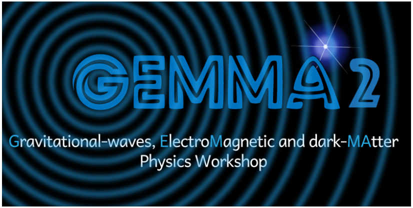
Testing GR with LVK data



Rome, 2024 Sep 19

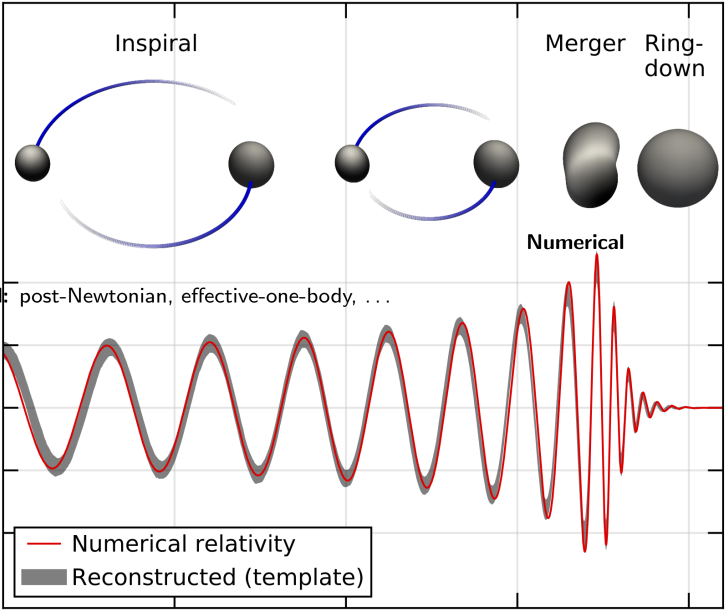
Archisman Ghosh

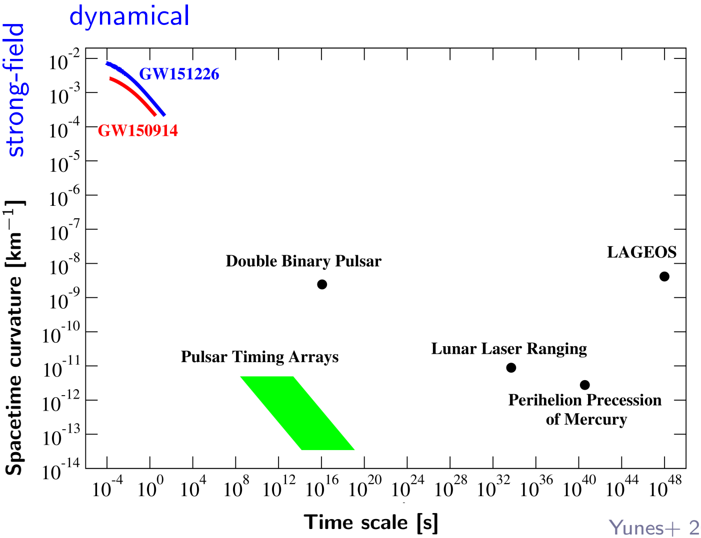
Ghent University

GHENT UNIVERSITY

LIGO VIRGO KAGRA

GW150914: LVC: Abbott+, PRL **116**, 061102 (2016)




dynamical
strong-field
GW151226
GW150914
Double Binary Pulsar
LAGEOS
Pulsar Timing Arrays
Lunar Laser Ranging
Perihelion Precession of Mercury
Spacetime curvature [km^{-1}]
Time scale [s]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-4} 10^{0} 10^{4} 10^{8} 10^{12} 10^{16} 10^{20} 10^{24} 10^{28} 10^{32} 10^{36} 10^{40} 10^{44} 10^{48}

Yunes+ 2016

Tests of GR

"Testing GR": a suite of tests

Consistency residuals
inpiral-merger-ringdown consistency

ringdown (search for "higher modes")

Generation generic parameterized deformations
specific deformations to test non-BH nature

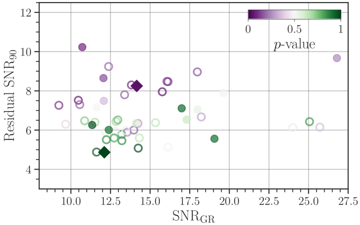
"echoes" from exotic compact objects

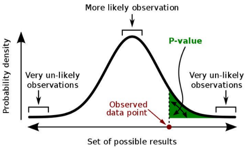
Propagation GW dispersion relation (Lorentz violation, m_g)

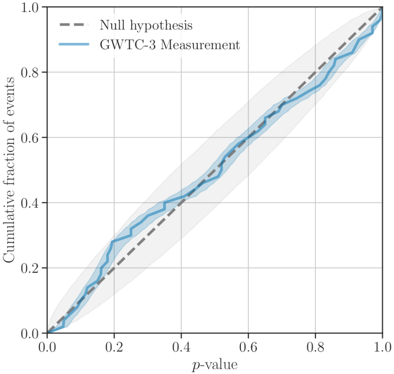
Polarization

Residuals test (using BayesWave)

Residual of the data after subtracting the best-fit waveform is statistically consistent with detector noise at other times when no signal is present.





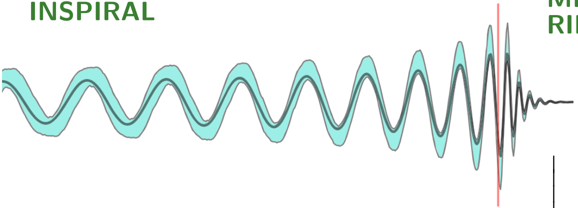


LVK: Abbott+ arXiv:2112.06861

Inspiral-merger-ringdown consistency test

INSPIRAL

MERGER-RINGDOWN



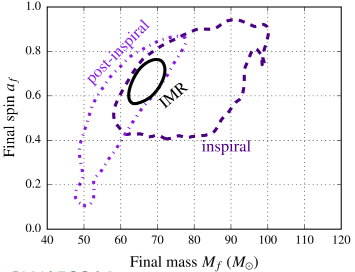
Final "remnant" mass and spin

⇕ COMPARE!

Initial "component" masses and spins —General relativity→ Independent prediction of final "remnant" mass and spin

Inspiral-merger-ringdown consistency test

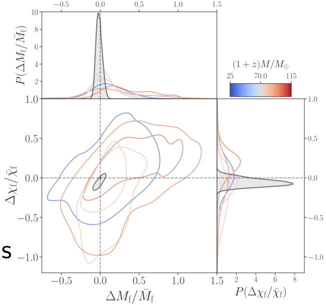
Ghosh+ 2016 (with **AG**); Ghosh+ 2018 (with **AG**)



GW150914

LVC: Abbott+, PRL **116**, 221101 (2016)

Mass and spin of the remnant object estimated from the inspiral and merger-ringdown parts agree with each other given GR predictions.



Combine information from multiple detections (assuming systematic deviations)

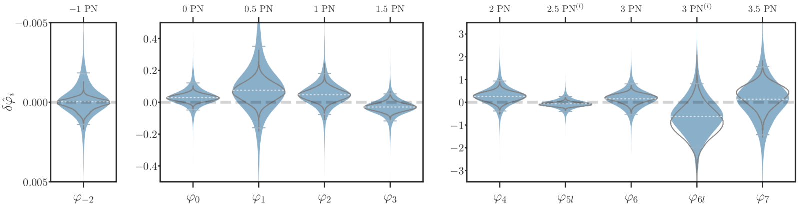
$\Rightarrow$ stronger constraints!

LVK: Abbott+ arXiv:2112.06861

Parameterized deformations from GR

Deviation parameters do not show any departure from their GR values.

LVK: Abbott+ arXiv:2112.06861



Dipole radiation

Measurement of orbital dynamics beyond leading order in v/c.

Deviation in $\left(\frac{v}{c}\right)^3$ coefficient constrained to $\mathcal{O}(10\%)$

Dynamical self-interaction of spacetime

Spin-orbit interaction

Modified dispersion

Modified dispersion relation: Will (1998); Mirshekari+ (2012)

different frequencies travel with different speeds

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

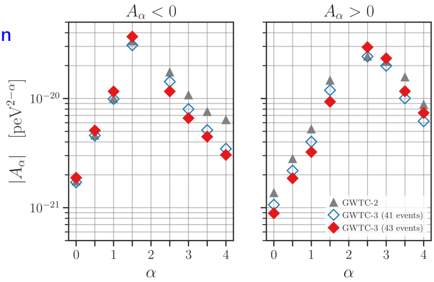
$$\lambda_{\mathbb{A}} \equiv hc\mathbb{A}^{1/(\alpha-2)}$$

$\alpha \neq 0 \quad \rightarrow \quad$ local Lorentz invariance violation

$\alpha = 0 \quad \rightarrow \quad$ massive graviton (for $\mathbb{A} > 0$)

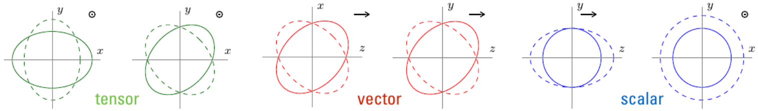
$$\lambda_g \equiv \frac{h}{m_g c} \gtrsim \times 10^{14}\,\text{km}$$

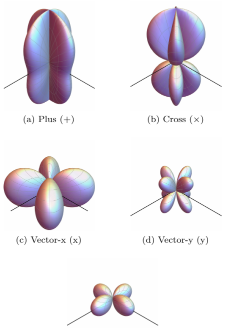
$$m_g < 1.27 \times 10^{-23} \text{eV}/c^2$$



LVK: Abbott+ arXiv:2112.06861

Polarization with multiple detectors





(a) Plus (+) (b) Cross (×)

(c) Vector-x (x) (d) Vector-y (y)

(e) Scalar (s)

six polarizations $\longrightarrow$ distinct antenna patterns

$$|F^I_{\rm t}(\alpha,\delta)| \equiv \sqrt{F^I_{+}(\alpha,\delta)^2 + F^I_{\times}(\alpha,\delta)^2}\,,$$

$$|F^I_{\rm v}(\alpha,\delta)| \equiv \sqrt{F^I_{\rm x}(\alpha,\delta)^2 + F^I_{\rm y}(\alpha,\delta)^2}\,,$$

$$|F^I_{\rm s}(\alpha,\delta)| \equiv \sqrt{F^I_{\rm b}(\alpha,\delta)^2 + F^I_{\rm l}(\alpha,\delta)^2}$$

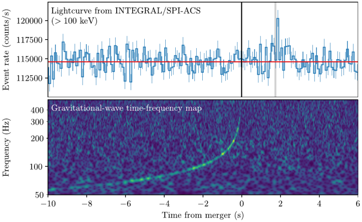
In GR: GW are transverse, traceless
only tensor polarizations

pure tensor / pure scalar = 1000 / 1
pure tensor / pure vector = 200 / 1

Isi & Weinstein (2017) **Need multiple detectors!** lensing? LVC: Abbott+, PRL **119**, 141101 (2017)

Constraints from GW170817+GRB

Delay of only a few seconds after a propagation over one hundred million light years.



$$t_{\rm EM} - t_{\rm GW} = 1.74 \pm 0.05\,{\rm s}$$

Constraints on speed of gravity assuming GRB emitted within 10s of GW

$$-3\times 10^{-15} \leqslant \frac{v_{\rm GW}-v_{\rm EM}}{v_{\rm EM}} \leqslant +7\times 10^{-16}$$

"Shapiro time delay" of GW and EM in gravitational potential of galaxy:

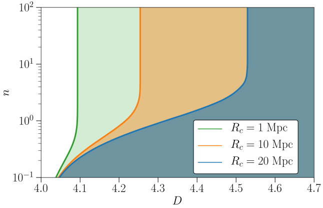
$$-2.6\times 10^{-7} \leqslant \gamma_{\rm GW} - \gamma_{\rm EM} \leqslant 1.2\times 10^{-6}$$

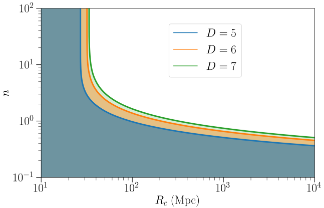
Test of the equivalence principle.

LVC: Abbott+ Astrophys. J. **848** #2, L13 (2017)

Tests of general relativity with GW170817

- Constraints on scalar-tensor theories $\alpha_T \equiv \frac{v_{\mathrm{GW}}^2}{v_{\mathrm{EM}}^2} - 1 < \mathcal{O}(10^{-15})$
- Constraints on Lorentz-violating extensions of the standard model
- Expected $1/r$ fall-off $\rightarrow$ constraints on extra dimensions





Exotic compact objects

Question: are we really seeing black holes?

Exotic compact objects mimicking black holes:

Boson stars, dark matter stars, gravastars, wormholes, fuzzballs, ...

Question: are we really seeing black holes?

Exotic compact objects mimicking black holes:

Boson stars, dark matter stars, gravastars, wormholes, fuzzballs, . . .

How to search for exotic compact objects?

Question: are we really seeing black holes?

Exotic compact objects mimicking black holes:

Boson stars, dark matter stars, gravastars, wormholes, fuzzballs, ...

How to search for exotic compact objects?

Three "complementary" ways in three different regimes:

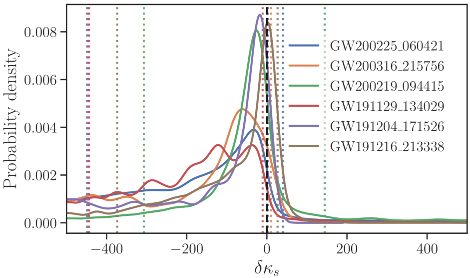
- **Finite size effects** during inspiral.
- No-hair conjecture with **ringdown** quasinormal modes.
- Search for post-merger oscillations or **"echoes"**.

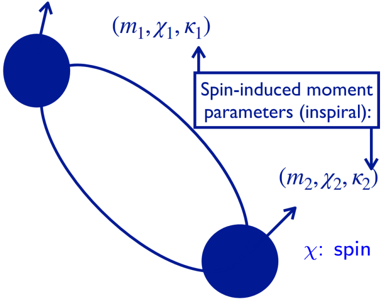
Spin-induced quadrupole moments

LVK: Abbott+ arXiv:2112.06861

$$Q = -\kappa\chi^2 m^3$$

$\kappa = 1$ for BH **[no hair]**





Credit: Krishnendu, Saleem

Search for "echoes" after the merger

In a large class of exotic compact objects,

Horizon-scale corrections $\Rightarrow$

Modulated and distorted train of "echoes".

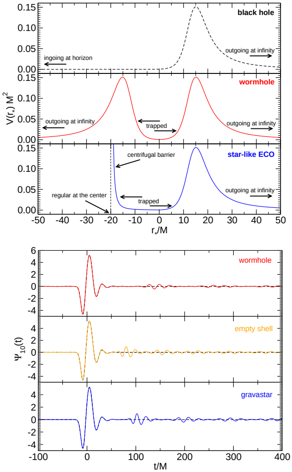
$$\Delta t = nM \log(M/\ell)$$

n=8: wormholes

n=4: empty shell

n=6: thin-shell gravastars

Cardoso+ 2016



Relatively soon even with ℓ_{Planck} corrections.

For an event like GW150914, $\Delta t = \mathcal{O}(100\,\text{ms})$, at aLIGO design can hope to see first few echoes.

Can search for "echoes" immediately following the binary-merger detection.

Search for echoes

Modelled search? waveforms not sufficiently modelled

Unmodelled search? unlikely to recover a signal

Robust features? Assuming that the remnant is relatively stable . . .

- Time difference between subsequent echoes.
- A "damping" at each reflection.
- A "phase-shift" at each reflection.
- Some change of the frequency content: "widening". Zachary+ 2017

A model-agnostic coherent search for echoes

Use wavelets that are trains of sine-Gaussians to reconstruct the signal

$$\Psi(t; A_n, f_0, \tau, t_n, \phi_n) = \sum_{n=0}^{N_{\text{echoes}}} A e^{-(t-t_n)^2/\tau_n^2} \cos\left(2\pi f_0 (t - t_n) + \phi_n\right)$$

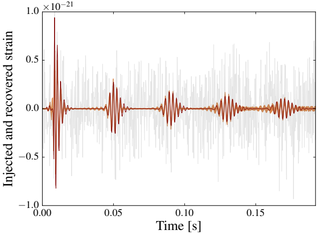
With:

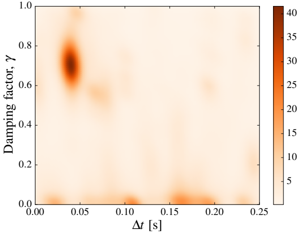
$A_n = \gamma^n A$	damping
$\tau_n = w^n \tau$	widening
$t_n = t_0 + n\Delta t$	time between subsequent echoes
$\phi_n = \phi_0 + 2\pi f_0 n\Delta t + n\Delta\phi$	phase shift subsequent echoes

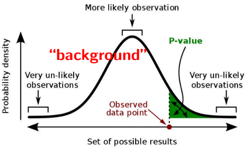
PHYSICAL REVIEW D **98,** 024023 (2018)

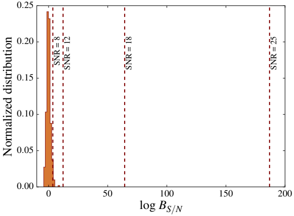
A morphology-independent data analysis method for detecting and characterizing gravitational wave echoes

Ka Wa Tsang,[1] Michiel Rollier,[1] Archisman Ghosh,[1] Anuradha Samajdar,[1] Michalis Agathos,[2] Katerina Chatziioannou,[3] Vitor Cardoso,[4] Gaurav Khanna,[5] and Chris Van Den Broeck[1,6]

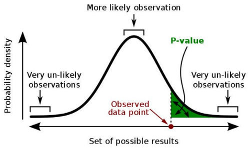


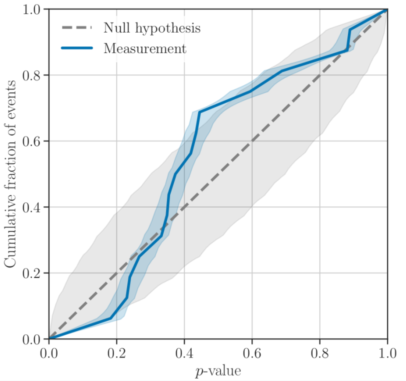






O3b / GWTC-3 observations





LVK: Abbott+ arXiv:2112.06861

Are we looking at GR violations?

Data in Tension with GR

Due to Noise Artifacts?	Caused by Waveform Systematics?	Due to Astrophysical Causes?
Non-Stationarity	Missing Physics: Eccentricity; Tides, Viscosity; Kicks; Ringdown Modes	Gravitational Lensing
Non-Gaussianity, Glitches		Environments
Overlapping Signals		Mistaken Source Class
Data Gaps, Detector Calibration	Inaccurate Modelling	Astrophysical Population

Gupta+ arXiv:2405.02197

The way forward

- Identification of potential candidates

- Classification of false violations

- What if we detect a violation?

  Assessing its significance

  "GR violation checklist"