Radio Pulsars in Globular Clusters

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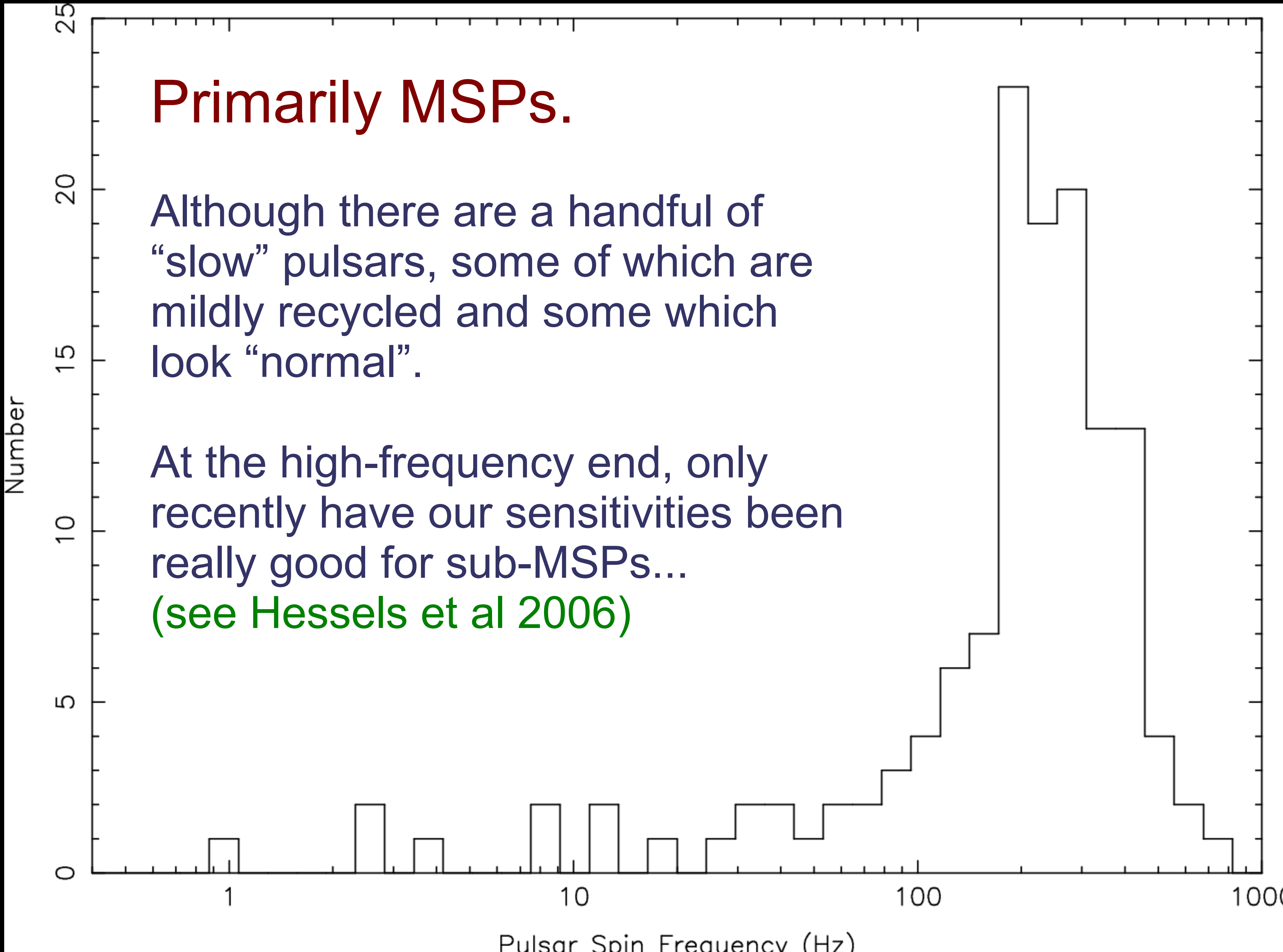
Recent Collaborators:

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

What kind of pulsars are in clusters?

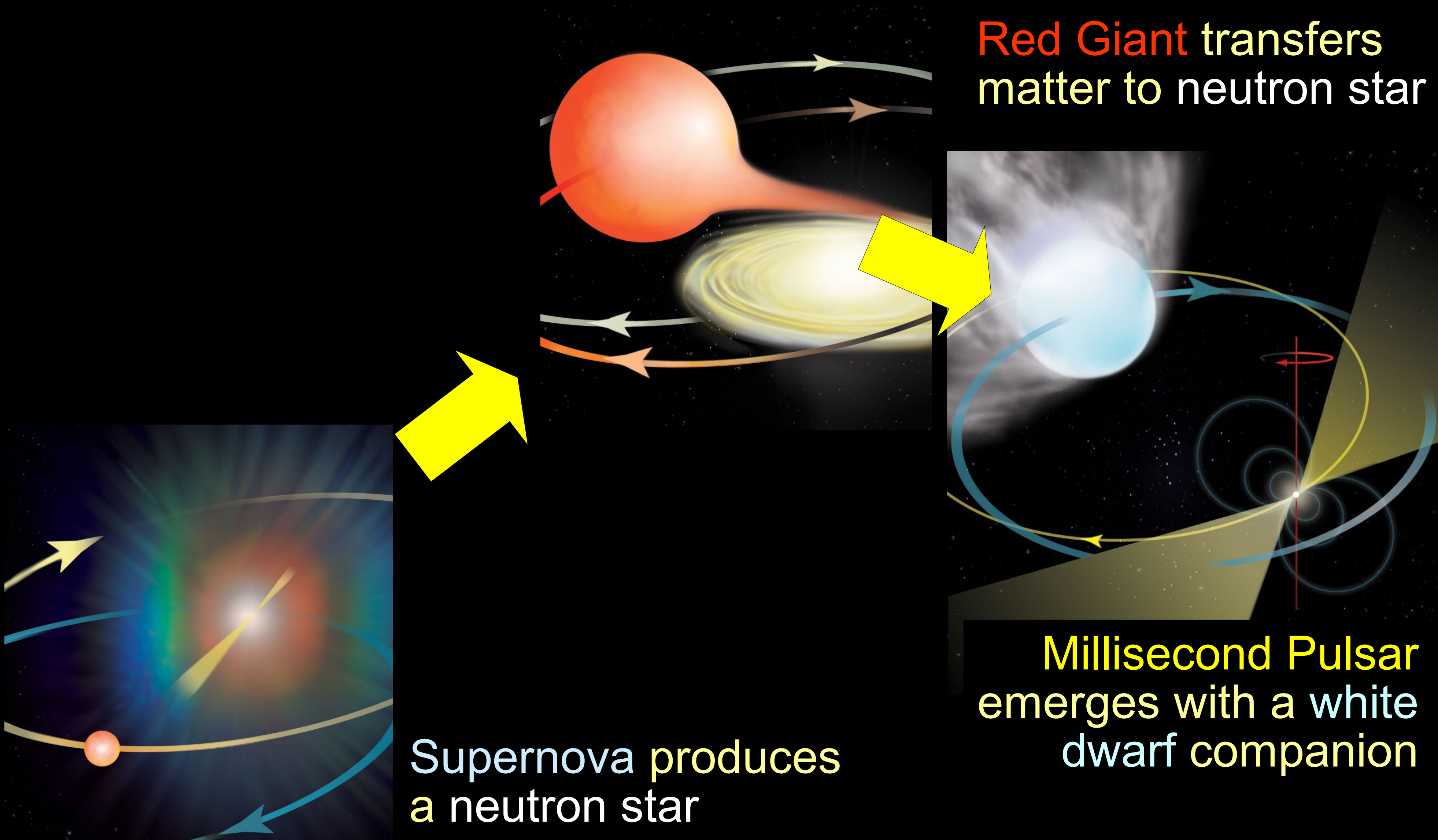


Primarily MSPs.

Although there are a handful of "slow" pulsars, some of which are mildly recycled and some which look "normal".

At the high-frequency end, only recently have our sensitivities been really good for sub-MSPs...
(see Hessels et al 2006)

Millisecond pulsars in GCs?

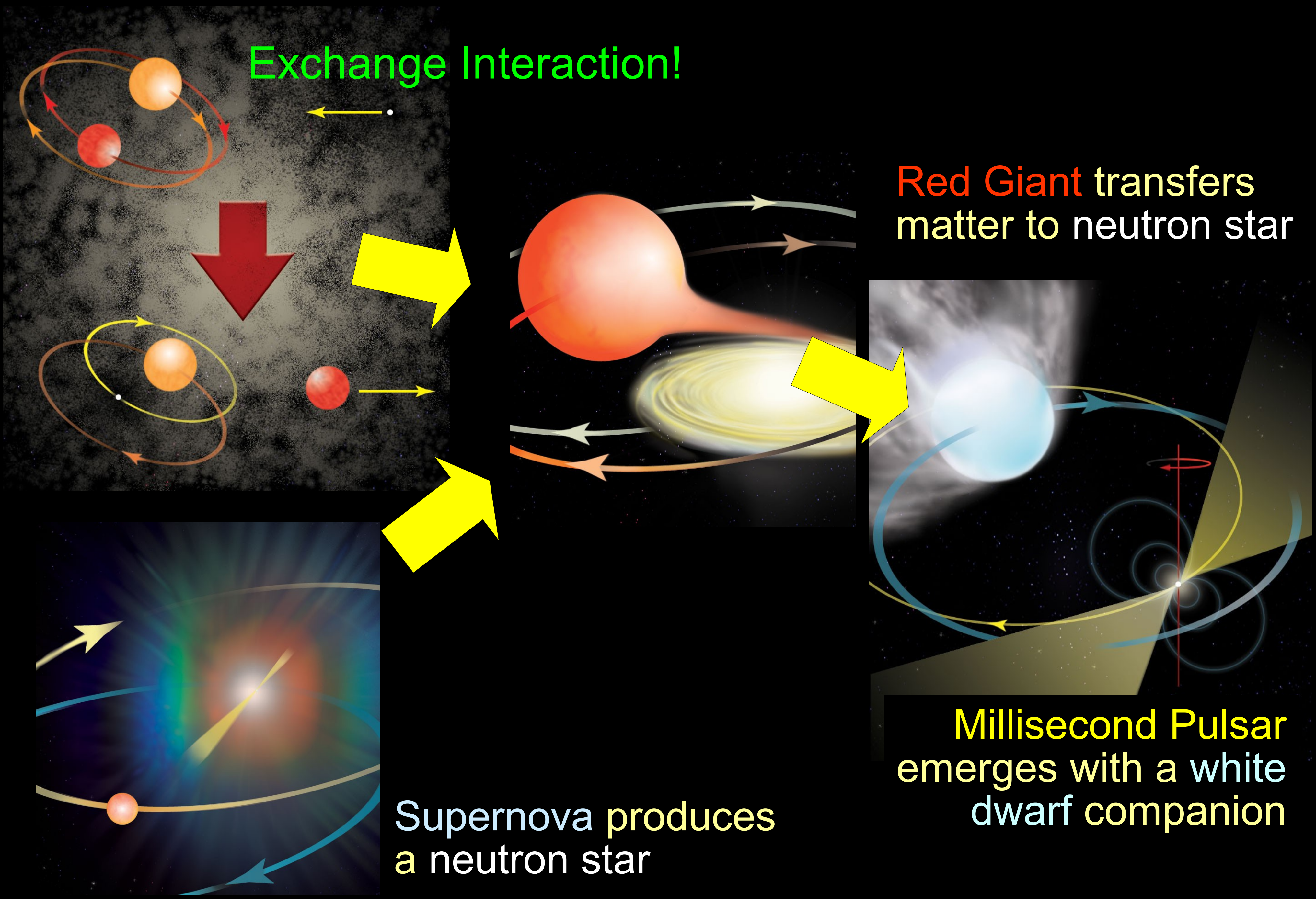


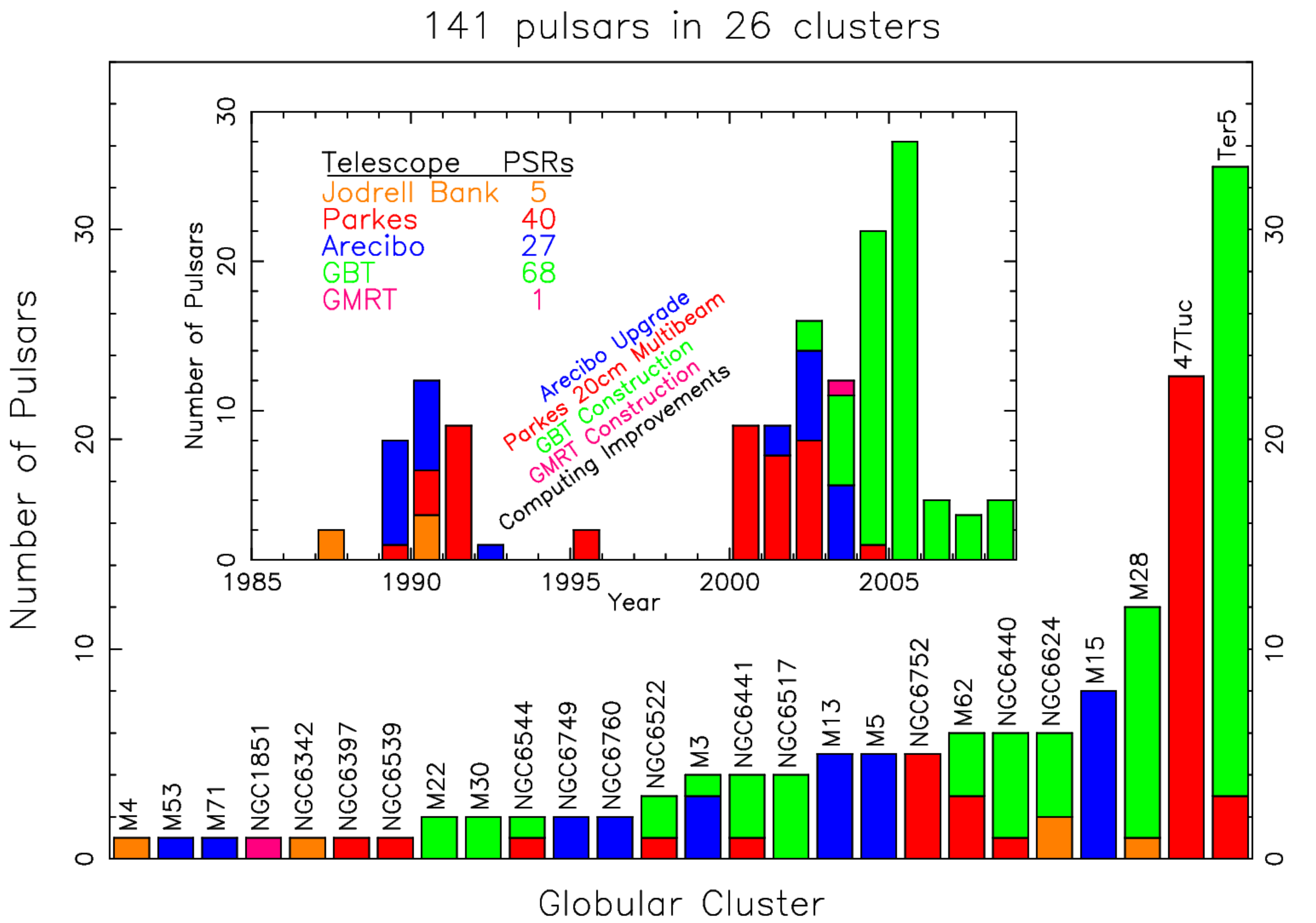
Red Giant transfers matter to neutron star

Millisecond Pulsar emerges with a white dwarf companion

Supernova produces a neutron star

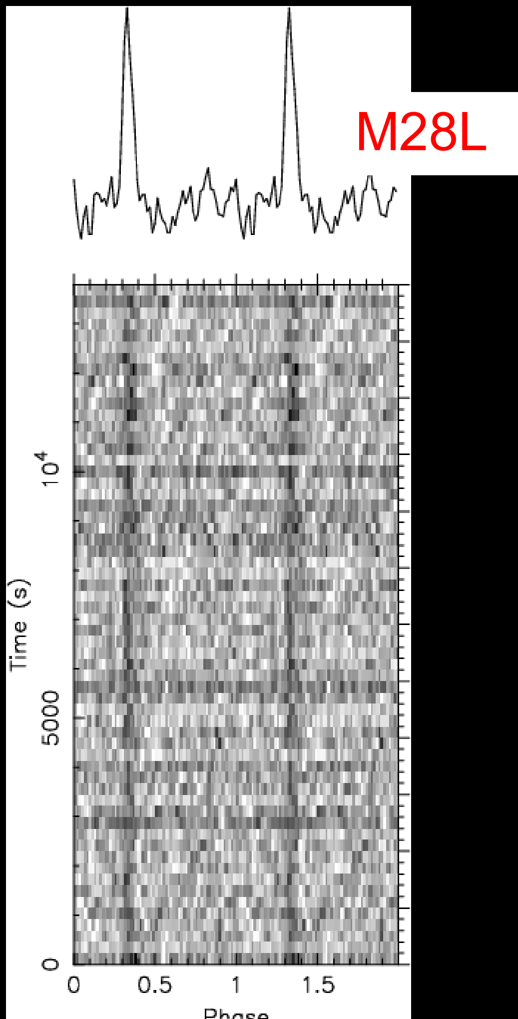
Millisecond pulsars in GCs?





141 pulsars in 26 clusters
Number of Pulsars
Globular Cluster
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
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

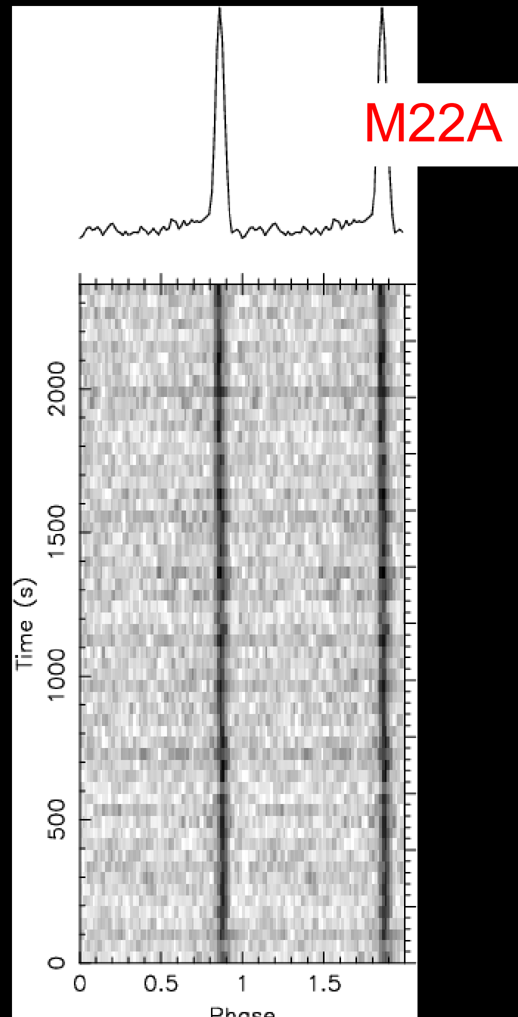
Three new binary pulsars



P_{psr} = 4.10 ms

P_{orb} = 5.41 hrs

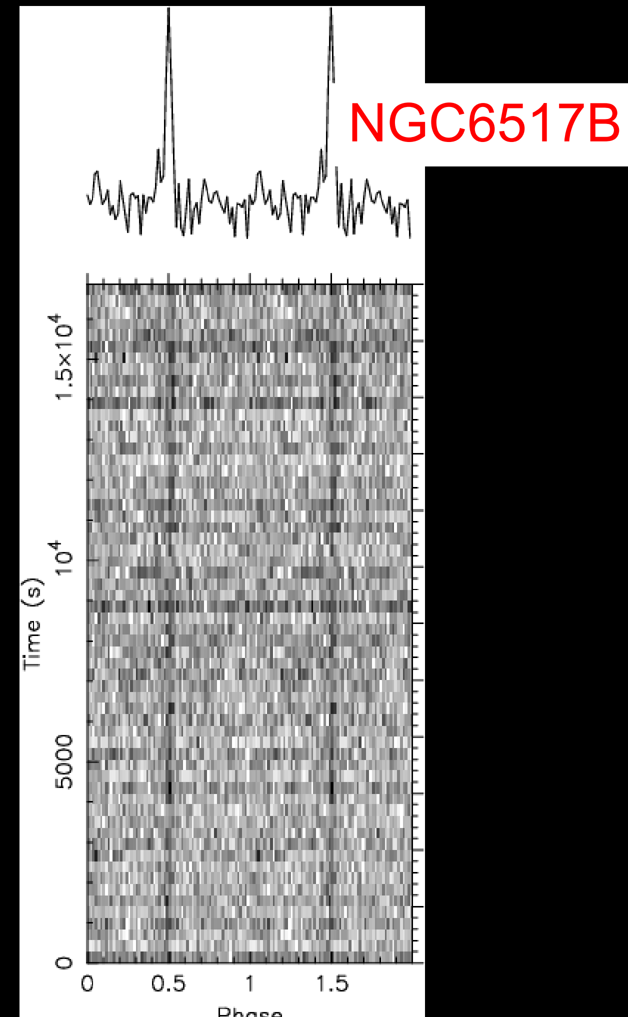
$M_{c,min} \sim 0.020\ M_\odot$



P_{psr} = 3.35ms

P_{orb} = 4.87 hrs

$M_{c,min} \sim 0.017\ M_\odot$



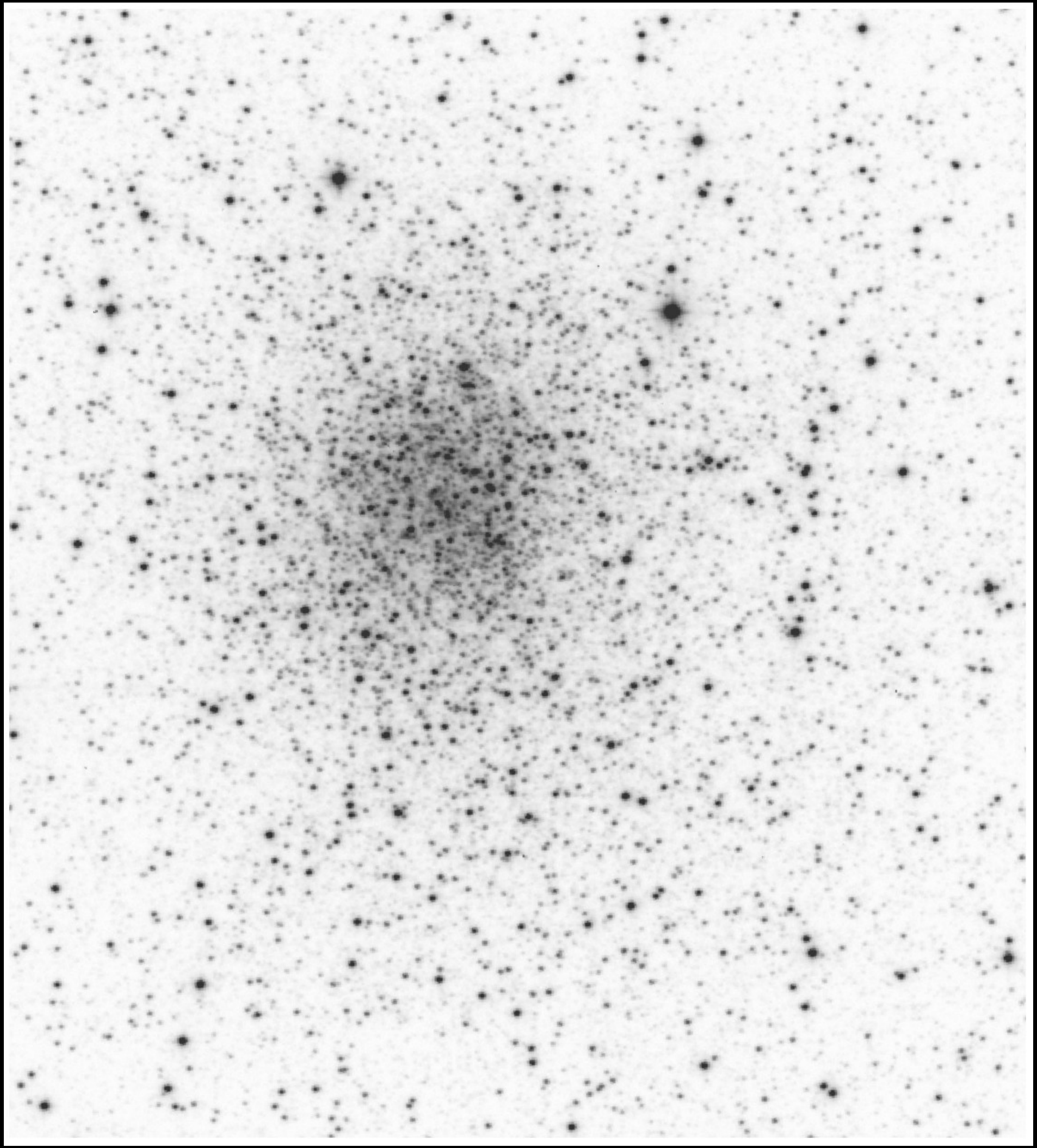
P_{psr} = 28.96 ms

P_{orb} = 59 days

$M_{c,min} \sim 0.32\ M_\odot$

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
  ~0.2-0.3” 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



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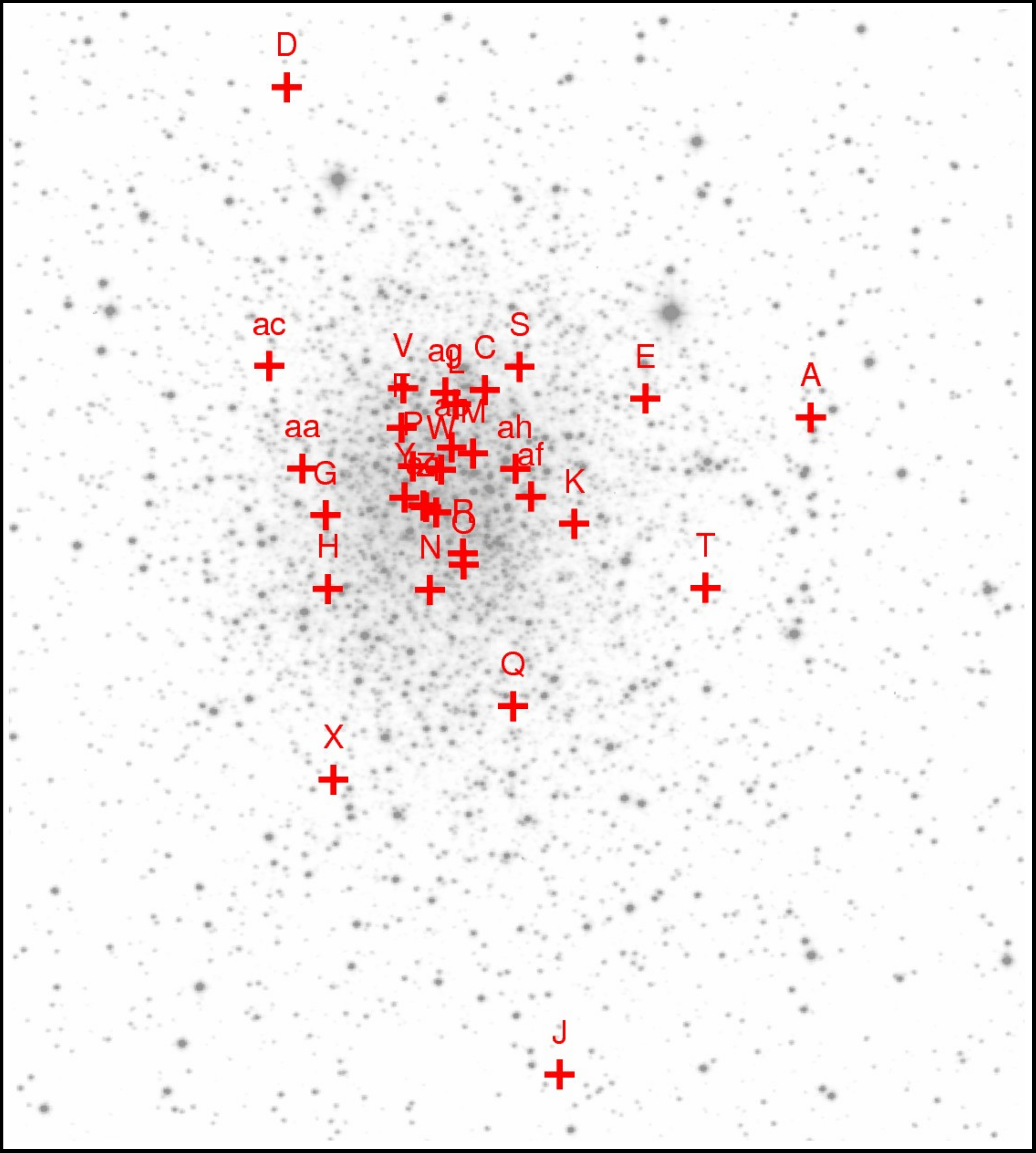

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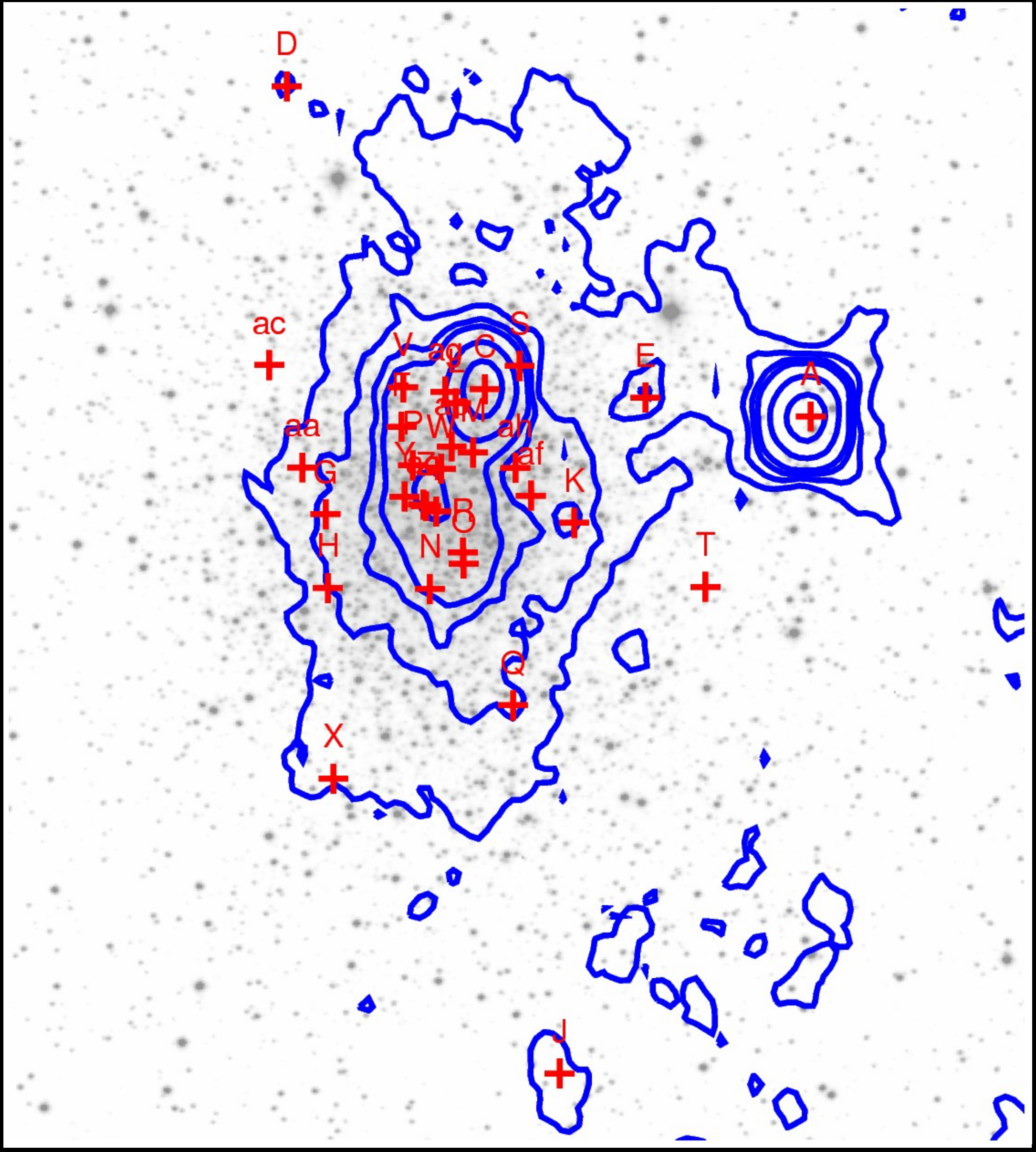
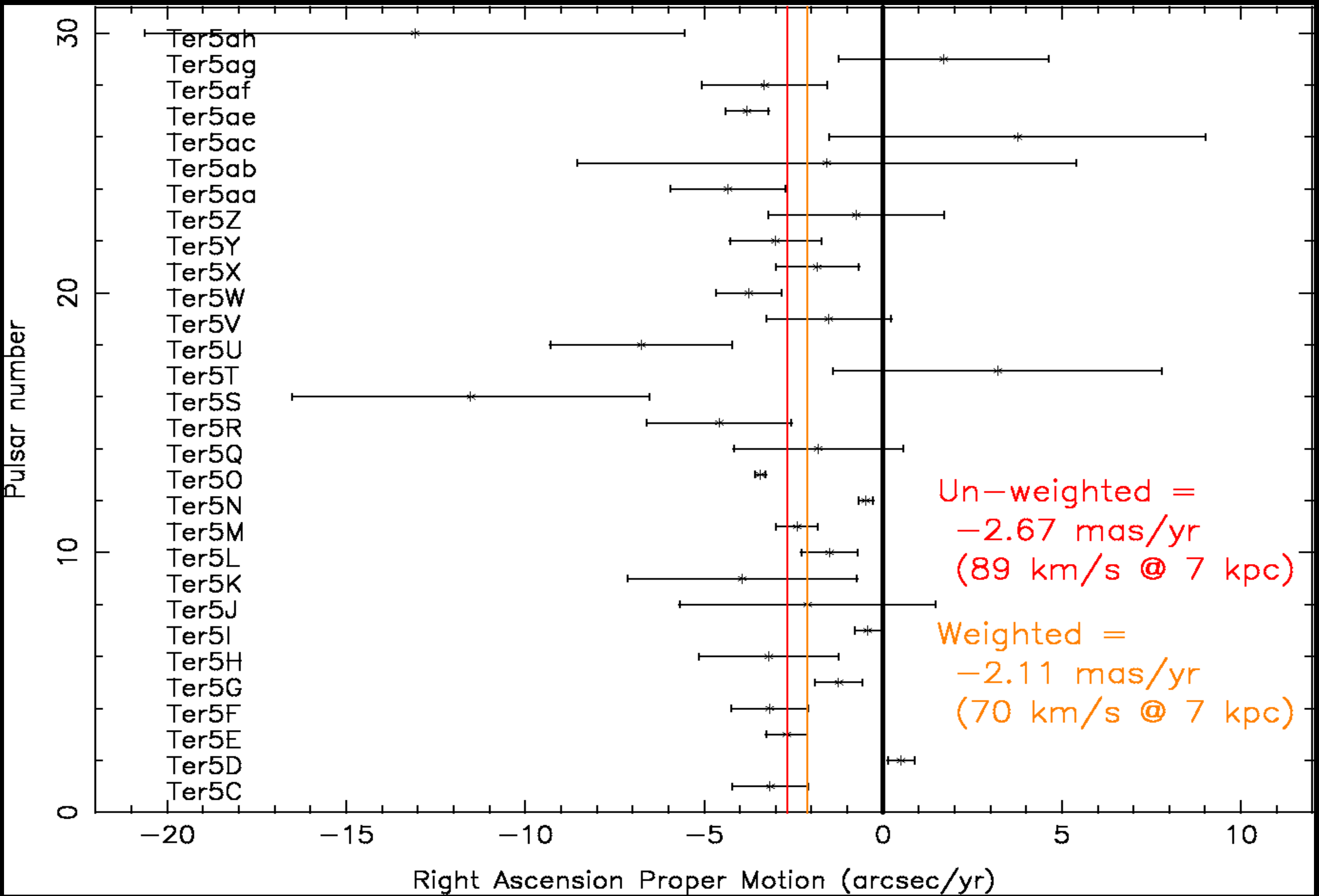
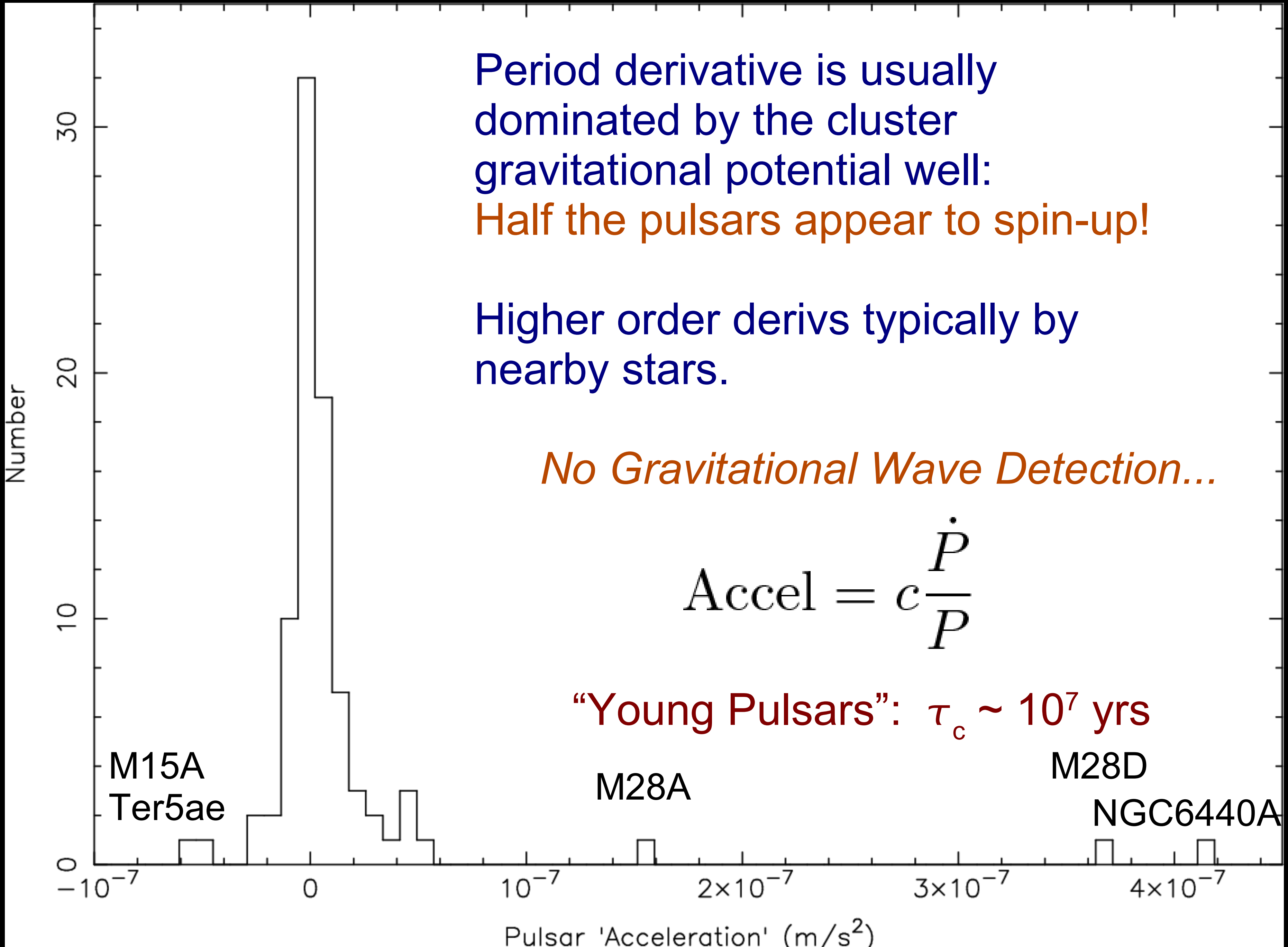


Part of Terzan5 Proper Motion?



Measured Pulsar "Accelerations"



Period derivative is usually dominated by the cluster gravitational potential well:
Half the pulsars appear to spin-up!

Higher order derivs typically by nearby stars.

No Gravitational Wave Detection...

$$\mathrm{Accel} = c\frac{\dot{P}}{P}$$

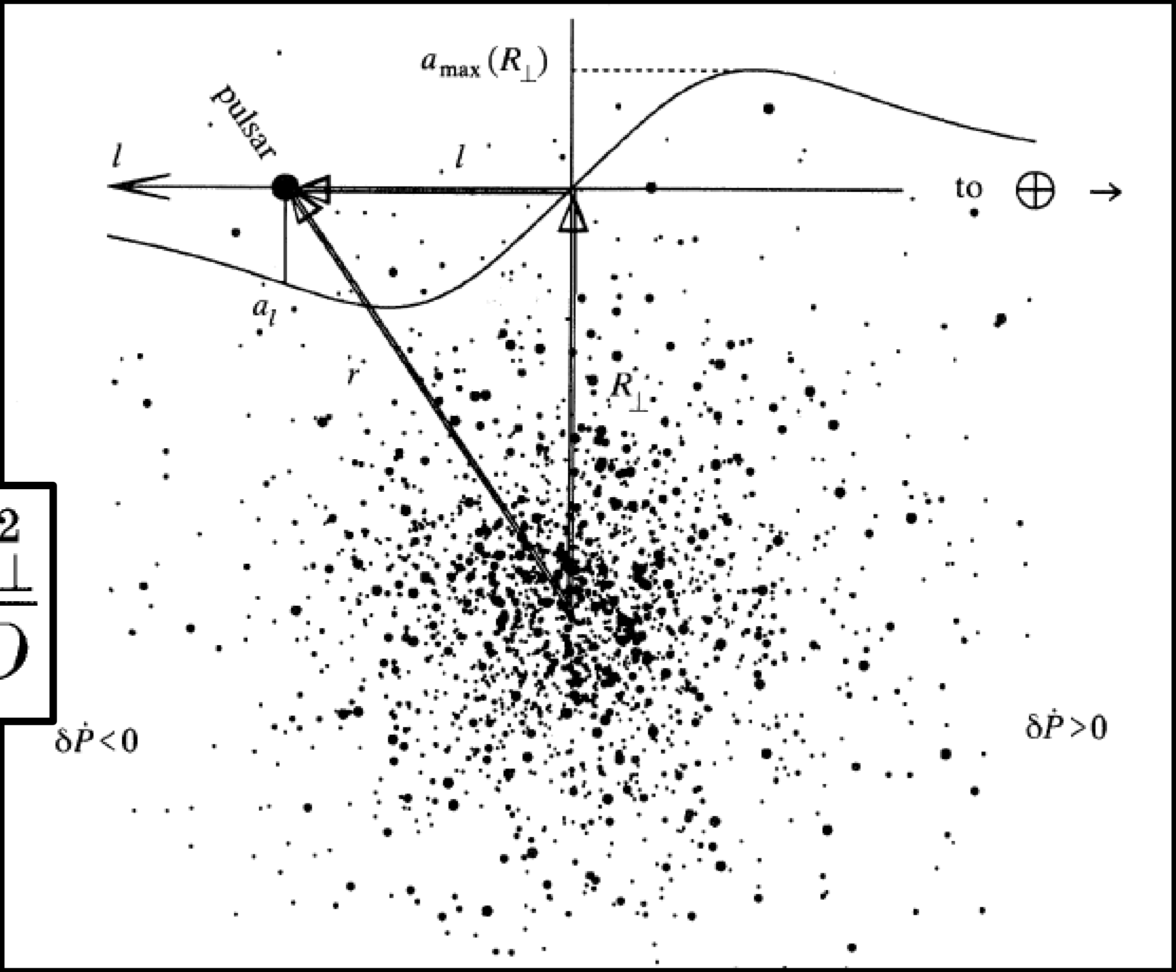
"Young Pulsars": $\tau_c \sim 10^7$ yrs

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 ($\sim 10^{-10}$)

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



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

Phinney 1992, 1993

Can we separate the components?

If the MSP is in a stable and compact binary orbit (P_{orb} < 1 day) and we are patient...

- P_{orb} is affected the same way!

$$\mathrm{Accel} = c\frac{\dot{P}}{P}$$

Ter5M: 3.56ms, P_{orb}=0.44d

$A_{spin} = 4.2\mathrm{x}10^{-8}$ m/s^2 vs $A_{orb} = 4.2\mathrm{x}10^{-8}$ m/s^2

Ter5N: 8.67ms, P_{orb}=0.38d

$A_{spin} = 1.92\mathrm{x}10^{-8}$ m/s^2 vs $A_{orb} = 1.83\mathrm{x}10^{-8}$ m/s^2

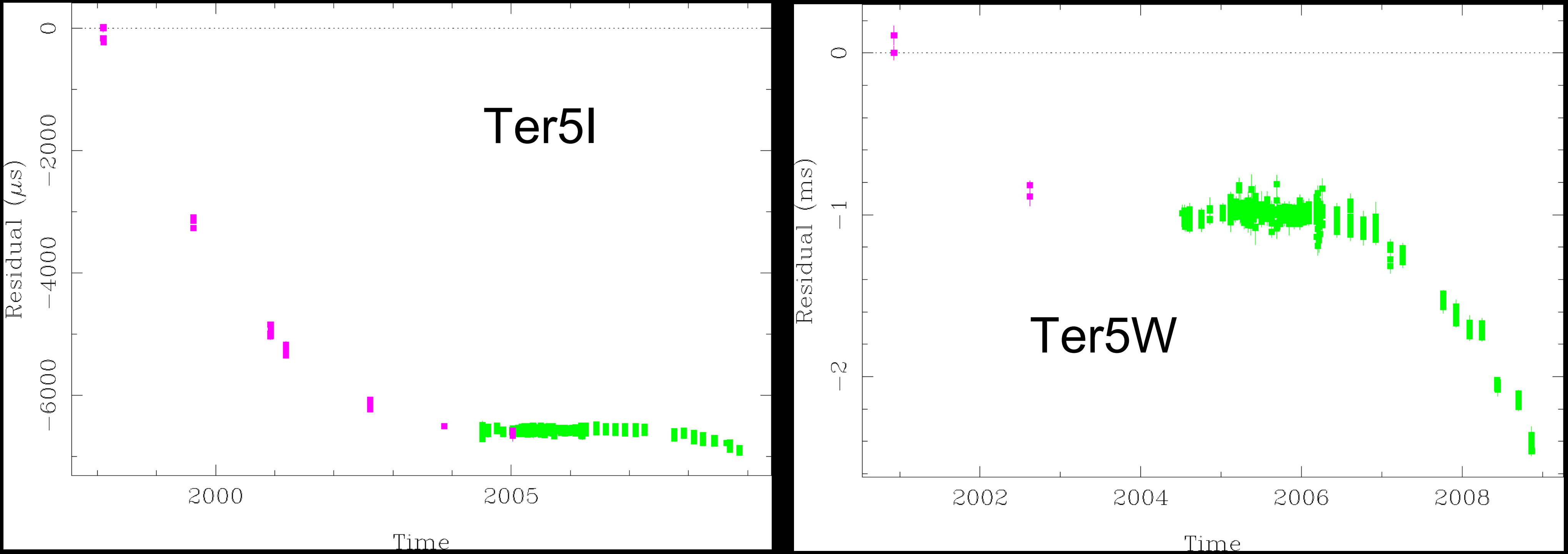
Ter5O: 1.67ms, P_{orb}=0.26d

$A_{spin} = -1.25\mathrm{x}10^{-8}$ m/s^2 vs $A_{orb} = -1.43\mathrm{x}10^{-8}$ m/s^2

Subtracting A_{orb} from A_{spin} gives us the intrinsic spin-down of the MSP (and B, Edot, and age)

Second Freq Derivs and "Jerk"

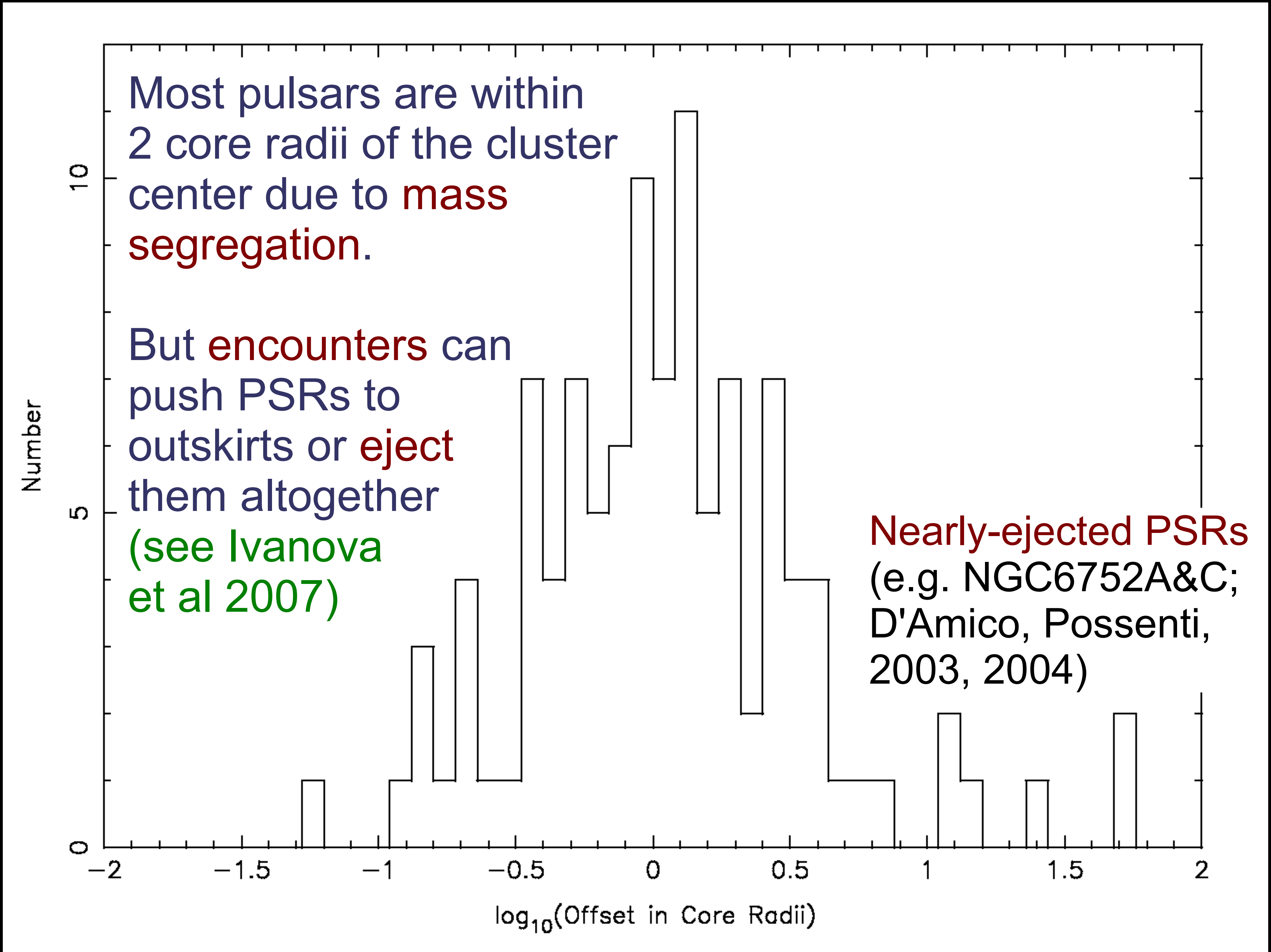
Recently, 7+ Terzan5 MSPs have measurements



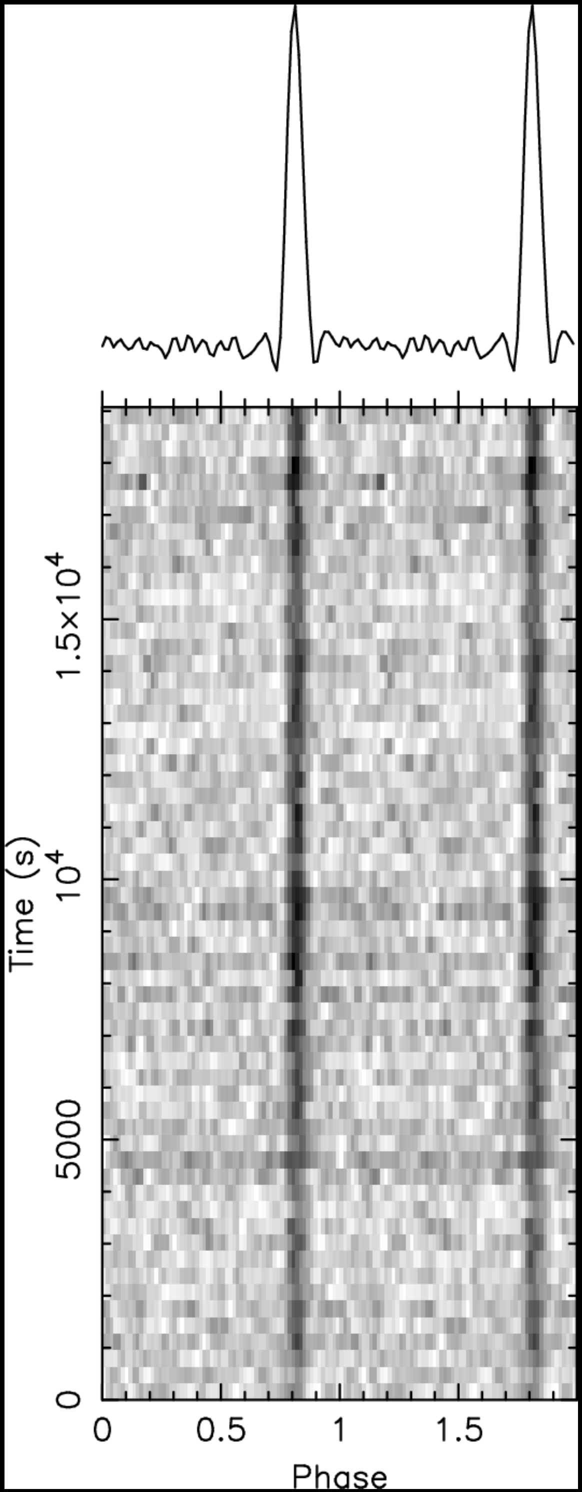
$$(\ddot{P}/P)_{\rm mf} = \frac{4}{3}\pi G \rho_0\, v_l / c = 6 \times 10^{-28}\, \rho_6\, v_{10}\ {\rm s}^{-2}$$

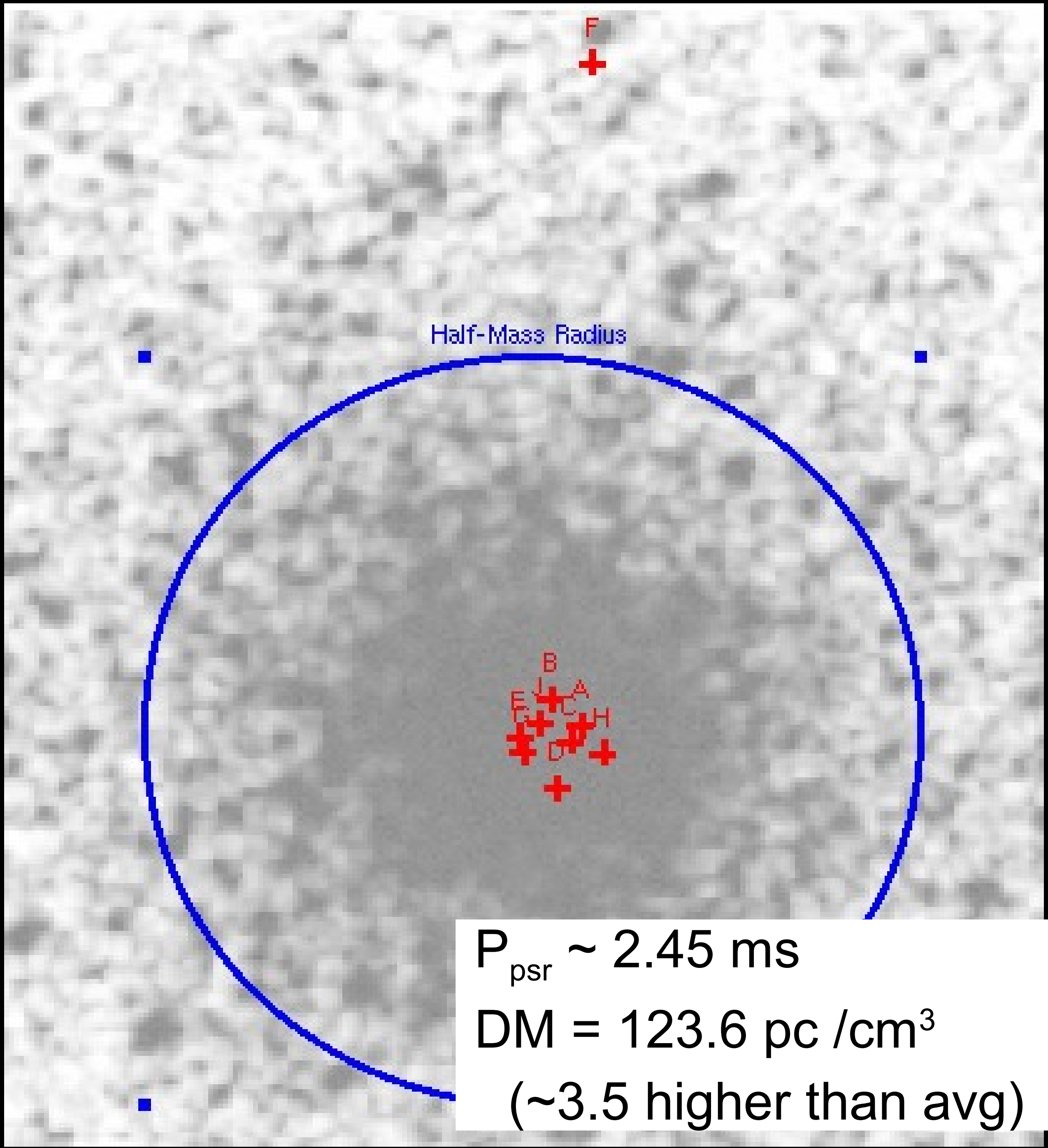
While typically contaminated by nearby stars, the "jerk" measurement can constrain the mean-field mass density of the cluster (Phinney 1992,1993)

Projected Cluster Positions



M28 Solutions (M28F ejection?)



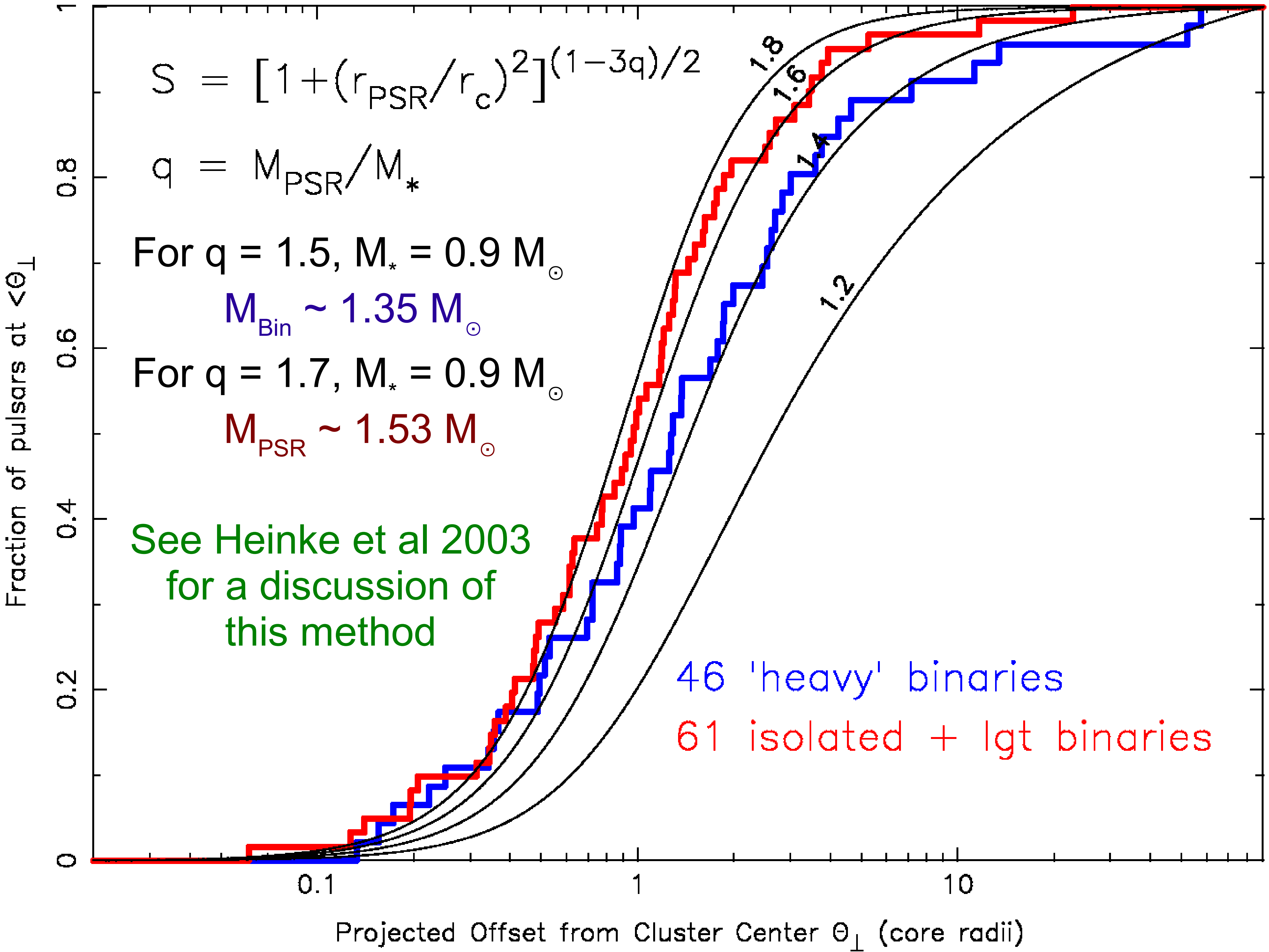


P_{psr} ~ 2.45 ms

DM = 123.6 pc /cm^3

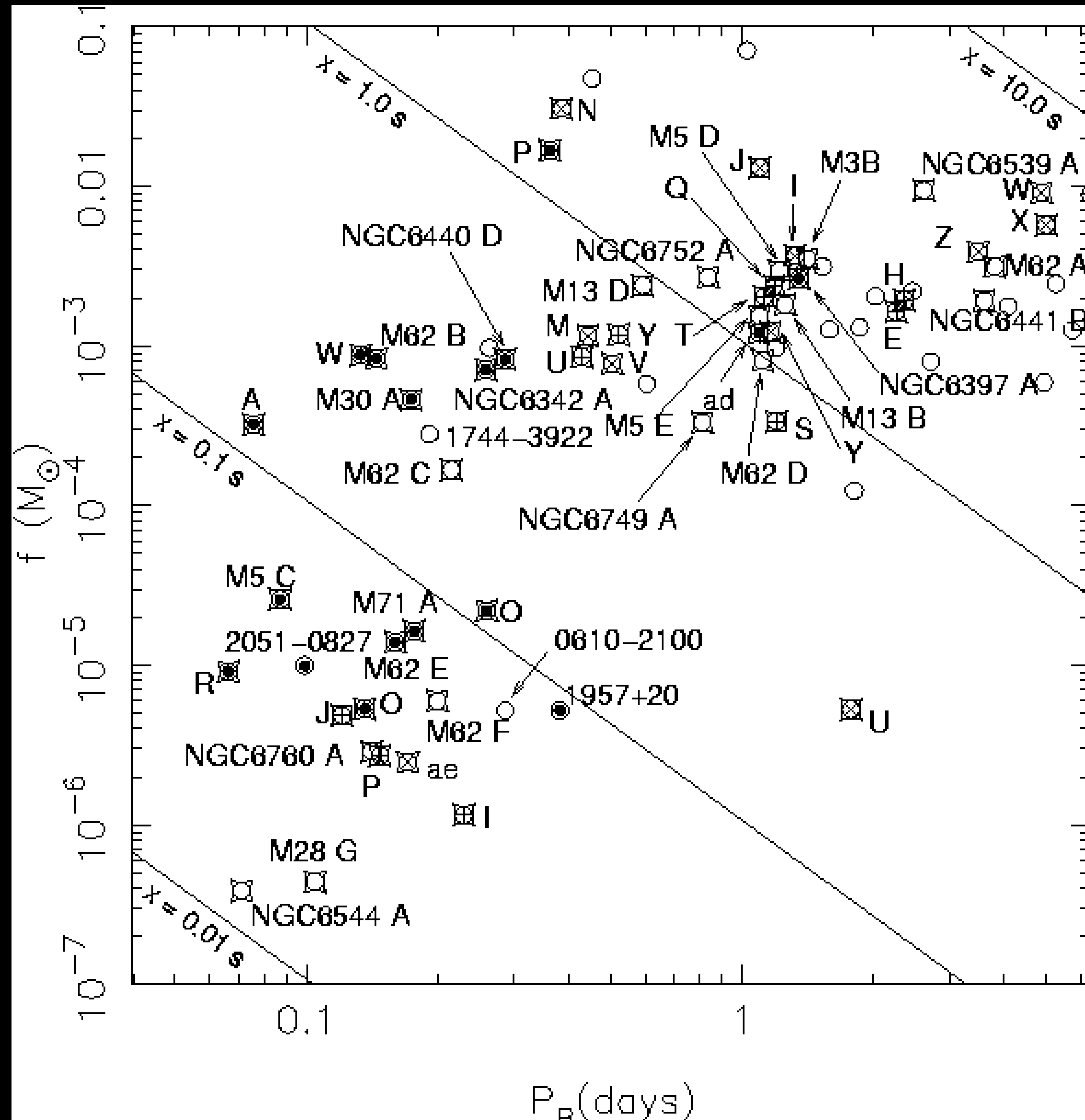
(~3.5 higher than avg)

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's GC Pulsar website

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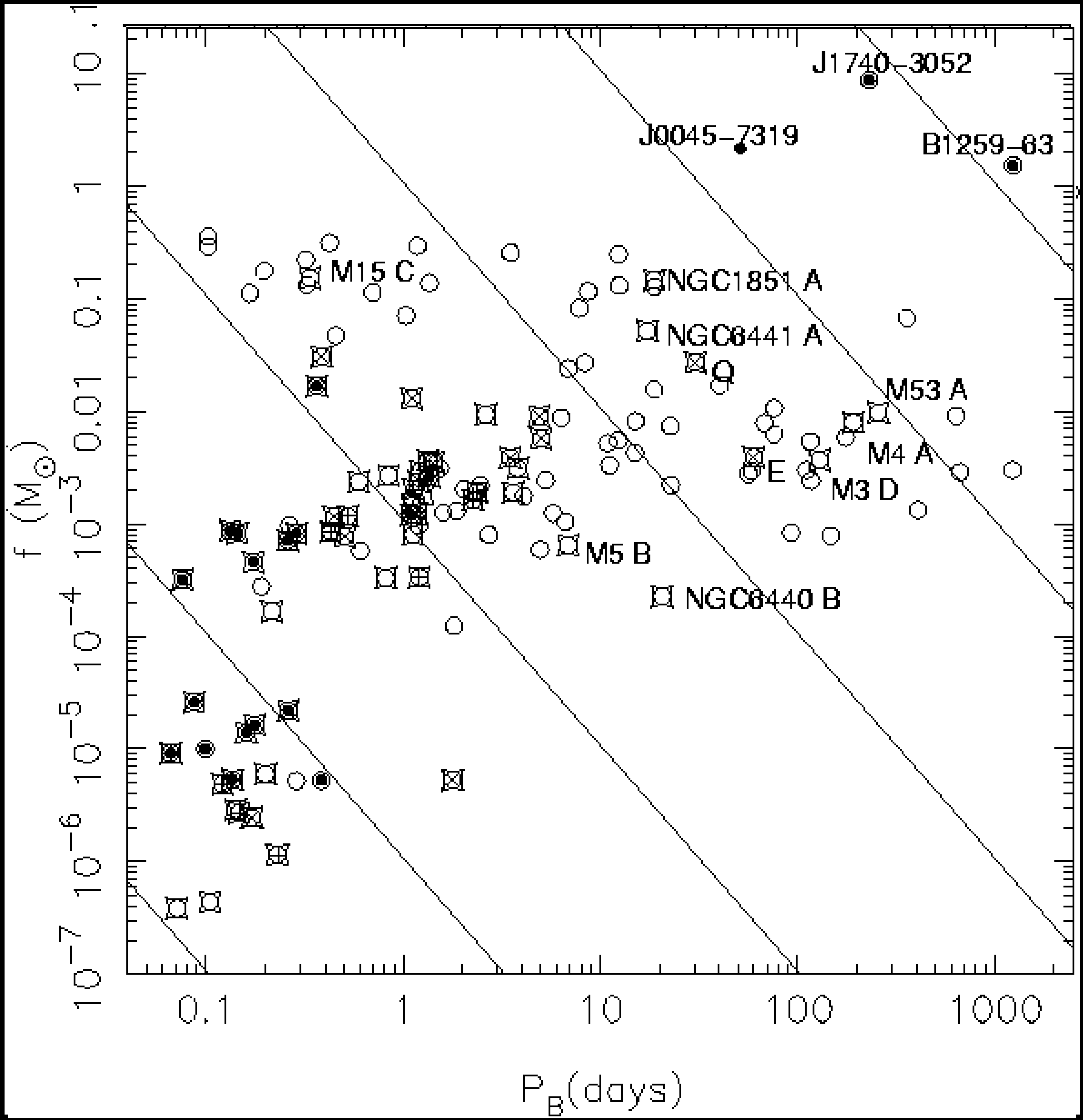

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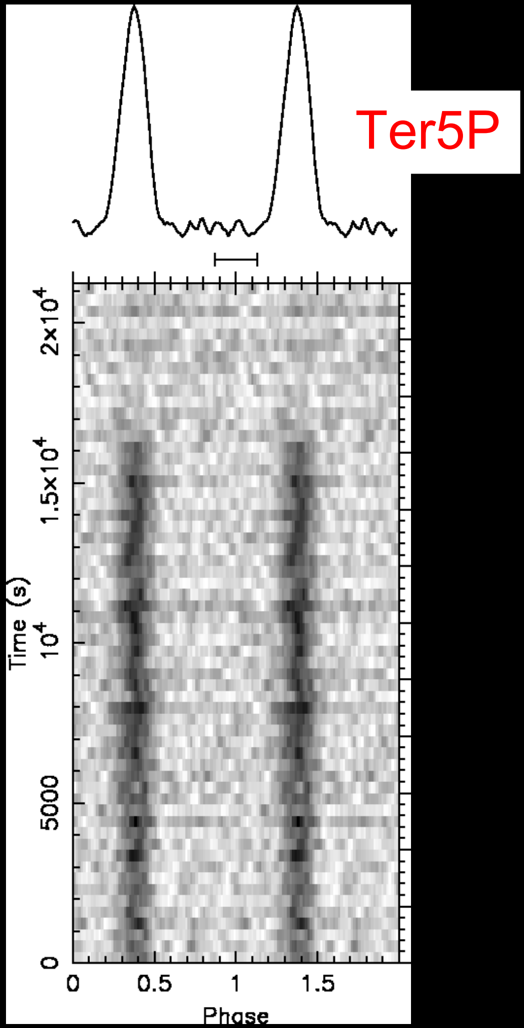
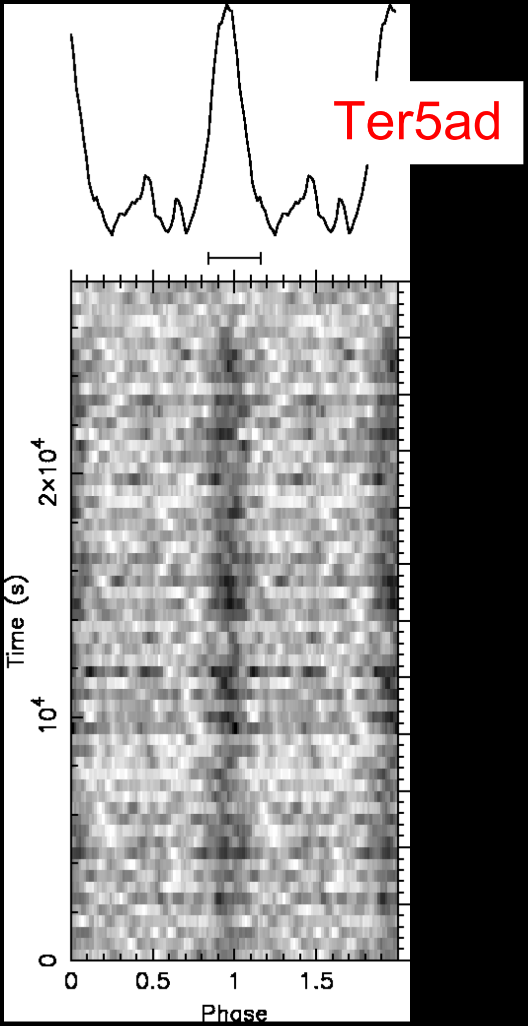
J1740-5340-like MSPs (D'Amico et al 2001a,b)



P_{psr} = 1.73 ms

P_{orb} = 8.70 hrs

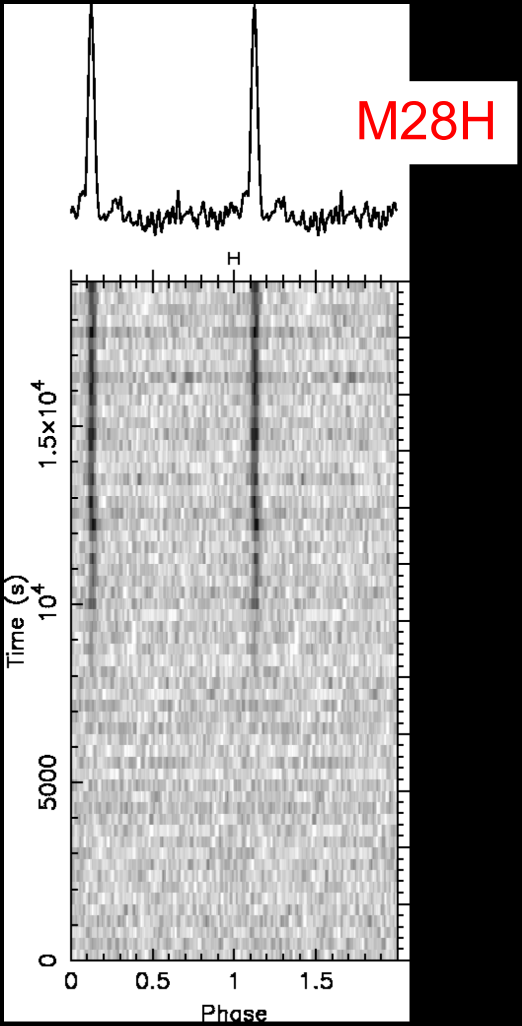
$M_{c,min}$ ~ 0.38 $M_{\odot}$



P_{psr} = 1.39 ms

P_{orb} = 1.09 days

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



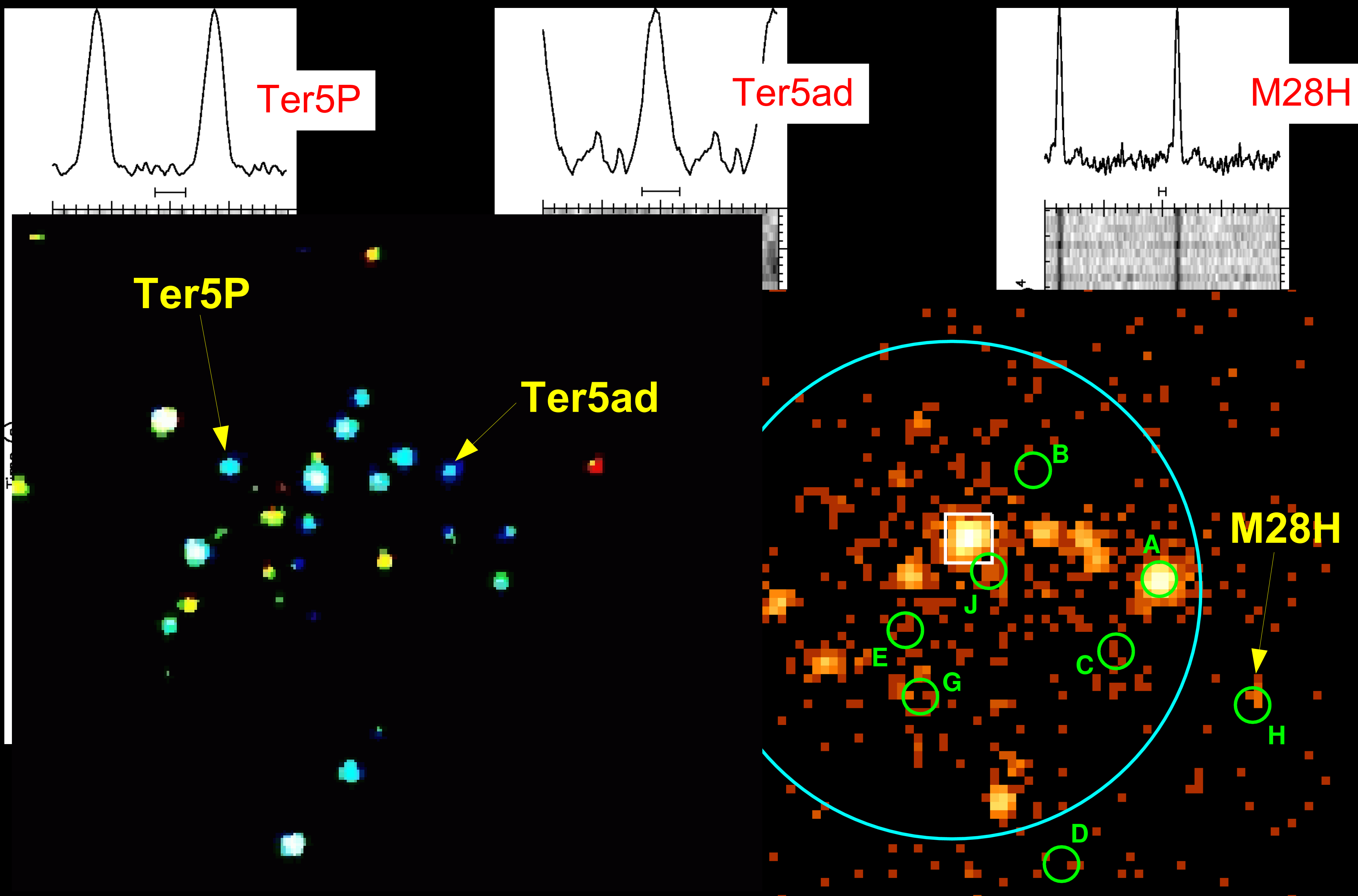
P_{psr} = 4.63ms

P_{orb} = 10.4 hrs

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

J1740-5340-like MSPs

(D'Amico et al 2001a,b)



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

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:

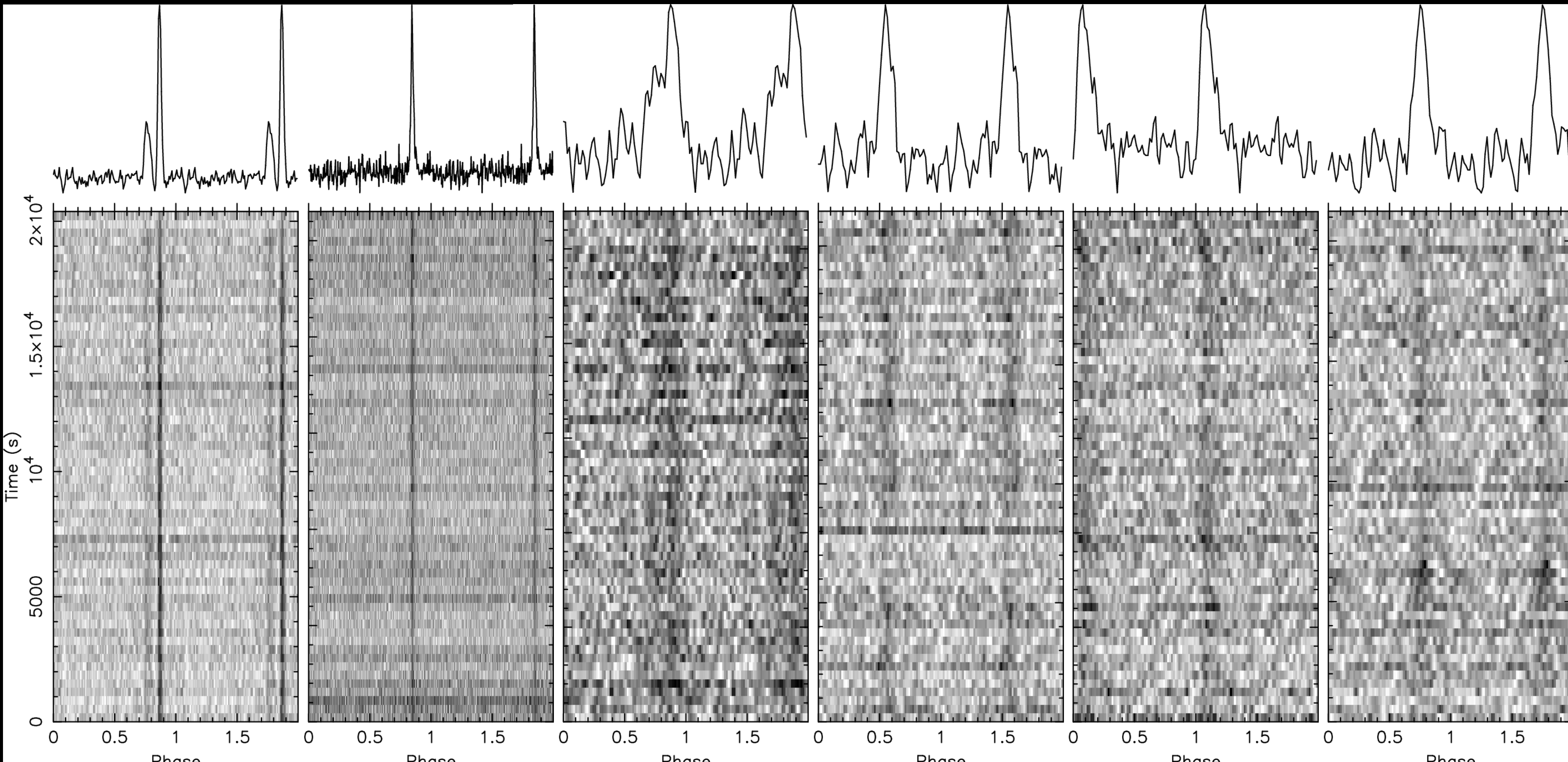
- the (precisely!) known Keplerian orbital parameters P_b, e, asin(i)
- the mass of the pulsar m_1 and the mass of the companion m_2

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

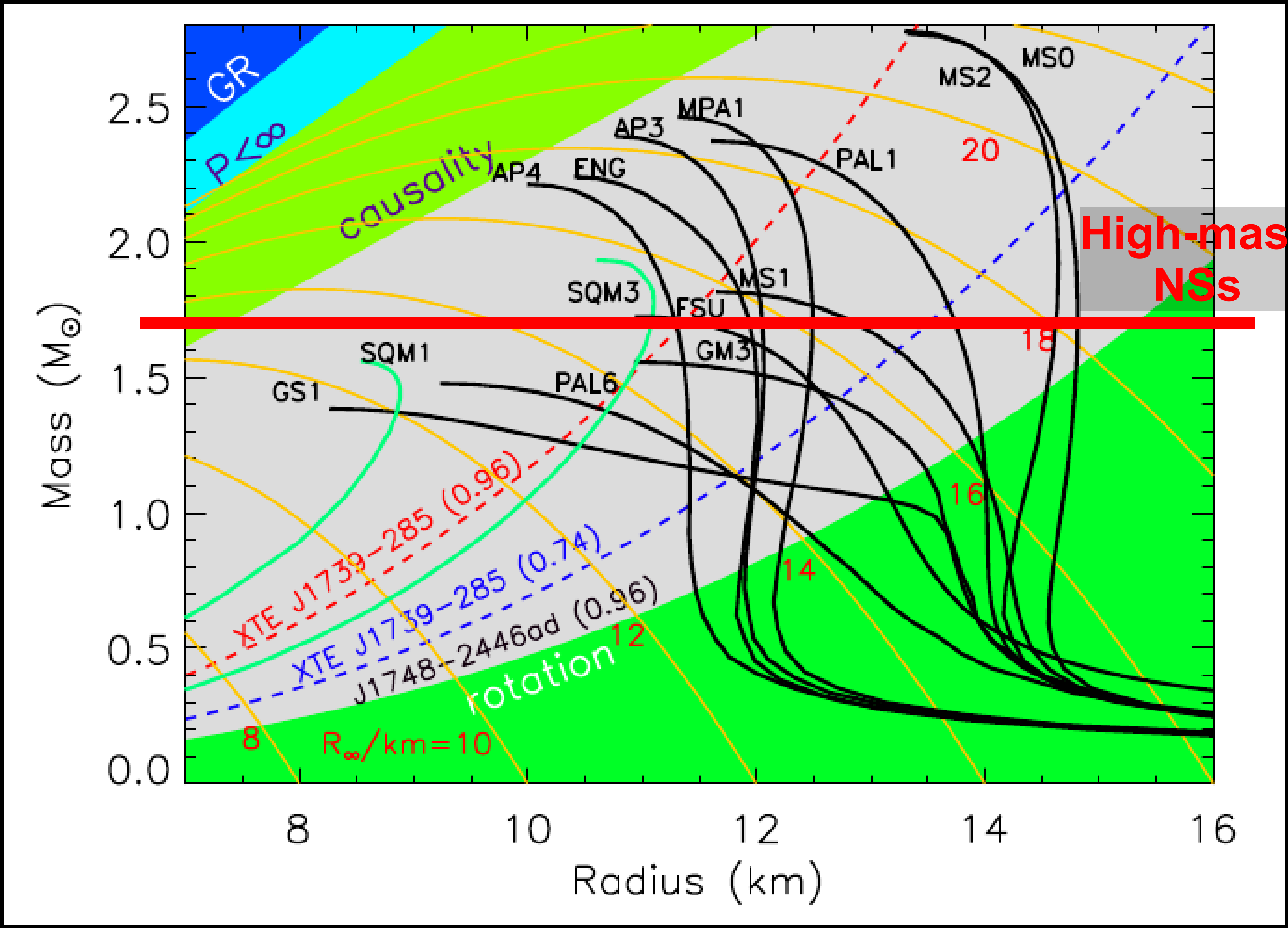
Six (!) Eccentric Binary MSPs in Ter5



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
$M_{c,min} \sim 0.21 M_\odot$	$M_{c,min} \sim 0.34 M_\odot$	$M_{c,min} \sim 0.45 M_\odot$	$M_{c,min} \sim 0.39 M_\odot$	$M_{c,min} \sim 0.25 M_\odot$	$M_{c,min} \sim 0.22 M_\odot$
ecc = 0.43	ecc = 0.35	ecc = 0.72	ecc ~ 0.61	ecc = 0.30	ecc = 0.76

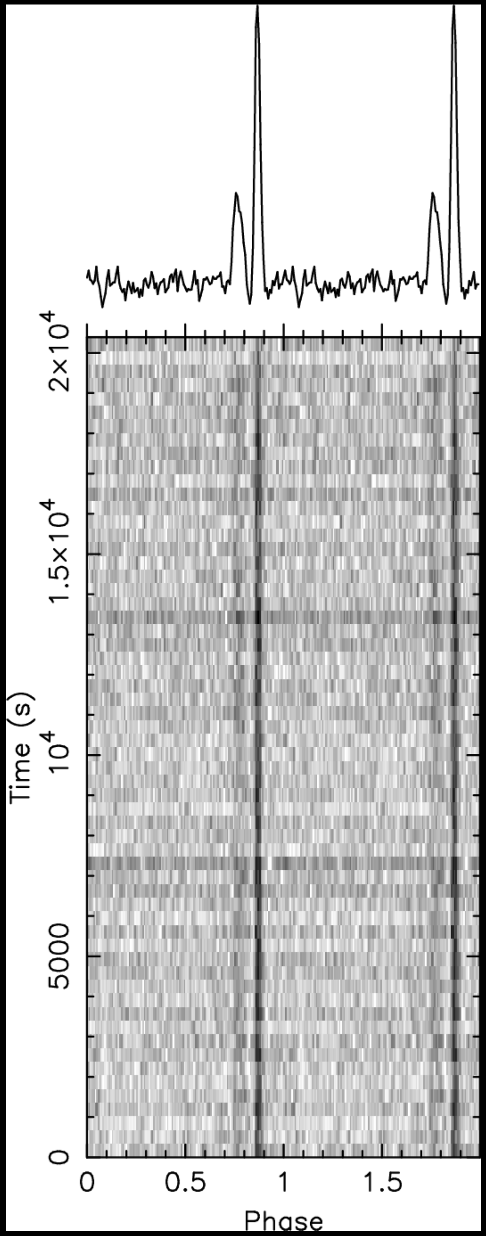
Neutron Star Equations of State:

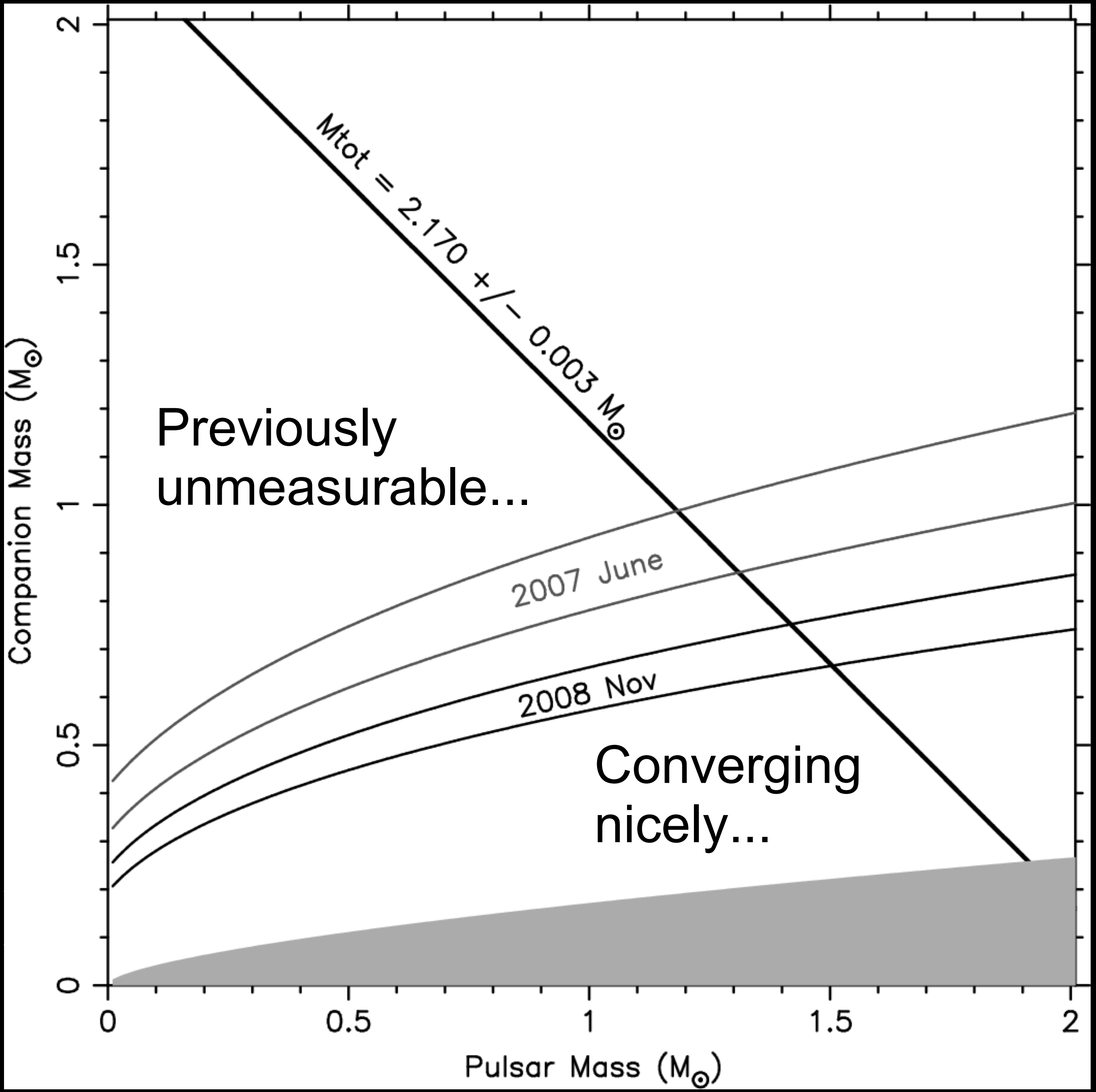
Understanding matter at supra-nuclear densities.



Adapted from Lattimer and Prakash 2007, *Physics Reports*

Ter5I:
Time dilation + redshift (gamma)



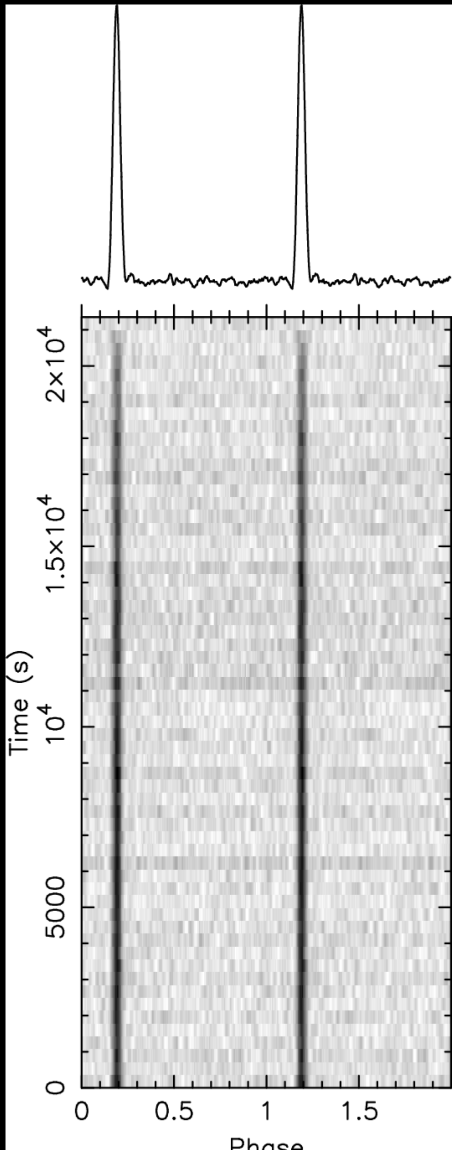


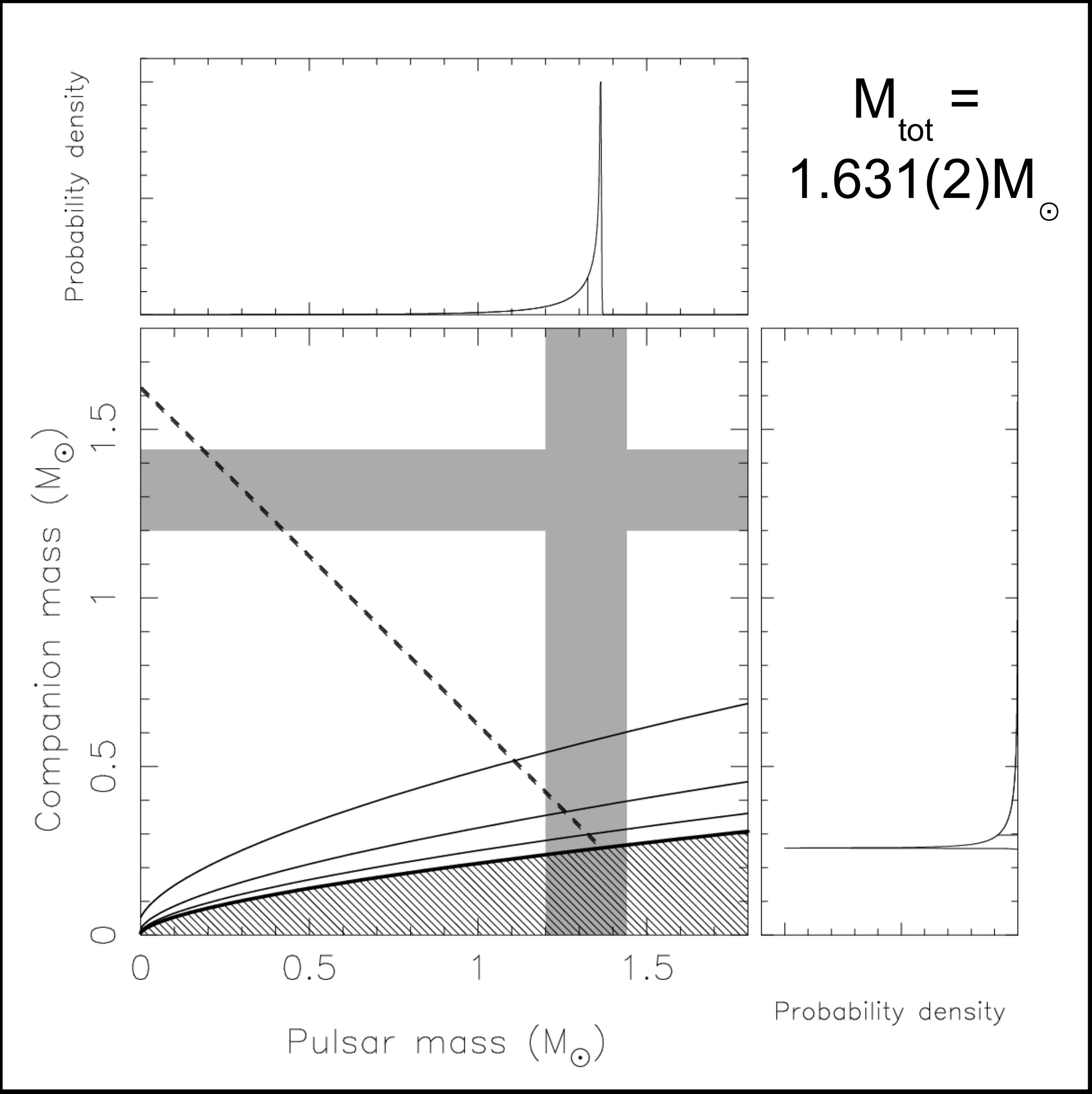
Highly eccentric (e=0.43

P_{psr} ~ 9.57 ms

P_{orb} = 31.87 hrs

M28C





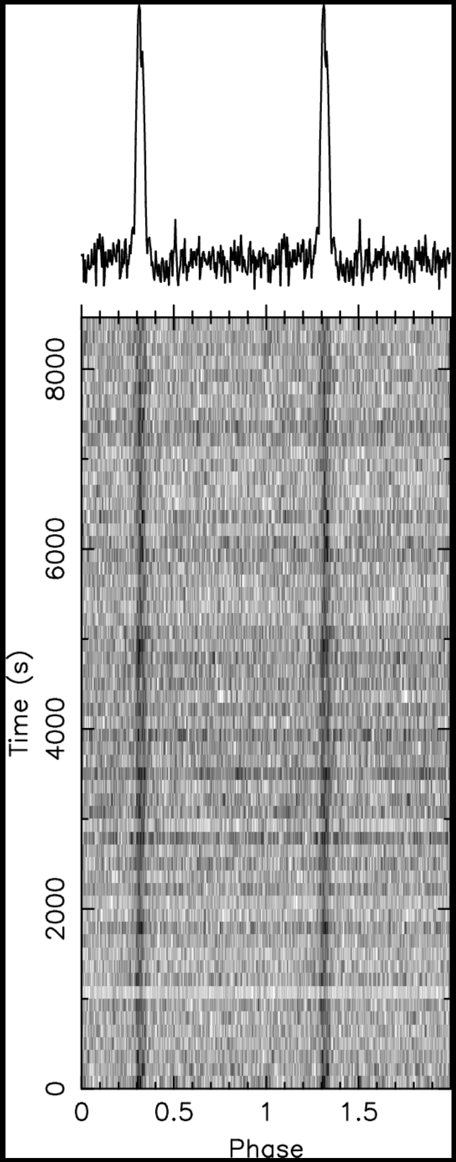
Highly eccentric (e=0.847)

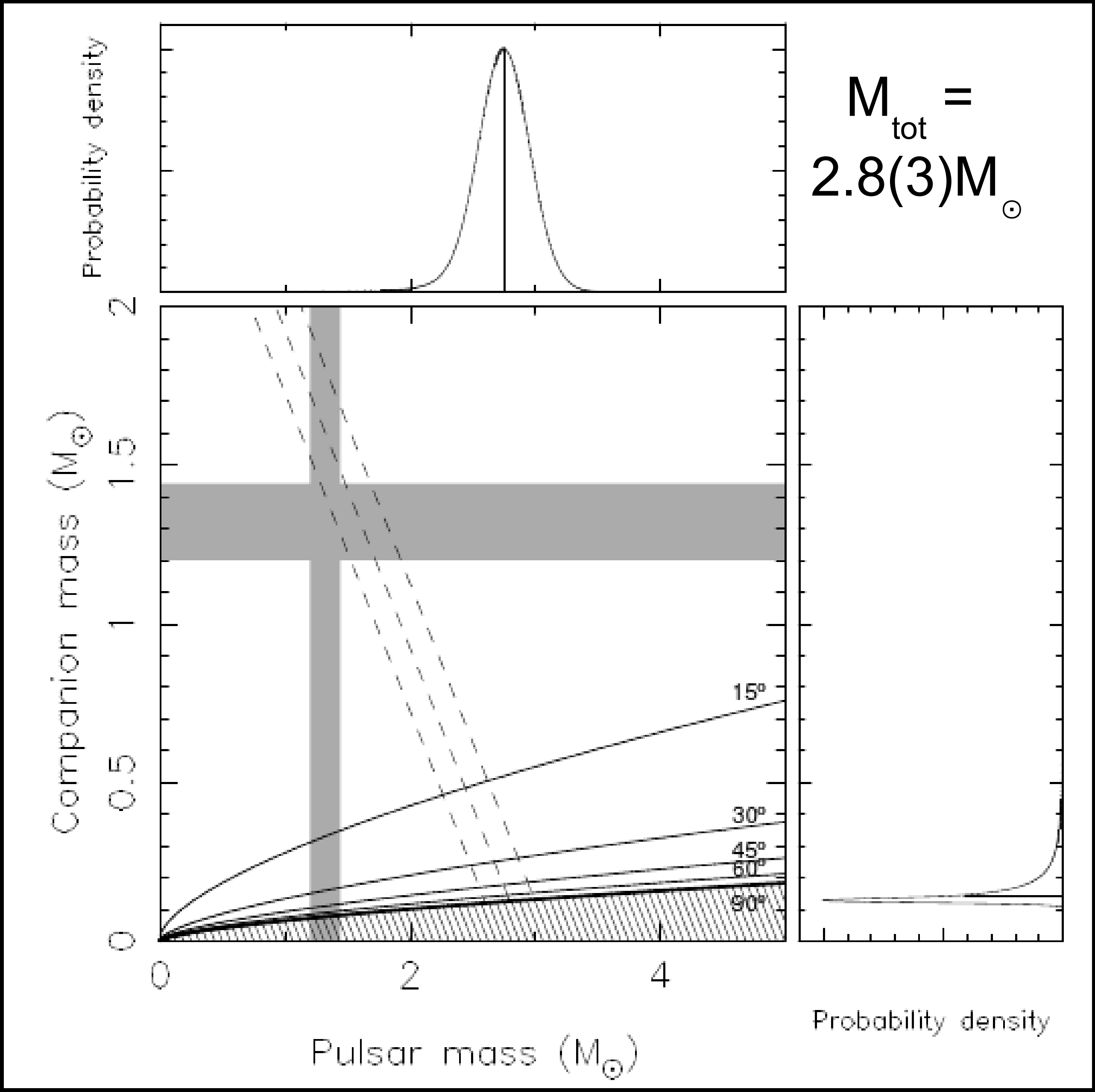
P_{psr} ~ 4.158 ms

P_{orb} = 8.07 days

~5μs timing in ~5min

NGC6440B: A Massive PSR?





M_{tot} = 2.8(3)$M_\odot$

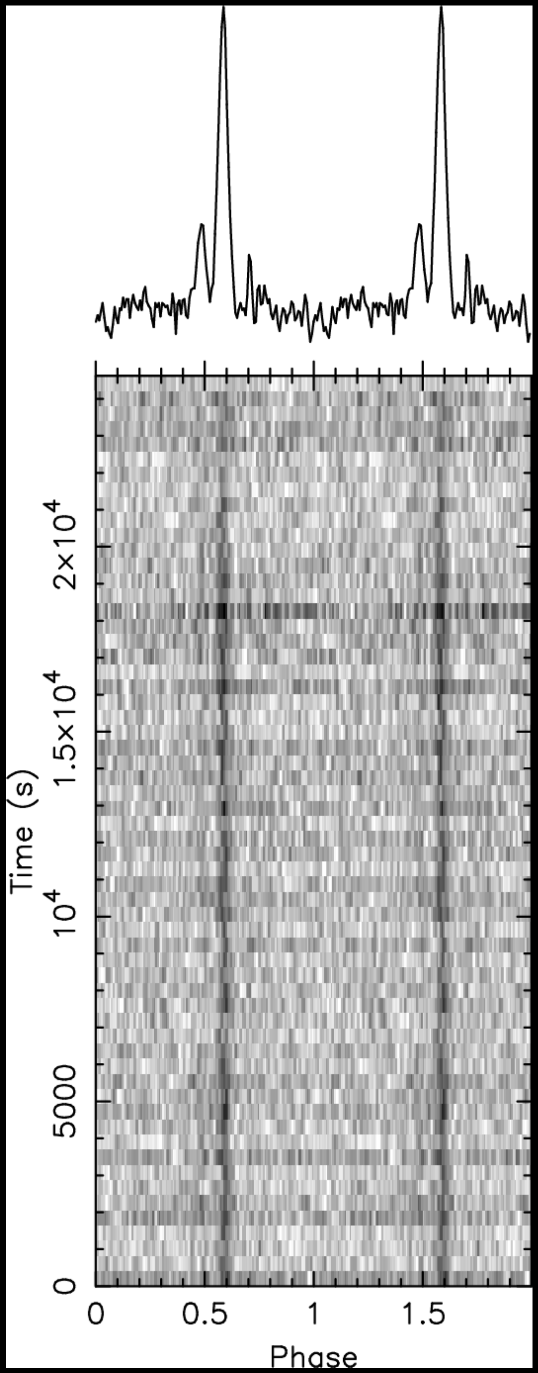
Highly eccentric (e=0.570)

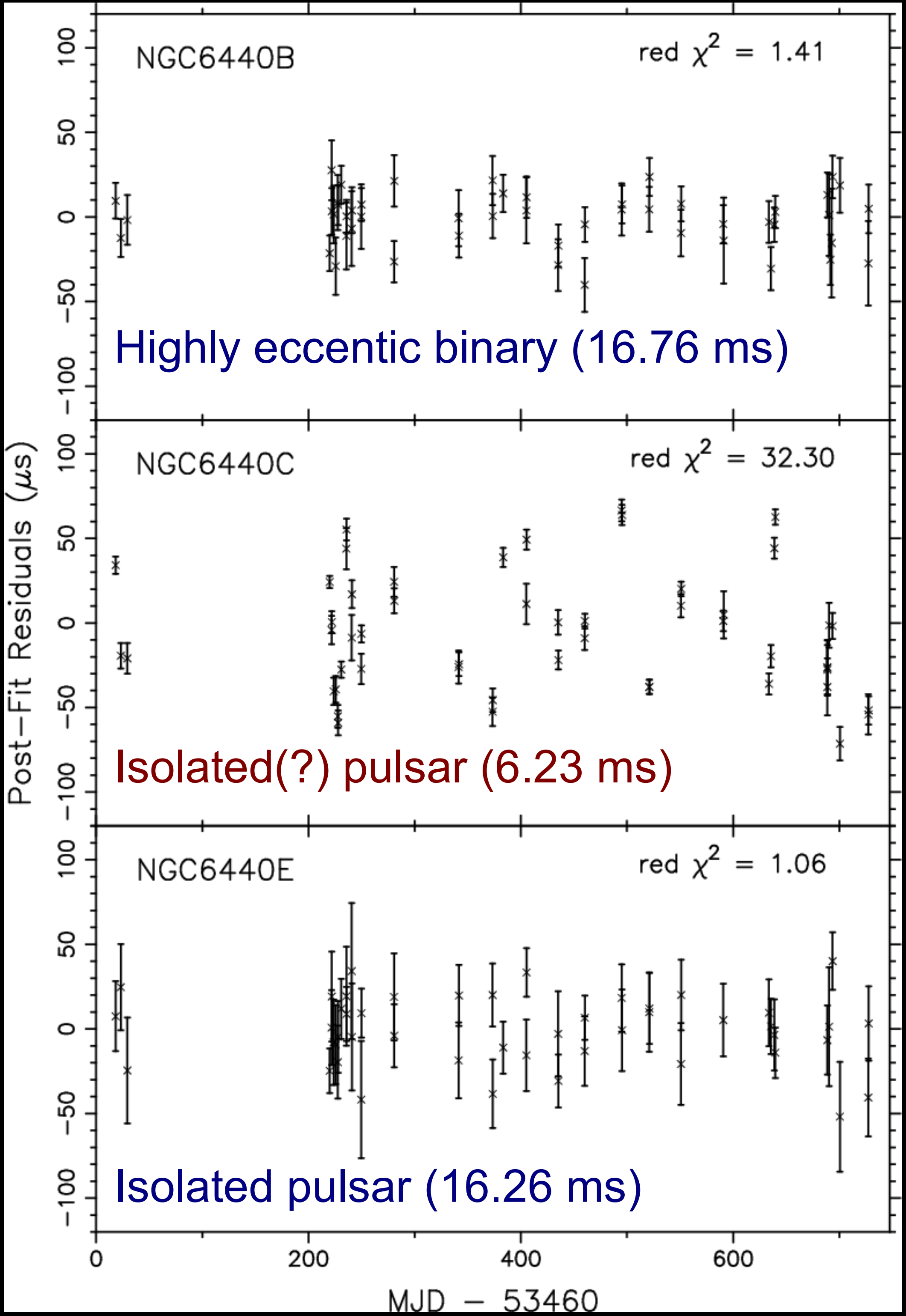
P_{psr} ~ 16.76 ms

P_{orb} = 20.6 days

Freire et al. 2008, ApJ, 675, 670

NGC6440C: Isolated?





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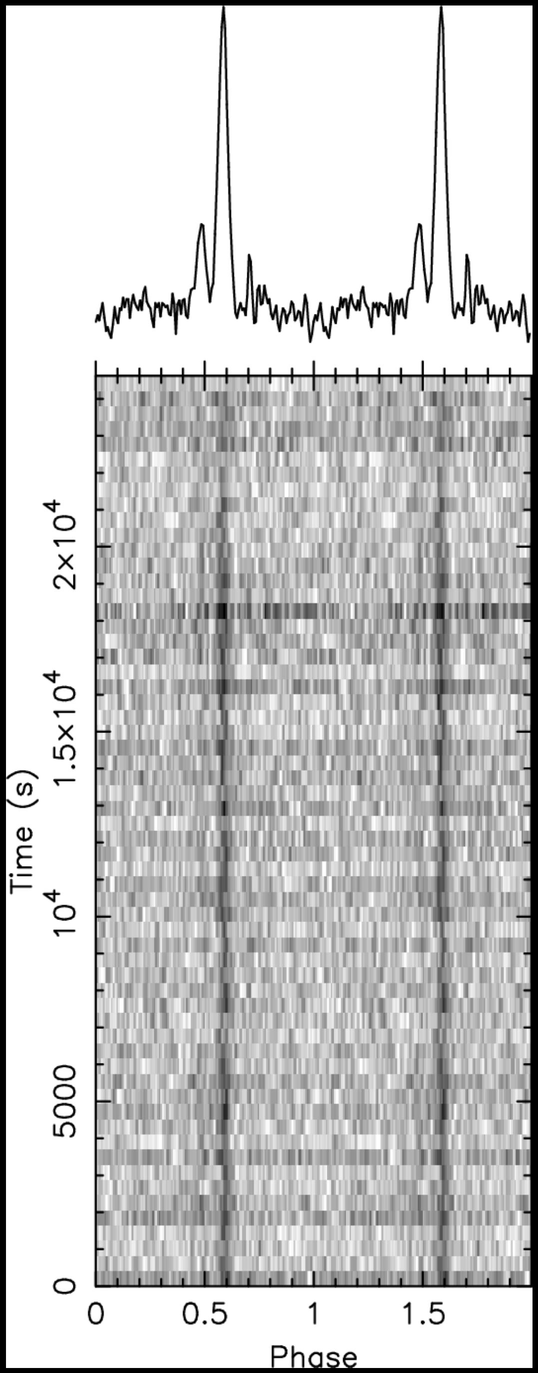

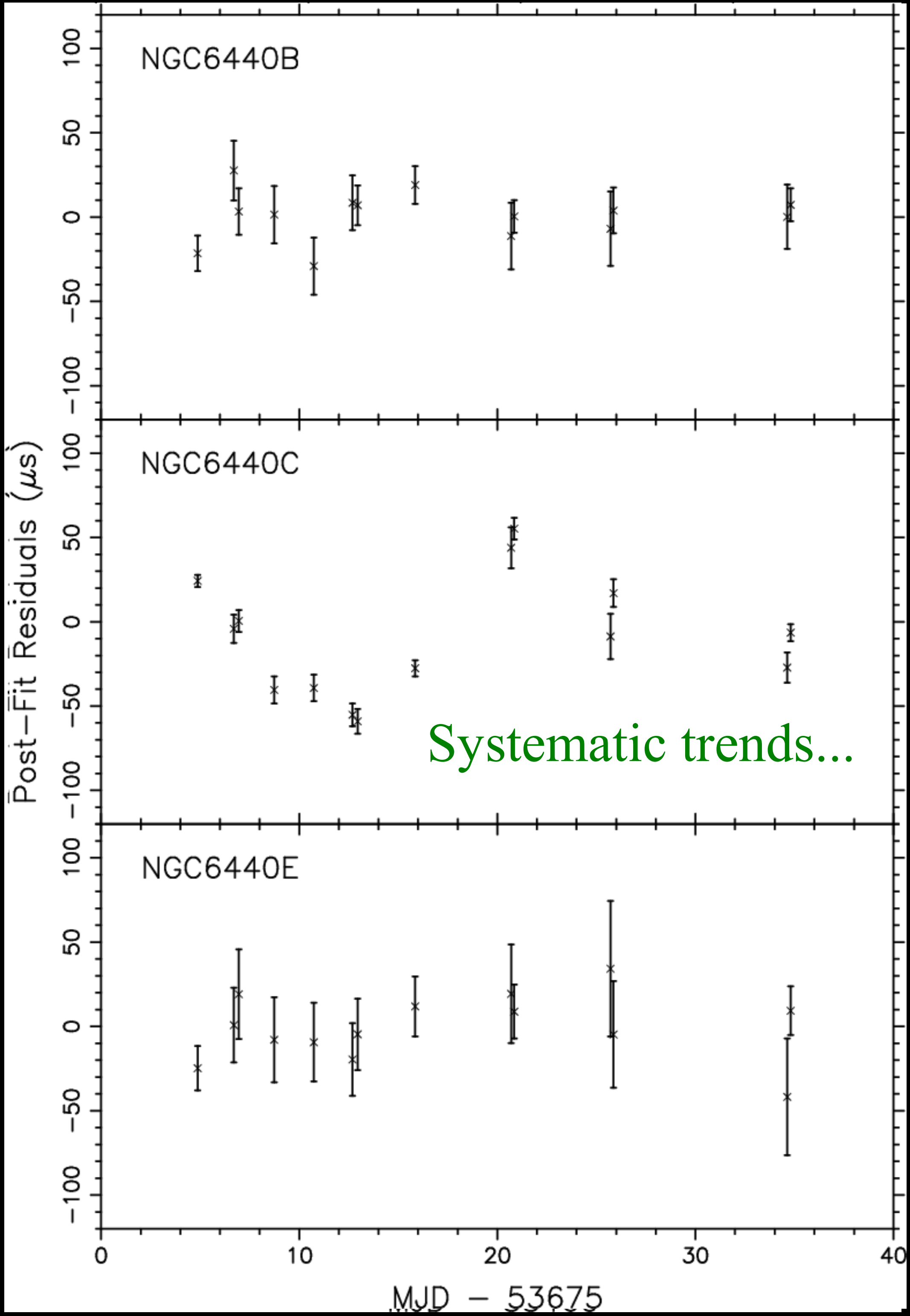

Outlook for the future...

- 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 cluster MSPs