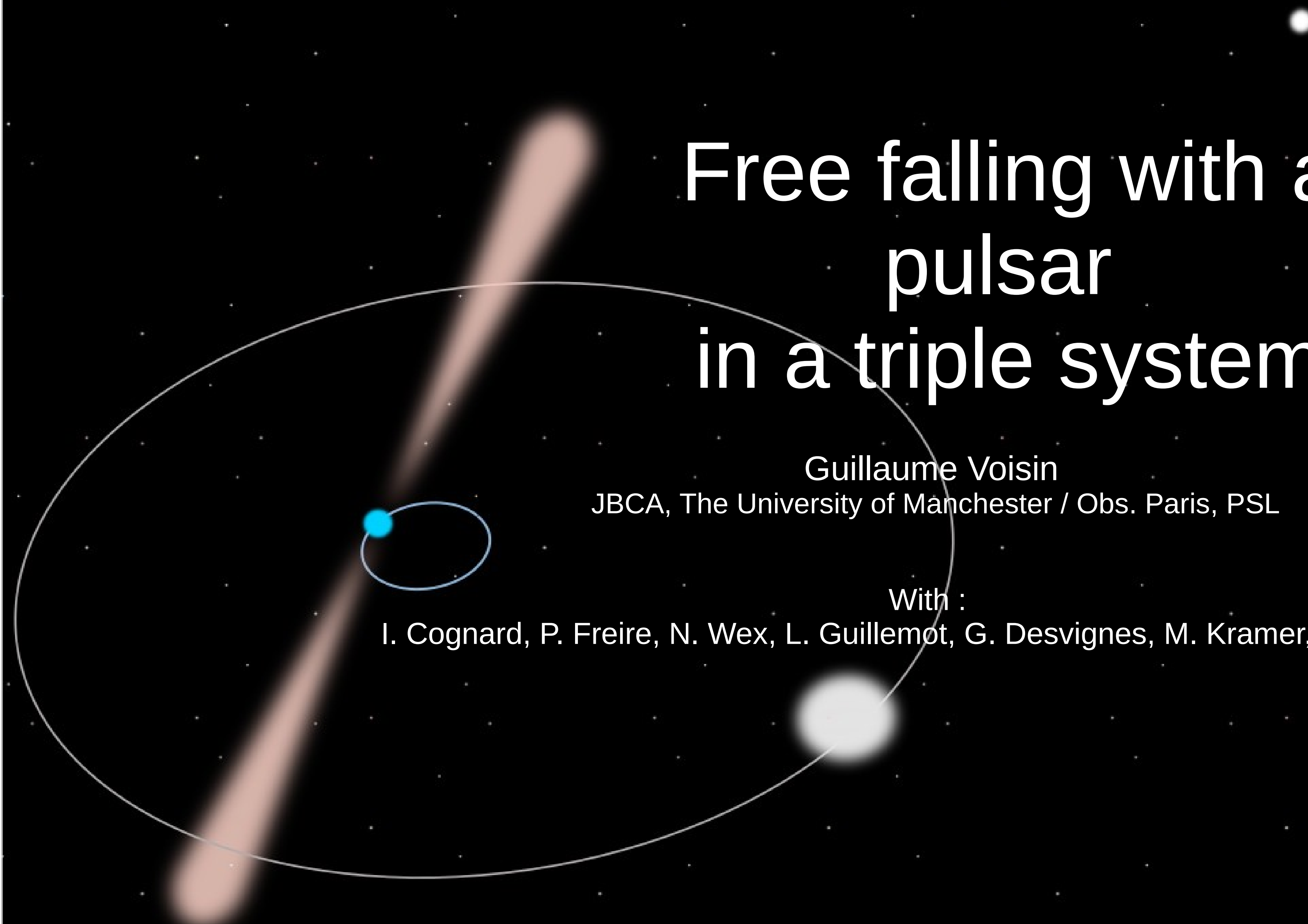


# Free falling with a pulsar in a triple system

Guillaume Voisin
JBCA, The University of Manchester / Obs. Paris, PSL

With :
I. Cognard, P. Freire, N. Wex, L. Guillemot, G. Desvignes, M. Kramer, G. Theureau

arXiv:2005.01388

# What is the equivalence principle ?

- Galileo :
  - Weak equivalence principle

- Newton :

$$m^{(I)}\vec{a} = m^{(G)}\vec{g} \quad \boxed{m^{(I)} = m^{(G)}}$$

- Einstein:
  - Weak equivalence principle
  - Local Lorentz invariance
  - Local position invariance

Einstein Equivalence Principle

Luigi Catani, Copyright Museo Galileo

- Shiff’s conjecture : WEP <=> EEP

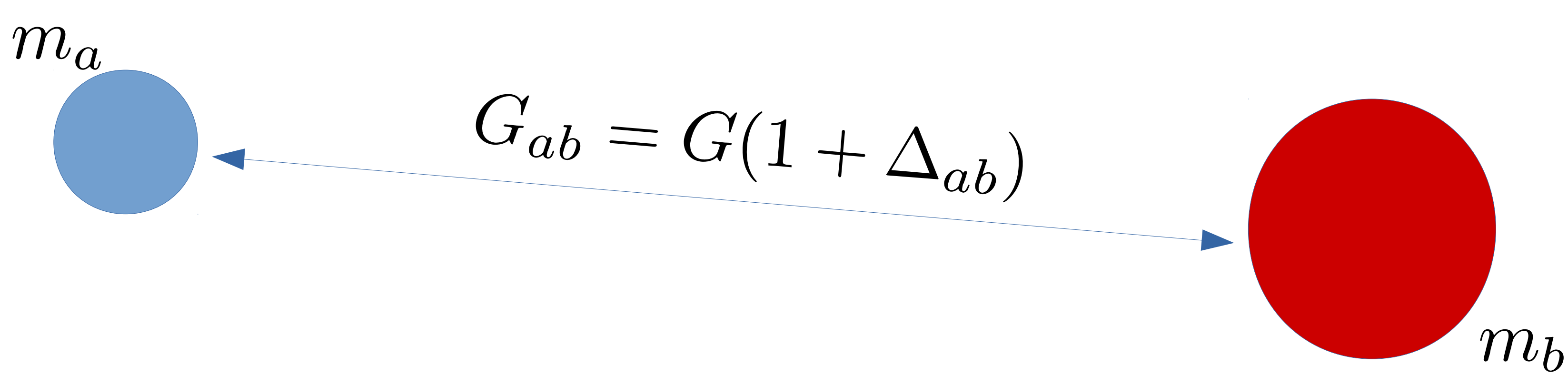
# In Newtonian formalism

A violation of the equivalence principle means the gravitational constant depends on the pair of objects in interaction :

$$\mathrm{m}_a^{(I)}\vec{a}_a = -m_a^{(G)} G m_b^{(G)} \frac{\vec{r}_{ab}}{|r_{ab}|^3} \Rightarrow \quad \vec{a}_a = G_{ab} m_b \frac{\vec{r}_{ab}}{|r_{ab}|^3}$$

with

$$G_{ab} = G\frac{m_a^{(G)}}{m_a^{(I)}}\frac{m_b^{(G)}}{m_b^{(I)}} = \boxed{G(1+\Delta_{ab})}$$

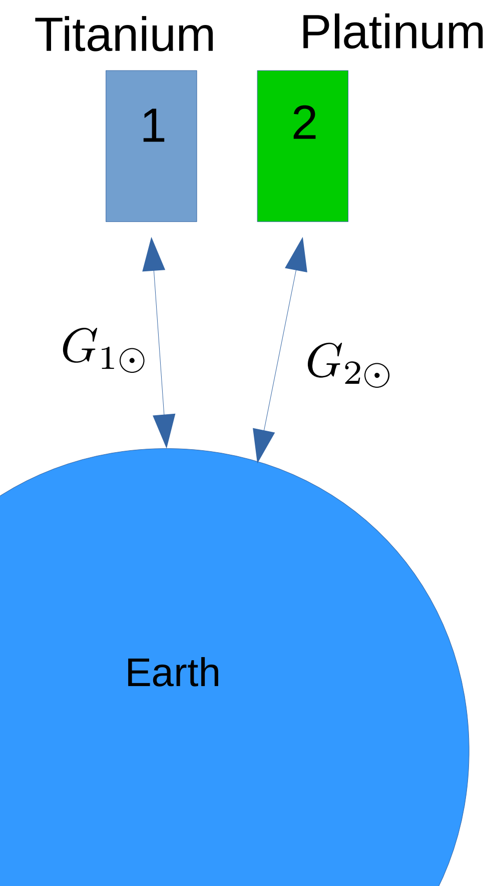


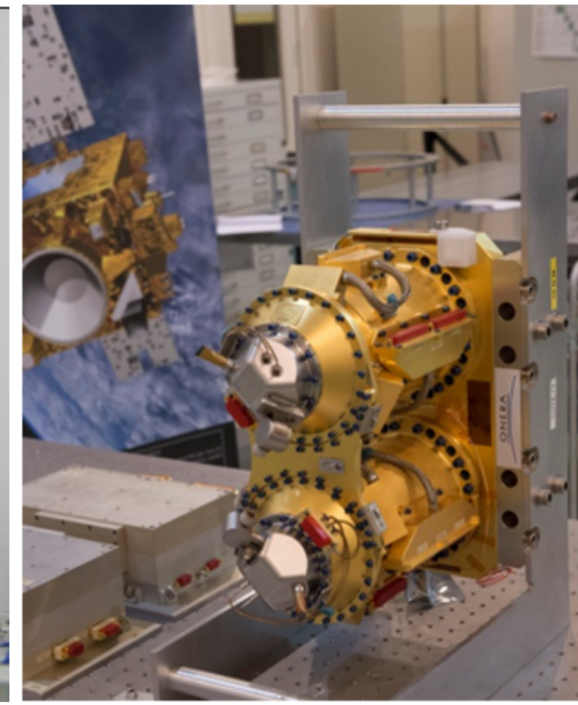
# Today’s Pisa tower: MICROSCOPE

Altitude: 710km

Launch: 04/2016
End: 10/2018

Two test masses:



Touboul+ 2019

Eötvös parameter:

$$|\Delta_{1\odot} - \Delta_{2\odot}| = [-1 \pm 9(\mathrm{stat}) \pm 9(\mathrm{syst})] \times 10^{-15}$$

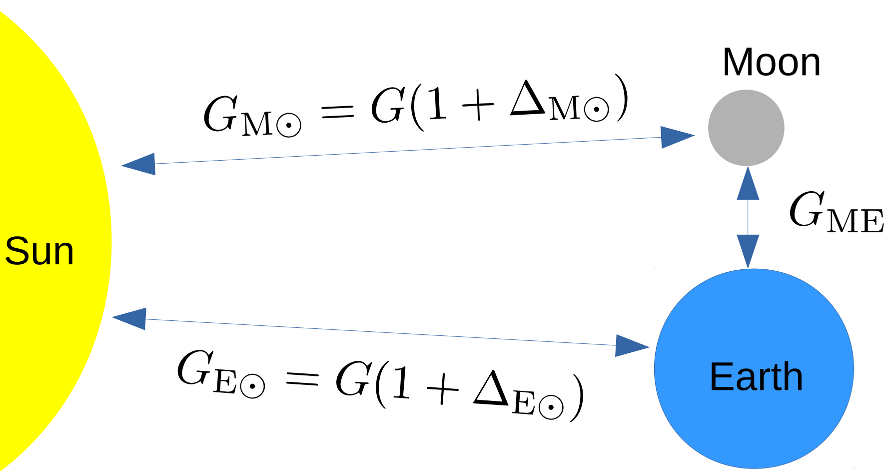
(1 σ confidence interval)

Touboul+ 2019

# Lunar laser ranging (LLR)

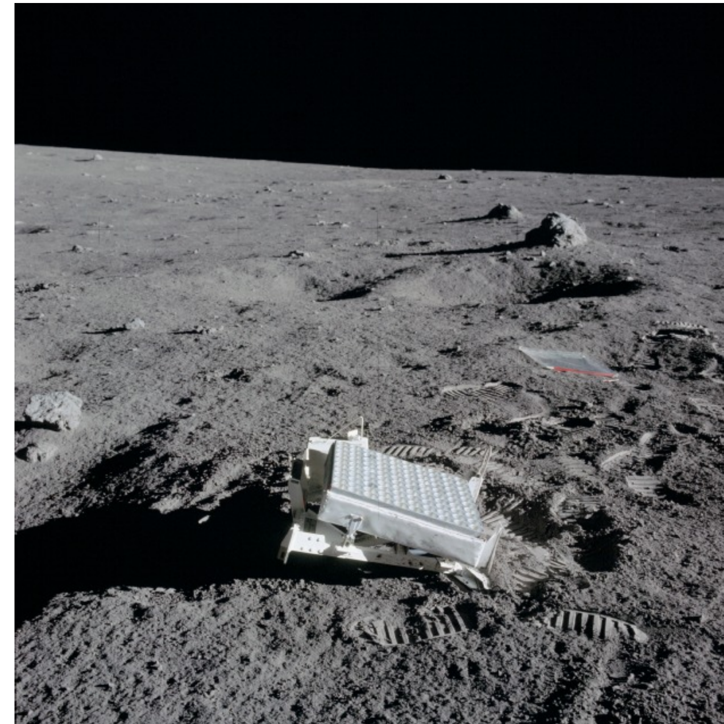
Test masses 1 and 2 → Earth and Moon

Earth → Sun




$$\Delta_{\mathrm{E}\odot} - \Delta_{\mathrm{M}\odot} = (-3 \pm 5) \times 10^{-14}$$

Hofmann and Müller 2018



Apollo 14 Retroreflector, (NASA)

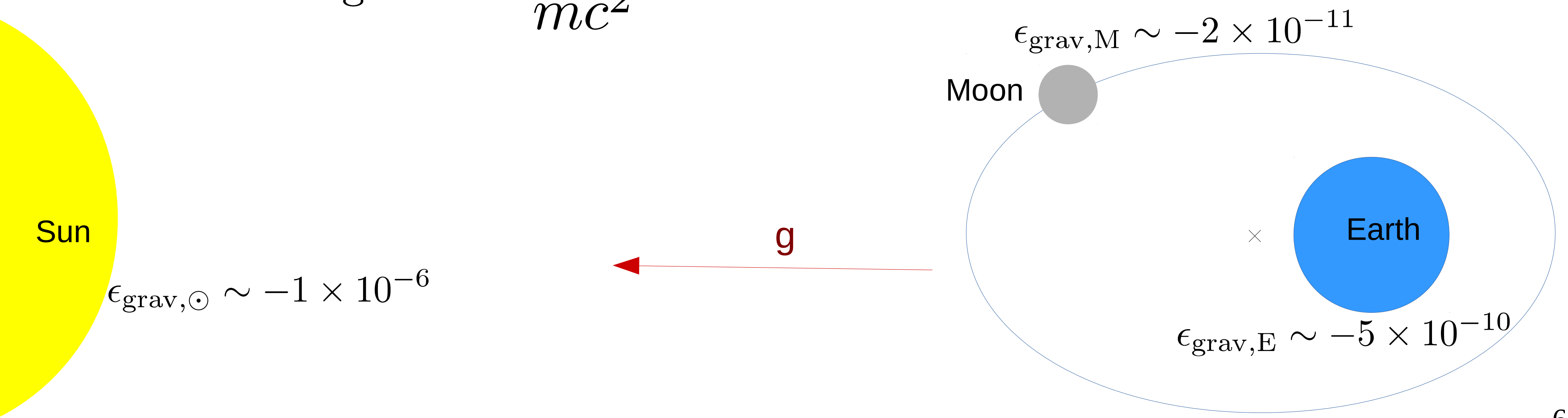
OCA’s laser ranging station (Hervé de Brus)

# Strong equivalence principle

- Extension of EEP to gravitational energy:
  - Grav. weak equivalence principle
  - Grav. Local Lorentz invariance
  - Grav. Local position invariance

Strong equivalence principle **(SEP)**

$$\epsilon_{\text{grav}} = \frac{E_{\text{grav}}}{mc^2}$$



# SEP can be tested with LLR

Nordtvedt parameter (Nordtvedt 1968)

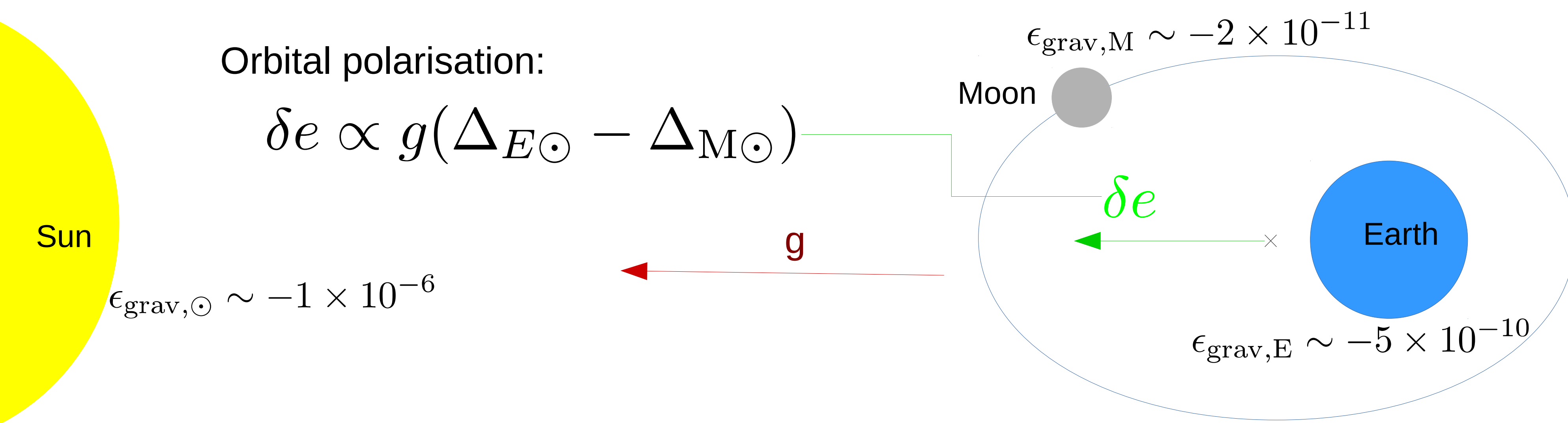
$$\Delta_{ab} \simeq \eta_a \epsilon_{\mathrm{grav},a} + \eta_b \epsilon_{\mathrm{grav},b}$$

$$\eta = (-0.2 \pm 1.1) \times 10^{-4}$$

Hofmann and Müller 2018

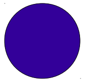
Orbital polarisation:

$$\delta e \propto g(\Delta_{E\odot} - \Delta_{\mathrm{M}\odot})$$

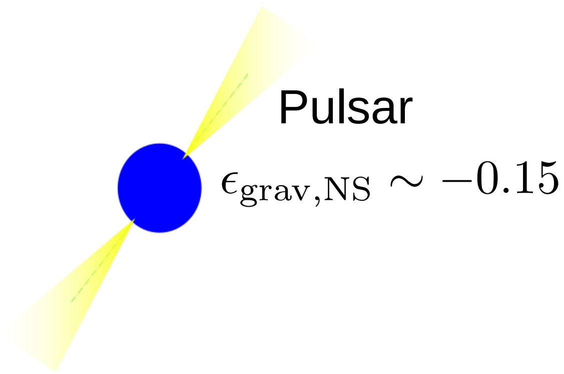


We need a compact object !

Neutron star

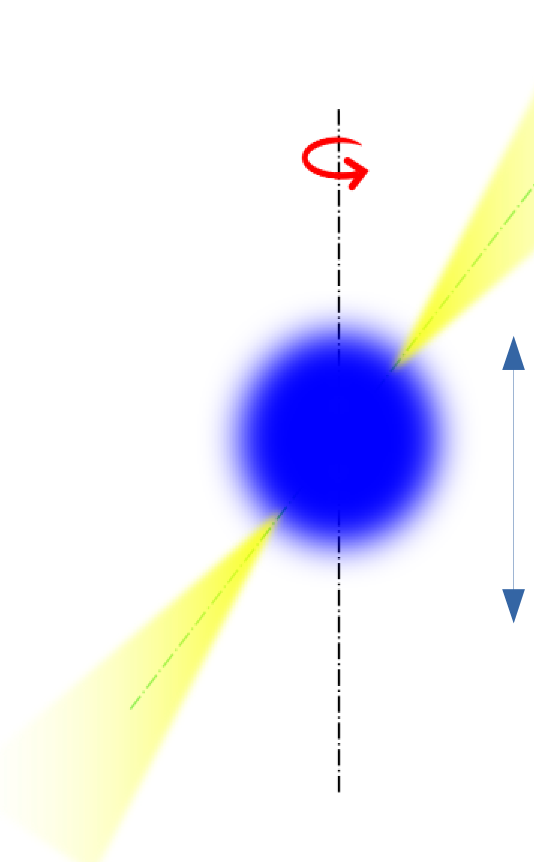


$\epsilon_{\mathrm{grav,NS}} \sim -0.15$


Pulsar
$\epsilon_{\mathrm{grav,NS}} \sim -0.15$

# What is a pulsar ?

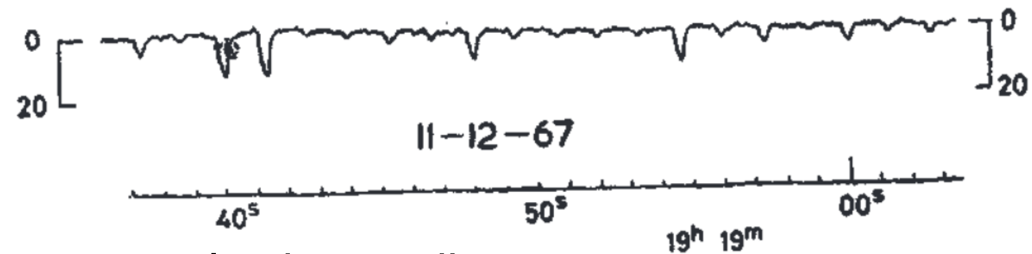
Highly magnetised rotating neutron star:



~25km

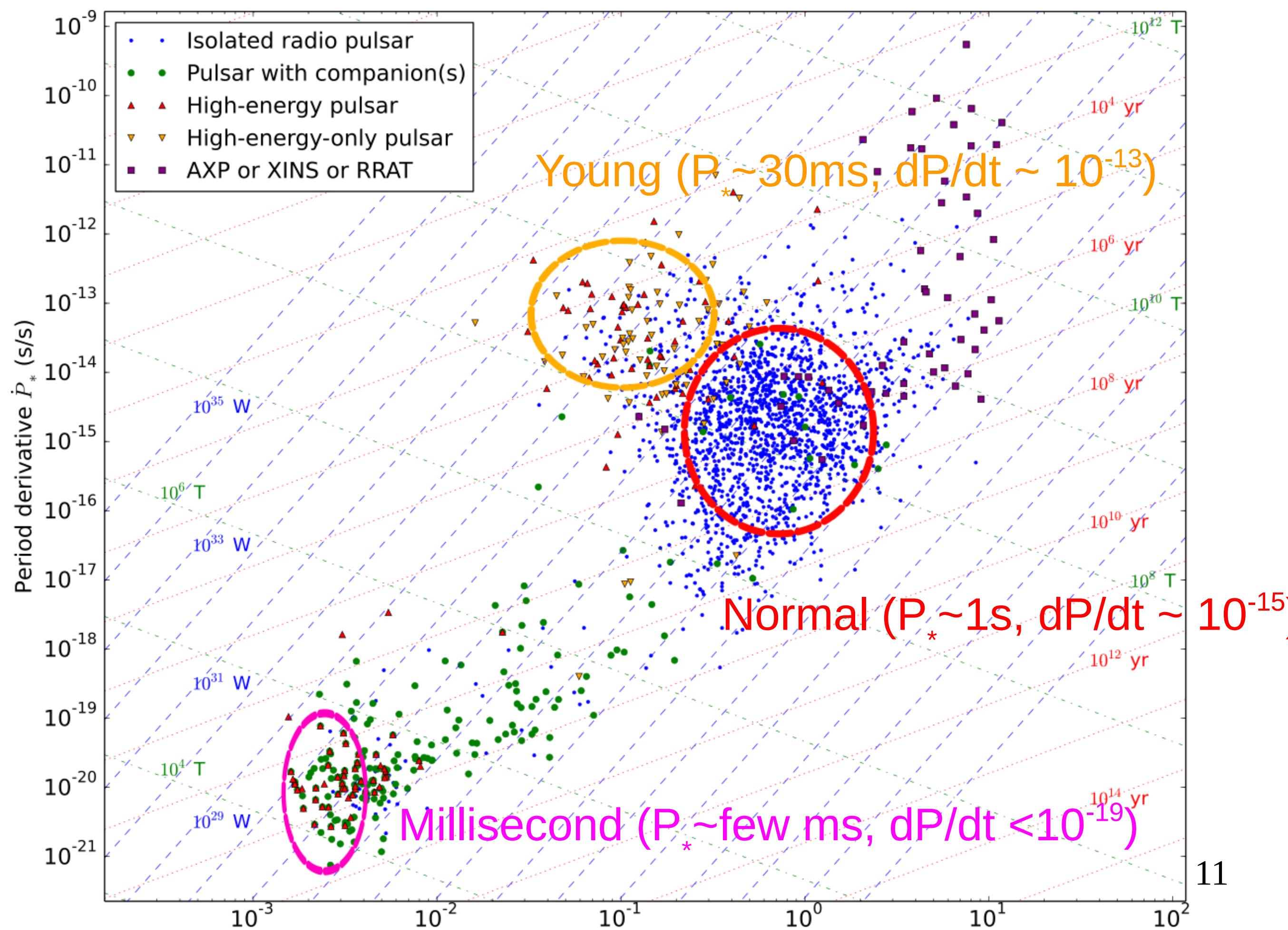
$$m_p \sim 1.4 M_\odot$$

$$B \sim 10^4 - 10^9 T$$



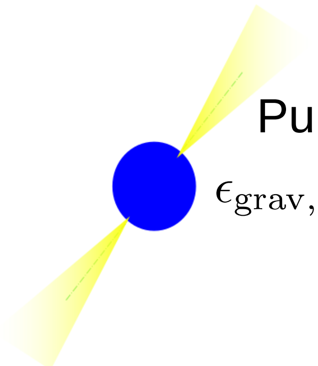

Pulsating Radio source

Hewish and Bell 1968




From ATNF pulsar catalogue

$\vec{a}_{NS} = 0$

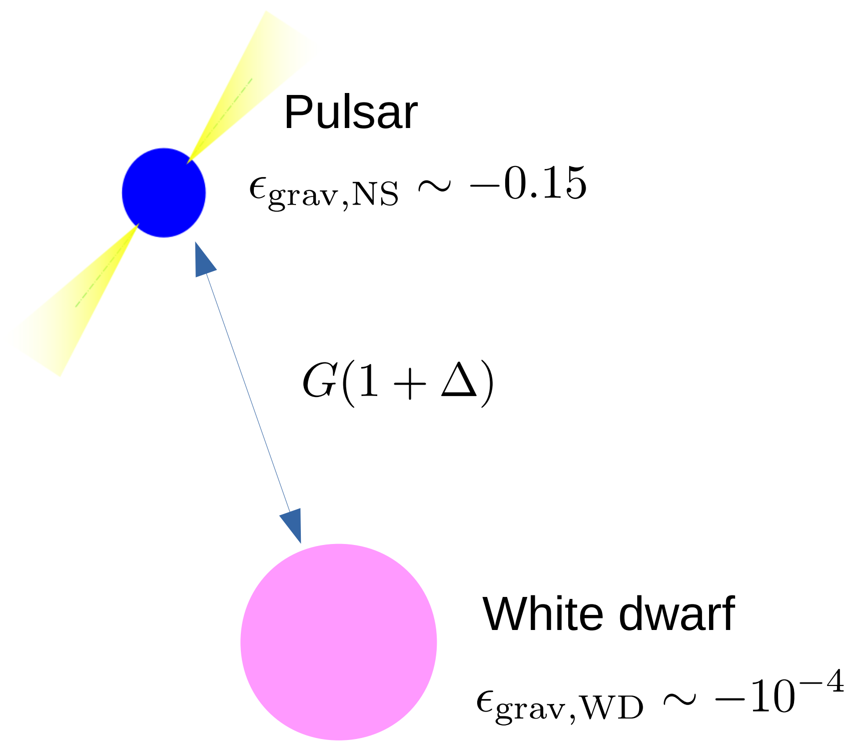


Pulsar

$\epsilon_{\mathrm{grav,NS}} \sim -0.15$

## Violation of SEP is not different from rescaling masses !

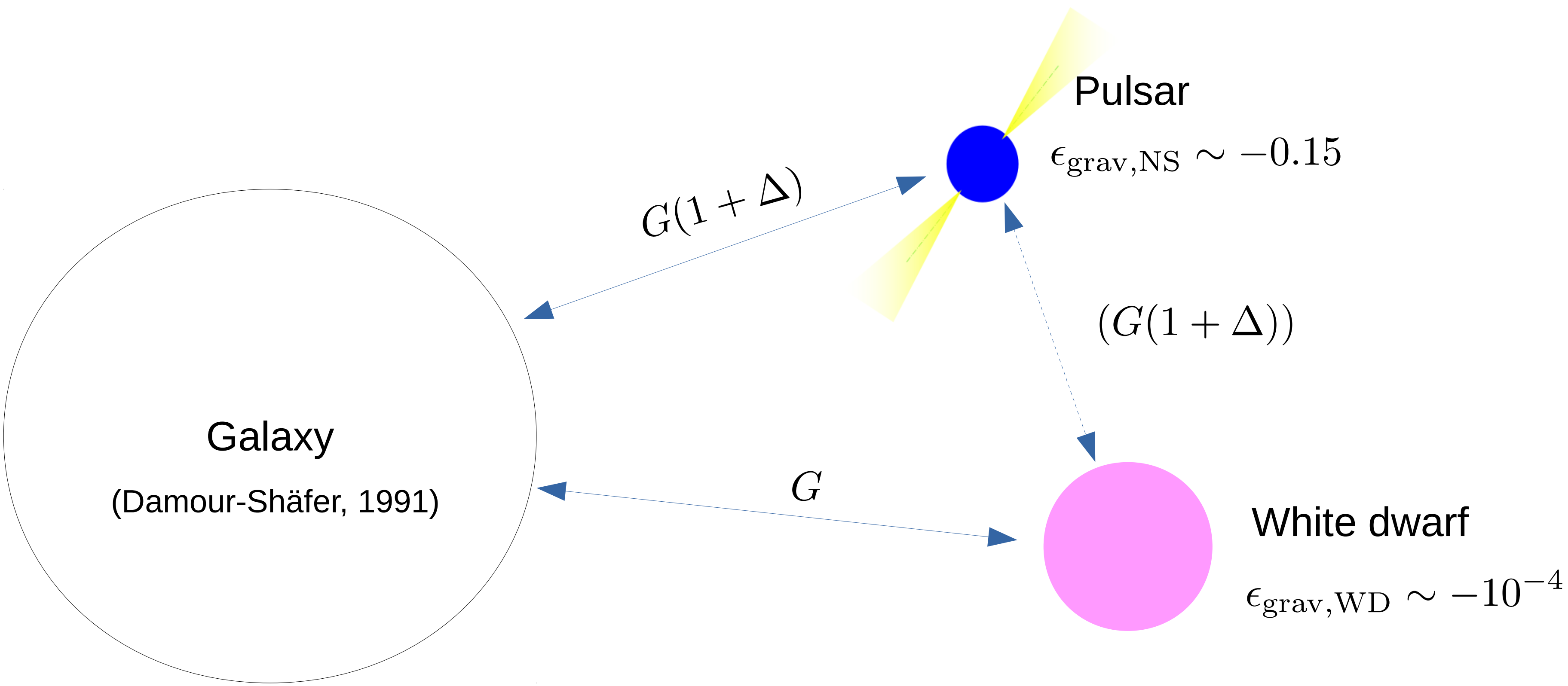
$$\begin{aligned} \vec{a}_{NS} &= -G(1+\Delta) m_{\rm WD} \frac{\vec{r}}{|r|^3} \\ \vec{a}_{WD} &= -G(1+\Delta) m_{\rm NS} \frac{\vec{r}}{|r|^3} \end{aligned}$$



With three bodies, we can make a test :

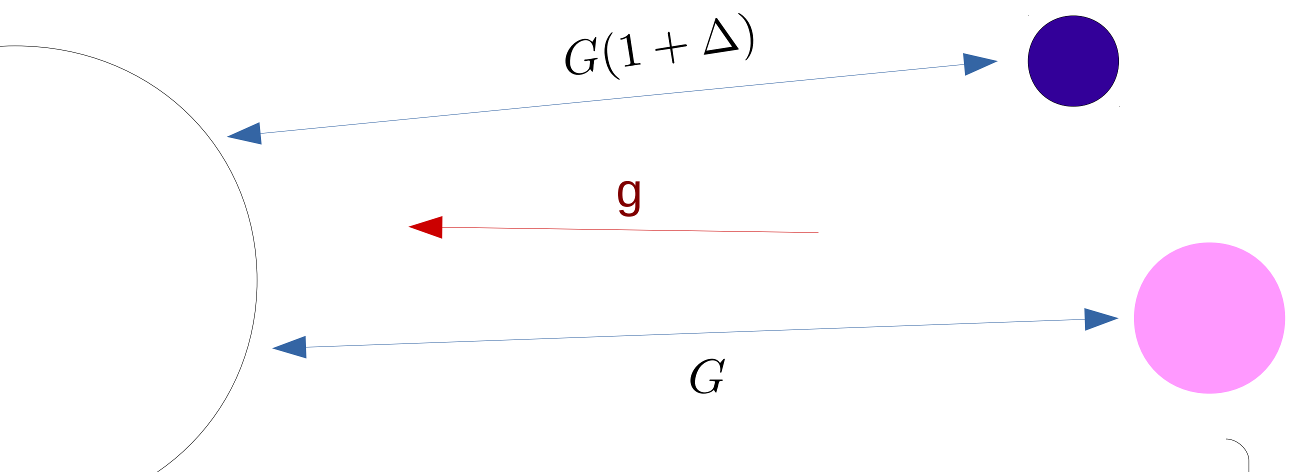
$$|\Delta| < 2 \times 10^{-3} \ (95\% \text{ confidence})$$ (Zhu et al 2019)

Nordtvedt parameter: $\eta \lesssim 0.01$ (but not very meaningful in strong-field regime!)




Note: NS strongly self-gravitating so interpretation in terms of initial and gravitational masses no longer holds. One needs to think in terms of effective gravitational constant.

# Let's summarise:




$$\left.\begin{aligned}\Delta &= \eta\epsilon_{\rm grav} + \eta_1\epsilon_{\rm grav}^2 + \bigcirc\left(\epsilon_{\rm grav}^3\right)\\ \Delta &\sim \frac{\Delta a}{g}\end{aligned}\right\} \quad \eta \sim \frac{\Delta a}{g\epsilon_{\rm grav}}$$

and $\Delta a \propto \delta r$

**Lunar Laser Ranging**

$$\begin{aligned}\delta r &\sim 1\,\mathrm{mm}\\ g &\sim 6\times10^{-3}\,\mathrm{ms}^{-2}\\ \epsilon_{\rm grav,E} &\sim -5\times10^{-10}\\ \hline \eta &\lesssim 10^{-4}\\ \Delta &\lesssim 10^{-14}\end{aligned}$$

(Hofmann and Müller 2018)

**Damour and Shäfer test with pulsar timing**

$$\begin{aligned}\delta r &\sim 100\,\mathrm{m}\\ g &\sim 2\times10^{-10}\,\mathrm{ms}^{-2}\\ \epsilon_{\rm grav,NS} &\sim -0.15\\ (\eta &\lesssim 10^{-2})\\ \Delta &\lesssim 2\times10^{-3}\end{aligned}$$

(Zhu 2019)

Freire+ 2012

2014

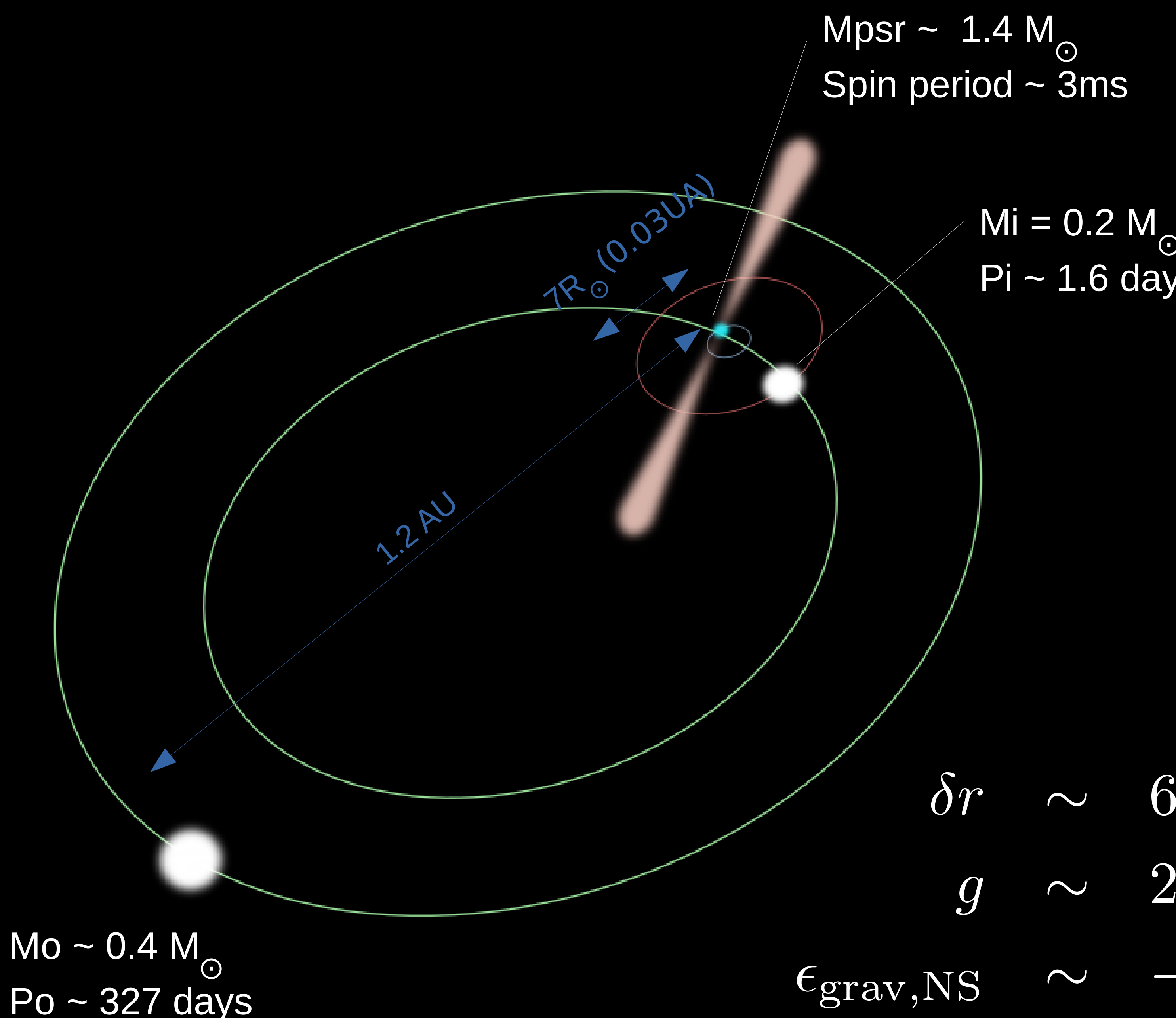
LETTER

doi:10.1038/nature12917

# A millisecond pulsar in a stellar triple system

S. M. Ransom[1], I. H. Stairs[2], A. M. Archibald[3,4], J. W. T. Hessels[3,5], D. L. Kaplan[6,7], M. H. van Kerkwijk[8], J. Boyles[9,10], A. T. Deller[3], S. Chatterjee[11], A. Schechtman-Rook[7], A. Berndsen[2], R. S. Lynch[4], D. R. Lorimer[9], C. Karako-Argaman[4], V. M. Kaspi[4], V. I. Kondratiev[3,12], M. A. McLaughlin[9], J. van Leeuwen[3,5], R. Rosen[1,9], M. S. E. Roberts[13,14] & K. Stovall[15,16]

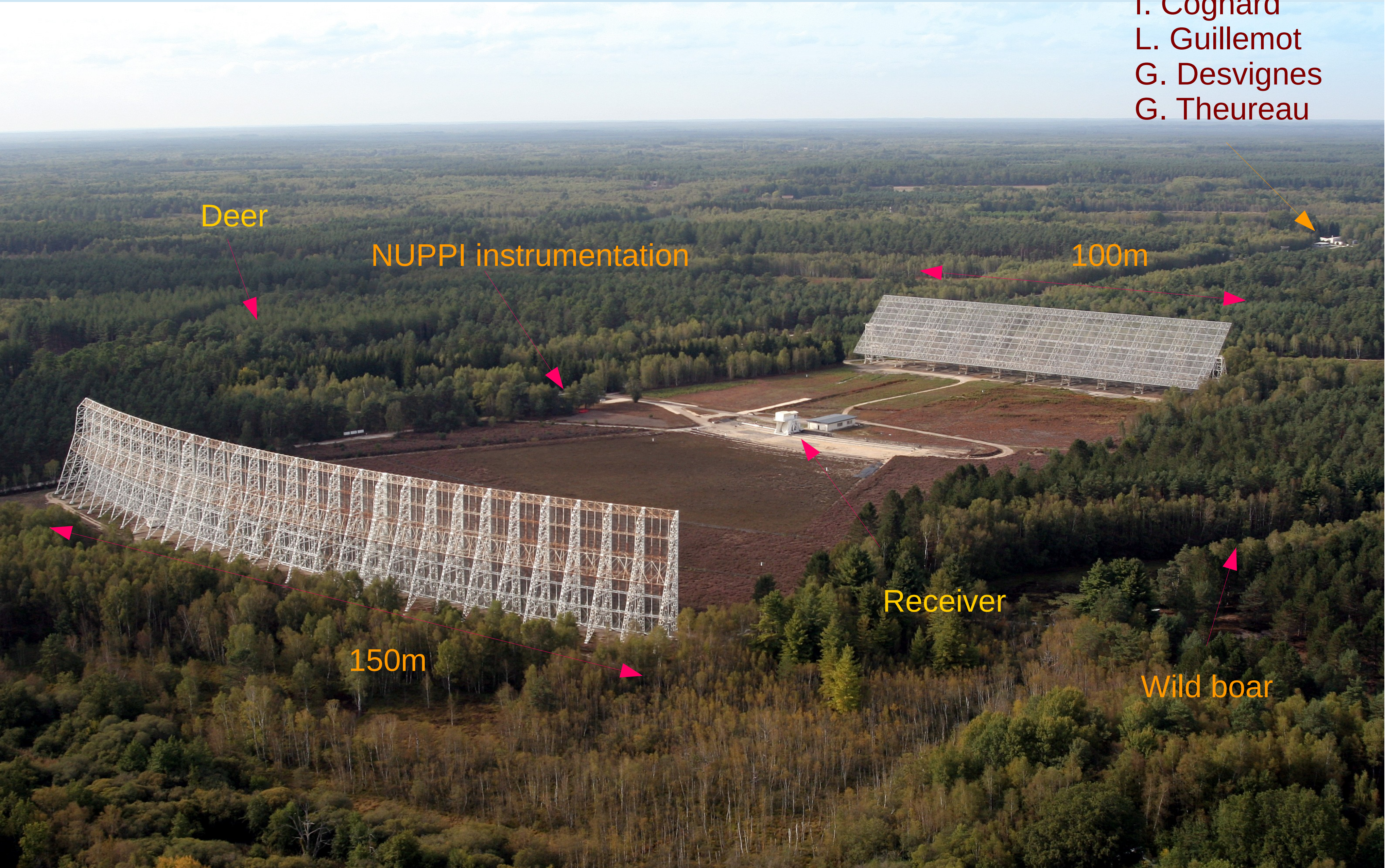
# PSR J0337+1715



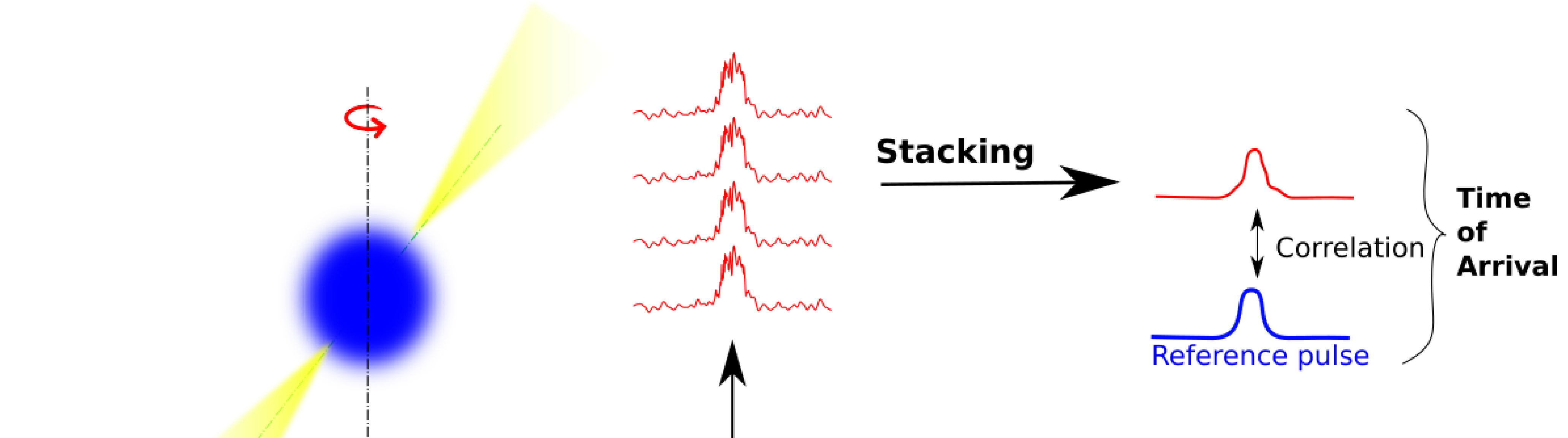

$$\delta r \sim 600\,\mathrm{m}$$
$$g \sim 2\times10^{-3}\,\mathrm{ms}^{-2}$$
$$\epsilon_{\mathrm{grav,NS}} \sim -0.15$$
$$\Delta \lesssim ??$$

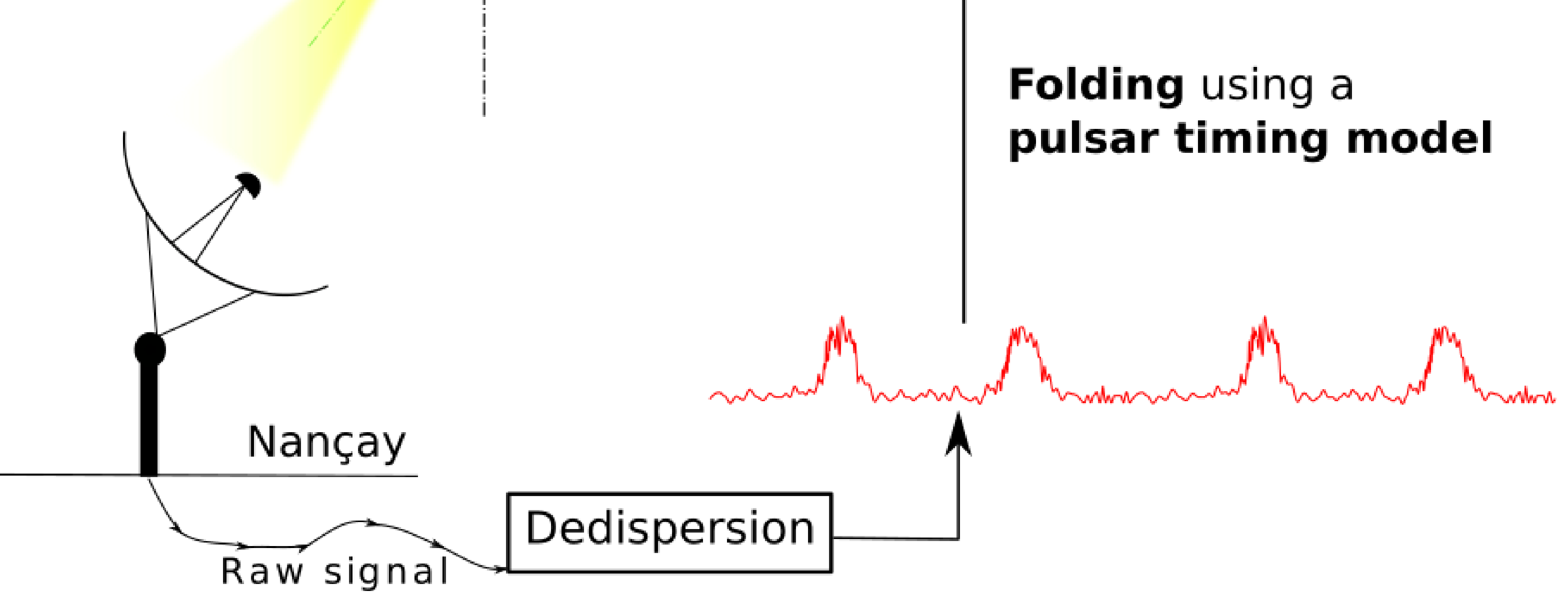
# Welcome to Nançay !

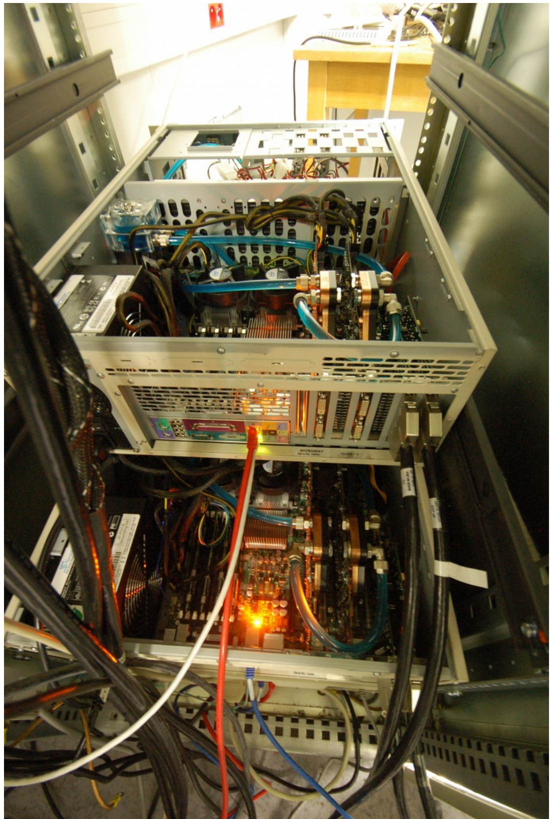
I. Cognard
L. Guillemot
G. Desvignes
G. Theureau



# Pulsar timing (Pulsar radio ranging)

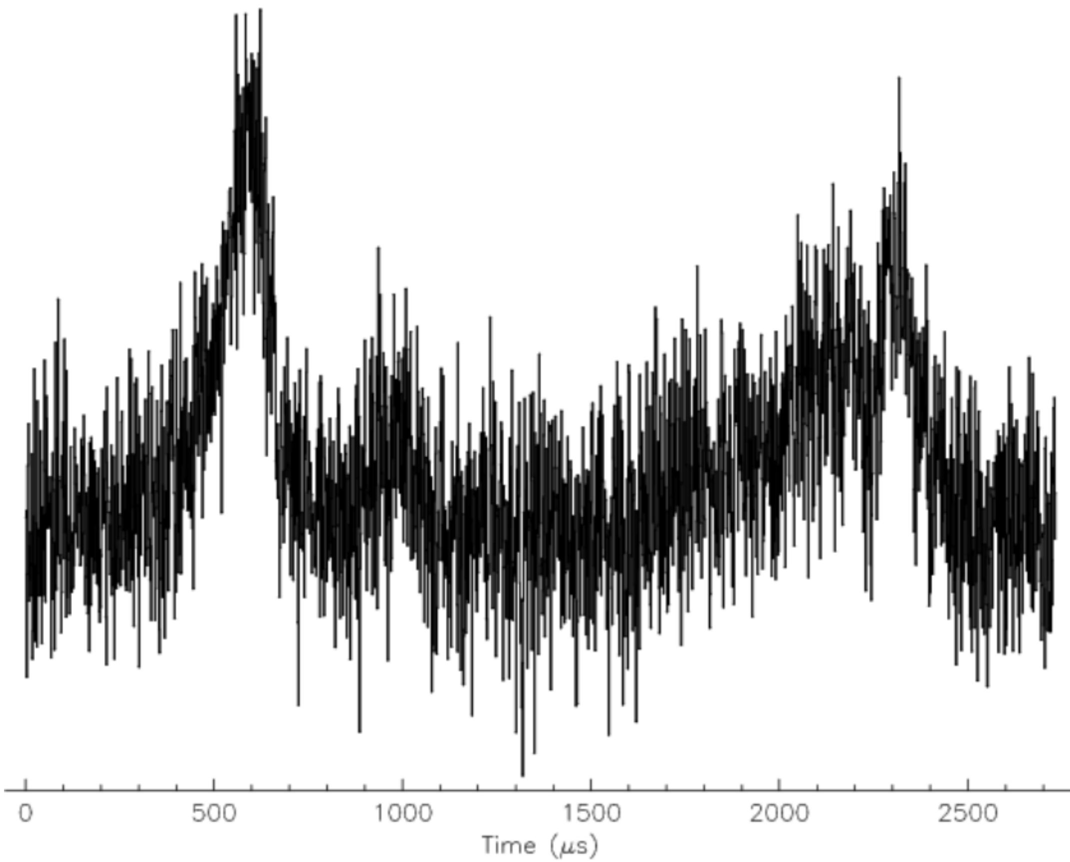


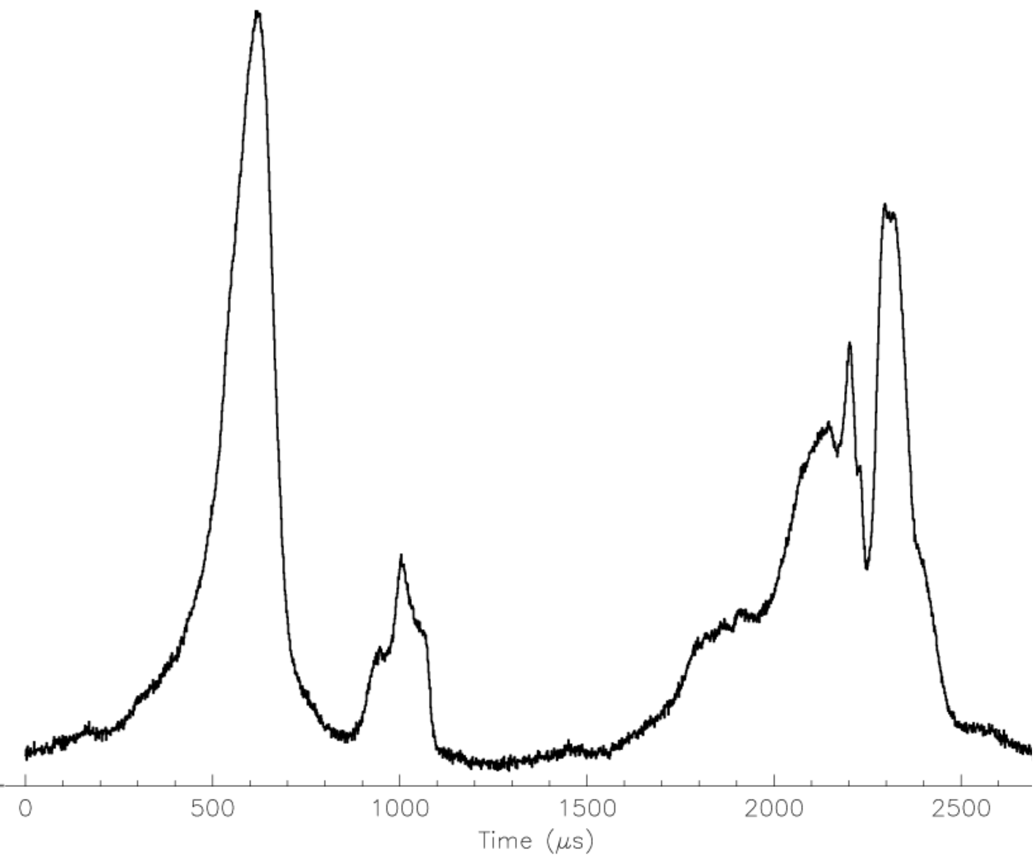



NUPPI
(Courtesy I.
Cognard)

# And here is PSR J0337+1715 !




''Good'' single pulse, October 4th 2014

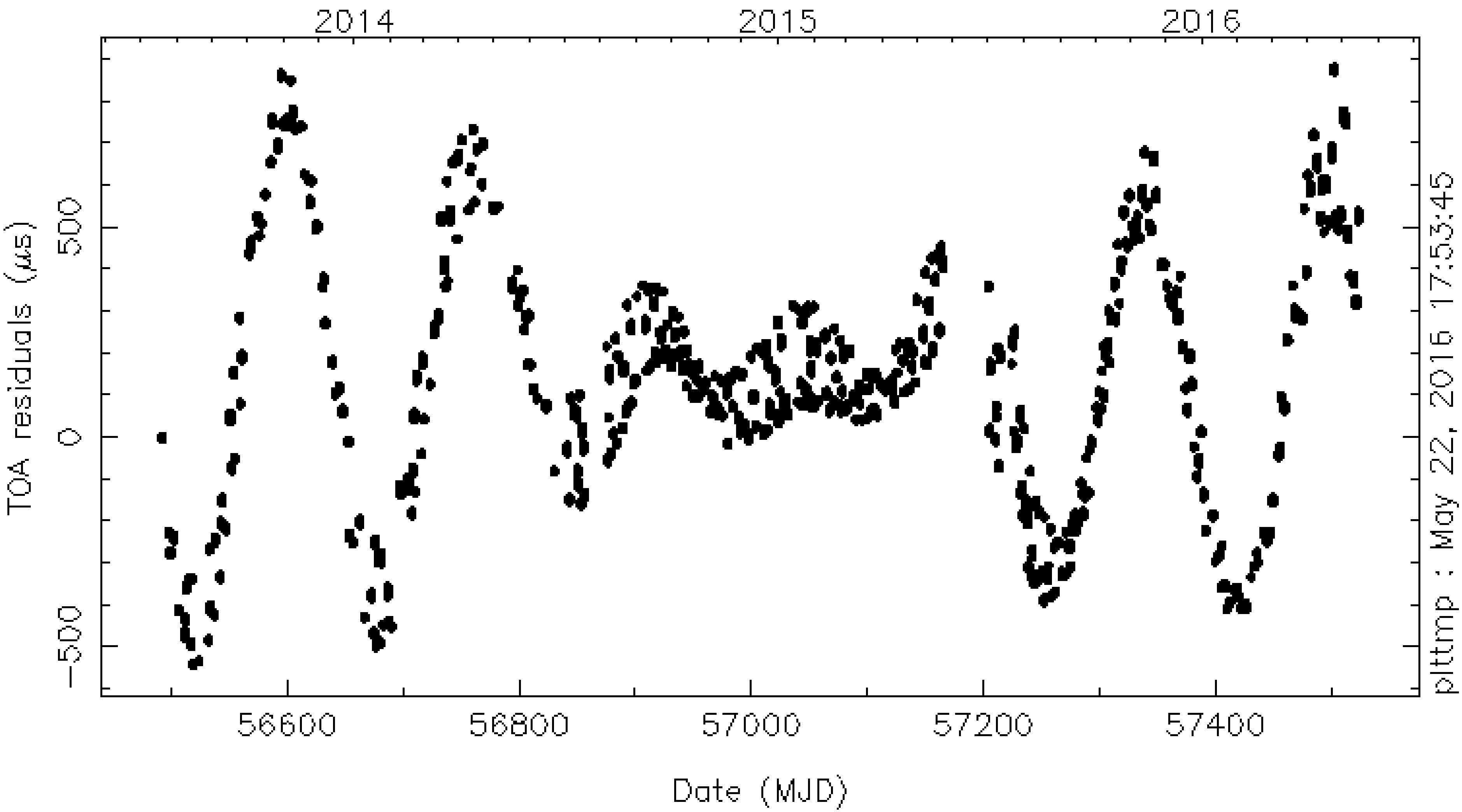



Template pulse profile
(450h of observation, 1230-1742MHz)

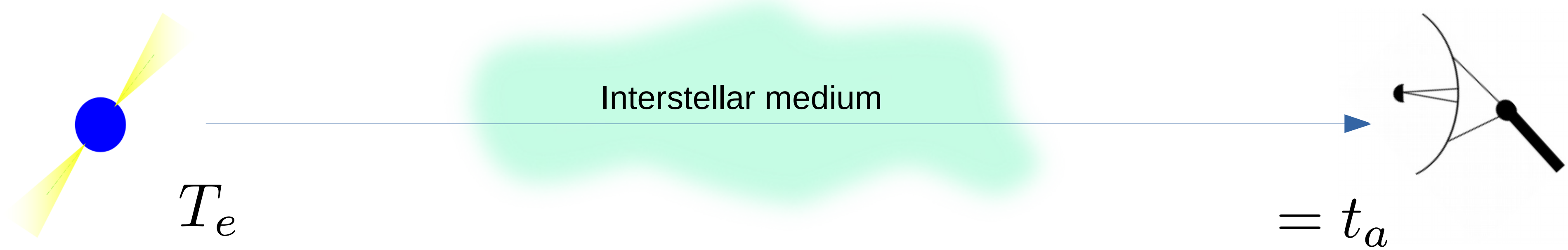


Voisin+ 2020

# Problem: there is no model to predict accurate times of arrival



# What is in a pulsar timing model ?




<u>Pulsar system delays:</u>
- Geometric (Roemer, Kopeikin..)
- Shapiro (light propagation)
- Einstein (time dilation)
- Aberration

<u>Interstellar propagation delays:</u>
- Dispersion measure

<u>Solar system delays:</u>
- Geometric
- Shapiro
- Einstein
- Astrometry...

***Nutimo*** (Voisin 2017, Voisin+2020)
***(NUmerical TIming MOdel*** )

*Tempo 2* (Edwards+ 2006, Hobbs+ 2006)

Number of turns

Spin frequency and derivative

$$N = f T_e + \frac{1}{2} f' T_e^2$$

$$T_e = t_a - \sum_i \Delta T_i$$

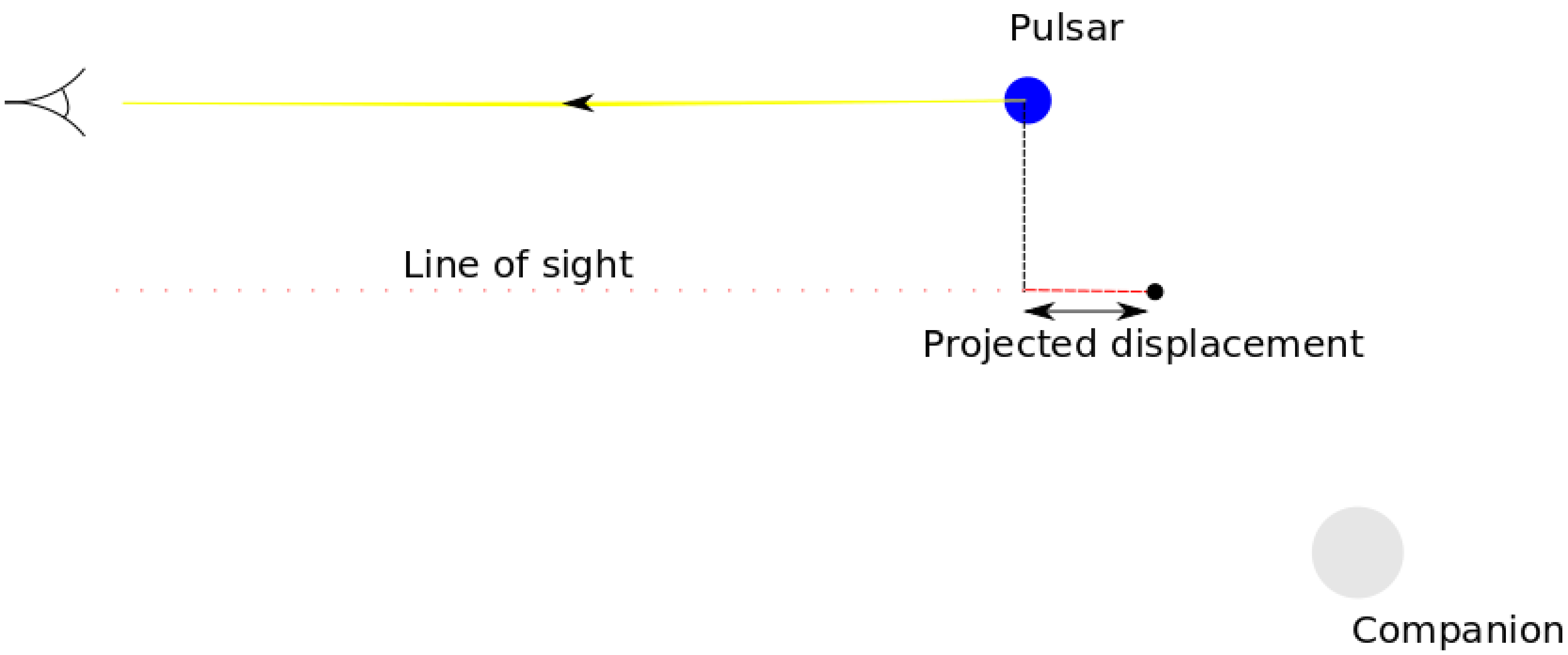
Emission time
in the pulsar frame

Delays

Arrival time in observer's frame

# Geometric delay

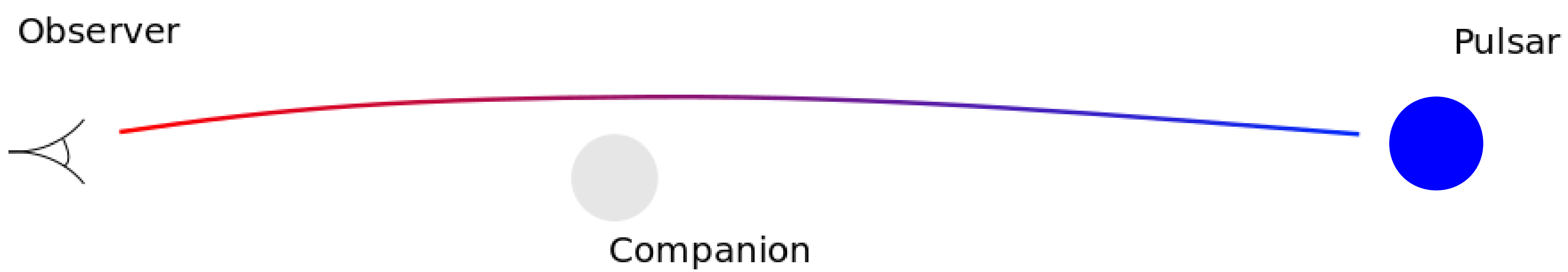
Displacement of 300m ↔ 1microsec delay



# Relativistic delays

**Einstein**: Apparent spin frequency of the pulsar depends on gravitational field of companions

**Shapiro**: Light travel time delayed by companion's gravitational field



# We need to solve the 3-body orbital motion at 1PN

Target accuracy: 1 ns ↔ 3m

Newtonian terms with body-dependent interaction constant

First order (1PN) relativistic corrections:

$$\frac{v^2}{c^2} \sim 10^{-6}$$

$$\begin{aligned}
\ddot{\boldsymbol{x}}_a = & \sum_{b\neq a} \boxed{\frac{G_{ab} m_b}{r_{ab}^2}\boldsymbol{n}_{ab}} \left[1 - \frac{1}{c^2}\left(4\boldsymbol{v}_a\cdot\boldsymbol{v}_b - \boldsymbol{v}_a^2 - 2\boldsymbol{v}_b^2\right.\right.\\
& \left.\left. + \frac{3}{2}(\boldsymbol{v}_b\cdot\boldsymbol{n}_{ab})^2 - \bar{\gamma}_{ab}(\boldsymbol{v}_a - \boldsymbol{v}_b)^2\right)\right]\\
& + \sum_{b\neq a} \frac{G_{ab} m_b}{r_{ab}^2 c^2}(\boldsymbol{v}_b - \boldsymbol{v}_a)\left[\boldsymbol{n}_{ab}\cdot(4\boldsymbol{v}_a - 3\boldsymbol{v}_b - 2\bar{\gamma}_{ab}(\boldsymbol{v}_b - \boldsymbol{v}_a))\right]\\
& + \sum_{b\neq a}\sum_{c\neq b} \frac{G_{ab}G_{bc} m_b m_c}{r_{ab} r_{bc} c^2}\left[\frac{1}{r_{bc}}\left(\frac{1}{2}(\boldsymbol{n}_{ab}\cdot\boldsymbol{n}_{bc})\boldsymbol{n}_{ab} + \frac{7}{2}\boldsymbol{n}_{bc}\right)\right.\\
& \left. - \frac{\boldsymbol{n}_{ab}}{r_{ab}} + 2\bar{\gamma}_{ab}\frac{\boldsymbol{n}_{bc}}{r_{bc}} - 2\bar{\beta}^b_{ca}\frac{\boldsymbol{n}_{ab}}{r_{ab}}\right]\\
& - \sum_{b\neq a}\sum_{c\neq a} \frac{G_{ab}G_{ac} m_b m_c}{r_{ab}^2 r_{ac} c^2}\boldsymbol{n}_{ab}\left[4 + \underline{2\bar{\gamma}_{ac}} + \underline{2\bar{\beta}^a_{bc}}\right]. \qquad \text{(A.2)}
\end{aligned}$$

Strong-field generalisation of Eddington PPN parameters
→ **Set to general relativity values**



(Damour and Taylor 1992; Will 1993)

# Additional constraints

Other deviations from GR at 1PN order:

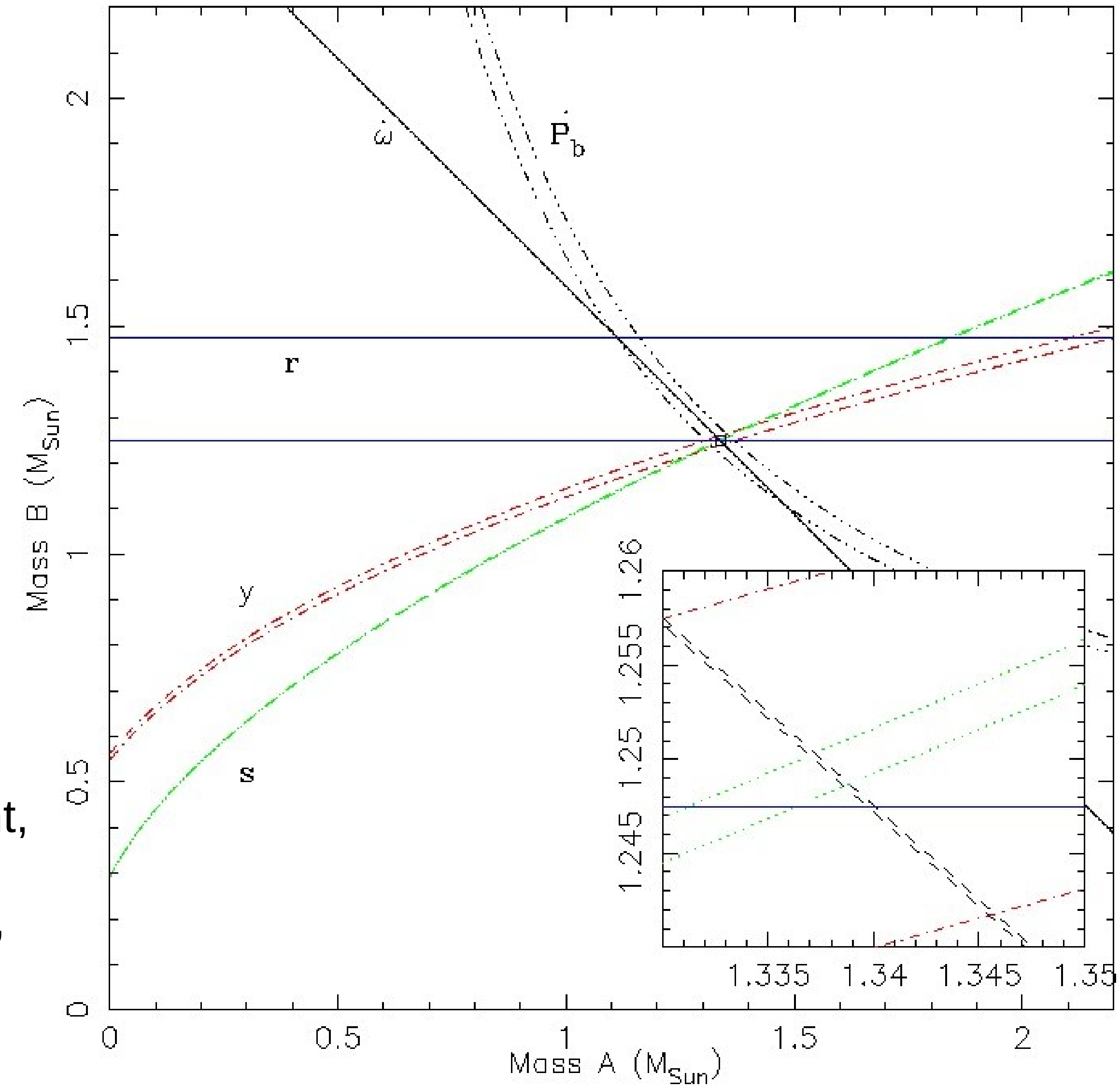
$$
\begin{aligned}
\mathscr{L} \;=\; & \sum_{a=1}^{n}\left(-m_a c^2 + m_a \frac{v_a^2}{2} + m_a \frac{v_a^4}{8c^2}\right) \\
& + \frac{1}{2}\sum_{a=1}^{n}\sum_{b\neq a}^{n}\left\{\frac{G_{ab} m_a m_b}{r_{ab}}\left[1 - \frac{(\boldsymbol{v}_a\cdot\boldsymbol{n}_{ab})(\boldsymbol{v}_b\cdot\boldsymbol{n}_{ab})}{2c^2}\right.\right. \\
& \qquad \left. - \frac{7}{2}\frac{\boldsymbol{v}_a\cdot\boldsymbol{v}_b}{c^2} + \frac{3}{2}\left(\frac{v_a^2}{c^2} + \frac{v_b^2}{c^2}\right) + \bar{\gamma}_{ab}\frac{(\boldsymbol{v}_a - \boldsymbol{v}_b)^2}{c^2}\right] \\
& \qquad \left. - \sum_{c\neq a}^{n}\frac{G_{ab}G_{ac} m_a m_b m_c}{c^2 r_{ab} r_{ac}}(1 + 2\bar{\beta}^a_{bc})\right\},
\end{aligned}
$$

(Damour and Taylor 1992; Will 1993)

We assume:

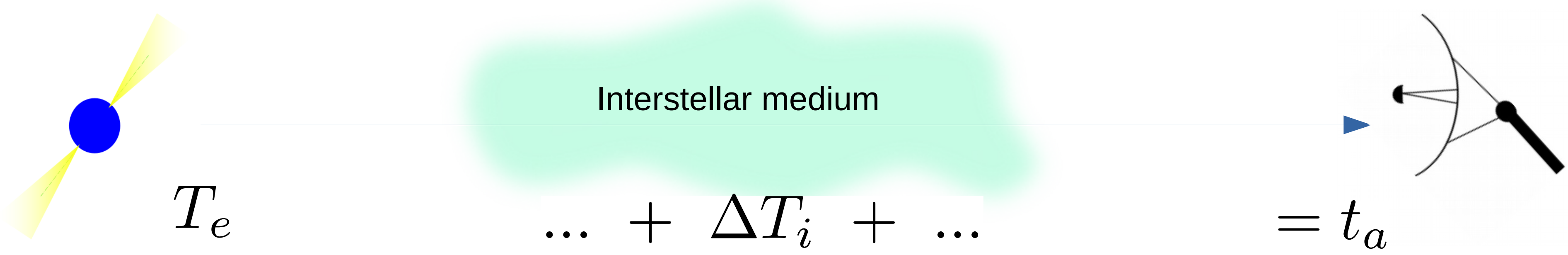
$$\bar{\beta}^c_{ab} = \bar{\gamma}_{ab} = 0 = \mathrm{GR}$$

Thanks to other observational constraint, particularly limits on dipolar gravitational waves from binary pulsars, and Solar system WEP tests.




PSR J0737-3039A, (Courtesy I.Cognard, G. Desvignes)

# In summary, Nutimo does...



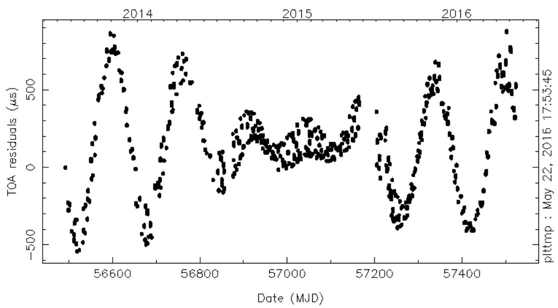

- **Solve motion numerically** at 1PN to meter accuracy
- **Calculate delays**: geometric, relativistic and propagation
- **Invert timing formula** to obtain times of arrival $t_a$ from spin phase N

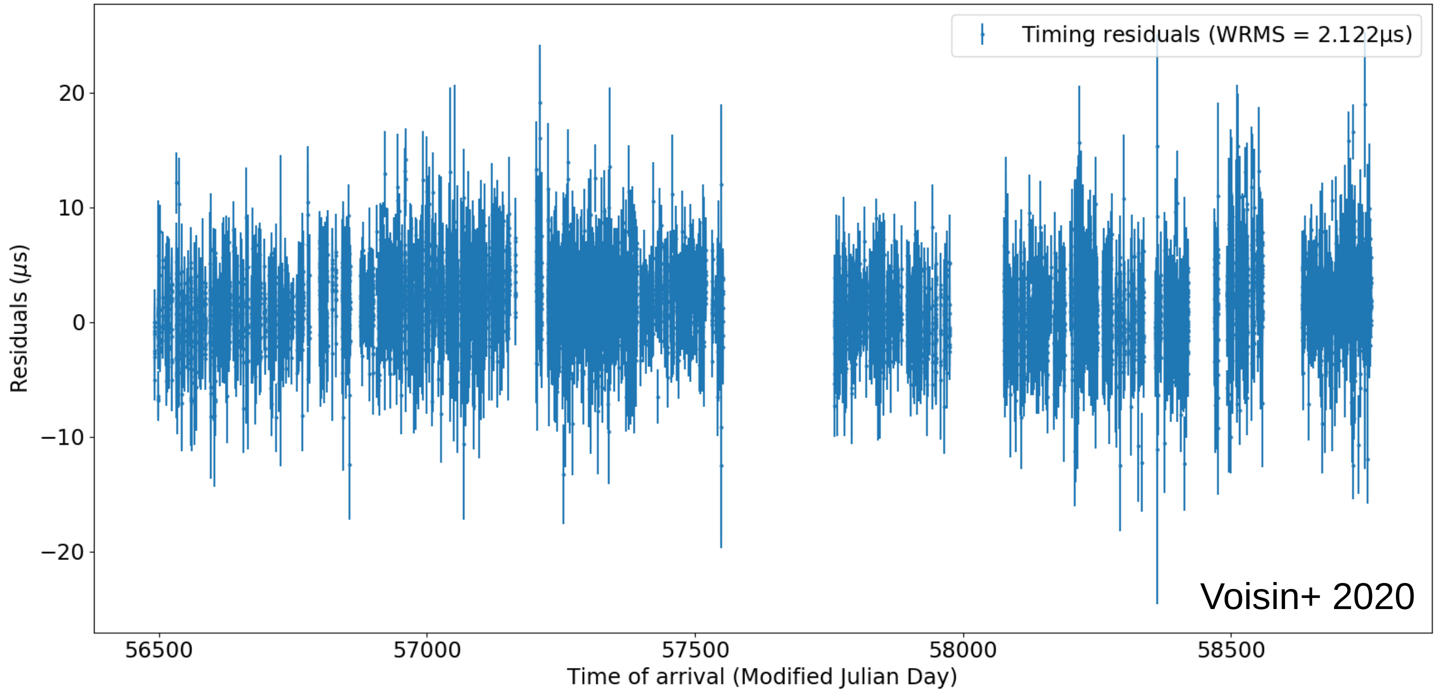
# Let’s fit the model to the data !

More easily said than done:

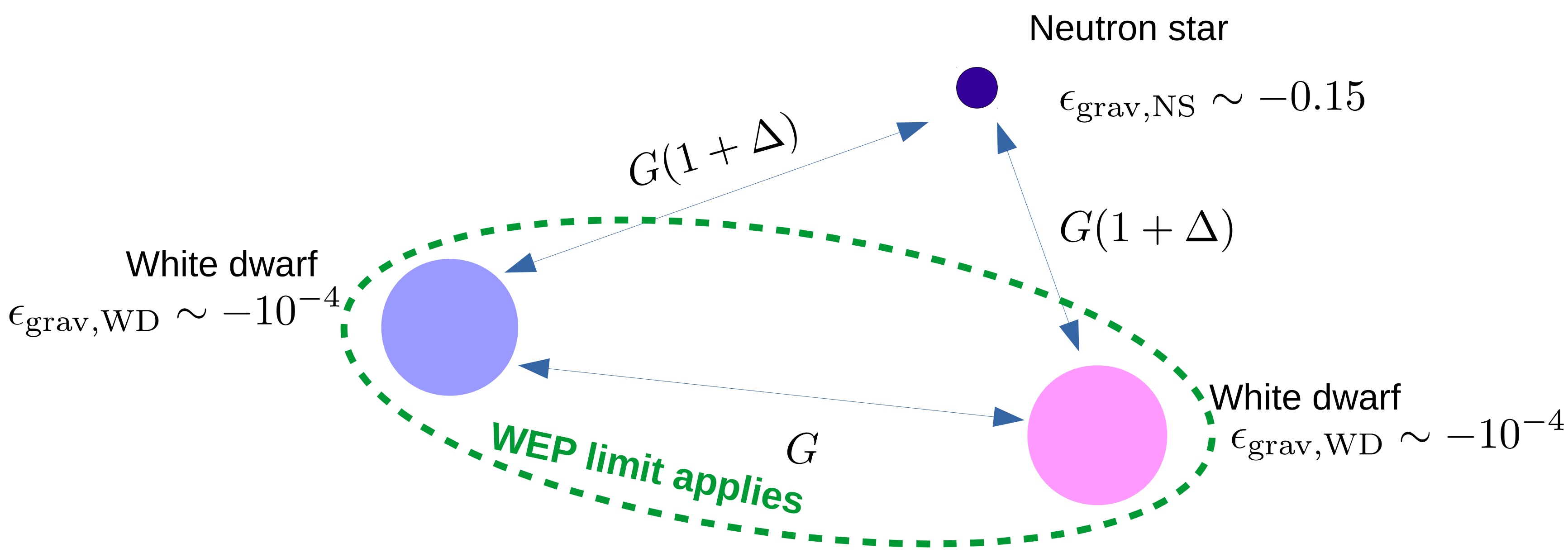
- 27 model parameters :
  - 2 pulsar spin
  - 2x6 orbital
  - 6 astrometric
  - 2 radio propagation (DM)
  - 1 SEP violation parameter
- 10 sec to calculate a single model
- Need reliable posterior distribution function on each parameter → **MCMC**

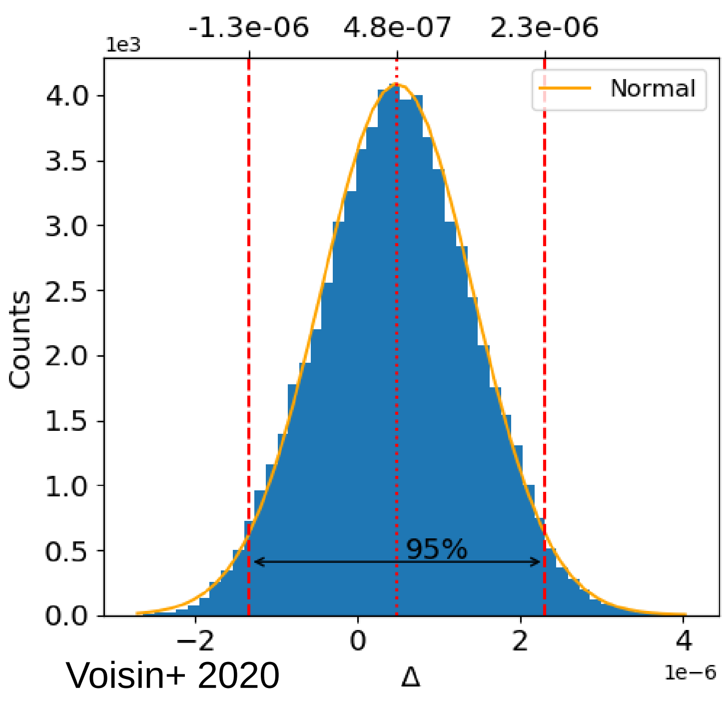
100,000 CPU hours on MESOPSL cluster

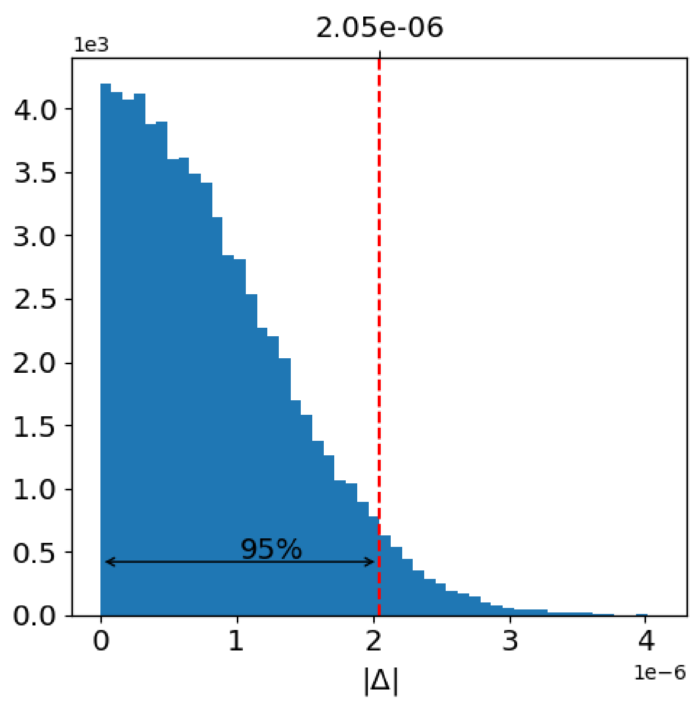


# What about the SEP ?




Voisin+ 2020

$$\Delta = (0.5 \pm 1.8) \times 10^{-6}$$

$$|\Delta| < 2.05 \times 10^{-6}$$

95% confidence

# Comparison to Archibald+2018

→ Archibald+ 2018: $|\Delta| < 2.8 \times 10^{-6}$ (95% confidence)

Uncertainty mostly systematic

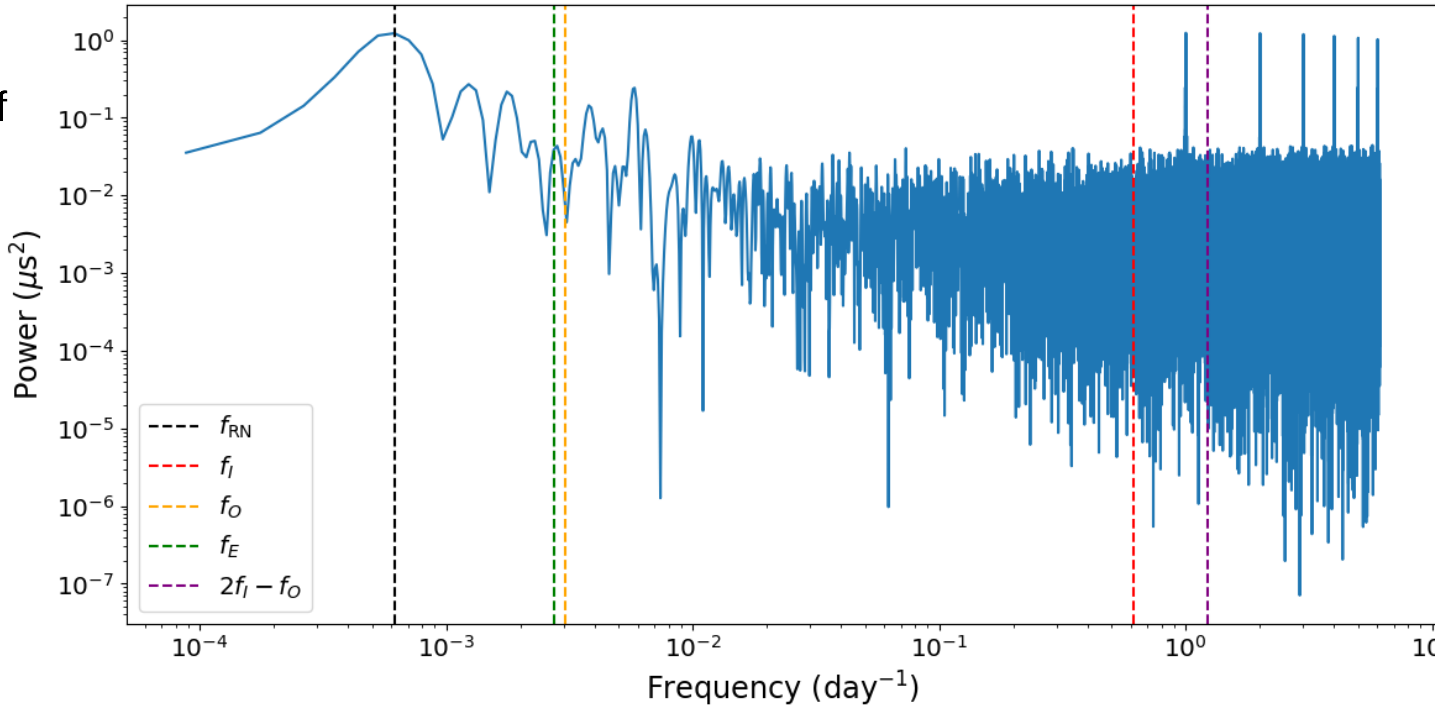
→ Voisin+ 2020: $|\Delta| < 2.05 \times 10^{-6}$ (95% confidence)

Uncertainty fully statistical

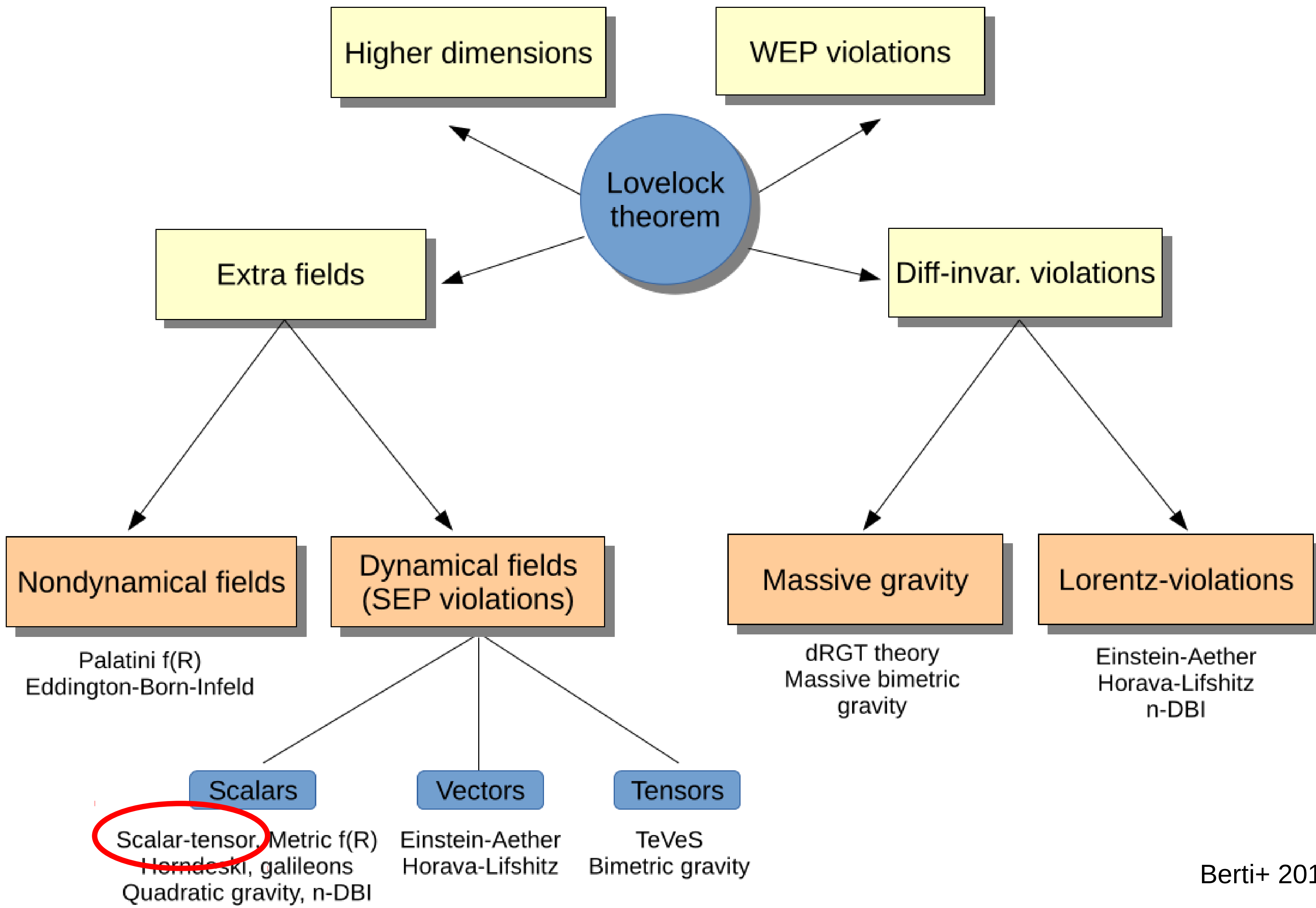
- Independent data
- Independent analysis software
- Additional effects in timing model (Kopeikin delay)

Other differences:

- 1st measurement of longitude of ascending node (Voisin+ 2020)
- 2.5 sigma tension in masses



# Beyond General Relativity




Berti+ 2015

# Bergmann-Wagonner theories

Bergmann 1968, Wagonner 1970

$$S_{\rm GR} = \frac{1}{16\pi G_0}\int \mathrm{d}^4x\sqrt{-g}R + S_{\rm mat}$$

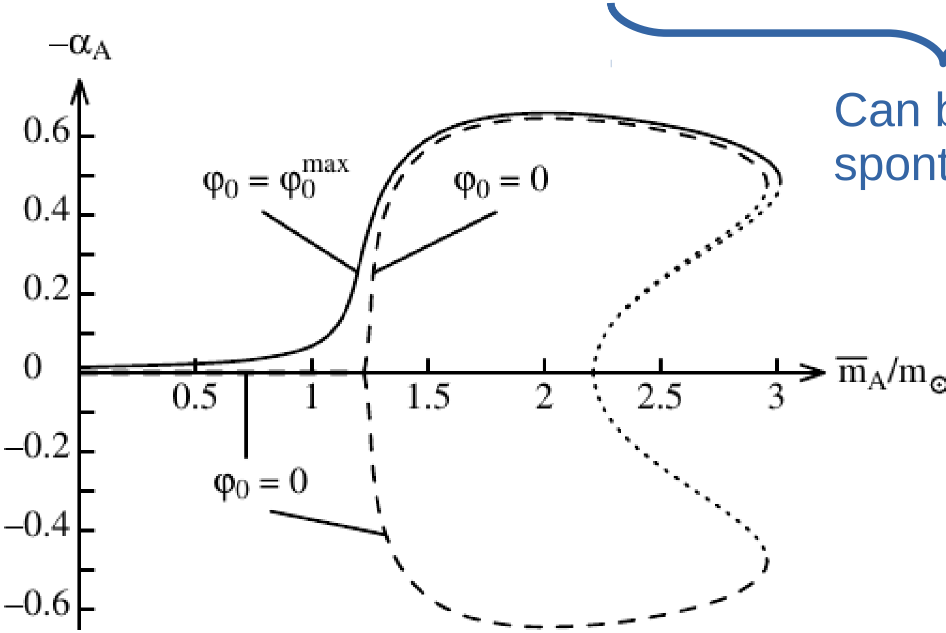
Coupling function

$$S = \frac{1}{16\pi G_0}\int \mathrm{d}^4x\sqrt{-g}\left(R\phi - \frac{\omega(\phi)}{\phi}\partial_\mu\phi\partial^\mu\phi - U(\phi)\right) + S_{\rm mat}$$

Scalar potential

$$\Delta = -2\zeta s_p \text{ with } s_p = \left.\frac{\mathrm{d}\ln m_p(\phi)}{\mathrm{d}\ln\phi}\right|_{\phi_0} \text{ and } \zeta = \frac{1}{2\omega(\phi_0)+4}$$

Can become arbitrarily large in case of spontaneous scalarisation !




Spontaneous scalarisation (Damour and Esposito-Farèse 1996)

Damour and Esposito-Farèse 1992

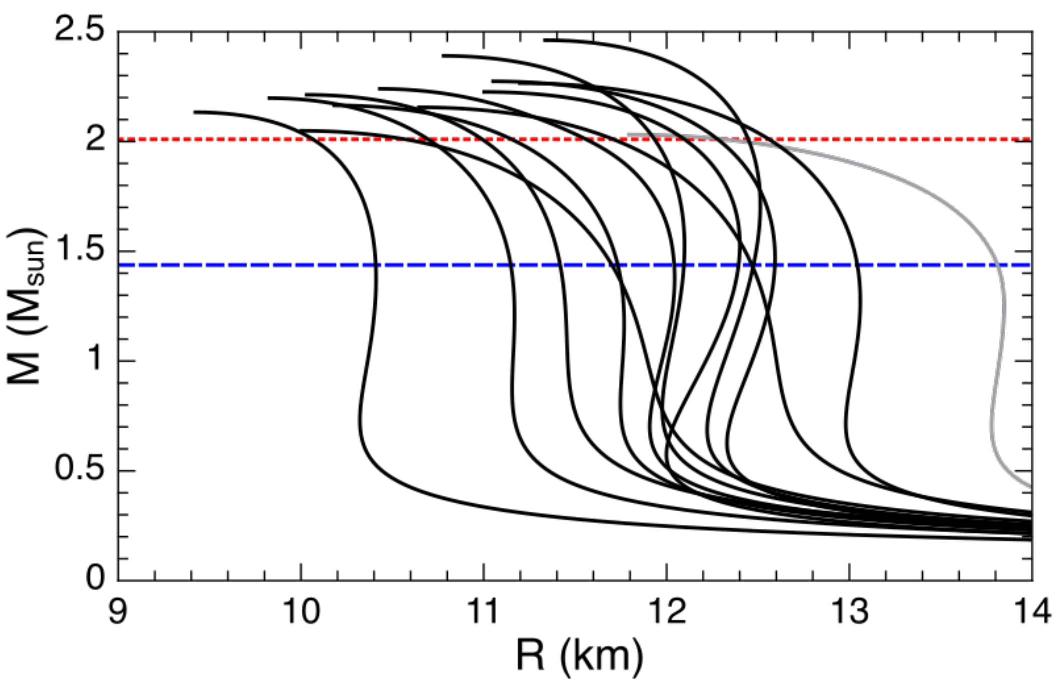
# Damour-Esposito-Farèse theory

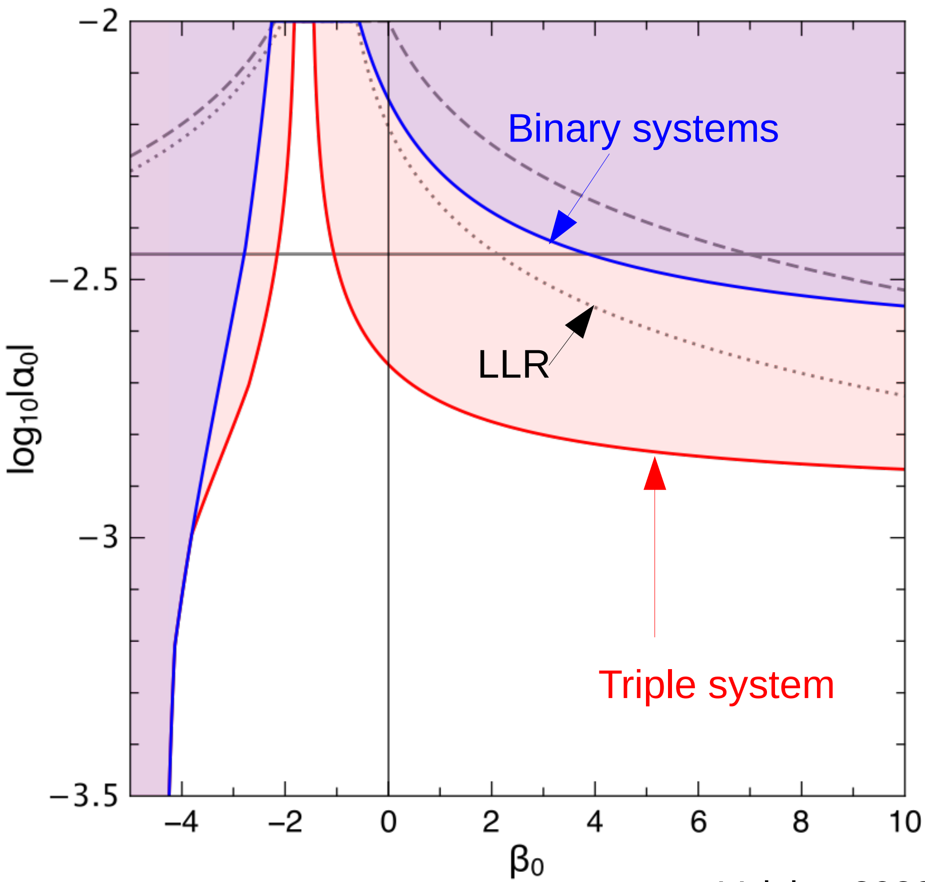
$$\omega(\phi) = \frac{1}{2}\left(\frac{1}{\alpha_0^2 - \beta_0 \ln \phi} - 3\right)$$

$$\zeta = \frac{\alpha_0^2}{1+\alpha_0^2}$$

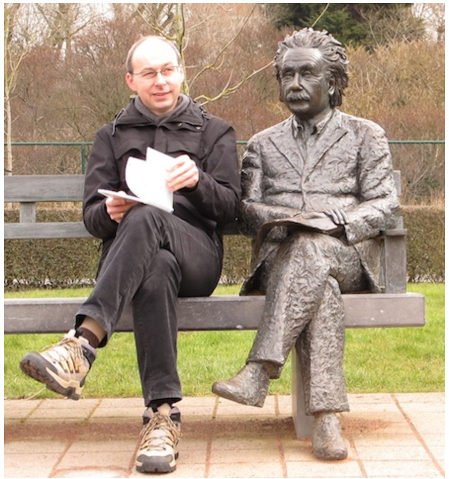
NS Sensitivity: $s_p$

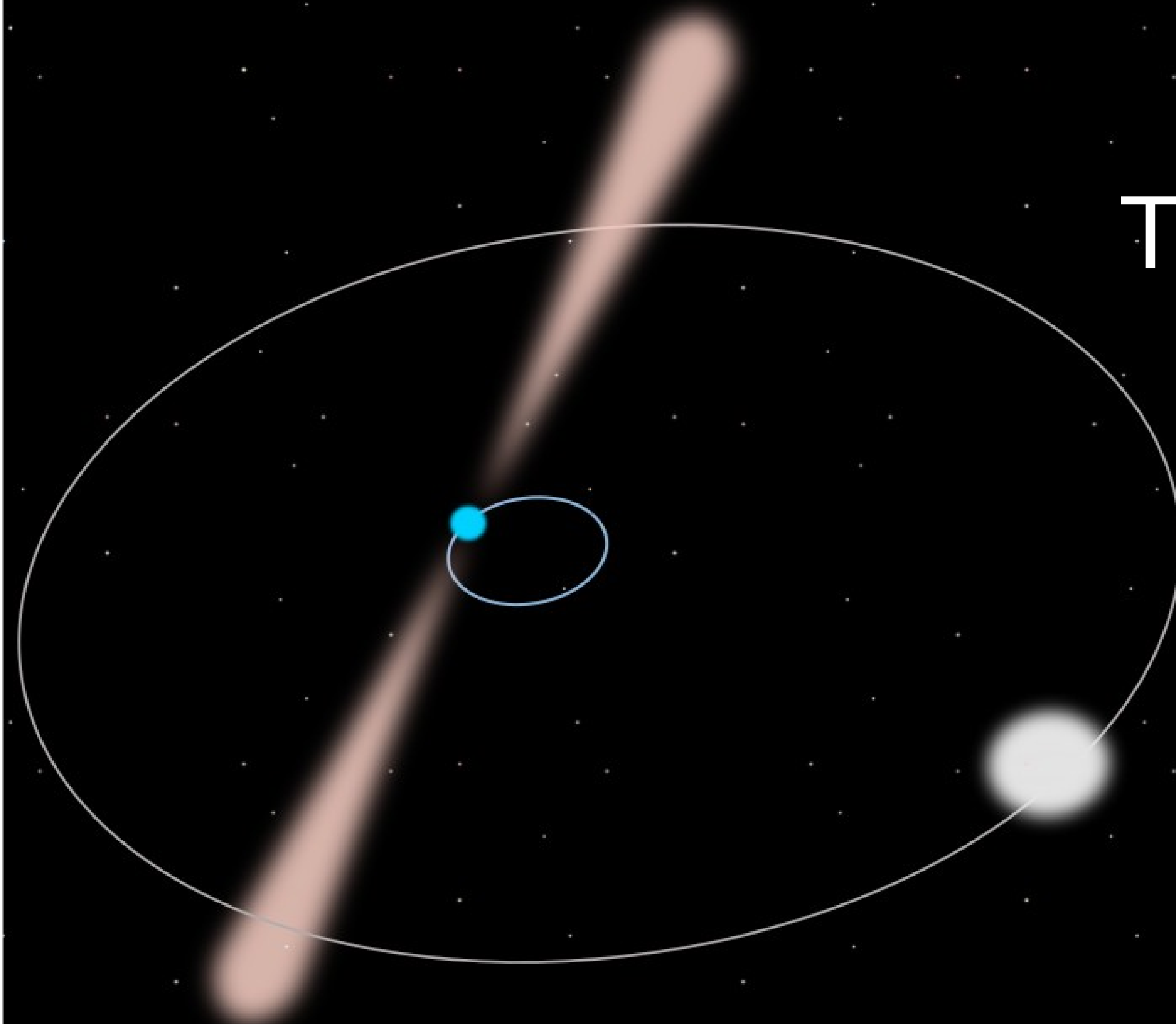
depends on the equation of state




Voisin+ 2020





Thank you !