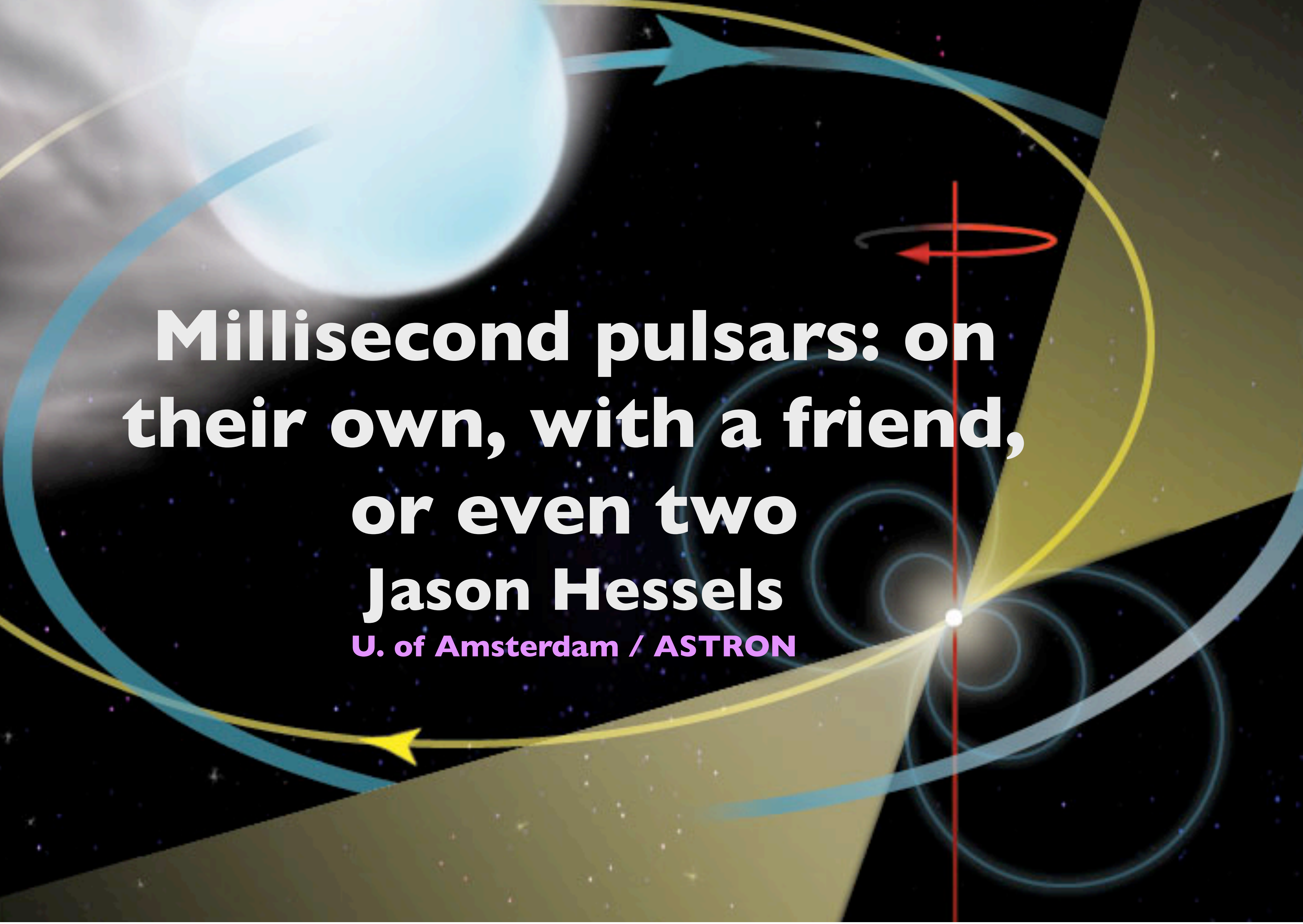


Millisecond pulsars: on their own, with a friend, or even two

Jason Hessels

U. of Amsterdam / ASTRON

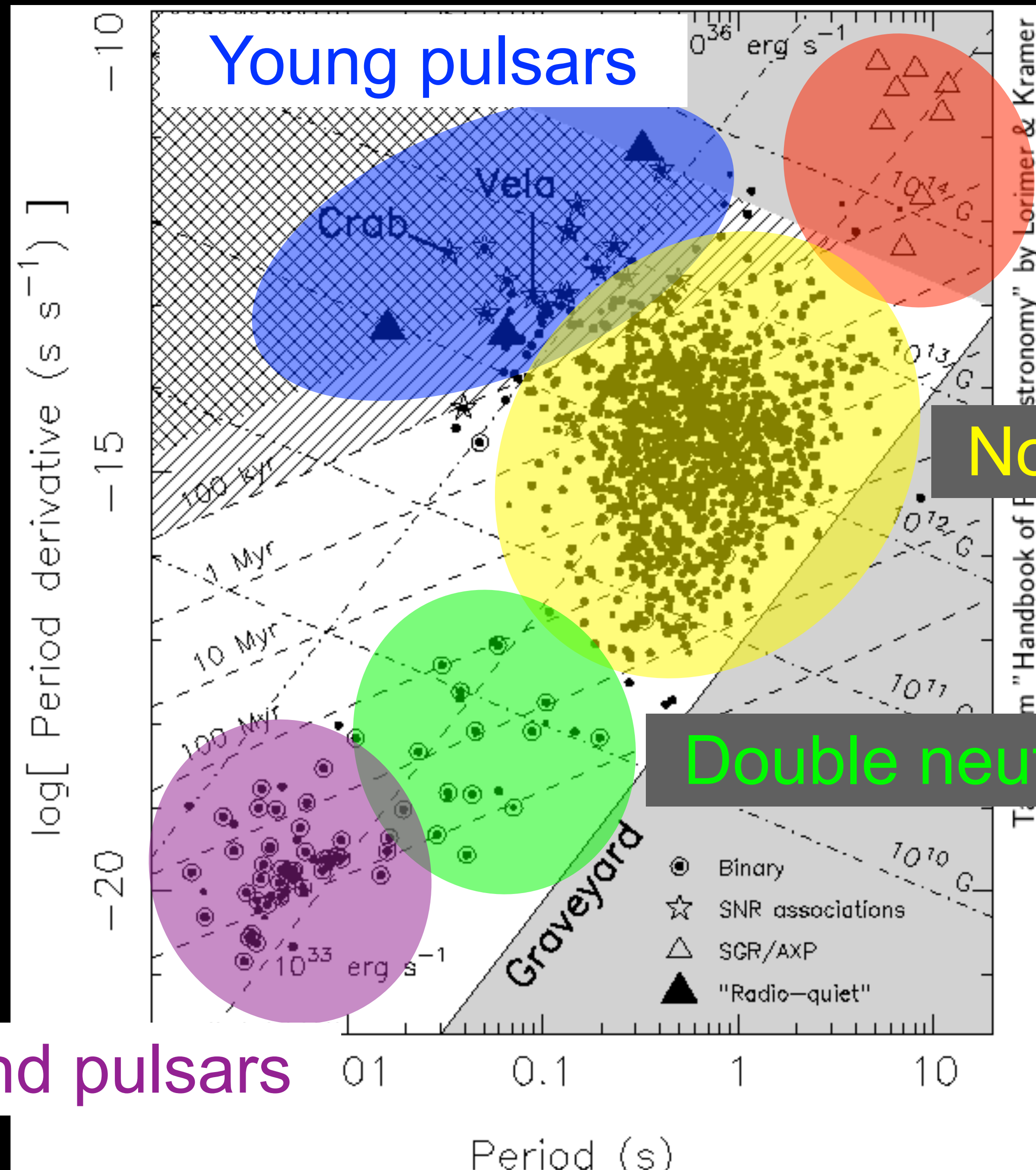
Outline

MSP = Millisecond Pulsar

- MSPs in the context of other pulsars
- Timing MSPs
- MSPs across the EM spectrum
- Pulsar triple system
- “Spiders” (black widows & redbacks)

MSPs in the context of other pulsars

MSP Formation



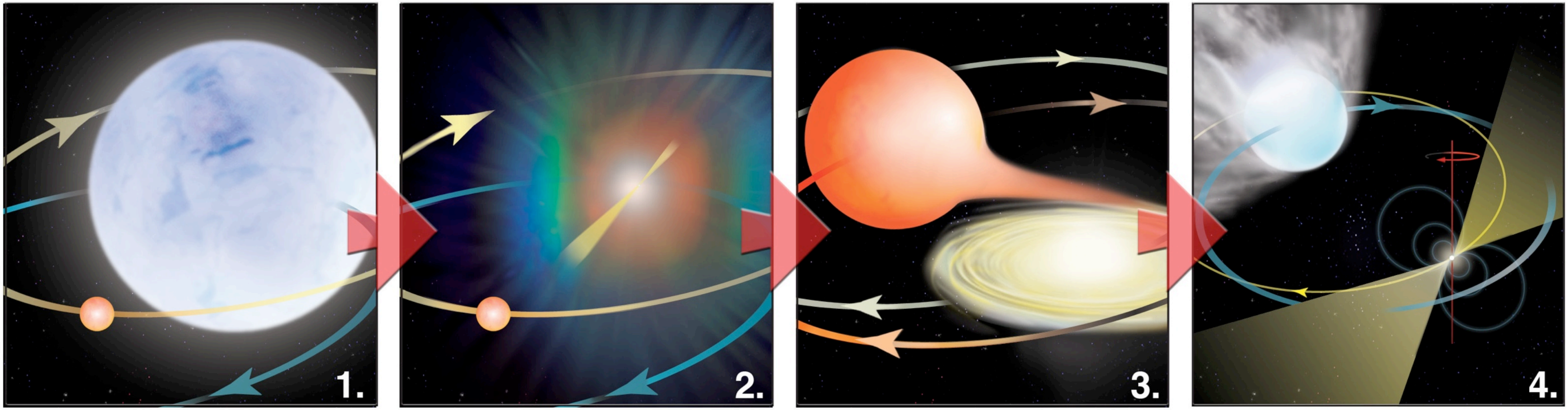
Lorimer & Kramer

See talk by:
Hermsen
(there's no `normal' when it comes to pulsars)

See talks by:
van Leeuwen
Berezina

See talks after coffee break

MSP Formation



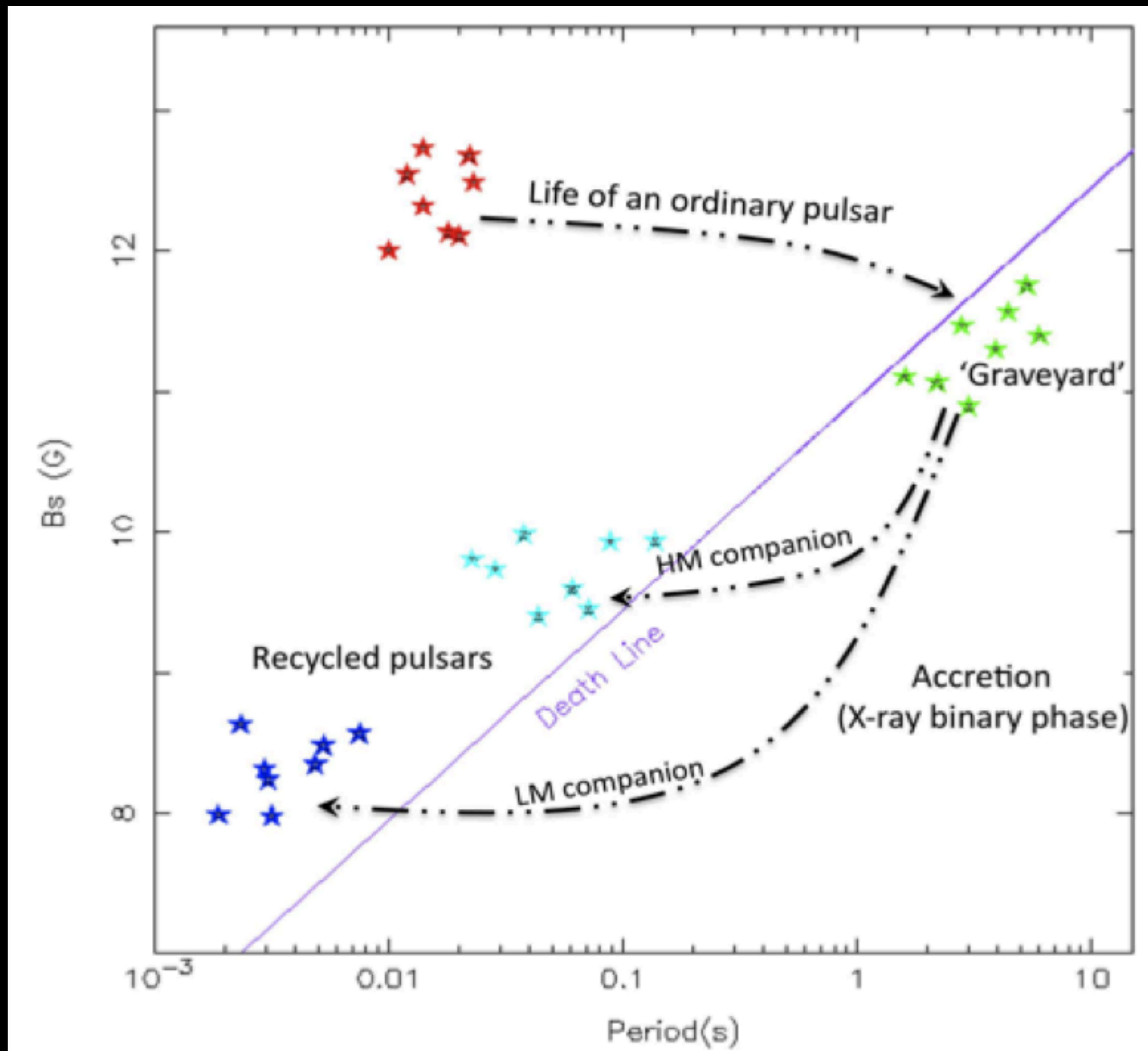
Saxton, NRAO

LMXB (some IMXB) Radio (some also g-ray)

Alpar, Cheng, Ruderman & Shaham1982

Rhadakrishnan & Srinivasan 1982

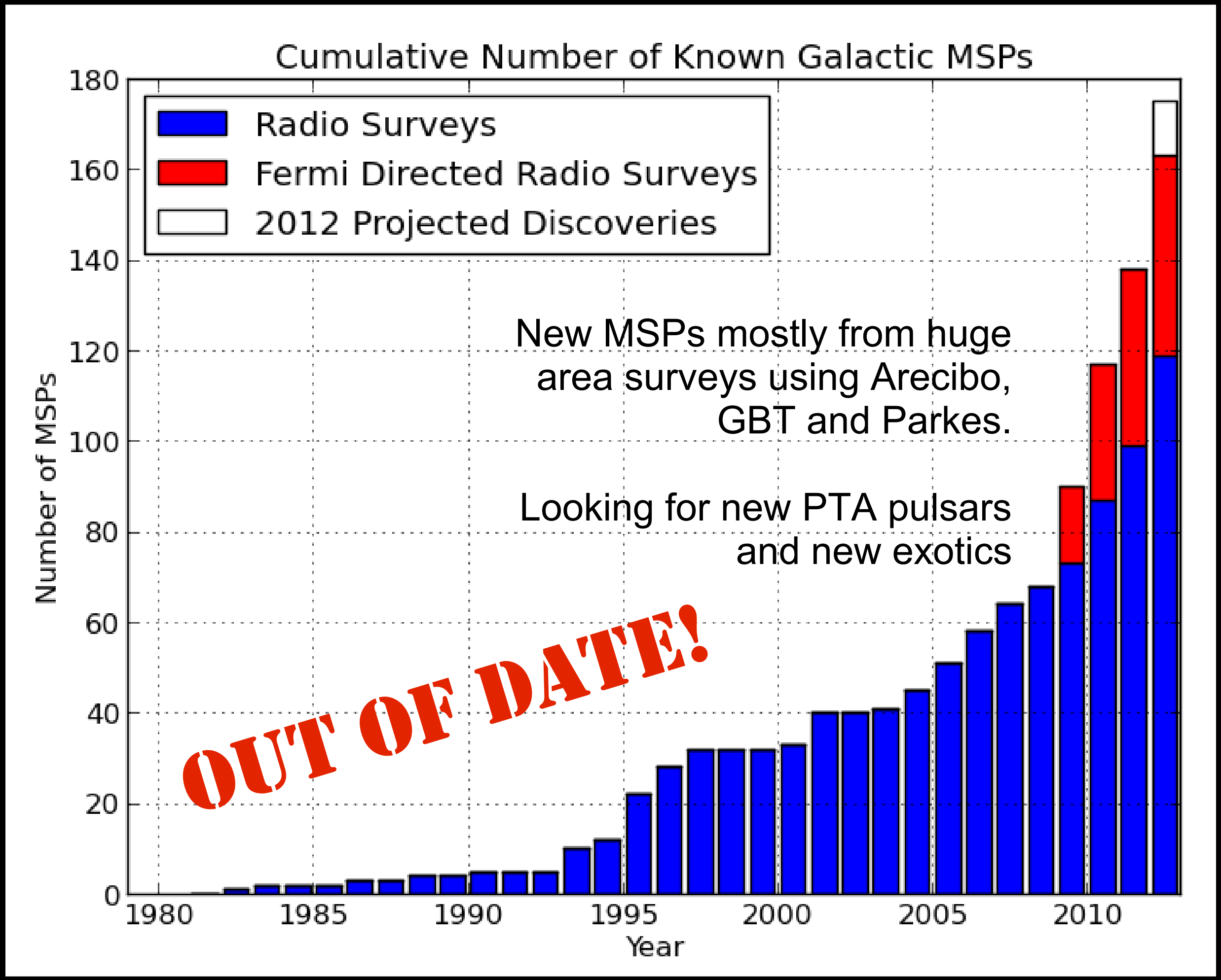
MSP Formation



Stairs

Afternoon spoiler: this simple picture is getting complicated!

Explosion in Discovery Rate



Ransom

43 Fermi targeted
27 HTRU (Parkes)
17 PALFA (Arecibo)
16 Drift/CC (GBT)

103 total
in 4 years

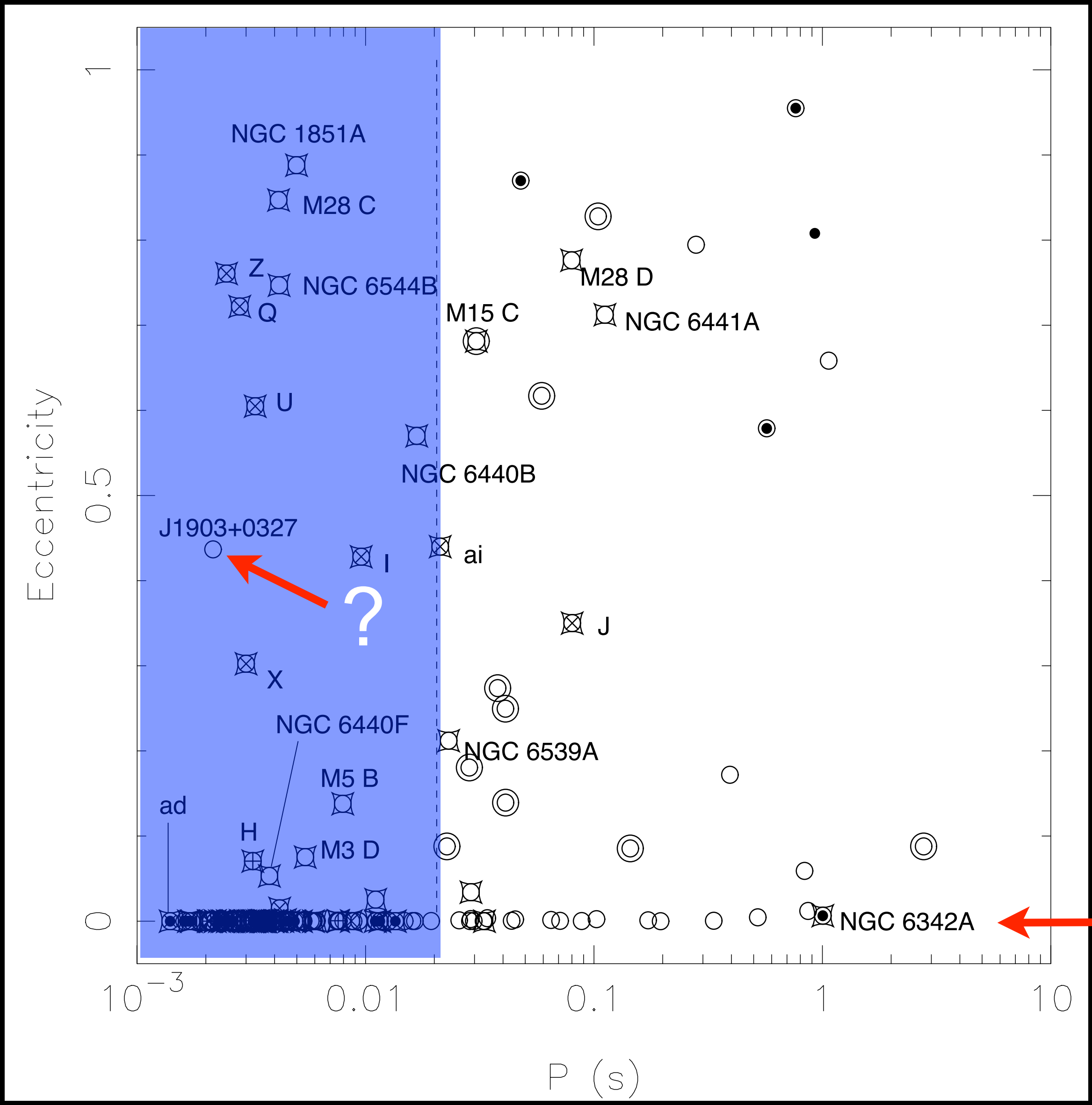
More Galactic MSPs than in GCs for the first time in a decade!

MSP Population

> 80% in binary; orbital eccentricity normally very small

(this is the "Binaries" session after all)

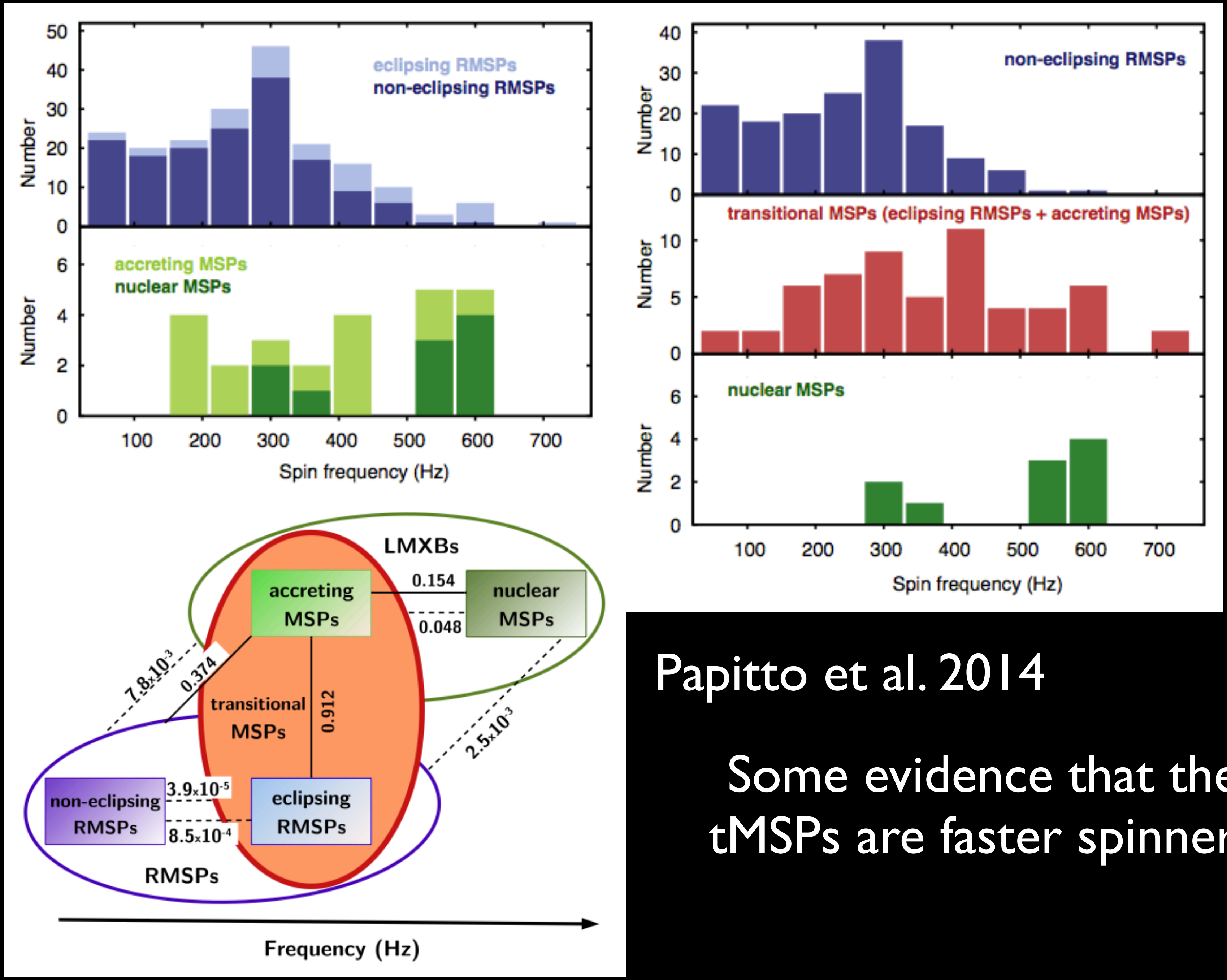
Freire (http://www.naic.edu/~pfreire/GCpsr.html)



- Lots of eccentric systems recently found in GCs.

Eccentricity still easily measurable

Connecting populations



Papitto et al. 2014

Some evidence that the tMSPs are faster spinners

The MSP Menagerie

See talk by Tauris

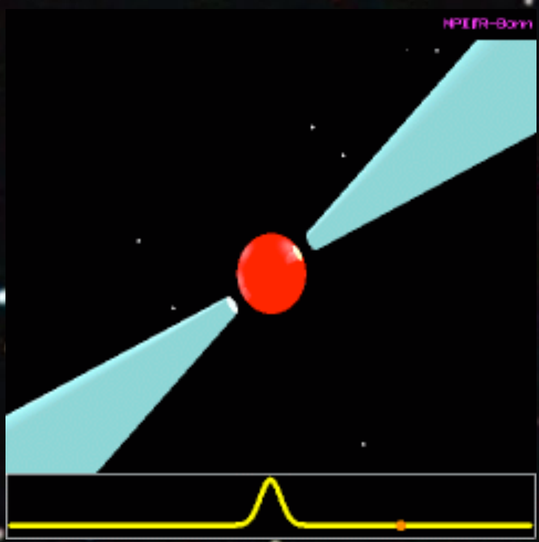
- Helium white dwarf.
- Carbon-oxygen white dwarf.
- Jupiter-mass companion (e.g. the "diamond planet").
- Bloated, post-main-sequence, (*non*)-degenerate companion (0.01 - 0.4 MSun).
- Solar-mass main sequence star (e.g. J1903+0327)
- Earth-mass planetary companions (e.g. B1257+12).
- Hierarchical triple systems (e.g. J0337+1715).
- Highly eccentric systems in GCs (e.g. J0514-4002 in NGC1851, e = 0.9!).
- MSPs in relativistic systems good for gravity tests.

The list is likely to continue increasing in diversity (MSP-MSP?; MSP-BH?; sub-MSP?)

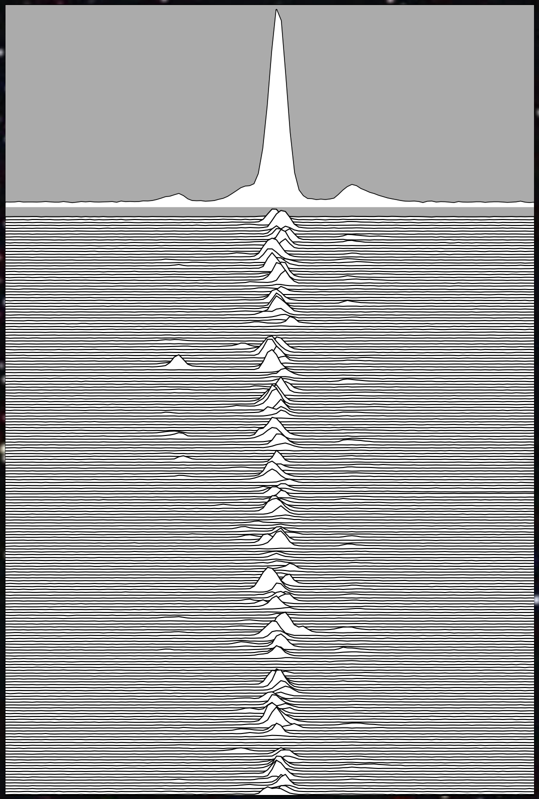
Timing MSPs

“Pulsar Timing”

Using pulsars as precision clocks



Record pulses



Average many pulses together

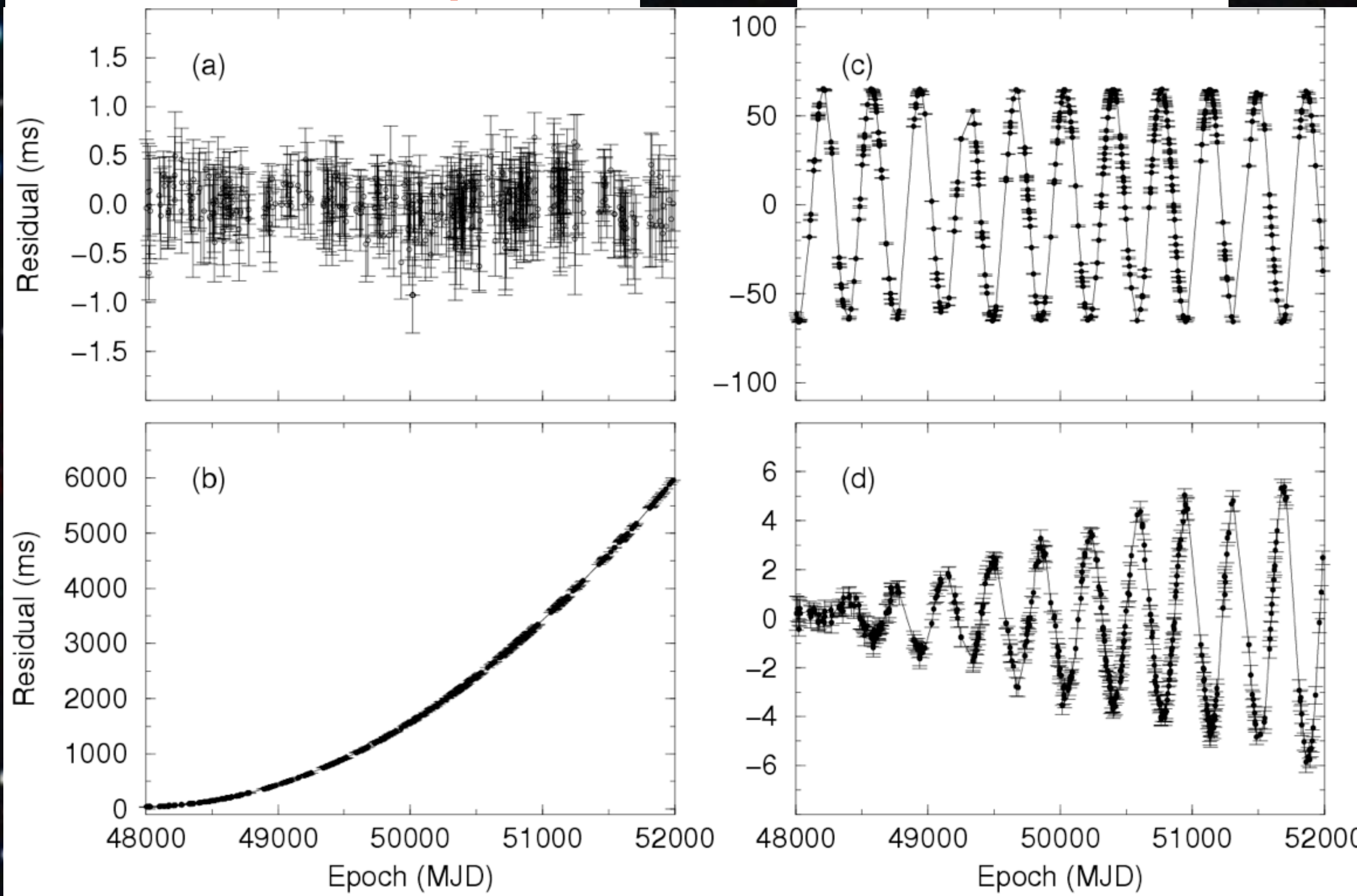
54255.1231254524233
54255.2643443523453
54255.3123524545899
54255.3513745623467
54255.4418456543355
54255.5001234234688

Measure the “times of arrival”

What can this teach us

Model is complete?

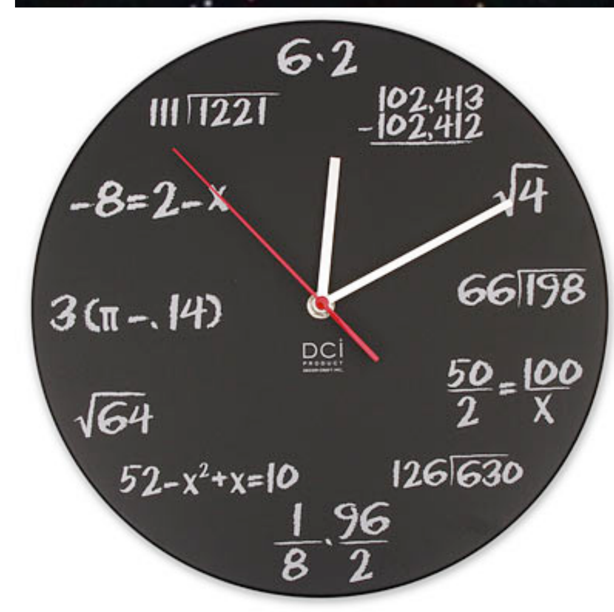
Position is wrong



Lorimer & Kramer

Pulsar spinning down faster than in model

Position is changing with time



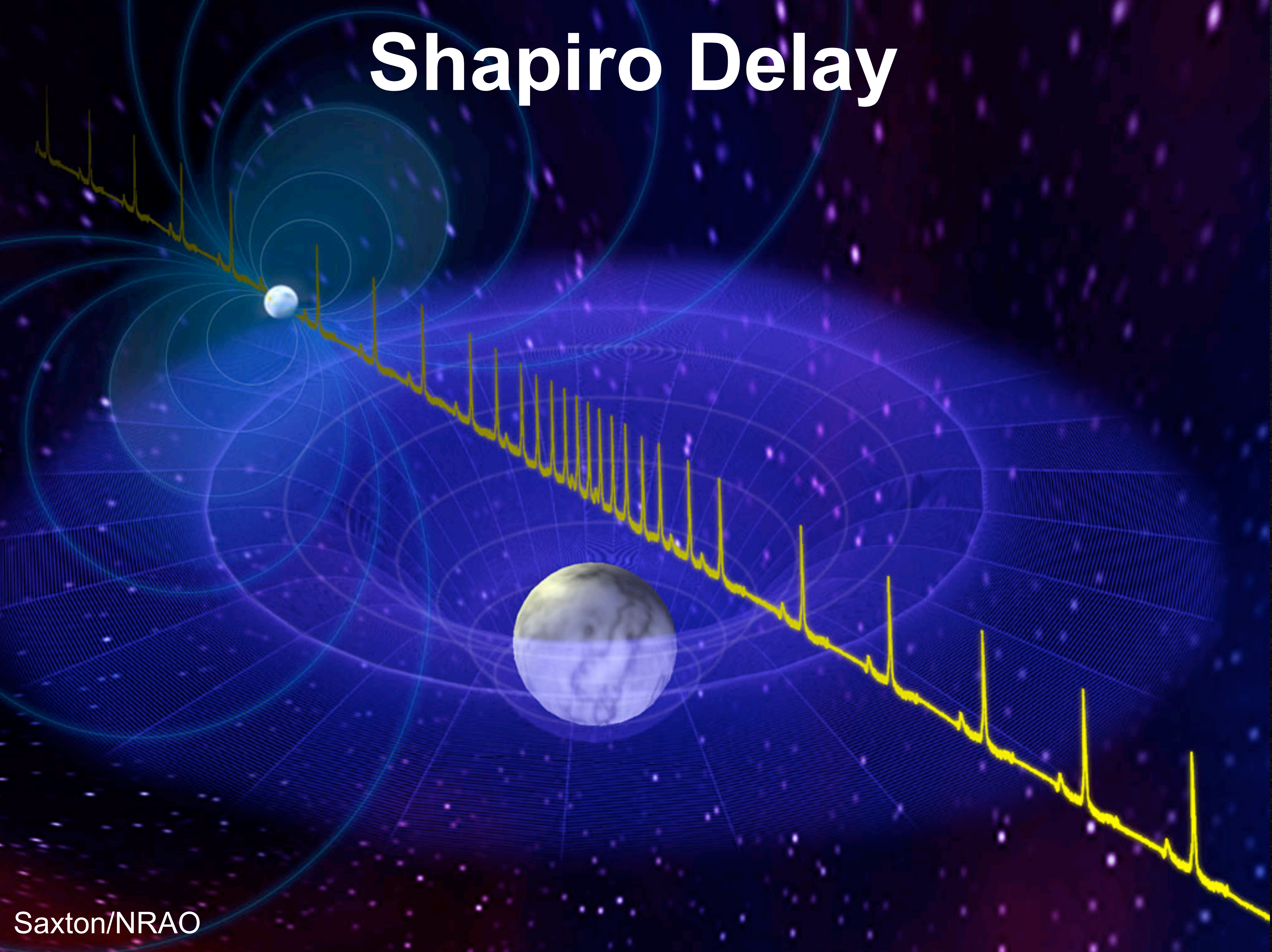
Account for each pulse; over years!

PSR J1012+5307:

P = 0.005255749014115410
+/- 0.000000000000000015s

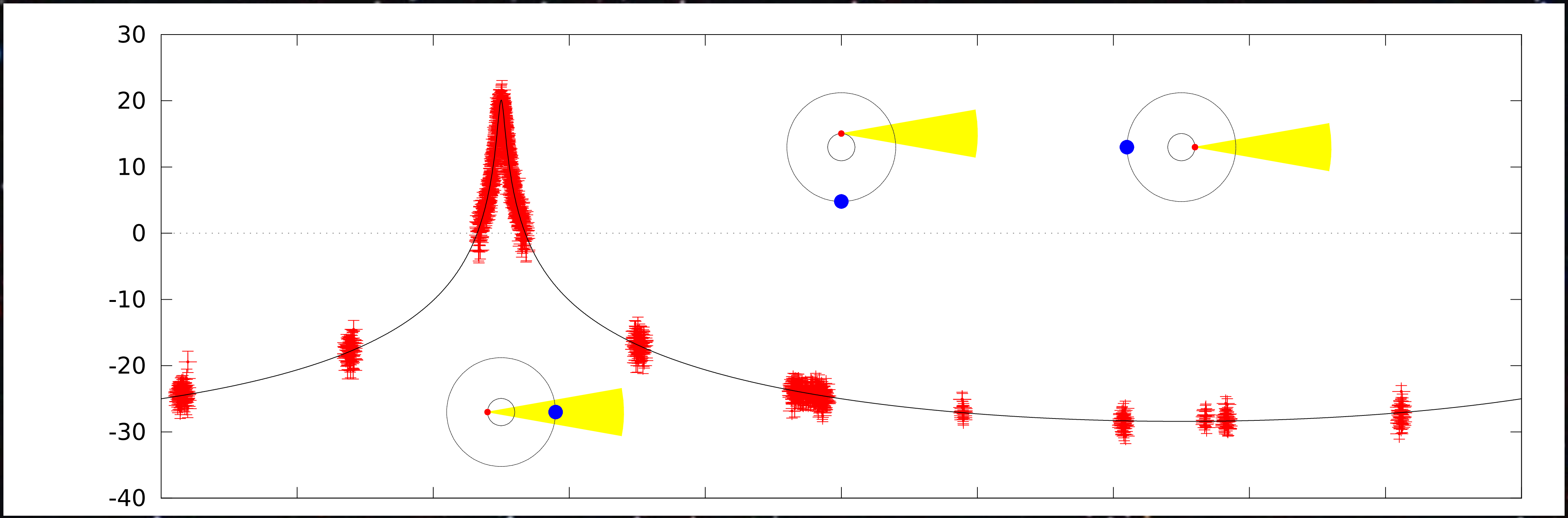
> 100 billion pulses in the last 15 years, and not a single rotation missed

Shapiro Delay



Saxton/NRAO

Shapiro Delay

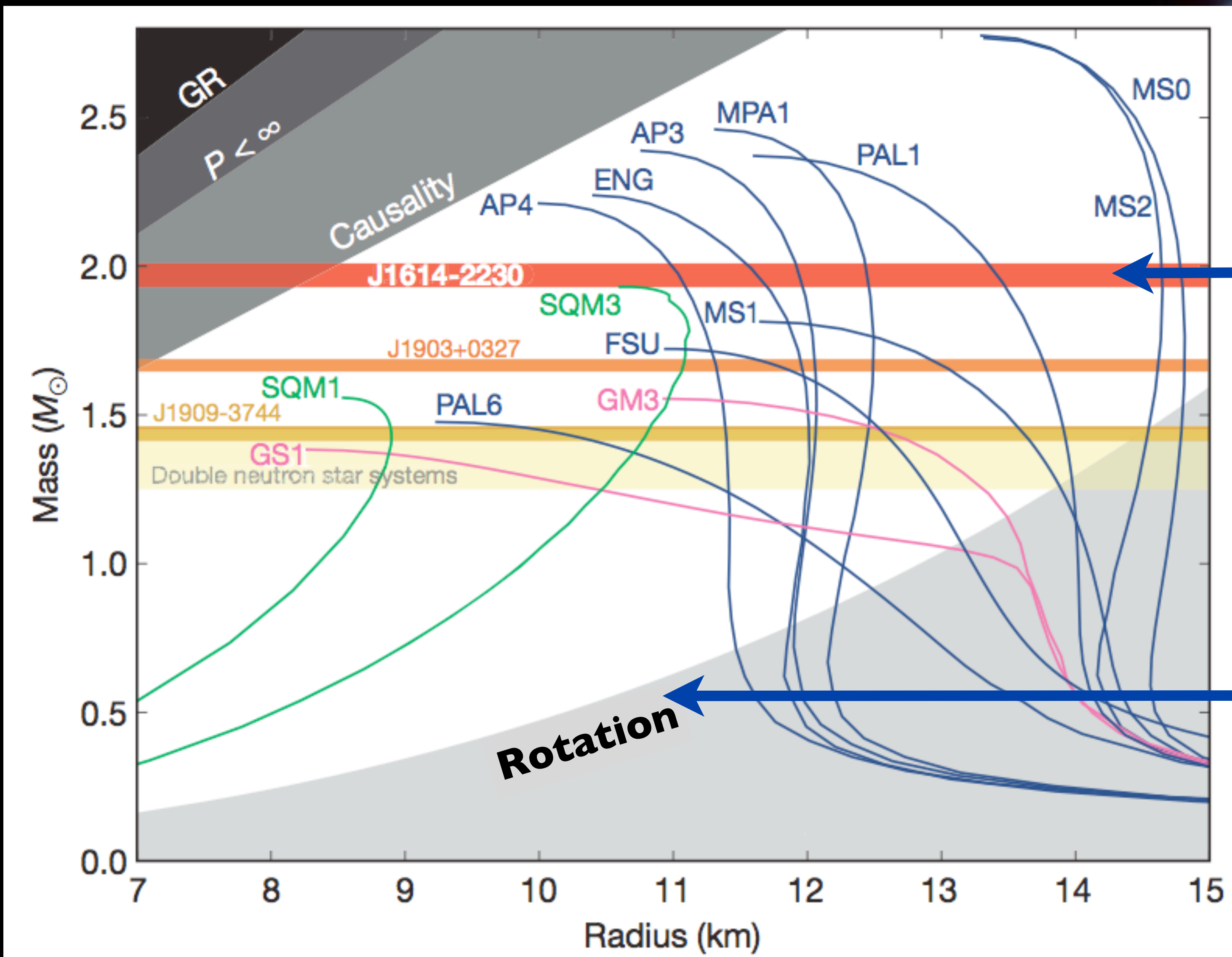


Demorest et al. 2010

Ultra-dense matter

See talk yesterday by Watts

Neutron star equation-of-state



2MSun Pulsar

Demorest, Pennucci, Ransom, Roberts & Hessels 2010, *Nature, 467, 1081*

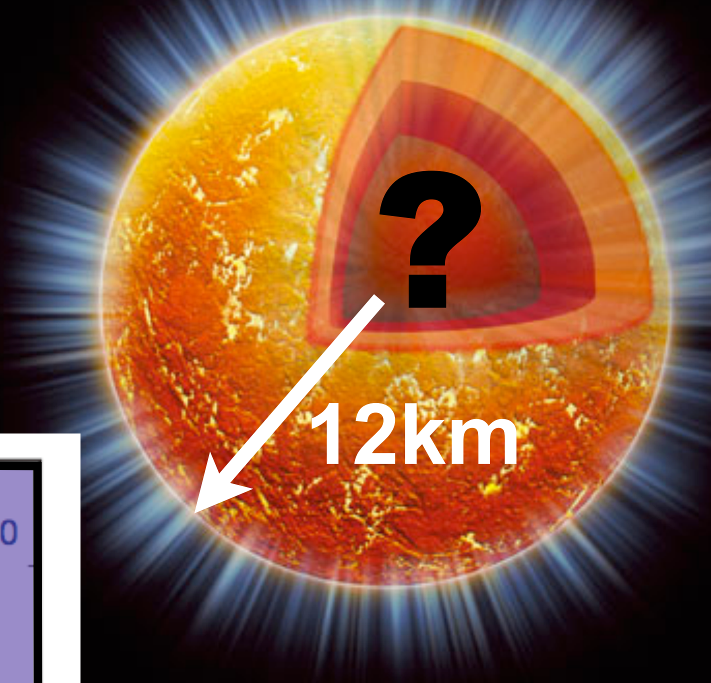
716Hz Pulsar

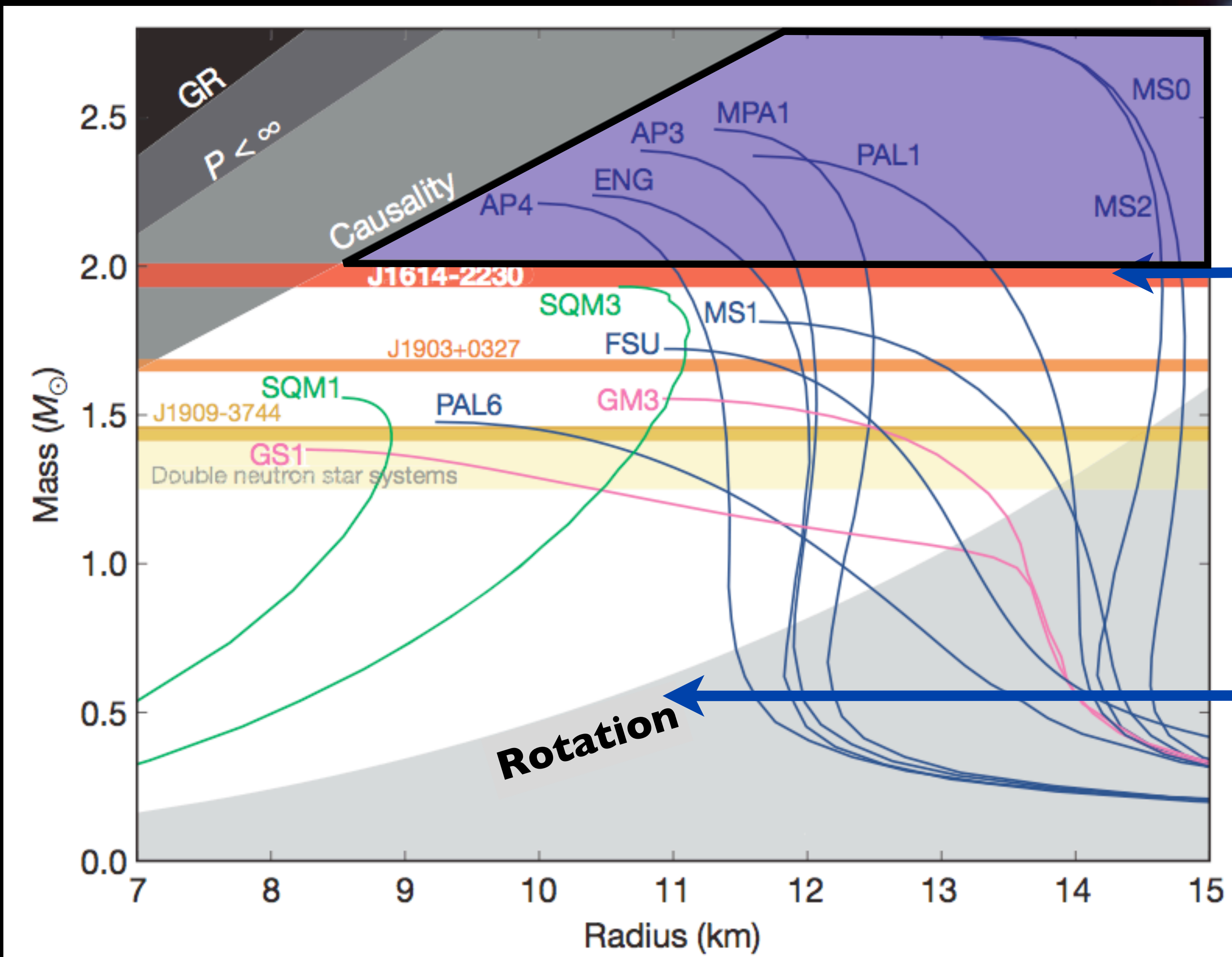
Hessels et al. 2006, *Science, 311, 1901*

Ultra-dense matter

See talk yesterday by Watts

Neutron star equation-of-state





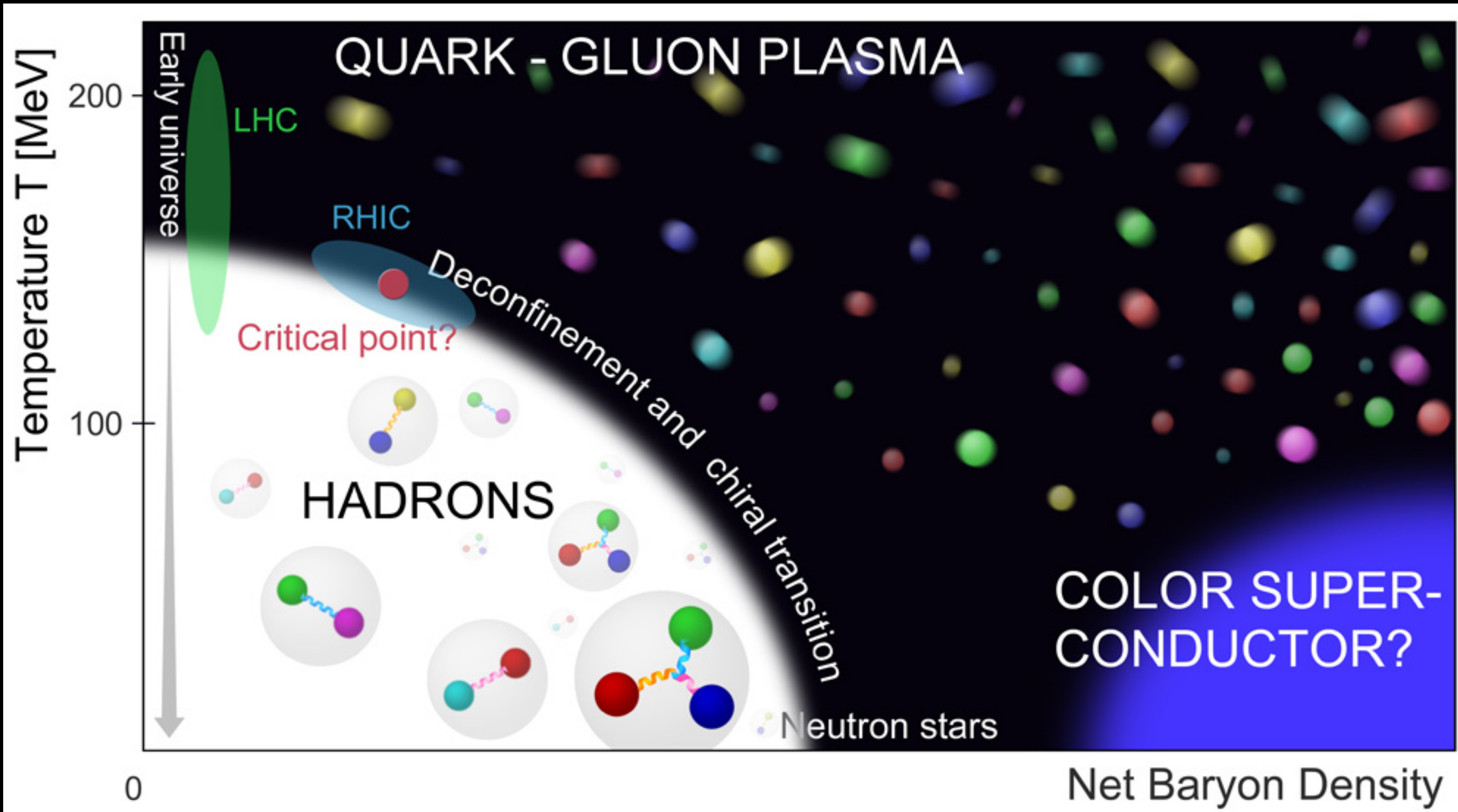
2MSun Pulsar

Demorest, Pennucci, Ransom, Roberts & Hessels 2010, *Nature, 467, 1081*

716Hz Pulsar

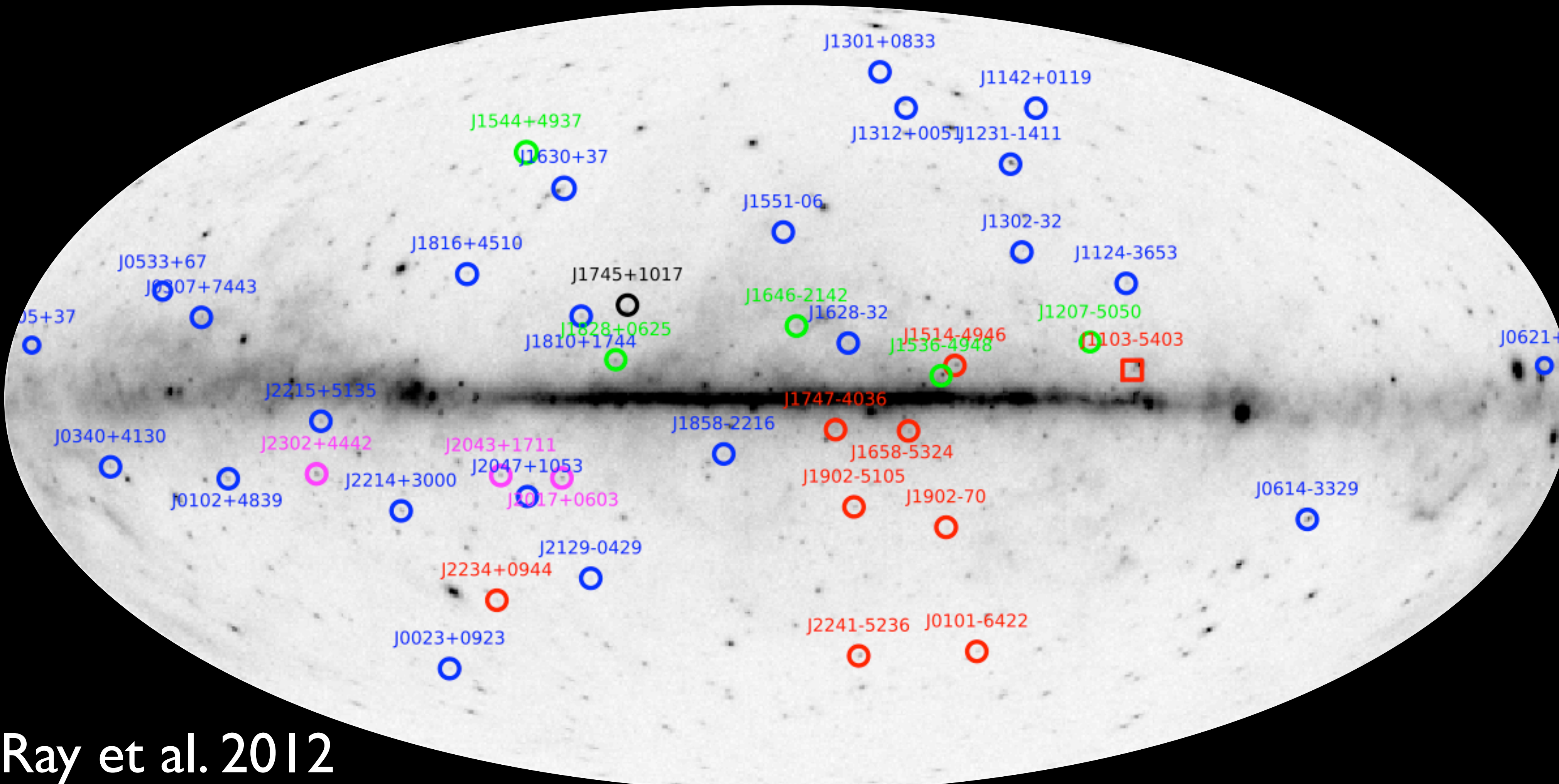
Hessels et al. 2006, *Science, 311, 1901*

QCD phase diagram



MSPs across the EM spectrum

Gamma-selected radio MSPs



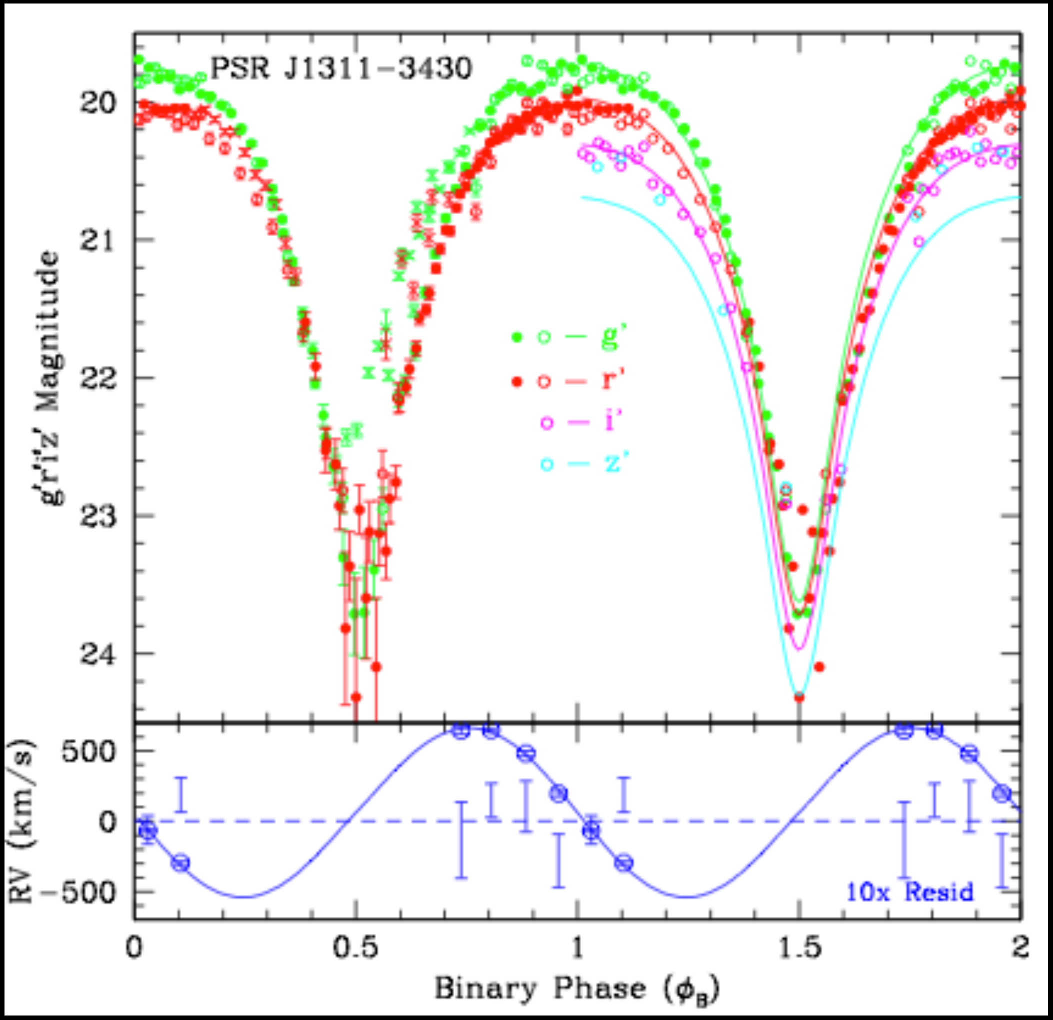
Ray et al. 2012

>60 as of the latest count!

Is gamma-ray emission dominated by pulsations?

(Almost) radio quiet MSPs

PSR J1311-3440, see also J2339-0533 (Romani et al.)

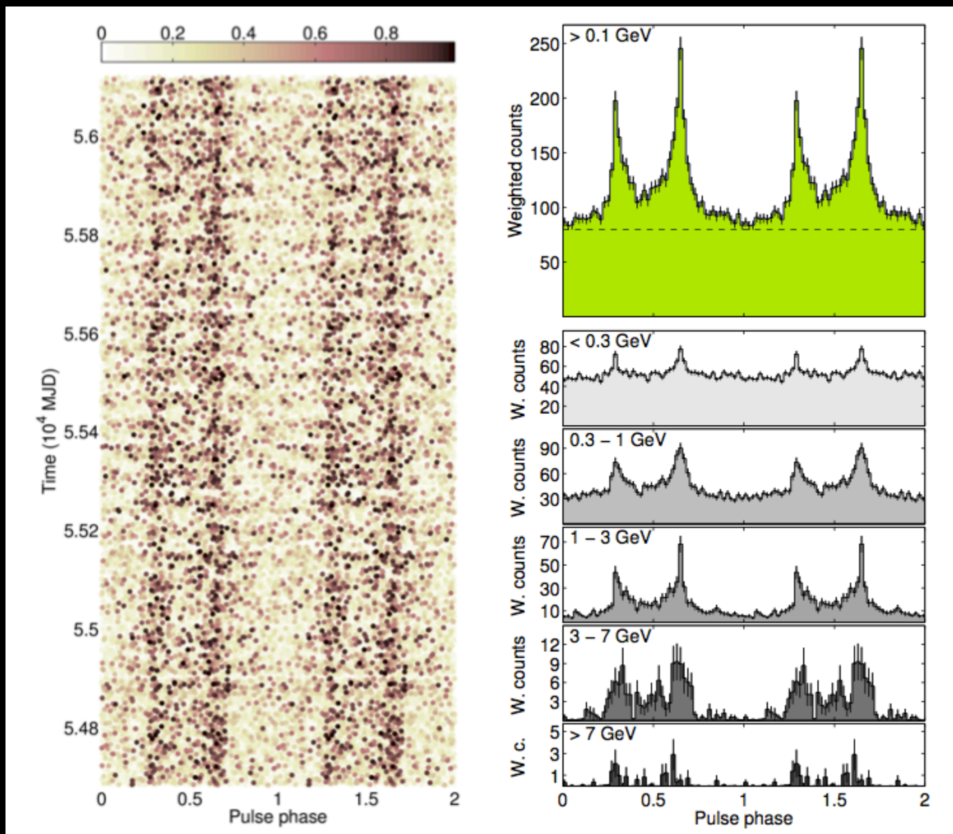


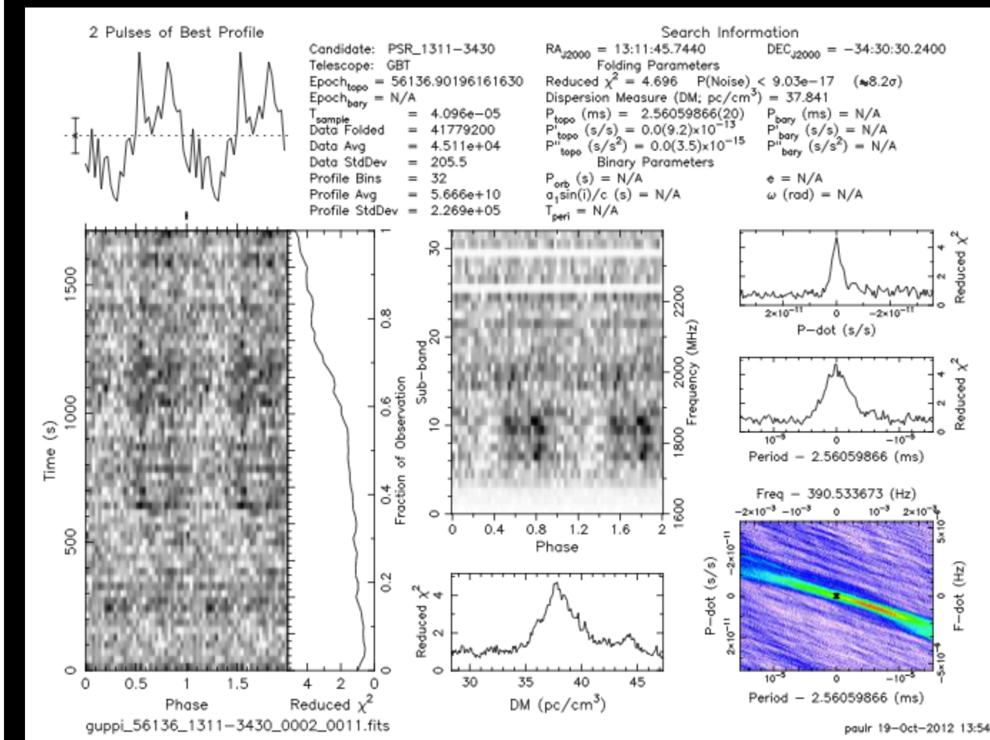
Romani et al. 2012

Discovery of “black widow” system through its optical companion

(Almost) radio quiet MSPs

Pletsch et al. 2012



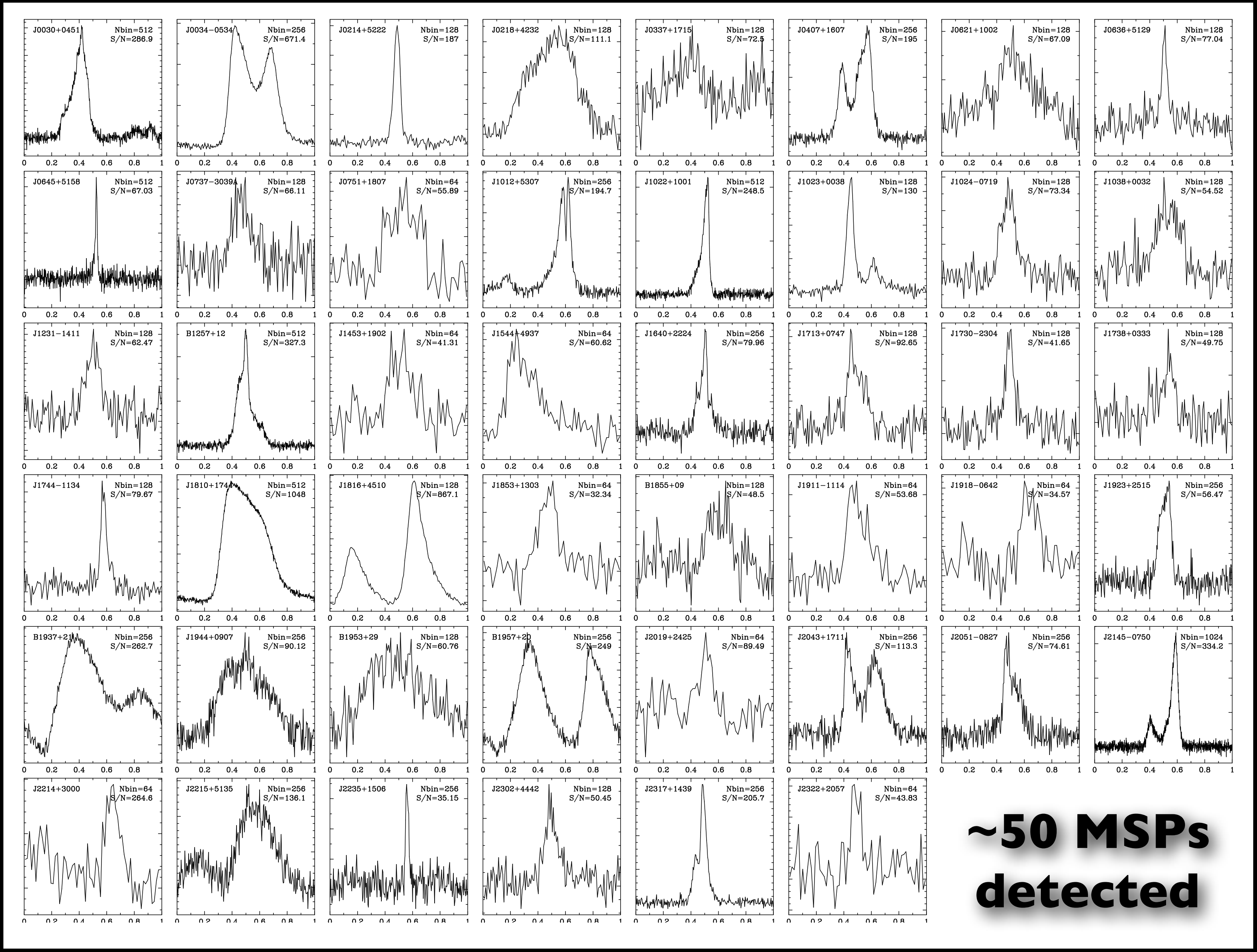


Ray et al. 2012

Discovery of MSP first through its gamma-ray pulsations.

Radio follow-up finds an almost undetectable radio pulsar.

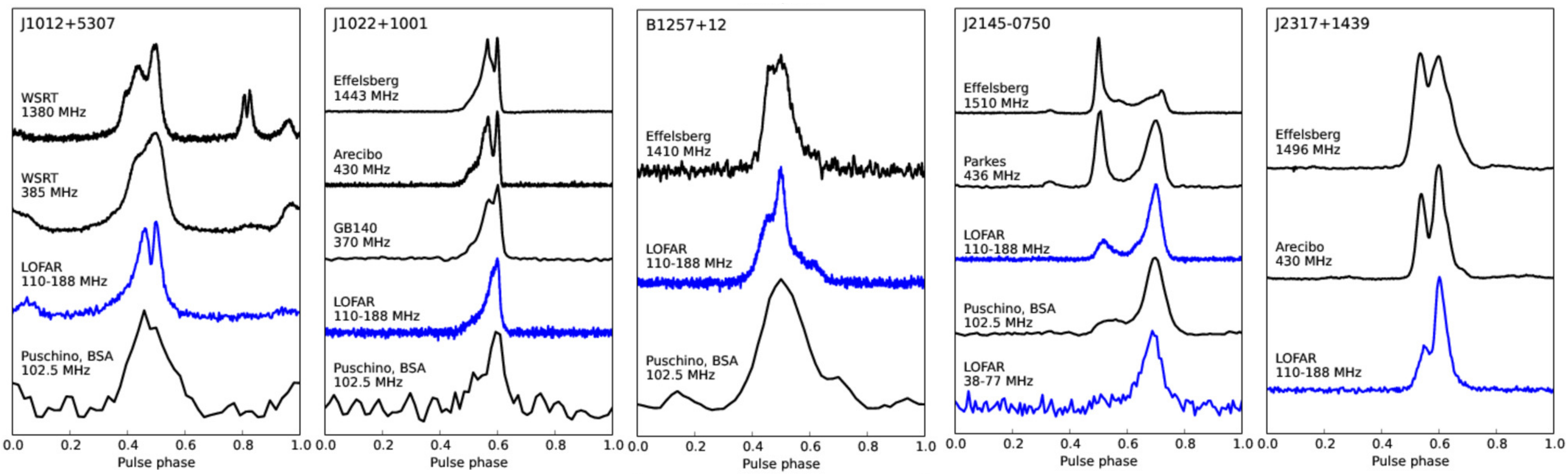
LOFAR Millisecond Pulsars



Kondratiev et al. 2015

The premier low-frequency sample

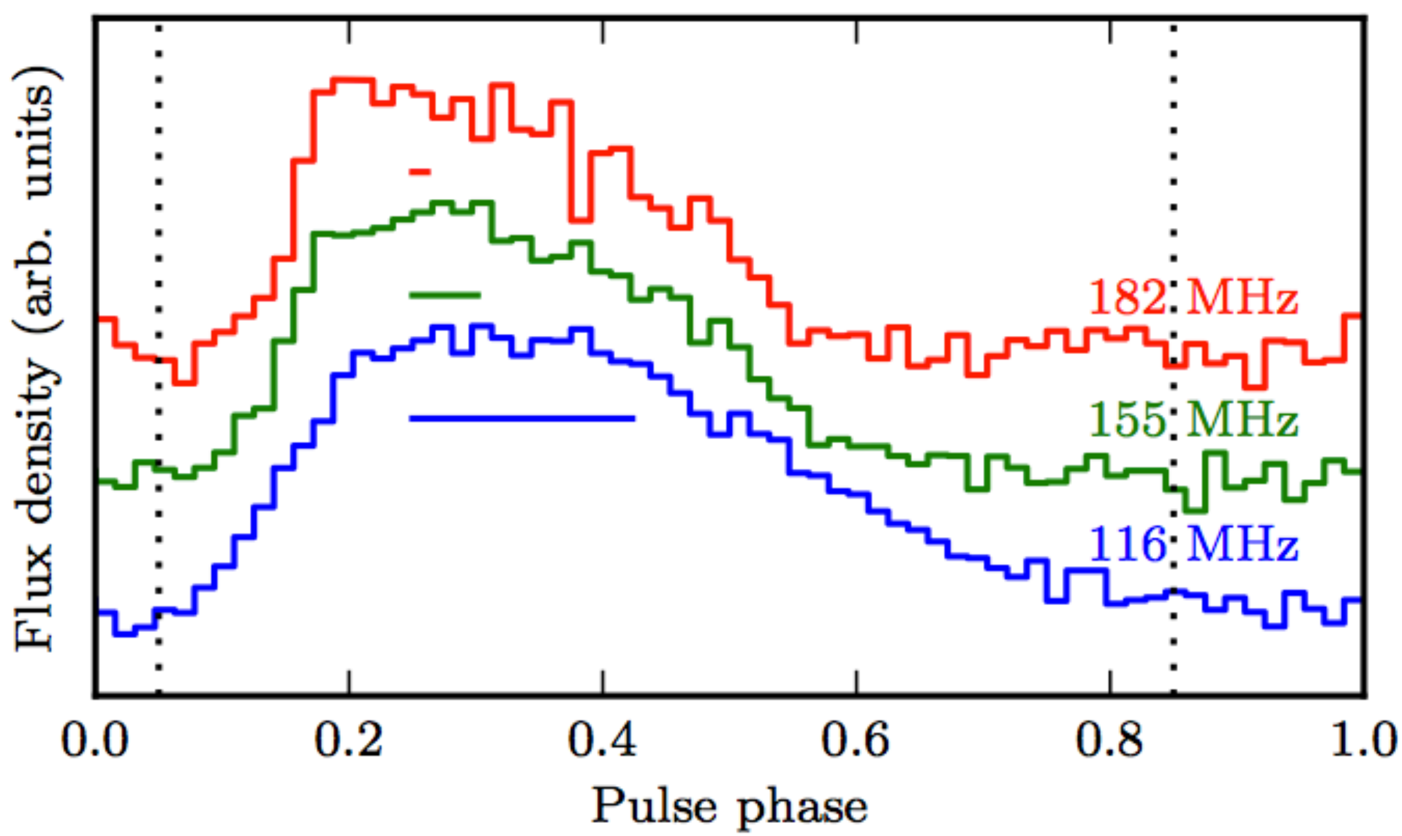
LOFAR Millisecond Pulsars

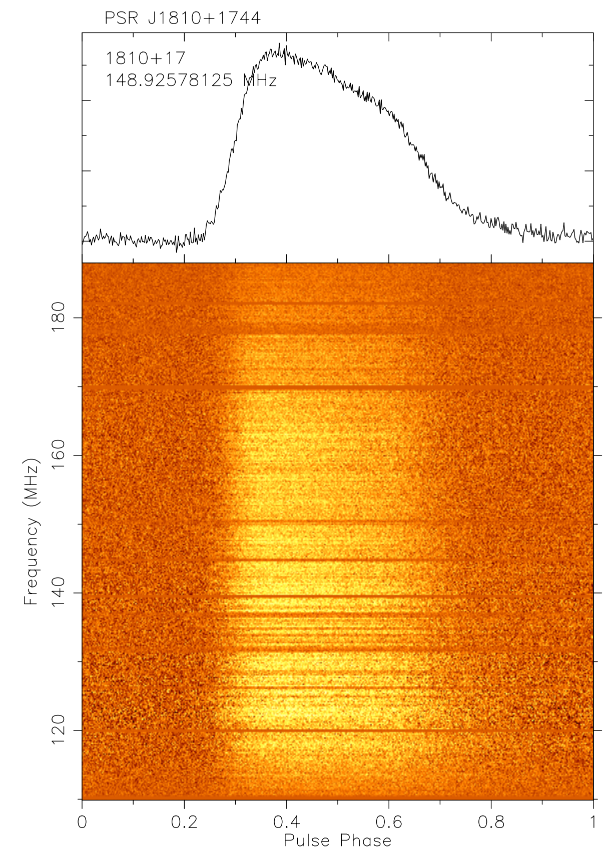


Kondratiev et al. 2015

Profile evolution related to compact magnetosperes?

Cyclic Spectroscopy

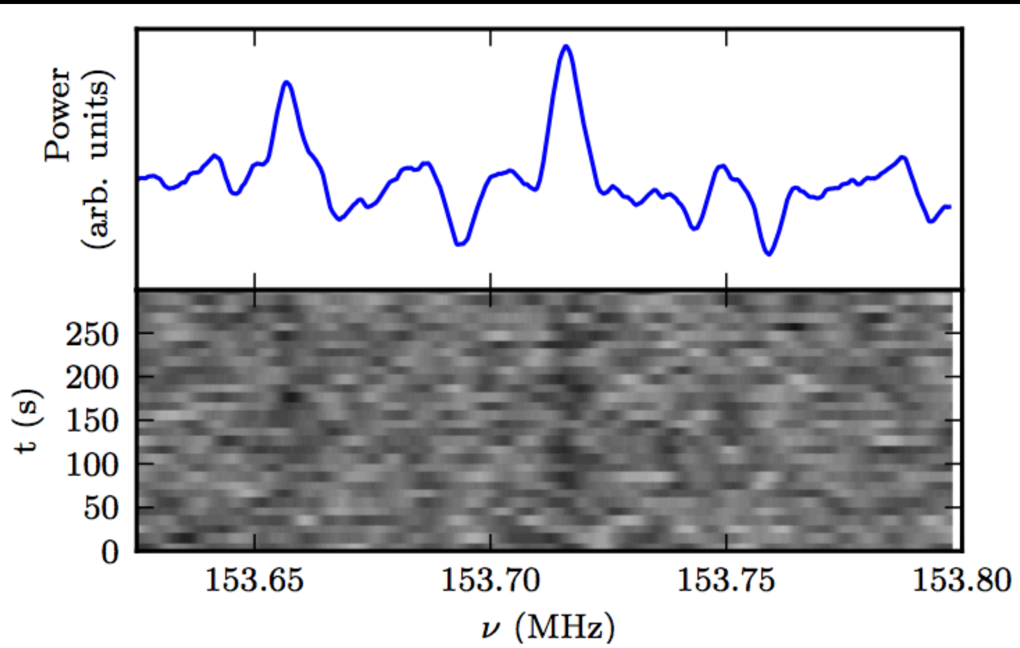




Horizontal bars indicate scattering time, τ, as inferred from the diffractive bandwidth, $\Delta\nu_{\rm d}$

Archibald et al. 2014

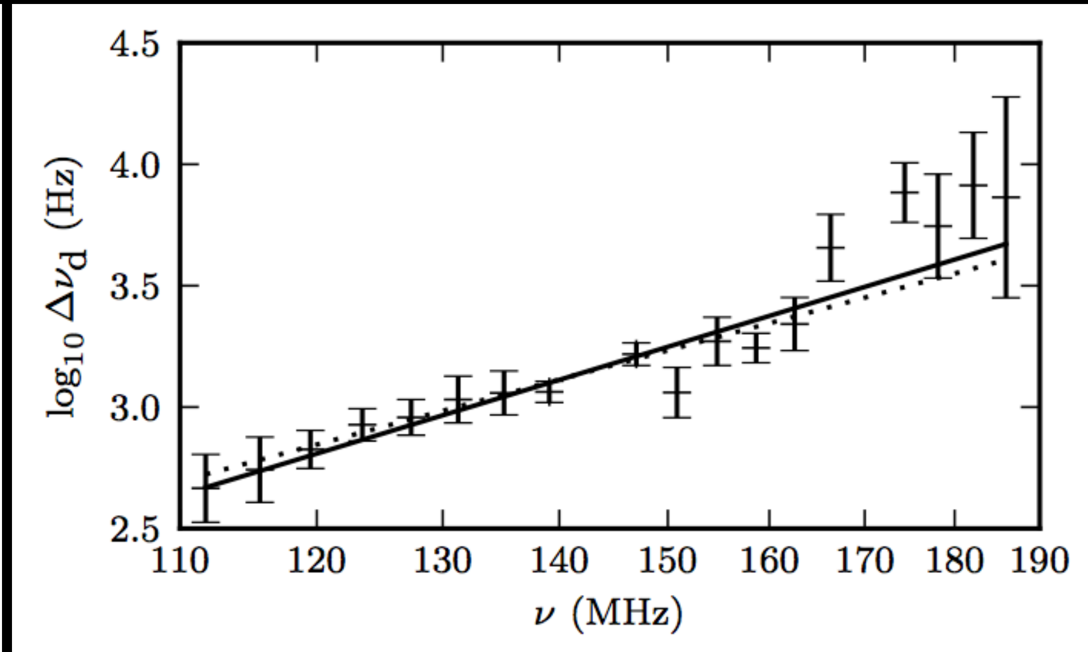
Cyclic Spectroscopy



200kHz

Example dynamic spectrum

Smoothed to ~2kHz resolution



Diffractive bandwidth vs. frequency

$$\Delta\nu_{\mathrm{d}} = \frac{1}{2\pi\tau}$$

Solid line: best-fit power-law

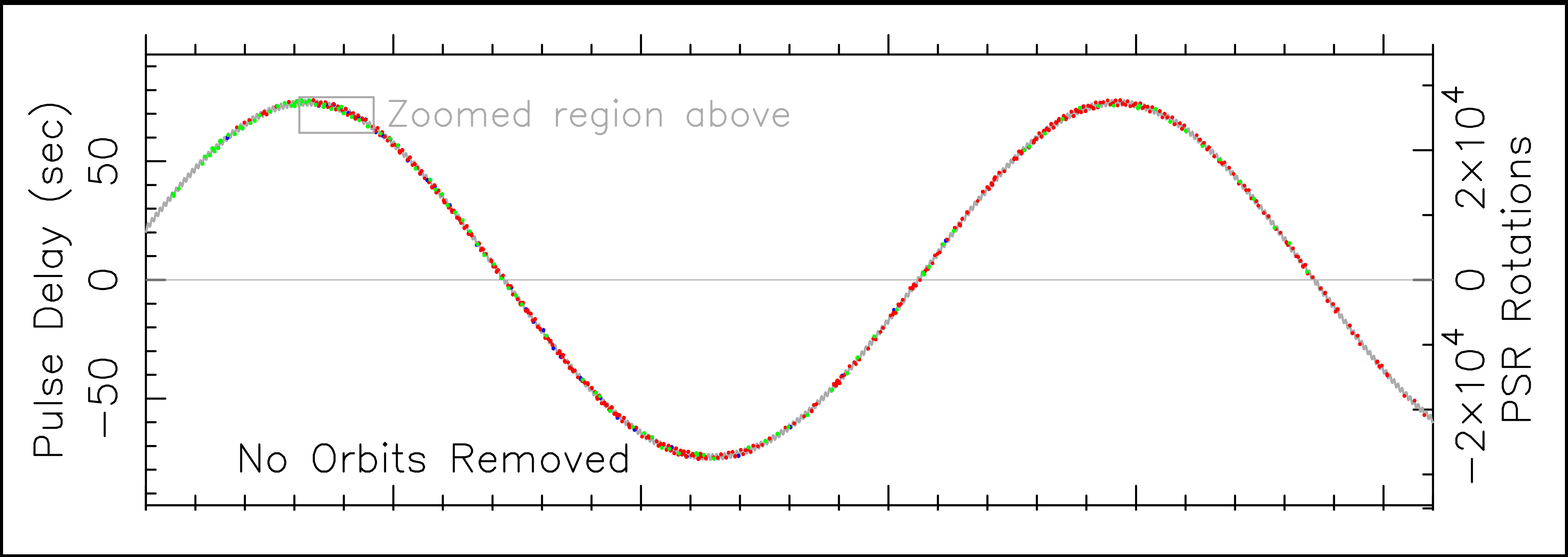
Dotted line: power-law of -4

Probes scattering in a previously unreachable regime

Archibald et al. 2014

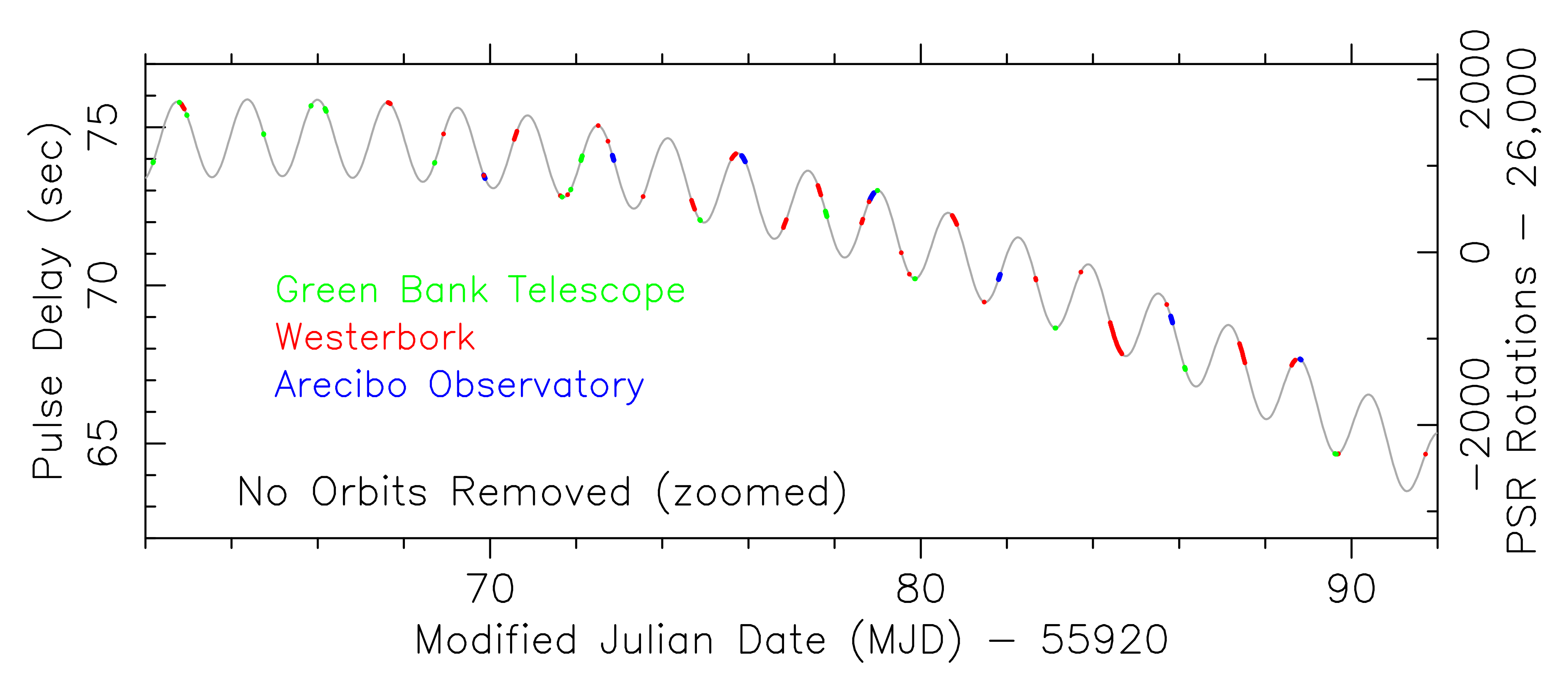
Pulsar triple system

A pulsar riddle

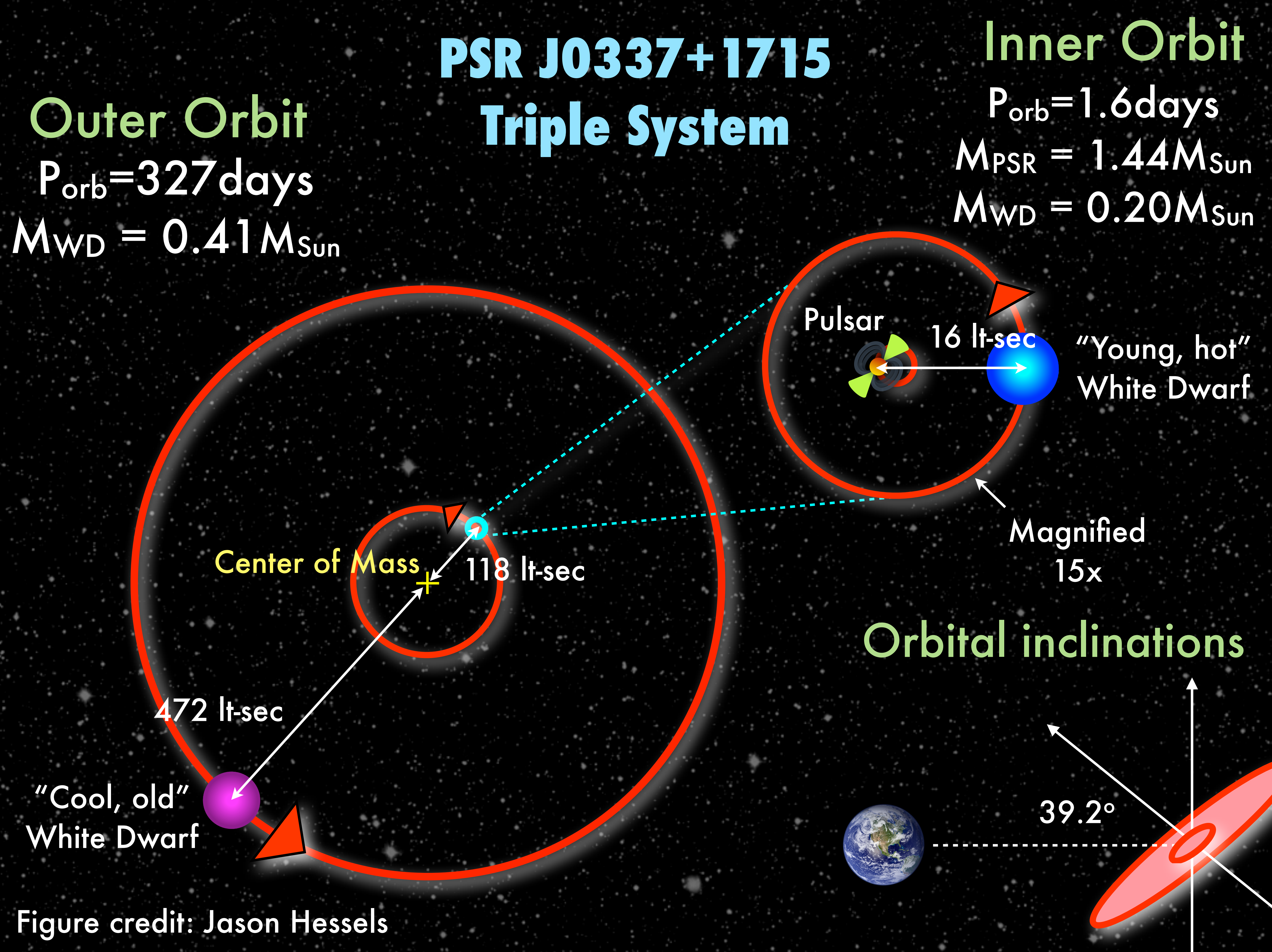


Ransom et al. 2014

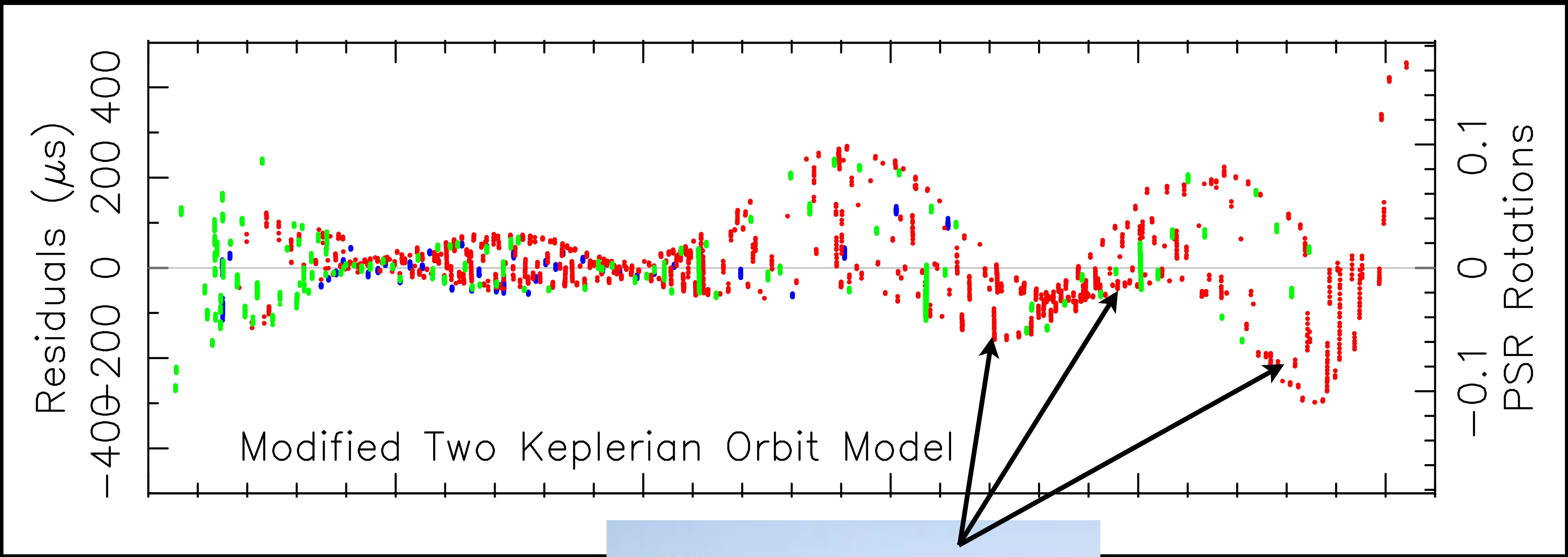
A pulsar riddle



Ransom et al. 2014


PSR J0337+1715
Triple System
Outer Orbit
P_{orb}=327days
M_{WD} = 0.41M_{Sun}
Inner Orbit
P_{orb}=1.6days
M_{PSR} = 1.44M_{Sun}
M_{WD} = 0.20M_{Sun}
Pulsar
16 lt-sec
"Young, hot"
White Dwarf
Magnified
15x
Center of Mass
118 lt-sec
472 lt-sec
"Cool, old"
White Dwarf
Orbital inclinations
39.2°
Figure credit: Jason Hessels

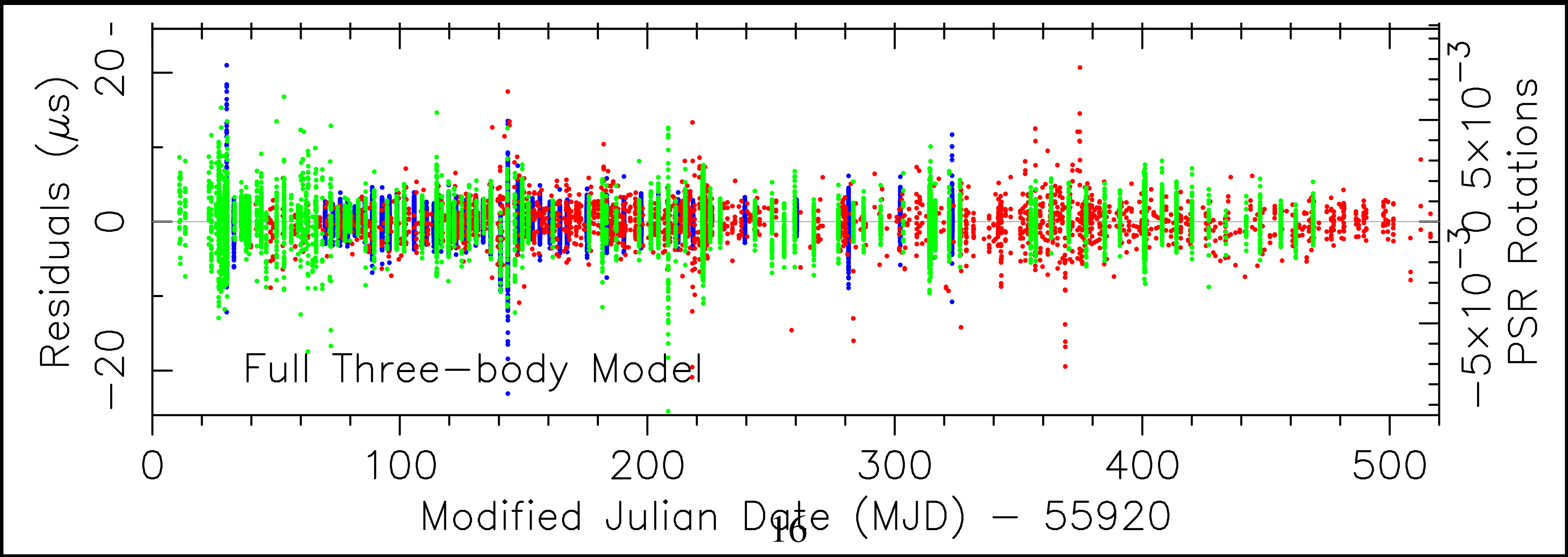
A pulsar riddle



Alle rode meetpunten zijn van Westerbork!

Ransom et al. 2014

A pulsar riddle



16

Ransom et al. 2014

J0337+1715 - Timing model

Parameter	Symbol	Value
Fixed values		
Right ascension	RA	$03^h37^m43^s.82589(13)$
Declination	Dec	$17°15'14''.828(2)$
Dispersion measure	DM	$21.3162(3)$ pc cm^{-3}
Solar system ephemeris		DE405
Reference epoch		MJD 55920.0
Observation span		MJD $55930.9 - 56436.5$
Number of TOAs		26280
Weighted root-mean-squared residual		$1.34\,\mu$s
Fitted parameters		
Spin-down parameters		
Pulsar spin frequency	f	365.953363096(11) Hz
Spin frequency derivative	$\dot{f}$	$-2.3658(12) \times 10^{-15}$ Hz s^{-1}
Inner Keplerian parameters for pulsar orbit		
Semimajor axis projected along line of sight	$(a \sin i)_I$	1.21752844(4) lt-s
Orbital period	$P_{b,I}$	1.629401788(5) d
Eccentricity parameter ($e \sin \Omega$)	$\epsilon_{1,I}$	$6.8567(2) \times 10^{-4}$
Eccentricity parameter ($e \cos \Omega$)	$\epsilon_{2,I}$	$-9.171(2) \times 10^{-5}$
Time of ascending node	$t_{\mathrm{asc},I}$	MJD 55920.407717436(17)
Outer Keplerian parameters for centre of mass of inner binary		
Semimajor axis projected along line of sight	$(a \sin i)_O$	74.6727101(8) lt-s
Orbital period	$P_{b,O}$	327.257541(7) d
Eccentricity parameter ($e \sin \Omega$)	$\epsilon_{1,O}$	$3.5186279(3) \times 10^{-2}$
Eccentricity parameter ($e \cos \Omega$)	$\epsilon_{2,O}$	$-3.462131(11) \times 10^{-3}$
Time of ascending node	$t_{\mathrm{asc},O}$	MJD 56233.935815(7)
Interaction parameters		
Semimajor axis projected in plane of sky	$(a \cos i)_I$	1.4900(5) lt-s
Semimajor axis projected in plane of sky	$(a \cos i)_O$	91.42(4) lt-s
Inner companion mass over pulsar mass	$q_I = m_{cI}/m_p$	0.13737(4)
Difference in longs. of asc. nodes	δ_Ω	$2.7(6) \times 10^{-3}$ °
Inferred or derived values		
Pulsar properties		
Pulsar period	P	2.73258863244(9) ms
Pulsar period derivative	$\dot{P}$	$1.7666(9) \times 10^{-20}$
Inferred surface dipole magnetic field	B	2.2×10^8 G
Spin-down power	$\dot{E}$	3.4×10^{34} erg s^{-1}
Characteristic age	τ	2.5×10^9 y
Orbital geometry		
Pulsar semimajor axis (inner)	a_I	1.9242(4) lt-s
Eccentricity (inner)	e_I	$6.9178(2) \times 10^{-4}$
Longitude of periastron (inner)	ω_I	97.6182(19) °
Pulsar semimajor axis (outer)	a_O	118.04(3) lt-s
Eccentricity (outer)	e_O	$3.53561955(17) \times 10^{-2}$
Longitude of periastron (outer)	ω_O	95.619493(19) °
Inclination of invariant plane	i	39.243(11) °
Inclination of inner orbit	i_I	39.254(10) °
Angle between orbital planes	δ_i	$1.20(17) \times 10^{-2}$ °
Angle between eccentricity vectors	$\delta_\omega \sim \omega_O - \omega_I$	$-1.9987(19)$ °
Masses		
Pulsar mass	m_p	$1.4378(13)\ M_\odot$
Inner companion mass	m_{cI}	$0.19751(15)\ M_\odot$
Outer companion mass	m_{cO}	$0.4101(3)\ M_\odot$

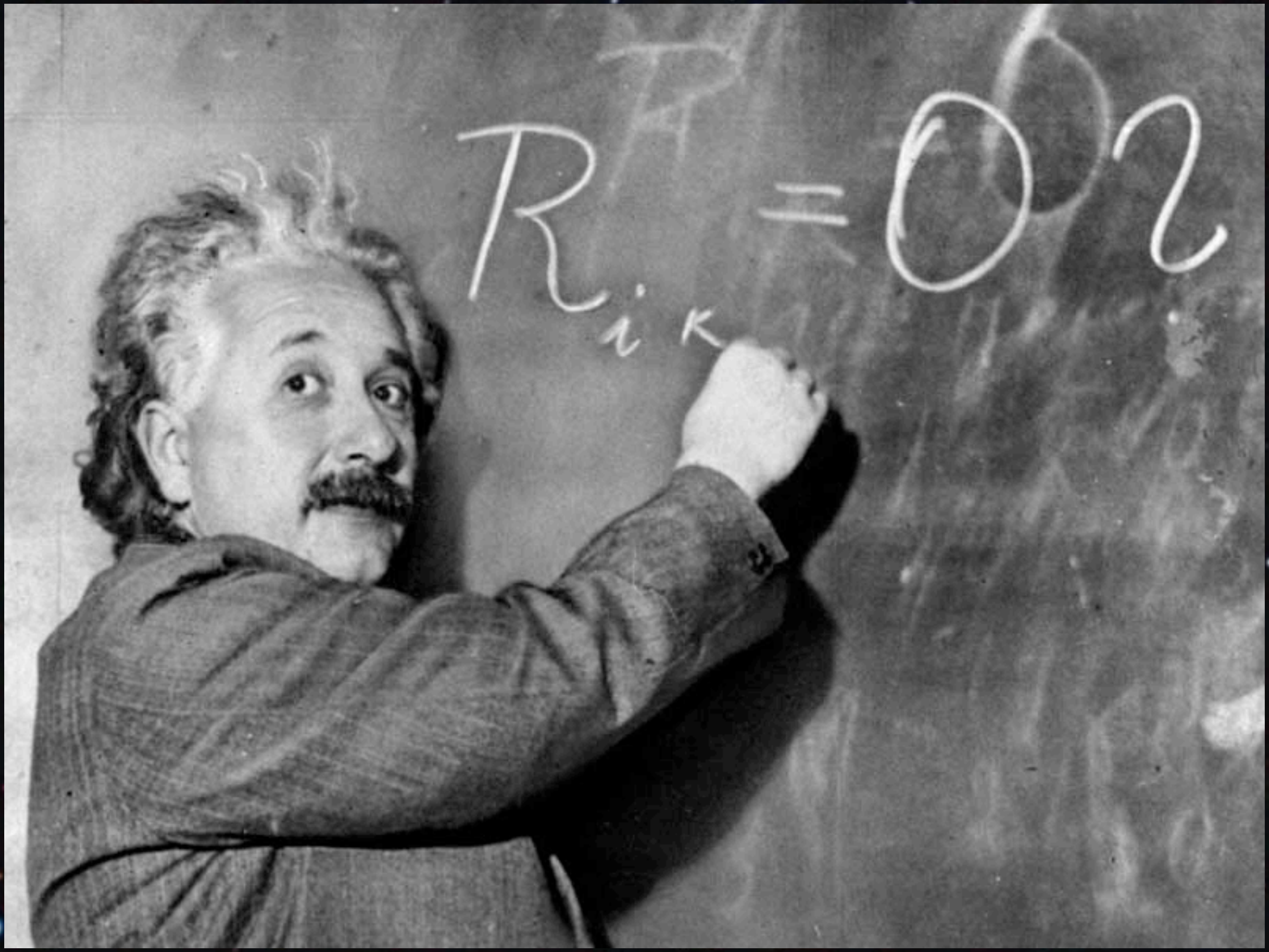
Model by Anne Archibald

Pulsar massa: 1.4378(13) Mzon
"Inner" WD massa: 0.19751(15) Mzon
"Outer" WD massa: 0.4101(3) Mzon

You are impressed by all these high-precision numbers

Was Einstein right?

See talk by Kramer this morning



Strong Equivalence Principle

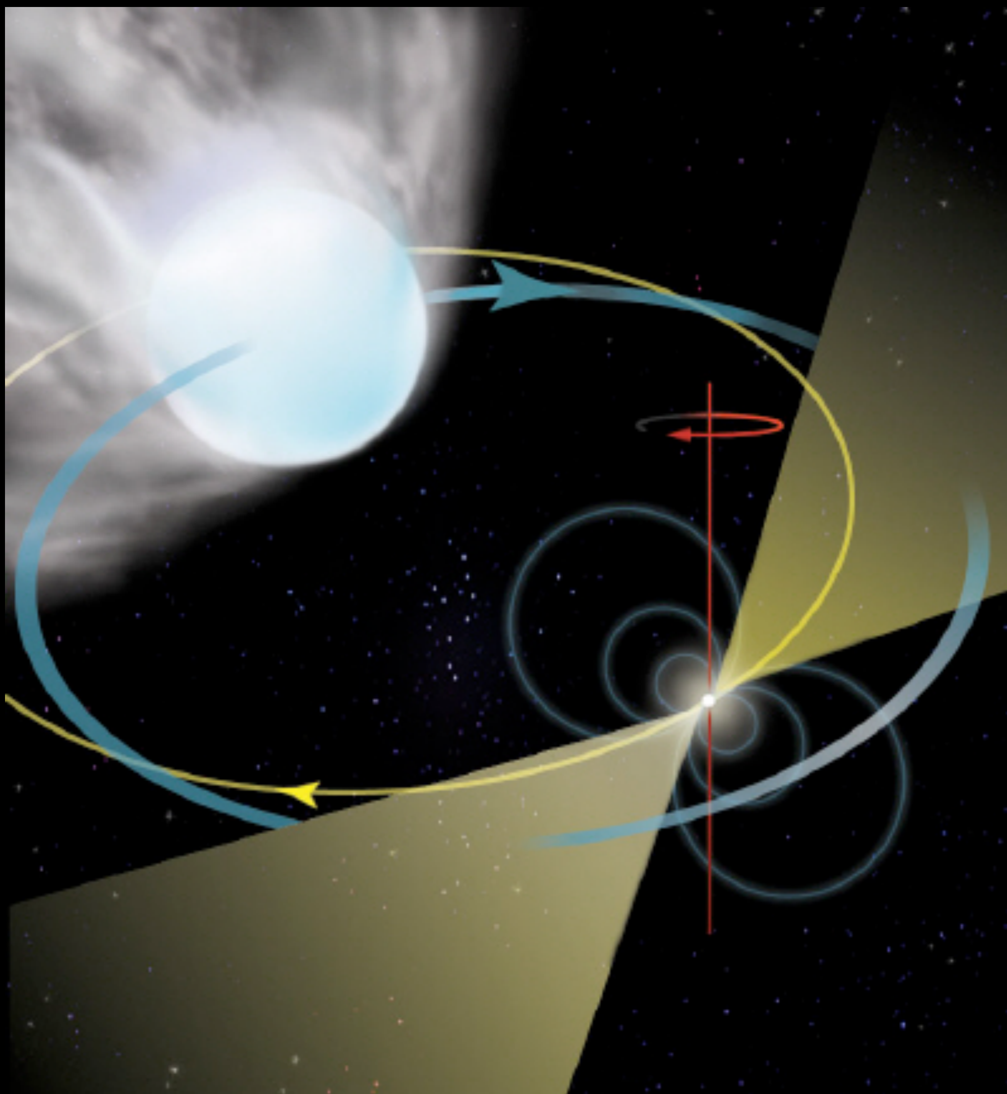
“Spiders”
(black widows & redbacks)

MSP “Spiders”

See talks by Papitto, Ferrigno, Wadiasingh

Blame Mallory Roberts

‘Black Widow’ and ‘Redback’ Pulsar Binaries



So named because these pulsars are ‘devouring’ (ablating) their companions

Black widows:
<< $0.1M_{Sun}$ (semi) degenerate companion

Redbacks:
~ $0.2M_{Sun}$ non-degenerate companion

Black Widows vs. Redbacks

Black widows

- Mcomp < 0.1Msun
- ~10% eclipse fraction
- Less Roche-lobe filling?
- Less T0 wander?

delta(T0) ~ 1-10s

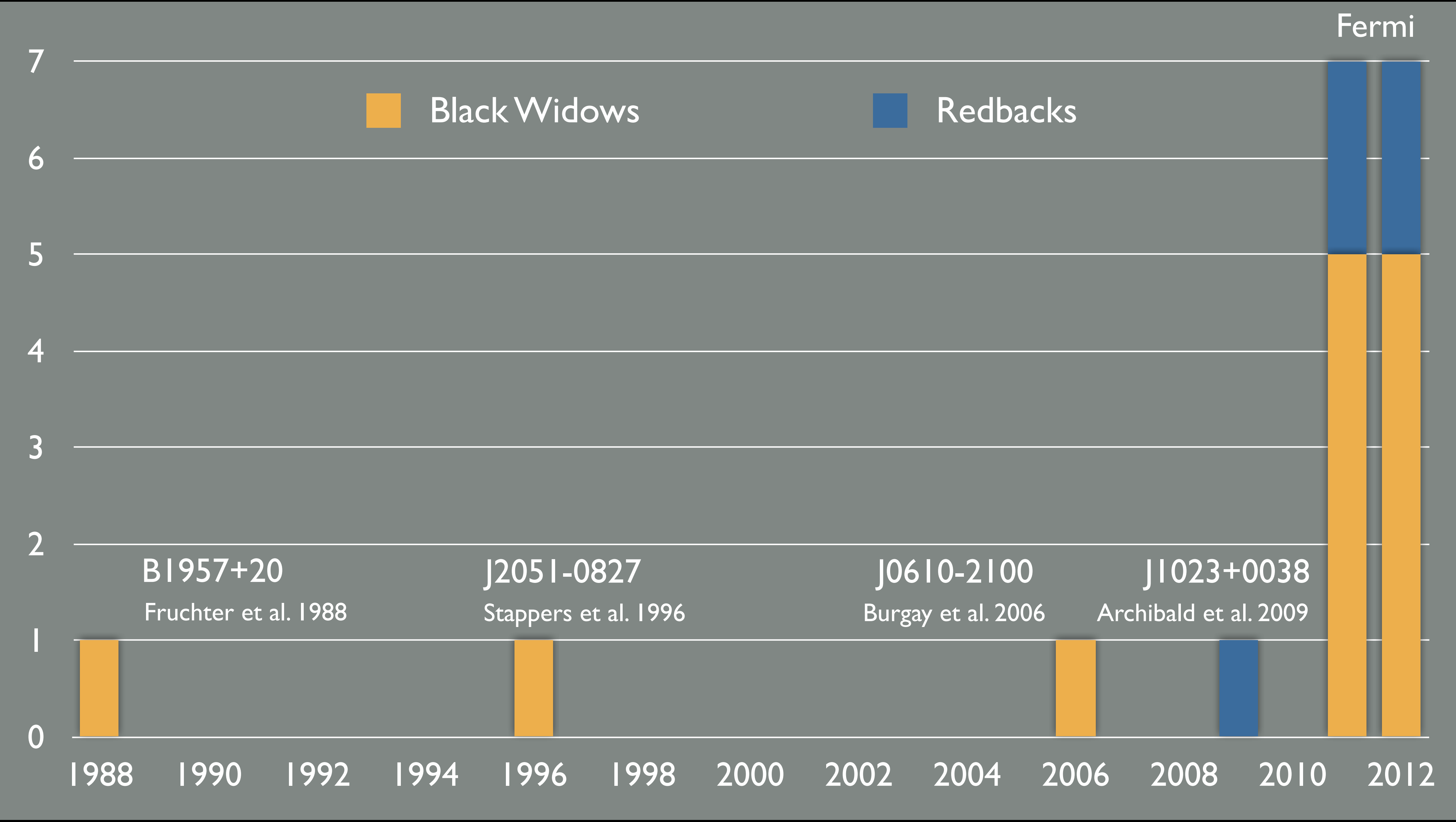
Redbacks

- Mcomp > 0.1Msun
- ~50% eclipse fraction
- Completely Roche-lobe filling?
- More T0 wander?

delta(T0) ~ 10-100s

Seems like we may have more types of eclipsing radio MSPs as well: ones earlier in the recycling process?

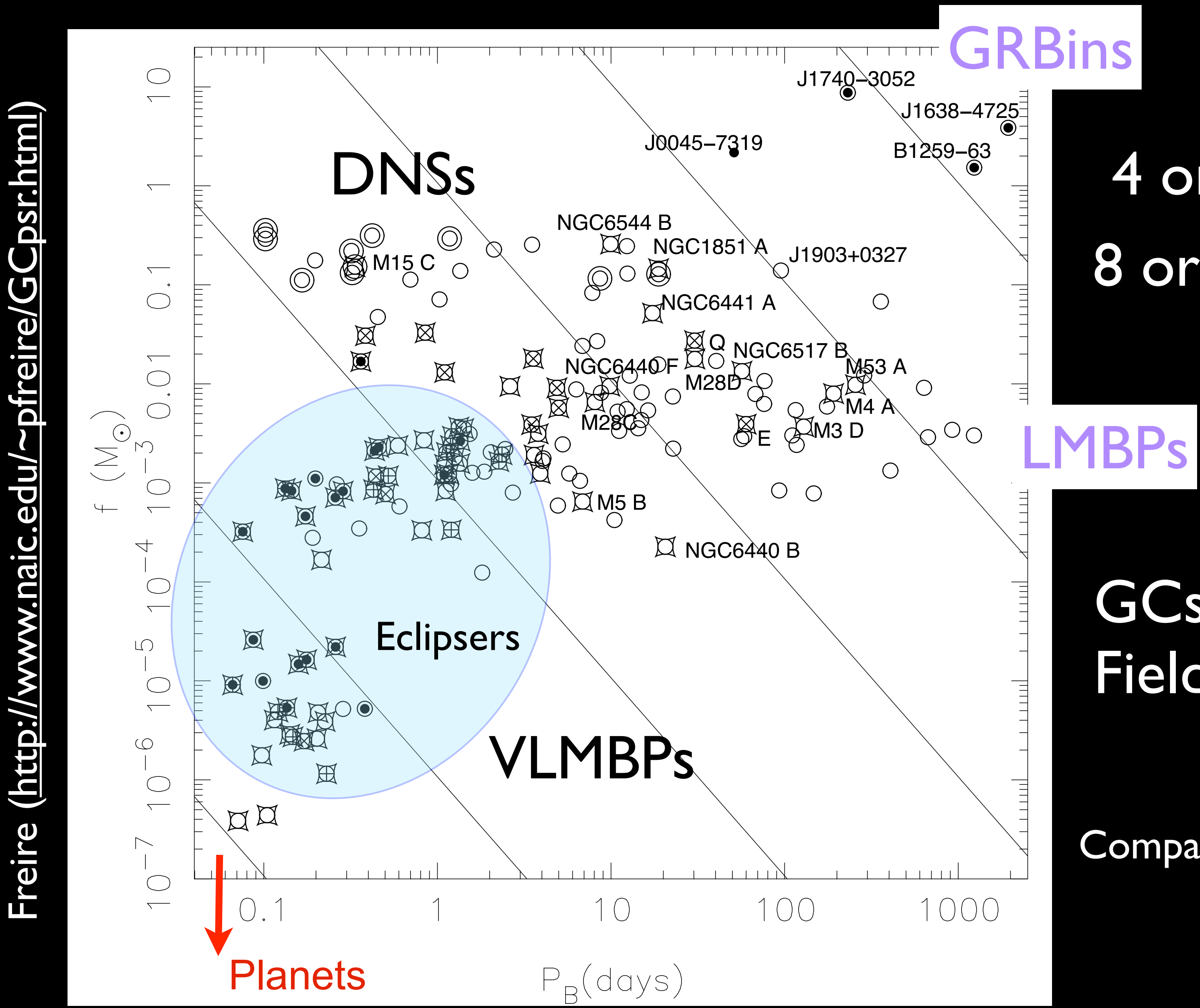
An Explosion of Spiders



Does not include all the (strange) systems in GCs

MSP Population

Orbits



4 orders of mag in PB

8 orders of mag in f(M)

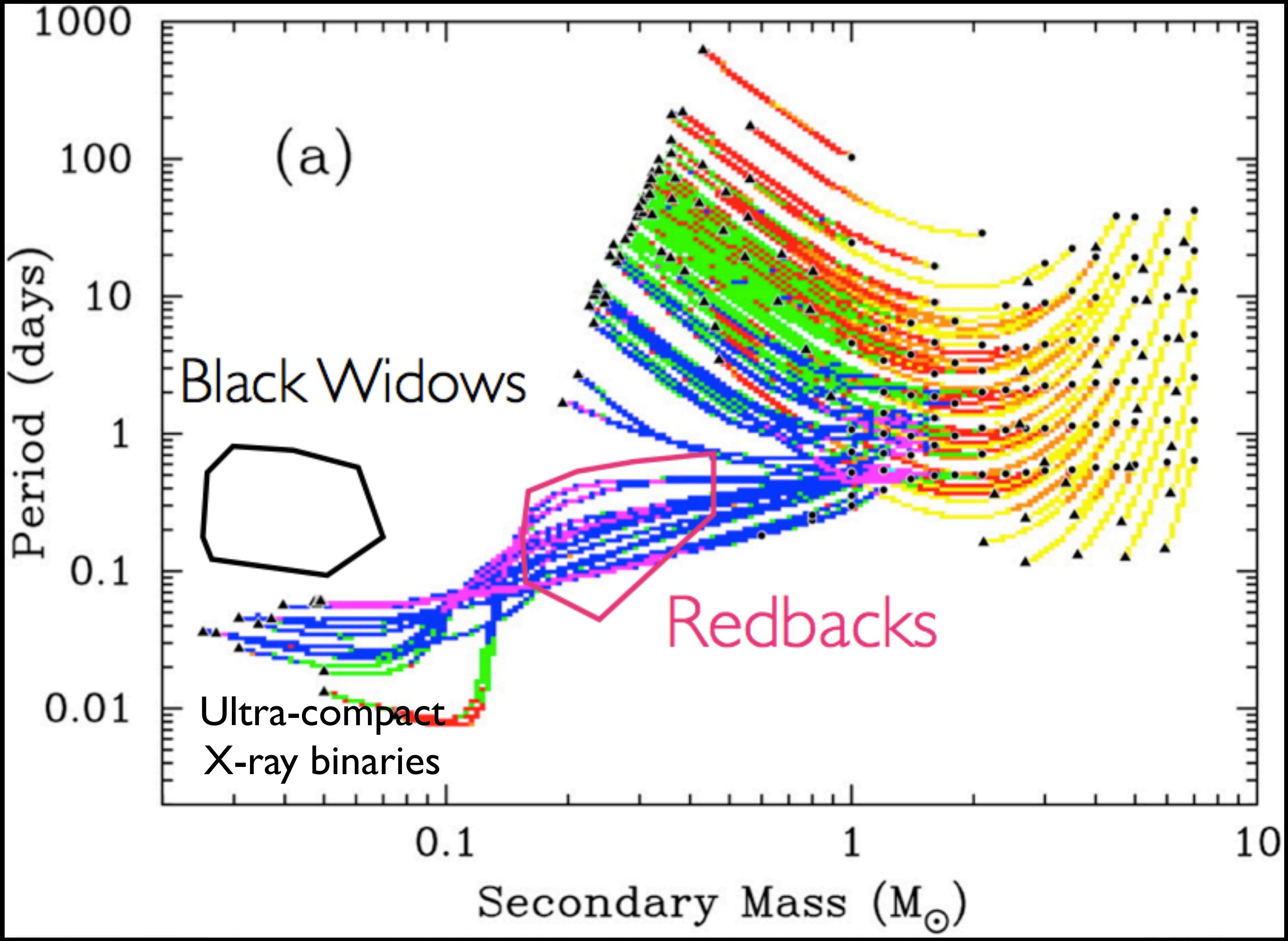
GCs: 18 BWs, 12 RBs

Field: 17 BWs, 8 RBs

Comparable numbers and properties!

Porb vs. Comp. Mass

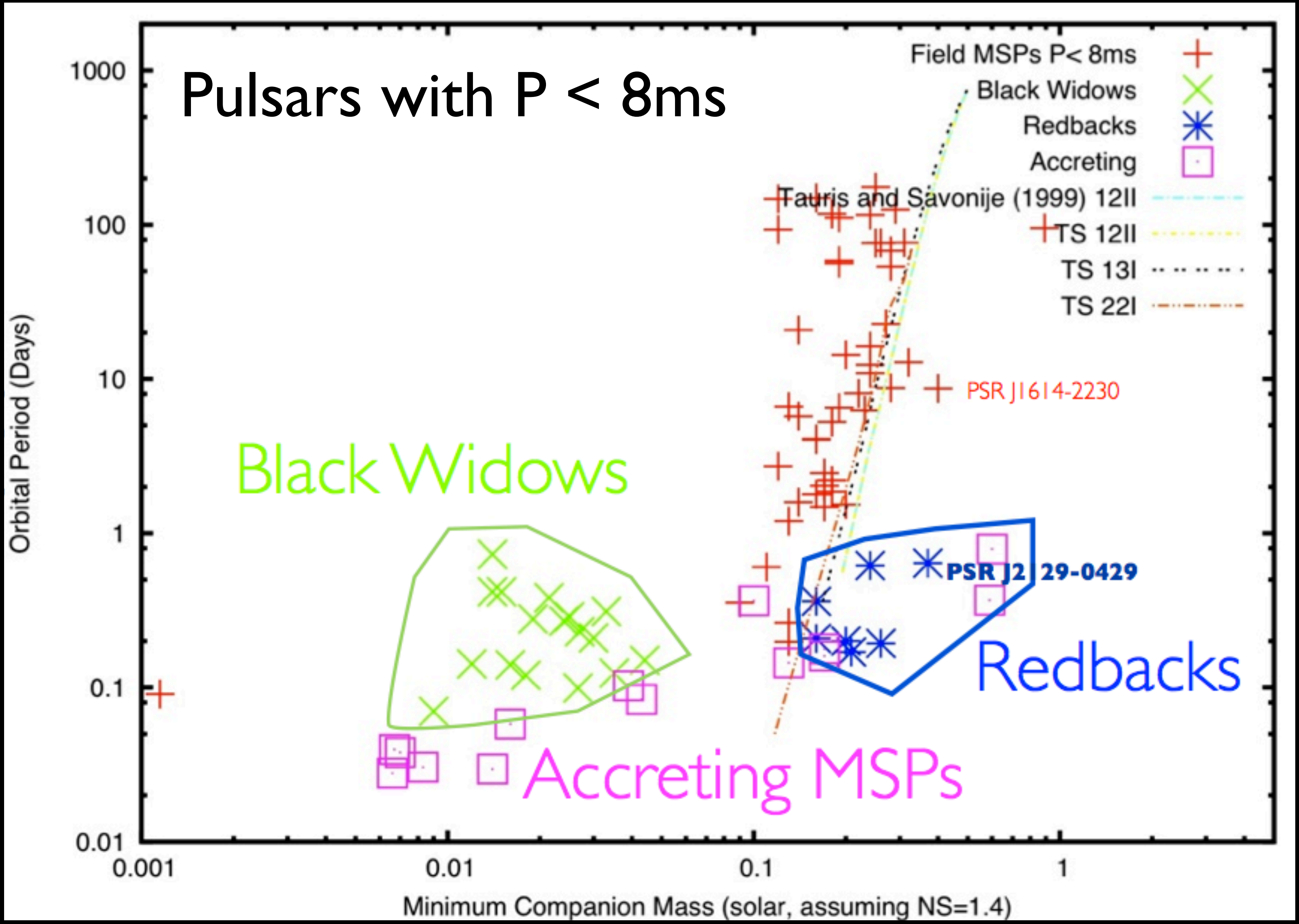
Adapted from Podsiadlowski et al. 2001



See talk by Thomas Tauris

What are the evolutionary links, if any?

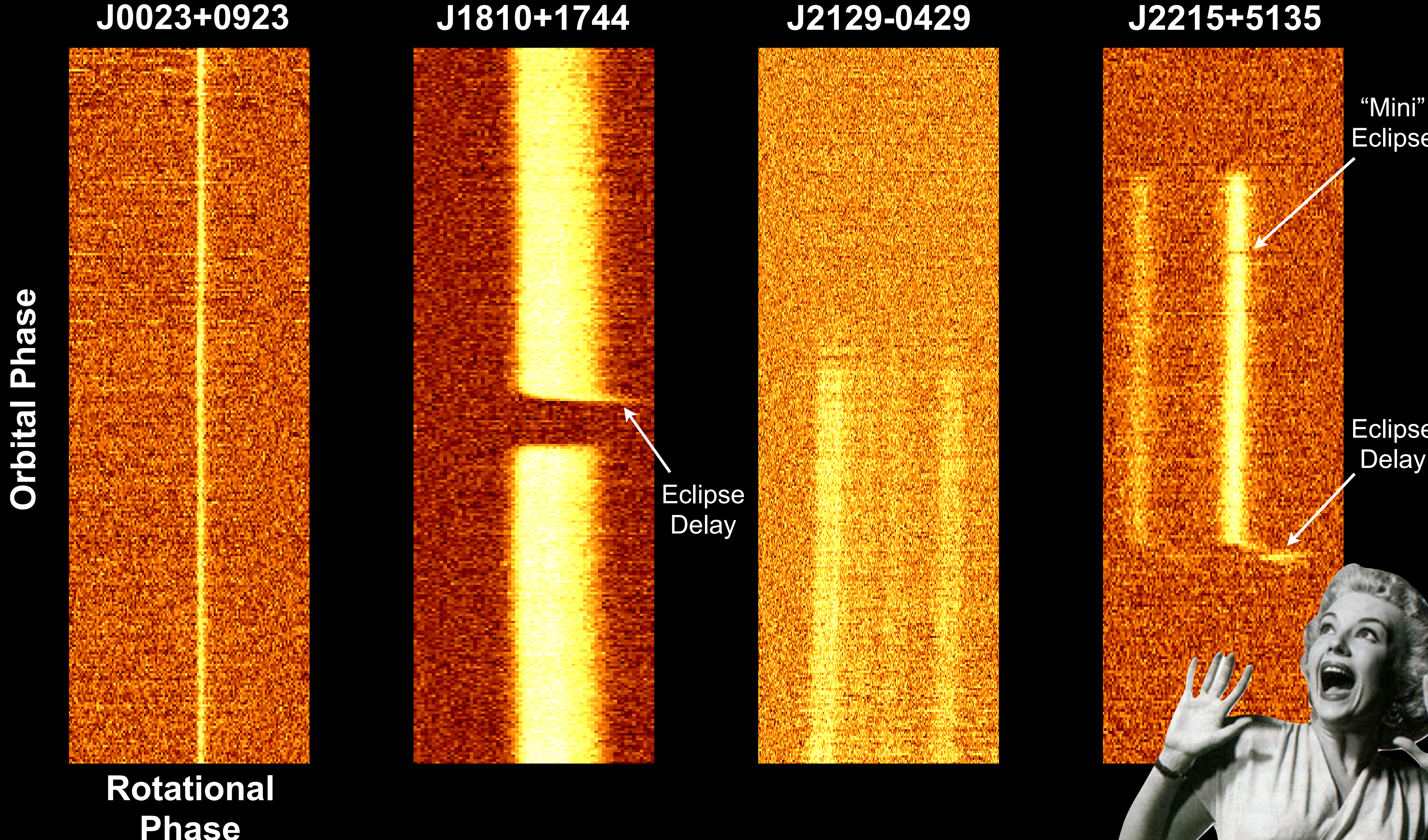
Porb vs. Comp. Mass



Roberts

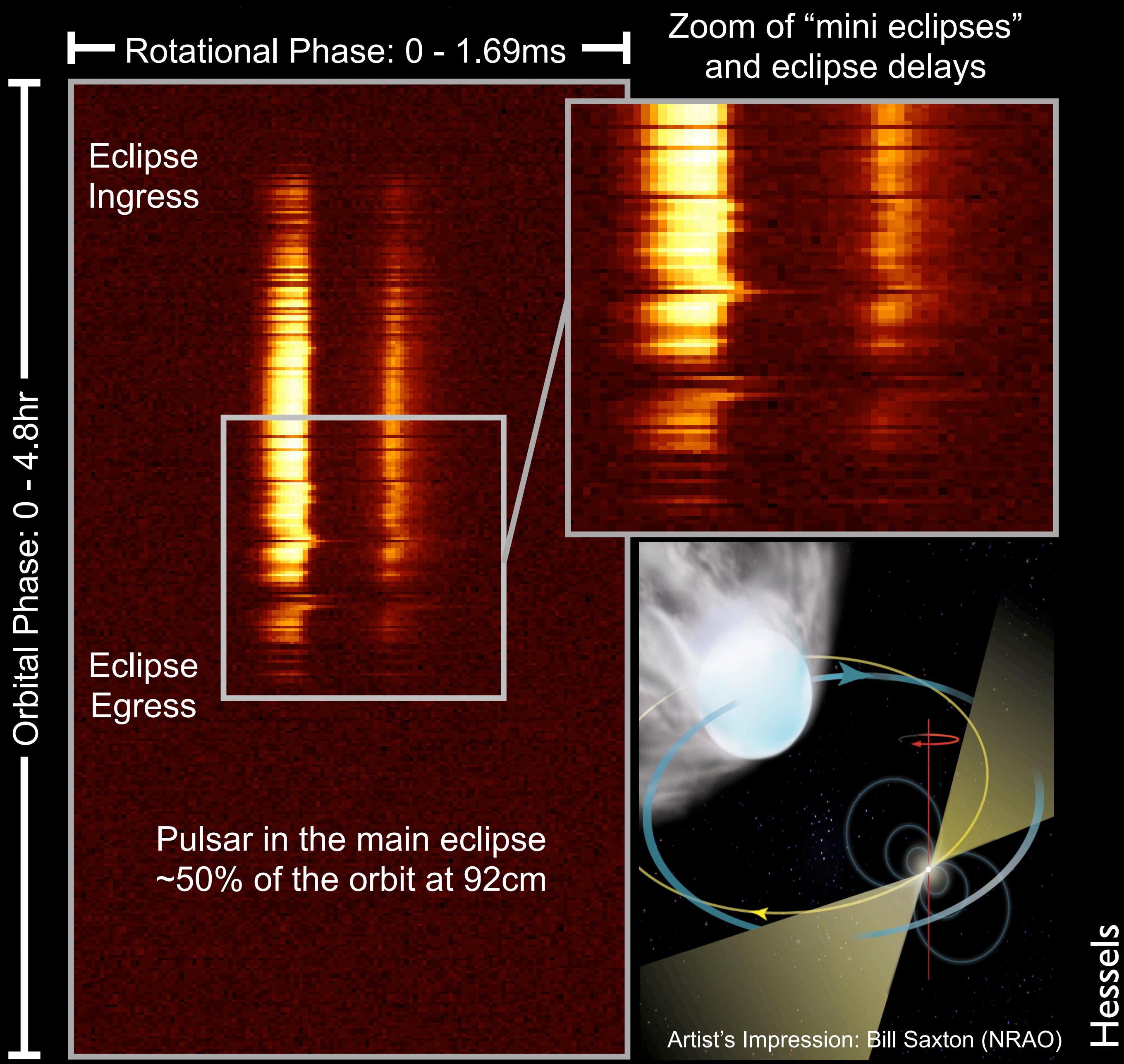
Eclipsing MSPs

Westerbork data

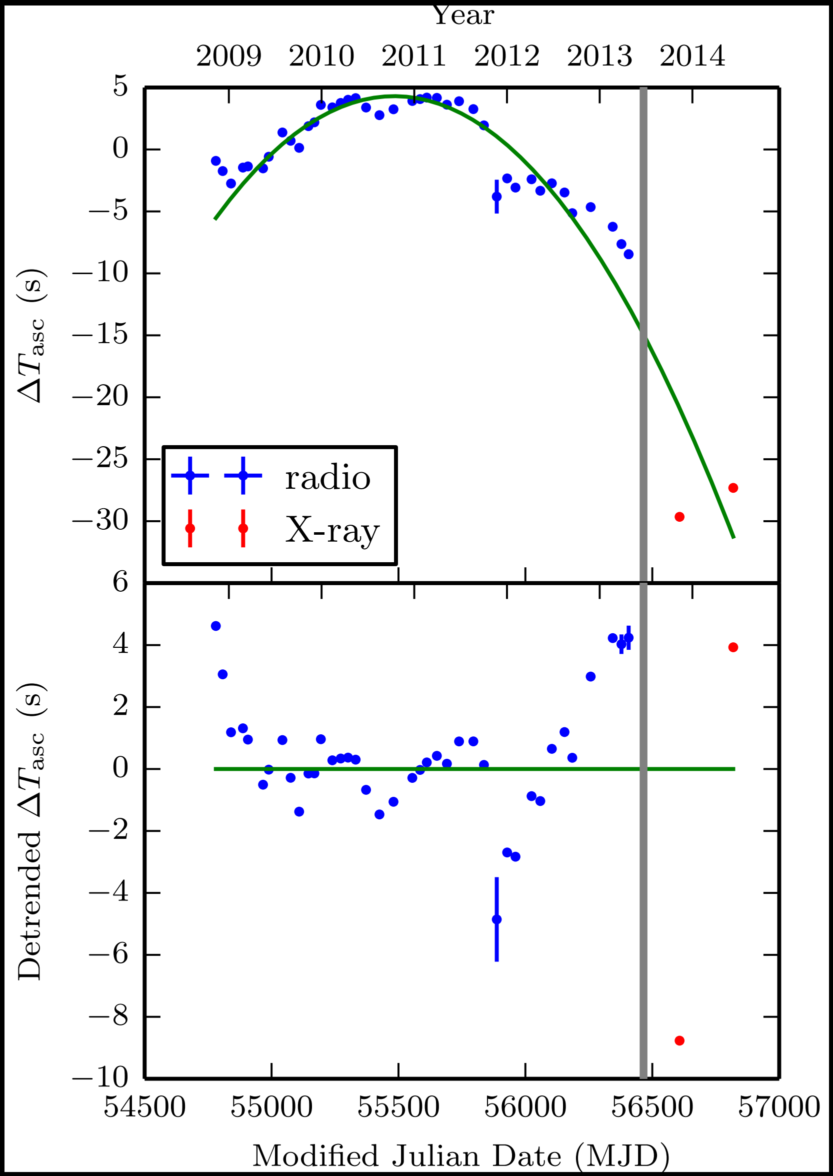


Hessels

MSP Eclipses



PSR J1023+0038

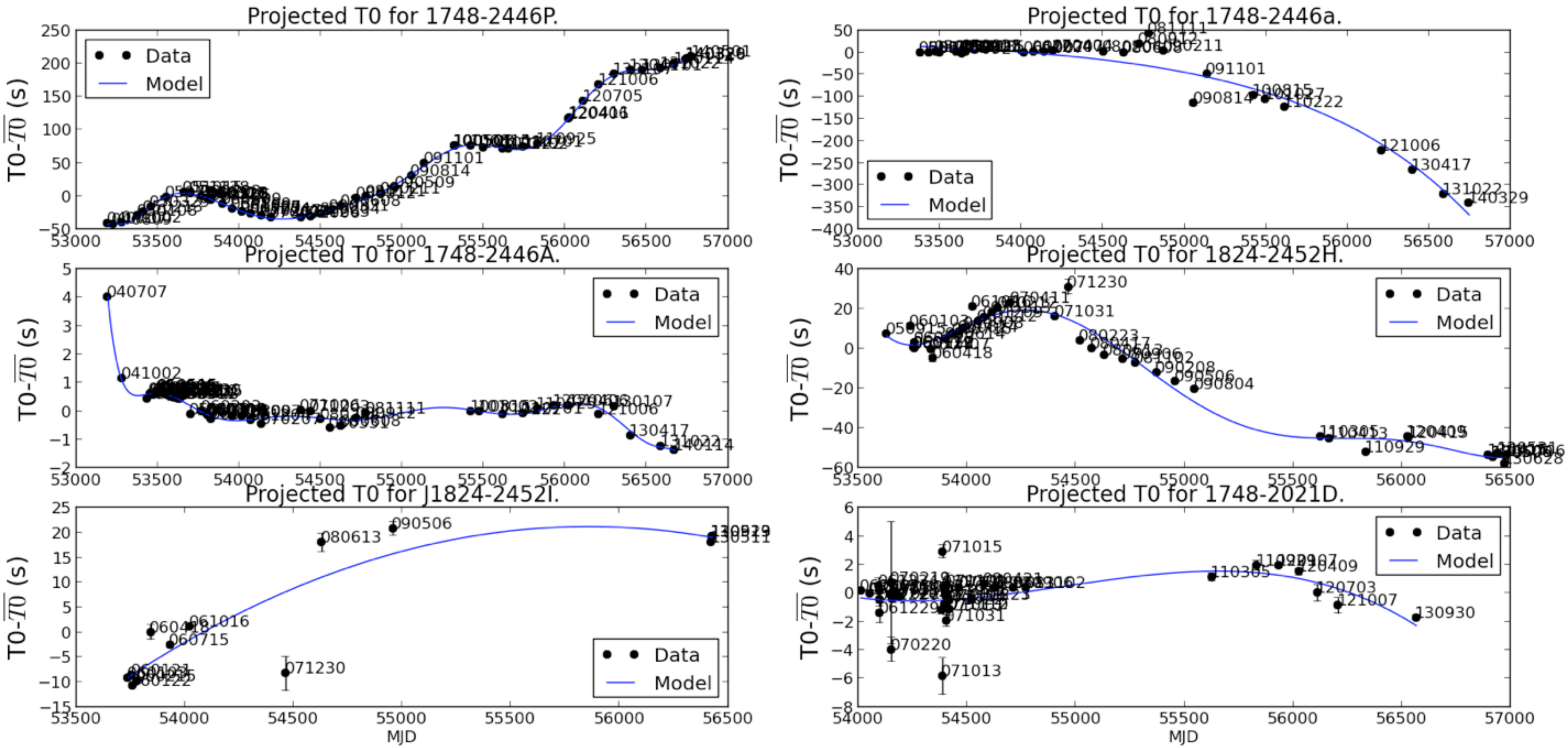


Pspin = 1.7ms
Porb = 0.20d
Mcomp = 0.13MSun

See talks by Amruta Jaodand and Kyle Parfrey

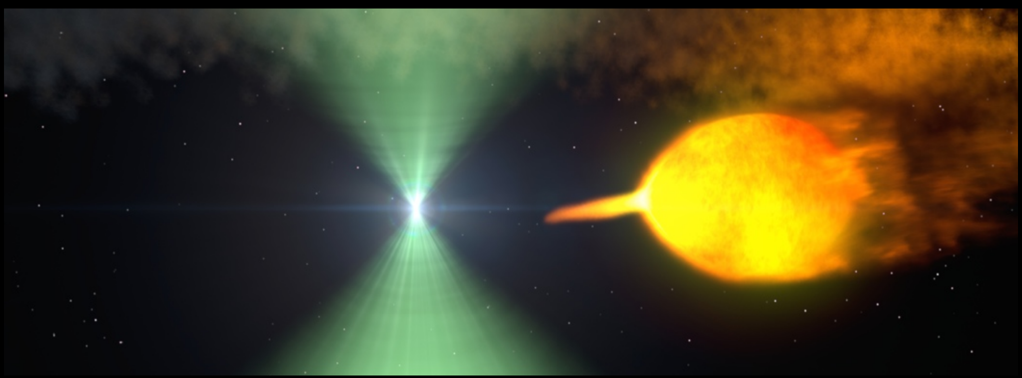
Archibald et al. 2015

Comparing T0 variations



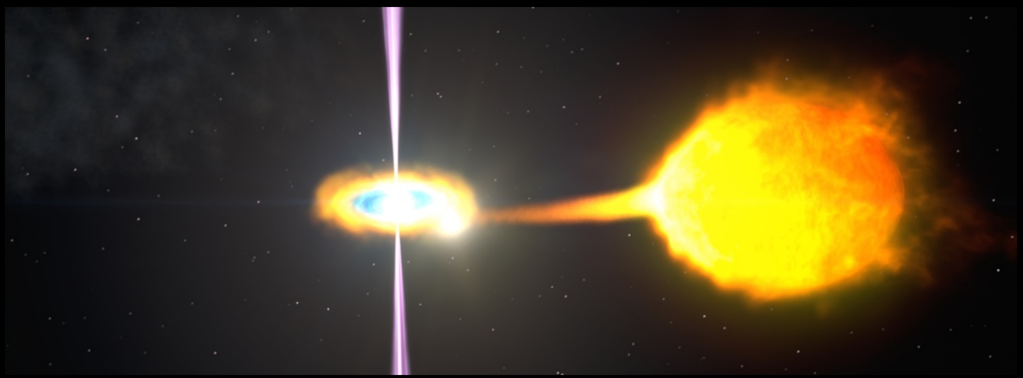
Prager

Radio Pulsar State



- Observed radio/gamma-ray pulsar.
- Likely radio eclipses.
- Lots of orbital timing noise.
- Modulation of X-rays at orbital period (shock).

Disk State



- No visible radio pulsar (off?).
- Increased optical, X-ray, and gamma-ray brightness.
- Double peaked optical emission lines.
- Flat-spectrum radio continuum source (jet?).
- No X-ray orbital modulation.
- X-ray dropouts and flares.

“Normal MSPs” vs. Spiders

- Gravity tests
- EOS constraints

- Accretion physics
- Pulsar wind
- Particle acceleration
- Shocks
- MSP formation and evolution
- EOS constraints?
- ...

Conclusions

- As the number of known MSPs increases, so do the number of scientific applications.
- The diversity of MSP systems is providing great puzzles in stellar evolution.
- Multi-wavelength observations are crucial for getting the most out of radio MSPs.
- ...and I didn't even talk about the *Fermi* Galactic bulge GeV excess.