Astrophysics and Basic Physics from Pulsars in Crowded Places

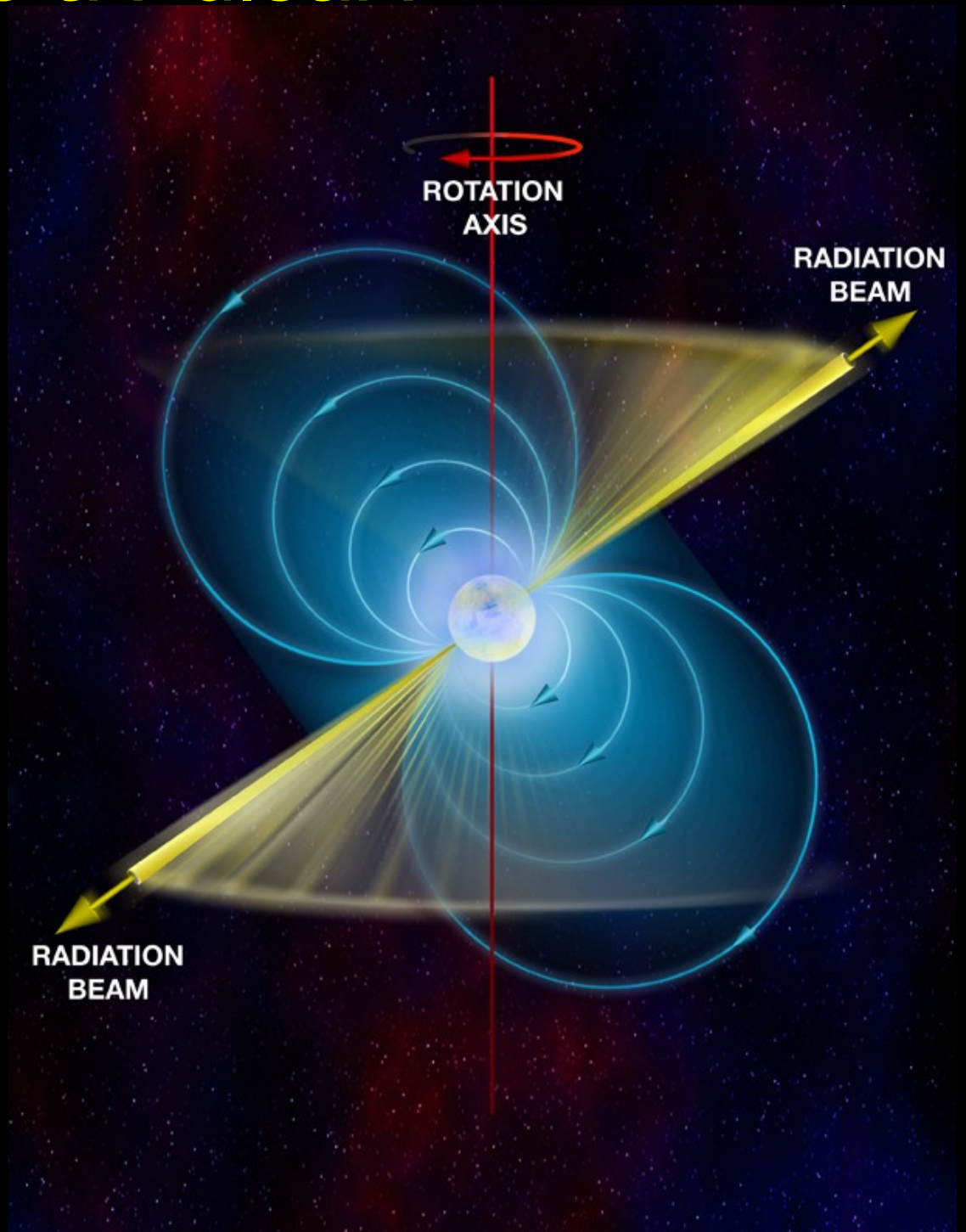
Scott Ransom
(NRAO Charlottesville, VA)

Recent Collaborators:

Ingrid Stairs, Paulo Freire, Jason Hessels,
Ryan Lynch, Steve Begin

What's a Pulsar?

- Rotating Neutron Star!
- Size of city:
  - R ~ 10-20 km
- Mass greater than Sun:
  - M ~ 1.4 M_{sun}
- Strong Magnetic Fields:
  - B ~ 10^{8}-10^{14} Gauss
- Pulses are from a "**lighthouse**" type effect
- "Spin-down" power up to 10,000 times more than the Sun's total output!



Pulsar Flavors

Normal PSRs

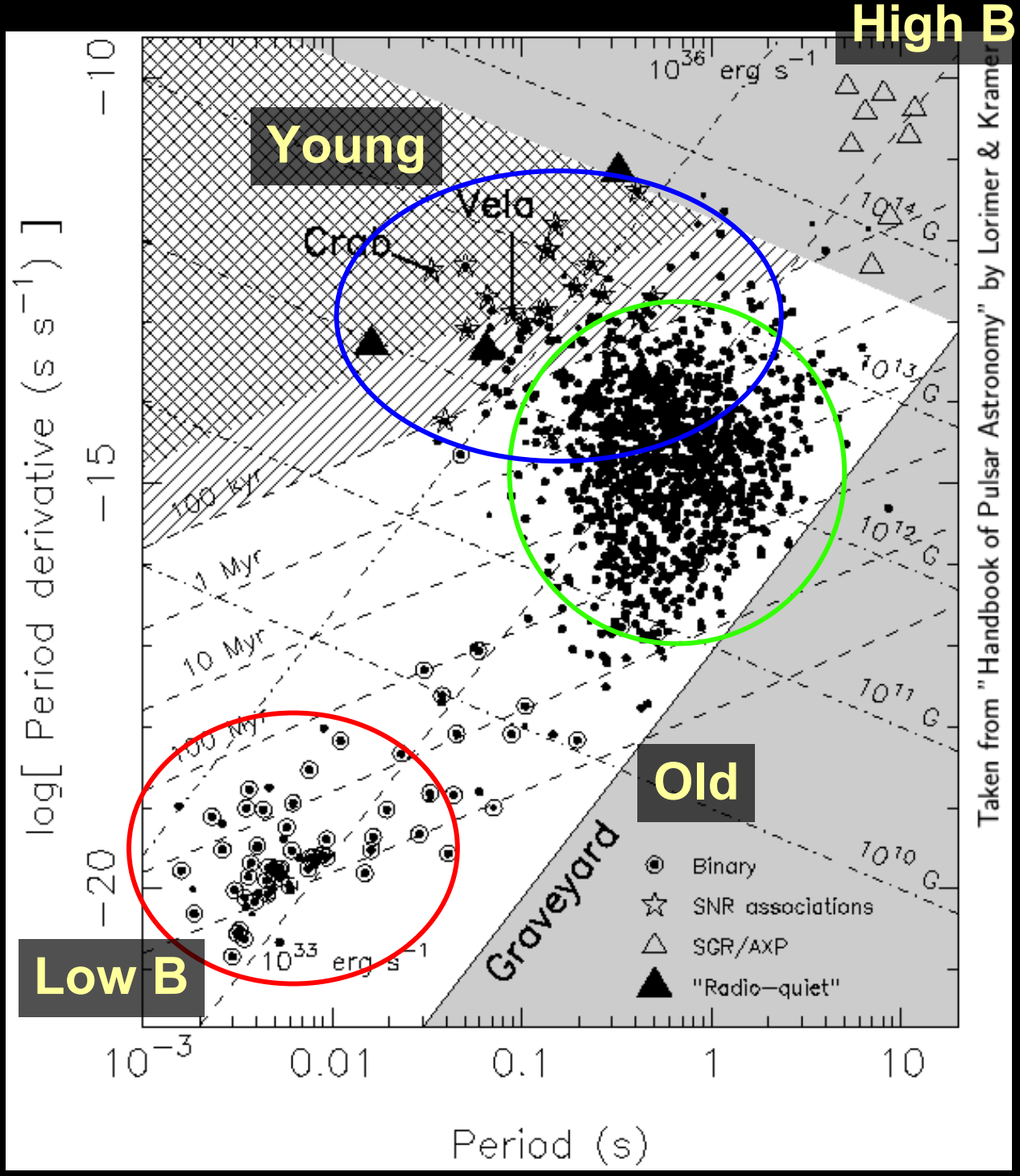
(average B, slow spin)

Young PSRs

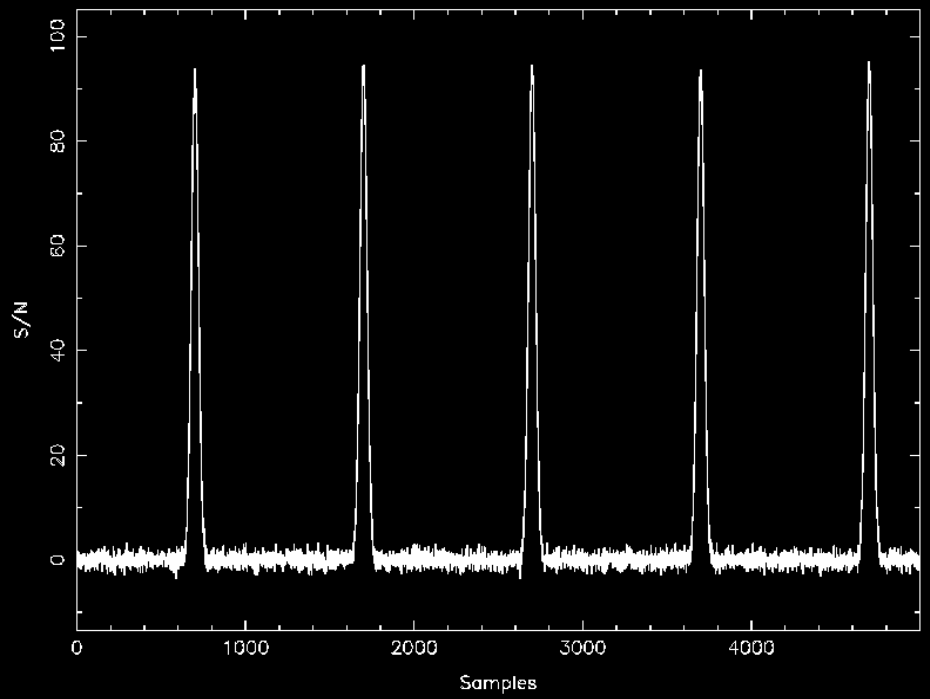
(high B, fast spin, very energetic)

Millisecond PSRs

(low B, very fast, very old, very stable spin, best for basic physics tests)



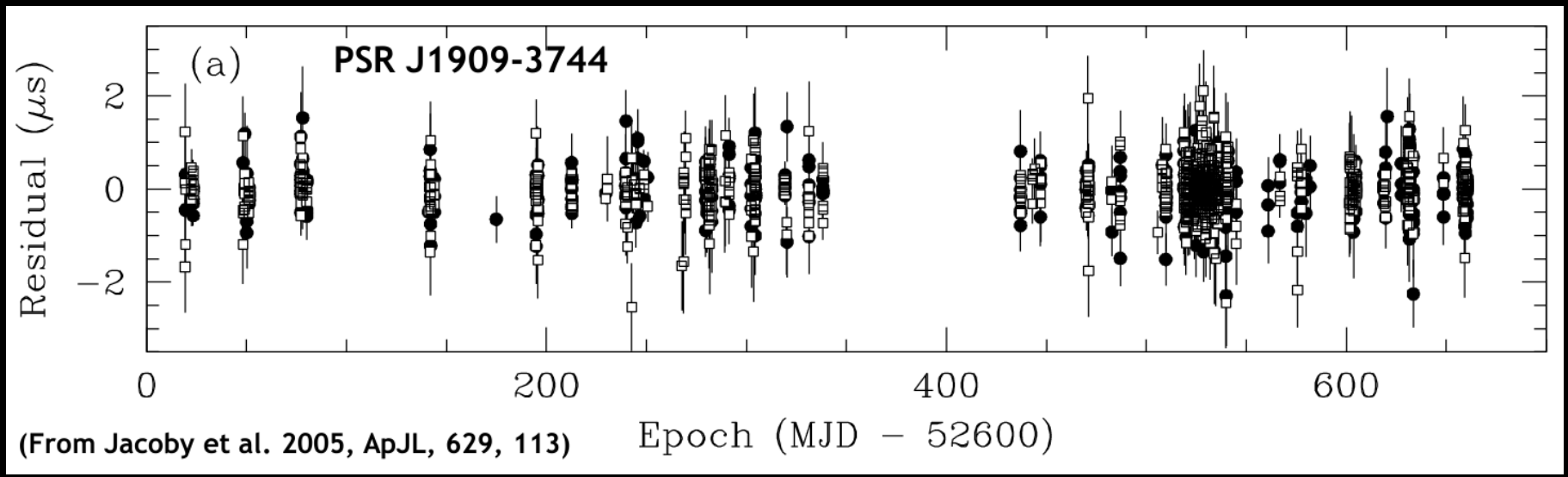
Science is from long-term timing



Accounts for every rotation of the pulsar

Fit the arrival times to a model accounting for spin, orbital, and astrometric parameters and various classical and Relativistic delays

Extraordinary precision for MSP timing!



(From Jacoby et al. 2005, ApJL, 629, 113)

Basic Physics with Pulsars

(see Blandford, 1992, PTRSLA, 341, 177 for a review)

Gravitational wave detection (e.g. high precision timing)

Physics at nuclear density (e.g. NS equations of state)

Strong-field gravity tests (e.g. binary pulsar dynamics)

Also many others:

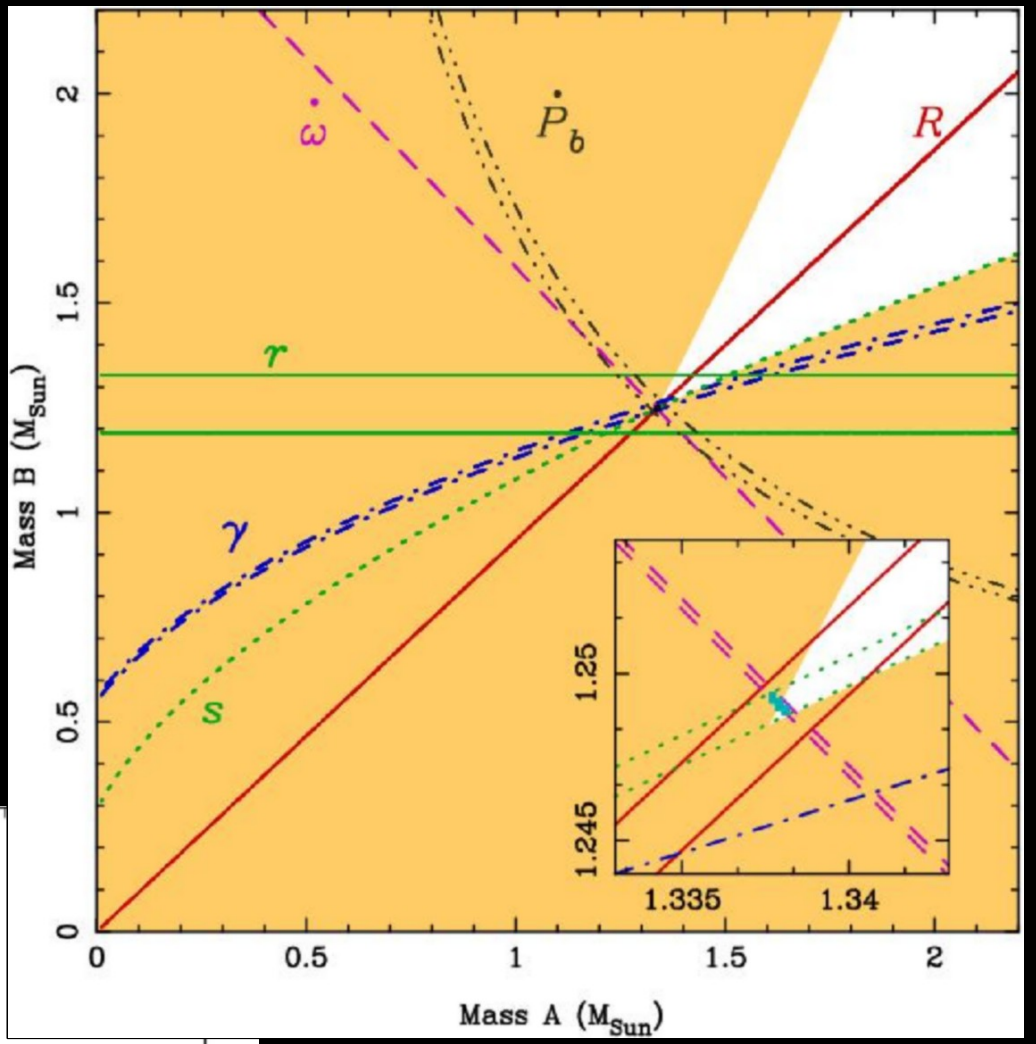
- Plasma physics (e.g. magnetospheres, pulsar eclipses)
- Astrophysics (e.g. stellar masses and evolution)
- Fluid dynamics (e.g. supernovae collapse)
- Magnetohydrodynamics (MHD; e.g. pulsar winds)
- Relativistic electrodynamics (e.g. pulsar magnetospheres)
- Atomic physics (e.g. NS atmospheres)
- Solid state physics (e.g. NS crust properties)

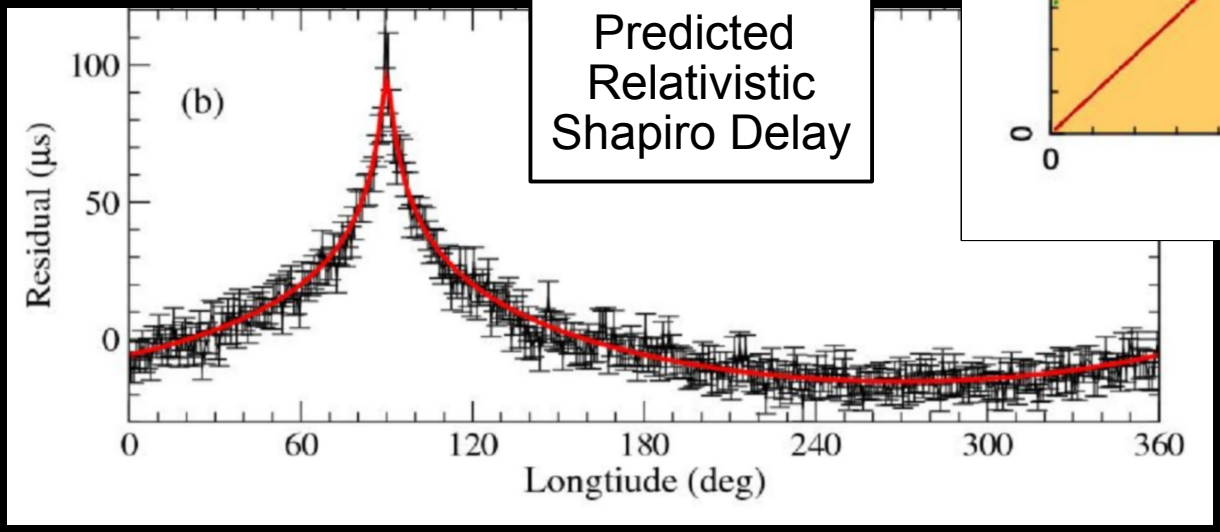
Timing of the Double Pulsar J0737-3039

GBT provides the best timing precision for this system

6(!) post-Keplerian orbital terms give neutron star masses and strong-field tests of general relativity to 0.05% accuracy

Timing may eventually allow measurement of the neutron star moment of inertia



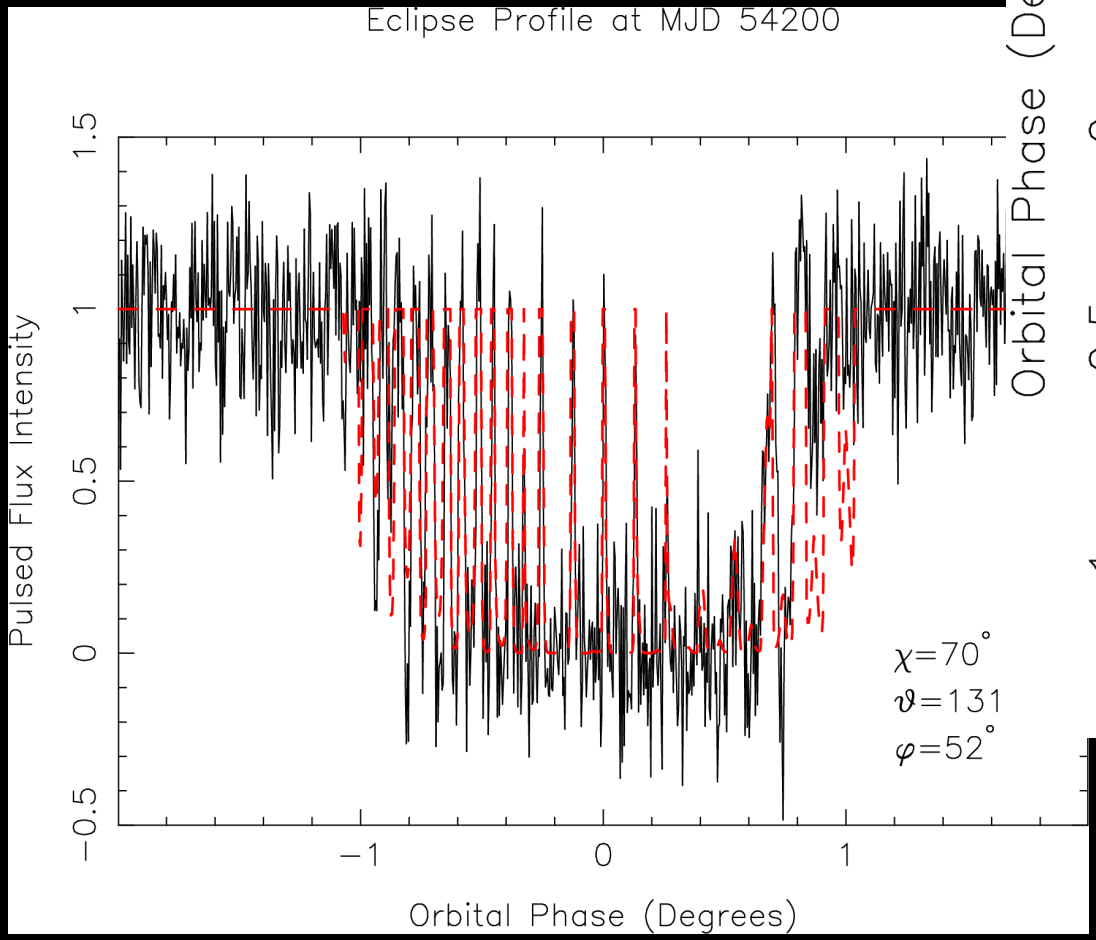


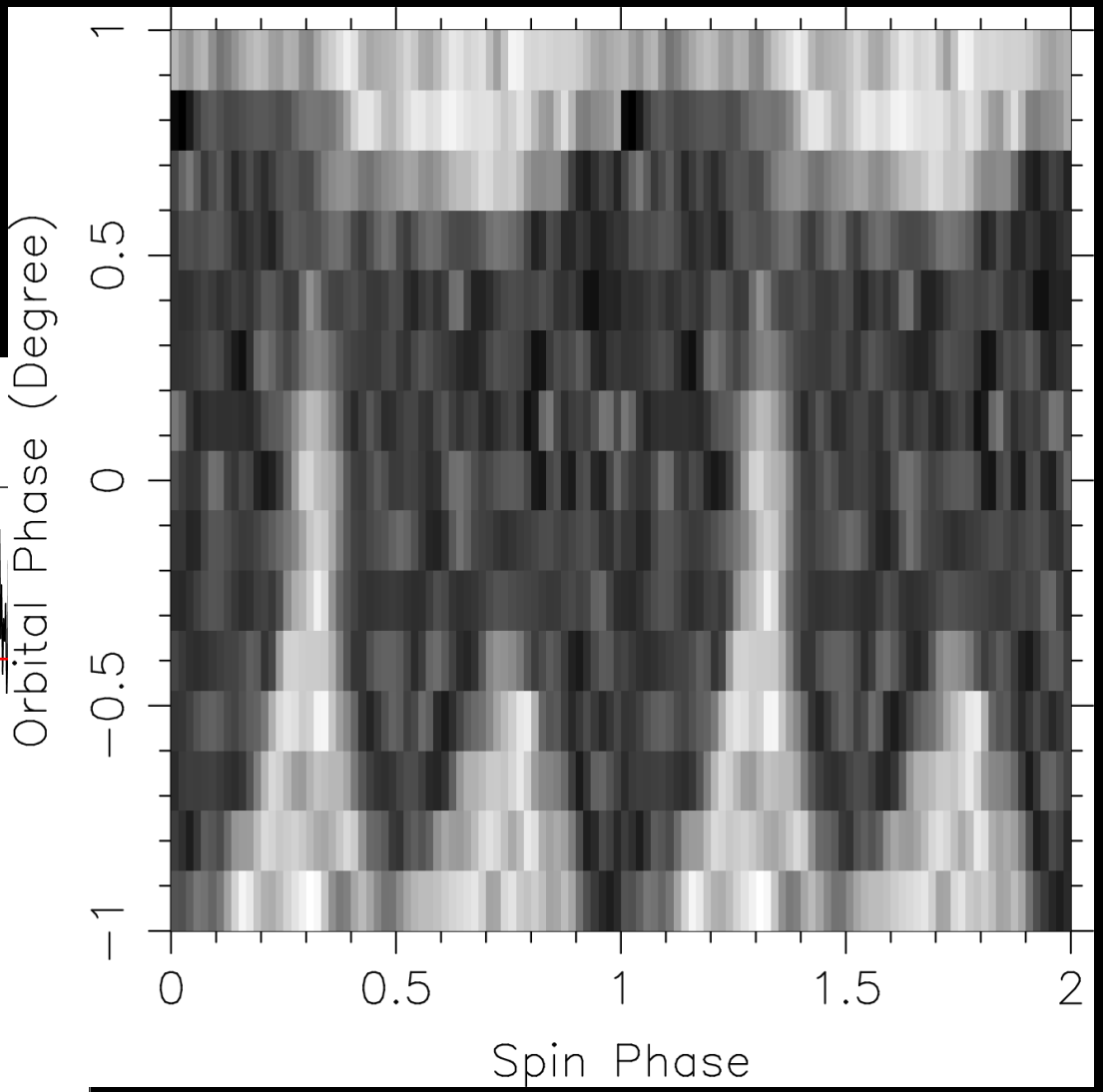
Measured vs Predicted Relativistic Shapiro Delay

Kramer et al., 2006, *Science*, 314, 97

Relativistic Spin Precession of PSR B!

The ~30sec eclipses of PSR A by PSR B are caused by a plasma effect in Pulsar B's dipolar magnetosphere (Lyutikov & Thompson 2005)

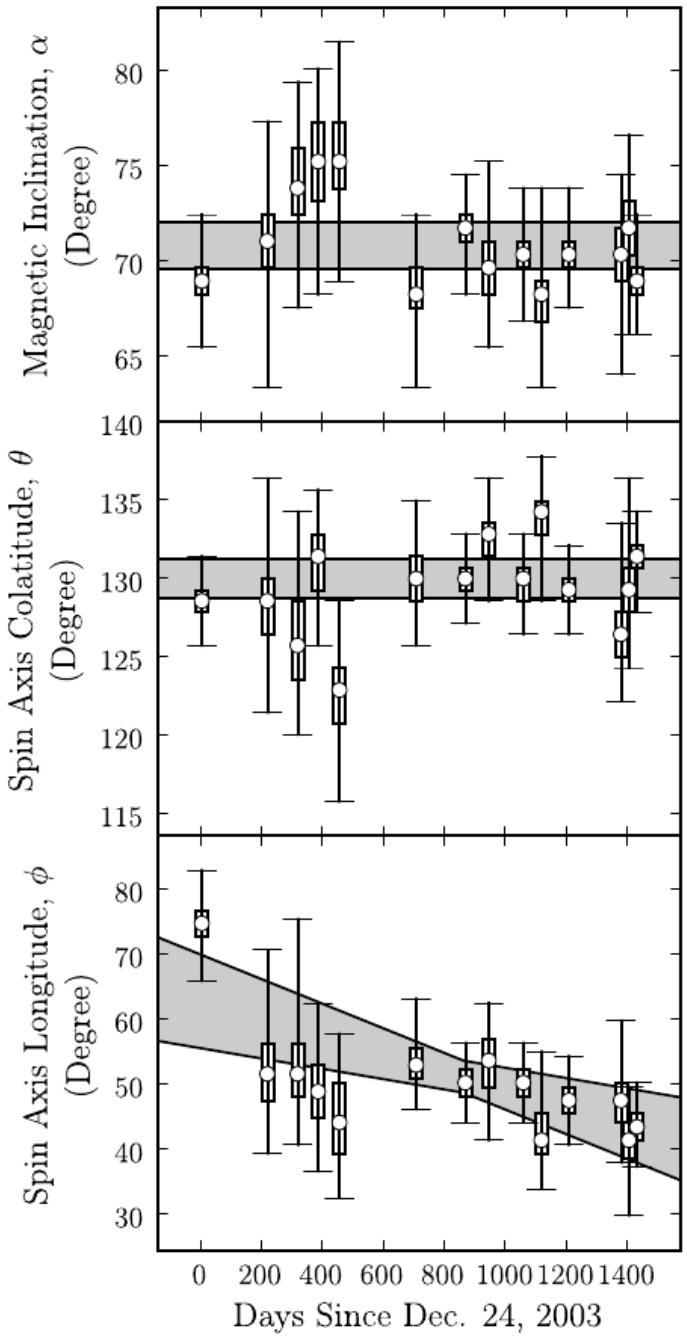


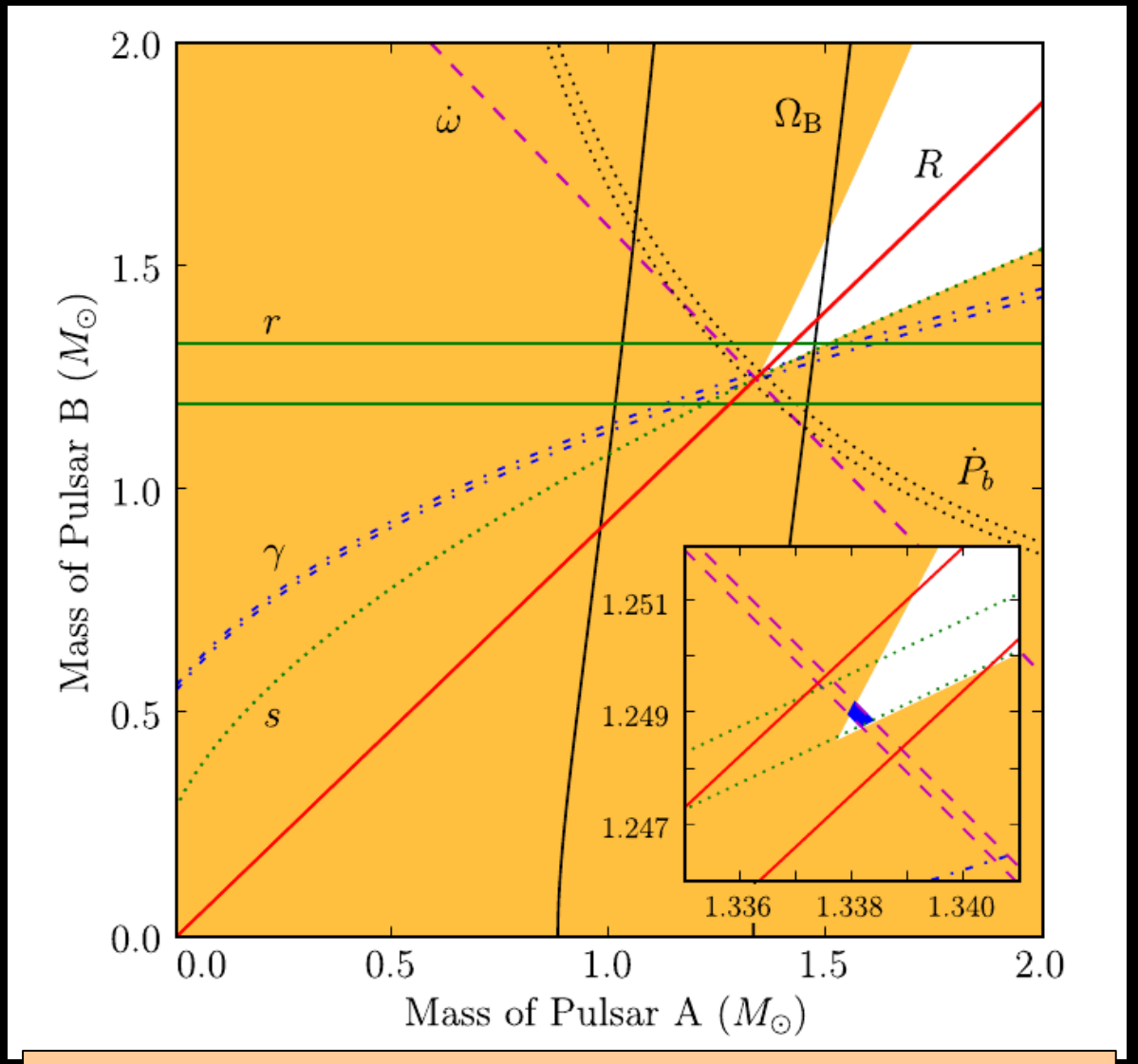


Measured precession rate is consistent with GR to ~12%
This is a brand new GR test.

Breton et al., 2008, *Science*, 321, 104

Relativistic Spin Precession of PSR B!





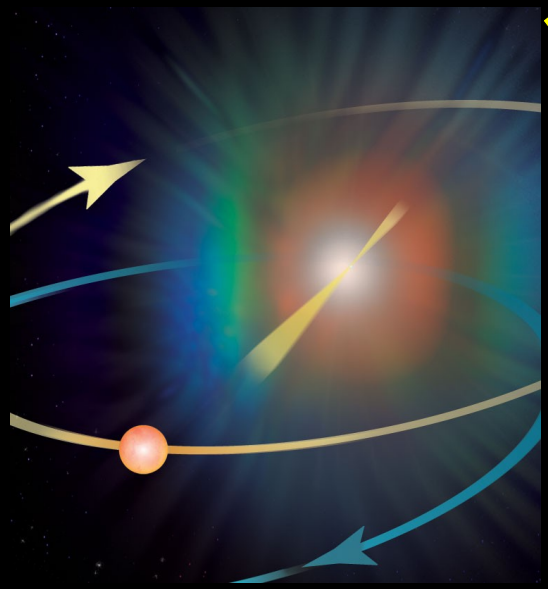
Breton et al., 2008, *Science*, 321, 104

Obs = 4.77+/- 0.66 deg/yr
GR = 5.07 deg/yr

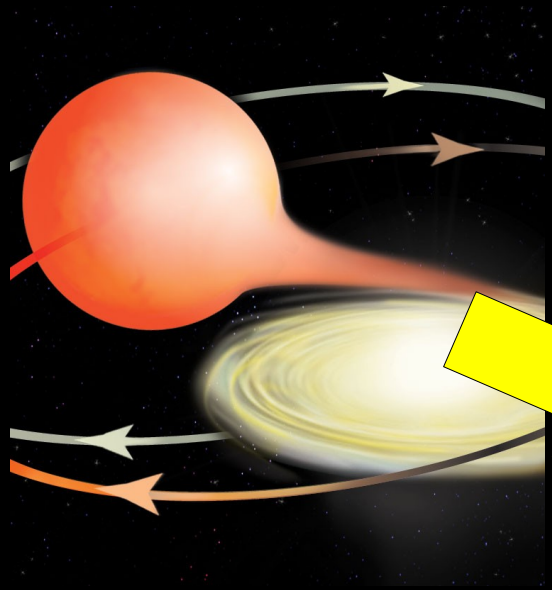
Pulsars in Globular Clusters

- Clusters of ancient stars (9-12 billion years old) that orbit our galaxy
- Contain 10^5-10^6 stars, many of which have binary companions
- Very high central densities (100-10,000 stars/ly^3) result in stellar encounters and collisions!

Millisecond pulsars in GCs?



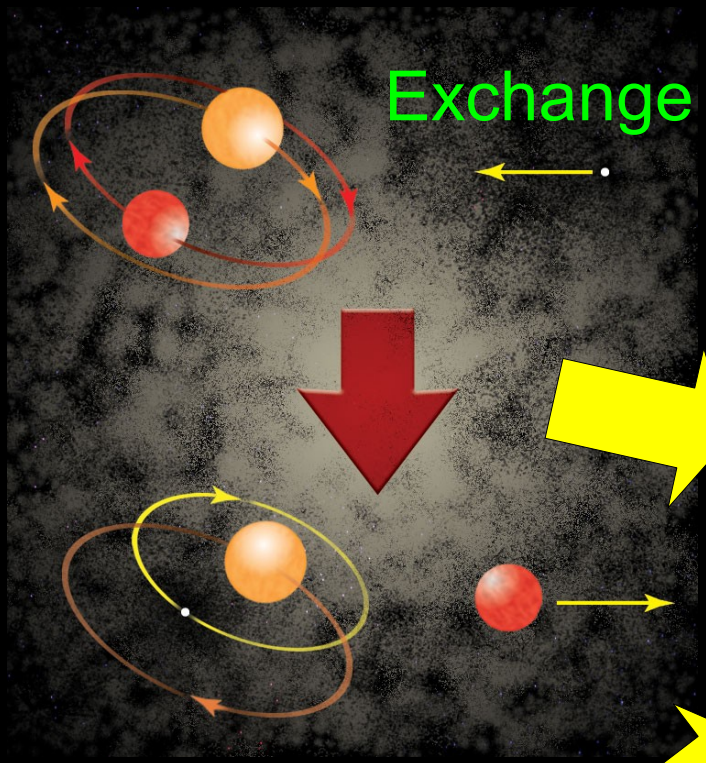
Supernova produces
a neutron star

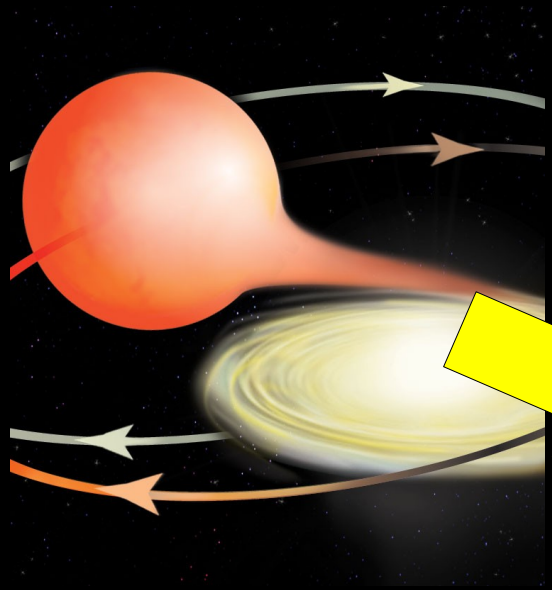


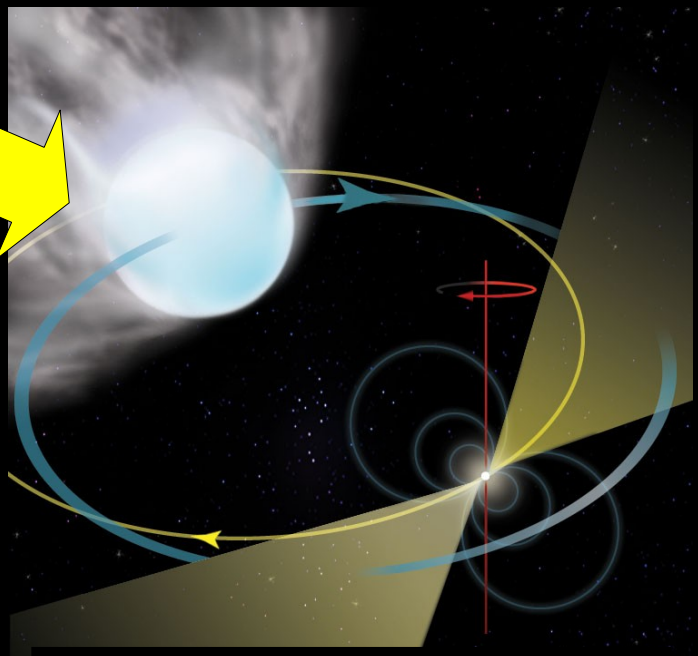
Red Giant transfers
matter to neutron star

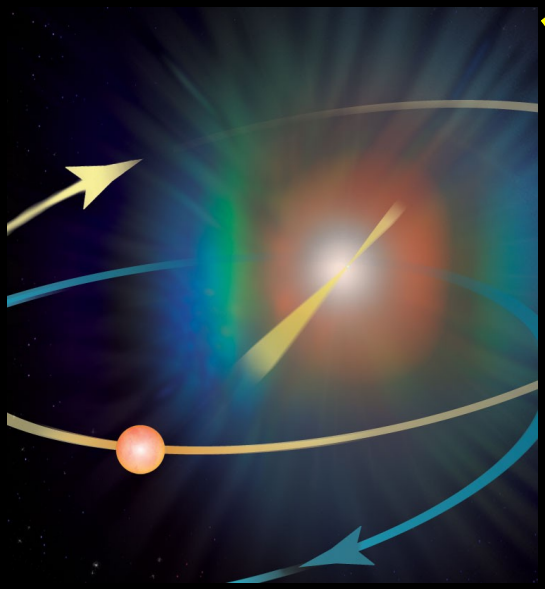
Millisecond Pulsar
emerges with a white
dwarf companion

Millisecond pulsars in GCs?





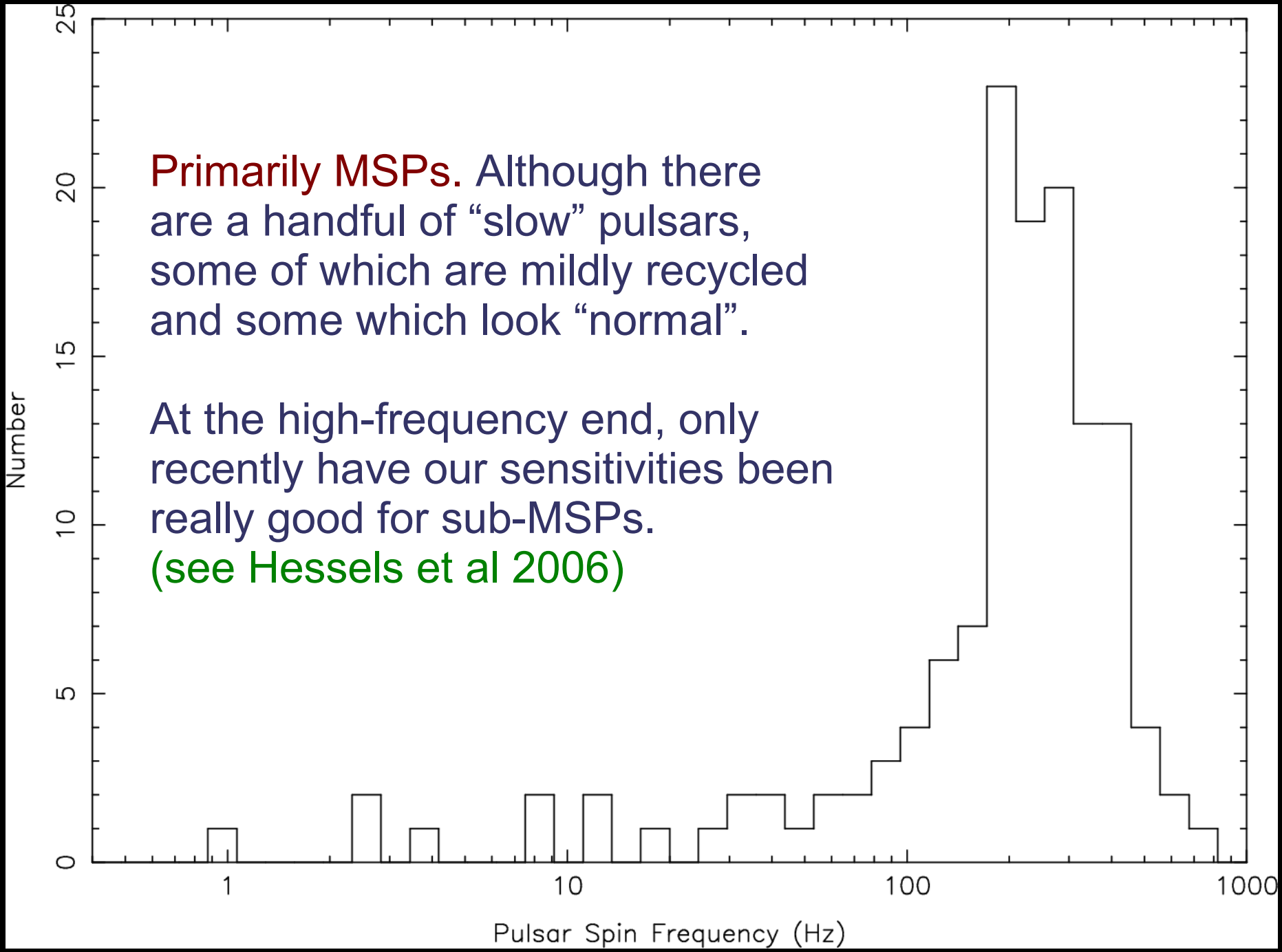


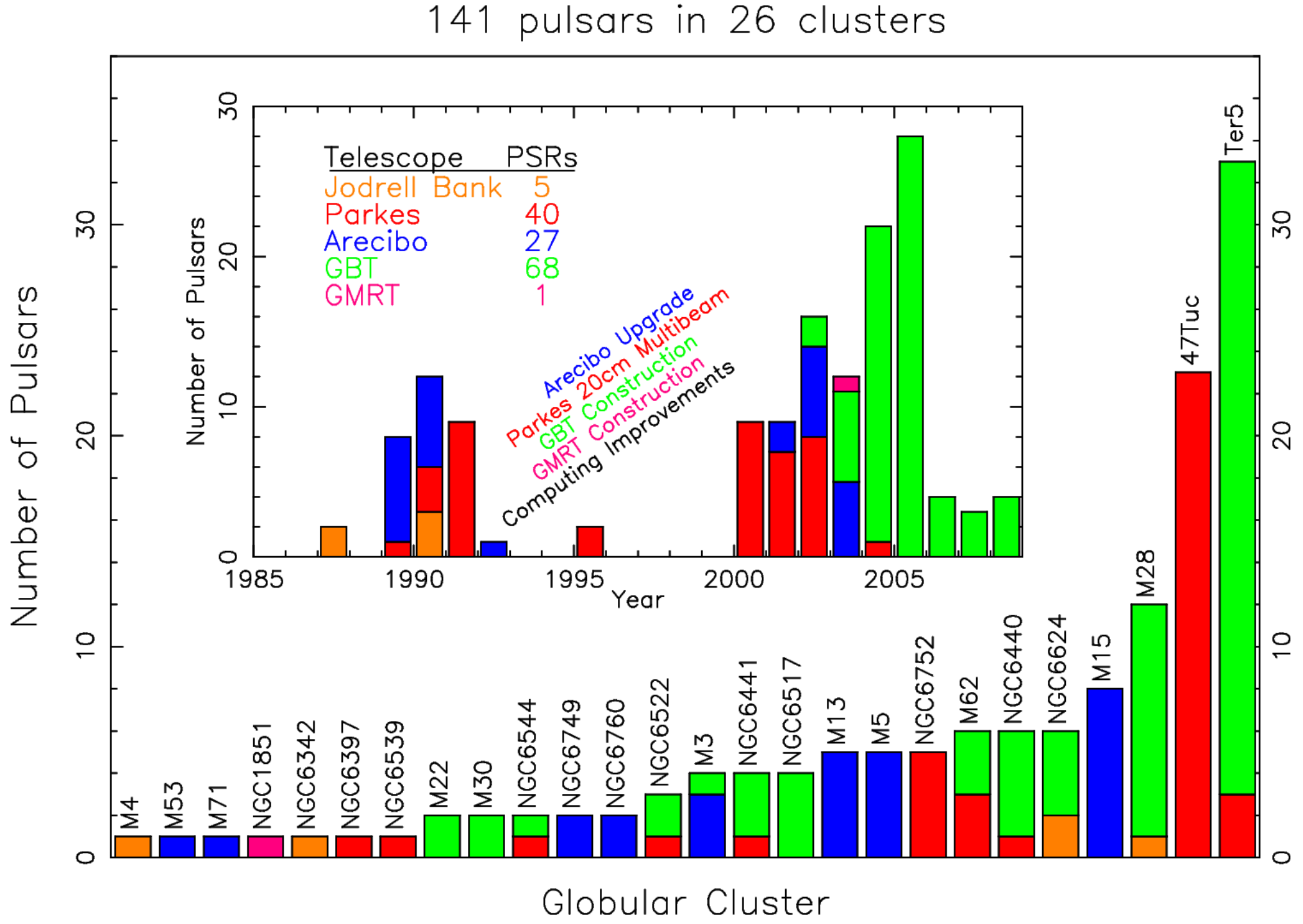


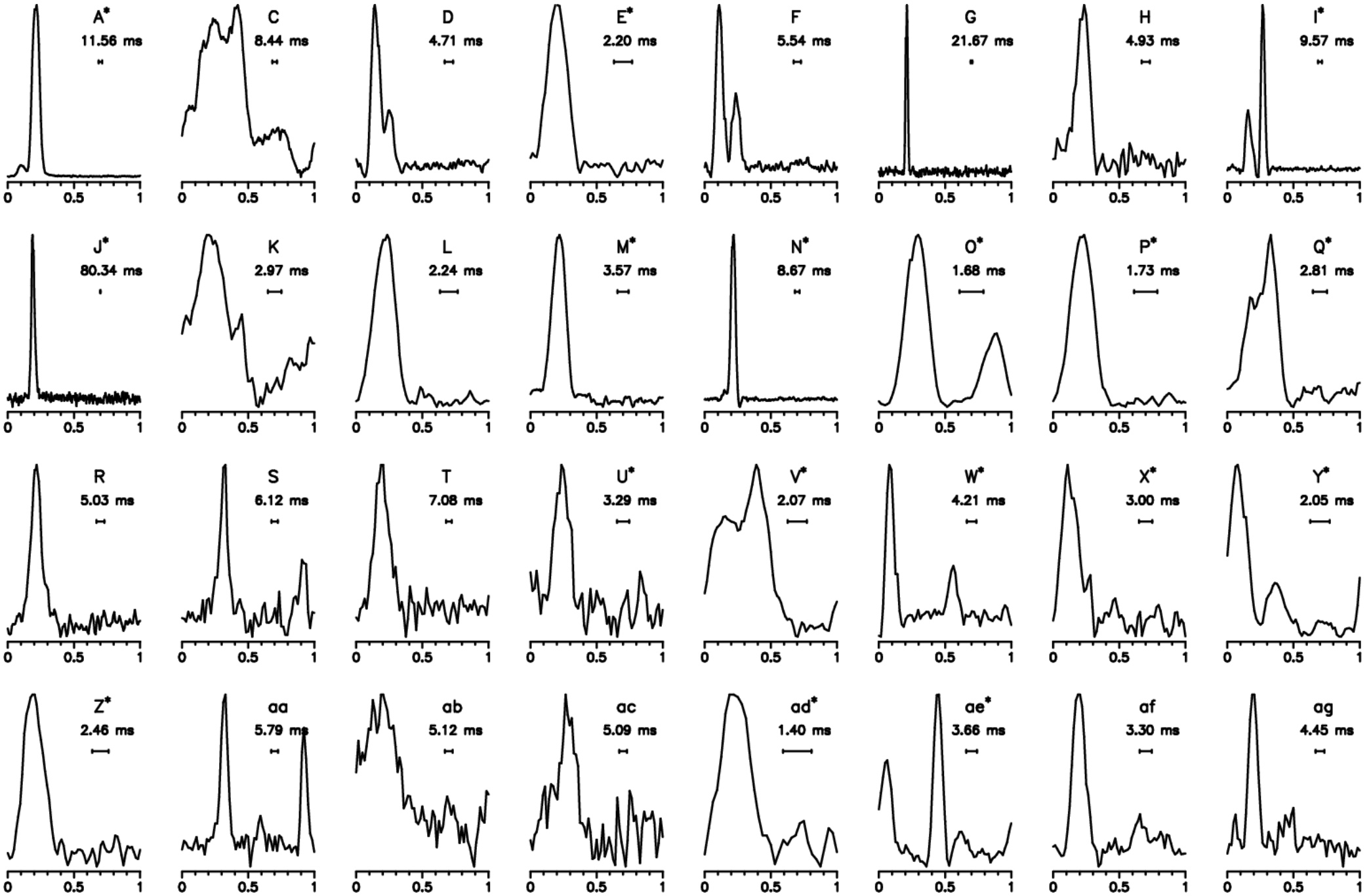
Pulsars in Globular Clusters

- Clusters of ancient stars (9-12 billion years old) that orbit our galaxy
- Contain 10^5-10^6 stars, many of which have binary companions
- Very high central densities (100-10,000 stars/ly^3) result in stellar encounters and collisions!
- They are effectively millisecond pulsar factories (and strange ones at that!)
- Number known has quadrupled since 2000

Measured Spin Frequencies




141 pulsars in 26 clusters
Number of Pulsars
Globular Cluster
Telescope PSRs
Jodrell Bank 5
Parkes 40
Arecibo 27
GBT 68
GMRT 1
Arecibo Upgrade
Parkes 20cm Multibeam
GBT Construction
GMRT Construction
Computing Improvements
Year
M4
M53
M71
NGC1851
NGC6342
NGC6397
NGC6539
M22
M30
NGC6544
NGC6749
NGC6760
NGC6522
M3
NGC6441
NGC6517
M13
M5
NGC6752
M62
NGC6440
NGC6624
M15
M28
47Tuc
Ter5

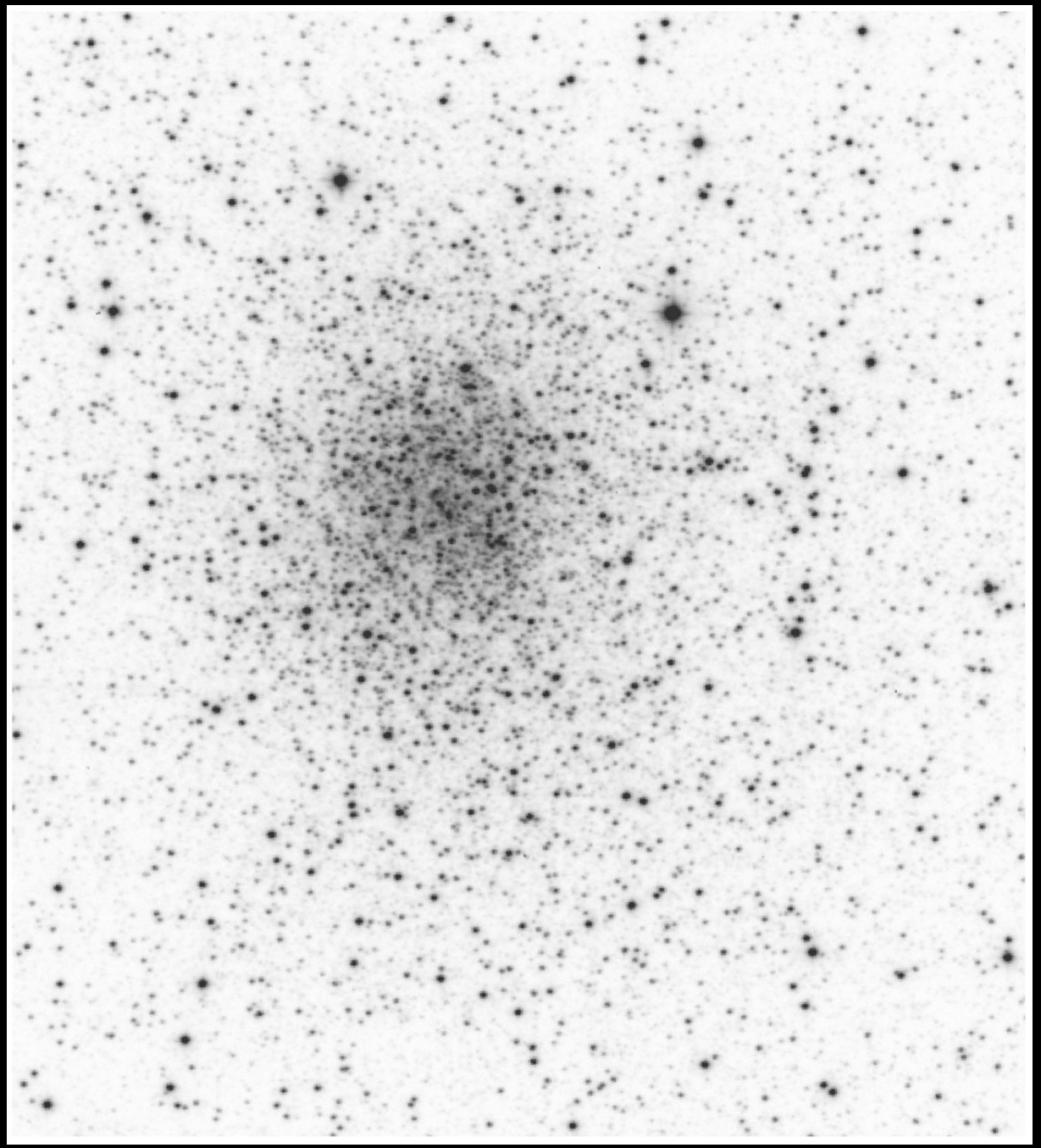


33 Millisecond Pulsars in Terzan 5!

(First 21 reported in Ransom et al., 2005, *Science*, 307, 892)

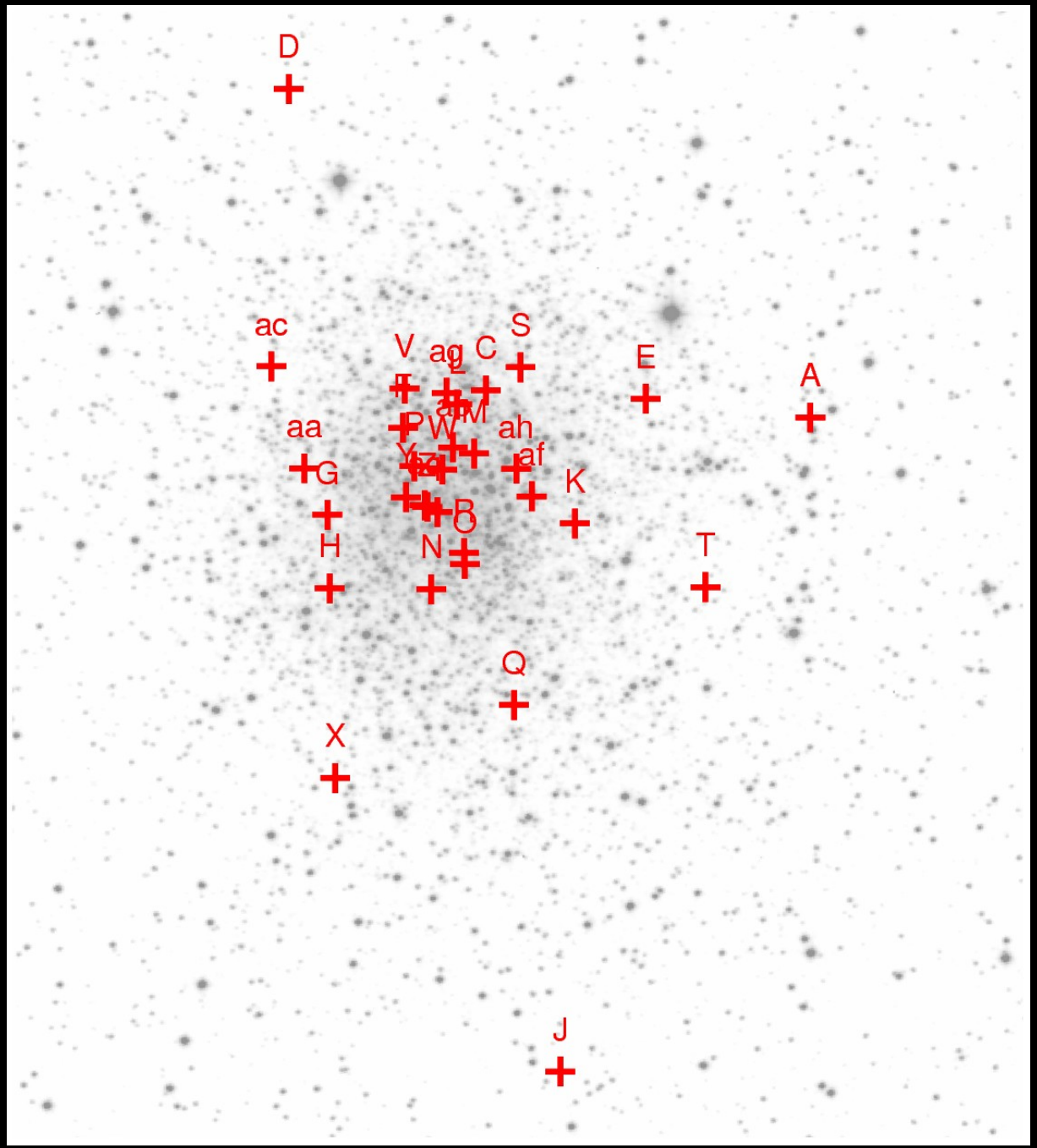
Timing Solutions for the Ter5 Pulsars

- Vast majority of the science comes from pulsar timing!
- Currently have timing solutions for all 33 known pulsars in Terzan5
- Typical position errors:
  ~0.01” in RA
  ~0.1” in DEC
- Period derivatives show that ~half of the pulsars are behind the cluster
- For many, we have connected to archival data for ~10 yr baseline



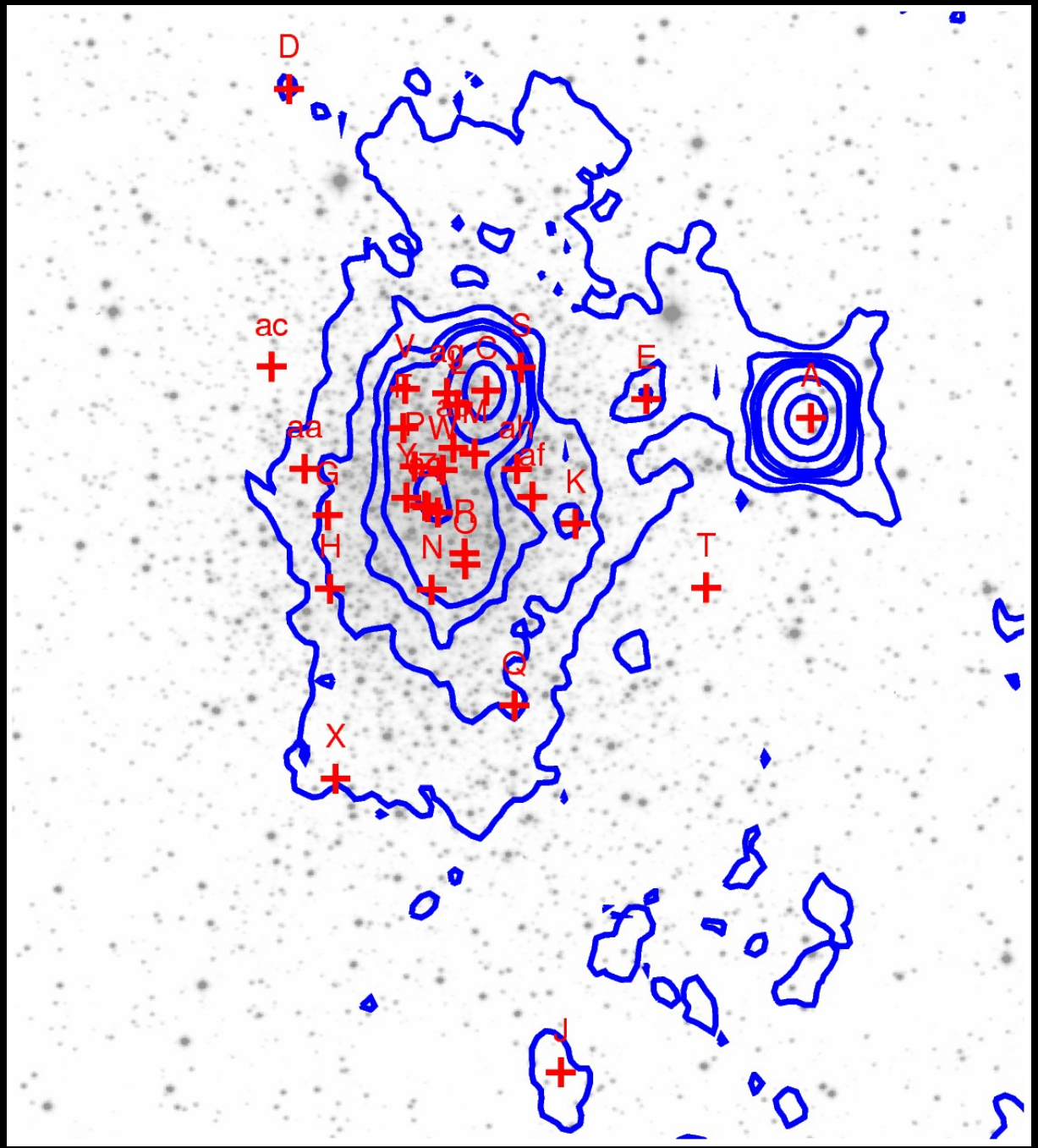
Timing Solutions for the Ter5 Pulsars

- Vast majority of the science comes from pulsar timing!
- Currently have timing solutions for all 33 known pulsars in Terzan5
- Typical position errors:
  ~0.01” in RA
  ~0.1” in DEC
- Period derivatives show that ~half of the pulsars are behind the cluster
- For many, we have connected to archival data for ~10 yr baseline



Timing Solutions for the Ter5 Pulsars

- Vast majority of the science comes from pulsar timing!
- Currently have timing solutions for all 33 known pulsars in Terzan5
- Typical position errors:
  ~0.01” in RA
  ~0.1” in DEC
- Period derivatives show that ~half of the pulsars are behind the cluster
- For many, we have connected to archival data for ~10 yr baseline



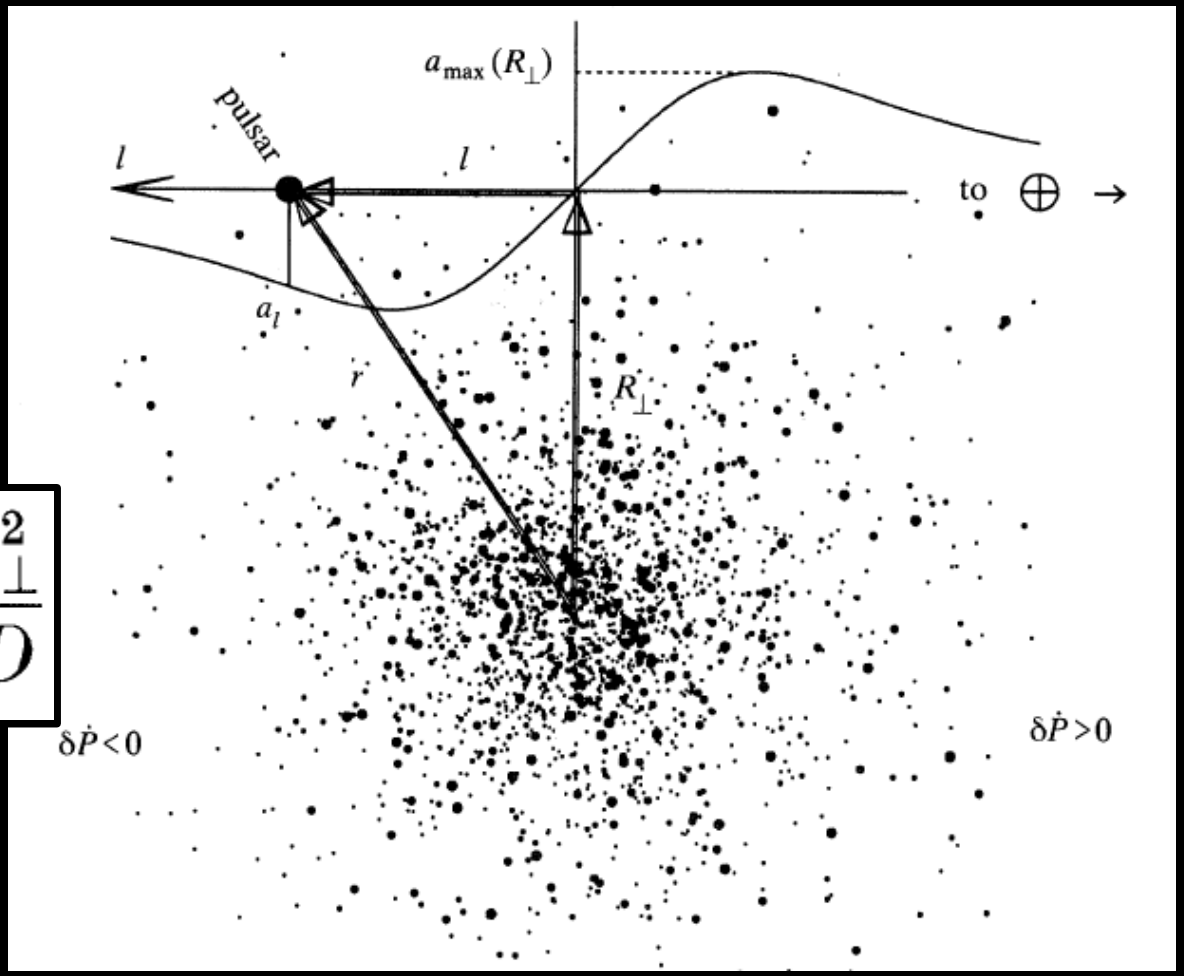
Measured Pulsar "Accelerations"

Apparent spin period derivative affected by:

- Pulsar ($a \sim 10^{-9}$ m/s^2)
- Cluster accel ($\sim 10^{-8}$)
- Galactic accel ($\sim 10^{-9}$)
- Proper motion ($\sim 10^{-10}$)

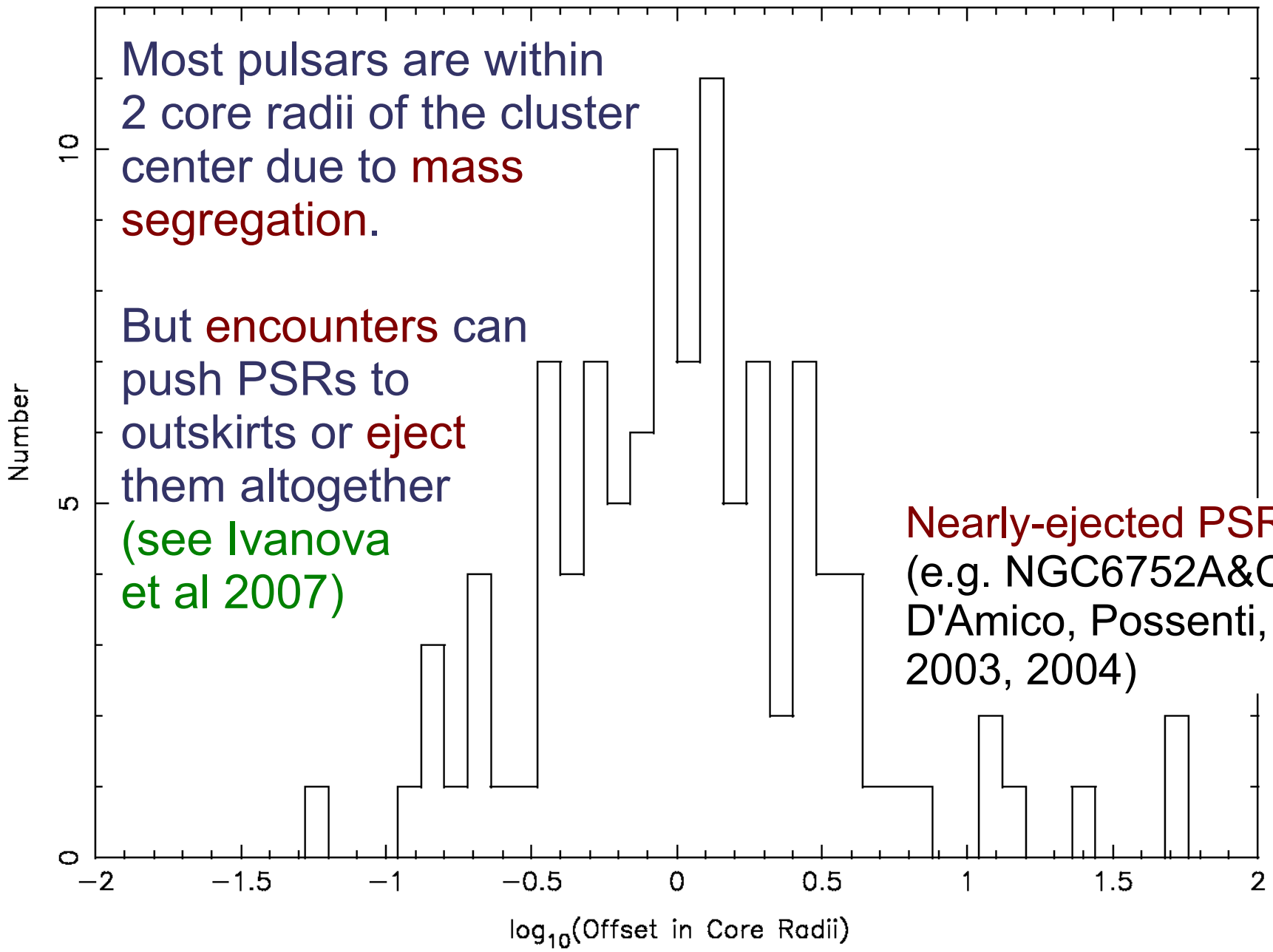
$$\frac{\dot{P}}{P} = \frac{\dot{P}_0}{P_0} + \frac{(\boldsymbol{a}_\mathrm{p} - \boldsymbol{a}_\mathrm{b}) \cdot \boldsymbol{n}}{c} + \frac{V_\perp^2}{cD}$$

Can constrain M/L, distance, velocity dispersion, etc

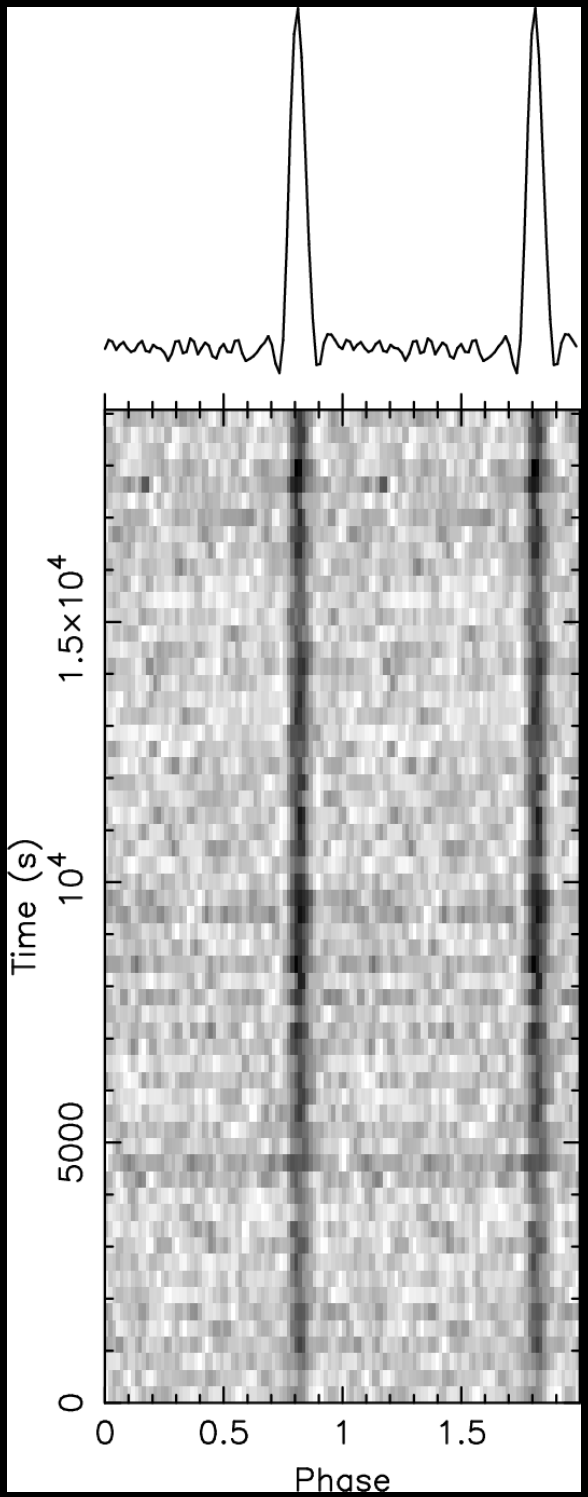


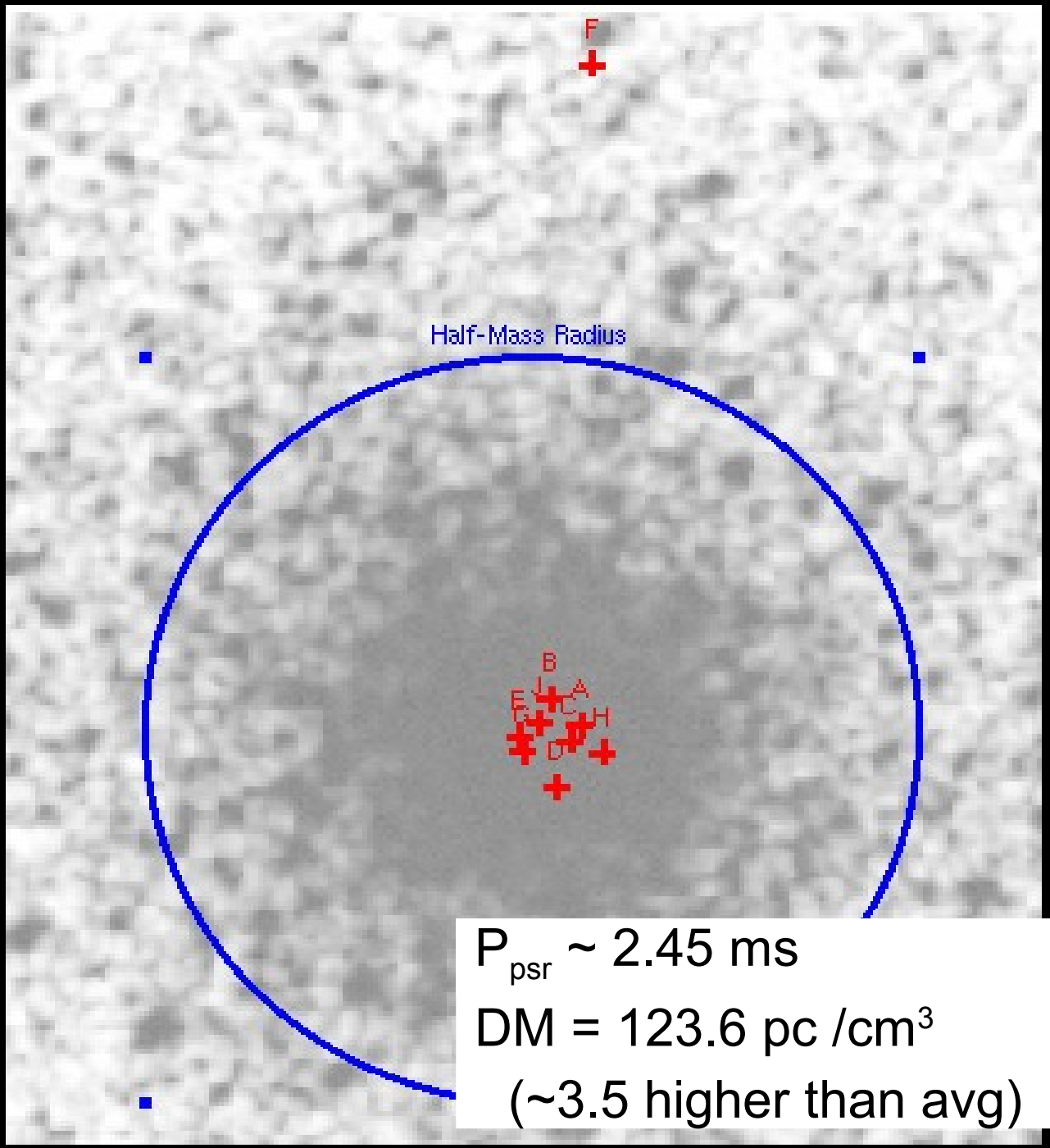
Phinney 1992, 1993

Projected Cluster Positions



M28 Solutions (M28F ejection?)



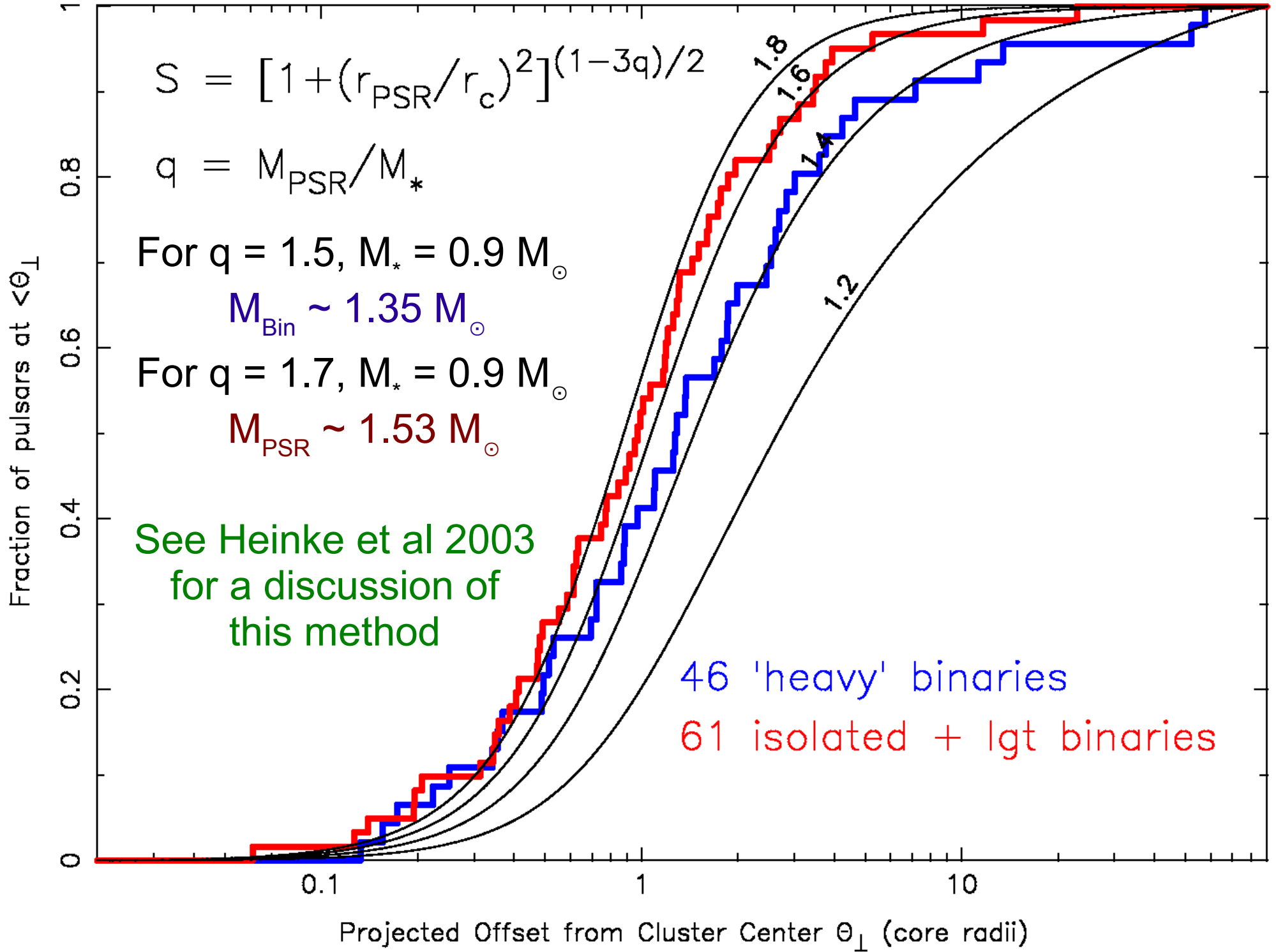


P_{psr} ~ 2.45 ms

DM = 123.6 pc /cm^3

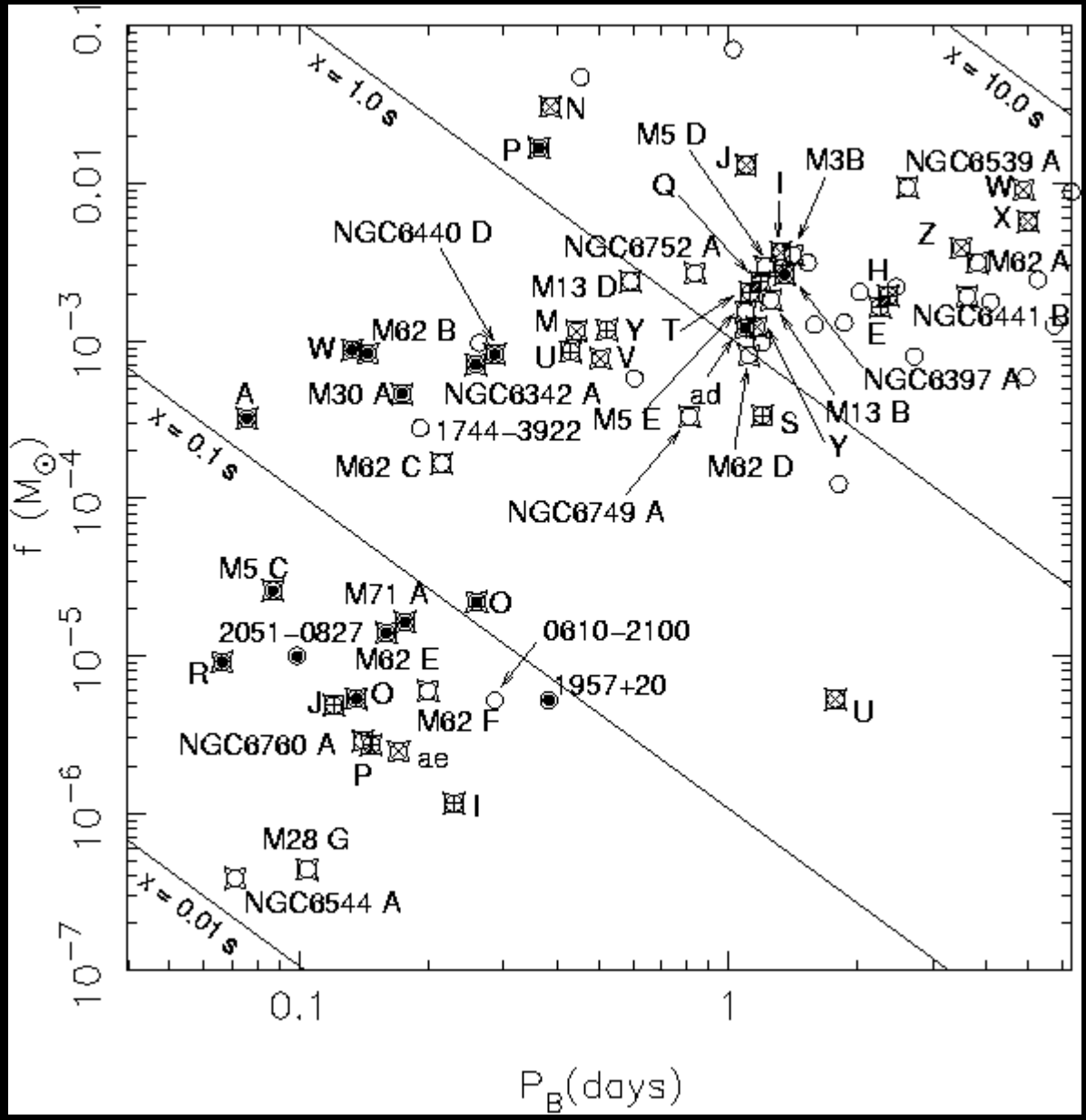
(~3.5 higher than avg)

Statistical Measurement of NS Masses



GC Pulsar Binaries

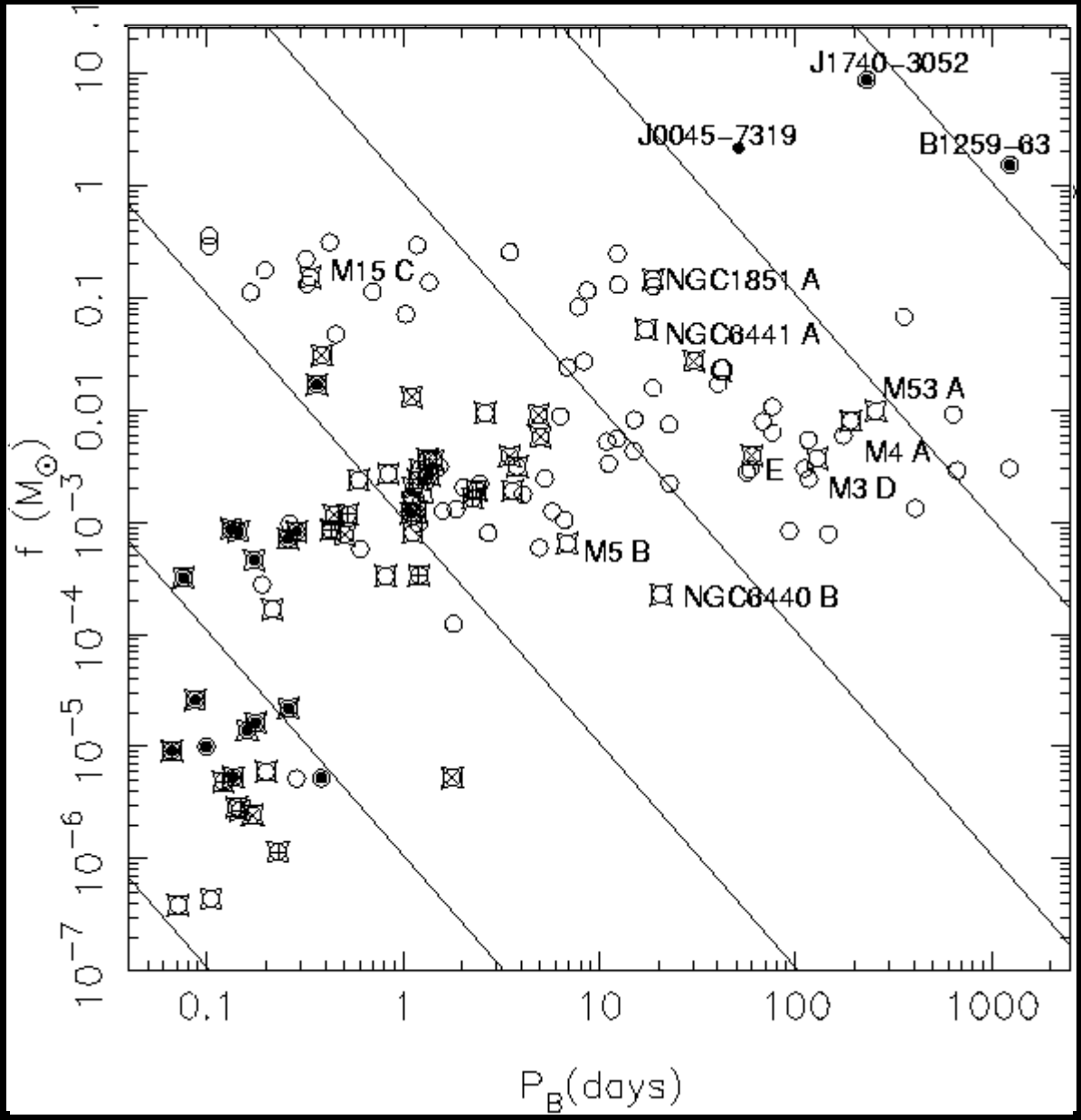
- Three main groups
  - "Black-Widows"
    - 0.001-0.1 Msun
    - Porb < 12 hrs
    - Circular
  - Low-mass "normal"
    - 0.1-0.4 Msun
    - Porb ~ 1-10 days
    - Mostly circular
  - Exotica



From Paulo Freire's GC Pulsar website

GC Pulsar Binaries

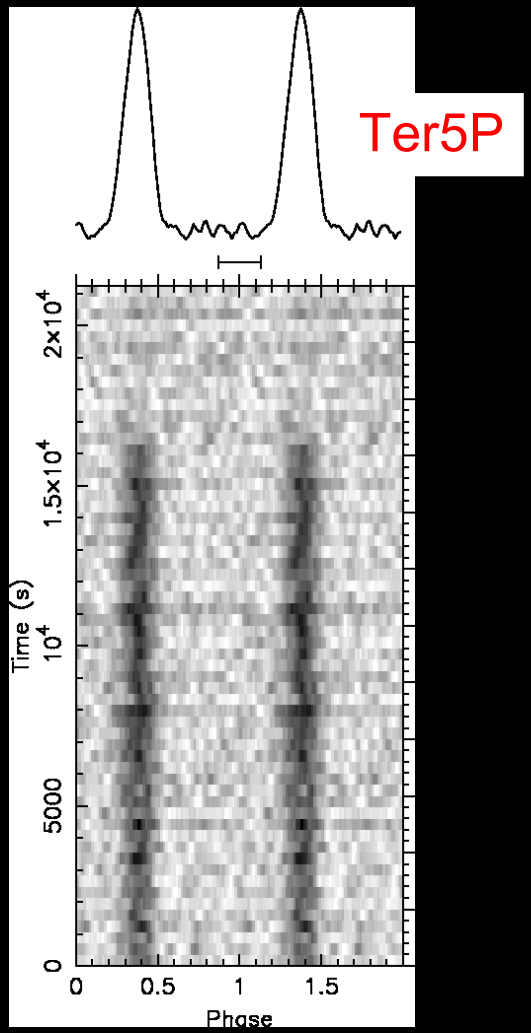
- Three main groups
  - "Black-Widows"
    - 0.001-0.1 Msun
    - Porb < 12 hrs
    - Circular
  - Low-mass "normal"
    - 0.1-0.4 Msun
    - Porb ~ 1-10 days
    - Mostly circular
  - Exotica



From Paulo Freire's GC Pulsar website

MSP + “Normal” Star?

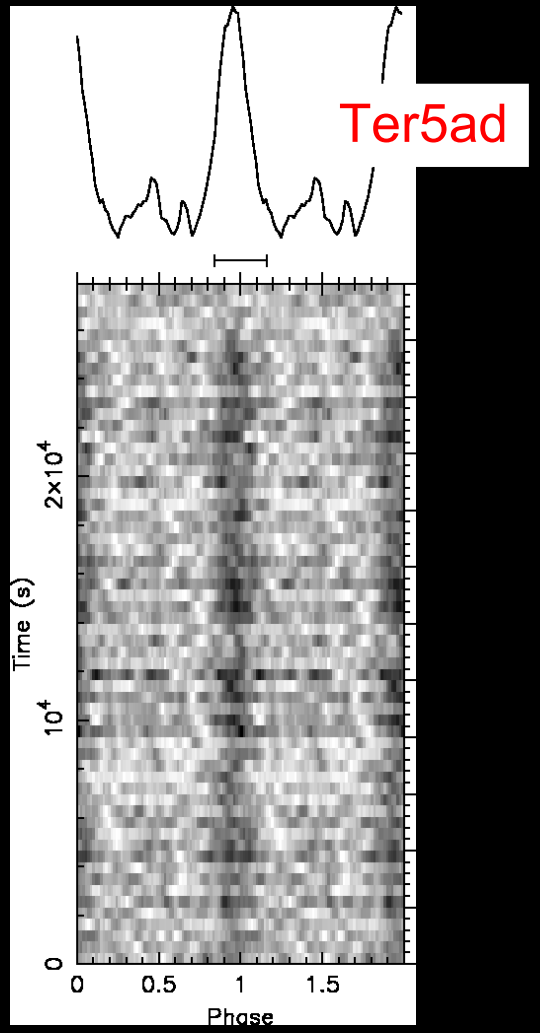
(First one in NGC6397
D'Amico et al 2001a,b)



P_{psr} = 1.73 ms

P_{orb} = 8.70 hrs

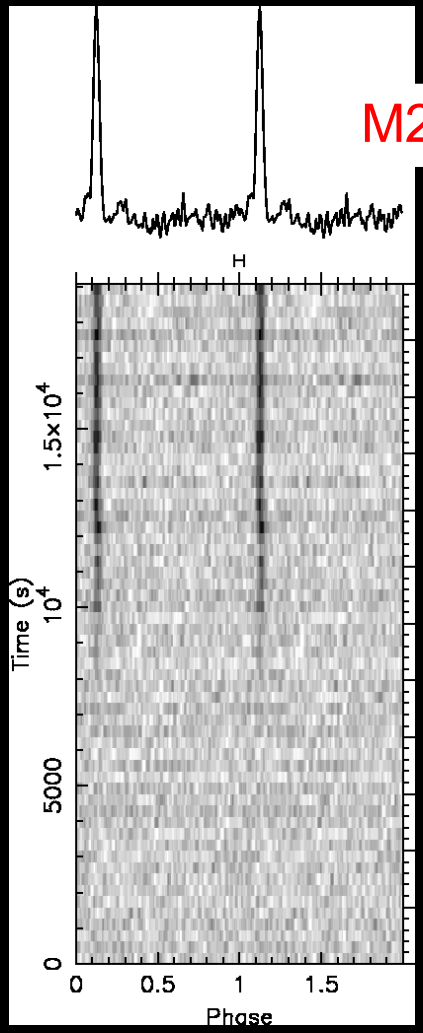
$M_{c,min}$ ~ 0.38 $M_{\odot}$



P_{psr} = 1.39 ms

P_{orb} = 1.09 days

$M_{c,min}$ ~ 0.14 $M_{\odot}$



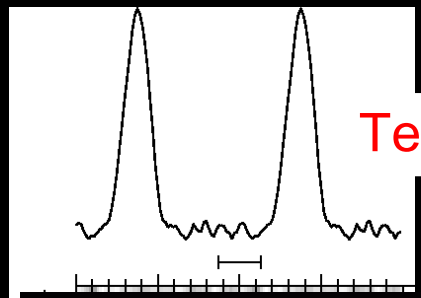
P_{psr} = 4.63ms

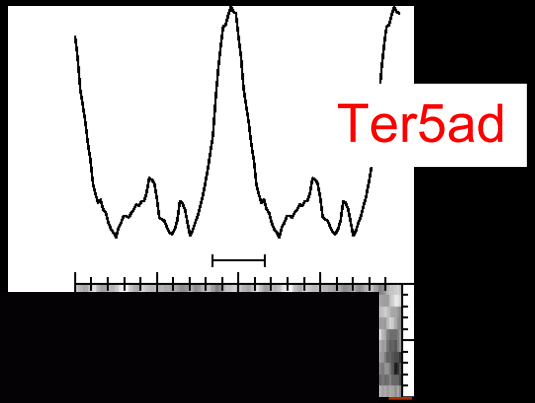
P_{orb} = 10.4 hrs

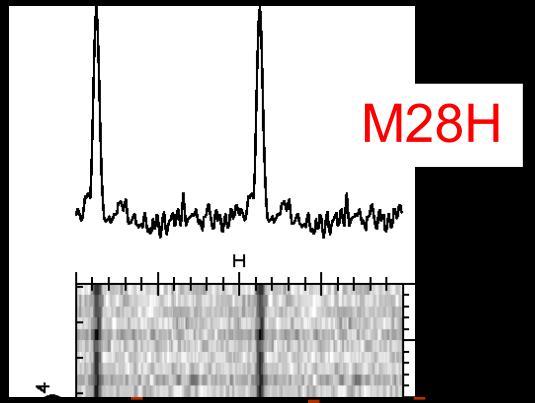
$M_{c,min}$ ~ 0.17 $M_{\odot}$

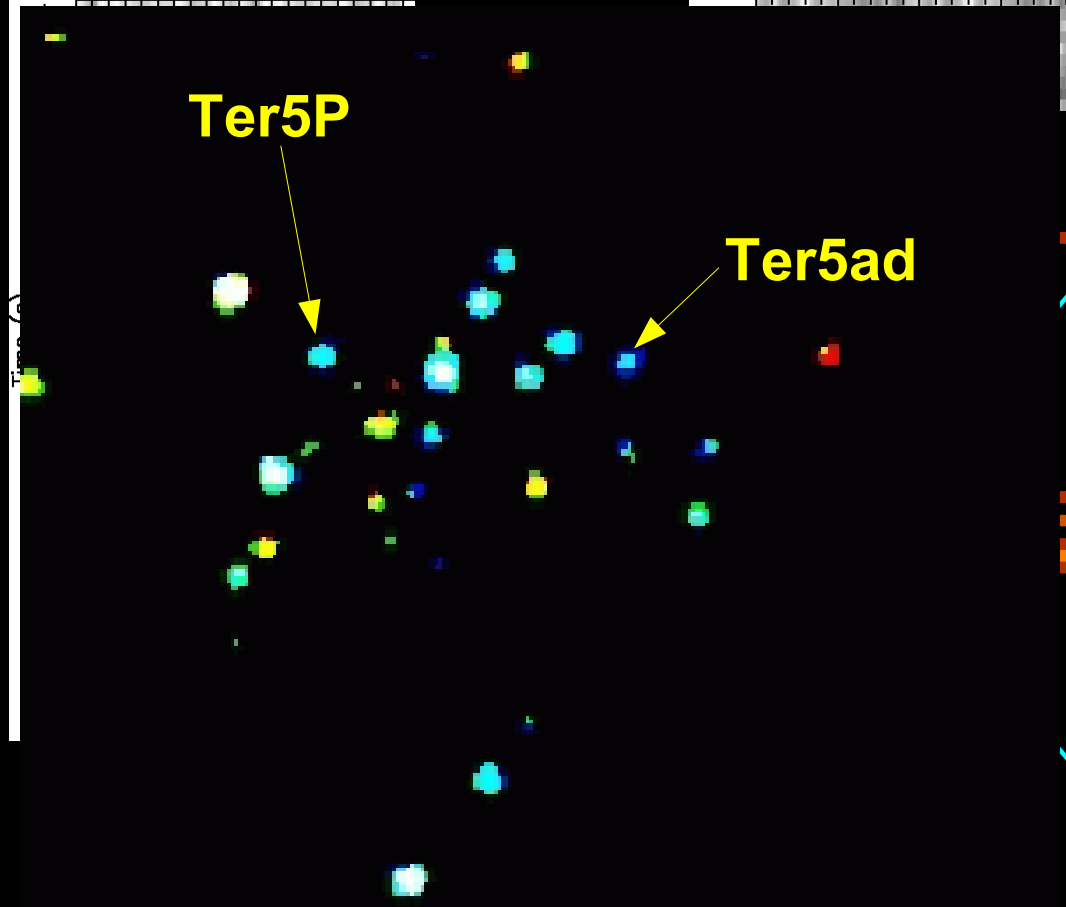
MSP + “Normal” Star?

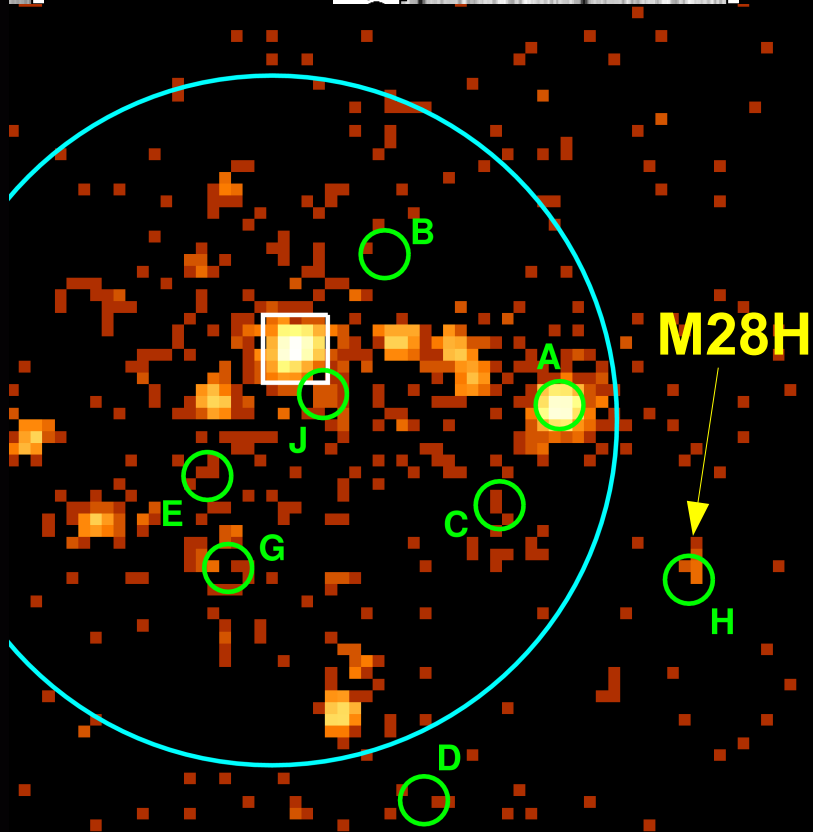
(First one in NGC6397
D'Amico et al 2001a,b)









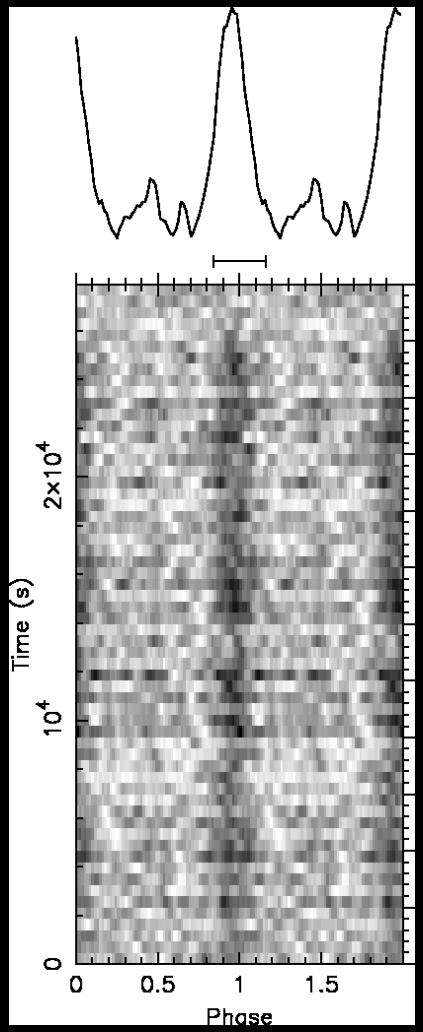


$M_{c,min}$ ~ 0.38 $M_{\odot}$

$M_{c,min}$ [illegible] $M_{\odot}$

$M_{c,min}$ [illegible] $M_{\odot}$

Eclipsing Millisecond Pulsars



Pulsar Name	Spin Freq. (Hz)	Eclipse Fraction	Location
J1748-2446ad	716	0.4	Terzan 5
B1937+21	642	Isolated	Gal. Plane
B1957+20	622	0.1	Gal. Plane
J1748-2446O	596	0.05	Terzan 5
J1748-2446P	578	0.4	Terzan 5
J1843-1113	542	Isolated	Gal. Plane
J0034-0534	533	None	Gal. Plane
J1748-2446Y	488	None	Terzan 5
J1748-2446V	483	None	Terzan 5
J0023-7203J	476	0.1	47 Tucanae

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

5 of the 10 fastest-spinning pulsars show eclipses.
5 of the 10 fastest-spinning pulsars are found in Terzan 5

Post-Keplerian Orbital Parameters

General Relativity gives:

$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3}(T_\odot M)^{2/3}(1-e^2)^{-1}$$ (Orbital Precession)

$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_2 (m_1 + 2m_2)$$ (Grav redshift + time dilation)

$$\dot{P}_b = -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2} T_\odot^{5/3} m_1 m_2 M^{-1/3}$$

$$r = T_\odot m_2$$

$$s = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_2^{-1}$$

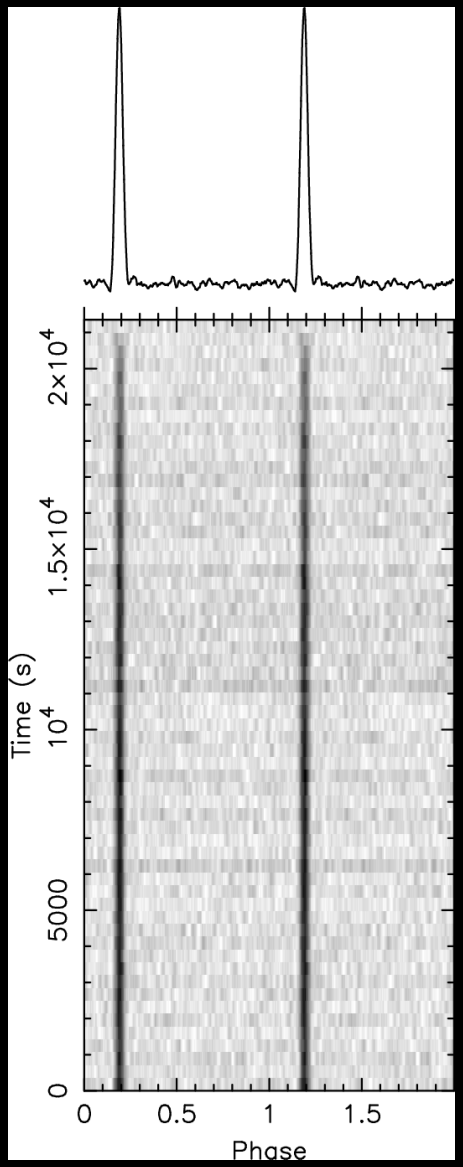
(Shapiro delay: "range" and "shape")

where: $T_\odot \equiv GM_\odot/c^3 = 4.925490947\ \mu$ s, $M = m_1 + m_2$, and $s \equiv \sin(i)$

These are only functions of:

- the (precisely!) known Keplerian orbital parameters P_b, e, asin(i)
- the mass of the pulsar m_1 and the mass of the companion m_2

M28C

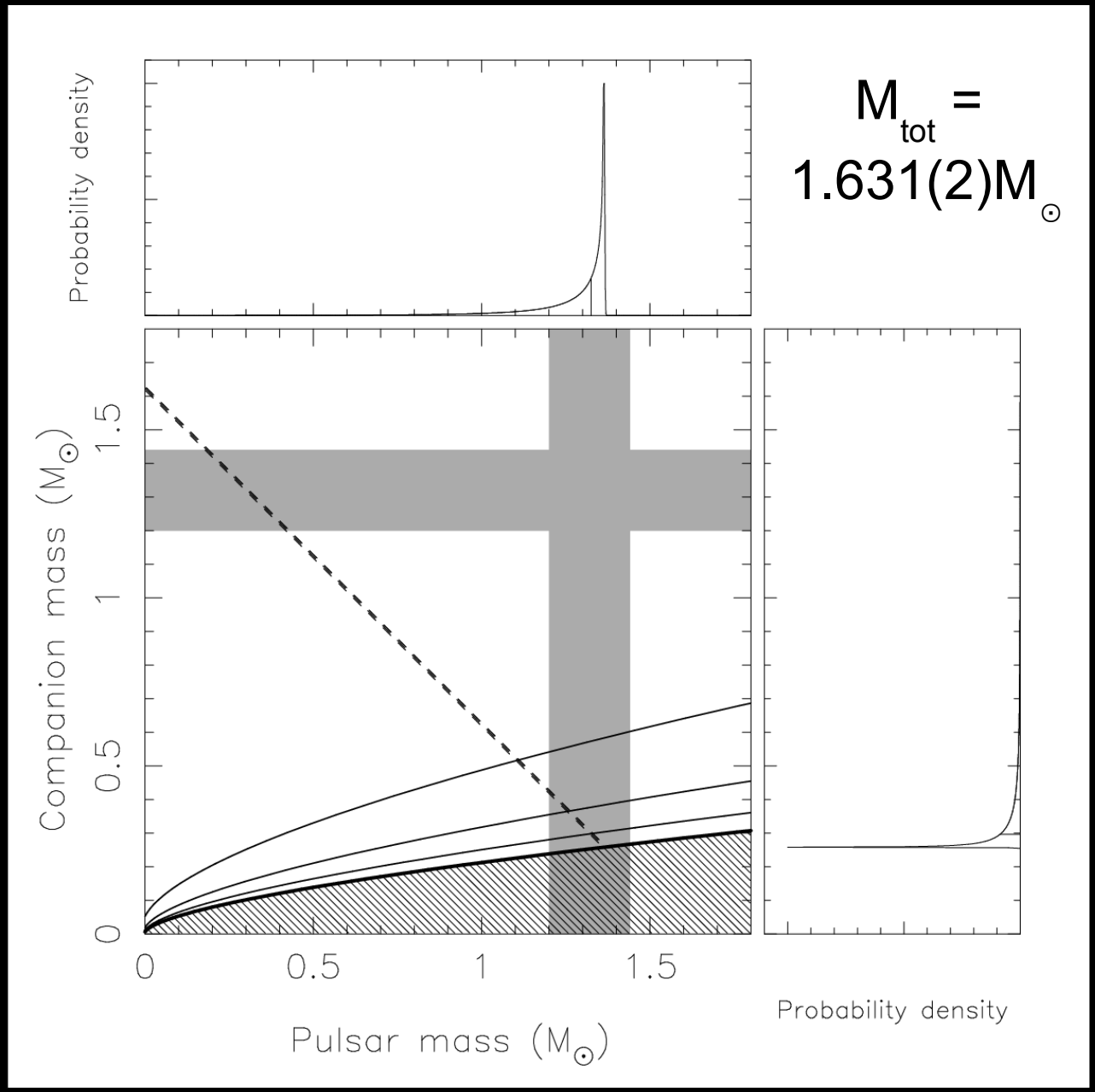


Highly eccentric (e=0.847)

P_{psr} ~ 4.158 ms

P_{orb} = 8.07 days

~5μs timing in ~5min

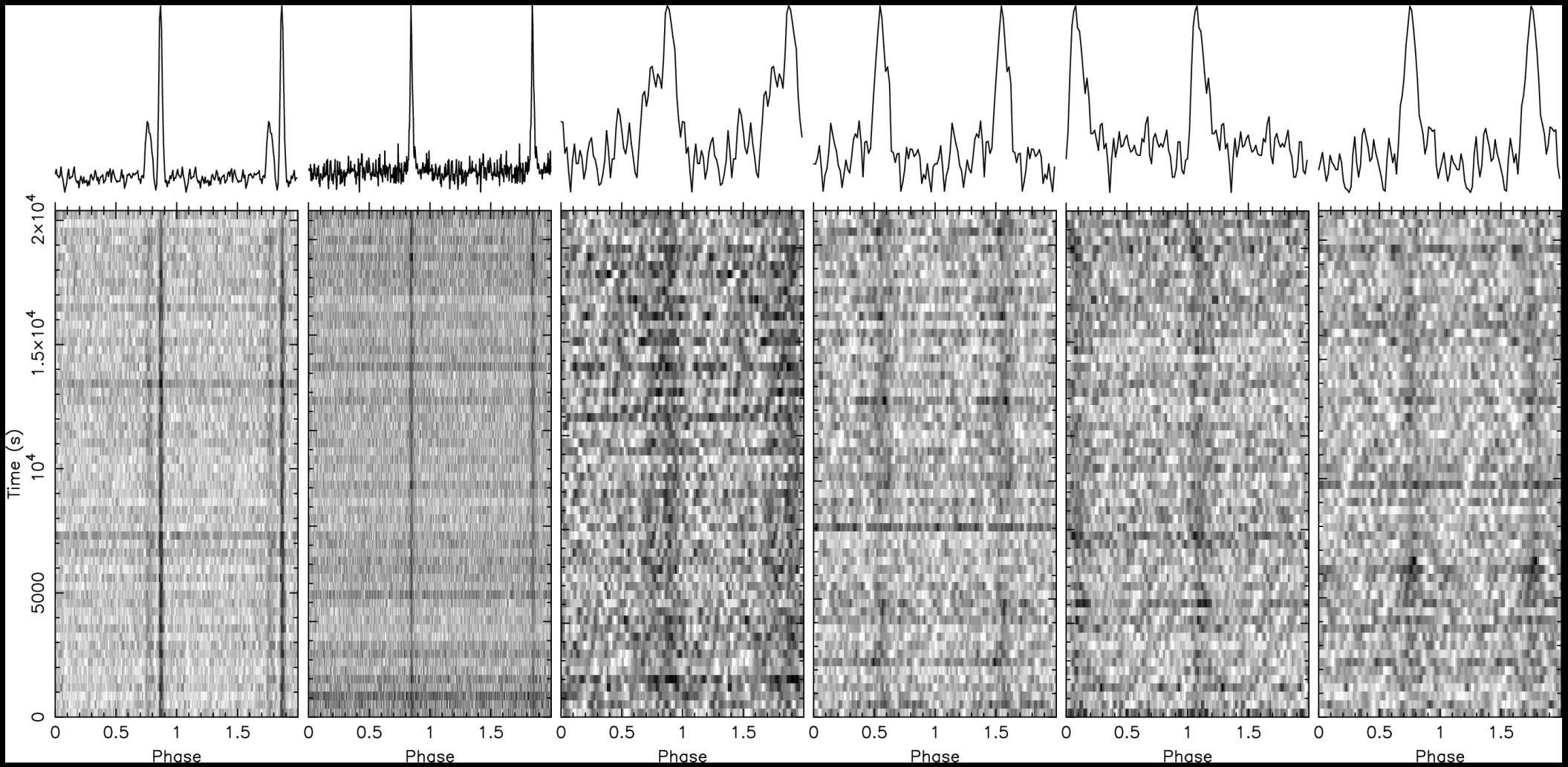


Timing 11 Eccentric (e>0.3) Binaries

Name	P(ms)	Pb(d)	E	Mcmin	Mtot	Mpmed
Ter5J	80.338	1.10	0.350	0.34	**2.19(2)**	**1.73**
Ter5I	9.570	1.33	0.428	0.21	**2.171(3)**	**1.87**
Ter5Z	2.463	3.49	0.761	0.22	**1.79(1)**	**1.53**
Ter5U	3.289	3.57	0.605	0.39	**2.26(1)**	**1.73**
Ter5X	2.999	5.00	0.302	0.25	**1.91(5)**	**1.60**
M5B	7.947	6.85	0.138	0.13	**2.3(1)**	**2.12**
M28C	4.158	8.08	0.847	0.26	**1.631(1)**	**1.33**
NGC6441A	111.601	17.33	0.712	0.59	**2.0(2)**	**1.35**
NGC1851A	4.991	18.79	0.888	0.92	**2.44(5)**	**1.34**
NGC6440B	16.760	20.55	0.570	0.08	**2.8(3)**	**2.68**
Ter5Q	2.812	30.30	0.722	0.46	**2.4(2)**	**1.79**
M28D	79.835	30.41	0.776	0.38	**1.2(7)**	

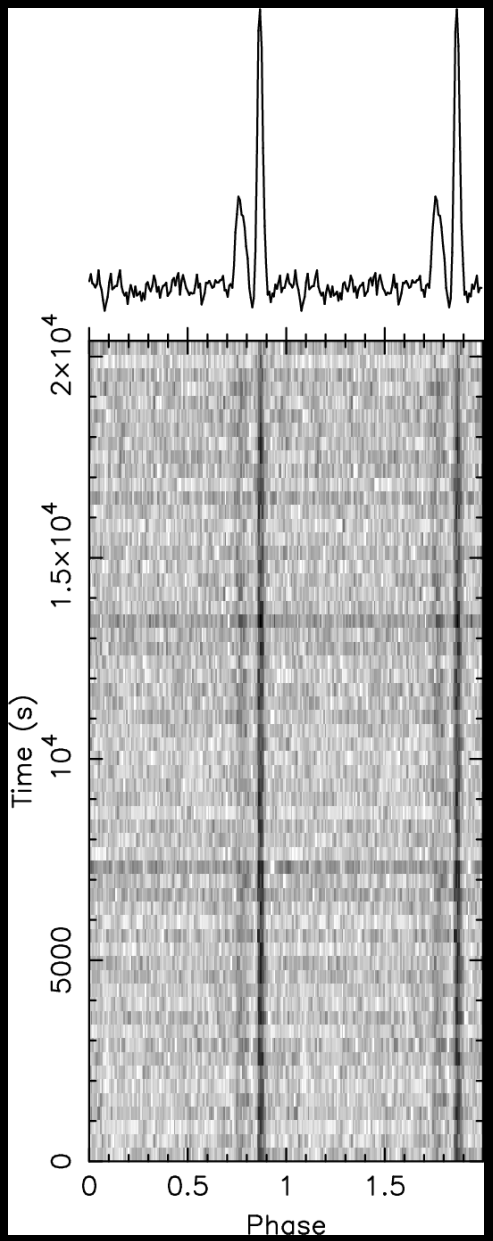
M5B: Freire et al 2008, ApJ, 679, 1433

Six (!) Eccentric Binary MSPs in Ter5



Ter5I	Ter5J	Ter5Q	Ter5U	Ter5X	Ter5Z
P_{psr} = 9.57 ms	P_{psr} = 2.81 ms	P_{psr} = 2.81 ms	P_{psr} = 3.29 ms	P_{psr} = 3.00 ms	P_{psr} = 2.46 ms
P_{orb} = 1.33 days	P_{orb} = 1.10 days	P_{orb} = 30 days	P_{orb} = 3.57 days	P_{orb} = 5.0 days	P_{orb} = 3.5 days
$M_{c,min}$ ~ 0.21 $M_\odot$	$M_{c,min}$ ~ 0.34 $M_\odot$	$M_{c,min}$ ~ 0.45 $M_\odot$	$M_{c,min}$ ~ 0.39 $M_\odot$	$M_{c,min}$ ~ 0.25 $M_\odot$	$M_{c,min}$ ~ 0.22 $M_\odot$
ecc = 0.43	ecc = 0.35	ecc = 0.72	ecc ~ 0.61	ecc = 0.30	ecc = 0.76

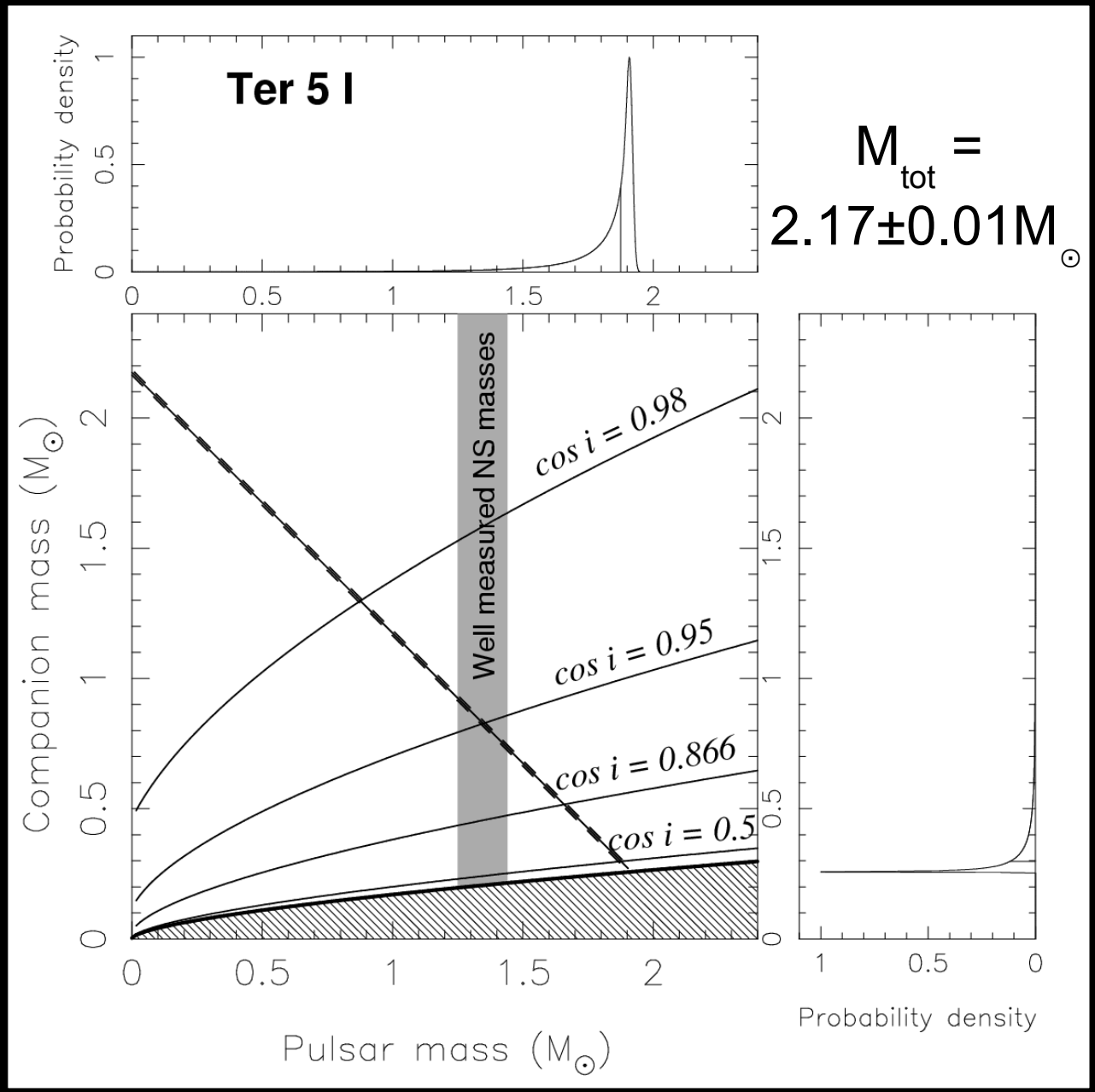
Eccentric Binary: Ter5I



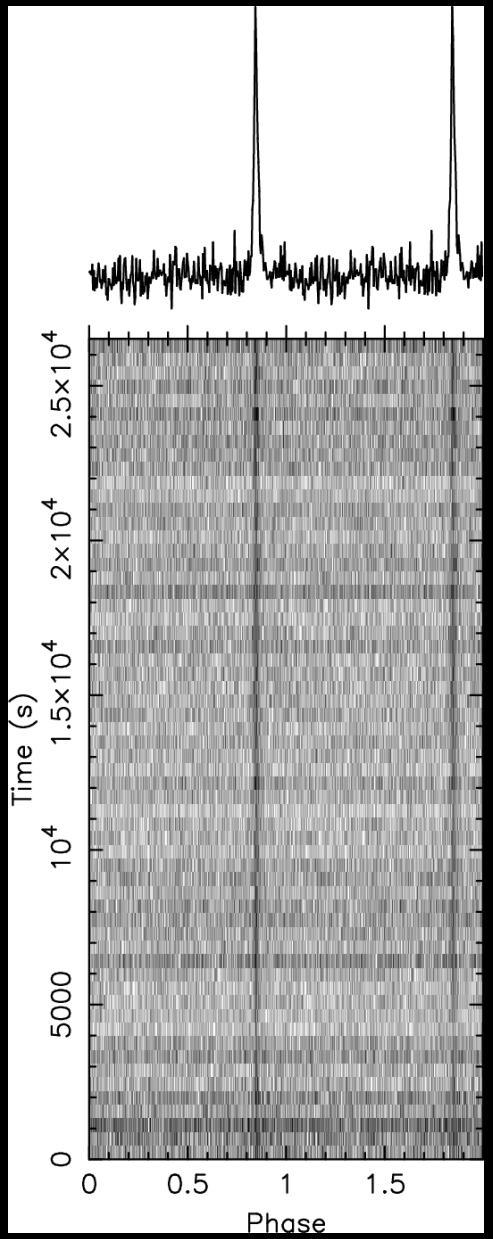
Highly eccentric (e=0.43)

P_{psr} ~ 9.57 ms

P_{orb} = 31.87 hrs



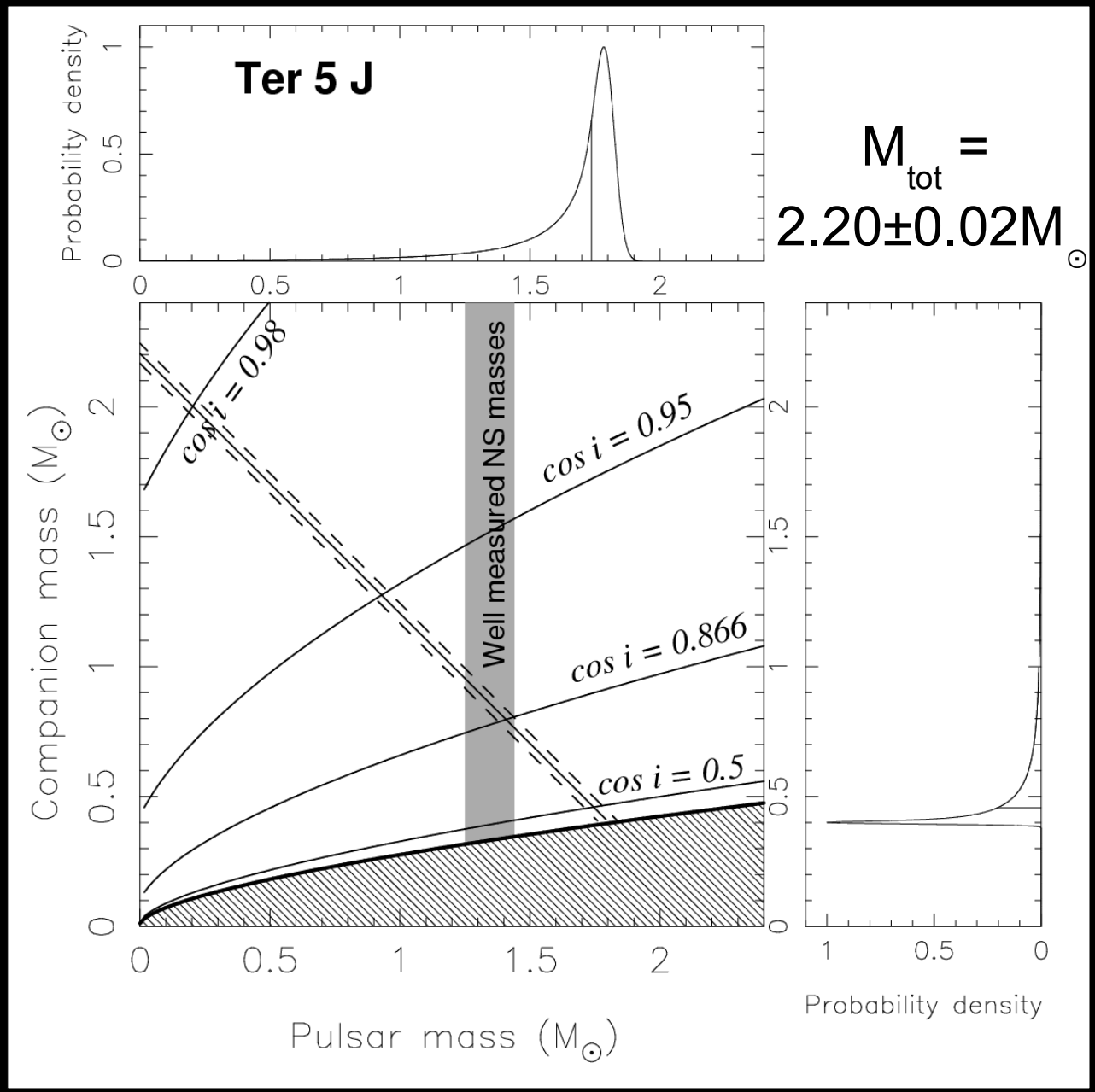
Eccentric Binary: Ter5J



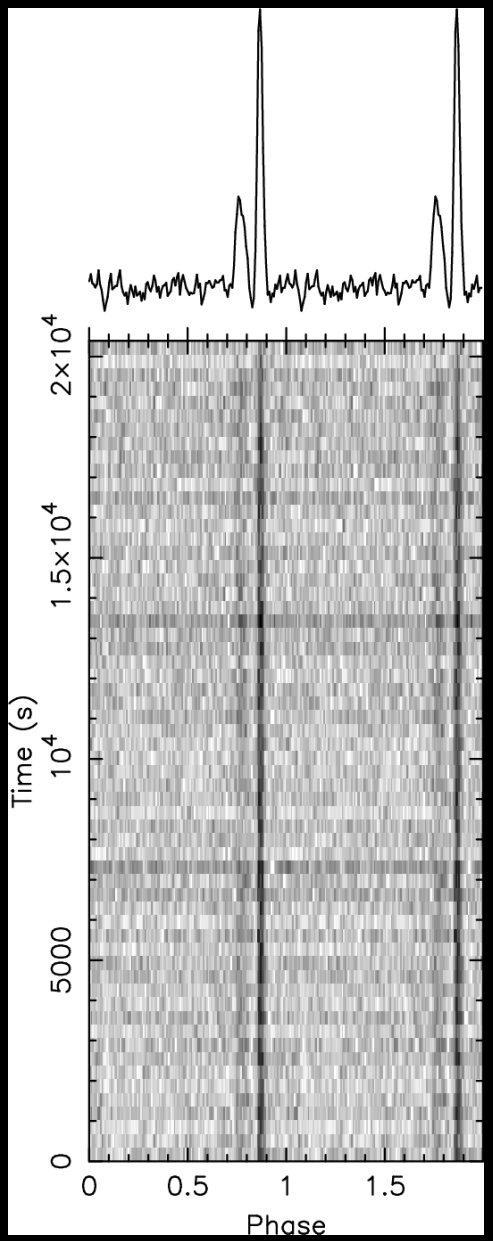
Highly eccentric (e=0.33)

P_{psr} ~ 80.34 ms

P_{orb} = 26.45 hrs



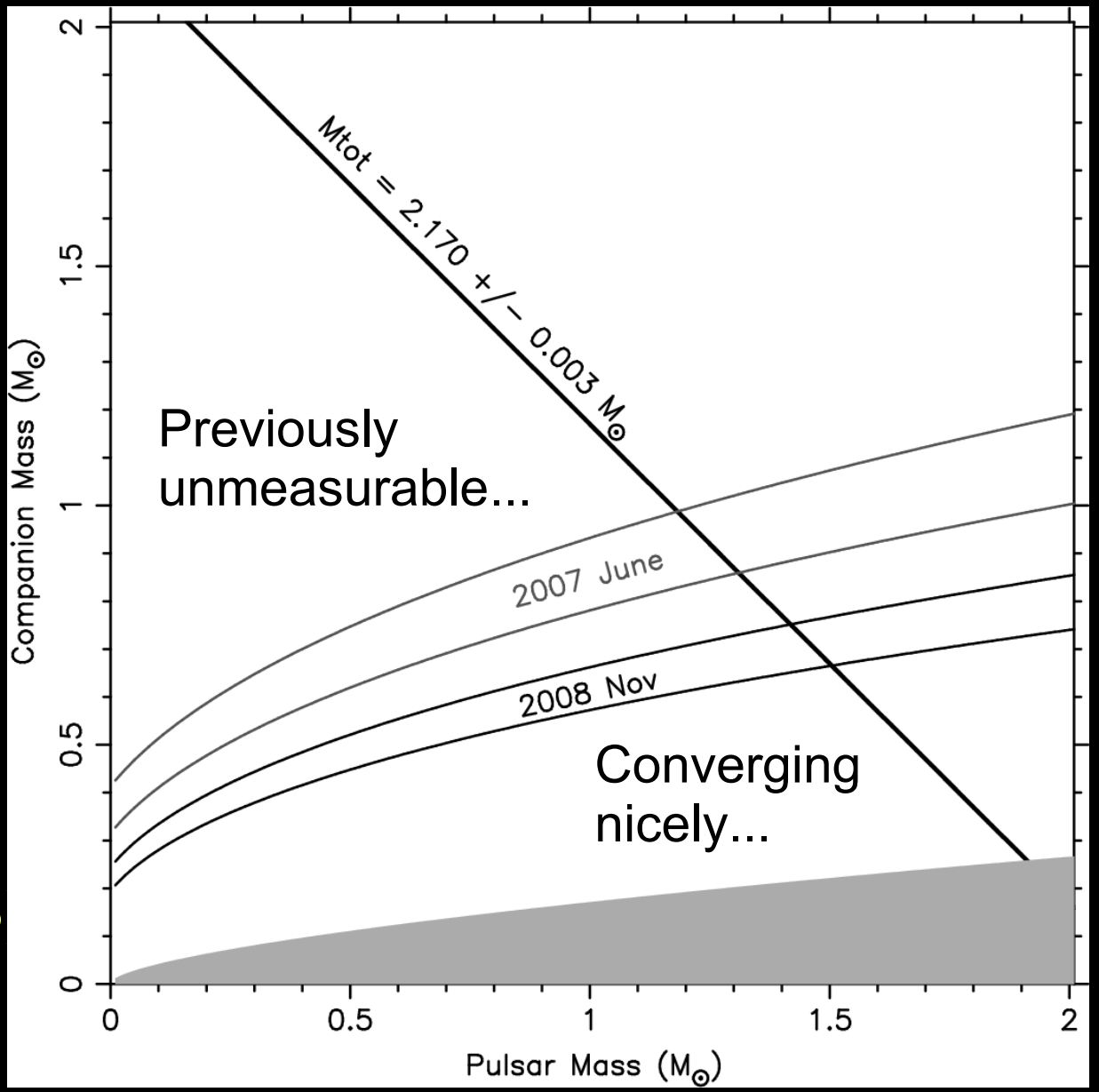
Ter5I:
Time dilation + redshift (gamma)



Highly eccentric (e=0.43

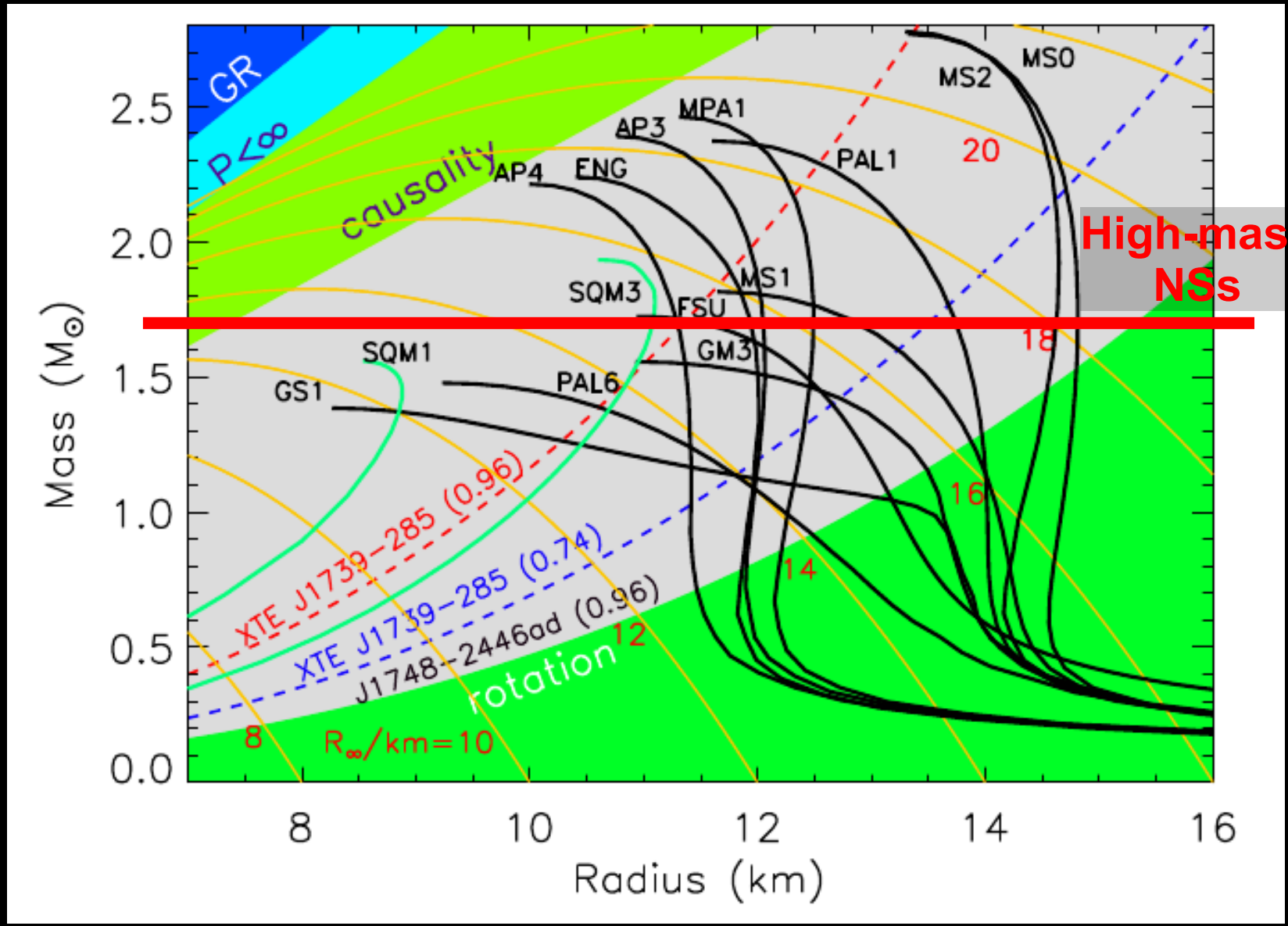
P_{psr} ~ 9.57 ms

P_{orb} = 31.87 hrs



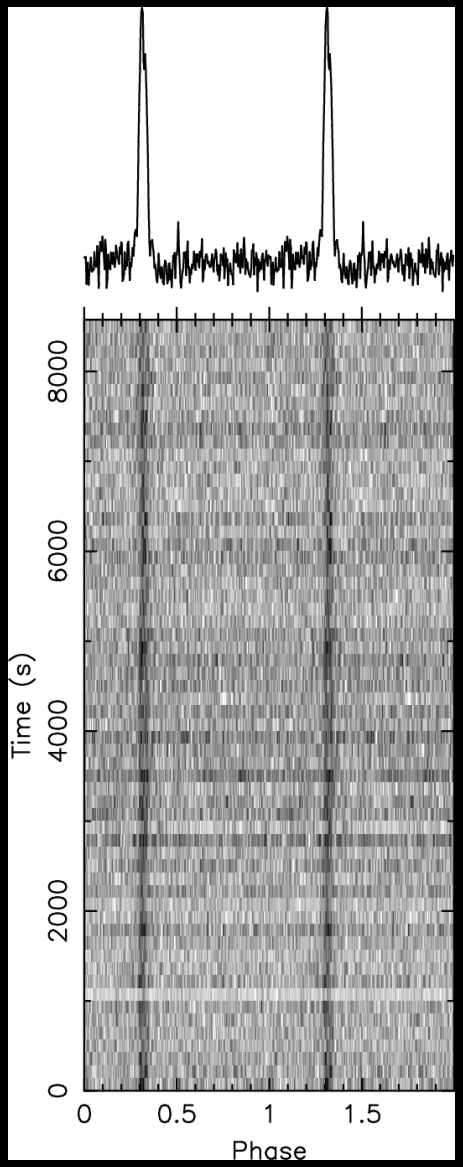
Neutron Star Equations of State:

Understanding matter at supra-nuclear densities.



Adapted from Lattimer and Prakash 2007, *Physics Reports*

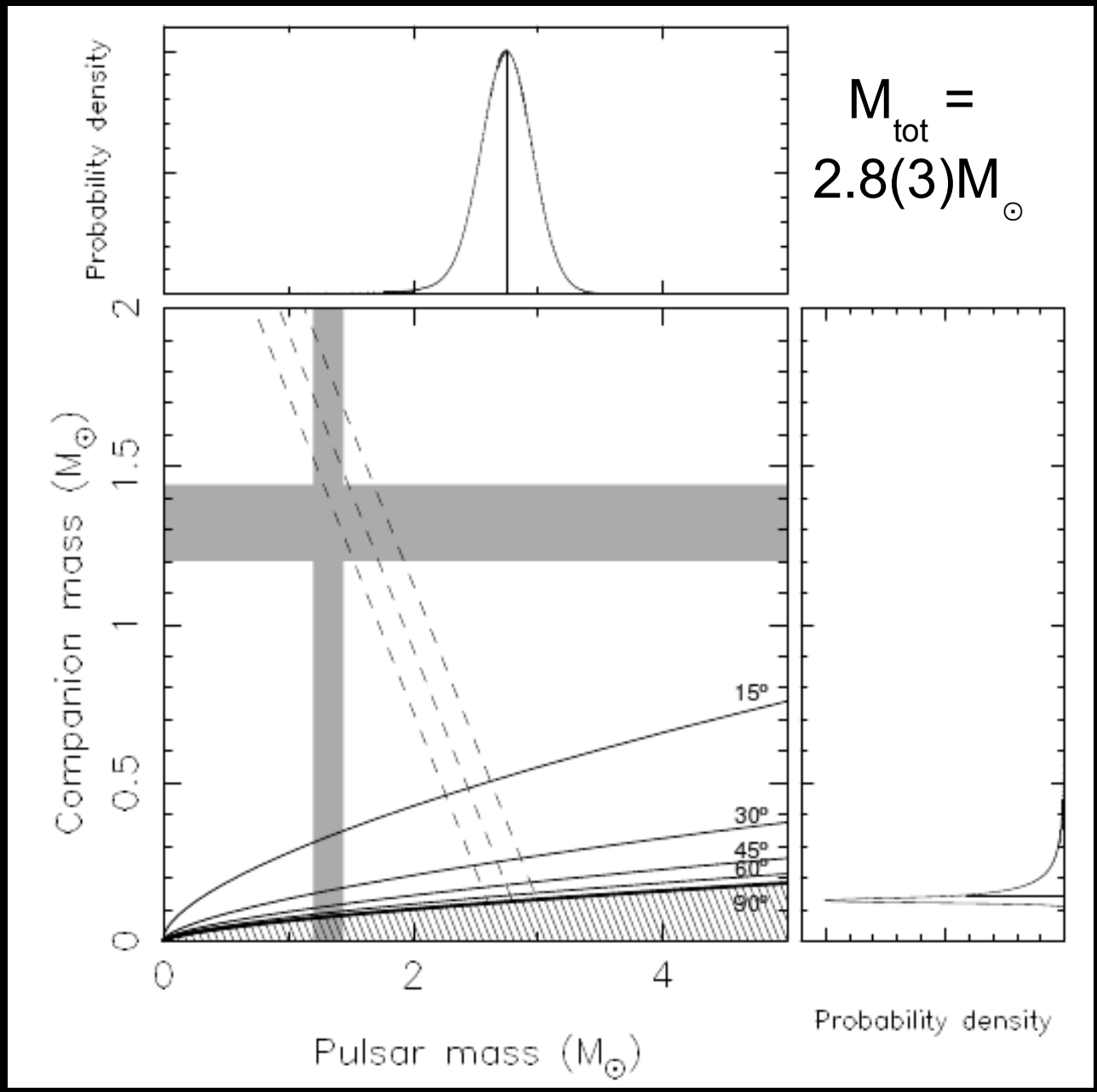
NGC6440B: A Massive PSR?



Highly eccentric (e=0.570)

P_{psr} ~ 16.76 ms

P_{orb} = 20.6 days



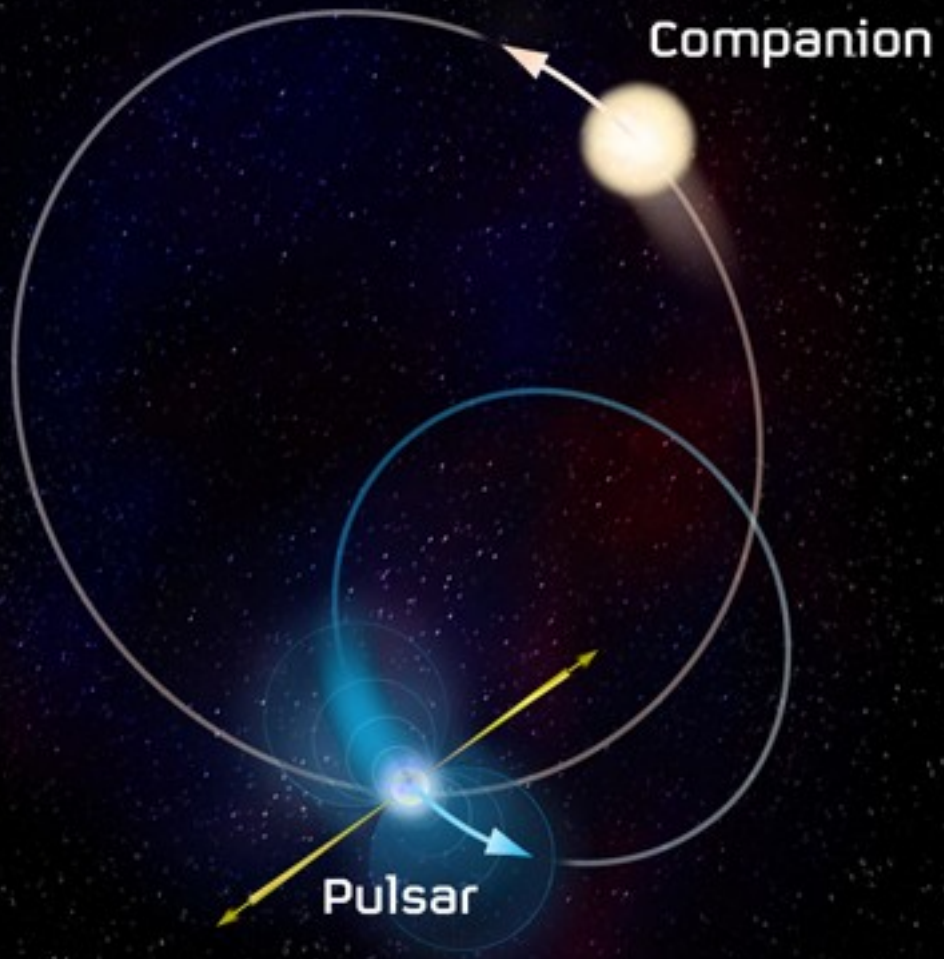
Freire et al. 2008, ApJ, 675, 670

PSR J1903+0327

Champion et al. 2008,
Science, 320, 1309

This thing is weird.

- Fully recycled (2.15 ms)
- Eccentric 90-day orbit
- Massive (MS?) companion with possible optical counterpart
- Quite bright in radio
- We have no idea how it formed (triple system?)



Bill Saxton, NRAO/AUI/NSF

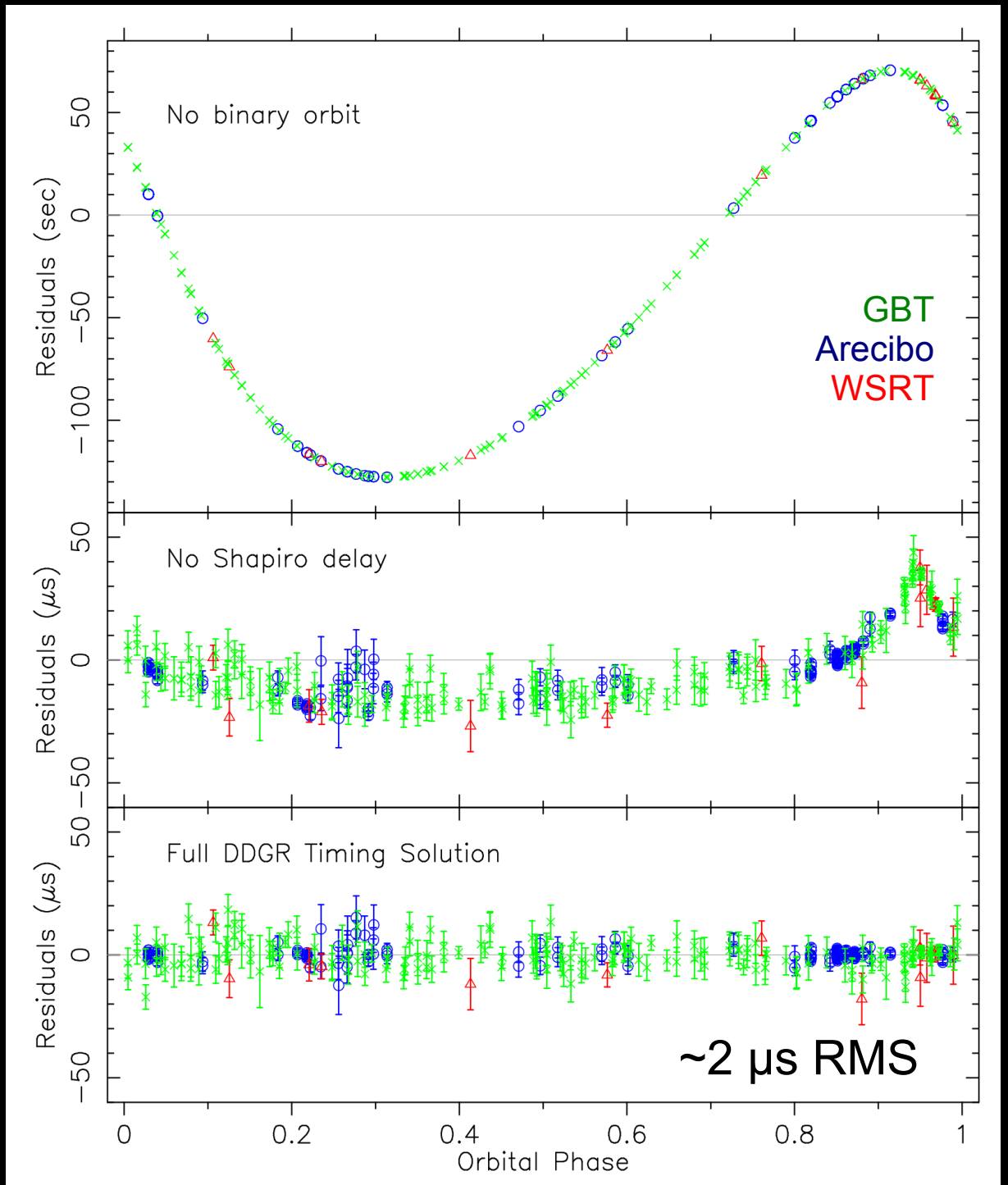
1903 Timing

Astrometry:
- Sub-milliarcsec posn

Spin-down:
- part in 10^3
- (age <2 Gyrs)

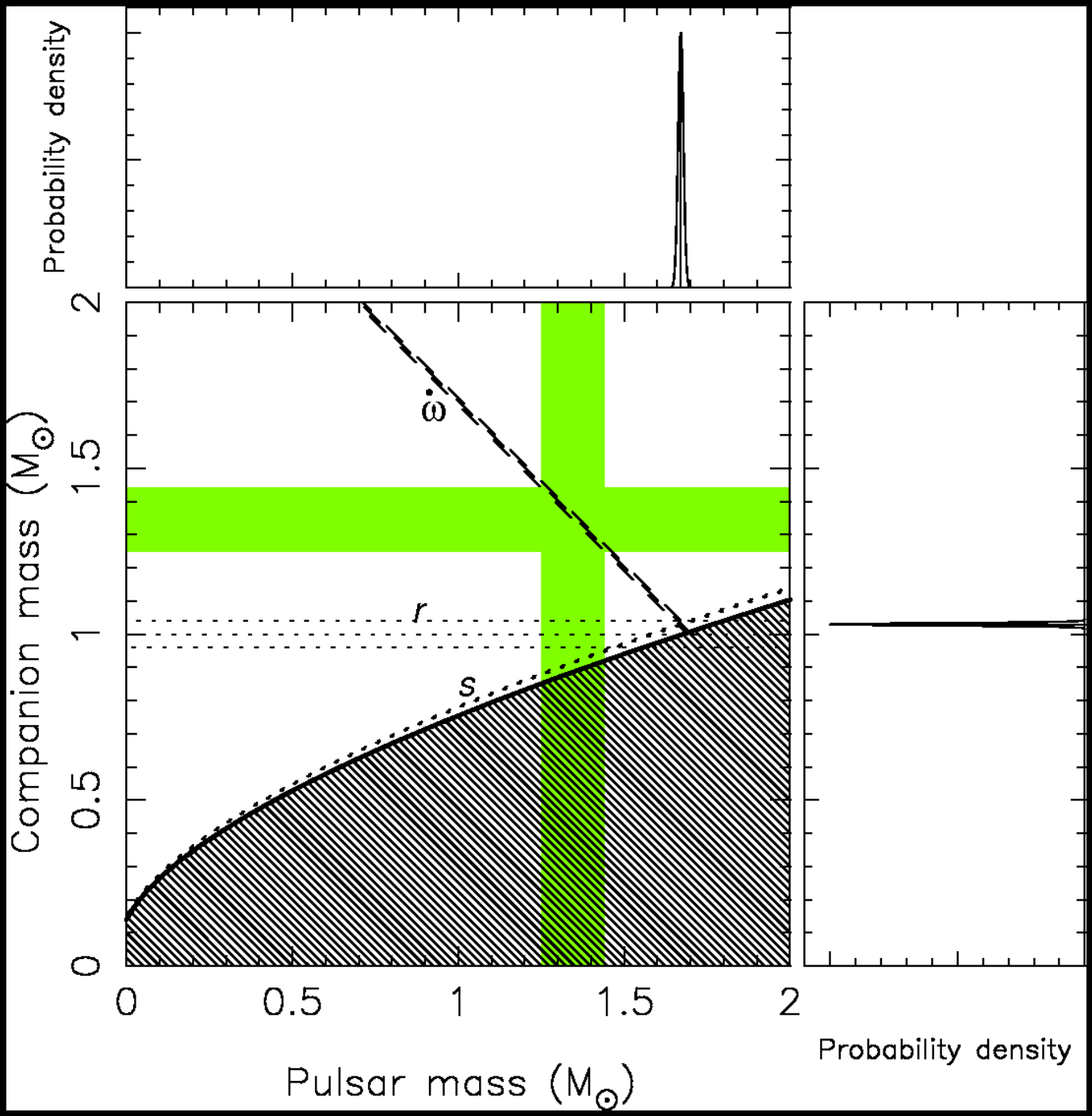
Keplerian Orbit:
- 6-9 sig figs in 5 params

Post-Keplerian:
- Orbital precession
- + Shapiro delay
- + GR assumed:
  - Mtot = 2.79(5) $M_\odot$
  - inclination = 78(2)°
  - Mc = 1.05(2) $M_\odot$
  - Mp = 1.74(4) $M_\odot$



Recent Arecibo timing

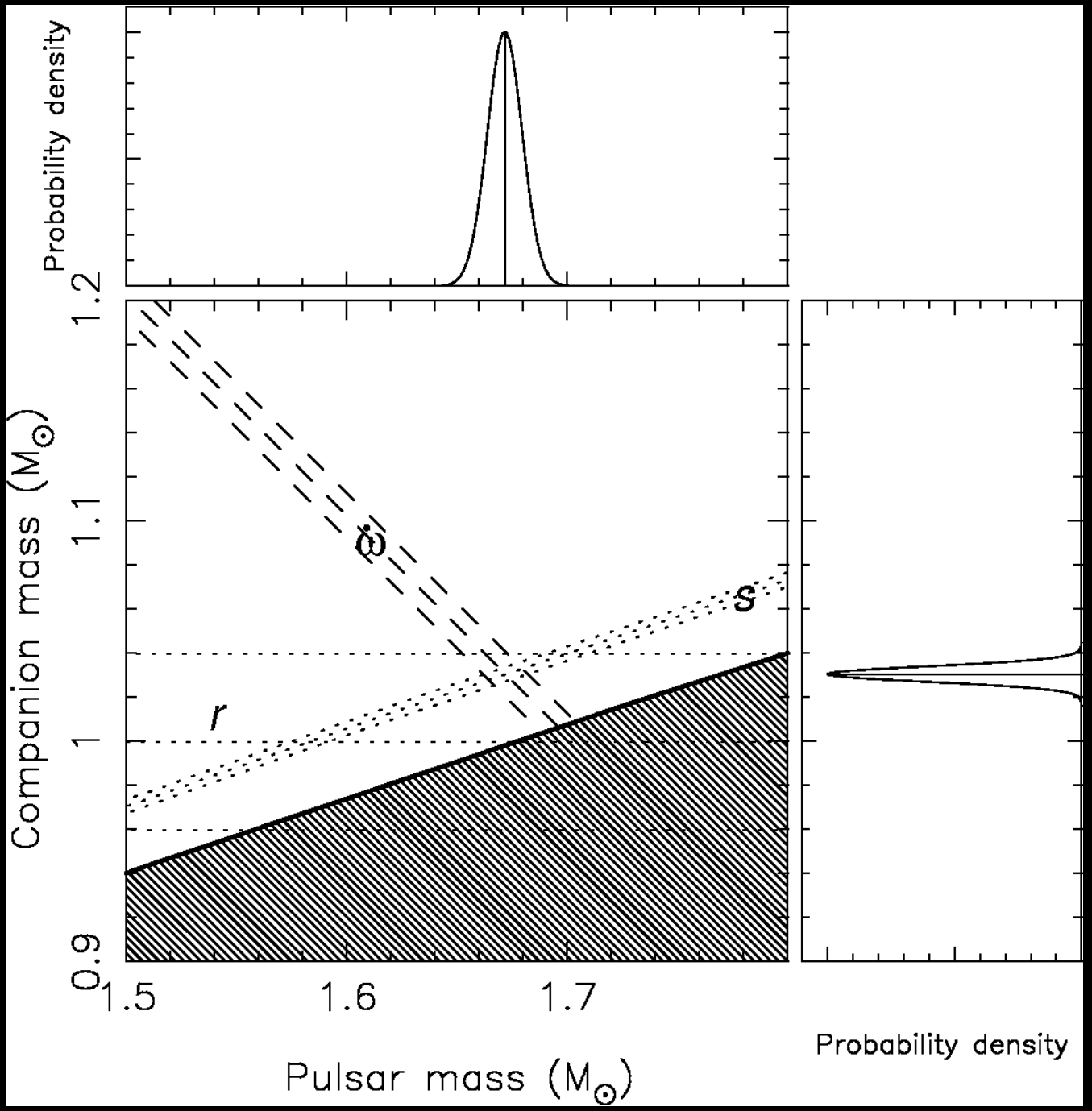
Much improved Shapiro delay



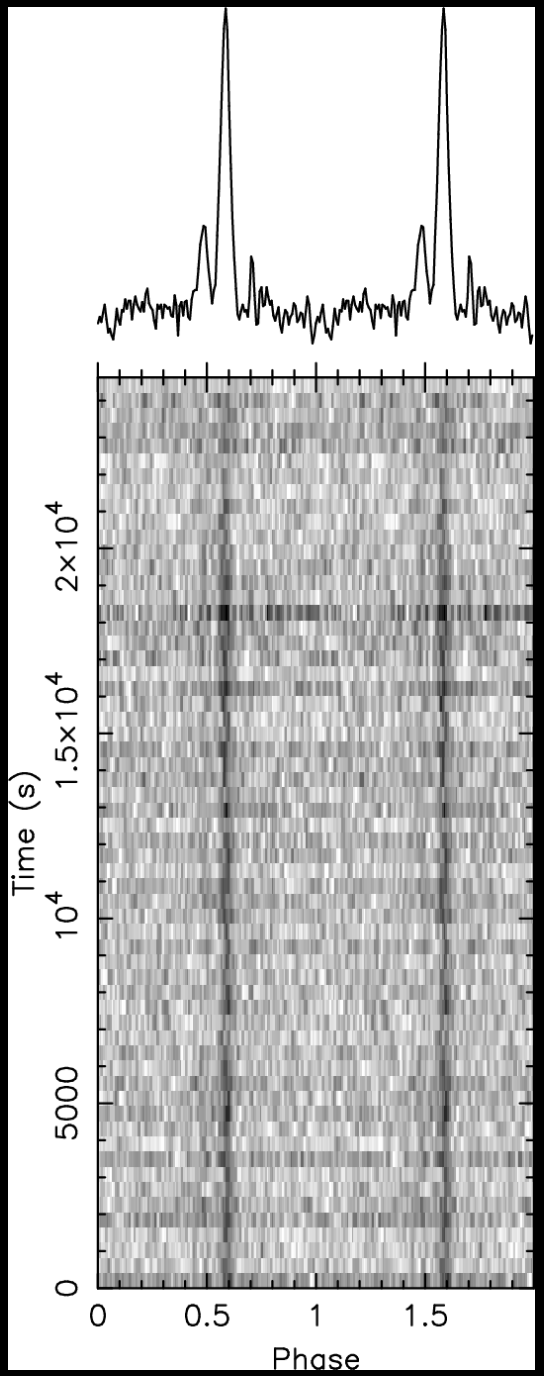
Recent Arecibo timing

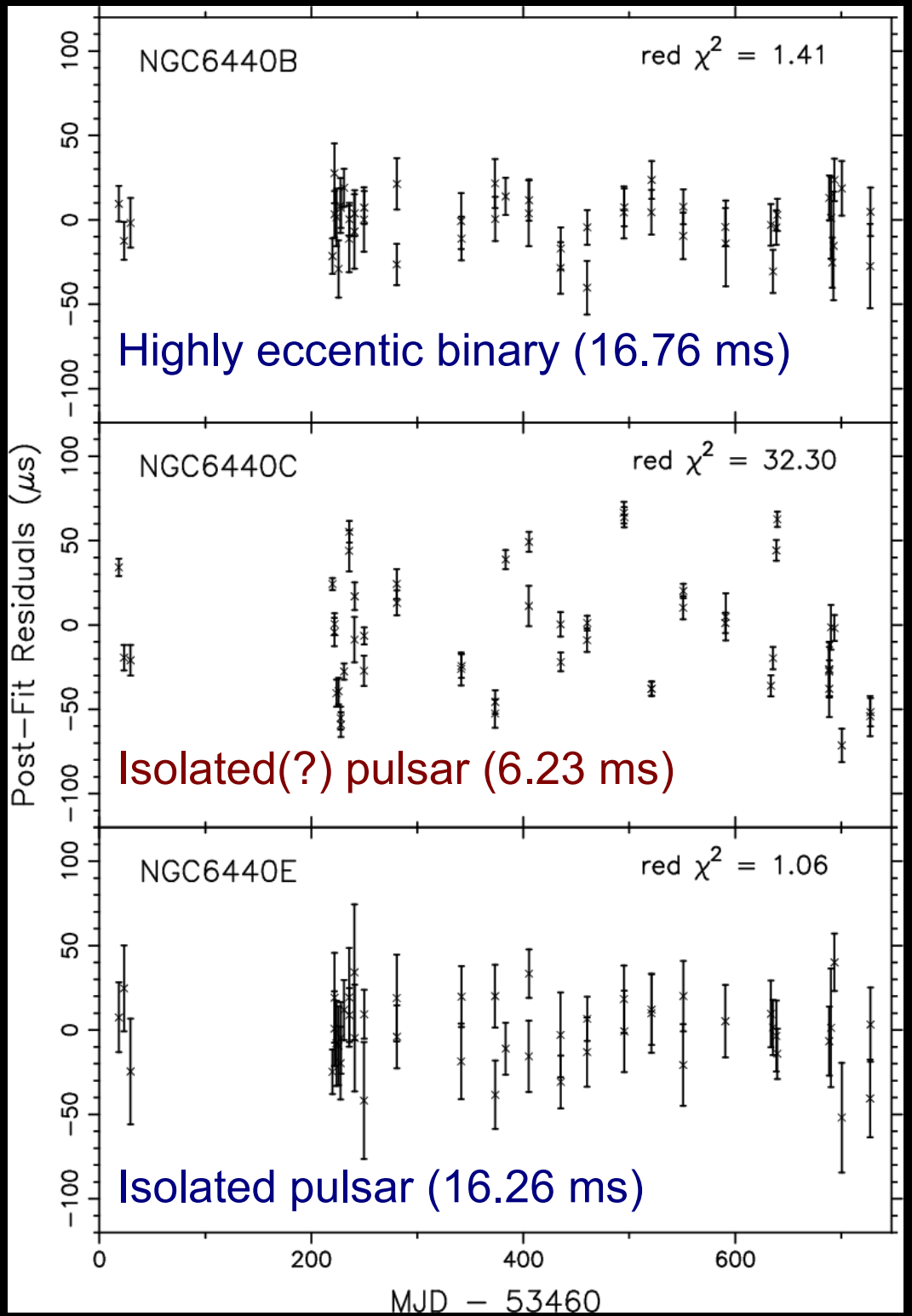
Much improved Shapiro delay

Freire et al. in prep

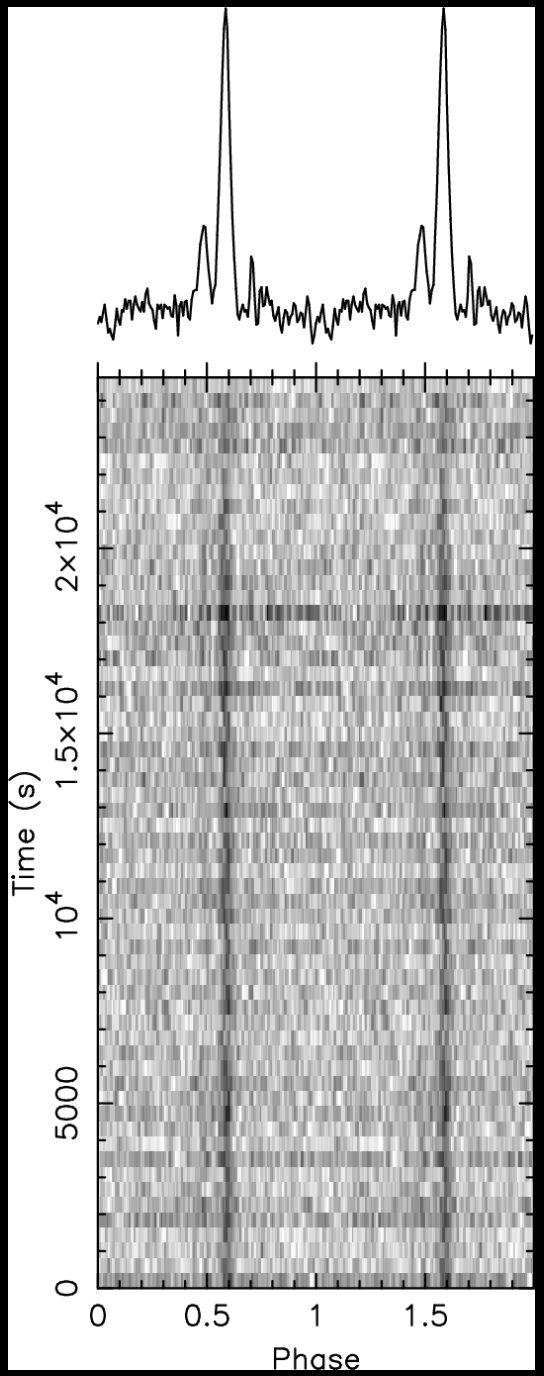


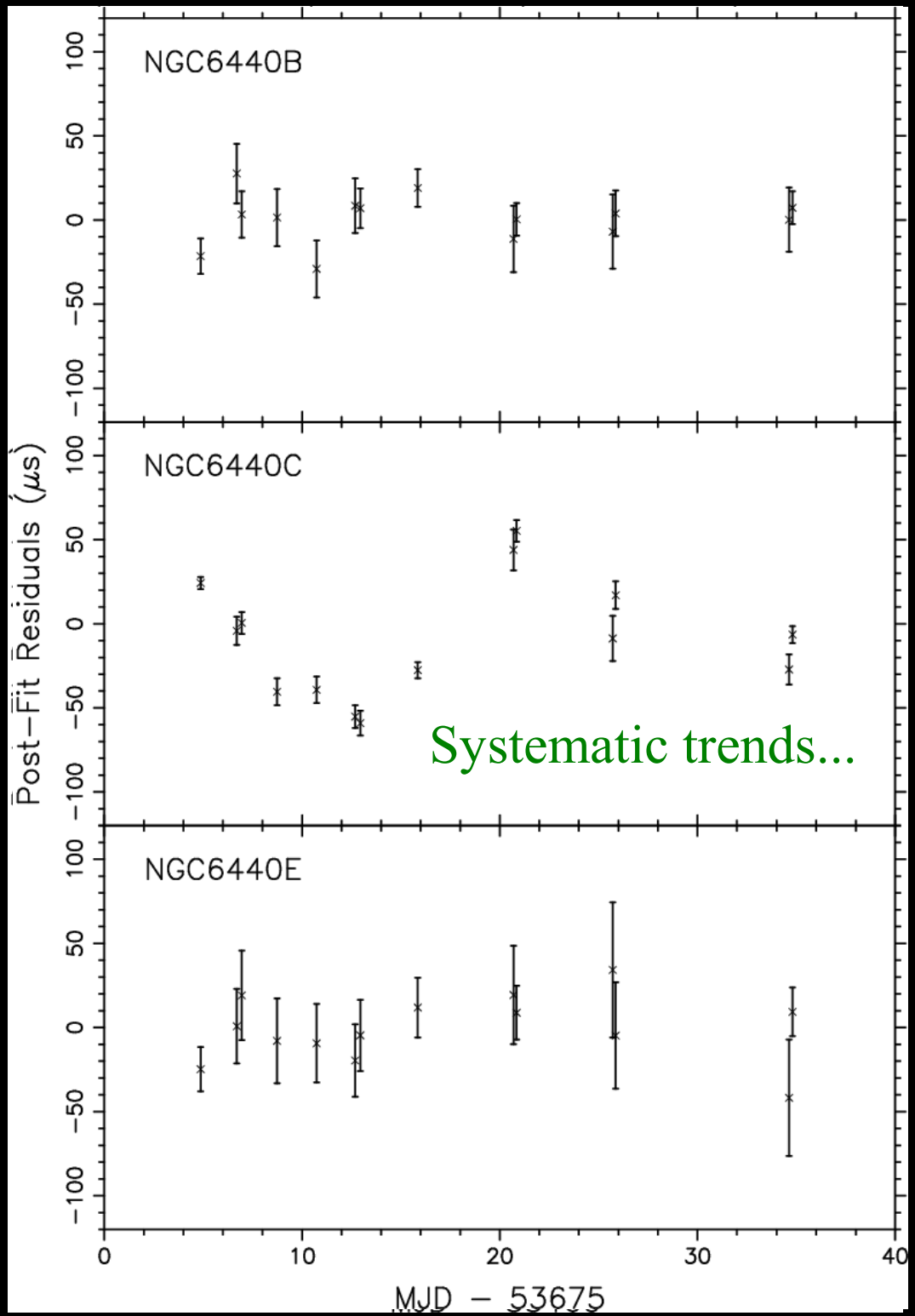
NGC6440C: Isolated?





NGC6440C: Isolated?





Outlook for the future...

- With the new generation of high resolution pulsar machines coming online, this field is is almost completely sensitivity limited
- Prospects for new discoveries with the GBT are *good*
  - Many more clusters to search
  - Lots more timing (several binaries still have unknown orbits)
- There are still good chances for another "Holy Grail":

  MSP-MSP binary / PSR-BH binary / sub-MSP
- SKA prototypes and/or *FAST* will find *hundreds* of new exotic MSPs, both in clusters and in the Galaxy