Scott Ransom

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Collaborators:

- Jason Hessels (McGill)
- Ingrid Stairs (UBC)
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- Lincoln Greenhill (CfA)
- Dunc Lorimer (Jodrell Bank)
- Paulo Freire (Arecibo)
- Don Backer (Berkeley)

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- First Millisecond Pulsar (MSP: spinning >600 times/sec !) discovered in 1982 (˚ Backer *et al*., 1982, Nature, 300, 615)
- "Recycled" nature of the MSP is promoted by Alpar *et al*. (1982, Nature, 300, 728)

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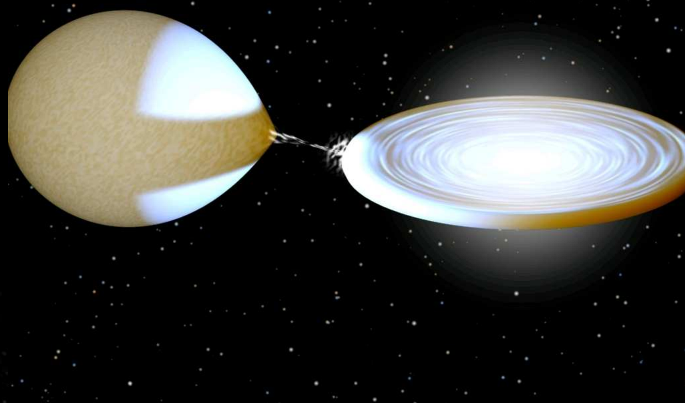
- Start with a “slow” pulsar or NS in a binary system
- When companion evolves off main sequence, it expands and fills its Roche lobe
- Matter from the companion “accretes” onto the NS, spinning it up
- During the process, the system is bright in x-rays (LMXB)
- MSP is the result



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- First Millisecond Pulsar (MSP: spinning >600 times/sec !) discovered in 1982 (˚ Backer *et al*., 1982, Nature, 300, 615)
- “Recycled” nature of the MSP is promoted by Alpar *et al*. (1982, Nature, 300, 728)
- Many theorists predict that globular clusters will contain a large population of MSPs
- First globular cluster MSP discovered in M28 after an extensive search (Lyne *et al*., 1987, Nature, 328, 399)
- First globular cluster binary MSP discovered in M4 (Lyne *et al*., 1988, Nature, 332, 45)
- As of 2001, ~60 cluster pulsars were known (with the majority being binary MSPs)

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- Science Reasons
  - 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
    - 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)

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- Technical Reasons
  - Recent cluster searches at higher radio frequencies (20 cm) using Parkes have been very successful (i.e. Camilo et al., 2000; D'Amico et al., 2001; Possenti et al., 2001)
  - New search techniques for compact binaries
  - Large dedicated computer cluster at McGill
  - Upgraded Arecibo and new GBT allow greatly increased sensitivities

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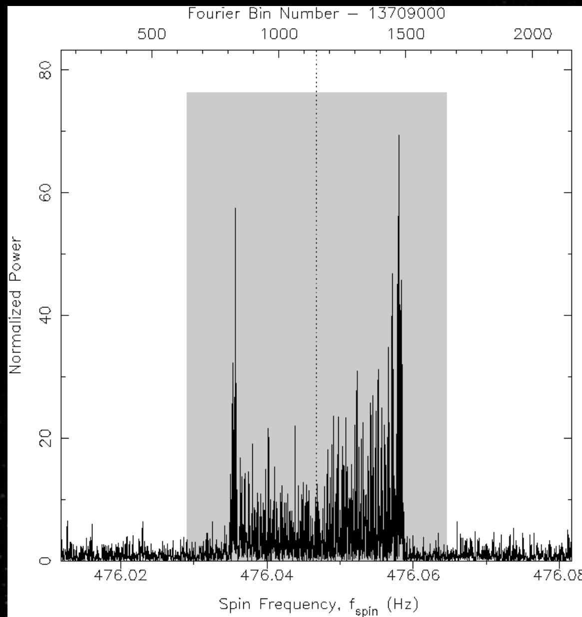
$T_{obs} \geq 1.5\ P_{orbit}$

- Figure shows powers from an 8 hr Parkes observation of 47TucJ
- P_{psr} = 2.1 ms
- P_{orb} = 2.9 hrs



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Name	GBT	AO	DM	PSRs	Name	GBT	AO	DM	PSRs
M2	X				M75	X			
M3	X	X		3	M79	X			
M4	X		63	1	M80	X			1?
M5		X	30	2+1	M92	X			
M13	X	X	30	2+2	NGC4147		X		
M15	X	X	67	8	NGC6342	X		71?	1?
M30	X		25	2	NGC6426		X		
M53		X	24	1	NGC6760		X	201	1
M71		X	117	1	Pal1	X			
					Pal2		X		

Total so far: 9 new pulsars in 5 clusters

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- All of the science comes from long-term timing
- Account for every single rotation of the pulsar
- Fit the arrival times of the pulse to a simple polynomial model after transforming the time:

$$T = t - t_0 + \Delta_C - D/f^2 + \Delta_{R\odot} + \Delta_{E\odot} - \Delta_{S\odot} - \Delta_R - \Delta_E - \Delta_S$$

- Extraordinary precision for MSP timing (10-15 significant figures are common for many parameters)
- For the past year and a half we have been timing 8 of the pulsars observable in these 4 clusters
- Science is just starting to come out…

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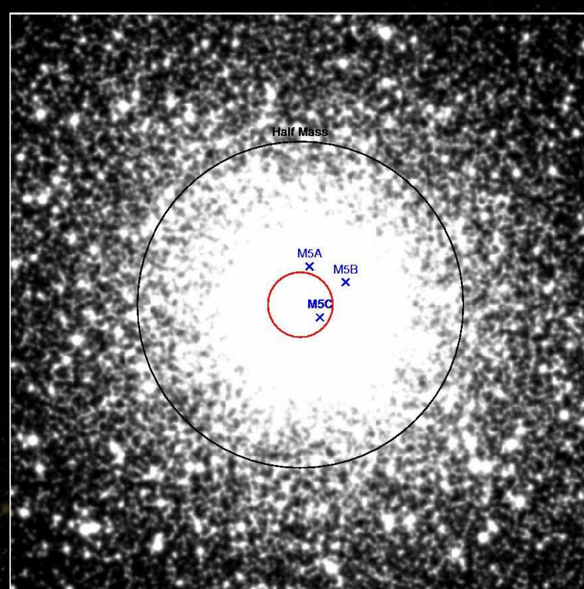
- Moderate density
- D ~ 7.9 ± 0.2 kpc (Carretta et al, 2000)
- 2 previously known MSPs:
  - M5A (5.5ms)
  - M5B (7.9ms / 6.9d)
- We have found 1 new eclipsing MSP:
  - M5C (2.5ms / 2.1h)



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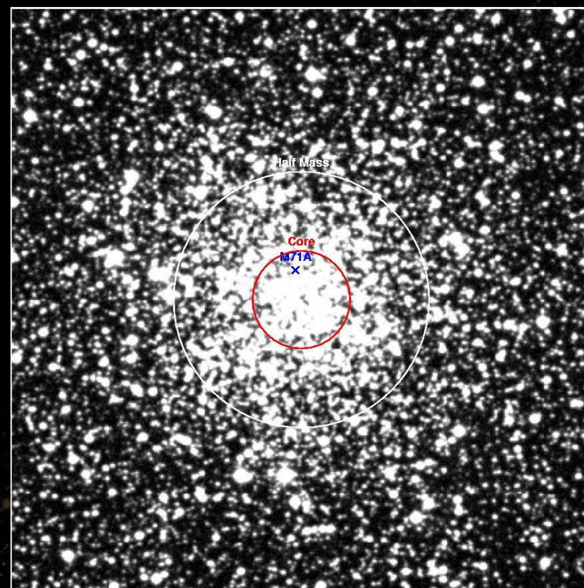
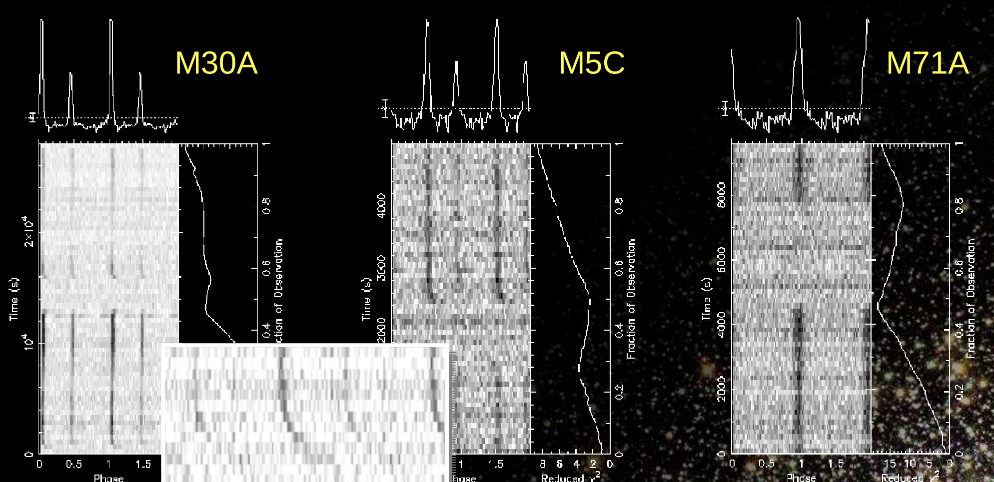
- Low density but reasonably close
- D ~ 4.3 ± 0.3 kpc (Carretta et al, 2000)
- No previously known MSPs
- We have found 1 new eclipsing binary MSP:
  - M71A (4.9ms / 4.2h)



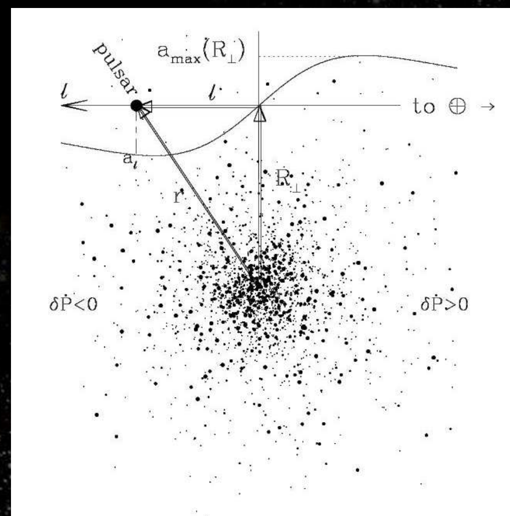


M30A	M5C	M71A
P_{psr} = 11.02 ms	P_{psr} = 2.48 ms	P_{psr} = 4.89 ms
P_{orb} = 4.18 hrs	P_{orb} = 2.08 hrs	P_{orb} = 4.24 hrs
$M_c \sim 0.21\ M_\odot$ (i = 60º)	$M_c \sim 0.043\ M_\odot$ (i = 60º)	$M_c \sim 0.037\ M_\odot$ (i = 60º)

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

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

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



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- Constrain pulsar parameters

$$\max \frac{|a_{clust}|}{c} = \frac{3}{2}\frac{v_z^2(0)}{cD\Theta_c}$$

  - Using the max cluster acceleration we can put an upper limit on the intrinsic period derivative
- Constrain cluster potential
  - If the pulsar is “spinning-up” you can calculate a lower limit to the surface mass density within the projected MSP position

$$\left.\frac{\dot{P}}{P}\right|^{meas} < \frac{|a_l|}{c} < \frac{a_{max}}{c} \simeq \frac{1.1G\bar{\Sigma}(<R_\perp)}{c}$$

  - Then calculate M/L ratio using the surface brightness within the pulsar’s position

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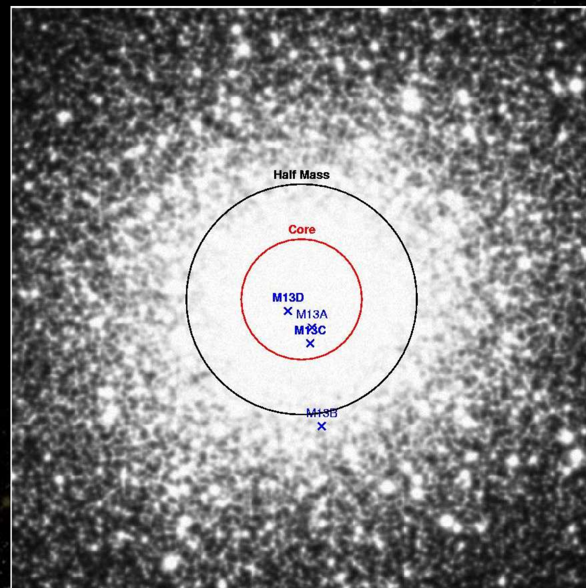
- Low density
- D ~ 7.6 ± 0.2 kpc (Carretta et al, 2000)
- 2 previously known MSPs:
  - M13A (10ms)
  - M13B (3.5ms / 1.26d)
- We have found 2 new MSPs:
  - M13C (3.7ms)
  - M13D (3.1ms / 14h)



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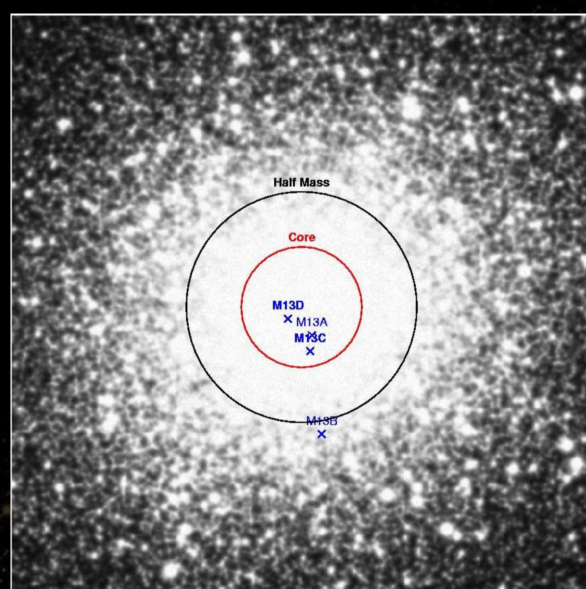
- Both pulsars have negative period derivatives
- M13A is at 0.53 r_c (0.75 pc)
- M13D is at 0.42 r_c (0.59 pc)
- M13D is significantly more constraining than M13A and gives:
  - $\sim 1.4\times10^4\ M_\odot/pc^2$
  - $M/L \geq 2.0\ M_\odot/L_\odot$



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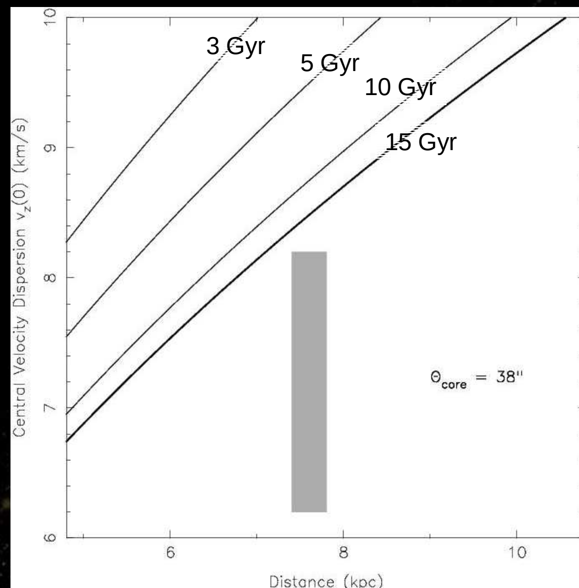
- Pulsars are seemingly old:
  - Ages > $2\text{-}4 \times 10^9$ yrs
- Have small magnetic fields
  - B < $2\text{-}8 \times 10^8$ G
- E-dots < 2×10^{34} ergs/s
- M13D's acceleration is too big
  - $V_z(0)$ = 7.2±1.0 km/s (Leonard et al 1992)
  - R_{core} = 38"±6" (Cohen et al 1997)



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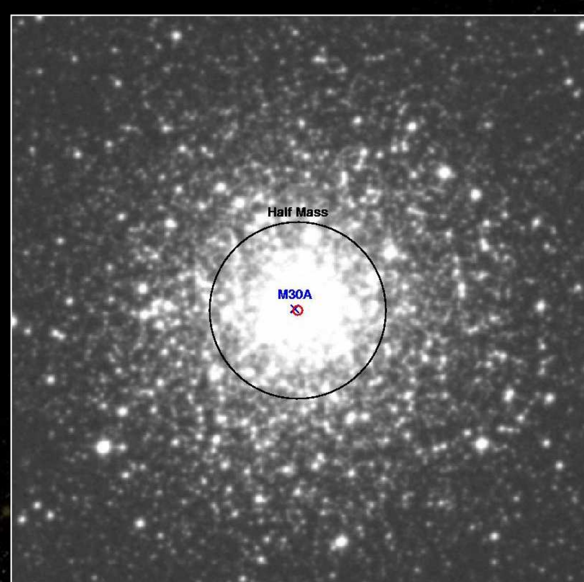
- Post-Core Collapse
- D ~ 9.0 ± 0.4 kpc (Carretta et al, 2000)
- Age ~ 12.3 ± 1.4 Gyr (Carretta et al, 2000)
- R_{core} ~ 1.8" / 0.08 pc (Yanny et al, 1994)
- No previously known MSPs
- 2 new binary MSPs:
  - M30A (11ms / 4.0h)
  - M30B (13ms / Unk)



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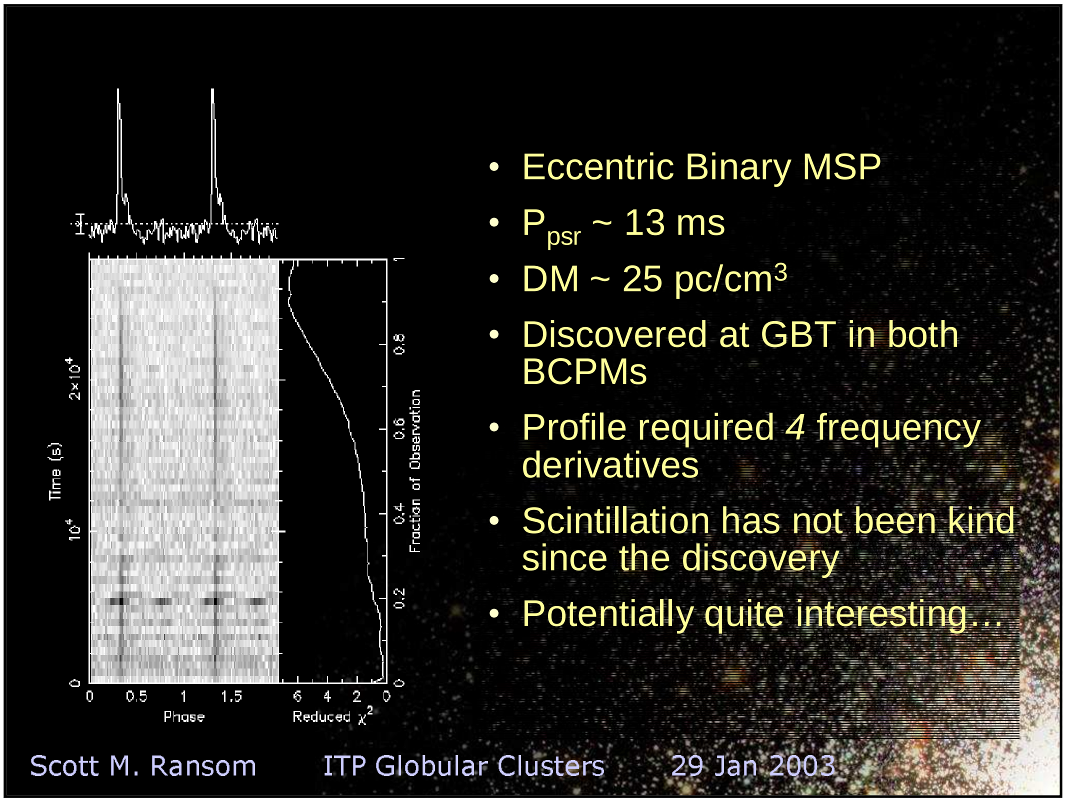

Time (s)
Phase
Reduced χ^2
Fraction of Observation
• Eccentric Binary MSP
• P_{psr} ~ 13 ms
• DM ~ 25 pc/cm^3
• Discovered at GBT in both BCPMs
• Profile required *4* frequency derivatives
• Scintillation has not been kind since the discovery
• Potentially quite interesting…
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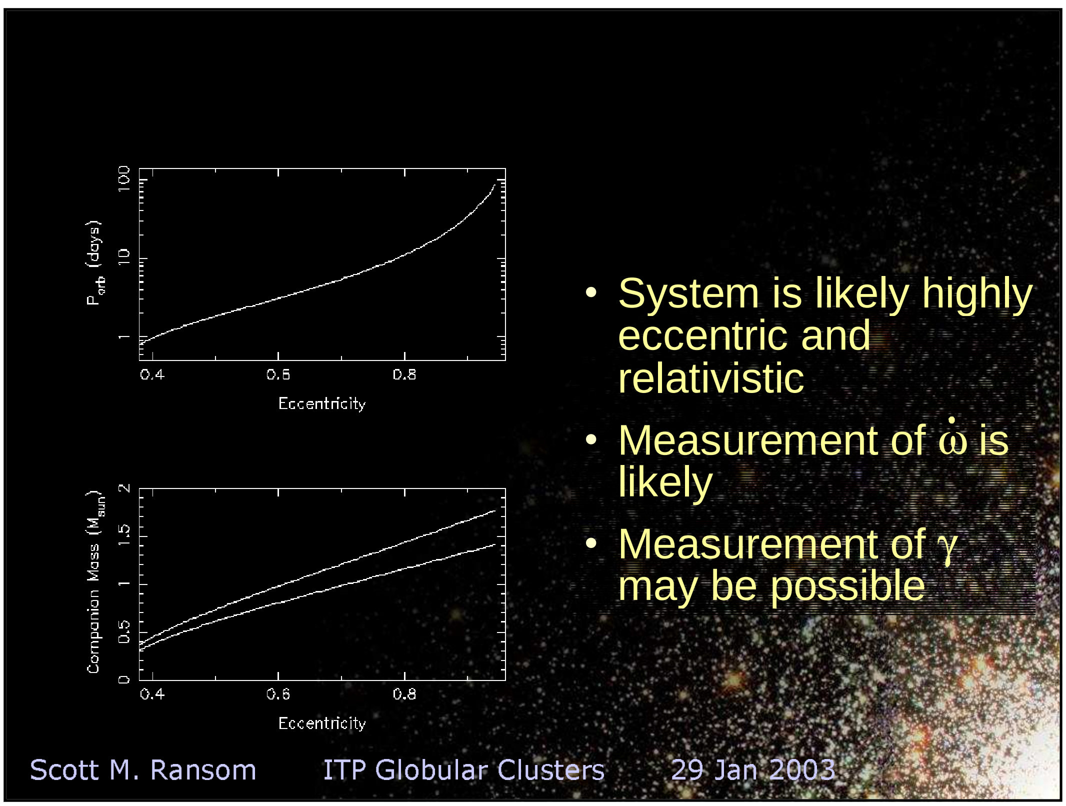

P_{orb} (days)
Eccentricity
Companion Mass (M_{sun})
Eccentricity
• System is likely highly eccentric and relativistic
• Measurement of $\dot{\omega}$ is likely
• Measurement of γ may be possible
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- Search the remaining ~3 TB of search data (including 10 new clusters from Arecibo and 6 from GBT)
- Continue timing new and old pulsars in order to extract as much science as possible
- Look for pulsars in optical (*HST*) and X-ray (*Chandra*)
- Search timing data for new pulsars that might become visible due to interstellar scintillation
- Search at potentially better radio bands at *GBT* and *Arecibo* as well as a new telescope in India (*GMRT*)
- Search using better receivers and instrumentation at GBT and Arecibo

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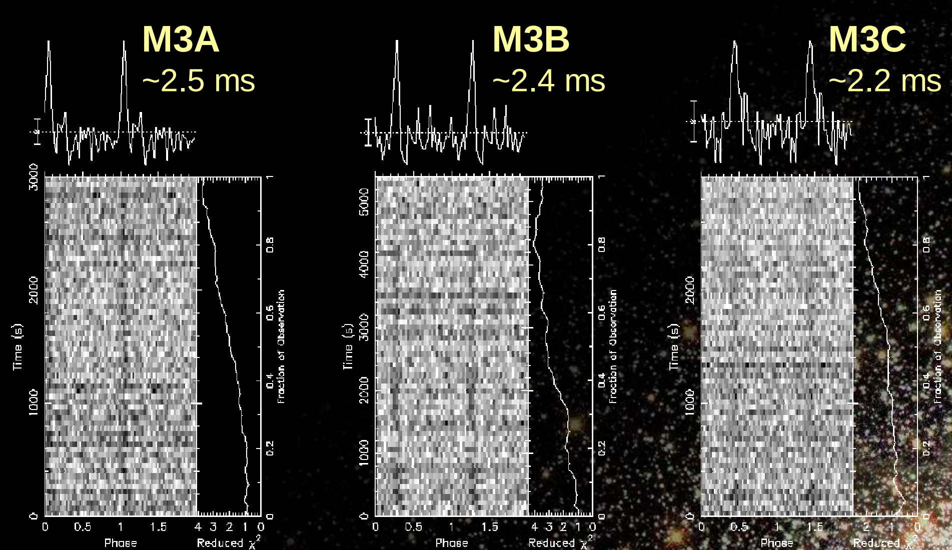

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