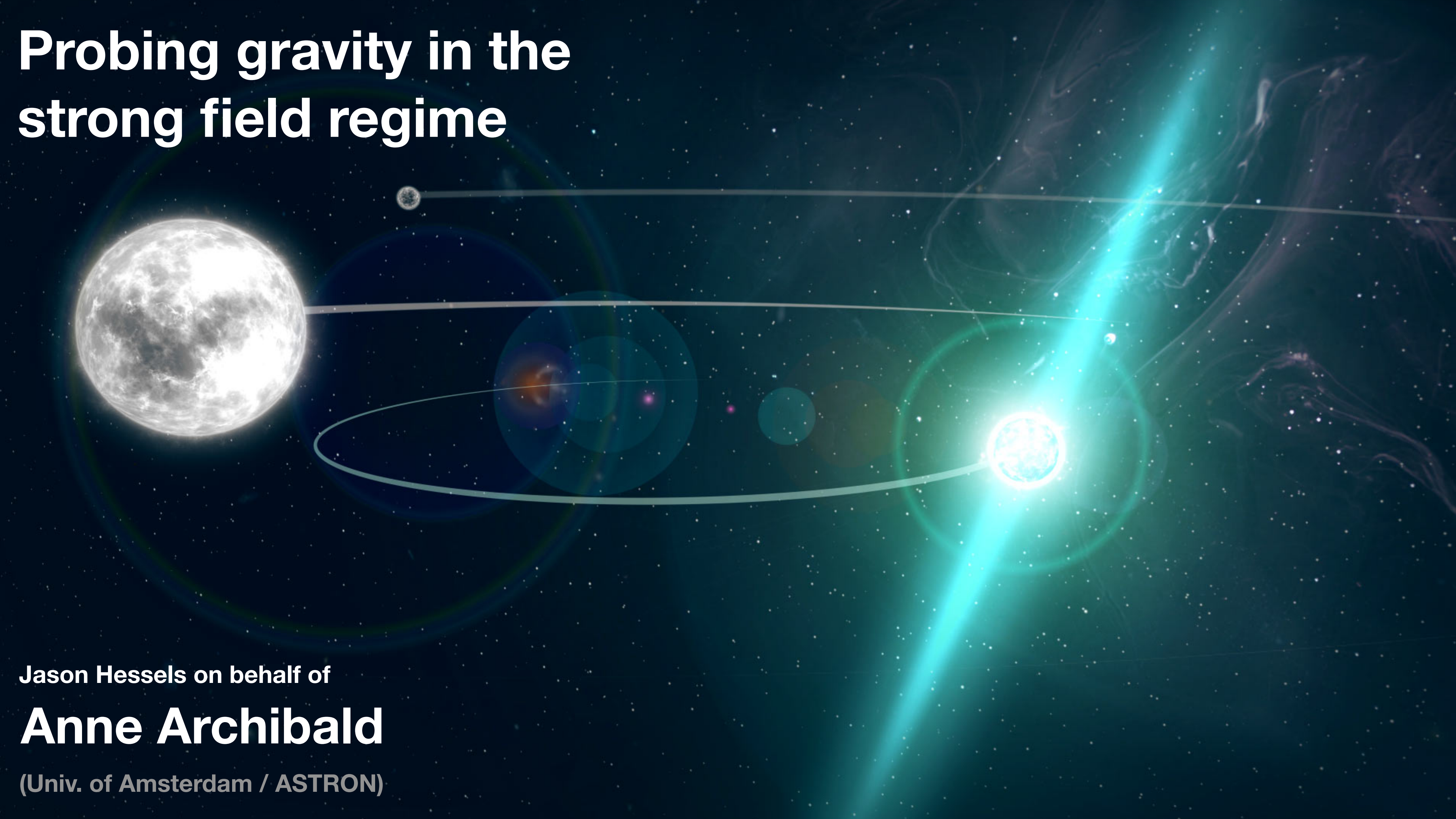
Probing gravity in the strong field regime



Jason Hessels on behalf of

Anne Archibald

(Univ. of Amsterdam / ASTRON)

LETTER

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Universality of free fall from the orbital motion of a pulsar in a stellar triple system

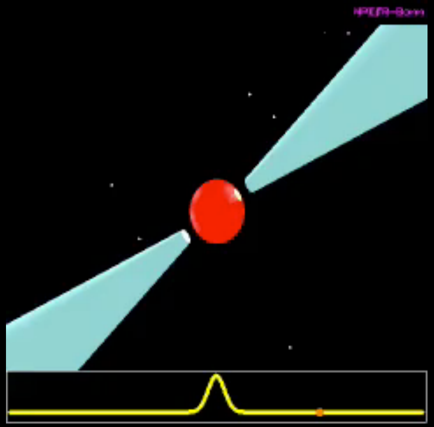
Anne M. Archibald[1,2]*, Nina V. Gusinskaia[1], Jason W. T. Hessels[1,2], Adam T. Deller[3,4], David L. Kaplan[5], Duncan R. Lorimer[6,7], Ryan S. Lynch[7,8], Scott M. Ransom[9] & Ingrid H. Stairs[10]

Einstein's theory of gravity—the general theory of relativity[1]—is based on the universality of free fall, which specifies that all objects accelerate identically in an external gravitational field. In contrast to almost all alternative theories of gravity[2], the strong equivalence principle of general relativity requires universality of free fall to apply even to bodies with strong self-gravity. Direct tests of this principle using Solar System bodies[3,4] are limited by the weak self-gravity of the bodies, and tests using pulsar–white-dwarf binaries[5,6] have been limited by the weak gravitational pull of the Milky Way. PSR J0337+1715 is a hierarchical system of three stars (a stellar triple system) in which a binary consisting of a millisecond radio pulsar and a white dwarf in a 1.6-day orbit is itself in a 327-day orbit

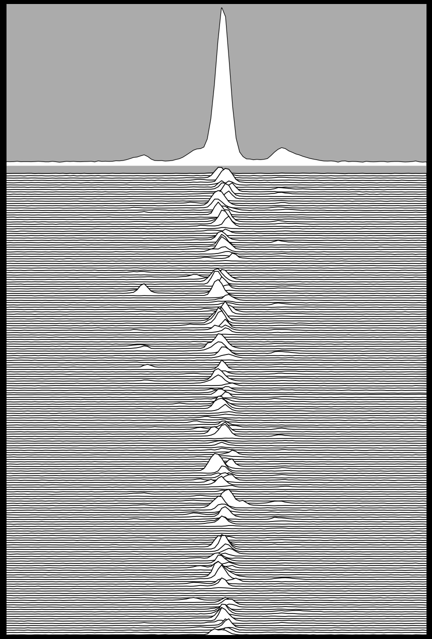
nonlinearity of gravity, and γ, which measures the degree to which gravity curves space-time. Both of these parameters take the value 1 in general relativity. We chose a point-particle Lagrangian that permits arbitrarily strong gravity internal to the bodies and parameterized post-Newtonian interactions between them[10]. We then used computer algebra[11] to construct equations of motion. Each orbit was specified by an initial system configuration at modified Julian date (MJD) 55,920.0 (2011 December 25 00:00:00 UTC). The evolution of this configuration was governed by β, γ and the strong equivalence principle (SEP)-violation parameter Δ. Because the self-gravity of the pulsar (which is a neutron star) exceeds that of the white dwarfs by a factor 10^4 and the SEP violation that we seek arises from self-gravity, we neglect possi-

“Pulsar Timing”

Using pulsars as precision clocks



Receive and record pulses



Stack pulses to get high S/N

54255.1231254524233
54255.2643443523453
54255.3123524545899
54255.3513745623467
54255.4418456543355
54255.5001234234688

Measure the pulse arrival times

Pulsar Timing Model

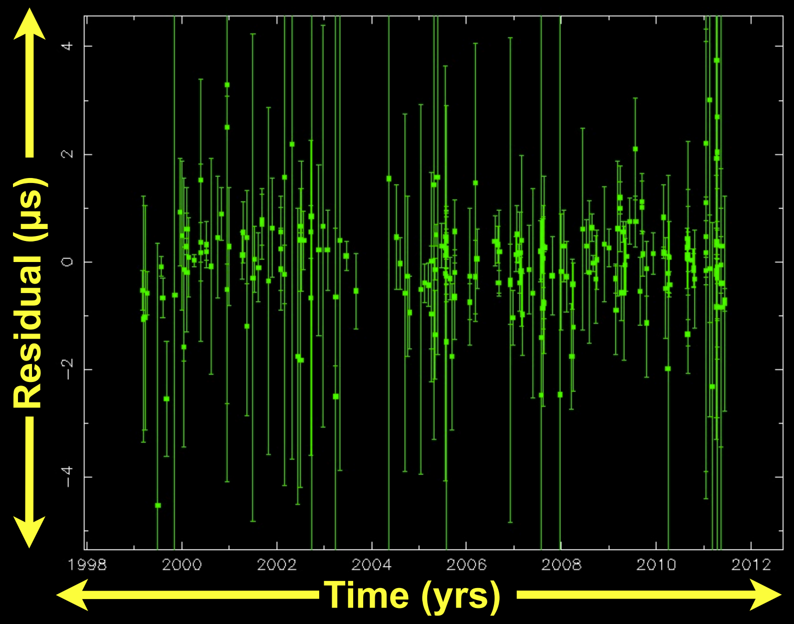
Input to PTAs

Basic Method:

Actual Pulse TOA

— Theoretical Model

= Timing Residual



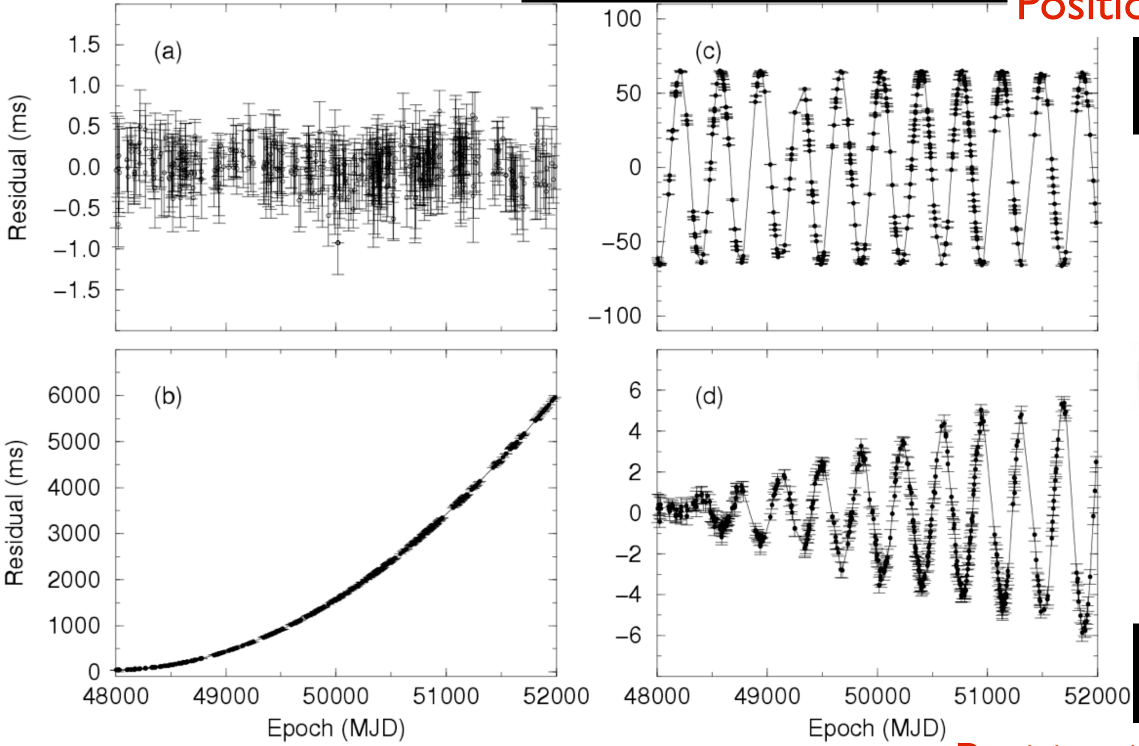
Courtesy Andrew Jameson (Swinburne)

$$T_{\mathrm{th}} = \nu t + \frac{1}{2}\dot{\nu}t^2 + D\frac{\int_0^d n_e dl}{f^2} - \frac{1}{c}(\vec{r}\cdot\hat{s}) + \frac{V_{\mathrm{T}}^2 t^2}{2cd} - \frac{(\vec{r}\times\hat{s})^2}{2cd} + \ldots$$

What does this teach us?

Model is complete!

Position is off



Pulsar is spinning down faster than in model

Position is changing

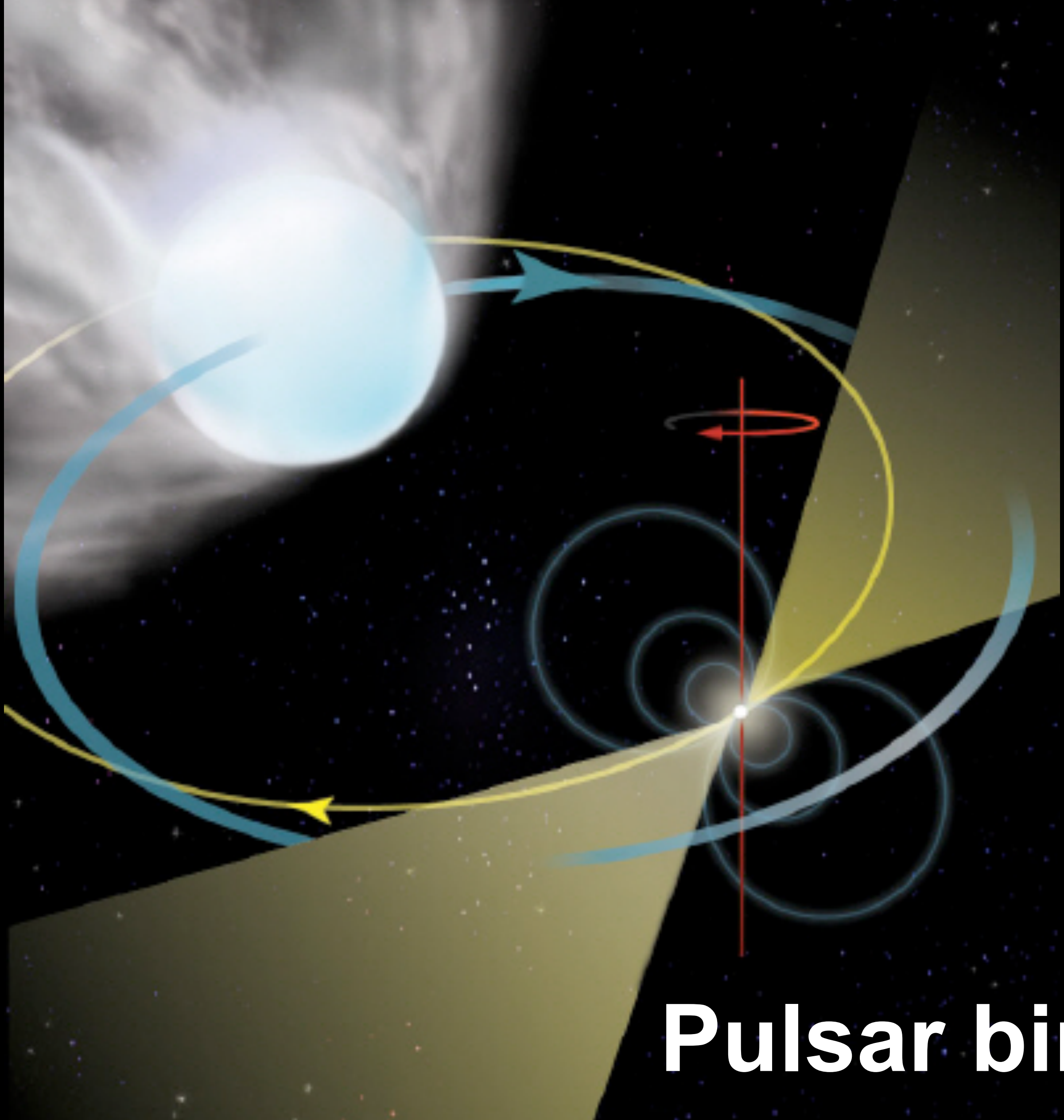
Count each pulse... for years.

PSR J1012+5307:

P = 0.005255749014115410

+/- 0.000000000000000015s

> 100 billion pulses in the last 15 years, and not a single one missed

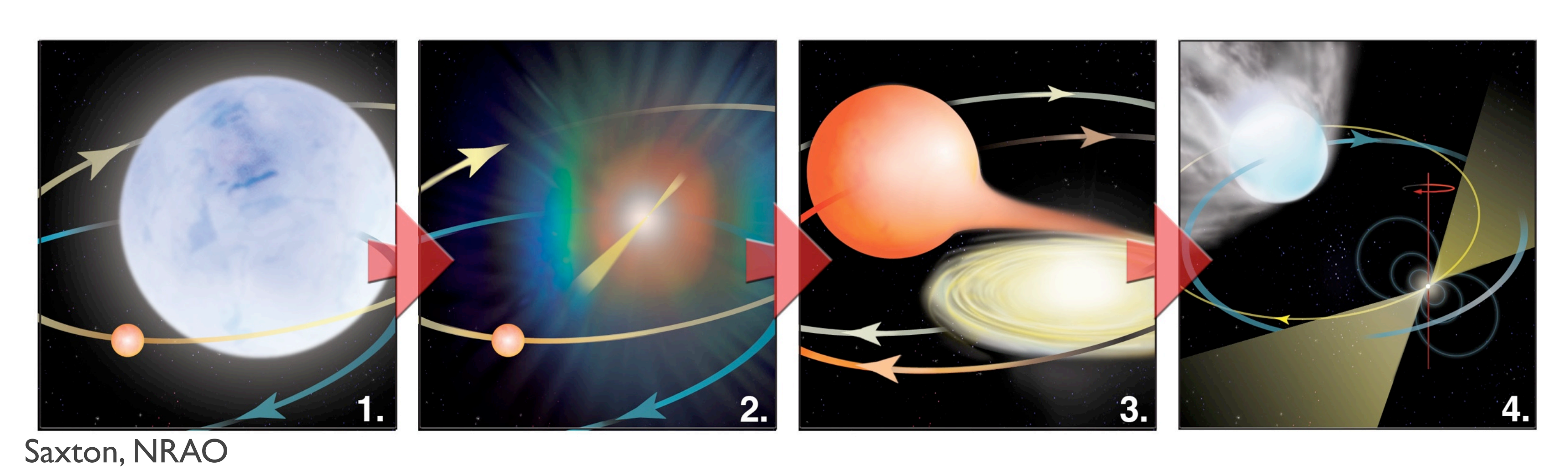


Pulsar binary

Pulsar Recycling

Alpar, Cheng, Ruderman & Shaham 1982

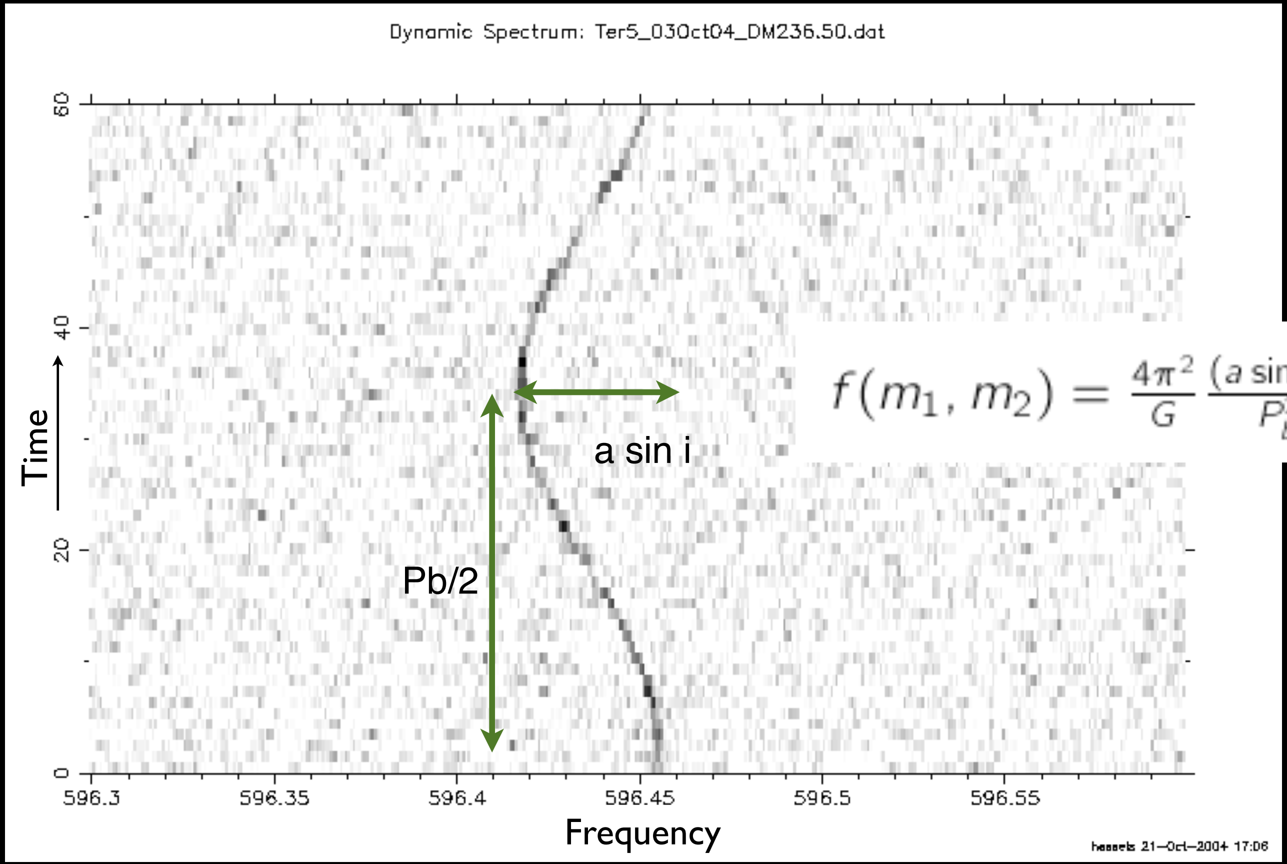
Rhadakrishnan & Srinivasan 1982



LMXB (some IMXB)   Radio (some also g-ray)

Millisecond pulsars are the products of astrophysical accretion

Keplerian Timing Effects



$$f(m_1, m_2) = \frac{4\pi^2}{G}\frac{(a \sin i)^3}{P_b^2} = \frac{(m_2 \sin i)^3}{(m_1+m_2)^2}$$

Can est. m2's min. mass

Need mass function + two other equations for m1, m2, and i

Post-Keplerian Effects

Periastron adv. $$\dot{\omega} = 3 \left(\frac{P_b}{2\pi}\right)^{-5/3} (T_\odot M)^{2/3} (1 - e^2)^{-1}$$

Grav. redshift $$\gamma = e \left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_2 (m_1 + 2m_2)$$

Orbital decay

$$\dot{P}_b = -\frac{192\pi}{5} \left(\frac{P_b}{2\pi}\right)^{-5/3} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) (1 - e^2)^{-7/2} T_\odot^{5/3} m_1 m_2 M^{-1/3}$$

Shapiro delay

$$r = T_\odot m_2$$ **"Range"**

$$s = x \left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_2^{-1} .$$ = sin i **"Shape"**

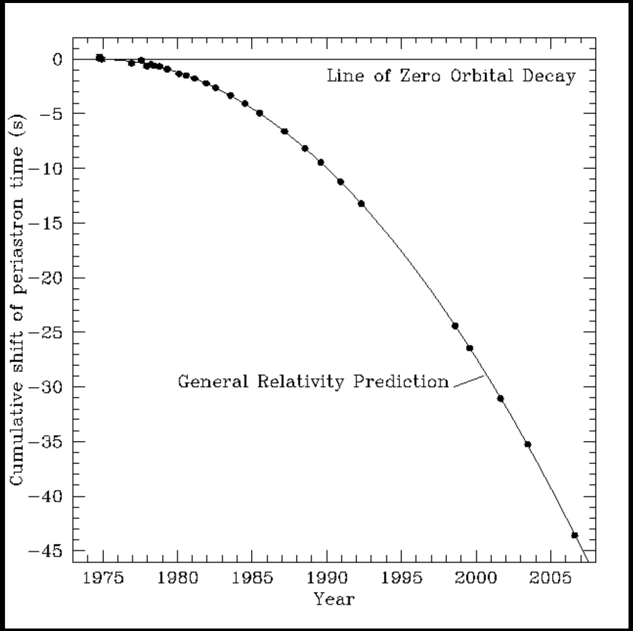
Depend on m1, m2, and the Keplerian parameters

Measure any 2 PK params and get m1, m2

Nobel Prize Physics 1993

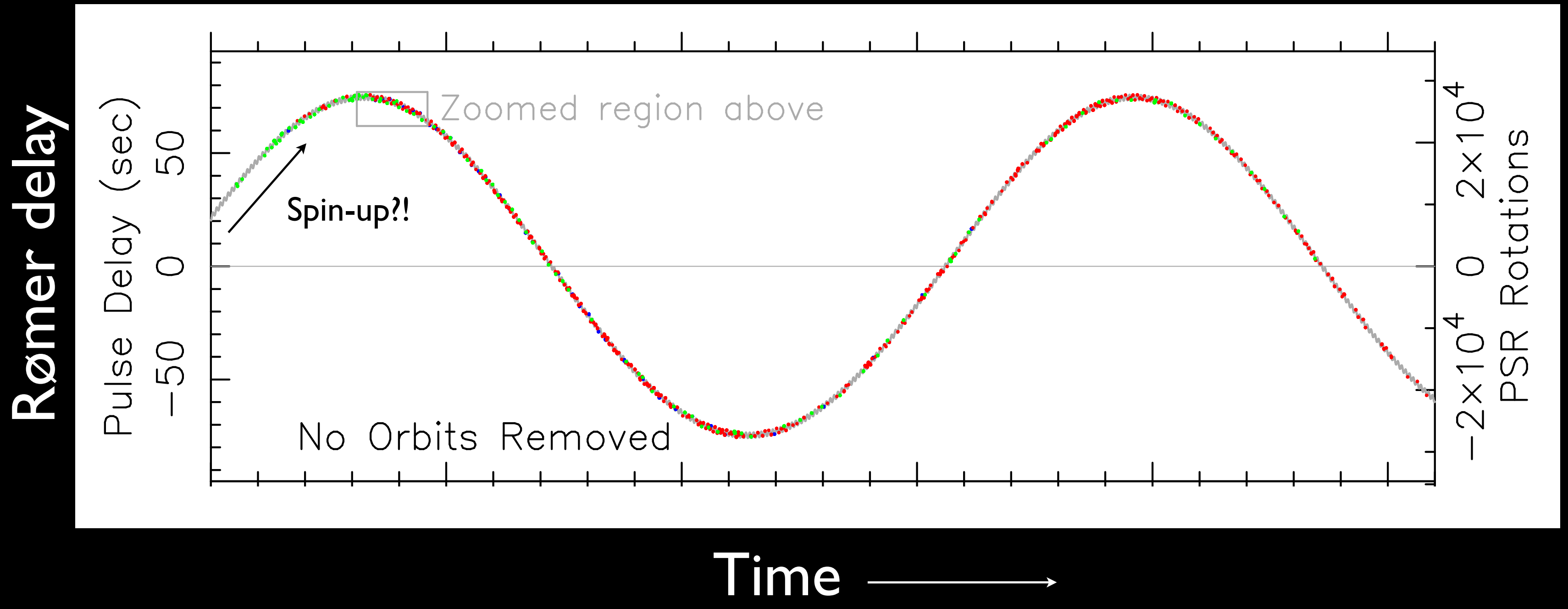
Russell Hulse & Joseph Taylor

"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"



Pulsar riddle

PSR J0337+1715



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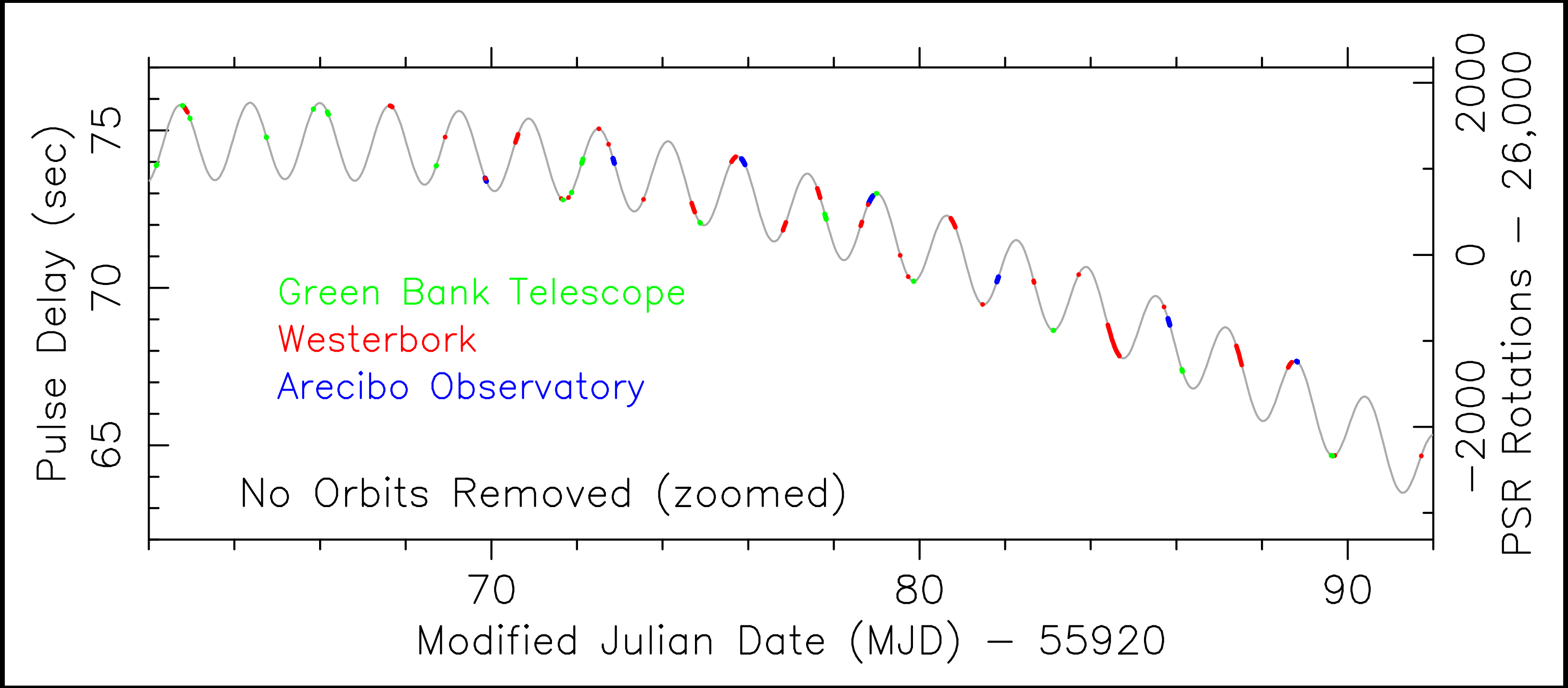
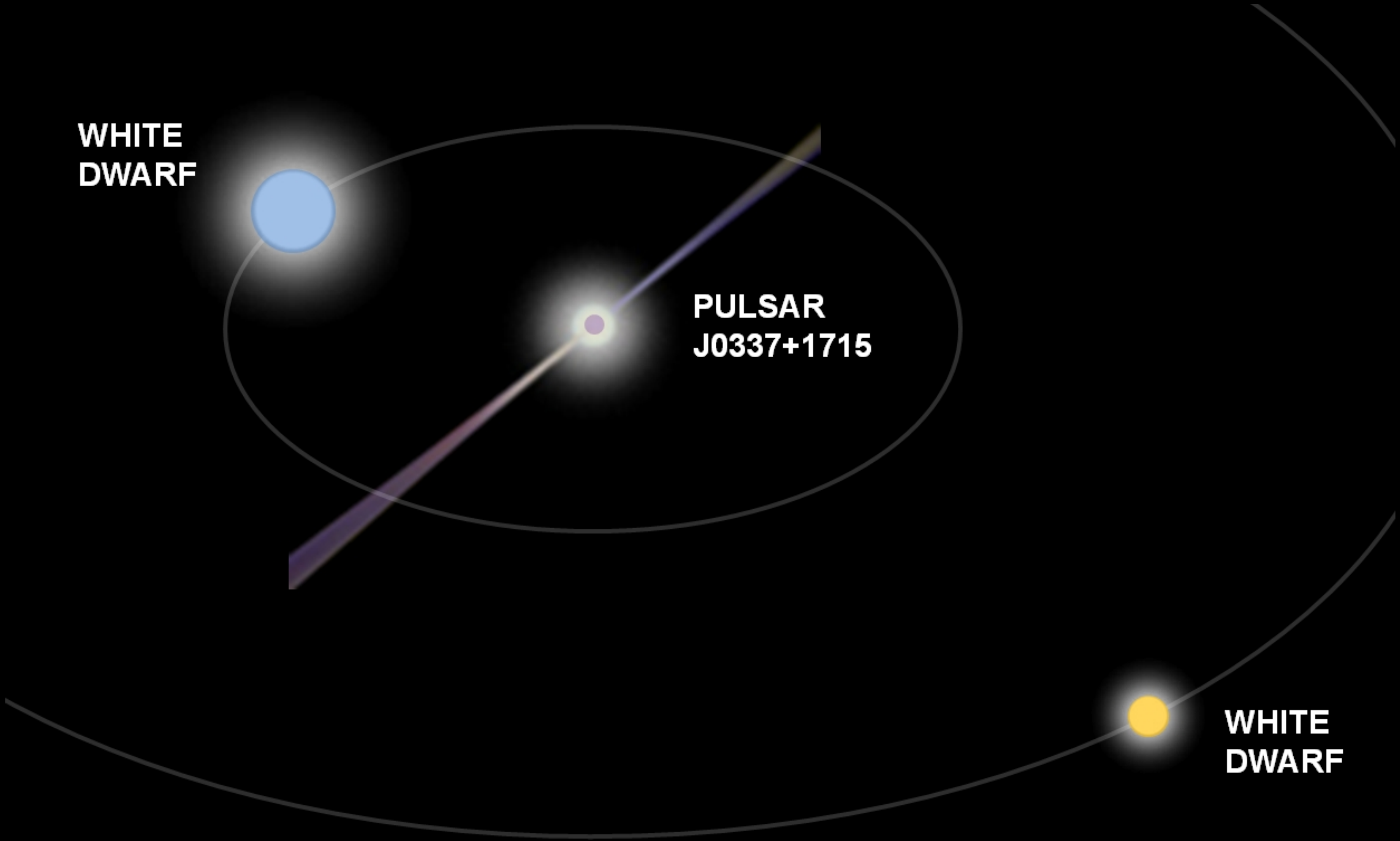



WHITE
DWARF
PULSAR
J0337+1715
WHITE
DWARF

PSR J0337+1715 Triple System

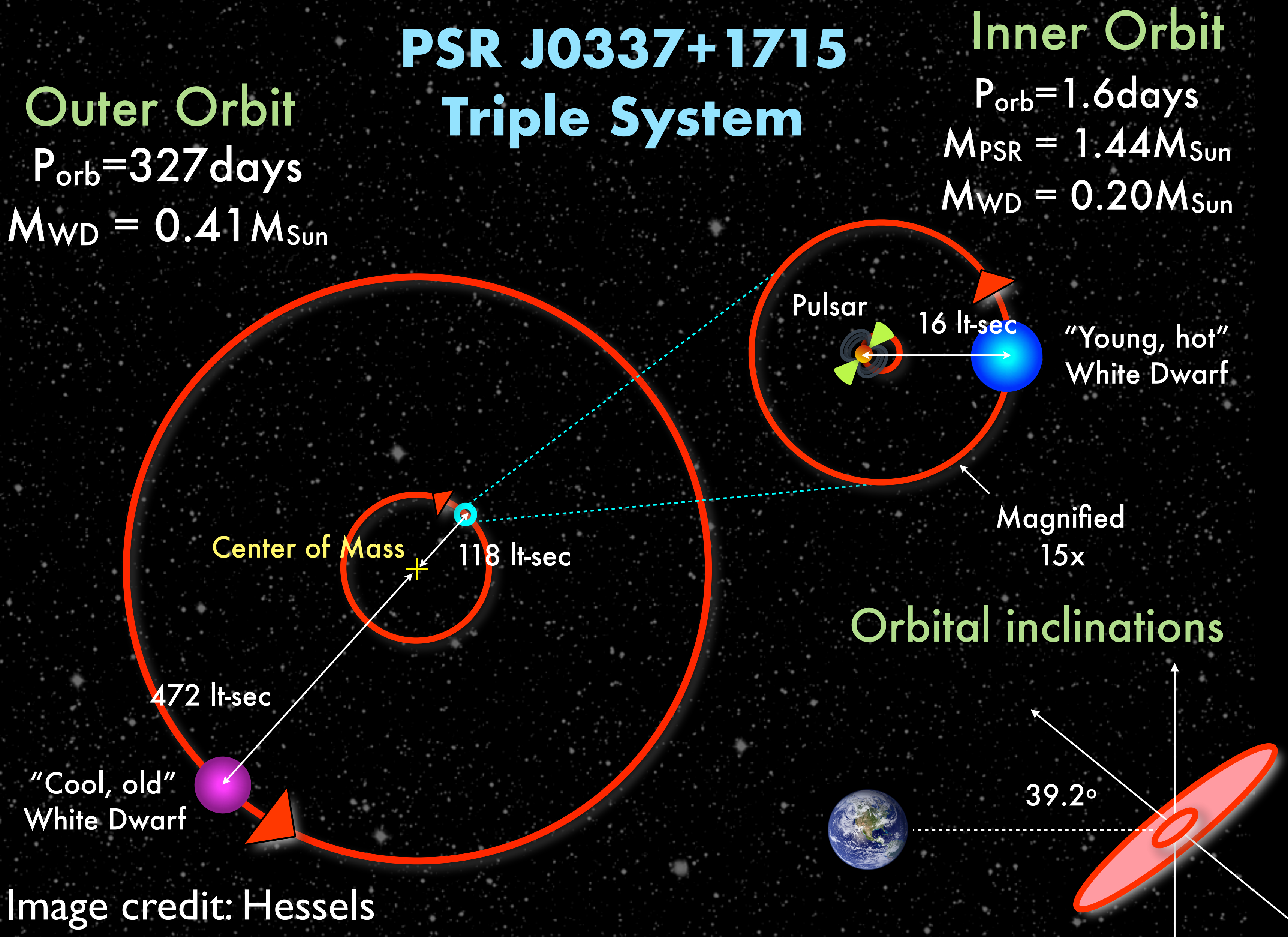
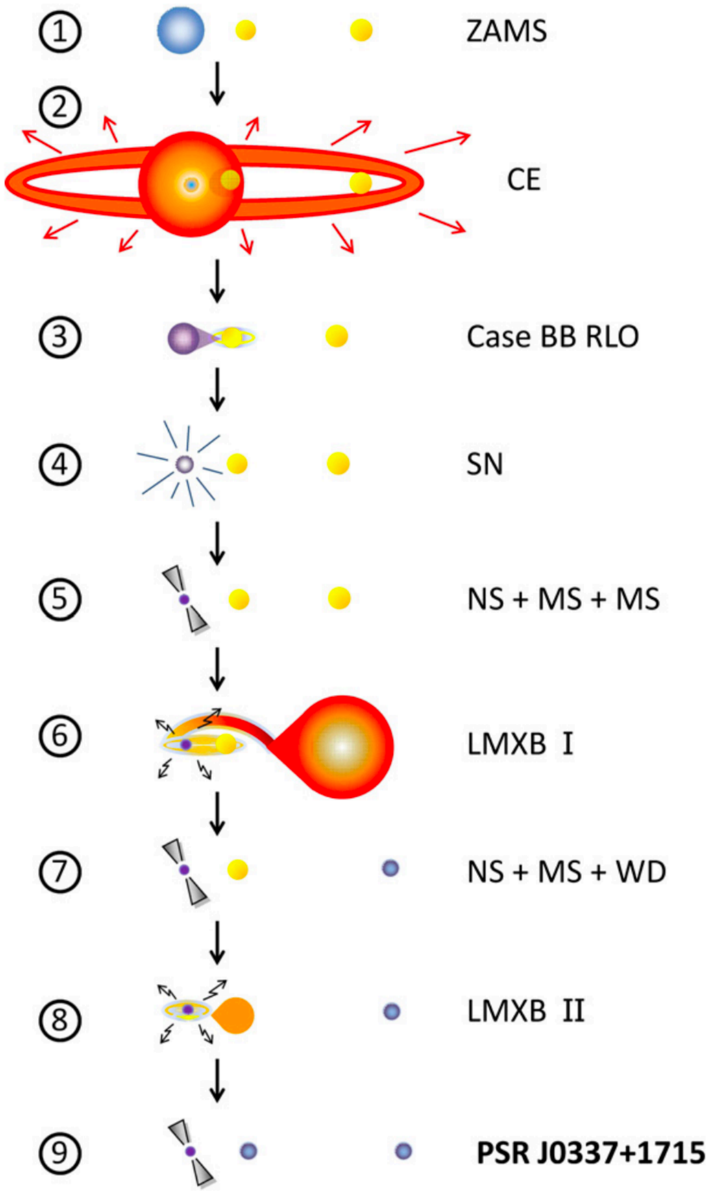


Image credit: Hessels

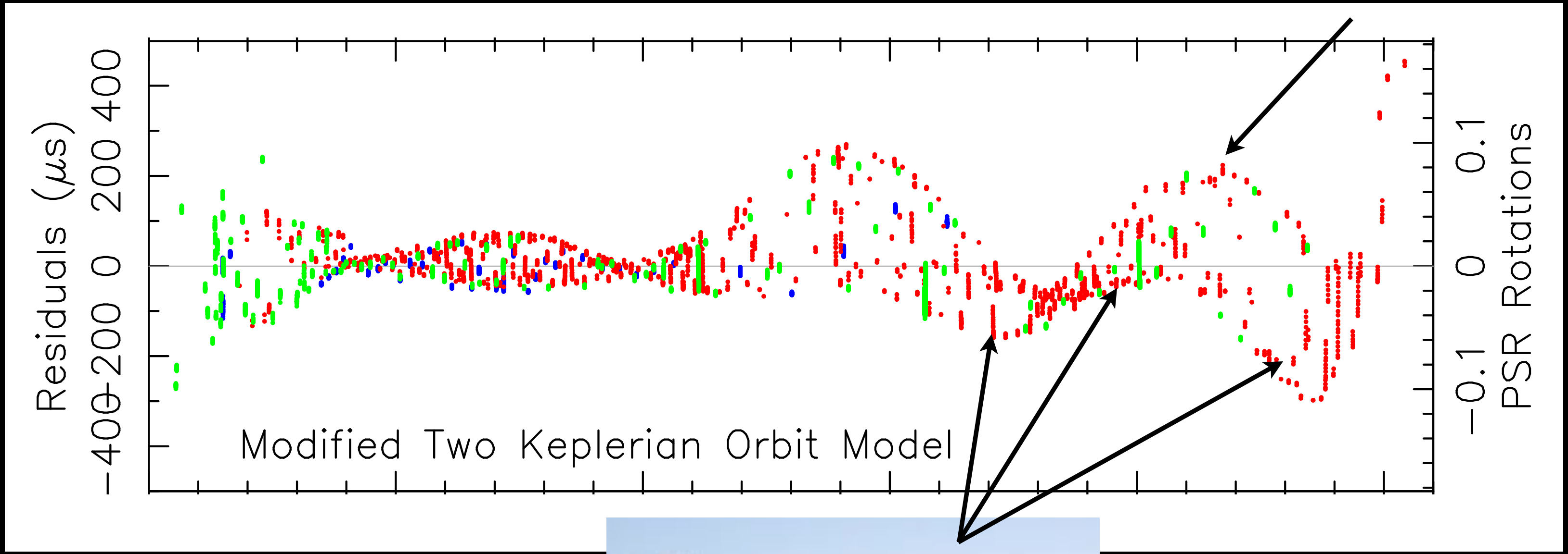


Tauris & van den Heuvel (2014)

Pulsar riddle

PSR J0337+1715

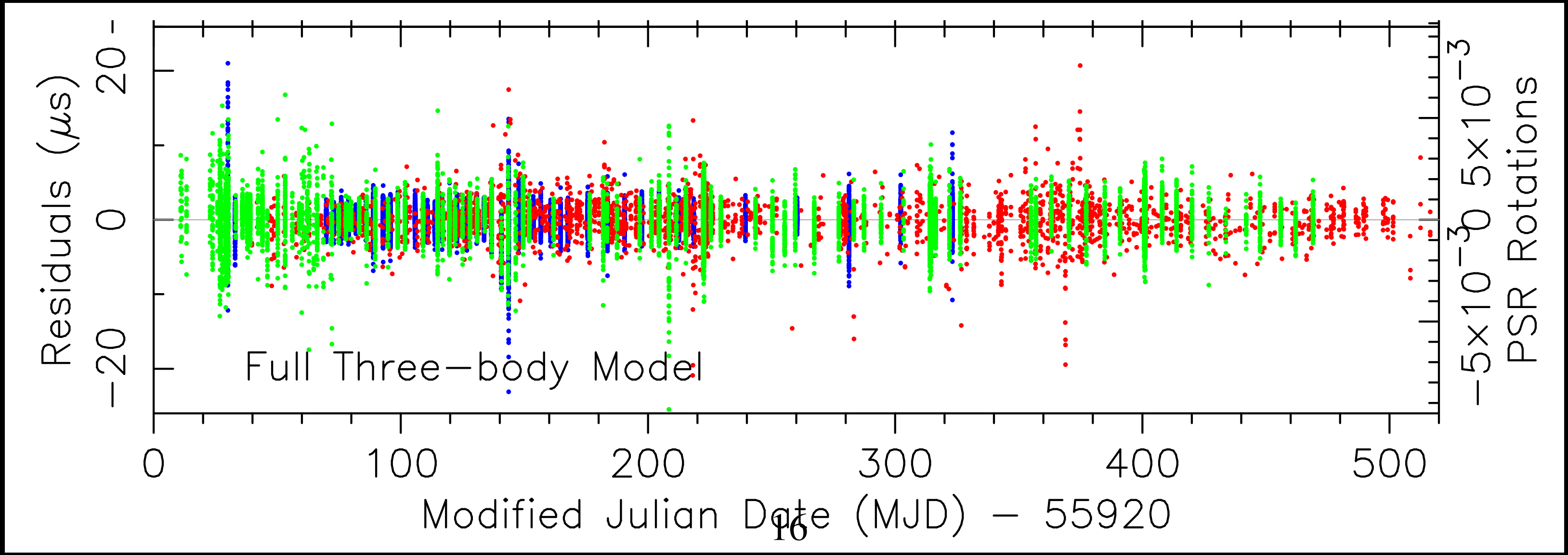
Dynamical interactions between the two nested binaries



Westerbork data

Pulsar riddle

PSR J0337+1715



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Work done by Anne Archibald, directly integrating the motions of the 3 bodies

J0337+1715 - Timing model

Parameter	Symbol	Value
Fixed values		
Right ascension	RA	$03^h37^m43^s.82589(13)$
Declination	Dec	$17°15'14''.828(2)$
Dispersion measure	DM	$21.3162(3)$ pc cm^{-3}
Solar system ephemeris		DE405
Reference epoch		MJD 55920.0
Observation span		MJD $55930.9 - 56436.5$
Number of TOAs		26280
Weighted root-mean-squared residual		$1.34\,\mu$s
Fitted parameters		
Spin-down parameters		
Pulsar spin frequency	f	$365.953363096(11)$ Hz
Spin frequency derivative	$\dot{f}$	$-2.3658(12) \times 10^{-15}$ Hz s^{-1}
Inner Keplerian parameters for pulsar orbit		
Semimajor axis projected along line of sight	$(a \sin i)_I$	$1.21752844(4)$ lt-s
Orbital period	$P_{b,I}$	$1.629401788(5)$ d
Eccentricity parameter ($e \sin \Omega$)	$\epsilon_{1,I}$	$6.8567(2) \times 10^{-4}$
Eccentricity parameter ($e \cos \Omega$)	$\epsilon_{2,I}$	$-9.171(2) \times 10^{-5}$
Time of ascending node	$t_{\mathrm{asc},I}$	MJD 55920.407717436(17)
Outer Keplerian parameters for centre of mass of inner binary		
Semimajor axis projected along line of sight	$(a \sin i)_O$	$74.6727101(8)$ lt-s
Orbital period	$P_{b,O}$	$327.257541(7)$ d
Eccentricity parameter ($e \sin \Omega$)	$\epsilon_{1,O}$	$3.5186279(3) \times 10^{-2}$
Eccentricity parameter ($e \cos \Omega$)	$\epsilon_{2,O}$	$-3.462131(11) \times 10^{-3}$
Time of ascending node	$t_{\mathrm{asc},O}$	MJD 56233.935815(7)
Interaction parameters		
Semimajor axis projected in plane of sky	$(a \cos i)_I$	$1.4900(5)$ lt-s
Semimajor axis projected in plane of sky	$(a \cos i)_O$	$91.42(4)$ lt-s
Inner companion mass over pulsar mass	$q_I = m_{cI}/m_p$	$0.13737(4)$
Difference in longs. of asc. nodes	δ_Ω	$2.7(6) \times 10^{-3}$ °
Inferred or derived values		
Pulsar properties		
Pulsar period	P	$2.73258863244(9)$ ms
Pulsar period derivative	$\dot{P}$	$1.7666(9) \times 10^{-20}$
Inferred surface dipole magnetic field	B	2.2×10^8 G
Spin-down power	$\dot{E}$	3.4×10^{34} erg s^{-1}
Characteristic age	τ	2.5×10^9 y
Orbital geometry		
Pulsar semimajor axis (inner)	a_I	$1.9242(4)$ lt-s
Eccentricity (inner)	e_I	$6.9178(2) \times 10^{-4}$
Longitude of periastron (inner)	ω_I	$97.6182(19)$ °
Pulsar semimajor axis (outer)	a_O	$118.04(3)$ lt-s
Eccentricity (outer)	e_O	$3.53561955(17) \times 10^{-2}$
Longitude of periastron (outer)	ω_O	$95.619493(19)$ °
Inclination of invariant plane	i	$39.243(11)$ °
Inclination of inner orbit	i_I	$39.254(10)$ °
Angle between orbital planes	δ_i	$1.20(17) \times 10^{-2}$ °
Angle between eccentricity vectors	$\delta_\omega \sim \omega_O - \omega_I$	$-1.9987(19)$ °
Masses		
Pulsar mass	m_p	$1.4378(13)\ M_\odot$
Inner companion mass	m_{cI}	$0.19751(15)\ M_\odot$
Outer companion mass	m_{cO}	$0.4101(3)\ M_\odot$

Pulsar mass: 1.4378(13) MSun

“Inner” WD mass: 0.19751(15) MSun

“Outer” WD mass: 0.4101(3) MSun

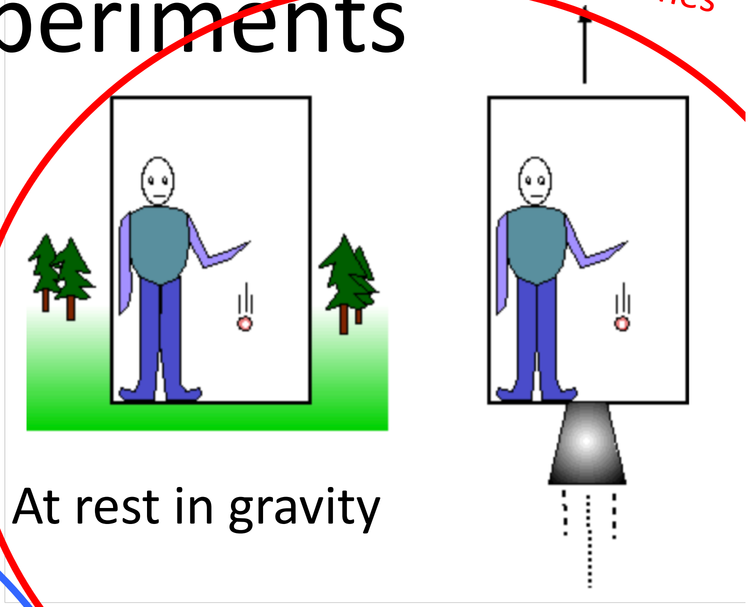
You are impressed by all these high-precision numbers!

Ransom et al. 2014

Einstein lift experiments

Can't distinguish by **local** experiment between effects of acceleration and gravity.

both are accelerated frames

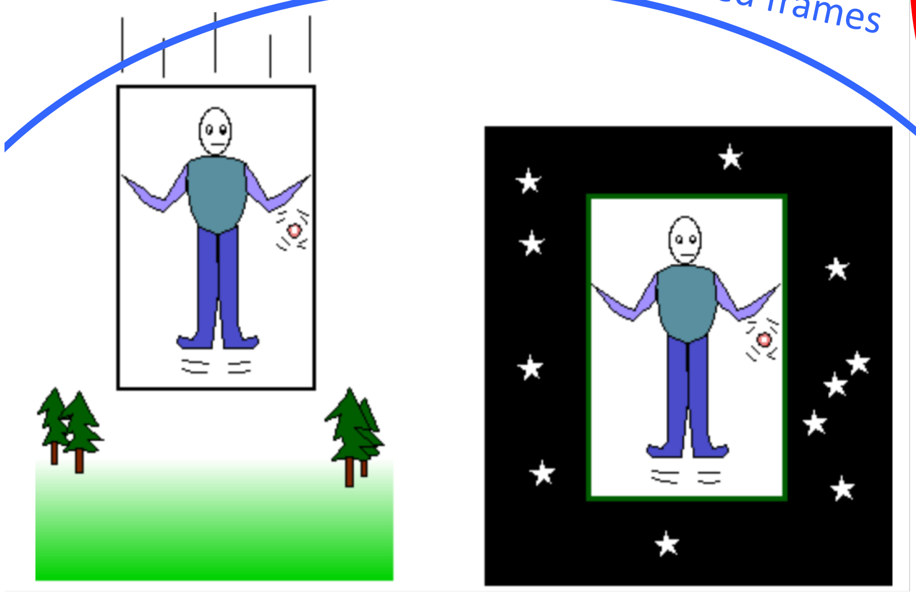


At rest in gravity

Accelerated by rocket

equivalent

both are inertial, i.e., not accelerated frames



Free fall

Float in space

equivalent

Nick Strobel, Astronomy Notes

Strong Equivalence Principle

All objects should fall with same acceleration regardless of their mass or composition

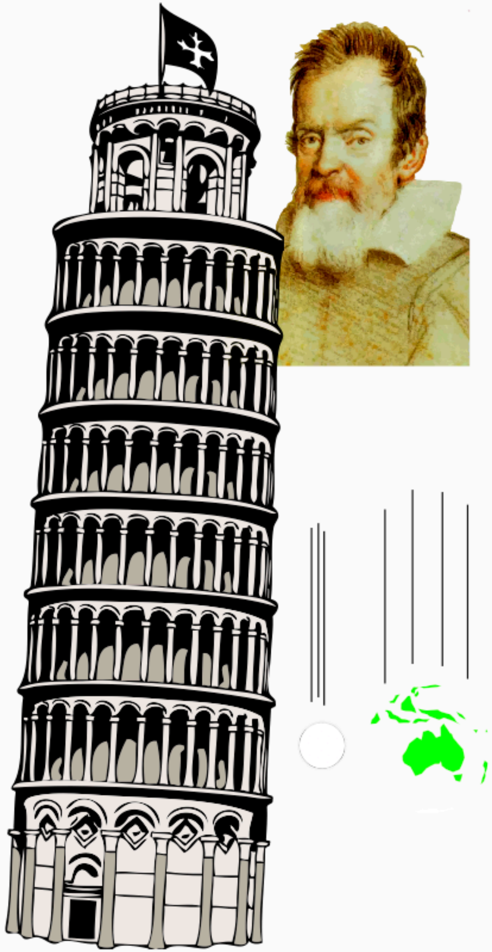
Effects of an SEP violation

Key idea: test whether two bodies fall the same way in the gravitational field of a third

Need: binary falling in an external gravitational field

- Earth and Moon falling in Sun's gravity (LLR)
- Pulsar-WD binary falling in Galactic potential (e.g. Gonzalez et al.)
- Triple system: pulsar and inner WD falling in gravity of outer WD

Fractional difference in acceleration ($\Delta = M_g/M_i - 1$) shifts the massive object's orbit in the direction of the external acceleration



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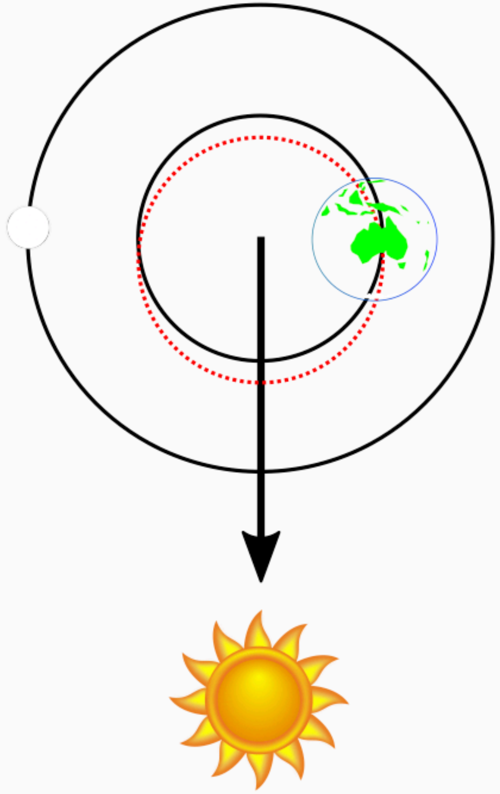

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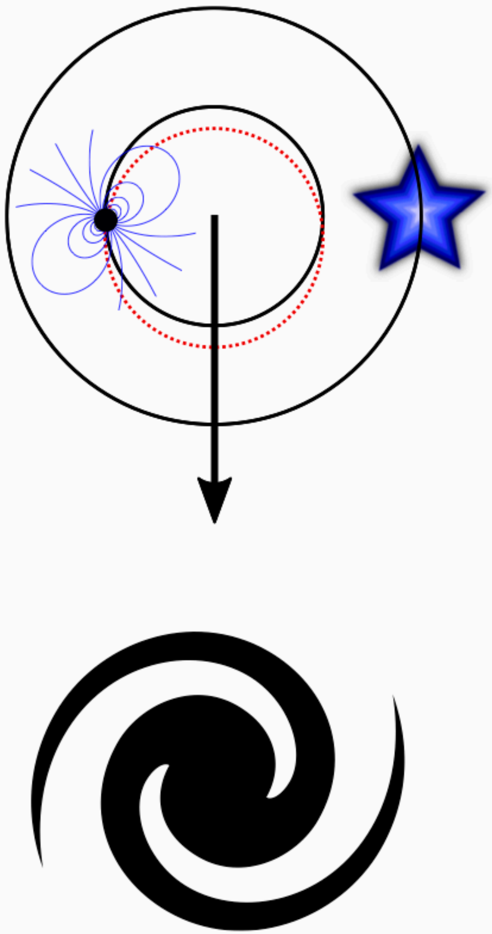

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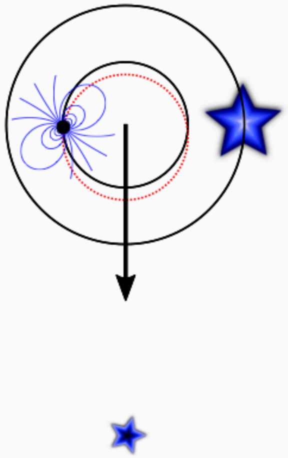

As the outer white dwarf orbits the inner binary, an SEP violation would raise an excess eccentricity directed at it.

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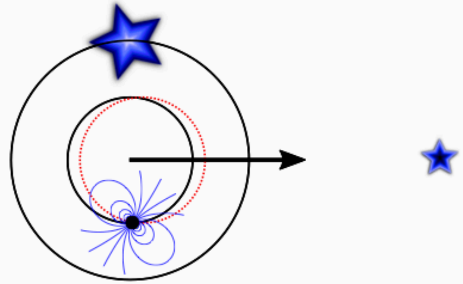

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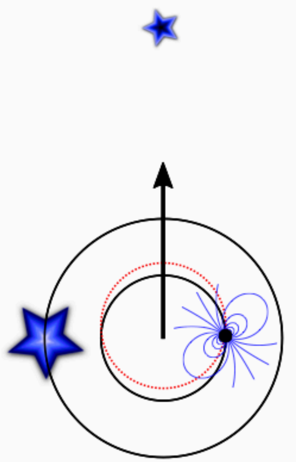

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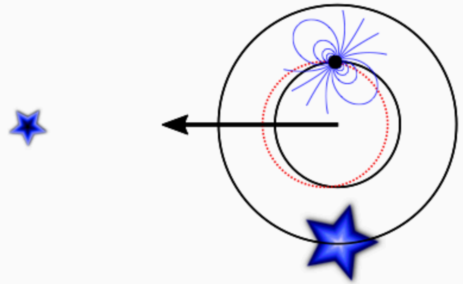

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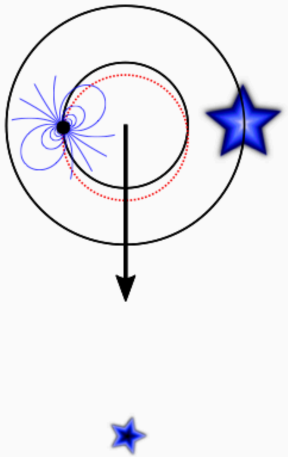

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Observations

Tel.	Band	Num.	Hours	Date range
AO	1400	92	58.9	2012 Mar – 2017 Mar
GBT	1400	172	236.0	2012 Feb – 2017 May
WSRT	1400	439	836.7	2012 Jan – 2013 Jul
AO	430	36	12.9	2012 May – 2017 Mar
WSRT	350	20	17.3	2012 Feb – 2013 Jul

Arecibo Observatory (AO)

Green Bank Telescope (GBT)

Westerbork Synthesis Radio Telescope (WSRT)

Timing model

No adequate formula is known for directly describing the three-body orbit, so we use direct integration of equations of motion:

$$F_j = M_{j,I} a_j, \tag{1}$$

and

$$F_j = -\sum_k \frac{G M_{j,G} M_{k,G}}{r_{jk}^2} \hat{r}_{jk} \tag{2}$$

A standard ODE solver allows us to calculate an orbit given initial conditions.

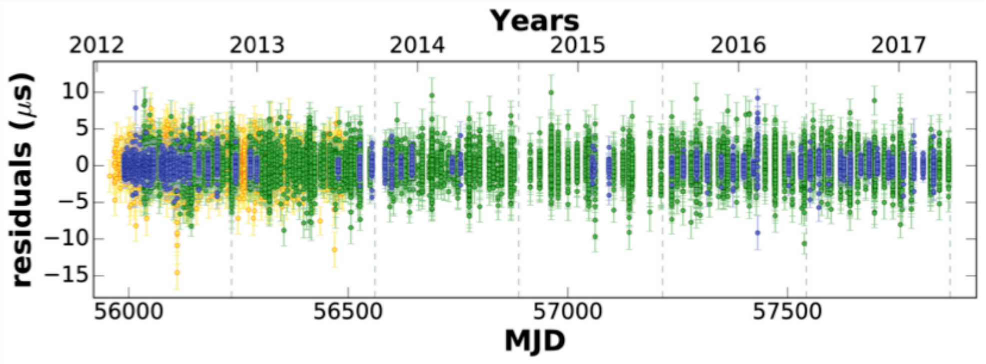
This scheme is easily adapted to allow gravitational mass different from inertial mass.

Relativistic timing model

- Nordtvedt (1985) derives a “point particle” Lagrangian
  - Taylor expansion around the Newtonian Lagrangian
  - Lorentz invariance and symmetry used to eliminate terms
  - Bodies may contain strong fields but internal structure is frozen
  - Fields away from bodies approximated to first post-Newtonian order
- Computer algebra straightforwardly yields equations of motion
  - Direct integration simulates orbits

$$\begin{aligned} L_{PPN} = &- \sum_i M_{i,I} \left(1 - \frac{v_i^2}{2} - \frac{v_i^4}{8}\right) \\ &+ \frac{1}{2} \sum_{i,j} \frac{M_{i,G} M_{j,G}}{r_{ij}} \left(1 + \frac{v_i^2 + v_j^2}{2} - \frac{3 v_i \cdot v_j}{2} - \frac{(v_i \cdot \hat{r}_{ij})(v_j \cdot \hat{r}_{ij})}{2}\right) \\ &+ \frac{\gamma}{2} \sum_{i,j} \frac{M_{i,G} M_{j,G}}{r_{ij}} (v_i - v_j)^2 + \left(\frac{1}{2} - \beta\right) \sum_{i,j,k} \frac{M_{i,G} M_{j,G} M_{k,G}}{r_{ij} r_{ik}} \end{aligned}$$

Testing the SEP



In principle we simply:

- include Δ in the timing model,
- fit timing model to TOAs, and
- determine best-fit values and uncertainties.

Ideally, the value of Δ and its uncertainty would determine how well we constrain SEP violation and whether GR is violated.

But: only correct once we've accounted for all systematics, and formally the effects of Δ are constrained at the 7 ns level.

Known systematics

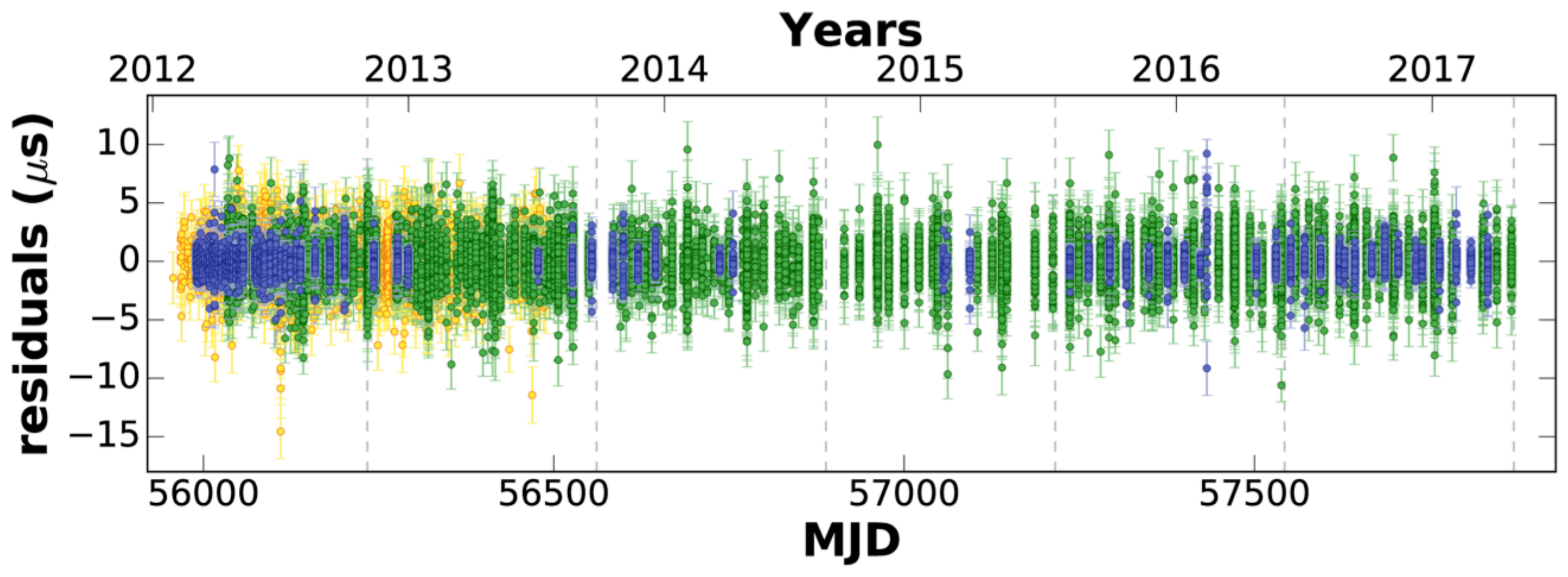
Cause	Remedy
Profile variation with frequency	TOAs no more than 20 MHz
Telescope polarization variations	Matrix template matching
Intrinsic profile variations	?
Interstellar DM variations	Variable DM fitting
Interplanetary medium effects	IPM fitting
Tidal effects in inner WD	Too small
GW losses	Too small
Red noise	Too small at freq. of interest
Uncertainty in DE435 ephemeris	Position fitting
Kopeikin and inverse parallax	Too small
Kabouters	?

We need to estimate the impact of unknown or poorly modeled systematics.

The signature of an SEP violation

Key idea: look for structure in the residuals that *looks like* SEP violations.

SEP violation produces a shift in the pulsar's orbit toward the the outer companion: approximately a sinusoid with frequency $2f_{\text{inner}} - f_{\text{outer}}$.



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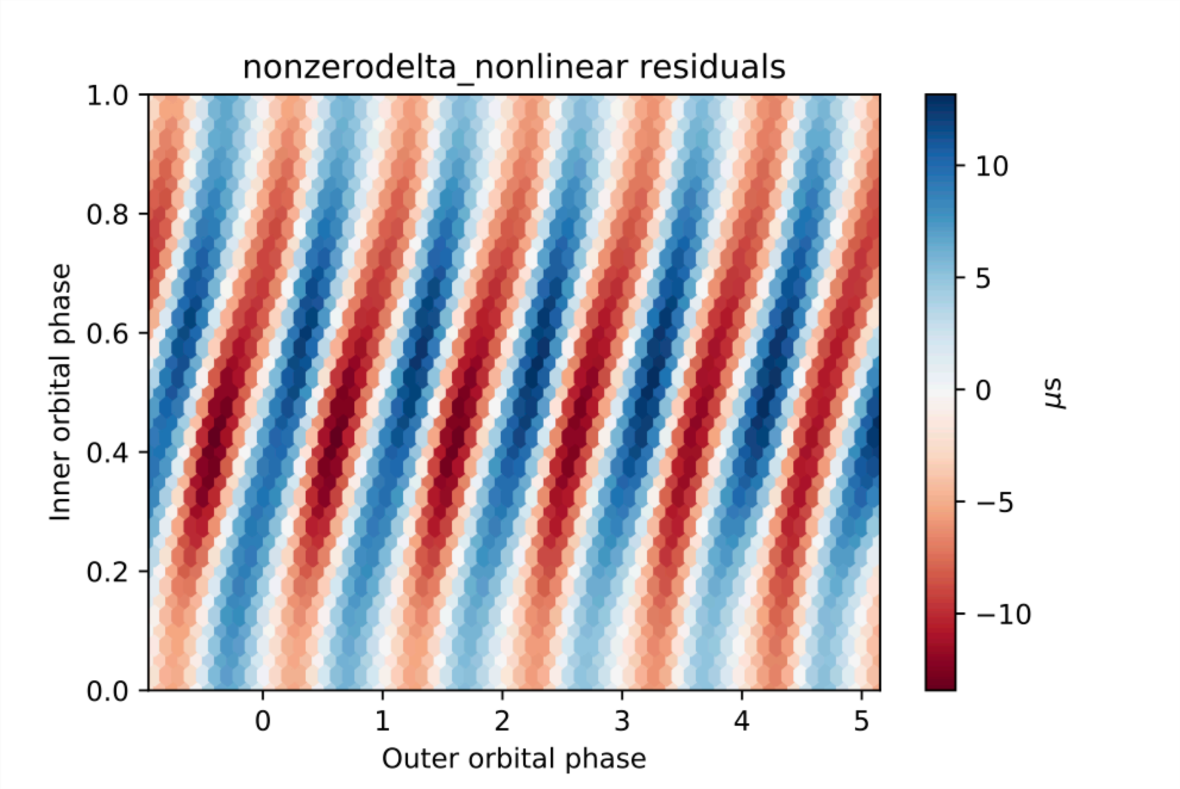
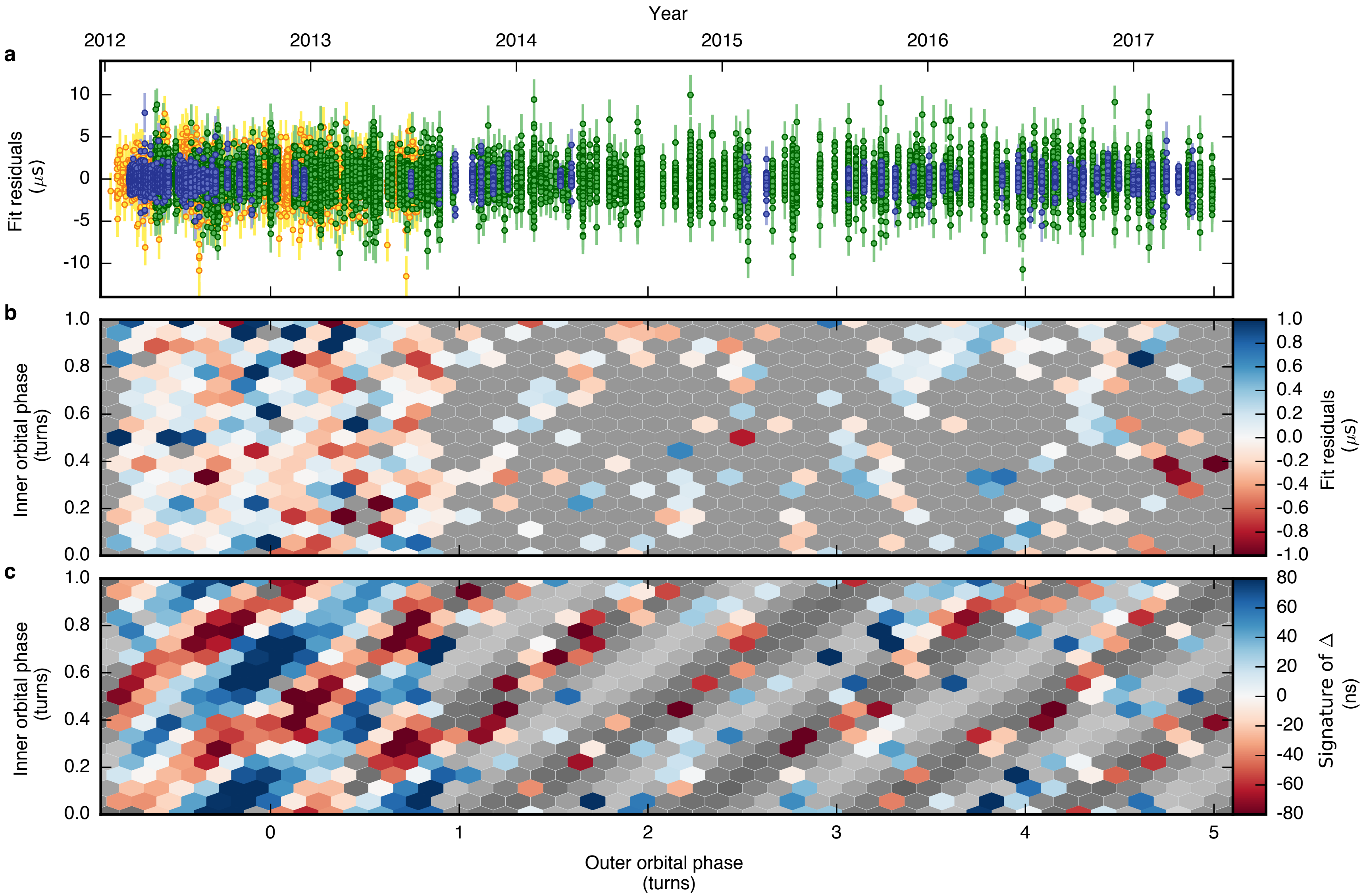
Key idea: look for structure in the residuals that *looks like* SEP violations.

SEP violation produces a shift in the pulsar's orbit toward the the outer companion: approximately a sinusoid with frequency $2f_{\text{inner}} - f_{\text{outer}}$.

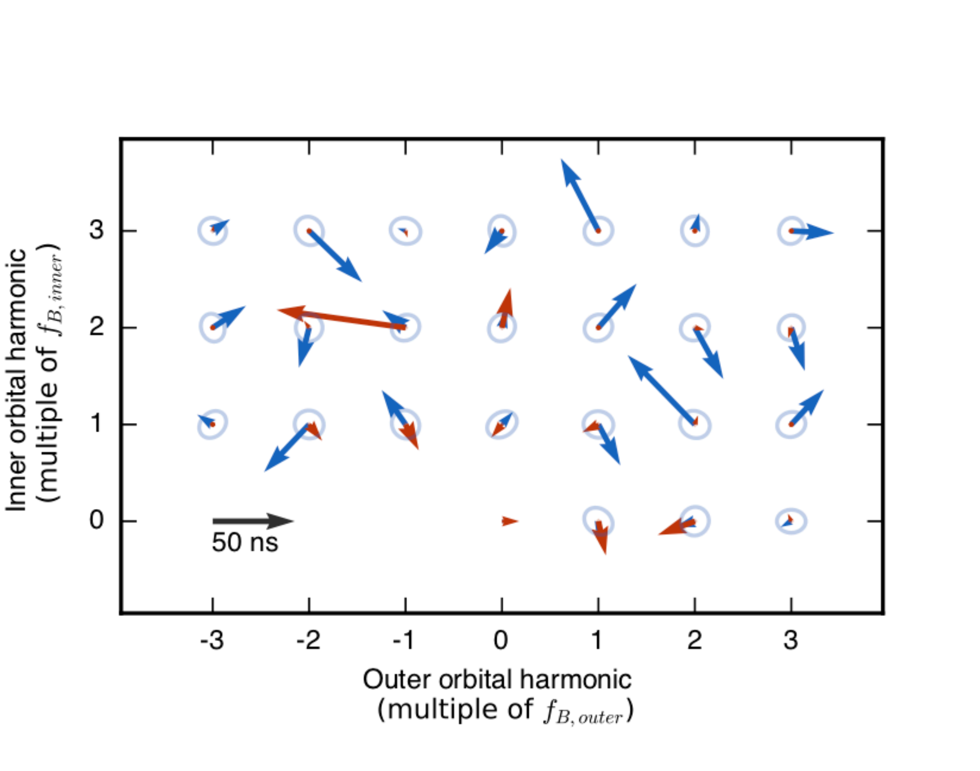




Year
2012
2013
2014
2015
2016
2017
a
Fit residuals
(μs)
10
5
0
-5
-10
b
Inner orbital phase
(turns)
1.0
0.8
0.6
0.4
0.2
0.0
Fit residuals
(μs)
-0.2
-0.4
-0.6
-0.8
-1.0
c
Signature of Δ
(ns)
80
60
40
20
-20
-40
-60
-80
0
1
2
3
4
5
Outer orbital phase
(turns)

Wiggles in our residuals

Look at sinusoids with frequency $kf_{\text{inner}} + lf_{\text{outer}}$:



Estimate no more than ~77 ns in the SEP position based on distribution of all arrows.

Best-fit values

When we carry out the basic fitting, we obtain

$$\Delta = (-1.1 \pm 0.2) \times 10^{-6}.$$

But: that's a σ corresponding to a 7 ns uncertainty. If we take into account all the wiggles we see in the data from our arrow plot we get a more realistic σ corresponding to a 22 ns uncertainty:

$$\boxed{\Delta = (-1.1 \pm 0.7) \times 10^{-6}}$$

We conclude that our result agrees with General Relativity at the 1.6σ level.

An upper limit on SEP violation

With the best-fit value and uncertainty we computed, we can set a 2σ upper limit on SEP violation. We can say that for a $1.4378M_{\odot}$ neutron star, its acceleration differs from that of its white dwarf companion:

$$\boxed{|\Delta| < 2.6 \times 10^{-6}} \qquad \text{(Triple system)}$$

Fundamentally, this difference in acceleration is the key quantity we limit. So we constrain any theory that predicts such an anomalous difference in acceleration, for example, Einstein-Aether or scalar-tensor theories.

But: how does our result compare to existing tests?

An upper limit on SEP violation

With the best-fit value and uncertainty we computed, we can set a 2σ upper limit on SEP violation. We can say that for a $1.4378 M_\odot$ neutron star, its acceleration differs from that of its white dwarf companion:

$$|\Delta| < 2.6 \times 10^{-6} \qquad \text{(Triple system)}$$

The wide pulsar-white-dwarf binary PSR J1713+0747 falling in the Galactic potential gives:

$$|\Delta| < 2 \times 10^{-3} \qquad \text{(WB)}$$

But: how do we compare this to lunar laser ranging or dipole gravitational wave tests?

The Nordtvedt parameter

In PPN we measure a theory's SEP violation by using the Nordtvedt parameter:

$$\Delta = \eta_N \frac{E_g}{Mc^2}$$

Lunar Laser Ranging constrains the Earth-Moon-Sun system to $|\Delta| < 1.3 \times 10^{-13}$, and for the Earth $E_g/Mc^2 \sim -4.5 \times 10^{-10}$, so $|\eta_N| < 2.4 \times 10^{-4}$.

In the triple system, the pulsar interior is not 1PN!

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In the triple system, the pulsar interior is not 1PN!

We can calculate the "strong-field Nordtvedt parameter" $\hat{\eta}_N$ the same way:

$$\Delta = \hat{\eta}_N \frac{E_g}{Mc^2}$$

Since $|\Delta| < 2.6 \times 10^{-6}$ and $E_g/Mc^2 \sim -0.1$, $|\hat{\eta}_N| < 2.6 \times 10^{-5}$ — improving on LLR by a factor of about ten.

But: funny things can happen in the strong field!

Quasi-Brans-Dicke scalar-tensor theories

These theories include a scalar field ϕ in addition to the metric that mediates gravity. Matter responds to a modified version of the metric:

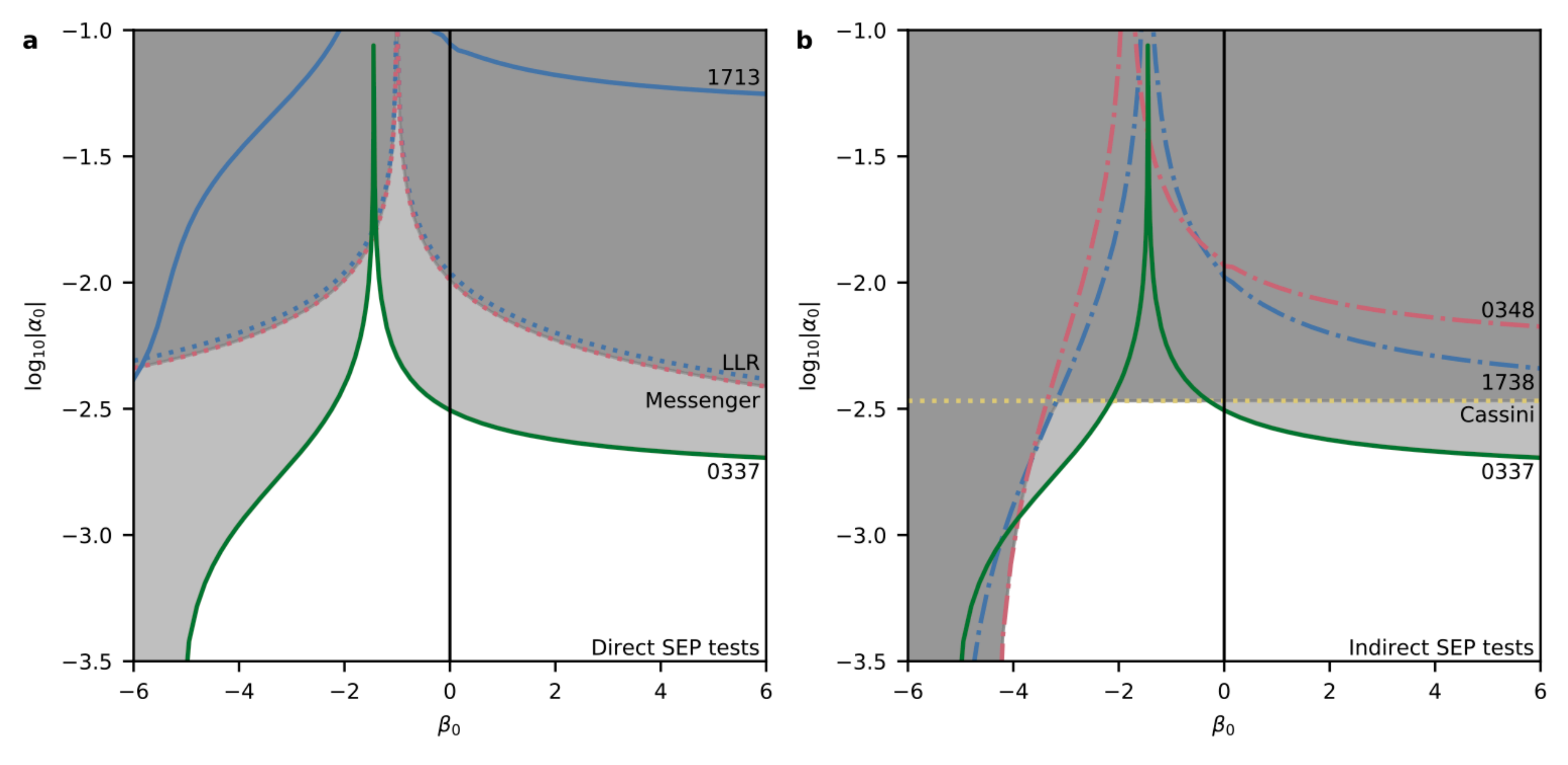
$$\tilde{g}_{\mu\nu} = e^{2(\alpha_0\phi+\beta_0\phi^2/2)} g^*_{\mu\nu}$$

The scalar field is sourced in matter:

$$\Box\phi = -\frac{4\pi G^*}{c^4}(\alpha_0 + \beta_0\phi) T_*$$

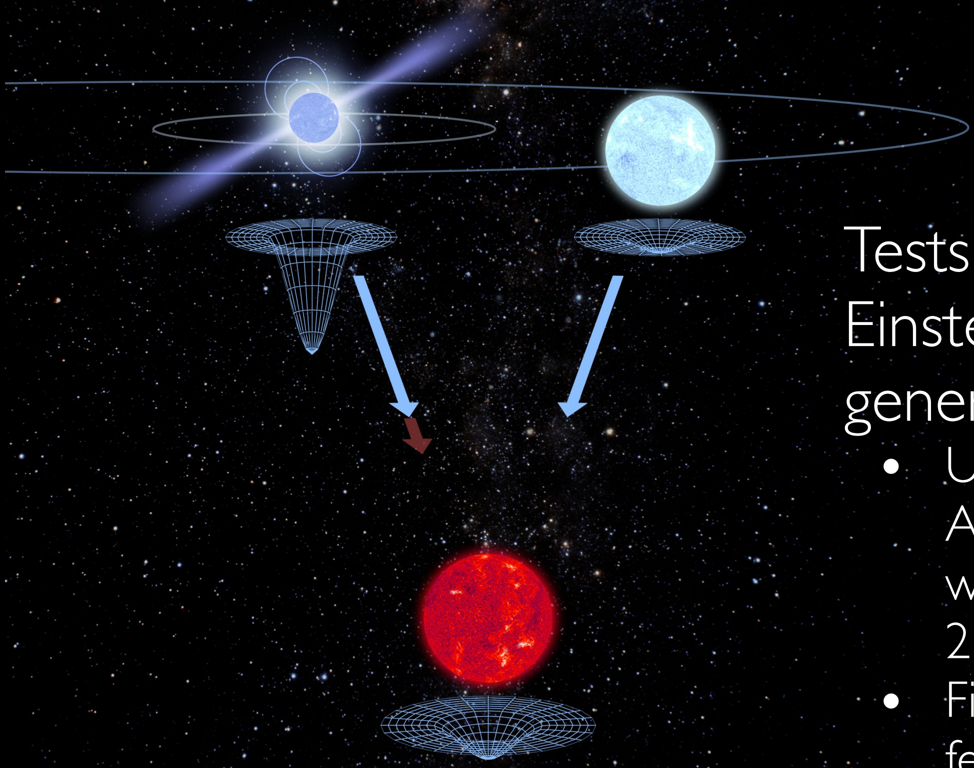
If $\beta_0 \lesssim -4$ spontaneous scalarization can occur, resulting in order-unity deviations from GR in strong fields, no matter how small the weak-field effects are.

Our constraint on quasi-Brans-Dicke theories



Our constraint $|\Delta| < 2.6 \times 10^{-6}$ rules out the light-gray area.

Universality of free fall



Pulsar triple system PSR J0337+1715

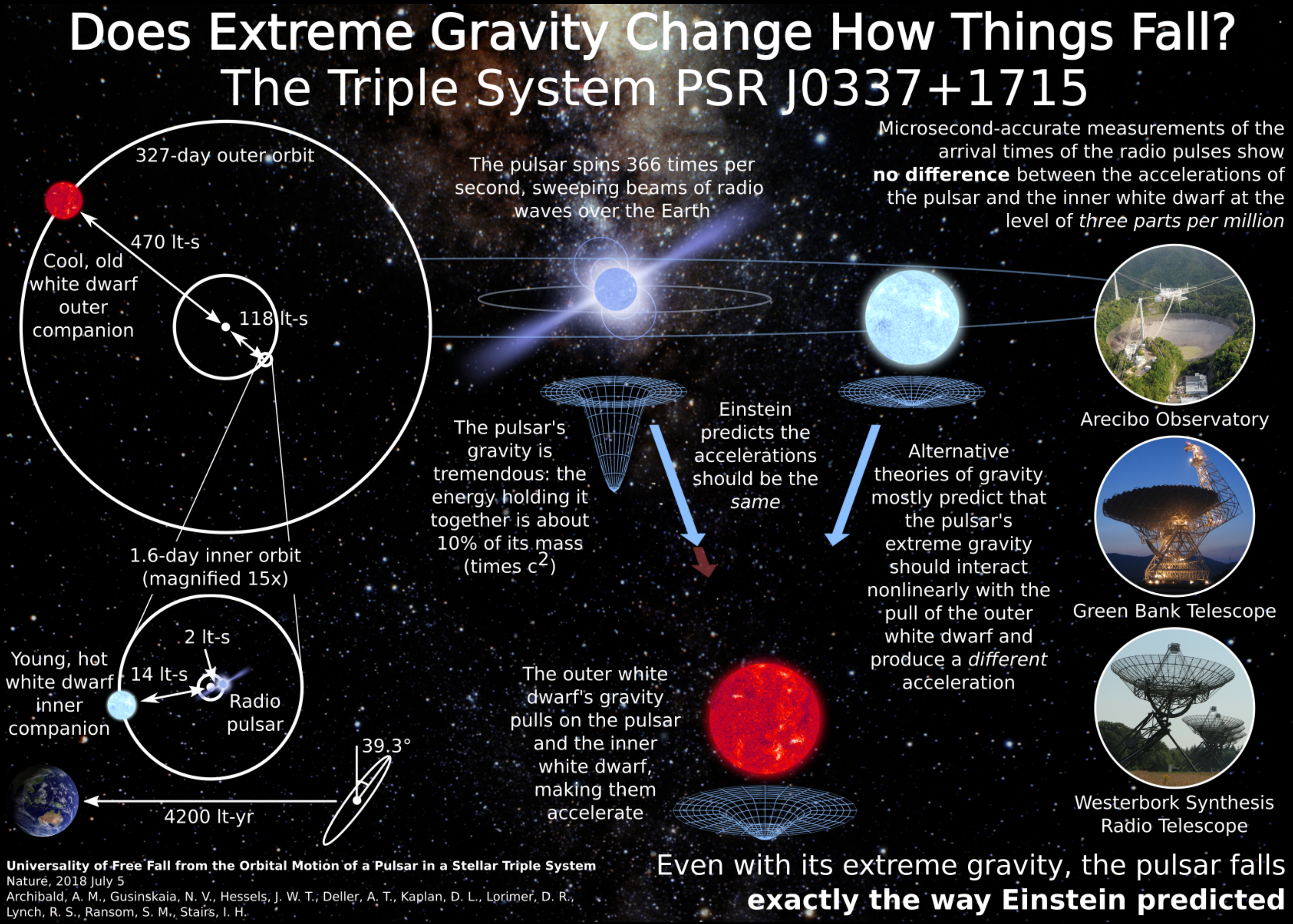
Archibald, Gusinskaia, Hessels et al. 2018, Nature

$$\Delta = \frac{m_G}{m_I} - 1$$

Tests the foundation on which Einstein's theory of gravity, general relativity, is built:

- Used 1200hr of WSRT, GBT and Arecibo data to see if pulsar and white dwarf fall differently towards a 2nd white dwarf companion.
- Find equal accelerations to within a few parts in a million. Best-ever test of the strong equivalence principle:

$$|\Delta| < 2.6 \times 10^{-6}$$


Does Extreme Gravity Change How Things Fall?
The Triple System PSR J0337+1715
327-day outer orbit
470 lt-s
Cool, old white dwarf outer companion
118 lt-s
1.6-day inner orbit (magnified 15x)
2 lt-s
14 lt-s
Young, hot white dwarf inner companion
Radio pulsar
39.3°
4200 lt-yr
The pulsar spins 366 times per second, sweeping beams of radio waves over the Earth
The pulsar's gravity is tremendous: the energy holding it together is about 10% of its mass (times c²)
Einstein predicts the accelerations should be the *same*
Alternative theories of gravity mostly predict that the pulsar's extreme gravity should interact nonlinearly with the pull of the outer white dwarf and produce a *different* acceleration
The outer white dwarf's gravity pulls on the pulsar and the inner white dwarf, making them accelerate
Microsecond-accurate measurements of the arrival times of the radio pulses show **no difference** between the accelerations of the pulsar and the inner white dwarf at the level of *three parts per million*
Arecibo Observatory
Green Bank Telescope
Westerbork Synthesis Radio Telescope
Universality of Free Fall from the Orbital Motion of a Pulsar in a Stellar Triple System
Nature, 2018 July 5
Archibald, A. M., Gusinskaia, N. V., Hessels, J. W. T., Deller, A. T., Kaplan, D. L., Lorimer, D. R., Lynch, R. S., Ransom, S. M., Stairs, I. H.
Even with its extreme gravity, the pulsar falls **exactly the way Einstein predicted**