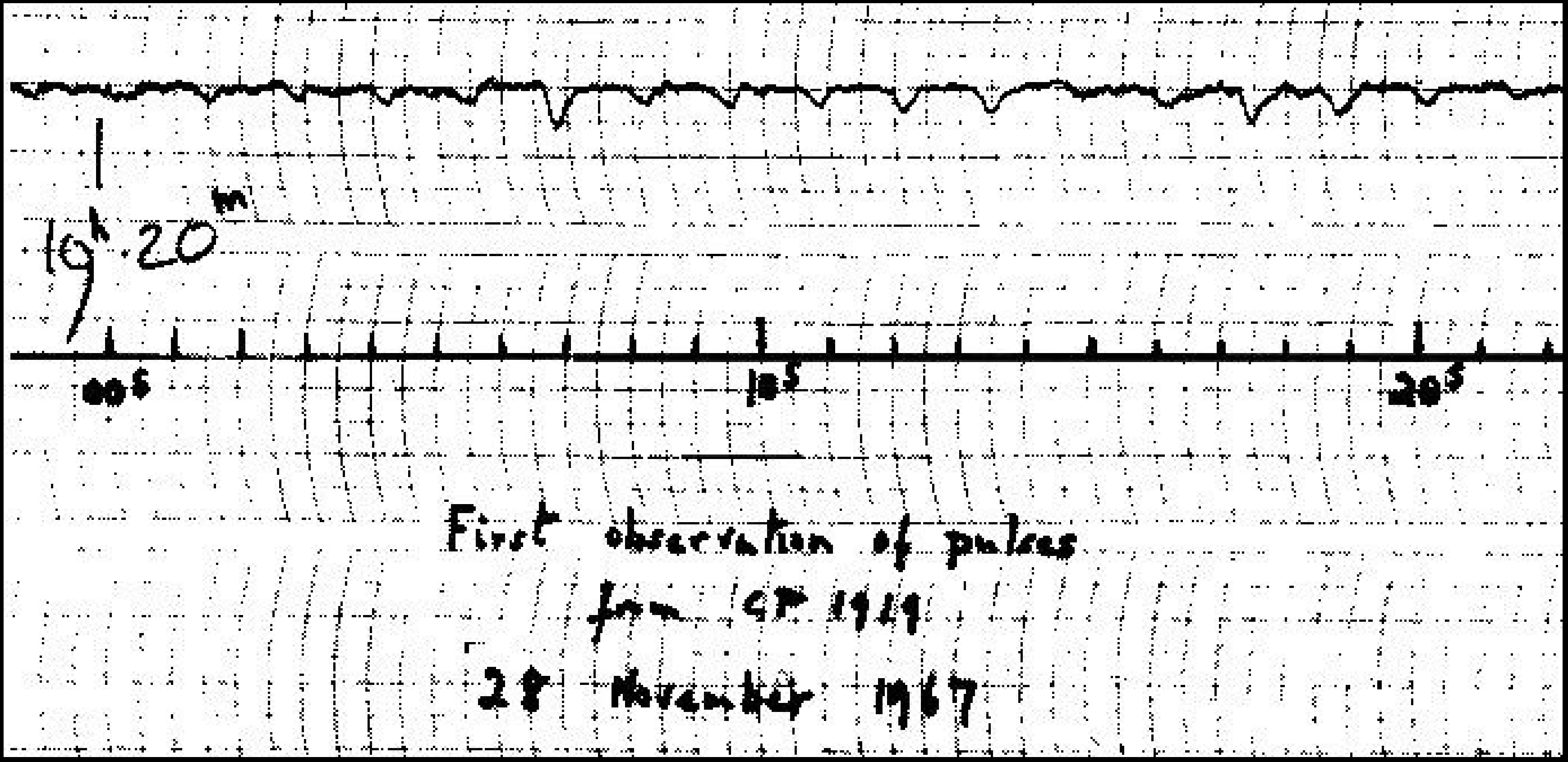
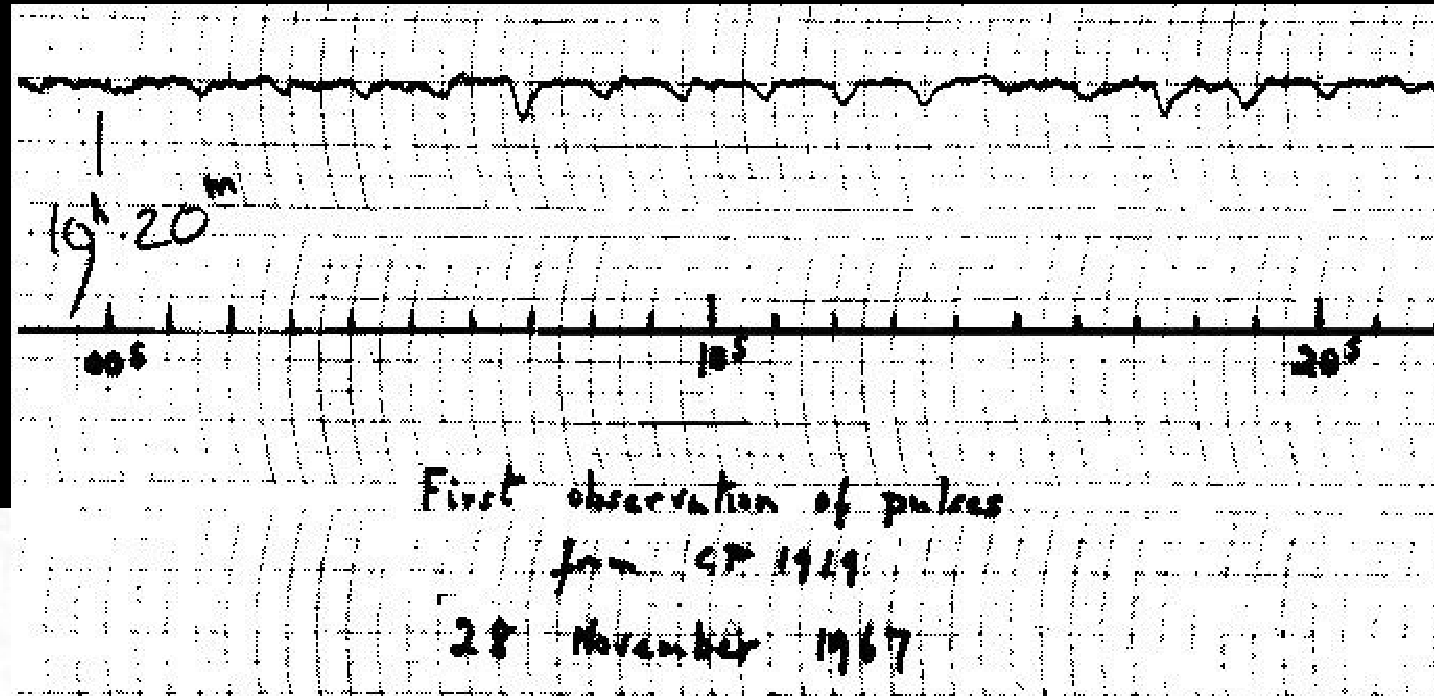
Pulsars: Observations and Science

Scott Ransom

NRAO Charlottesville

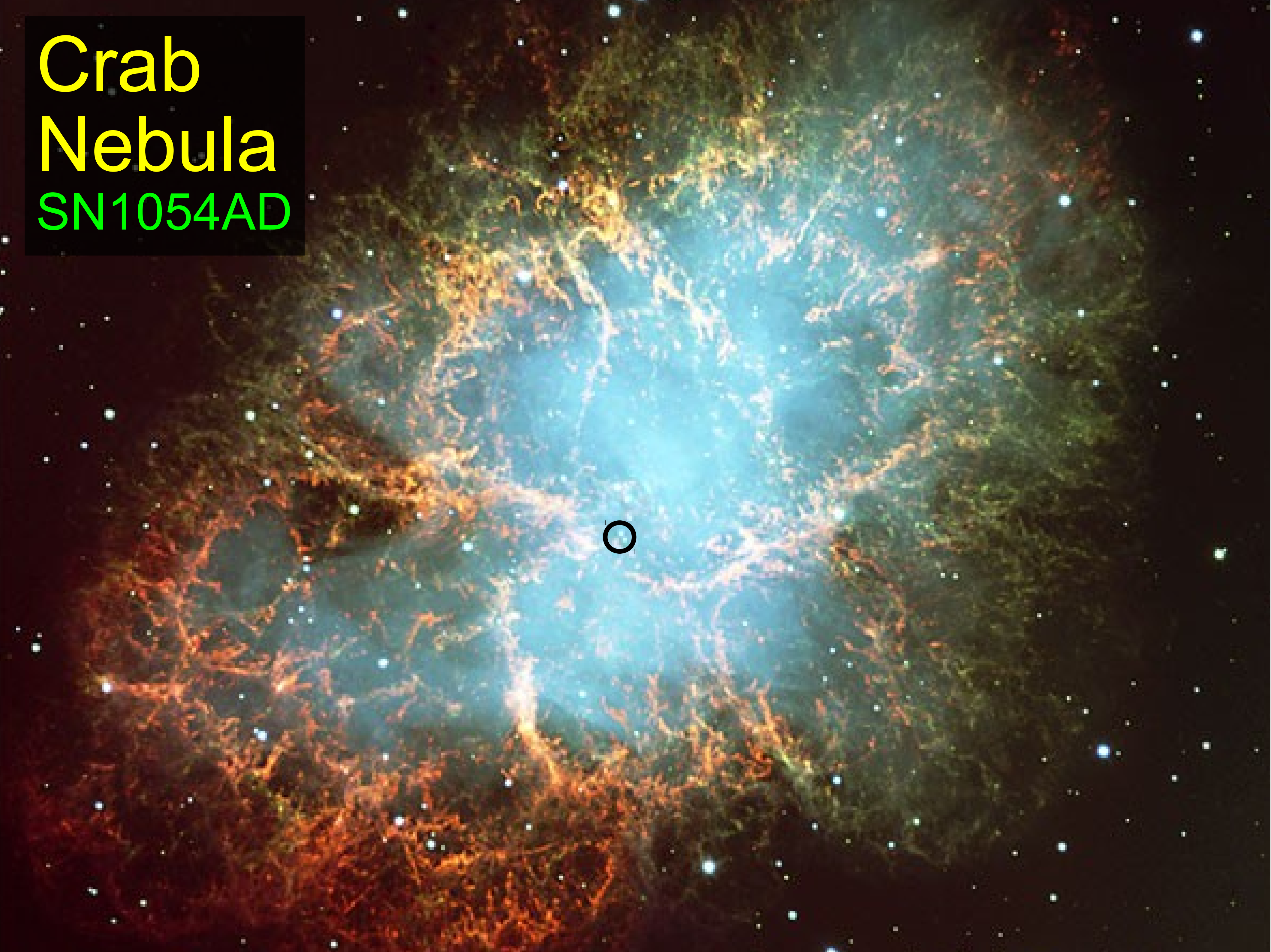


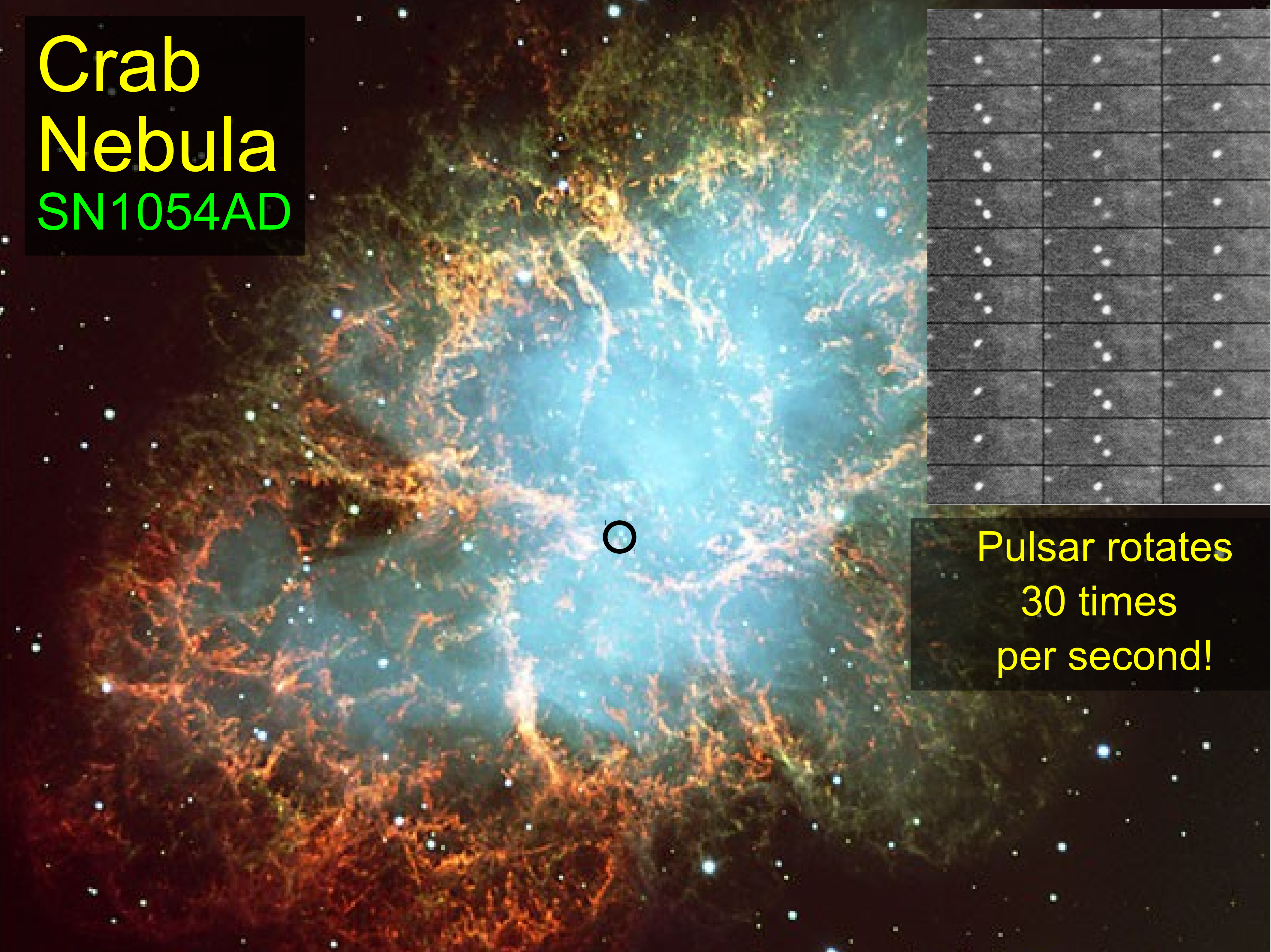
The Discovery of Pulsars

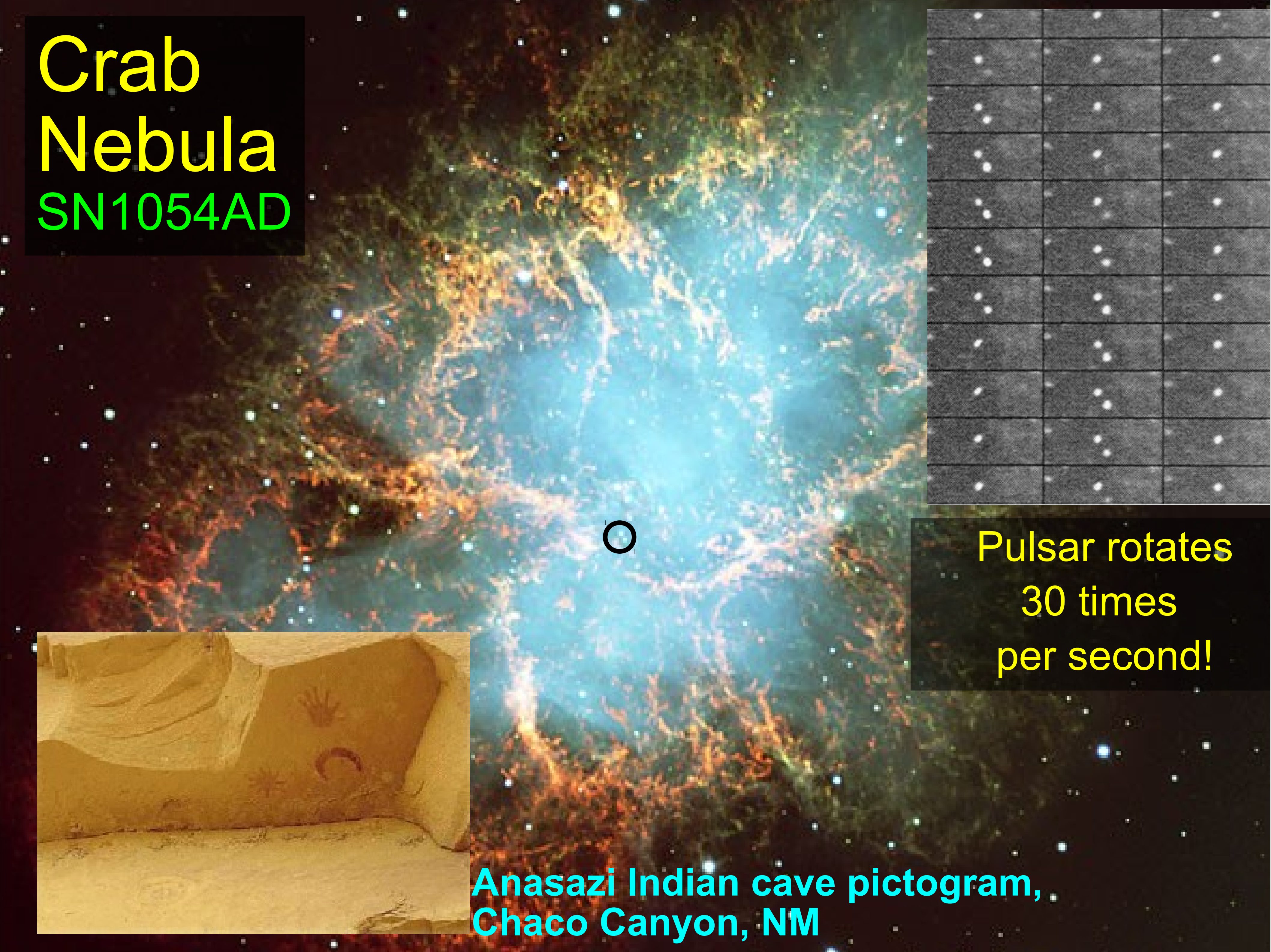


PhD student **Jocelyn Bell** and
Prof. **Antony Hewish**
Initially "**Little Green Men**"
Hewish won Nobel Prize in 1974


Crab
Nebula
SN1054AD

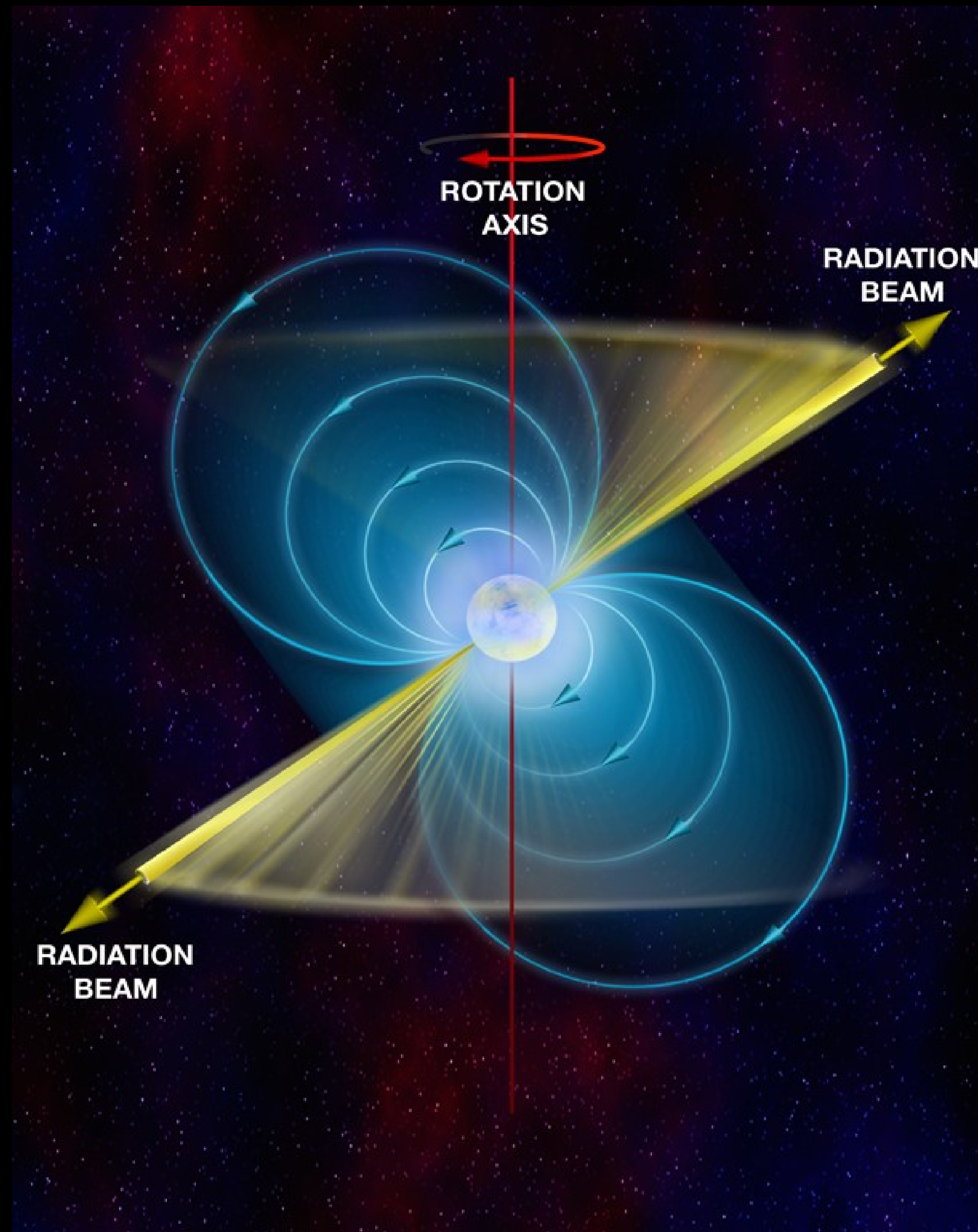

Crab
Nebula
SN1054AD


Crab Nebula
SN1054AD
Pulsar rotates 30 times per second!


Crab
Nebula
SN1054AD
Pulsar rotates
30 times
per second!
Anasazi Indian cave pictogram,
Chaco Canyon, NM

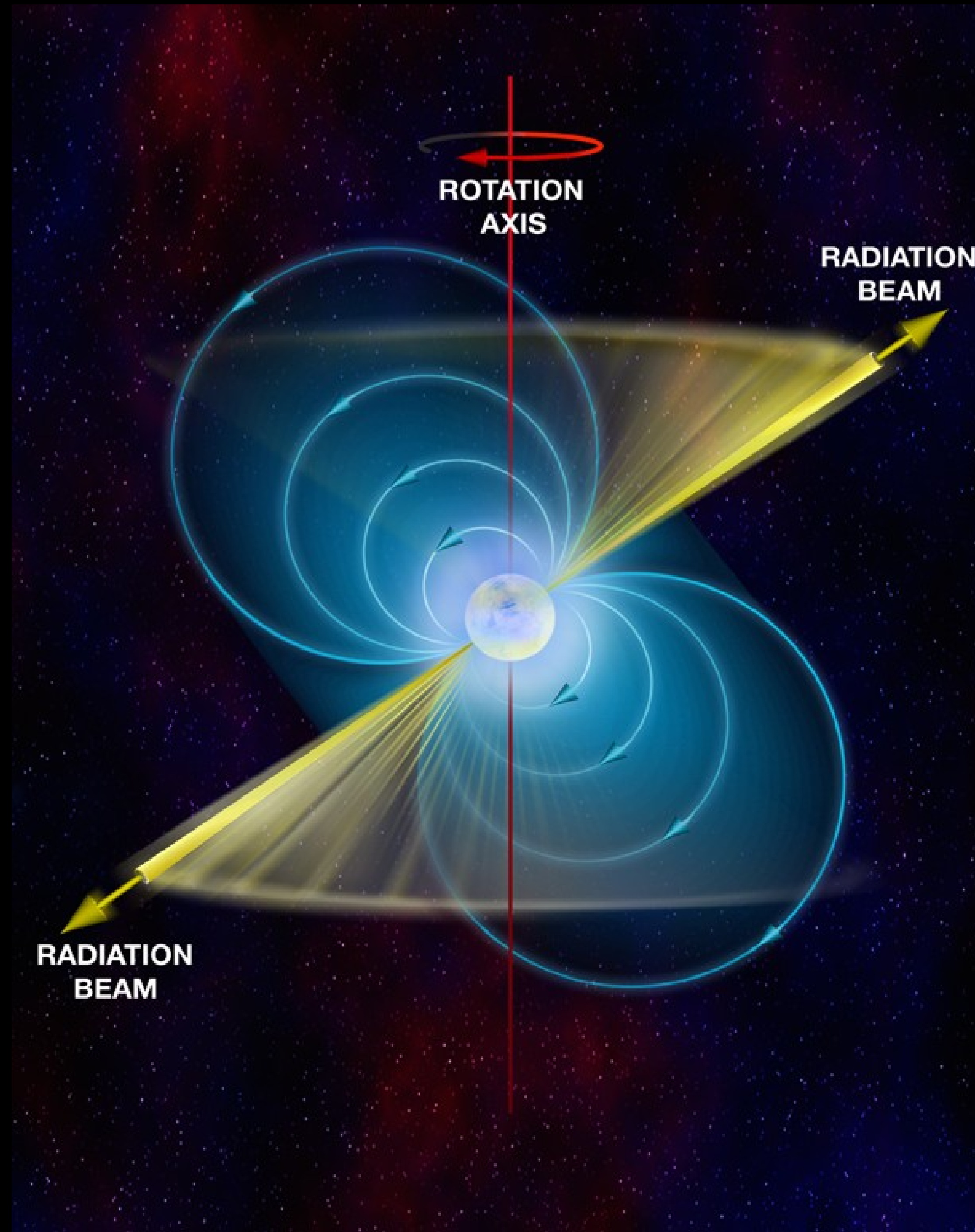
What's a Pulsar?

- Rotating Neutron Star!
- Size of city:
  - R ~ 10-20 km
- Mass greater than Sun:
  - M ~ 1.4 M_{sun}
- Strong Magnetic Fields:
  - B ~ 10^{8}-10^{14} Gauss
- Pulses are from a "**lighthouse**" type effect
- "Spin-down" power up to 10,000 times more than the Sun's total output!



What are their radio properties?

- Continuum sources
- Typically somewhat to highly linearly polarized
- Steep radio spectra (index of -1 to -3, typical obs freqs 0.3-3 GHz)
- Point sources
  - Special ISM effects (freq dependent)
- Highly time variable
  - Wide variety of timescales
- Very weak average flux density (~mJy)



Confusion?

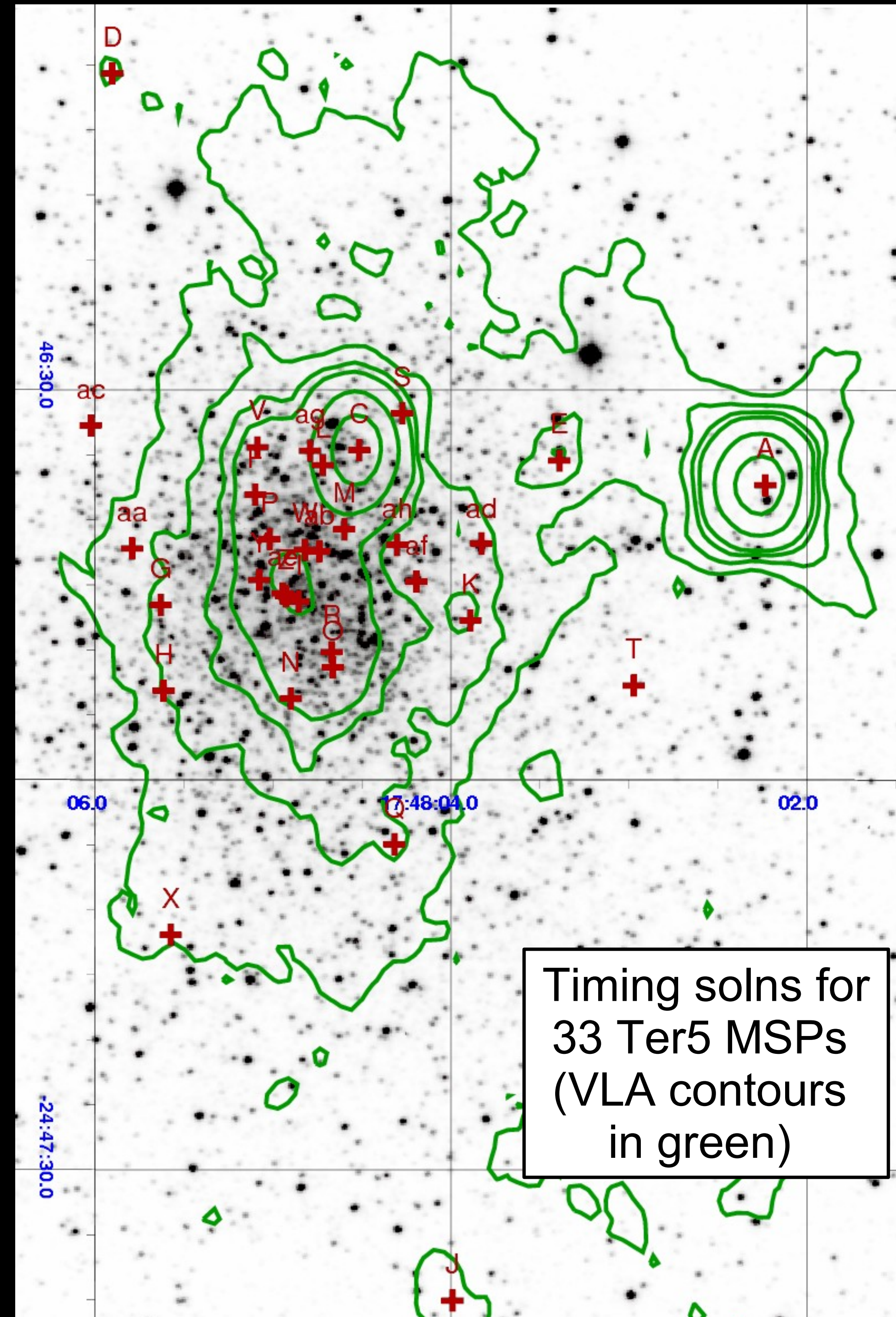
None for pulsars!

Pulsars separated via *time* (or spin frequency!) rather than spatially. Observations Are both “on” and “off”!

Large beam?

Doesn't matter!

Sub-arcsec positions come frompulsar *timing* rather than the telescope beam size and/or position.



Basic Physics with Pulsars

(see Blandford, 1992, PTRSLA, 341, 177 for a review)

Gravitational wave detection (e.g. high precision timing)

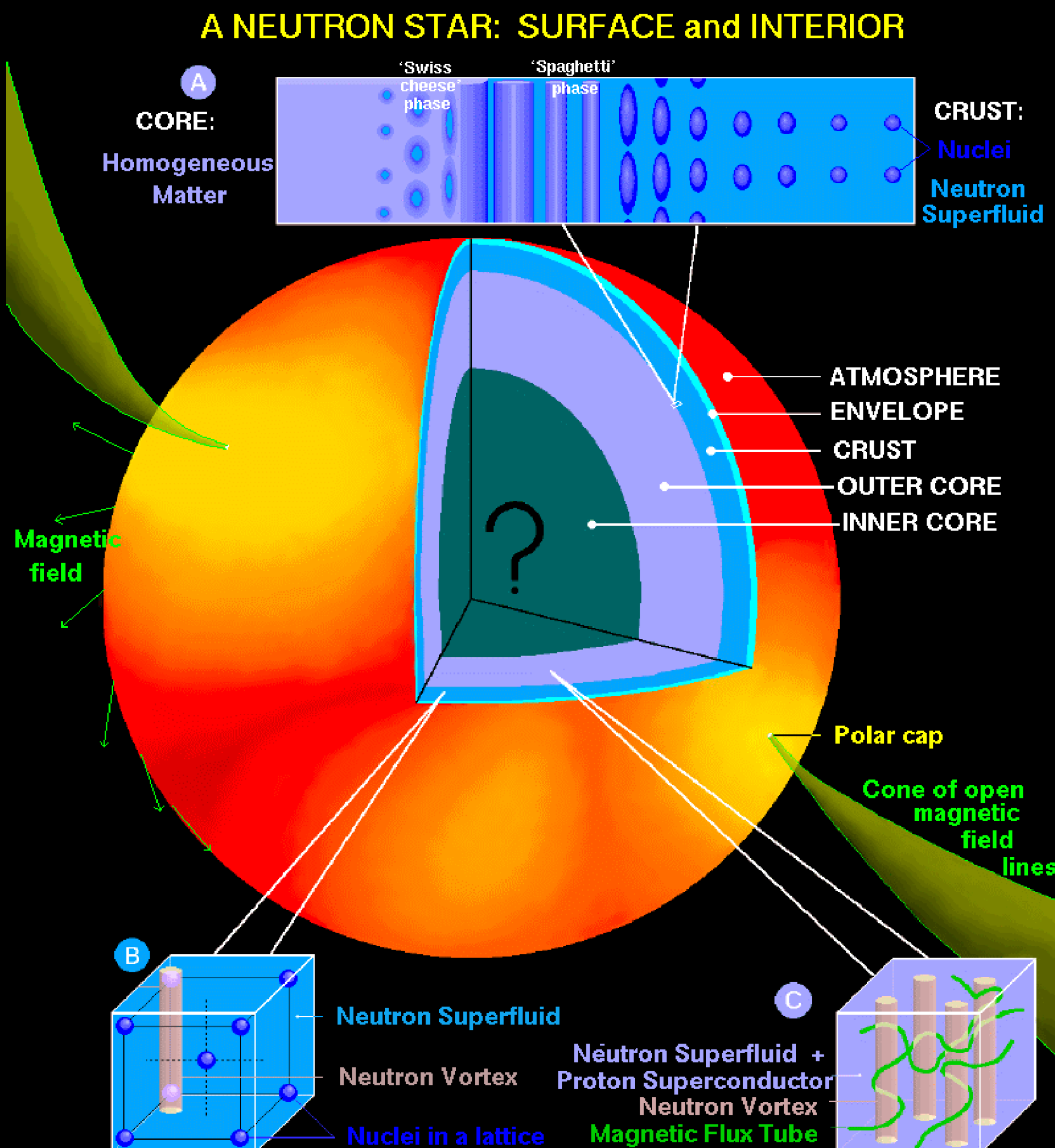
Physics at nuclear density (e.g. NS equations of state)

Strong-field gravity tests (e.g. binary pulsar dynamics)

Also many others:

- Plasma physics (e.g. magnetospheres, pulsar eclipses)
- Astrophysics (e.g. stellar masses and evolution)
- Fluid dynamics (e.g. supernovae collapse)
- Magnetohydrodynamics (MHD; e.g. pulsar winds)
- Relativistic electrodynamics (e.g. pulsar magnetospheres)
- Atomic physics (e.g. NS atmospheres)
- Solid state physics (e.g. NS crust properties)

Neutron Stars are Not Well Understood!



Composed of:

unusual stuff on outside

unknown stuff in core

The physics required to describe the composition involves particle and nuclear physics at extreme densities and (surpisingly) effectively zero temperatures!

From Lattimer and Prakash 2004, *Science*

Basic Physical Information from Pulsars

- Rotating dipole magnet in a vacuum (I = 10^{45} g cm^2):
  - radiates energy and spins-down (p-dot)

- Surface magnetic field strength (B)

$$B_{\rm surf} = 3.2 \times 10^{19}\,{\rm G}\,\sqrt{P\dot{P}} \simeq 10^{12}\,{\rm G}\,\left(\frac{\dot{P}}{10^{-15}}\right)^{1/2}\,\left(\frac{P}{\rm s}\right)^{1/2}$$

- Spin-down luminosity (E-dot)

$$\dot{E} = -4\pi^2 I\nu\dot{\nu} = 4\pi^2 I\dot{P}P^{-3} \simeq 3.95 \times 10^{31}\,{\rm erg s^{-1}}\,\left(\frac{\dot{P}}{10^{-15}}\right)\,\left(\frac{P}{\rm s}\right)^{-3} \propto B_{\rm surf}^2\nu^4$$

- Age (T) and Characteristic Age (τ_c) (braking index: n ~ 3)

$$T = \frac{P}{(n-1)\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right]$$

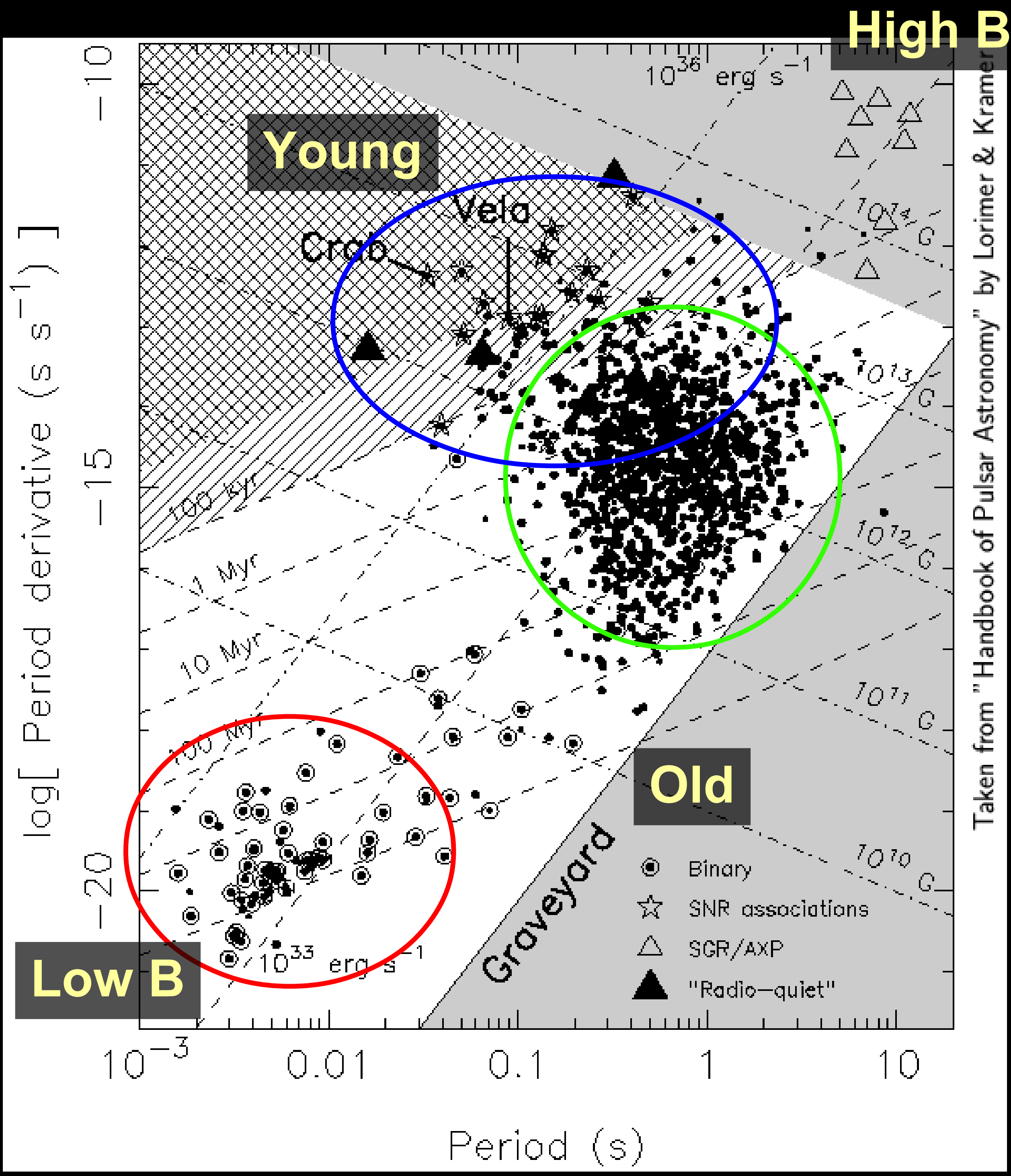
$$\tau_c \equiv \frac{P}{2\dot{P}} \simeq 15.8\,{\rm Myr}\,\left(\frac{P}{\rm s}\right)\,\left(\frac{\dot{P}}{10^{-15}}\right)^{-1}$$

Pulsar Flavors

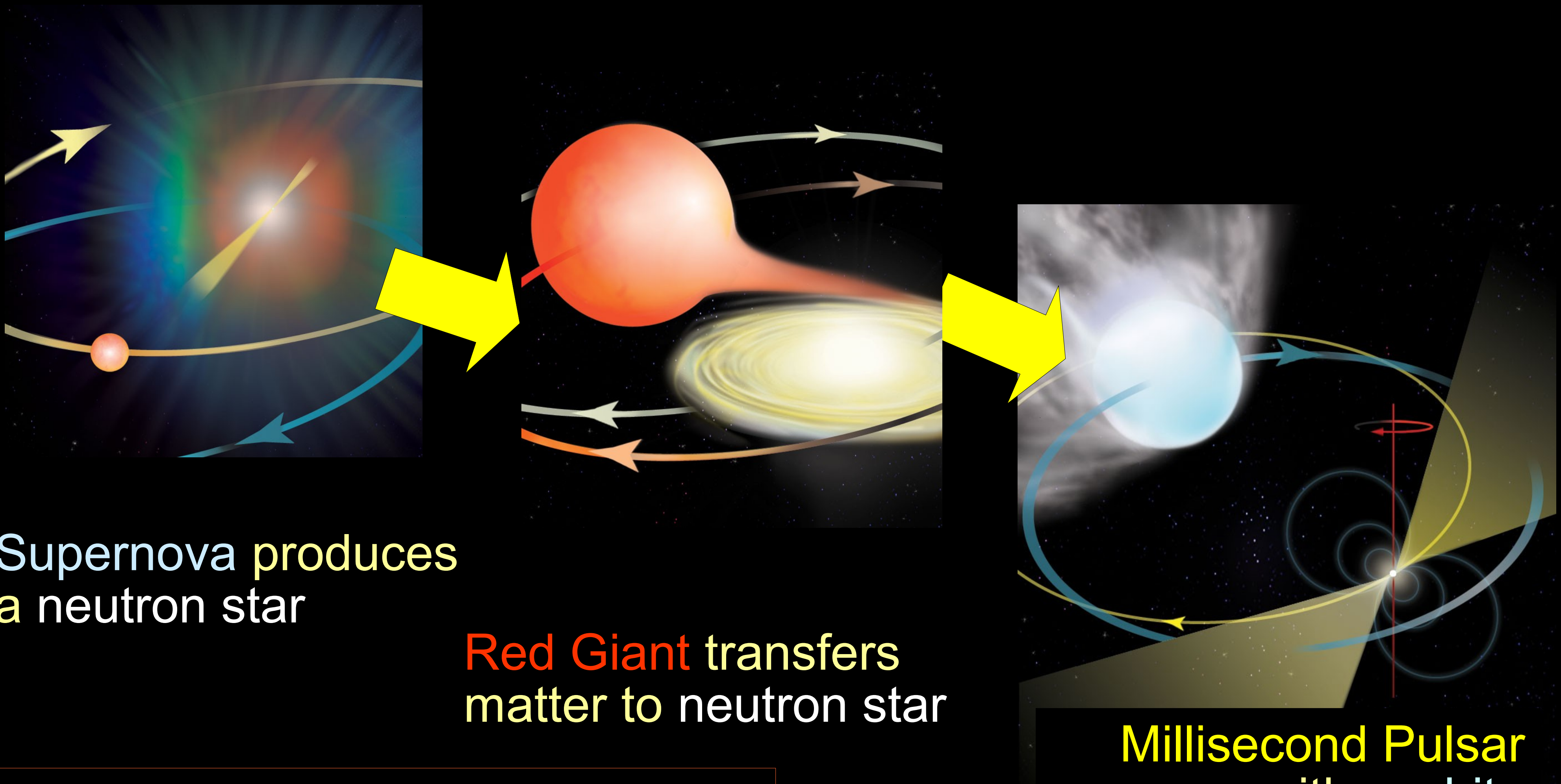
Normal PSRs
(average B, slow spin)

Young PSRs
(high B, fast spin, very energetic)

Millisecond PSRs
(low B, very fast, very old, very stable spin, best for basic physics tests)



Pulsar "Recycling"



Supernova produces a neutron star

Red Giant transfers matter to neutron star

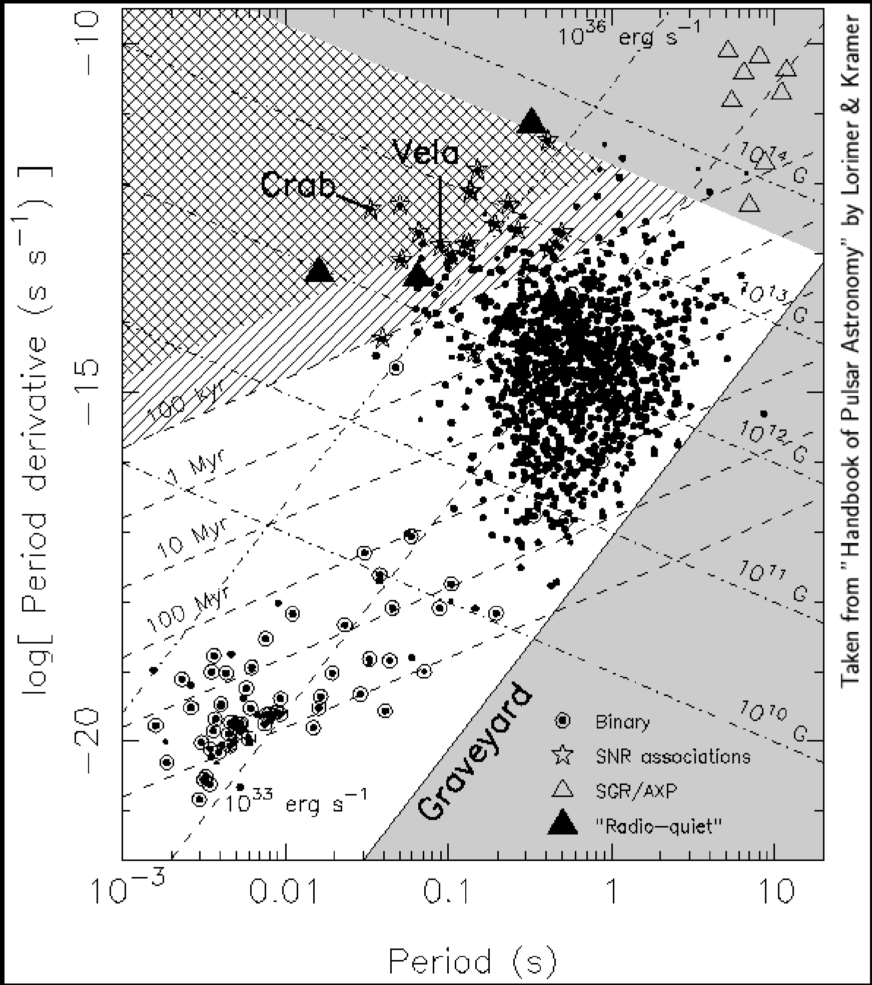
Millisecond Pulsar emerges with a white dwarf companion

Alpar et al 1982
Radhakrishnan & Srinivasan 1984

Picture credits: Bill Saxton, NRAO/AUI/NSF

Recently: A pulsar Renaissance

- Low-noise, wide BW, receivers from 1-2 GHz
  - Can see much deeper into the Galaxy (i.e. volume)
  - Greatly reduced scattering and/or smearing
- Better telescope systems
  - Parkes Multibeam system
  - Arecibo upgrade
  - GBT
- Much better pulsar backends
  - Faster sampling
  - Better frequency resolution
- Improved computational resources



The Primary Pulsar Telescopes

Arecibo

GBT

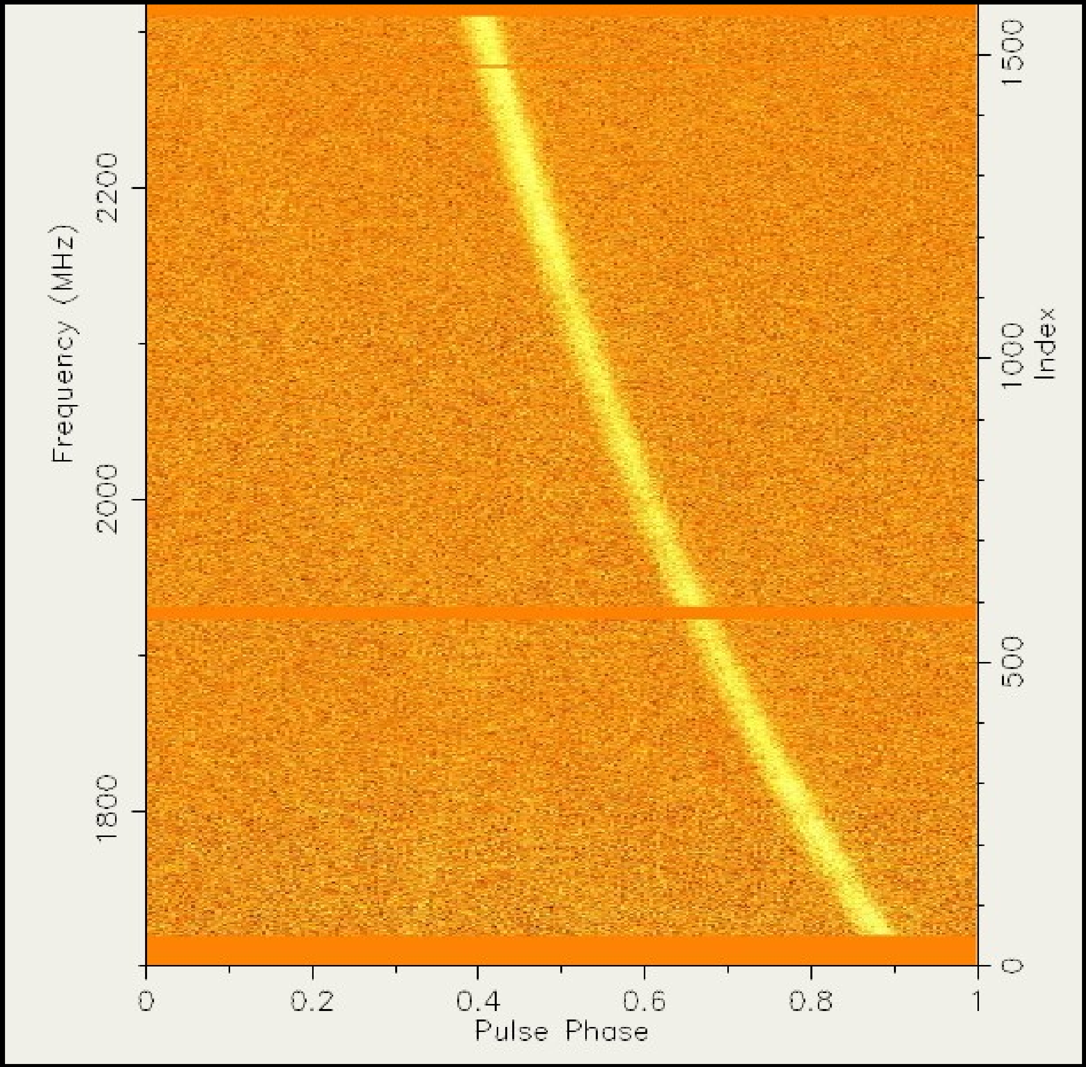
Parkes

Jodrell Bank

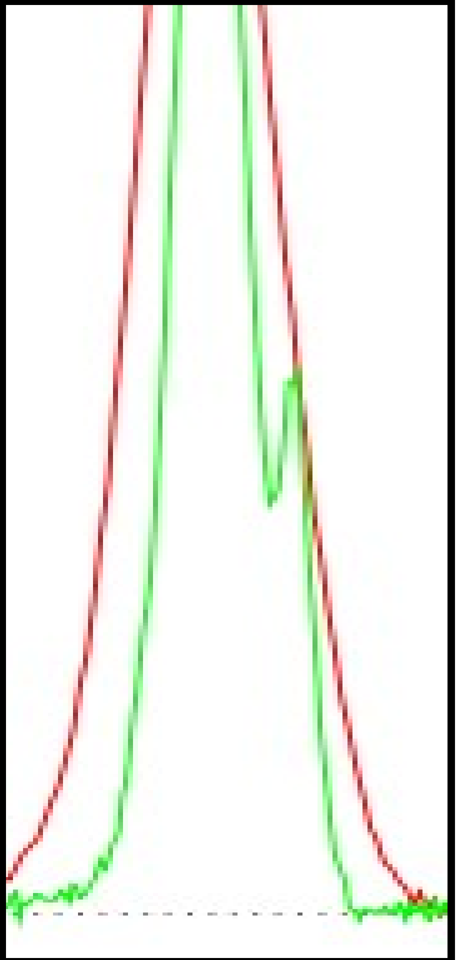
Dispersion

Lower frequency radio waves are delayed with respect to higher frequency radio waves by the ionized interstellar medium

$\Delta t \propto DM\nu^{-2}$ (DM = Dispersion Measure)

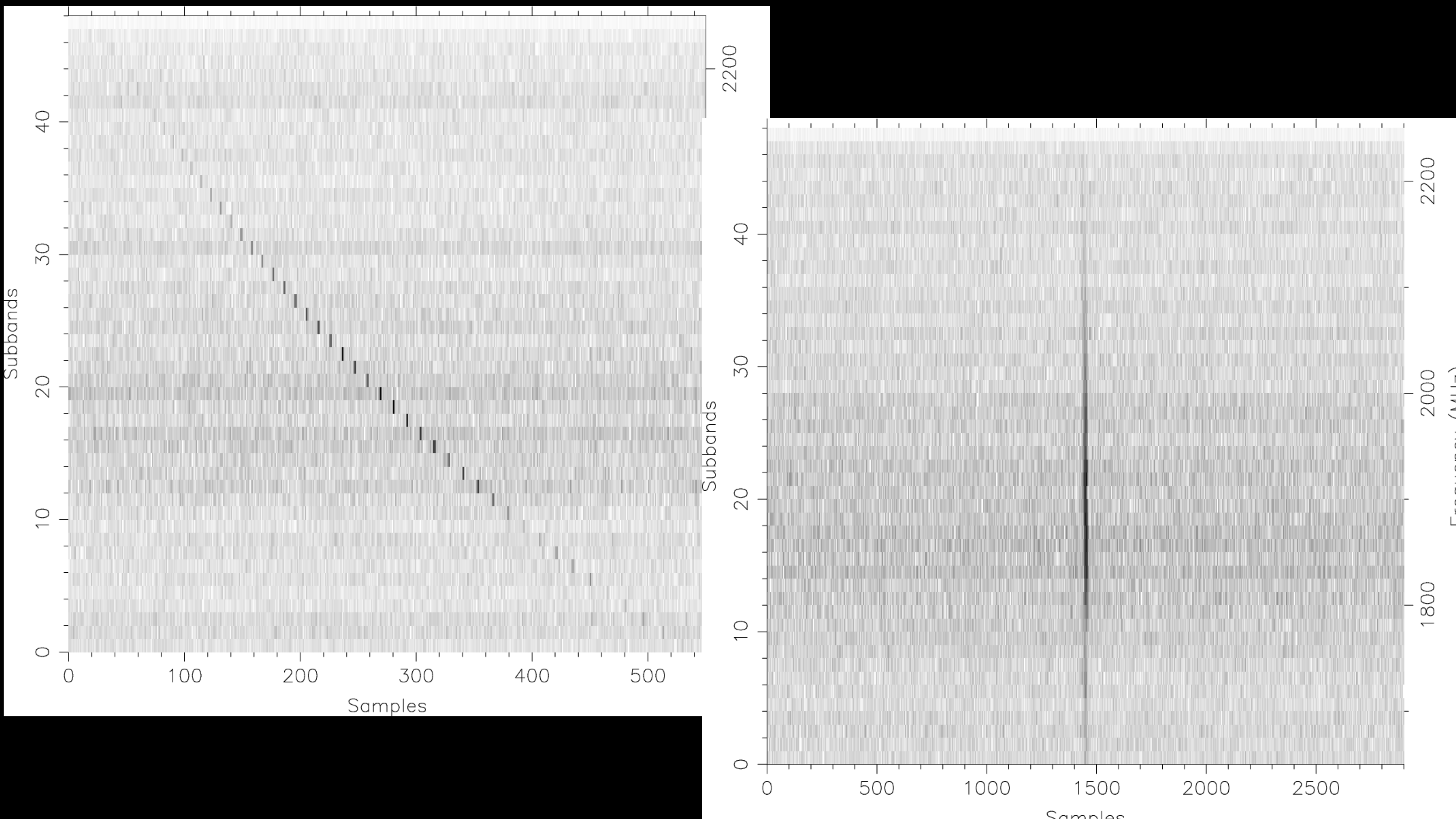


Coherent Dedispersion *exactly* removes this effect, but is very computationally difficult



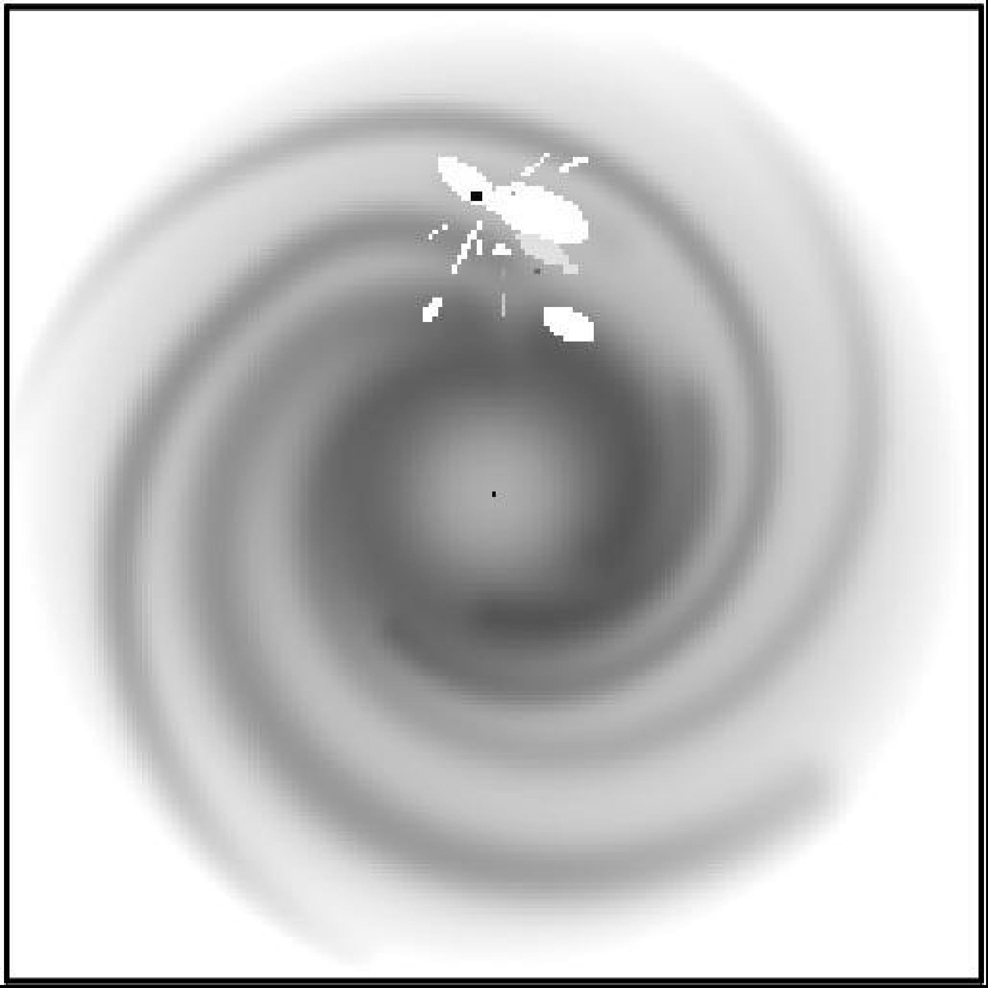
De-Dispersion for Searching

DM is unknown so we must search over different possible DMs!



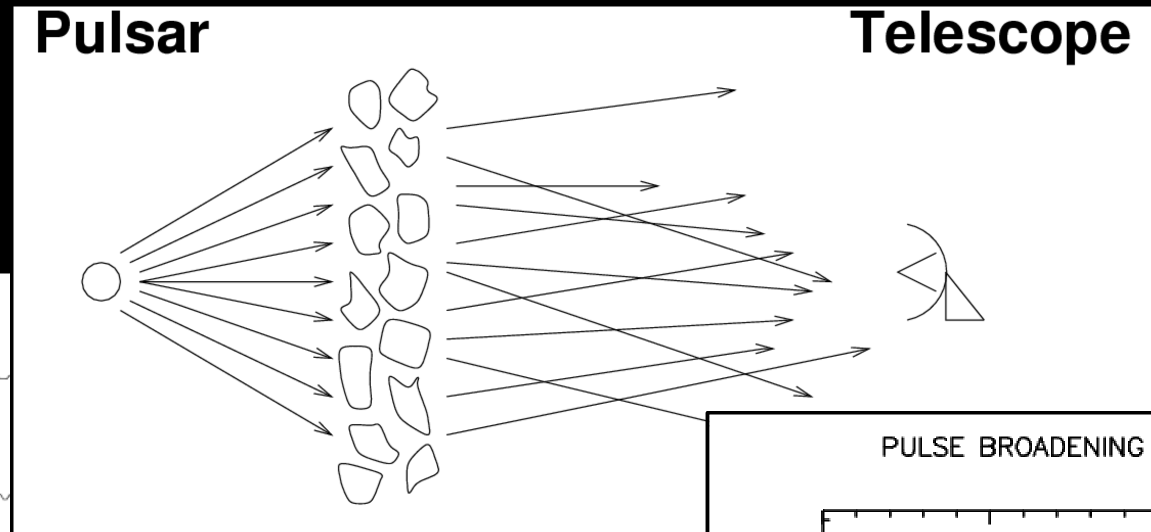
Galactic Electron Density Models

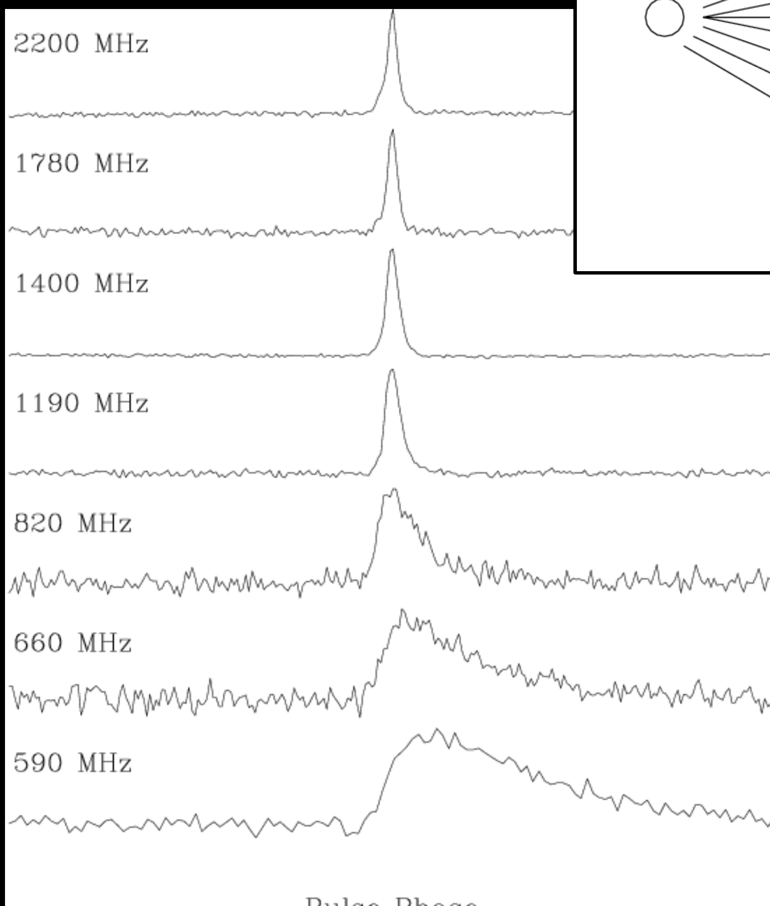
- All pulsars provide:
  P, P-dot, and DM
- DM important for:
  - Detailed studies of the ISM
  - Distance estimates for pulsars
  - Interpretation of scattering and scintillation of radio sources
  - RM helps with B fields
- Models are made using pulsars with "known" distances: in globular clusters, parallax, SNRs, HI absorption...



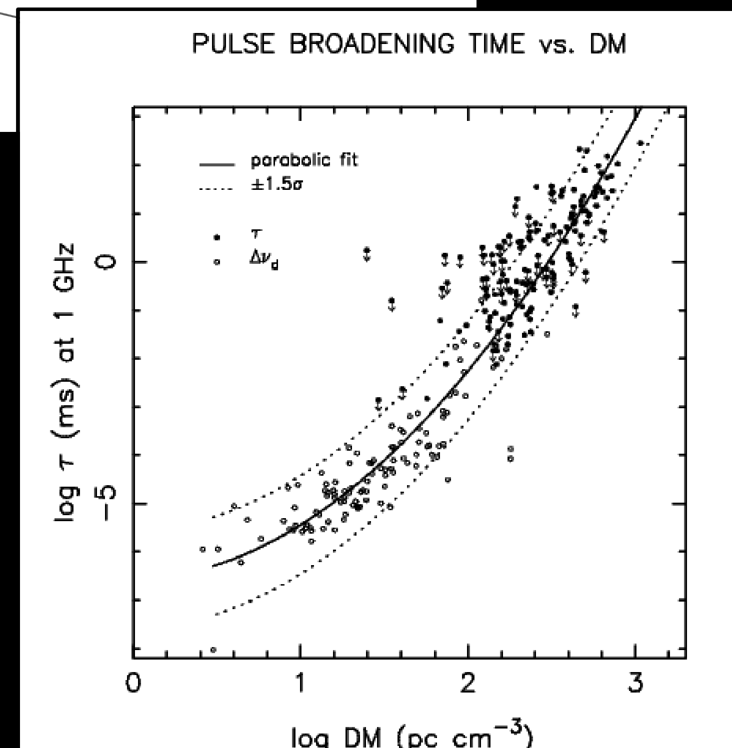
From Cordes and Lazio 2001 (NE2001)

Scattering and Pulse Broadening





$$\Delta\tau \propto \nu^{-4.4}$$



Multipath propagation causes frequency dependent pulse broadening.

Searching for (Interesting) New Pulsars

- Pulsars are:
  - Very weak radio sources
  - Binary pulsars show Doppler effects
  - Often distant (therefore weaker and high DM)
  - Predominantly found in the Galactic Plane (ISM effects)

Sensitivity $\propto (A / T_{tot}) (t_{int} BW)^{1/2}$ 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 advanced algorithms to optimize sensitivity to weak binary MSPs (the hardest PSRs to detect)

Basic Radio Pulsar Search Recipe

(GBT350 Driftscan Example)

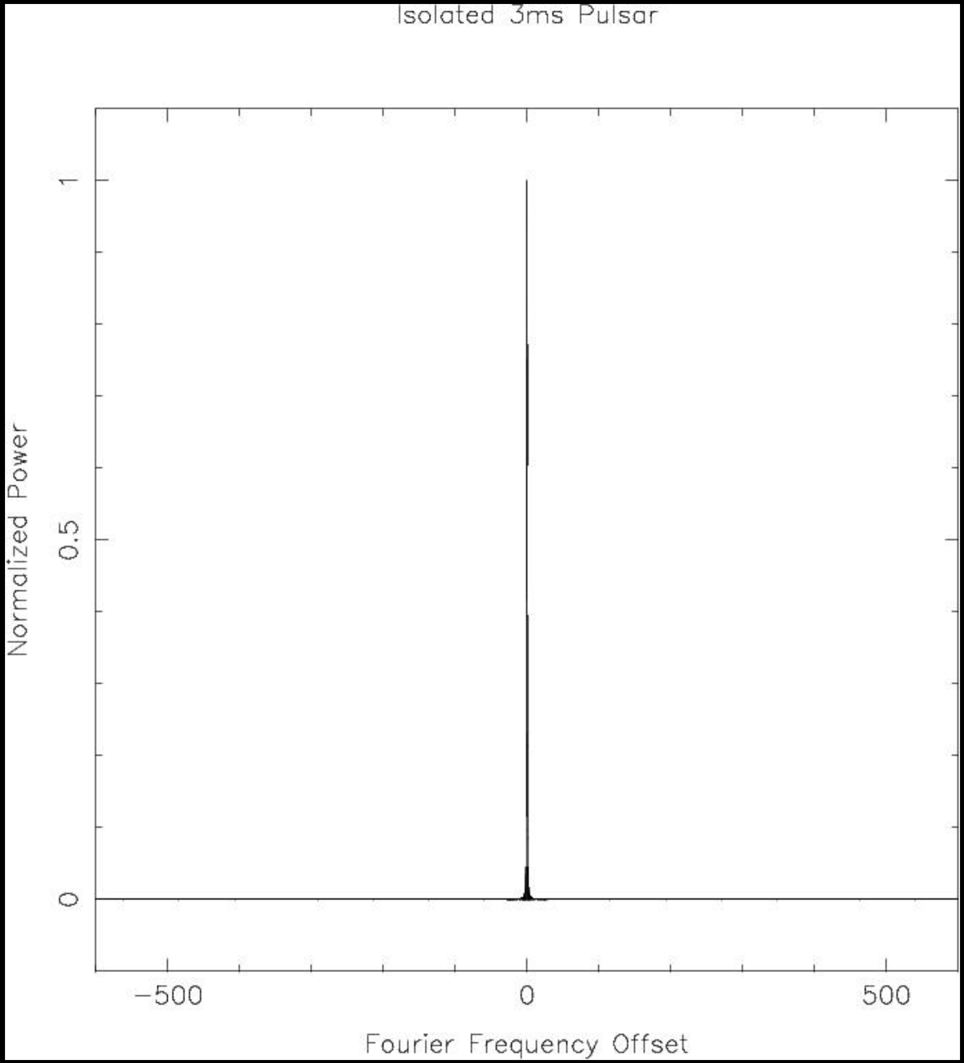
Step	(% of CPU Time)
1. Interference identification and removal	(1%)
2. De-dispersion of the raw data	(4%)
3. Normal FFT search (slow pulsars)	(17%)
4. Acceleration search (binary MSPs)	(57%)
5. Single-pulse search	(17%)
6. Sifting of candidates	(<1%)
7. Folding of candidates	(3%)

Processing a single ~150 sec “pointing” takes 12-32 hours!

We have ~65,000 pointings, therefore *2-3 CPU centuries!*

Binary Pulsar Search Techniques

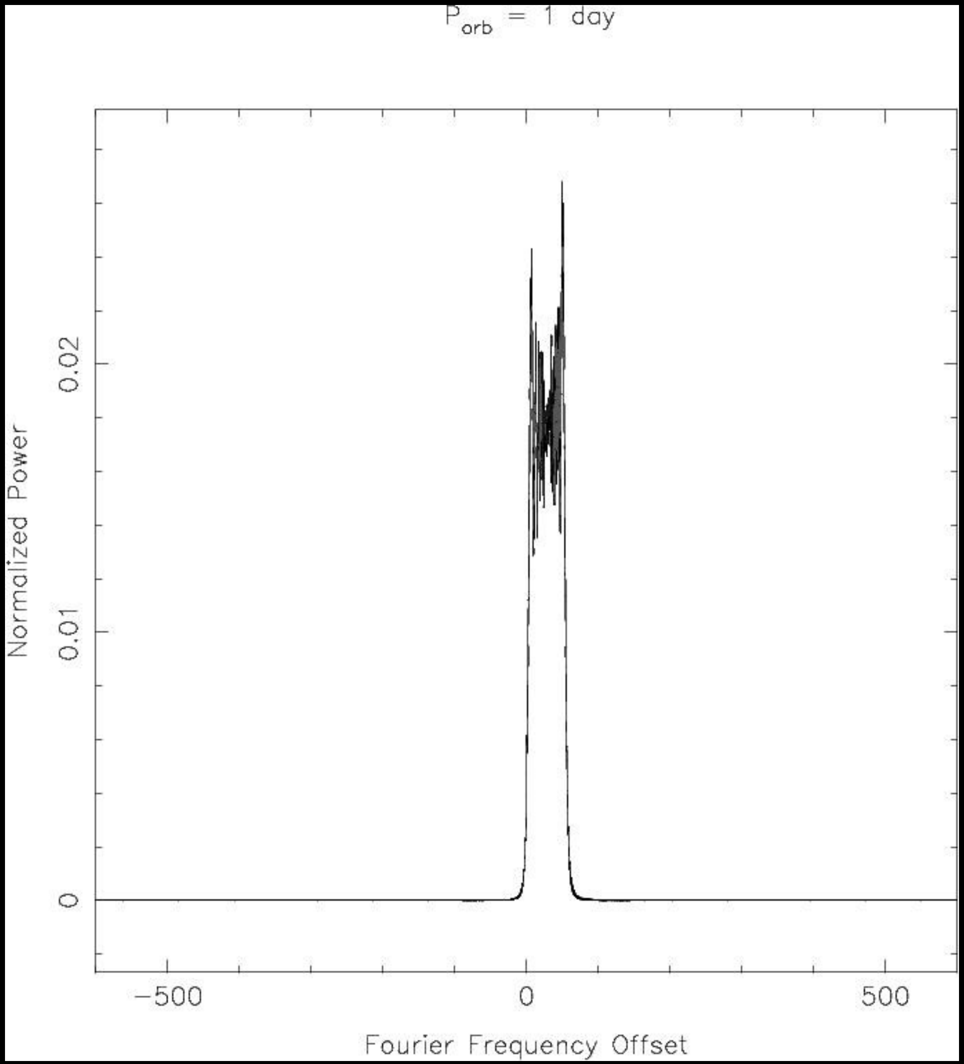
- Isolated Pulsars
  - Fourier analysis



3ms pulsar, 2 hr obs

Binary Pulsar Search Techniques

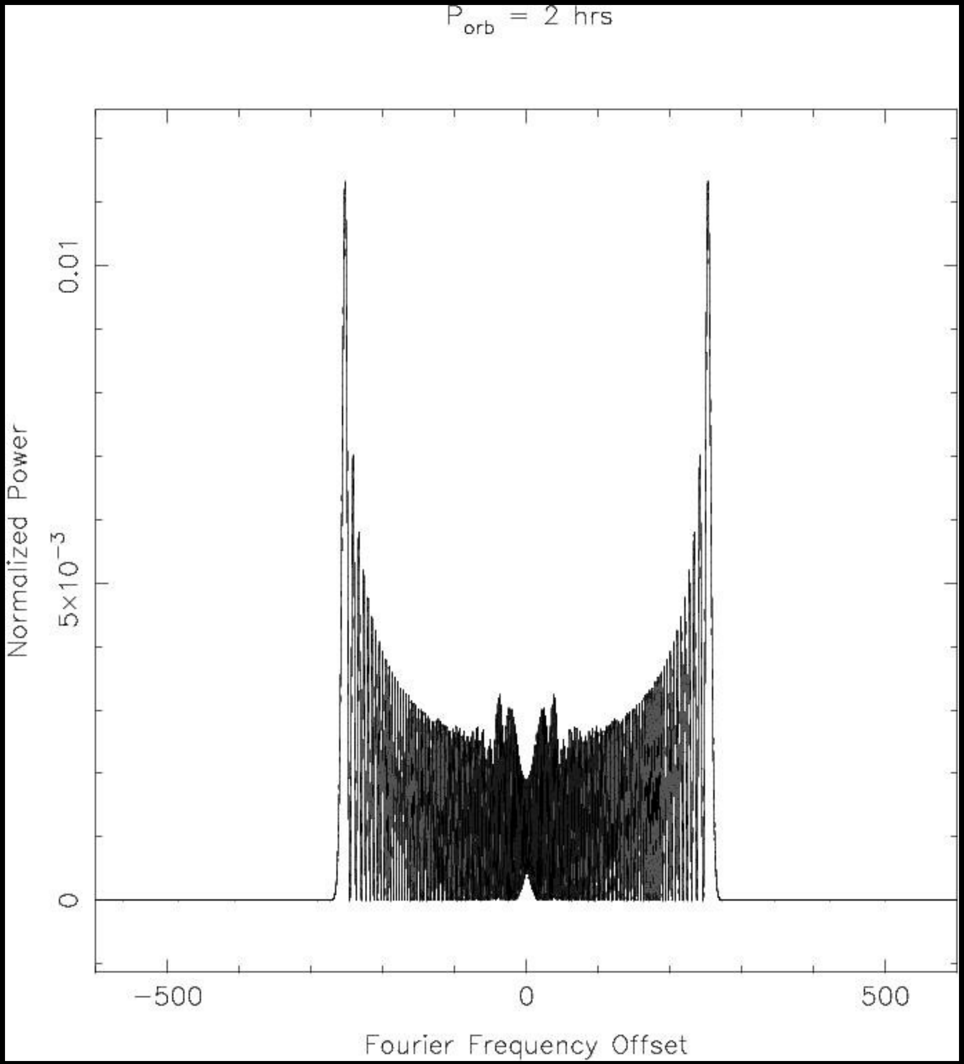
- Isolated Pulsars
  - Fourier analysis
- Binary $P_{orb} > 10T_{obs}$
  - "Acceleration" Searches



3ms pulsar, 2 hr obs

Binary Pulsar Search Techniques

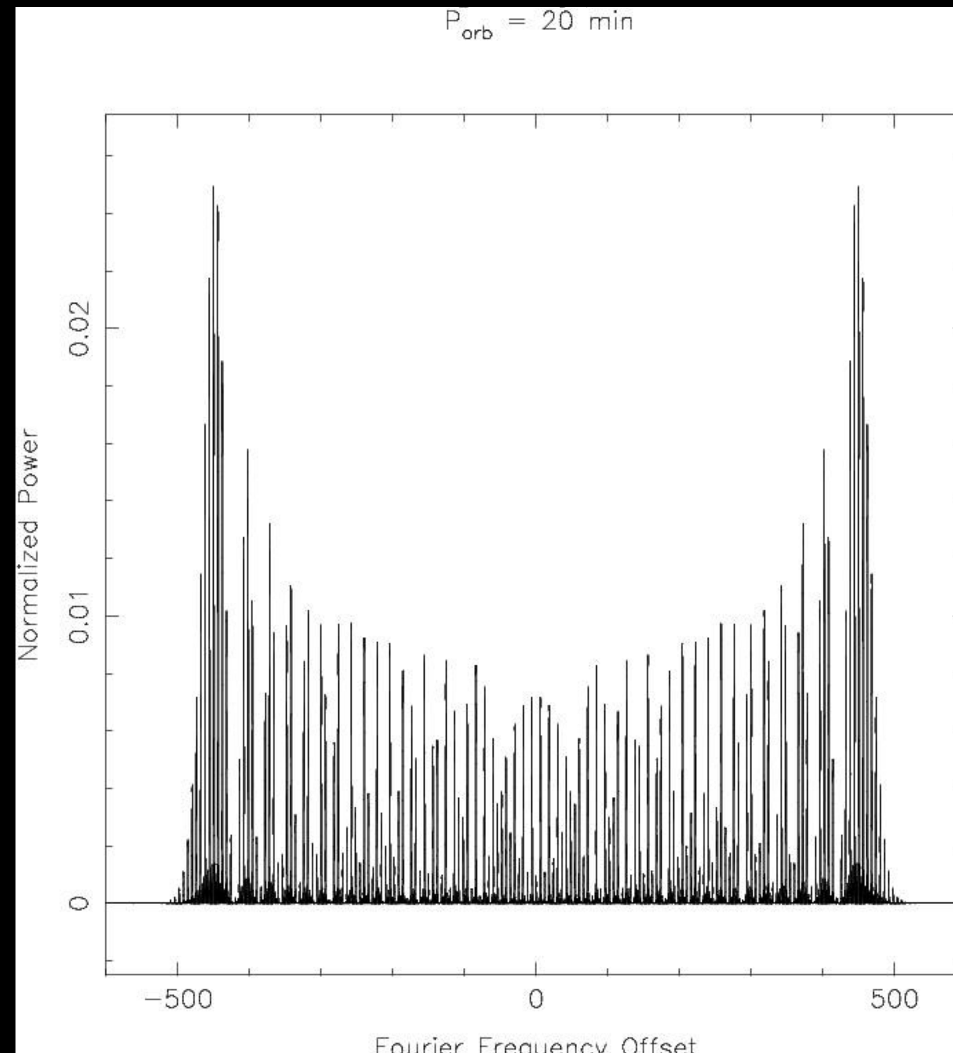
- Isolated Pulsars
  - Fourier analysis
- Binary $P_{orb} > 10T_{obs}$
  - "Acceleration" Searches
- Binary $P_{orb} \sim T_{obs}$
  - "Dynamic" Power Spectra



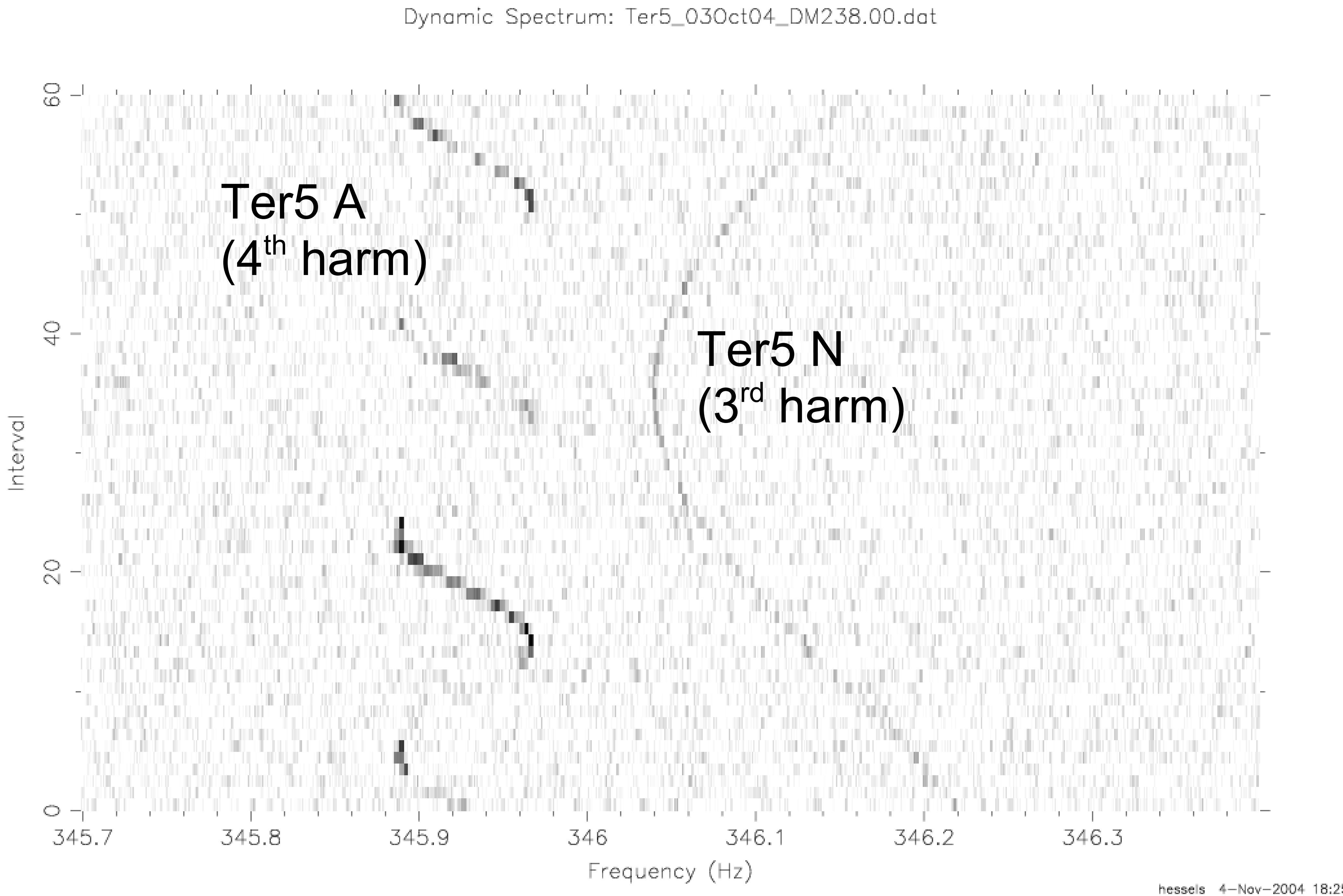
3ms pulsar, 2 hr obs

Binary Pulsar Search Techniques

- Isolated Pulsars
  - Fourier analysis
- Binary $P_{orb} > 10T_{obs}$
  - "Acceleration" Searches
- Binary $P_{orb} \sim T_{obs}$
  - "Dynamic" Power Spectra
- Binary $P_{orb} << T_{obs}$
  - "Sideband" Searches



3ms pulsar, 2 hr obs



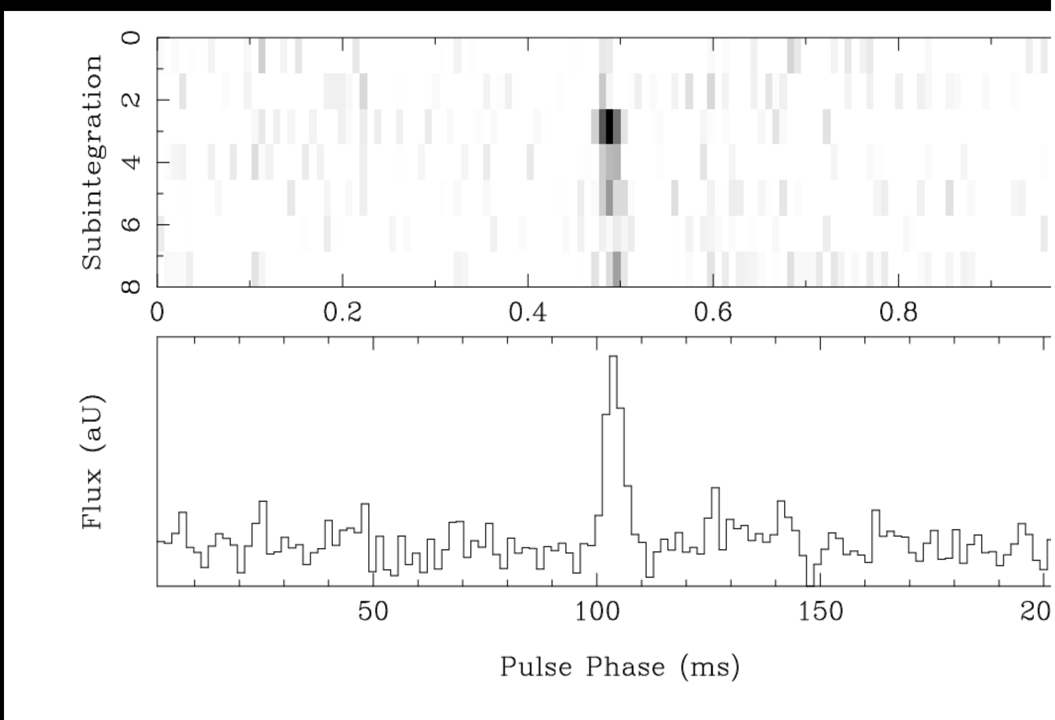
Dynamic Spectrum: Ter5_03Oct04_DM238.00.dat
Ter5 A
(4th harm)
Ter5 N
(3rd harm)
Interval
0
20
40
60
345.7
345.8
345.9
346
346.1
346.2
346.3
Frequency (Hz)
hessels 4-Nov-2004 18:25

Single Pulse Searches

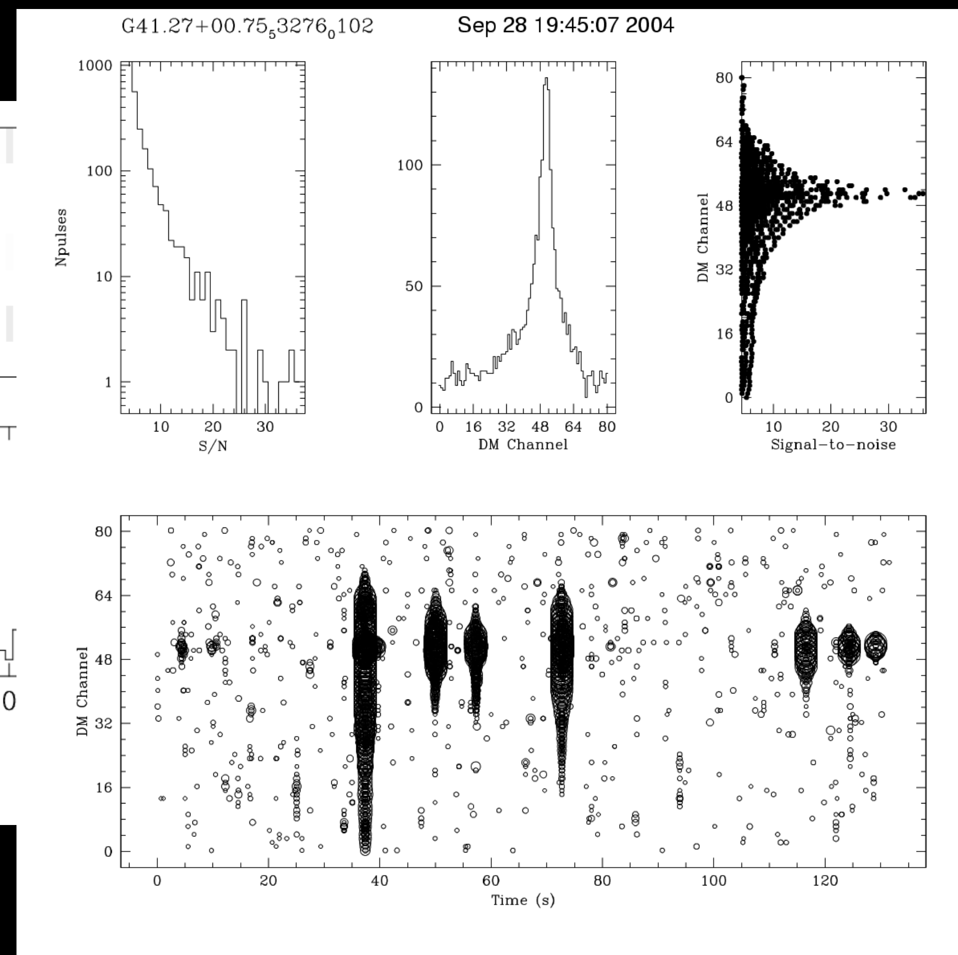
- Some pulsars have highly variable pulse amplitudes or shut off completely (*i.e.* nulling)

RRATs

- Look for dispersed individual pulses (e.g. McLaughlin & Cordes, 2003, ApJ, 596, 982)



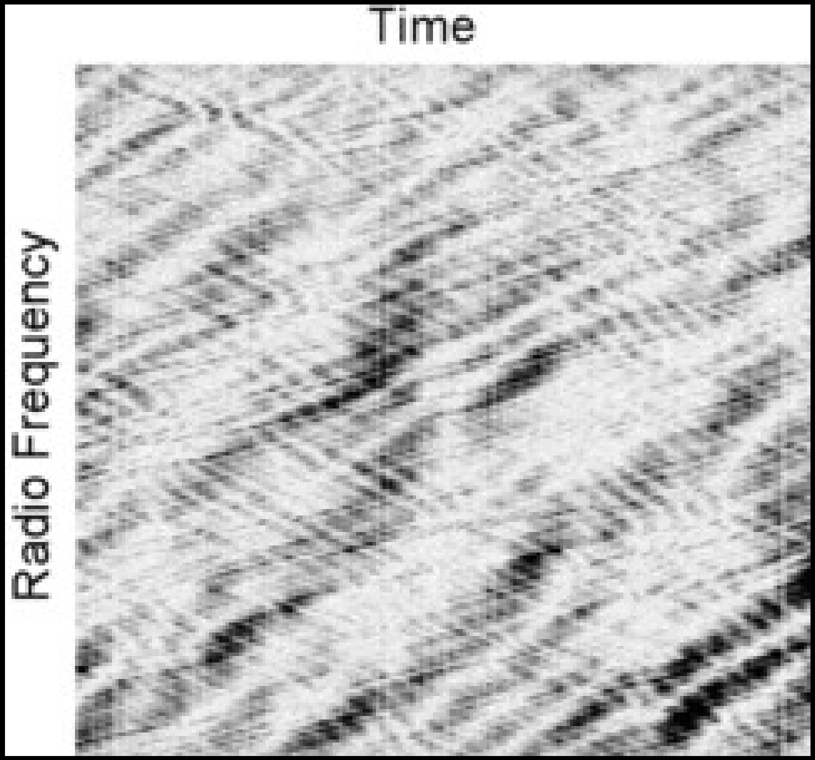
New PALFA Pulsar J1904+07



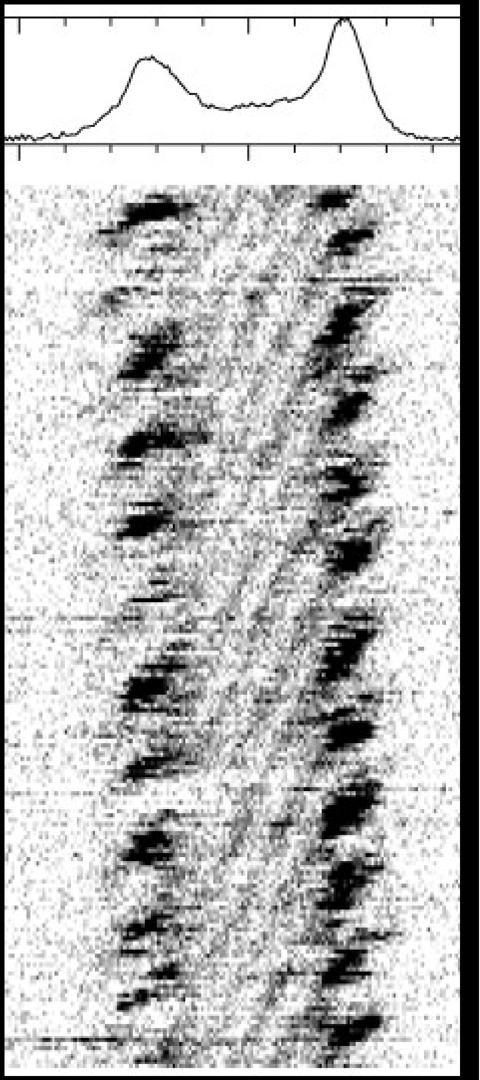
Single Pulse Studies

Used to

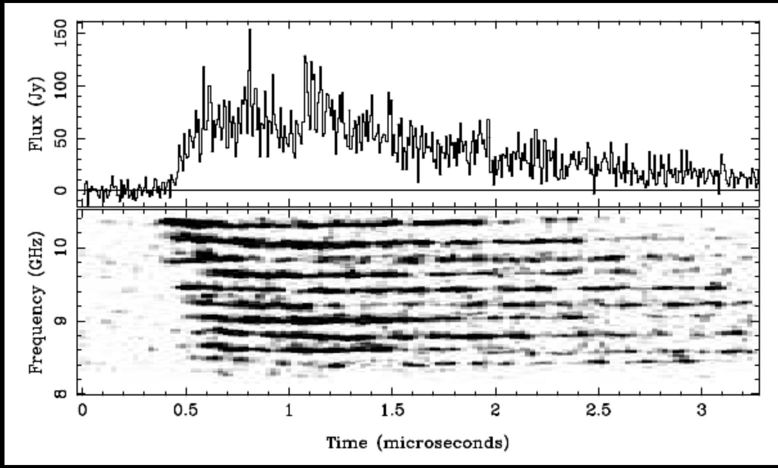
- study the unknown pulsar emission mechanism
- probe the interstellar medium
- Measure PSR distances (HI absorption)



Scintillation
Walker et al 2008



Drifting Sub-pulses
Bhattacharyya et al 2007

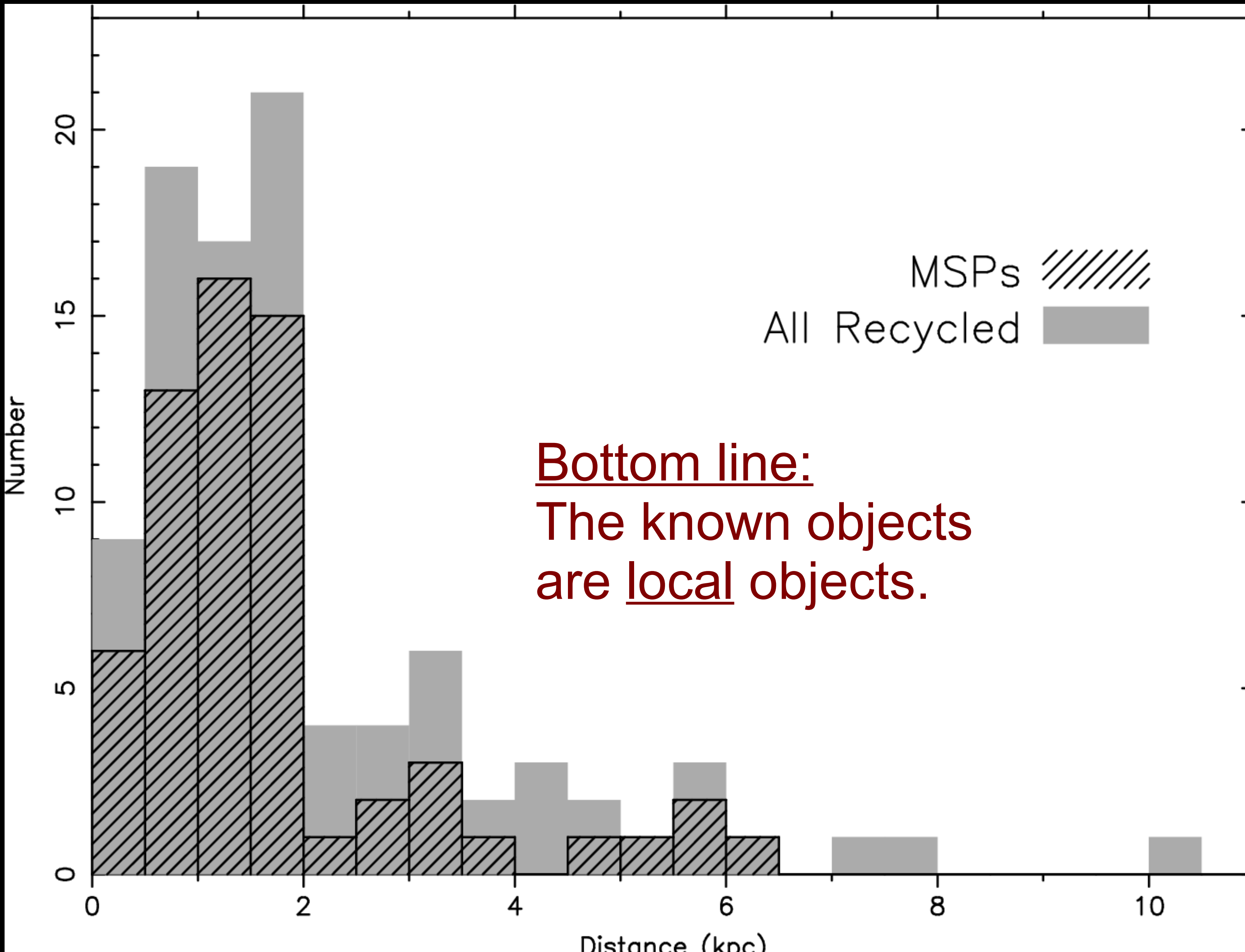


Giant Pulses Hankins & Eilek 2007

GBT 350 MHz Surveys

- Drift Scan (during track repair):
  - Lorimer, McLaughlin, Ransom, Boyles, Hessels, Champion, Kondratiev, Lynch, Stairs, van Leeuwen, Kasian, Kaspi, Roberts, Cordes, Deneva, Jenet... and the Pulsar Search Collaboratory!
  - ~1350 hrs @25 MB/s ~135 TB (~30% of the full sky!)
- Green Bank North Celestial Cap Survey:
  - Same basic cast (PI Ransom)
  - 1300 hrs @50 MB/s ~250 TB (~20% of the full sky!)
- Together we expect ~20 new MSPs (~10 so far)...

Recycled PSR Distances



<u>Bottom line:</u>
The known objects are <u>local</u> objects.

Parkes Multibeam Survey for Pulsars

System:
    13 beam L-band receiver system

Survey Area:
    -260 < l < 50 deg , -5 < b < 5 deg

Center Freq:
    1374 MHz

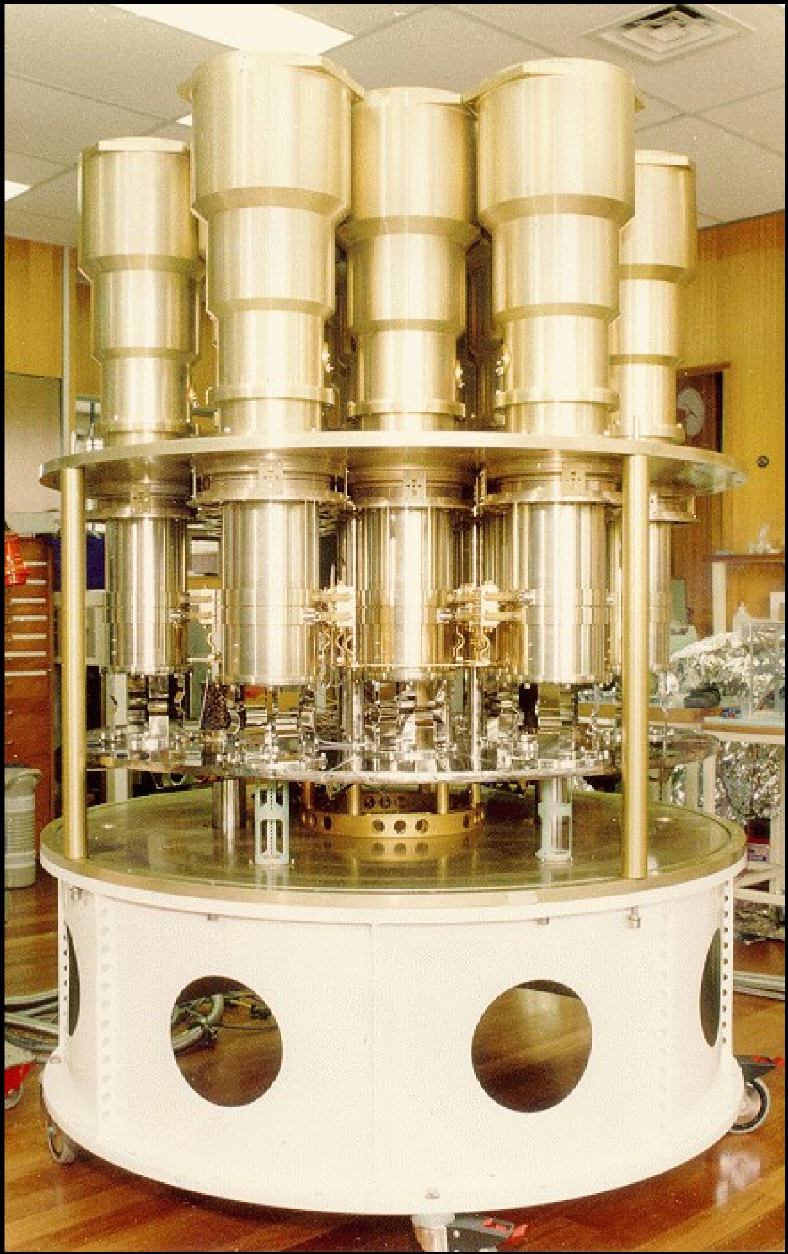
Bandwidth:
    288 MHz (96 chan x 3 MHz x 2 pol)

Sampling Rate:
    0.25 ms x 1 bit/chan

Integration Time:
    35 min per pointing

Sensitivity:
    ~7 times better than previous
    400 MHz surveys

Started in 1997 and
results are still coming!



But there are more Holy-Grails to find!

ALFA
Arecibo L-Band Feed Array

Pulsar-ALFA Survey

- Galactic plane and mid-latitude surveys
- More sensitive than Parkes survey in ~60s!
- Should find hundreds of new pulsars (have already found 40+)

Pulsars in Globular Clusters

- Clusters of ancient stars (9-12 billion years old) that orbit our galaxy
- Contain 10^5-10^6 stars, many of which have binary companions
- Very high central densities (100-10,000 stars/ly^3) result in stellar encounters and collisions!
- They are effectively millisecond pulsar factories (and strange ones at that!)
- Number known has quadrupled since 2000 (about 140 known now)

Pulsars are Precise Clocks

PSR J0437-4715

At 00:00 UT Jan 18 2011:

P = 5.7574519420243 ms

Pulsars are Precise Clocks

PSR J0437-4715

At 00:00 UT Jan 18 2011:

P = 5.7574519420243 ms

+/- 0.0000000000001ms

Pulsars are Precise Clocks

PSR J0437-4715

At 00:00 UT Jan 18 2011:

P = 5.75745194120243 ms
+/- 0.00000000000001ms

The last digit changes by 1 every half hour!

This digit changes by 1 every 500 years!

Pulsars are Precise Clocks

PSR J0437-4715

At 00:00 UT Jan 18 2011:

P = 5.757451924362137 ms

+/- 0.000000000000001ms

The last digit changes by 1 every half hour!

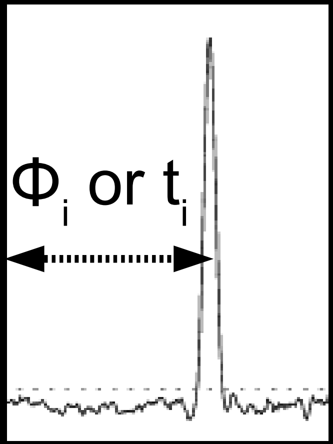
This digit changes by 1 every 500 years!

This extreme precision is what allows us to ***use pulsars as tools*** to do unique physics!

Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years

All about the phase (Φ) ...



TOAs: Times of Arrival

For MSPs: TOA precision is <1μs *or* ΔΦ ~ 0.0001

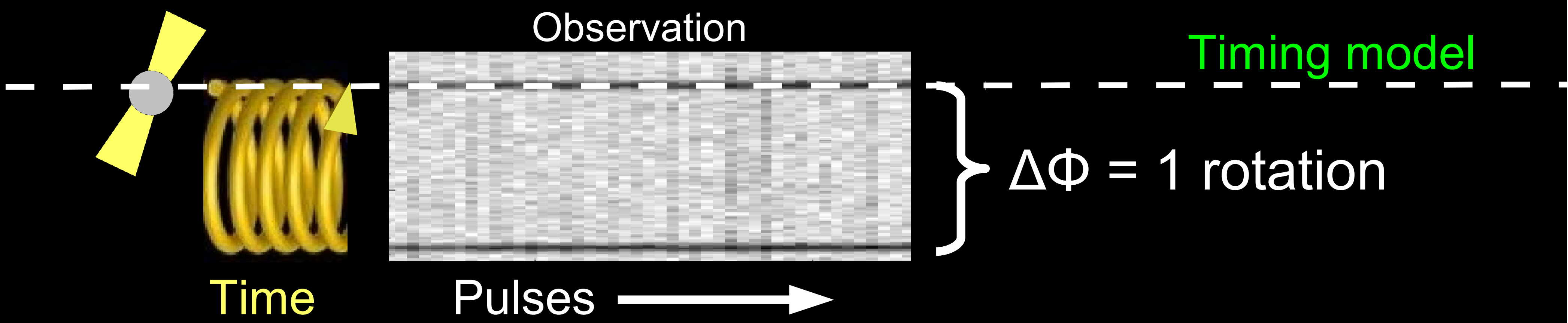
So for a 3 year set of observations....

$$\text{Frequency Error} \sim \frac{\Delta\phi}{\Delta T} \sim \frac{10^{-4}}{10^{8}\,\text{sec}} \sim 10^{-12}\,\text{Hz}$$

That is about 14 significant figures!

Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years



Pulsar Timing:

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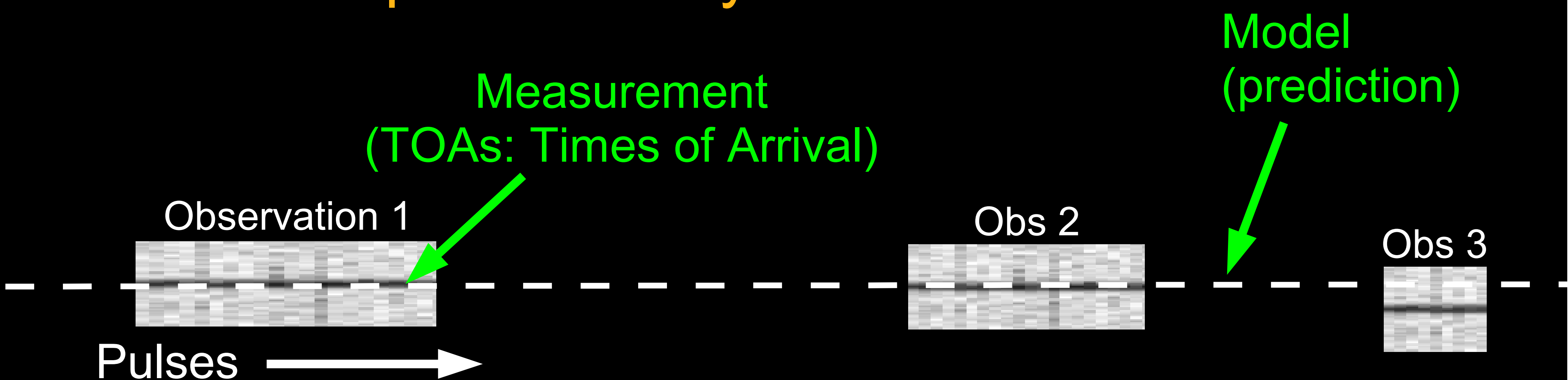
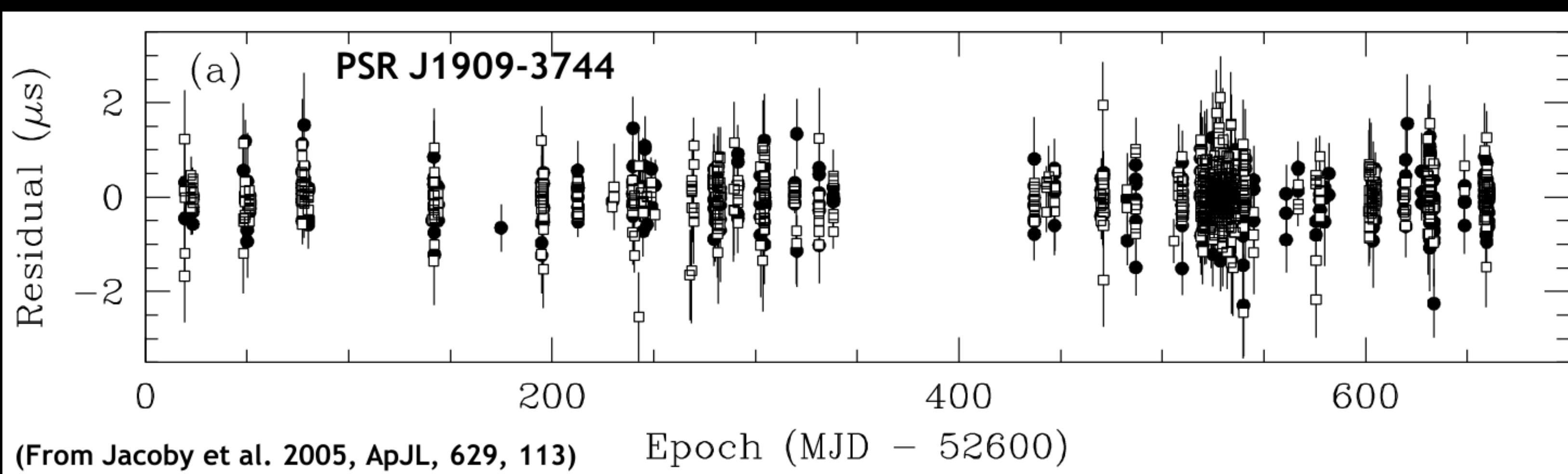


Measurement - Model = Timing Residuals



(From Jacoby et al. 2005, ApJL, 629, 113)

200ns RMS over 2 yrs

Precision Timing Example

- Astrometric Params
  - RA, DEC, μ, π
- Spin Params
  - P_{spin}, $\dot{P}_{spin}$
- Keplerian Orbital Params
  - P_{orb}, x, e, ω, T_0
- Post-Keplerian Params
  - ω, γ, $\dot{P}_{orb}$, $\dot{r}$, s

Table 1 PSR J0437–4715 physical parameters

Right ascension, α (J2000) ...	$04^h37^m15\overset{s}{.}7865145(7)$
Declination, δ (J2000)	$-47°15'08\overset{''}{.}461584(8)$
μ_α (mas yr^{-1})	121.438(6)
μ_δ (mas yr^{-1})	-71.438(7)
Annual parallax, π (mas)	7.19(14)
Pulse period, P (ms)	5.757451831072007(8)
Reference epoch (MJD)	51194.0
Period derivative, $\dot{P}$ (10^{-20}) ..	5.72906(5)
Orbital period, P_b (days)	5.741046(3)
x (s)	3.36669157(14)
Orbital eccentricity, e	0.000019186(5)
Epoch of periastron, T_0 (MJD)	51194.6239(8)
Longitude of periastron, ω (°) .	1.20(5)
Longitude of ascension, Ω (°) .	238(4)
Orbital inclination, i (°)	42.75(9)
Companion mass, m_2 ($M_\odot$) ...	0.236(17)
$\dot{P}_b$(10^{-12})	3.64(20)
$\dot{\omega}$ (°yr^{-1})	0.016(10)

~100 ns RMS timing residuals!

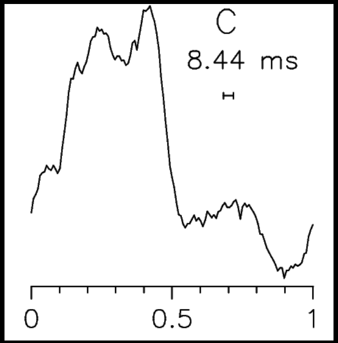
Recent work (e.g. Verbiest et al 2009) shows this is sustainable over 5+ yrs for several MSPs

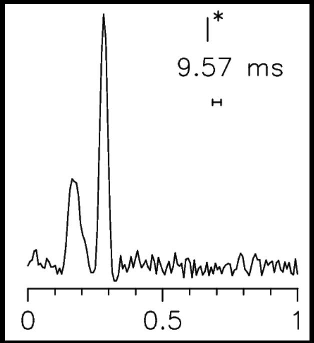
van Straten et al. 2001, Nature, 412, 158

Timing Sensitivity

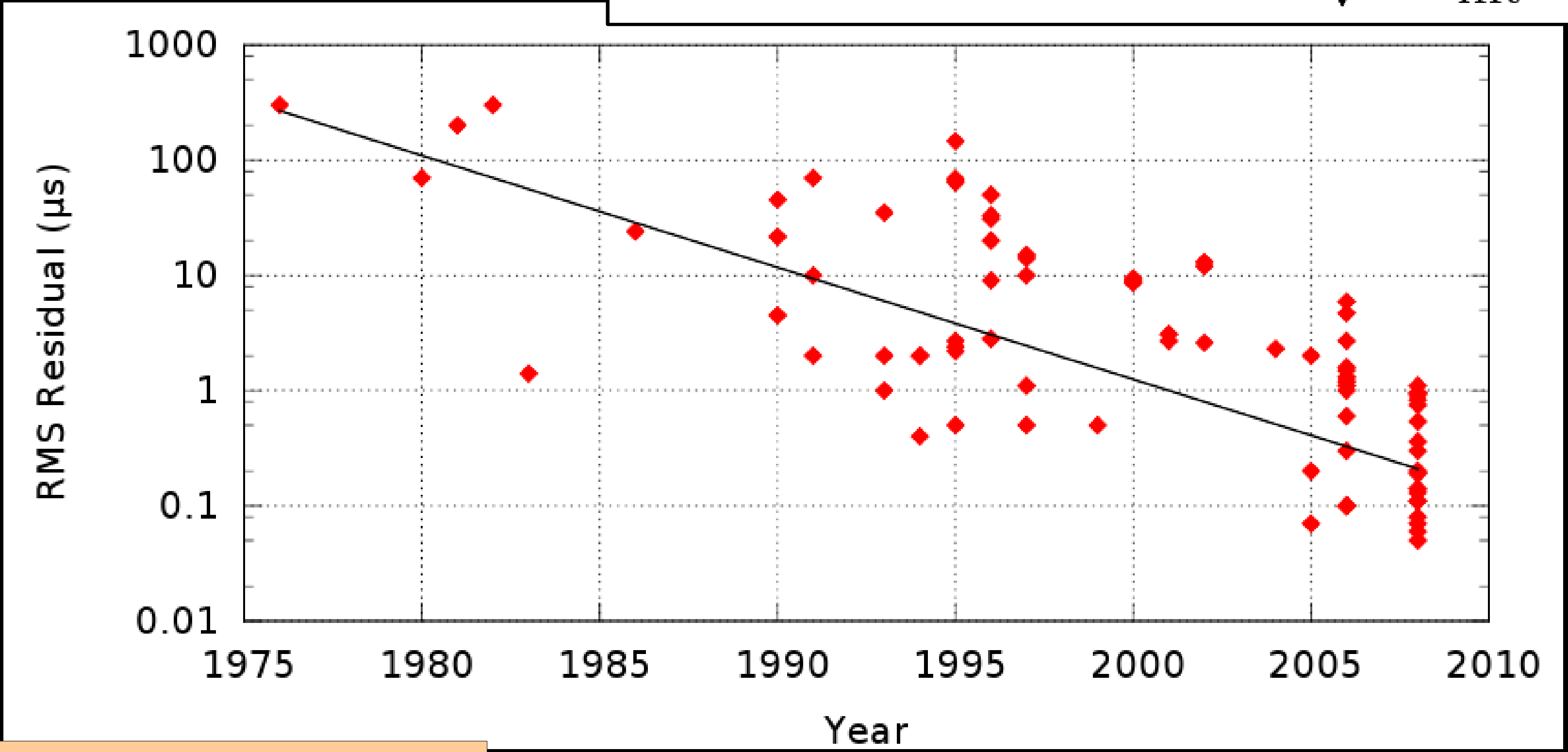
Timing precision depends on:

- Sensitivity (A/Tsys)
- Pulse width (w)
- Pulsar flux density (S)
- Instrumentation

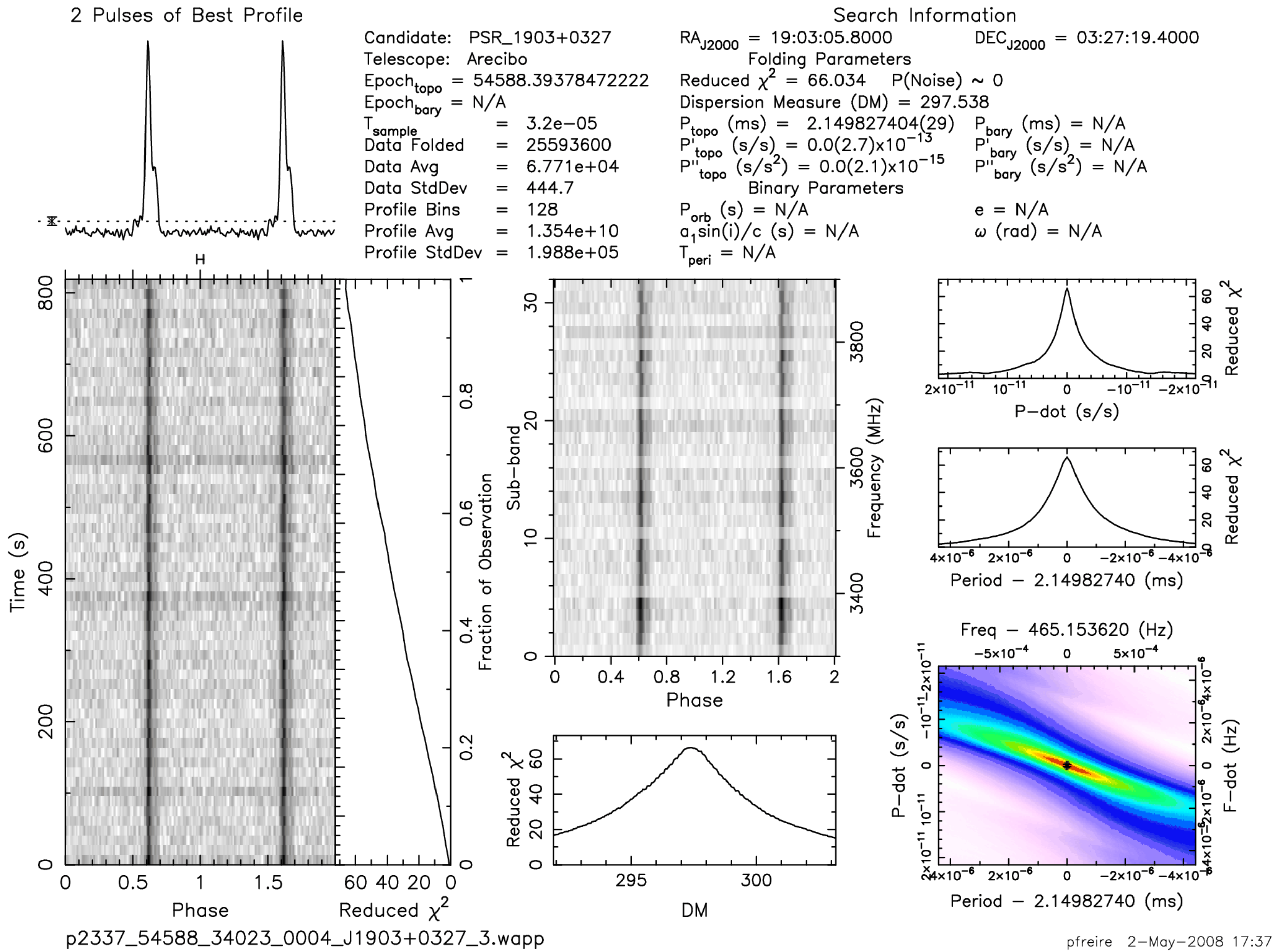




$$\sigma_{\mathrm{TOA}} \sim \frac{w}{\mathrm{SNR}} \propto \frac{w}{S_{\mathrm{PSR}}} \frac{1}{\sqrt{Bt_{\mathrm{int}}}} \frac{T_{\mathrm{sys}}}{A}$$

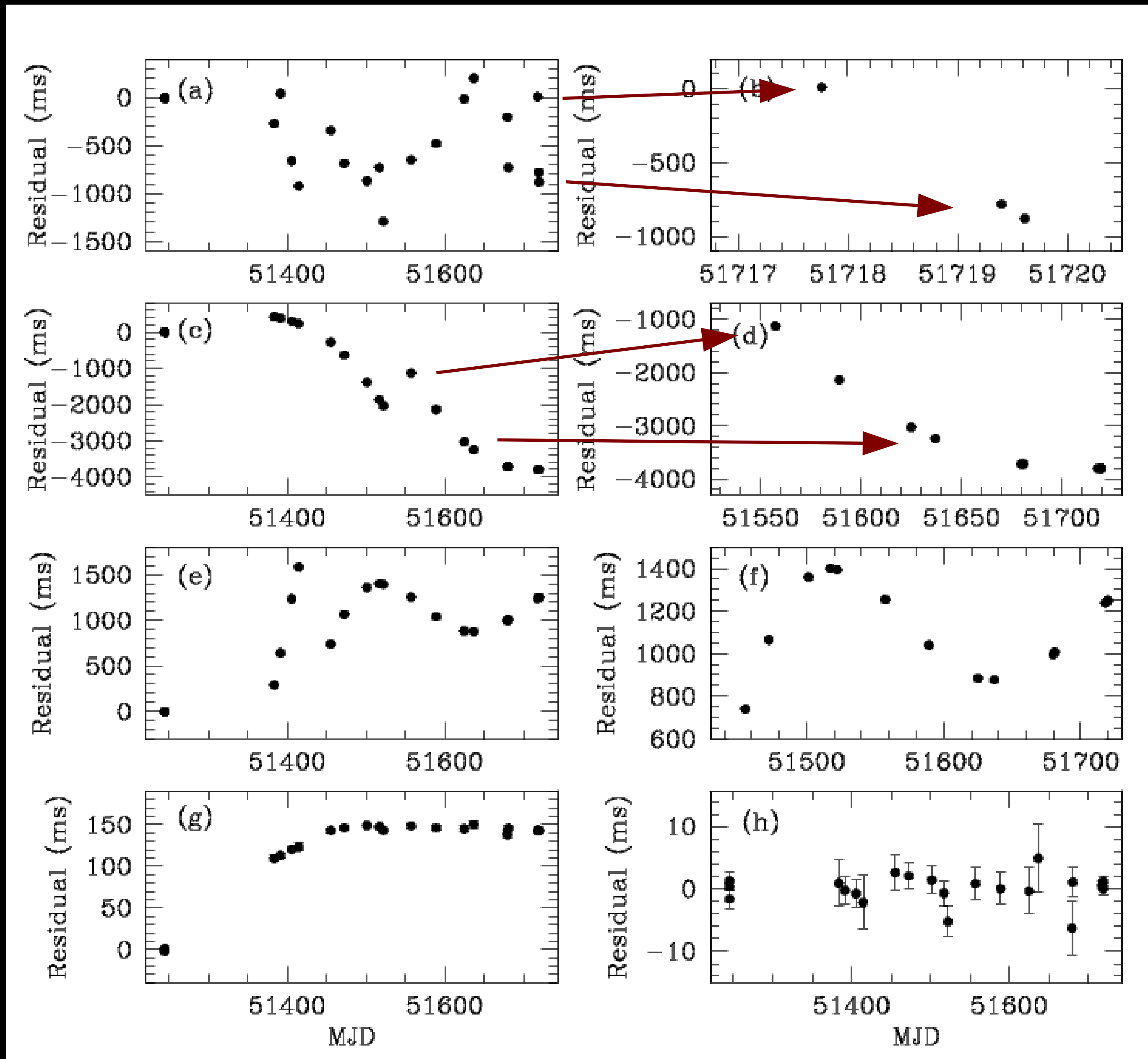


From Jenet & Demorest


2 Pulses of Best Profile
Search Information
Candidate: PSR_1903+0327
Telescope: Arecibo
Epoch_topo = 54588.39378472222
Epoch_bary = N/A
T_sample = 3.2e−05
Data Folded = 25593600
Data Avg = 6.771e+04
Data StdDev = 444.7
Profile Bins = 128
Profile Avg = 1.354e+10
Profile StdDev = 1.988e+05
RA_J2000 = 19:03:05.8000
DEC_J2000 = 03:27:19.4000
Folding Parameters
Reduced χ2 = 66.034 P(Noise) ~ 0
Dispersion Measure (DM) = 297.538
P_topo (ms) = 2.149827404(29)
P_bary (ms) = N/A
P'_topo (s/s) = 0.0(2.7)x10−13
P'_bary (s/s) = N/A
P''_topo (s/s2) = 0.0(2.1)x10−15
P''_bary (s/s2) = N/A
Binary Parameters
P_orb (s) = N/A
e = N/A
a1sin(i)/c (s) = N/A
ω (rad) = N/A
T_peri = N/A
Time (s)
Phase
Reduced χ2
Fraction of Observation
Sub-band
Frequency (MHz)
DM
P−dot (s/s)
Period − 2.14982740 (ms)
Freq − 465.153620 (Hz)
F−dot (Hz)
p2337_54588_34023_0004_J1903+0327_3.wapp
pfreire 2−May−2008 17:37

Establishing a timing solution

Initial scatter



Establish Phase

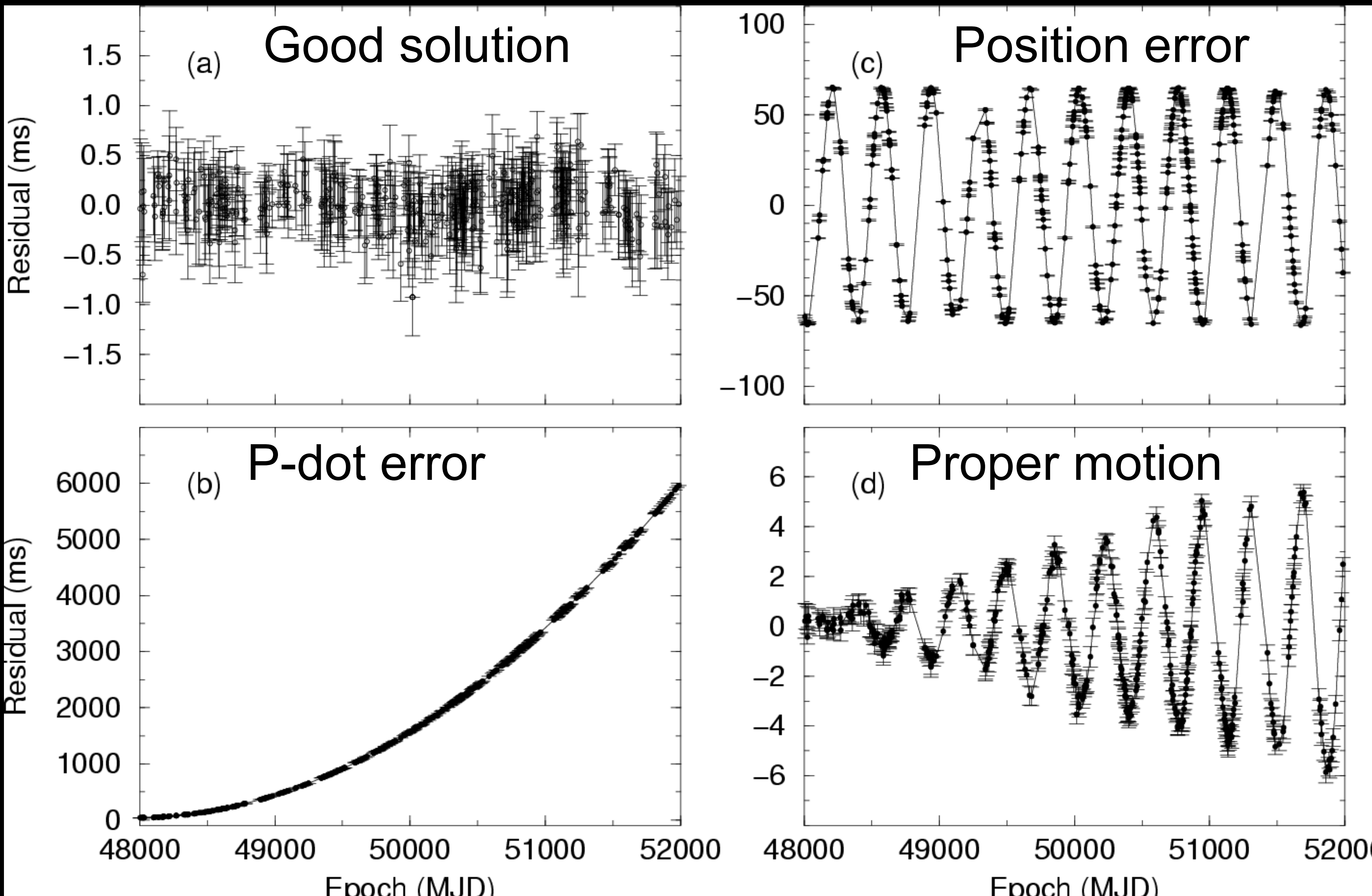
$f = d\phi/dt$

Fit RA, Dec, *or* f-dot

Fit RA, Dec, *and* f-dot

Final Solution (notice scale)

Timing Example



Post-Keplerian Orbital Parameters

Besides the normal 5 "Keplerian" parameters (P_{orb}, e, $a\sin(i)/c$, T_0, ω), 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: $T_\odot \equiv GM_\odot/c^3 = 4.925490947$ μs, $M = m_1 + m_2$, 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

Post-Keplerian Orbital Parameters

Besides the normal 5 “Keplerian” parameters (P_{orb}, e, *a*sin(*i*)/c, T_0, ω), General Relativity gives:

$\dot{\omega}$ = Need eccentric orbit and time for precession (Orbital Precession)

γ = (Grav redshift + time dilation)

$\dot{P}_b$ = Need compact orbit and a lot of patience

r = Need high precision, Inclination, and m_2 (Shapiro delay: “range” and “shape”)

s =

where: $T_\odot \equiv GM_\odot/c^3$ = 4.925490947 μs, $M = m_1 + m_2$, and $s \equiv \sin(i)$

These are only functions of:

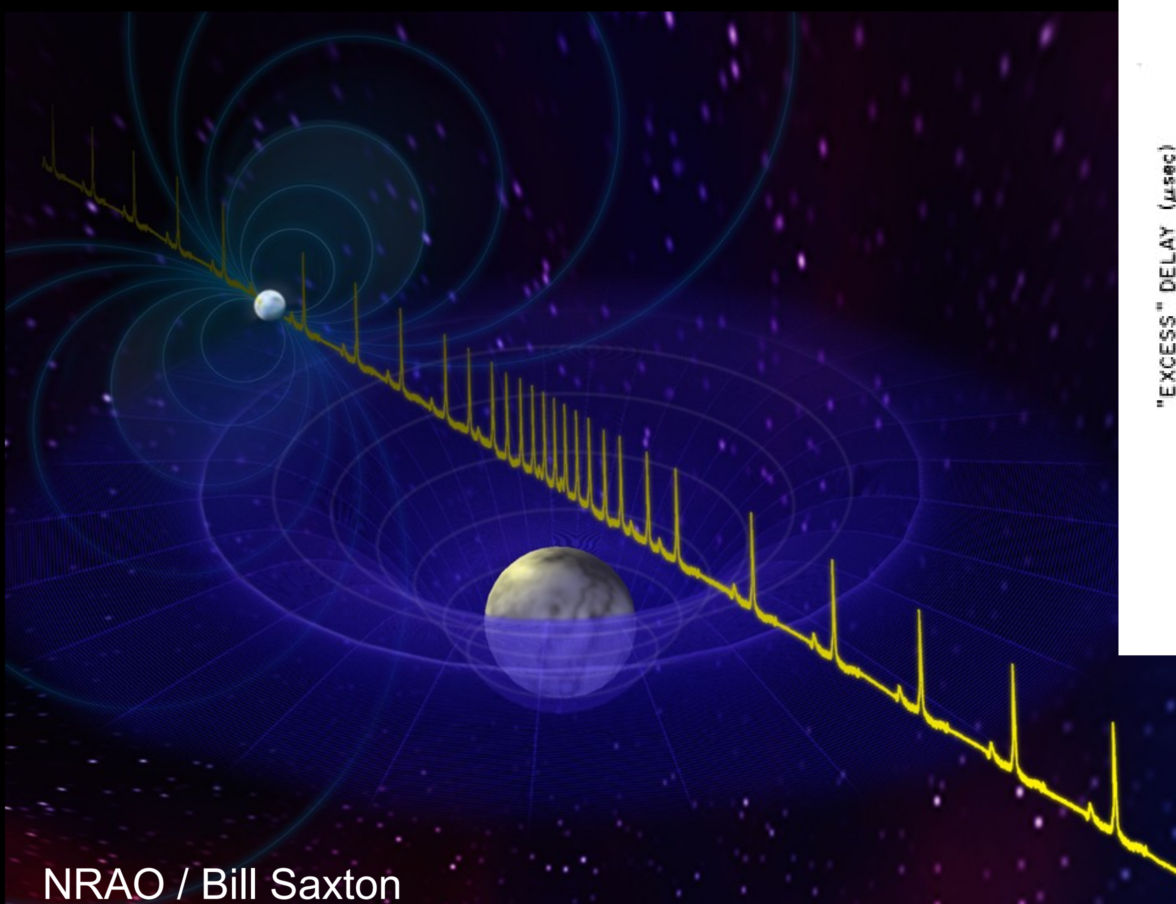
- the (precisely!) known Keplerian orbital parameters P_b, e, asin(i)
- the mass of the pulsar m_1 and the mass of the companion m_2

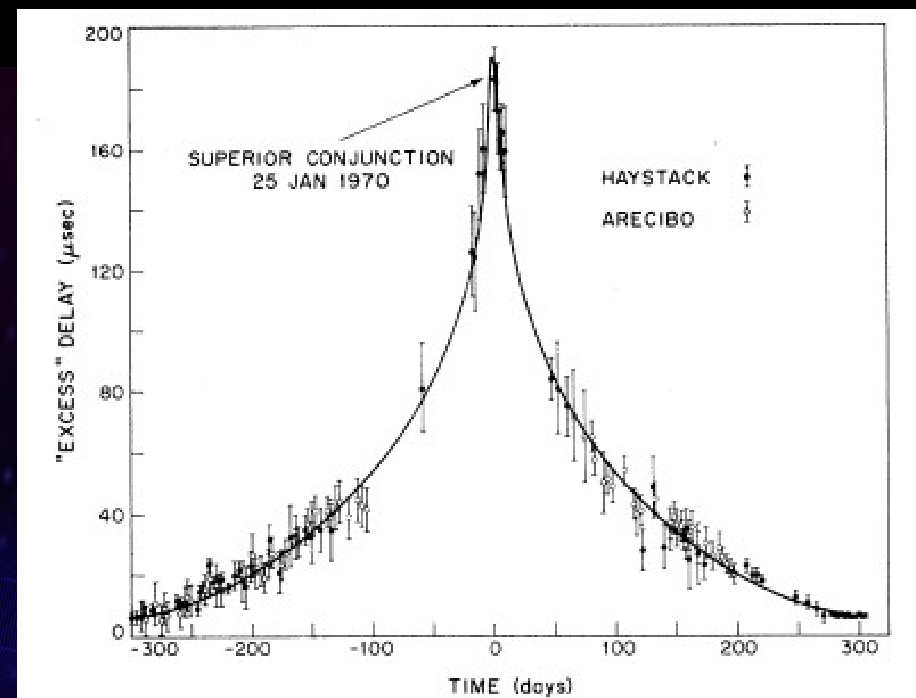
Shapiro Delay

VOLUME 13, NUMBER 26 PHYSICAL REVIEW LETTERS 28 DECEMBER 1964

FOURTH TEST OF GENERAL RELATIVITY

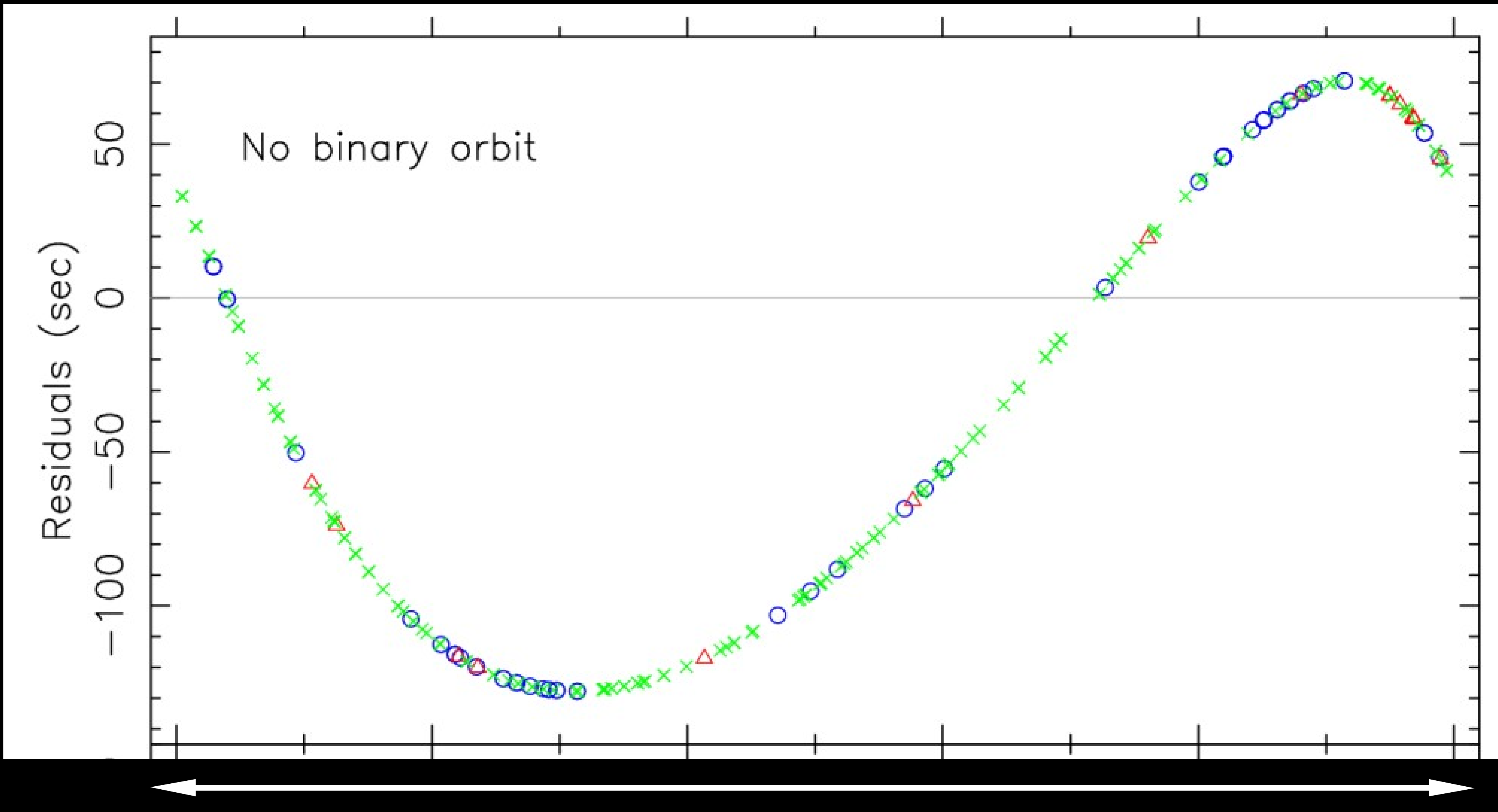
Irwin I. Shapiro
Lincoln Laboratory,* Massachusetts Institute of Technology, Lexington, Massachusetts
(Received 13 November 1964)





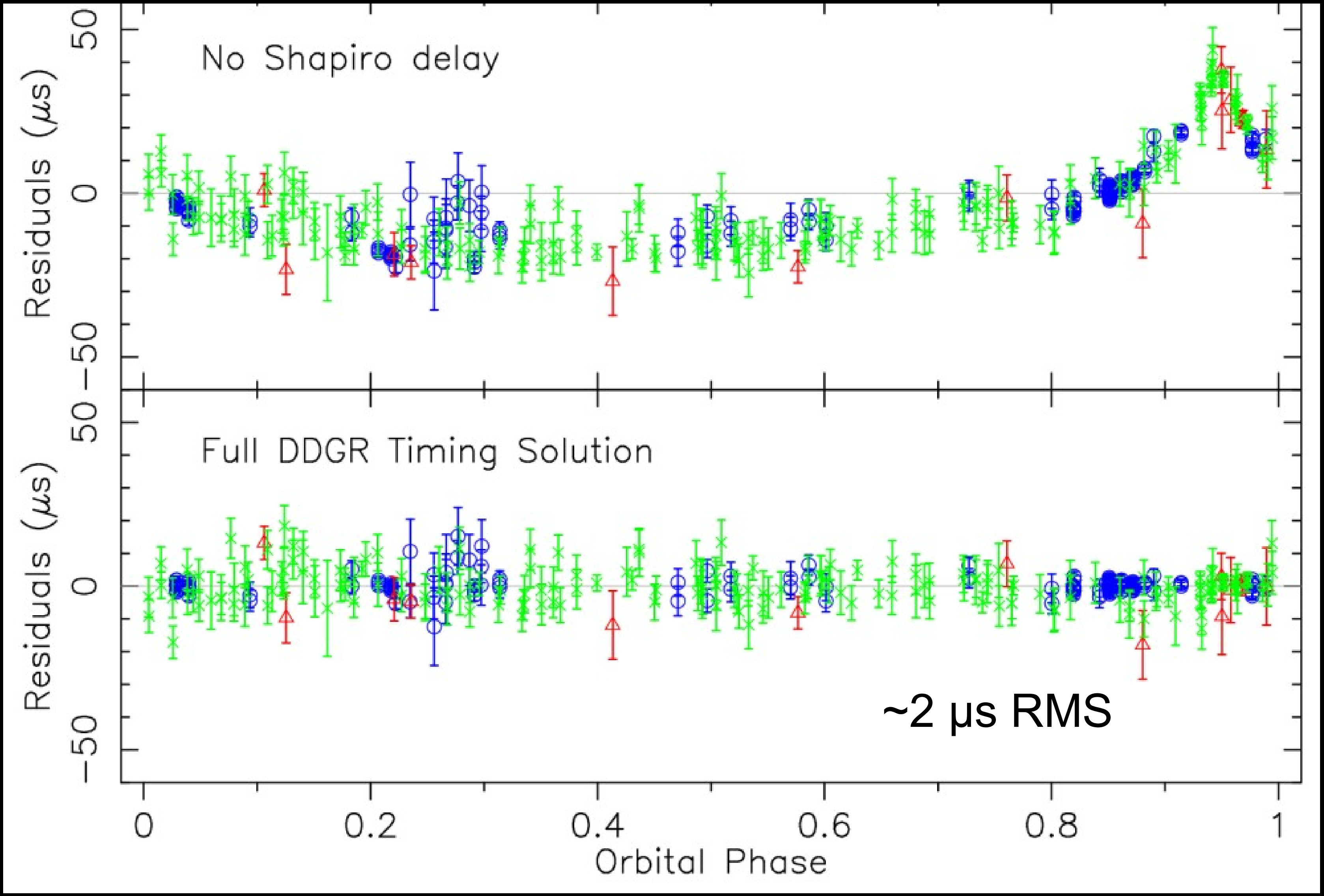
Irwin Shapiro 1964
Shapiro et al. 1968, 1971

J1903+0327 (Eccentric MSP) Timing



Champion et al. 2008, *Science*, 320, 1309

J1903+0327 (Eccentric MSP) Timing



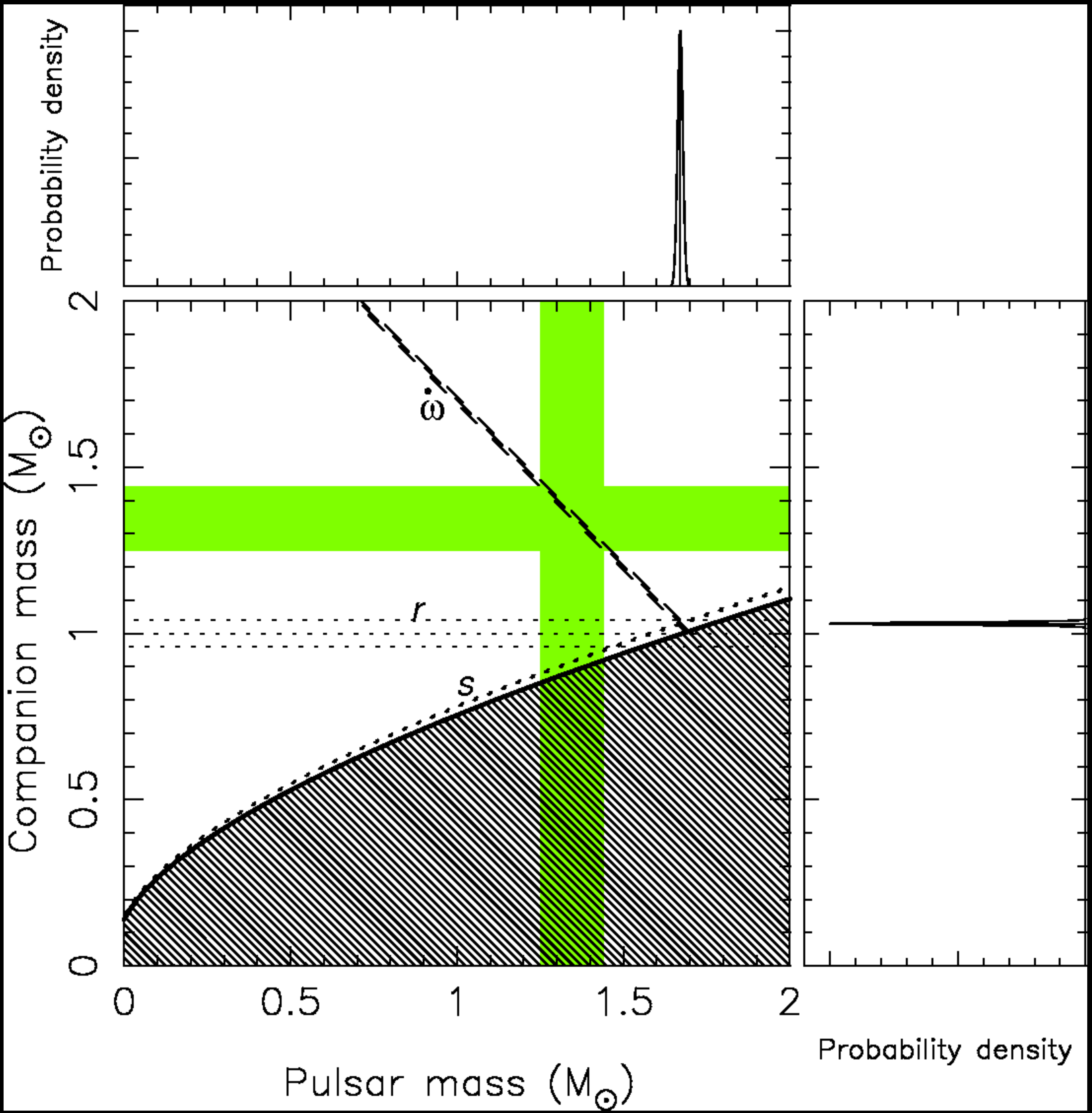
Champion et al. 2008, *Science*, 320, 1309

Recent Arecibo timing

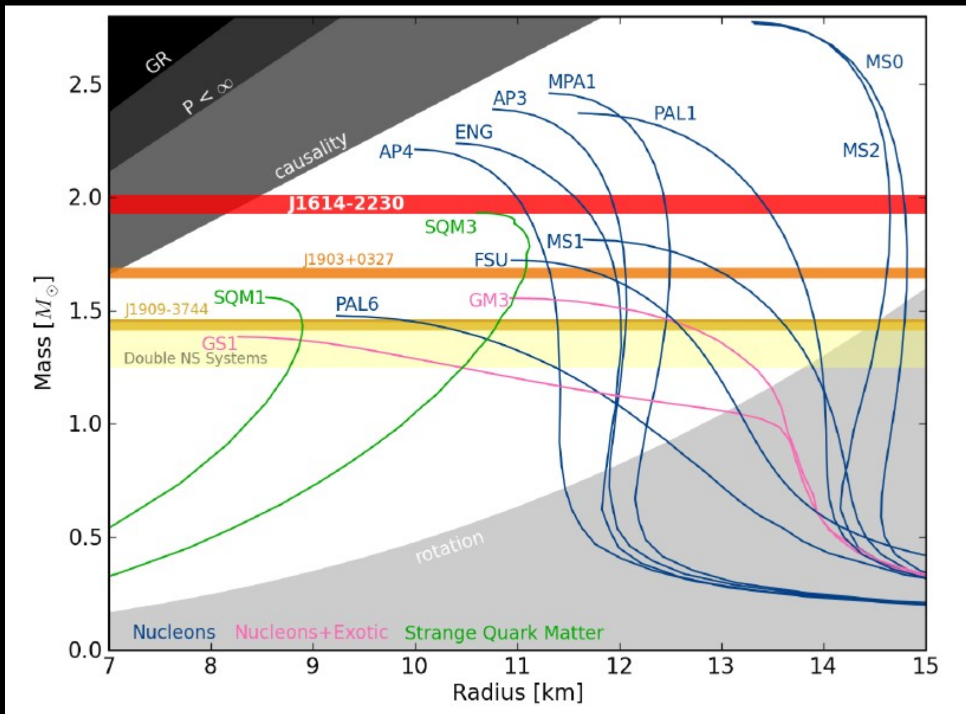
Much improved Shapiro delay

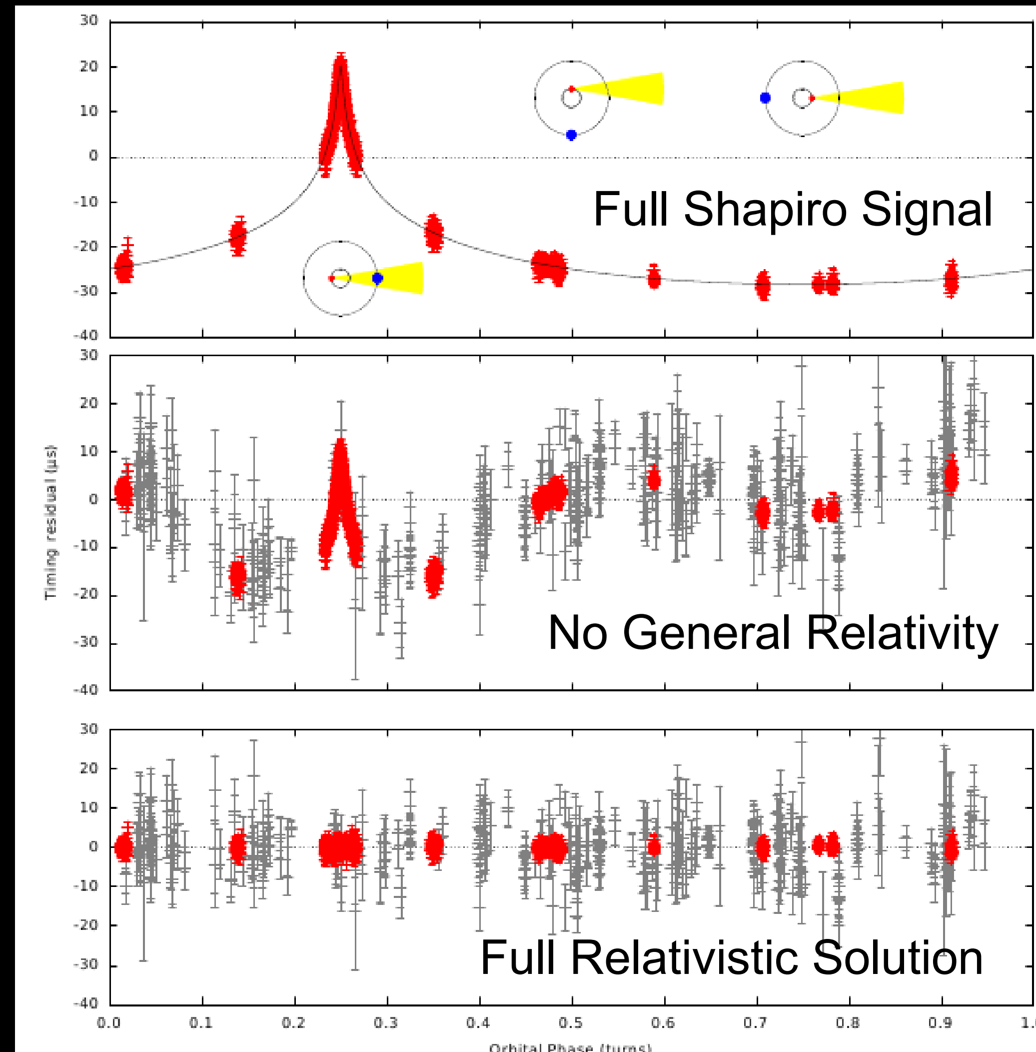
PSR = 1.67(2) $M_\odot$

Freire et al. 2011



MSP J1614-2230: Incredible Shapiro Delay Signal





Mwd = 0.500(6) $M_\odot$

Mpsr = **1.97(4) $M_\odot$**!

Inclination = 89.17(2) deg!

Demorest et al. 2010, *Nature*, 467, 1081D
see Ozel et al. 2010, ApJL, 724, 1990

The Binary Pulsar: B1913+16

First binary pulsar discovered at Arecibo Observatory by Hulse and Taylor in 1974 (1975, ApJ, 195, L51)

NS-NS Binary

P_{psr} = 59.03 ms

P_{orb} = 7.752 hrs

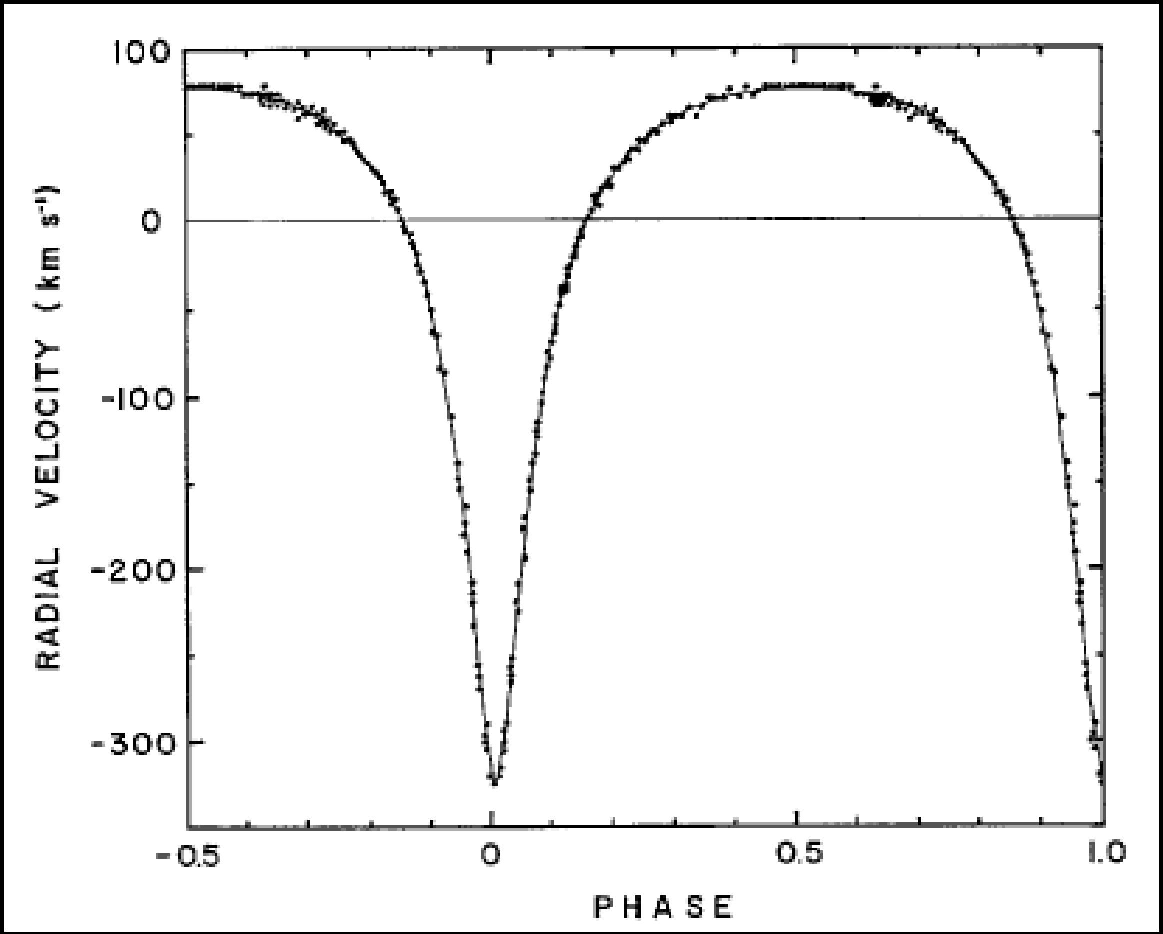
a sin(i)/c = 2.342 lt-s

e = 0.6171

$\dot{\omega}$ = 4.2 deg/yr

M_c = 1.3874(7) $M_\odot$

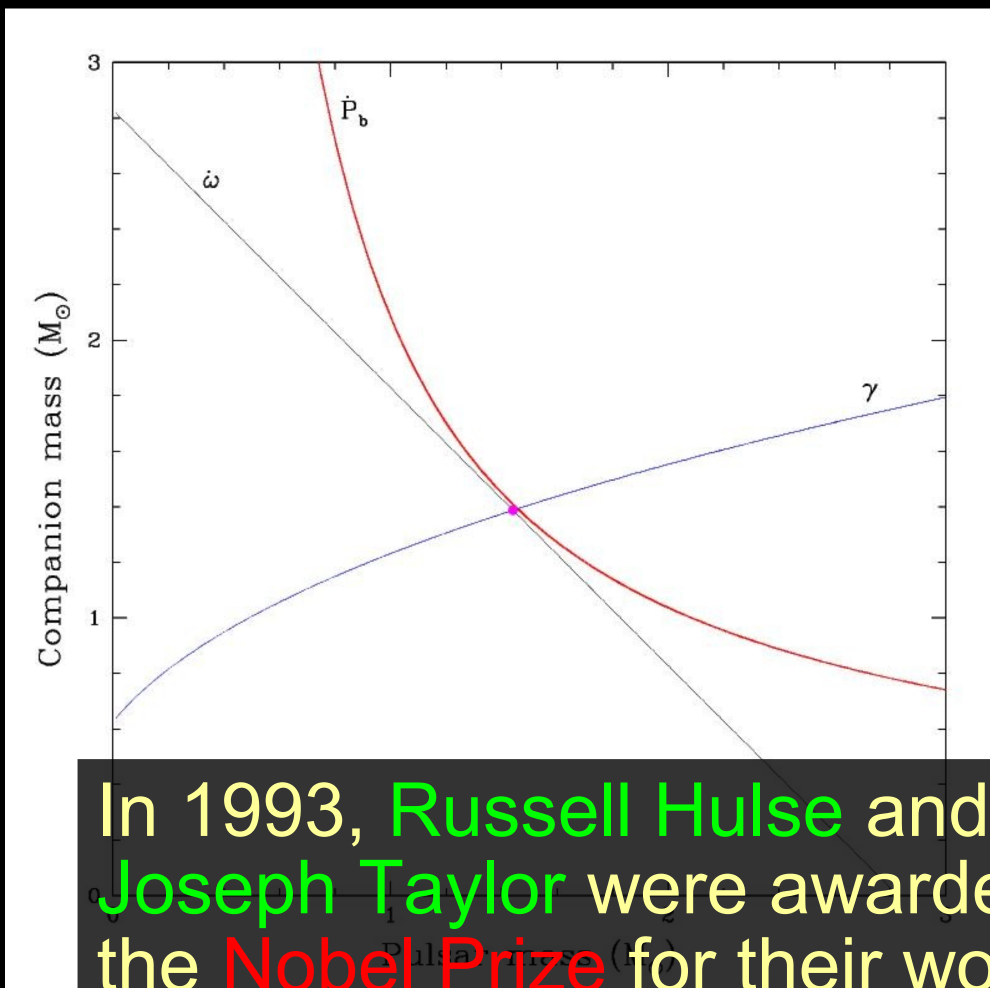
M_p = 1.4411(7) $M_\odot$



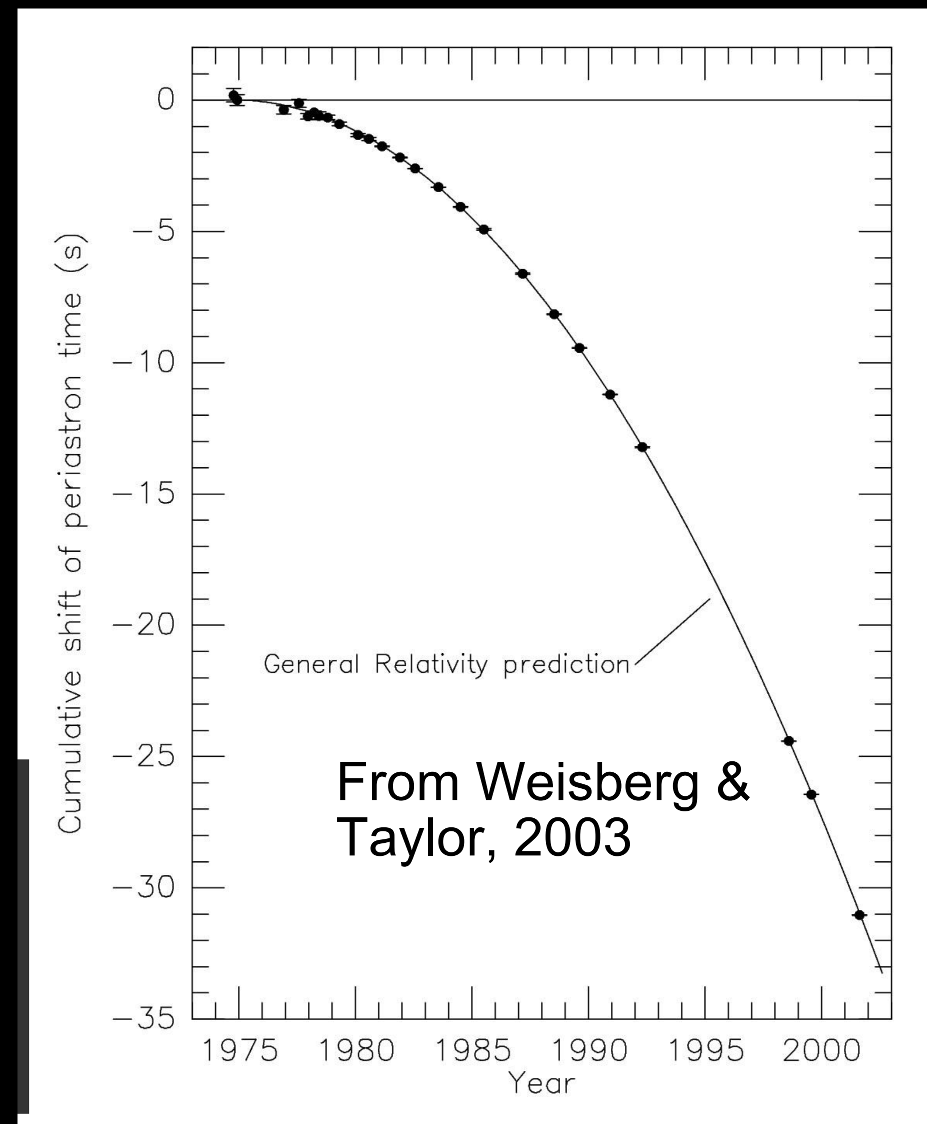
The Binary Pulsar: B1913+16

Three post-Keplerian Observables: $\dot{\omega}$, γ, $\dot{P}_{orb}$

Indirect detection of Gravitational Radiation



In 1993, Russell Hulse and Joseph Taylor were awarded the Nobel Prize for their work on PSR B1913+16!



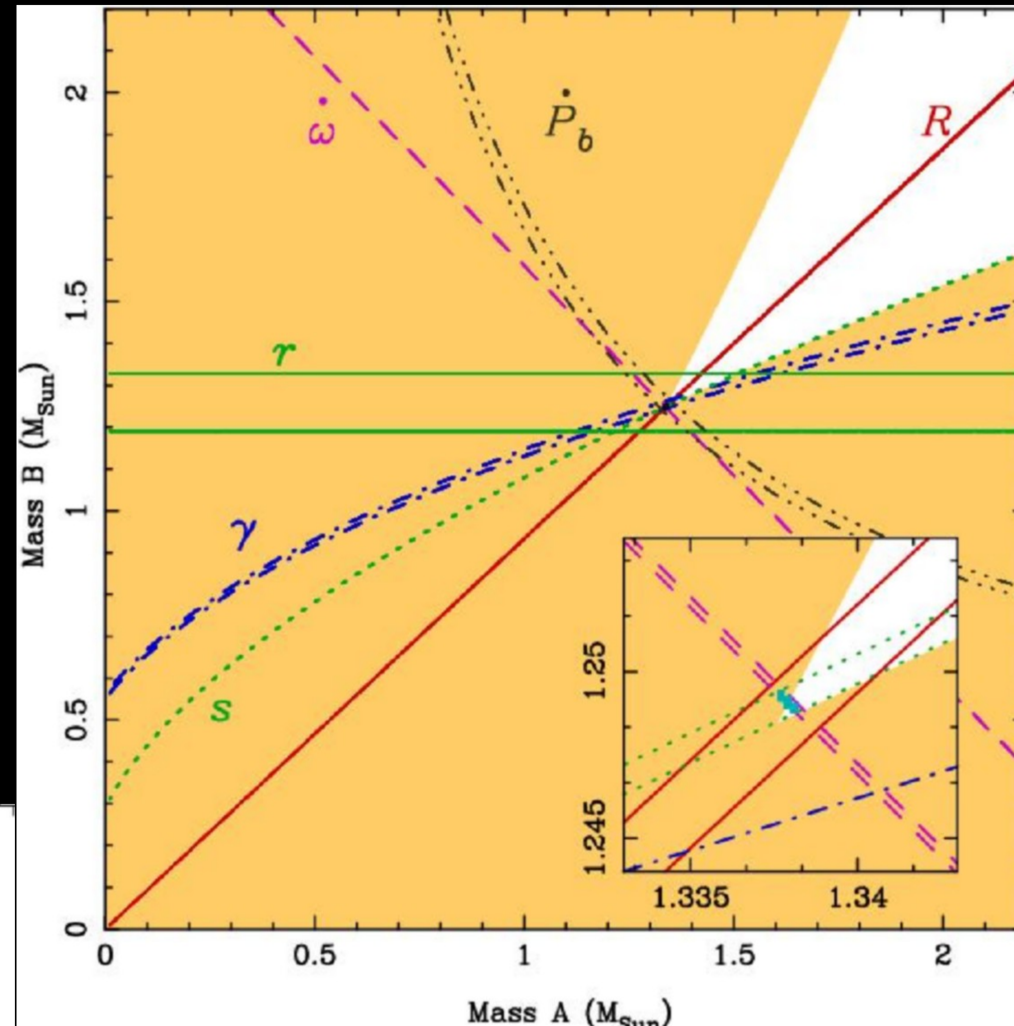
From Weisberg & Taylor, 2003

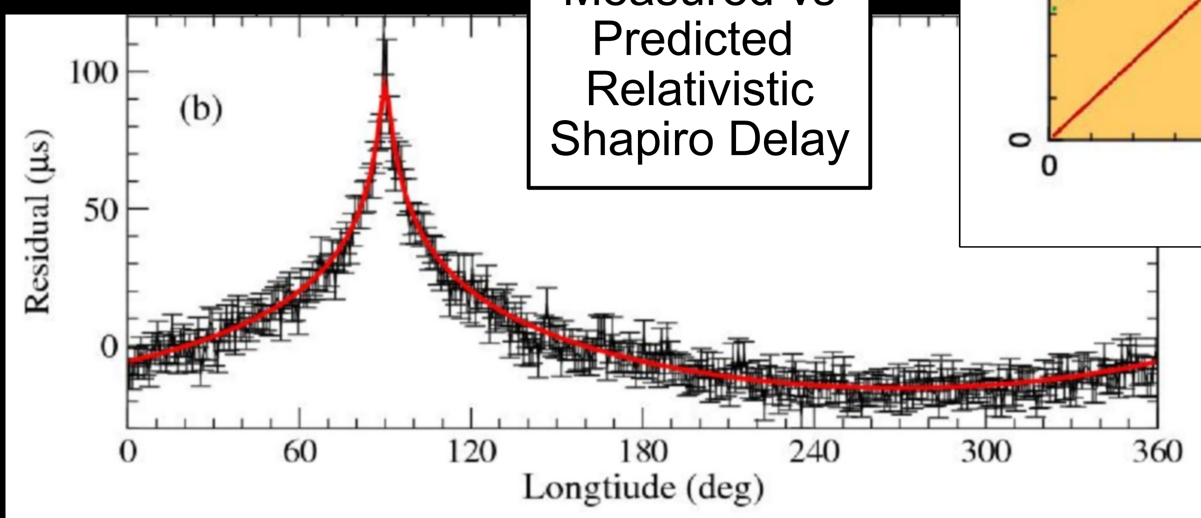
Timing of the Double Pulsar J0737-3039

GBT provides the best timing precision for this system

6(!) post-Keplerian orbital terms give neutron star masses and strong-field tests of general relativity to 0.05% accuracy

Timing may eventually allow measurement of the neutron star moment of inertia



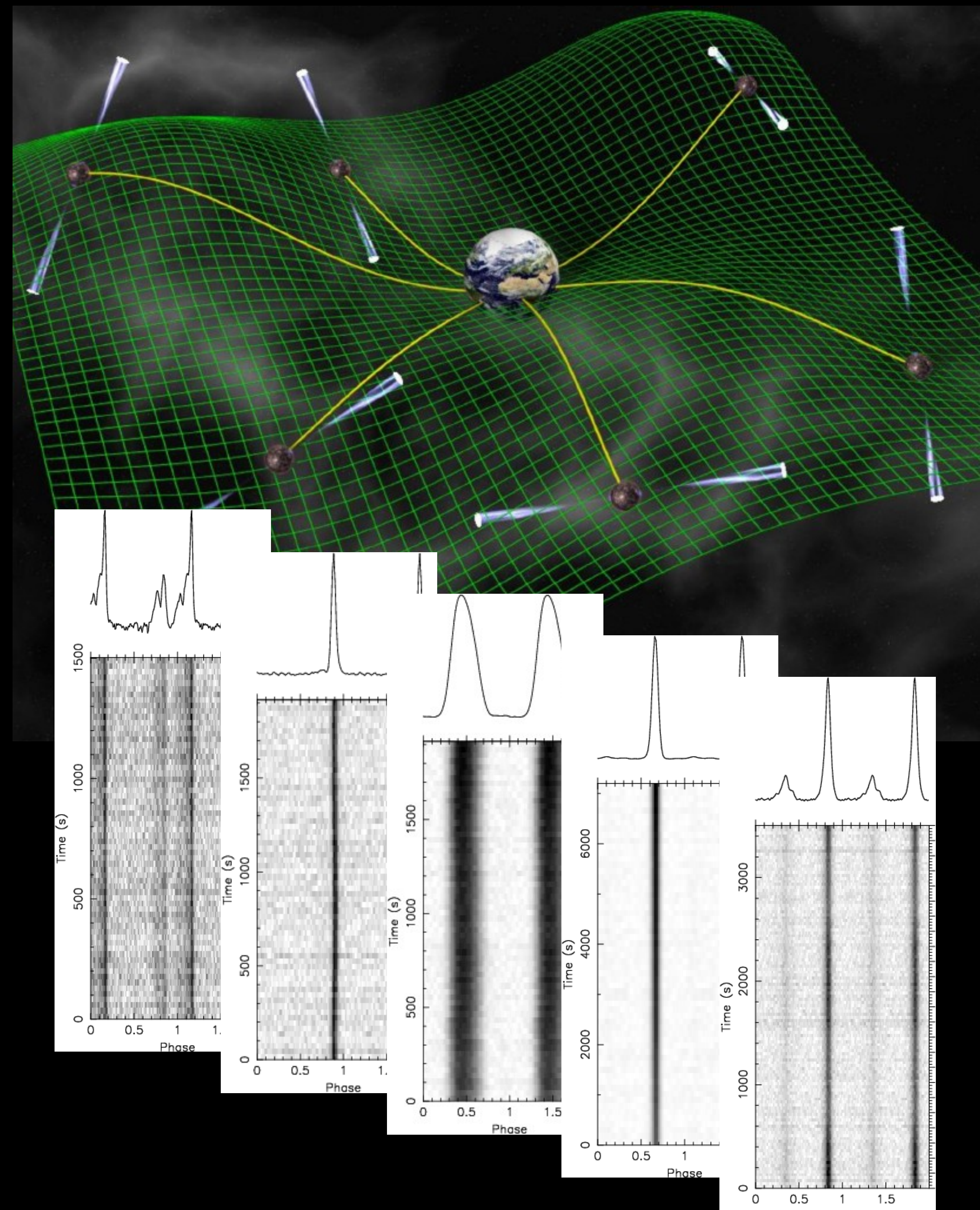


Measured vs Predicted Relativistic Shapiro Delay

Kramer et al., 2006, *Science*, 314, 97

Grav Wave Detection with a Pulsar Timing Array

- Need good MSPs
- Significance scales directly with the number of MSPs being timed. Lack of good MSPs is currently the biggest limitation
- Must time the pulsars for 5-10 years at a precision of 100-200 nano-sec!
- North American (**NANOGrav**), European (EPTA), and Australian (PPTA) efforts



Summary

- Pulsars are intrinsically interesting objects worth studying, but are perhaps most useful as tools
- We know of ~2000 pulsars, there are >30,000 more to find, and only ~1% are "interesting"
- Radio pulsars can, do, and will make extremely important contributions to **basic physics**
  - High precision tests of gravitational theories
  - Probes the nature of matter at supra-nuclear densities
  - Direct detection of gravitational radiation
  - Study the advanced stages of stellar+binary evolution
- Currently the US has the World's best telescopes for these studies: the GBT and Arecibo