GPhys Presentation

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(M2 internship)

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Constraints on masses and post-keplerian effects in PSR J0751+1807

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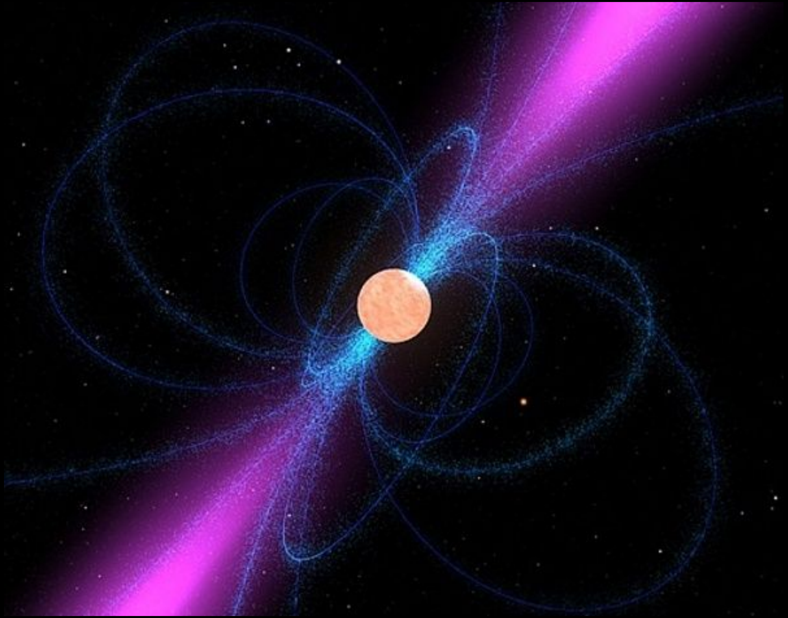
Introduction



Artist view of a pulsar

First *pulsar* discovered by accident by Jocelyn Bell and Antony Hewish in 1967
First *binary pulsar* discovered in 1974 by Joseph Taylor and Russell Hulse

What is the pulsar phenomenon?

- Magnetised fast rotating neutron star $P \sim 1ms - 1s$
- Coherent radio emission along its magnetic poles

Why study them?

- Tests of gravity theories
- Probes of the interstellar medium
- Ultra-dense matter constraints
- Gravitational wave?

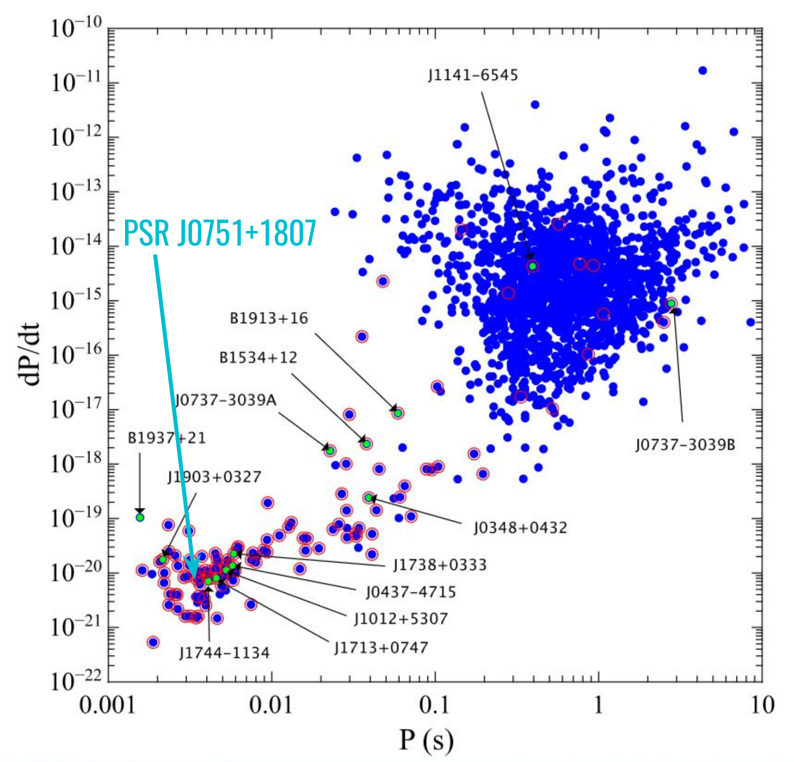
PSR J0751+1807 System

Two types of pulsars:

- Normal pulsars
- Millisecond pulsars → re-accelerated by accretion of matter and angular momentum from the companion

PSR J0751+1807

- Millisecond pulsar $P = 3.48\ ms$
- White dwarf companion $mc = 0.13\ M_\odot$
- Quasi-circular orbit $e = 3.3.10^{-6}$
- Orbital period $P_b = 6.32\ h$



Testing Relativistic Gravity with Radio Pulsars, Norbert Wex (2013)

Keplerian and post-keplerian parameters

Newtonian gravitation theory

- The pulsar’s orbit is described by the *keplerian parameters (KP)* P_b, e, a, ω, T_0

$$\boxed{E = -\frac{Gm_p m_c}{2a} \qquad L^2 = \frac{G{m_p}^2{m_c}^2 a(1-e^2)}{(m_p+m_c)}}$$

Relativistic gravitation theory

- Angular momentum and energy losses by emission of gravitational waves
- The pulsar’s orbit is described by the *post-keplerian parameters (PKP)* $\dot{\omega}$, r, s, γ

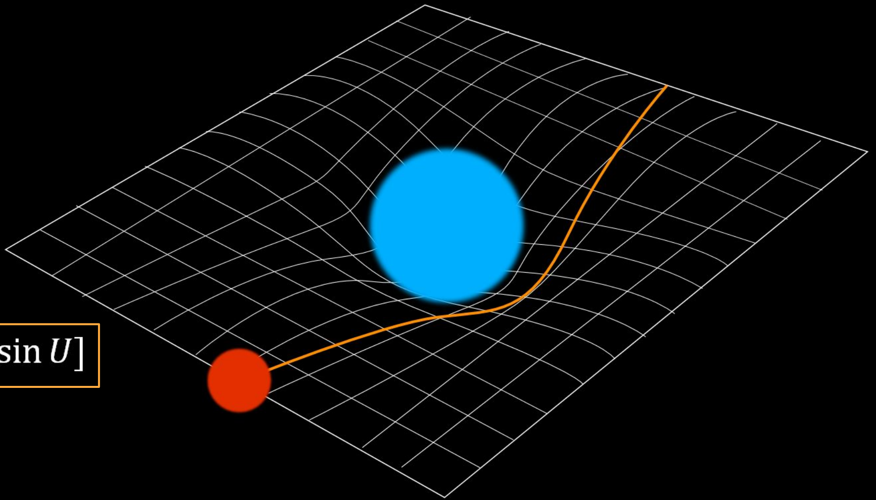
$$\boxed{\left\langle\frac{dE}{dt}\right\rangle = -\frac{32}{5}\frac{G^4{m_p}^2{m_c}^2(m_p+m_c)}{c^5a^{7/2}(1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right) \qquad \left\langle\frac{dL}{dt}\right\rangle = -\frac{32}{5}\frac{G^{7/2}{m_p}^2{m_c}^2\left(m_p+m_c\right)^{1/2}}{c^5a^{7/2}(1-e^2)^2}\left(1+\frac{7}{8}e^2\right)}$$

Relativistic effects

Shapiro effect

- Delay introduced by the curvature of space-time around the companion

$$\boxed{\Delta_S = -2r\ln\left[1 - e\cos U - \sin\omega\,(\cos U - e) - s\cos\omega(1 - e^2)\sin U\right]}$$



Einstein effect

- Delay introduced by the gravitational potential difference between emission and reception of the pulse

$$\boxed{\Delta E_\odot = \gamma \sin(U)}$$

RR & GR

Relativistic effects

Periastron advance

- The periastron position is shifted with time

$$\boxed{\dot{\omega} = \frac{6\pi G(m_p + m_c)}{c^2 a(1 - e^2)}}$$

Gravitational wave emission

- Angular momentum and energy losses
- Variation of the KP with time

$$\boxed{\left\langle\frac{dP_b}{dt}\right\rangle = -\frac{192\pi}{5c^5}\frac{m_p m_c}{(m_p + m_c)^2}\left(\frac{2\pi G(m_p + m_c)}{P_b}\right)^{5/3}\frac{1 + \frac{73}{24}e^2 + \frac{37}{96}e^4}{(1 - e^2)^{7/2}}}$$

Pulsar timing

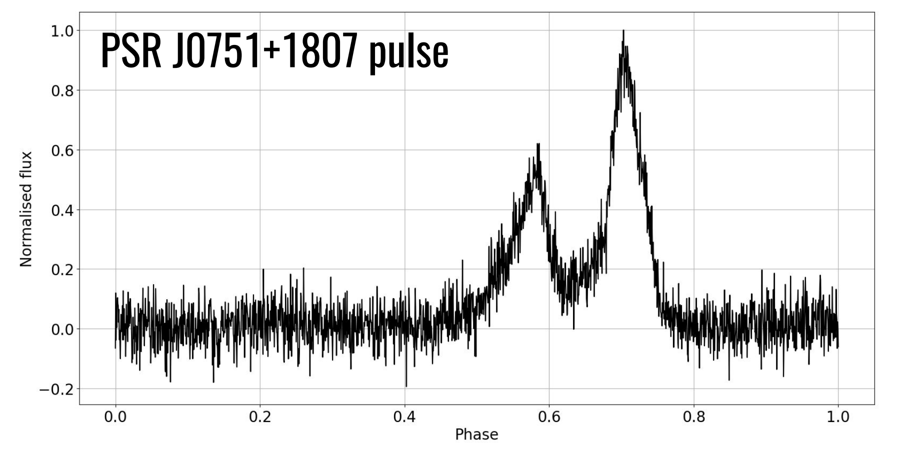
Principle: tracking the Times Of Arrival (TOAs) of the pulses recorded at the observatory and comparing them to the prediction of a best-fit model.

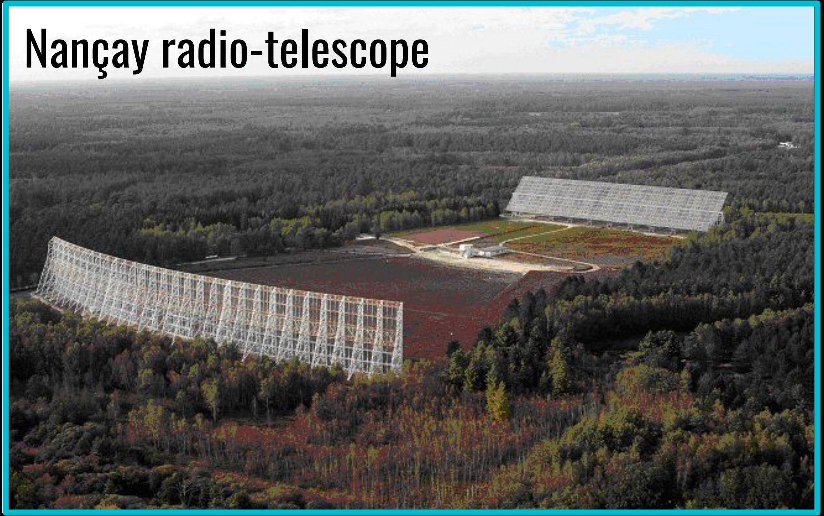
The model? → includes rotational and orbital parameters

Timing model

$$\Delta t = \overbrace{\Delta_c}^{\text{Clock}} + \underbrace{\Delta_A}_{\text{Atmosphere}} + \overbrace{\Delta_{E\odot}}^{\text{Einstein }\odot} + \underbrace{\Delta_{R\odot}}_{\text{Roemer }\odot} + \overbrace{\Delta_{S\odot}}^{\text{Shapiro }\odot} - \underbrace{\frac{D}{f^2}}_{\text{ISM dispersion}} + \overbrace{\Delta_{VP}}^{\text{Proper motion}} + \underbrace{\Delta_B}_{\text{Orbital motion}}$$

Pulsar timing



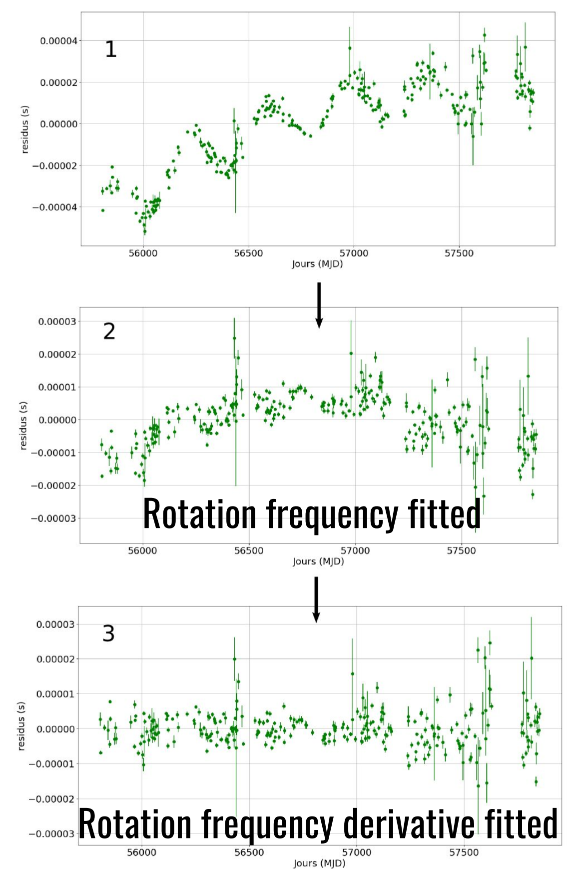


Data from Nançay radio-telescope → NUPPI Data

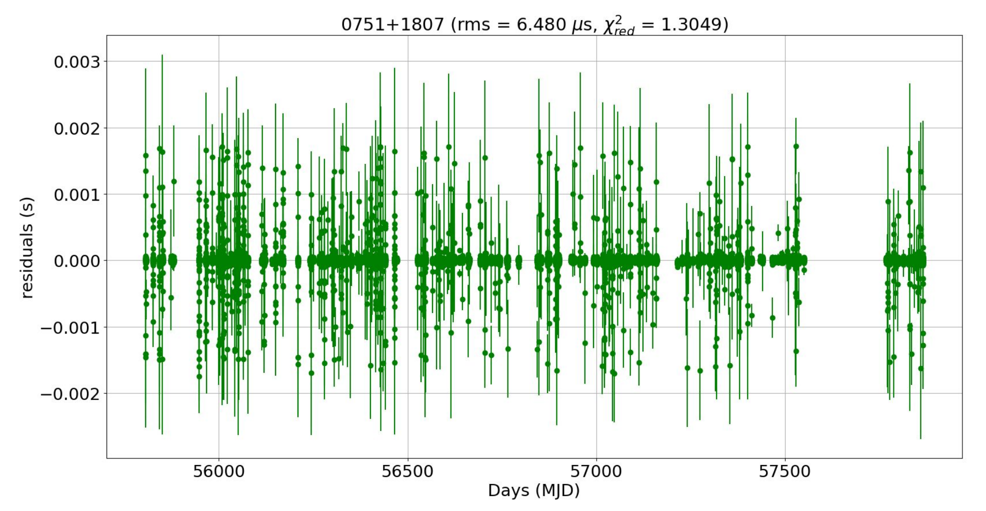
- Observations recorded between MJD 55800 and 57600 (August 2011 to July 2016)
- Observations at 1.4 GHz divided in 128 frequency channels
- Data recorded every 30 seconds

Pulsar timing

The best residuals



Residuals are the differences between observed TOAs and those predicted by the model.



Residuals obtained from 20 137 TOAs

EPTA Data (European Pulsar Timing Array)

European collaboration of 5 telescopes (Germany, United Kingdom, Italy, The Netherlands and France)

- Timing pulsars with the highest possible precision
- Discovering new pulsars

We combined data from all EPTA (2000-2014) telescopes with the NUPPI data

- Data from before 2000 were removed → presence of unexplainable systematic effects
- Better residuals than those of *G. Desvignes et al. (2016)* (EPTA data without NUPPI data) → $\boxed{\chi^2_{red} = 1.44 \longrightarrow \chi^2_{red} = 1.32}$

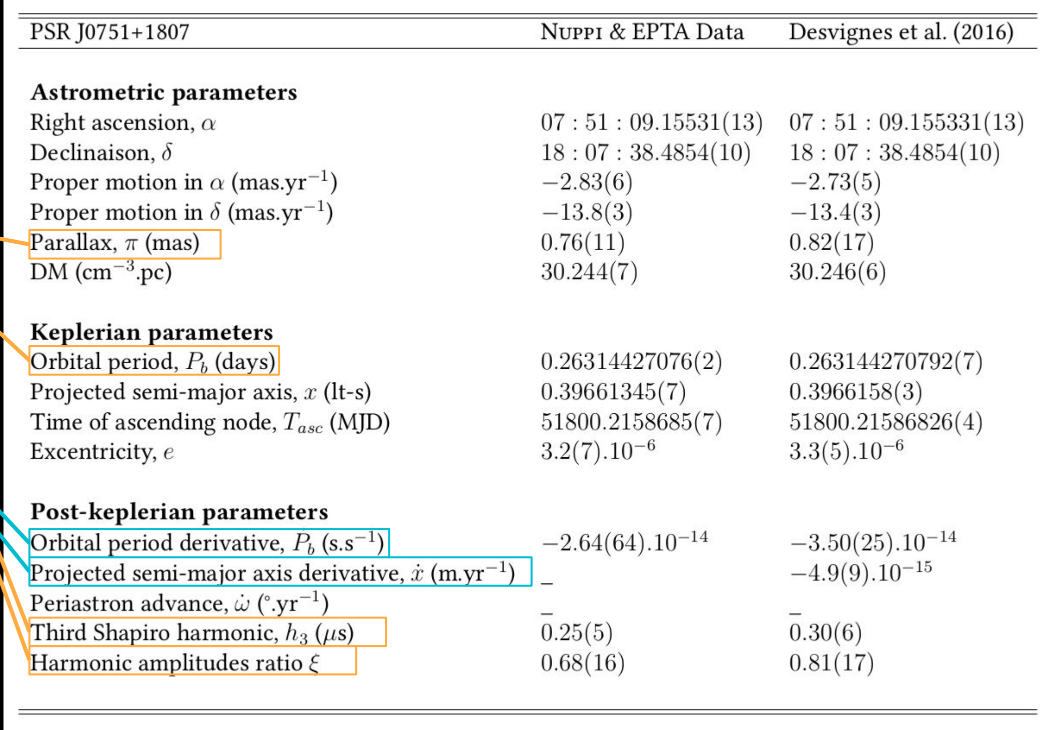
EPTA Data (European Pulsar Timing Array)

Calculation of our parameters with our new TOAs

Our parameters are consistent with EPTA ones (from Desvignes et al.)
Improvement of uncertainties

Minor differences in the orbital period derivative and no semi-major axis derivative detected

No detection of the periastron advance (as expected)



PSR J0751+1807	NUPPI & EPTA Data	Desvignes et al. (2016)
Astrometric parameters		
Right ascension, α	07 : 51 : 09.15531(13)	07 : 51 : 09.155331(13)
Declinaison, δ	18 : 07 : 38.4854(10)	18 : 07 : 38.4854(10)
Proper motion in α (mas.yr^{-1})	$-2.83(6)$	$-2.73(5)$
Proper motion in δ (mas.yr^{-1})	$-13.8(3)$	$-13.4(3)$
Parallax, π (mas)	0.76(11)	0.82(17)
DM (cm^{-3}.pc)	30.244(7)	30.246(6)
Keplerian parameters		
Orbital period, P_b (days)	0.26314427076(2)	0.263144270792(7)
Projected semi-major axis, x (lt-s)	0.39661345(7)	0.3966158(3)
Time of ascending node, T_{asc} (MJD)	51800.2158685(7)	51800.21586826(4)
Excentricity, e	3.2(7).10^{-6}	3.3(5).10^{-6}
Post-keplerian parameters		
Orbital period derivative, $\dot{P}_b$ (s.s^{-1})	$-2.64(64).10^{-14}$	$-3.50(25).10^{-14}$
Projected semi-major axis derivative, $\dot{x}$ (m.yr^{-1})	_	$-4.9(9).10^{-15}$
Periastron advance, $\dot{\omega}$ (°.yr^{-1})	_	_
Third Shapiro harmonic, h_3 (μs)	0.25(5)	0.30(6)
Harmonic amplitudes ratio ξ	0.68(16)	0.81(17)

Statistical analysis

Construction of a grid with the companion mass and the orbit inclination

For each point in the grid:

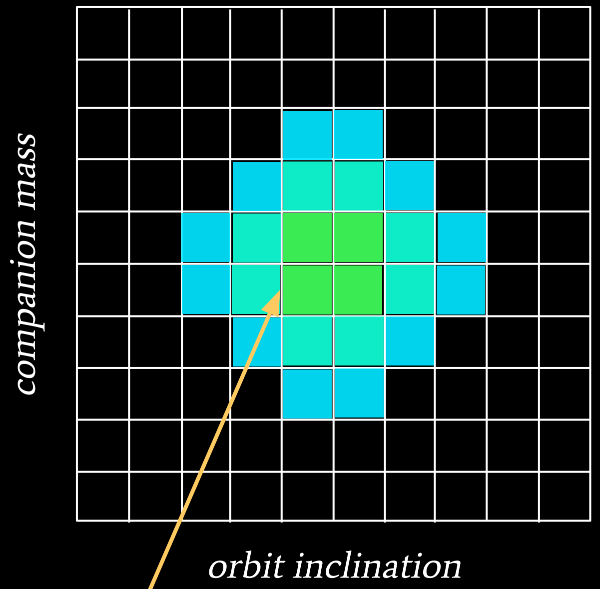
- The PKP are fixed at the values predicted by the GR while other parameters are allowed to vary
- TOAs are fitted → residuals → extract χ^2 value

$$\Delta\chi^2 = \chi^2 - \chi^2_{min}$$

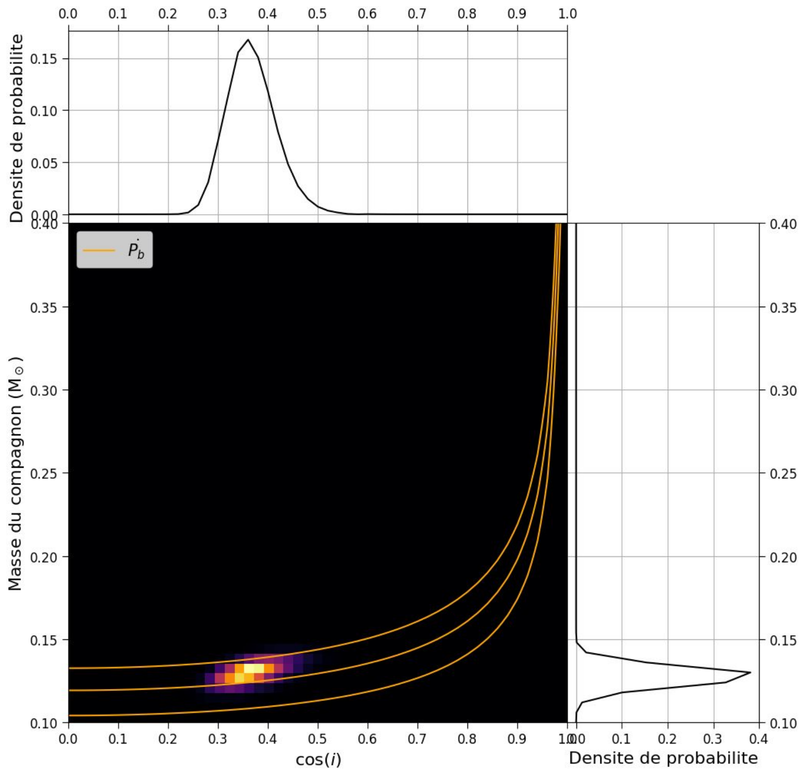
$$P(\text{TOAs}\,|m_c, \cos(i)) = \frac{1}{2} e^{-\frac{\Delta\chi^2}{2}}$$

Bayes

$$\boxed{P(m_c, \cos(i)|\text{TOAs}) = \frac{P(\text{TOAs}|m_c, \cos(i))}{P(\text{TOAs})} P(m_c, \cos(i))}$$



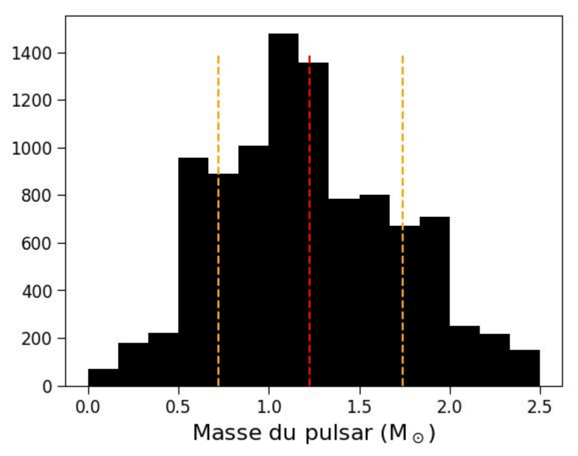
Results



$$m_c = 0.13 \pm 0.06\ M_\odot$$
$$\cos(i) = 0.36 \pm 0.06$$

$$f = \frac{(m_c sini(i))^3}{(m_p + m_c)^2}$$

mp = 1.2 ± 0.5 M☉



Comparison with other results

D. Nice et al. (2005)	D. Nice et al. (2008)	EPTA (2016)
$mc = 0.191 \pm 0.015\ M\odot$	$mc = 0.12 \pm 0.03\ M\odot$	$mc = 0.16 \pm 0.01\ M\odot$
$mp = 2.1 \pm 0.2\ M\odot$	$mp = 1.26 \pm 0.14\ M\odot$	$mp = 1.64 \pm 0.15\ M\odot$
$\cos(i) = 0.41 \pm 0.09$	$\cos(i) = 0.36 \pm 0.09$	$\cos(i) = 0.41 \pm 0.09$

$mc = 0.13 \pm 0.06\ M\odot$

$mp = 1.2 \pm 0.5\ M\odot$

$\cos(i) = 0.36 \pm 0.06$

Conclusion

- Analysis of EPTA and NUPPI data to determine new parameters

- Statistical analysis with these new TOAs and these new parameters in order to calculate probabilities of mc and cos(i)

- New value of the pulsar mass close to the one found by D. Nice et al. (2008).

Perspectives?

- Understand NUPPI data systematics
  - Solar wind influence in our measurements?
  - Better cleaning of the interferences?

Thanks for your attention...