Radio Pulsars in Globular Clusters

Scott Ransom

National Radio Astronomy Observatory
Charlottesville, VA

Why pulsars in globular clustere?

- Observations of multiple MSPs in a single cluster provide a wide variety of science about the pulsars, their companions, and the clusters where they live
  - Intracluster gas and/or ISM

    Freire et al. 2001, ApJL, 557, 105
  - M/L ratio limits and/or probes for central IMBH

    Jenet, Creighton, & Lommen, 2005, ApJL, 627, 125
  - Binary evolution and dynamics and many others

    Freire et al. 2001, MNRAS, 326, 901

    Freire et al. 2003, MNRAS, 340, 135
- Truly exotic objects are predicted to exist:

  i.e. sub-MSPs, PSR-BH binaries, MSP-MSP binaries

Searching for Cluster Pulsars (is hard!)

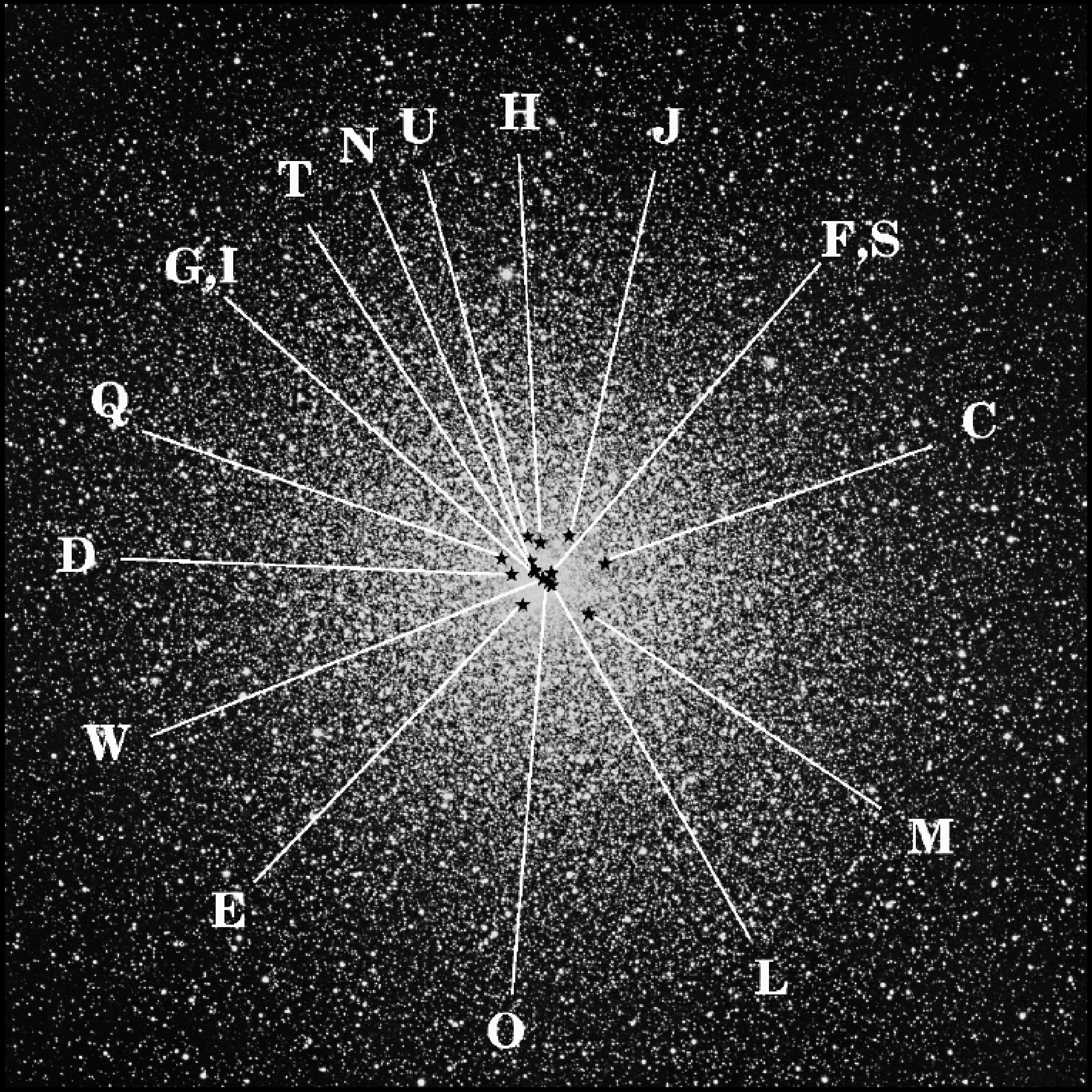
- Globular cluster pulsars are:
  - Intrinsically weak radio sources
  - Often in binaries (show Doppler accelerations)
  - Distant (weaker, large dispersion (DM), scatter-broadening)

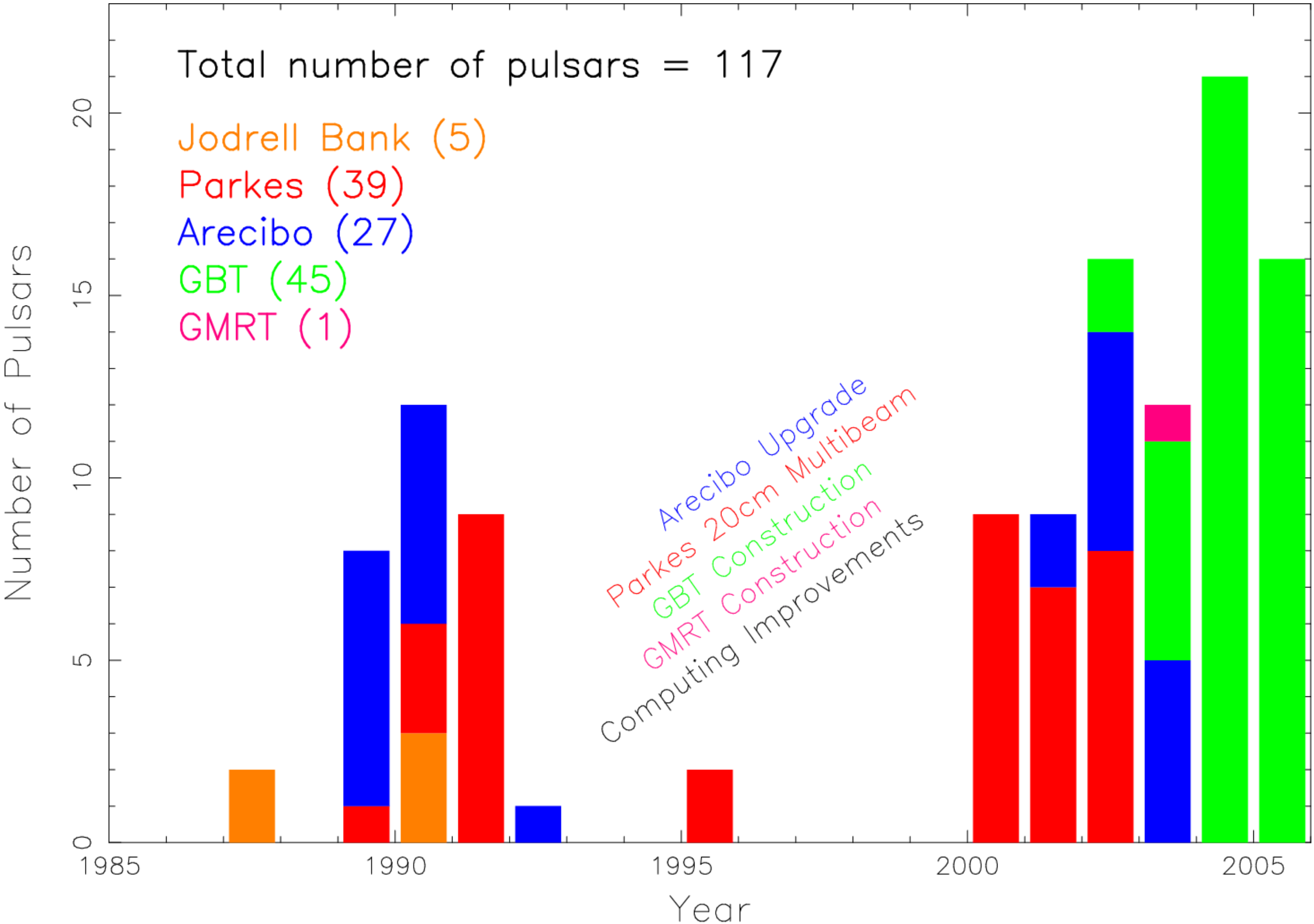
Sensitivity $\propto A\ T_{tot}^{-1}\ t_{int}^{1/2}\ \Delta\nu^{1/2}$ Computations $\propto f_{spin}^{3}\ t_{int}^{2}$

- Solutions:
  - Use large telescopes and sensitive receivers
  - Use longer integration times
  - Use advanced algorithms to adaptively remove interference
  - Use specialized binary search algorithms to improve sensitivity to weak binary MSPs (the hardest PSRs to detect)
  - Use *lots* of CPU cycles!

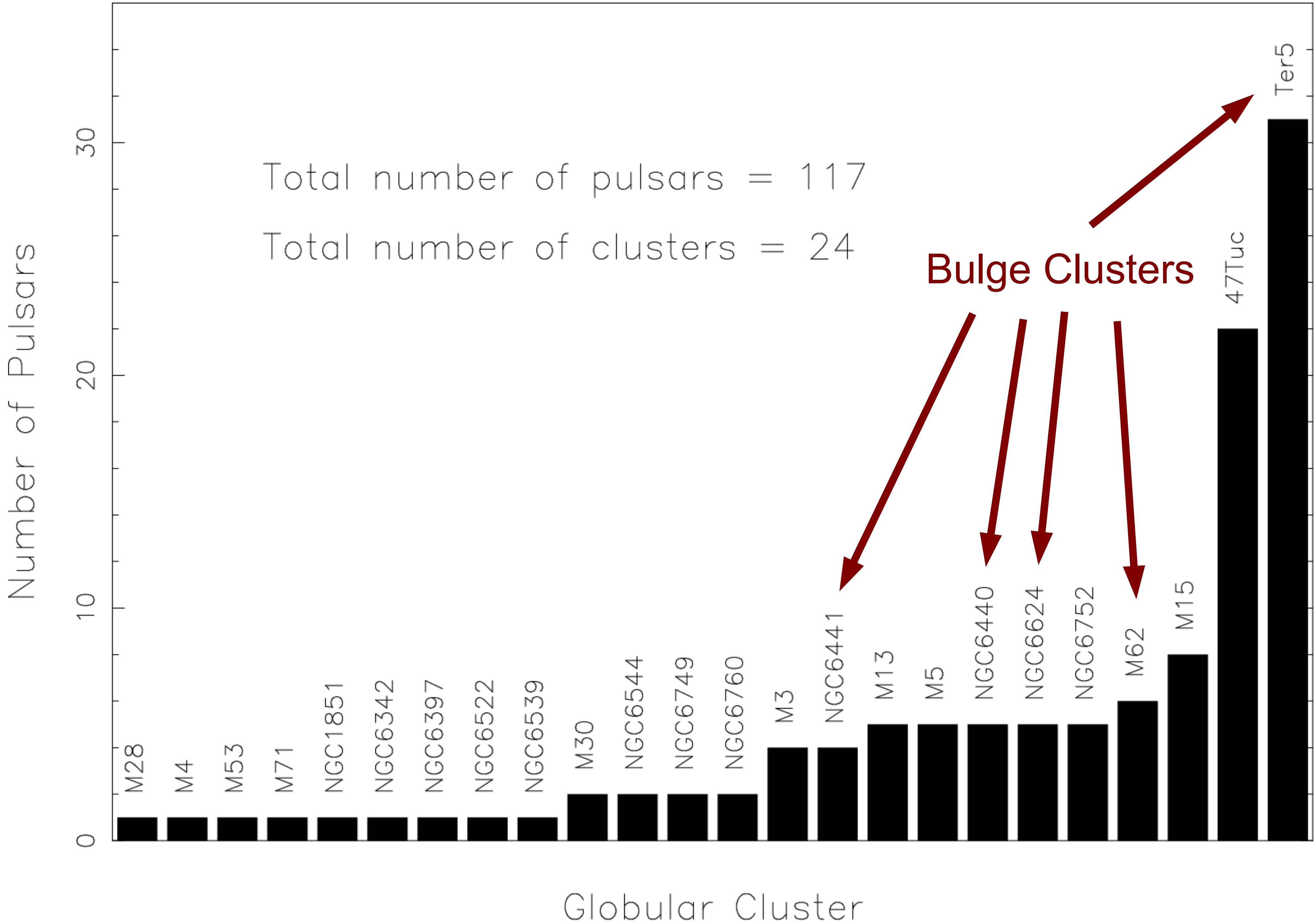
Status as of early 2004: A Pulsar Renaissance

- 46 PSRs from 2000-2004
  - New/upgraded telescopes observing at 1400 MHz
  - “Beneficial” scintillation
  - Advanced algorithms
  - Lots of computing
- Most successful by far is 47 Tucanae
  - 22 MSPs (14 binaries)
  - *1200+ hrs* of Parkes time
  - Camilo et al. 2000; Freire et al. 2001, 2003; Lorimer 2003





Total number of pulsars = 117
Jodrell Bank (5)
Parkes (39)
Arecibo (27)
GBT (45)
GMRT (1)
Arecibo Upgrade
Parkes 20cm Multibeam
GBT Construction
GMRT Construction
Computing Improvements
Number of Pulsars
Year
0
5
10
15
20
1985
1990
1995
2000
2005


Total number of pulsars = 117
Total number of clusters = 24
Bulge Clusters
Number of Pulsars
Globular Cluster
0
10
20
30
M28
M4
M53
M71
NGC1851
NGC6342
NGC6397
NGC6522
NGC6539
M30
NGC6544
NGC6749
NGC6760
M3
NGC6441
M13
M5
NGC6440
NGC6624
NGC6752
M62
M15
47Tuc
Ter5

Terzan 5

- Very massive, and metal rich cluster with a high central density
- Verbunt and Hut (1987) calculated that it had one of the highest interaction rates of any cluster
- Distance ~ 8.7 ± 2 kpc (Cohn et al. 2001)
- Within ~ 1 kpc of Galactic center (l,b) = (3.8º, 1.7º)
- Interstellar electrons (i.e. Dispersion Measure or DM) make deep searches quite difficult (e.g. scattering and smearing)

S. Ortolani, I-band NTT image (ESO)

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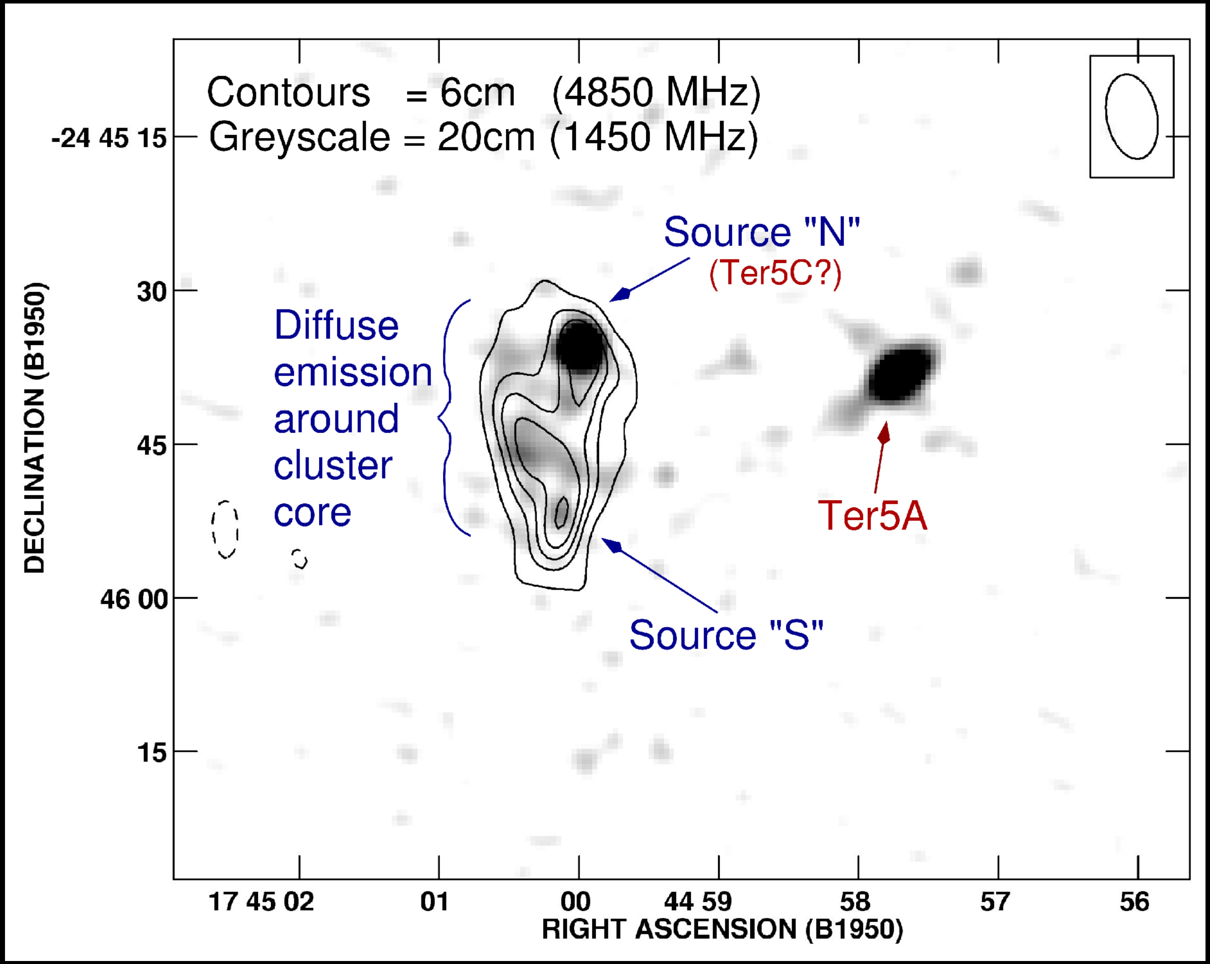


- Deep VLA observations by Fruchter and Goss (1990, 2000) found point sources and ~ 2 mJy of diffuse emission in core: 60-200 MSPs?
- From 1990-2001, though, only 3 MSPs were discovered

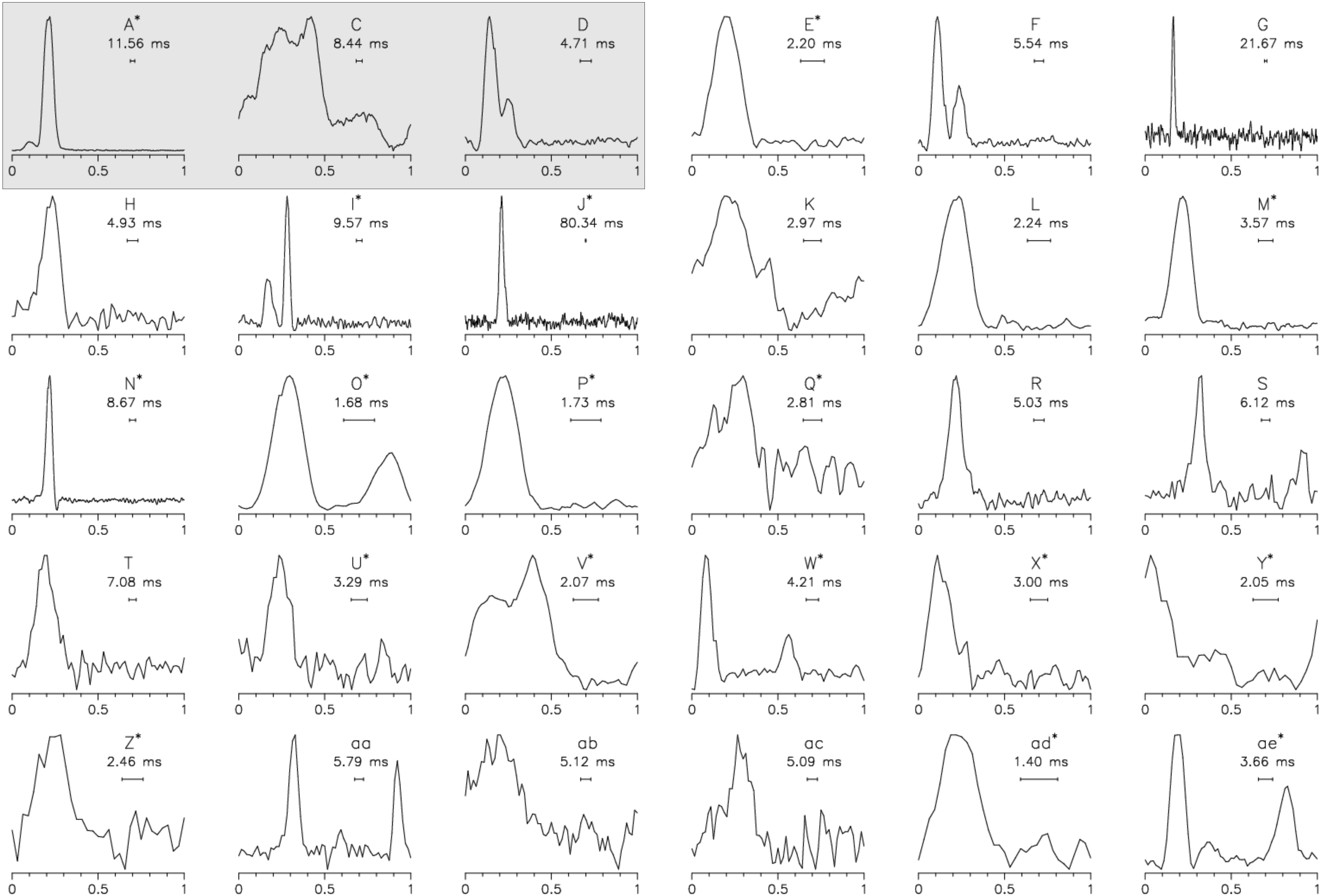
Why look bulge clusters with the GBT?

5-20 times more sensitive

to MSPs than earlier searches

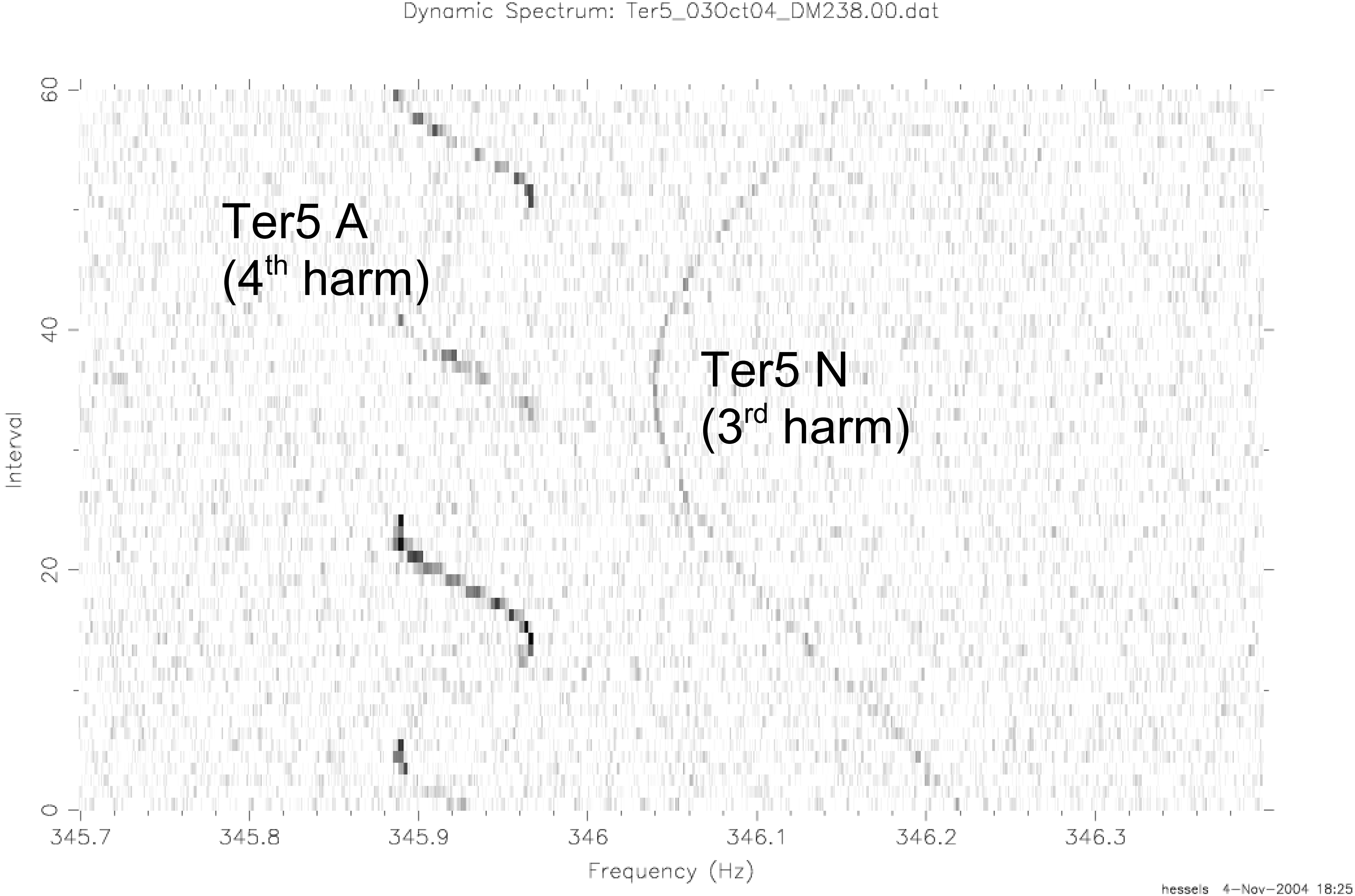
- Gain (i.e. area) is almost 3 times larger than Parkes
- "Clean" 600 MHz of bandwidth at low S-band (ν_{ctr}=1950 Mhz)
  - Reduces DM-smearing ($\propto\nu^{-3}$) and scatter-broadening ($\propto\nu^{-4.4}$)
  - But pulsars tend to be steep spectrum...
- New SPIGOT card (82-μs sampling, 1024 x 16-bit lags)
  - *Soon*: 82-μs sampling, 2048 x 8-bit lags *or*

    41-μs sampling, 4096 x 4-bit lags



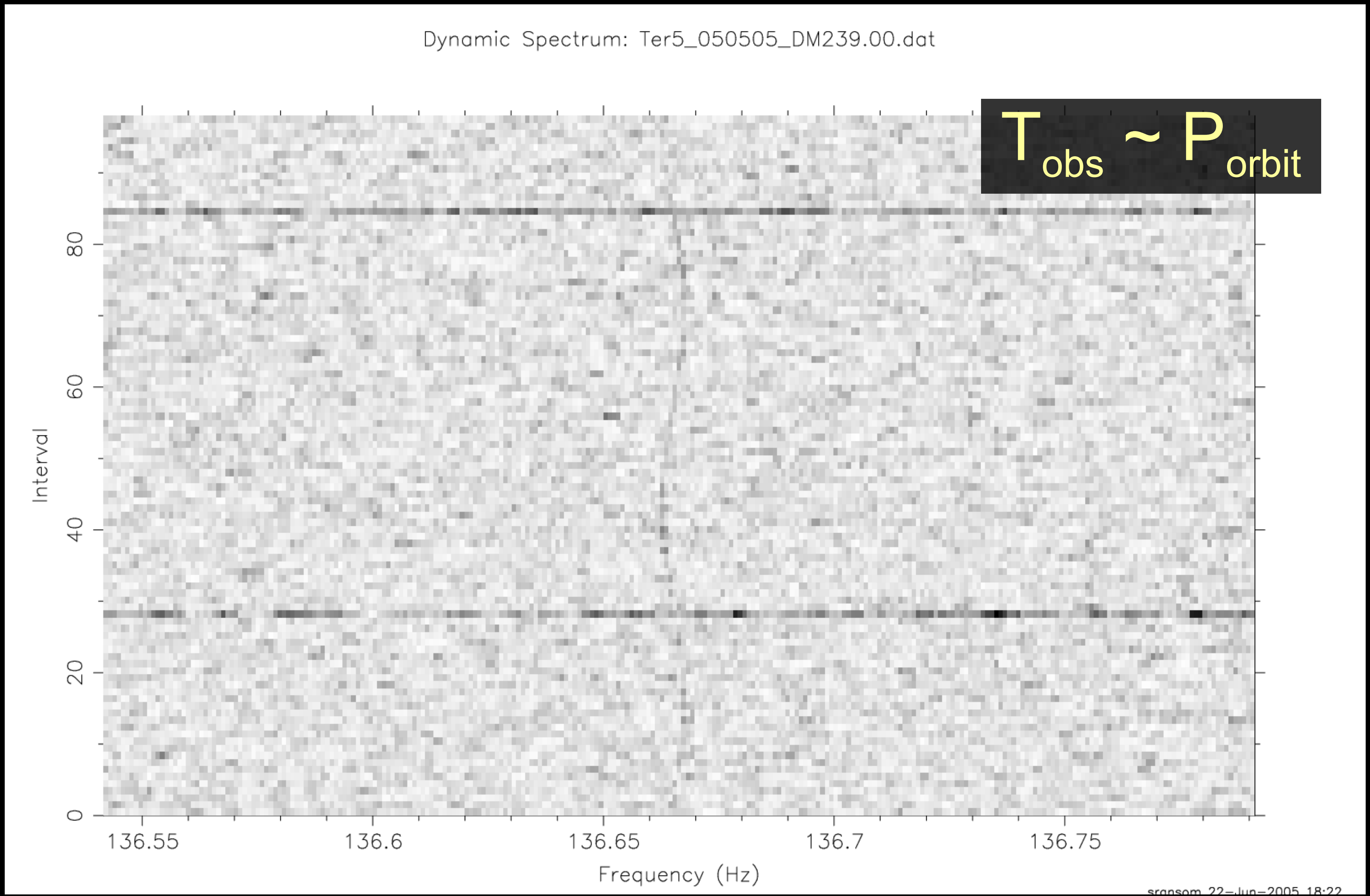
28 new MSPs in Terzan5 = 31 in total!

Ransom et al., 2005, Science, 307, 892



Dynamic Spectrum: Ter5_03Oct04_DM238.00.dat
Ter5 A
(4th harm)
Ter5 N
(3rd harm)
Interval
0
20
40
60
345.7
345.8
345.9
346
346.1
346.2
346.3
Frequency (Hz)
hessels 4-Nov-2004 18:25

Dynamic Power Spectra

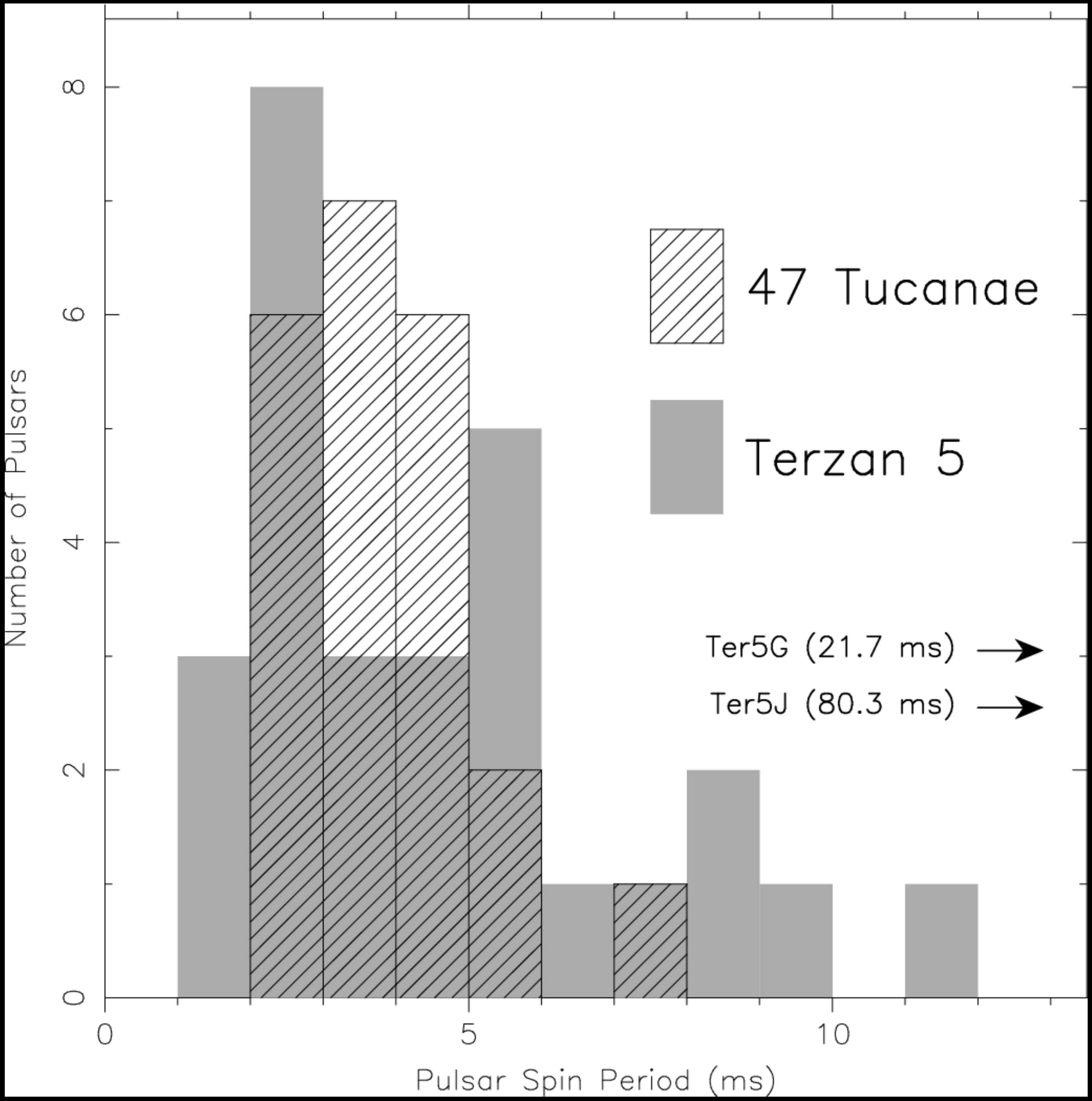


Discovery of Ter5ae

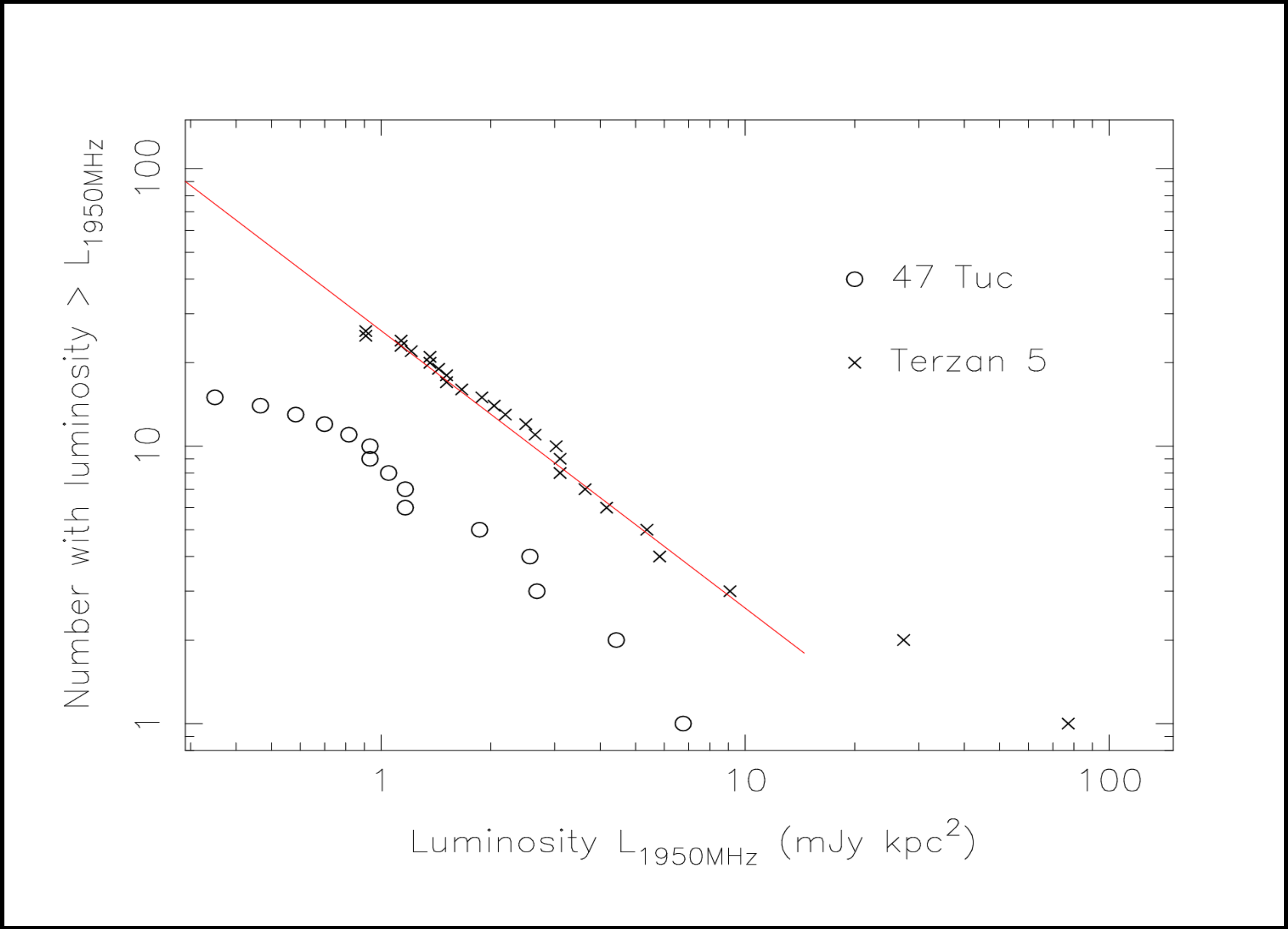
(P_{psr} = 3.65 ms, P_{orb} = 4.1 hrs, $M_c > 18\ M_{Jup}$)

Spin Period Comparison with 47 Tuc

- 47 Tuc periods are much more uniform (2-7 ms), no pulsars with P_{spin} > 8 ms
- Ter5 pulsars have a flatter (and broader) distribution
- KS-test suggests distributions are different at ~90% confidence
- Does this tell us something about the dynamical state of Ter5's core?



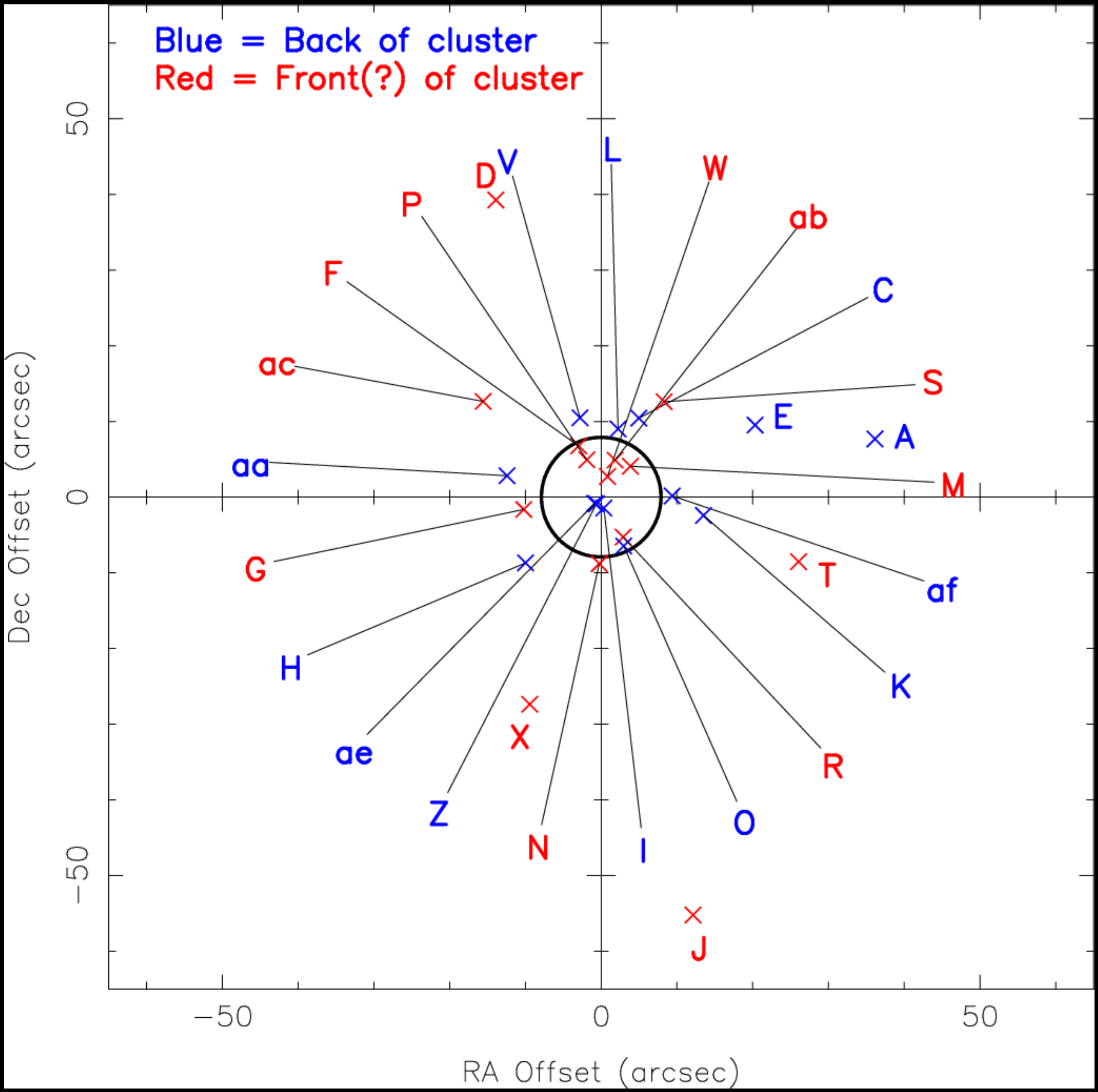
1950 MHz Pulsar Luminosities



For a given pulsar luminosity, Ter5 has ~3x more pulsars than 47 Tuc!

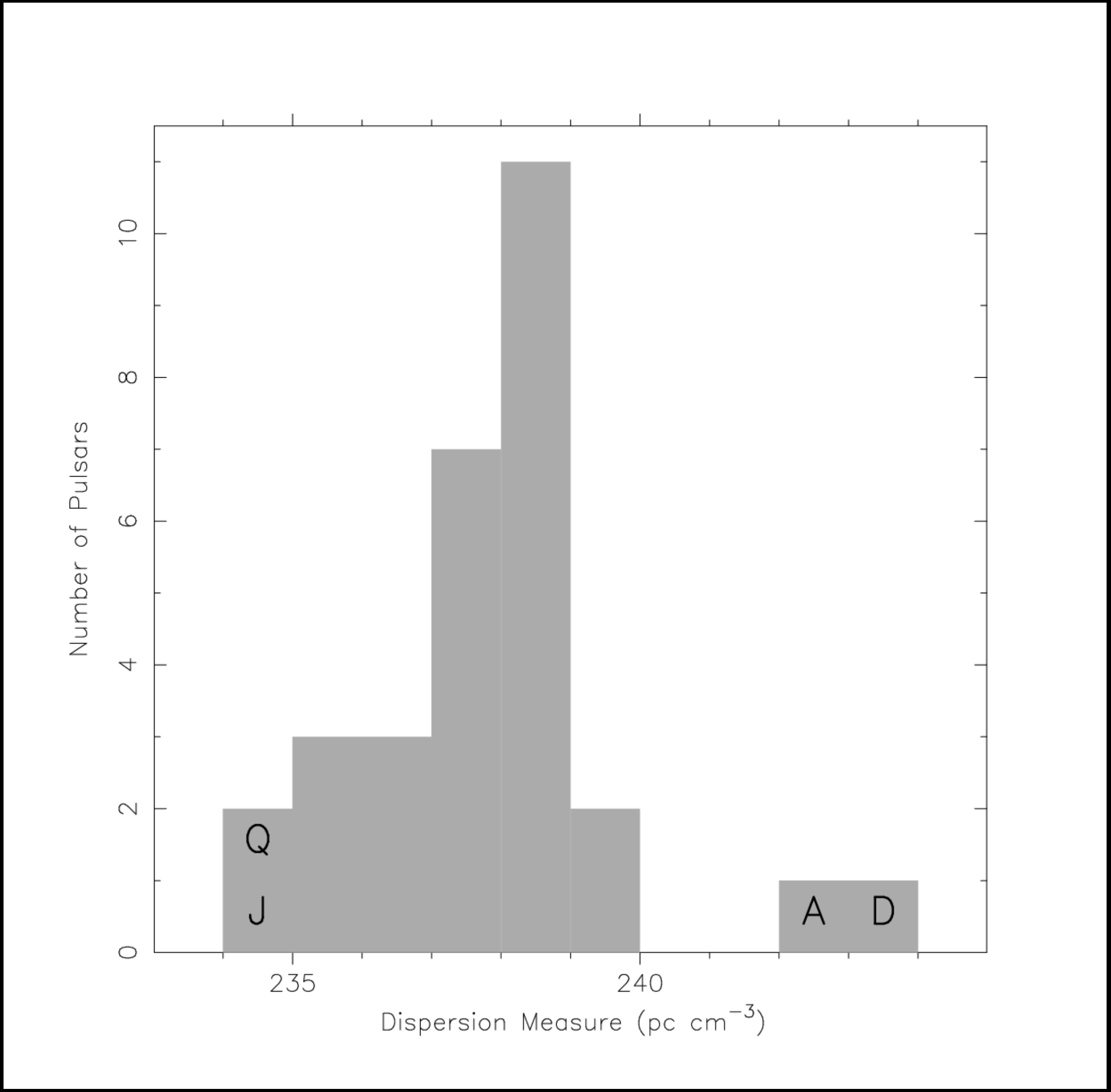
New Timing Solutions

- All of the science comes from pulsar timing!
- Currently have timing solutions for 27 of the 32 pulsars
- 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
- Initial estimates show that core M/L > 2



DM Distribution

- DM range from ~234-244 pc/cm^3
- Constrains the distance to Ter5 (argues for < 8kpc)
- Highest range of any cluster
- This implies a steep gradient in electrons (0.17 pc/cm^3/arcsec) across only a couple arcminutes of sky
- But positions show that things are quite complicated...



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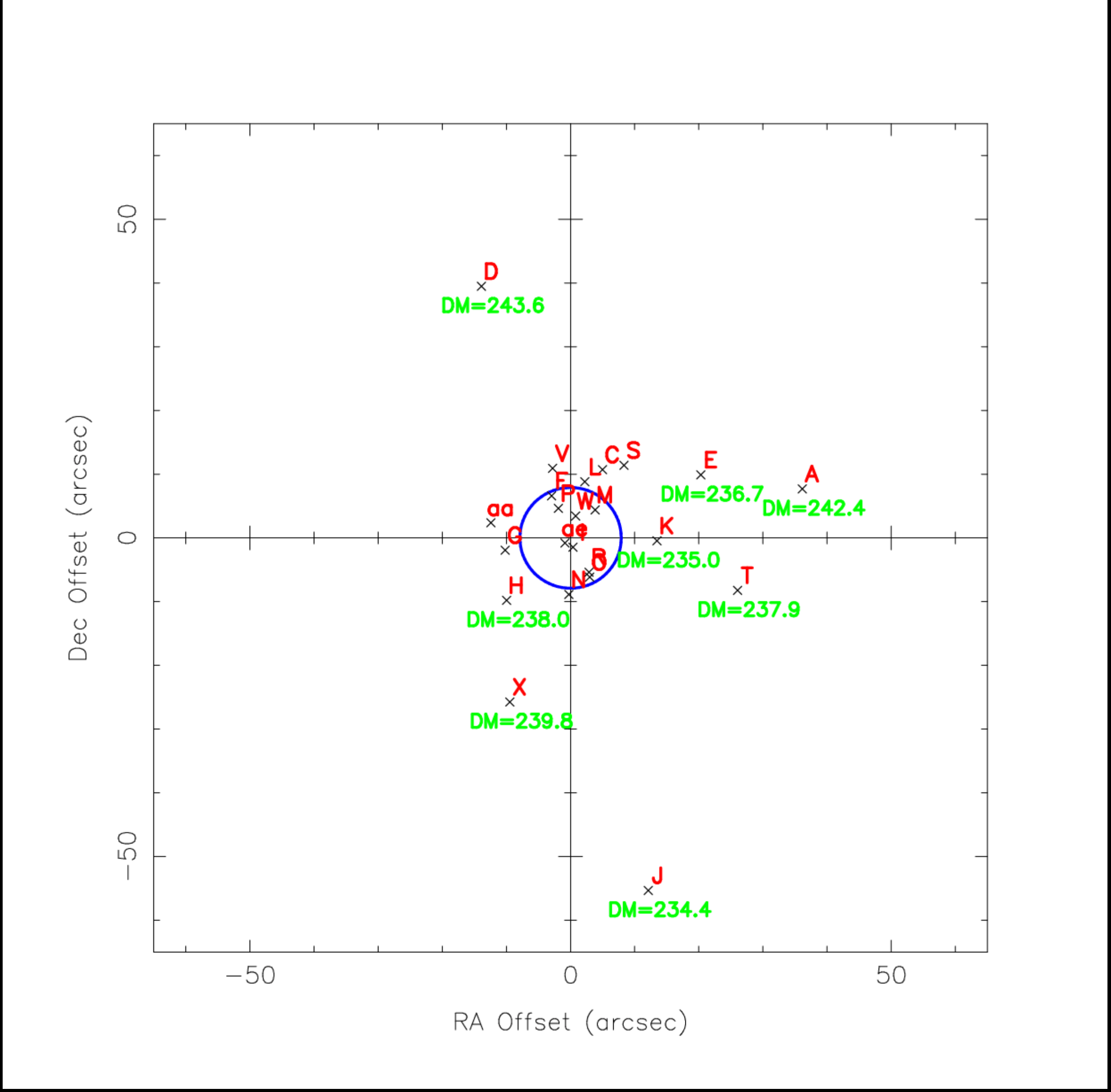
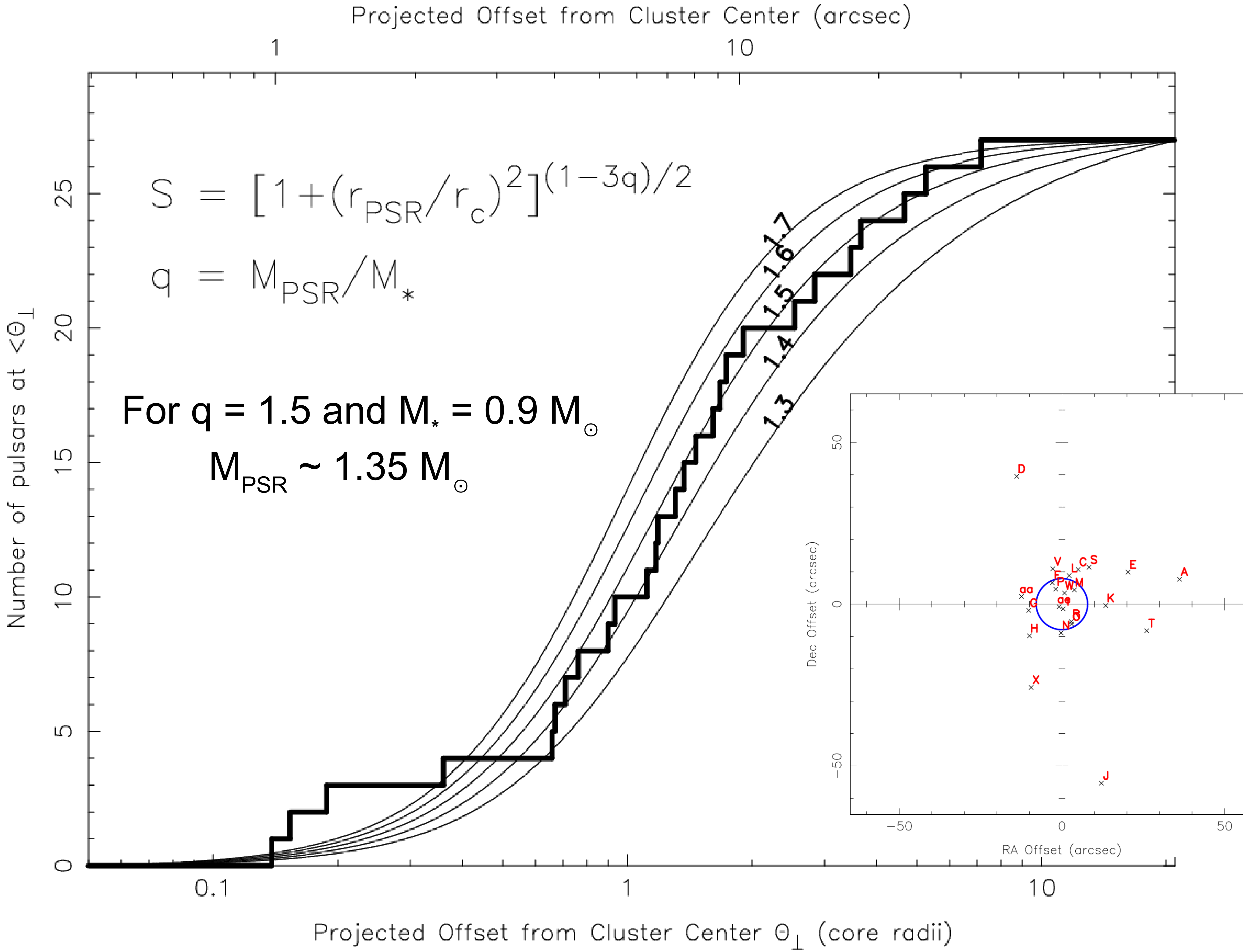
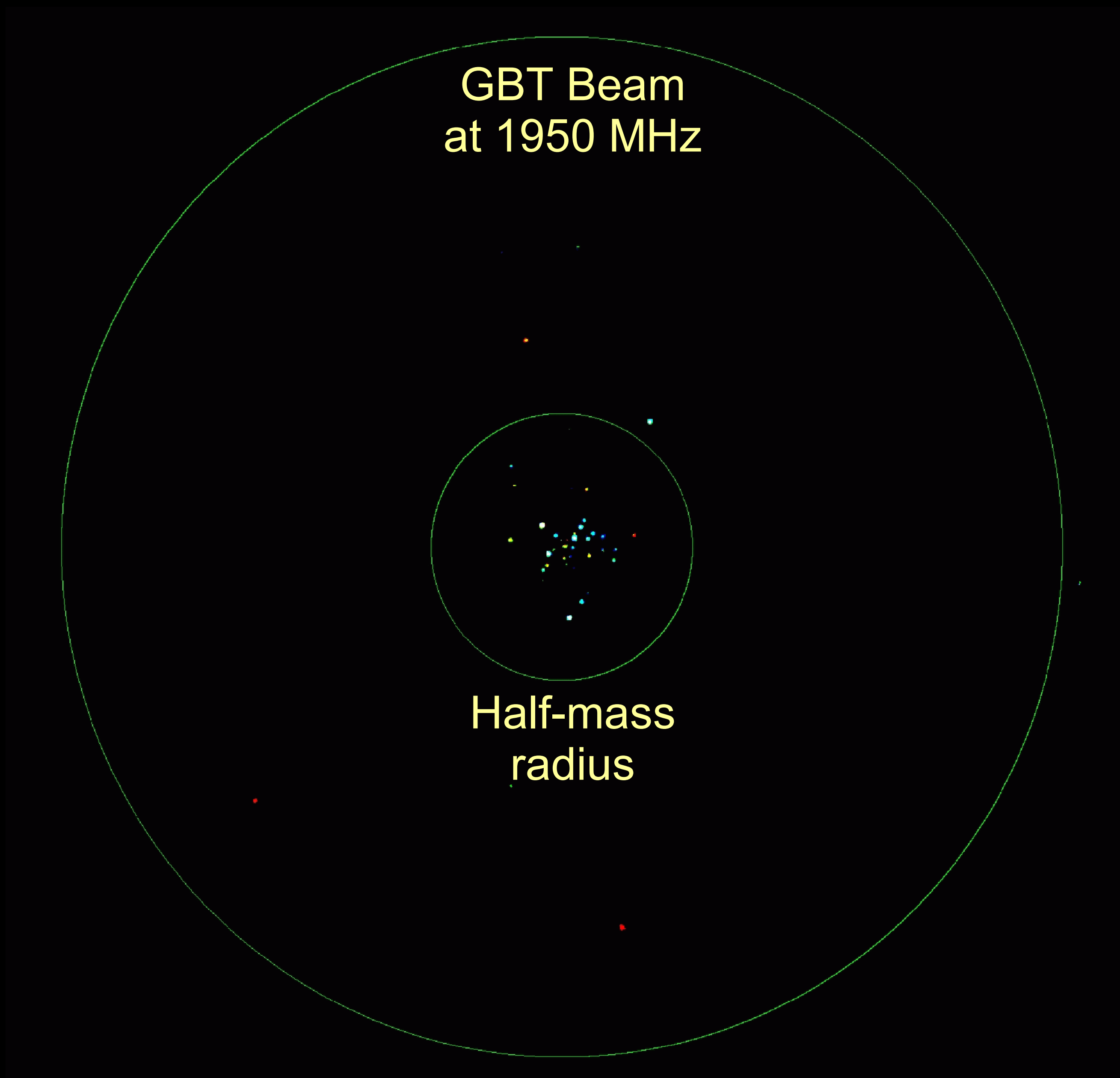




Projected Offset from Cluster Center (arcsec)
1
10
$S = [1+(r_{PSR}/r_c)^2]^{(1-3q)/2}$
$q = M_{PSR}/M_*$
1.7
1.6
1.5
1.4
1.3
For q = 1.5 and $M_* = 0.9\ M_\odot$
$M_{PSR} \sim 1.35\ M_\odot$
Number of pulsars at $<\Theta_\perp$
0
5
10
15
20
25
0.1
1
10
Projected Offset from Cluster Center $\Theta_\perp$ (core radii)
Dec Offset (arcsec)
RA Offset (arcsec)
50
0
−50
D
V
F
P
C
S
L
E
A
W
M
aa
G
K
T
H
N
X
J

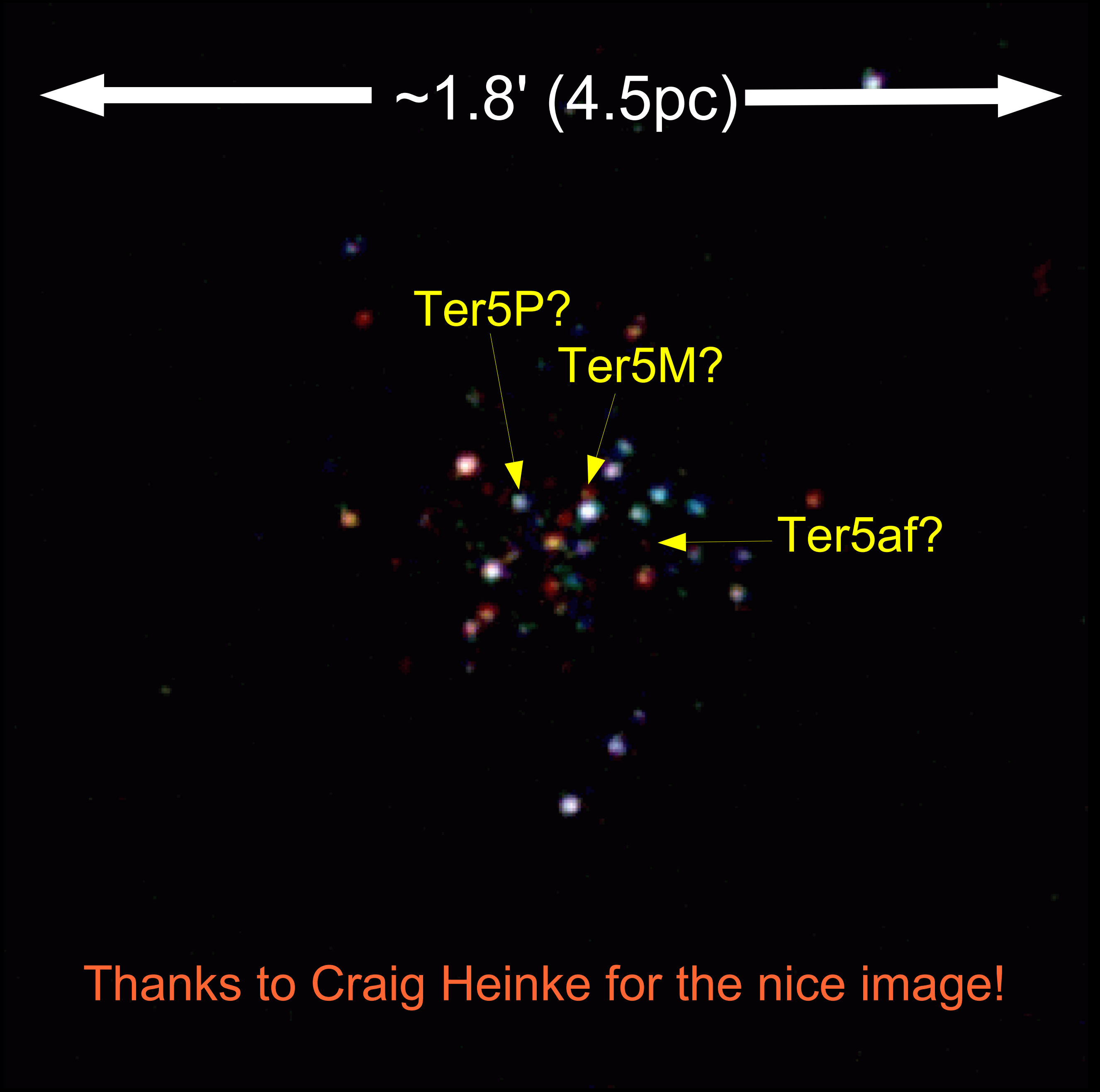
Archival Chandra Observation

- Public 40ks Chandra ACIS-S observation
- 35+ sources within cluster half-mass radius (0.83')
- Absorption is high: $N_H \sim 10^{22}\ cm^{-2}$

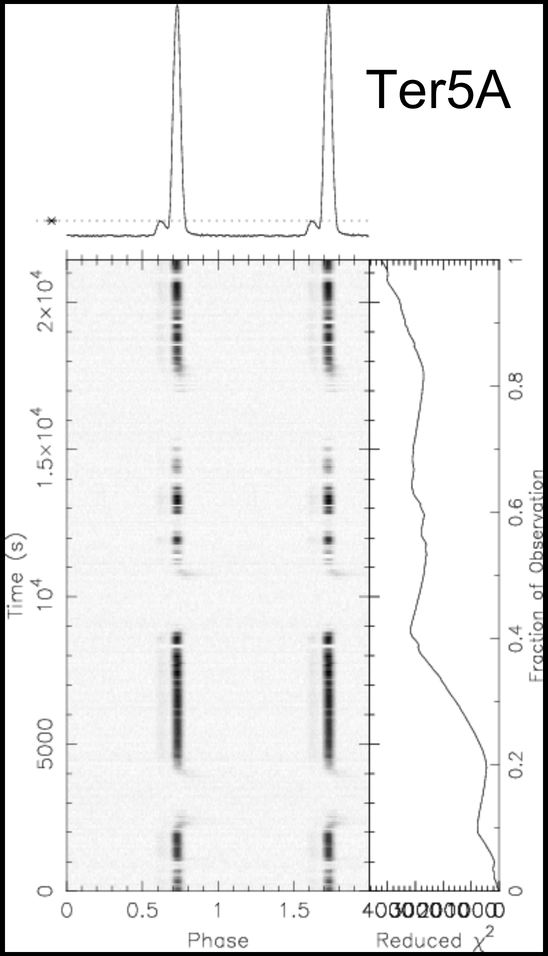


Archival Chandra Observation

- Public 40ks Chandra ACIS-S observation
- 35+ sources within cluster half-mass radius (0.83')
- Absorption is high: $N_H \sim 10^{22}$ cm^{-2}
- 2-3 possible MSP counterparts already



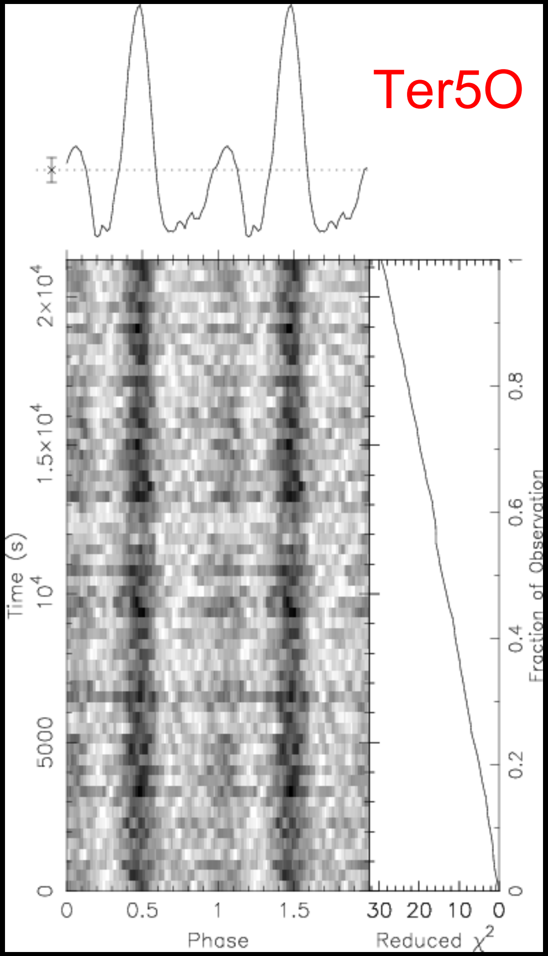
Eclipsing Binary MSPs in Terzan 5



P_{psr} = 11.56 ms

P_{orb} = 1.82 hrs

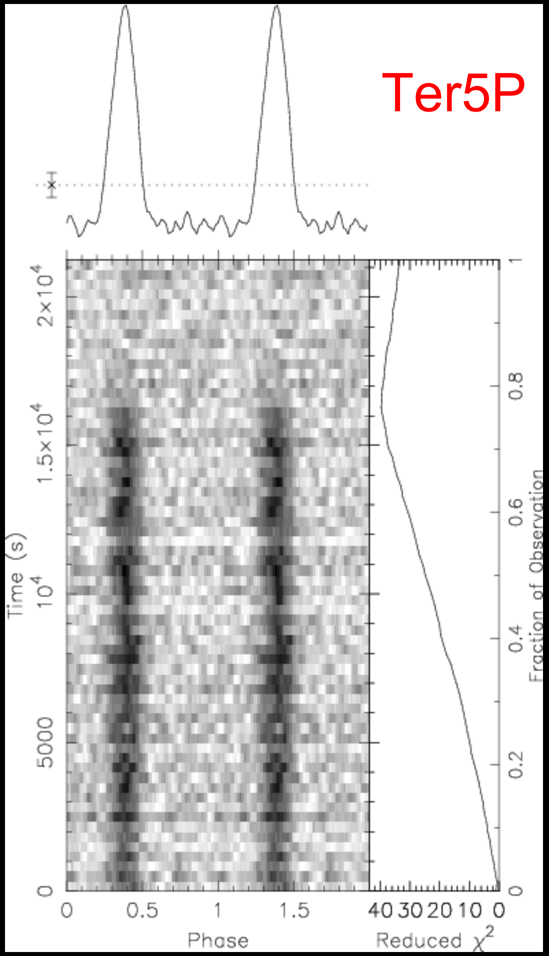
$M_{c,min}$ ~ 0.089 $M_\odot$



P_{psr} = 1.67 ms

P_{orb} = 6.22 hrs

$M_{c,min}$ ~ 0.036 $M_\odot$

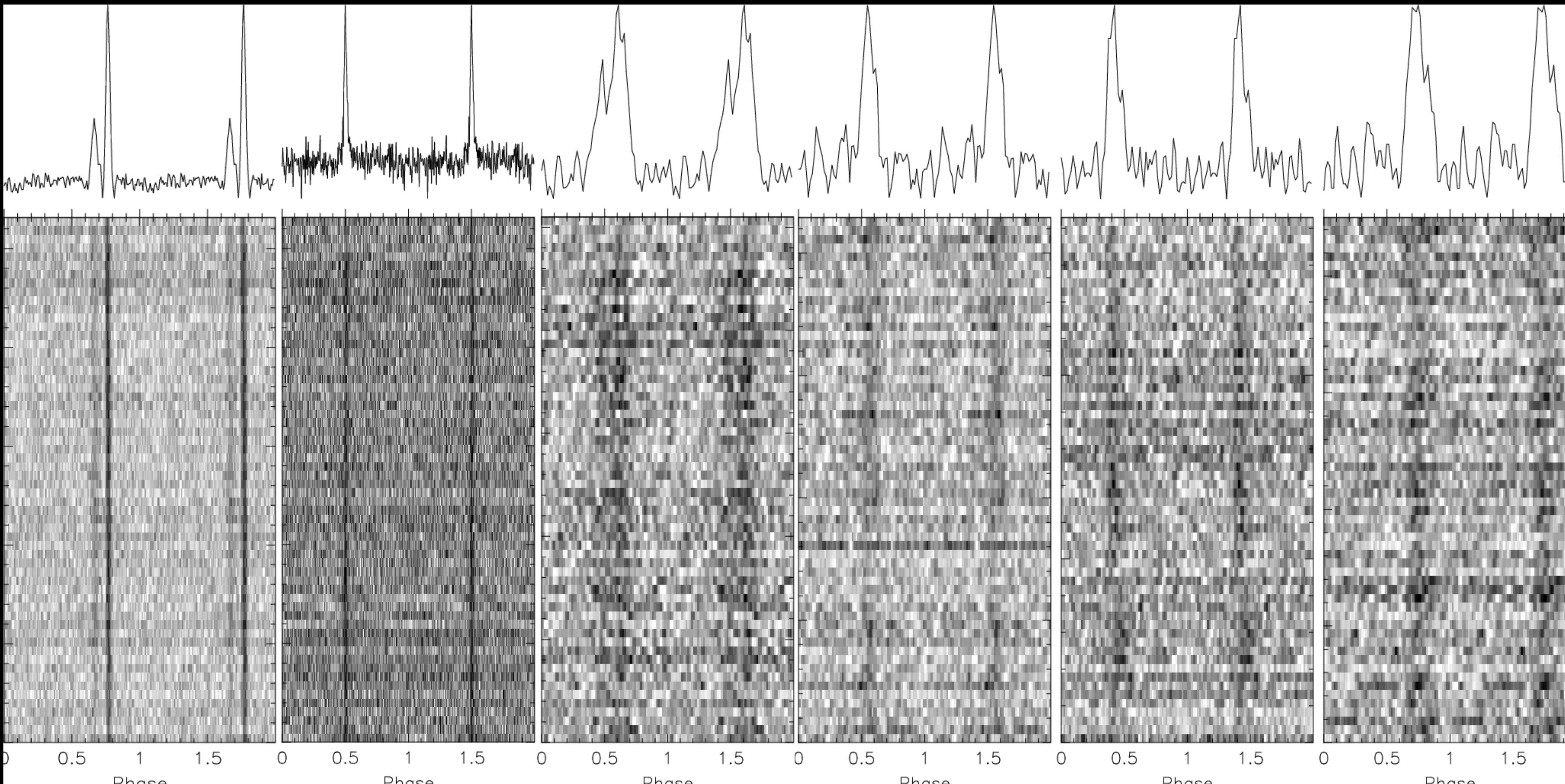


P_{psr} = 1.73 ms

P_{orb} = 8.70 hrs

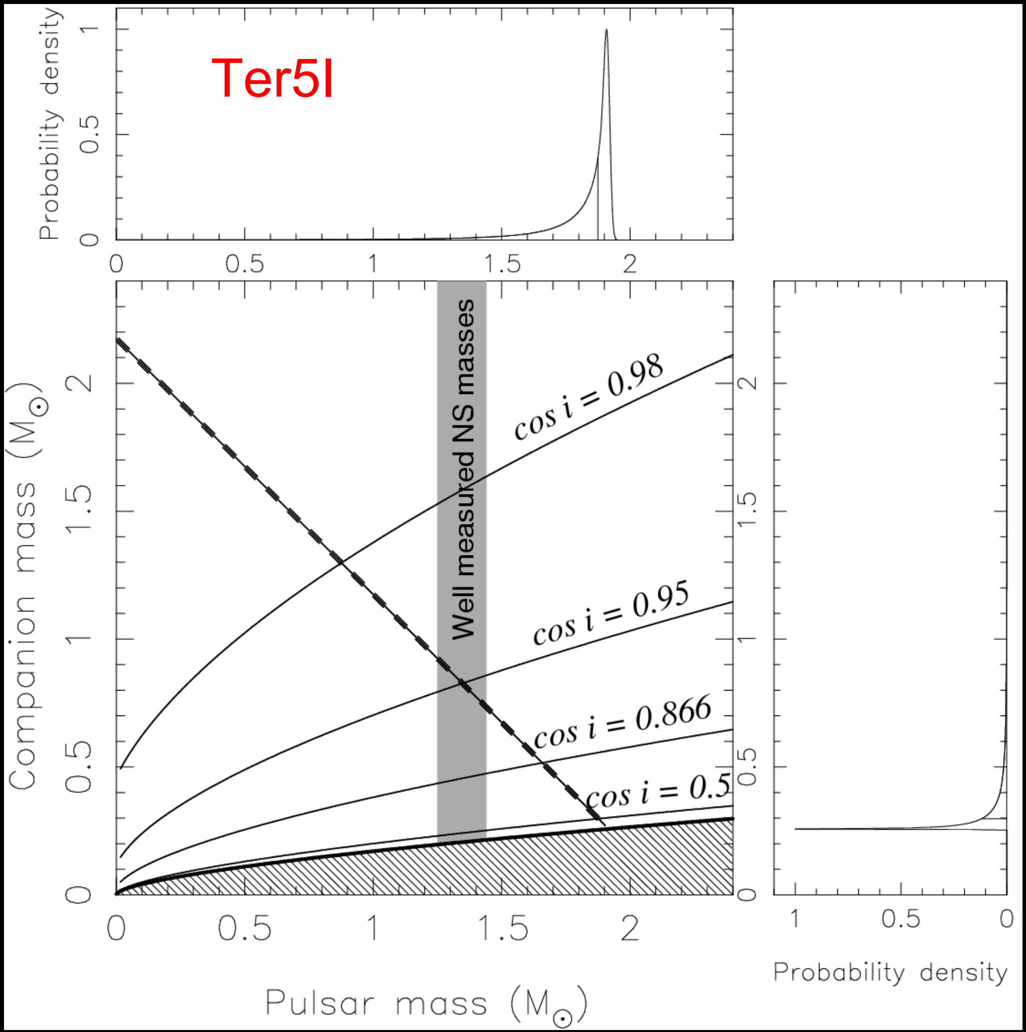
$M_{c,min}$ ~ 0.38 $M_\odot$

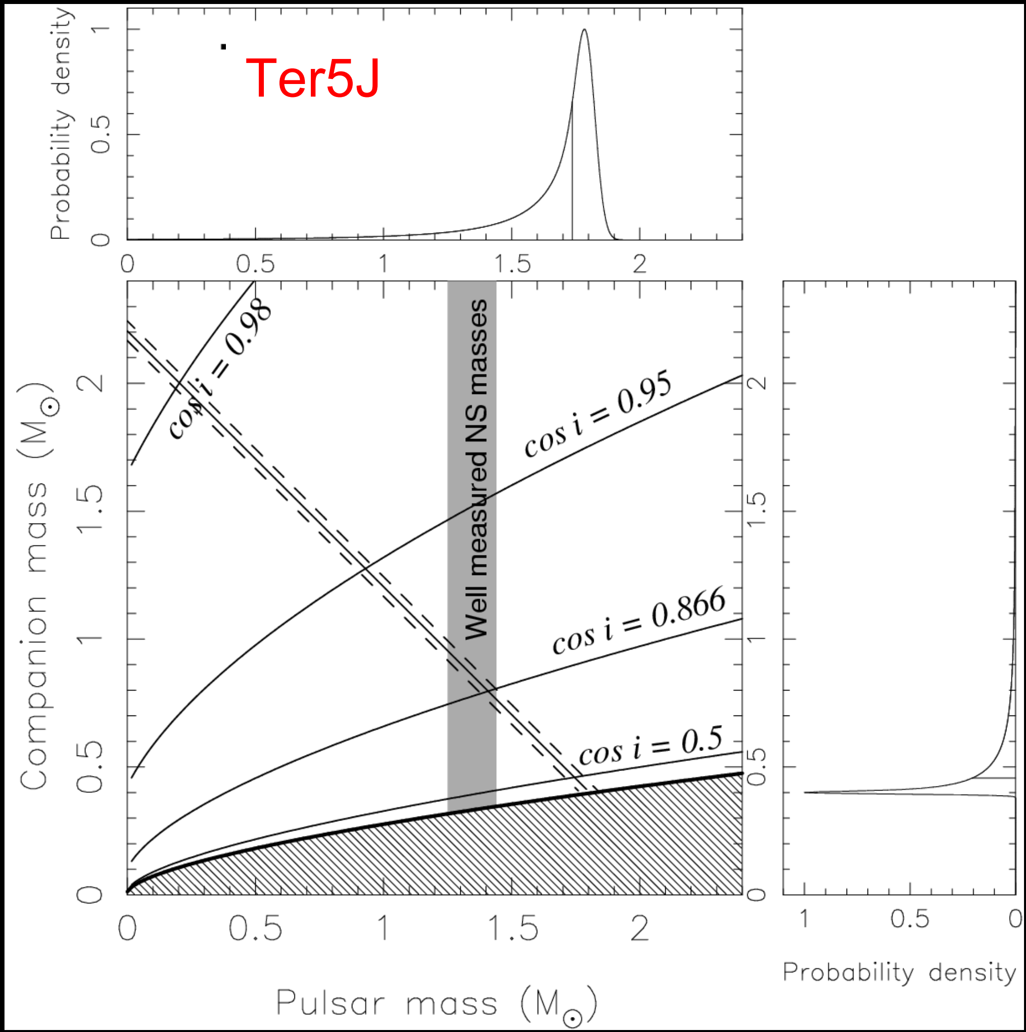
Six (!) Eccentric Binary MSPs in Ter5



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} = 1.8 days	P_{orb} = 5.0 days	P_{orb} = 3.5 days
$M_{c,min} \sim 0.21\ M_\odot$	$M_{c,min} \sim 0.34\ M_\odot$	$M_{c,min} \sim 0.45\ M_\odot$	$M_{c,min} \sim 0.02\ M_\odot$	$M_{c,min} \sim 0.25\ M_\odot$	$M_{c,min} \sim 0.22\ M_\odot$
ecc = 0.43	ecc = 0.35	ecc = 0.72	ecc = 0.27	ecc = 0.30	ecc = 0.76

Ter5I and J: Eccentric and Relativistic Systems



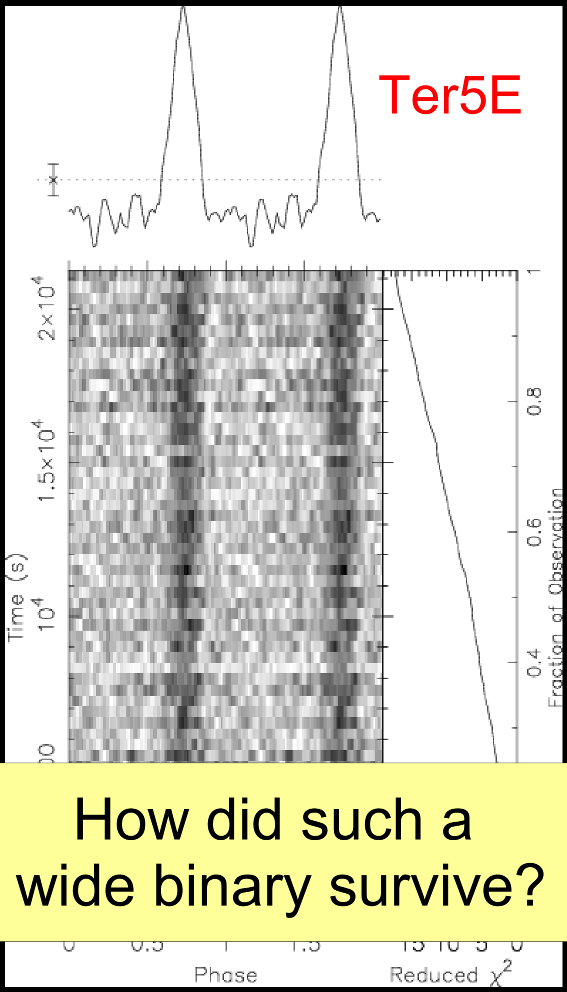


From measurement of the relativistic advance of periastron:

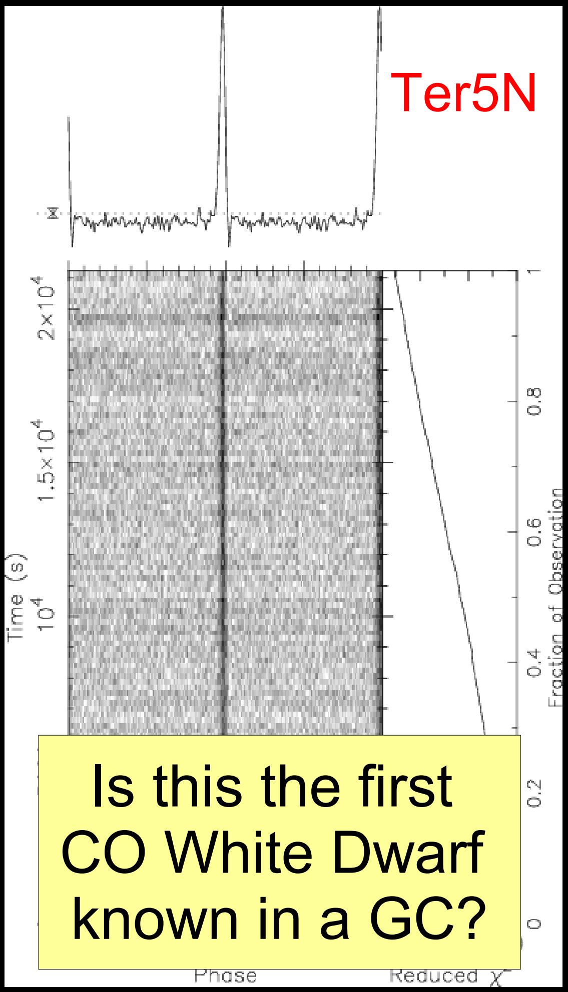
$M_{tot} = 2.17 \pm 0.02 M_\odot$

$M_{tot} = 2.20 \pm 0.04 M_\odot$

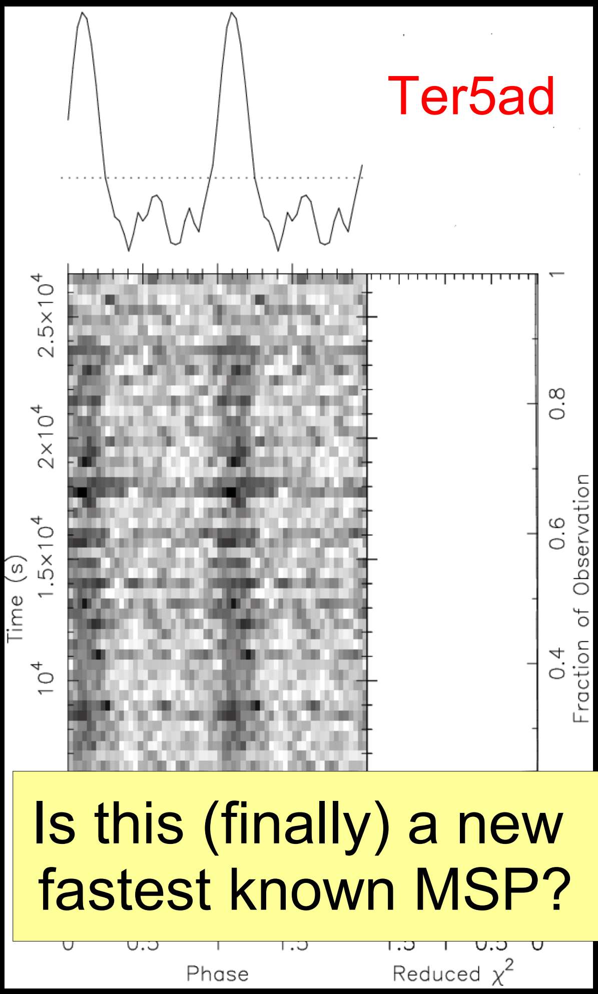
A Few Interesting Binary PSRs in Ter5



How did such a wide binary survive?



Is this the first CO White Dwarf known in a GC?



Is this (finally) a new fastest known MSP?

P_{psr} = 2.20 ms

P_{orb} = 60.06d (e~0.02)

$M_{c,min} \sim 0.22\ M_\odot$

P_{psr} = 8.67 ms

P_{orb} = 9.25 hrs (e~4.7×10^{-5})

$M_{c,min} \sim 0.48\ M_\odot$

P_{psr} = 1.39 ms

P_{orb} = 1.09 days

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

Ter5ad: The Original MSP Beater?

P_{spin} = 1.396ms

f_{spin} = 716Hz

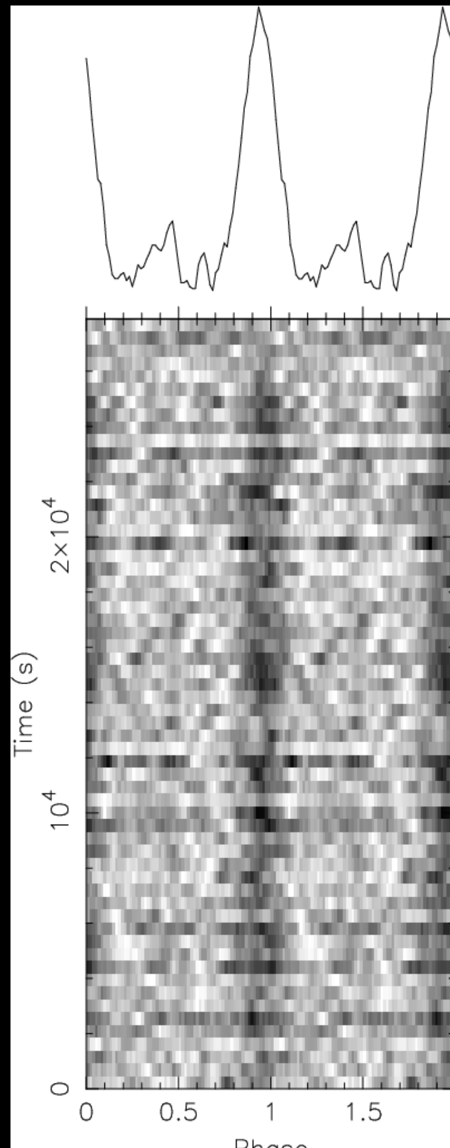
P_{orb} = 1.09d

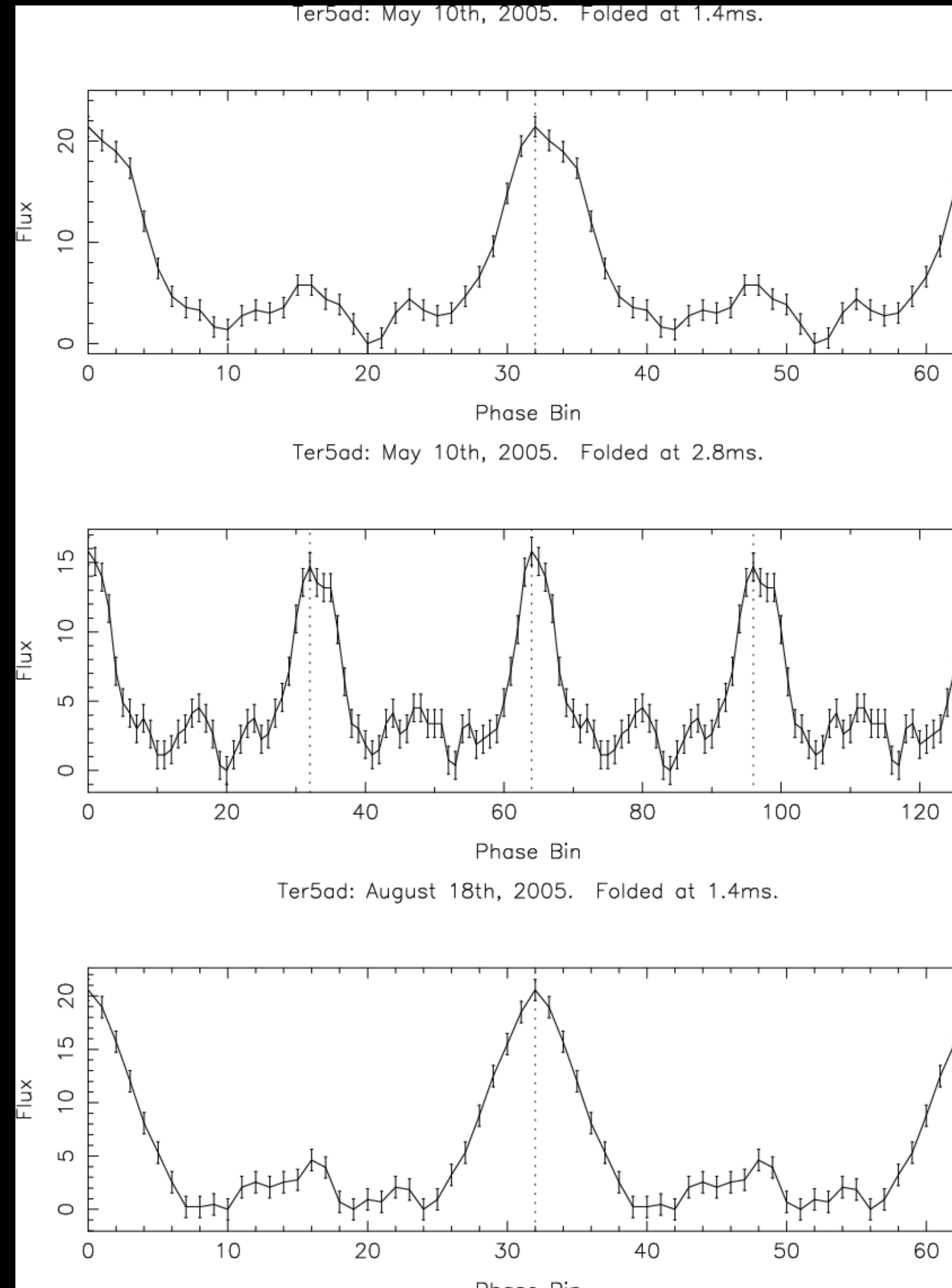
$M_{c,min} > 0.14\ M_{\odot}$

Observed 12+ times

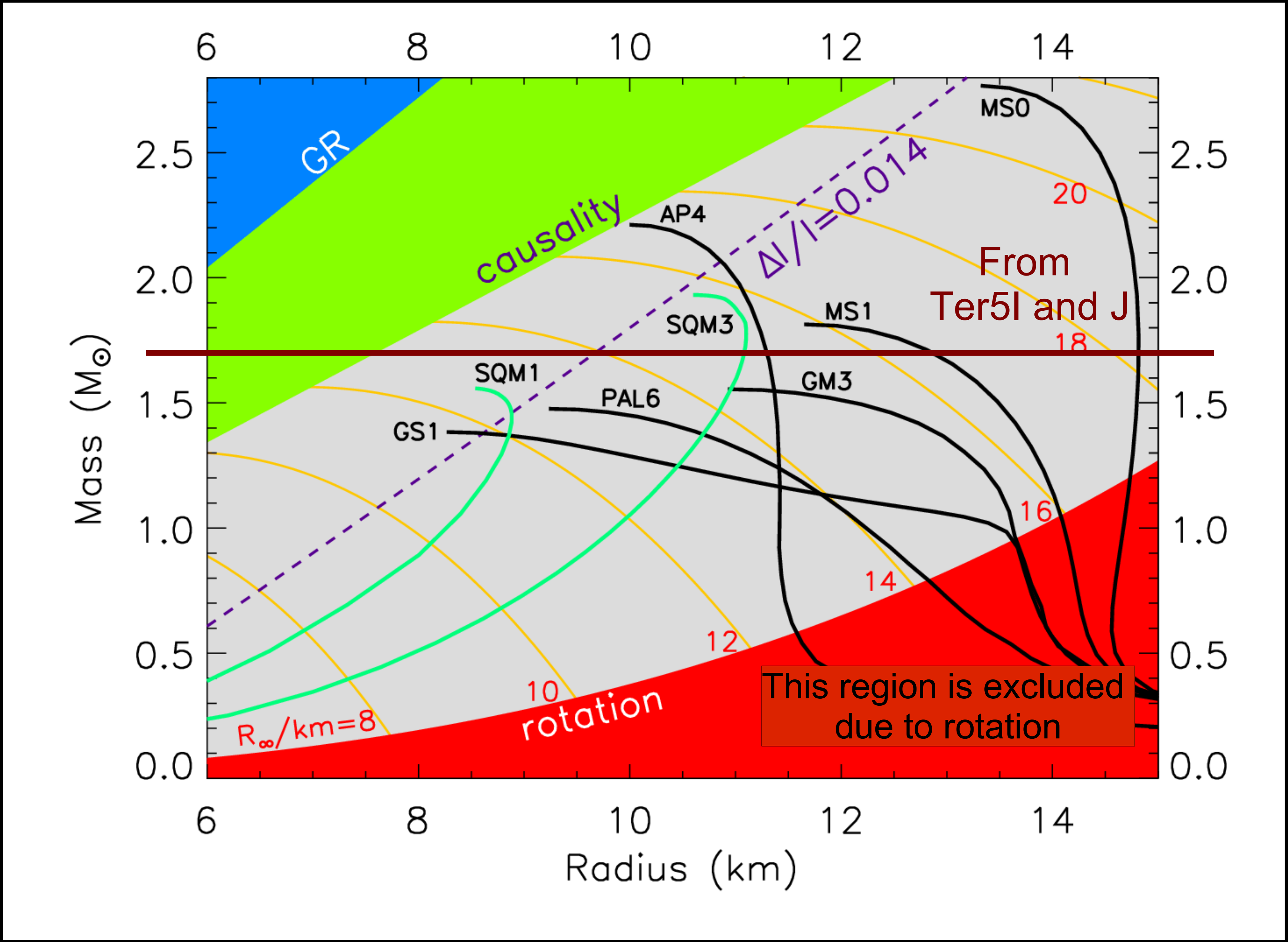
Eclipsed ~50%

Flickering?



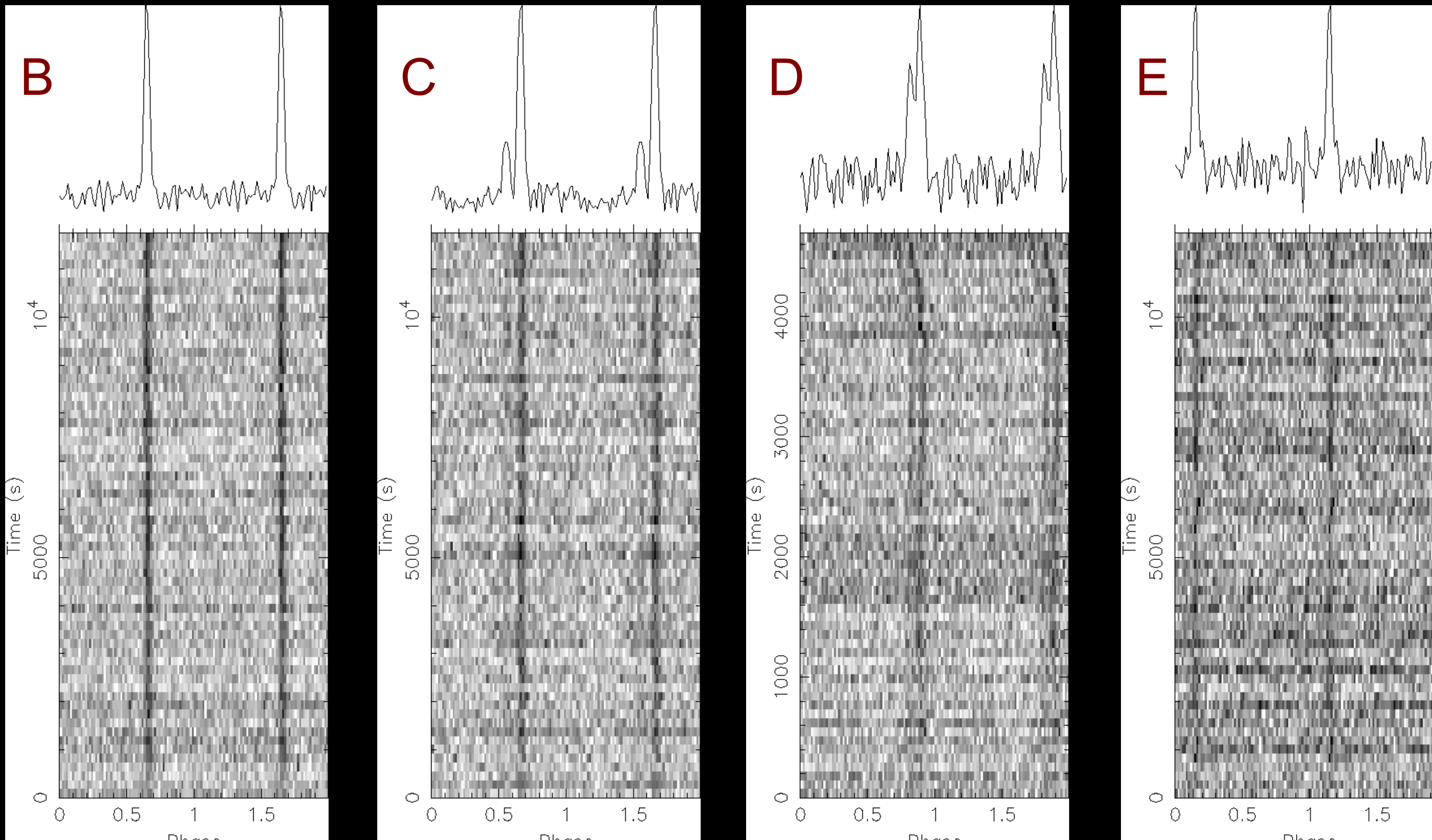


Neutron Star Equations of State



From Lattimer and Prakash 2004, *Science*

New MSPs in rich clusters: NGC6440



P_{psr} ~ 16.76 ms
P_{orb} > days?

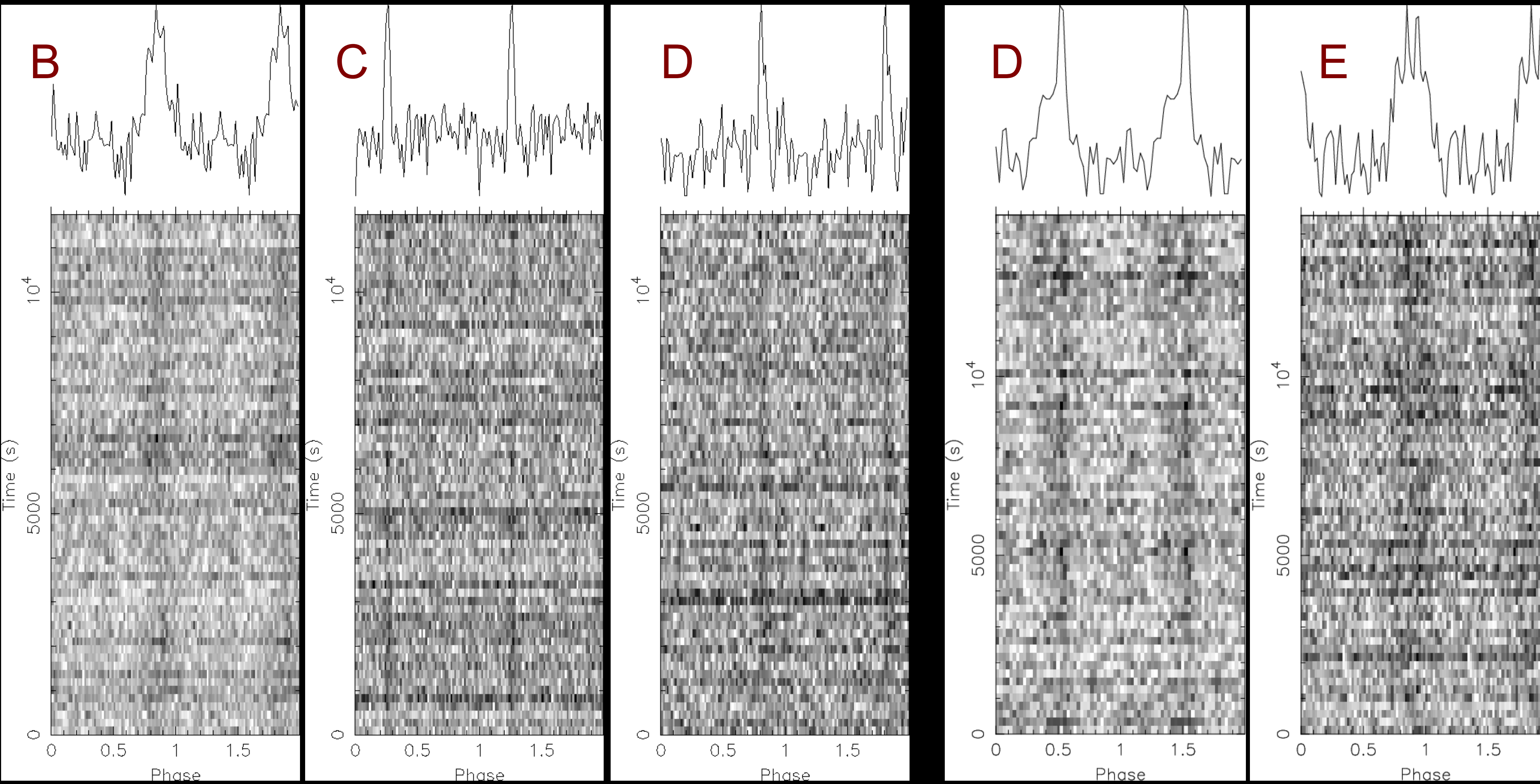
P_{psr} ~ 6.23 ms
Isolated?

P_{psr} ~ 13.49 ms
P_{orb} ~ 6.5 hr

P_{psr} ~ 16.26 ms
Isolated?

NGC6441

NGC6624



P_{psr} ~ 6.07 ms
P_{orb} > days?

P_{psr} ~ 26.57 ms
Isolated?

P_{psr} ~ 5.14 ms
Isolated?

P_{psr} ~ 3.02 ms
Isolated?

P_{psr} ~ 4.39 ms
Isolated?

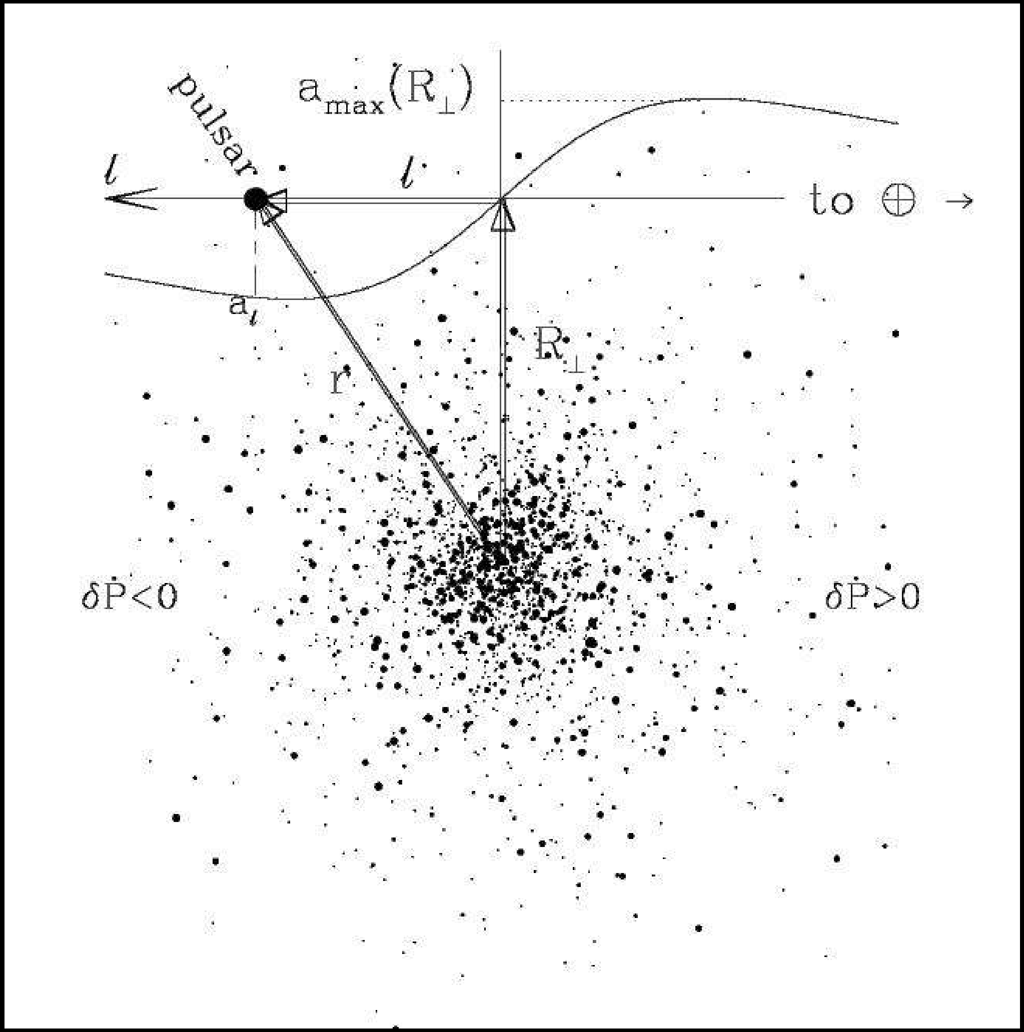
Summary and Outlook

- Globular cluster pulsars provide unique probes into binary evolution, cluster dynamics, pulsar astrophysics, and even basic physics
- We are currently only seeing the tip of the iceberg (i.e. just the brightest pulsars in each cluster)
- New pulsars will continue to be discovered with each major improvement to our observing systems
- The greatest number of new discoveries will probably come from the bulge globulars, where the large DMs have prevented earlier systems from detecting MSPs
- Multi-wavelength follow-up will allow us to identify a handful of the strangest beasts

Observed Changes in Pulsar Periods

- Pulsar spin periods can be affected by more than magnetic spin-down

$$\frac{\dot{P}}{P}^{meas} = \frac{\dot{P}_o}{P_o} + \frac{(\mathbf{a}_{PSR} - \mathbf{a}_{Bary}) \cdot \mathbf{n}}{c} + \frac{V_\perp^2}{cD}$$

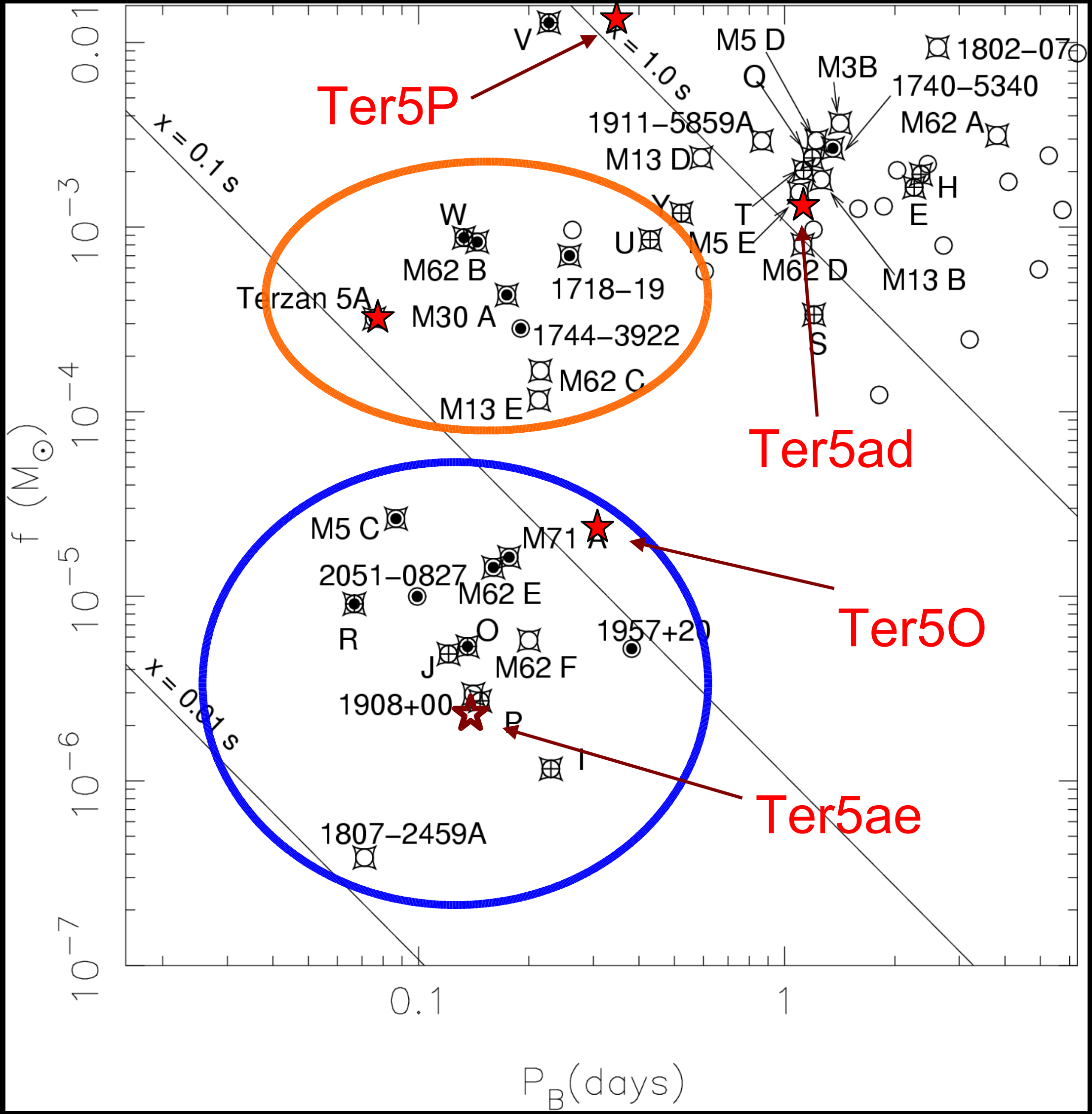


- Some pulsars seem to spin faster over time
  - Explained by their position behind the cluster

(Phinney 1992, 1993)

Eclipsing Binary MSPs

- Seem to be 2 families of eclipsing MSPs, separated by companion mass
- Systems with ~0.1$M_\odot$ companions formed normally but have compact orbits
- Systems with lower mass companions (<0.05 $M_\odot$) formed via exchange and binary evolution (Rasio, Pfahl, and Rappaport, 2000; King, Davies, and Beer, 2003)



From Freire et al., 2003