Does extreme gravity affect how objects fall?

Anne Archibald, Nina Gusinskaia, Jason Hessels, Adam Deller, David Kaplan, Duncan Lorimer, Ryan Lynch, Scott Ransom, and Ingrid Stairs

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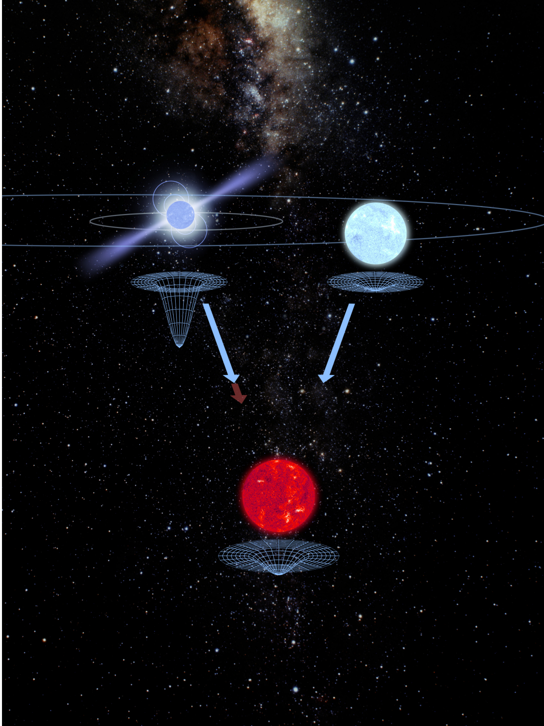
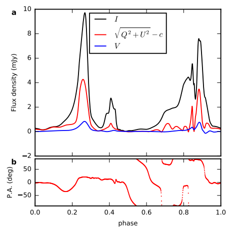


For more information:

Universality of Free Fall from the Orbital Motion of a Pulsar in a Stellar Triple System



Archibald et al.
Nature, 2018 July 5

For less information:

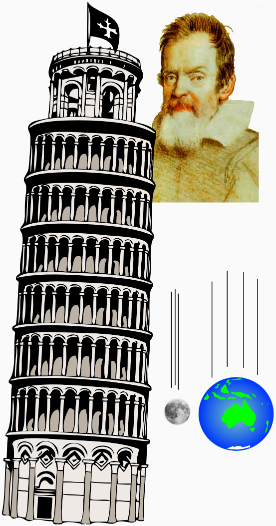
Einstein's theory still passes the test: weak and strong gravity objects fall the same way

`https://youtu.be/hc3mrta7J9I`

A brief history of dropping things

Aristotle and Galileo

- Aristotle's physics claimed that heavier objects fell faster than light objects
- Galileo questioned this for logical reasons
  - Imagine two light objects tied together — do they fall like one heavy object? do they slow down if the rope breaks?
- Galileo may or may not have actually dropped anything off the Leaning Tower of Pisa
  - Simon Stevin dropped cannonballs from the Nieuwe Kerk in Delft
  - Dave Scott on Apollo 15 demonstrated that a hammer and a feather fell the same way



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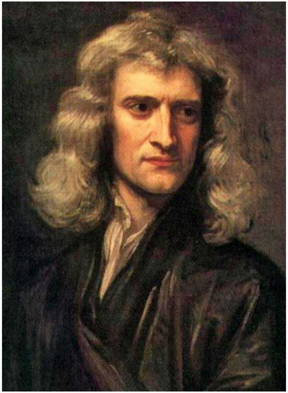
Painting by Alan Bean

Newton's theory of gravity

- Newton created the first mathematical theory of gravity
  - He created the mathematics too
  - Revolutionary idea: celestial objects obey the same rules as terrestrial
- All objects fall the same way in Newton's theory
  - Newton tested pendulums of different compositions to check this



Mathematically:

$$F = m_I a \qquad F = \frac{G m_G m'_G}{r^2}$$

The mass that appears in these two equations is the same:

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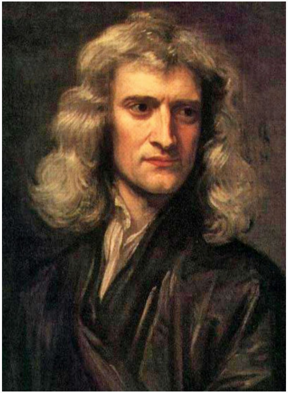

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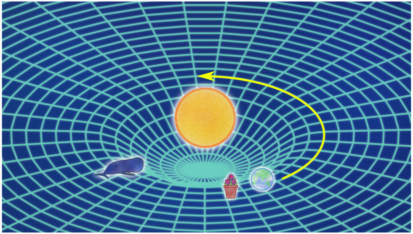
Einstein's theory of gravity

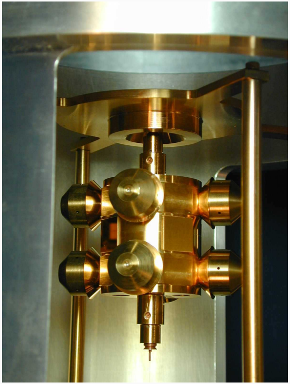
Einstein's idea:

> *Maybe if everything falls exactly the same way, gravity isn't really a force at all — instead it's geometry. Falling things are just trying to go in straight lines in curved spacetime.*



This idea, that gravity is geometry, Einstein developed into a full theory of gravity called general relativity (GR).

The Weak Equivalence Principle



Torsion pendulum for WEP tests; from Wagner et al. 2012

The Weak Equivalence Principle states:

- All non-gravitational experiments give the same result regardless of which inertial frame they are carried out in

And in particular:

- The following fall identically: proton rest mass, nuclear binding energy, magnetic fields..., or
- gravitational mass equals inertial mass regardless of composition

This has been tested to exquisite accuracy (10^{-13}) in laboratory experiments.

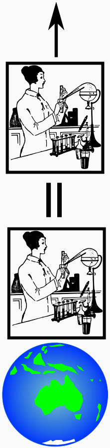
The Strong Equivalence Principle

The Strong Equivalence Principle (SEP) states:

- All experiments, including gravitational ones, give the same result regardless of which inertial frame they are carried out in

And in particular (Universality of Free Fall):

- $m_G = m_I$ even for objects with strong gravity, or
- gravitational binding energy falls the same way as other mass, or
- all objects, no matter how strong their gravity, fall the same way



Most alternatives to GR violate the SEP at some level.

- In post-Newtonian theories, gravity has nonlinear superposition

Why would the Strong Equivalence Principle fail?

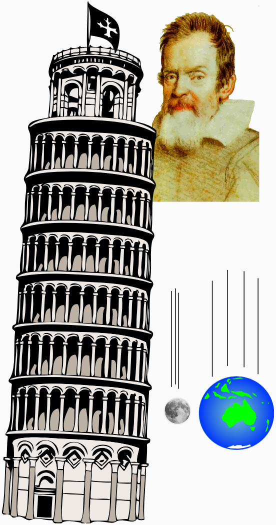
One specific alternative theory worth considering is Brans-Dicke gravity (Jordan-Fierz-Brans-Dicke). This is an extension of general relativity meant to satisfy Mach's principle.

In Brans-Dicke gravity, in addition to the geometry of spacetime, there is an additional scalar field ϕ. Its effect on local physics is minimal:

$$\tilde{g}_{\mu\nu} = e^{2\alpha_0\phi} g^*_{\mu\nu}$$

- Local non-gravitational physics unaffected (WEP satisfied)
- Value of G measured locally ($\tilde{G}$) depends on ϕ (SEP fails)
- Parameter α_0 determines how strongly ϕ affects physics
- ϕ is sourced in matter: large near (e.g.) neutron stars

Testing the Strong Equivalence Principle



Testing the SEP requires dropping objects with substantial gravity. But remember objects in orbit are falling too.

- Lunar laser ranging looks at the Earth and Moon falling towards the Sun — Earth's gravity not so strong
- Zhu et al. look at a pulsar and a white dwarf falling into the Galaxy — Galaxy's pull not so strong

We have a system where the test body's gravity is strong — a pulsar — and the external acceleration is strong.

Testing the Strong Equivalence Principle

Lunar Laser Ranging ground station in operation.
Photo courtesy of NASA.

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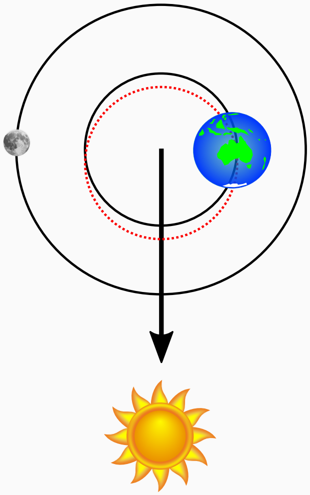

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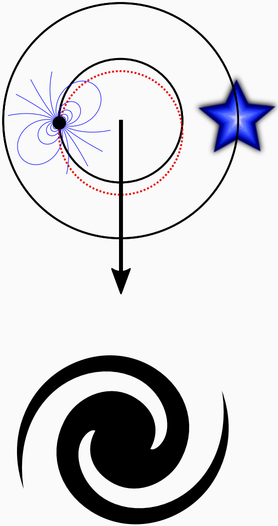

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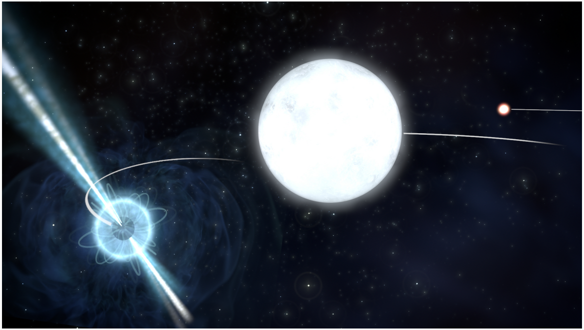
A pulsar in a triple system

PSR J0337+1715

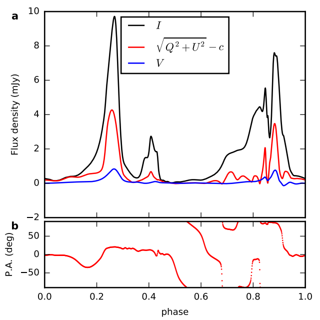


- Discovered as part of the 2007 GBT drift scan survey
- Consists of a hierarchical triple:
  - $1.4M_\odot$ radio pulsar with a period of 2.73 ms — precision timing
  - $0.2M_\odot$ inner white dwarf in a 1.6-day orbit — optically observed
  - $0.4M_\odot$ outer white dwarf in a 327-day orbit — inferred

Pulsar Timing

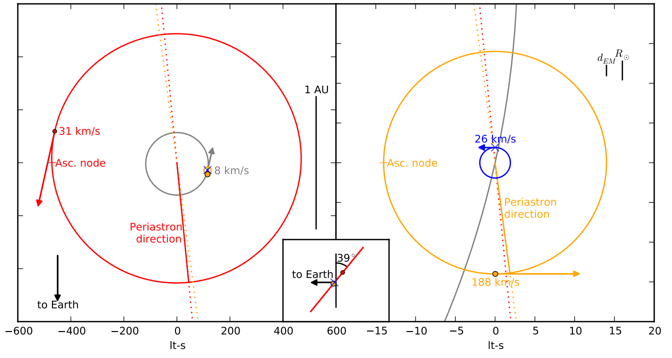
Pulsar timing is a powerful tool:

- Average pulse profiles are stable
- Approximate ephemeris allows averaging over (say) 20 minutes
- Cross-correlation with a template can measure the ephemeris error
    - Arrival-time uncertainty $\sim 1\,\mu$s
- Can account for every single pulse since observations began
    - Pulse number 56,528,015,489 arrived at 2017-05-14 19:51:17.9937500(16) UTC



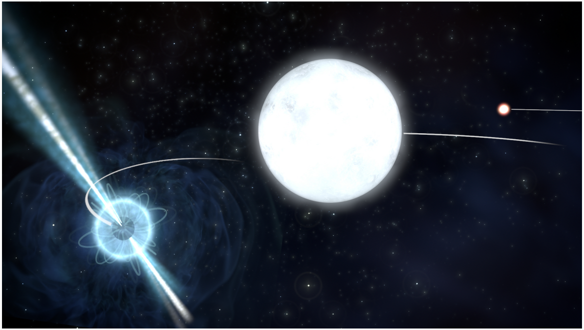
Pulse arrival times (TOAs) measure line-of-sight distance to the pulsar with $\sim$300 m accuracy.

Basic System Properties from Timing



- Microsecond-level timing allows measurement of the system
- Orbits are computed by direct integration
- Three-body interactions break the usual degeneracies without reference to relativistic effects, for example:
    - System inclination is 39.3° and the orbits are nearly coplanar
    - Pulsar mass is $1.4359(3) M_\odot$

Astrophysics



- System formation is puzzling
  - Triples are easy to disrupt — how did it survive the supernova explosion?
  - Why are the orbits coplanar? Eccentricities aligned?
- Inner white dwarf is unusual
  - Hotter than models expect
  - $0.2\,M_\odot$ is a difficult mass for modelers

Testing the SEP

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)

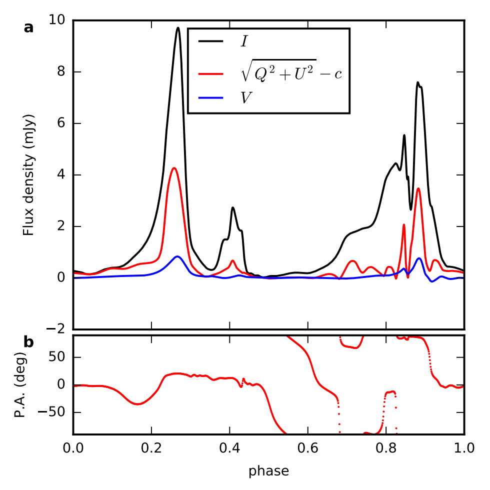
Green Bank Telescope (GBT)

Westerbork Synthesis Radio Telescope (WSRT)

Timing measurements

We compared the radio signal to our pulse template to extract timing information:

- All usable data is from 1100–1900 MHz
- One pulse arrival time every 20 minutes $\times$ 20 MHz
- 27194 pulse arrival times currently in use
- 1.0 μs weighted RMS uncertainty



Timing model

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

$$F_j = M_j a_j, \tag{1}$$

and

$$F_j = -\sum_k \frac{G M_j M_k}{r_{jk}^2} \hat{r}_{jk} \tag{2}$$

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

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

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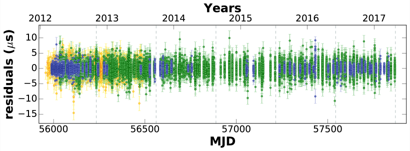
Testing the SEP



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.

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:

$$\boxed{|\Delta| < 2.6 \times 10^{-6}} \quad (0337)$$

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?

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The wide pulsar-white-dwarf binary PSR J1713+0747 falling in the Galactic potential gives (Zhu et al. 2018):

$$|\Delta| < 2 \times 10^{-3} \tag{1713}$$

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 $|\eta_N| < 2.4 \times 10^{-4}$.

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In the triple system, the pulsar interior is not 1PN, but:

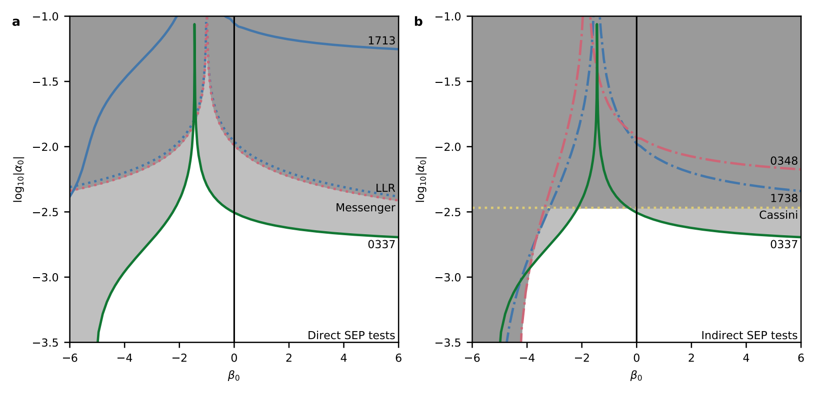
We can calculate the "strong-field Nordtvedt parameter" $\hat{\eta}_N$ the same way:

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

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!

Our constraint on quasi-Brans-Dicke theories



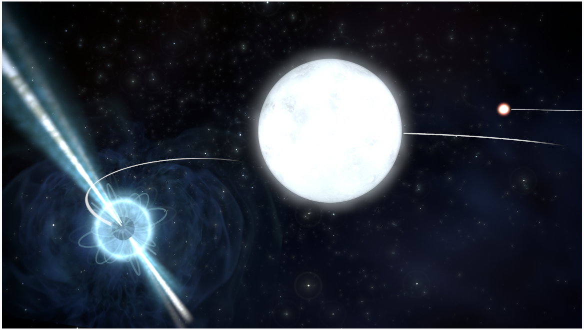
Our constraint $|\Delta| < 2.6 \times 10^{-6}$ rules out the light-gray area.

This result is possible because of this wonderful natural laboratory: a millisecond pulsar in a stellar triple system.

Appendix

Slides that follow are in case of questions.

PSR J0337+1715



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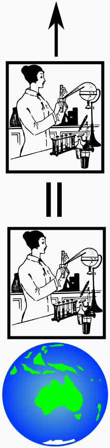

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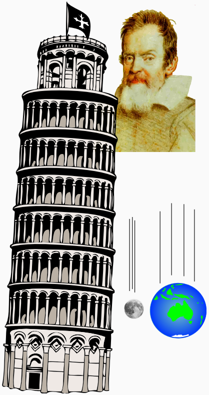
- For example, string theories generically predict a scalar field, the dilaton, that affects how objects fall
- In post-Newtonian theories, gravity has nonlinear superposition

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. Zhu et al. 2018)
- 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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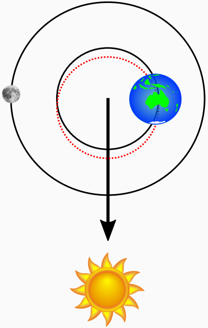

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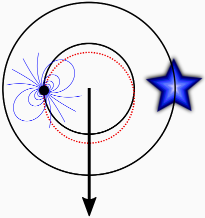

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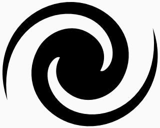

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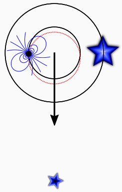

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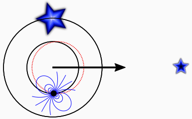

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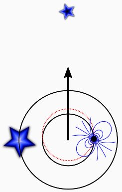

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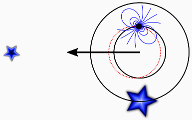

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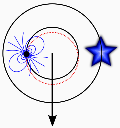

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Data processing

- Custom data processing pipeline
- Follows NANOGrav “how we do it” paper except:
  - Include WSRT
  - Realign with short-term ephemeris
  - Matrix template matching
  - Extra manual RFI zapping
  - Summary plot per observation
- TOAs every 20 minutes $\times$ 20 MHz at 1400 MHz
  - 27194 TOAs currently in use
  - 1.0 μs weighted RMS uncertainty

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

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

Future prospects

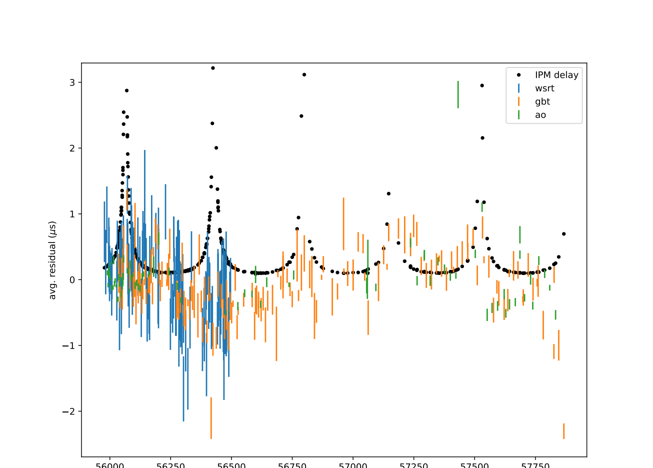
What are the possibilities for improving on this test?

- GAIA is expected to provide a light-bending test that improves dramatically upon Cassini (weak-field, indirect test of SEP)
- Spontaneous scalarization is a "loophole" we can't address
  - Pulsar tests with different pulsar masses (e.g. $1.6M_\odot$) may rule it out
  - Better equation-of-state constraints may rule it out
  - Gravitational-wave inspirals involving problem pulsar masses may rule it out
- Outside spontaneous scalarization, we provide the best SEP constraints, direct or indirect
  - GW observatories may detect waveform changes due to dipole GW losses
    - aLIGO less sensitive than current observations
    - Cosmic Explorer and the Einstein Telescope less sensitive than PSR J0337+1715

So: CE and ET templates need only consider dipole GW losses in regimes where spontaneous scalarization is still possible: NS

Effects of the interplanetary medium

The ecliptic latitude of our source is only 2.1 degrees, so our line of sight passes close to the Sun every March. Using a simple model of the IPM, and assuming a density of 10 electrons per cubic centimeter at 1 AU, we obtain:



Known systematics

Cause	Remedy
Profile variation with frequency	TOAs no more than 20 MHz, FDn
Telescope polarization variations	Matrix template matching
Scattering time variations	Drop low-frequency data
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, wrong timescale
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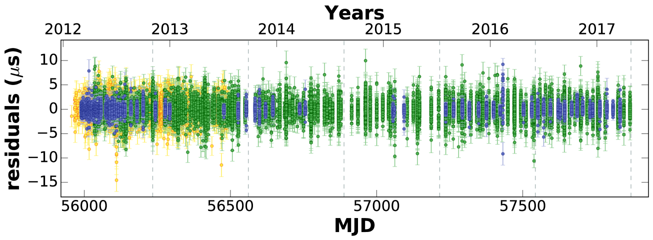
We need to esti[...]te the impact of unknown or poorly modeled systematics

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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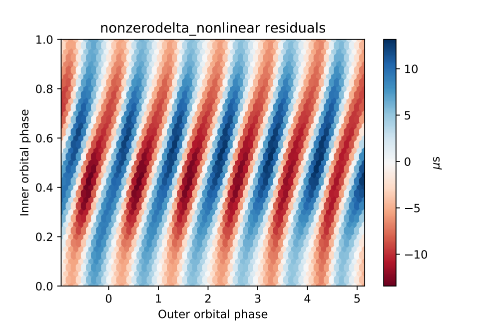
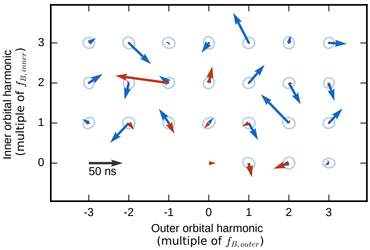


Wiggles in our residuals

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.

Weak- versus strong-field tests

Within the PPN framework, there's a simple relation,

$$\Delta = \eta E_B, \tag{3}$$

where E_B is the fractional binding energy of the test mass. For the earth, $E_B = 4.6 \times 10^{-10}$ and lunar laser ranging can constrain $|\eta| \lesssim 10^{-3}$.

In general, though,

$$\Delta = \eta E_B + \eta_2 E_B^2 + \cdots, \tag{4}$$

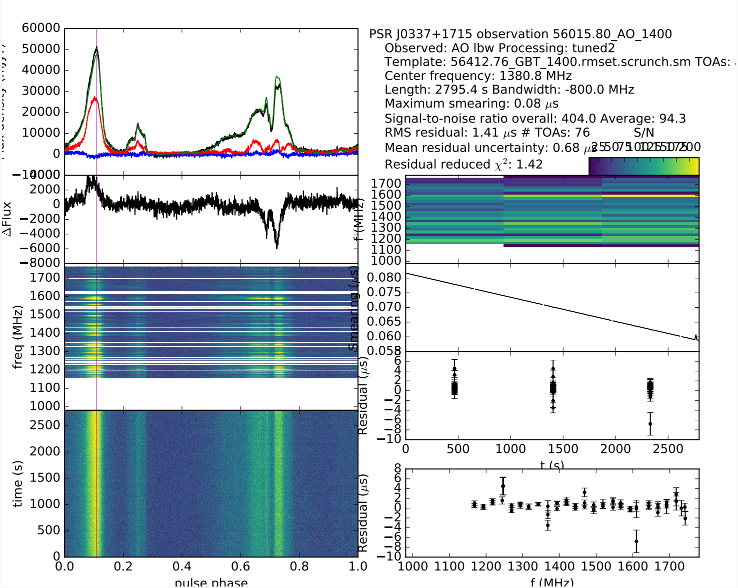
and our pulsar has an E_B of 0.1–0.15, so we can't obtain a clean constraint on η.

We must use strong-field theories to compare different tests.

Data processing

- Custom data processing pipeline
- Follows NANOGrav “how we do it” paper except:
    - Include WSRT
    - Realign with short-term ephemeris
    - Matrix template matching
    - Extra manual RFI zapping
    - Summary plot per observation

Data processing



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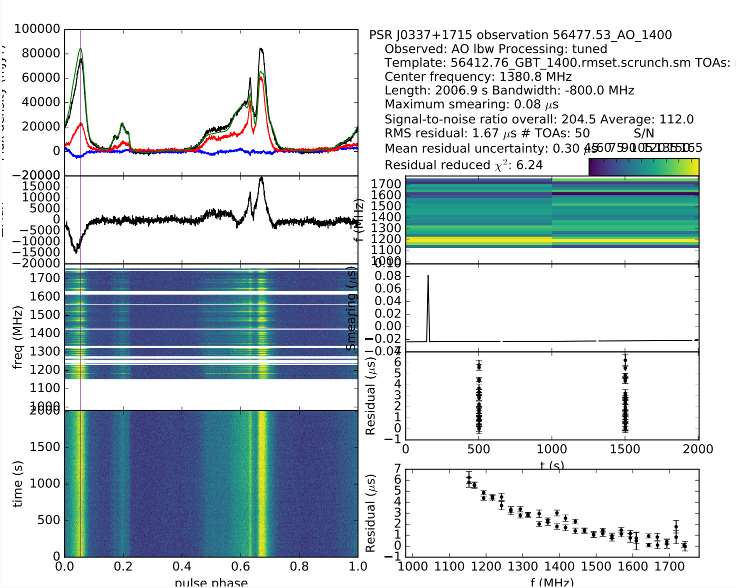

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    - Include WSRT
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    - Summary plot per observation
- TOAs every 20 minutes $\times$ 20 MHz at 1400 MHz
    - 27194 TOAs currently in use
    - 1.0 μs weighted RMS uncertainty
- "Timing RMS": 260 ns for all, 140 ns for Arecibo

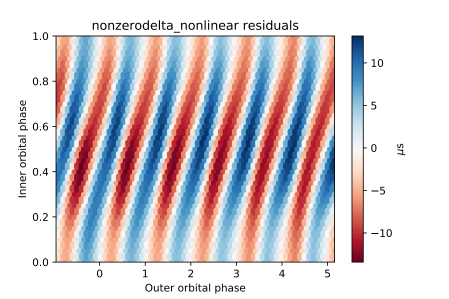
Why were these different techniques needed for PSR J0337+1715?

Signatures

If you have one parameter you're interested in (Δ), what structure in the data affects your parameter of interest?

Partial derivative with respect to Δ is not the right answer.

So: Change Δ and re-fit all other parameters to isolate the **signature** of Δ.



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.

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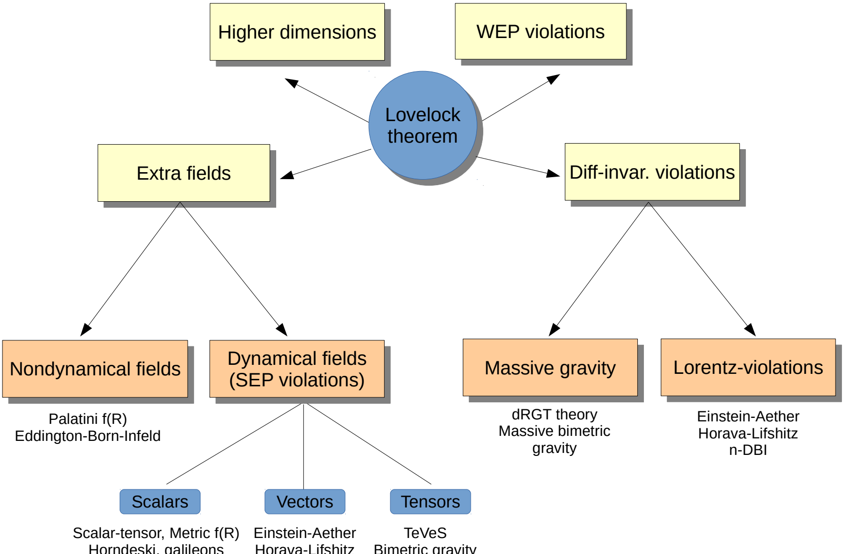
Alternative theories of gravity



Quasi-Brans-Dicke/Damour-Esposito-Farèse 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.

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