# Radio Timing Properties of Black Widow & Redback Millisecond Pulsars


## Jason Hessels

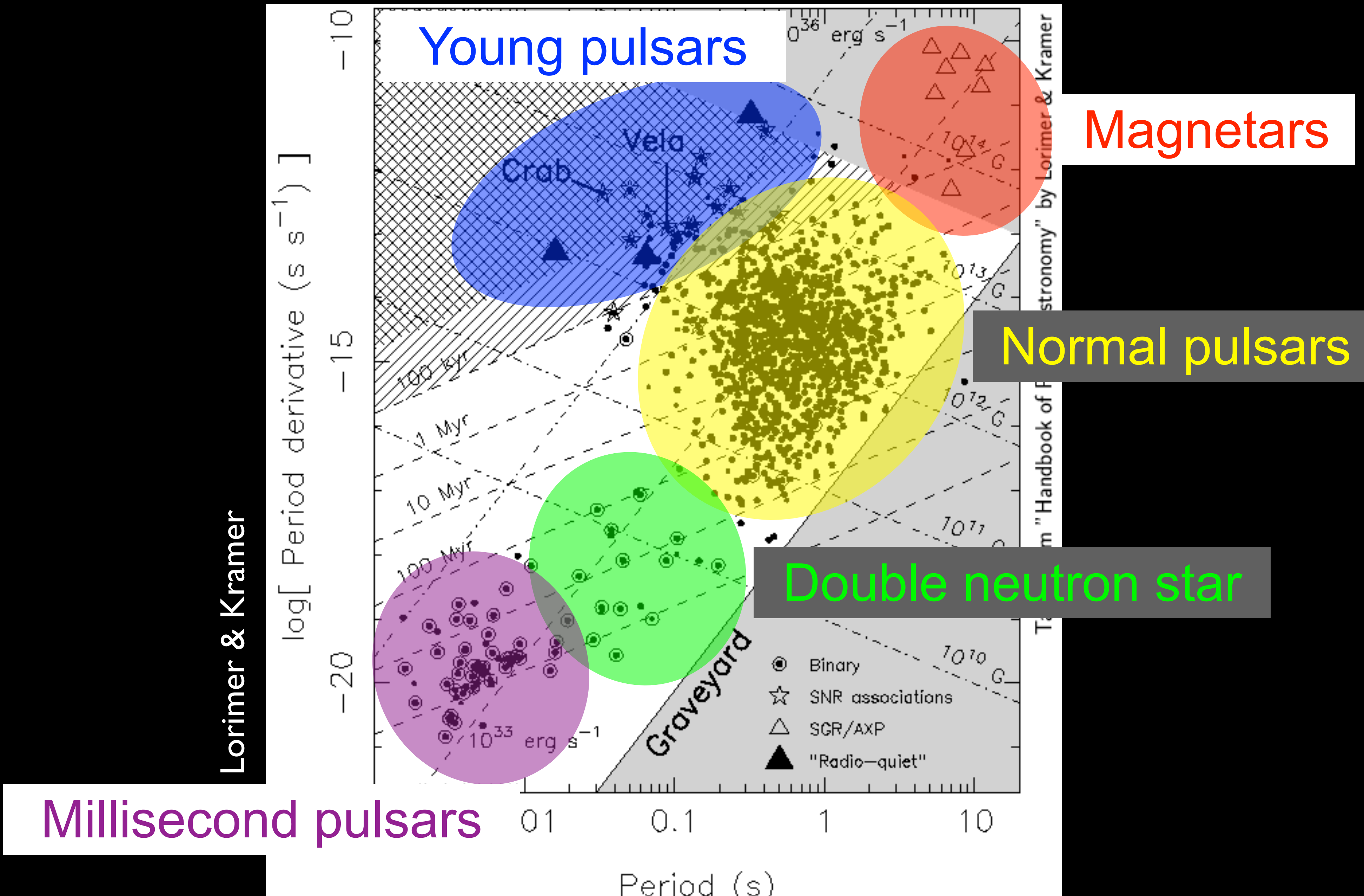
**U. of Amsterdam / ASTRON**

# Outline

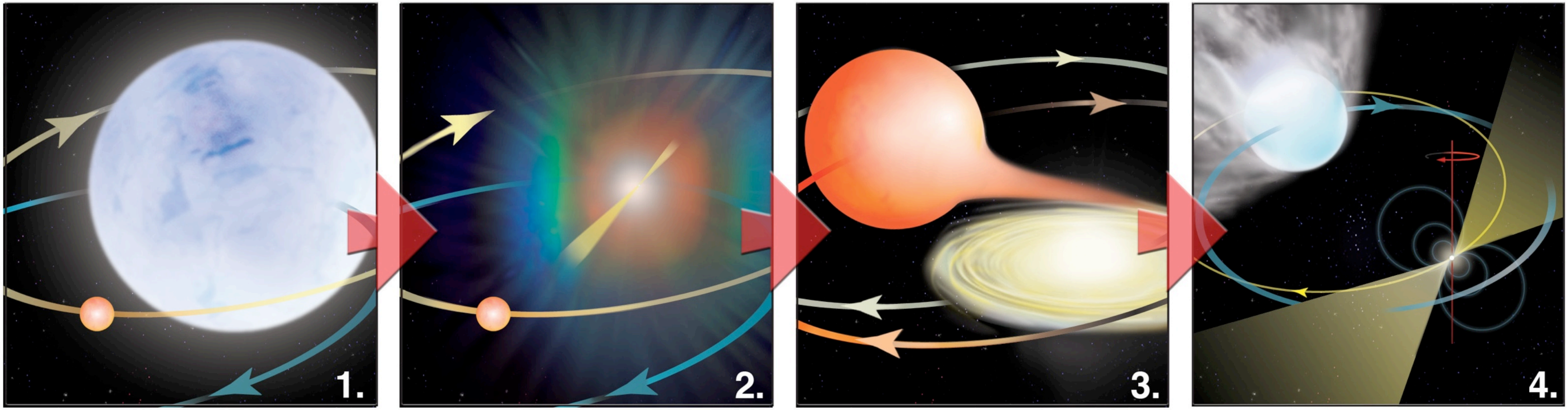
- Black Widows and Redbacks in the context of other radio millisecond pulsars
- Radio eclipses
- Orbital variability
- Black Widows and Redbacks as Transitional millisecond pulsars

# Black Widows and Redbacks in the context of other radio millisecond pulsars

# MSP Formation



# MSP Formation



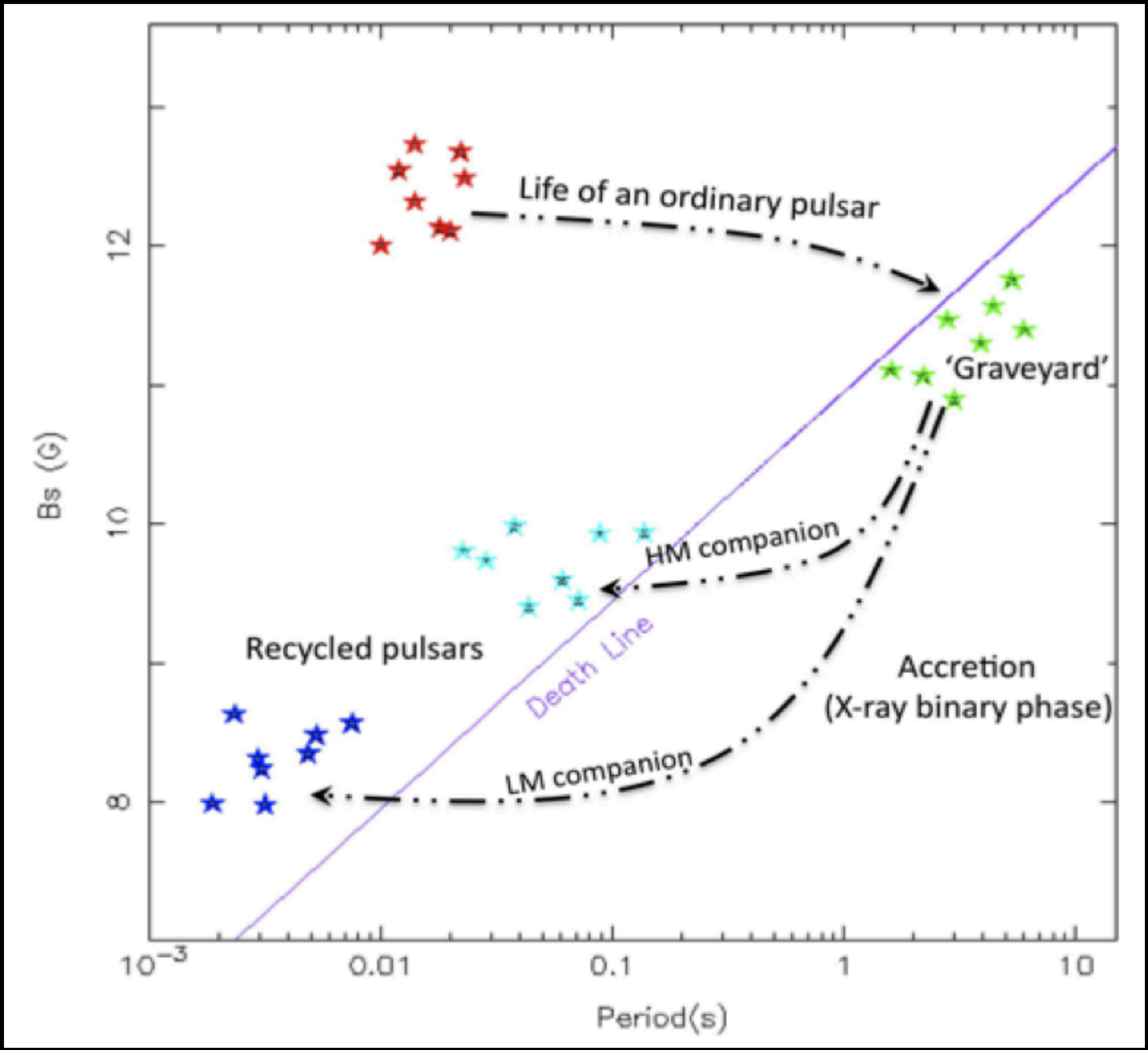

Saxton, NRAO

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

Alpar, Cheng, Ruderman & Shaham1982

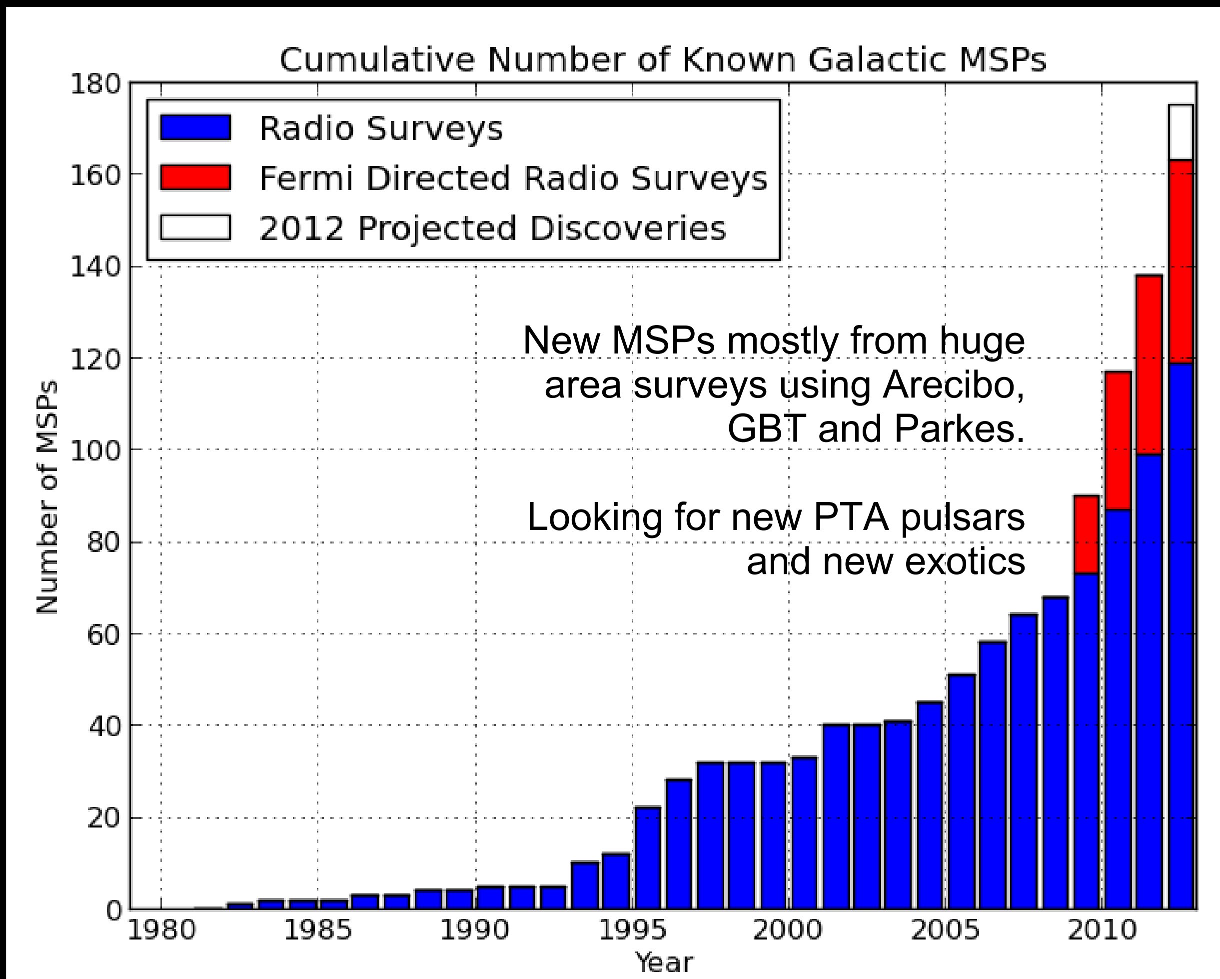
Rhadakrishnan & Srinivasan 1982

# MSP Formation




Stairs

# 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!

# The MSP Menagerie

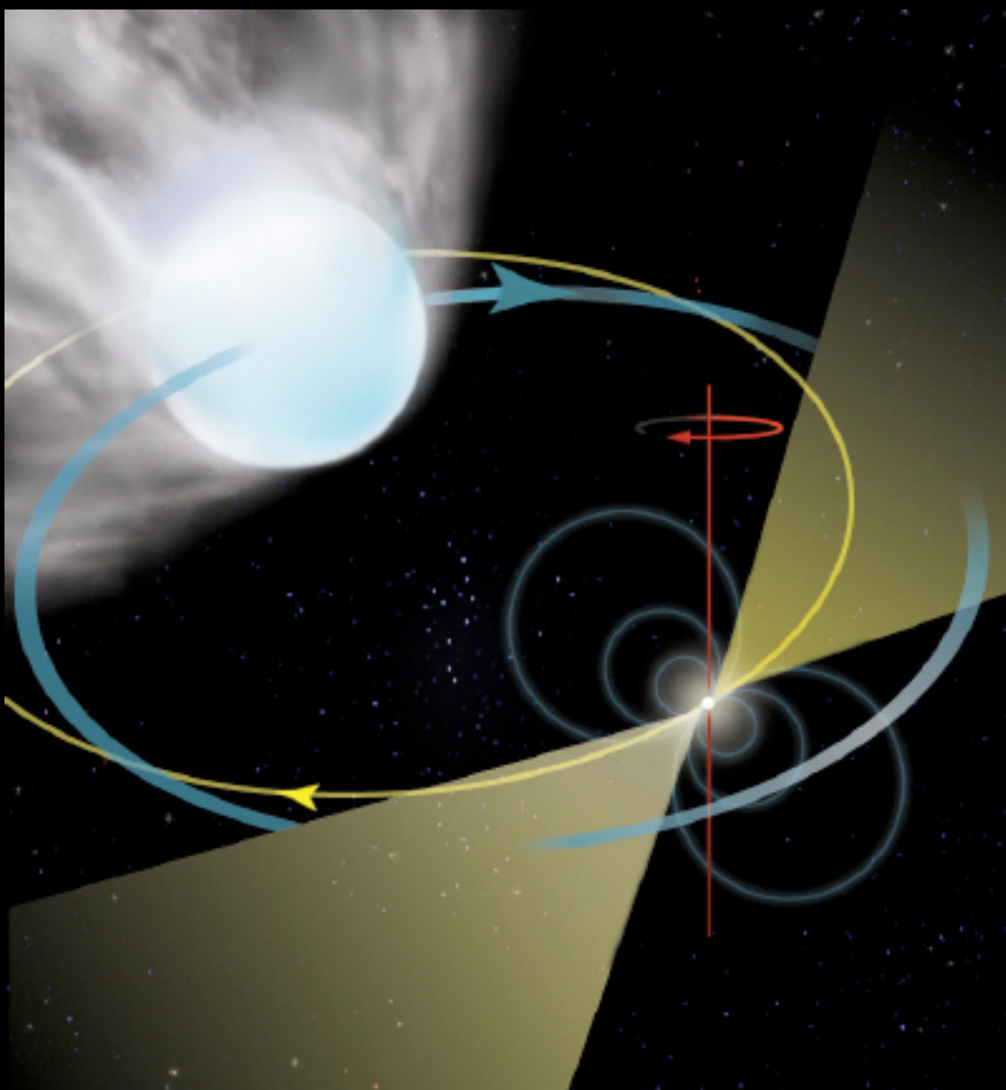
- Helium white dwarf.
- Carbon-oxygen white dwarf.
- Jupiter-mass companion (e.g. the "diamond planet").
- Bloated, post-main-sequence, (*non*)-degenerate companion (0.01 - 0.4 MSun).
- Solar-mass main sequence star (e.g. J1903+0327 )
- Earth-mass planetary companions (e.g. B1257+12).
- Hierarchical 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?)

# MSP "Spiders"

Blame Mallory Roberts

## 'Black Widow' and 'Redback' Pulsar Binaries



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

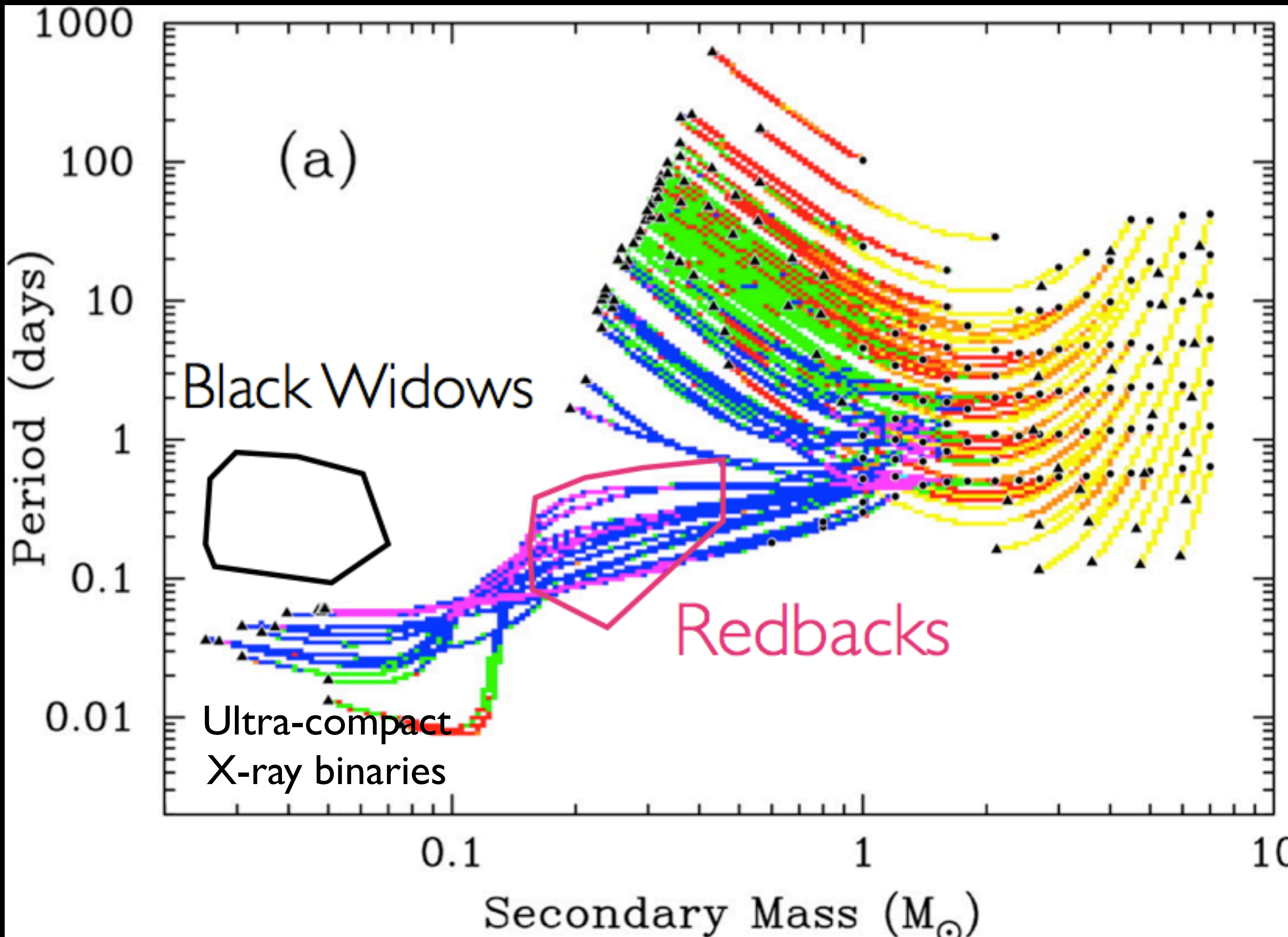
**Black widows:**

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

**Redbacks:**

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

# Porb vs. Comp. Mass

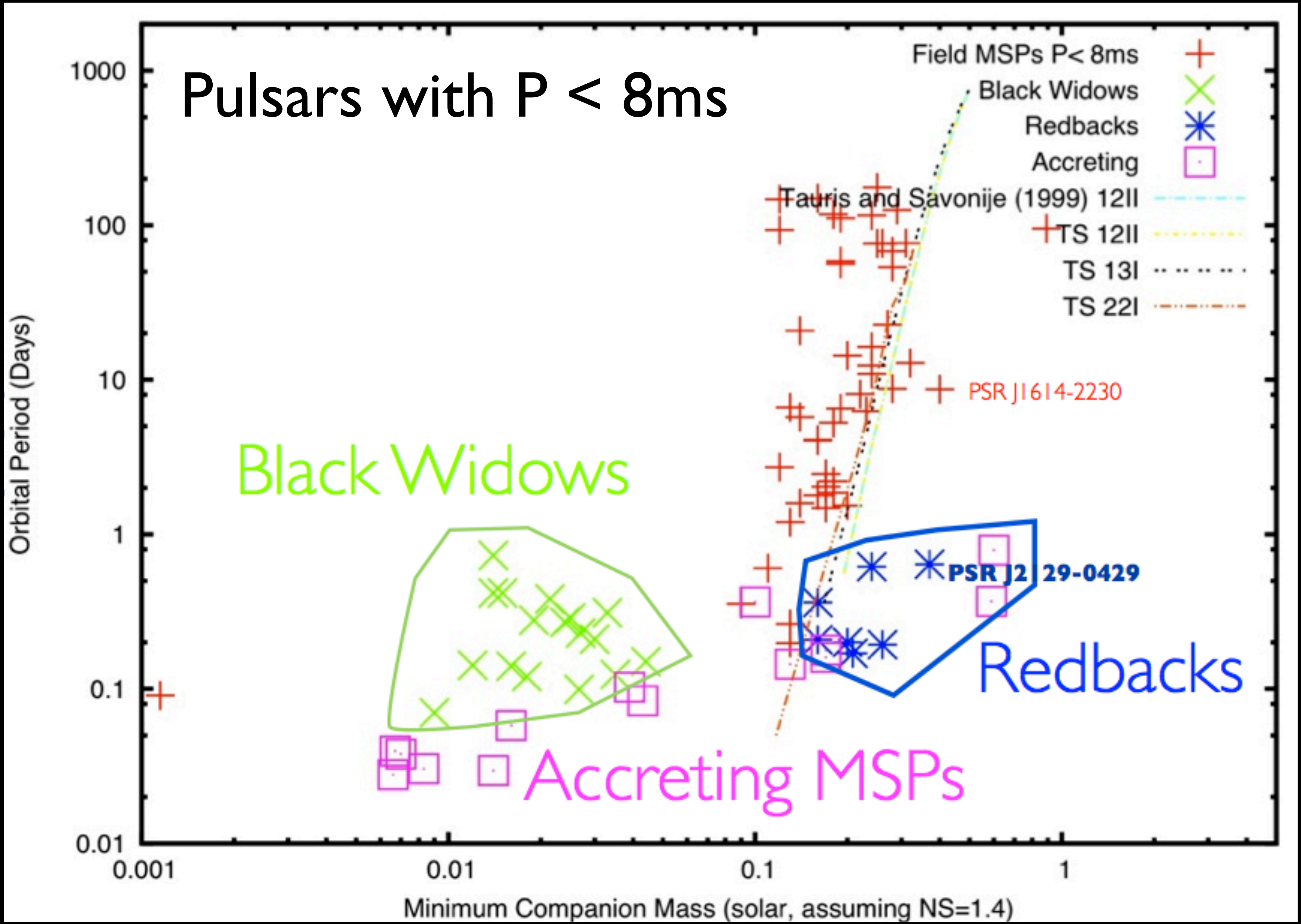



Adapted from Podsiadlowski et al. 2001

What are the evolutionary links, if any?

See talk by Thomas Tauris

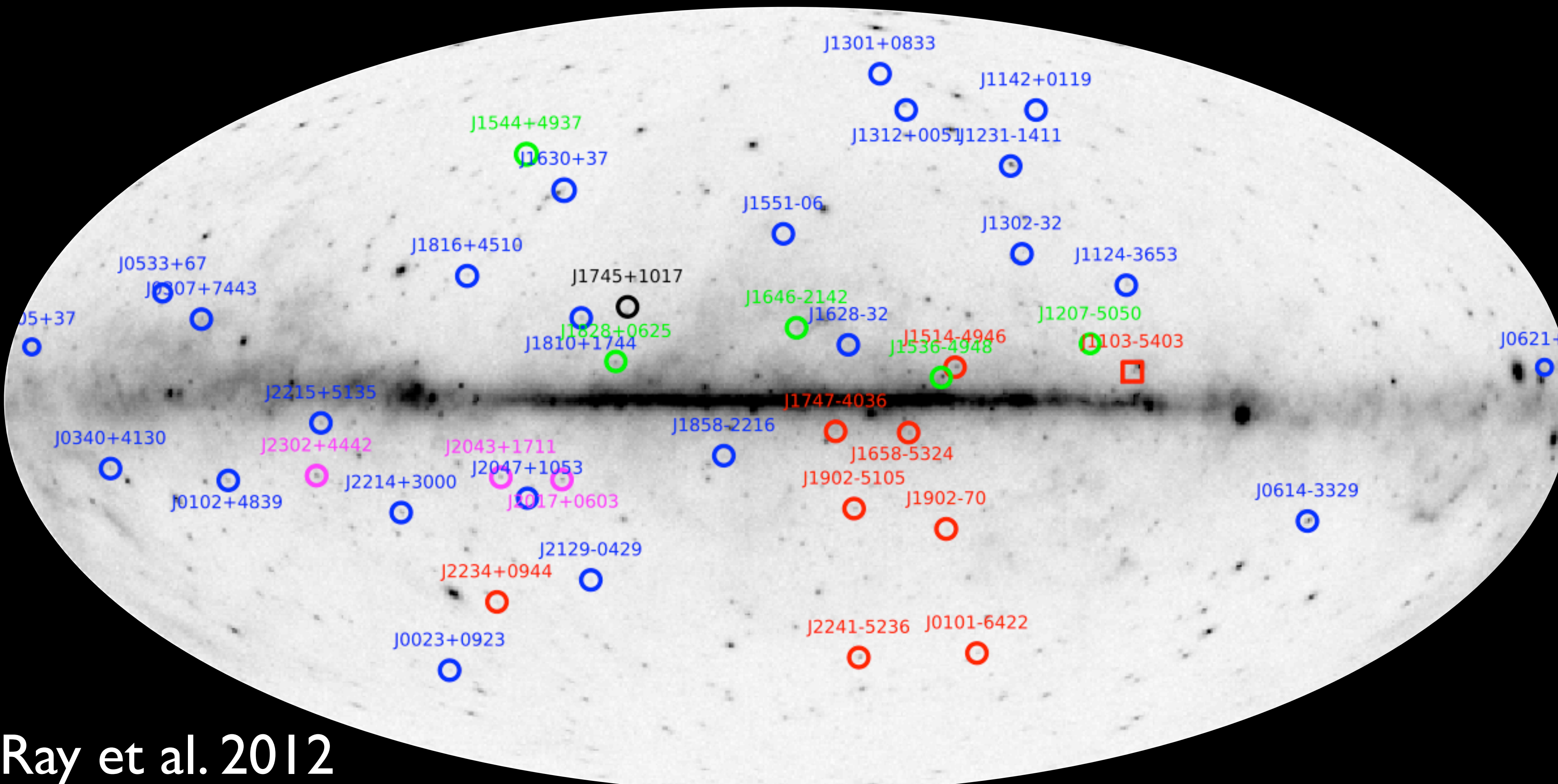
# Porb vs. Comp. Mass




Roberts

See talk Ale Patruno

# Gamma-selected radio MSPs

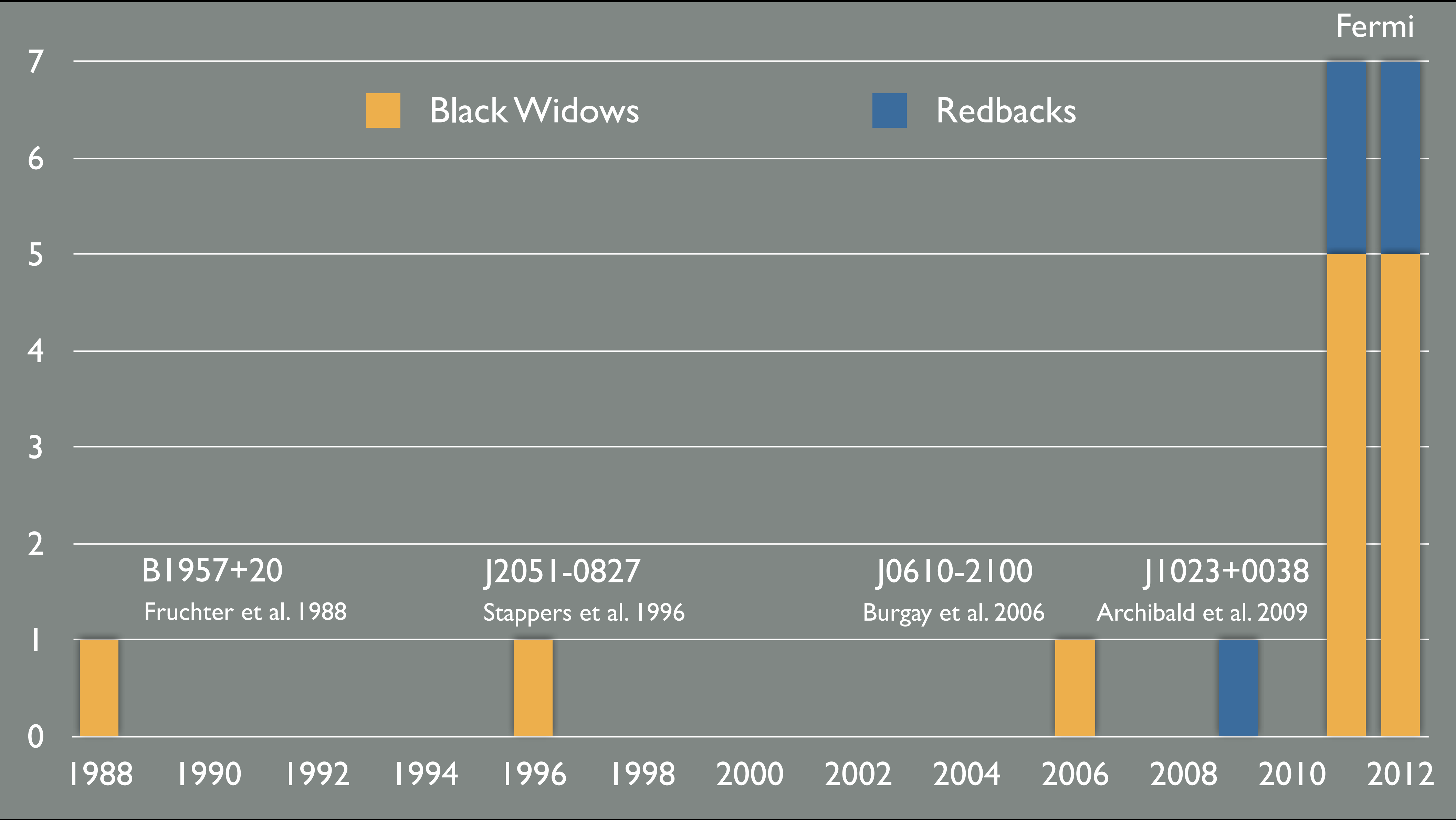



Ray et al. 2012

**>60 as of the latest count!**

Is gamma-ray emission dominated by pulsations?

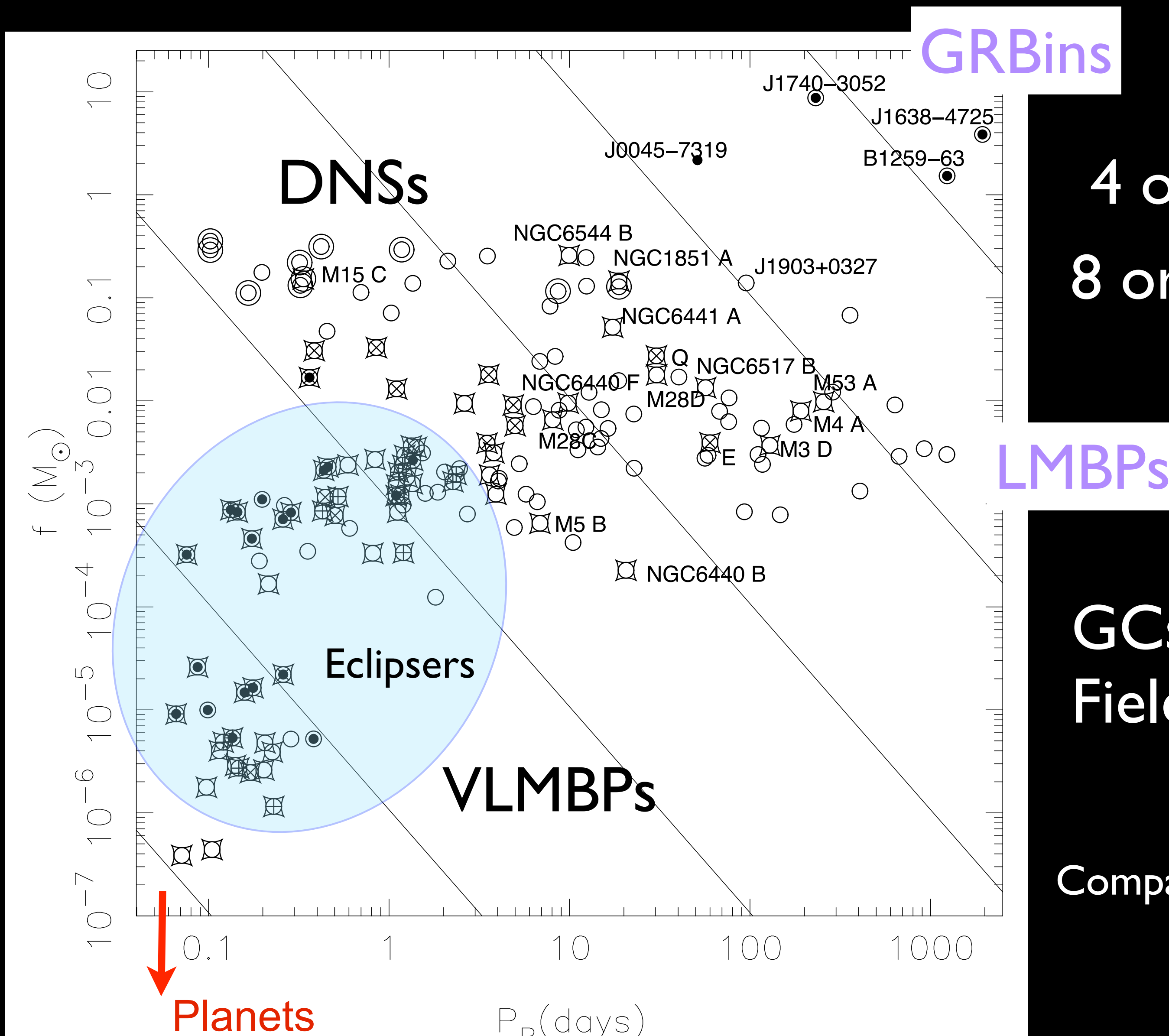
# An Explosion of Spiders




Does not include all the (strange) systems in GCs

# MSP Population

## Orbits




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

4 orders of mag in PB

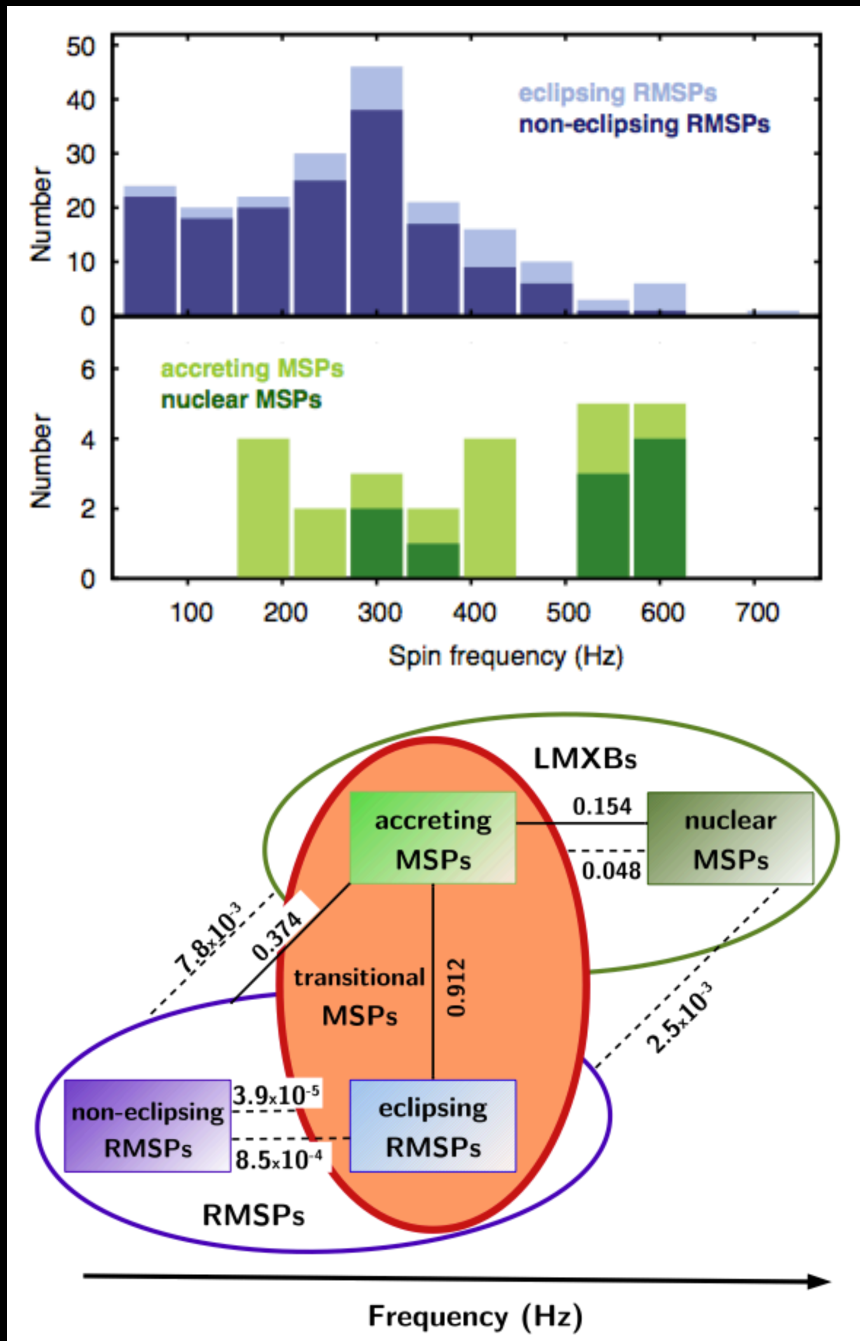
8 orders of mag in f(M)

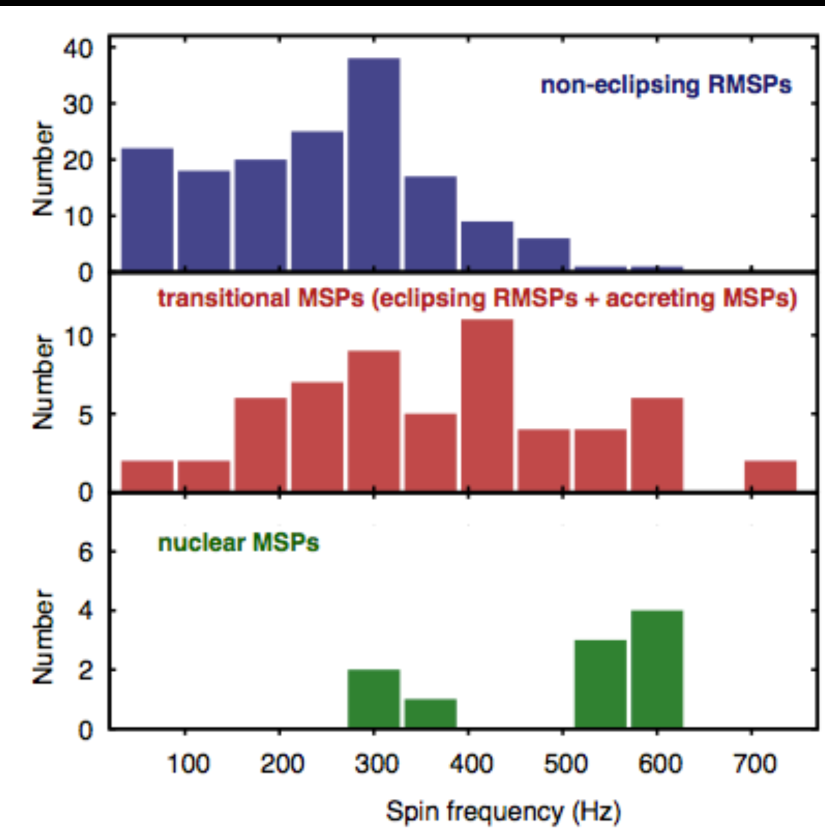
GCs: 18 BWs, 12 RBs

Field: 17 BWs, 8 RBs

Comparable numbers and properties!

# Connecting populations




Papitto et al. 2014

Some evidence that the tMSPs are faster spinners

# “Normal MSPs” vs. Spiders

- Gravity tests
- EOS constraints

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

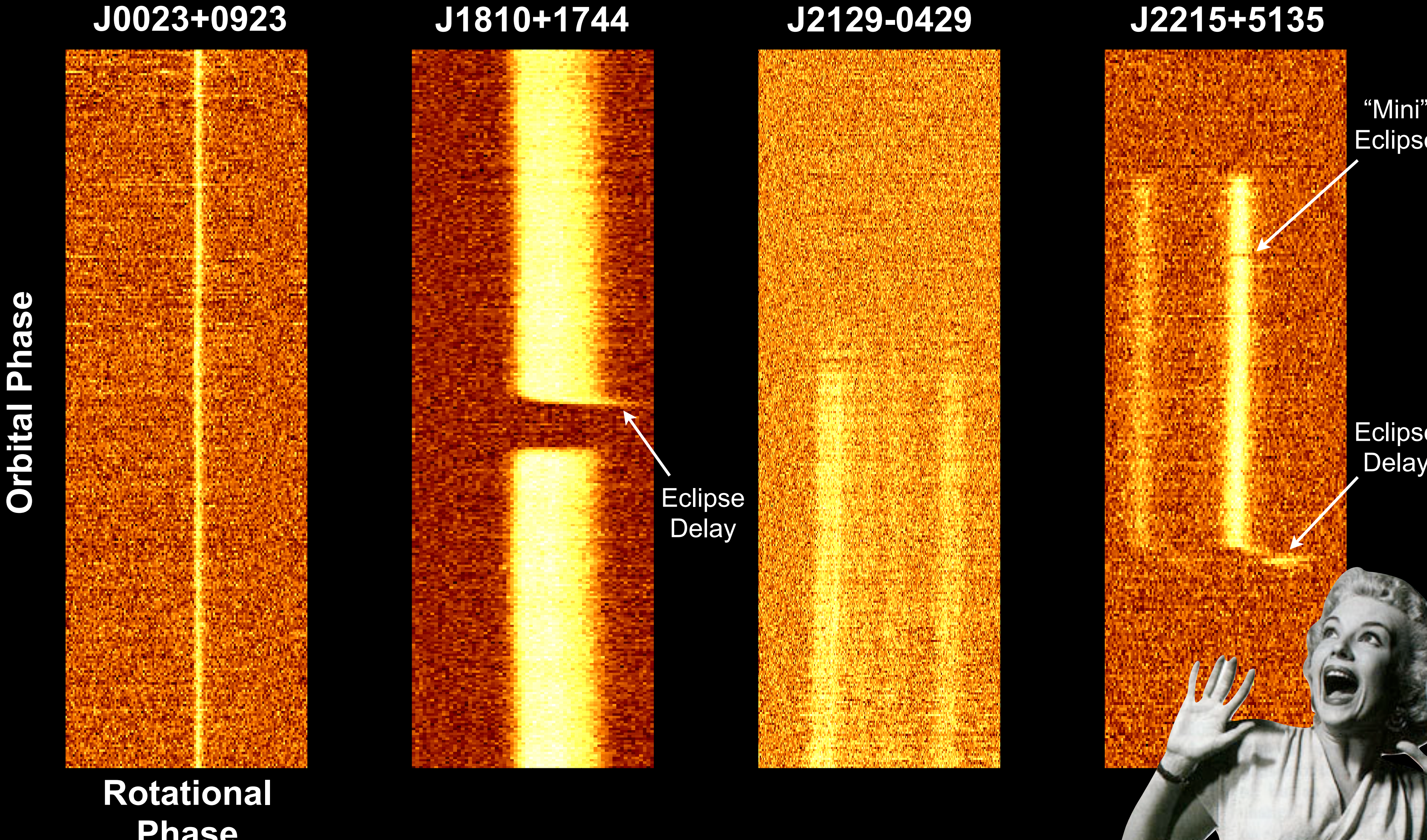
# Summary 1

- Black widows and redbacks aren't *the* formation path to millisecond pulsars.
- Mapping the *rich* formation scenarios of millisecond pulsars.
- MSPs: ~15% black widows and redbacks, ~10% isolated?
- Might be a good place to find the fastest spinners.
- Radio timing critical for maximizing multi-wavelength data.

# Radio eclipses

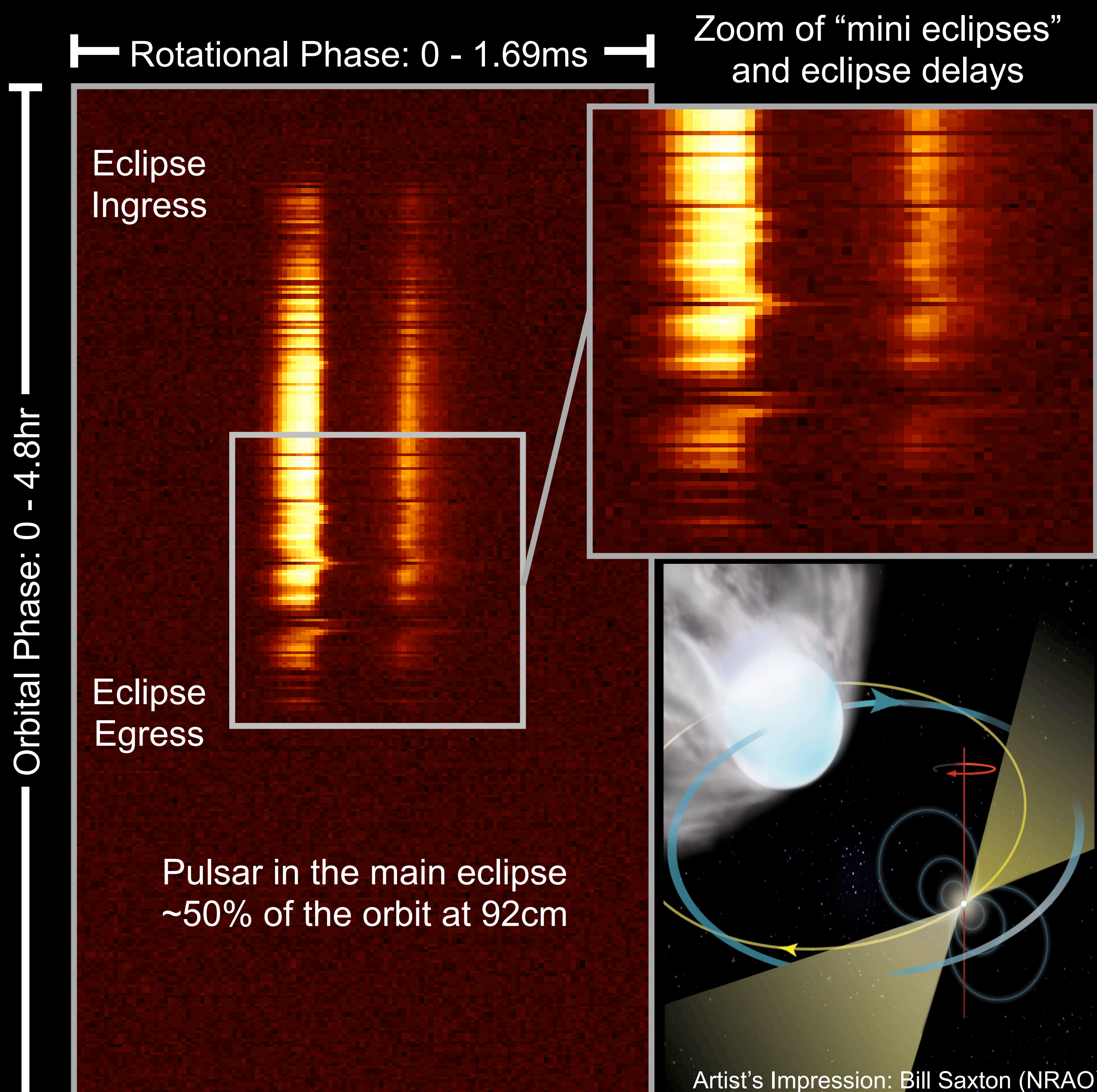
# Eclipsing MSPs

## Westerbork data




Hessels

# MSP Eclipses

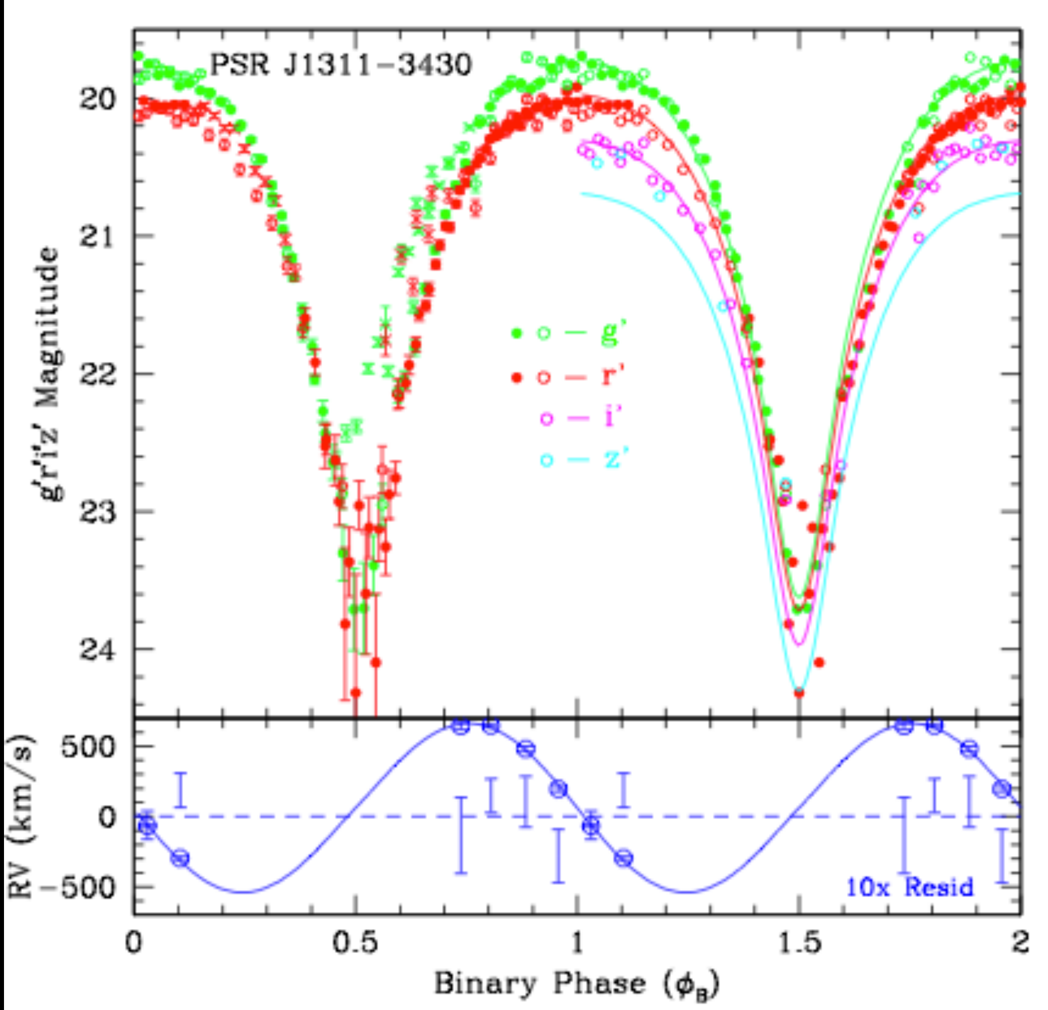



See talk by Stefan Osłowski

Hessels

# (Almost) radio quiet MSPs

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



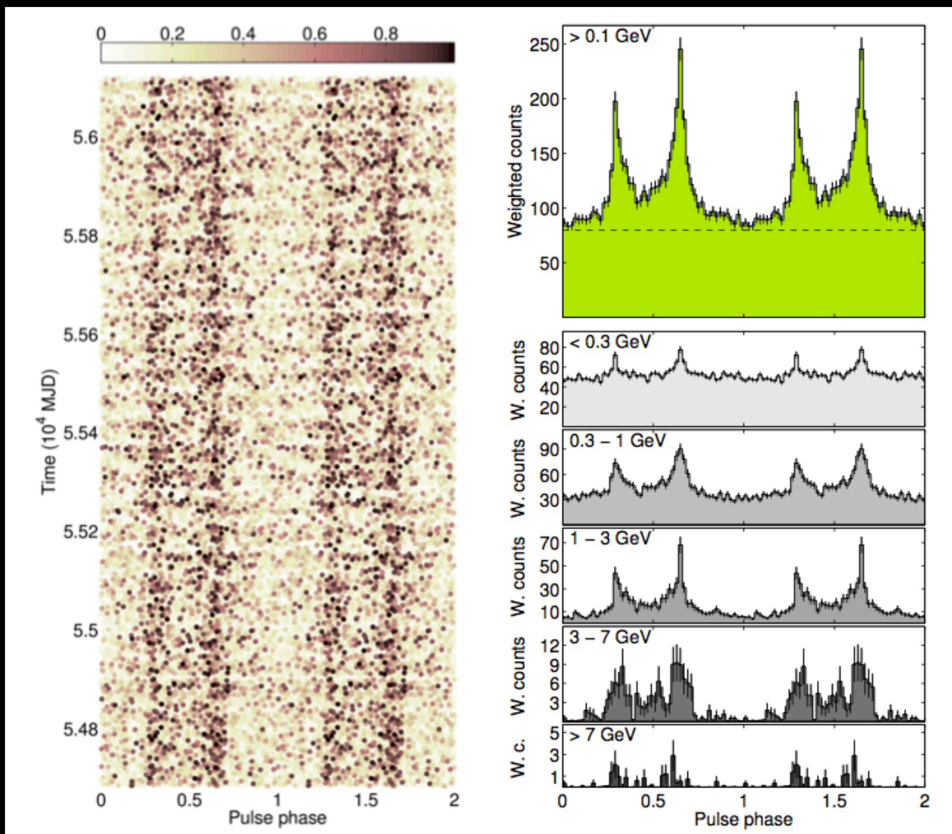

Romani et al. 2012

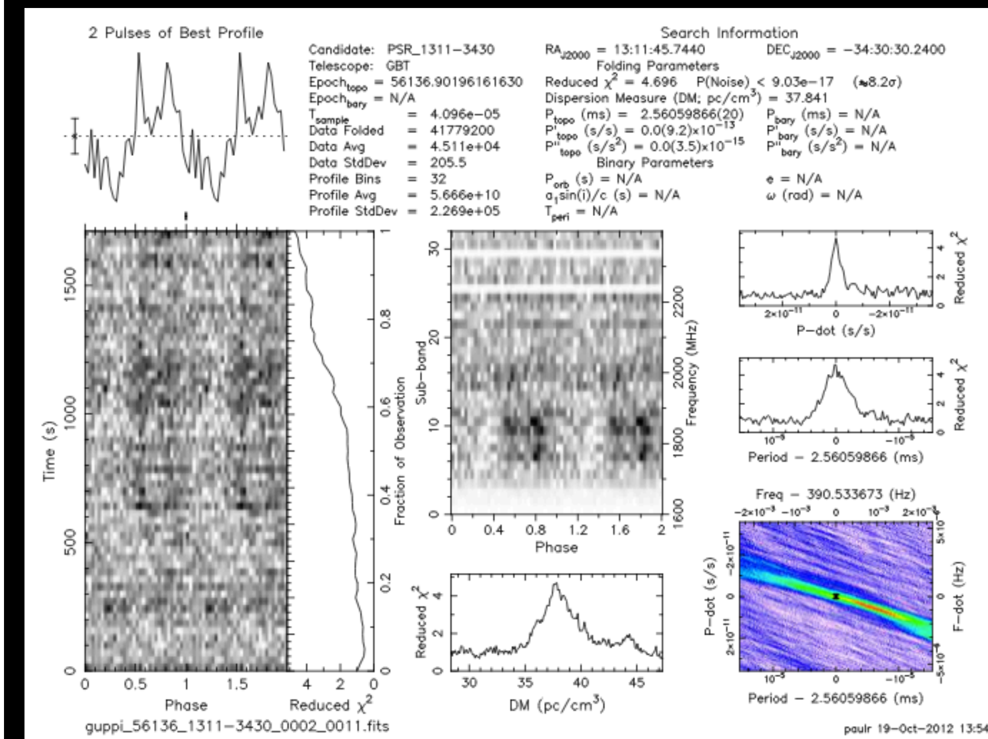
See talk by Roger Romani

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.

See talk by Paul Ray on J2339

# Observational biases

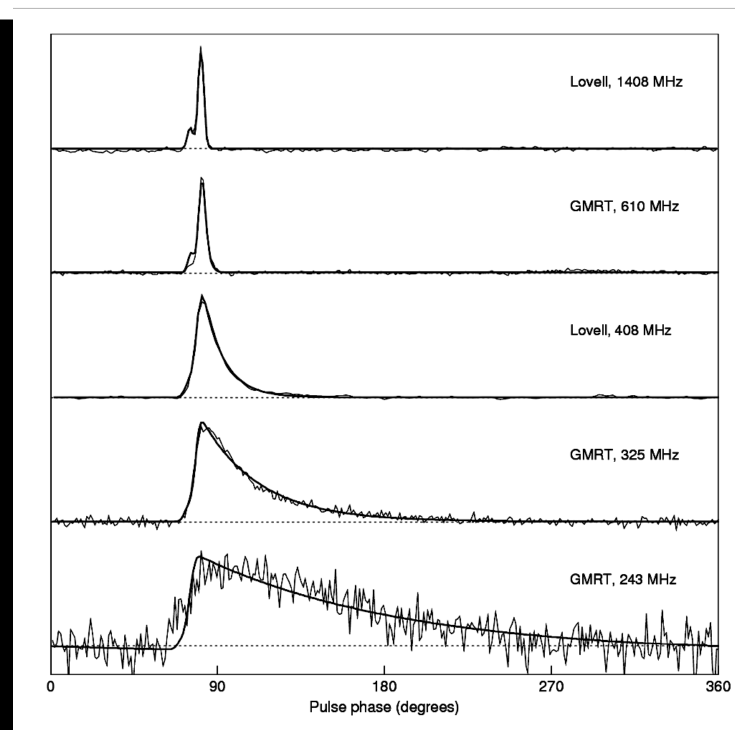
## Propagation effects in the ionized interstellar medium

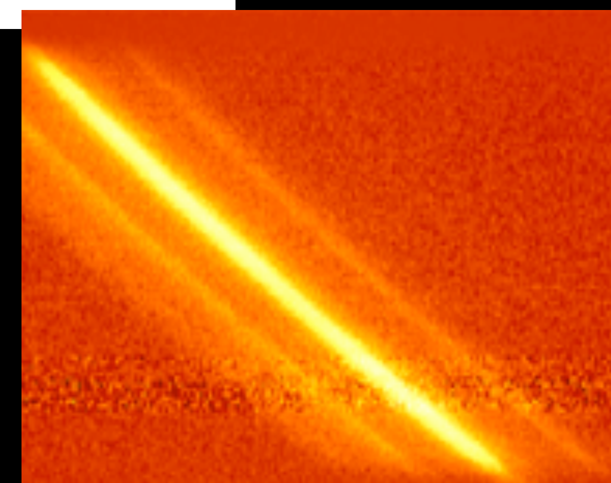
$$I(t) = g_r g_d S(t) * h_{\mathrm{DM}}(t) * h_d(t) * h_{\mathrm{Rx}}(t) + N(t)$$

**Scattering:** multi-path propagation

**Dispersion:** freq. dependent arrival time

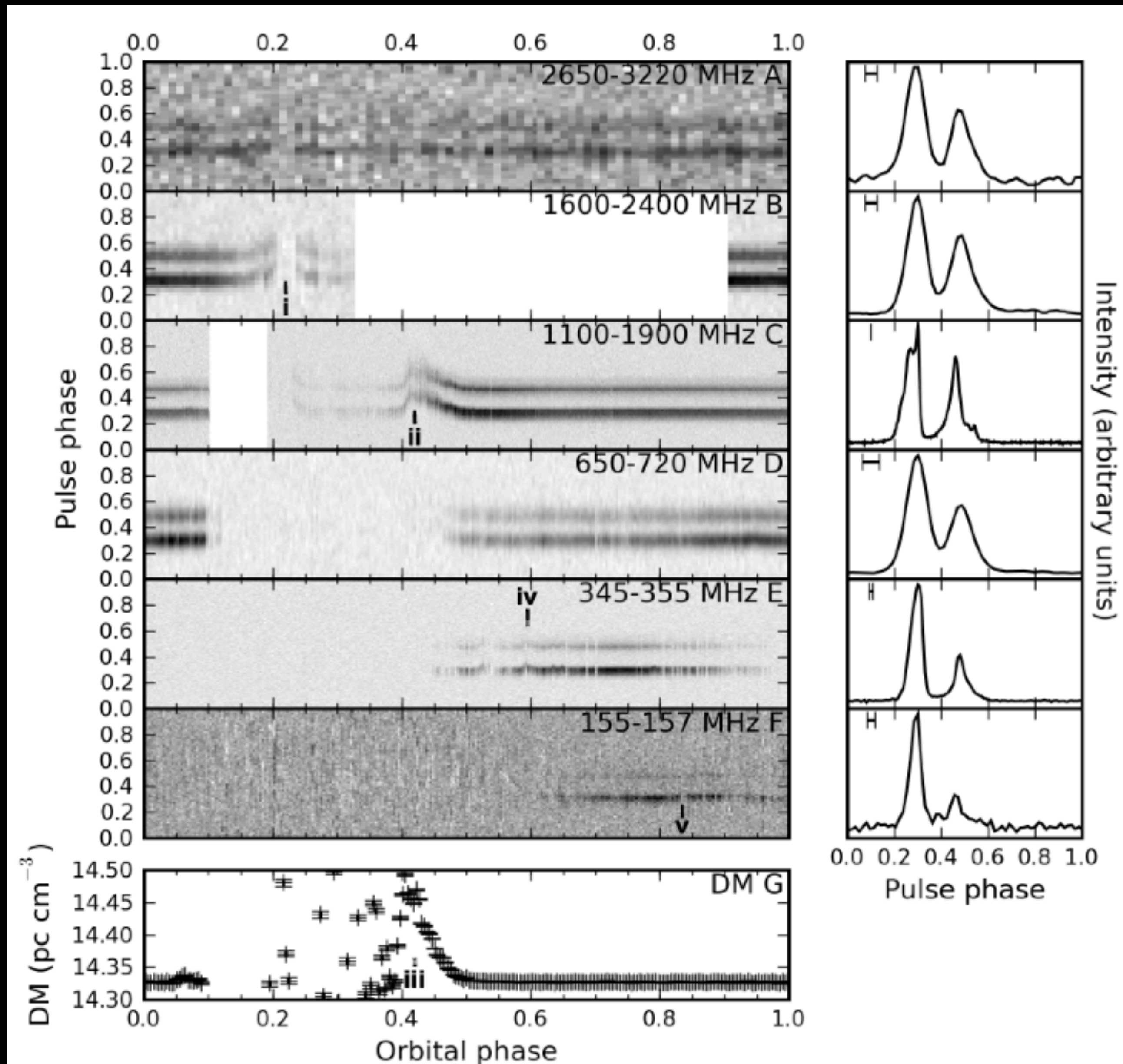
**Scintillation:** const./dest. interference



These are being mitigated better than ever before but they still limit our "detection horizon"

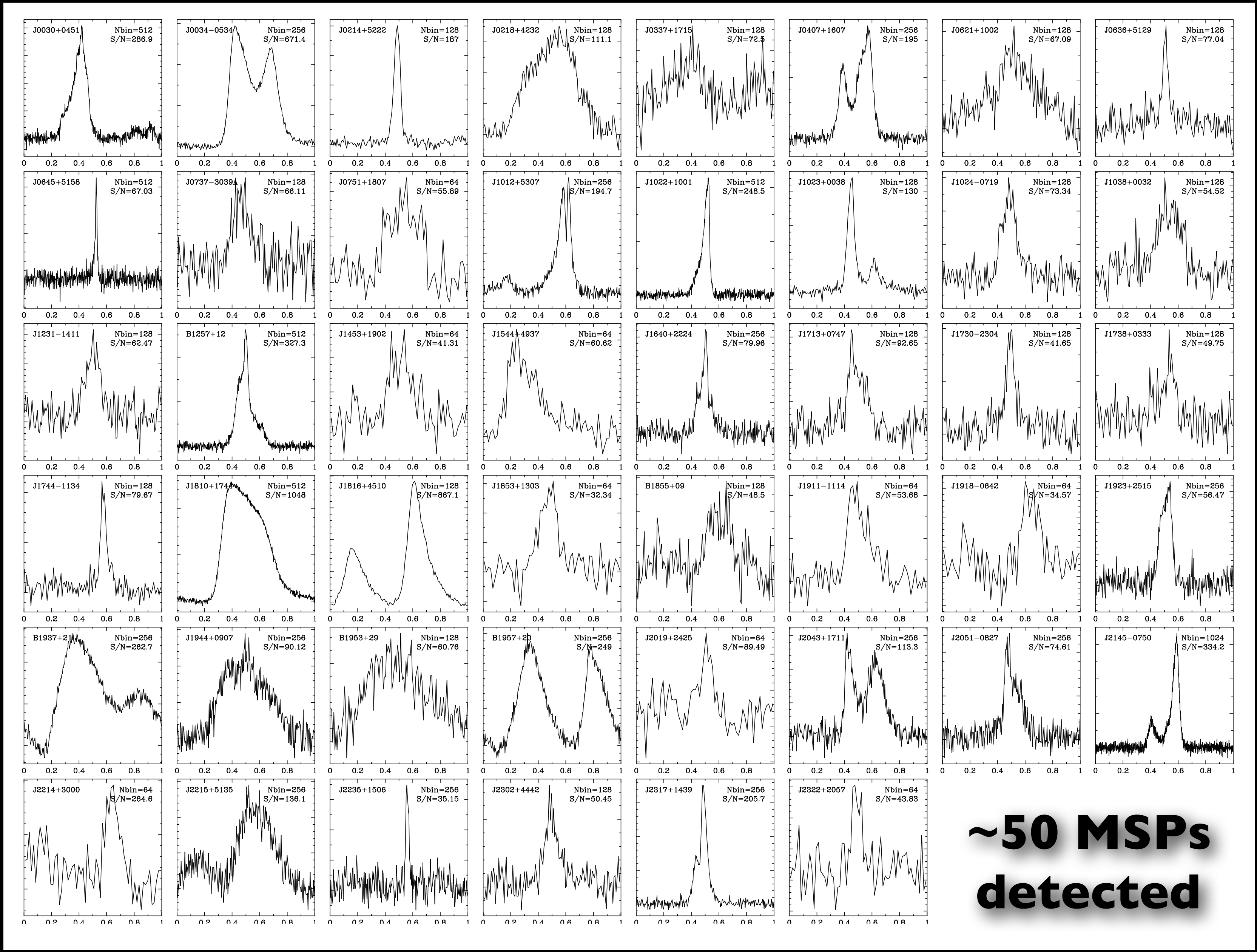
# Eclipse Frequency Evolution




Archibald et al. 2009

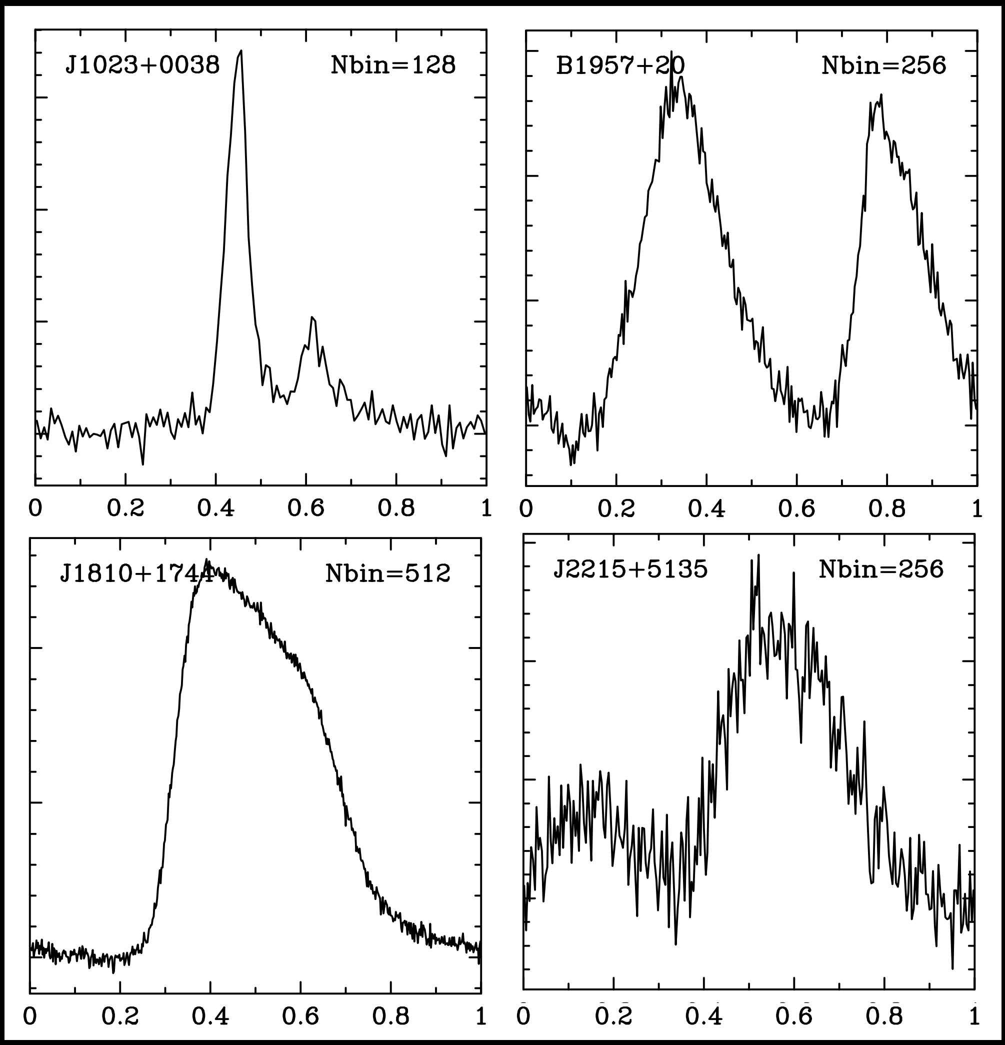
...and this is why we're trying to find J1023 with Arecibo at 5GHz

# LOFAR Millisecond Pulsars

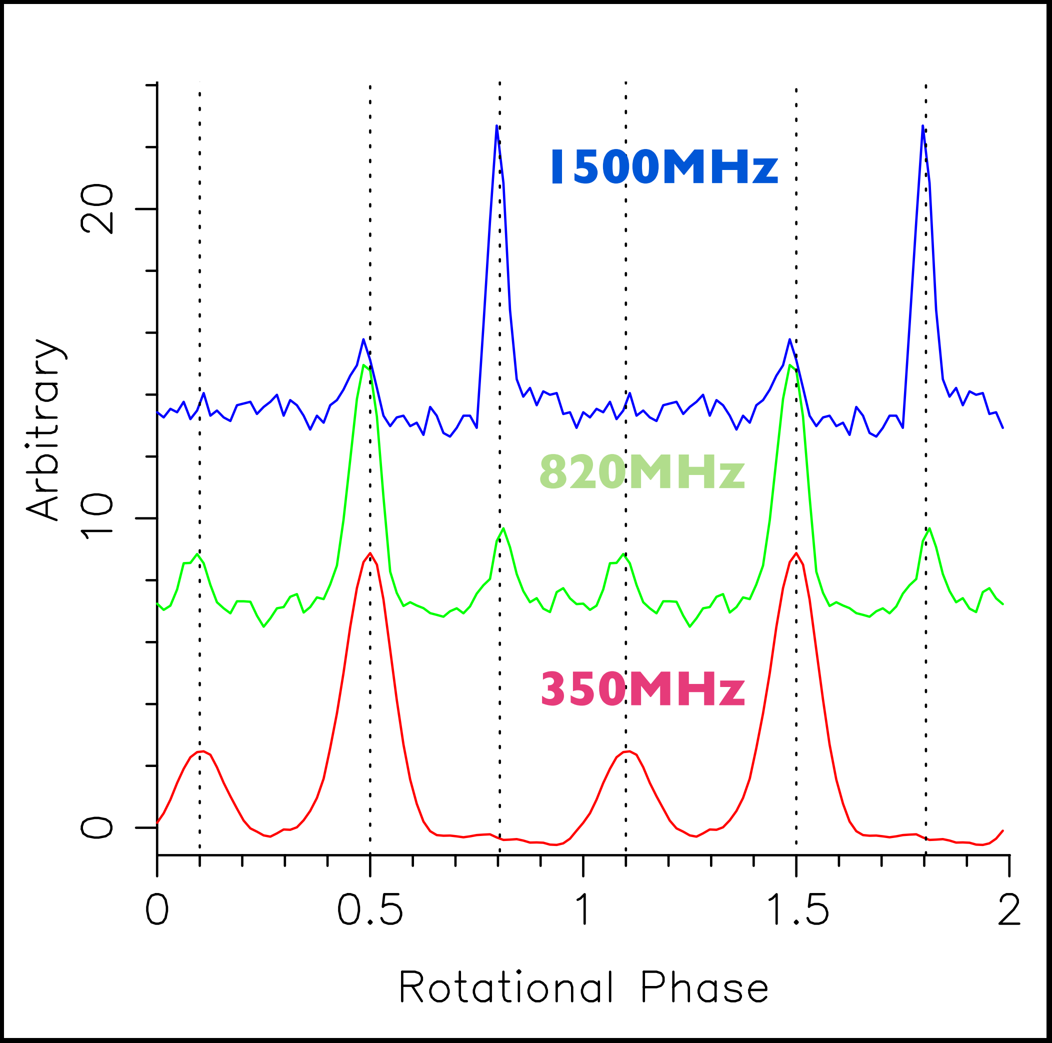



Kondratiev The premier low-frequency sample

# Some LOFAR Spiders

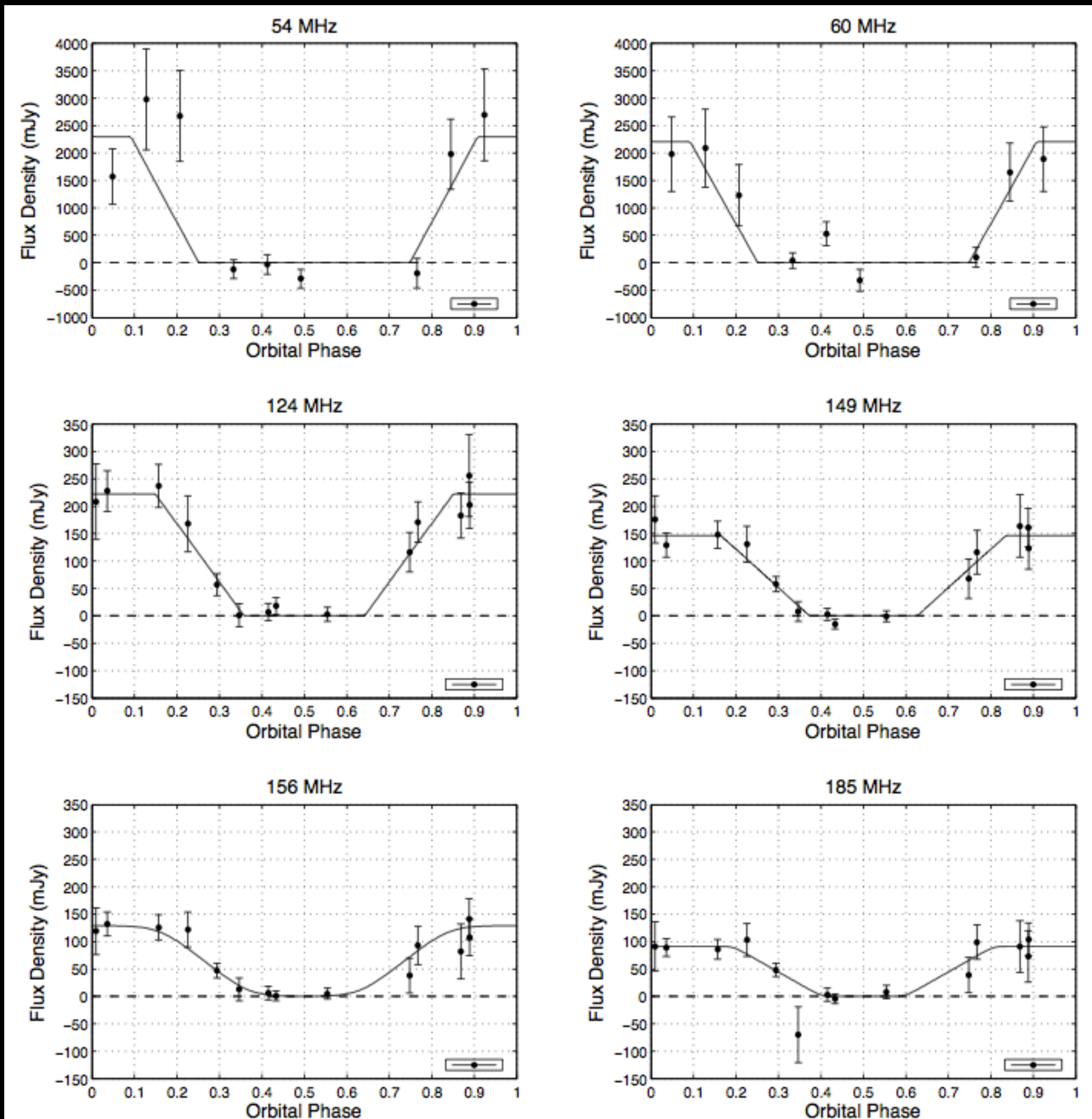



Kondratiev




Hessels

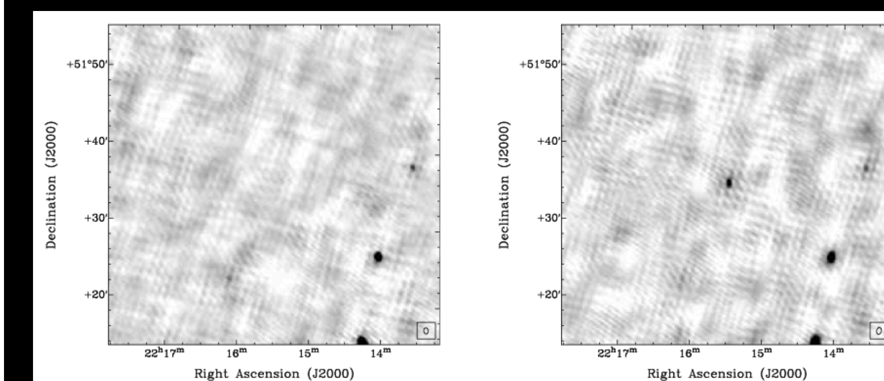
# LOFAR Radio Sky Monitor




PSR J2215+5135

In eclipse

Out of eclipse



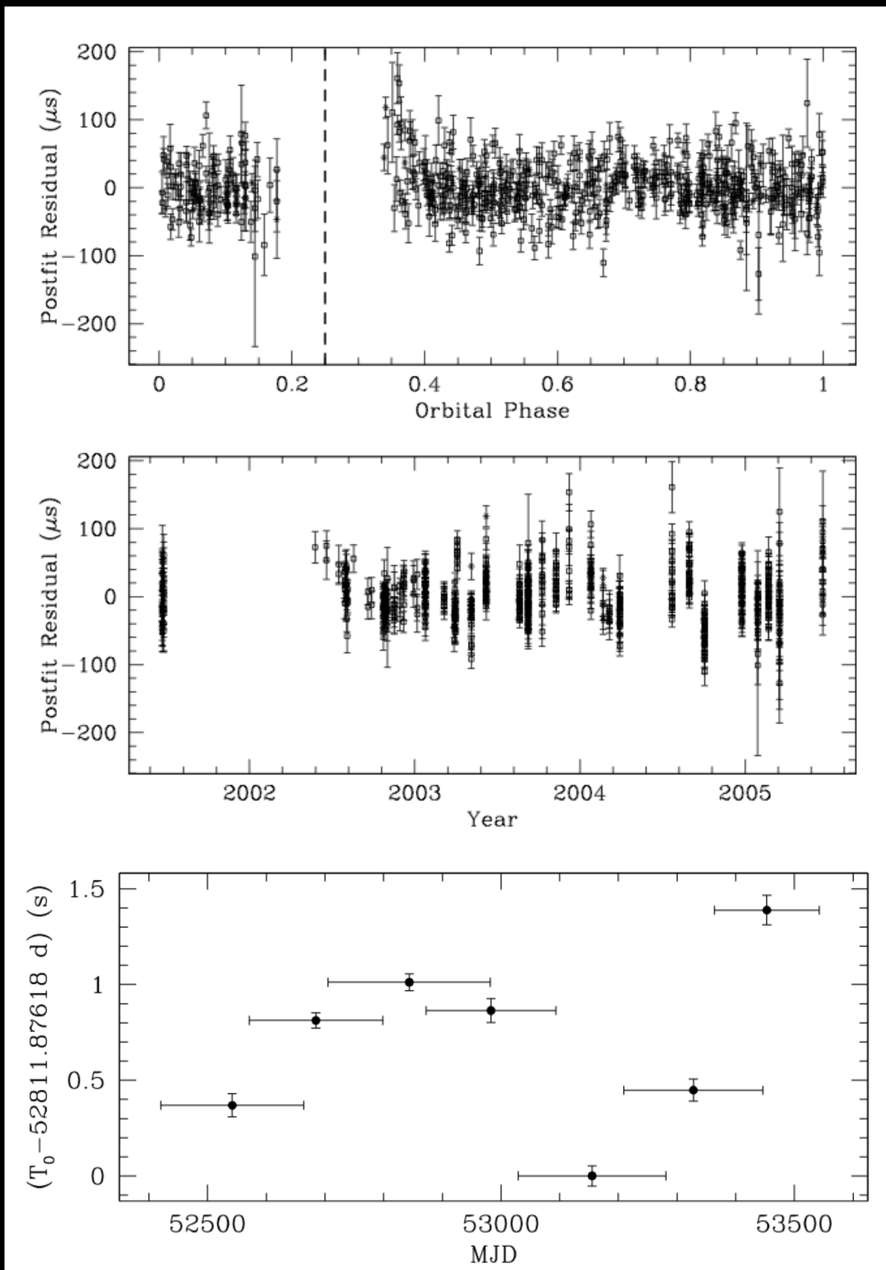

Broderick et al. 2015, submitted

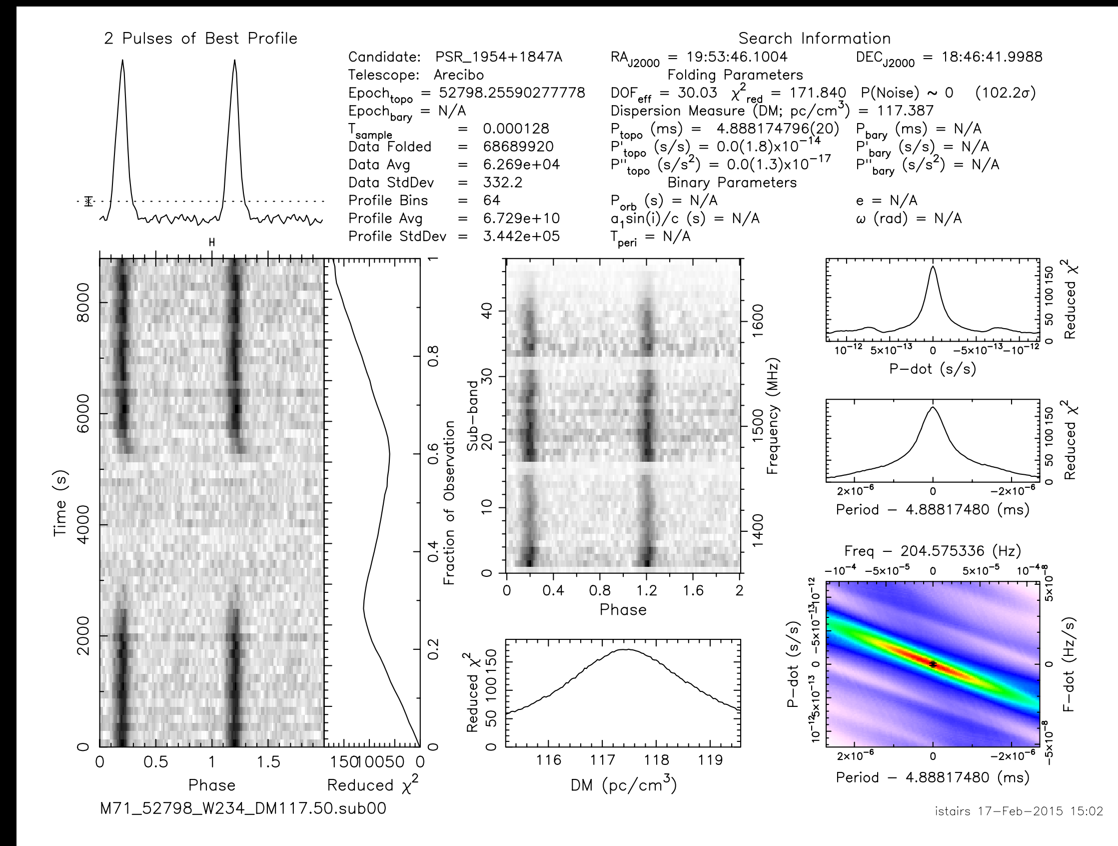
# Summary 2

- Radio eclipsing larger for redbacks than black widows.
- Frequency dependent.
- Some sources (e.g. J2339) are (nearly) perpetually enshrouded.
- Several “spiders” are really bright at the lowest radio frequencies (we’re going to try a blind search).
- Blind searches in the imaging domain hold some promise.

# Orbital variability

# M71A



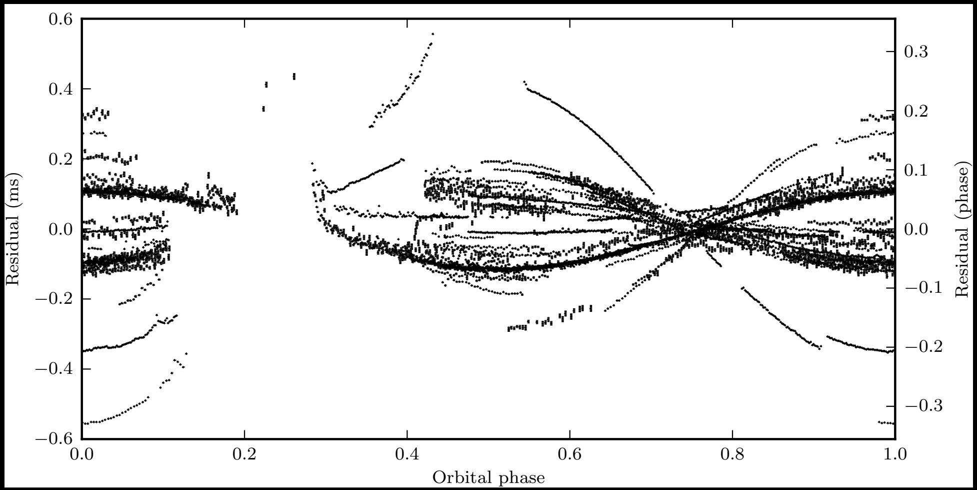



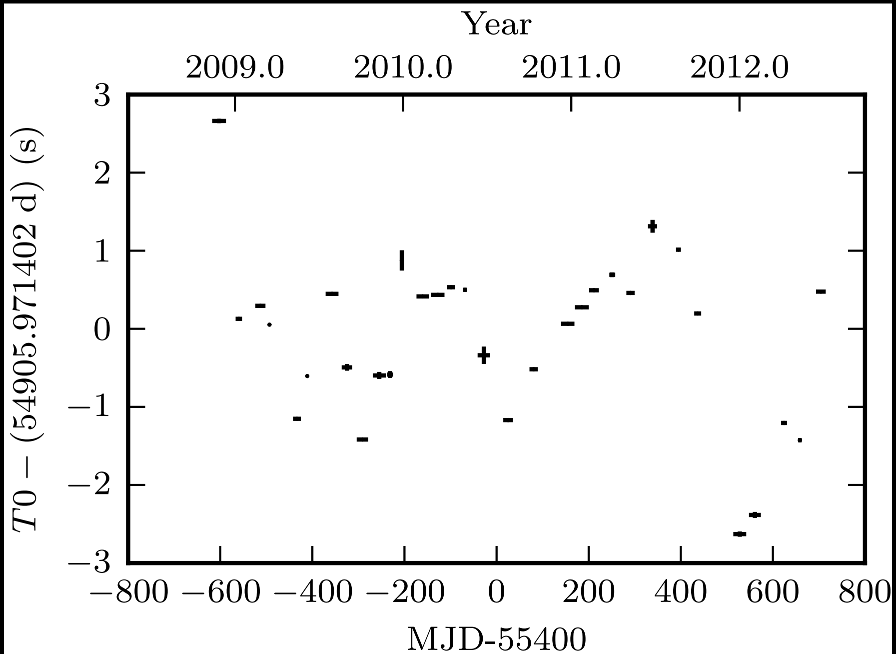

Pspin = 4.9ms
Porb = 0.18d
Mcomp = 0.03MSun

See talk by Mario Cadelano

Cadelano et al. 2015

# PSR J1023+0038




Archibald et al. 2013

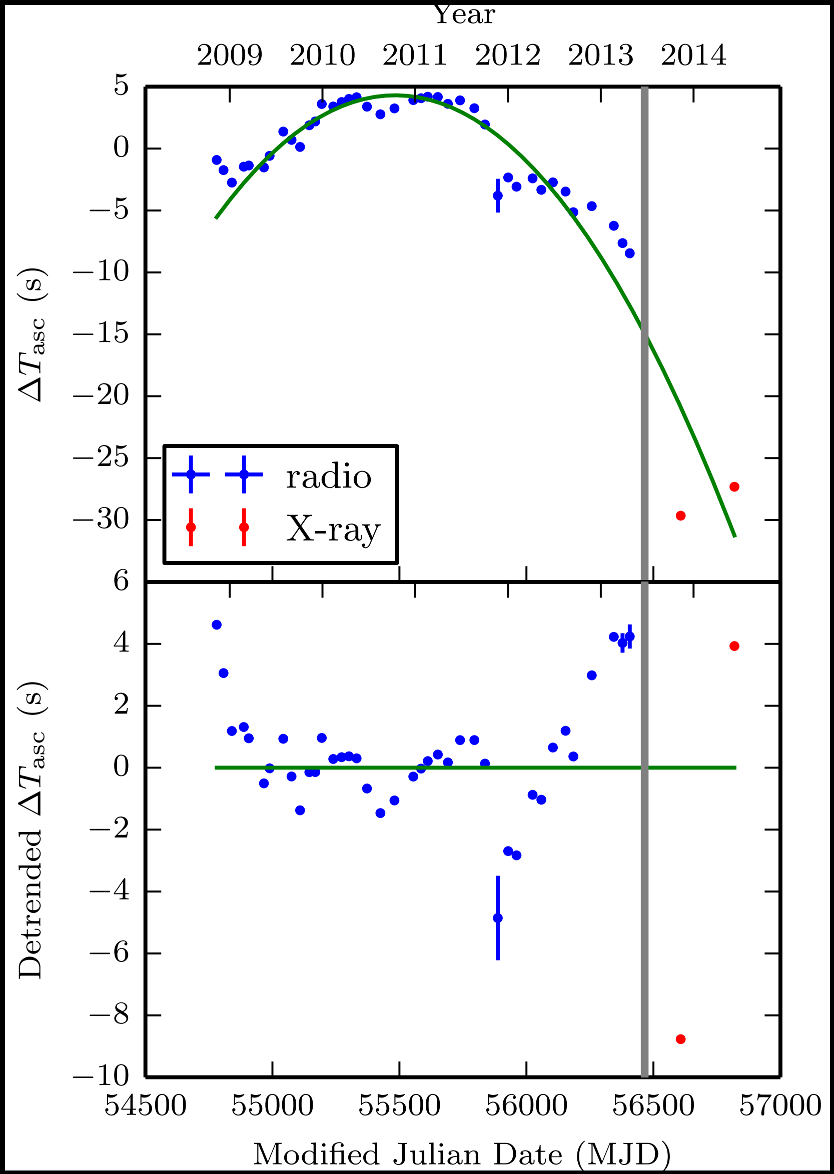
For the benefit of the non experts: this is a mess!

Can we disentangle the orbital noisiness from the (clean?) pulsar spin.

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

See talk by Anne Archibald

# PSR J1023+0038

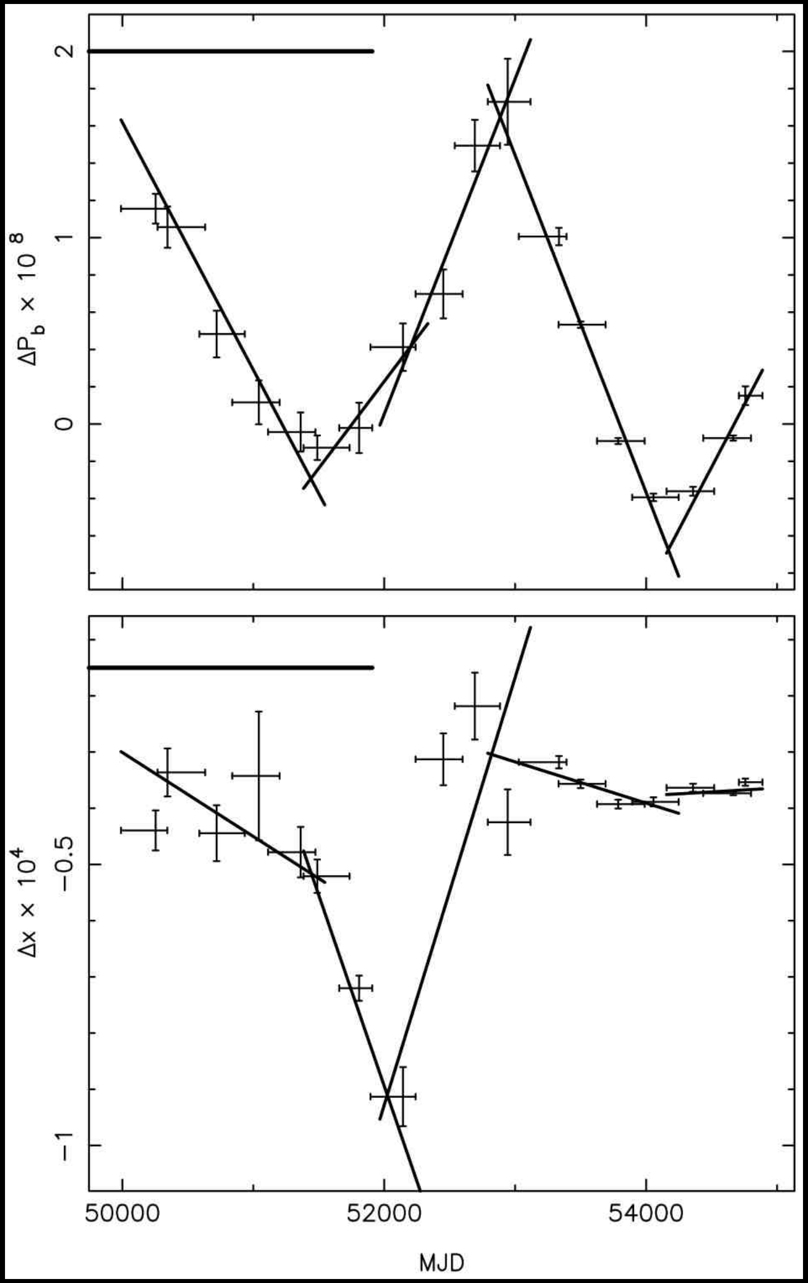



Pspin = 1.7ms
Porb = 0.20d
Mcomp = 0.13MSun

See talk by Amruta Jaodand

Archibald et al. 2015

# PSR J2051-0827



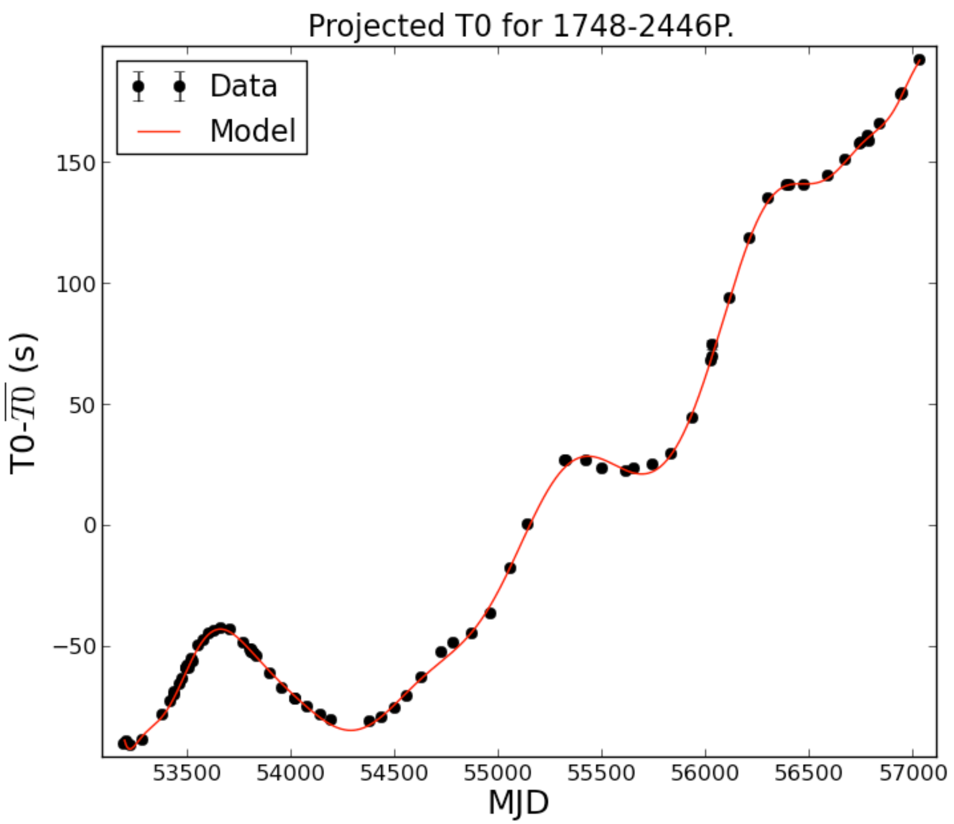

Lazaridis et al. 2011

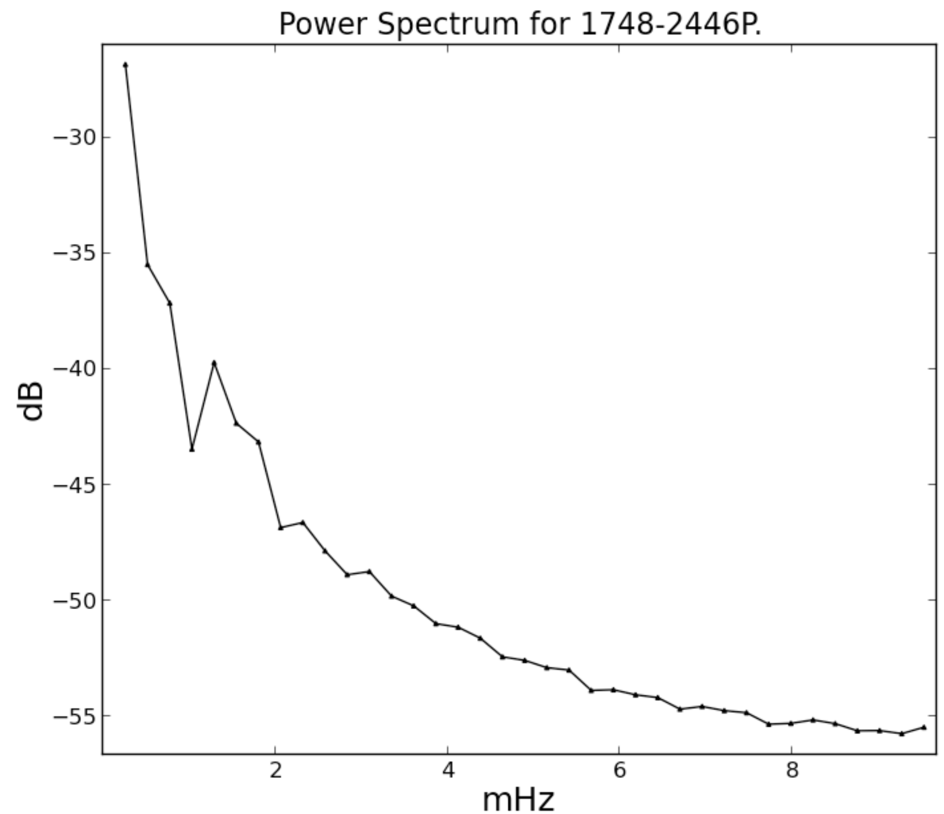
This variability isn't secular or periodic.

See talk by Stefan Osłowski

Pspin = 4.5ms
Porb = 0.10d
Mcomp = 0.03MSun

# Ter5P



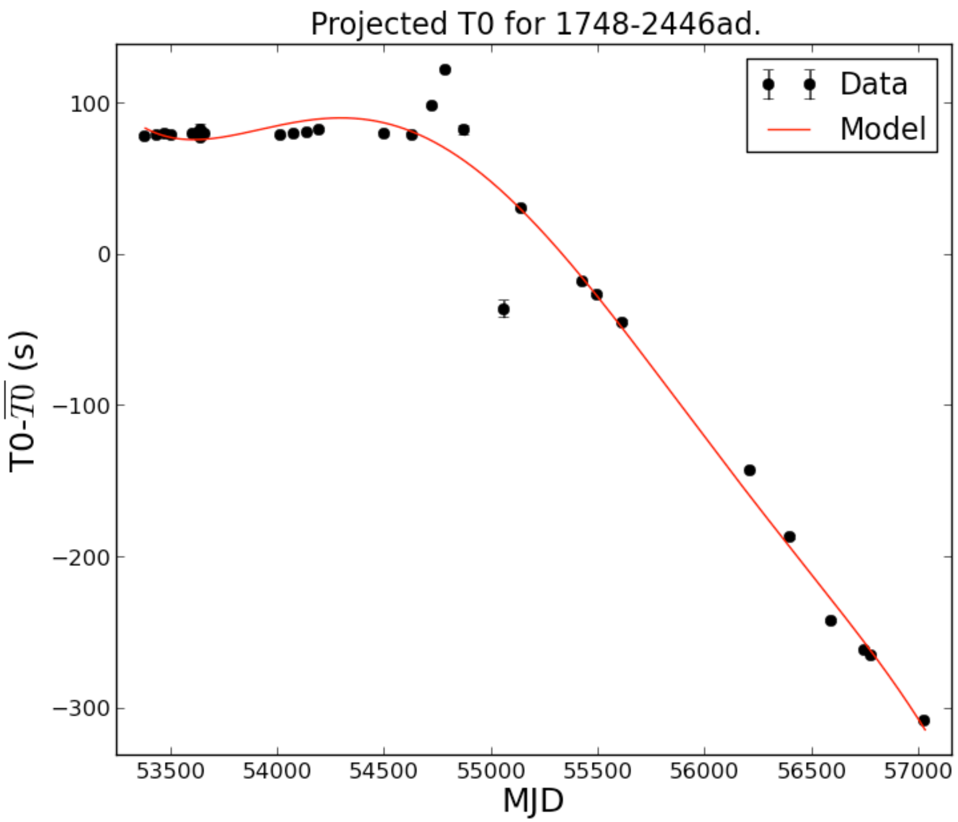



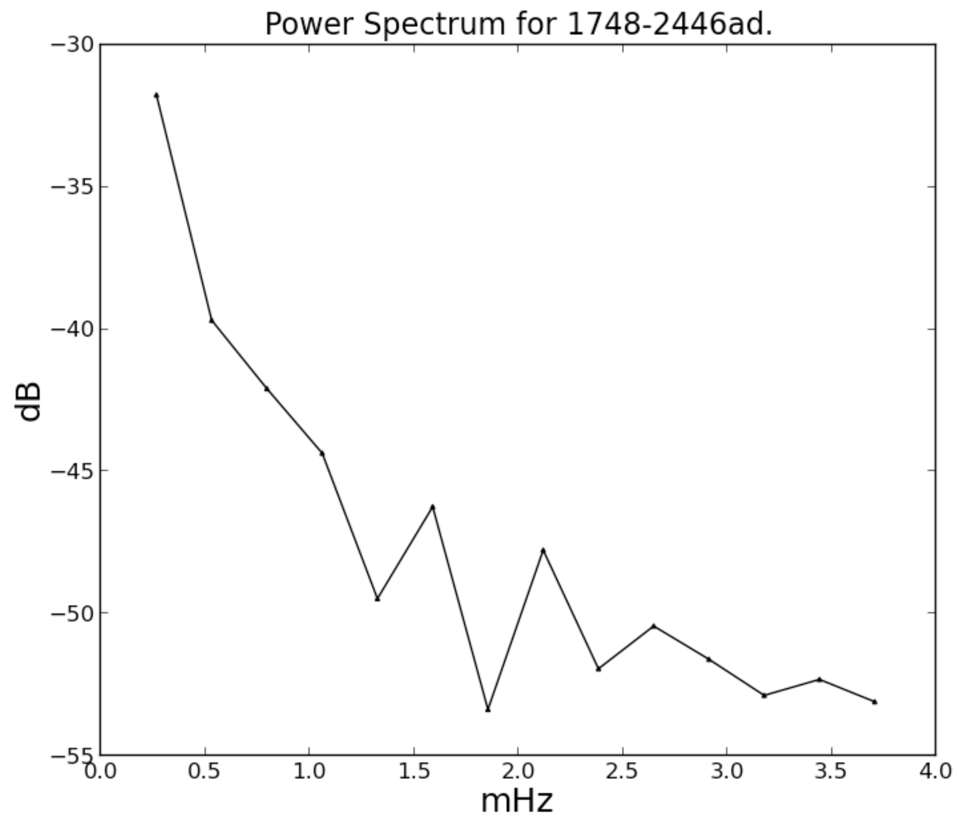

Prager

Talk to Brian Prager at coffee, dinner!

Pspin = 1.7ms
Porb = 0.4d
Mcomp = 0.44MSun

# Ter5ad

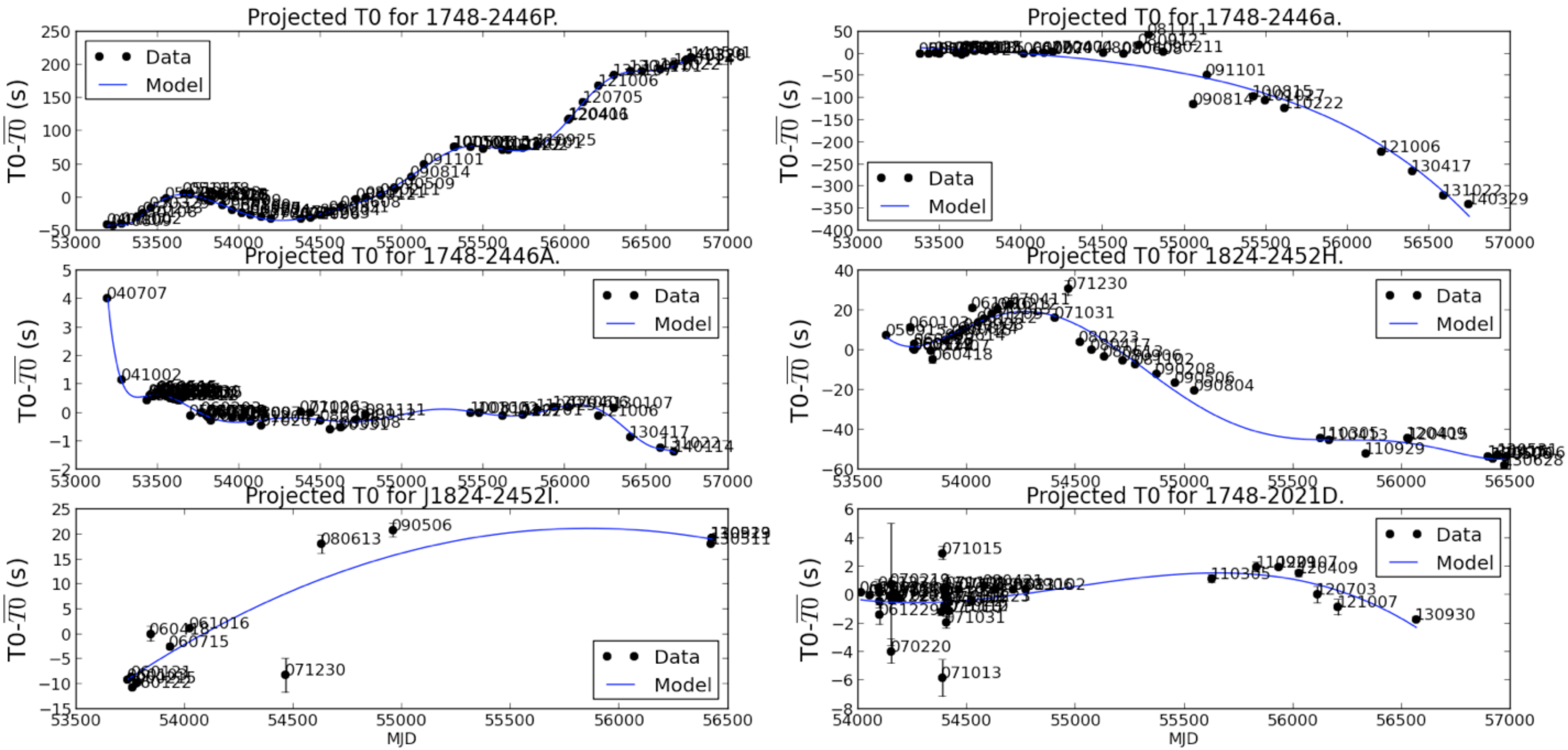



Prager

Pspin = 1.4ms
Porb = 1.1d
Mcomp = 0.16MSun

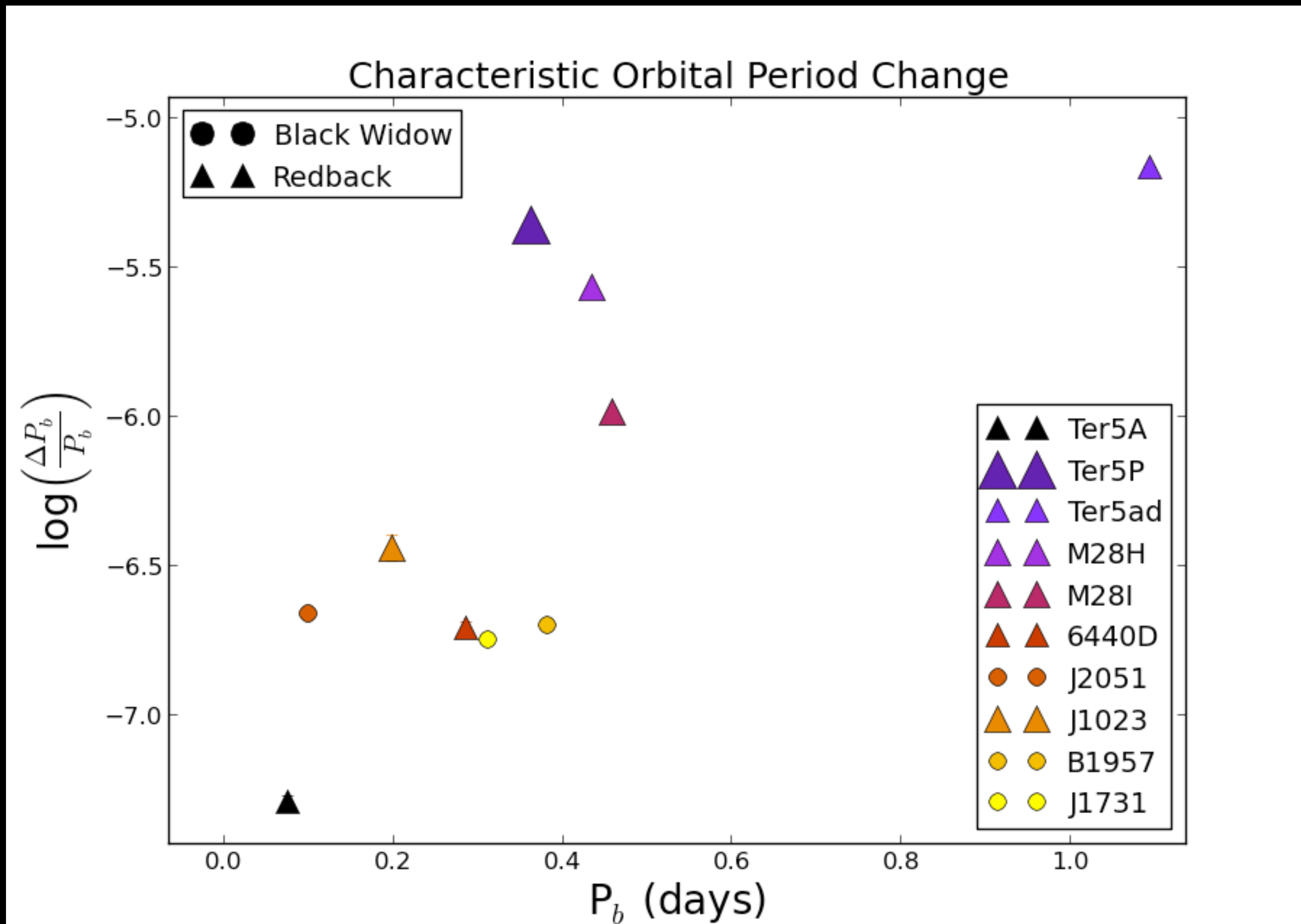
# Comparing T0 variations




Prager

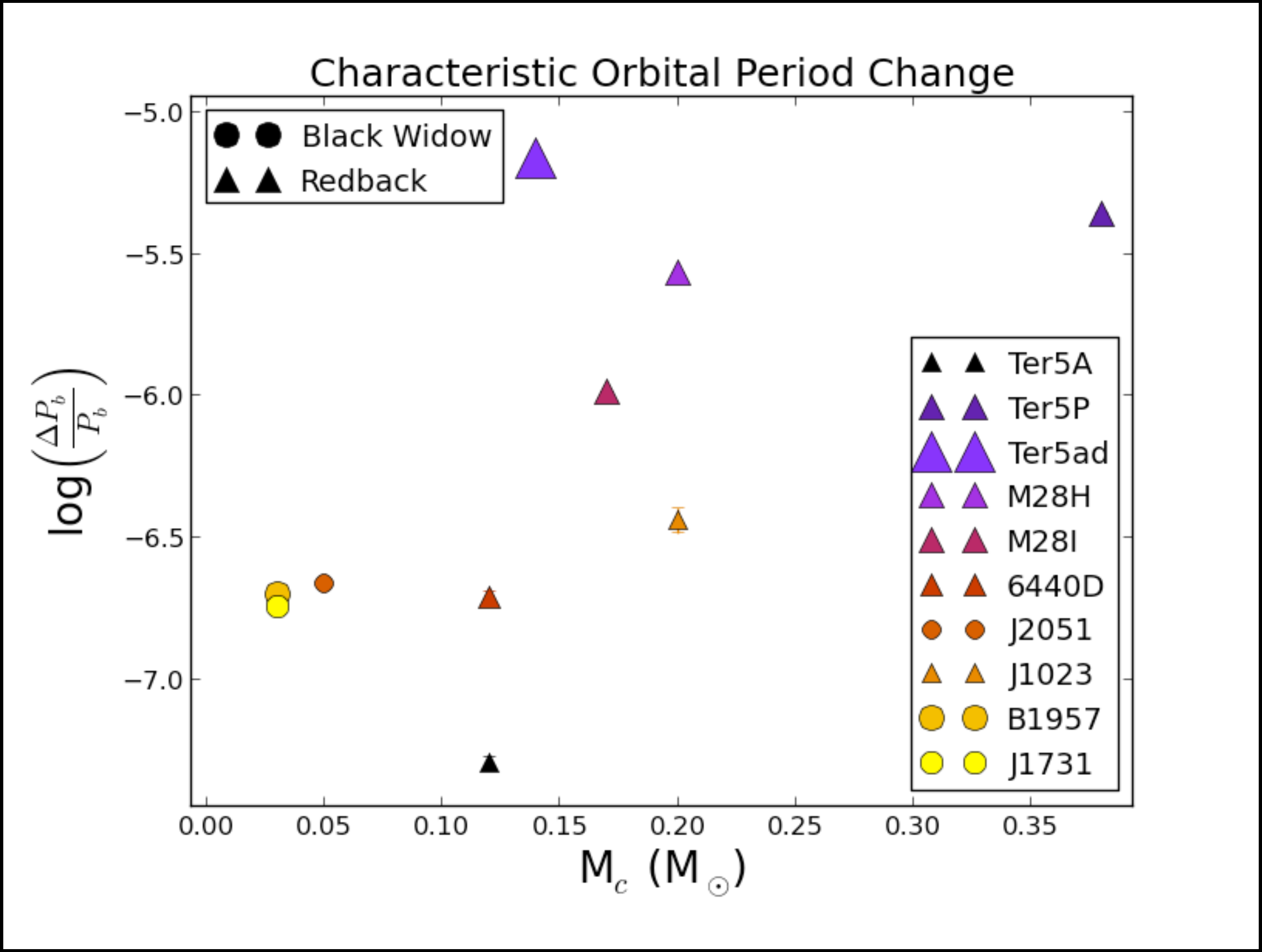
# Characteristic Porb Change

## (vs. Porb)




Prager

# Characteristic Porb Change
## (vs. Mcomp)




Prager

# Summary 3

• Most "spiders" (but not all) suffer from orbital variability, which looks like a rednoise process.
• Due to quadrupolar deformations in the companion? But where does the energy come from?
• Redbacks more affected than black widows.
• Hampers some efforts (e.g. folding the Fermi photons), but we're learning how to deal with this.

# Black Widows and Redbacks as Transitional millisecond pulsars

# 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

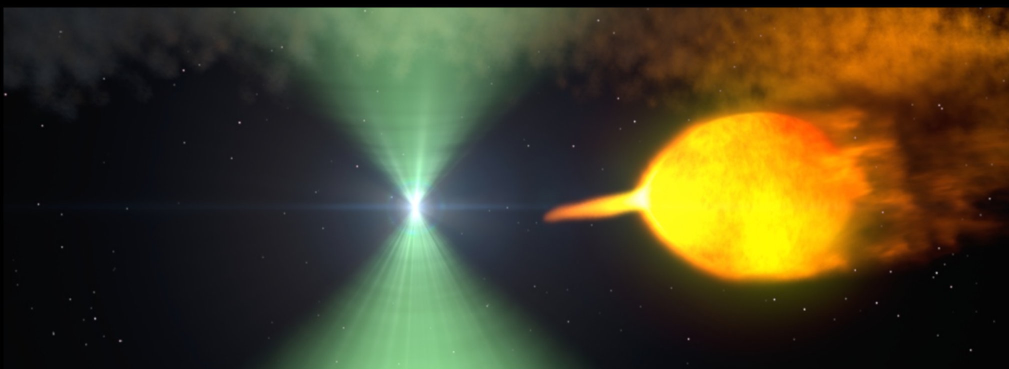
Seems like we may have more types of eclipsing radio MSPs as well: ones earlier in the recycling process?

# Open Questions

- How do we really produce the observed population of radio millisecond pulsars?
- What causes the state transitions and why haven't the new "spiders" shown more of this?
- Do such sources transition back and forth for Gyrs?
- Can we find a *sub*-MSP in such a system?
- What causes the eclipses?
- What fraction of the "spiders" are perpetually enshrouded?
- What causes the orbital variation?

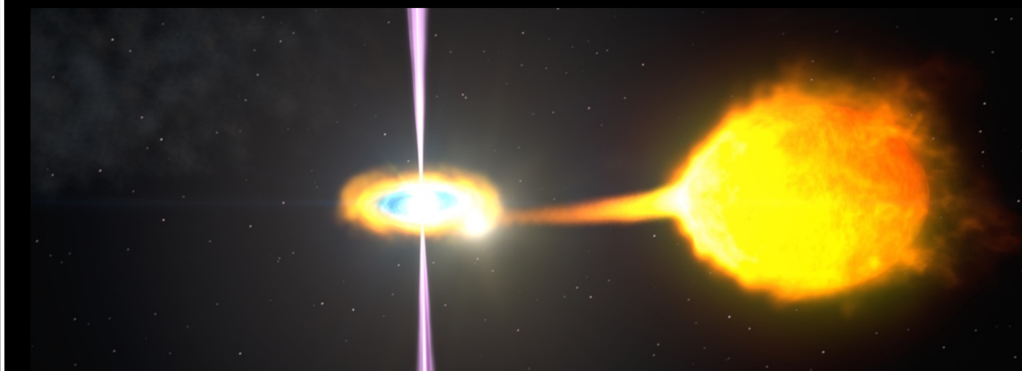
# Extra Slides

# Radio Pulsar State



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

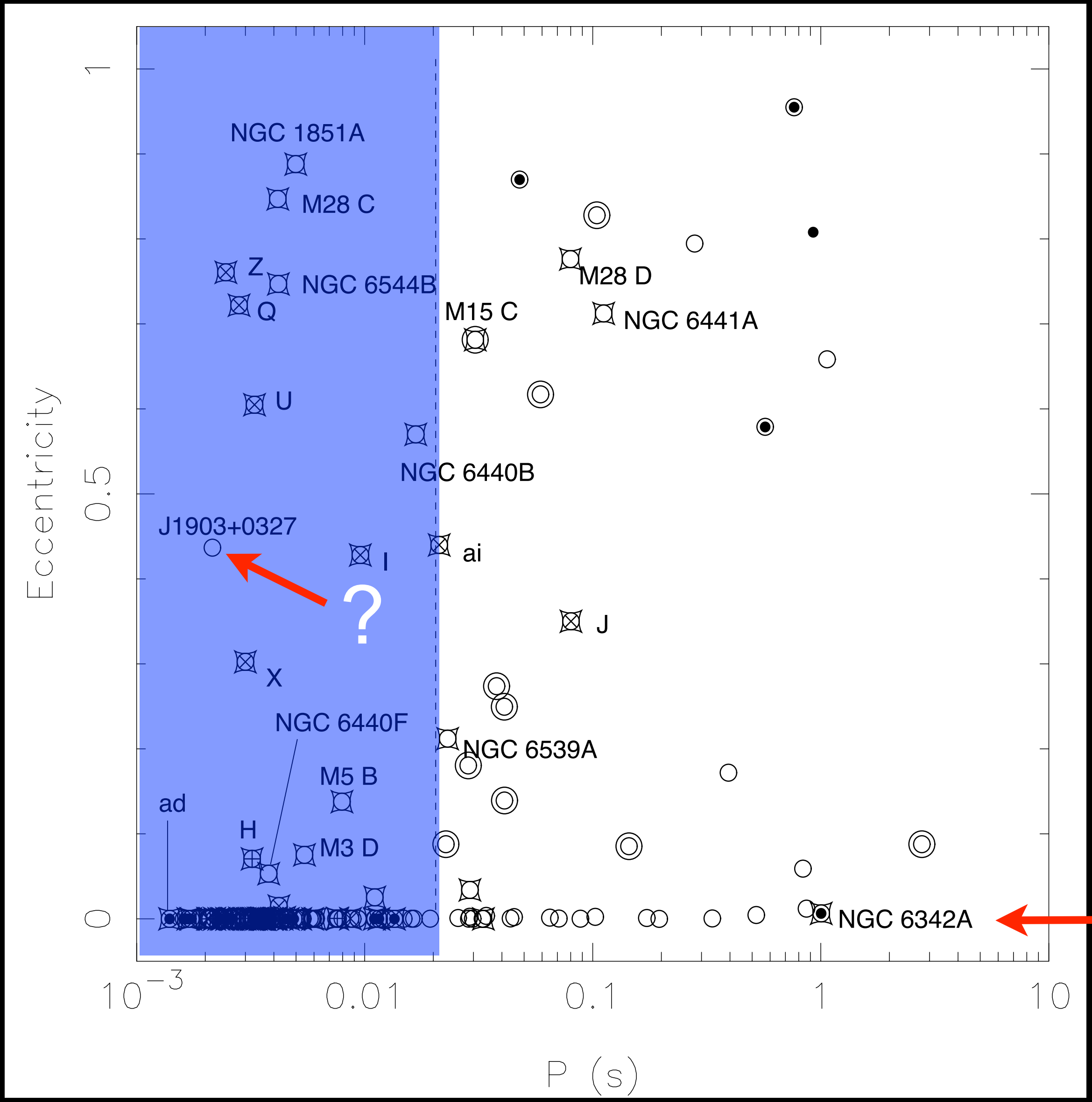
# Disk State



- 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.

# MSP Population

> 80% in binary; orbital eccentricity normally very small

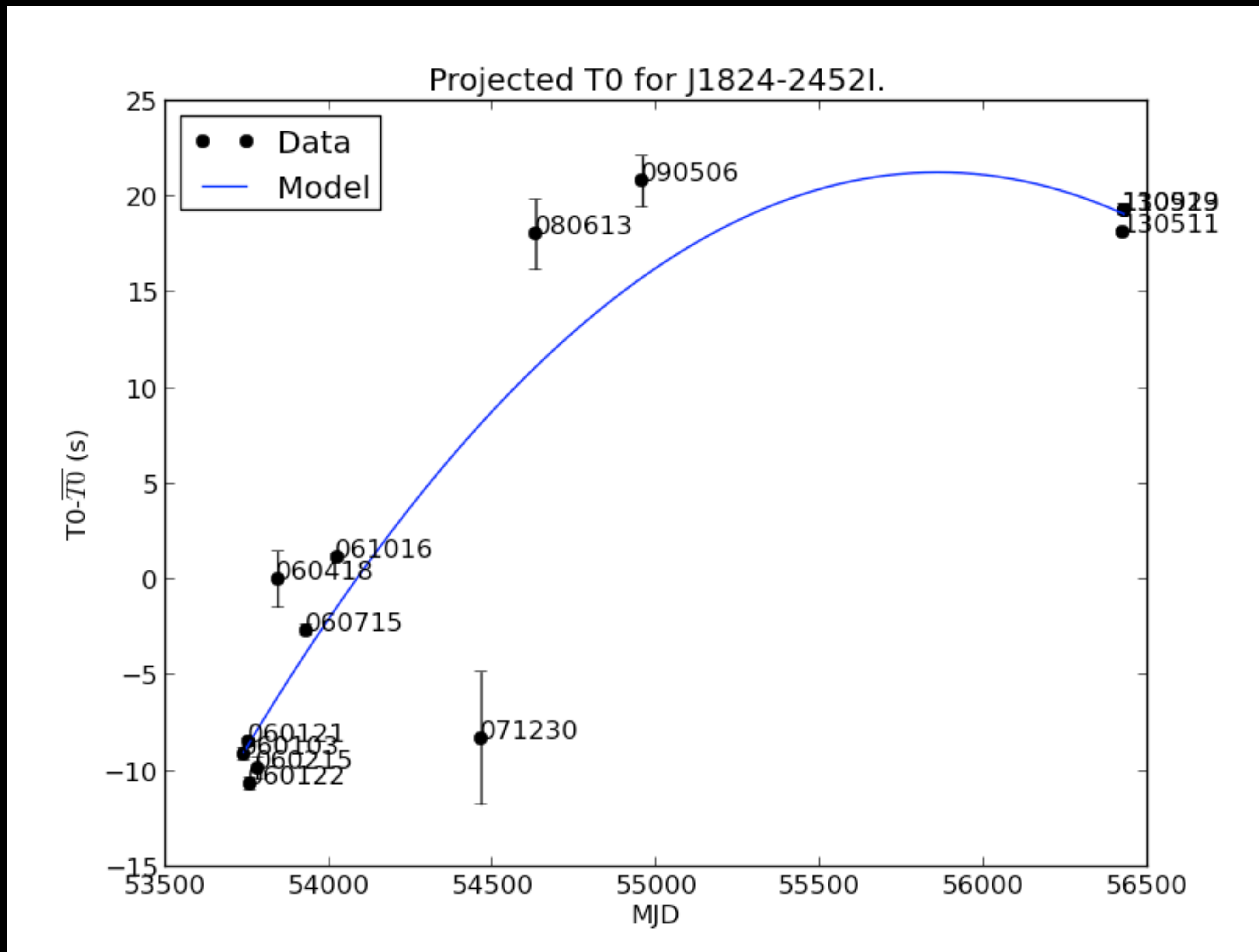



Freire (http://www.naic.edu/~pfreire/GCpsr.html)

- Lots of eccentric systems recently found in GCs.

Eccentricity still easily measurable

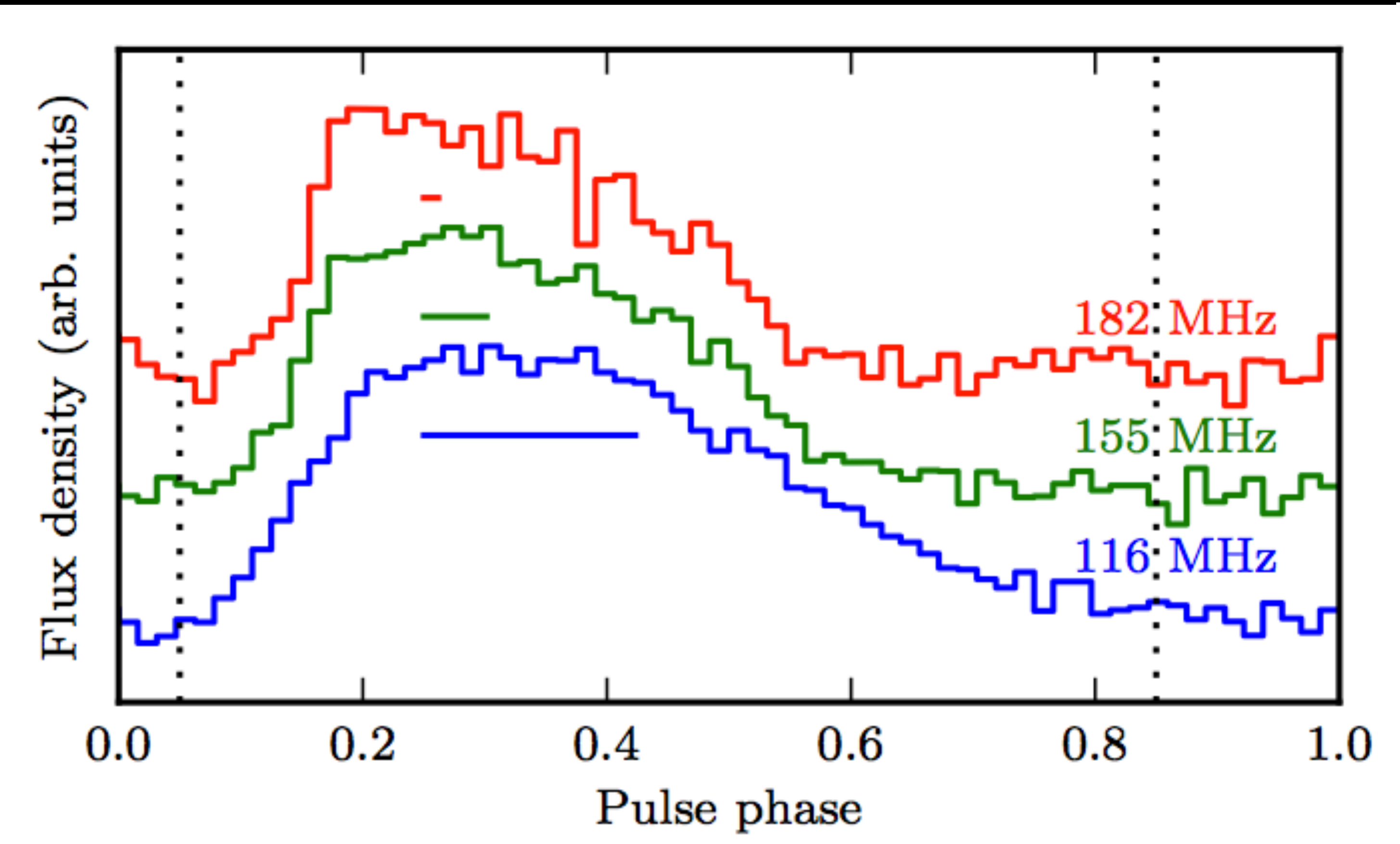
# M28I

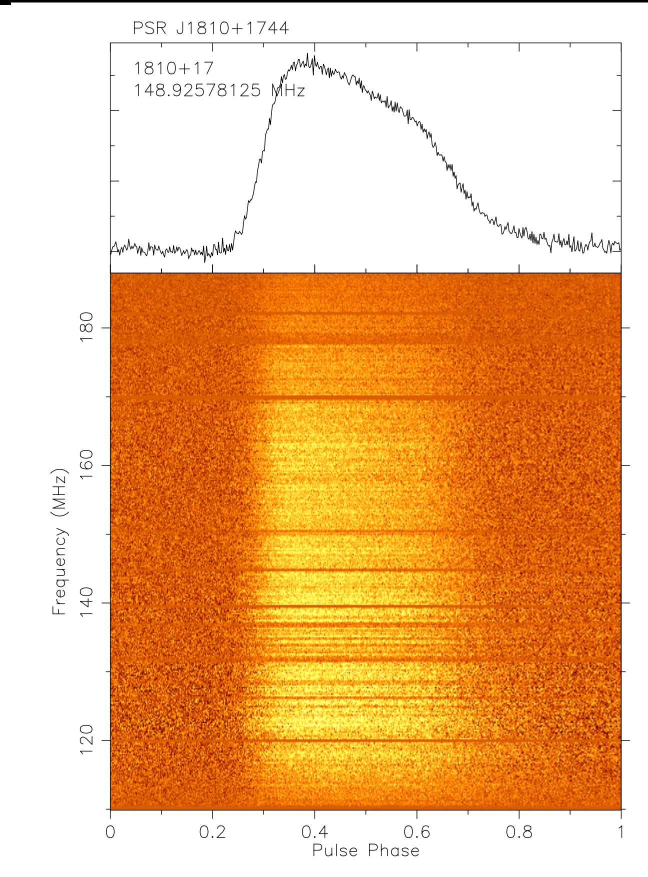



Prager

Pspin = 4.5ms
Porb = 0.1d
Mcomp = 0.03MSun

# Cyclic Spectroscopy

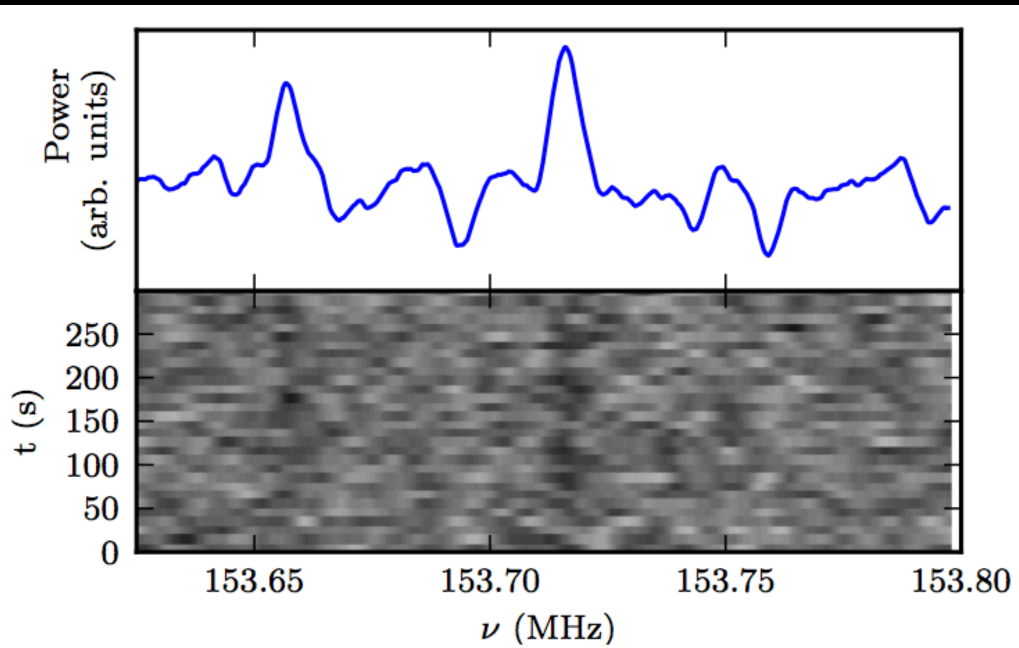



Horizontal bars indicate scattering time, τ, as inferred from the diffractive bandwidth, $\Delta\nu_{\rm d}$

**Archibald et al. 2014, *ApJL***

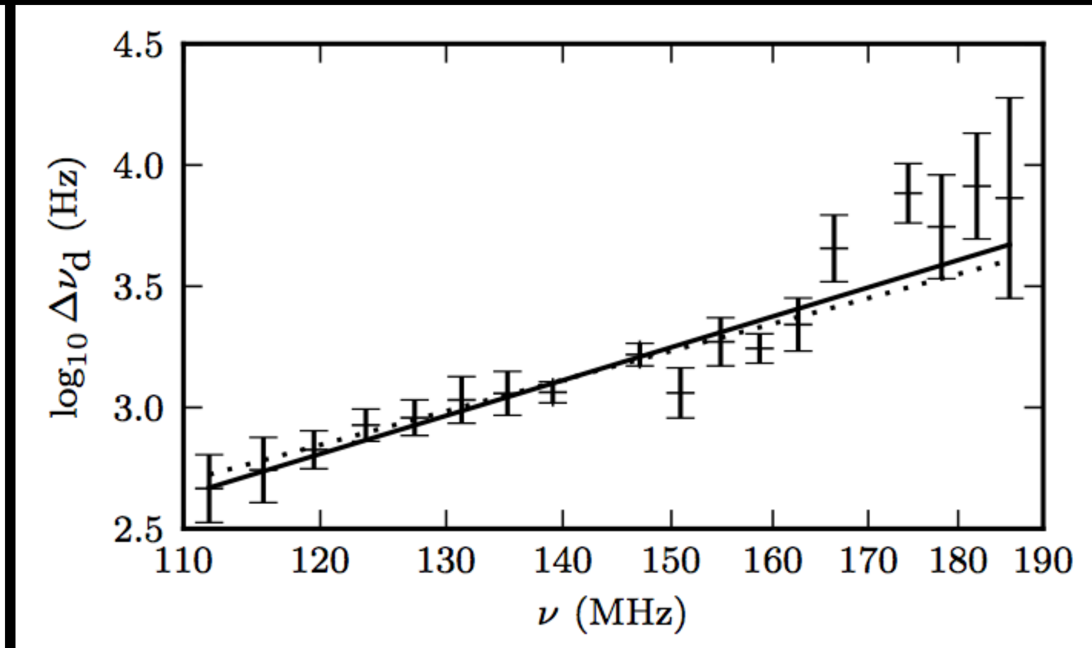
# Cyclic Spectroscopy




← 200kHz →

Example dynamic spectrum

Smoothed to ~2kHz resolution




Diffractive bandwidth vs. frequency

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

Solid line: best-fit power-law

Dotted line: power-law of -4

Probes scattering in a previously unreachable regime

**Archibald et al. 2014, *ApJL***