The strong equivalence principle with the pulsar in a triple system PSR J0337+1715

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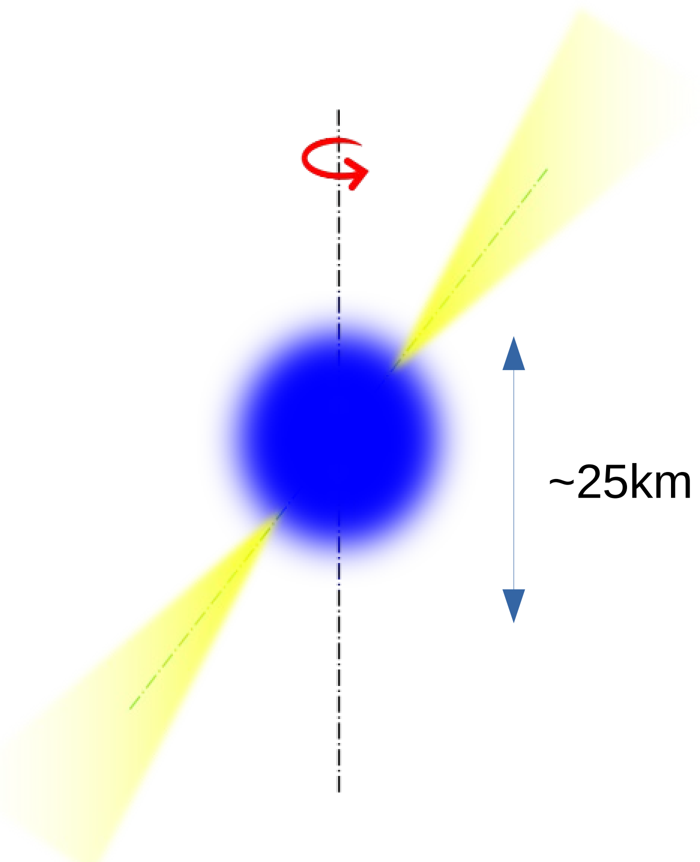
arXiv:2005.01388

Pulsar timing

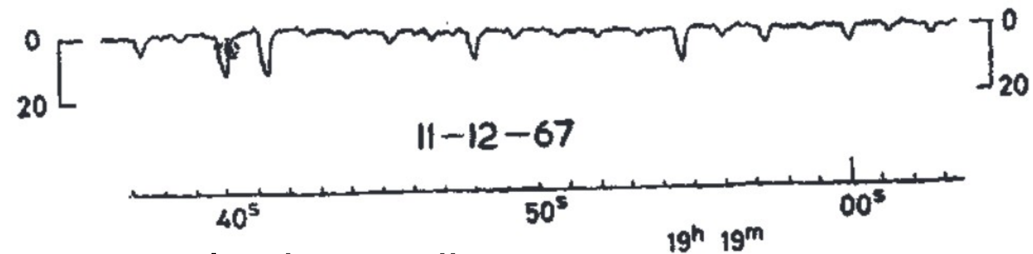
What is a pulsar ?

Highly magnetised rotating neutron star:



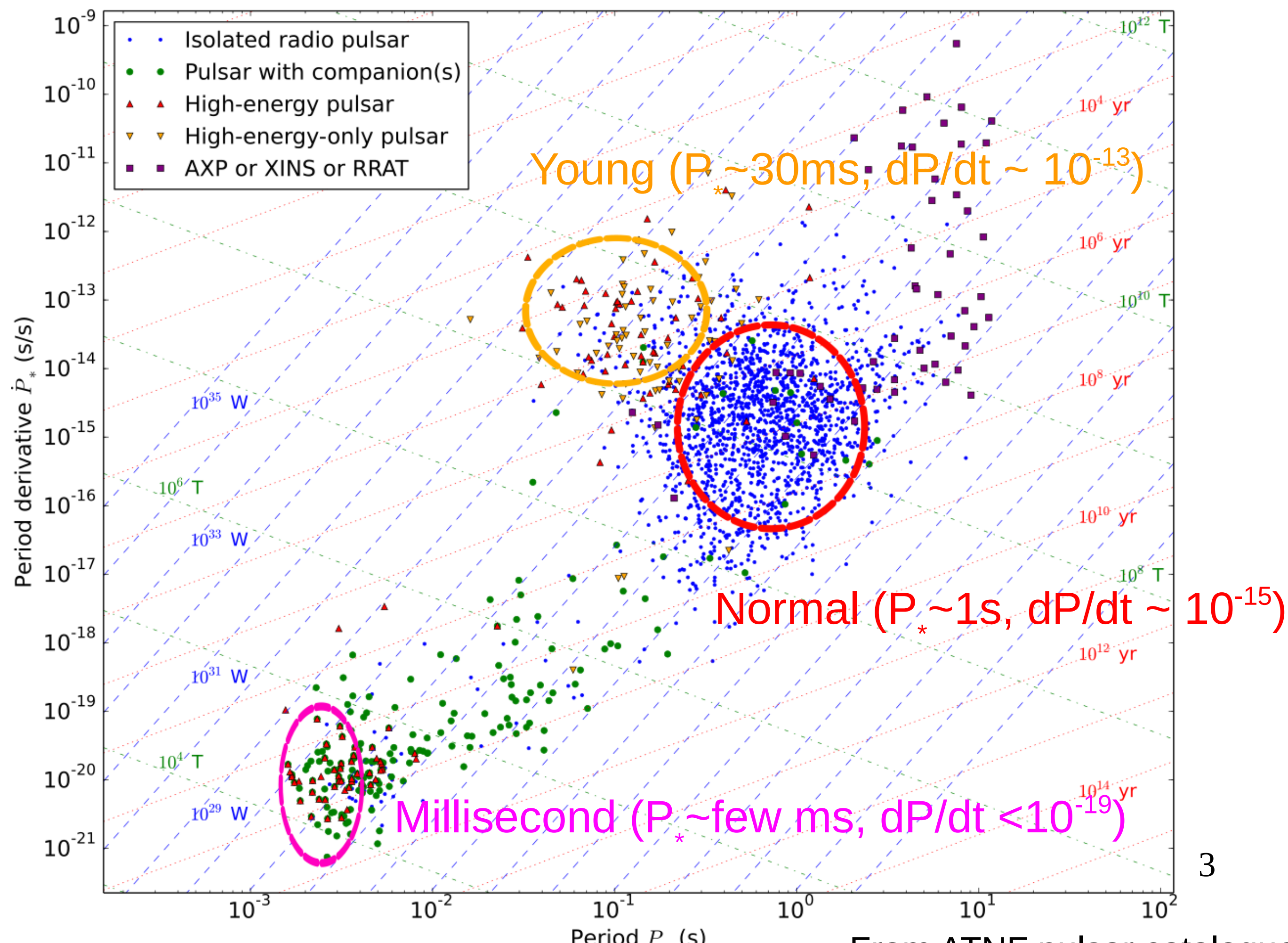
$$m_p \sim 1.4 M_{\odot}$$

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



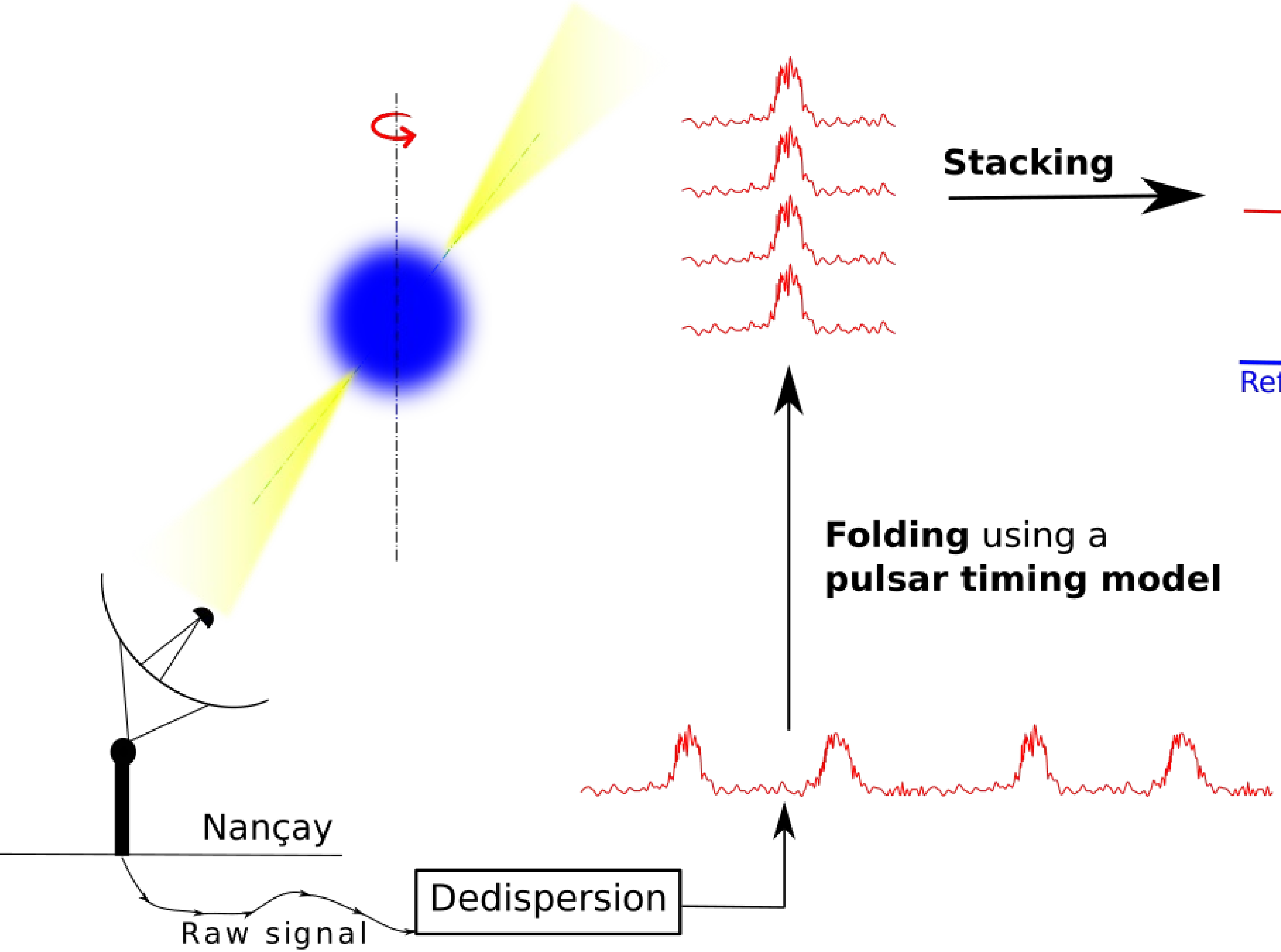
Pulsating Radio source

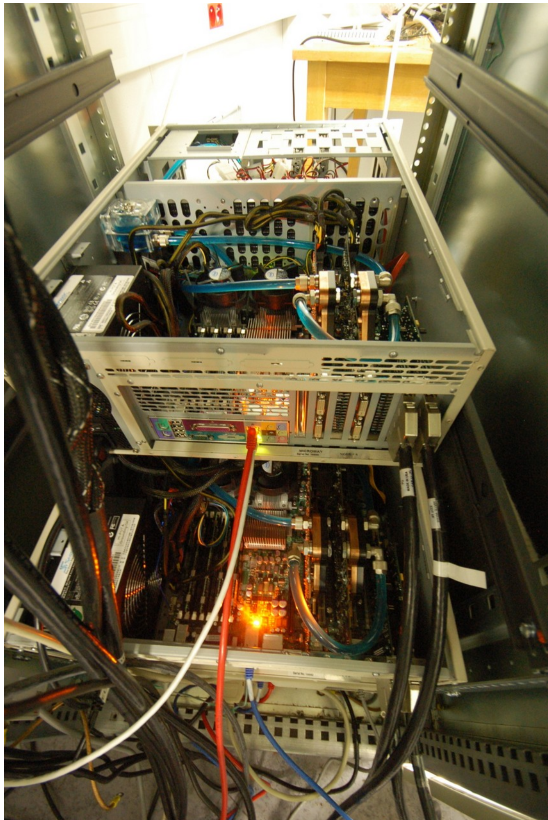
Hewish and Bell 1968



From ATNF pulsar catalogue

Pulsar timing (Pulsar radio ranging)

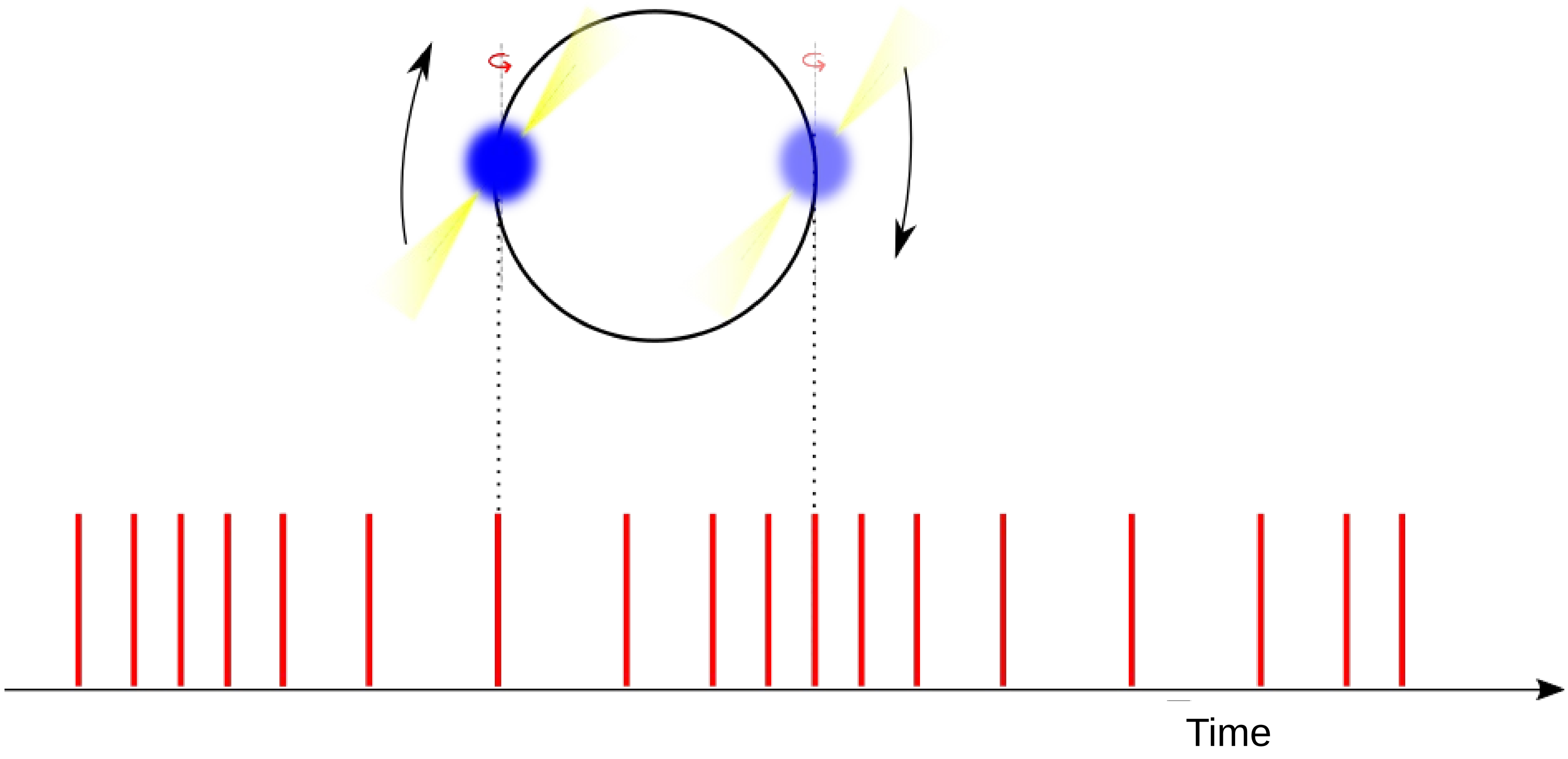




NUPPI
(Courtesy I. Cognard)

Timing a pulsar in a binary system

Timing accuracy 1μs ↔ 300 m



Timing: Binary parameters

Binary system described by 8 (9) - 1 parameters :
6 (7) orbital + 2 masses – 1 mass function = 7 (8) independent parameters

With Roemer delay (leading order geometric), 5 parameters :

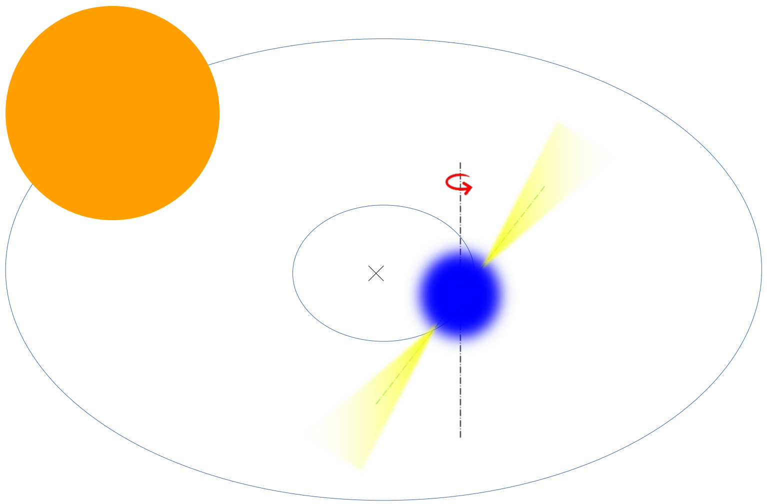
- P : Period
- $a_p \sin(i)$: Projected semi-major axis
- e : Eccentricity
- T_p : Time of periastron passage
- ω : Longitude of periastron

Mass function (Kepler's 3rd law):

$$\frac{(a_p \sin i)^3}{P^2} \propto \frac{(m_c \sin i)^3}{(m_p + m_c)^2}$$

Missing 2 parameters among:

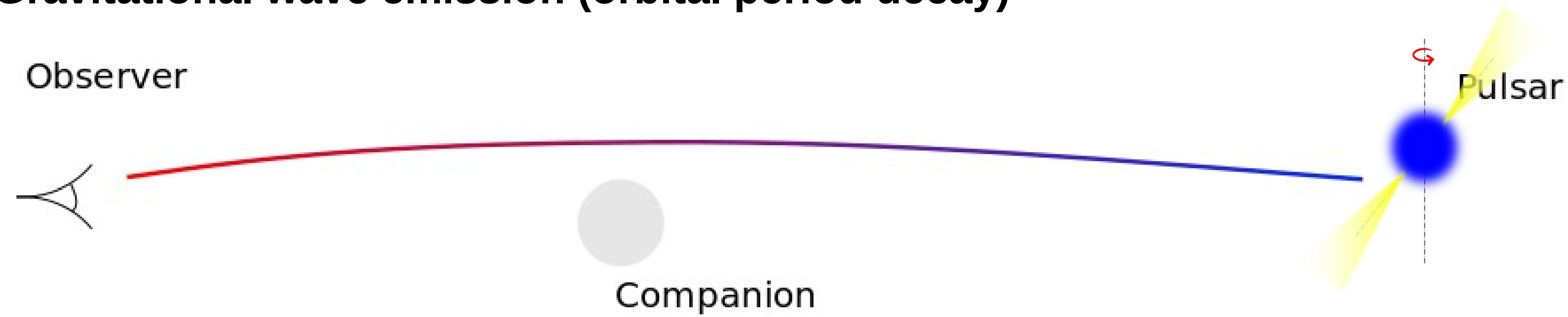
- i : orbital inclination
- (Ω : longitude of ascending node)
- m_p : pulsar mass
- m_c : companion mass



→ **Need for additional effects to lift 2 degeneracies**

Timing: Lifting degeneracies

- **With relativistic effects**
  - **Einstein**: Apparent spin frequency of the pulsar depends on gravitational field of companions
  - **Shapiro**: Light travel time delayed by companion's gravitational field
  - **Precession of periastron**
  - **Gravitational wave emission (orbital period decay)**

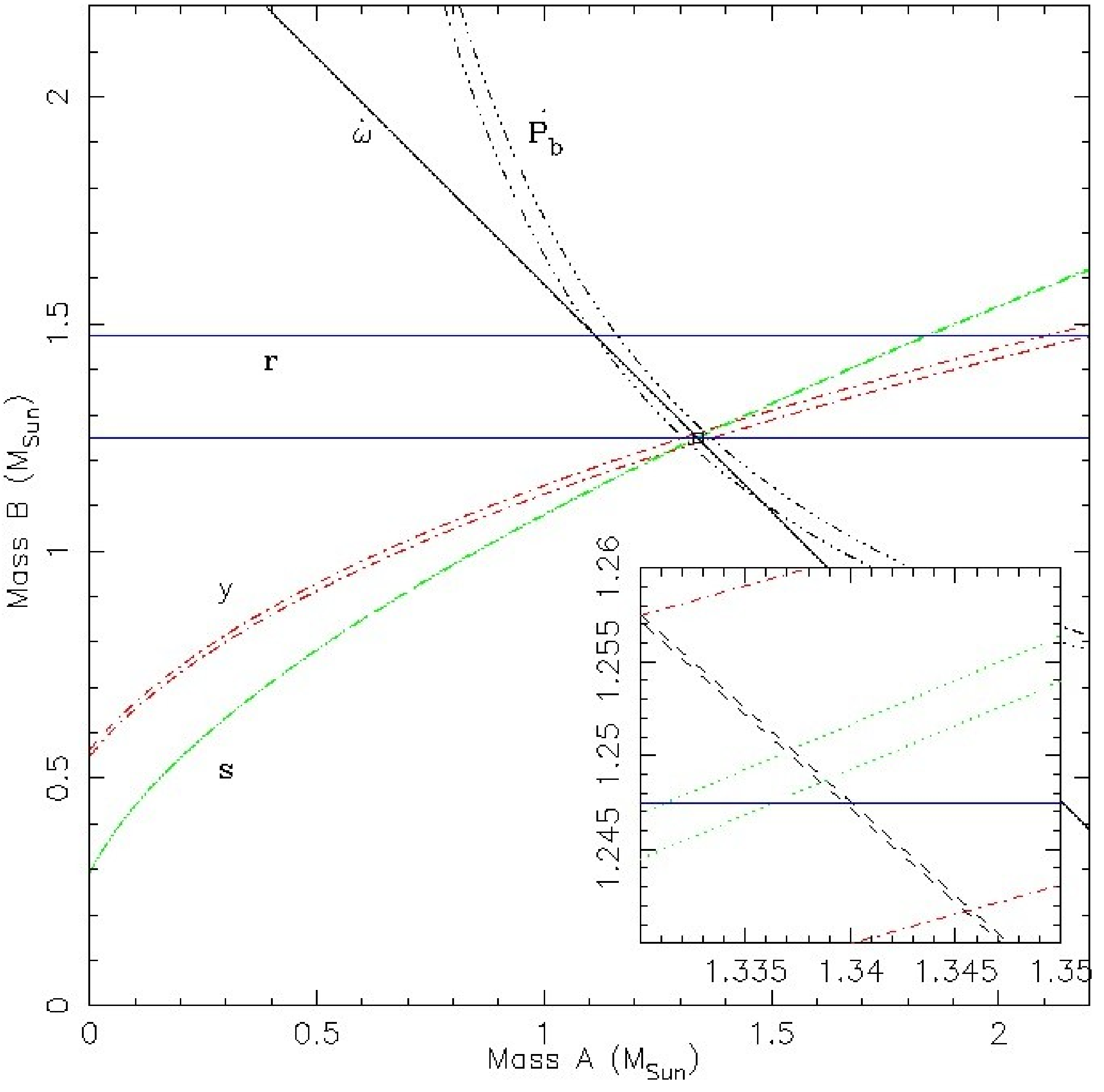


- **With mutual interactions in a triple system : e.g. triple system around PSR J0337+1715**

- **With complementary observations : e.g. optical observations in spider systems**

Testing gravity with pulsars

Binary pulsar: Post-Keplerian tests of GR



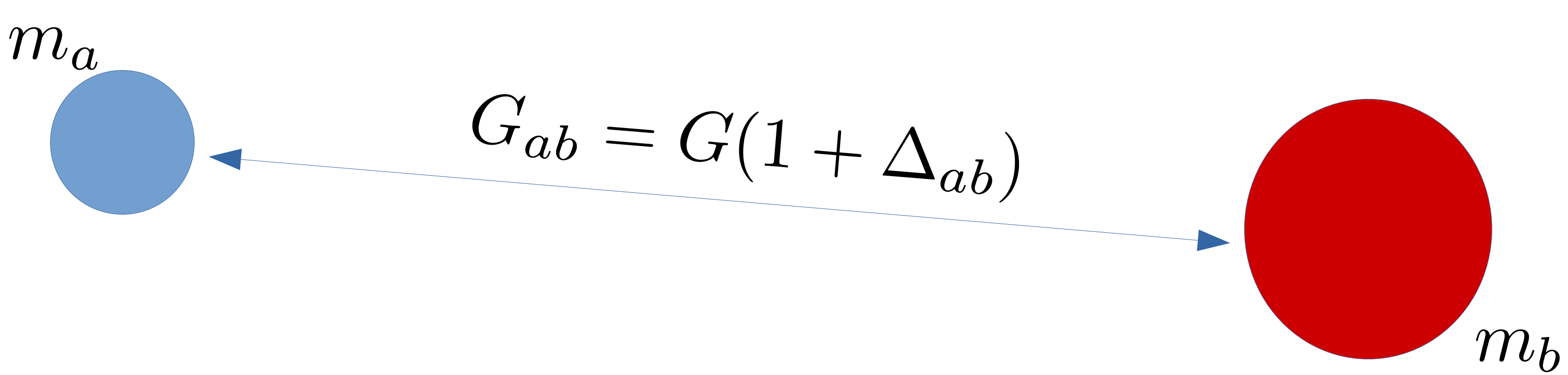
PSR J0737-3039A, (Courtesy I.Cognard, G. Desvignes)

- Relativistic effects break timing degeneracies at post-Newtonian order i.e. with corrections of order $v^2/c^2 \sim 10^{-4}$ at best.
- If more than 2 post-Keplerian parameters measured → Test of GR
- **Equivalence principle test can be done at Newtonian order but requires more than 2 bodies.**

Strong Equivalence Principle (SEP)

- **Strong** equivalence principle ~ Universality of free fall of **self-gravitating** masses
- In the weak-field regime: Solar system tests, e.g. Lunar Laser Ranging in the Earth-Moon-Sun system (Hoffman+2018), planetary ephemerides (Mariani+2023).
- In the strong-field regime: requires compact objects → Pulsars
- At Newtonian order:

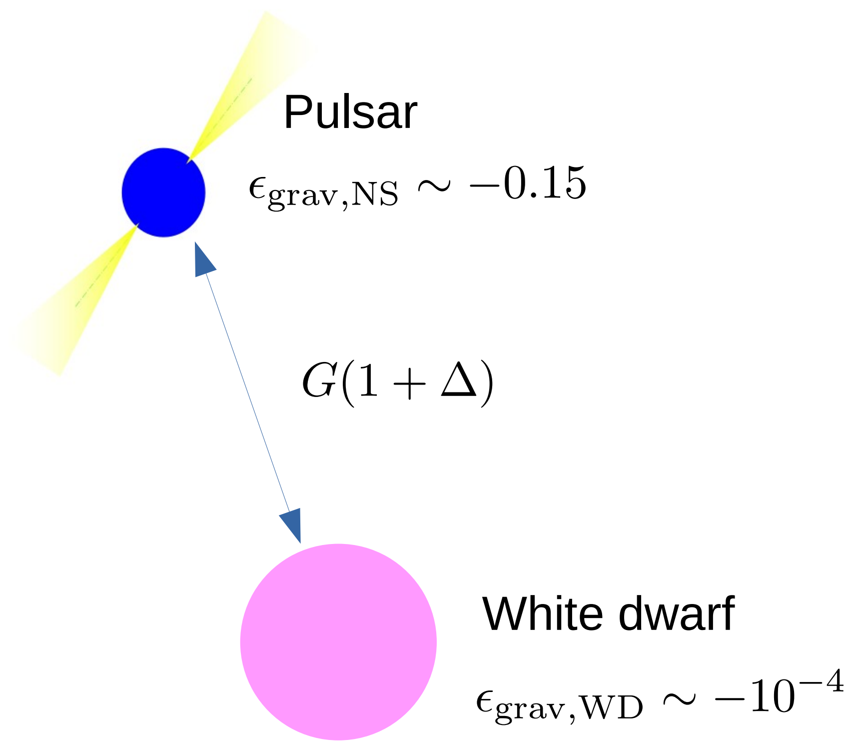
$$m^{(I)} = m^{(G)} \implies G_{ab} = G\frac{m_a^{(G)}}{m_a^{(I)}}\frac{m_b^{(G)}}{m_b^{(I)}} = \boxed{G(1+\Delta_{ab})}$$



Violation of SEP in binaries is not different from rescaling masses !

$$\vec{a}_{NS} = -G(1+\Delta)m_{\text{WD}}\frac{\vec{r}}{|r|^3}$$

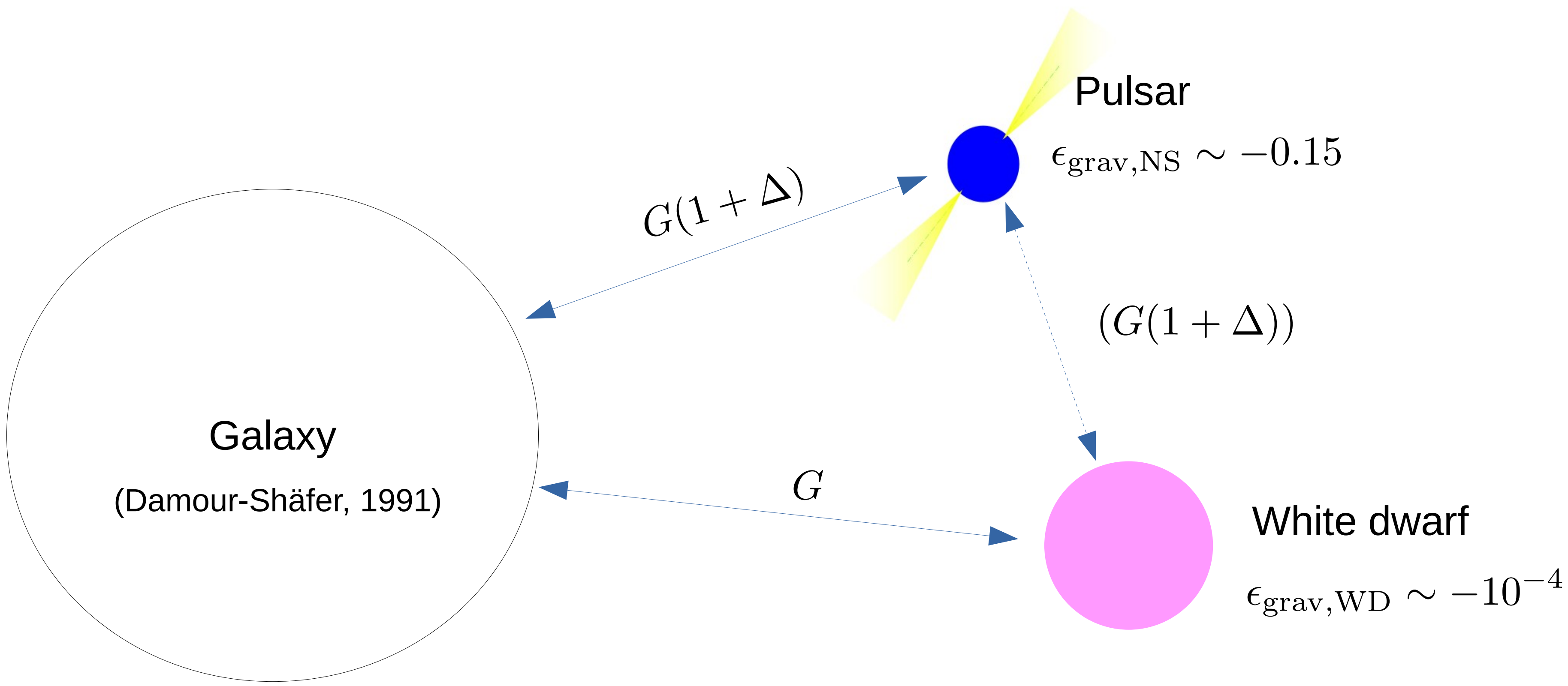
$$\vec{a}_{WD} = -G(1+\Delta)m_{\text{NS}}\frac{\vec{r}}{|r|^3}$$



With three bodies, we can make a test :

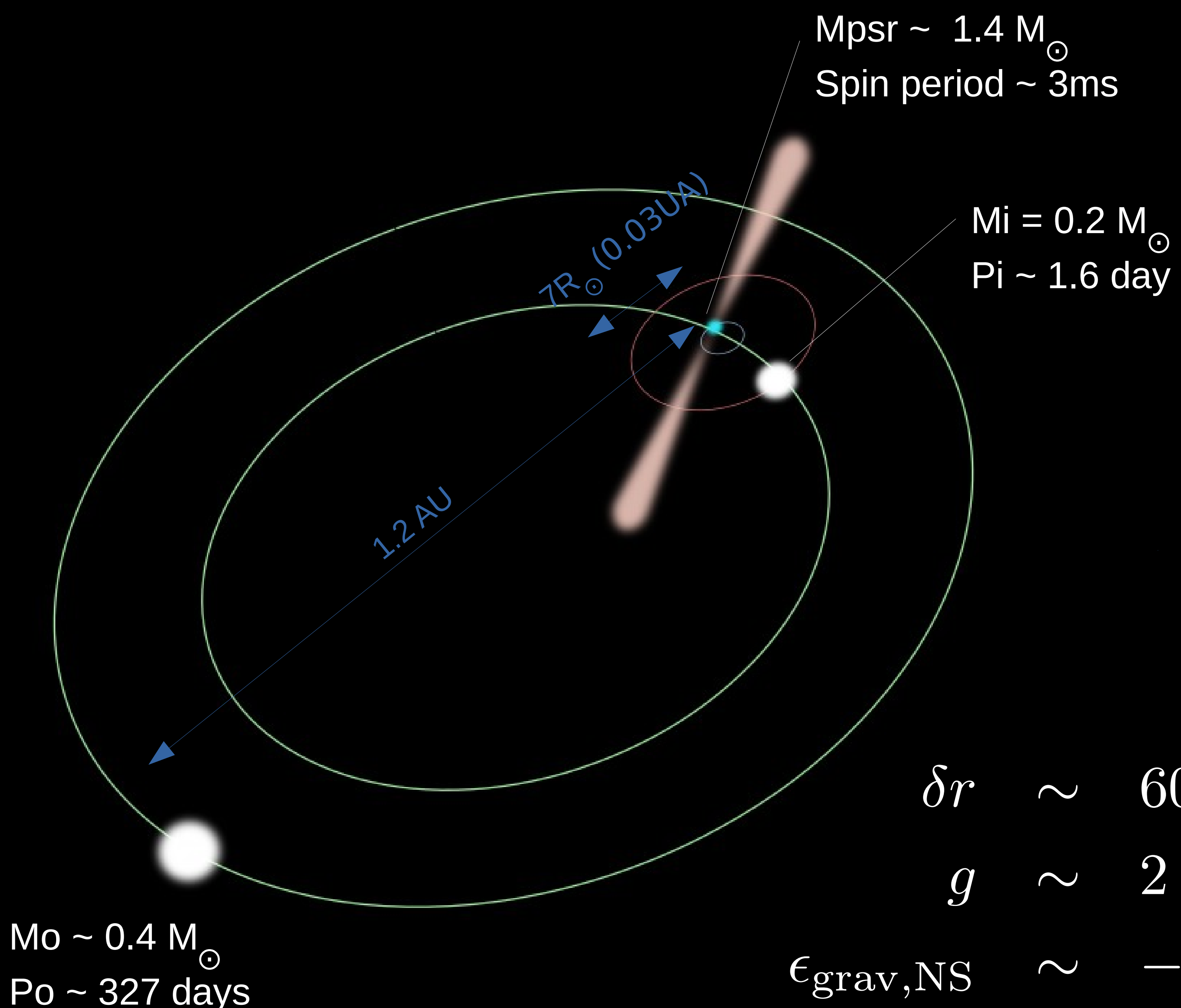
$$|\Delta| < 2 \times 10^{-3} \, (95\% \text{ confidence})$$ (Zhu et al 2019)

(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.

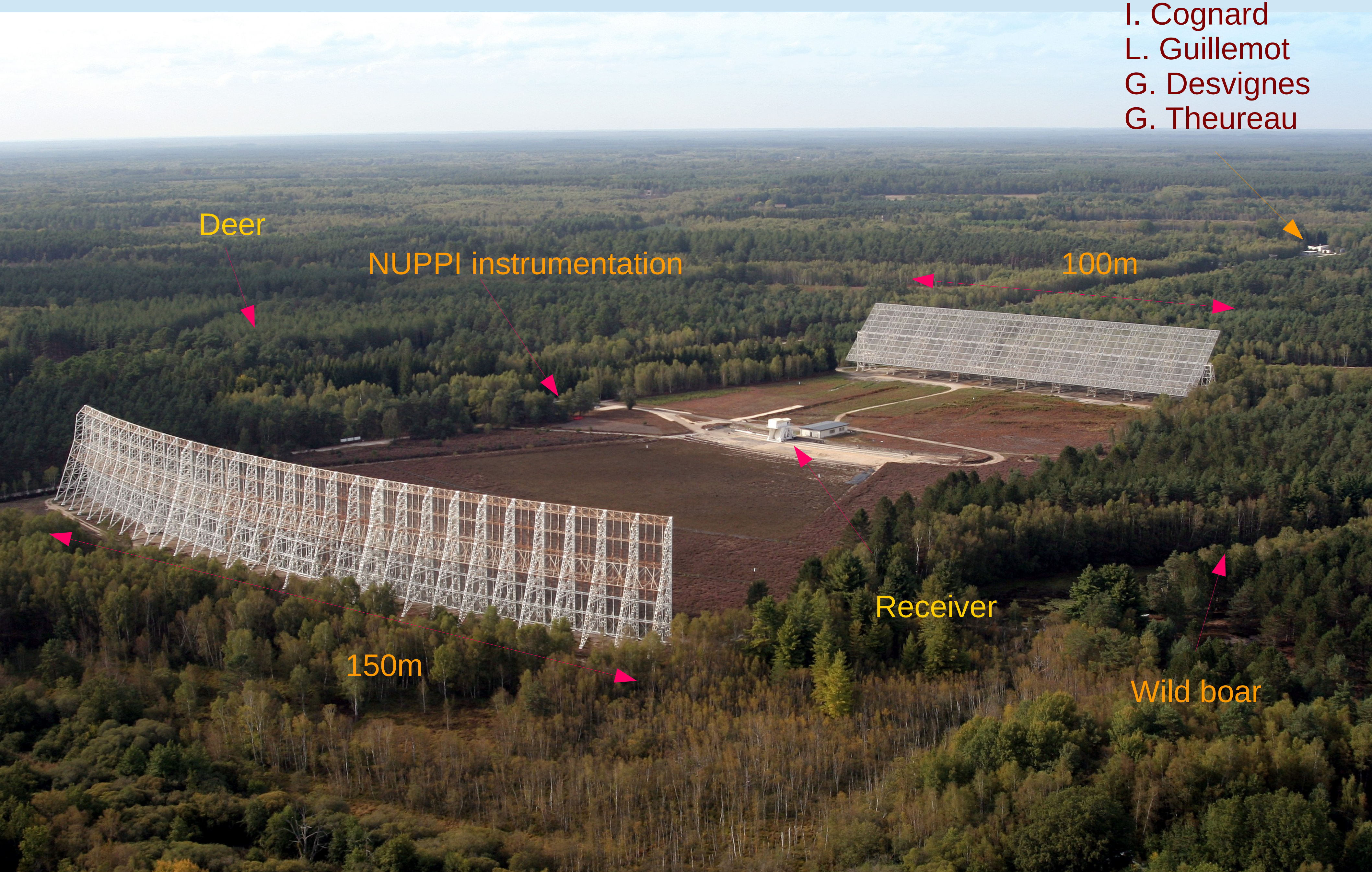
PSR J0337+1715 (Discovery: Ransom+2013)



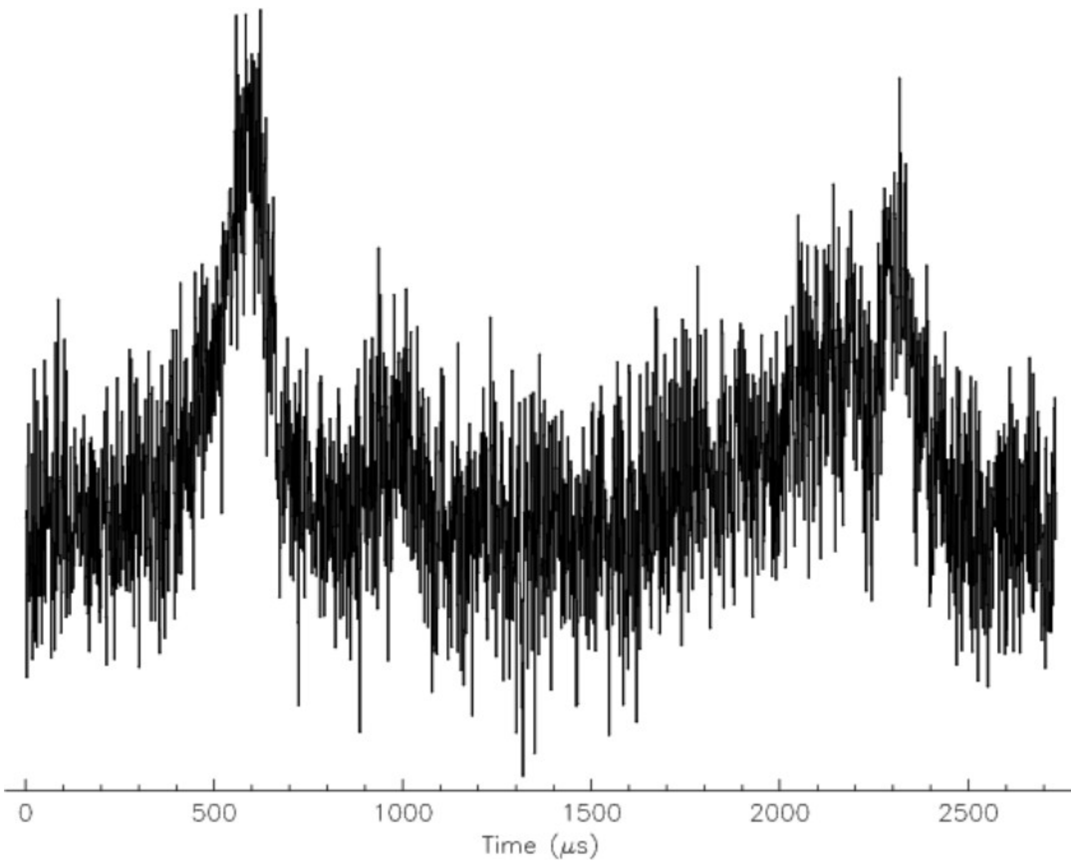
$$\delta r \sim 600\,\mathrm{m}$$
$$g \sim 2\times10^{-3}\,\mathrm{ms}^{-2}$$
$$\epsilon_{\mathrm{grav,NS}} \sim -0.15$$
$$\Delta \lesssim ??$$

Welcome to Nançay !

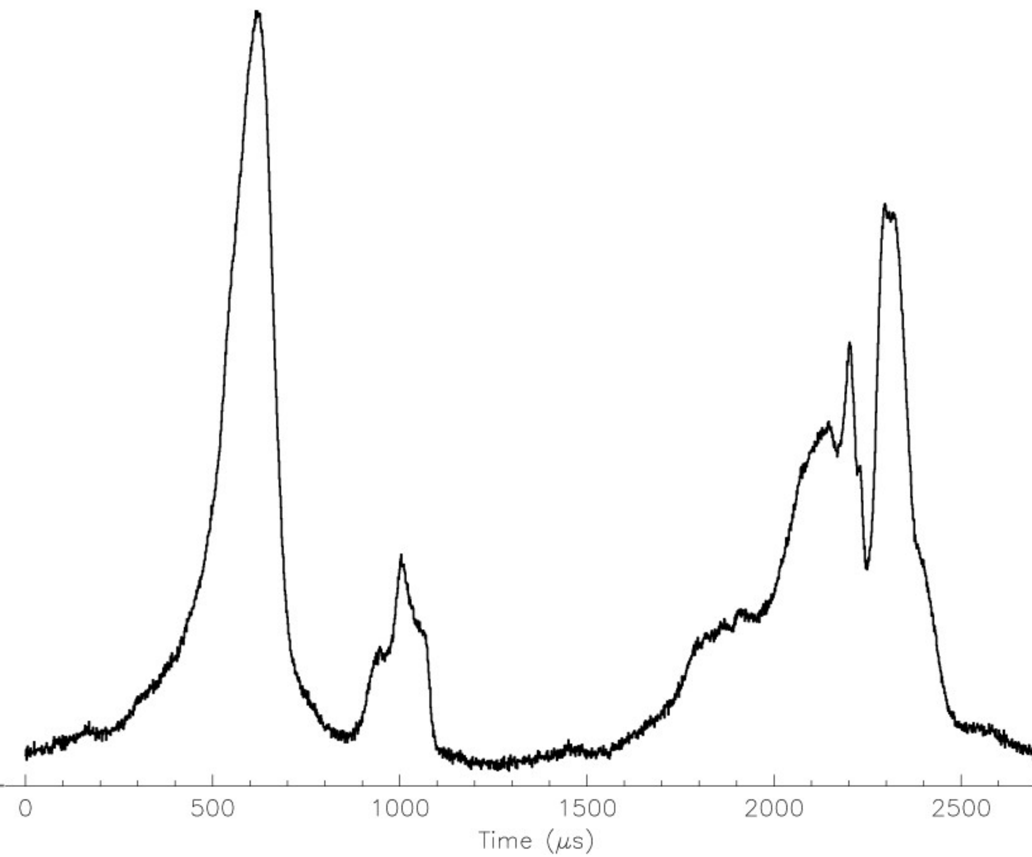
I. Cognard
L. Guillemot
G. Desvignes
G. Theureau



And here is PSR J0337+1715...



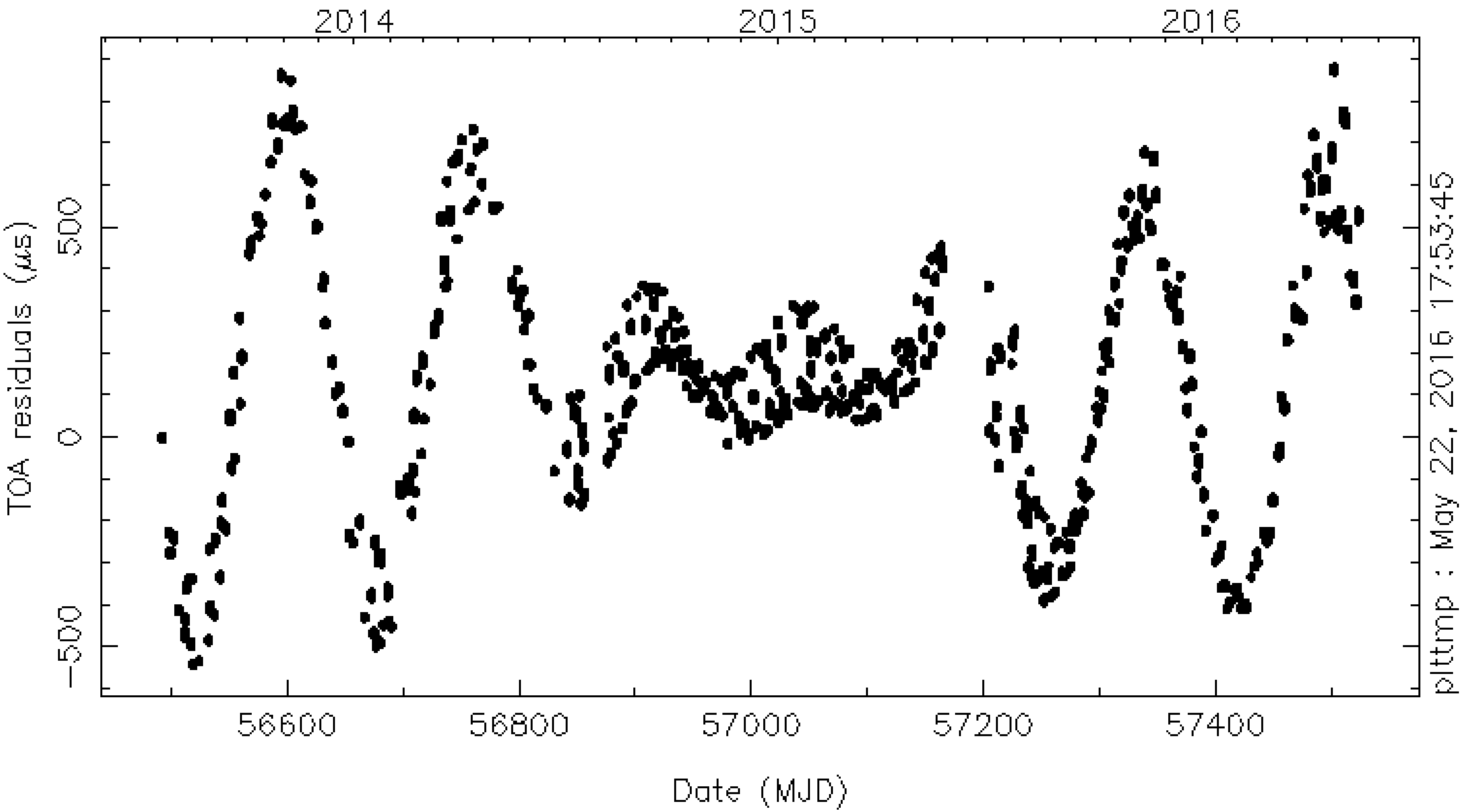
''Good'' single pulse, October 4th 2014



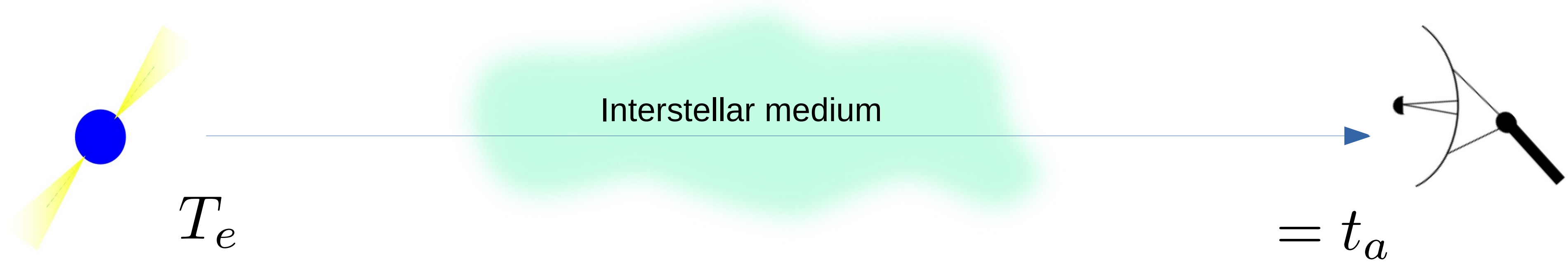
Template pulse profile
(450h of observation, 1230-1742MHz)

Voisin+ 2020

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



Need for a dedicated timing model



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

Interstellar propagation delays:
- Dispersion measure

Solar system delays:
- 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

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

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

Emission time in the pulsar frame

Arrival time in observer's frame

Delays

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:

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

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

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

(Damour and Taylor 1992; Will 1993)

Additional constraints other experiments

Other deviations from GR at 1PN order:

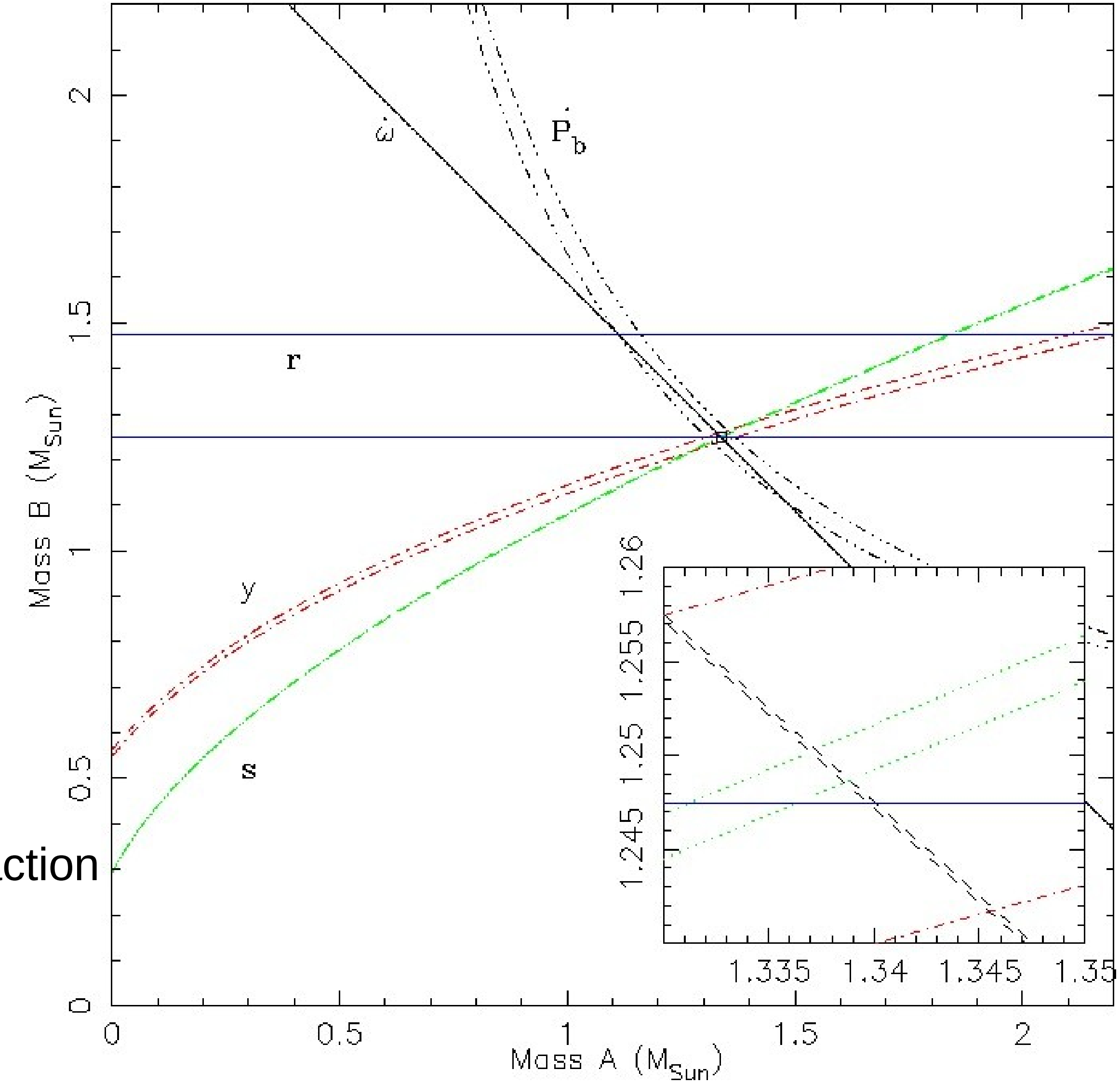
$$\begin{aligned}\mathscr{L} &= \sum_{a=1}^{n}\left(-m_a c^2 + m_a\frac{v_a^2}{2} + m_a\frac{v_a^4}{8c^2}\right)\\ &+\frac{1}{2}\sum_{a=1}^{n}\sum_{b\neq a}^{n}\left\{\frac{G_{ab}m_a m_b}{r_{ab}}\left[1-\frac{(\boldsymbol{v}_a\cdot\boldsymbol{n}_{ab})(\boldsymbol{v}_b\cdot\boldsymbol{n}_{ab})}{2c^2}\right.\right.\\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

(Damour and Taylor 1992; Will 1993)

We assume:

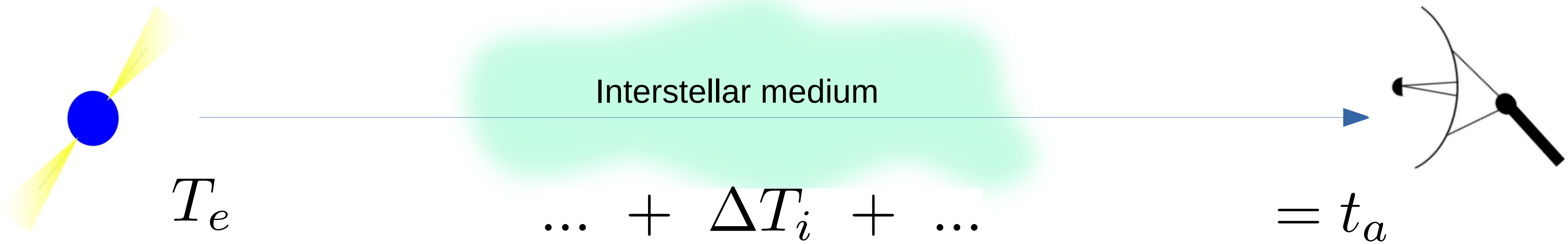
$$\bar{\beta}^c_{ab} = \bar{\gamma}_{ab} = 0 = \mathrm{GR}$$

From Solar System tests (e.g. LLR) :
→ No deviation of GR for WD-WD interaction



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

In summary, Nutimo does...



$$T_e \quad \ldots + \Delta T_i + \ldots = t_a$$

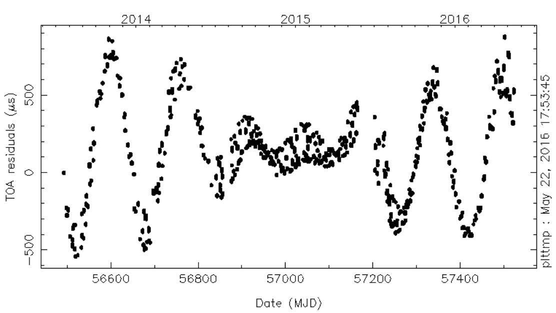
- **Solve motion numerically** at 1PN to meter accuracy
- **Calculate delays**: geometric, relativistic and propagation
- **Invert timing formula** to obtain times of arrival t_a from spin phase N

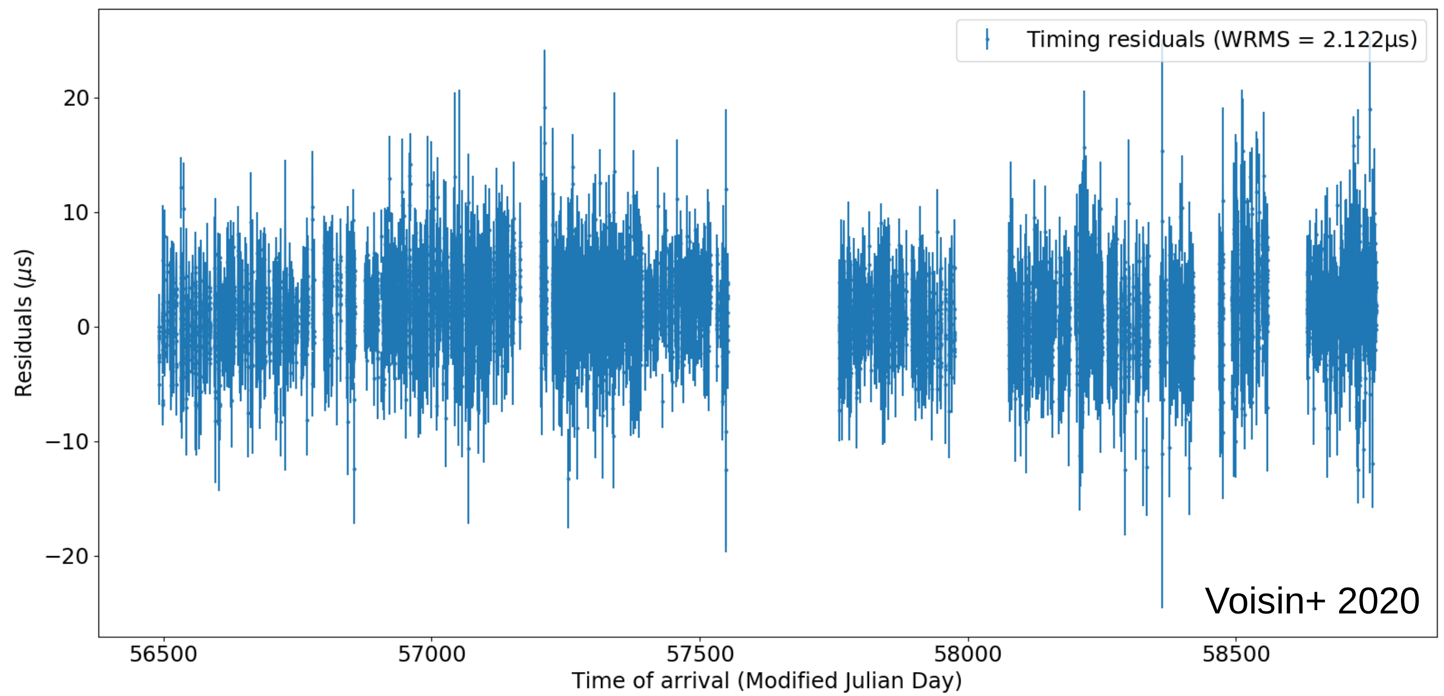
Let's fit the model to the data !

More easily said than done:

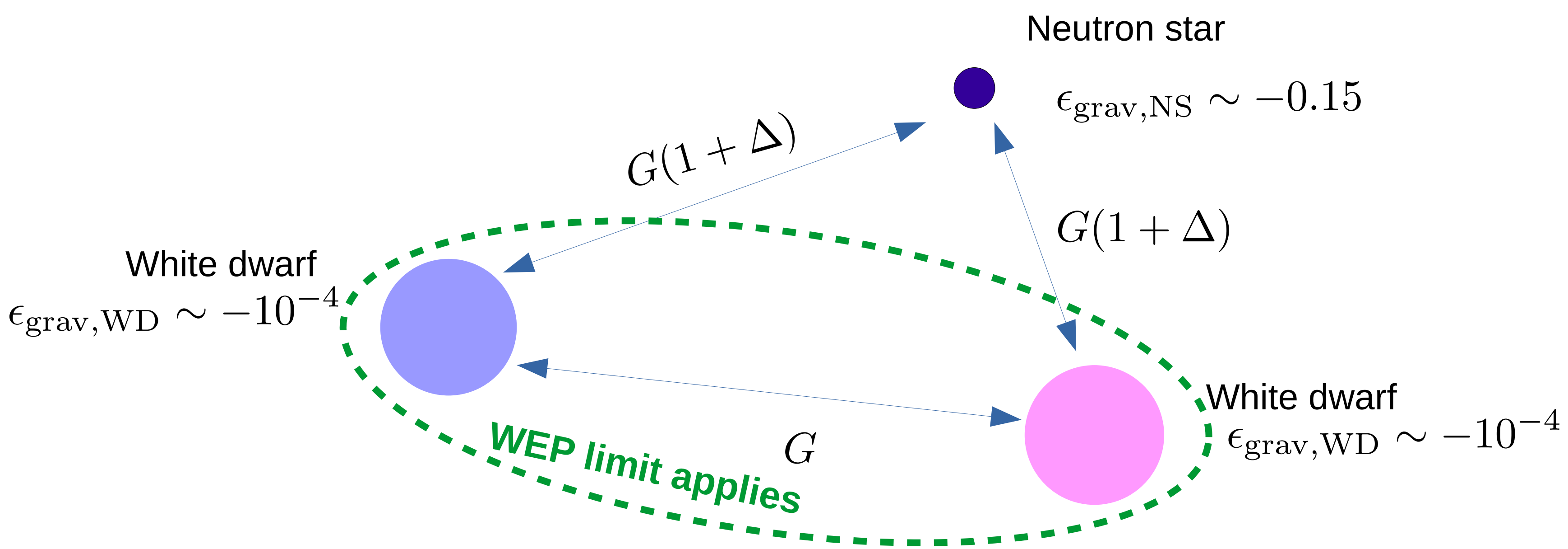
- 27 model parameters :
  - 2 pulsar spin
  - 2x6 orbital
  - 6 astrometric
  - 2 radio propagation (DM)
  - 1 SEP violation parameter
- 10 sec to calculate a single model
- Need reliable posterior distribution function on each parameter → **MCMC**

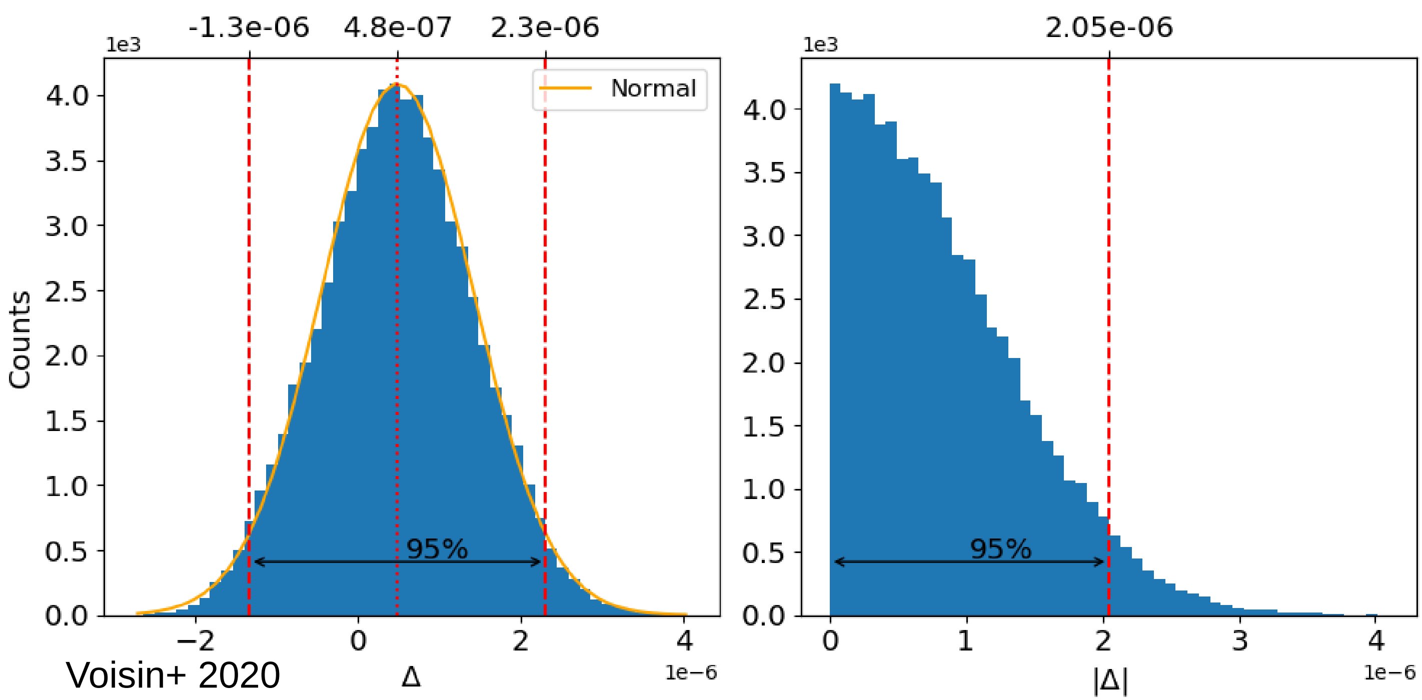
100,000 CPU hours on MESOPSL cluster





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 <u>systematic</u>

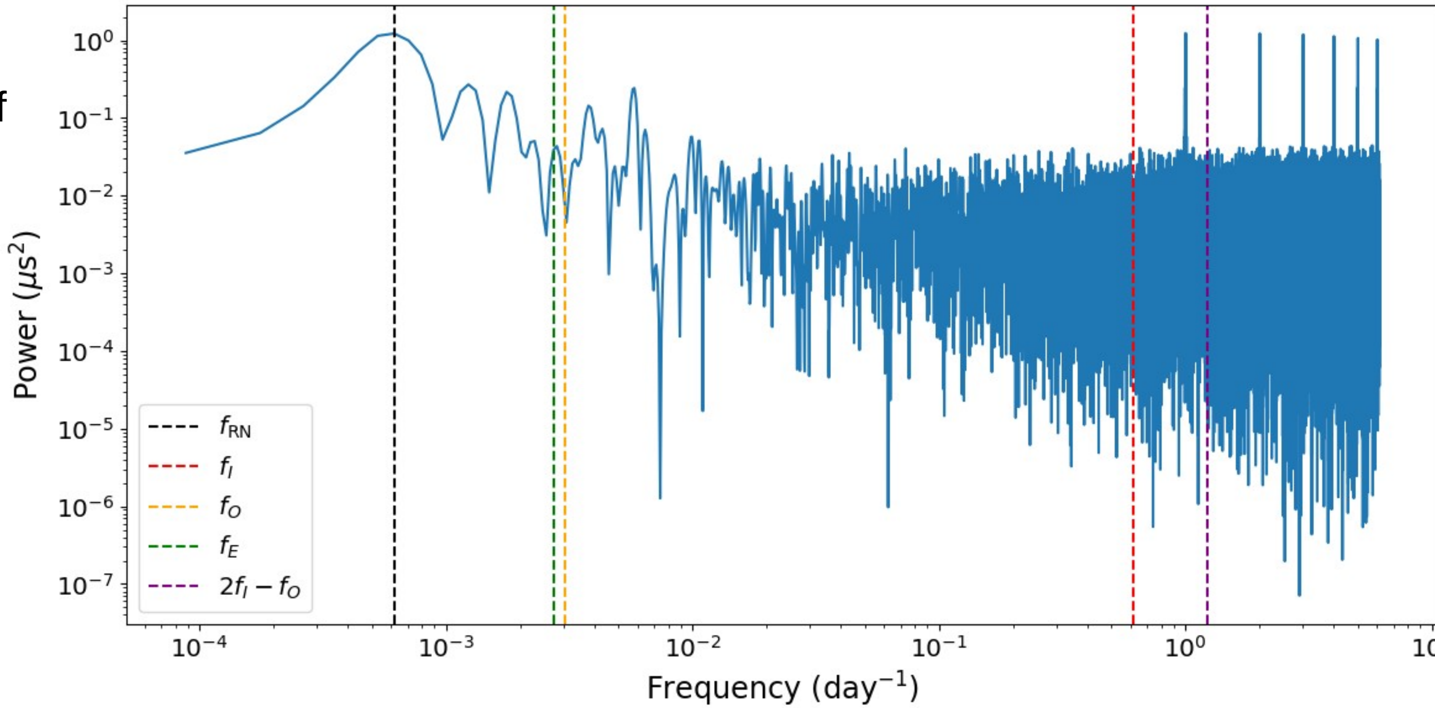
→ Voisin+ 2020: $|\Delta| < 2.05 \times 10^{-6}$ (95% confidence)

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

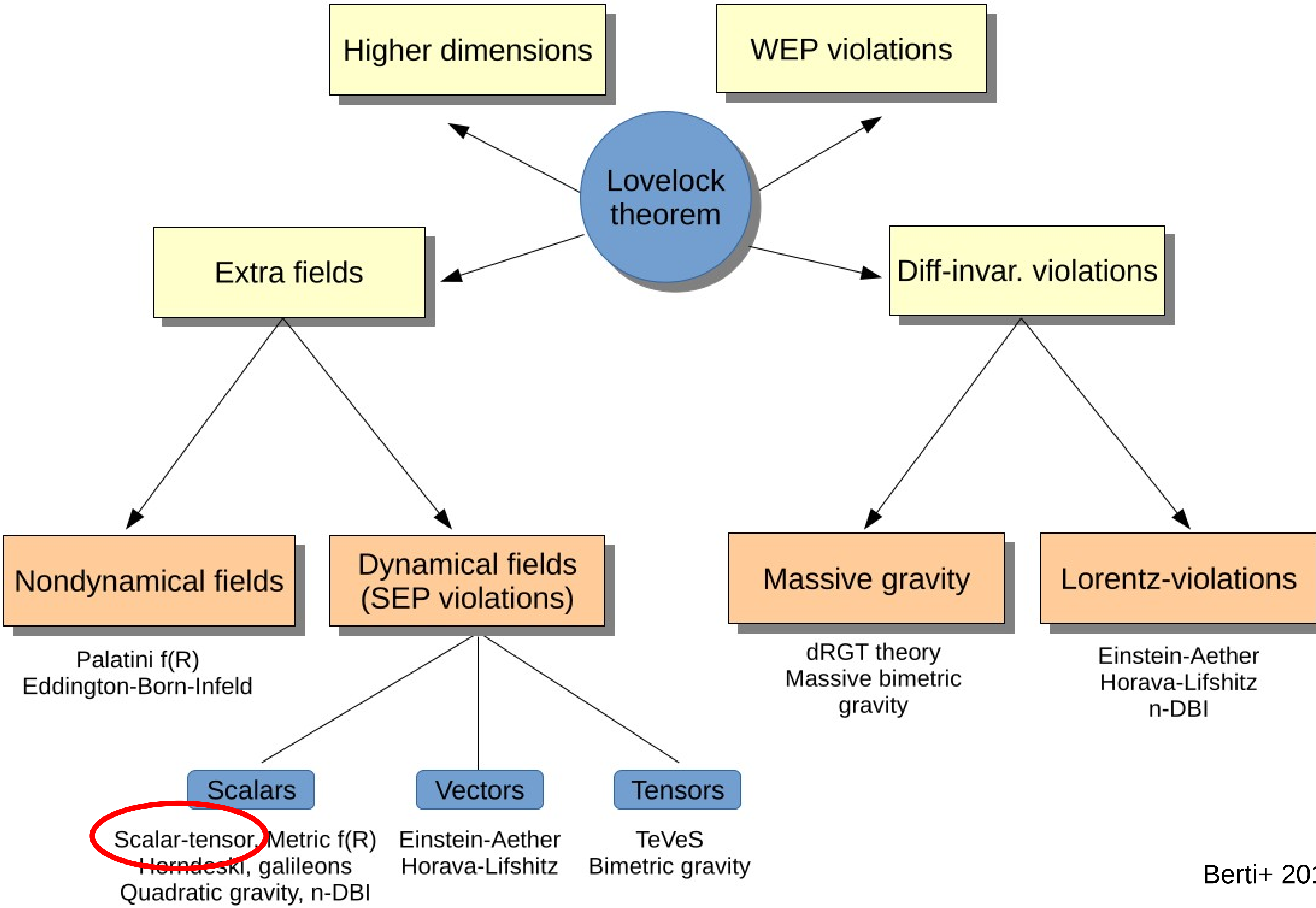
Uncertainty <u>statistical+systematic</u>

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

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

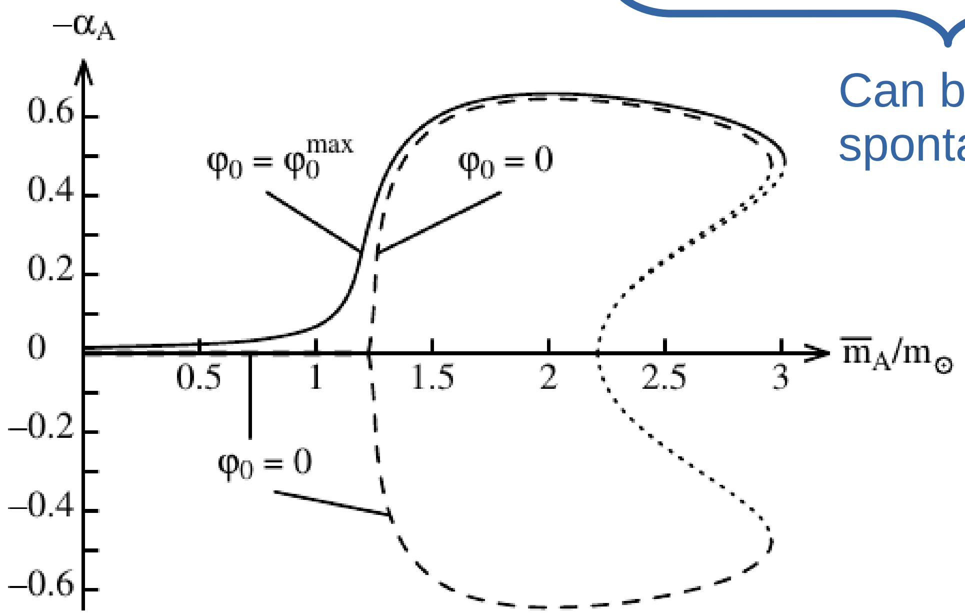
Coupling function

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

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

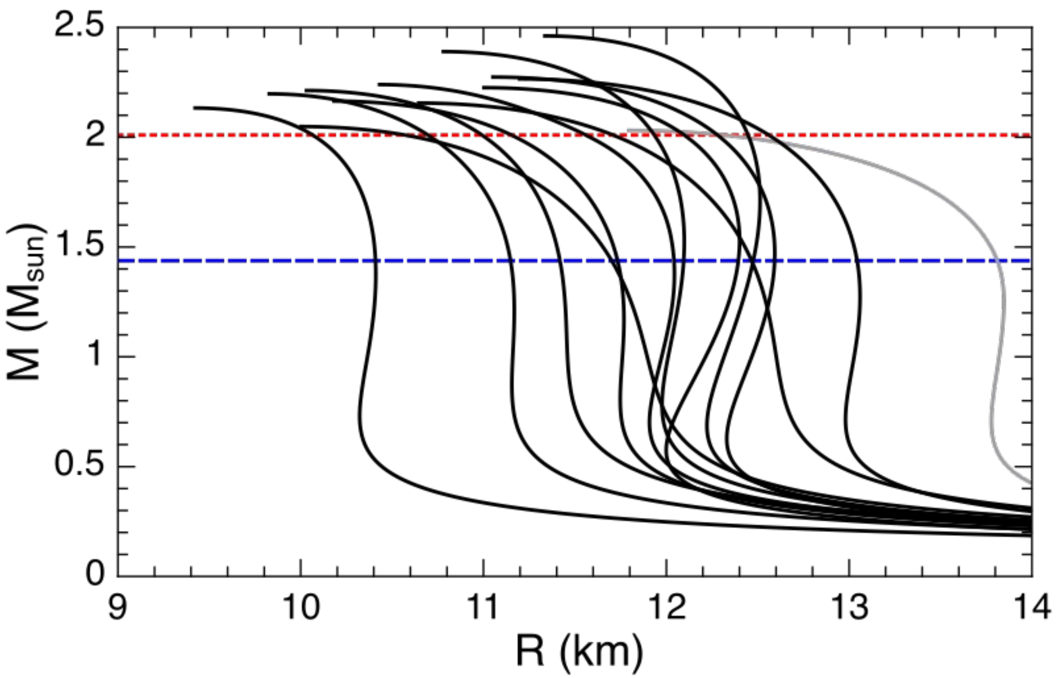
Damour-Esposito-Farèse theory

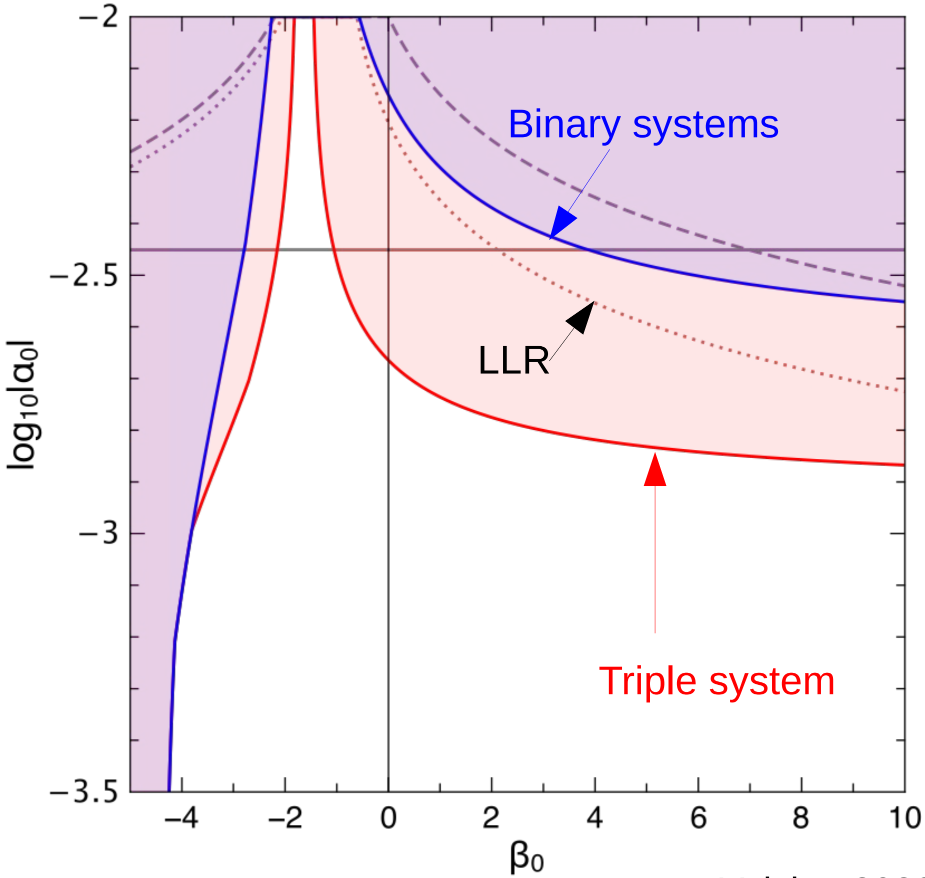
$$\omega(\phi) = \frac{1}{2}\left(\frac{1}{\alpha_0^2 - \beta_0 \ln\phi} - 3\right)$$

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

NS Sensitivity: s_p

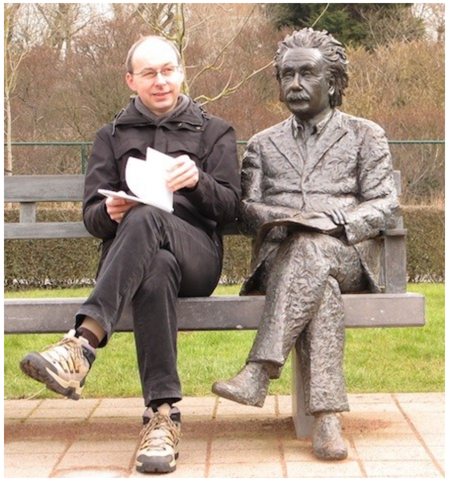
depends on the equation of state





Voisin+ 2020

N. Wex



Conclusions

- Pulsars provide an excellent test-bed for test of gravity with compact objects

- The triple system around PSR J0337+1715 is a unique opportunity to test SEP violations at Newtonian order:

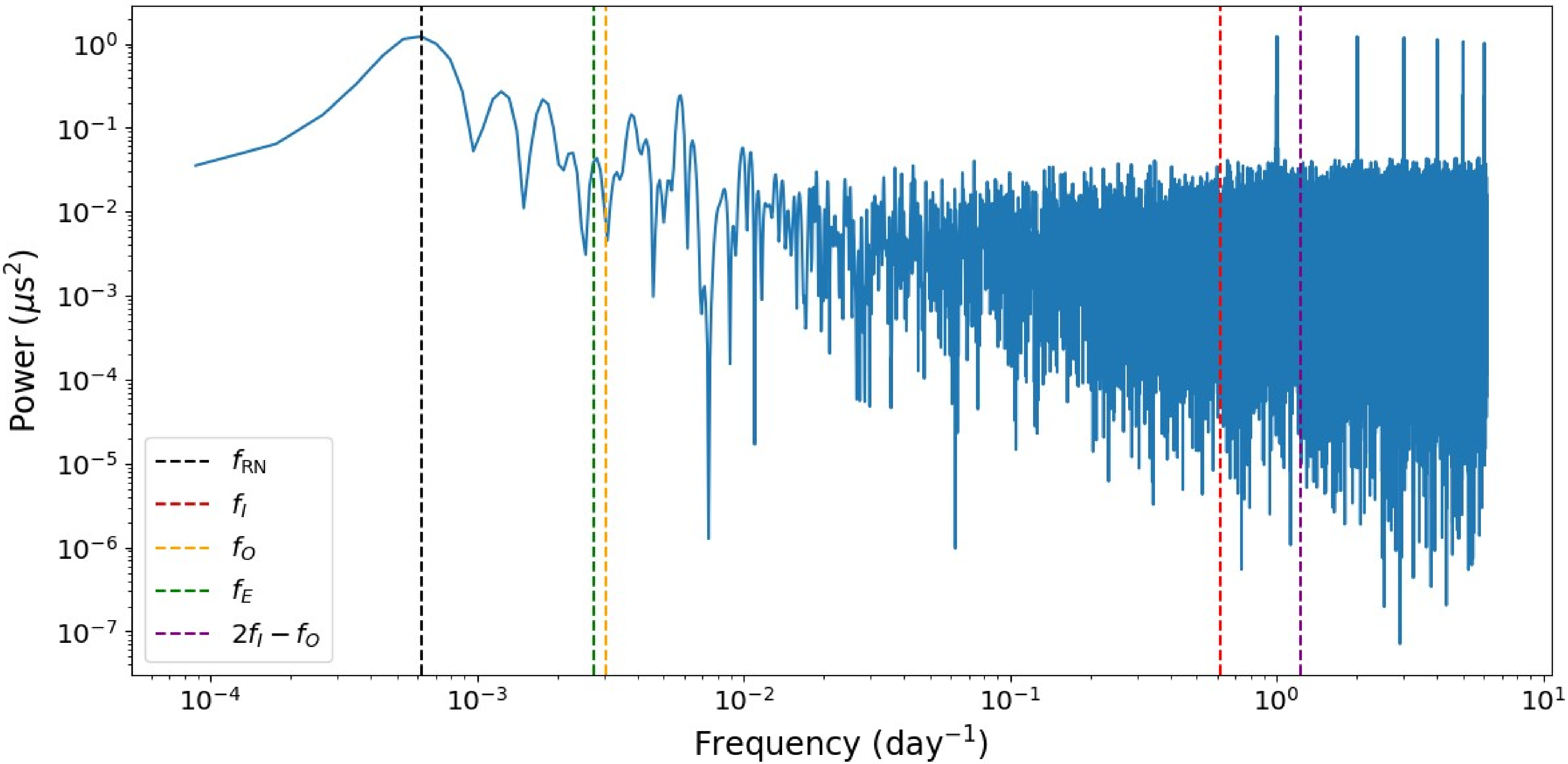
$$|\Delta| < 2.05 \times 10^{-6}$$

- Coming soon: hints of a small planet in a hierarchical orbit around the triple system !

Back-up slides

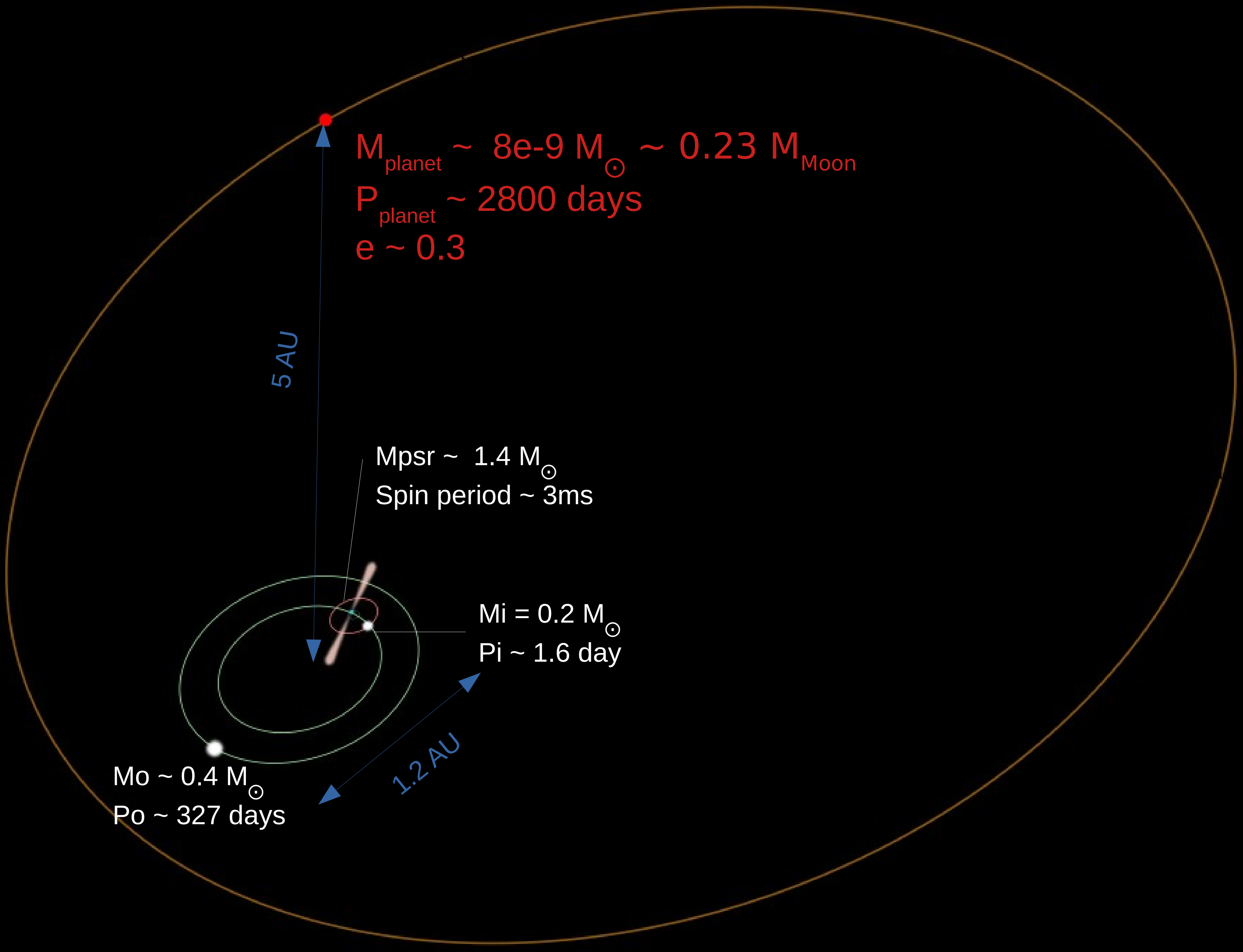
Is that all ?
Some preliminary results

Periodogram: a bump ?



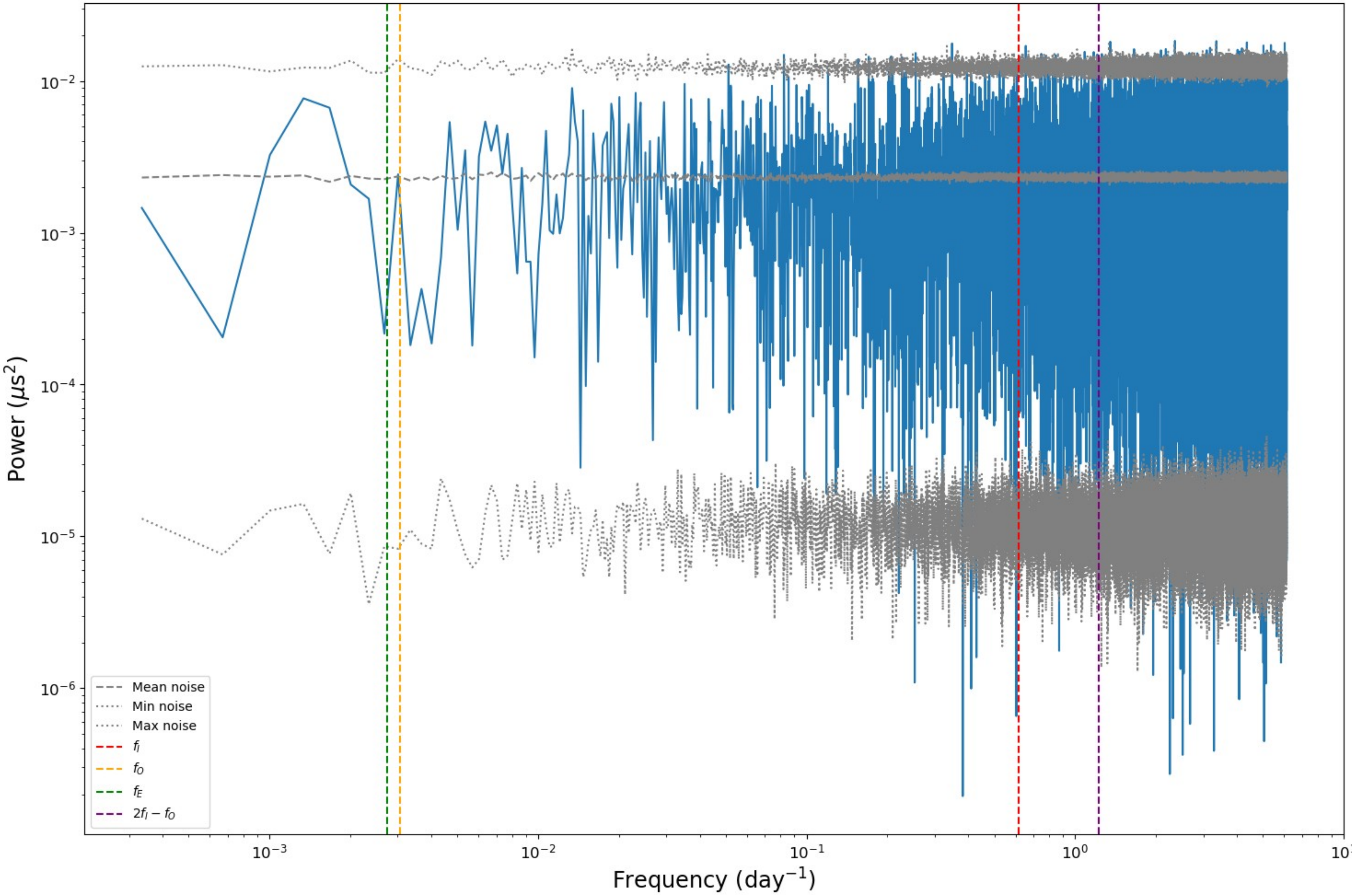
Preliminary!

Could this be a planet ?



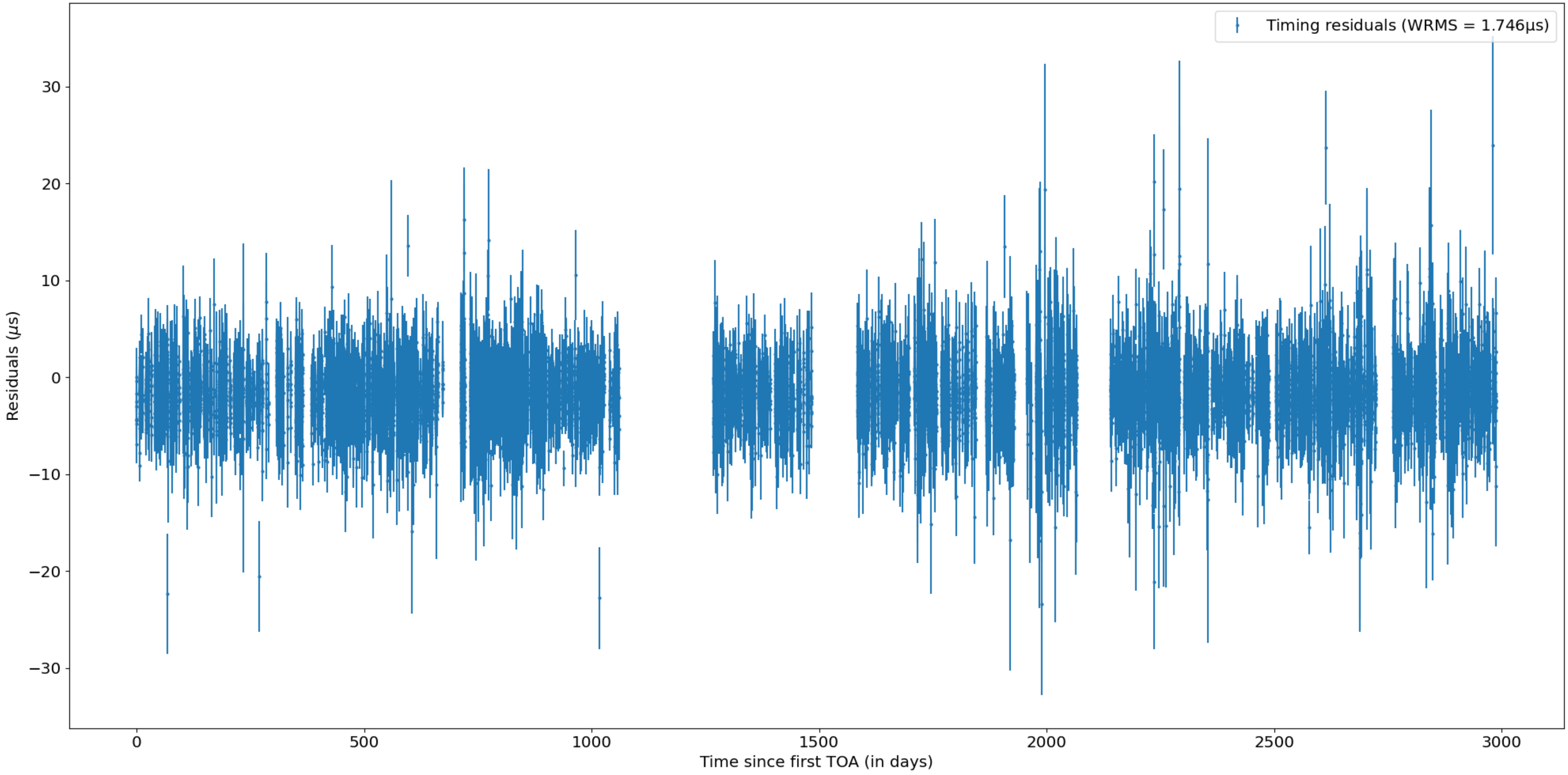
Preliminary!

Almost only white noise left !



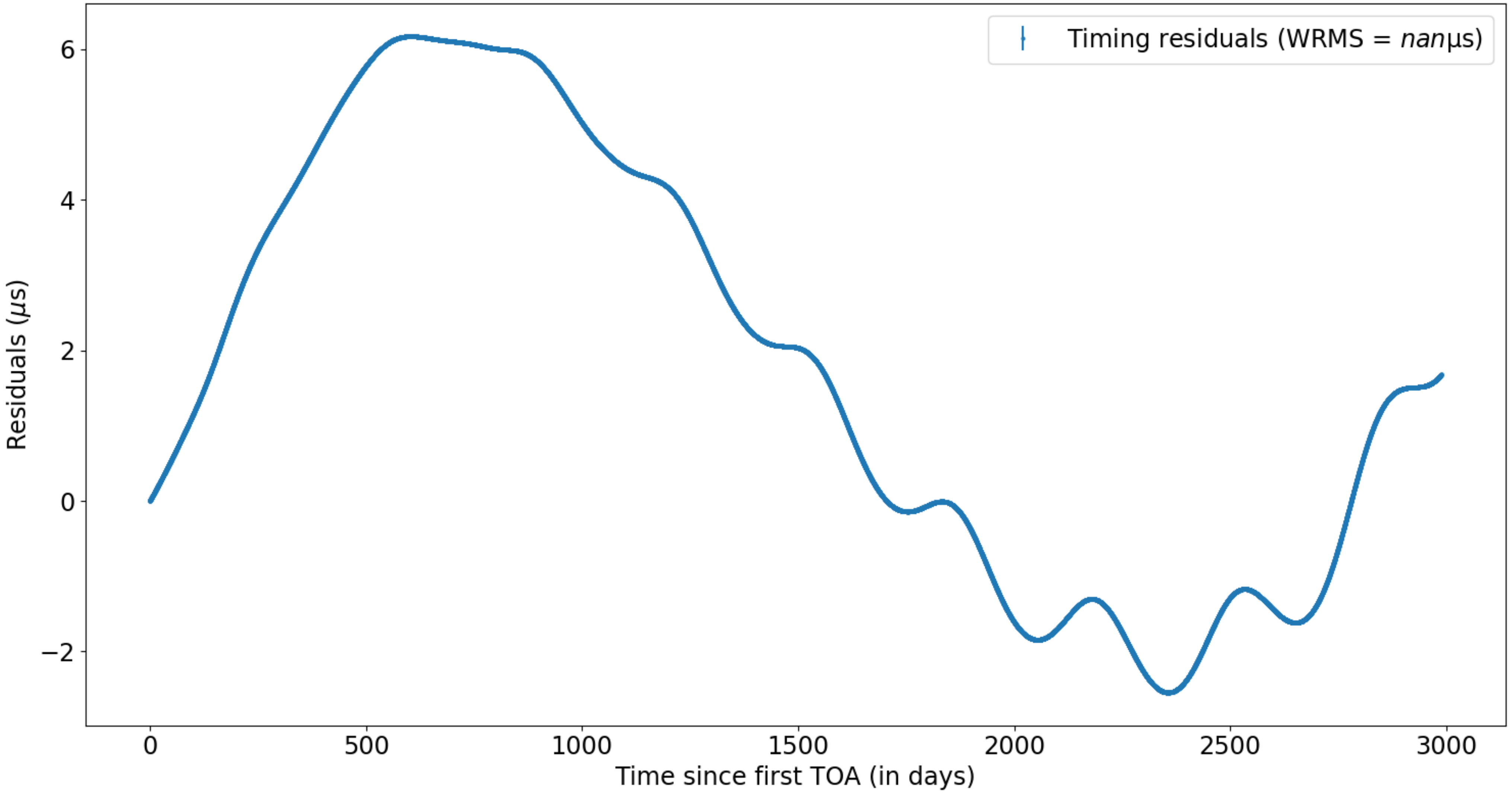
Preliminary!

Statistical error improves by 25%



Preliminary!

The signal due to the planet is not trivial



Preliminary!

Is this real ?

Great statistical significance

- Akaike and Bayesian information criterion ~ 2000

Alternative hypothesis:

- interstellar medium propagation : should be chromatic
- clock drifting
- **intrinsic pulsar "red noise" → possible but extreme**

Internal consistency:

- Stability of the orbit: not chaotic due to strong hierarchy
- Formation/origin of the planet : appears possible

Conclusions on tests of Gravity

- Pulsars are the ideal compact objects for testing gravity
- The triple system around PSR J0337+1715 is unique with its 2 white dwarf companions
- This allows for the best test of SEP in the strong field regime:

$$|\Delta| < 2.05 \times 10^{-6}$$ (95% confidence)

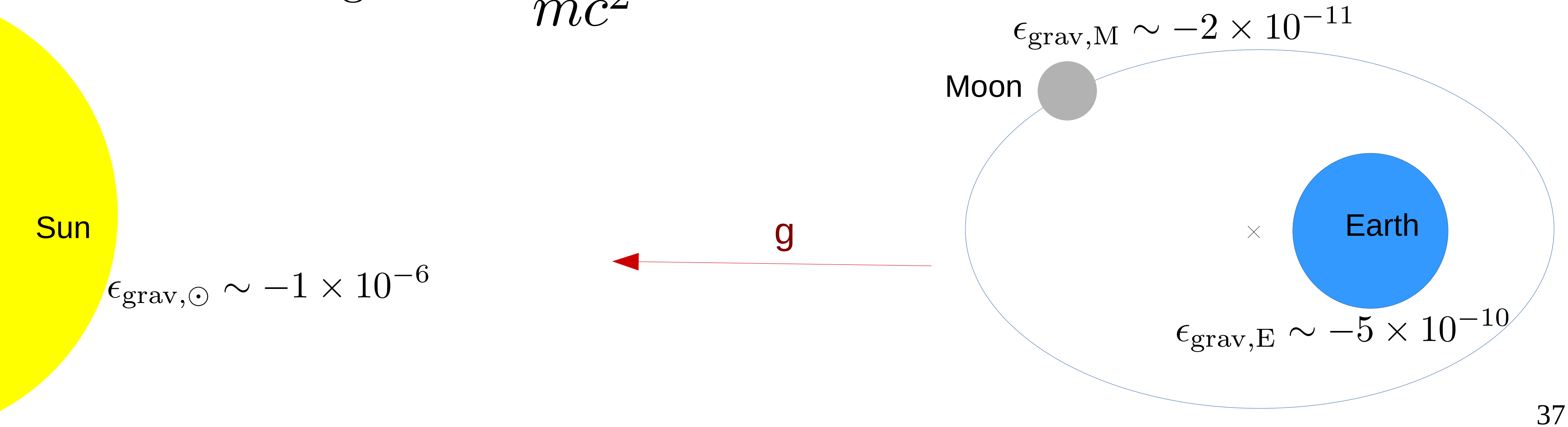
- Hints of a small distant planet making this system even more unusual (preliminary).

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)**

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



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:

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