Recent results from LIGO, Virgo, and KAGRA

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be.HEP Meeting
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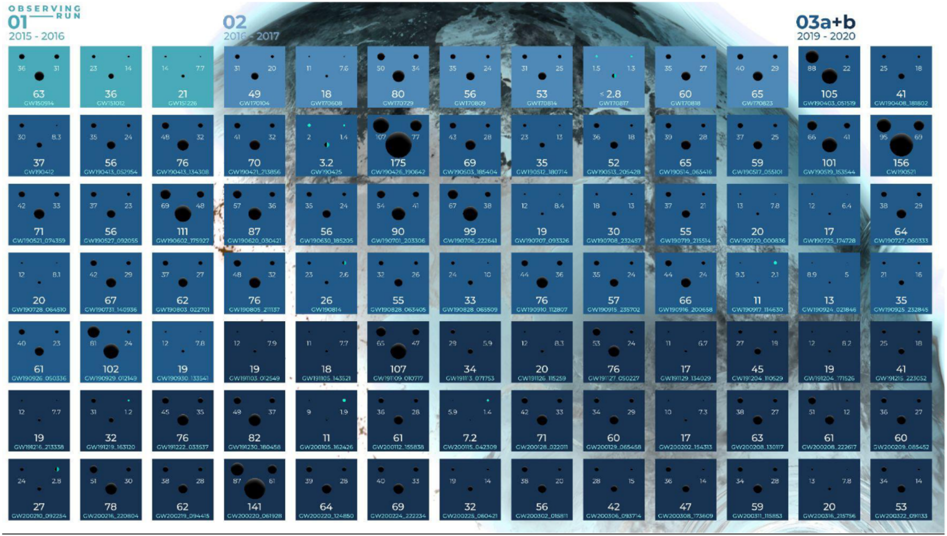
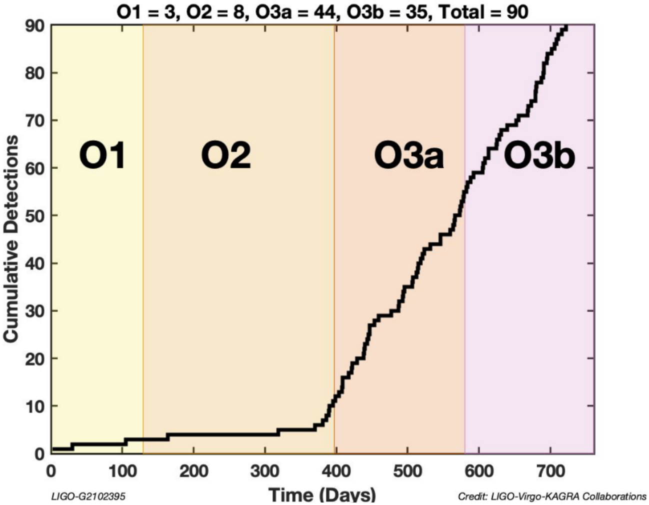
GHENT UNIVERSITY

Compact binary coalescences



Compact binary coalescences



GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run

The population of merging compact binaries inferred using gravitational waves through GWTC-3

Tests of General Relativity with GWTC-3

Constraints on the cosmic expansion history from GWTC–3

Plan of this talk

- Overview ✓

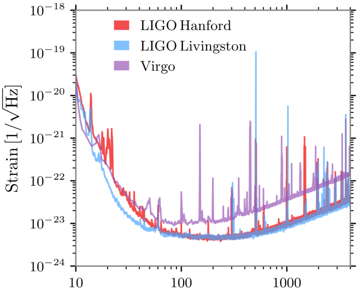
- Tests of GR with compact binaries

- Cosmology with compact binaries

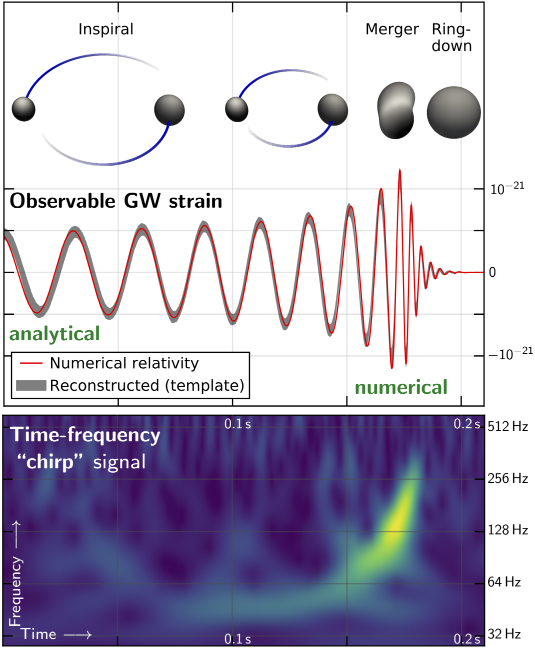
- Outlook and a zoom-out

Tests of GR

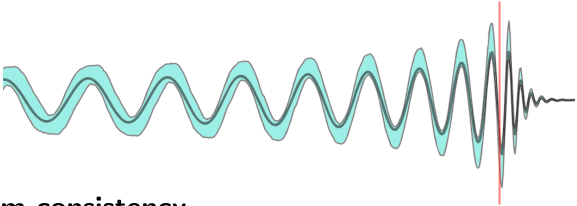
GW150914: LVC: Abbott+, PRL **116**, 061102 (2016)



LVK: Abbott+ arXiv:2111.03606



Tests of GR: rely on the GW waveform model



Waveform consistency

For example: Ghosh *et al.* (2016); Ghosh *et al.* (2017)

Parameterized deformations

For example: Li *et al.* (2011); Agathos *et al.* (2013); Meidam *et al.* (2017)

For example: Samajdar & Arun (2017)

Generation **Propagation**

Constraints from modified dispersion

Modified dispersion relation:

Will (1998); Mirshekari *et al.* (2012)

different frequencies travel with different speeds

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

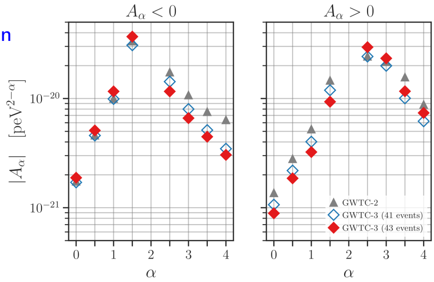
$$\lambda_{\mathbb{A}} \equiv hc\mathbb{A}^{1/(\alpha-2)}$$

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

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

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

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



LVC: Abbott+ arXiv:2112.06861

Probing the nature of compact objects

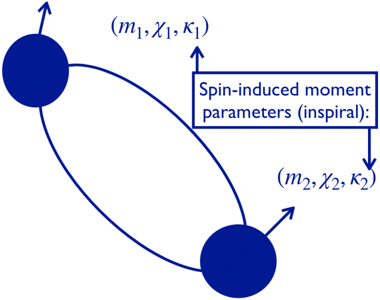
Are they really black holes, or exotic objects mimicking black holes?

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

Three "complementary" ways in three different regimes:

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

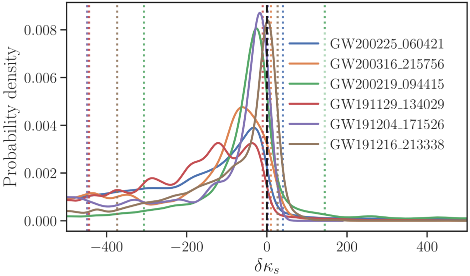
Spin-induced quadrupole moments

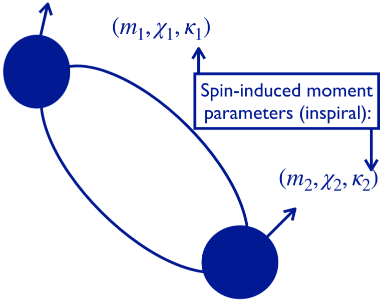


Credit: Krishnendu, Saleem

Spin-induced quadrupole moments

LVC: Abbott+ arXiv:2112.06861





Credit: Krishnendu, Saleem

A search for echoes from exotic compact objects

Wavelets (trains of sine-Gaussians) to reconstruct the signal. UNMODELLED

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

$A_n = \gamma^n A$ damping

$\tau_n = w^n \tau$ widening

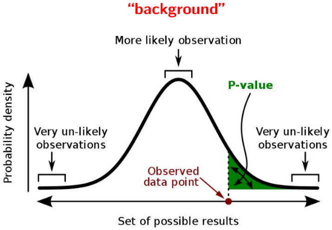
$t_n = t_0 + n\Delta t$ time between subsequent echoes

$\phi_n = \phi_0 + 2\pi f_0 n\Delta t + n\Delta\phi$ phase shift subsequent echoes

Tsang+ 2018

LVC: Abbott+ arXiv:2112.06861

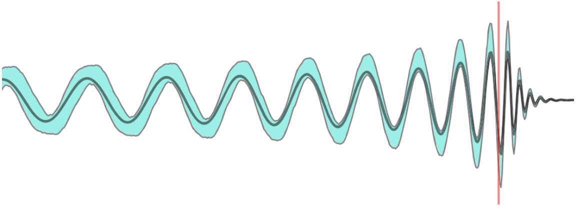
Event	p-value
GW191109_010717	0.35
GW191129_134029	0.35
GW191204_171526	0.37
GW191215_223052	0.23
GW191216_213338	0.88
GW191222_033537	0.89
GW200115_042309	0.44
GW200129_065458	0.33
GW200202_154313	0.43
GW200208_130117	0.24
GW200219_094415	0.18
GW200224_222234	0.59
GW200225_060421	0.69
GW200311_115853	0.42
GW200316_215756	0.27



Cosmology

Gravitational-wave standard sirens

Schutz (1986), Holz & Hughes (2005)



Phase evolution $\Rightarrow \mathcal{M}^z \equiv \mathcal{M}(1+z)$ "redshifted chirp mass"

Amplitude $\sim \frac{\mathcal{M}^z}{d_L} \times \text{fn.(angles)} \Rightarrow d_L$ "luminosity distance" (inclination)

GW from compact binaries give direct access to distance!

self-calibrated independent of, in particular, the **distance ladder**

$(d_L, z) \rightarrow$ cosmological parameters

Distance-redshift relation:

Late-time expansion / acceleration parameters

$$d_L = c(1+z)\int^z \frac{dz'}{H(z')}\,,\quad H(z') = H_0\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}$$

$\uparrow$

Lemaître-Hubble law

Hubble constant

Where can z come from?

Spectral lines for GW?

For BBH, z degenerate with mass

NS physics / population astrophysics

EM counterparts | galaxy catalogs

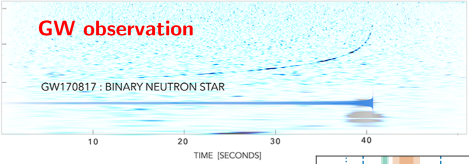
doi:10.1038/nature24471

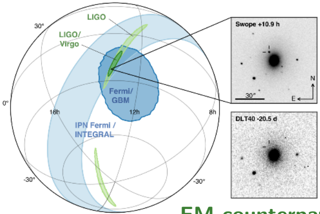
A gravitational-wave standard siren measurement of the Hubble constant

↖ self-calibrated distance indicator

The LIGO Scientific Collaboration and The Virgo Collaboration*, The 1M2H Collaboration*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory Collaboration*, The VINROUGE Collaboration* & The MASTER Collaboration*

GW observation





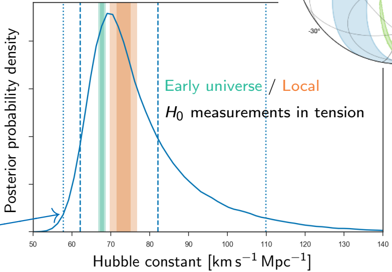
EM counterpart

↓

redshift, z

↓

distance, d_L

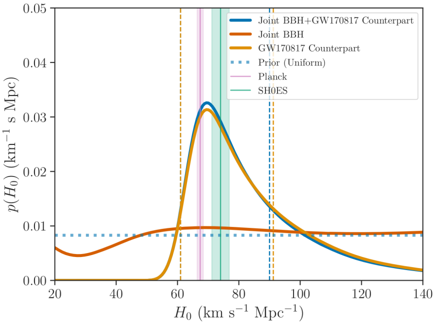


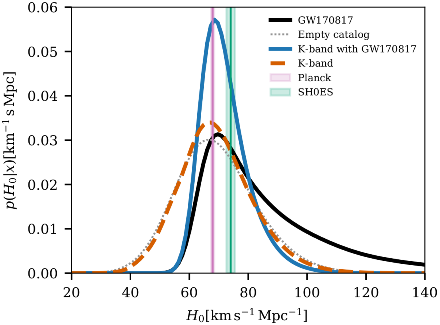
Early universe / Local

H_0 measurements in tension

First GW standard siren measurement of H_0

Results with inclusion of "dark sirens"

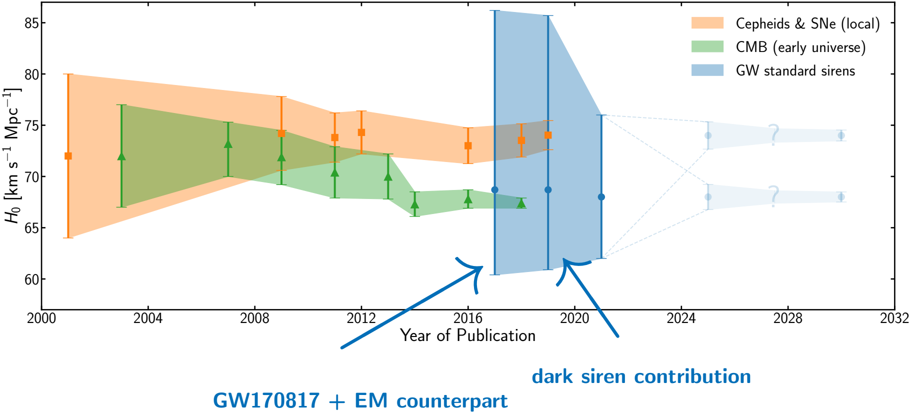




O2 BBH: LVC: Abbott+ Astrophys. J. **909** #2, 218 (2021)

O3 BBH: LVC: Abbott+ arXiv:2111.03604

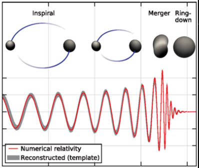
Gravitational-waves to resolve the Hubble tension?



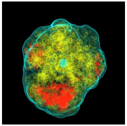
A new era of observational cosmology?

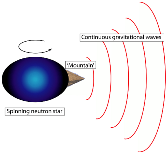
Zoom-out

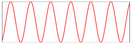
Other gravitational-wave sources

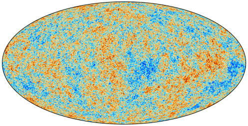


	Modelled	Unmodelled
Transient	Compact binary coalescences NS-NS, NS-BH, BBH	Bursts Supernova explosions
Persistent	Continuous waves Spinning deformed NS	Stochastic background Astrophysical + Cosmological









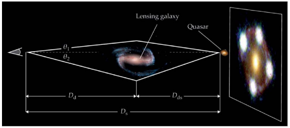
What will we see next?

Exotic physics around black holes **neutron stars**

GW **lensing**

Strong lensing: search for lensed pairs, time delays

Weak lensing: cross-correlations



Supernova burst *together with neutrinos?*

Dark matter with GW

Stochastic GW background

Extra slides

"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

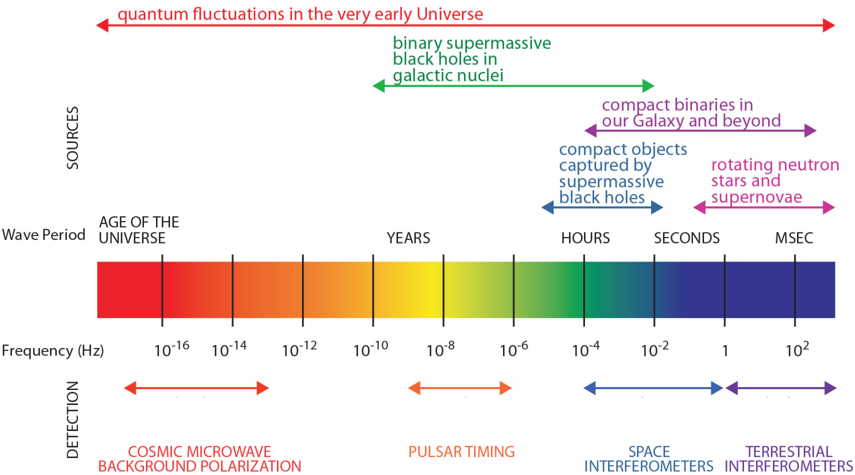
"echoes" from exotic compact objects

Propagation GW dispersion relation (Lorentz violation, m_g)

Polarization

Challenge: connecting theory to modelling!
how small are non-BH effects?

GW detectors



Slide from: **Samaya Nissanke**

Future detectors

Moore, Cole, & Berry, http://gwplotter.com/