Principe et applications de la chronométrie des pulsars

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Séminaire au LPNHE

11 septembre 2014

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UNIVERSITE D'ORLEANS

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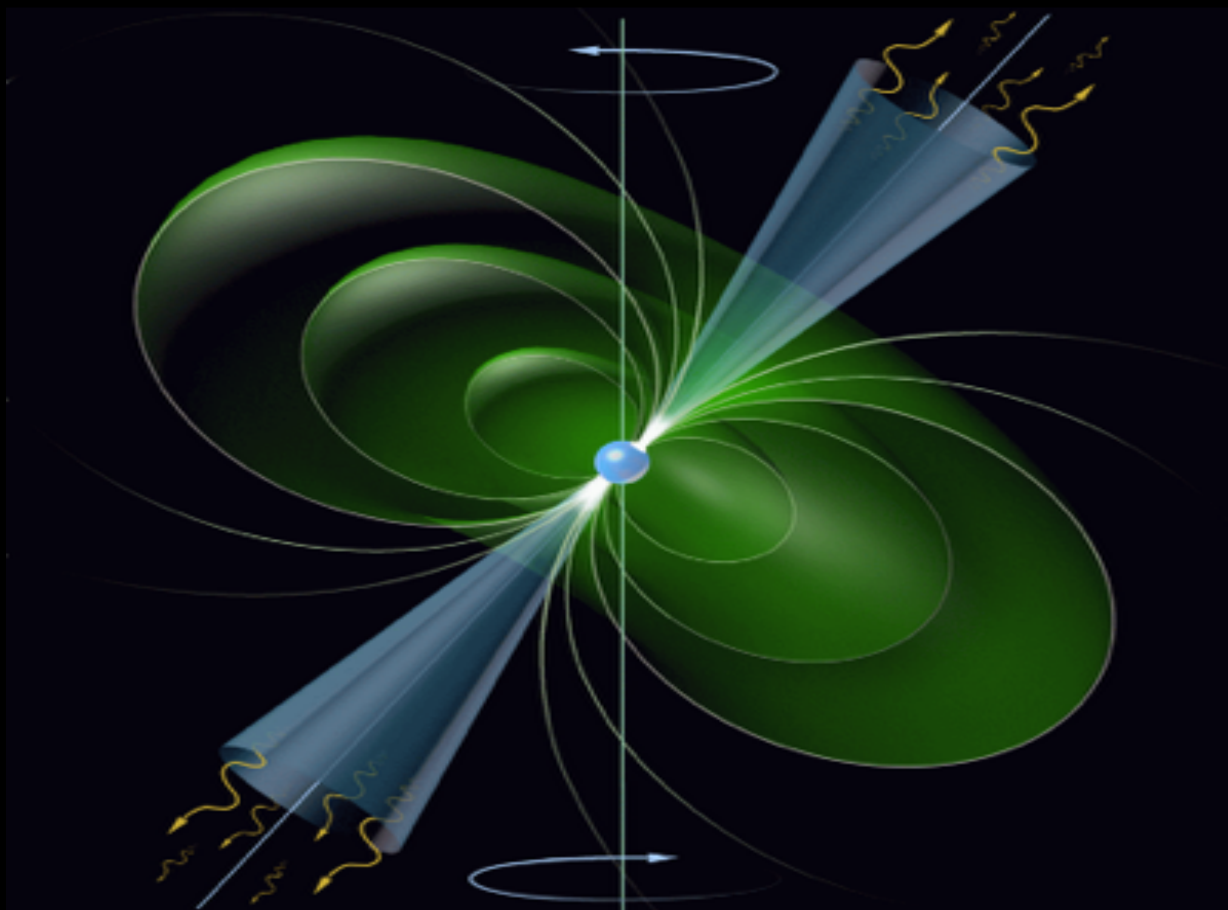
Pulsars

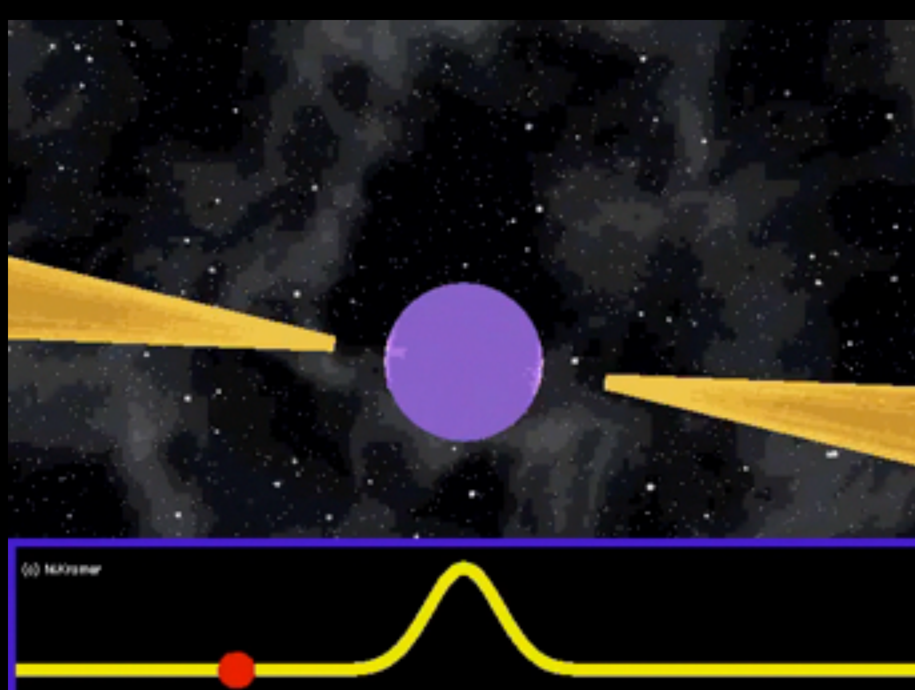


Pulsars are rapidly rotating highly magnetized neutron stars, born in supernova explosions of massive stars.

Masses: 1.2 - 2 $M_\odot$, Radii ~ 13 km.

Emission (radio, optical, X-ray, gamma rays…) produced in beams around the star.

Pulsars are cosmic lighthouses!



Extreme objects:

- Luminosities up to 10^4 $L_\odot$
- Surface temperature ~ 10^6 K
- Surface gravity ~ 10^{11} Earth's
- Surface magnetic fields: 10^8 - 10^{15} G

Pulsars are exotic objects

Masses: 1.2 - 2 $M_{\odot}$

Radii ~ 10 km

Central densities several times higher than atomic nuclei

Rotational frequencies up to 716 Hz

Luminosities up to 10^4 $L_{\odot}$

Surface temperature ~ 10^6 K

Surface gravity ~ 10^{11} Earth's

Surface magnetic fields: 10^8 - 10^{15} G

Also incredibly precise clocks:
P = 5.757451924362137(2) ms for J0437-4715 (Verbiest et al. 2008)

Tools to do fundamental physics!

The pulsar population

Kinetic energy loss rate:

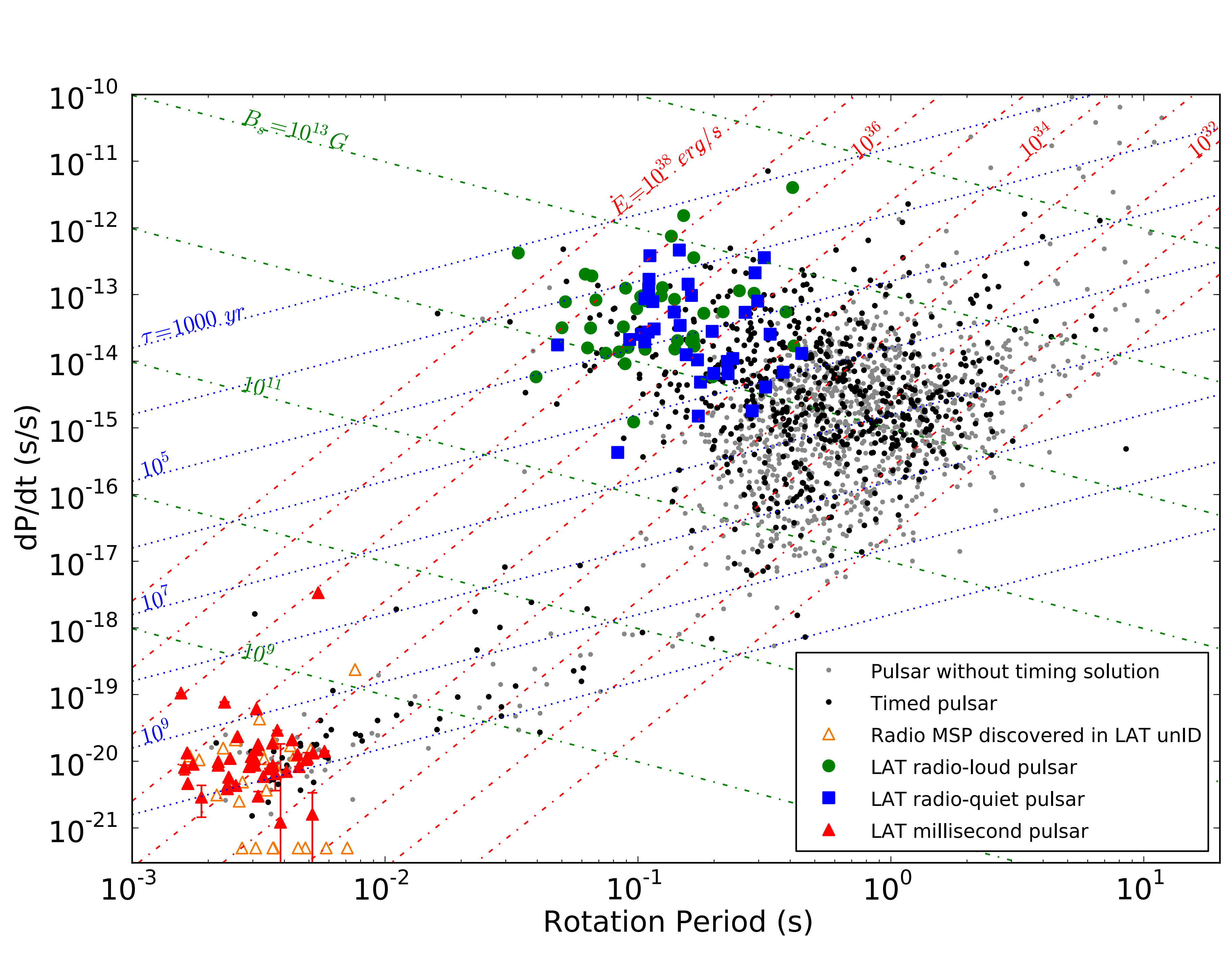
$$\dot{E} = 4\pi^2 I \frac{\dot{P}}{P^3}$$

⇒ Pulsars spin down.

Most MSPs are in binary systems.

~2300 known today (mostly from radio observations)

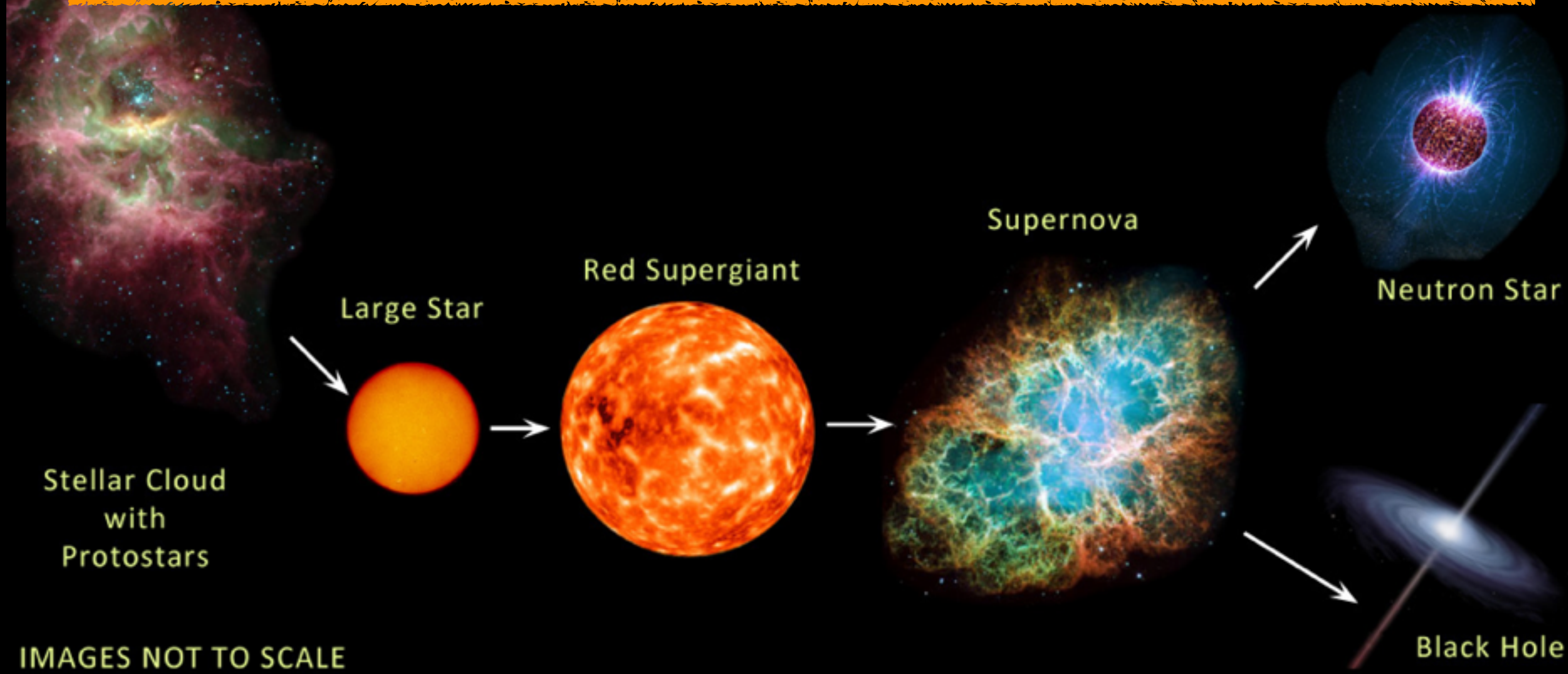
Fermi LAT: 147 pulsars (85 normal, 62 MSPs)



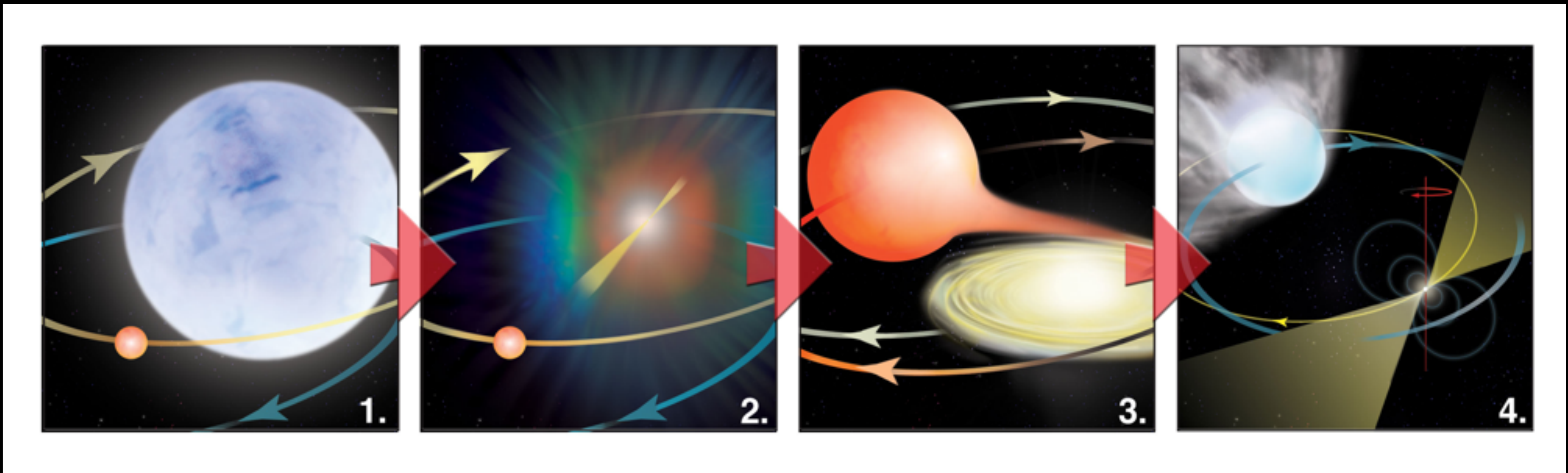
Massive stars (> 5 $M_\odot$) explode as supernovae.

Elements heavier than iron dispersed into space.

➡ Supernova remnants, pulsars and their nebulae.



Millisecond pulsar recycling

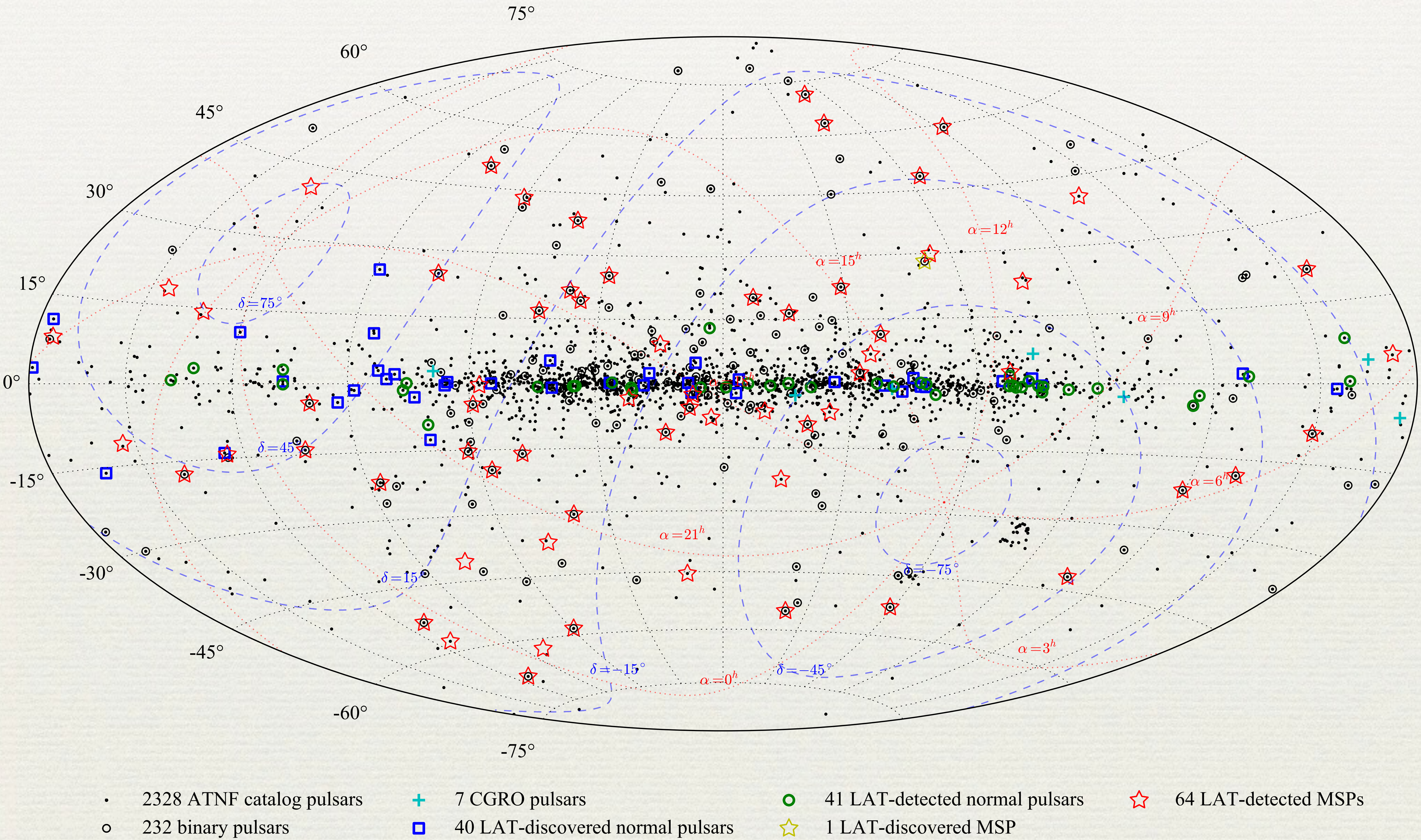


1 & 2: Starting with a binary system, a pulsar is formed after the supernova explosion of the more massive star.

3: After evolution of the secondary star and Roche lobe overflow, transfer of matter and angular momentum to the pulsar (spin up!).

4: An MSP is formed, with a white dwarf companion.

Sky distribution

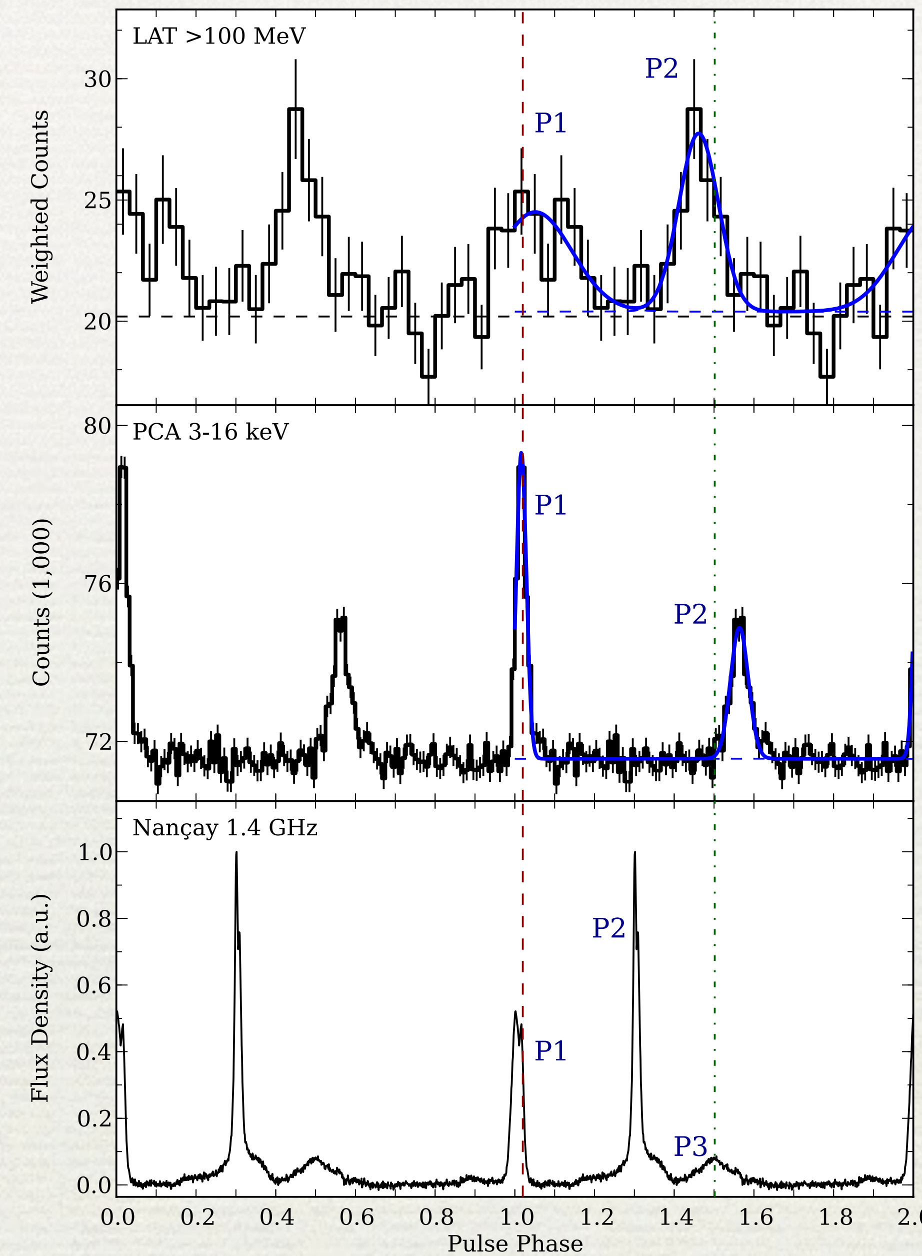


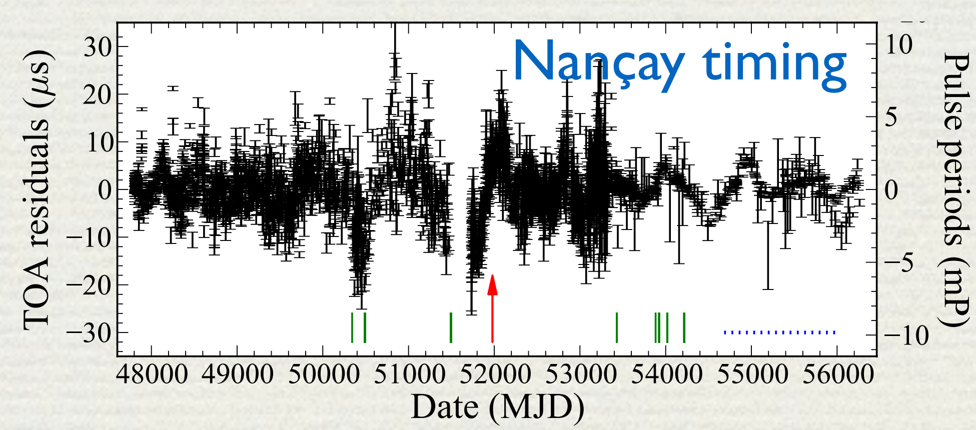
A large variety of applications

- Plasma physics and electrodynamics (e.g., eclipses, magnetospheres)
- Astrophysics (stellar evolution, binary evolution)
- Gravity tests in the strong field regime
- Gravitational wave searches
- Solid state physics (NS equations of state)
- Magnetic field in the Galaxy and interstellar medium
- Astrometry, planetary ephemerides

Non-exhaustive list…

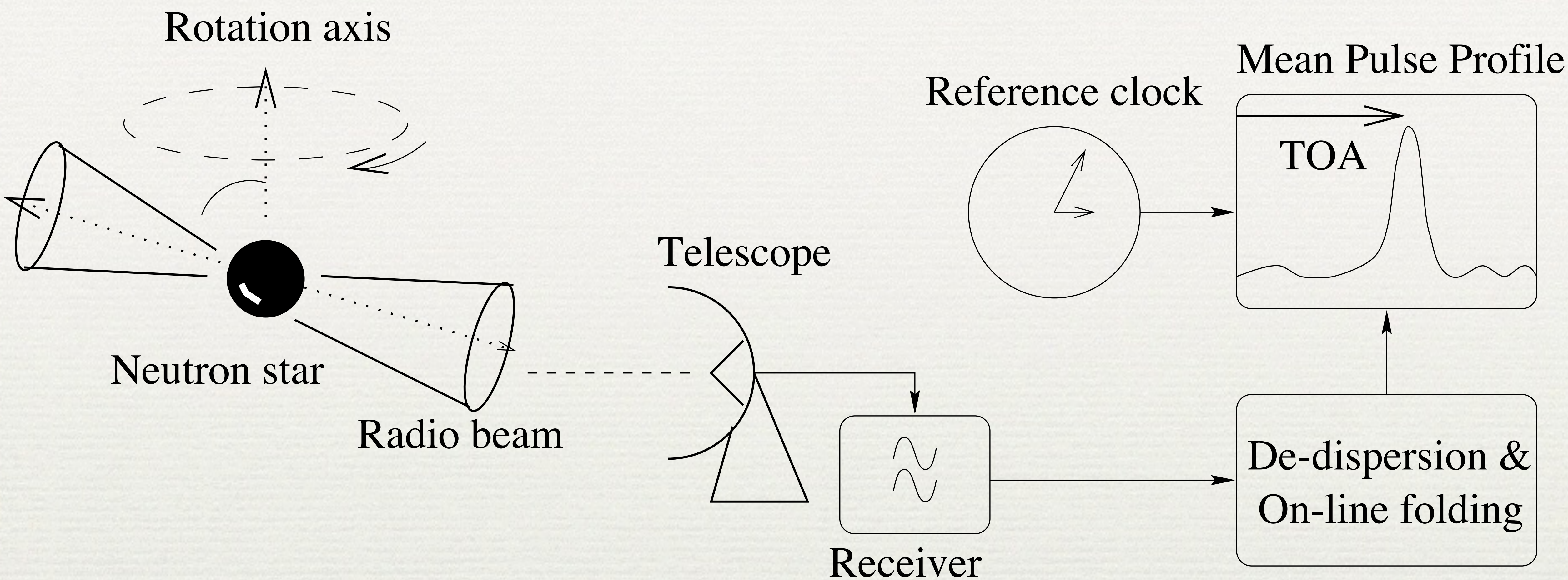
Numerous applications in a wide range of astrophysics and fundamental physics!





Radio, X-ray, and gamma-ray observations of B1821-24A (Johnson et al. ApJ 2013)

A pulsar timing experiment



(Courtesy Duncan Lorimer)

In a pulsar timing experiment:

- a pulsar is observed a few times a month (typically) with a dedicated instrumentation.
- pulses are « dedispersed » to correct for the interstellar dispersion, and added to form a mean pulse profile.
- data receive a time stamp, and the mean profiles are compared to a « template » profile to extract a « time of arrival » (TOA).

The Nançay Radio Telescope

~94-m equivalent meridian telescope, located in Sologne, 180 km South of Paris.

Minimum declination: -39°

Pulsar observations at Nançay

First observations in 1986.

1988-2004: dispersion with a swept local oscillator.

2000: construction of a coherent dedispersion machine.

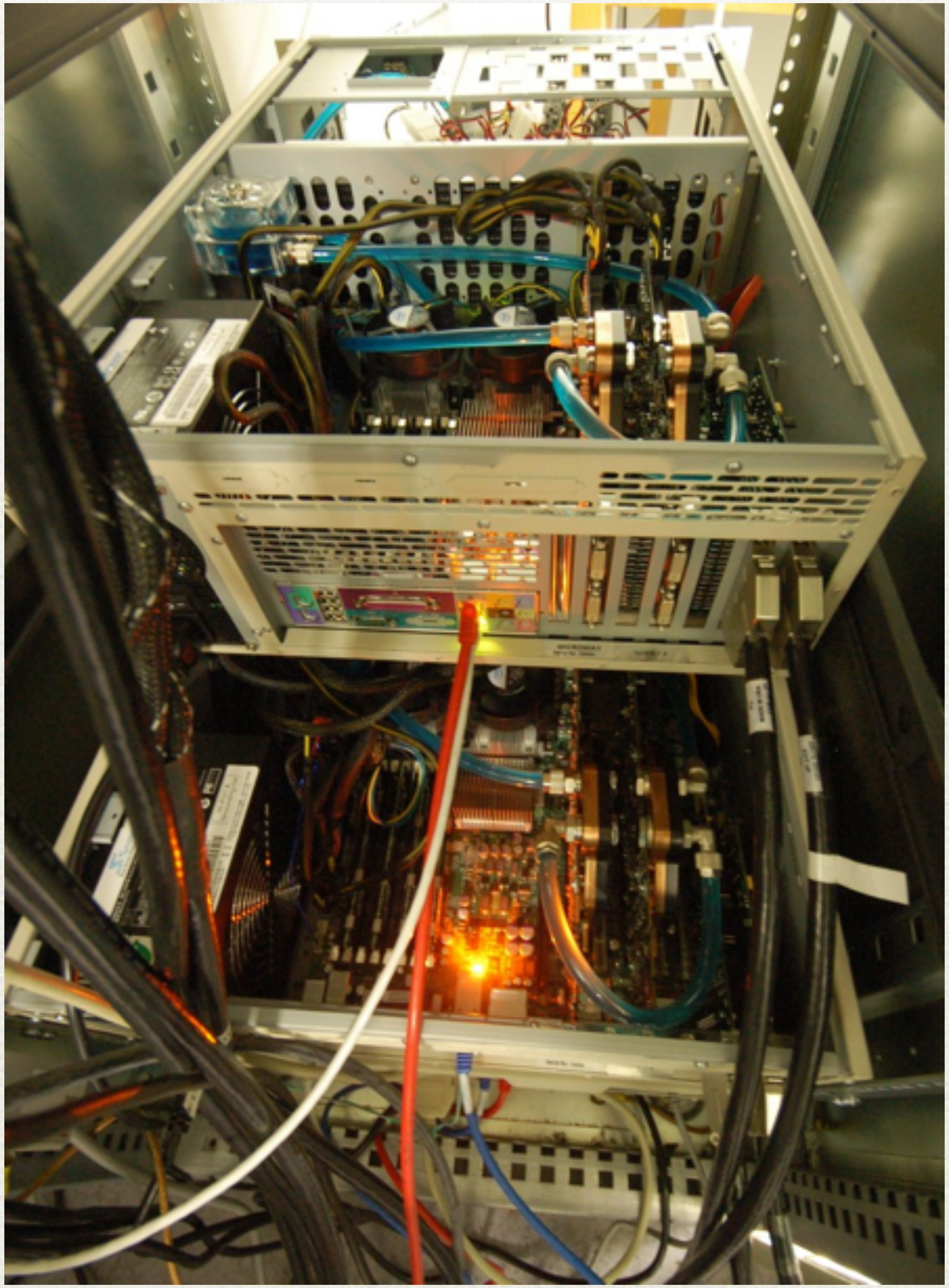
2011 onwards: NUPPI backend.

NUPPI: 512 MHz of bandwidth, realtime coherent dedispersion of the data (2 computers with 4 GPUs, ~4 Gb/s).

Observations typically made a 1.4 and 2 GHz.

Accuracy on individual TOAs can be as good as 30 ns for the best pulsars!

Pulsar observations make ~50% of the total telescope time (pulsar timing and searching). More than 200 pulsars are observed at Nançay.



Interstellar dispersion

The group velocity of radio pulses propagating through the ionized component of the interstellar medium is frequency dependent.

Pulses emitted at lower radio frequencies arrive later than those emitted at higher radio frequencies!

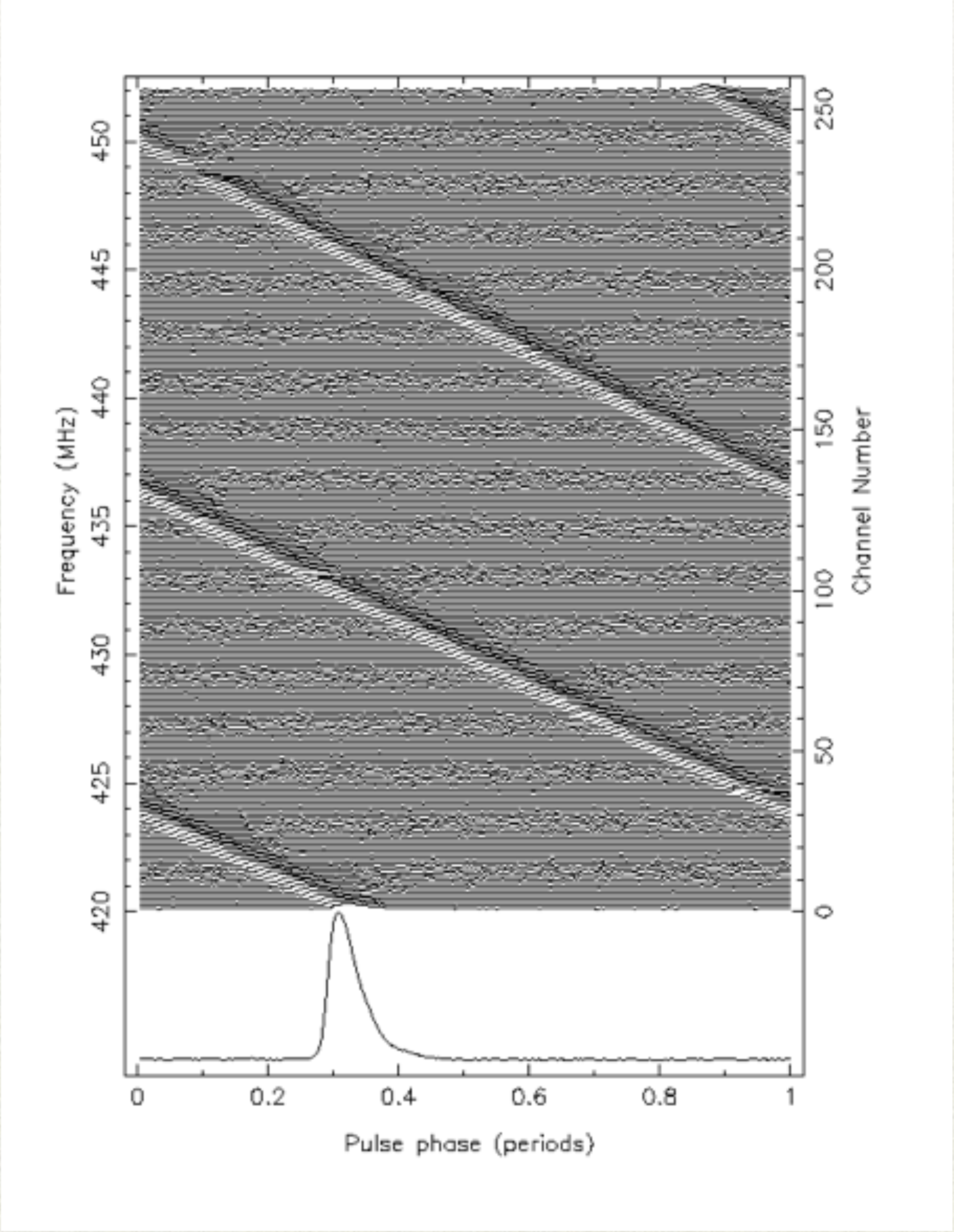
It is therefore necessary to « dedisperse » the signal received from pulsars.

Dispersion delay:

$$\Delta t = k \frac{DM}{f^2}$$

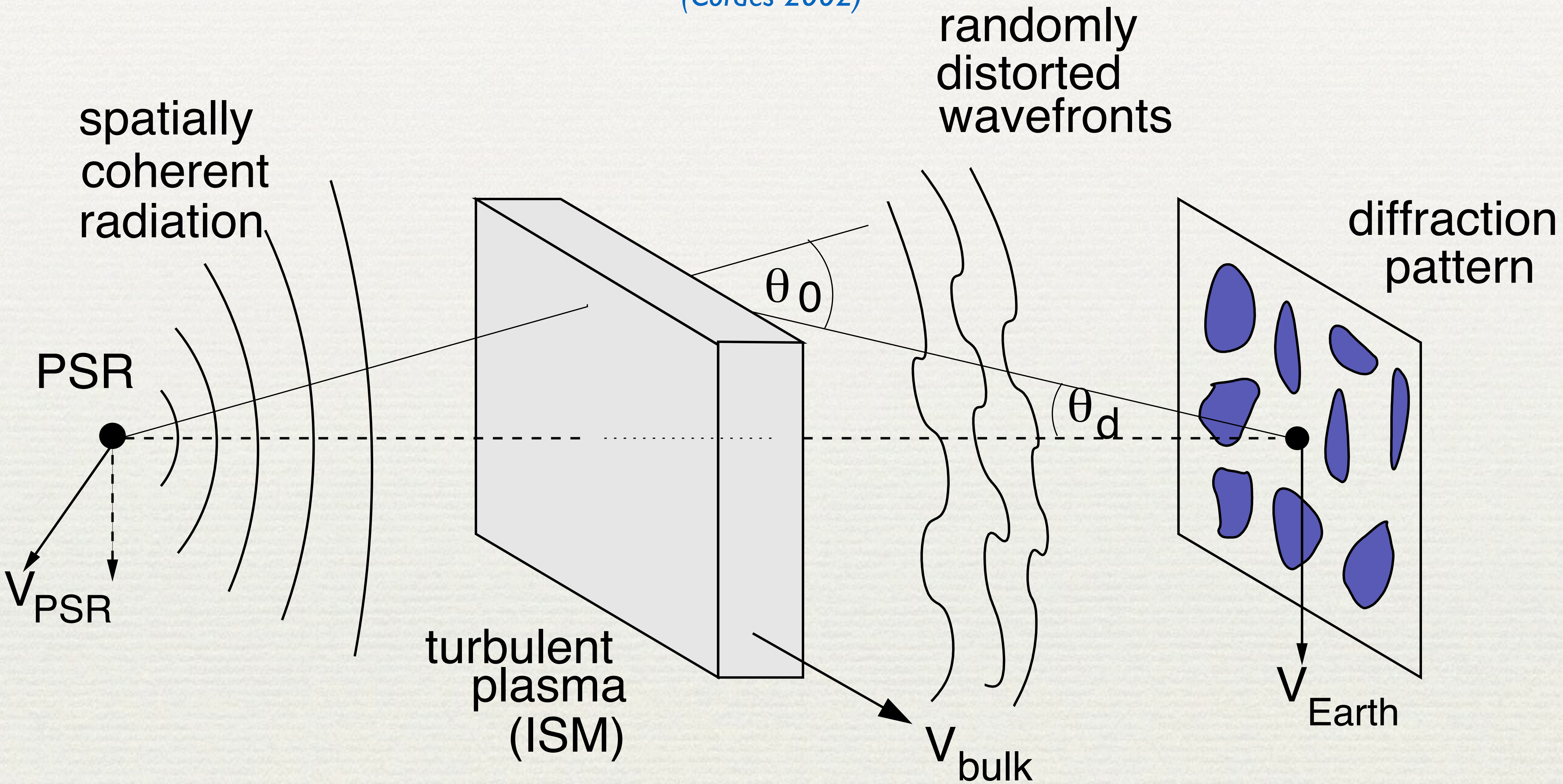
With:

$$k = \frac{e^2}{2\pi m_e c} \qquad DM = \int n_e dl$$



Turbulence in the ISM

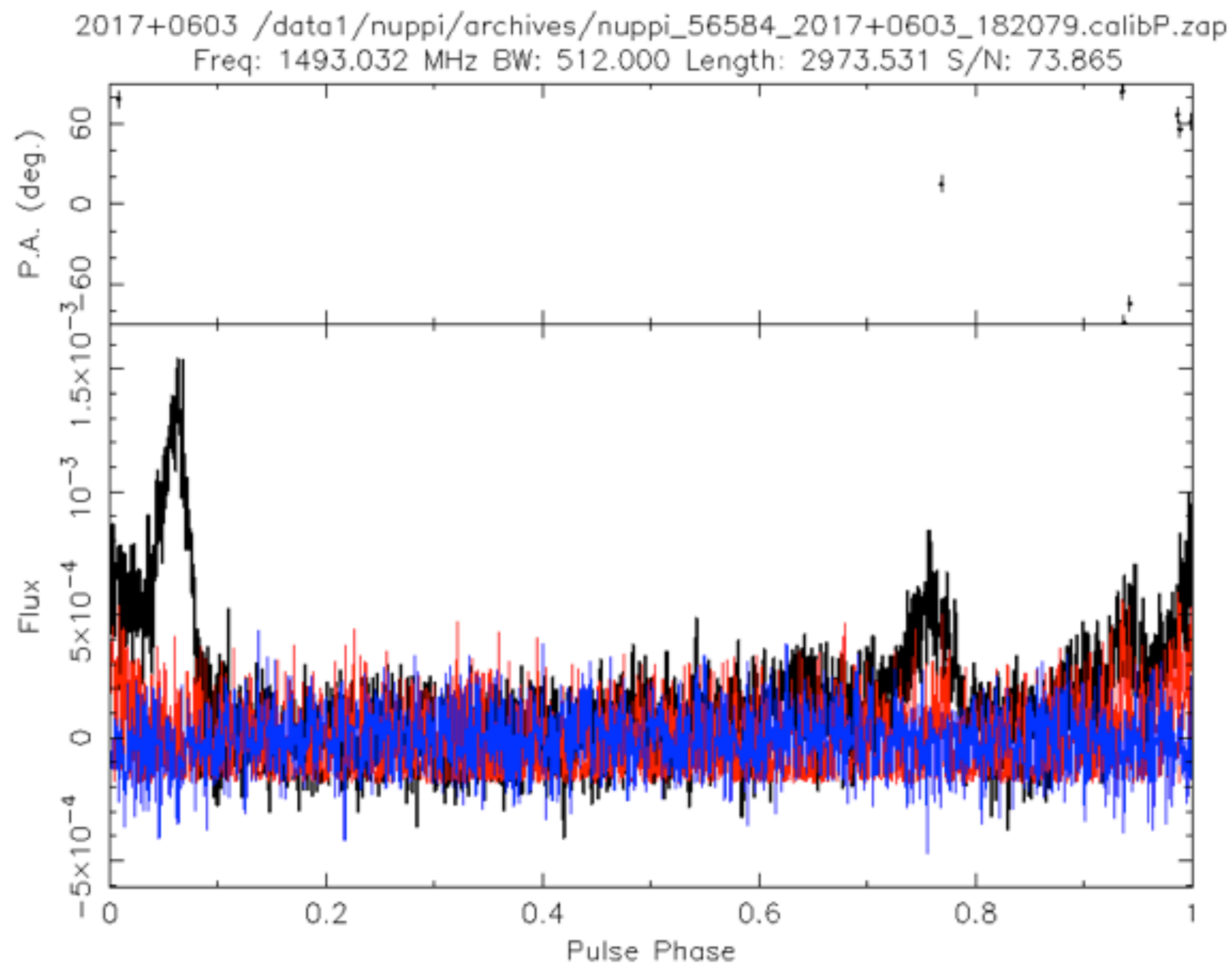
(Cordes 2002)



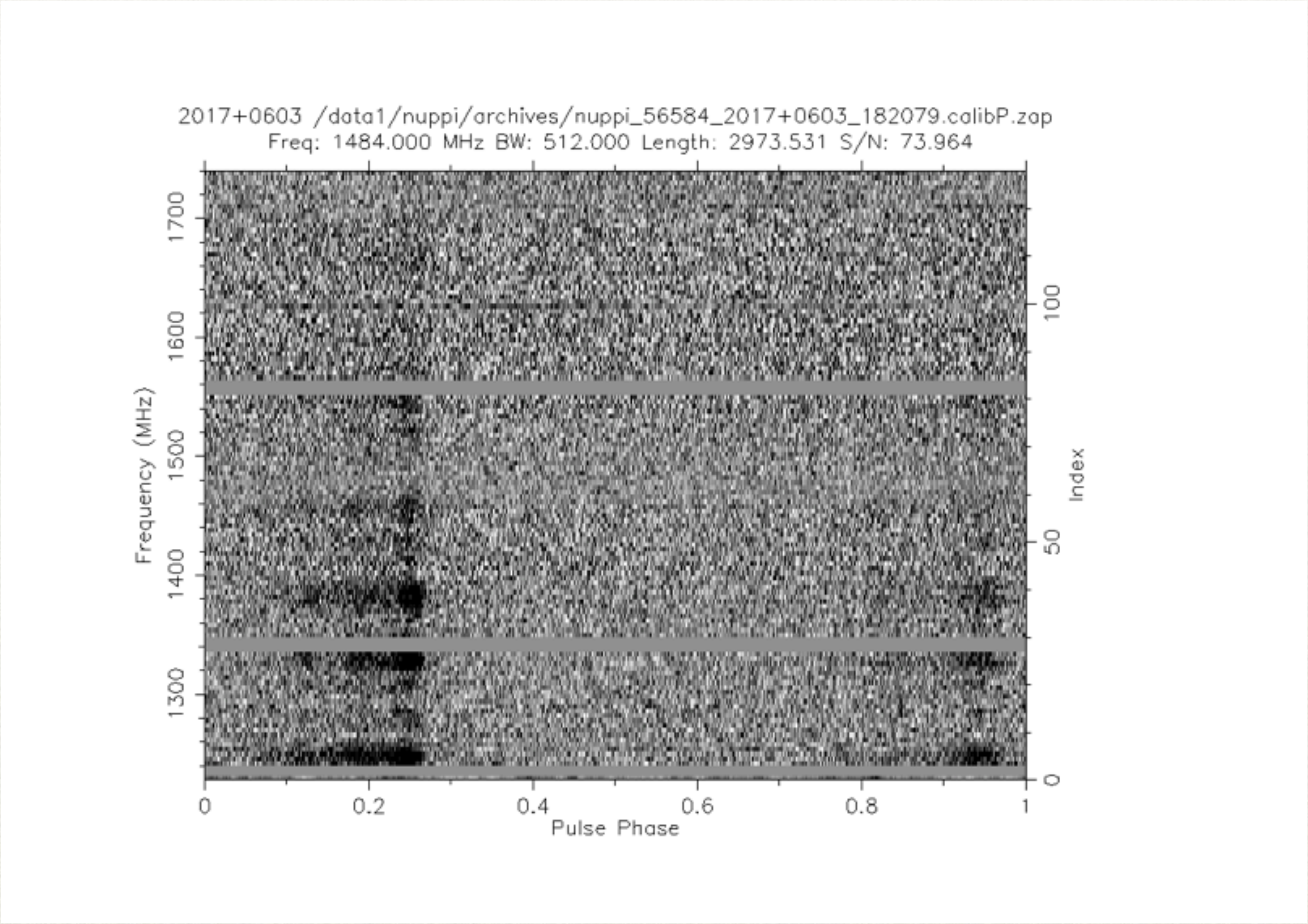
Inhomogeneities in the ISM perturb the phase of propagating waves, due to the changing refractive index.

Has various consequences, such as scintillation in time & frequency.

Example radio observation: integrated profile

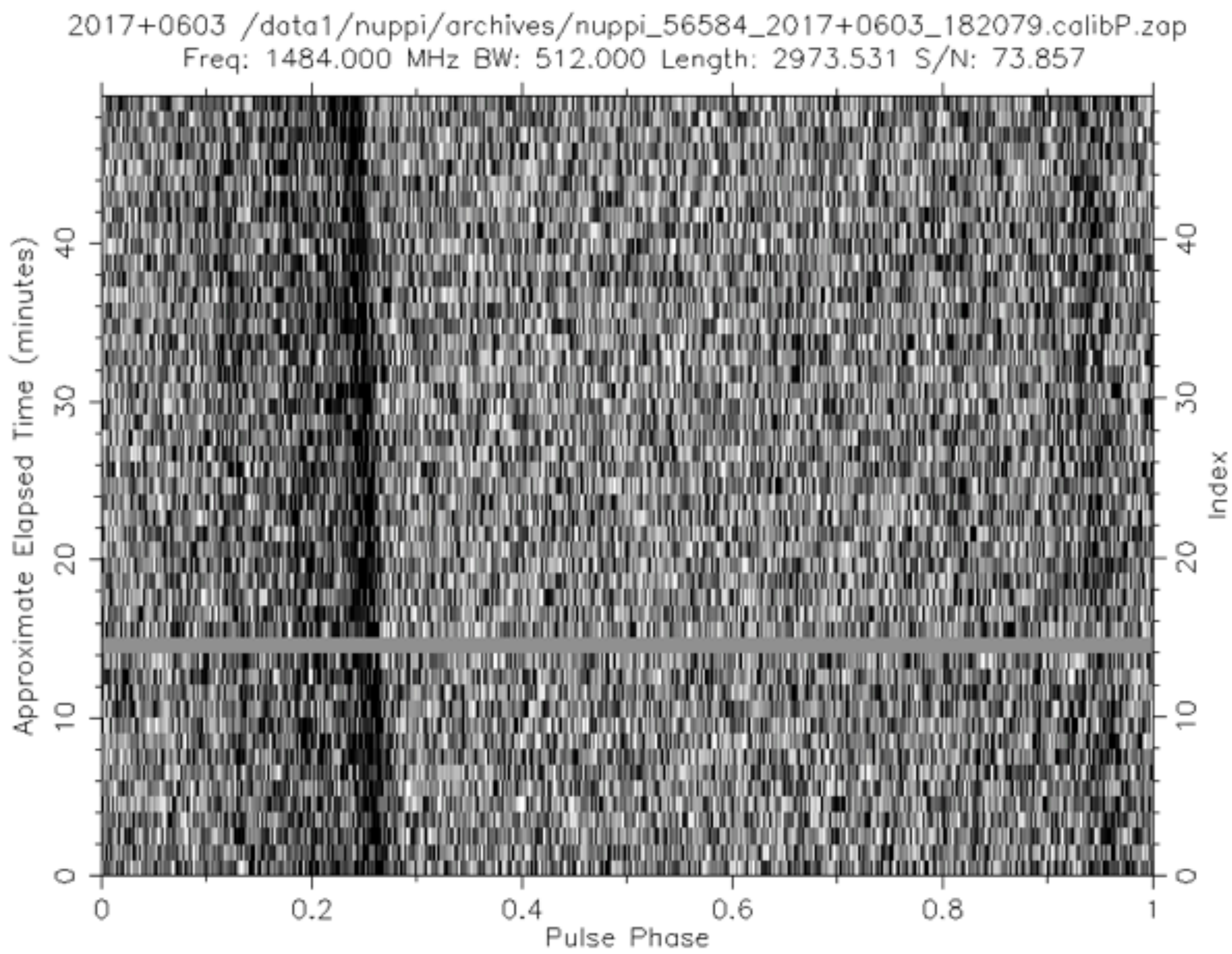


Frequency vs phase diagram



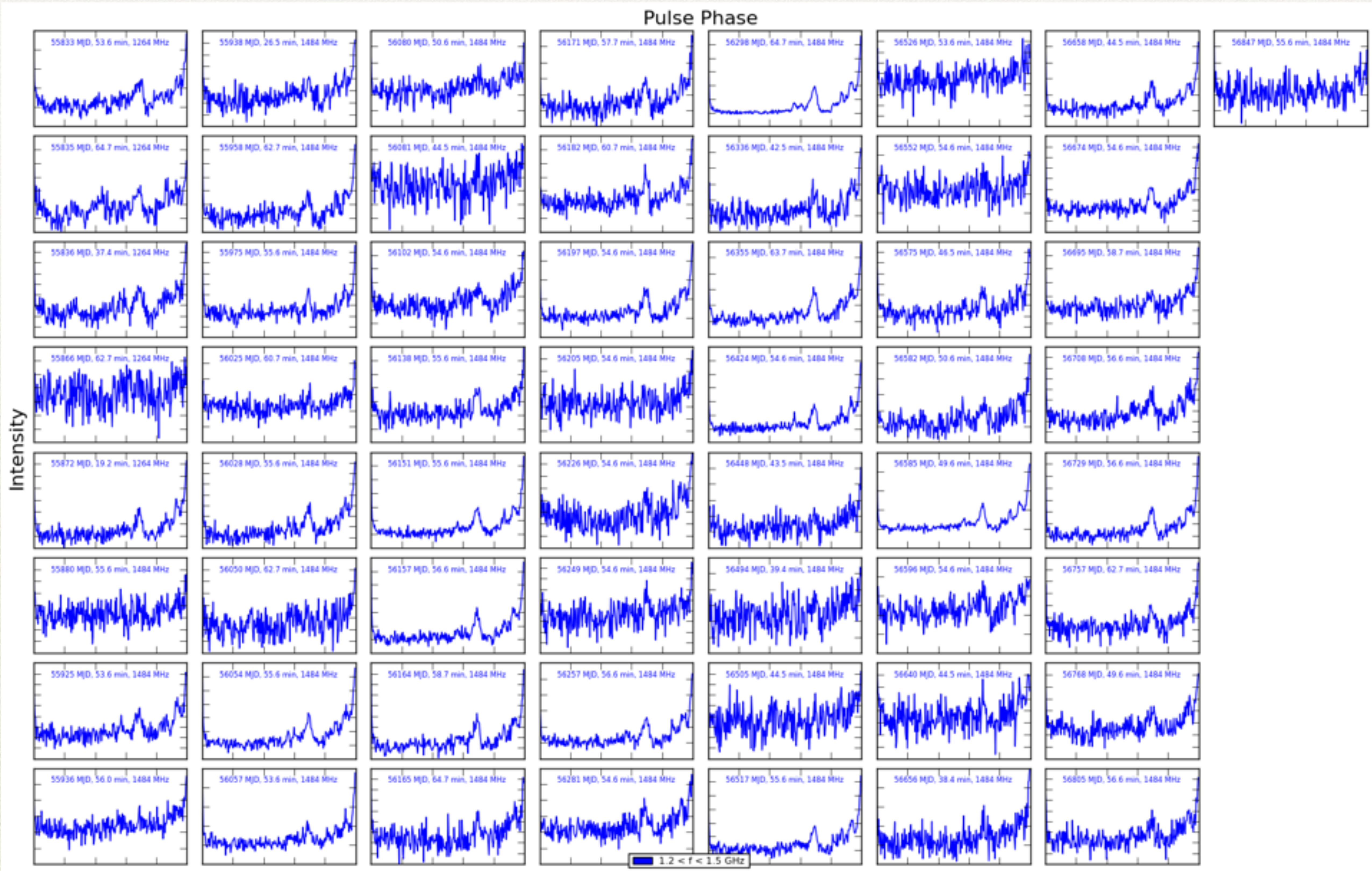
Importance of large bandwidth!

Time vs phase diagram

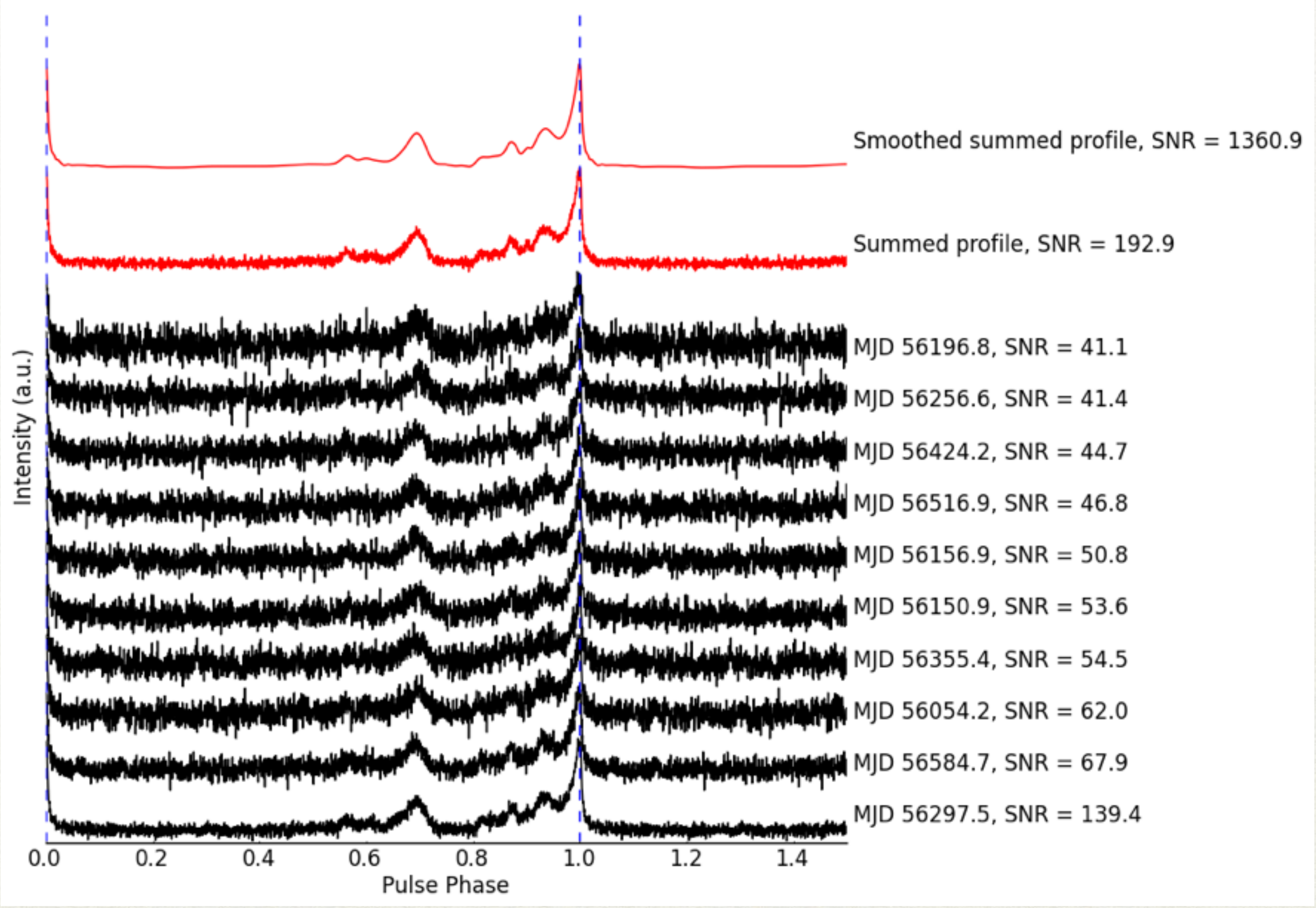


Phase drift during the observation: the data need to be refolded with an improved timing model.

J2017+0603 NUPPI observations



High S/N reference profile



Science from long term timing of MSPs

Pulse « Times of Arrival » (ToAs) are fit to a model accounting for the pulsar's spin, motion, and binary orbit.

Superb precision for « millisecond » pulsars (MSPs)!

Examples: 15 years of EPTA observations of J1012+5307 yielded:

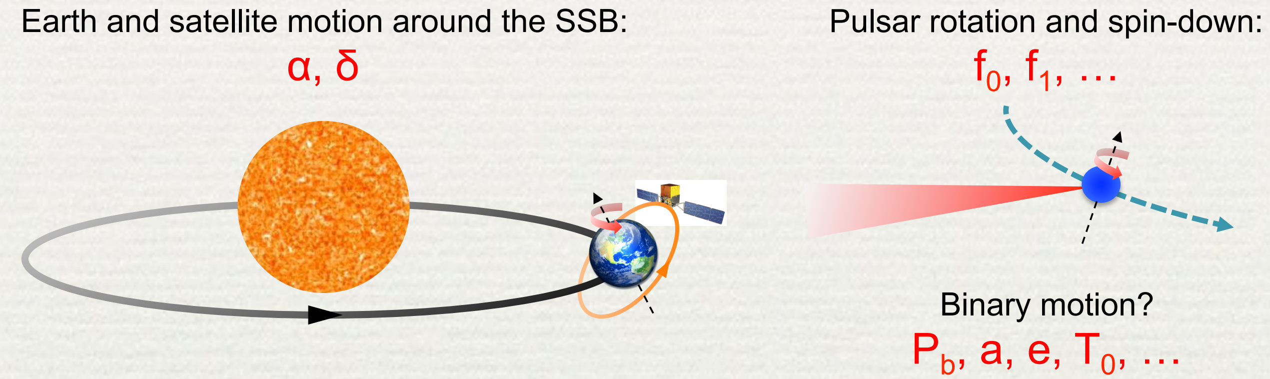
P = 0.005255749014115410(15) s

(Lazaridis et al. 2009)

Validity of GR: 1.0000(5), with J0737-3039A (Kramer et al. in prep)

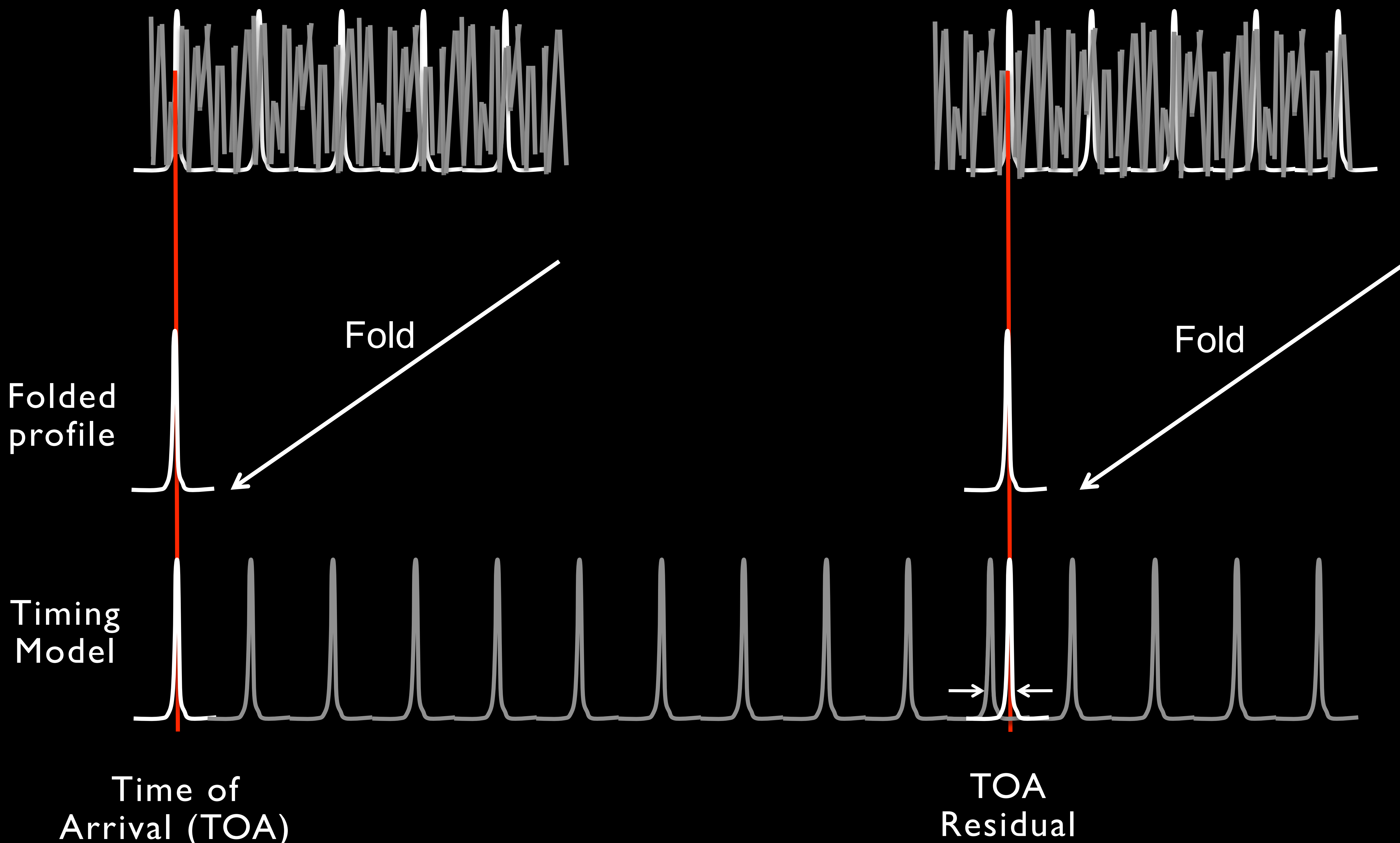
Mass and Jupiter and moons: 9.547921(2)e-4 $M_\odot$ (Champion et al. 2010)

⇒ Simple and clean experiment!



$$\phi(t) = \phi_0 + \sum_{n\geq 1} \frac{f_{n-1}}{n!} (t_{\rm psr} - T_0)^n$$

In practice



(Courtesy David Champion)

Times of arrival

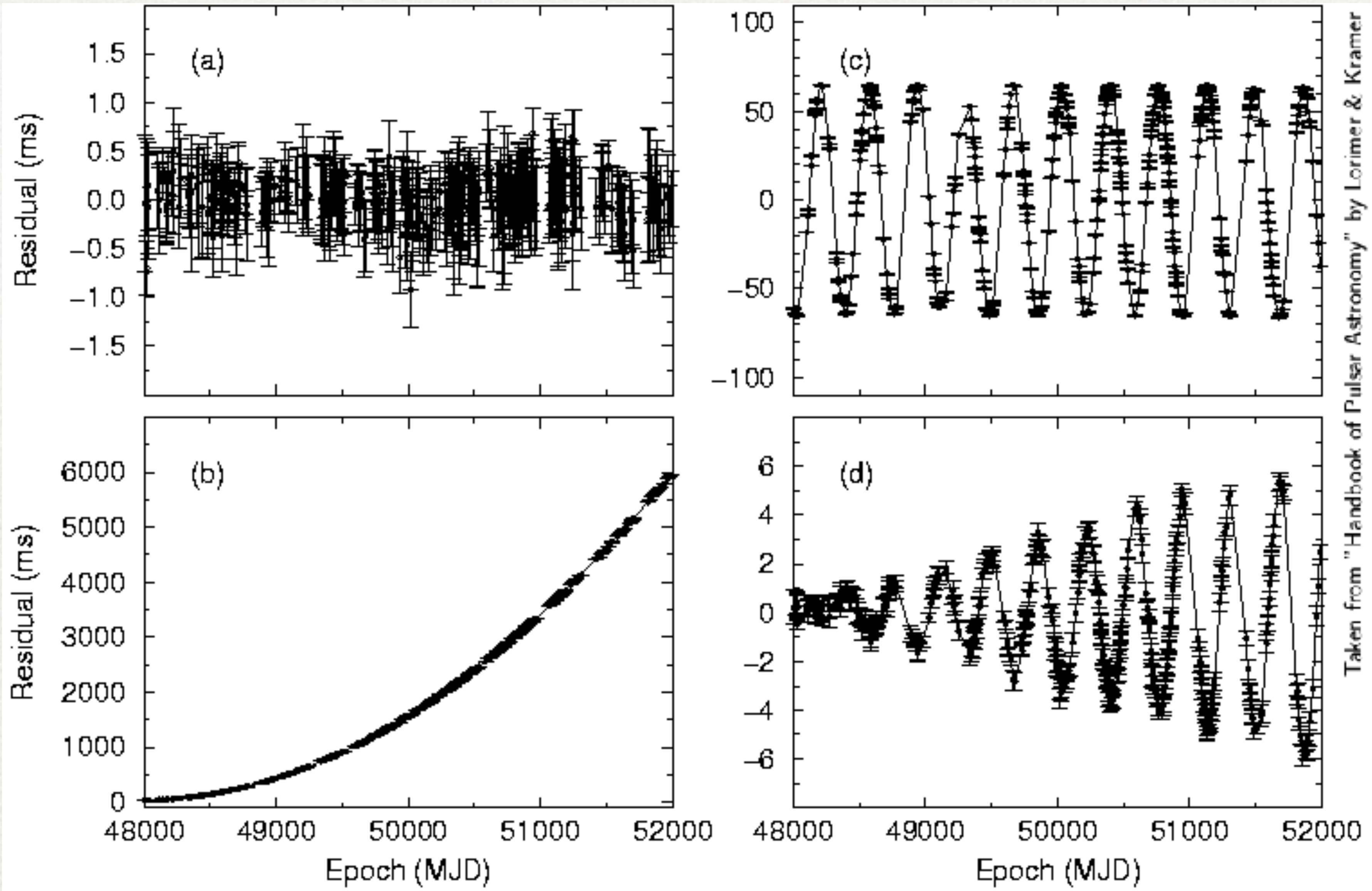
File name	Frequency (MHz)	TOA (MJD)	Uncertainty (μs)	Observatory
nuppi_55832_2017+0603_156215.calibP.DFTp	1264.00000000	55832.81576973428558830	1.01100	ncyobs
nuppi_55834_2017+0603_156273.calibP.DFTp	1264.00000000	55834.81394112309136091	2.11100	ncyobs
nuppi_55835_2017+0603_156296.calibP.DFTp	1264.00000000	55835.80199852991921006	1.57600	ncyobs
nuppi_55871_2017+0603_157333.calibP.DFTp	1264.00000000	55871.72078272672535348	0.99000	ncyobs
nuppi_55879_2017+0603_157592.calibP.DFTp	1484.00000000	55879.69390751315181021	2.59900	ncyobs
nuppi_55924_2017+0603_159196.calibP.DFTp	1484.00000000	55924.57044618721751661	1.26600	ncyobs
nuppi_55935_2017+0603_159562.calibP.DFTp	1484.00000000	55935.54016766197301891	3.98900	ncyobs
nuppi_55937_2017+0603_159625.calibP.DFTp	1484.00000000	55937.54432314176097663	1.51400	ncyobs
nuppi_55958_2017+0603_160288.calibP.DFTp	1484.00000000	55958.47477715766045492	0.97200	ncyobs
nuppi_55975_2017+0603_160846.calibP.DFTp	1484.00000000	55975.43178149237387942	1.26000	ncyobs
nuppi_56025_2017+0603_162681.calibP.DFTp	1484.00000000	56025.29341946745196879	2.96300	ncyobs
nuppi_56028_2017+0603_162782.calibP.DFTp	1484.00000000	56028.28672266420056047	0.82300	ncyobs
nuppi_56050_2017+0603_163580.calibP.DFTp	1484.00000000	56050.22366108771390358	2.12200	ncyobs
nuppi_56054_2017+0603_163725.calibP.DFTp	1484.00000000	56054.21570098695444173	0.48700	ncyobs
nuppi_56057_2017+0603_163818.calibP.DFTp	1484.00000000	56057.20447536734480209	1.02000	ncyobs
nuppi_56080_2017+0603_164615.calibP.DFTp	1484.00000000	56080.13966968803277169	2.70800	ncyobs

Timing solution (« ephemeris »)

	PSRJ	J2017+0603		
Equatorial coordinates	RAJ	20:17:22.7050850	1	0.00000716047636445762
	DECJ	+06:03:05.56876	1	0.00023005672580914071
Rotational frequency and derivative	F0	345.27813114331743324	1	0.00000000000296857177
	F1	-9.5273152703430764566e-16	1	2.6422517641347411217e-19
	PEPOCH	56300		
	POSEPOCH	56300		
	DMEPOCH	56300		
Dispersion measure and derivative	DM	23.923510257527913688		0.00045437151488037349
	DM1	-0.00089367159351270407894		0.00068356978100947874
Proper motion	PMRA	2.4448580272467790298	1	0.17127183658713390768
	PMDEC	0.5634060021627185809	1	0.38542399666539695069
Binary parameters	BINARY	T2		
	PB	2.1984811698446565084	1	0.00000000034895587934
	A1	2.1929228990167317643	1	0.00000029831020903501
	TASC	55202.532346352915109	1	0.00000018923531075229
	EPS1	1.2688228293799280817e-06	1	0.00000026237102674185
	EPS2	-6.6973148743993104 2e-06	1	0.00000022544146418619
Other useful parameters	START	55832.814769734286529		
	FINISH	56847.046762698686507		
	TZRMJD	56336.444542103491653		
	TZRFRQ	1484		
	TZRSITE	ncyobs		
	TRES	0.936		
	EPHVER	5		
	CLK	TT(BIPM2011)		
	MODE 1			
	EPHEM	DE421		
	NITS	1		
	NTOA	54		
	CHI2R	0.9979 42		

Timing residuals

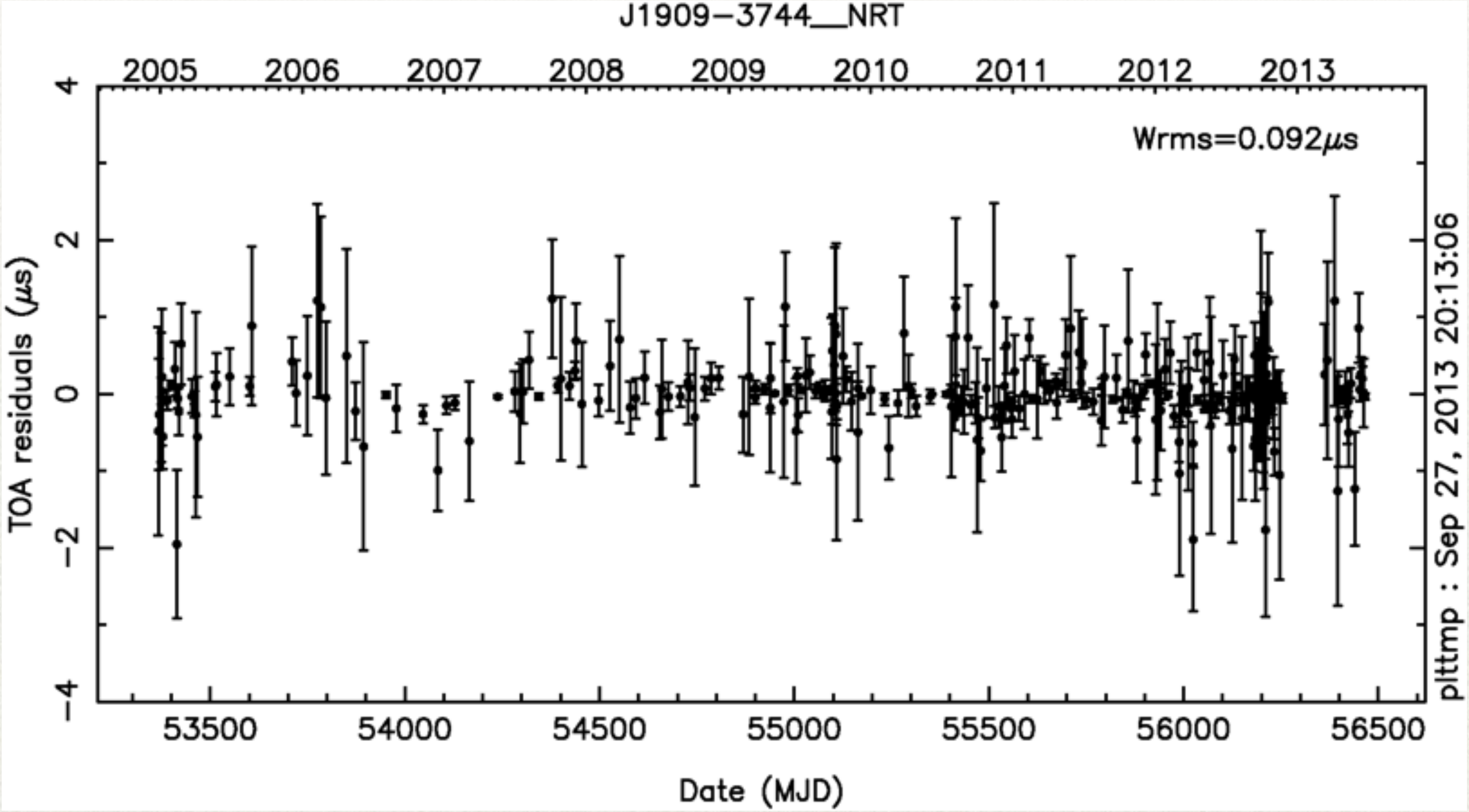
Residuals: differences between measured and predicted TOAs.



(a) good timing model; (b) overestimated period derivative;

(c) wrong coordinates; (d) wrong proper motion parameters.

Nançay timing residuals for J1909-3744



MSP J1909-3744 (P ~ 2.95 ms, P_b ~ 1.53 d) observed at the Nançay Radio Telescope, BON backend data.

W_{rms} < 100 ns!

Max-Planck-Institut
für Radioastronomie

High precision measurements indeed! – "Best of" examples...

Masses:

- Masses of neutron stars: $m_1 = 1.4398(2)\ M_\odot$ and $m_2 = 1.3886(2)\ M_\odot$ (Weisberg et al. 2010)
- Mass of WD companion: $0.207(2)\ M_\odot$ (Hotan et al. 2006)
- Mass of millisecond pulsar: $1.67(2)\ M_\odot$ (Freire et al. 2010)
- Main sequence star companion: $1.029(8)\ M_\odot$ (Freire et al. 2010)
- Mass of Jupiter and moons: $9.547921(2) \times 10^{-4}\ M_\odot$ (Champion et a. 2010)

Spin parameters:

- Period: 5.757451924362137(2) ms Note: 2 atto seconds uncertainty! (Verbiest et al. 2008)

Orbital parameters:

- Period: 0.102251562479(8) day (Kramer et al. in prep.)
- Eccentricity: $3.5\ (1.1) \times 10^{-7}$ (Freire et al. in 2012)

Astrometry:

- Distance: 157(1) pc (Verbiest et al. 2008)
- Proper motion: 140.915(1) mas/yr (Verbiest et al. 2008)

Tests of general relativity:

- Periastron advance: 4.226598(4) deg/yr (Weisberg et al. 2010)
- Shrinkage due to GW emission: 7.152(8) mm/day (Kramer et al. in prep)
- GR validity (obs/exp): 1.0000(5) (Kramer et al. in prep.)
- Constancy of grav. Constant, dG/dt/G: $(9 \pm 12) \times 10^{-13}\ \mathrm{yr}^{-1}$ (Zhu et al. in prep)

Gravitational wave detection:

- Change in relative distance: 100m / 1 lightyear (PTAs)

But with the SKA...we can do so much more, for instance:

- Measure SGR A* properties: mass to 10^{-6}, spin to 10^{-4} to 10^{-3}, no hair to 10^{-3} to 10^{-2}: No hair! (Liu et al. 2012)

The University of Manchester
Jodrell Bank Observatory

(Courtesy Michael Kramer)

Tests of theories of gravity

J0737-3039: only known double pulsar system with both pulsars detected in radio.

P_A ~ 22.7 ms, P_B ~ 2.77 s.

Orbital period P_{orb} ~ 147 min

Orbital size ~ 2.93 lt-s

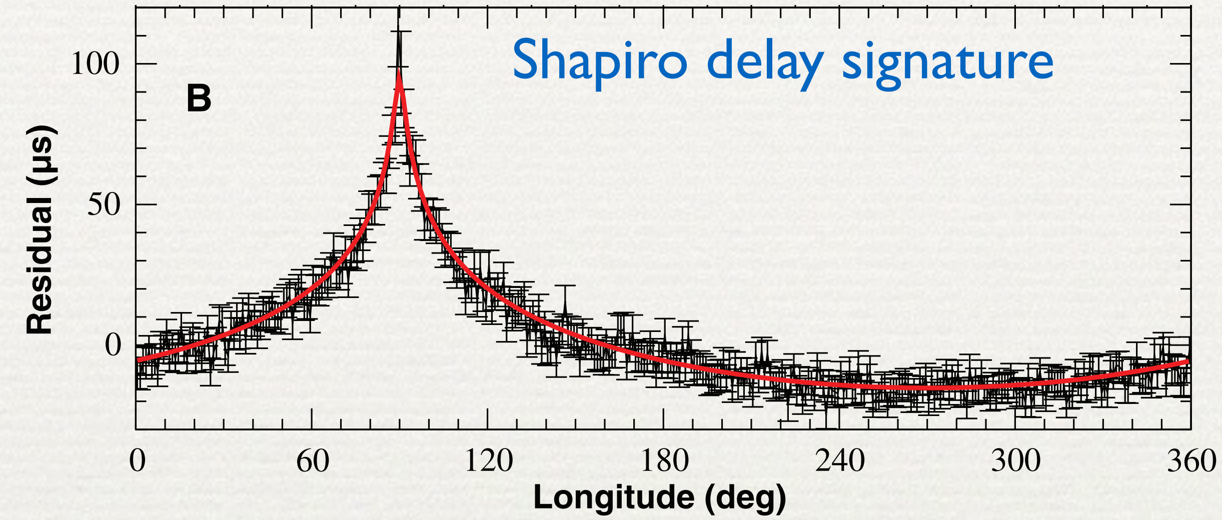
6 post-Keplerian parameters measured!

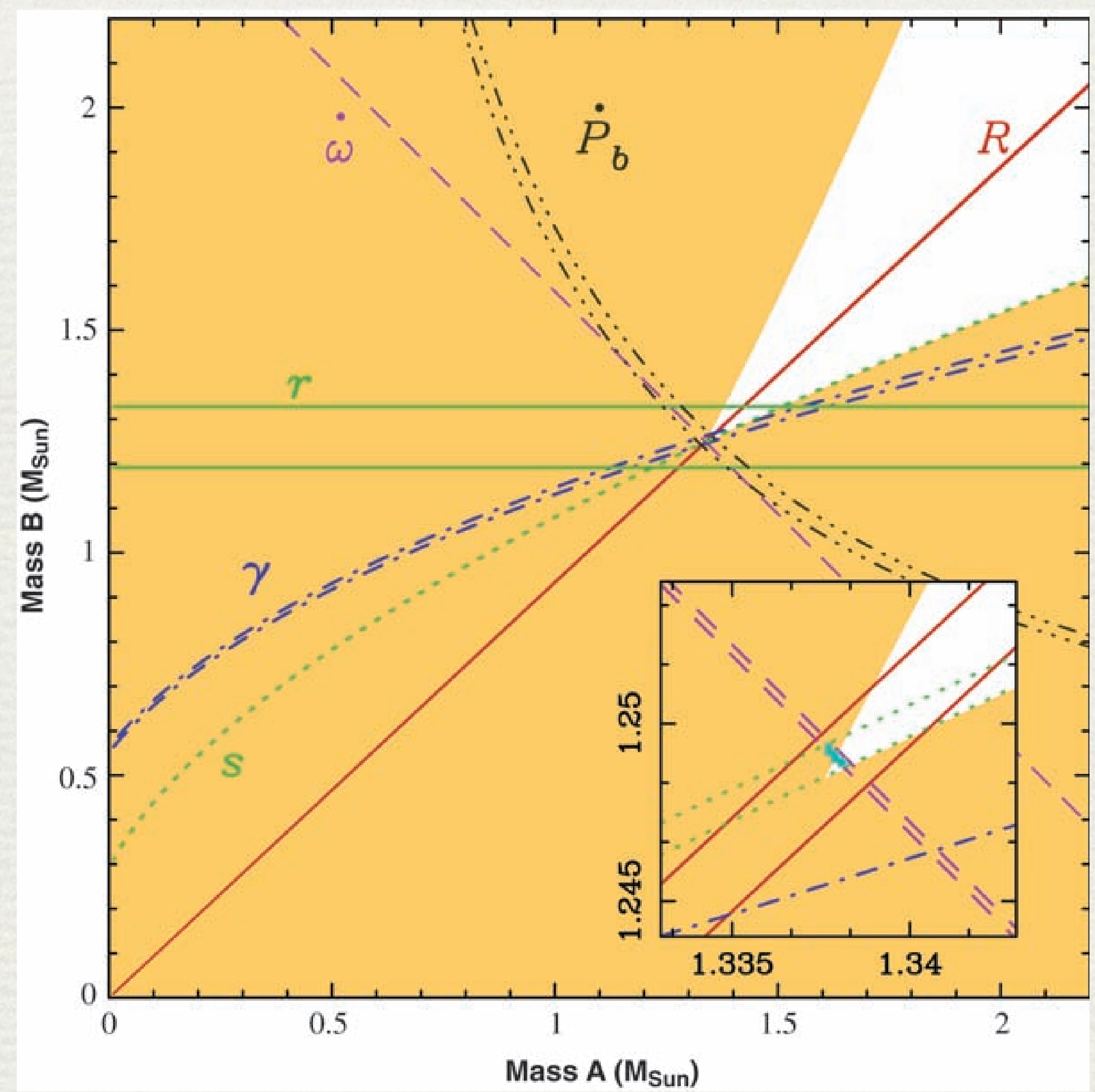
Most precise tests of GR in the strong field regime: ~ 0.05%.

System seen edge-on (i ~ 89°) + massive companion (pulsar B): strong Shapiro delay signature in the radio timing of pulsar A.

⇒ very accurate mass measurements:

$m_A = 1.3381(7)\ M_\odot$, $m_B = 1.2489(7)\ M_\odot$.





Kramer et al., Science 2006

A pulsar in a stellar triple system

See Ransom et al., Nature 2014.

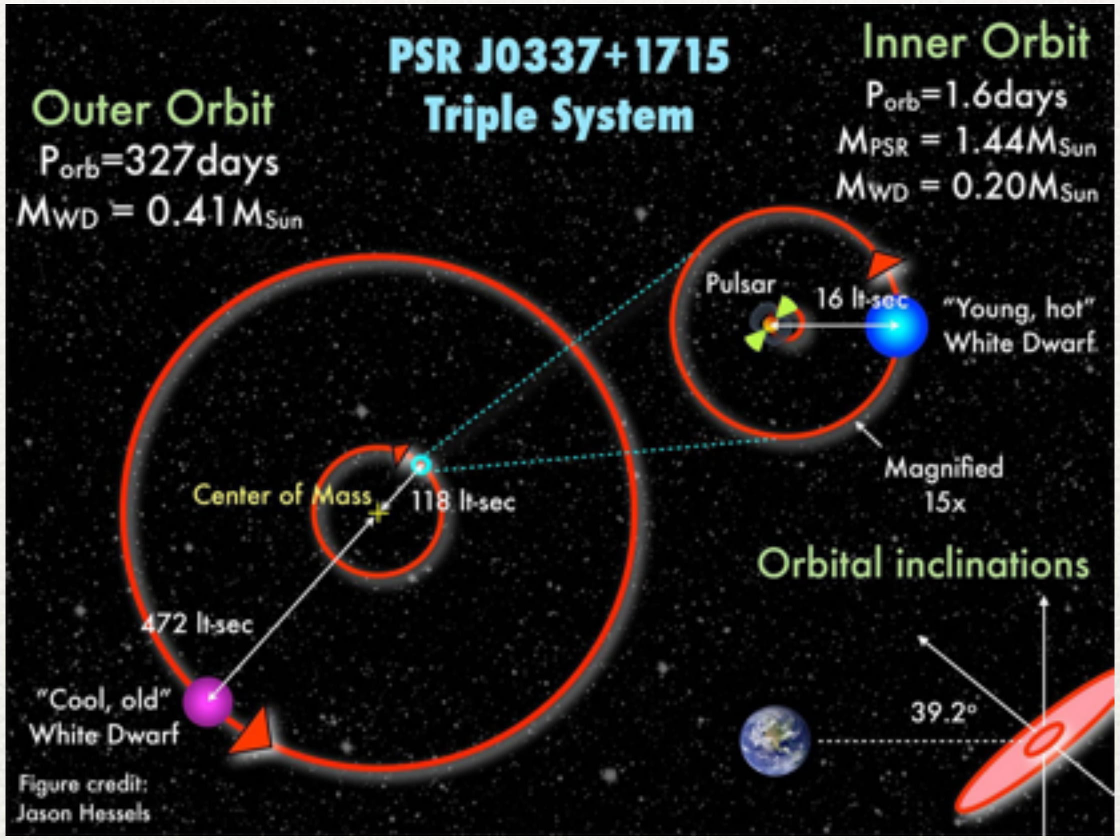
J0337+1715: 2.73 ms pulsar discovered at the Green Bank Telescope (USA). Timing at GBT, Arecibo and WSRT (Netherlands).

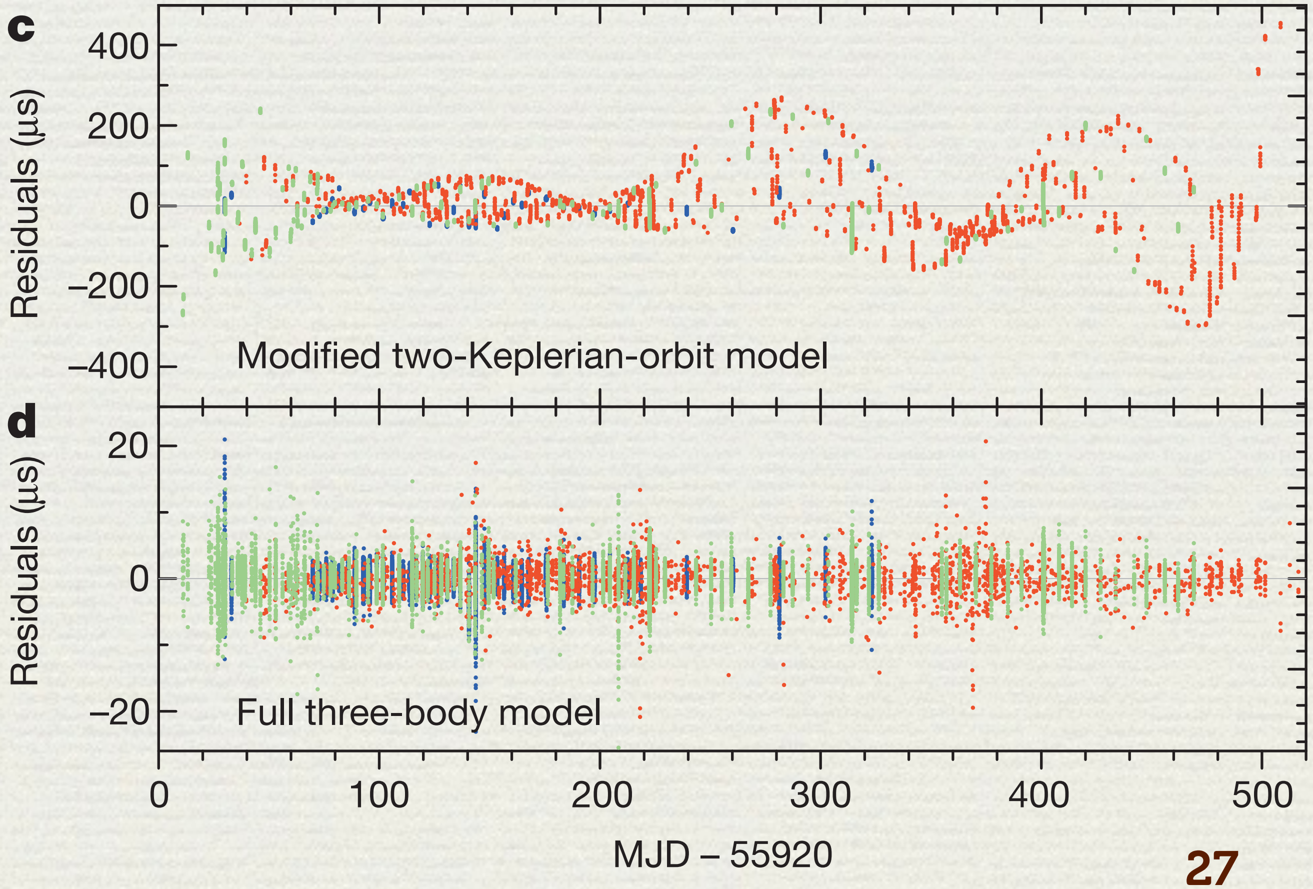
Only known MSP in a stellar triple system!

Strong gravitational interactions are observed. Masses and inclinations measured with great accuracy.

Ideal laboratory to test the strong equivalence principle of General Relativity!

(are the two inner stars falling in the field of the outer star in the same way?)





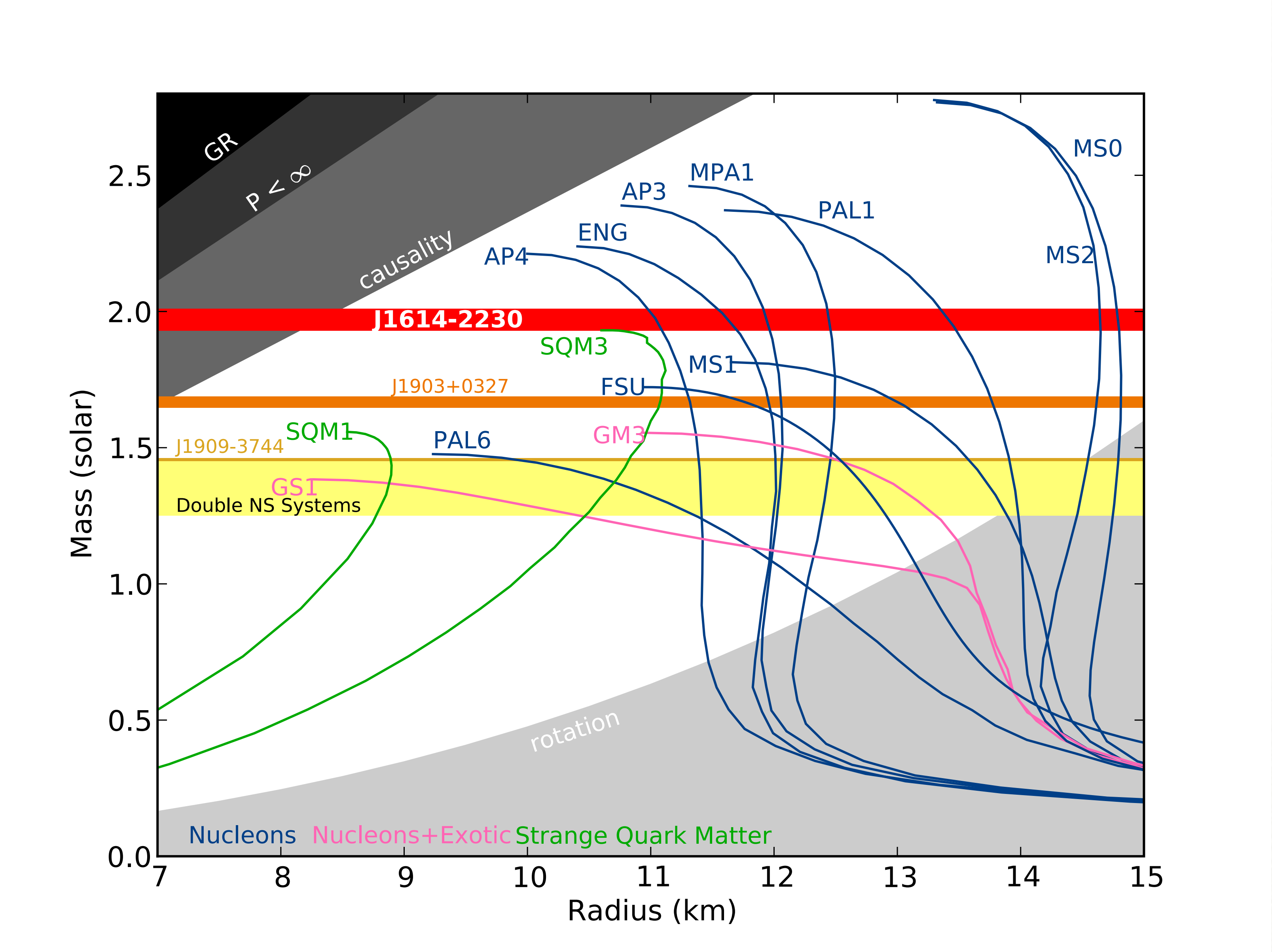
Constraints on NS equations of state

Pulsar timing measurements: mass constraints!

Can rule out (or severely constrain) NS equations of state.

Highest measured today: J0348+0432, 2.01 +/- 0.04 $M_\odot$ (Antoniadis et al. 2013)

Continued timing of J0737-3039A might also allow a direct measurement of its moment of inertia (spin-orbit coupling).



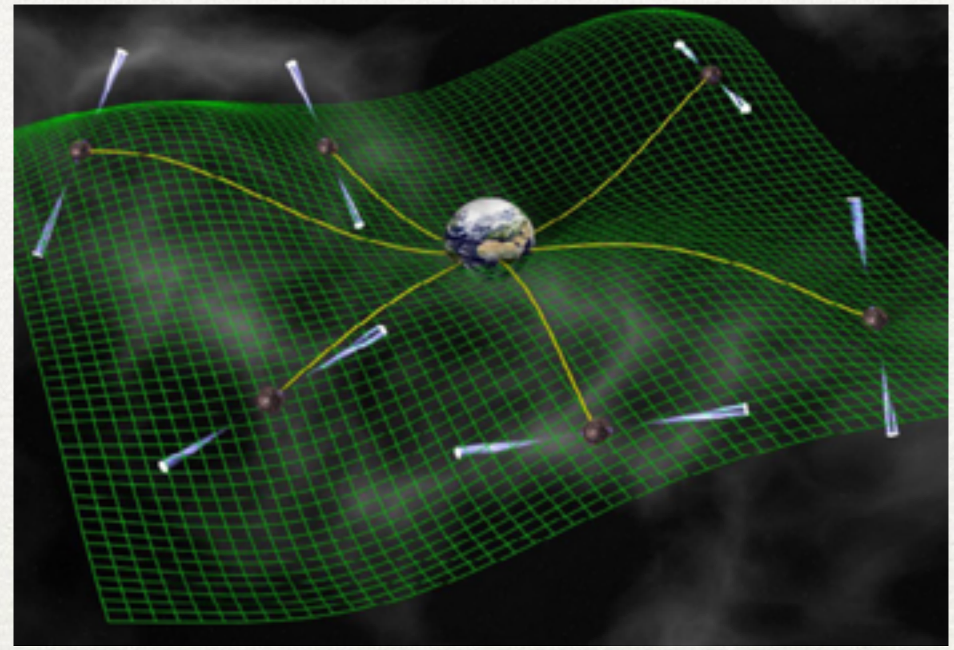
Non-rotating mass vs physical radius for different equations of state.

J1614-2230: Demorest et al. 2010 (1.97 +/- 0.04 $M_\odot$)

J0348+0432: Antoniadis et al. 2013 (2.01 +/- 0.04 $M_\odot$)

Other constraints: see Lattimer & Prakash 2007, in particular « rotation » = J1748-2446ad (716 Hz), Hessels et al. 2006

A cosmic-scale GW detector



In a « Pulsar Timing Array » (PTA), pulsars act as the arms of a cosmic GW detector.

Sources: supermassive black hole binaries, cosmic strings, stochastic background.

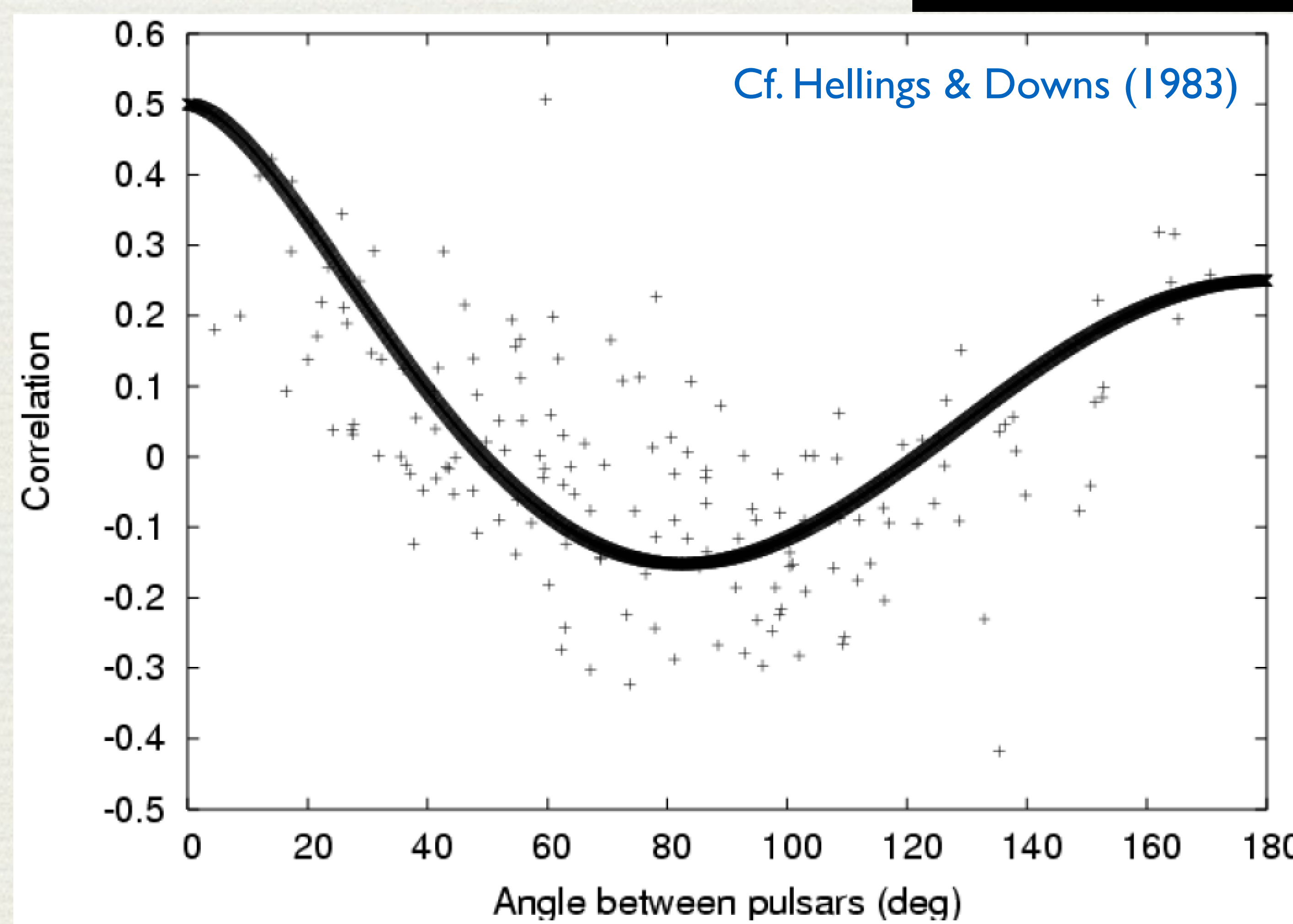
Current efforts: EPTA (Europe), PPTA (Australia), NANOGrav (North Am.), IPTA (International).

Need 5 to 10 years of timing of 20 pulsars with <100 ns accuracy.

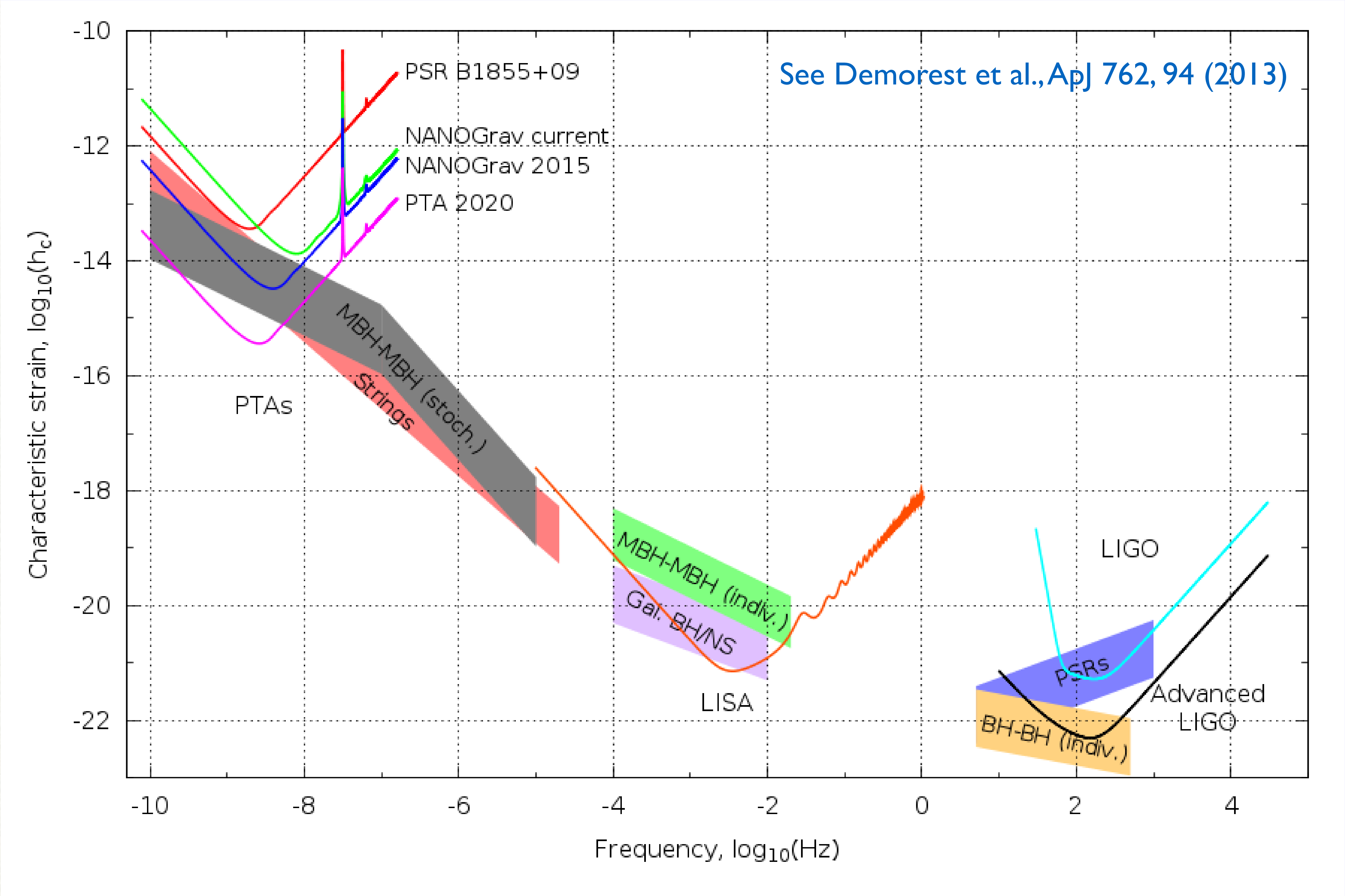
<u>Current best limits:</u>

- van Haasteren et al. 2011 (EPTA)
- Shannon et al. 2013 (PPTA)
- Demorest et al. 2013 (NANOGrav)

Very similar and close to expected detection limit!



Complementary experiments



GW detection is within reach

e.g., Sesana et al., MNRAS Lett. 433, 1 (2013)

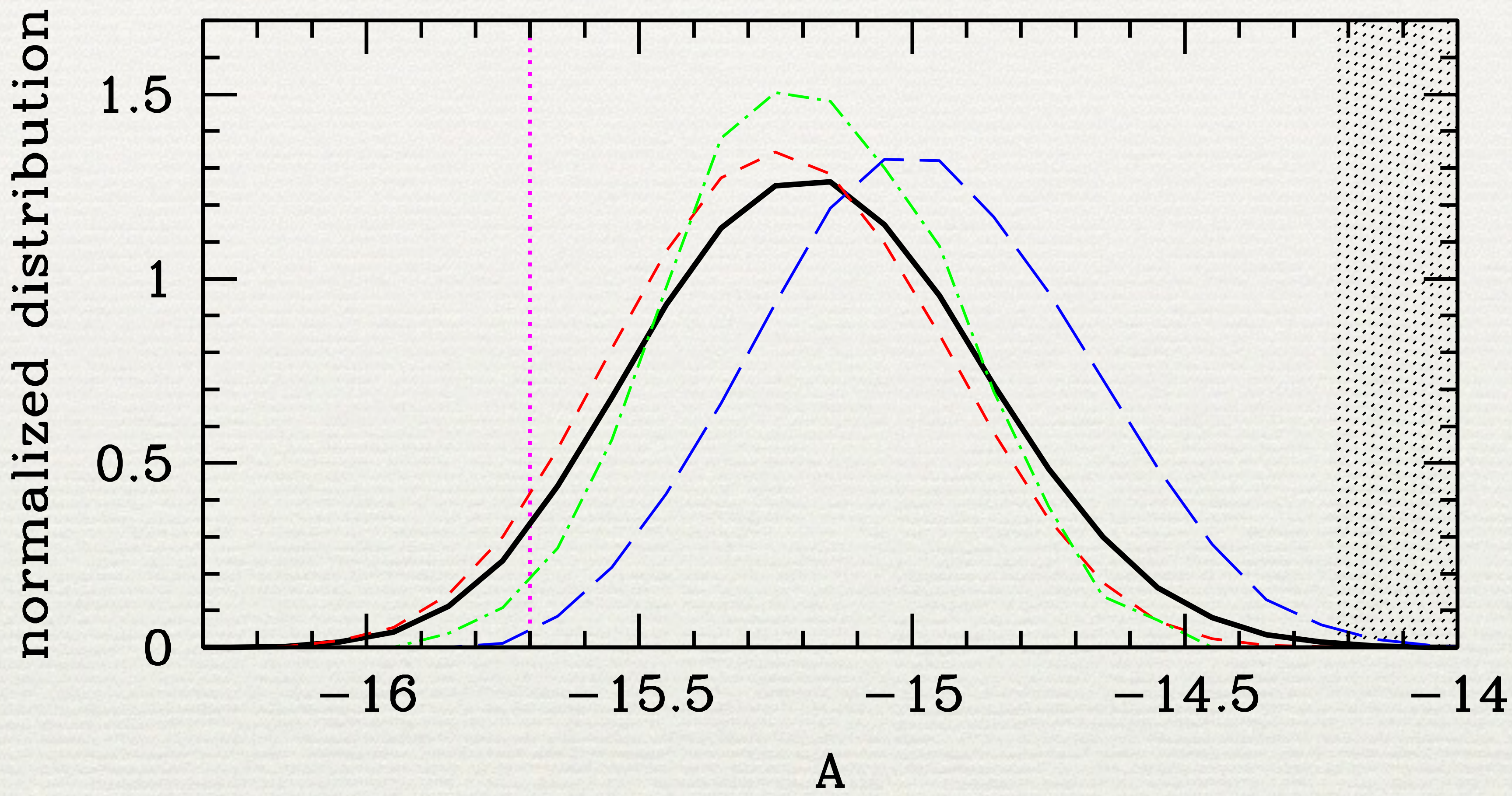


Figure 3. Normalized distributions of the expected GW amplitude A at $f = 1\mathrm{yr}^{-1}$. Black solid line, all models; green dot–dashed line, fiducial models only; red short–dashed line, models antecedent SMBH measurements in BCGs; blue long–dashed, models including SMBH measurements in BCGs. The shaded area marks the region excluded by current PTA limits, whereas the solid dotted line represent what can be achieved by timing 20 pulsars at 100ns rms precision for 10 years.

Pulsars as probes of the interstellar medium

MSPs are stable rotators, generally unaffected by intrinsic timing irregularities.

Turbulence in the ionized ISM can cause dispersive delay variations! Importance of monitoring DM changes for precision timing.

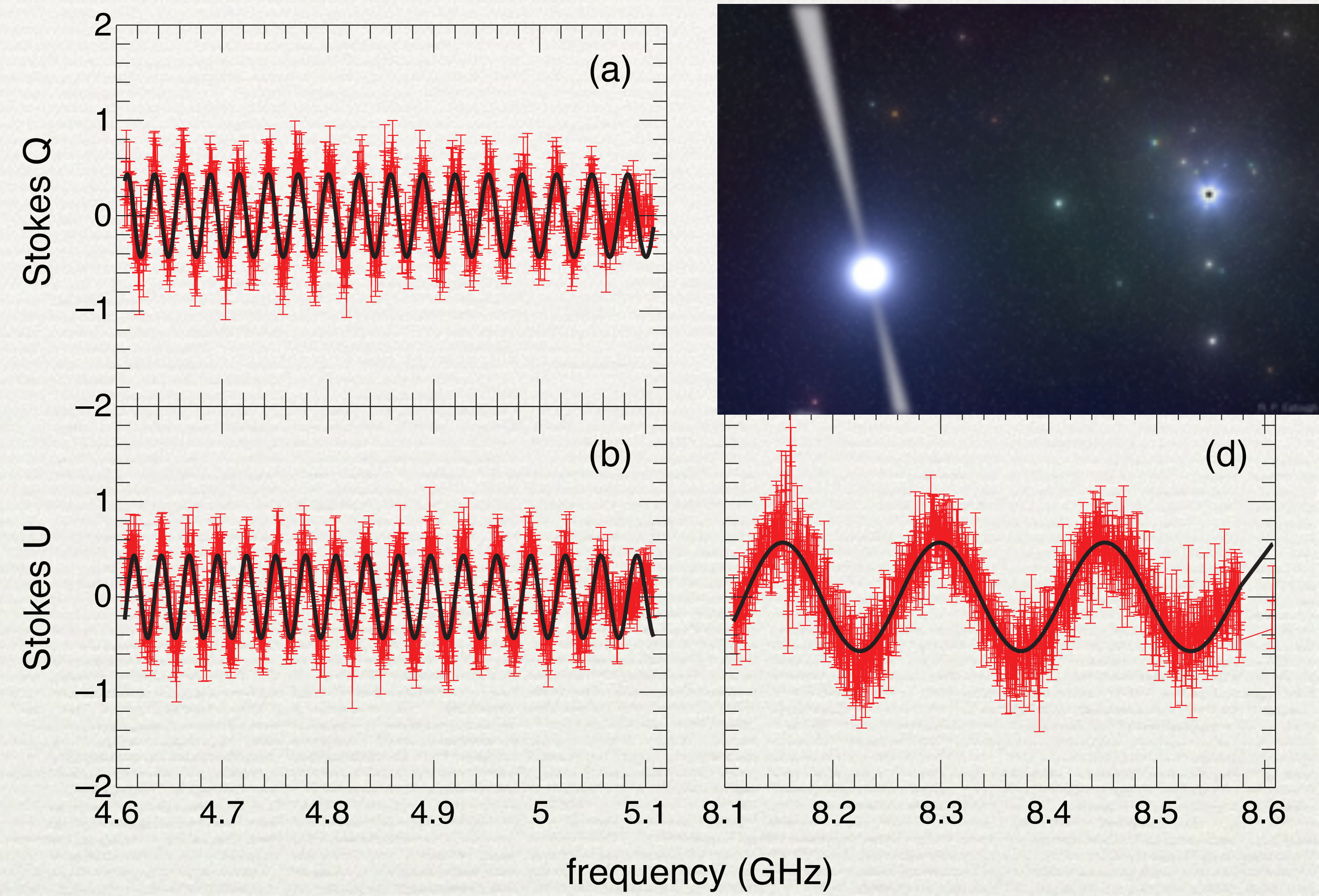
Dispersive delay:

$$t_{\mathrm{DM}} = \lambda^2 \left[\frac{e^2}{2\pi m_e c^3} \int_{path} n_e(l)\mathrm{d}l \right]$$

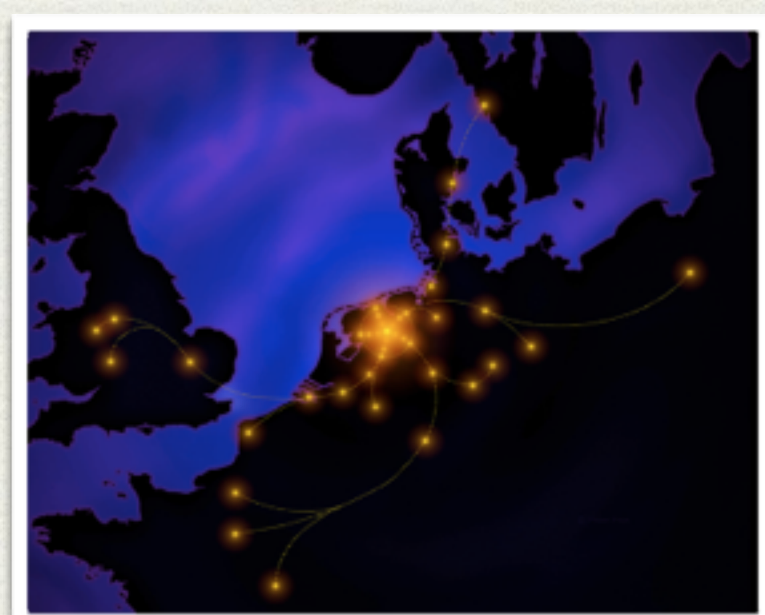
DM measurements allow us to probe the density of free electrons in the ISM!

DM measurements more precise at low frequencies.

Also: magnetic field constraints from Rotation Measure (RM) measurements (Faraday rotation).



Eatough et al., Nature (2013). Rotation synthesis analysis for J1745-2900. RM ~ -6.7 10^4 rad m^{-2} !



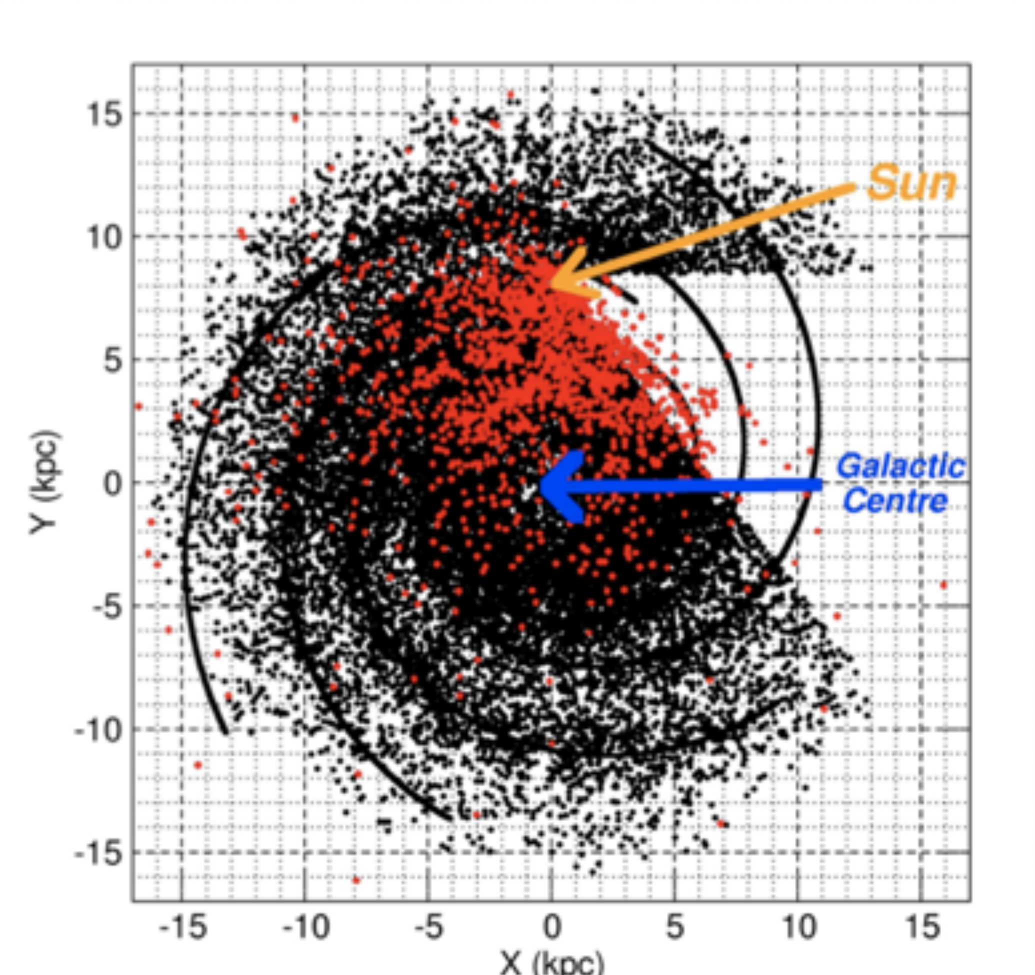
LOFAR

(30-240 MHz)

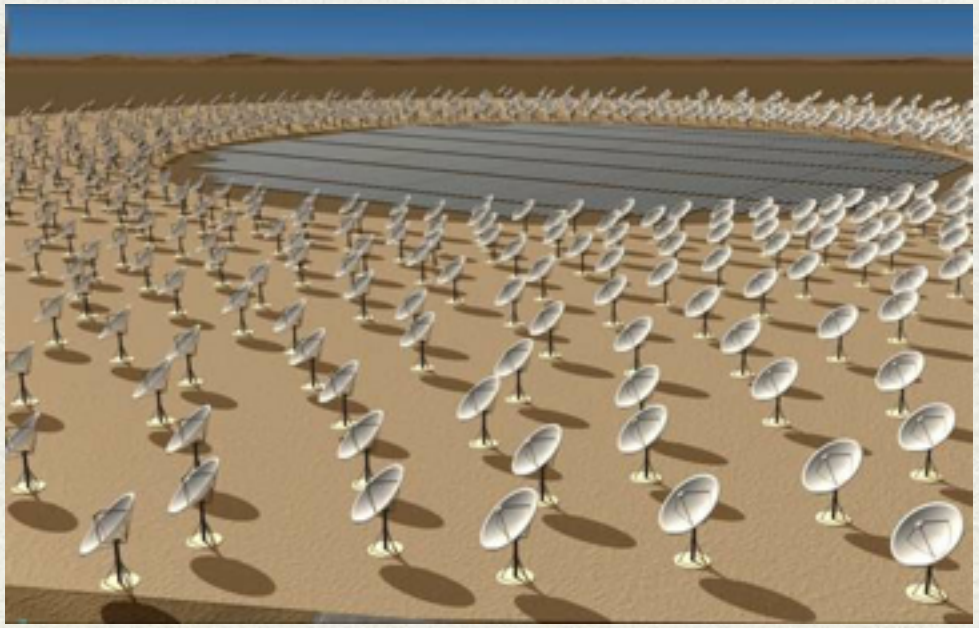
+ NenuFAR project at Nançay

(10-80 MHz)

The future: SKA



Credit: MPIfR, Kramer



SKA1 construction: 2018-2023, early science: 2020.

SKA2 construction: 2023-2030.

Full SKA: frequency coverage from 70 MHz to 30 GHz.

Expect:

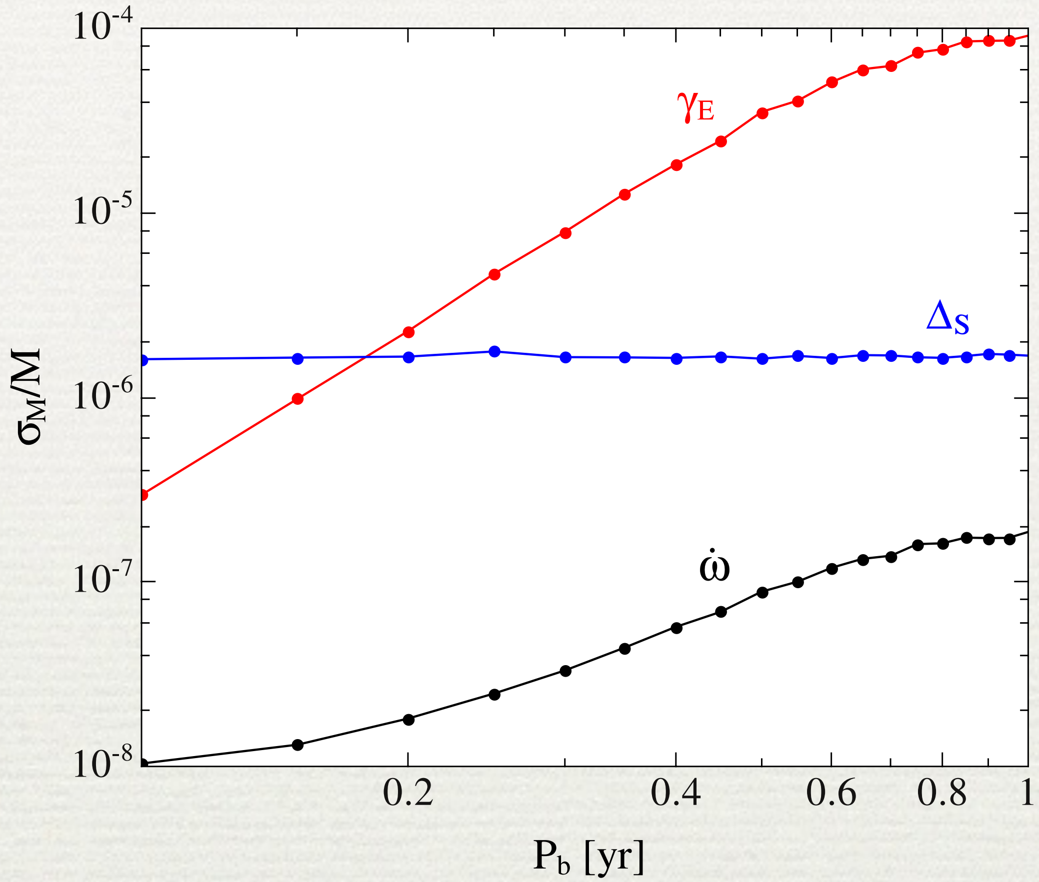
- 14000 « normal pulsars »
- 6000 MSPs
- hundreds of highly relativistic binary systems
- pulsar orbiting the Galactic center?
- extragalactic pulsars?

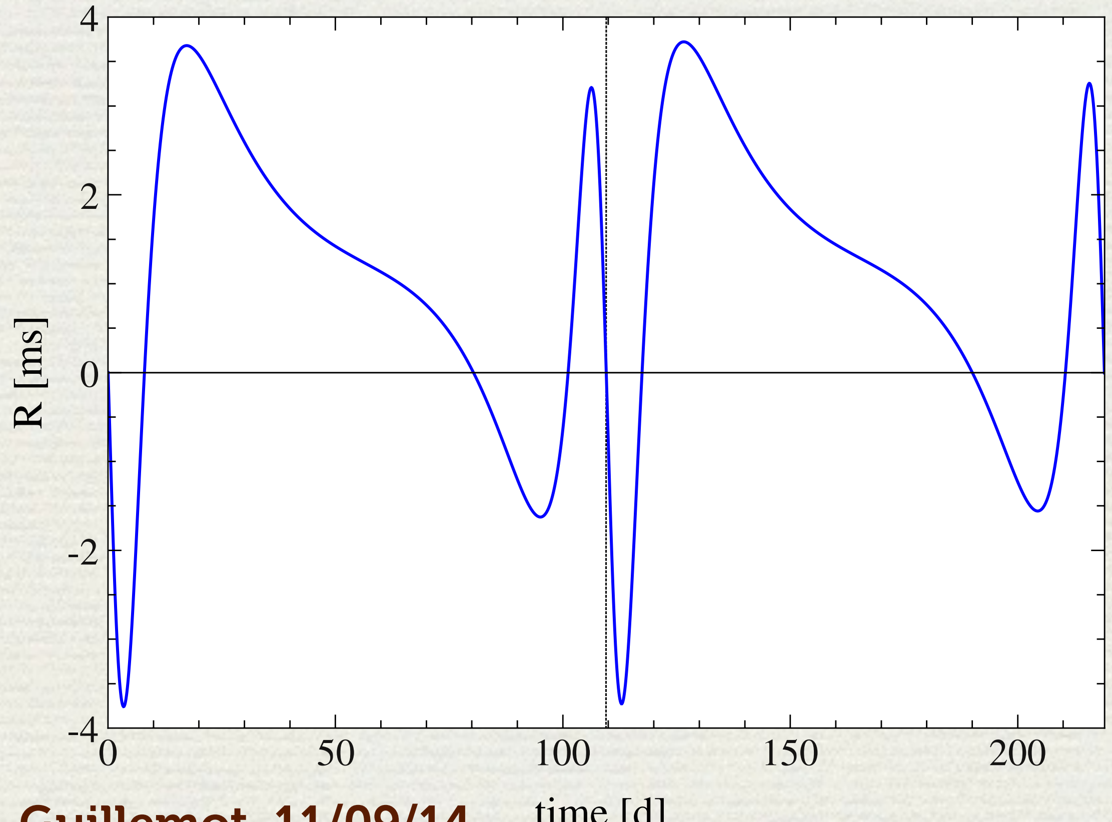
Many more rare and interesting systems!
(i.e.: pulsar orbiting a black hole?)

Also, follow-up timing studies greatly enhanced:

$$\sigma_{\mathrm{TOA}} \sim \frac{wT_{sys}}{S_{\mathrm{PSR}} A \sqrt{BT}}$$

Characterizing the central black hole





See Liu et al. 2012.

Timing of a pulsar orbiting Sgr A* at 100 μs: detailed investigation of the space-time around it, new tests of GR.

Mass measurement for Sgr A* with <0.01% precision.

Spin with <0.1% precision: cosmic censorship.

$$\chi = \frac{c}{G}\frac{S}{M^2} \leq 1$$

Quadrupole moment with 1% precision: no-hair theorem.

$$q = \frac{c^4}{G^2} Q M^3 = -\chi^2$$

Bottom: residuals from quadrupole moment vs orbital phase.

Top: Fractional precision for the mass determination of Sgr A* from three different effects (e = 0.5, i = 60°, 5 years of timing with 100 μs unc)

Conclusions

Pulsar timing has many applications from GW searches to NS equations of state or theories of gravity.

Not talked about today:

emission physics (e.g. high energy with *Fermi*), pulsar searches, pulsar transients, etc.

Thank you for your attention!