Fundamental Physics with Pulsars

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Journées radio SKA-LOFAR

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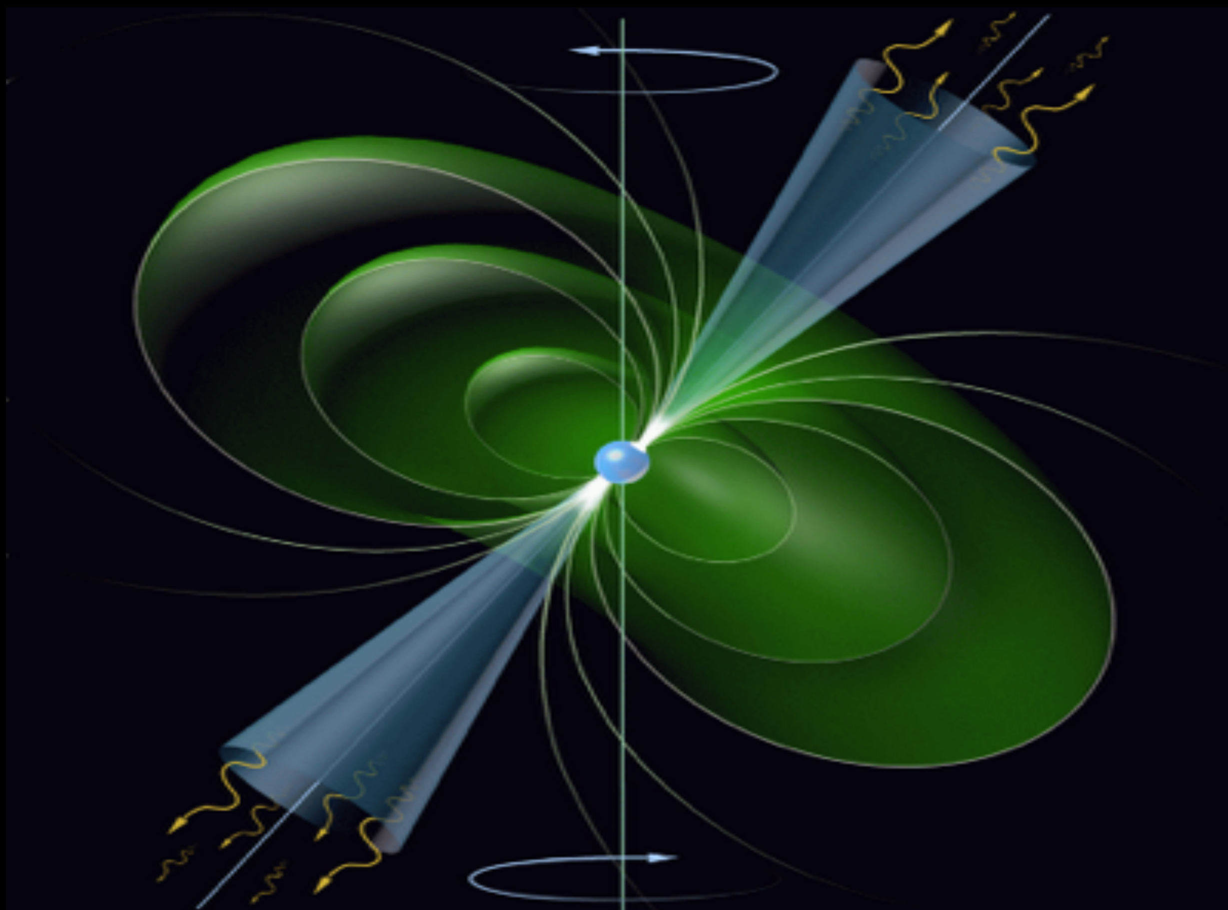
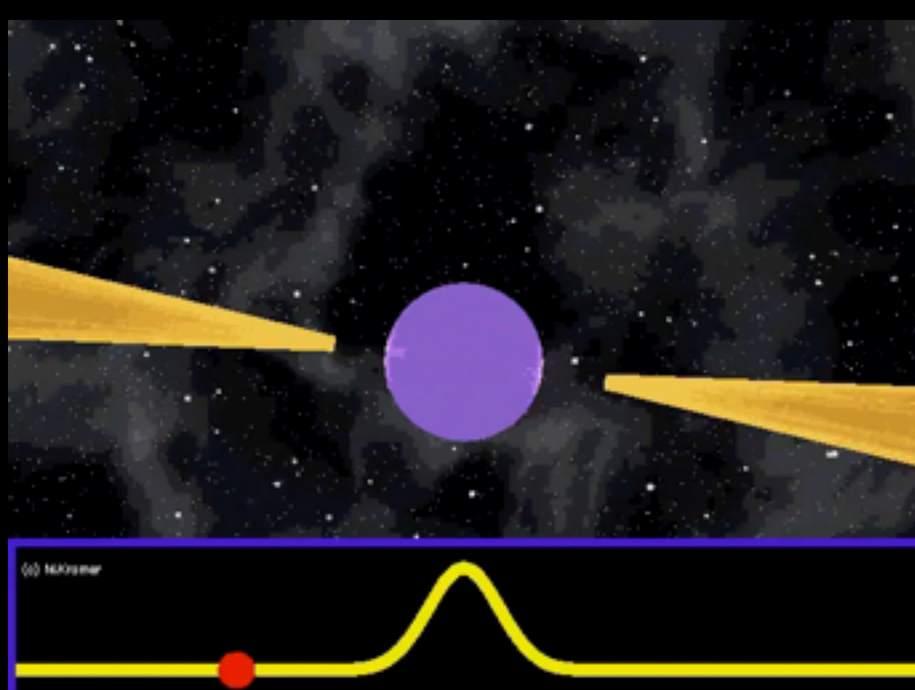
Pulsars





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

Masses: 1.2 - 2 $M_{\odot}$, Radii ~ 10 km.

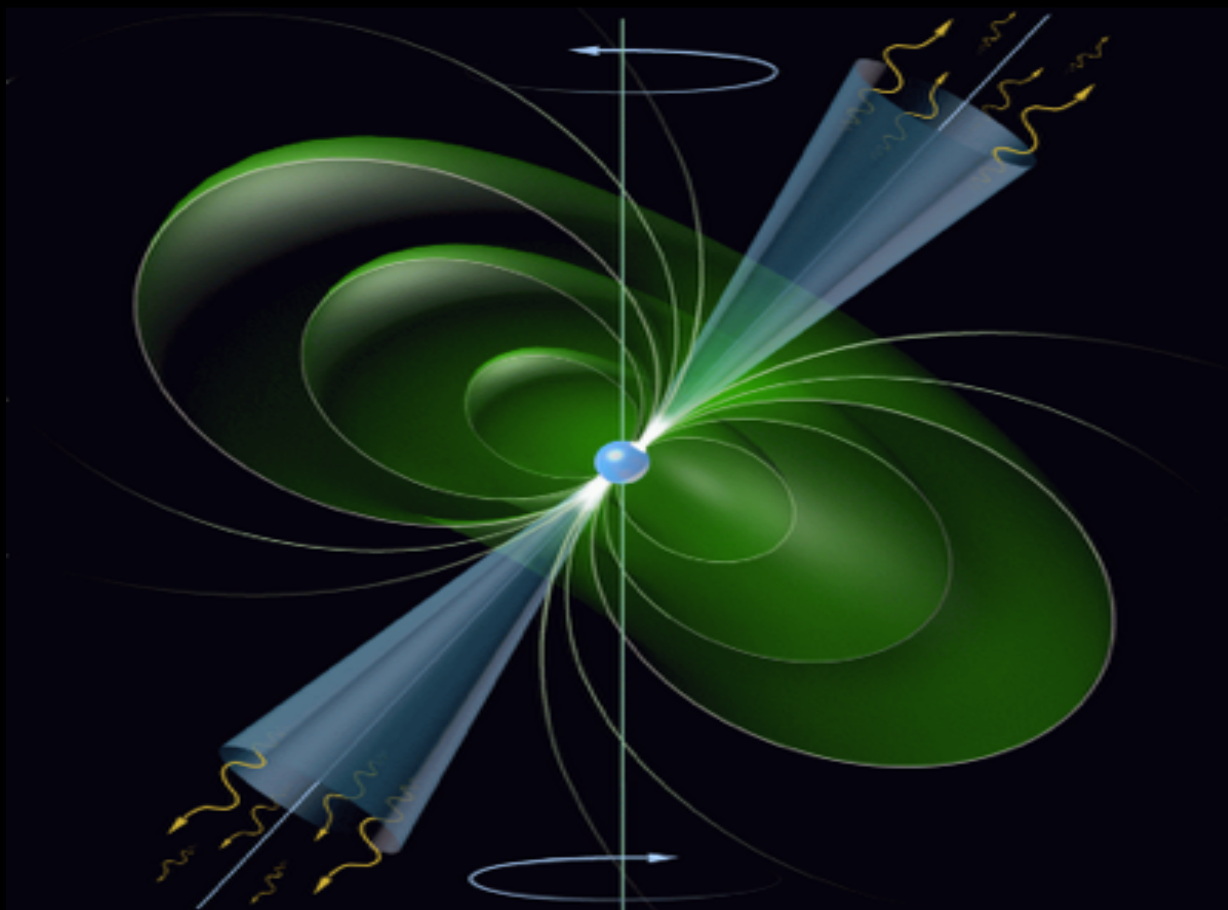
Magnetosphere extending to the "light cylinder", where $\Omega \times R_{LC} = c$.

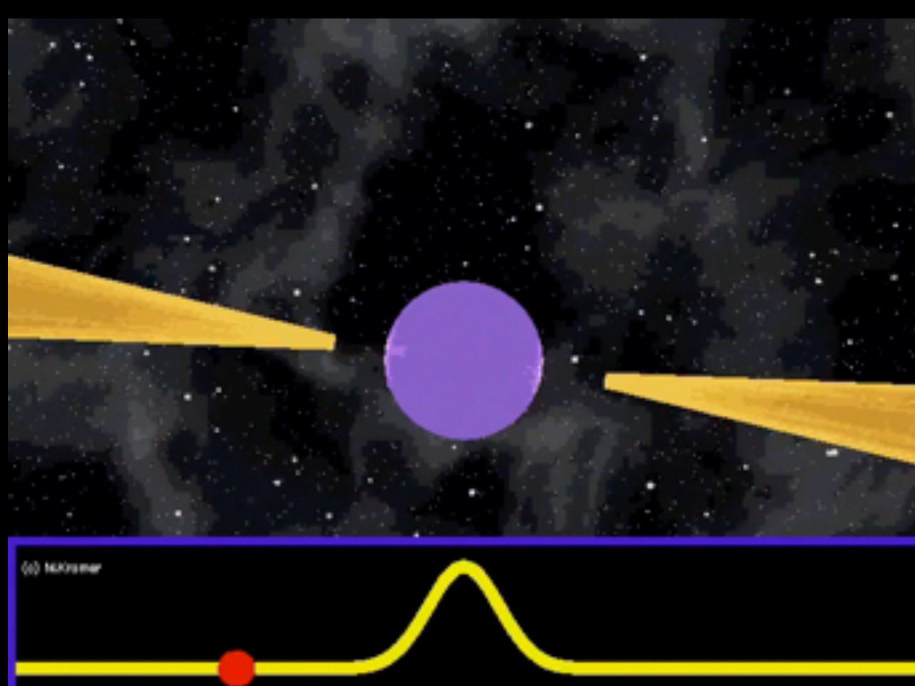
Emission (radio, optical, X-ray, gamma rays…) produced in beams around the star.

~2300 known today (mostly from radio observations)

Pulsars are cosmic lighthouses!

Pulsars





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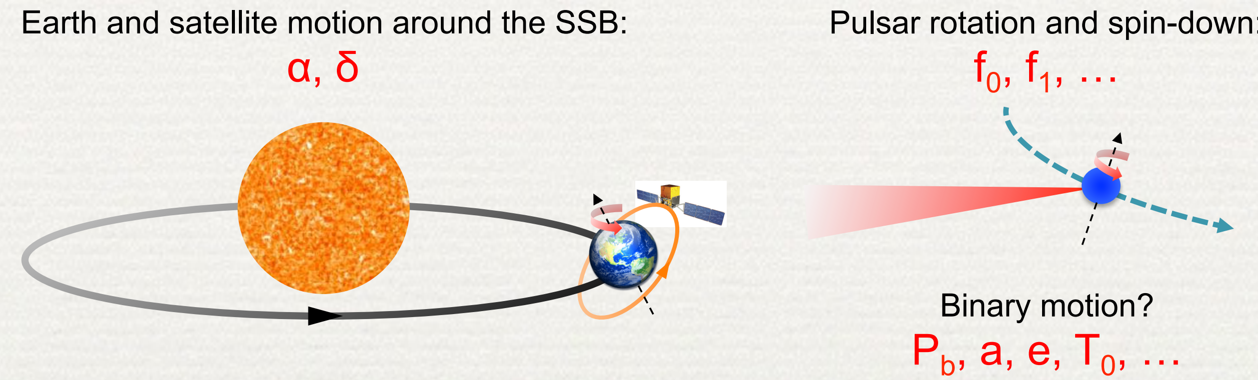
Science from long term timing of pulsars

Goal: account for every single rotation of the pulsar over a certain time interval.



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

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

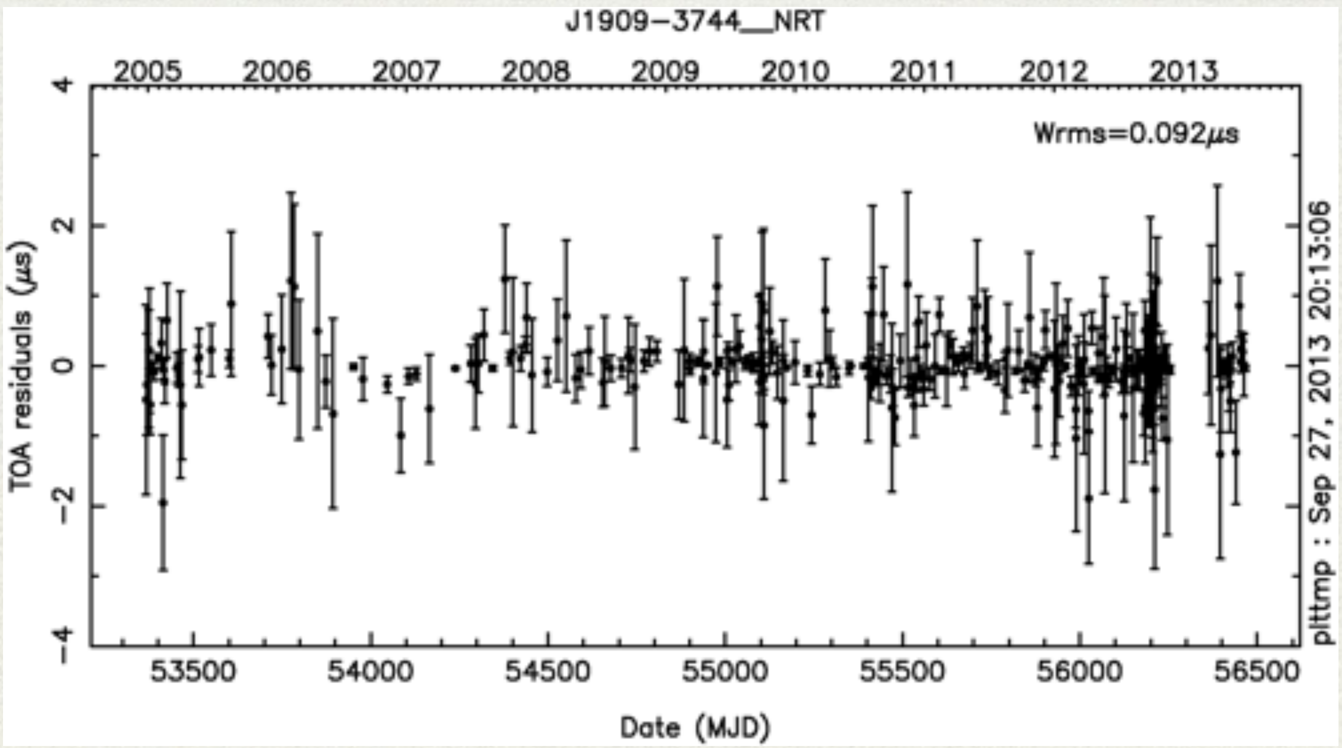
Superb precision for « millisecond » pulsars (MSPs)!

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

P = 0.00525574901411540 ± 0.00000000000000015 s

(Lazaridis et al. 2009)

⇒ Simple and clean experiment!



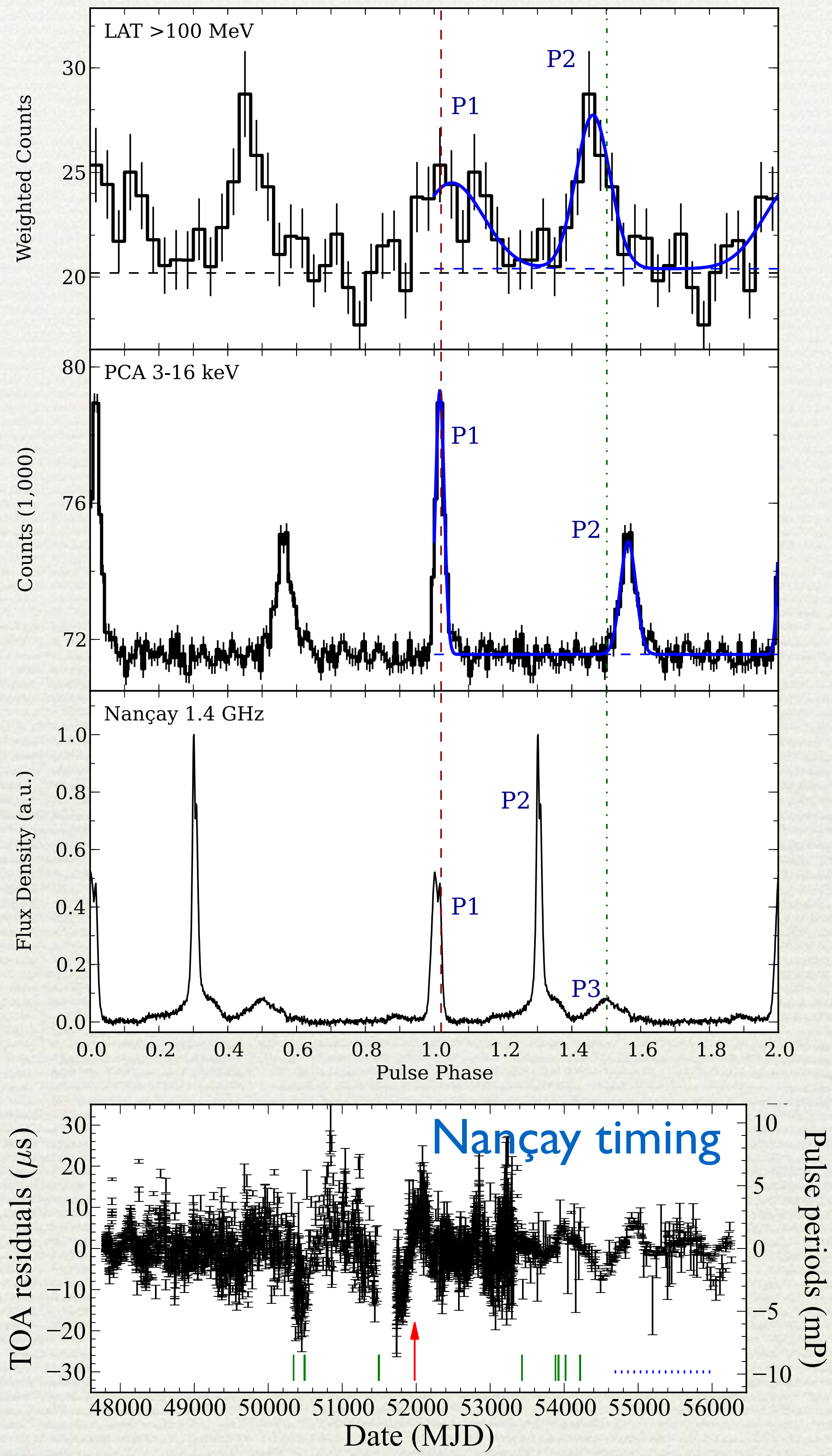
MSP J1909-3744 observed at the Nançay Radio Telescope. W_{rms} < 100 ns!

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

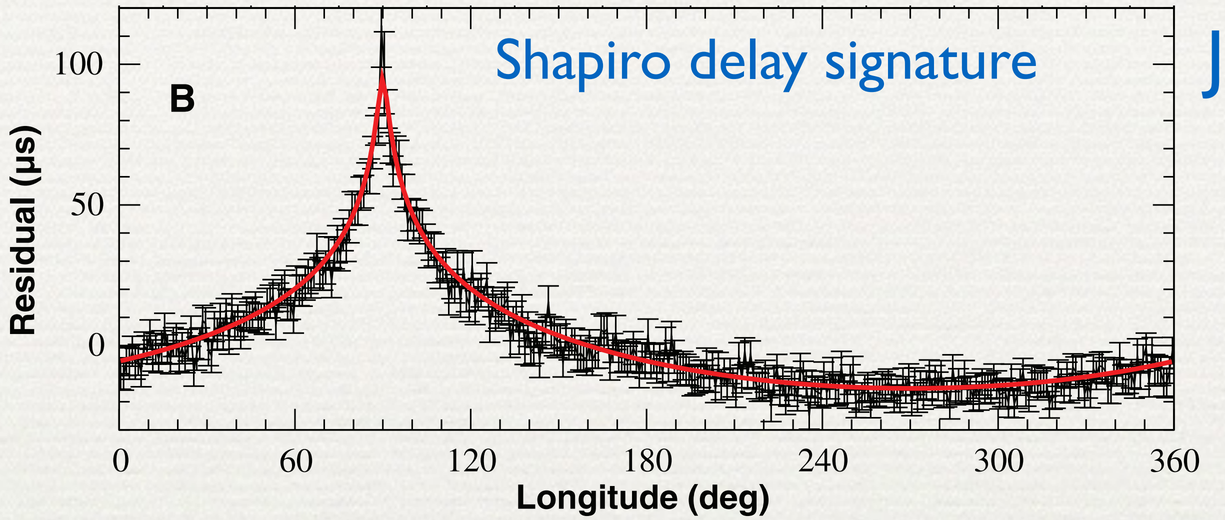
Non-exhaustive list…

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)

The « double pulsar » J0737-3039

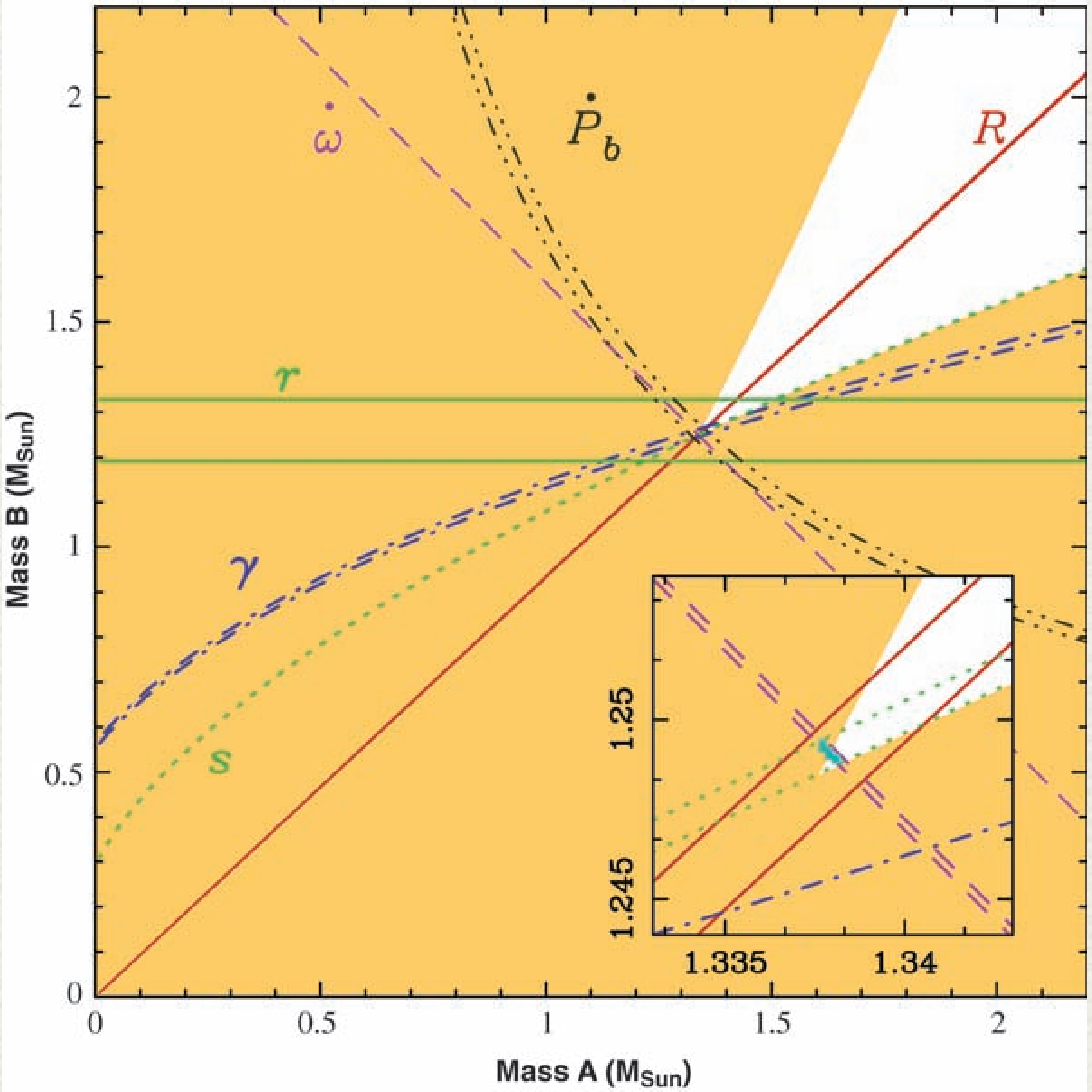


J0737-3039: only known double pulsar system with both pulsars detected in radio.

$P_A \sim 22.7$ ms, $P_B \sim 2.77$ s.

Orbital period $P_{orb} \sim 147$ min

Orbital size ~ 2.93 lt-s



6 post-Keplerian parameters measured!

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

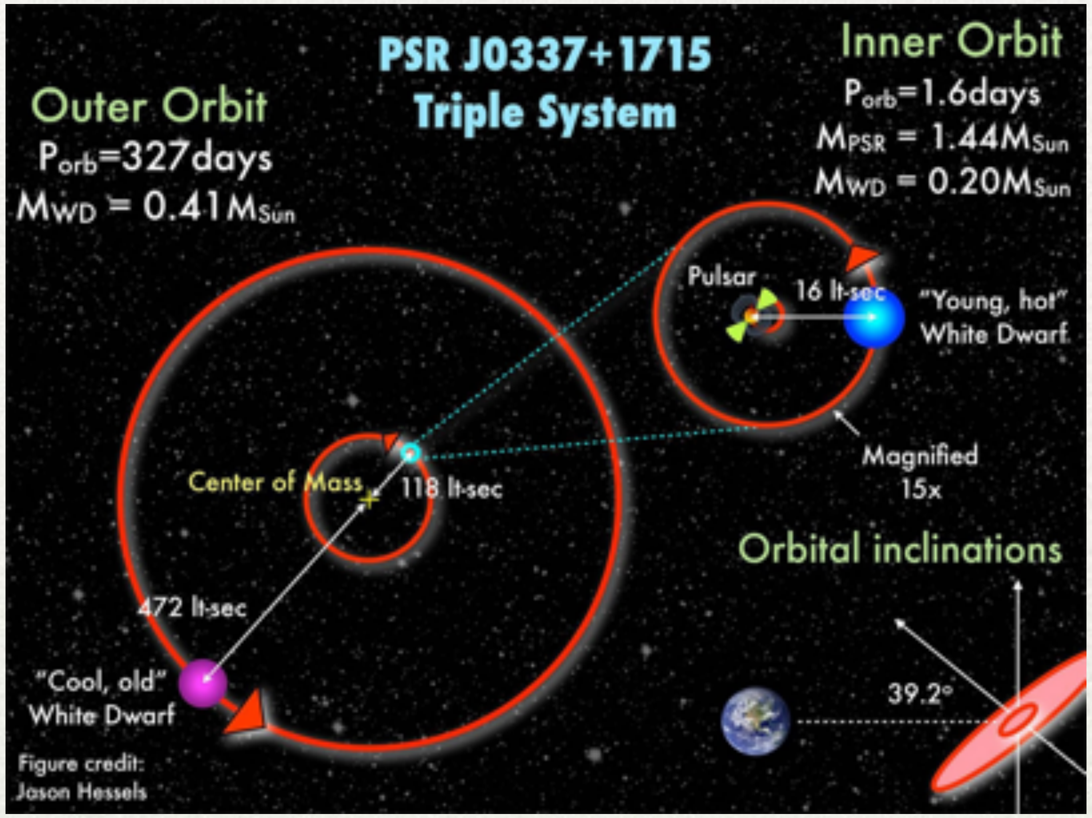
System seen edge-on (i ~ 89°) + massive companion (pulsar B): strong Shapiro delay signature in the radio timing of pulsar A.

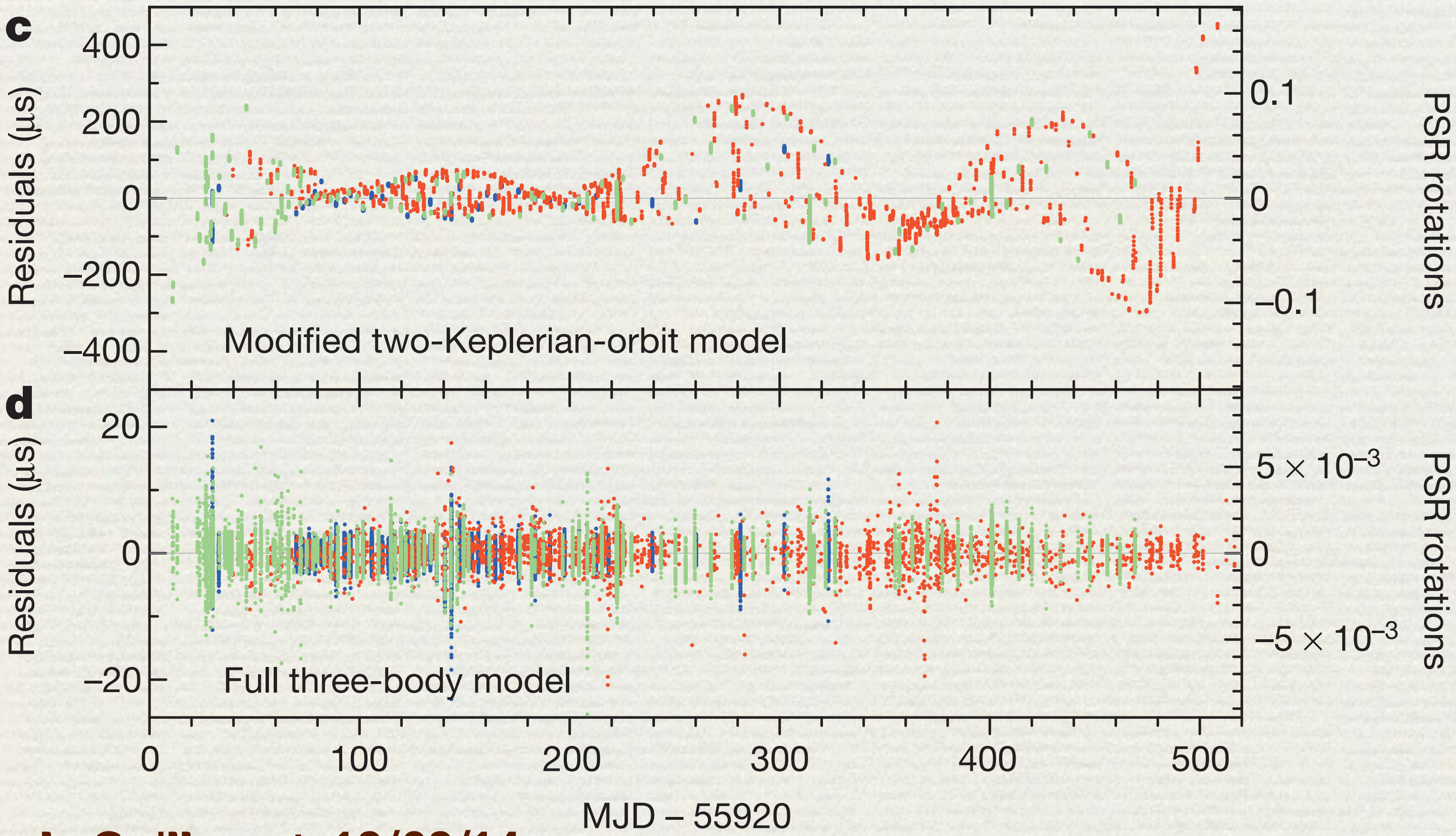
⇒ very accurate mass measurements:

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

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?)

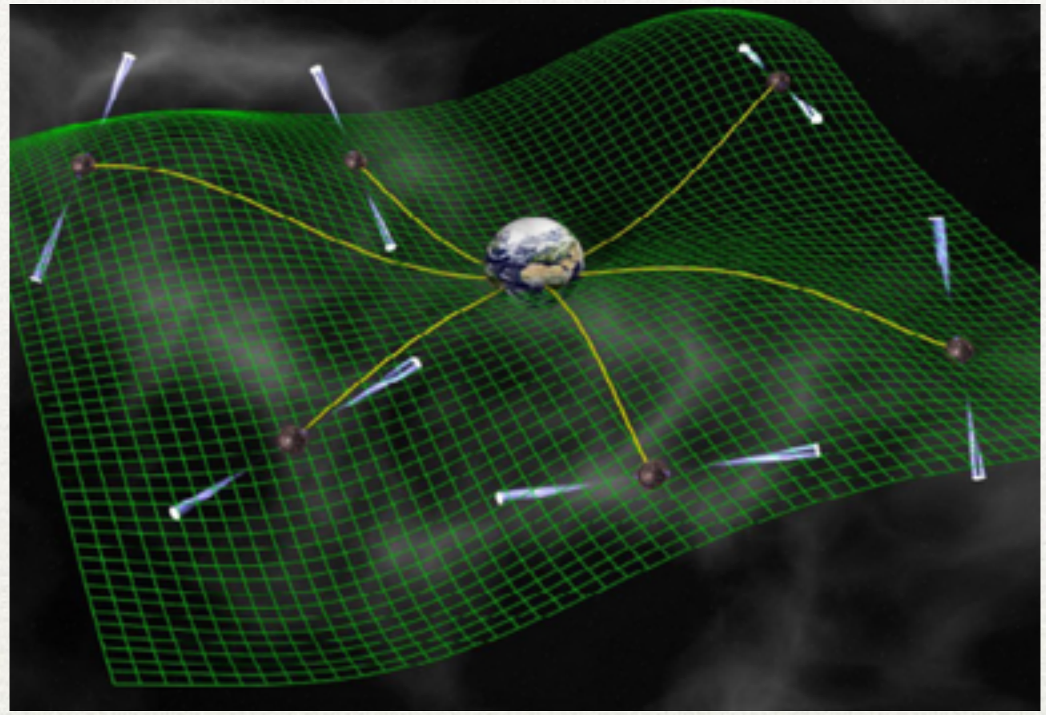
A cosmic-scale GW detector

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).

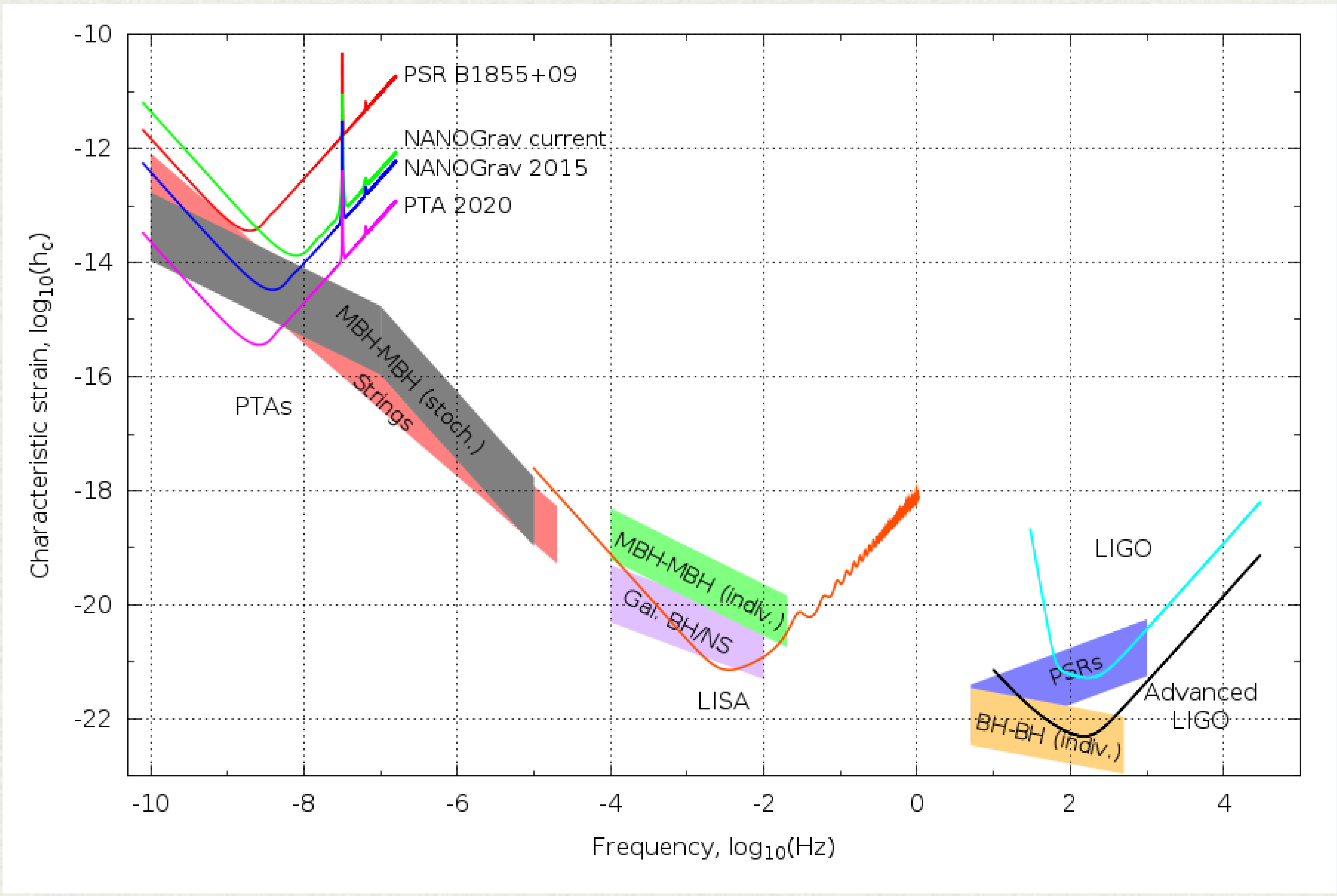
Need 5 to 10 years of timing of 20 pulsars with <100 ns accuracy.



Current best limits:

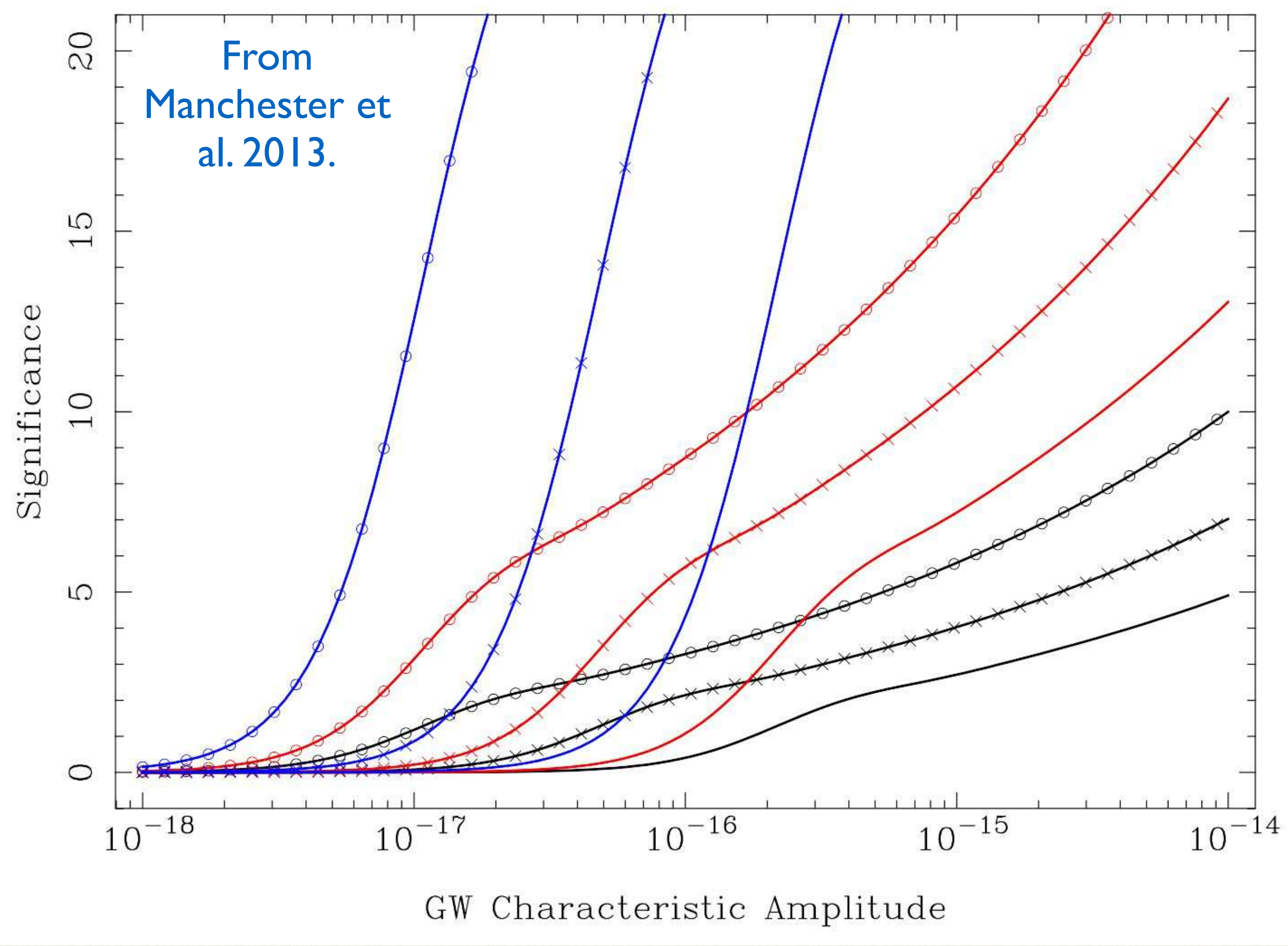
- van Haasteren et al. 2011 (EPTA)
- Shannon et al. 2013 (PPTA)
- Demorest et al. 2013 (NANOGrav)

Very similar and close to expected detection limit!



L. Guillemot, 12/02/14

Sensitivity of PTAs



Black lines: 20 pulsars, red: 50, blue: 200.

Plain lines: 5 years of timing, crosses: 10 years, 20 years: circles.

Assumed weekly observations and 100 ns accuracy.

Detection significance of an isotropic stochastic GW background as a function of signal strength.

Need many more « good » MSPs and long time spans!

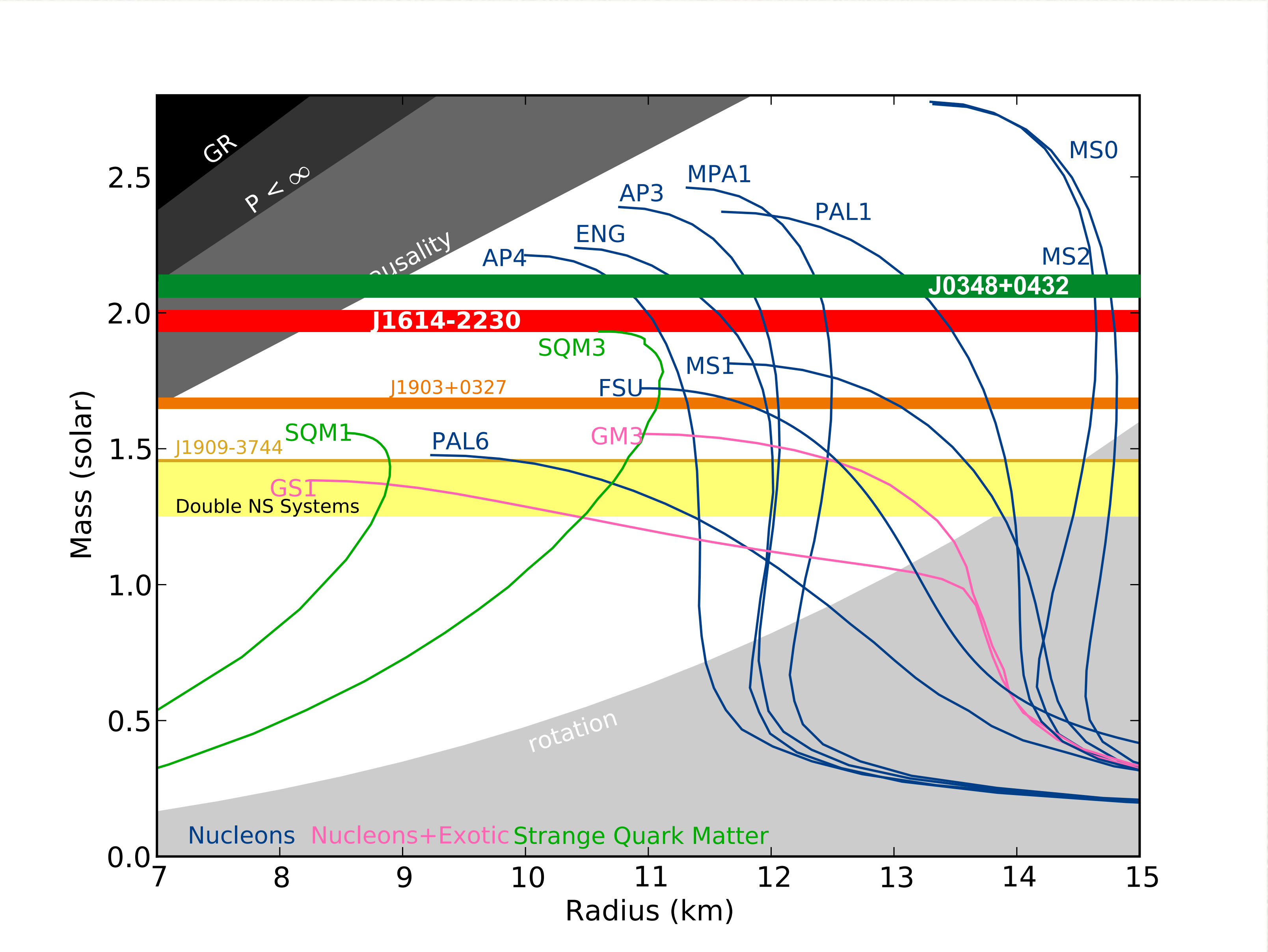
Constraints on NS equations of state

Pulsar timing measurements: mass constraints!

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

Highest known 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)



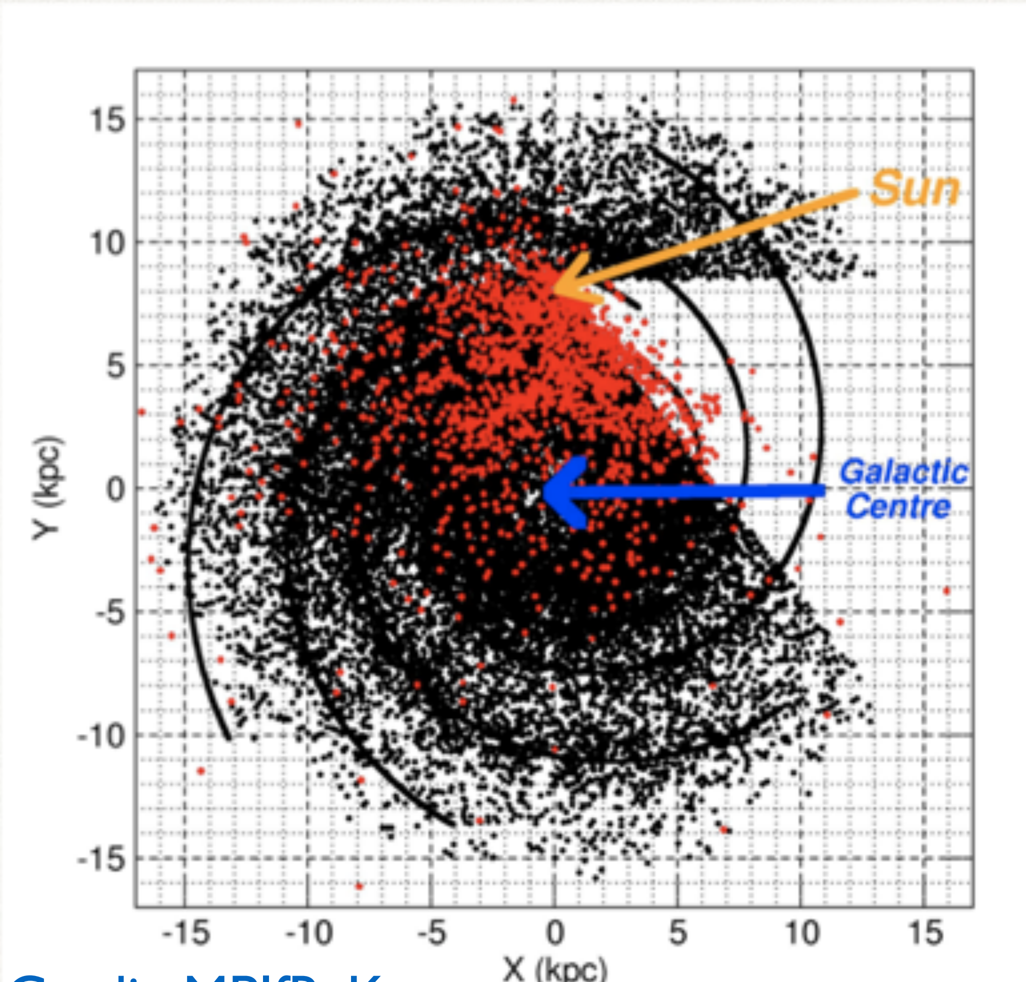
Non-rotating mass vs physical radius for different equations of state.

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

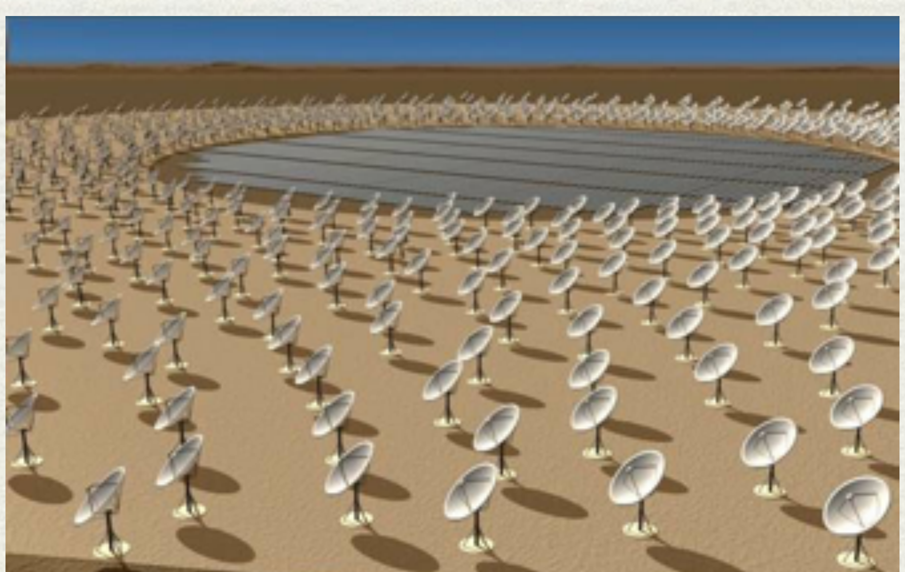
J0348+0432: Antoniadis et al. 2013 (2.01 +/- 0.04 $M_\odot$)

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

Pulsar searches with the SKA



Credit: MPIfR, Kramer



See e.g. Cordes et al. 2004, Kramer et al. 2004, Smits et al. 2009.

Expect:

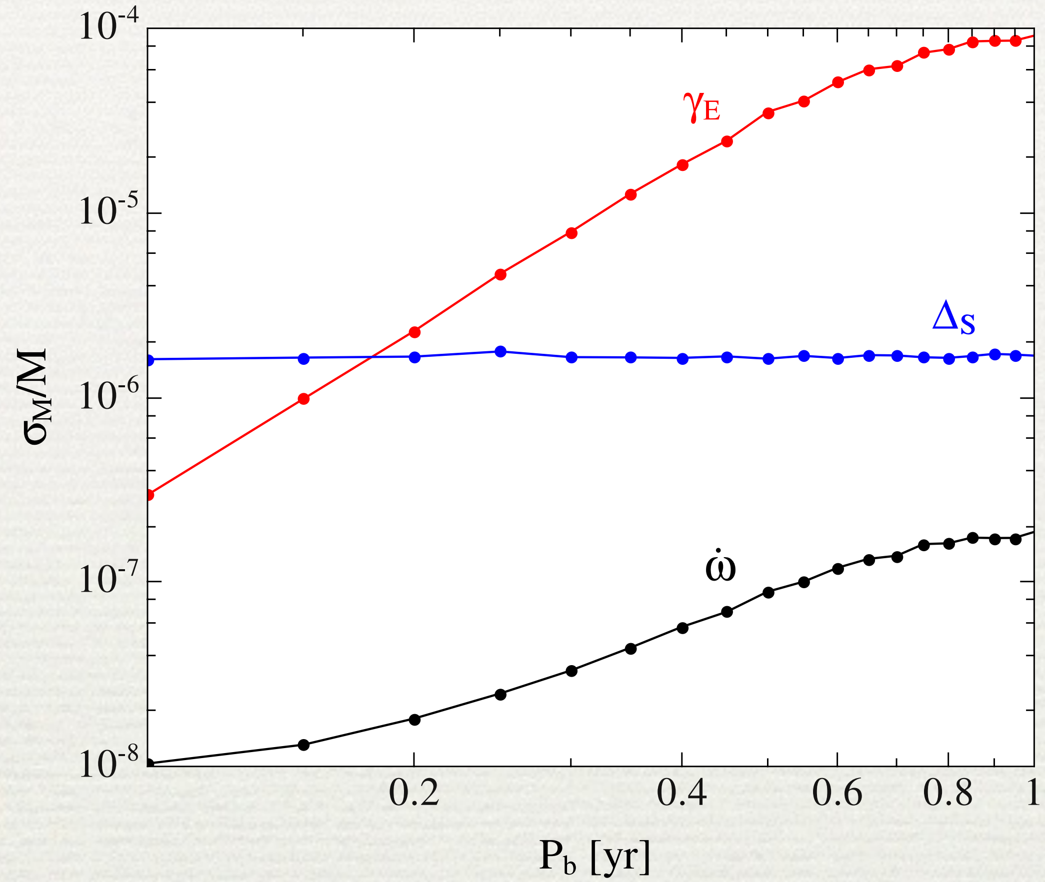
- 14000 « normal pulsars »
- 6000 MSPs
- hundreds of highly relativistic binary systems
- pulsar orbiting the Galactic center?
- extragalactic pulsars?

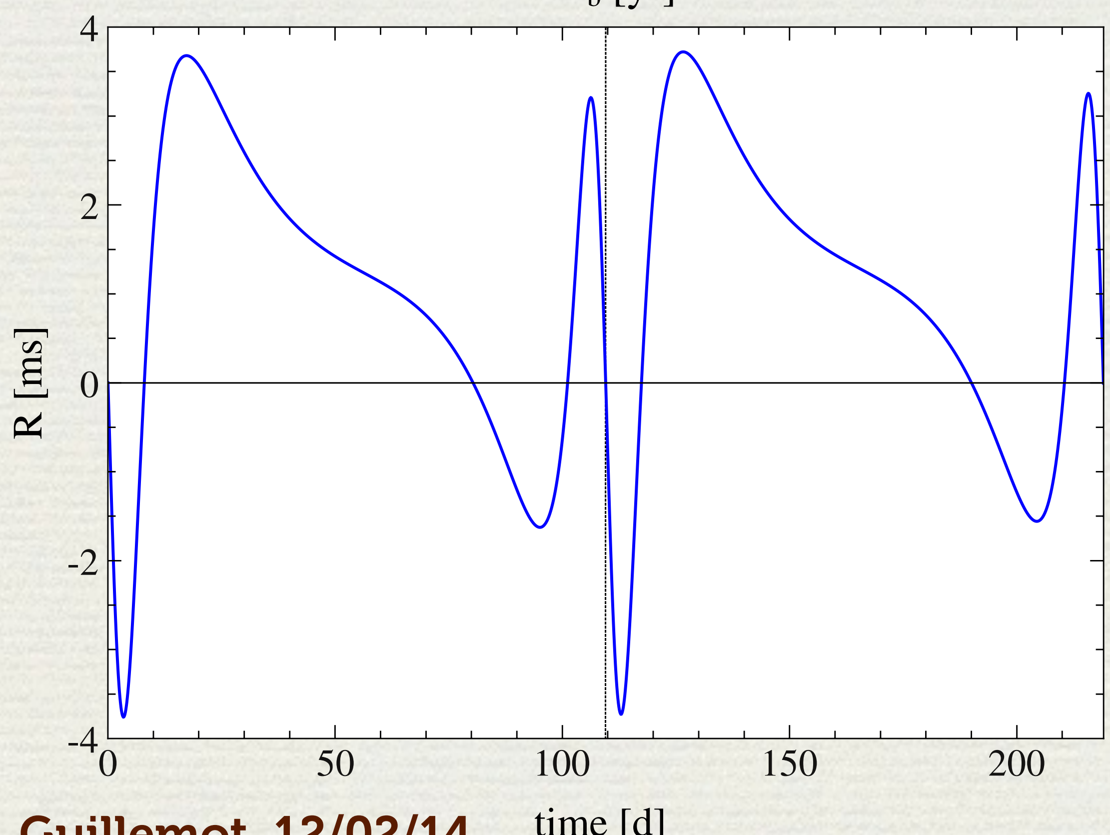
Many more rare and interesting systems! (i.e.: pulsar orbiting a black hole?)

Also, follow-up timing studies greatly enhanced:

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

Characterizing the central black hole





See Liu et al. 2012.

SKA timing of a pulsar orbiting Sgr A*: detailed investigation of the space-time around it.

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

Spin with <0.1% precision: cosmic censorship.

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

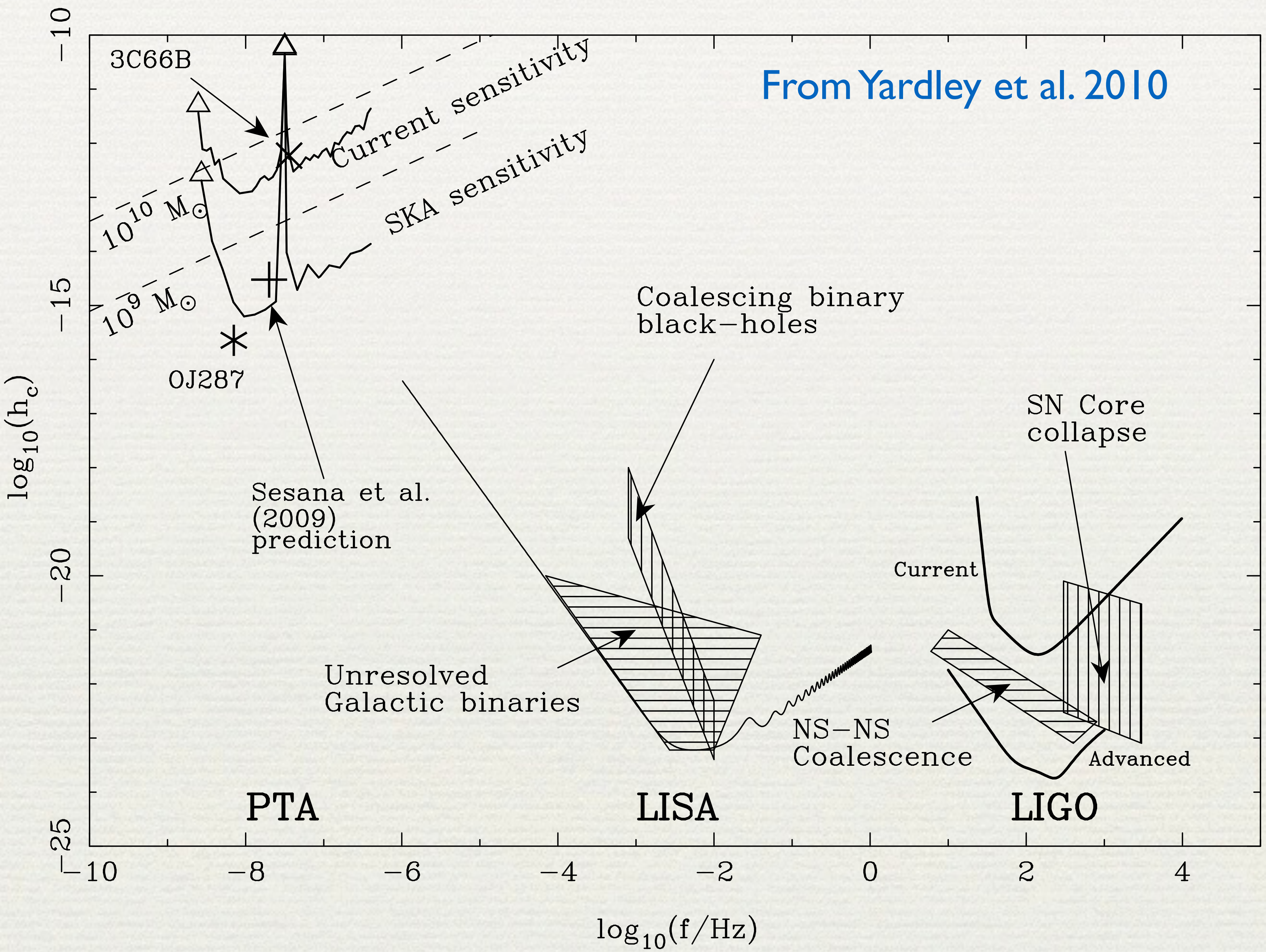
Quadrupole moment with 1% precision: no-hair theorem.

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

Top: residuals from quadrupole moment vs orbital phase.

Bottom: 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)

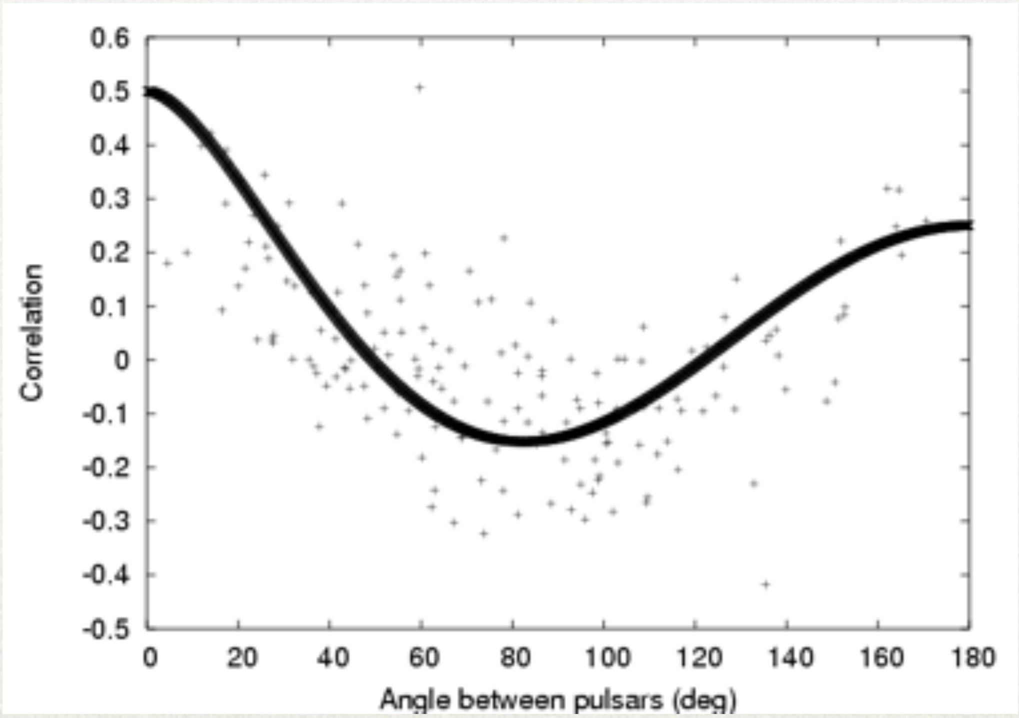
Searching for GWs with the SKA



Assumption for the SKA limit: 100 pulsars timed with an accuracy of 20 ns, observed once every two weeks over 5 years.

Improvement on the current sensitivity by several orders of magnitude!

Studying GW properties

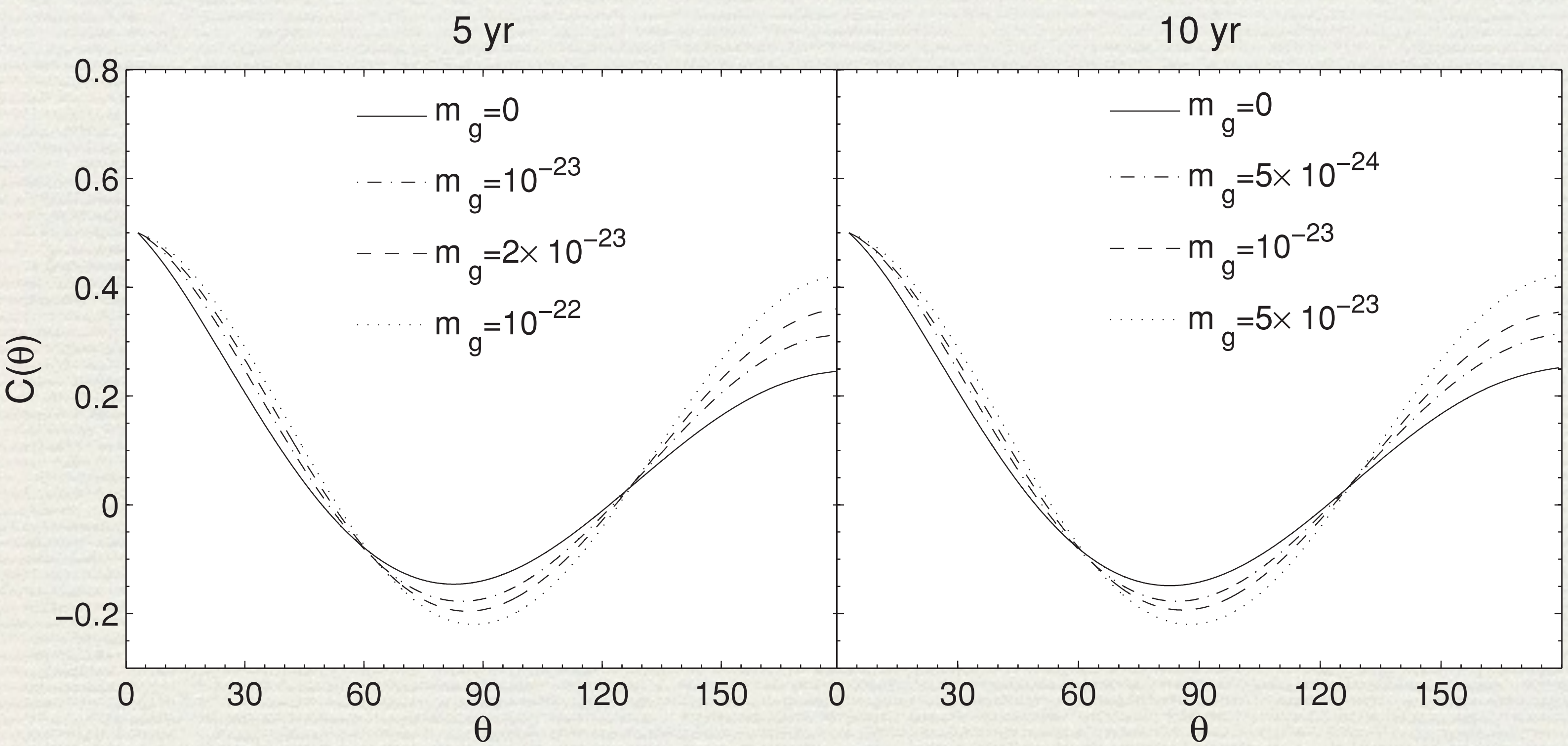


SKA: also possible to study the properties of GWs (polarization, graviton mass).

The shape of the Hellings & Downs curve depends on the graviton mass!

(GR: graviton mass-less).

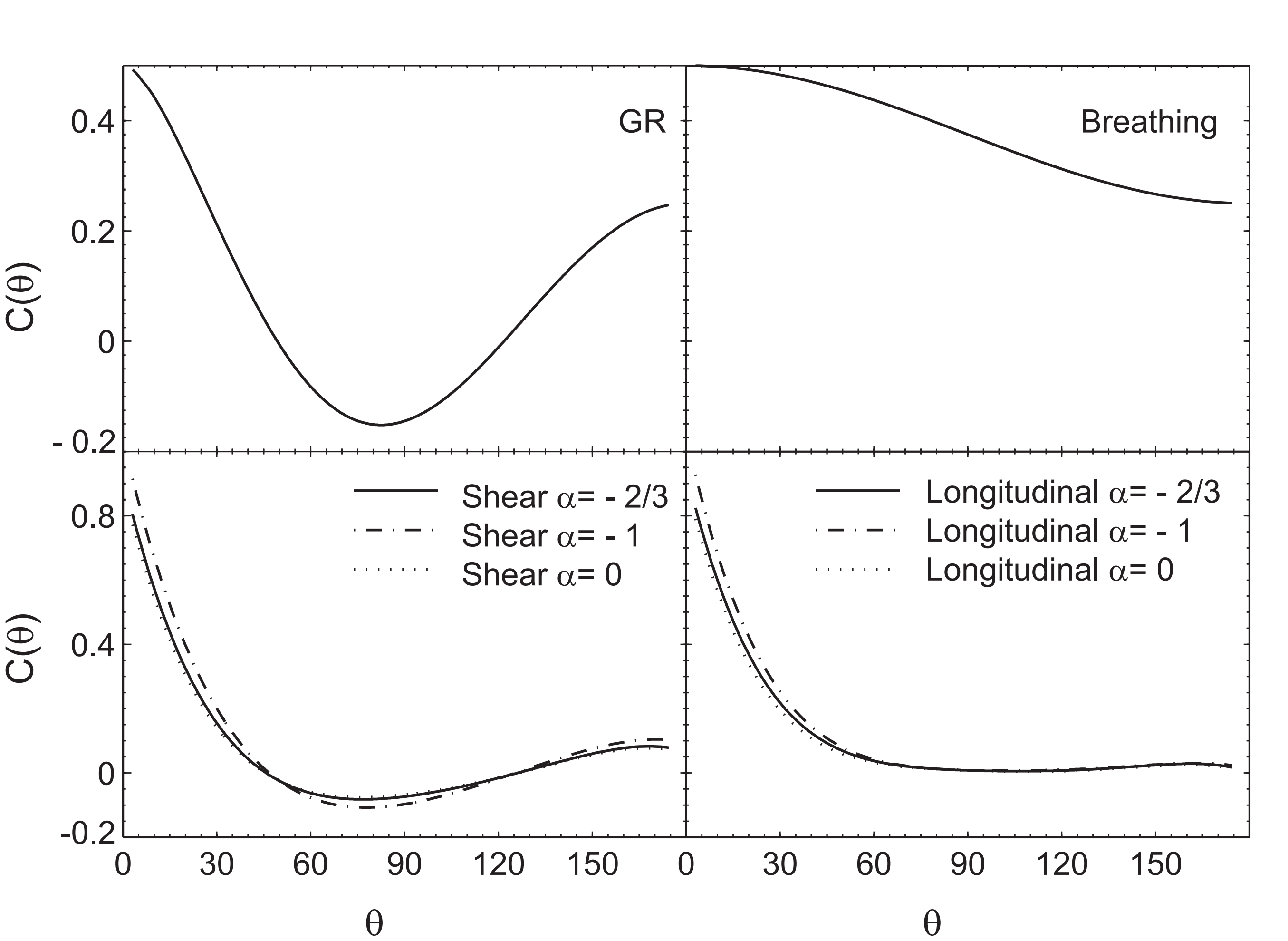
See Lee et al. 2010.



Cross-correlation functions for different graviton masses, and for 5 and 10 years of timing of 300 pulsars with 100 ns accuracy.

Top left: expected correlation between residuals for pairs of pulsars for a stochastic GW background, and relation derived by Hellings & Downs (1983).

Studying GW properties (continued)



Cross-correlation functions for different GW polarizations, for various GW spectral indices, for 5 years of timing of ~60 pulsars with 100 ns accuracy.

See Lee et al. 2008.

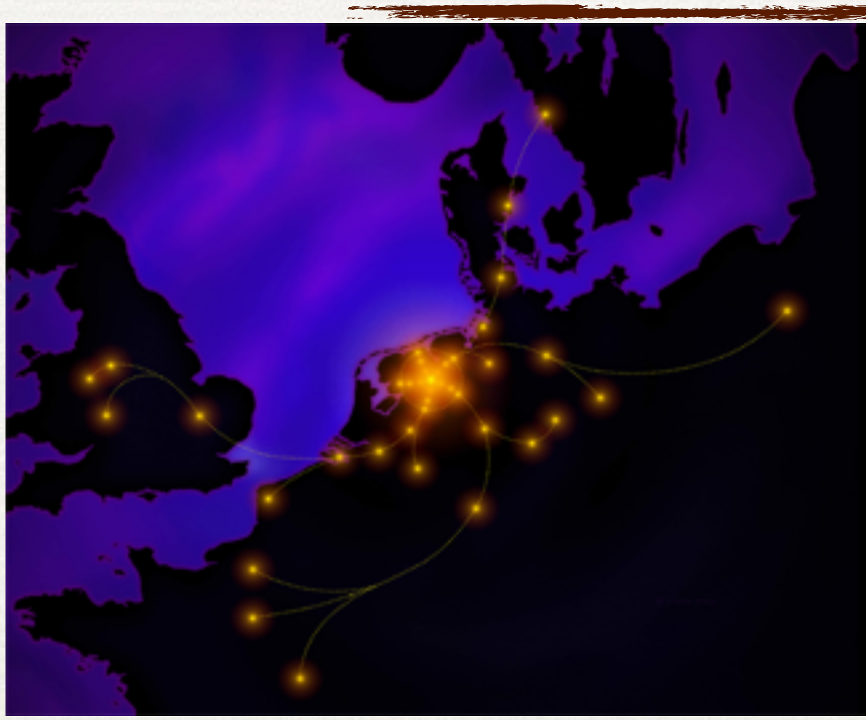
The shape of the Hellings & Downs curve depends on GW polarization!

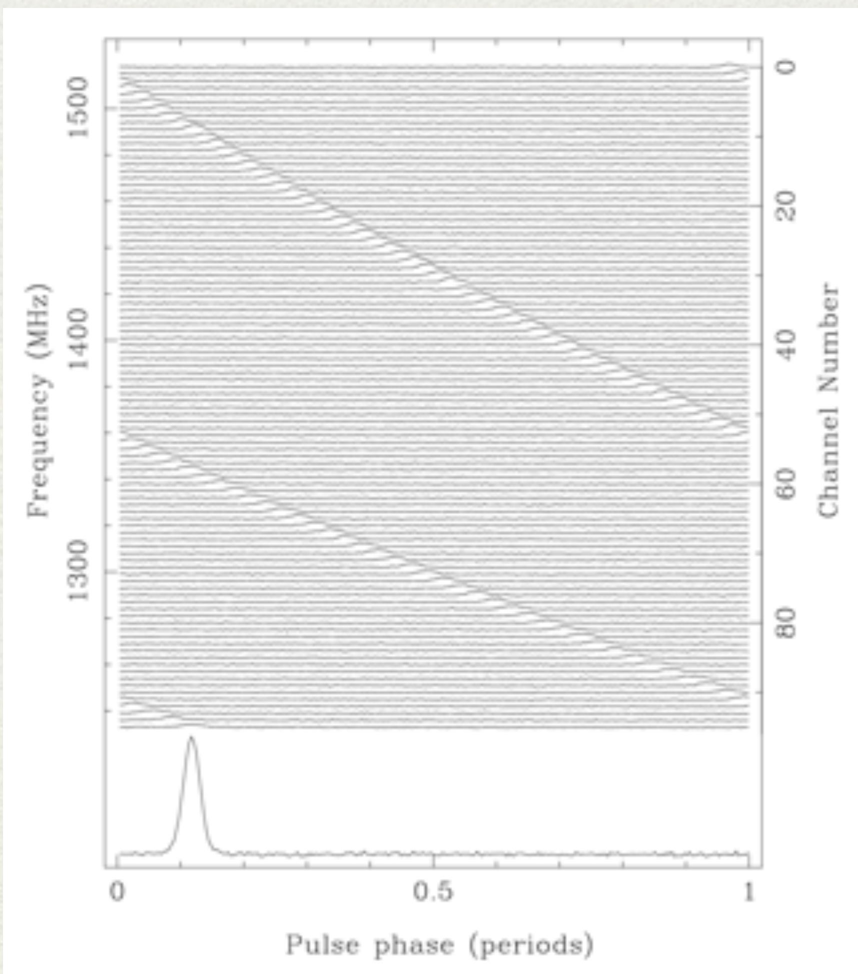
GR: 2 degrees of polarization, more in alternative theories of gravity.

Tests of gravity theories!

Required accuracies (~100 ns or so) achievable with the SKA.

Summary - Conclusions





Pulsar studies find their applications in a wide range of astrophysics and fundamental physics.

SKA: many new pulsars, new tests of GR, Sgr A*, GW characterization, etc.

Road to SKA:

- many precursors such as LOFAR: properties of the interstellar medium = crucial for timing studies!
- SKA phase 1: sensitivity to many new pulsars already.