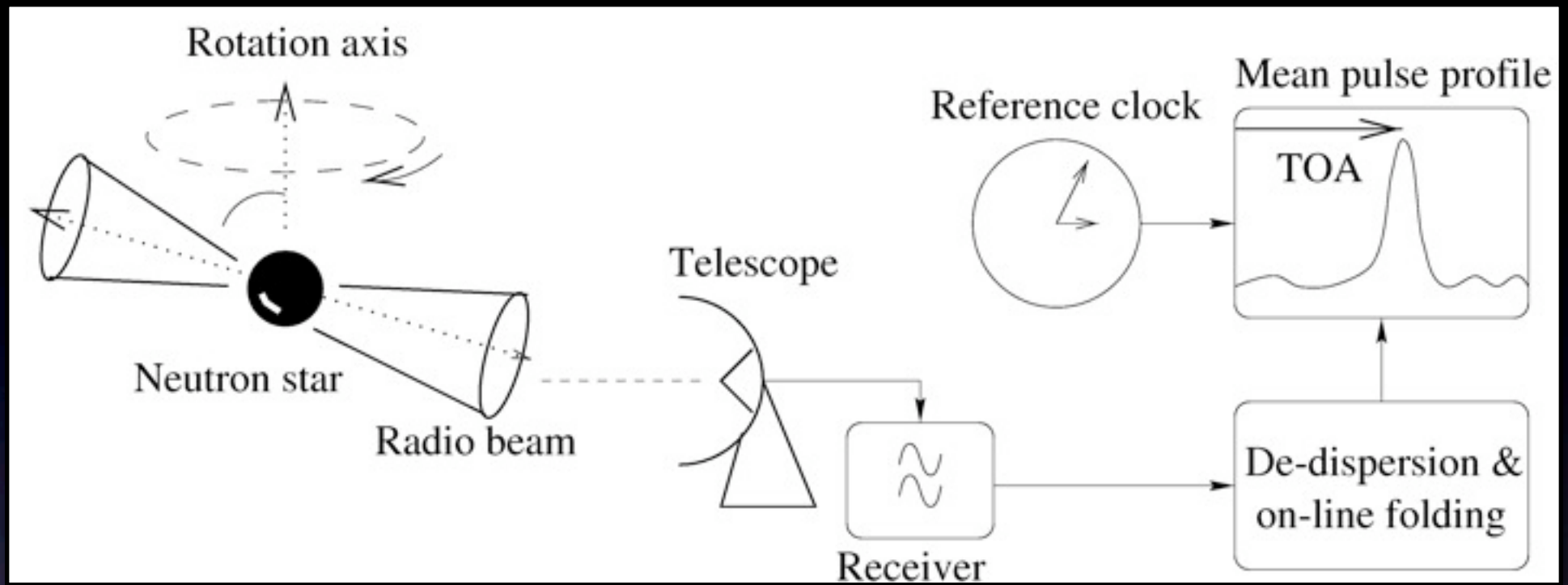
Constraining Fundamental Physics with Pulsars and CARPE

David Kaplan (UCSB) on behalf of CARPE collaboration
(especially M. McLaughlin (WVU))

see talk by Judd Bowman for what CARPE is

Outline

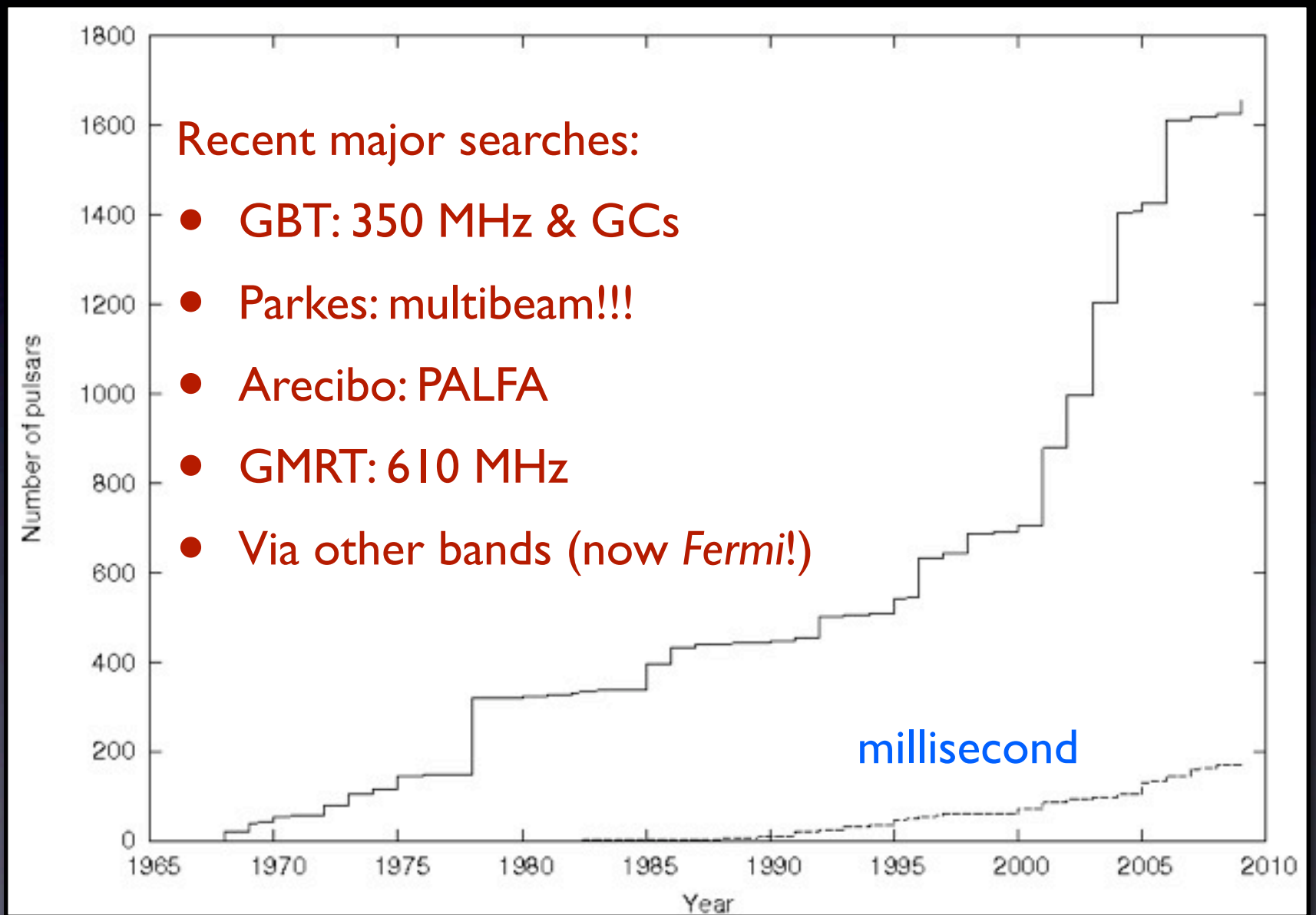


- Neutrino physics
- Equation of State
- Stellar evolution
- Binary evolution
- Emission mechanisms
- General Relativity

- Neutron star masses
- Gravitational Waves
- Supernovae
- Superfluids

- What can CARPE do?

Almost 2000 Pulsars...



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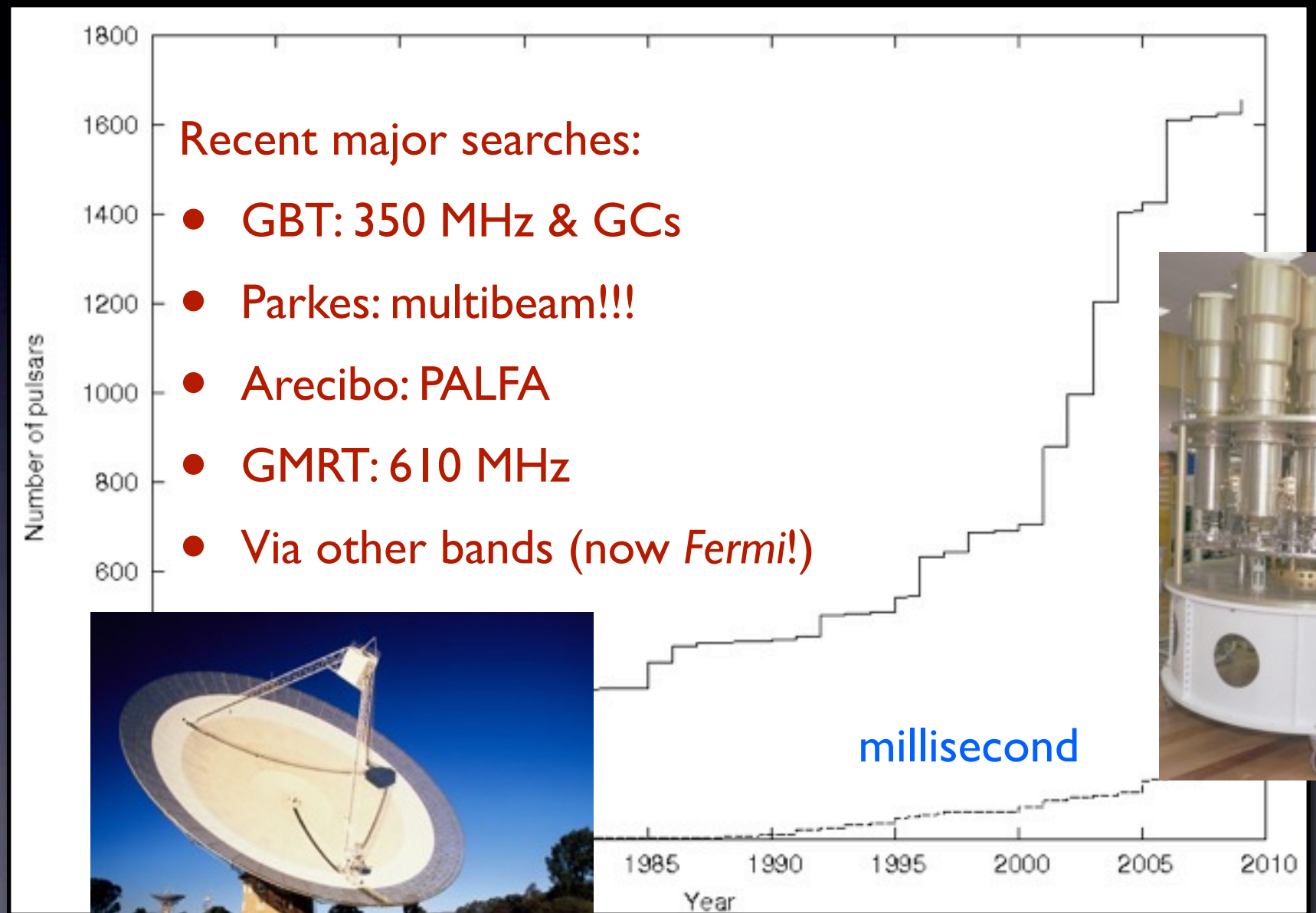
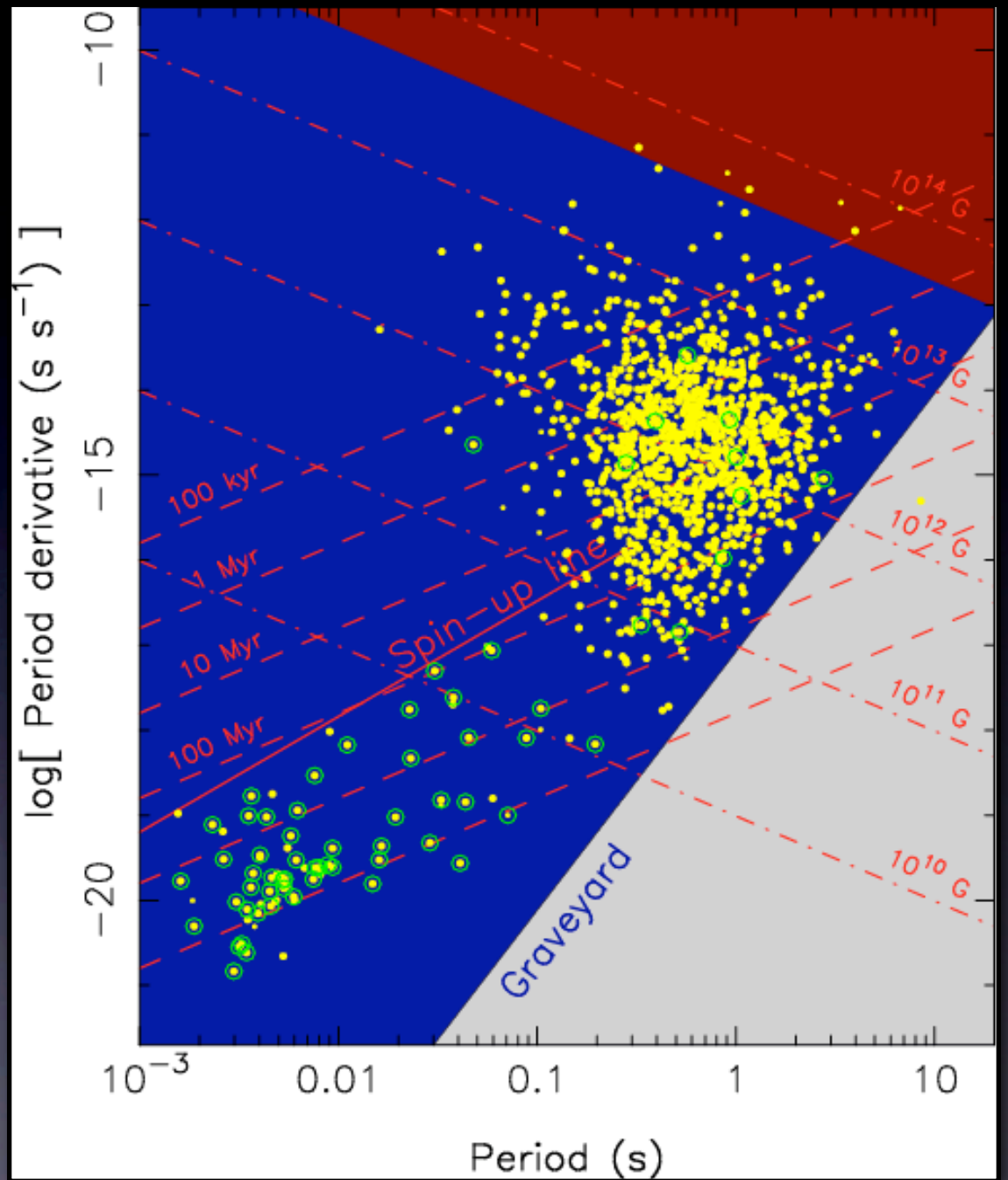


Recent major searches:

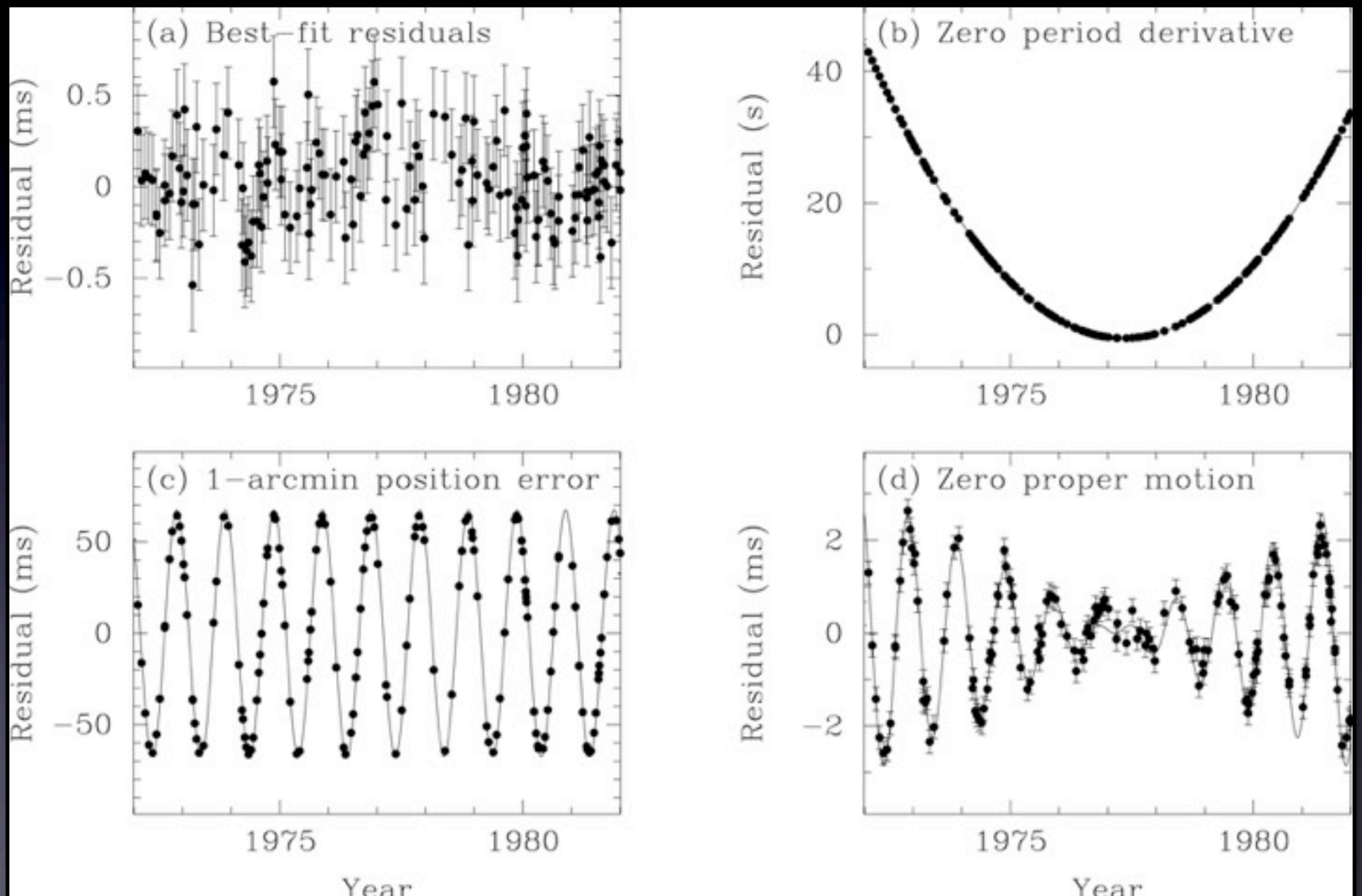
- GBT: 350 MHz & GCs
- Parkes: multibeam!!!
- Arecibo: PALFA
- GMRT: 610 MHz
- Via other bands (now *Fermi*!)

Evolution

- supernovae
- stellar evolution
- binary evolution
- stellar winds
- white dwarf cooling
- magnetars



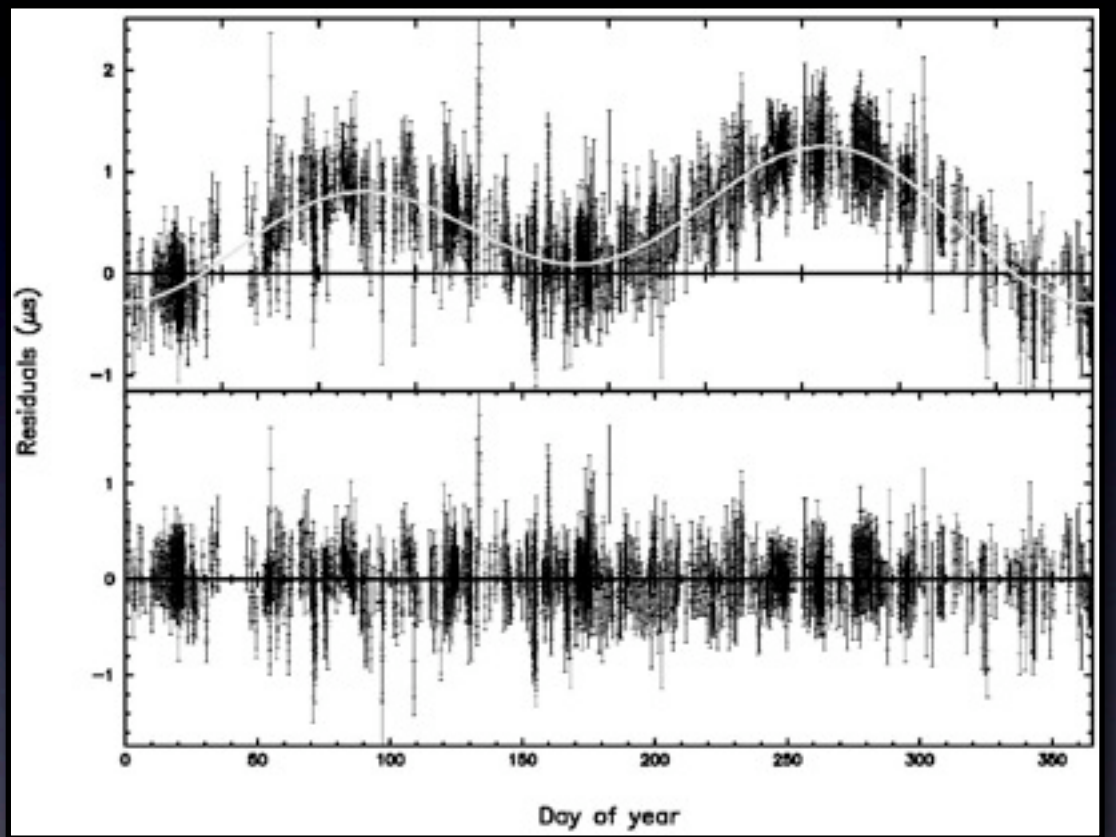
Pulsar Timing: The Basics



Lorimer & Kramer (2005)

The Best We Can Do

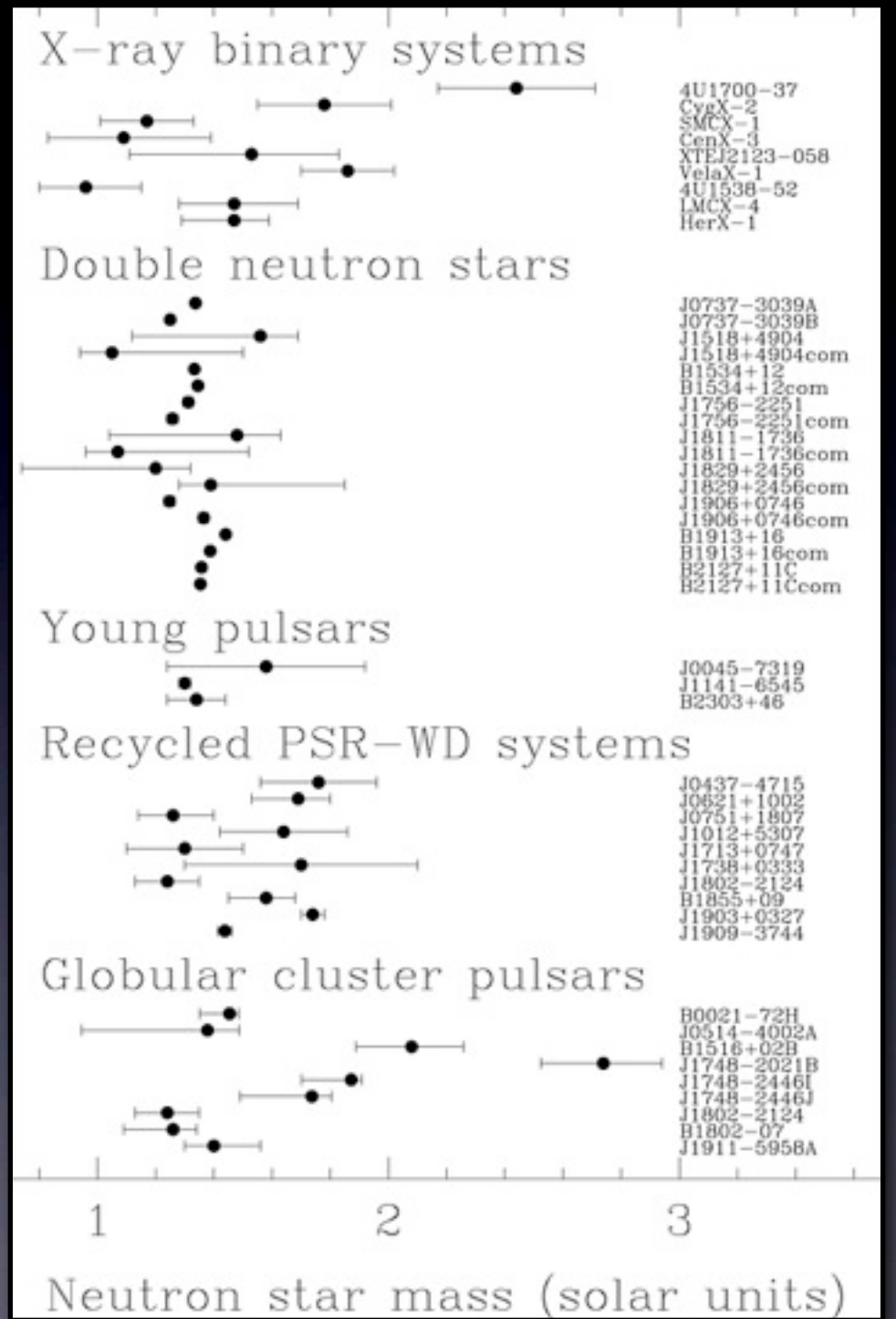
- PSR J0437-4715:
  - Distance via orbital period derivative
  - Or via parallax fit
  - 200 ns rms over 10 years
- Combine with VLBI parallax:
  - D=156.3(1.3) pc (Deller et al. '09)
  - $\dot{G}/G=-5(26)\times10^{-13}$ yr^{-1}: like LLR!



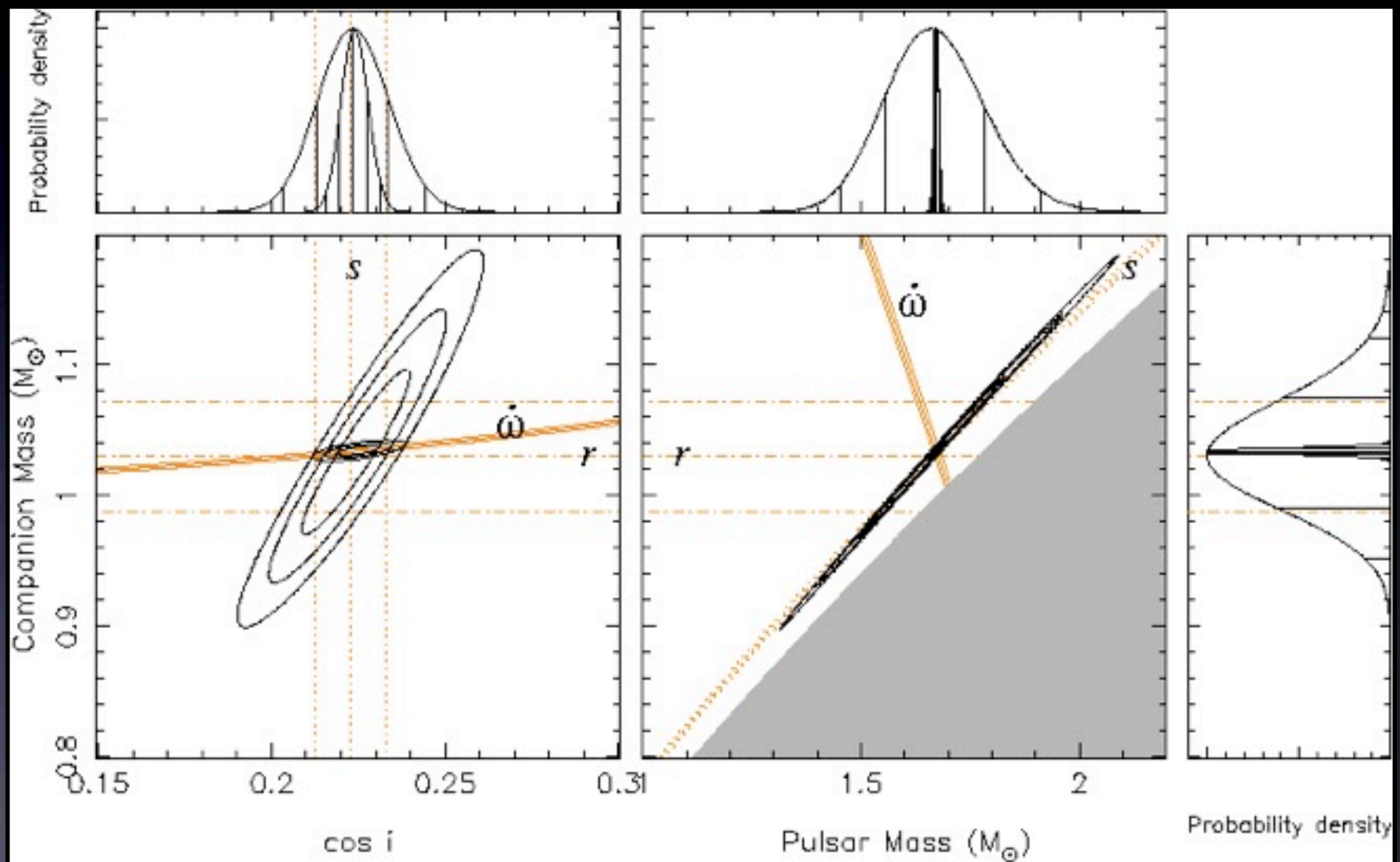
Verbiest et al. (2008)

Neutron Star Masses

- ~40 NS masses from radio timing: post-Keplerian parameters:
  - Periastron advance
  - Shapiro delay
  - Grav. wave damping
  - Grav. redshift/time dilation
- 1903+0327/1909-3744 are most precise for MSPs…



J1903+0327: 1.67(1) $M_\odot$



Freire et al. (2009)

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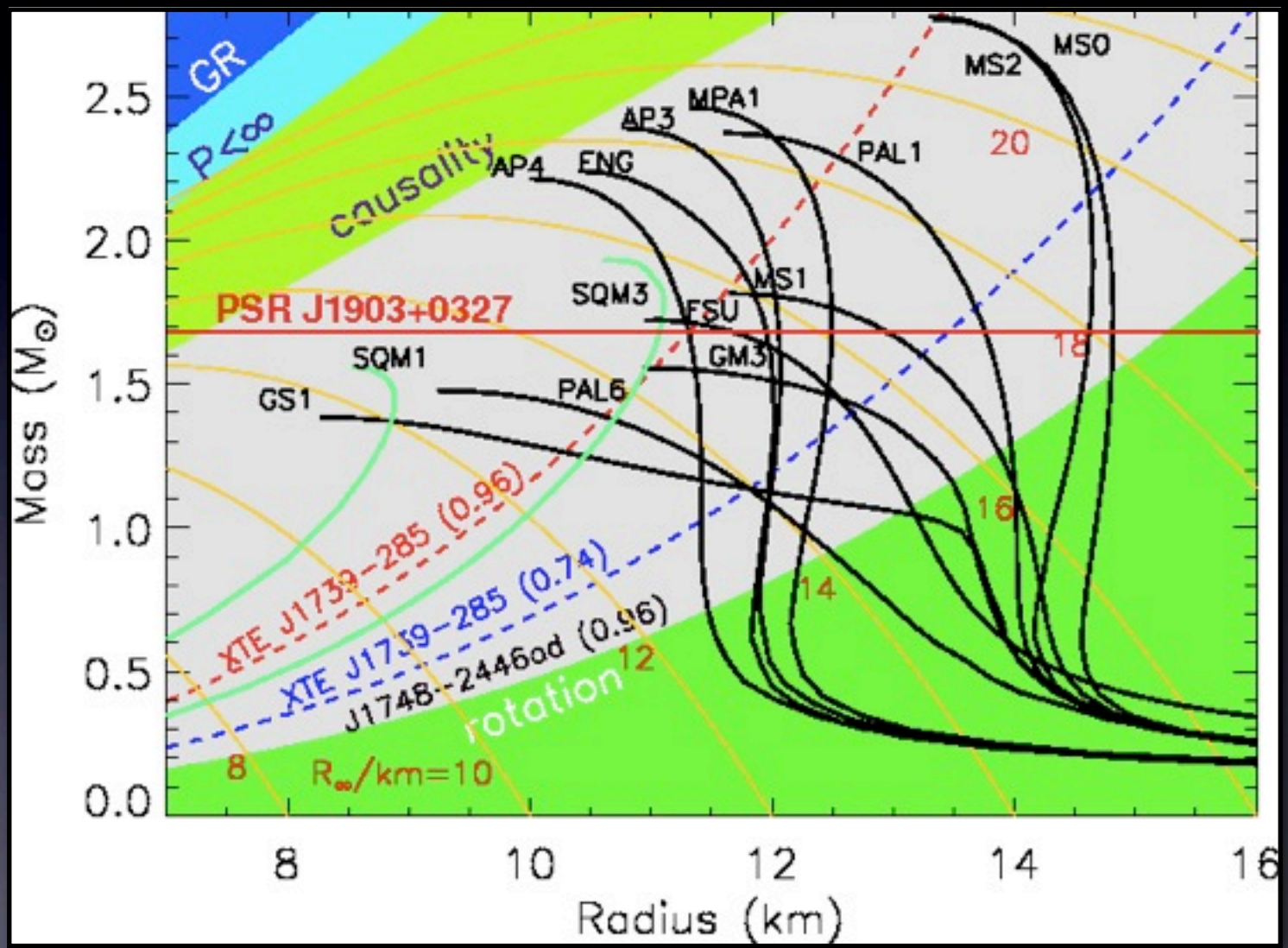
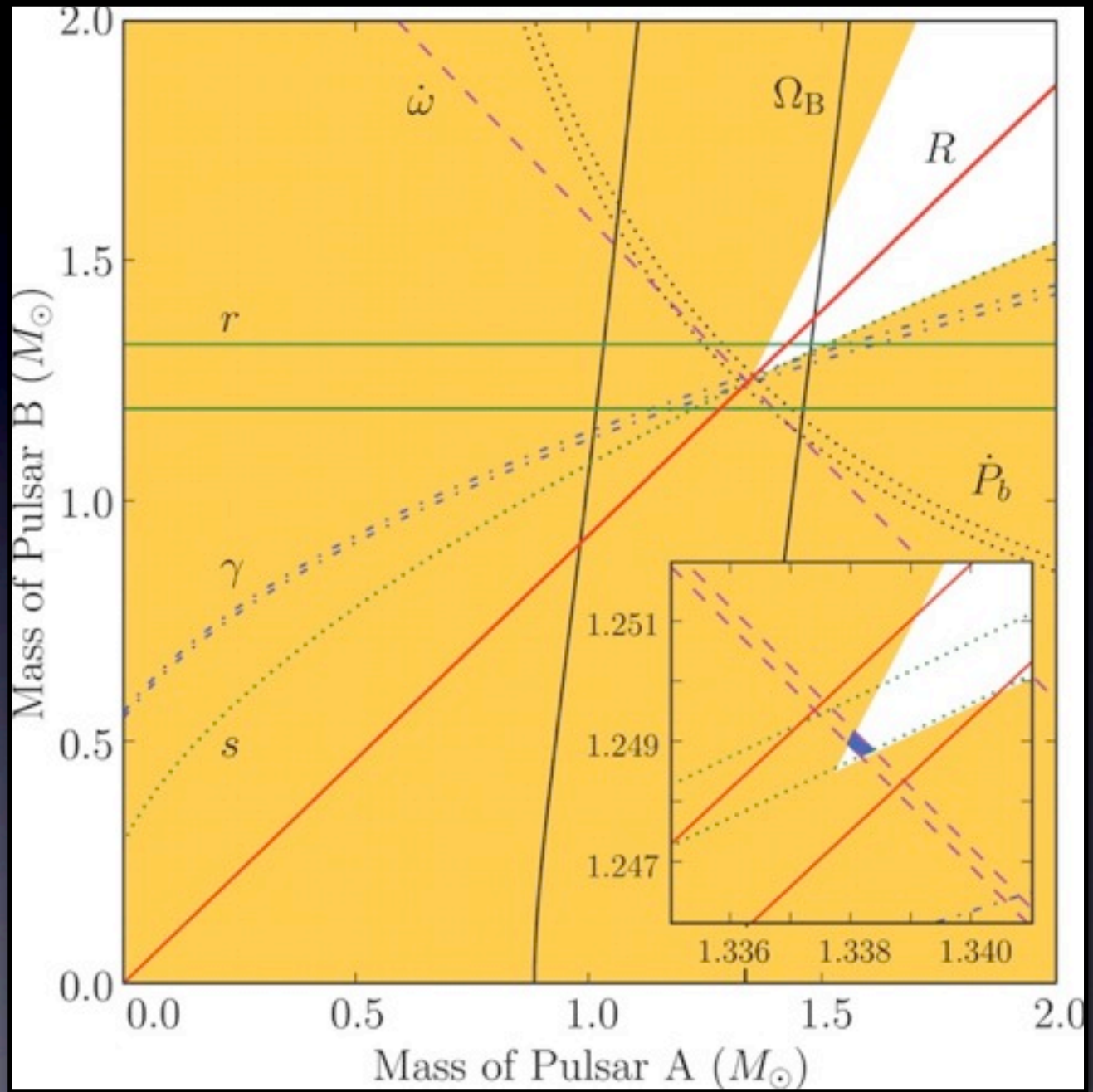


Freire et al. (2009)

Double Pulsar: GR Tests

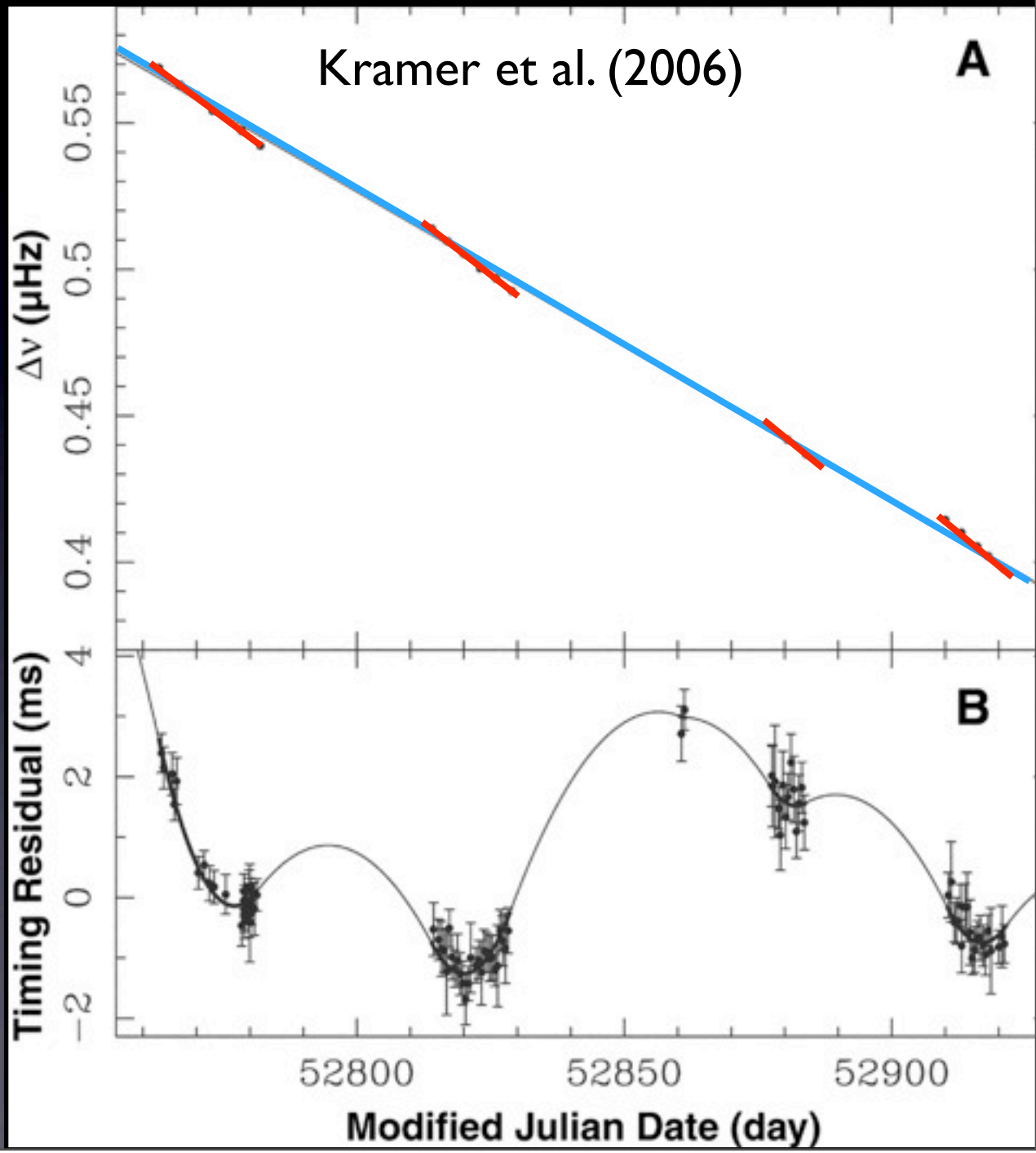
- Use mass ratio + 6 PK parameters
  - Orbit shrinks by 7 mm/day
- All lines intersect: GR is consistent!
  - As good as 0.05%
- GR also passes additional tests unique to this system
- Could also measure moment of inertia via spin-orbit coupling: sensitive test of NS EoS



Kramer et al. (2006); Breton et al. (2008)

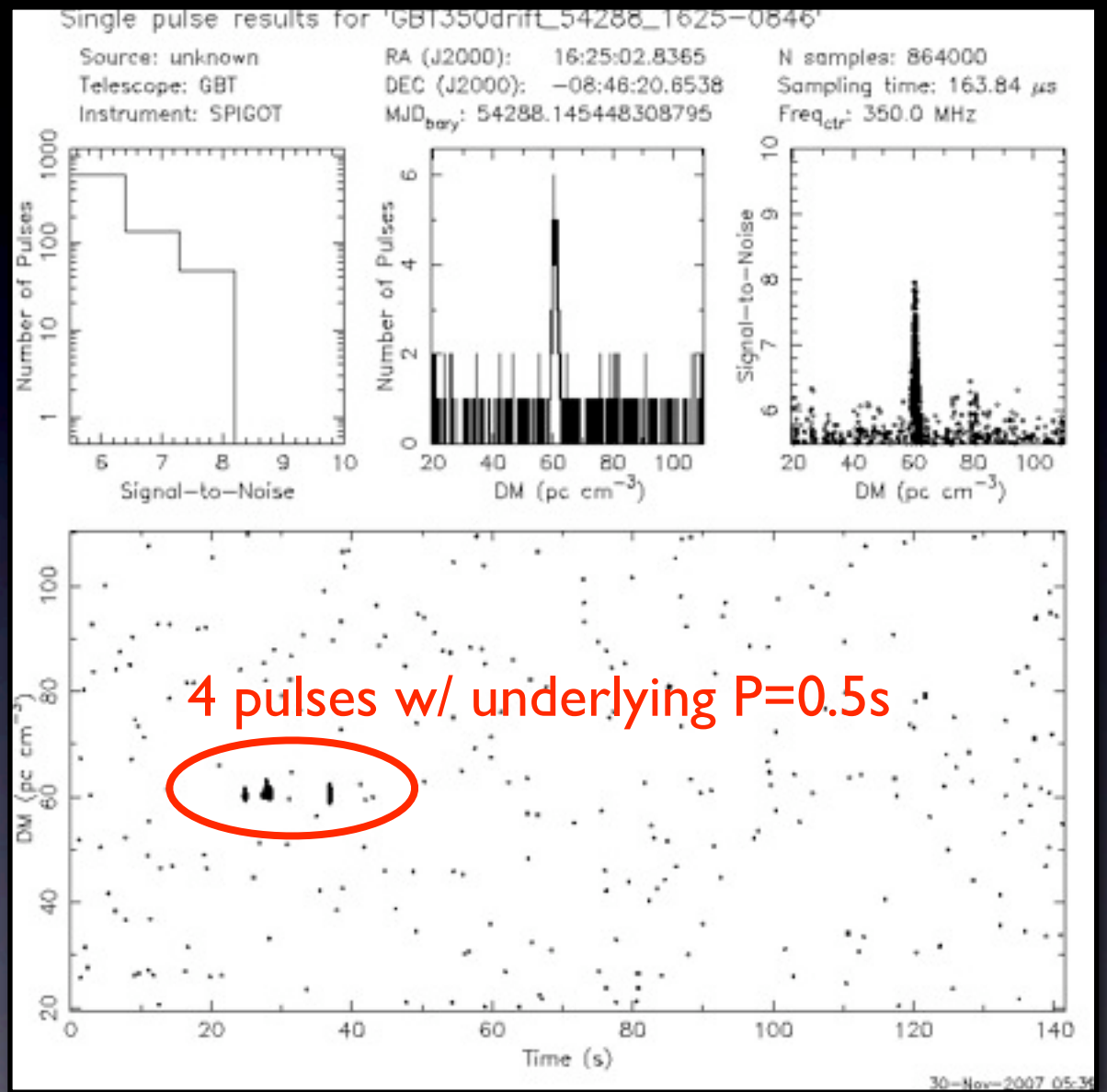
Magnetospheres

- PSR B1931+24:
  - Pulses for ~1 week/ month
  - Spin-down when "on" different from average
  - Change in torque: agrees with charge density predicted by Goldreich & Julian (1969)!
  - What causes change???
- Other objects now known, with large variation in timescales



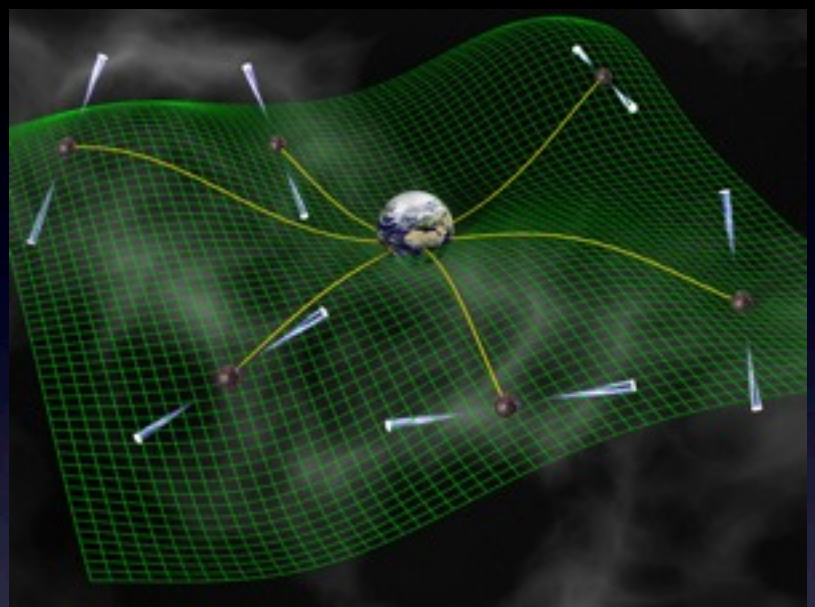
Rotating RAdio Transients

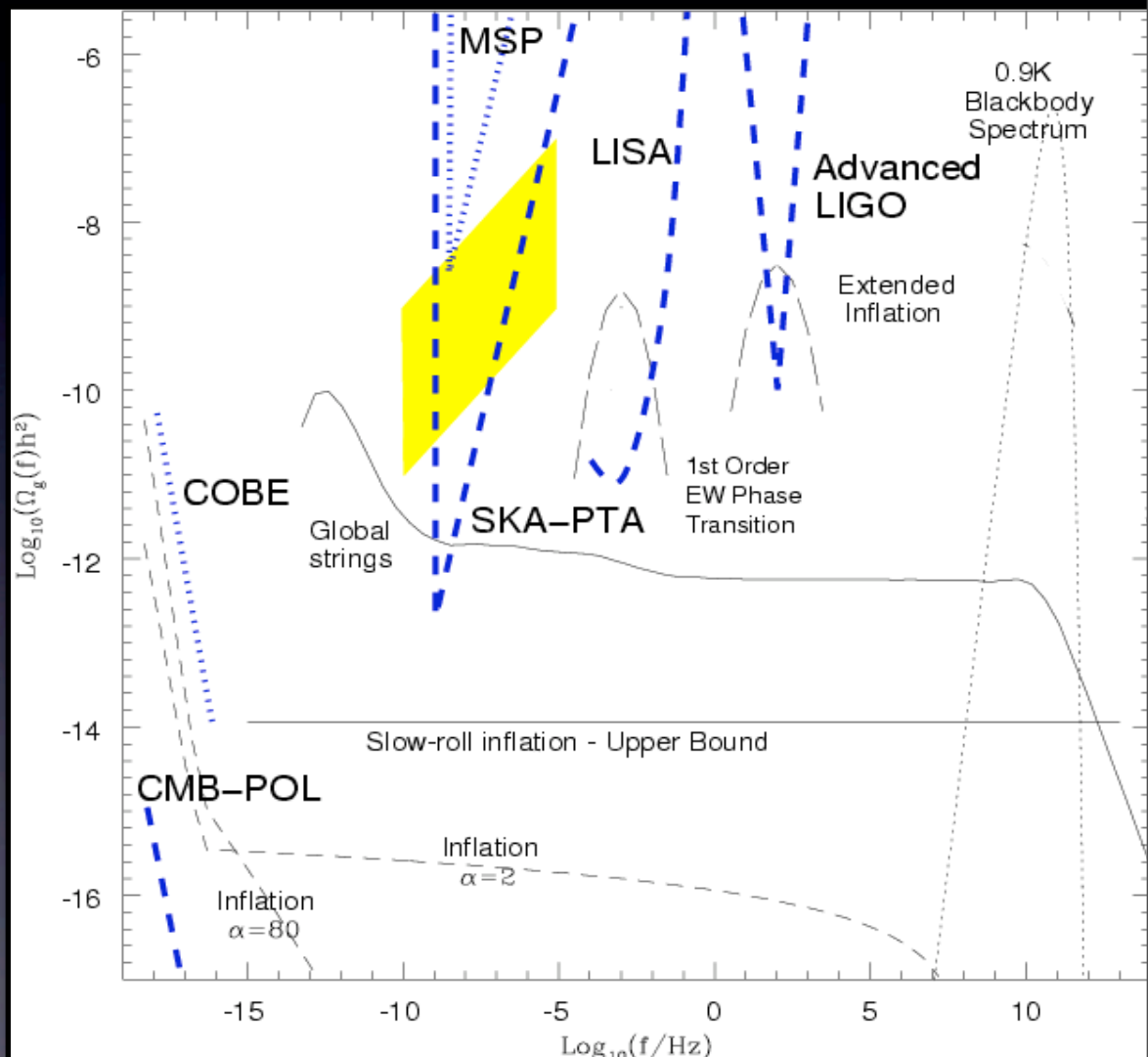
- A number of sources discovered by individual pulses
- Underlying periodicity discovered later
- RRATs: Rotating RAdio Transients
- Some are just pulsars w/ weird amplitude distribution (e.g., Weltevrede et al. 2006)
- Others really are random



McLaughlin et al. (2006)

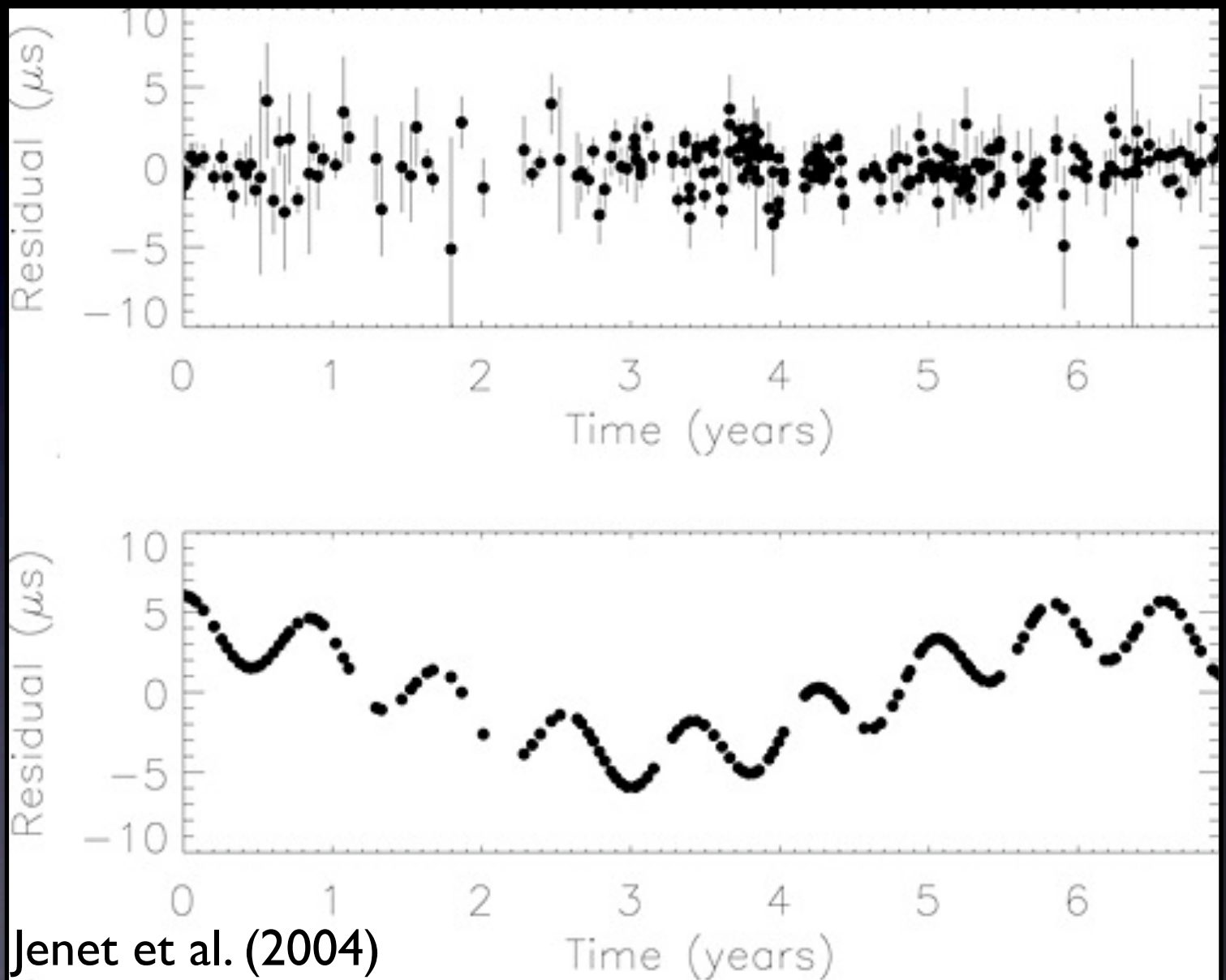
GW Detectors





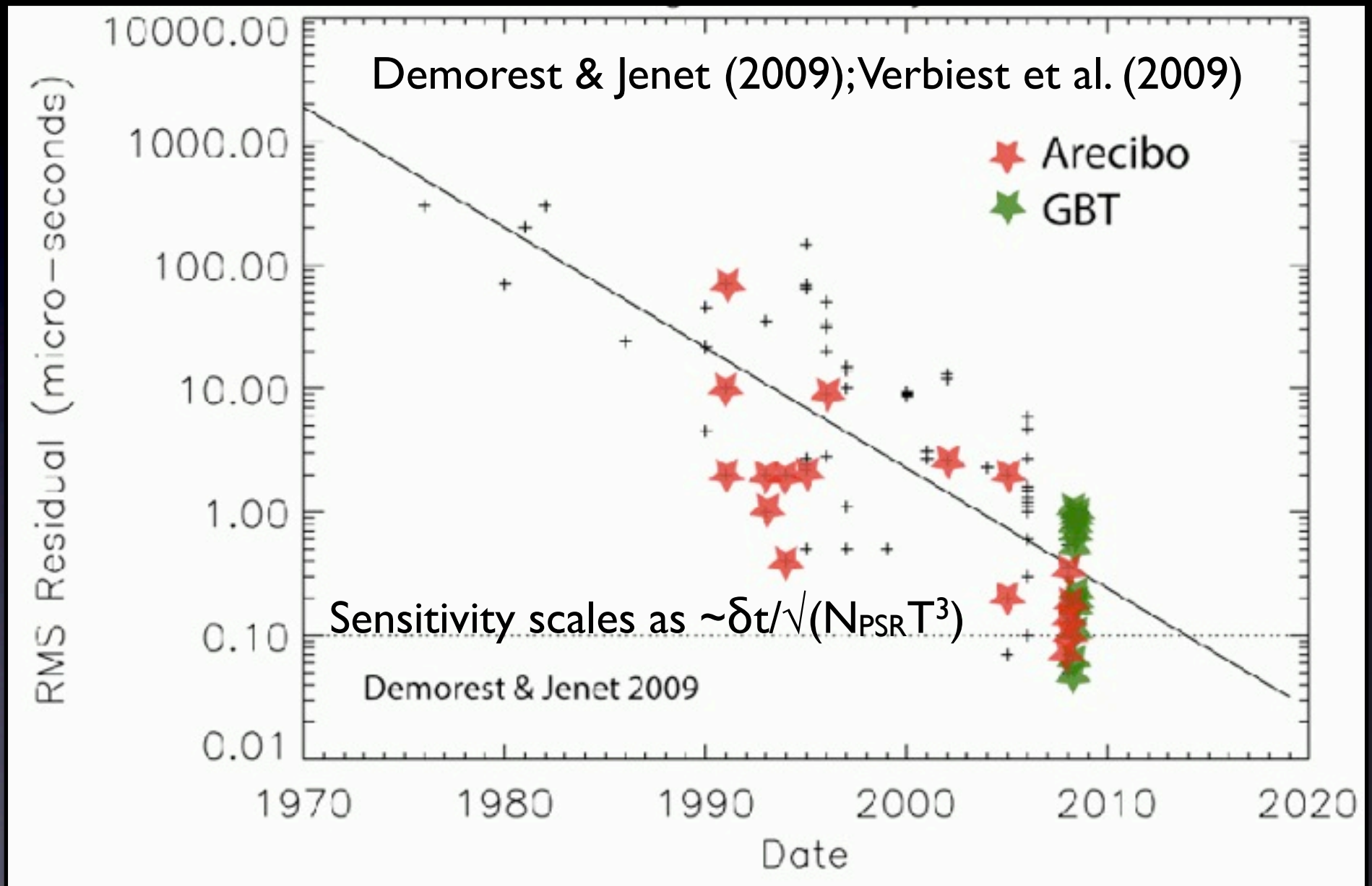
- Parkes Pulsar Timing Array
- European Pulsar Timing Array
- NanoGRAV

Pulsar Timing & GW Waves



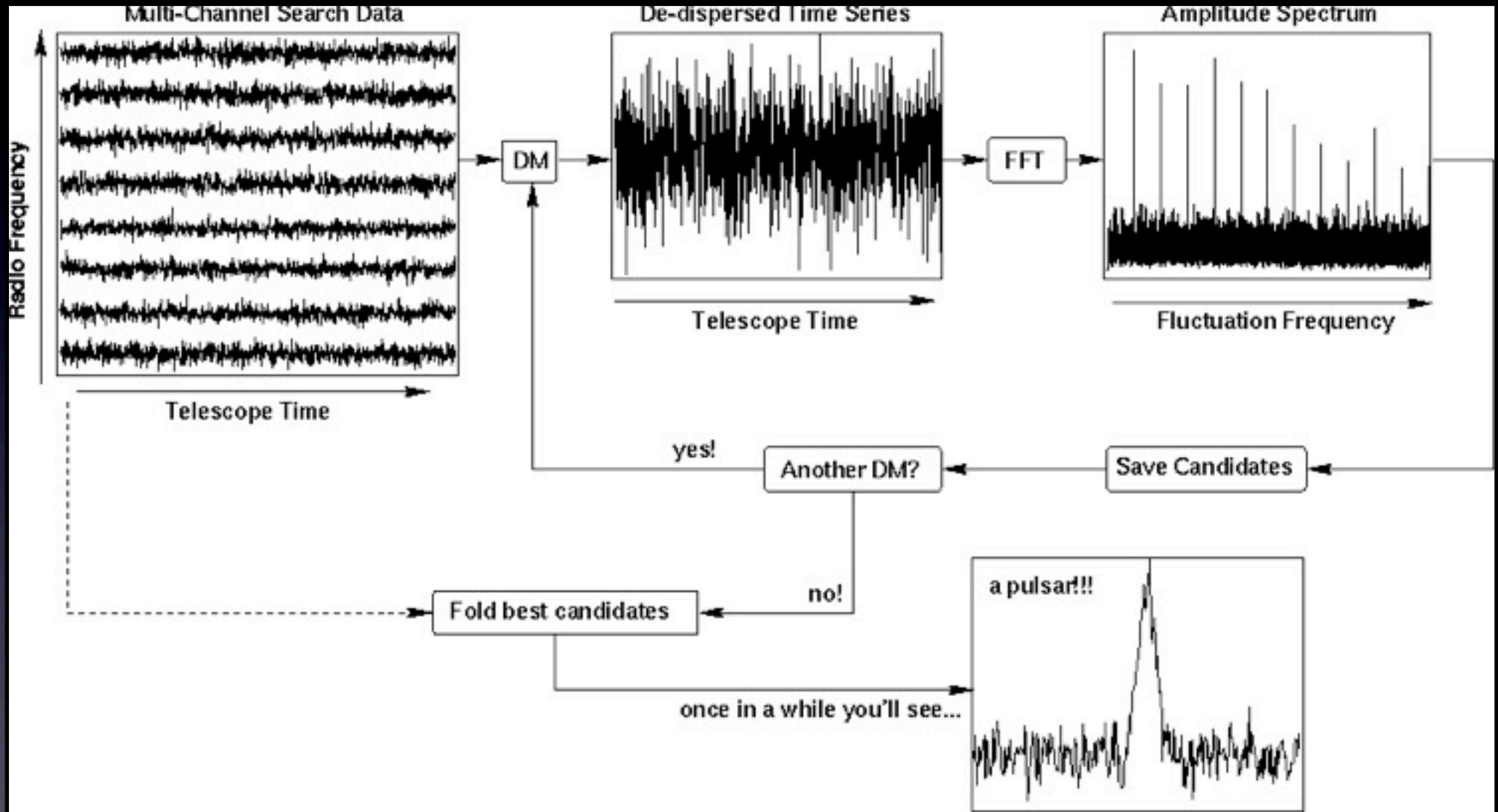
Jenet et al. (2004)

Pulsar Timing & GW Waves



Need ~100 ns precision on 20 pulsars for 5 years

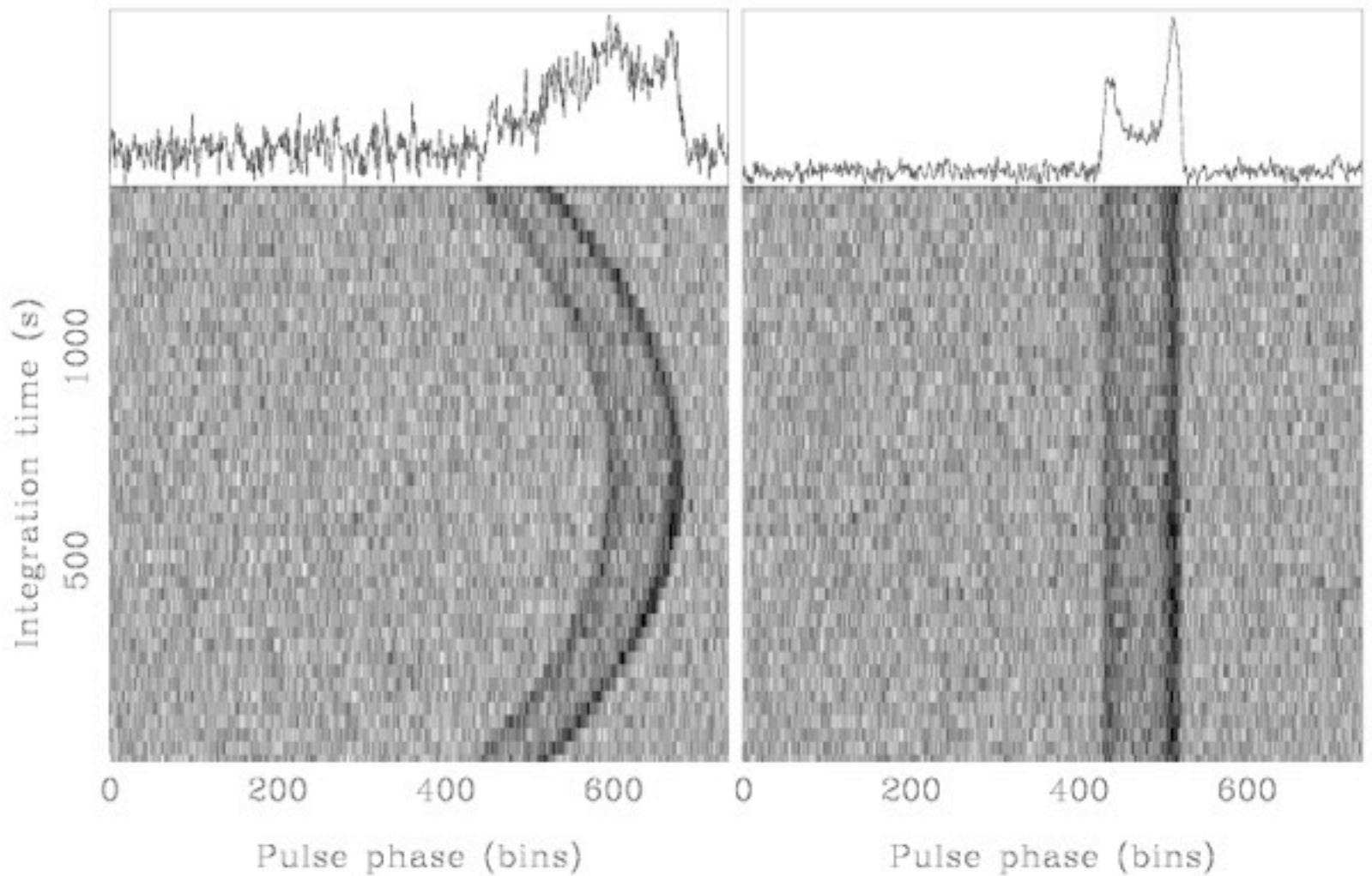
Searching



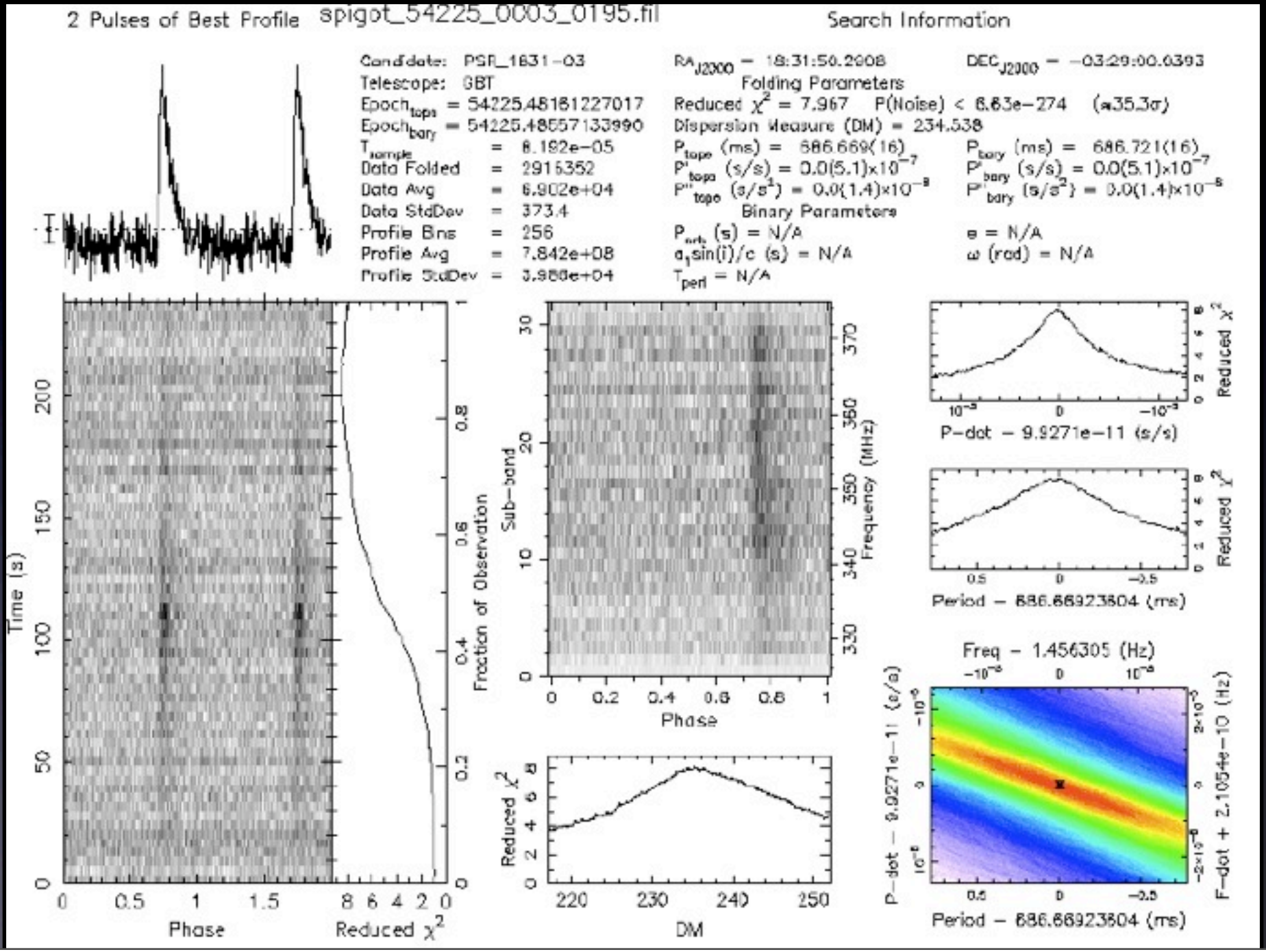
Basic search: faint dispersed pulses

Refinement: Acceleration

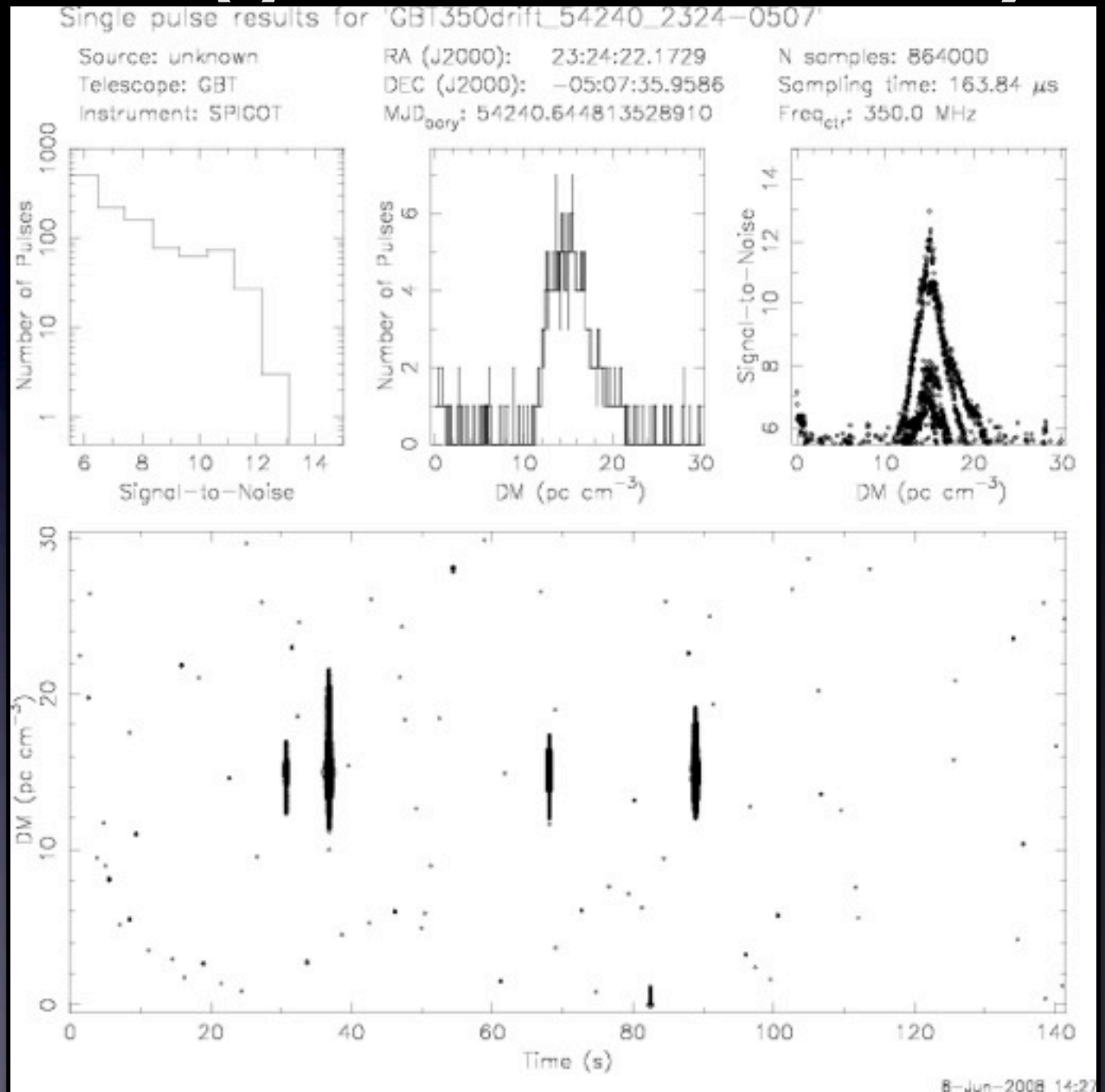
Search for varying acceleration in binary systems



Results from Search



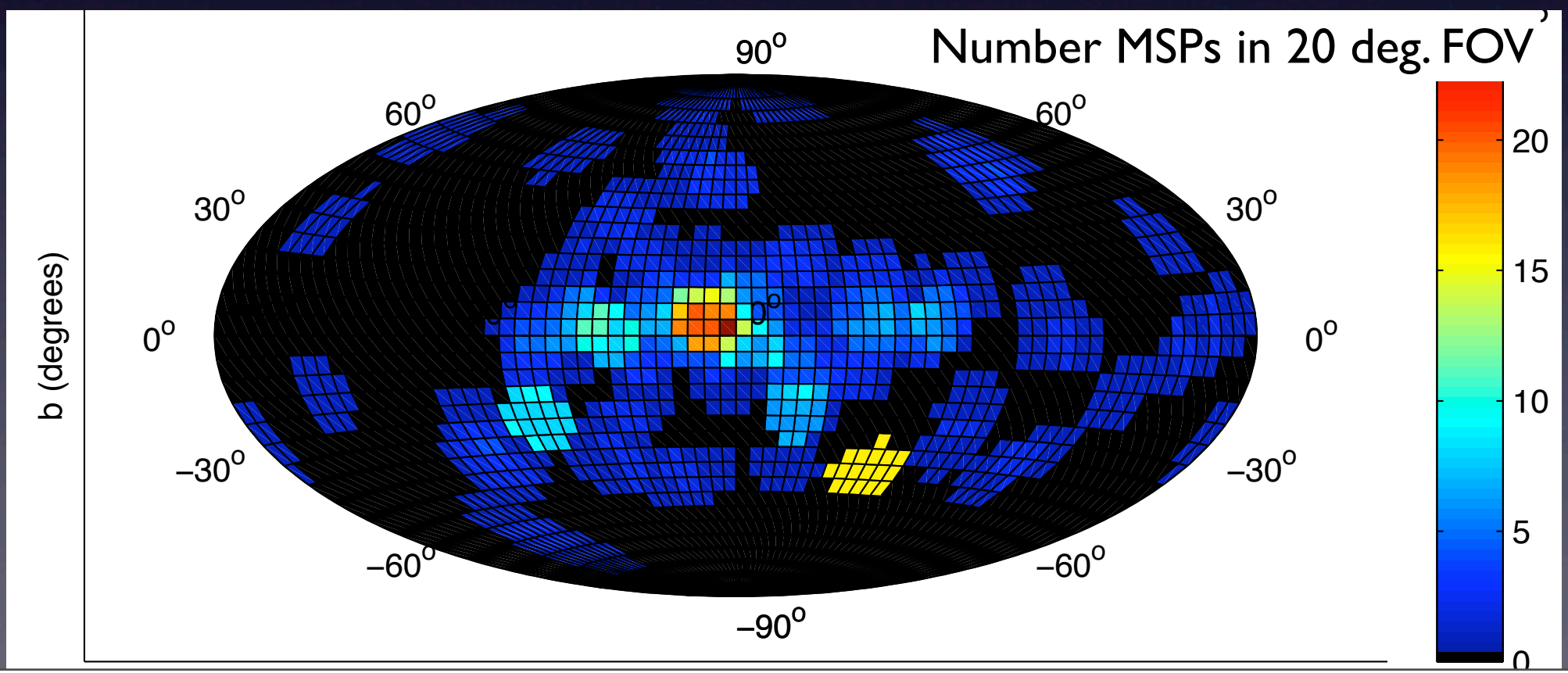
Single Pulses Only

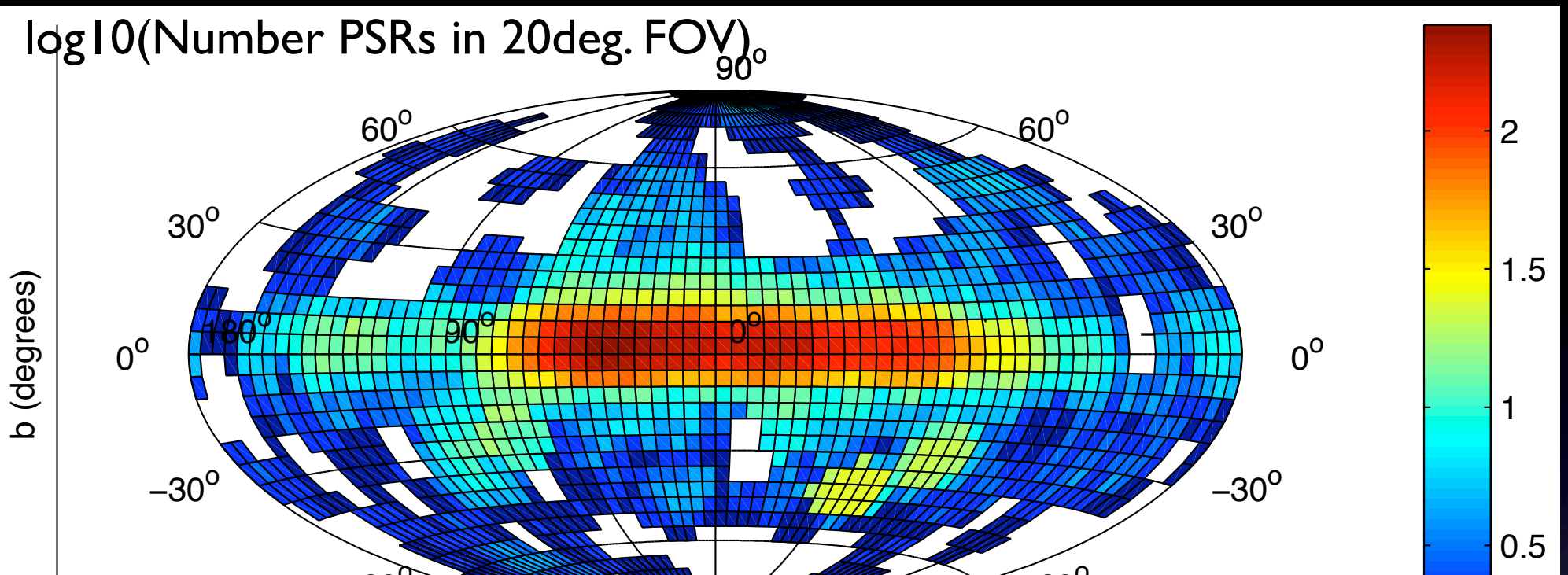


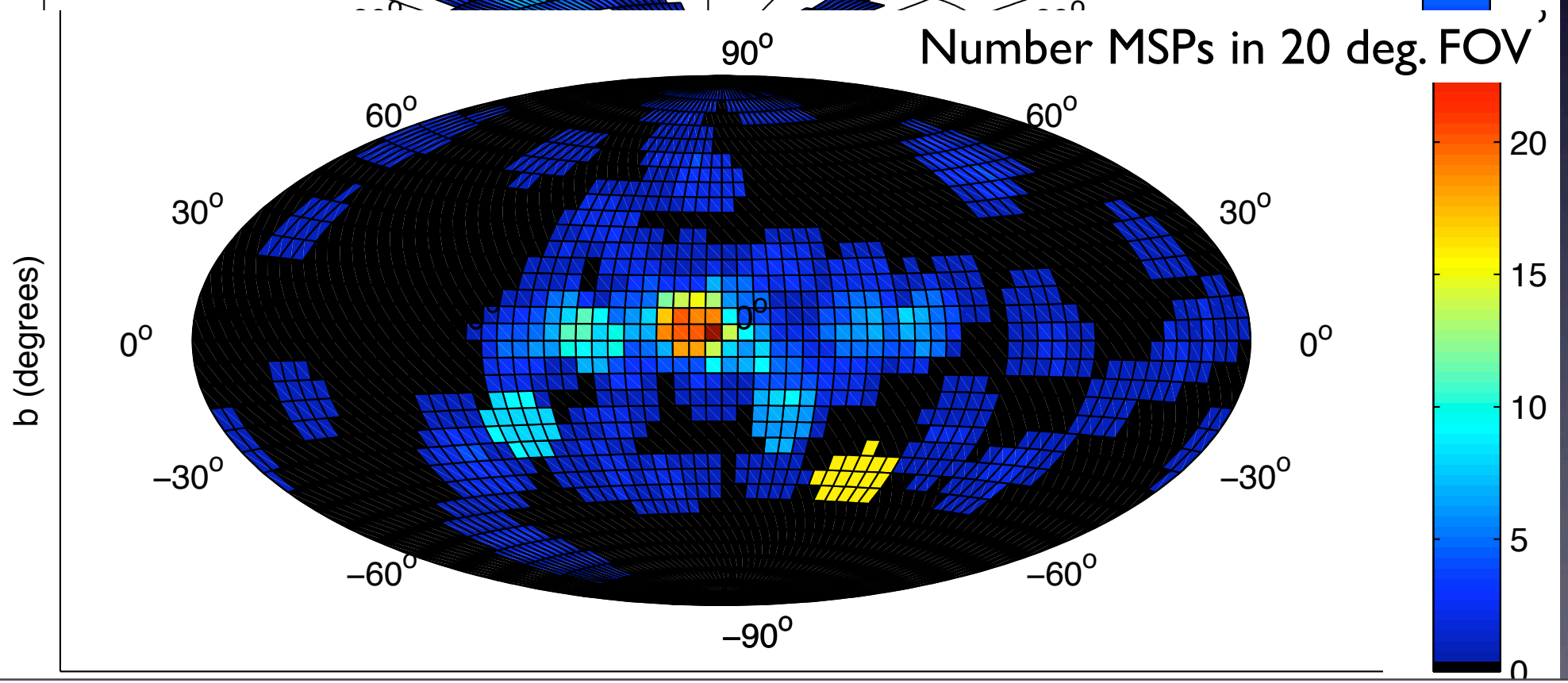
Ideal Pulsar Timing Telescope

- Large:
  - area
  - bw (not necessarily contiguous)
  - time available
- Good frequency range:
  - pulsars brighter at low freq.
  - but ISM is worse

	CARPE	
Area	2500-12500 m^2	>Parkes
BW	~400 MHz	>Parkes, esp. at low freq.
Time	>50%	>>anything
Freq. range	300-1400 MHz	~Parkes


Number MSPs in 20 deg. FOV
b (degrees)
90°
60°
30°
0°
−30°
−60°
−90°
60°
30°
0°
−30°
−60°
0°
20
15
10
5
0


log10(Number PSRs in 20deg. FOV)
b (degrees)
90°
60°
30°
0°
−30°
−60°
−90°
−180°
2
1.5
1
0.5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90°
60°
30°
0°
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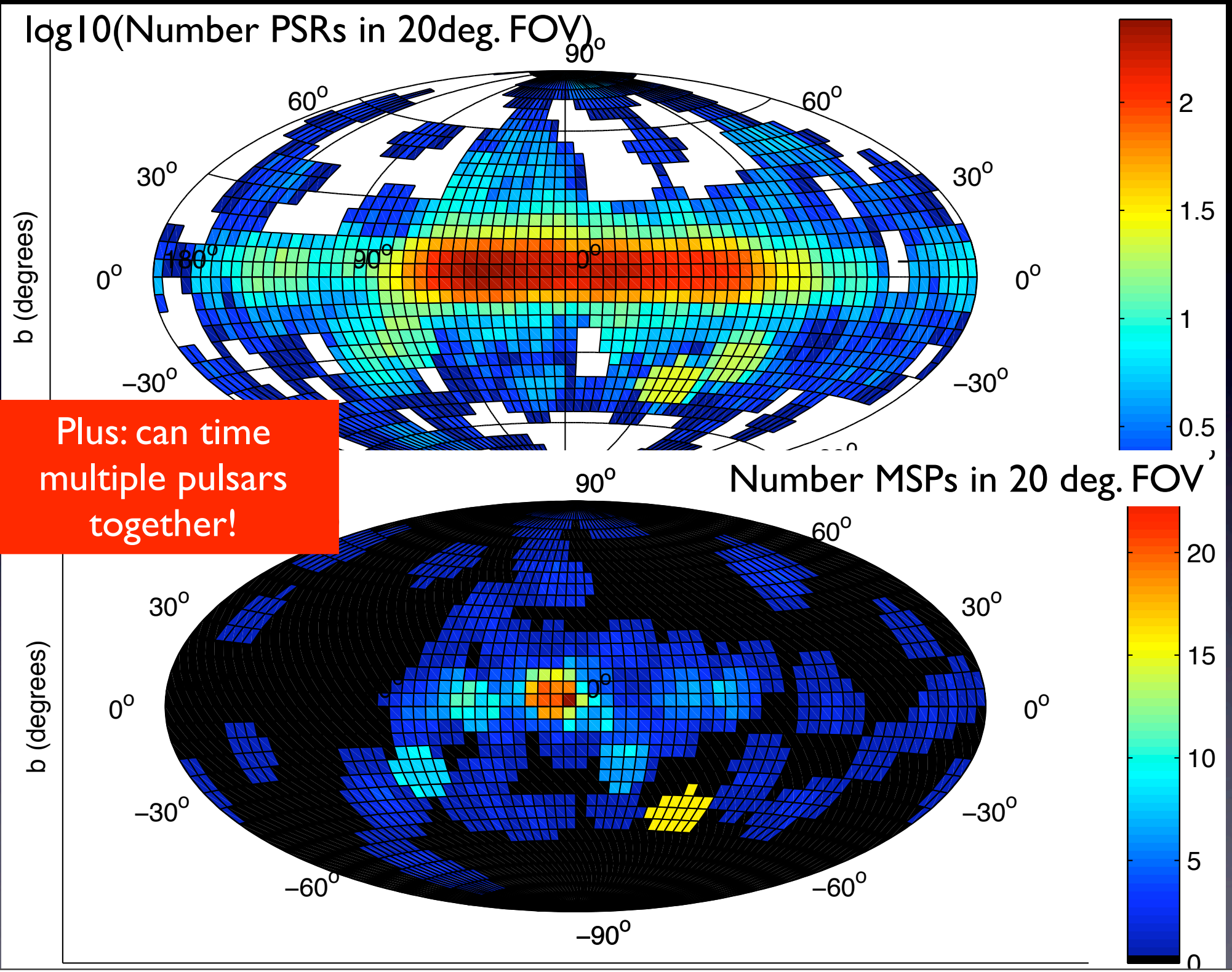
−60°
−90°
20
15
10
5
0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90°
60°
60°
30°
30°
0°
0°
−30°
−30°
−180°
90°
0°
b (degrees)
2
1.5
1
0.5
Plus: can time multiple pulsars together!
Number MSPs in 20 deg. FOV
90°
60°
30°
30°
0°
0°
−30°
−30°
−60°
−60°
−90°
b (degrees)
20
15
10
5
0

Lots of Interesting PSRs

- Most come from normal large-scale searches
- Still looking to find:
  - sub-millisecond
  - PSR-BH binary
- Need to survey a lot of volume
  - Current systems: $N_{beams} \sim 10$

Need to Find Them First

- Area, BW, Time still key
- High freq:
  - Deep searches, faster PSRs
- Low freq:
  - Local population, low luminosity
- Huge FOV improvement:
  - Discoveries limited by processing
  - Can incorporate dedispersion into correlator
  - Still need to search for P, DM, derivatives

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FOV	20 deg.	1 Parkes beam=11'

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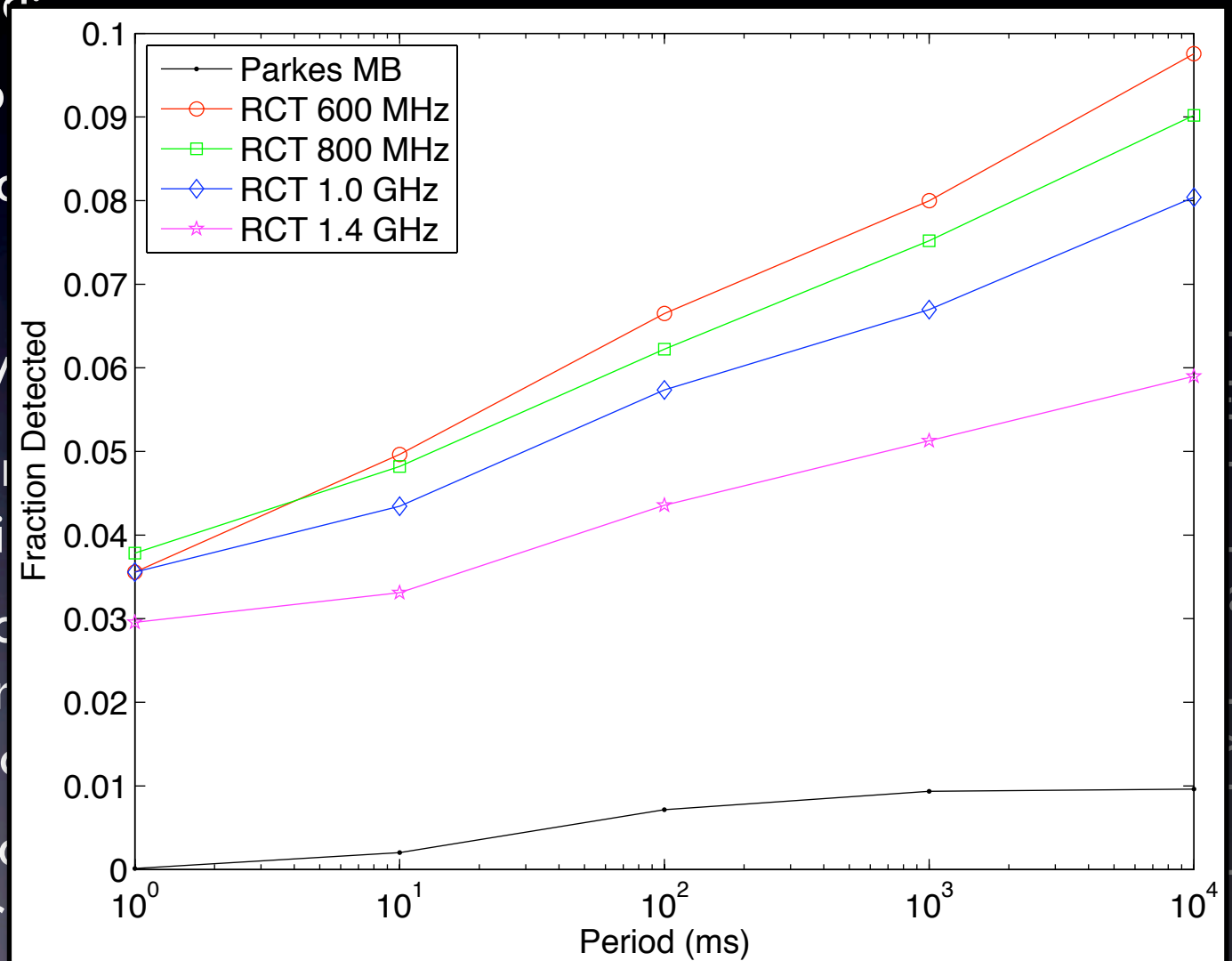

		>Parkes
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		>>anything
		~Parkes
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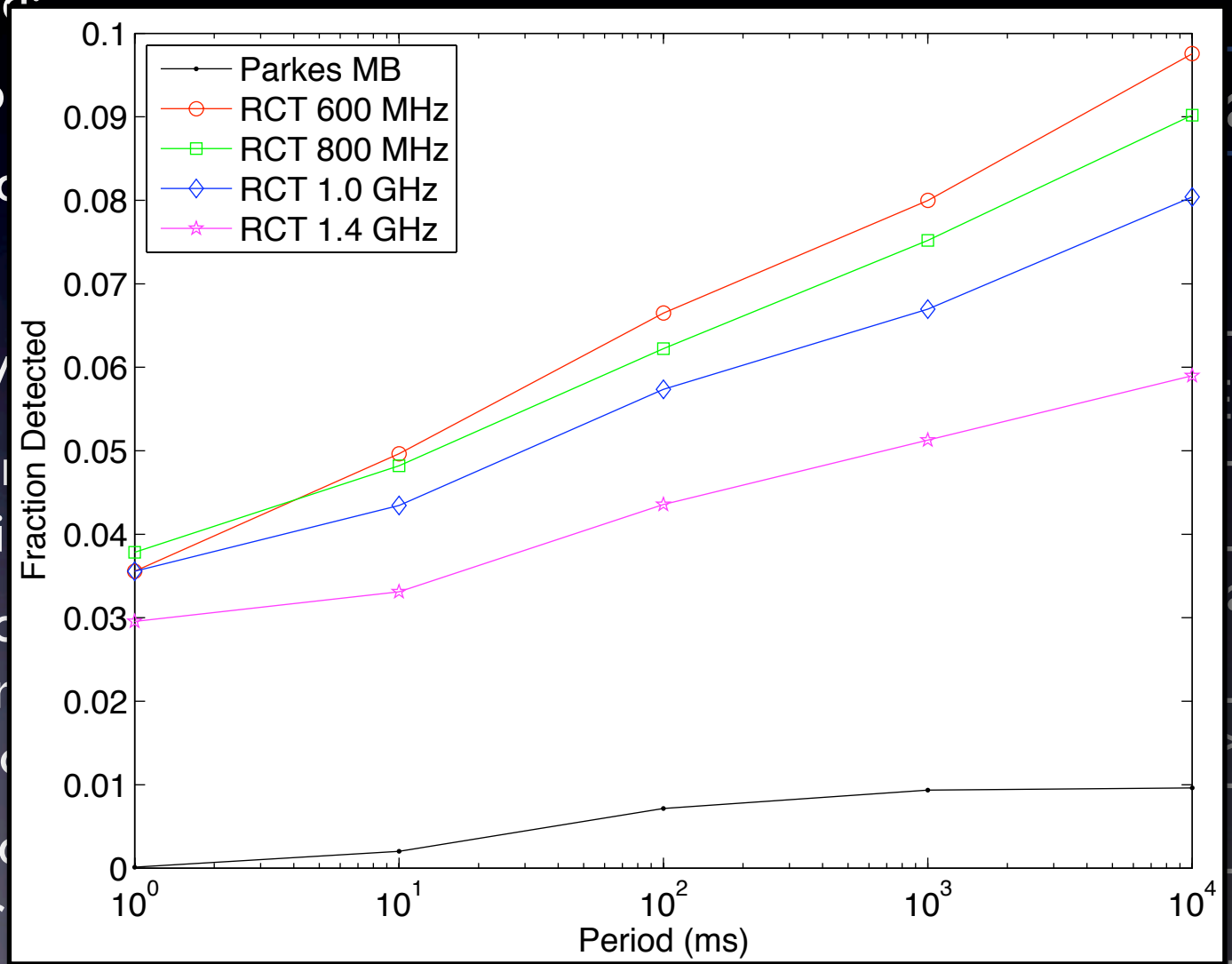

as SKA

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Same problem as SKA

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Cost of Searching

$$\mathrm{DataRate} = \frac{1}{t_{\mathrm{samp}}} \frac{\mathrm{BW}}{\Delta\nu} N_{\mathrm{pol}} \frac{N_{\mathrm{bits}}}{8} \mathrm{Bps}$$

- Channel size $\Delta\nu \sim t_{samp}/\nu^3 DM_{max}$ (~10's of kHz)
  - set by max dispersion: $DM = \int n_e dl$
- Can easily be 10's-100's of MB/s for each beam

$$\mathrm{Ops} = N_{\mathrm{DM}} N_{\mathrm{accel}} \times 5 N_{\mathrm{samp}} \log_2 N_{\mathrm{samp}}$$

- for each beam; $N_{accel} \sim N_{samp}^2$
- ~10^{10} op/s for one beam for ~1800s observations
- Hundreds(?) of beams
  - what is optimal number? Loose long baselines
  - Compact arrays better
  - Better than SKA: no additional cost for beamforming

see Smits et al. (2009)

Benefits of CARPE Searches

- Flexible frequency
- Can tune number of beams depending on science/bandwidth
- Cosmology and Galactic plane play well together
- Repeated searches: find all sorts of interesting time-domain phenomena (transient, intermittent, precessing, scintillating)
- Major challenge is data-rate: can we come up with new strategy (SKA et al. need this too)
  - Don't save data (storage/transport vs. processing)
  - Short observations, except for best candidates
  - Repeated sampling better than long integrations
  - Real-time processing, progressively winnow candidates

Conclusions

- Pulsars:
  - Lots of interesting physics & astrophysics
- Excitement comes from:
  - Large samples
  - Interesting individual objects (hard to find)
  - Need high-precision timing of many objects regularly, at multiple freqs.
- CARPE can:
  - Find many pulsars with repeated, deep surveys
  - Time multiple PSRs simultaneously