Testing General Relativity and Extended Gravitational Theories

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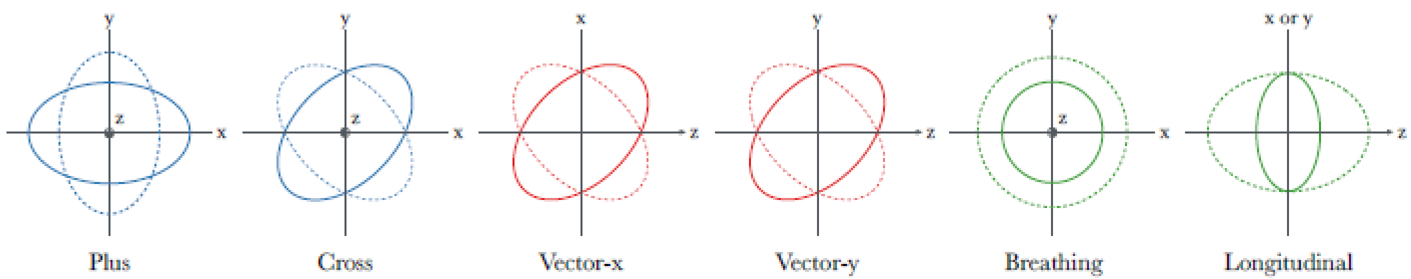
4th LISA Cosmology Working Group Workshop
16-20 October 2017, Mainz

Tests of General Relativity with the Stochastic Gravitational-Wave Background

Thomas Callister,[1,*] Sylvia Biscoveanu,[2] Nelson Christensen,[3,4] Maximiliano Isi,[1] Andrew Matas,[5] Olivier Minazzoli,[6,4] Tania Regimbau,[4] Mairi Sakellariadou,[7] Jay Tasson,[3] and Eric Thrane[8,9]

e-Print: arXiv:1704.08373 [gr-qc] PRX (in press)

We present a Bayesian method to detect and characterize the polarization of the stochastic background.



LIGO detectors alone can rule out GR
(i.e. detect non-GR polarization modes)

LIGO detector + Virgo detector can distinguish between scalar and vector modes
(i.e. can distinguish different alternative theories of gravitation)

How about LIGO + Virgo + LIGO India + KAGRA?

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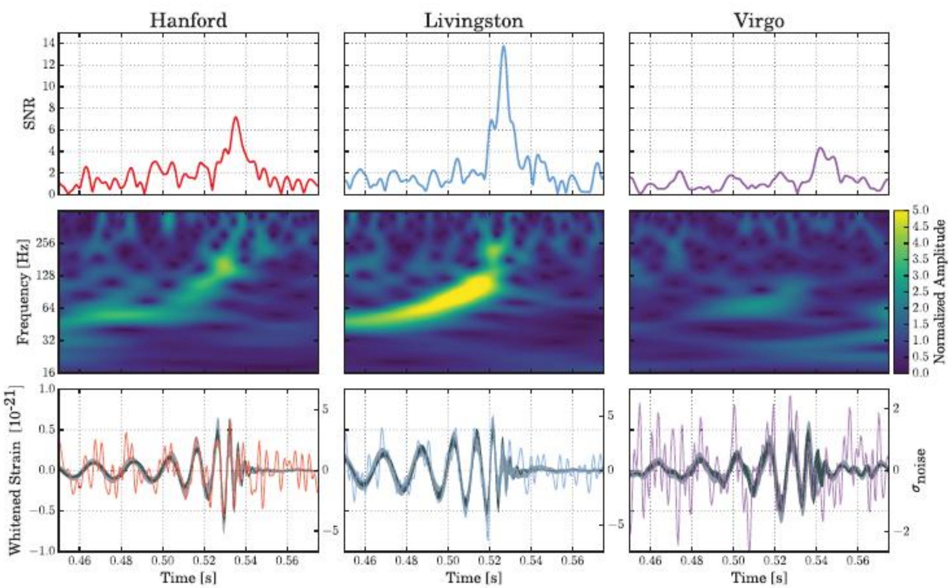

GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence

LIGO/Virgo PRL (2017)

Simple (first) test: compare the tensor-only mode with scalar-only and vector-only modes.

Purely tensor polarization is strongly favoured over purely scalar or vector polarizations, showing consistency with GR

GW 170817 and GRB 170817A : Implications for fundamental physics

ApJ Lett (2017)

Temporal offset of $(+1.74 \pm 0.05)$ s across a distance greater than 100 million l.y.

Constraints on:

- deviation of speed of gravity from the speed of light
- violation of Lorentz invariance
- violation of equivalence principle

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- **deviation of speed of gravity from the speed of light**

Δt small ⇒ $$\Delta v / v_{\rm EM} \approx v_{\rm EM} \Delta t / D,$$ $$\Delta v = v_{\rm GW} - v_{\rm EM}$$

$$D = 26 \text{ Mpc}$$

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$D = 26$ Mpc

If simultaneous emission: the $(+1.74 \pm 0.05)$ s due to faster travel by GW signal

⇨ Upper bound on Δv

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If two signals emitted at times differing more than $(+1.74 \pm 0.05)\ \mathrm{s}$ with the faster EM signal making up some of the difference ⇨ Lower bound on Δv

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If SGRB emitted 10 s after GW

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}.$$

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If SGRB emitted 10 s after GW

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}.$$

If SGRB emitted (-10, 1000) after GW, you gain 2 orders of magnitude in either side

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- **violation of Lorentz invariance**

Standard Model Extension (SME) (*an EFT description of Lorentz violation*)

$\Delta v = v_{\mathrm{GW}} - v_{\mathrm{EM}}$ controlled by differences in coefficients for Lorentz violation in the gravitational sector and the photon sector at each mass dimension

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Concentrate on mass dimension d=4

$$\Delta v = -\sum_{\substack{\ell m \\ \ell \leqslant 2}} Y_{\ell m}(\hat{n}) \left(\frac{1}{2}(-1)^{1+\ell} \bar{s}^{(4)}_{\ell m} - c^{(4)}_{(I)\ell m} \right).$$

spherical harmonic basis

sky position of event

spherical coefficients for Lorentz violation in GW/EM sector

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- **violation of Lorentz invariance**

Standard Model Extension (SME) (*an EFT description of Lorentz violation*)

Constrain gravity sector coefficients one at a time, by setting all other coefficients including those from EM sector, to zero.

⇨ The isotropic upper bound gets improved by 10 orders of magnitude

Coefficient	This Work Upper	Previous Upper
$\bar{s}_{00}^{(4)}$	5×10^{-15}	8×10^{-5}

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- **violation of equivalence principle**

Probe whether EM radiation and GWs are affected in the same way by background potentials

Shapiro effect: the propagation time of massless particles in curved spacetime (i.e. through gravitational fields) is slightly increased with respect to flat spacetime

$$\delta t_S = -\frac{1+\gamma}{c^3}\int_{r_e}^{r_o} U(\boldsymbol{r}(l))\,dl$$

parametrizes deviation from Einstein-Maxwell theory, which minimally couples classical EM to GR

$$\gamma_{EM} = \gamma_{GW} = 1$$

in Einstein-Maxwell theory

gravitational potential

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Consider only effect of Milky Way outside sphere of 100 kpc and use Keplerian potential with mass $2.5 \times 10^{11} M_\odot$

$$\Longrightarrow \quad -2.6 \times 10^{-7} \leqslant \gamma_{GW} - \gamma_{EM} \leqslant 1.2 \times 10^{-6}$$

Best absolute bound from Shapiro delay with Cassini spacecraft: $\gamma_{EM} - 1 = (2.1 \pm 2.3) \times 10^{-5}$

Neutron star mergers within f(R) gravity

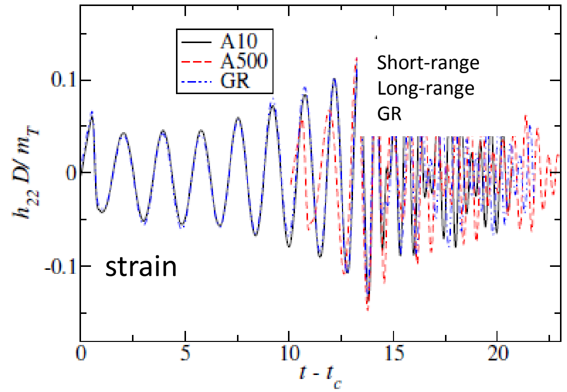
arXiv:17 09.06634 (gr-qc)

Sagunski, Zhang, Johnson, Lehner, Sakellariadou, Liebling, Palenzuela, Neilsen

$$f(R) = R + a_2 R^2$$

In theories where NS obtain a significant scalar charge, the resulting attractive finite-range attractive scalar force has implications for both the inspiral and merger phases of binary systems.

In the case of a short-range scalar force, the inspiral waveform is quite near that of GR.



As the stars merge, they form a massive NS which rotates at a varying frequency as the object compresses and decompresses.

Plotting the square root of the power spectral density, one sees a shift towards higher frequencies in the case of the short-range scalar force as compared to GR, implying that in this case the scalar force inside the NS plays a non-trivial role in the post-merger dynamics.