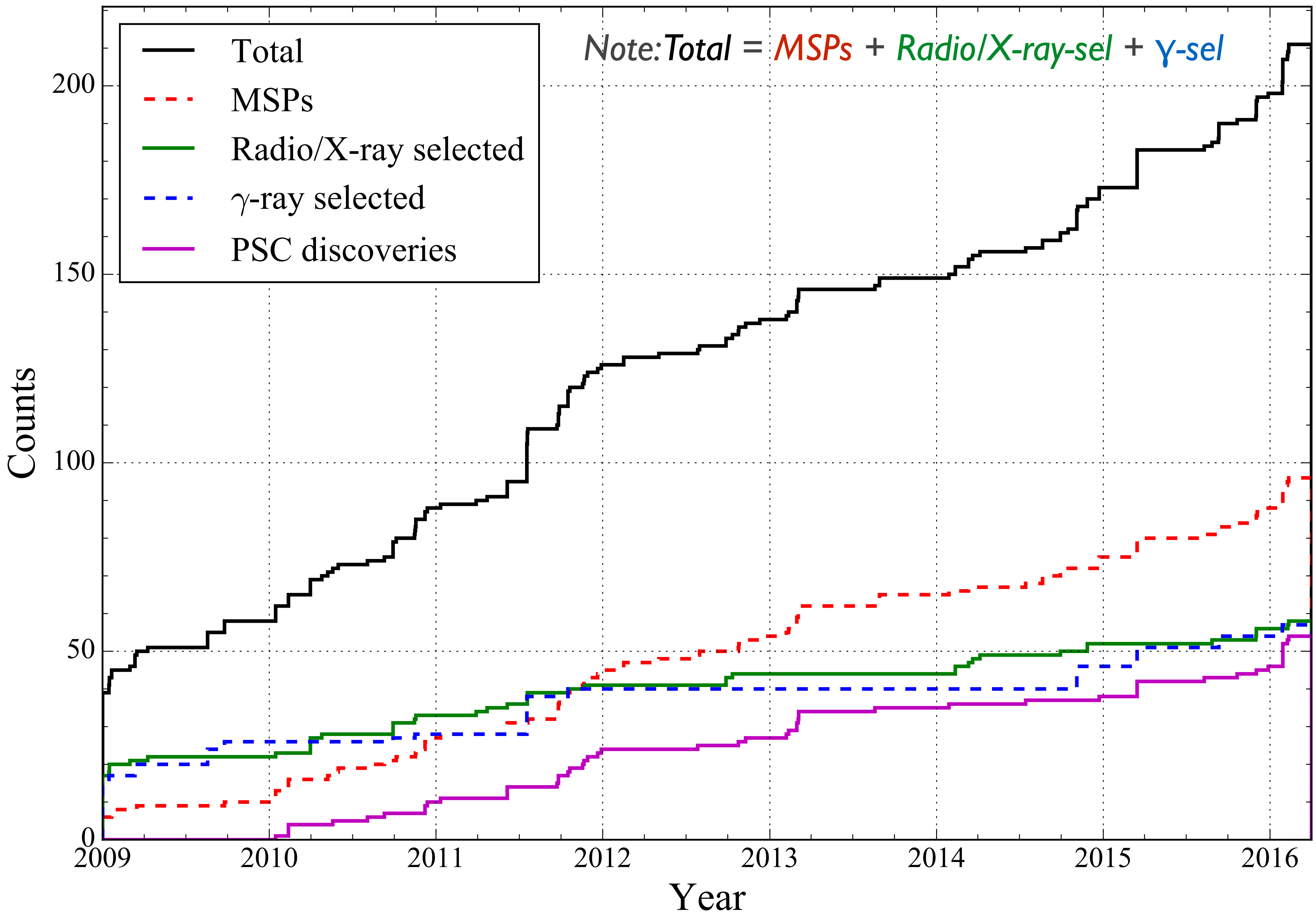
58 young radio- and X-ray-selected (green circles, cyan crosses: EGRET pulsars)

54 young gamma-ray-selected (white squares)

92 radio-selected MSPs (red diamonds), 1 gamma-ray-selected MSP (yellow diamonds)

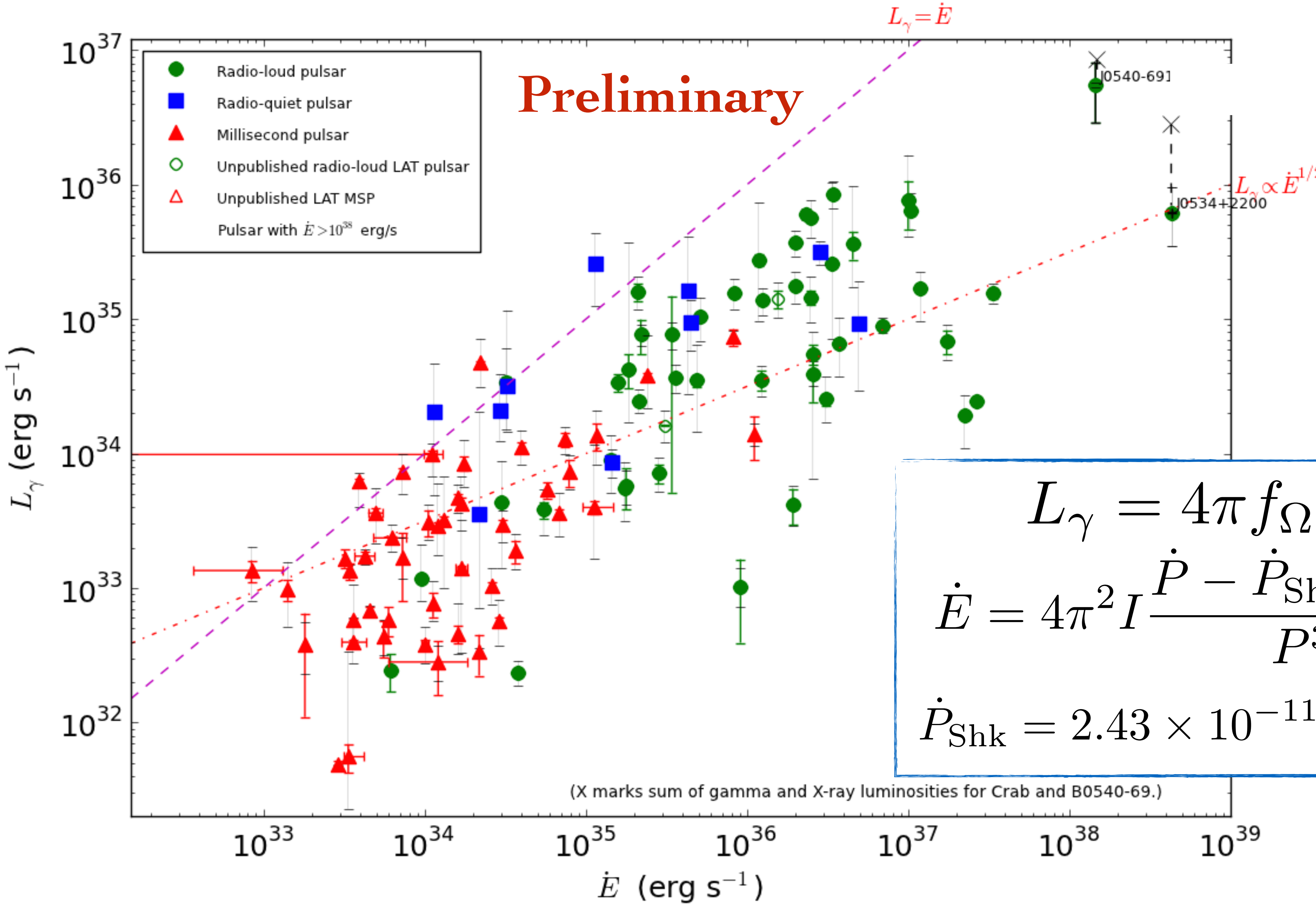
205 in total!

Detected pulsars versus time



Gamma-ray pulsar detection rate impressively steady!

Pulsar energetics



$$L_\gamma = 4\pi f_\Omega h d^2$$

$$\dot{E} = 4\pi^2 I \frac{\dot{P} - \dot{P}_{\text{Shk}} - \ldots}{P^3}$$

$$\dot{P}_{\text{Shk}} = 2.43 \times 10^{-11} \mu_\perp^2 \ d \ P$$

Can we get a clearer view of the L_γ vs $\dot{E}$ relationship?

Where does the deathline for gamma-ray emission lie?

We need good proper motion and distance measurements (Shklovskii effect): radio timing!

Importance of accurate proper motions and distances

We want to probe the gamma-ray emission deathline, i.e. the limit in spin-down power below which MSPs cease to produce detectable gamma-ray emission.

Spin-down power: $\dot{E} = 4\pi^2 I \dot{P} / P^3$

With I the moment of inertia, P the rotational period and $\dot{P}$ the spin-down rate. The apparent $\dot{P}$ value that we measure can be very different from the intrinsic one!

$$\dot{P}_{\rm int} = \dot{P}_{\rm obs} - \dot{P}_{\rm Gal} - \dot{P}_{\rm Shk}$$

$$\dot{P}_{\rm Shk} \simeq 2.43 \times 10^{-21} \left(\frac{\mu_\perp}{\rm mas\ yr^{-1}} \right)^2 \left(\frac{d}{1\ \rm kpc} \right) \left(\frac{P}{\rm s} \right)$$

Acceleration in the Galactic potential, depends on d

Shklovskii correction, depends on d and PM

Example with J0437-4715: ($\dot{E}_{\rm int}$ / $\dot{E}_{\rm obs}$) ~ 0.25! Importance of accurate proper motions and distances.

We also want to constrain the spin-down power - gamma-ray luminosity relationship. The luminosity crucially depends on the distance (d^2).

MSP selection

19 radio & gamma-ray MSPs with missing/incomplete PM information.

Nançay data for all pulsars (BON backend until mid-2011, NUPPI backend afterwards).

Timing dataset complemented with Westerbork (NL) data for J0931-1902.

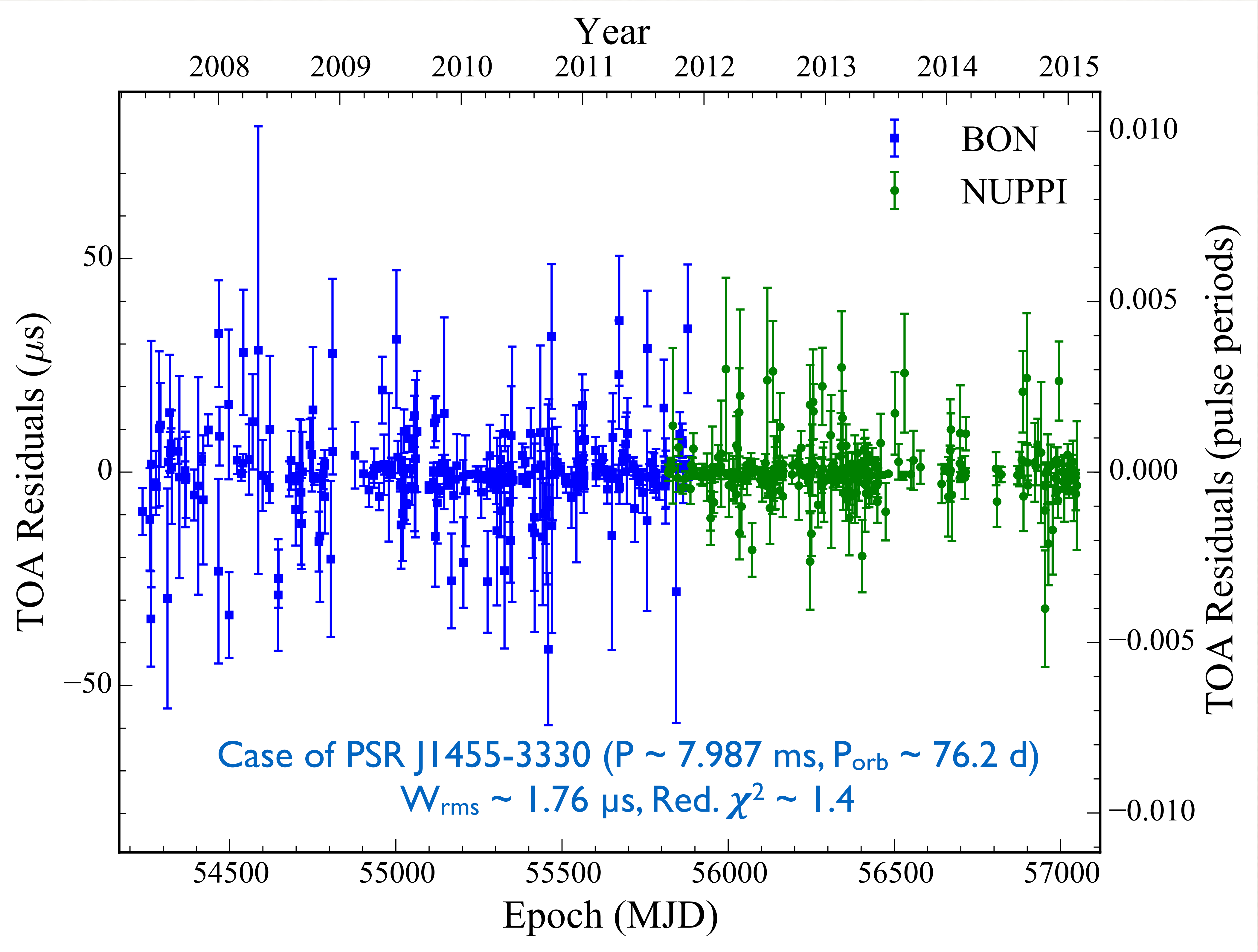
Note: timing parallax amplitude =

$$\frac{(1\ \mathrm{AU})^2 \cos\beta}{2cd}$$

1.2 μs for d=1 kpc and β=0°.

Pulsar Name	Residual RMS (μs)	Backend	N_{TOA}	MJD Range	Time span (yrs)	σ_{med} (μs)
J0034−0534	7.99	BON	66	53761.7 — 55808.1	5.6	21.02
		NUPPI	30	55935.7 — 57032.7	3.0	16.13
J0340+4130	3.31	BON	170	55309.6 — 55862.0	1.5	2.73
		NUPPI	143	55823.2 — 56805.5	2.7	2.10
J0610−2100	2.19	BON	89	54270.5 — 55805.3	4.2	2.60
		NUPPI	49	55854.2 — 57047.9	3.3	1.40
J0614−3329	1.53	BON	60	55160.1 — 55857.2	1.9	2.20
		NUPPI	54	55838.2 — 57038.9	3.3	1.69
J0740+6620	0.46	NUPPI	43	56675.0 — 57037.0	1.0	1.05
J0751+1807	1.17	BON	198	53373.0 — 55880.2	6.9	2.05
		NUPPI	153	55825.3 — 57047.0	3.3	0.83
J0931−1902	4.76	NUPPI	27	56399.8 — 57044.0	1.8	4.98
		PuMa-II (1.4 GHz)	23	56113.7 — 57061.9	2.6	10.29
		PuMa-II (0.35 GHz)	32	56113.7 — 57118.8	2.8	10.51
J1024−0719	0.96	BON	184	53714.2 — 55807.5	5.7	1.65
		NUPPI	118	55819.5 — 57047.1	3.4	1.12
J1231−1411	4.42	BON	174	55168.3 — 55878.4	1.9	3.62
		NUPPI	207	55877.4 — 57046.2	3.2	3.40
J1455−3330	1.75	BON	248	54238.0 — 55881.5	4.5	4.63
		NUPPI	260	55819.6 — 57049.3	3.4	2.94
J1614−2230	0.47	BON	80	54896.2 — 55881.5	2.7	0.65
		NUPPI	142	55853.6 — 57032.4	3.2	0.45
J1730−2304	1.22	BON	113	53385.4 — 55852.7	6.8	2.15
		NUPPI	47	55923.5 — 57047.4	3.1	0.65
J1741+1351	1.21	BON	38	54085.5 — 55903.5	5.0	2.24
		NUPPI	18	55812.8 — 57051.4	3.4	1.58
J1811−2405	0.48	BON	4	55597.4 — 55735.0	0.4	0.46
		NUPPI	43	55871.6 — 57048.4	3.2	0.37
J1823−3021A	3.77	BON	28	53784.3 — 55889.6	5.8	4.47
		NUPPI	22	55980.3 — 57038.4	2.9	2.44
J2017+0603	1.22	BON	50	55246.4 — 55871.7	1.7	2.34
		NUPPI	57	55879.7 — 57048.5	3.2	1.60
J2043+1711	1.19	BON	23	55425.0 — 55841.8	1.1	2.56
		NUPPI	22	55877.7 — 57029.6	3.2	2.62
J2214+3000	2.54	BON	98	55136.8 — 55856.8	2.0	2.82
		NUPPI	78	55819.9 — 56954.8	3.1	1.94
J2302+4442	2.57	BON	94	55150.8 — 55869.8	2.0	3.99
		NUPPI	93	55852.9 — 57047.6	3.3	2.19

Example timing residuals



Note: no artificial whitening! Only physical parameters: ra, dec, PM, PX, P, $\dot{P}$, and orbital parameters.

Proper motion and parallax measurements

Table 3. Proper motion and parallax measurements for the pulsars considered in this study. Quoted uncertainties on the measured parameters PMRA, PMDEC, and PX, are the 1σ statistical error bars from Tempo2. In the cases where the parallax was not measurable, we quote 2σ upper limits based on the radio timing data. For pulsars with previously reported proper motion or parallax values, we report these results and give the associated references. References: (1) – Hobbs et al. (2005), (2) – Burgay et al. (2006), (3) – Nice et al. (2005), (4) – Verbiest et al. (2009), (5) – Hotan et al. (2006), (6) – Ransom et al. (2011), (7) – Toscano et al. (1999), (8) – Bhalerao & Kulkarni (2011), (9) – Demorest et al. (2010), (10) – Espinoza et al. (2013), (11) – Ng et al. (2014), (12) – Guillemot et al. (2012)

Pulsar	PMRA (mas yr^{-1})		PMDEC (mas yr^{-1})		PMTOT (mas yr^{-1})		PX (mas)		Derived PX distance (kpc)		References
	This work	Prev.	This work	Prev.	This work	Prev.	This work	Prev.	This work	Prev.	
J0034−0534	7.9(8)	–	−9.9(17)	–	12.6(14)	31(9)	< 7.4	–	> 0.14	–	–, –, 1, –
J0340+4130	−0.59(16)	–	−3.81(34)	–	3.85(33)	–	< 1.3	–	> 0.77	–	–, –, –, –
J0610−2100	9.21(6)	7(3)	16.73(8)	11(3)	19.10(8)	13(3)	< 1.3	–	> 0.77	–	2, 2, 2, –
J0614−3329	0.58(9)	–	−1.92(12)	–	2.00(11)	–	< 2.2	–	> 0.45	–	–, –, –, –
J0740+6620	−6(11)	–	−32(4)	–	32.6(41)	–	<11.7	–	> 0.09	–	–, –, –, –
J0751+1807	−2.71(7)	–	−13.2(4)	–	13.51(35)	6.0(20)	0.66(15)	1.6(8)	1.51(35)	0.62(31)	–, –, 3, 3
J0931−1902	−1.1(8)	–	−4.4(12)	–	4.6(12)	–	< 5.0	–	> 0.20	–	–, –, –, –
J1024−0719	−35.247(23)	−35.3(2)	−48.14(5)	−48.2(3)	59.67(4)	59.7(3)	0.89(14)	1.9(8)	1.13(18)	0.53(22)	4, 4, 4, 5
J1231−1411	−62.03(26)	−100(20)	6.2(5)	−30(40)	62.34(26)	104(22)	< 1.8	–	> 0.56	–	6, 6, 6, –
J1455−3330	7.88(5)	5(6)	−1.90(12)	24(12)	8.11(5)	25(12)	0.99(22)	–	1.01(22)	–	7, 7, 7, –
J1614−2230	3.87(12)	–	−32.3(7)	–	32.5(6)	32(3)	1.30(9)	0.5(6)	0.77(5)	2.0(24)	–, –, 8, 9
J1730−2304	20.7(4)	20.27(6)	8.3(83)	–	22.3(31)	–	1.19(27)	–	0.84(19)	–	4, –, –, –
J1741+1351	−8.93(8)	–	−7.43(17)	–	11.62(13)	11.71(1)	< 1.2	0.93(4)	> 0.83	1.08(5)	–, –, 10, 10
J1811−2405	0.65(14)	0.53(13)	−9.1(52)	–	9.2(51)	–	< 0.4	–	> 2.50	–	11, –, –, –
J1823−3021A	0.31(24)	–	−8.2(17)	–	8.2(17)	–	< 7.0	–	> 0.14	–	–, –, –, –
J2017+0603	2.35(8)	–	0.17(16)	–	2.35(8)	–	1.2(5)	–	0.9(4)	–	–, –, –, –
J2043+1711	−6.12(27)	−7(2)	−11.2(5)	−11(2)	12.8(4)	13(2)	< 4.4	–	> 0.23	–	12, 12, 12, –
J2214+3000	20.90(11)	–	−1.55(15)	–	20.96(11)	–	1.7(9)	–	0.60(31)	–	–, –, –, –
J2302+4442	−0.05(13)	–	−5.85(12)	–	5.85(12)	–	< 2.5	–	> 0.40	–	–, –, –, –

New PM estimates for many northern MSPs, new PX distances for 4 ⇒ improved $\dot{E}$ and L_γ constraints.

(Pulsar parallax database: http://www.astro.cornell.edu/research/parallax/ — 70 as of Feb 2016)

A few interesting cases:

- J0610-2100: the new PM estimate leads to $L_\gamma/\dot{E}$ > 200! Distance very likely overestimated.
- J1024-0719: see next page.

J1024-0719

J1024-0719: PM and d very accurately known, but $\dot{E}_{int} < 0$!

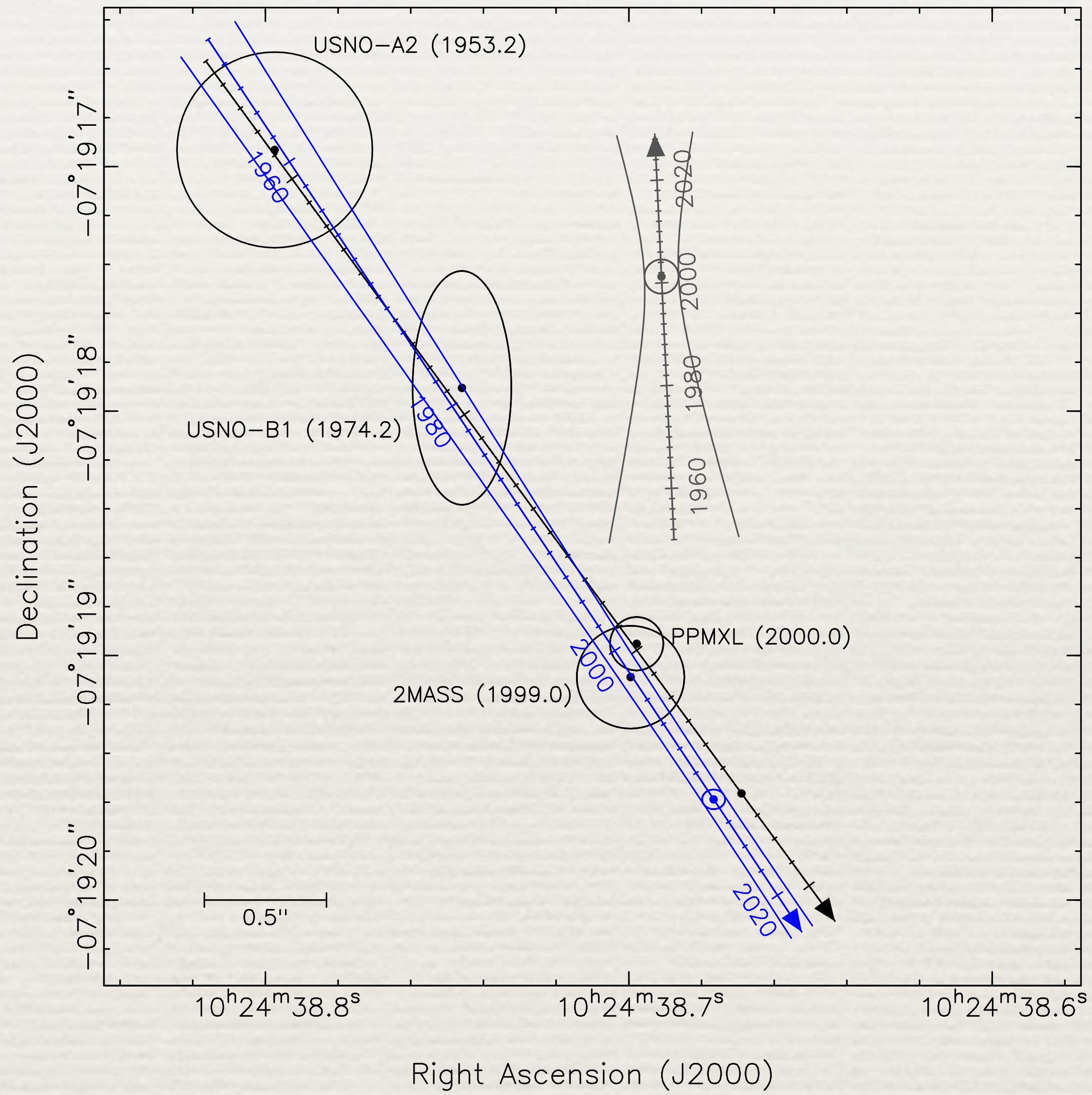
Guillemot et al. (2016): P0, P1, P2 detected with ~9 yrs of timing.

Bassa et al. (2016): P0… P4 with ~20 yrs of timing!

Acceleration along the line of sight, caused by the presence of a nearby object?

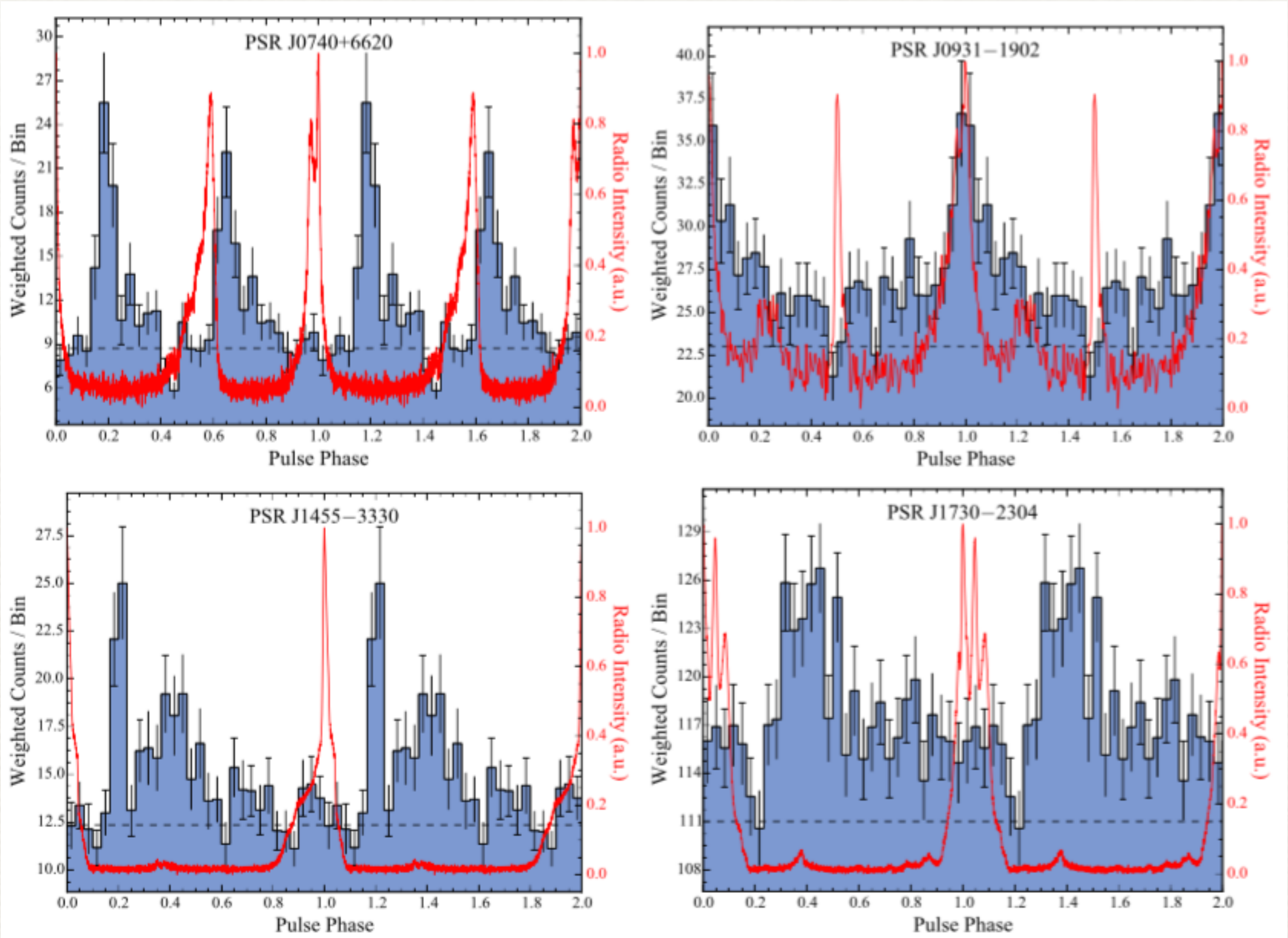
Bassa et al. (2016): J1024-0719 and 2MASS J10243869−0719190 form a common proper motion pair and are gravitationally bound.

Timing measurements suggest a wide (P_b > 200 yr) orbit.



From Bassa et al., accepted to MNRAS (2016)

Four new gamma-ray MSPs



Faint gamma-ray pulsations from four MSPs detected using ~7 years of Pass 8 LAT data, and the timing solutions presented earlier.

« Standard » spectral and light curve properties.

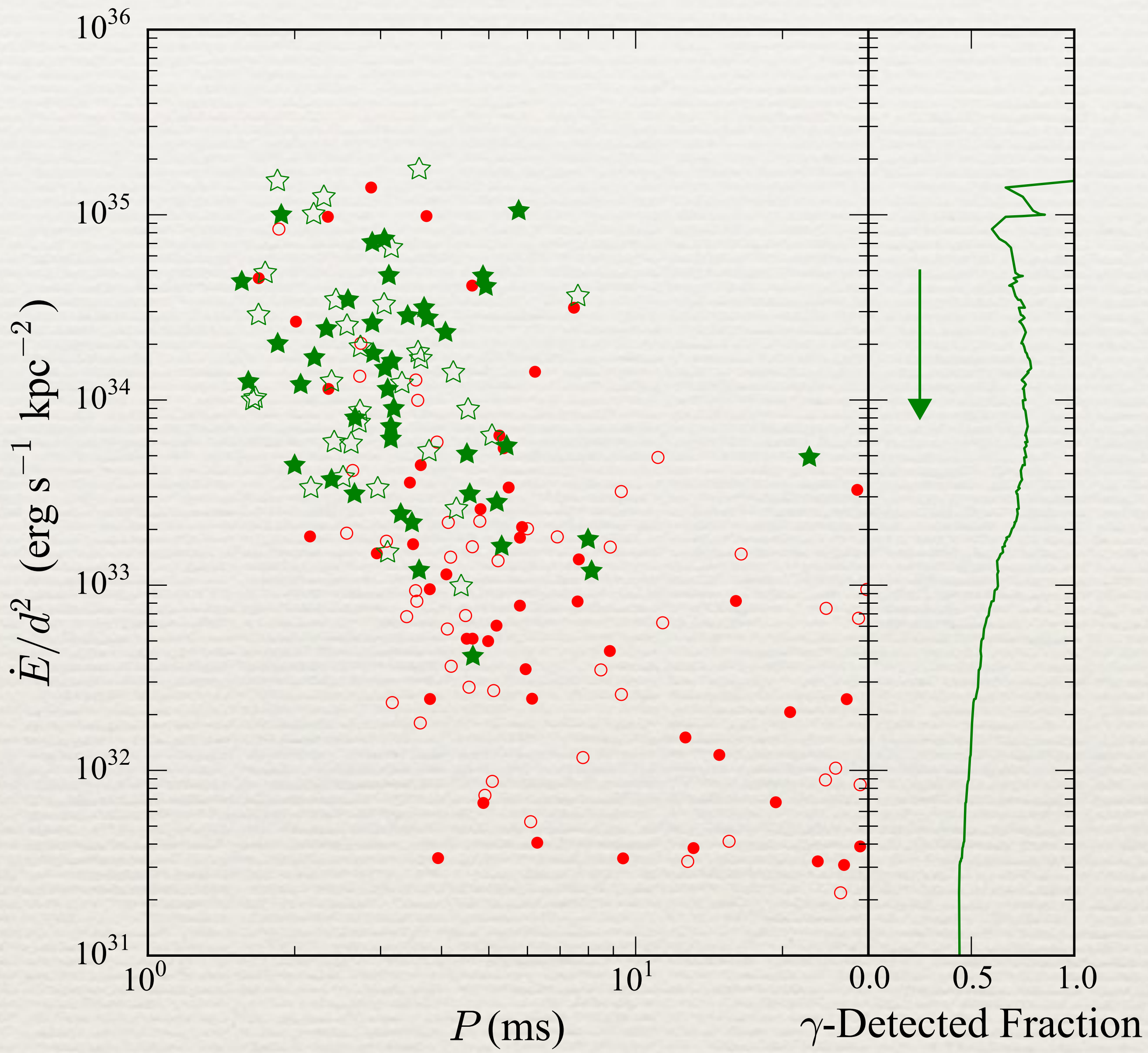
MSP gamma-ray detectability

$\dot{E}/d^2$ versus P for MSPs in the Galactic disk (adding gamma-ray MSPs in GCs, PSR J1823A and J1824A).

A large majority of energetic and nearby MSPs are seen in gamma rays: 75% above $\dot{E}/d^2$ = 5e33 erg/s/kpc^2!

Confirmation that the gamma-ray detectability of MSPs depends crucially on $\dot{E}$ (and the distance).

Non-detections due to unfavorable beaming geometries? (Guillemot & Tauris, 2014)

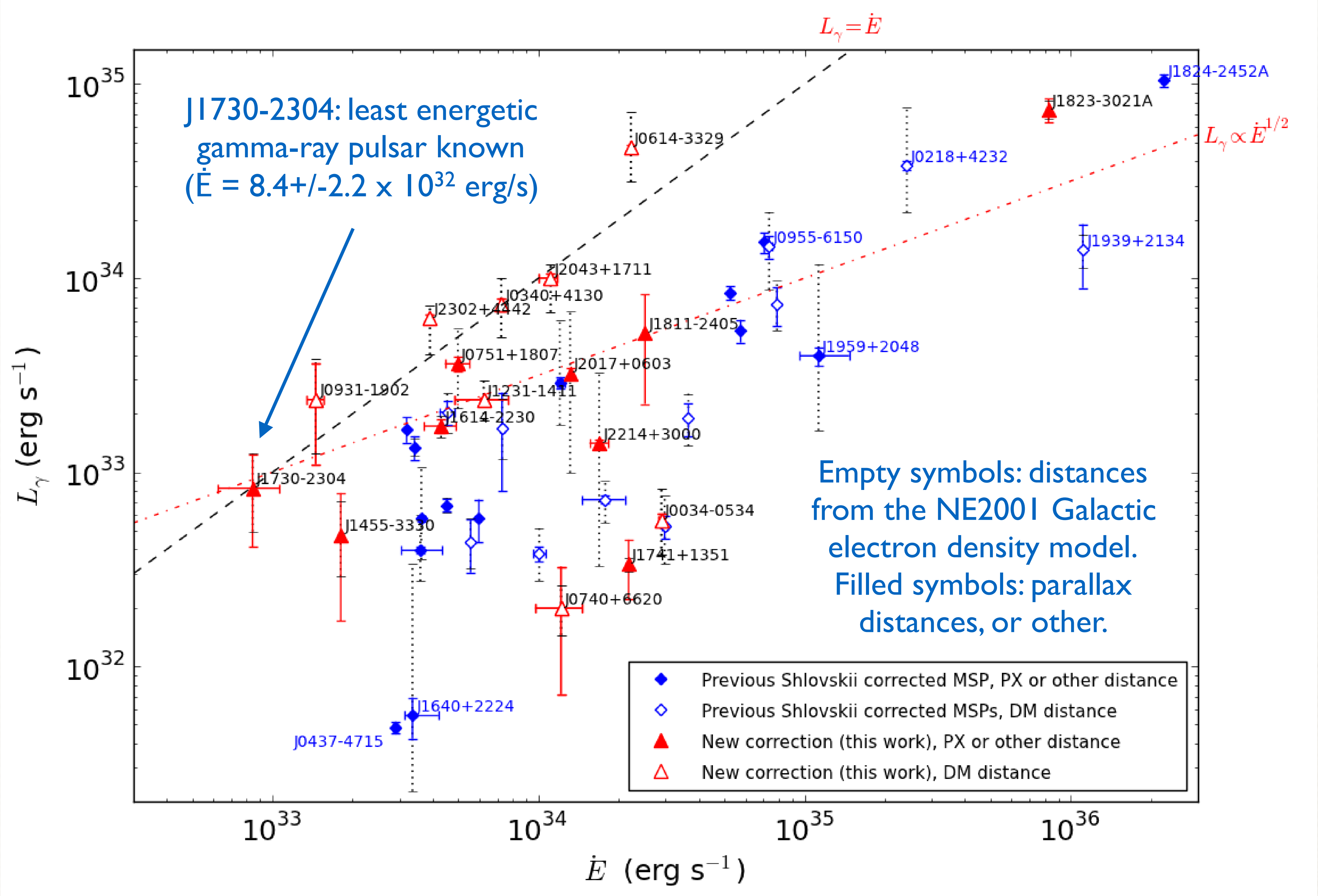


Green stars: gamma-ray-detected MSPs.

Red circles: undetected ones.

Filled symbols: Shklovskii-corrected.

Spin-down power vs luminosity relationship



Empirical deathline: $\dot{E}$ ~ 1e33 erg/s or lower. Lack of clear correlation between $\dot{E}$ and L_γ!

Varying moments of inertia, emission geometries and more realistic energy budget estimates could mitigate the lack of apparent correlation.

Gamma-ray MSP deathline(s)

Various studies have shown that MSPs could contribute to the diffuse gamma-ray emission in the Milky Way, and to the galactic center excess.

(e.g., Calore et al. 2014, Brandt & Kocsis 2015, Petrovic et al. 2015, etc.)

These studies indicate that gamma-ray flux estimates from MSP populations crucially depend on the maximum luminosity of MSPs.

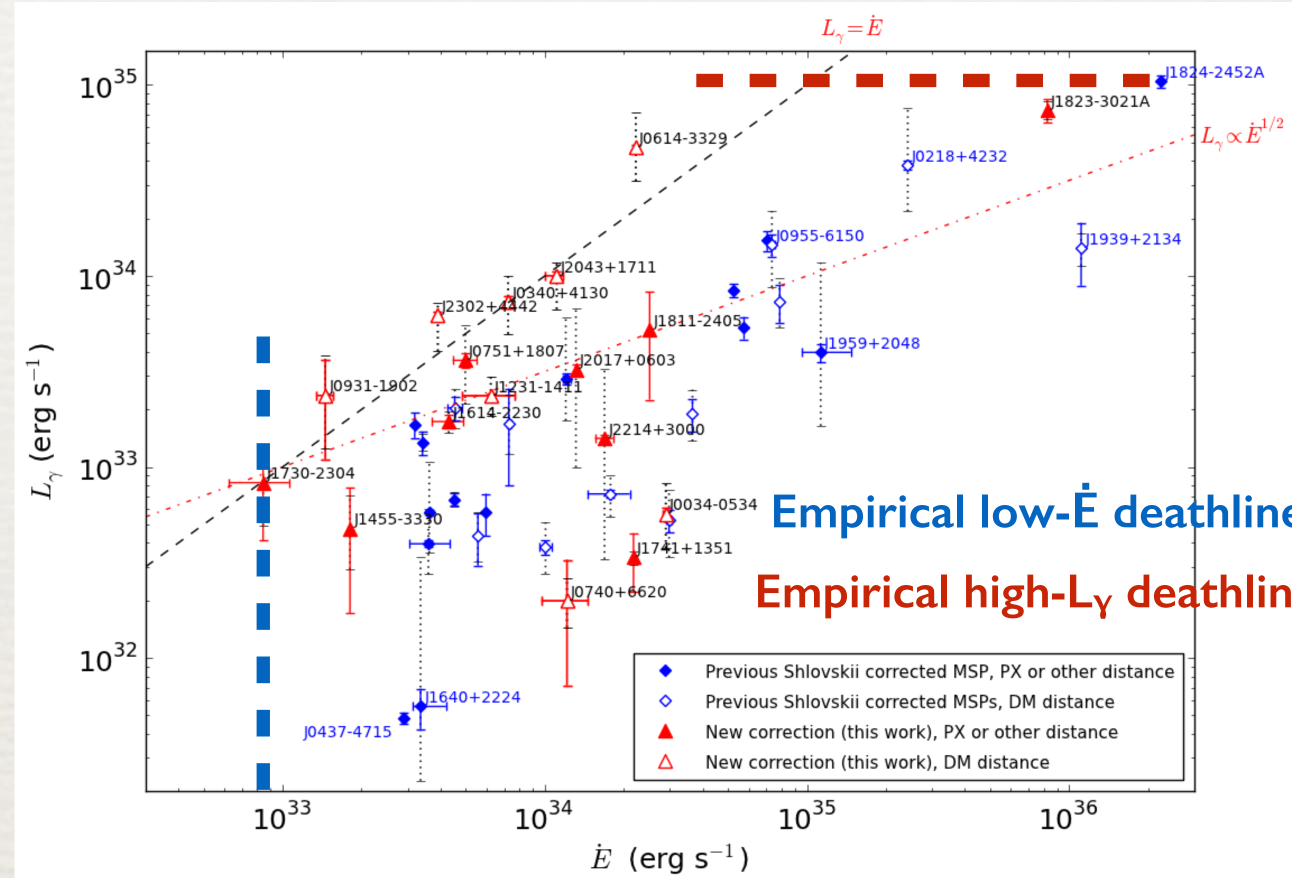
(not so much on the low luminosities)

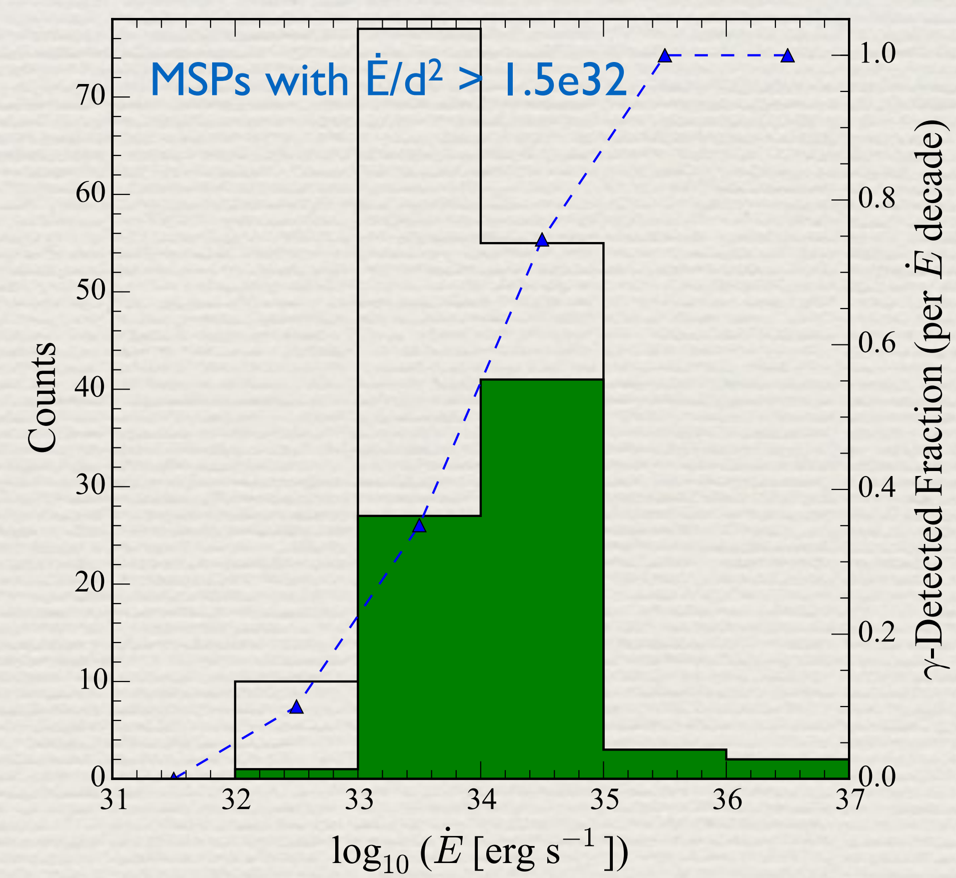
High-L_γ « deathline » poorly known!

Our study: low-$\dot{E}$ deathline ~ 1e33 erg/s. Most MSP $\dot{E}$ values around that threshold!

Also: uncertainties in d, f_Ω, moment of inertia, $\dot{E}$ calculation, L_γ vs $\dot{E}$…

Current results (in favor or against the MSP scenario) to be taken with a grain of salt.





Summary and conclusions

- Analysis of Nançay/Westerbork timing data yielded new proper motion estimates for a selection of northern radio and gamma-ray MSPs, and new parallax distances for some of them.

- Improved spin-down power and gamma-ray luminosity estimates.

- PSRs J0740+6620, J0931-1902, J1455-3330, and J1730-2304 are gamma-ray pulsars.

- PSR J1730-2304 is now the least energetic gamma-ray pulsar known. Empirical deathline for gamma-ray MSP emission slightly decreased. MSP population contributes more to diffuse gamma-ray emission than previously thought.

- Lack of clear correlation between $\dot{E}$ and L_γ in the gamma-ray MSP population.

Thank you for your attention!