Hittin' the Pulsar *Jackpot* in Terzan 5 with the GBT

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Collaborators:

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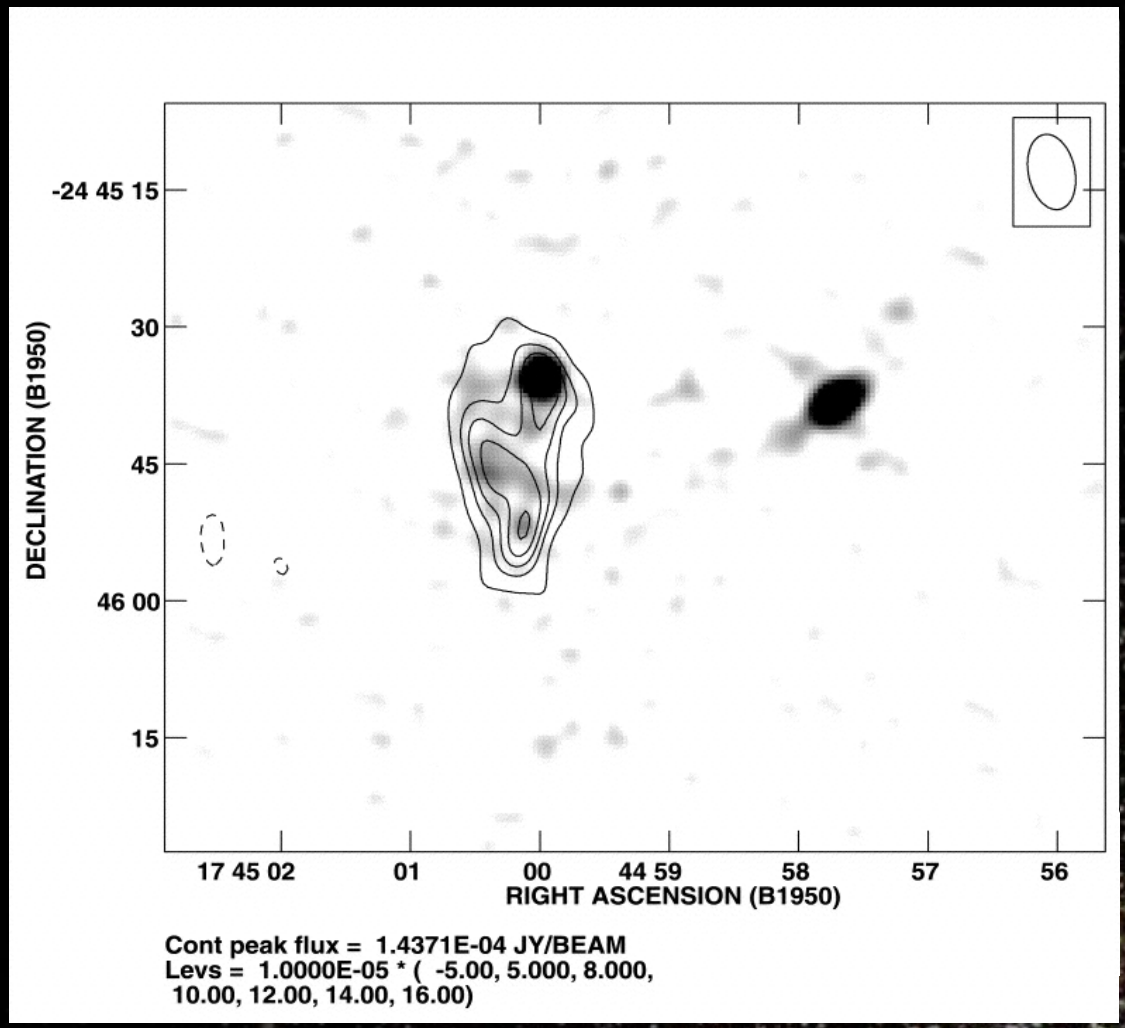
- Paulo Freire (Arecibo Obs)
- David Kaplan (Caltech/MIT)

Why search for GC pulsars?

- Long term timing of multiple MSPs in a single cluster can provide lots of cluster and stellar science (i.e. Freire et al., 2001 and 2002)
  - Constrain the gravitational potential of the cluster
  - Constrain the ionized gas content of clusters and ISM itself
  - Measure of cluster proper motion
  - Determine masses for the pulsar and/or the companion in some binaries
  - Study eclipse mechanisms of eclipsing MSPs
  - Examine systems in x-rays or optical
- Exotic objects are predicted to exist (i.e. sub-MSPs, PSR-BH, PSR-PSR binaries)

Terzan 5

- Very rich cluster with high central density
- Verbunt and Hut (1987) calculated that it would have the highest interaction rate of any GC
- Dist = 8.7±2 kpc (Cohn et al. 2001)
- Within ~1kpc of Galactic Center
- High DM and scattering make deep searches quite difficult



- Deep VLA observations by Fruchter and Goss (1990, 2000)
- Showed steep-spectrum point sources and continuum in core

Why look at Terzan 5 with the GBT?

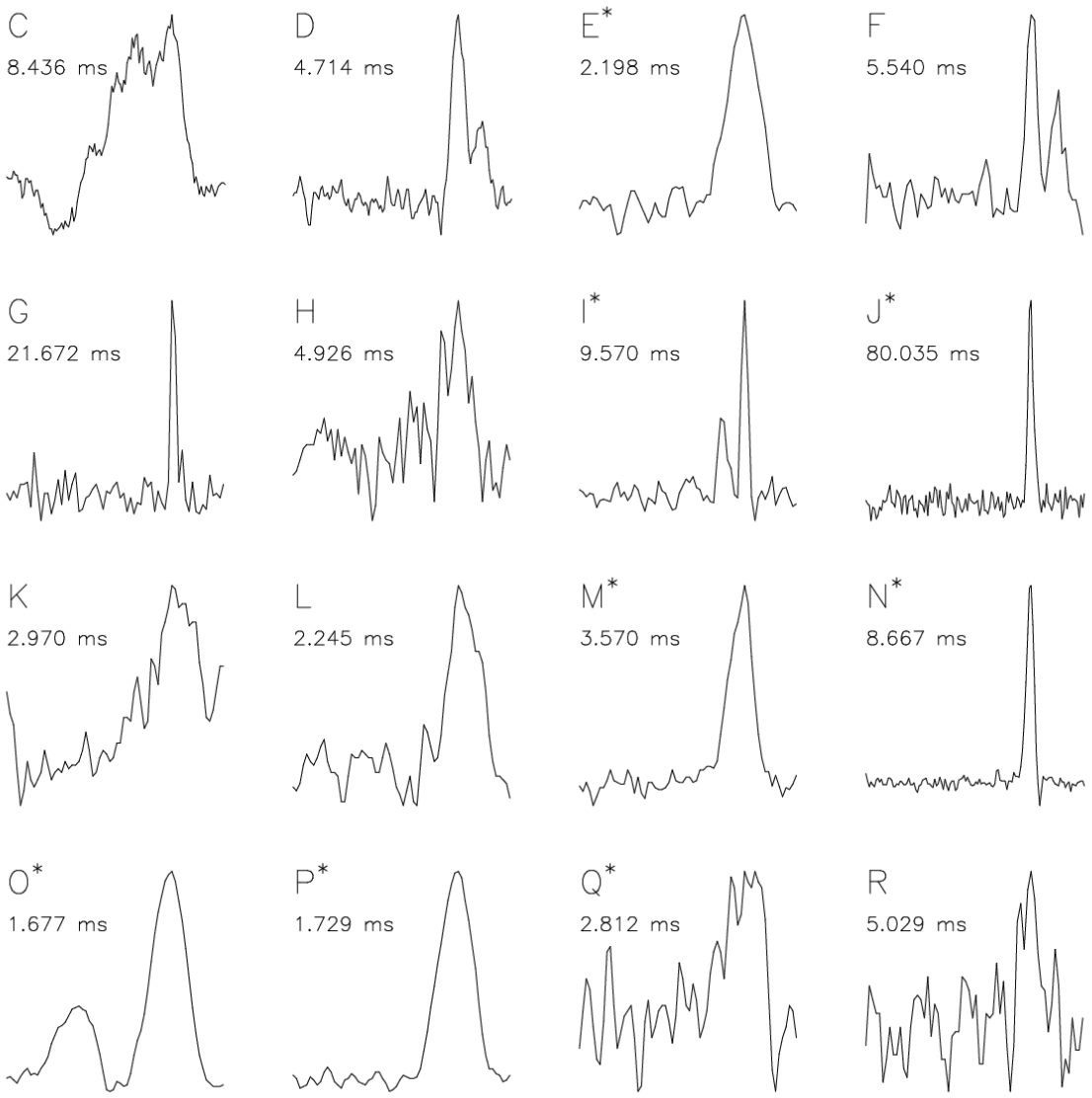
5-20 times more sensitive to MSPs than earlier searches

- Gain (i.e. area) is almost 3 times larger than Parkes
- "Clean" 600 MHz of bandwidth at low S-band ($_{ctr}$=1950 Mhz)
  - Reduces DM-smearing ($\propto$ $^{-3}$) and scatter-broadening ($\propto$ $^{-4.4}$)
  - But pulsars tend to be steep spectrum, so we lose some flux...
- 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

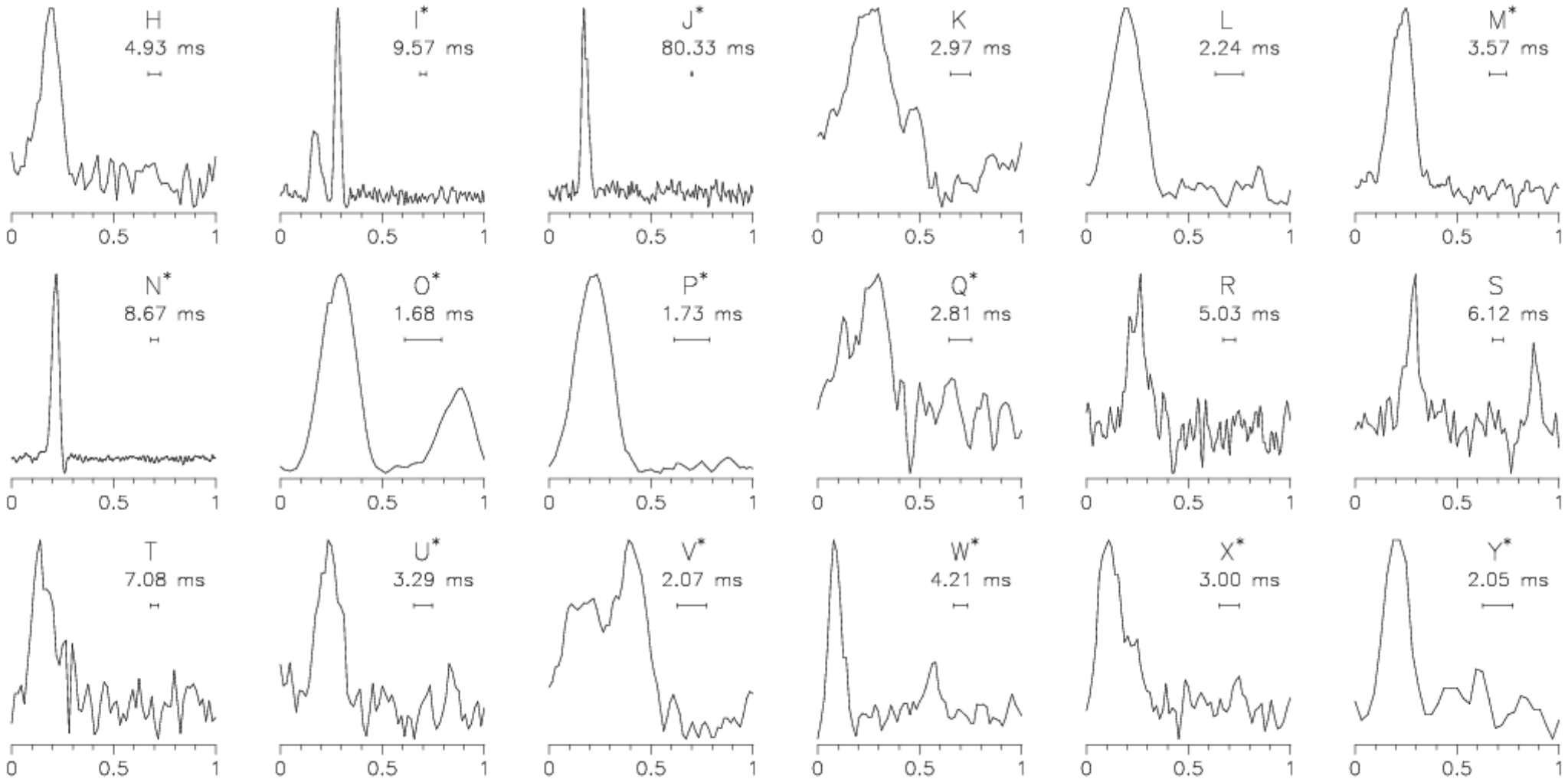
Observations had 3 goals:

1. See if Ter5D could be timed at S-band
2. Confirm 2.2 ms candidate (from Ransom 2001)
3. Search for new pulsars

Results from 17 July Observation



Pulsar Jackpot! 14 New MSPs!

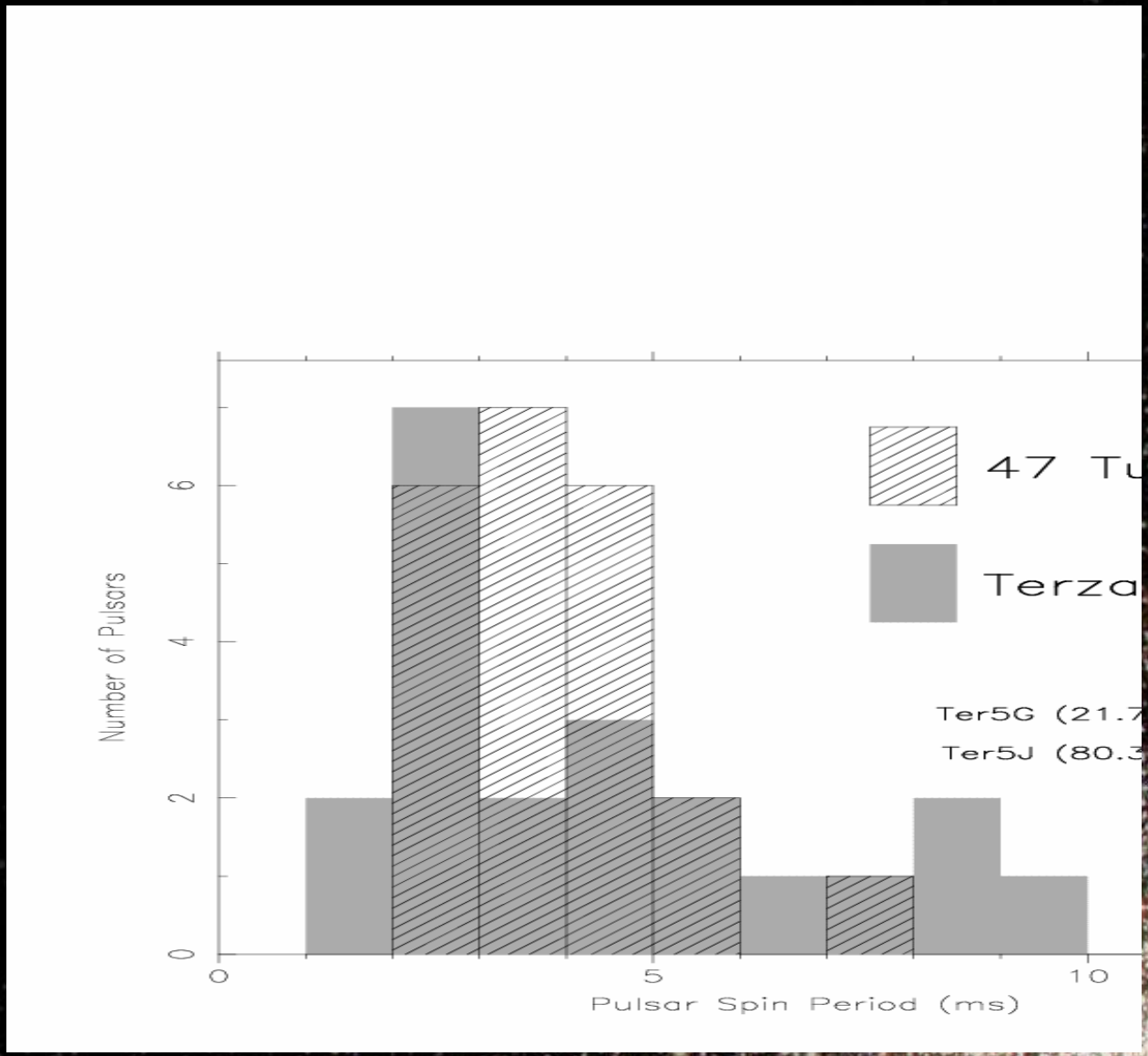


* denotes a binary PSR

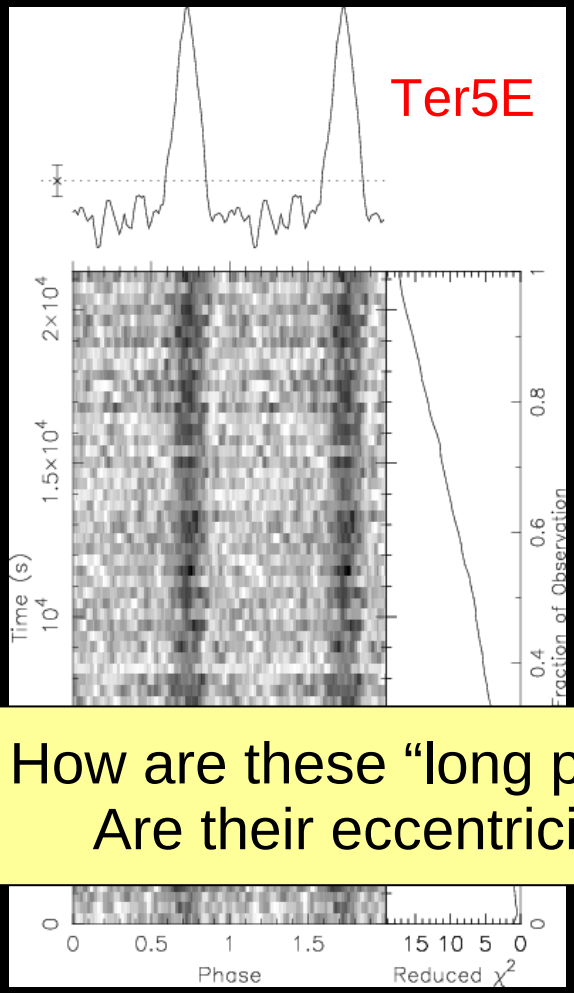
24 Pulsars so far!

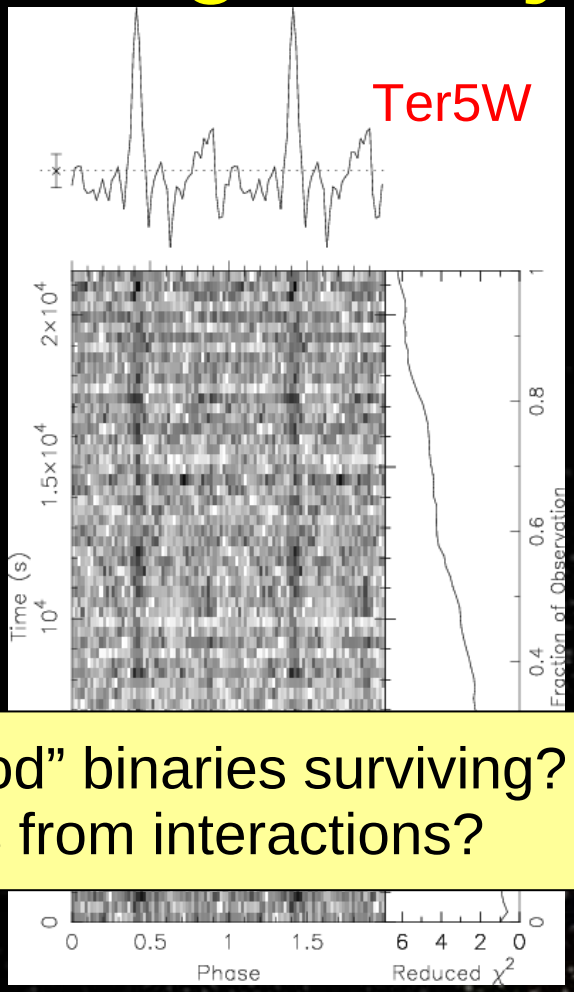
Spin Period Comparison with 47 Tuc

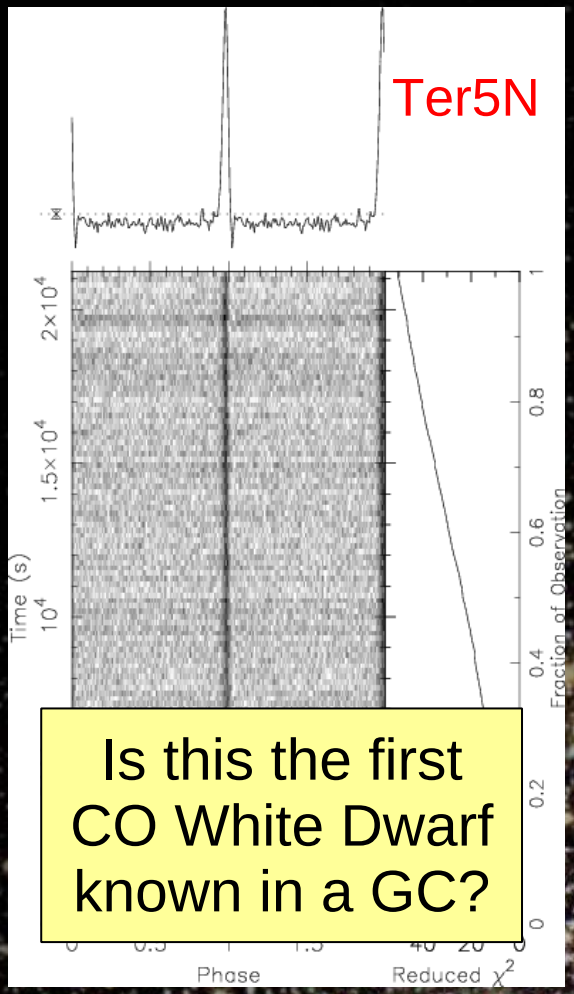
- 47 Tuc periods are much more uniform (2-5 ms), no pulsars with P_{psr} > 8 ms
- Ter5 pulsars have a much flatter (and broader) distribution
- Does this tell us something about the dynamical state of Ter5's core?



A Few Interesting Binary PSRs in Ter5







How are these "long period" binaries surviving? Are their eccentricities from interactions?

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

P_{psr} = 2.20 ms

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

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

P_{psr} = 4.21 ms

P_{orb} = 4.88d (e~0.015)

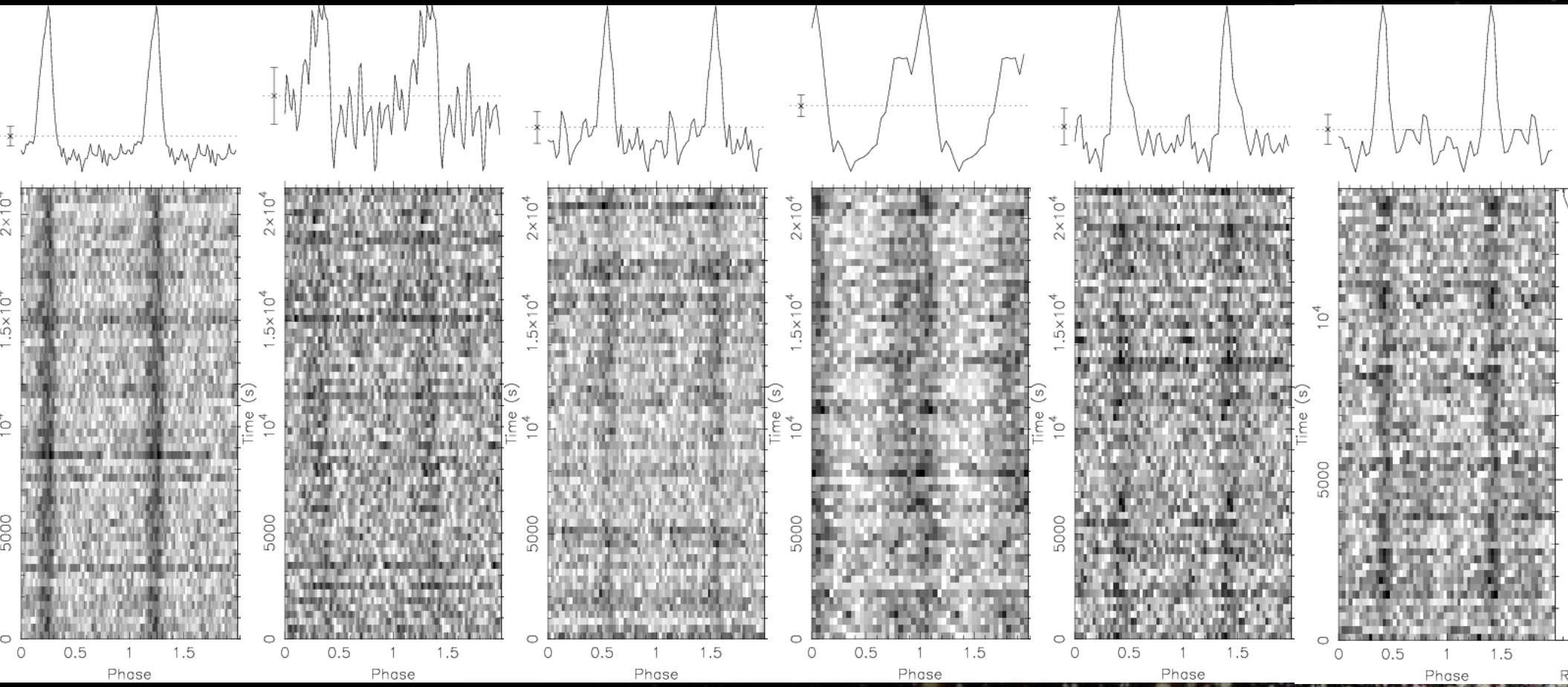
$M_{c,min}$ ~ 0.30 $M_\odot$

P_{psr} = 8.67 ms

P_{orb} = 9.25 hrs (e~4.5×10^{-5})

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

Some Binary MSPs in Ter5



Ter5M	Ter5Q	Ter5U	Ter5V	Ter5X	Ter5Y
P_{psr} = 3.57 ms	P_{psr} = 2.81 ms	P_{psr} = 3.29 ms	P_{psr} = 2.07 ms	P_{psr} = 3.00 ms	P_{psr} = 2.05 ms
P_{orb} = 10.6 hrs	P_{orb} = ?? hrs	P_{orb} = ?? hrs	P_{orb} = 12.1 hrs	P_{orb} = ?? hrs	P_{orb} = 28.1 hrs
$M_{c,min}$ ~ 0.14 $M_\odot$	$M_{c,min}$ ~ ?? $M_\odot$	$M_{c,min}$ ~ ?? $M_\odot$	$M_{c,min}$ ~ 0.12 $M_\odot$	$M_{c,min}$ ~ ?? $M_\odot$	$M_{c,min}$ ~ 0.14 $M_\odot$

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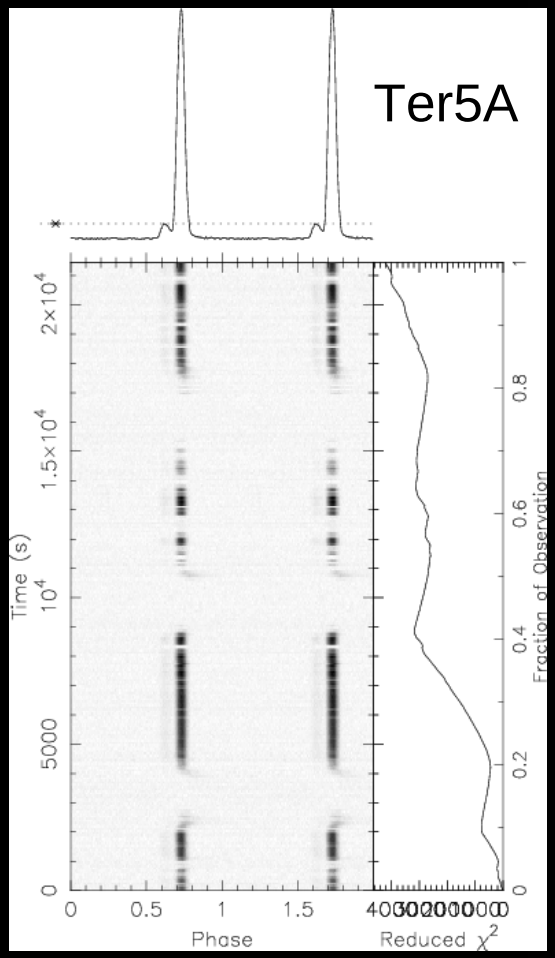
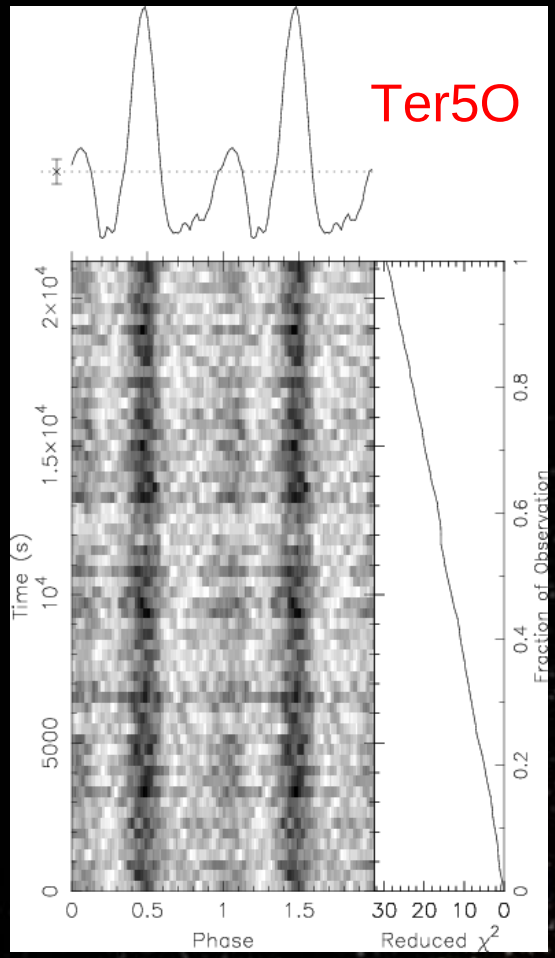
Eclipsing Binary MSPs in Terzan 5



P_{psr} = 11.56 ms

P_{orb} = 1.82 hrs

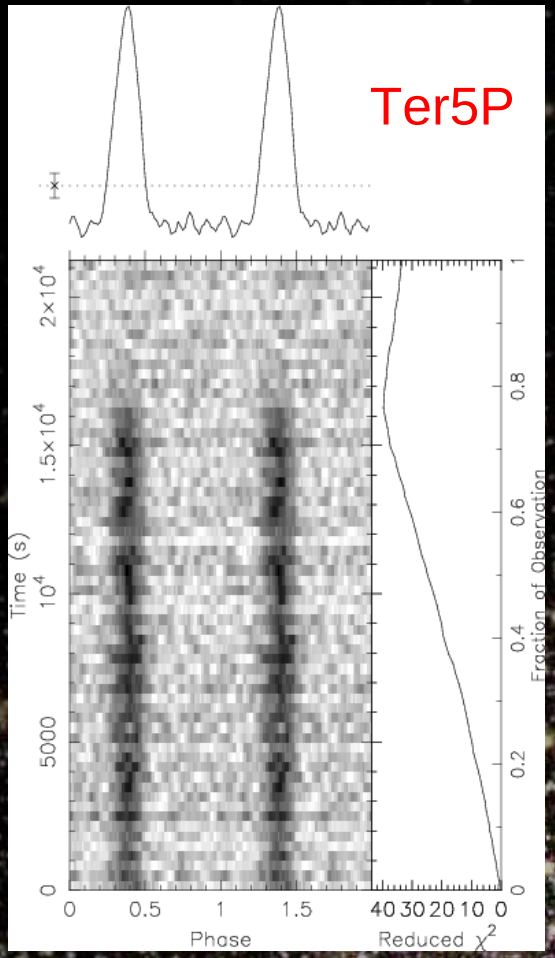
$M_{c,min}$ ~ 0.089 $M_\odot$



P_{psr} = 1.67 ms

P_{orb} = 6.22 hrs

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

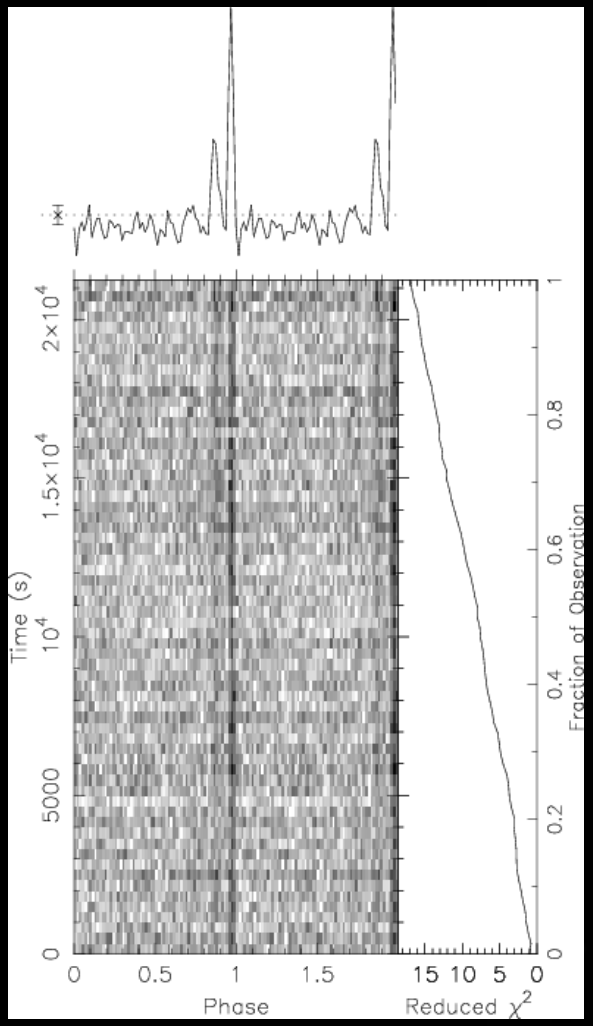


P_{psr} = 1.73 ms

P_{orb} = 8.70 hrs

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

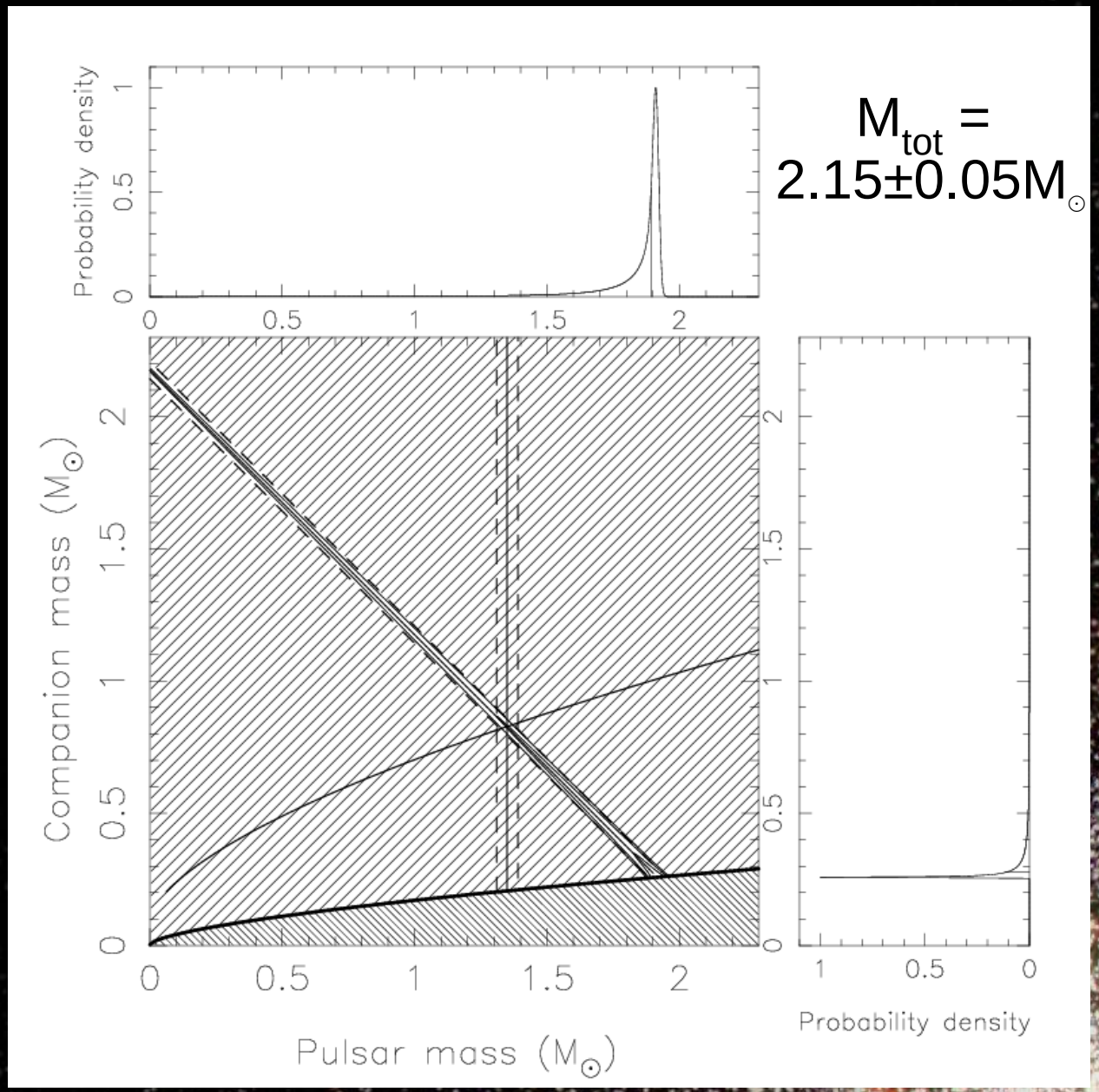
Eccentric and Relativistic Systems: Ter5I



Highly eccentric (e=0.43)

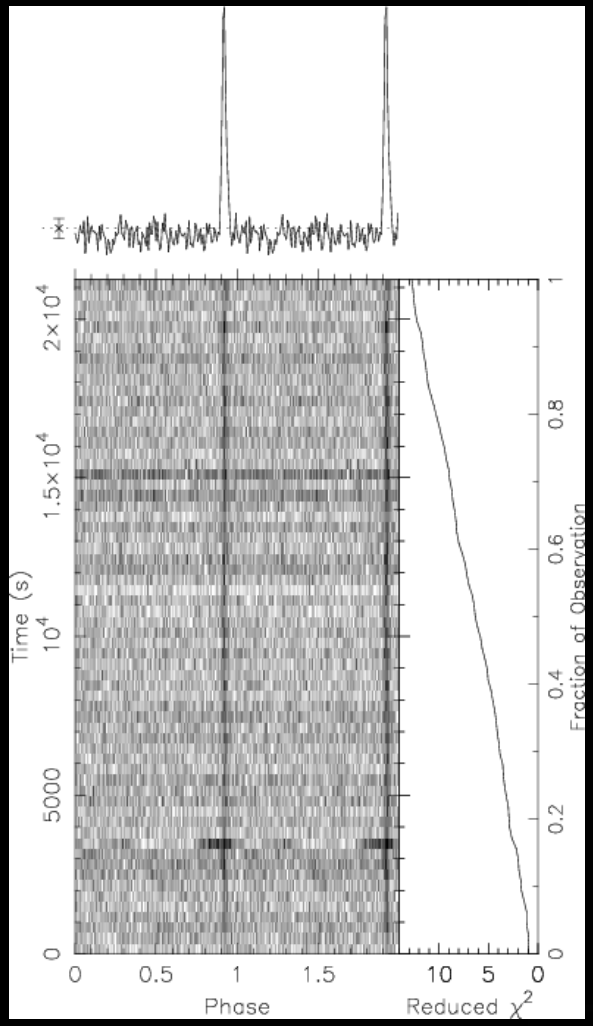
P_{psr} ~ 9.57 ms

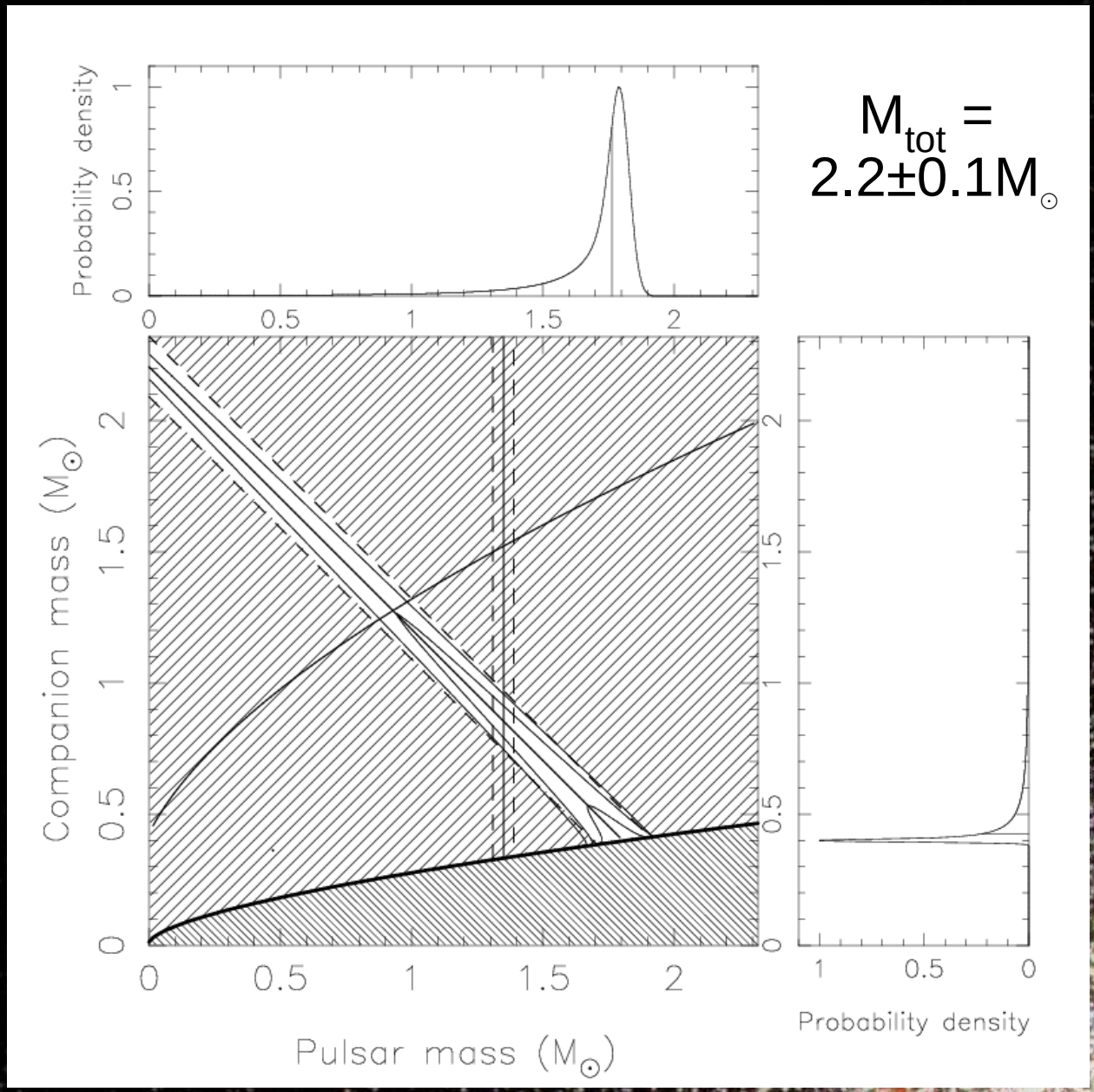
P_{orb} = 31.87 hrs



M_{tot} = 2.15±0.05$M_\odot$

Eccentric and Relativistic Systems: Ter5J





$M_{tot} = 2.2 \pm 0.1 M_\odot$

Highly eccentric (e=0.33)

P_{psr} ~ 80.34 ms

P_{orb} = 26.45 hrs

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Future Prospects and Work

- Use dynamic power-spectra and phase modulation searches to search all data
- Search all other observations to look for binaries that were missed (unfortunate orbital phases or eclipes)
- Search at other bands (particularly 820MHz) using the GBT+SPIGOT
- Start timing the new pulsars with GBT
- Look for pulsars in optical/IR (*HST/Gemini*) and X-rays (*Chandra*)