Testing Lorentz violation in the gravity sector using Gravitational Waves

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Probing dark sector and GR at all scales

CERN
23 August, 2017

LIGO detections of binary black holes

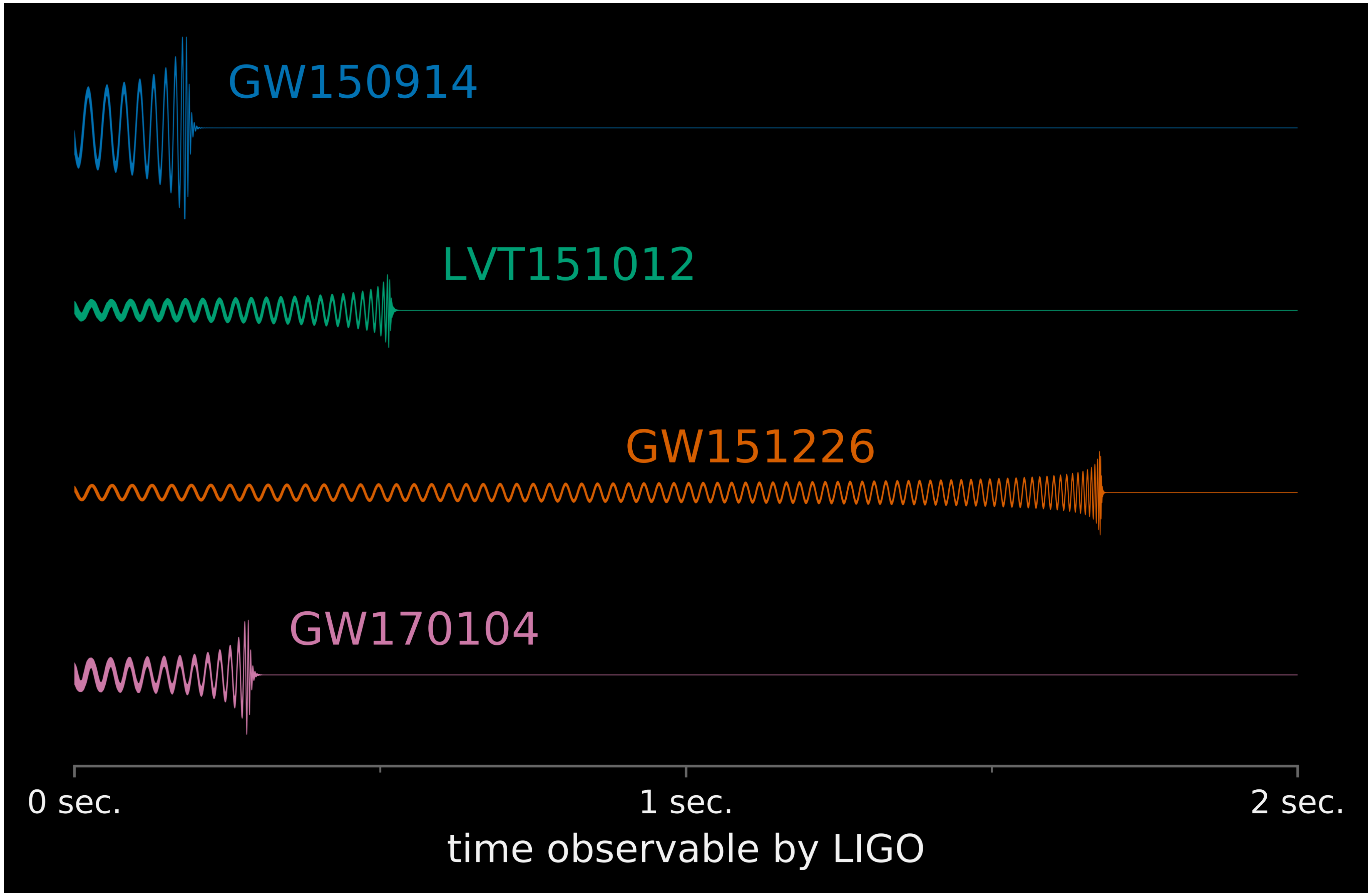
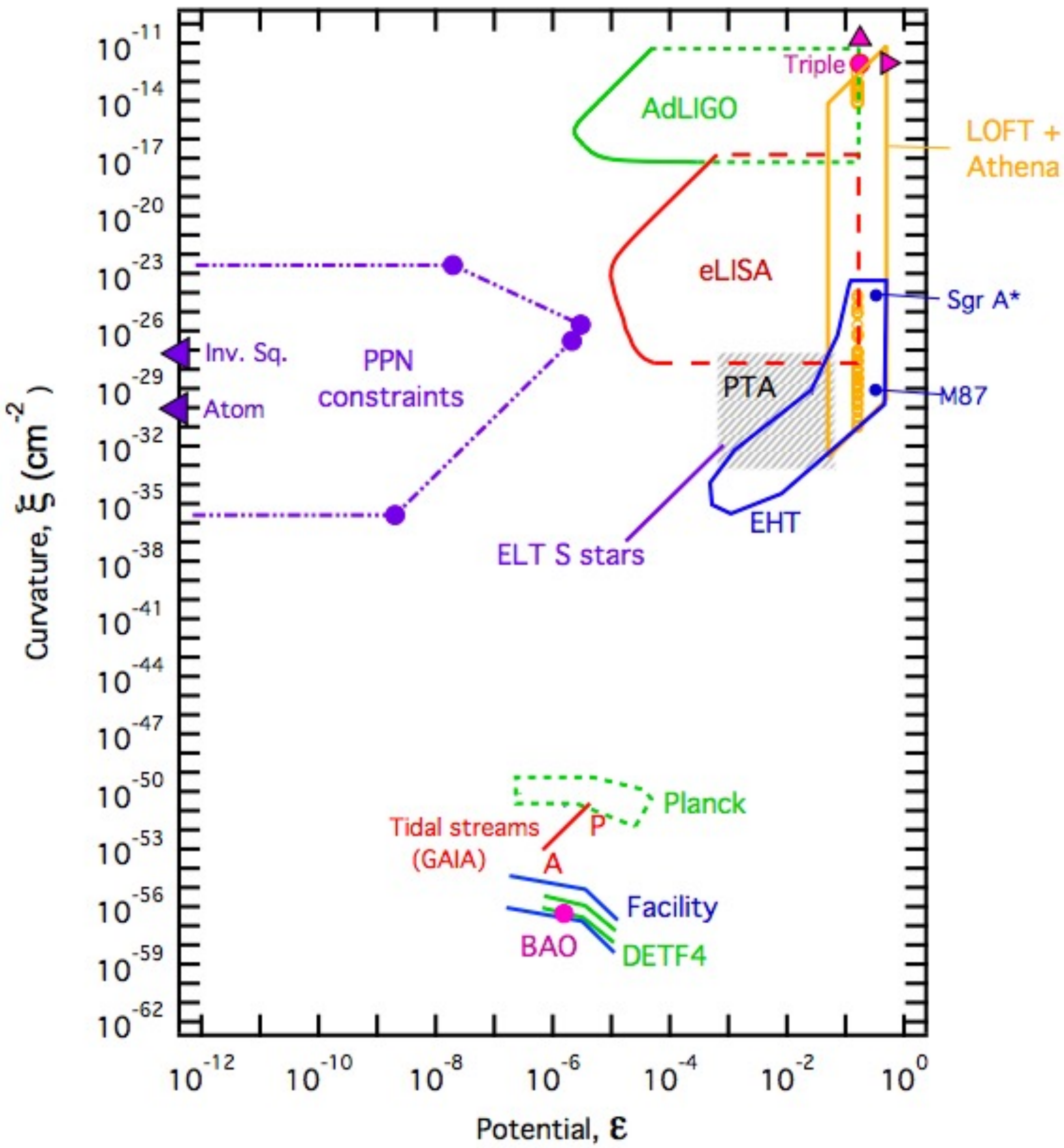


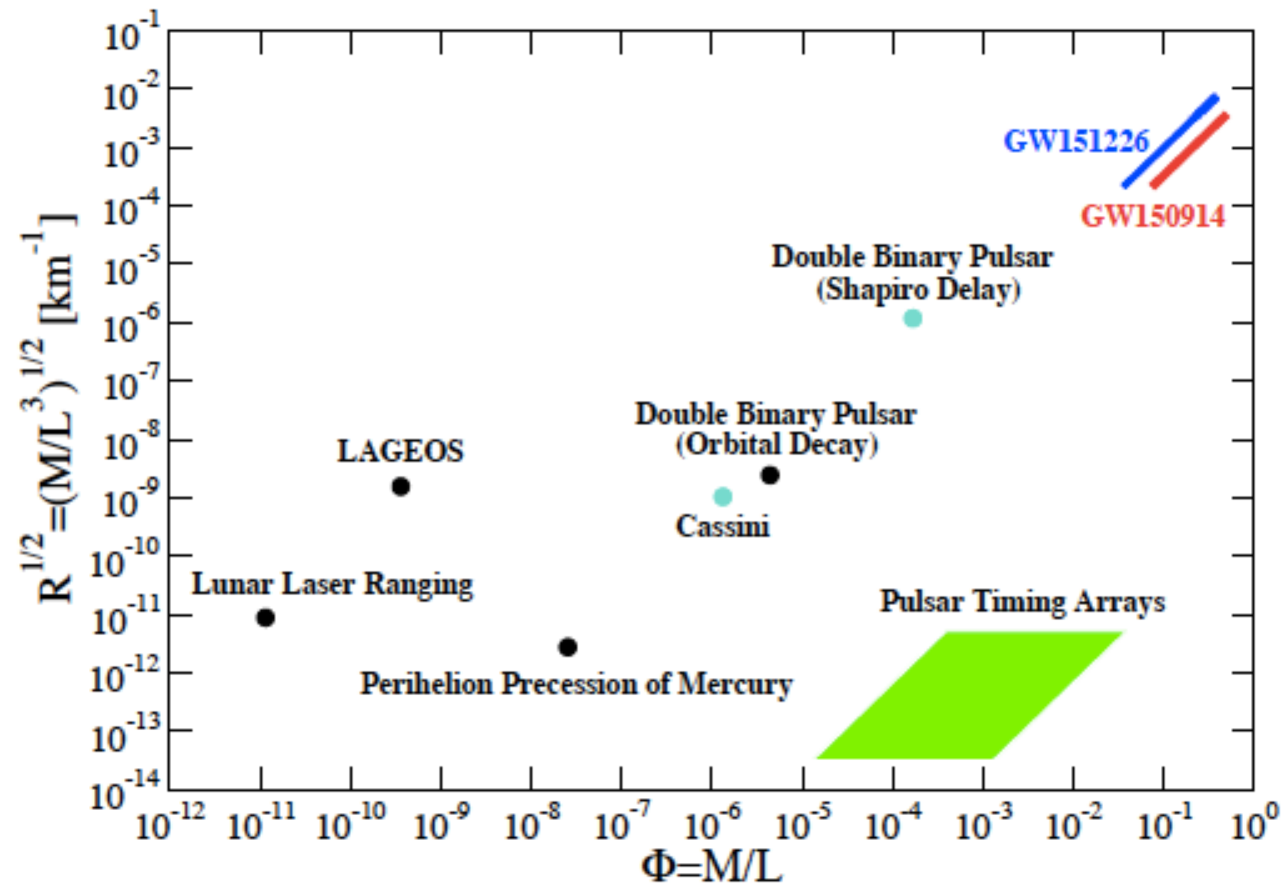
Fig courtesy: LSC

Gravitational Waves

A new probe of strong-gravity

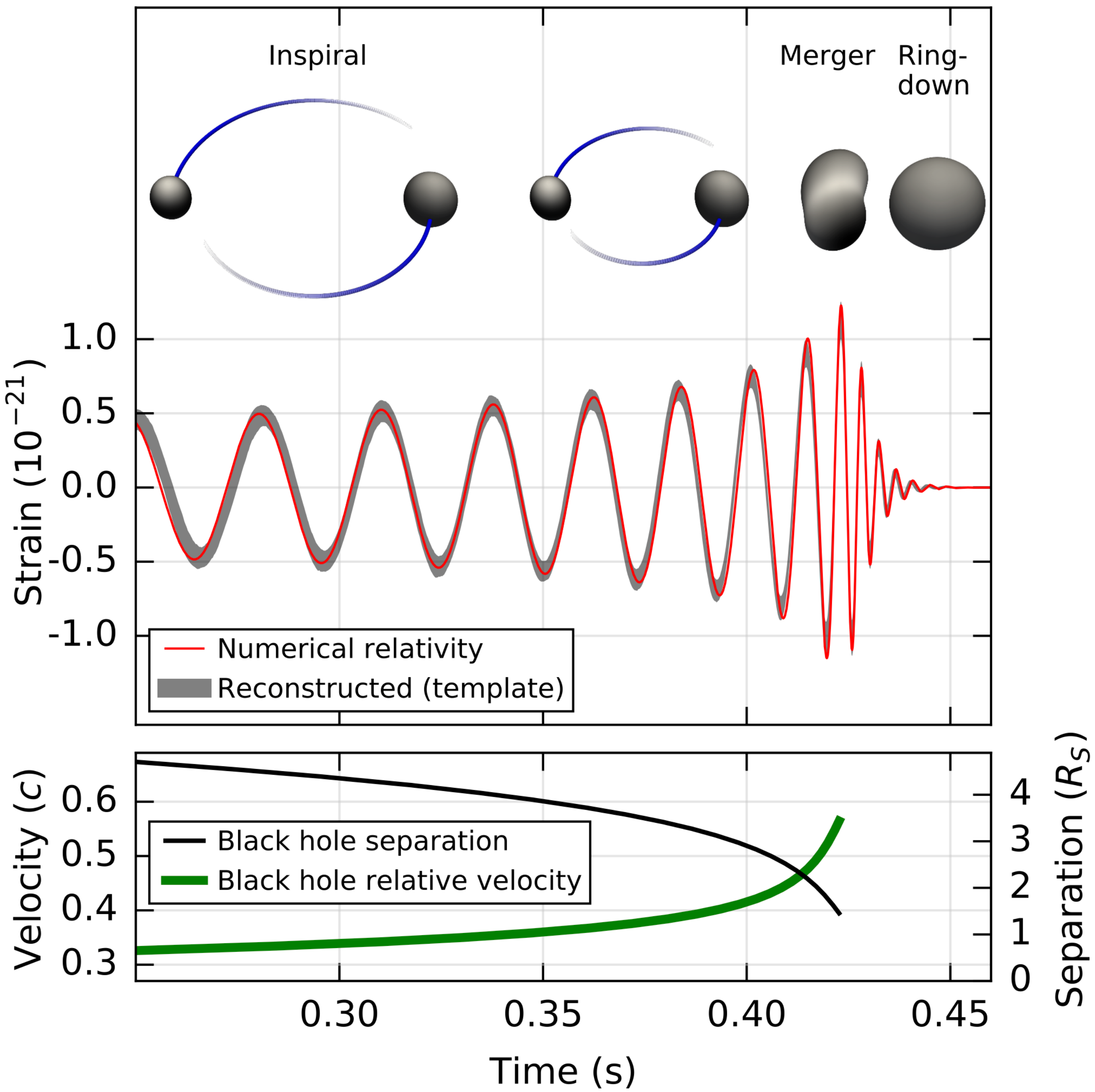


Baker+ 2014



Yunes+ 2016

Binary Black hole Dynamics



LVC, Phys. Rev. Lett. 116, 061102 (2016)

Gravitational Waveform

Schematic Gravitational Waveform →

$$\boxed{\tilde{h}(f) = A(f)\, e^{i\Psi(f)}}$$

$$A(f) = \frac{\mathcal{A}(\text{angles, masses})}{D_L}\,\alpha(f)$$

$\alpha_{\text{inspiral}} = -7/6$

$\alpha_{\text{merger}} = 2/3$

$\alpha_{\text{ringdown}} = \mathcal{L}(f)$

$$\Psi(f) = 2\pi f t_c - \phi_c + \frac{3}{128\eta\, v^5}\sum_{k=0}^{N} \psi_k v^k$$

Masses, Spins, Eccentricity, Tidal, non-GR

Accurately measure Phase

How to Test GR using GWs?

$$\psi = \psi_{\rm GR} + \delta\psi \longleftarrow \text{non-GR signature}$$

GW observations can constrain the dephasing generically or for particular theories of gravity

With future detectors, we may use amplitude information too.

Testing Lorentz violations

- Model/Theory dependent constraints
  - Compute the dephasing in a particular Lorentz violating theory of gravity and obtain the constrain from observations.
- Model independent constraints.
  - Look for generic signatures of Lorentz violation such as modified dispersion relation, propagation speed etc

Generation effects Vs Propagation effects

Speed of gravitational waves

Difference in time of arrival of the GW signal at the two LIGO detectors can be used to place bounds on the speed of GWs

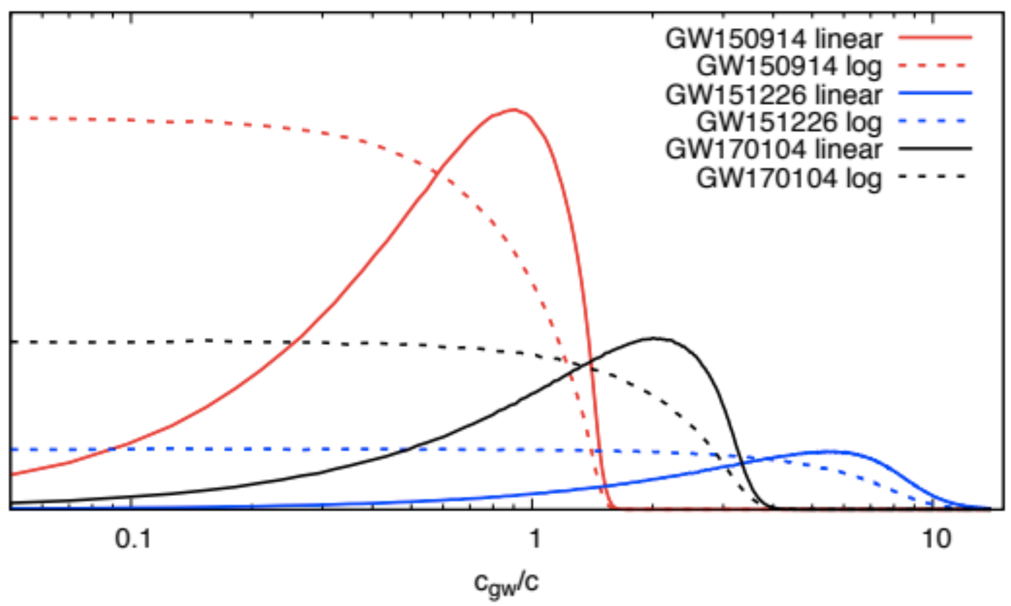


FIG. 1. Posterior distributions for the gravitational wave propagation speed derived from each of the individual LIGO events for prior distributions uniform in $c_{\rm gw}$ or $\ln c_{\rm gw}$.

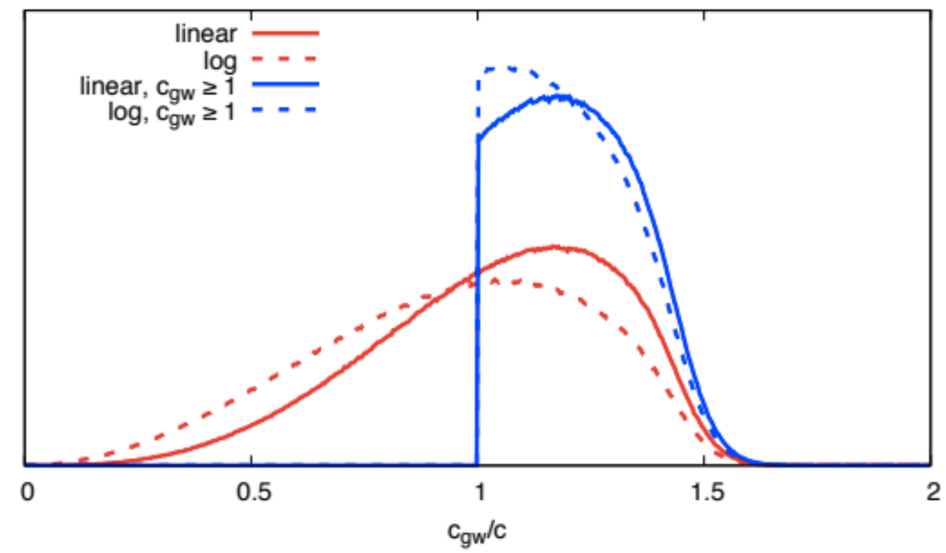


FIG. 2. Posterior distributions for the gravitational wave propagation speed derived by combining the first three LIGO detections. Prior distributions uniform in $c_{\rm gw}$ or uniform in $\ln c_{\rm gw}$ were considered, with the interval starting at either $c_{\rm L} = c/100$ or $c_{\rm L} = c$.

Blas+ 2016, Cornish+ 2017

Constraining modified dispersion relation

Dispersion and Massive Graviton

C.Will, 1998

Modified Dispersion Relation

$$E^2 = p^2c^2 + m_g^2c^4$$

Compton wavelength of graviton

$$\lambda_g = \frac{h}{m_g c}$$

$$\left(\frac{v_{\rm gw}}{c}\right)^2 = 1 - \frac{h^2c^2}{\lambda_g^2\,E^2}$$

High frequency GWs arrive earlier than low frequency ones

$$\boxed{D = \frac{1+z}{a_0}\int_{t_e}^{t_a} a(t)dt}$$

Dephasing is large for large distance and small frequencies

$$\delta\psi_{\rm MG} = -\frac{\pi D c}{\lambda_g^2(1+z)\,f}$$

Dephasing due to Massive Graviton

Projected bounds pre-detection

Inspiral only

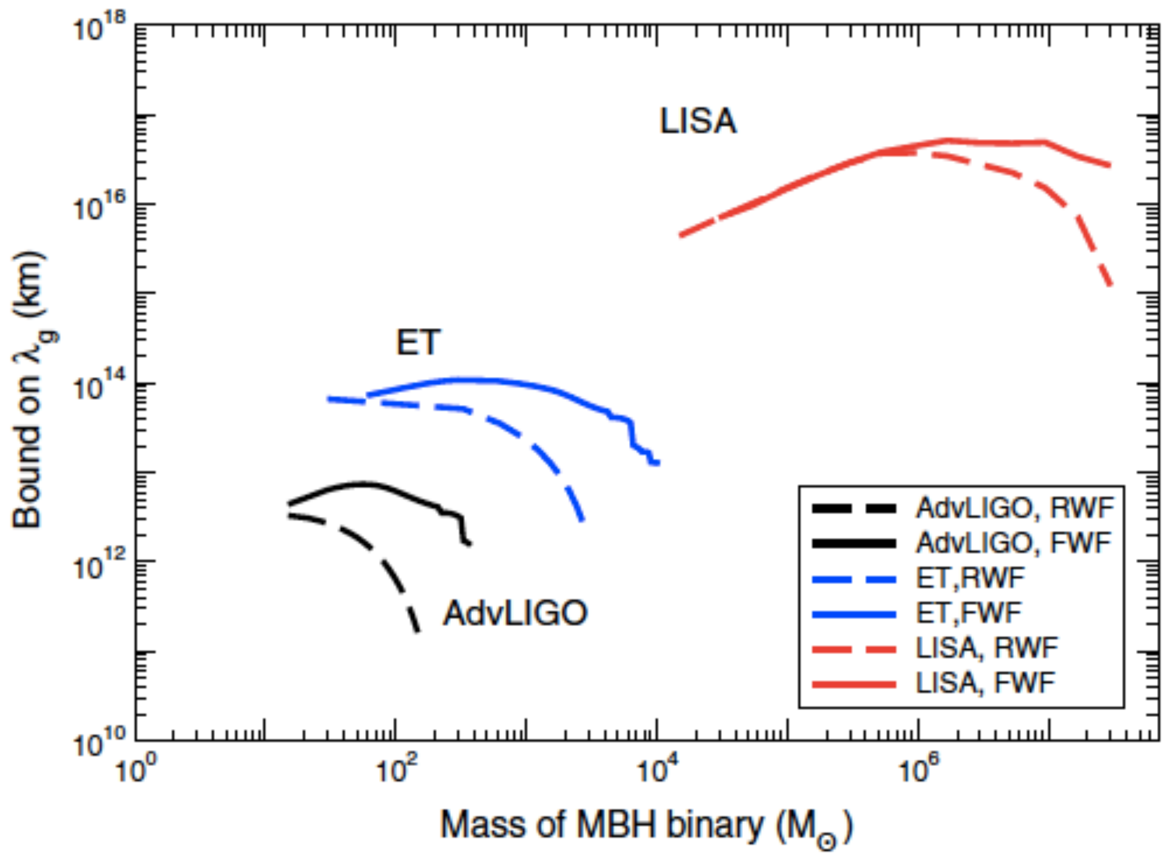
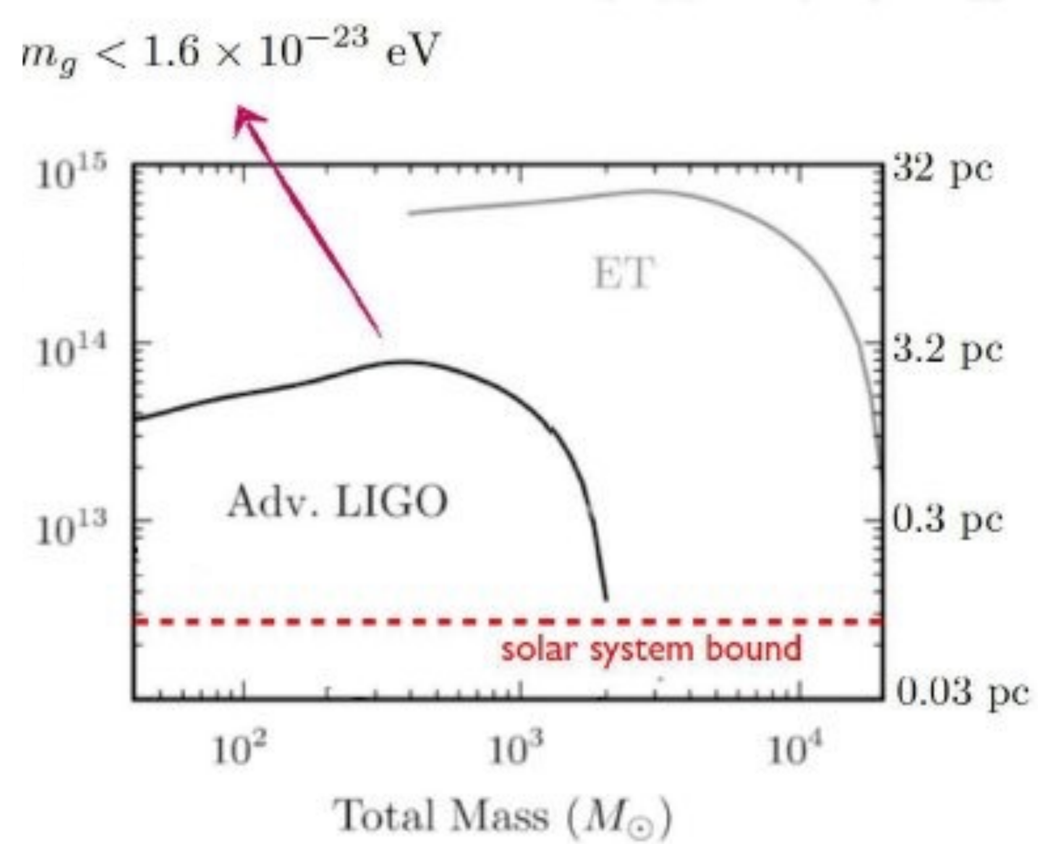


Figure 1. Bounds on the graviton Compton wavelength that can be deduced from AdvLIGO, Einstein telescope and LISA. The mass ratio is 2. The distance to the source is assumed to be 100 Mpc for AdvLIGO and ET, and 3 Gpc for LISA.

KGA, Will, 2009

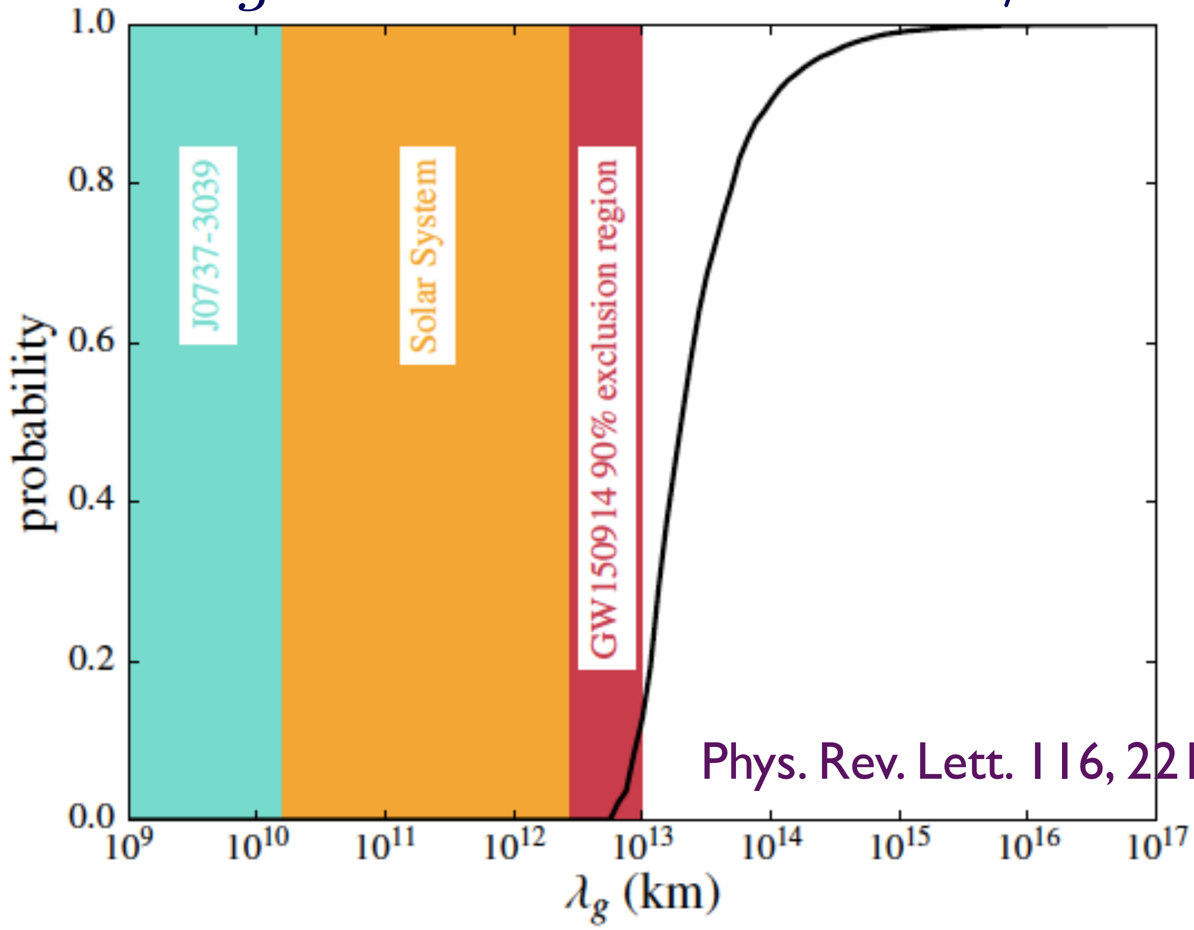
Inspiral + Merger + Ringdown



Keppel and Ajith, 2011

Graviton mass: Current GW bound

$$m_g \leq 1.2 \times 10^{-22} \mathrm{eV}/c^2$$



Phys. Rev. Lett. 116, 221101 (2016)

FIG. 8. Cumulative posterior probability distribution for λ_g (black curve) and exclusion regions for the graviton Compton wavelength λ_g from GW150914. The shaded areas show exclusion regions from the double pulsar observations (turquoise), the static Solar System bound (orange) and the 90% (crimson) region from GW150914.

Current Bound from 3 detections

$$\boxed{m_g \leq 7.7 \times 10^{-23} \mathrm{eV}/c^2}$$

LVC, Phys. Rev. Lett., 118, 221101 (2017)

Lorentz violating dispersion relation

Mirshekari, Yunes, Will, 2011

$$E^2 = p^2c^2 + A\,p^\alpha c^\alpha$$

Exponent of LV

magnitude of LV

wavelength scale

$$\lambda_A = hA^{\frac{1}{\alpha-2}}$$

$$\frac{v_{\rm gw}}{c} \simeq 1 + \frac{\alpha-1}{2} A E^{\alpha-2}$$

GWs propagate subliminally
or superluminally depending on alpha
and A

Dephasing

$$\delta\psi_{\alpha\neq1} = -\frac{\pi}{1-\alpha}\frac{D_\alpha}{\lambda_A^{2-\alpha}}\frac{f^{\alpha-1}}{(1+z)^{1-\alpha}}$$

$$\delta\psi_{\alpha=1} = \frac{\pi D_1}{\lambda_A}\ln\left(\pi\mathcal{M}f\right)$$

Aim: Use phase information to bound energy scale of LV

alpha=2 case

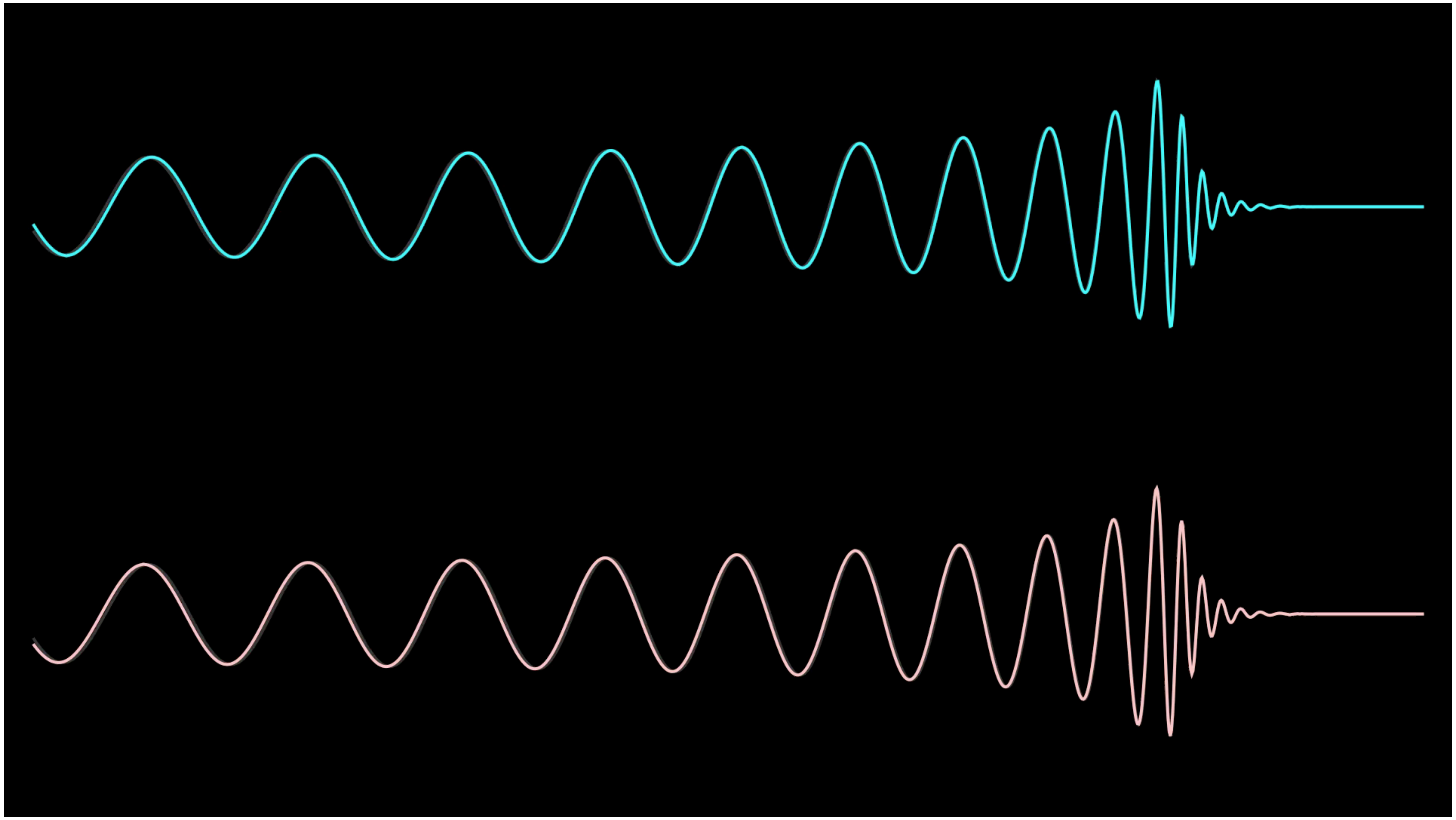
$$E^2 = p^2 c^2 (1 + A) = p^2\, \bar{c}^2$$ ← change in the speed of GWs

Dephasing due to this is completely degenerate with time of arrival term in the phasing.

$$\delta\psi \sim 2\pi f t_c$$

Same as in Blas+, Cornish+

Animation



Courtesy: Tyson+

Actual parameter estimation

Samajdar+ (In preparation, 2017)

- Use phenomenological Inspiral-Merger-Ringdown waveforms in frequency domain. (Effective One-body waveforms calibrated to numerical relativity is also used to verify).

- Add the dephasing due to LV to the overall phase.

- Bayesian parameter estimation using a set of parameters

$$\{t_c, \phi_c, \theta, \phi, \psi, \iota, D_L, M, \eta, \chi_{\rm eff}, \chi_p, A\}$$

- Redshift and the new distance scale are accounted for in the post-processing using luminosity distance and standard cosmological model

Results

- Bounds on A are always upper bounds.
- Bounds on energy scale of LV are upper bounds for alpha <2 and lower bounds for alpha >2.
- For alpha <2, wavelength bounds may be more appealing as they give a sense of the "screening length" or "range" which is infinity in GR.

$$E \sim A^{\frac{1}{2-\alpha}}$$

$$\alpha < 2 : \;\; A \leq xx, E \leq yy$$
$$\alpha > 2 : \;\; A \leq xx, E \geq yy$$

$$\lambda_A = hA^{\frac{1}{\alpha-2}}$$

$$\alpha < 2 : \;\; A \leq xx, \;\; \lambda_g \geq yy$$

Bounds from GW observations

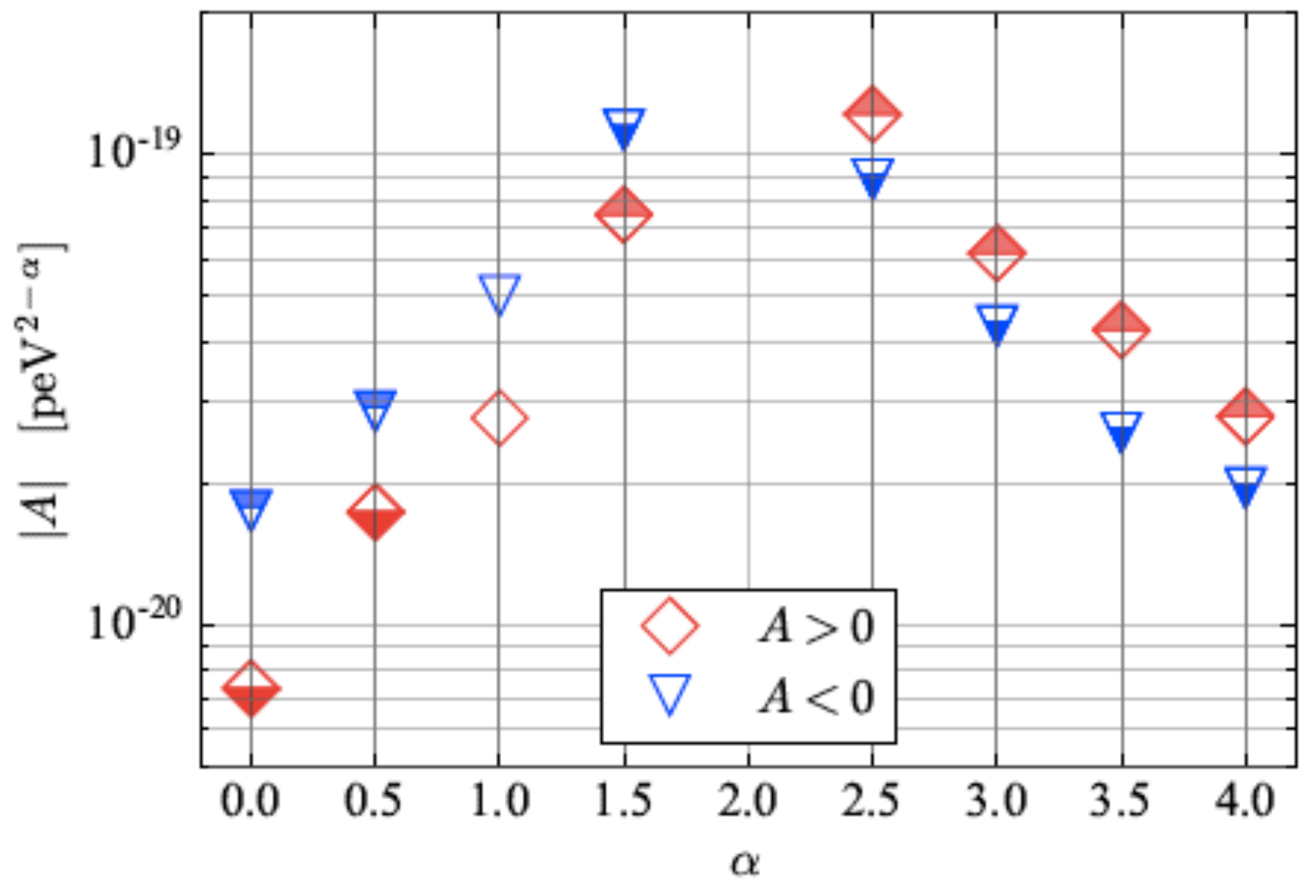


FIG. 5. 90% credible upper bounds on $|A|$, the magnitude of dispersion, obtained combining the posteriors of GW170104 with those of GW150914 and GW151226. General relativity corresponds to $A = 0$. Markers filled at the top (bottom) correspond to values of $|A|$ and α for which gravitational waves travel with superluminal (subluminal) speed.

1peV ~ h x 250 Hz

LVC, Phys. Rev. Lett., 118, 221101 (2017)

Constraints on screening lengths ($\alpha < 2$)

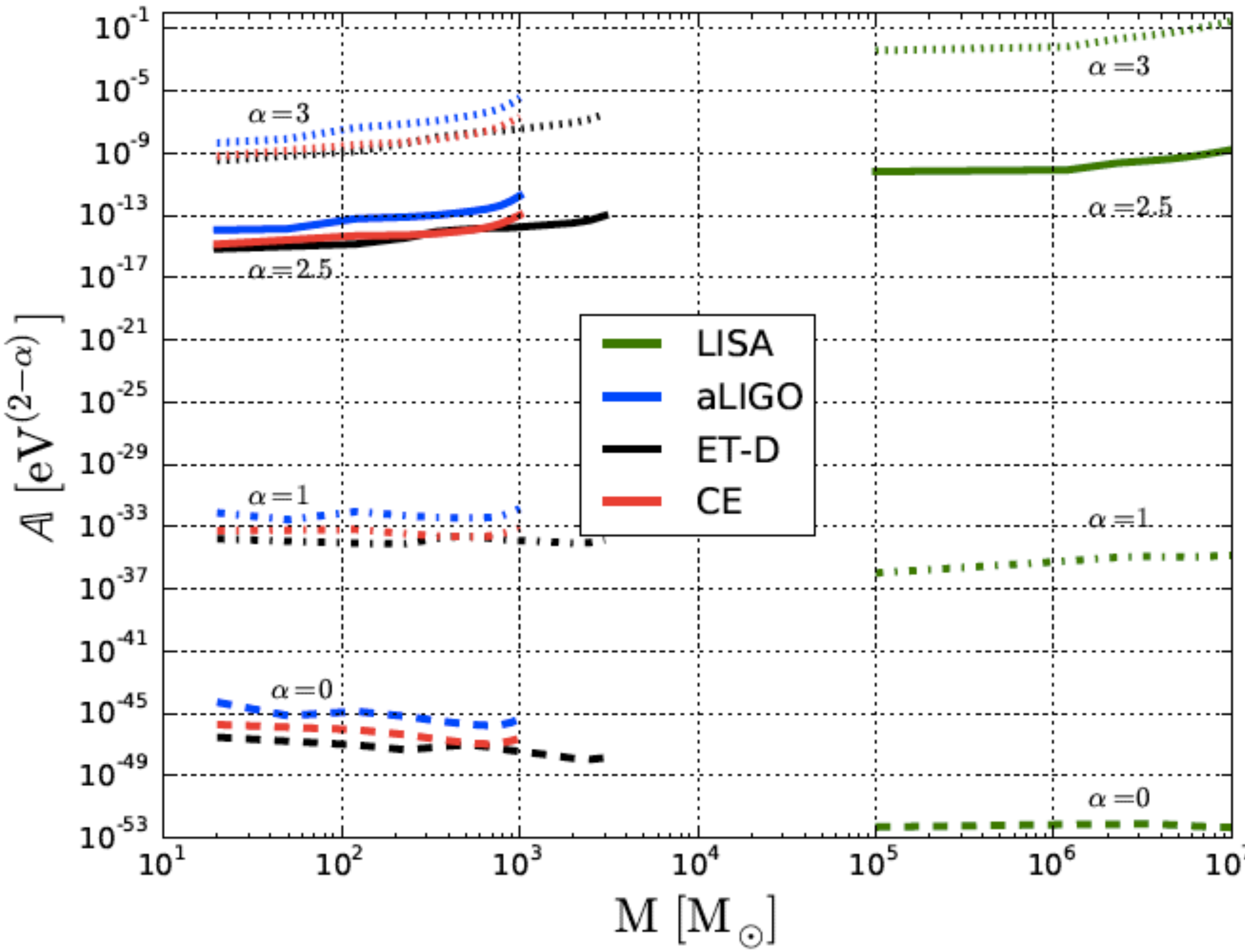
TABLE IV. 90% credible level lower bounds on the length scale λ_A for Lorentz invariance violation test using GW170104 alone.

	$A > 0$	$A < 0$
$\alpha = 0.0$	1.3×10^{13} km	6.6×10^{12} km
$\alpha = 0.5$	1.8×10^{16} km	6.8×10^{15} km
$\alpha = 1.0$	3.5×10^{22} km	1.2×10^{22} km
$\alpha = 1.5$	1.4×10^{41} km	2.4×10^{40} km

Hubble Radius $\sim 10^{23}$ km

LVC, Phys. Rev. Lett., 118, 221101 (2017)

Projections for future



Samajdar, KGA, 2017 (Also, Chamberline and Yunes 2017)

Comparison with other observations

TABLE V. 90% confidence level lower bounds on the energy scale at which quantum gravity effects might become important $E_{\rm QG}$. Bounds are grouped into theories which produce subluminal and superluminal gravitational-wave propagation. The results from GW170104 are considerably less constraining than those obtained with other methods, but they are the first direct constraints of Lorentz invariance violation in the superluminal gravity sector.

		$\alpha = 3$	$\alpha = 4$
Sub	GW170104	1.1×10^{7} eV	3.6×10^{-3} eV
	Gamma rays [210]	5×10^{24} eV	1.4×10^{16} eV
	Neutrino [211]	1.2×10^{26} eV	7.3×10^{20} eV
	Cherenkov [207, 209]	4.6×10^{35} eV	5.2×10^{27} eV
Super	GW170104	6.0×10^{6} eV	3.2×10^{-3} eV
	Neutrino [208]	1.2×10^{33} eV	1.2×10^{24} eV

LVC, Phys. Rev. Lett., 118, 221101 (2017)

Summary

- GW observations can be used to constrain dispersion of GWs.
- This may be interpreted as possible bounds on Lorentz violation, as different LV theories of gravity may predict dephasing at different orders in the phasing.
- Propagation effects and no generation effect.
- Best constraints are for alpha between 2 and 2.5.
- Constraints on ranges for alpha < 2, can probe Trans-Hubble screening lengths.