Fundamental physics and cosmology from gravitational-wave observations

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Nikhef, Amsterdam

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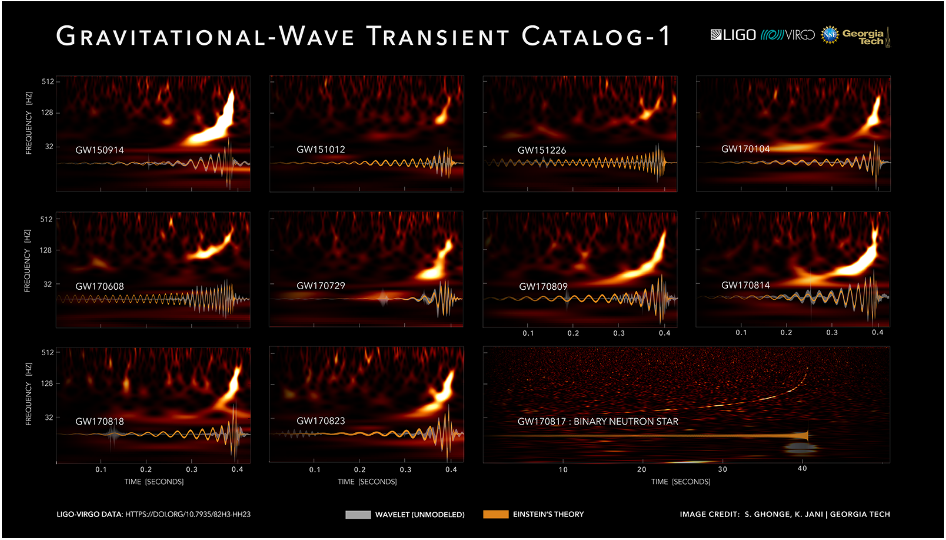
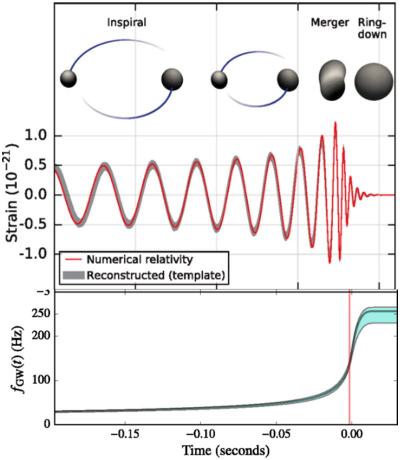
2019 January 10



GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
LIGO VIRGO Georgia Tech
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1
0.2
0.3
0.4
10
20
30
40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH

Abbott *et al.*, PRL **116**, 061102 (2016)



Abbott *et al.*, PRL **116**, 221101 (2016)

Selected for a Viewpoint in *Physics*

PRL **116,** 221101 (2016) PHYSICAL REVIEW LETTERS week ending 3 JUNE 2016

Tests of General Relativity with GW150914

B. P. Abbott *et al.**

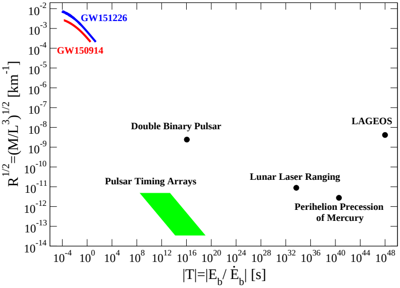
(LIGO Scientific and Virgo Collaborations)

(Received 26 March 2016; revised manuscript received 9 May 2016; published 31 May 2016)

Probing strong-field gravity

First probes into the dynamical regime of strong field general relativity (GR).

Yunes *et al.* (2016)

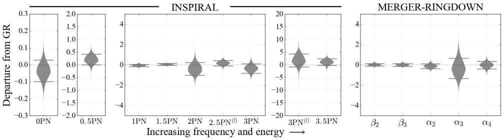


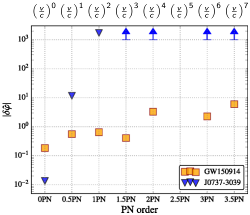
Constraints on parameterized deformations from GR

Allowing coefficients in waveform models to deviate from their GR values, the deviation parameters do not show any departure from their GR values.

Li *et al.* (2011); Agathos *et al.* (2013); Meidam (PhD thesis, 2017); Meidam *et al.* (2017)

GW150914 + GW151226 + GW170104





GW150914

Abbott *et al.*, PRL **116**, 221101 (2016)

Abbott *et al.*, PRL **118**, 221101 (2017)

First-ever 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

Constraints from modified dispersion

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

Modified dispersion relation:

(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

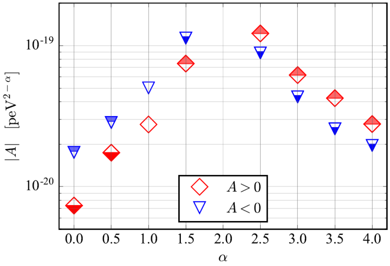
$\alpha = 0 \quad \rightarrow \quad$ massive graviton (for $\mathbb{A} > 0$)

GW150914 + GW151226 + GW170104

$$\lambda_g \equiv \frac{h}{m_g c} > 1.6 \times 10^{13}\text{km}$$

$$m_g < 7.7 \times 10^{-23}\text{eV}/c^2$$

Effect gets enhanced with propagation over a distance!



GW150914 + GW151226 + GW170104
Abbott *et al.*, PRL **118**, 221101 (2017)

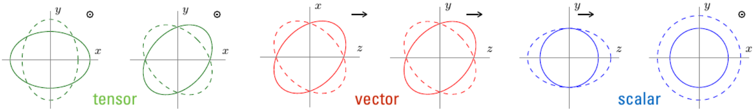
TABLE III. 90% credible level lower bounds on the length scale λ_A for Lorentz invariance violation test using GW170104 alone. GW170104

	$A > 0$	$A < 0$
$\alpha = 0.0$	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

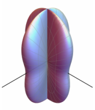
Agathos (PhD thesis, 2016); Samajdar (PhD thesis, 2017); Samajdar & Arun (2017)

Hubble scale $\approx 1.3 \times 10^{23}$km

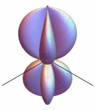
Polarization from 3-detector observation of GW170814



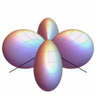
six polarizations ⟶ distinct antenna patterns



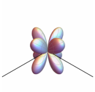
(a) Plus (+)



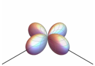
(b) Cross (×)



(c) Vector-x (x)



(d) Vector-y (y)



(e) Scalar (s)

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

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

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

In GR: GW are transverse, traceless
only tensor polarizations

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

Isi & Weinstein (2017)

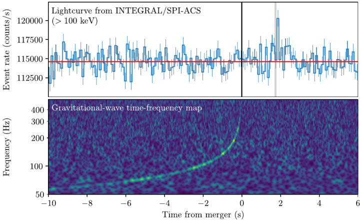
Need multiple detectors: **thanks to Virgo!**

Abbott *et al.*, PRL **119**, 141101 (2017)

Constraints from GW170817+GRB

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

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



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

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

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

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

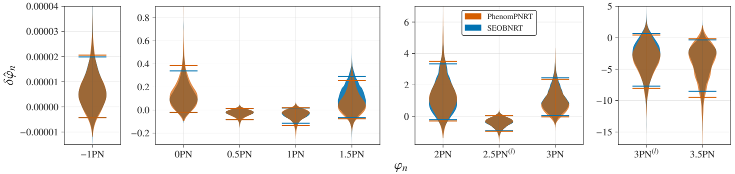
Test of the equivalence principle.

Abbott *et al.* Astrophys. J. **848** #2, L13 (2017)

Tests of general relativity with GW170817

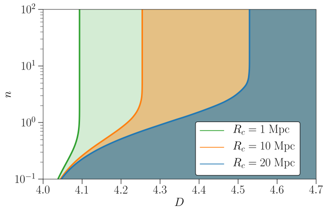
Dipole radiation

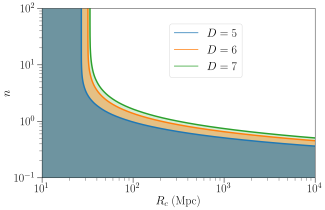
Abbott *et al.* arXiv:1811.00364 [gr-qc]



- Parameterized deviations do not show any departures from GR values.

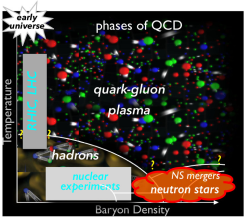
- "Inverse square law" $\rightarrow$ constraints on extra dimensions.

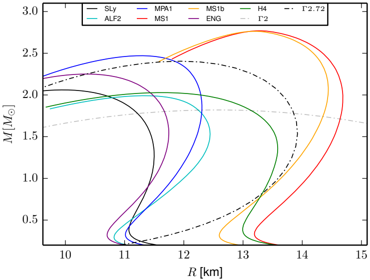


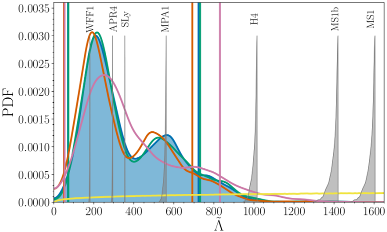


GW170817: measurement of properties of the neutron star

Figure from: Dietrich *et al.* (2015)

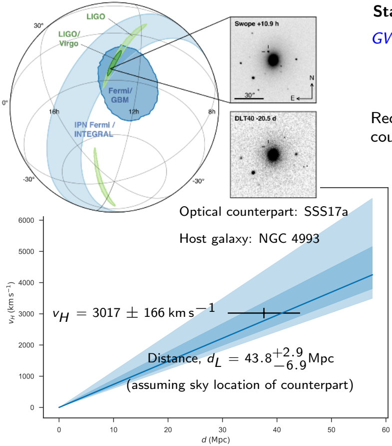






Abbott *et al.* arXiv:1805.11579 [gr-qc]

Cosmology: Hubble parameter with GW170817



Optical counterpart: SSS17a

Host galaxy: NGC 4993

$v_H = 3017 \pm 166\ \mathrm{km\,s^{-1}}$

Distance, $d_L = 43.8^{+2.9}_{-6.9}$ Mpc

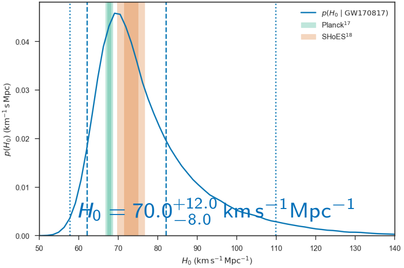
(assuming sky location of counterpart)

Standard siren Schutz (1986), Holz & Hughes (2005)

GWs provide a direct measurement of the luminosity distance!

$$v_H = H_0 d_L$$

Recession velocity (or redshift) can come from a transient EM counterpart or an identified host galaxy.



$H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$

Independent of any distance ladder!

Abbott *et al.* Astrophys. J. **848** #2, L12 (2017); LSC-EPO

Abbott *et al.* Nature **551** #7678, 85-88 (2017)

Plan of the talk

- Overview of LIGO-Virgo detections and science-results ✓
- Probing strong-field gravity

  The inspiral-merger-ringdown consistency test

  Probing into the nature of compact objects

    Ringdown

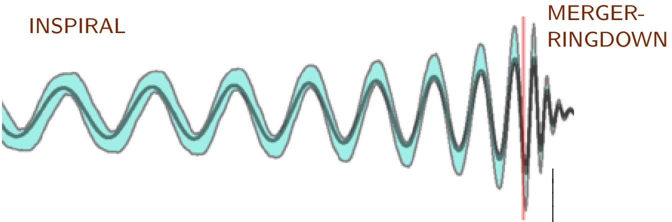
    Echoes
- Cosmology

  A "standard siren" measurement of H_0

  "H_0-statistical" and beyond
- Future prospects

Strong-field gravity

Inspiral-merger-ringdown consistency test



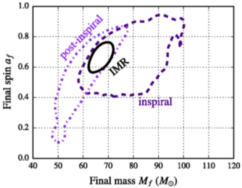
Final mass and spin

⇕ COMPARE!

NR fit

Initial masses and spins ⟶ Independent prediction of final mass and spin

Inspiral-merger-ringdown consistency test

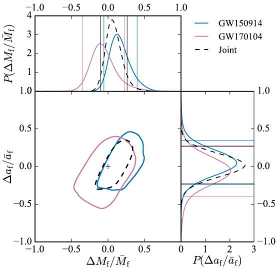


GW150914

Abbott *et al.*, PRL **116**, 221101 (2016)

Abbott *et al.*, PRL **118**, 221101 (2017)

GW150914 + GW170104

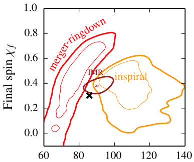


One of the first tests of GR carried out with GW150914

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

Ghosh *et al.* (2016); Ghosh *et al.* (2017)

Might not have been true in modified GR.



RAPID COMMUNICATIONS

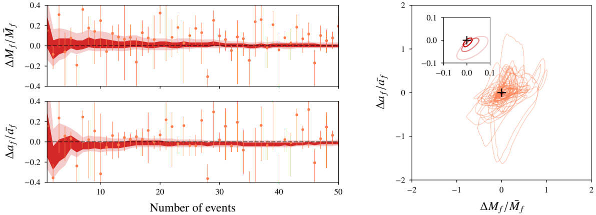
PHYSICAL REVIEW D **94**, 021101(R) (2016)

Testing general relativity using golden black-hole binaries

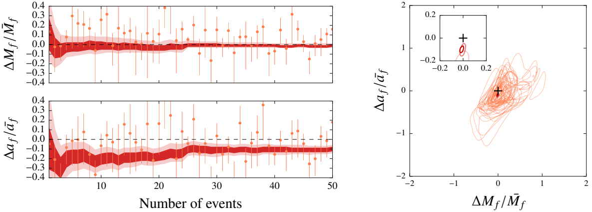
Abhirup Ghosh,[1] Archisman Ghosh,[1] Nathan K. Johnson-McDaniel,[1] Chandra Kant Mishra,[1] Parameswaran Ajith,[1] Walter Del Pozzo,[2] David A. Nichols,[3] Yanbei Chen,[4] Alex B. Nielsen,[5] Christopher P. L. Berry,[2] and Lionel London[6]

Stronger constraints on systematic departures from GR combining information from multiple detections.

Inspiral-merger-ringdown consistency test



Ghosh *et al.* (2017)



Stronger constraints on systematic departures from GR combining information from multiple detections.

Some prospects of doing better . . .

- Searching for systematic **systematic** departures.

- Is this the optimal way of testing?

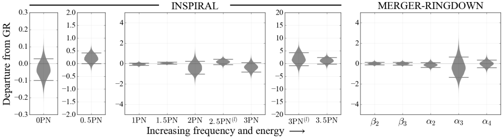
- Use theoretically motivated combinations.

  Multipole moments: Kastha *et al.* (2018)

- Use correlations between parameters.

  Insights from simulations in modified gravity?

GW150914 + GW151226 + GW170104



Abbott *et al.*, PRL **118**, 221101 (2017)

Probing the nature of the progenitor and remnant compact objects

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

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

Three "complementary" ways in three different regimes:

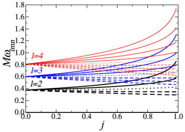
- Finite size effects during inspiral.
- No-hair conjecture with quasinormal modes.
- Search for post-merger oscillations or "echoes".

Testing the no-hair conjecture with ringdown quasinormal modes

No-hair conjecture:

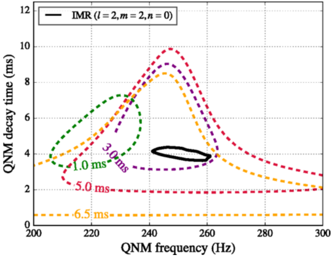
A stationary black hole in Einstein's general relativity is described only by its mass and spin.

During ringdown, the quasinormal mode frequencies and damping times will depend only on the mass and spin of the remnant black hole, which can be obtained from linearized Einstein equations on Kerr background.



Berti *et al.* (2006)

$\Rightarrow$ Test for dependences $\omega_{lmn}(M_f, J_f)$, $\tau_{lmn}(M_f, J_f)$.



Abbott *et al.*, PRL **116**, 221101 (2016)

Difficult to measure leading QNM for GW150914.

Design sensitivity $\sim$ 3 times higher.

Testing the no-hair conjecture with ringdown quasinormal modes

• Even where one is not able to isolate the individual modes, one can look for systematic departures in the QNM frequencies and damping times from their GR values.

Gossan *et al.* (2011) Meidam *et al.* (2014)

$$\omega_{lmn} = \omega_{lmn}^{GR}(1 + \delta\omega_{lmn}) \,, \quad \tau_{lmn} = \tau_{lmn}^{GR}(1 + \delta\tau_{lmn})$$

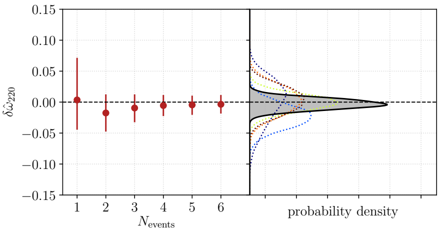
• The general expectation was that such tests would become effective only for sources detected by third generation or space-based detectors.

PHYSICAL REVIEW D **98**, 104020 (2018)

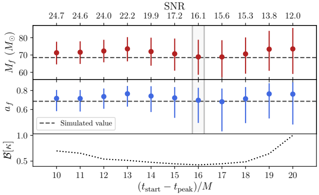
Empirical tests of the black hole no-hair conjecture using gravitational -wave observations

Gregorio Carullo,[1,2,*] Laura van der Schaaf,[2] Lionel London,[3] Peter T. H. Pang,[4] Ka Wa Tsang,[2] Otto A. Hannuksela,[4] Jeroen Meidam,[2] Michalis Agathos,[5] Anuradha Samajdar,[2] Archisman Ghosh,[2] Tjonnie G. F. Li,[4] Walter Del Pozzo,[1,6] and Chris Van Den Broeck[2,7]

- With $\mathcal{O}(5)$ BBH sources similar to GW150914, the systematic departures can be measured with an accuracy of $\sim 1.5\%$ by the Adv LIGO-Virgo at design sensitivity.



Carullo *et al.* (2018)



- Effective criterion for "start of ringdown" from point of view of parameter estimation.

Search for "echoes" after the merger

In a large class of exotic compact objects,

Horizon-scale corrections $\Rightarrow$ secondary bursts of radiation.

Modulated and distorted train of "echoes".

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

n=8: wormholes

n=4: empty shell

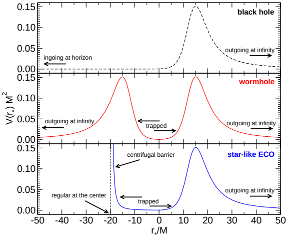
n=6: thin-shell gravastars

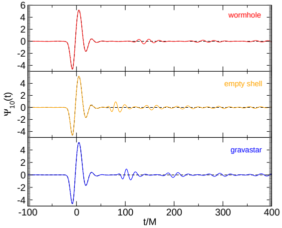
Planck-scale corrections can appear relatively soon.

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

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

Cardoso *et al.* (2016)





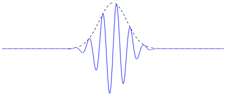
Not sufficiently modelled; Exotic objects not envisaged in literature.

One feature expected to be reasonably robust: constancy of time difference between the subsequent echoes.

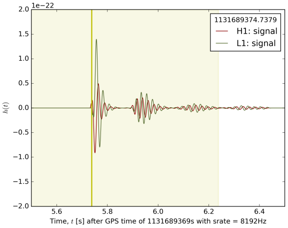
Model-agnostic search and characterization using BayesWave

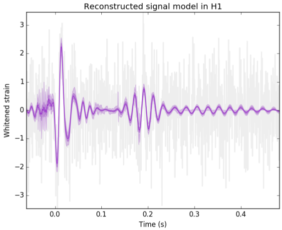
- BayesWave: Morlet-Gabor wavelet reconstruction: Cornish & Littenberg (2015)

$$h(t) = \sum_{j=0}^{N_s} \Psi(t; A_j, f_{0j}, \tau_j, t_{0j}, \phi_{0j})$$



$$\Psi(t; A, f_0, \tau, t_0, \phi_0) = Ae^{-(t-t_0)^2/\tau^2} \cos\left(2\pi f_0(t - t_0) + \phi_0\right)$$





A model-agnostic coherent search for echoes

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

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

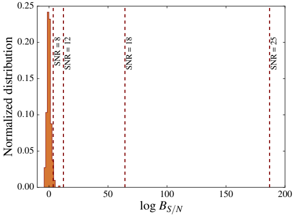
With:

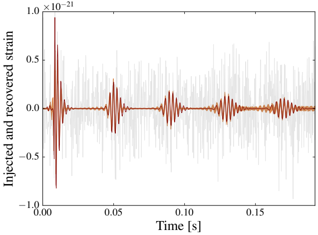
$A_n = \gamma^n A$	damping
$\tau_n = w^n \tau$	widening
$t_n = t_0 + n\Delta t$	time between subsequent echoes
$\phi_n = \phi_0 + 2\pi f_0 n\Delta t + n\Delta\phi$	phase shift subsequent echoes

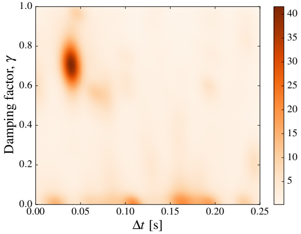
PHYSICAL REVIEW D **98,** 024023 (2018)

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]







Runs with O1 data

We extend our analysis to O1 C02 data.
The segments being used have good data quality (passed CBC CAT1,2,3)
Runs with O1 data:

1. Simulated signal with O1 noise
2. Background distribution
3. Echo searches at O1 BBH events

Abedi et al. results are within the prior ranges.

	GW150914	GW151012	GW151226
dt (s)	0.30068	0.09758	0.19043

Prior:

- $dt = [0., 0.7]s$
- $d\phi = [0., 2\pi]$
- $\gamma = [0., 1.]$
- $w = [1., 2.]$
- $T = 2s$
- $f_{low} = 20Hz$
- $srate = 2048Hz$

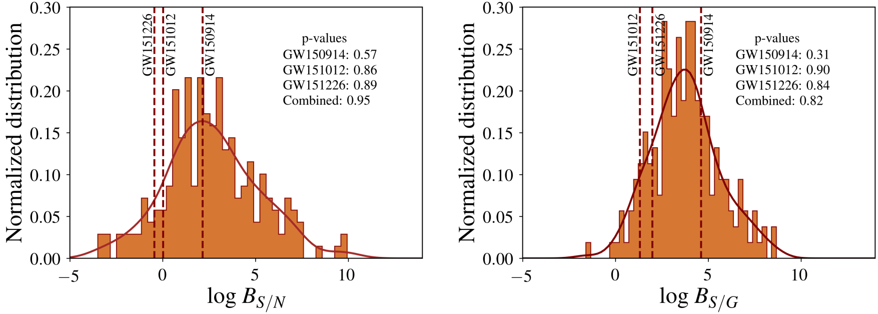
Echoes search at O1 BBH detections

- t_0 prior is $[t_{\rm trig} + 4\tau_{220},\ t_{\rm trig} + 4\tau_{220} + 0.5]$
- QNM decay time $\tau_{220}(M_f, a_f, z)$ can be obtained from fitting formula
  Berti et al., Class. Quantum .Grav. 26, 163001 (2009)
- Take M_f, a_f, z to be upper bound of 90 % confidence interval to have conservatively large value for τ_{220}
- All events info are obtained from O2 catalog paper

Event	$m_1^{\rm src}/M_\odot$	$m_2^{\rm src}/M_\odot$	$\mathcal{M}^{\rm src}/M_\odot$	$\chi_{\rm eff}$	$M_{\rm f}^{\rm src}/M_\odot$	$a_{\rm f}$	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/({\rm erg\,s^{-1}})$	$D_{\rm L}/{\rm Mpc}$	z	$\Delta\Omega/{\rm deg}^2$
GW150914	$35.4^{+4.8}_{-3.0}$	$30.3^{+2.9}_{-4.3}$	$28.5^{+1.5}_{-1.4}$	$-0.03^{+0.10}_{-0.12}$	$62.7^{+3.2}_{-2.9}$	$0.68^{+0.05}_{-0.05}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	410^{+150}_{-170}	$0.09^{+0.03}_{-0.04}$	194.01
GW151012	$22.6^{+15.0}_{-4.9}$	$13.9^{+3.8}_{-5.1}$	$15.2^{+1.7}_{-1.1}$	$0.04^{+0.27}_{-0.19}$	$35.4^{+10.4}_{-3.5}$	$0.67^{+0.11}_{-0.10}$	$1.6^{+0.5}_{-0.5}$	$3.3^{+0.8}_{-1.8} \times 10^{56}$	1030^{+510}_{-480}	$0.20^{+0.09}_{-0.09}$	1490.79
GW151226	$14.1^{+9.1}_{-3.5}$	$7.5^{+2.2}_{-2.5}$	$8.9^{+0.3}_{-0.3}$	$0.19^{+0.21}_{-0.12}$	$20.7^{+6.8}_{-1.6}$	$0.71^{+0.03}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.3^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1074.50

Echoes search at O1 BBH detections - Bayesian evidences

Background calculation:
Analyze $\sim$ 200 8s-segments from GPSTime 1126073529 to 1126075217



All three events are well within the background.

Cosmology

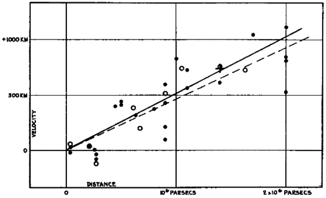
Cosmology: Hubble's law

recession velocity of a galaxy in the local universe $\longrightarrow$ $v_H = H_0 \; d$ $\longleftarrow$ distance to the galaxy

$\uparrow$ Hubble parameter

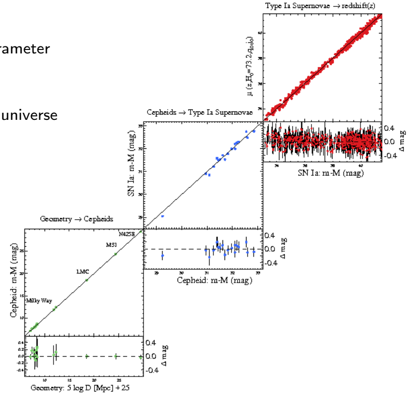
recession $\rightarrow$ stretching of spacetime itself $\rightarrow$ expansion of the universe

usually measured as a cosmological redshift $v_H = c\, z$



Edwin Hubble, *Proc. Nat. Acad. Sciences.* (1929)

Note: significant overestimate!

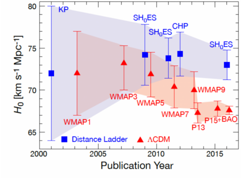


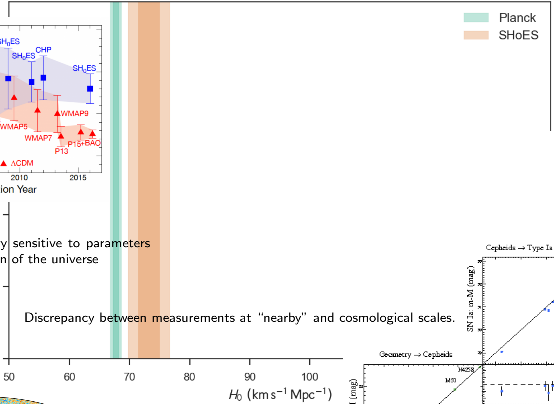
Cosmic distance ladder: Reiss *et al.* (2016)

State-of-the-art measurements of H_0

Two contrasting methods applied on nearby and very distant cosmological scales

Freedman (2017)



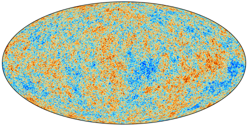


Standard candles

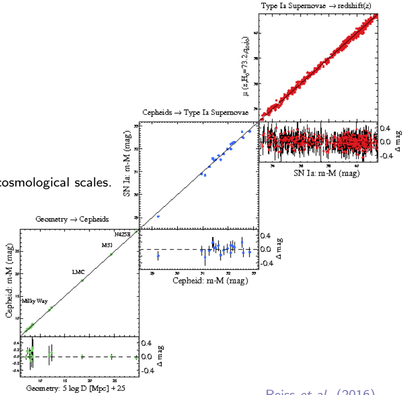
Cosmic distance ladder

CMB anisotropies: very sensitive to parameters that drive the expansion of the universe

Discrepancy between measurements at “nearby” and cosmological scales.

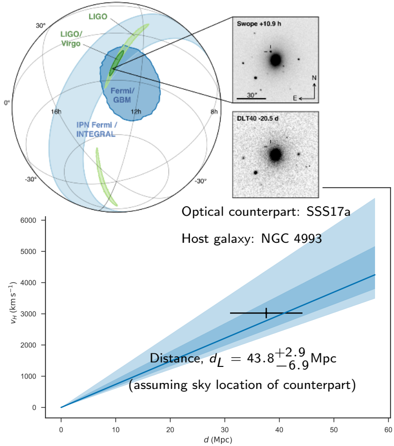


Planck collaboration (2015)



Reiss *et al.* (2016)

Hubble parameter with GW170817



Optical counterpart: SSS17a

Host galaxy: NGC 4993

Distance, $d_L = 43.8^{+2.9}_{-6.9}$ Mpc

(assuming sky location of counterpart)

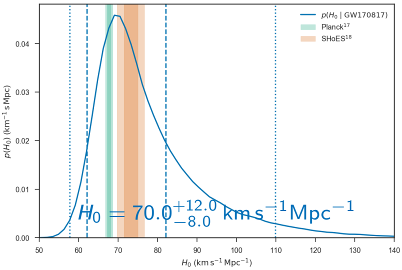
observed $v_{\mathrm{recession}} = v_H + v_{\mathrm{peculiar}}$

universe is not homogeneous at small scales:
galaxies attracted towards local matter overdensities

NGC 4993: $v_{\mathrm{recession}} = 3327 \pm 72\ \mathrm{km\,s}^{-1}$

Correct for peculiar velocity of group of galaxies

$$v_H = 3017 \pm 166\ \mathrm{km\,s}^{-1}$$



$H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\,s}^{-1}\,\mathrm{Mpc}^{-1}$

Independent of any distance ladder!

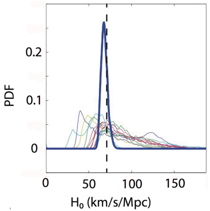
Abbott *et al.* Astrophys. J. **848** #2, L12 (2017); LSC-EPO

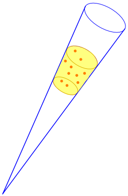
Abbott *et al.* Nature **551** #7678, 85-88 (2017)

Era of precision GW-cosmology ahead?

Nissanke *et al.* (2013)

Multiple observations with transient counterparts.

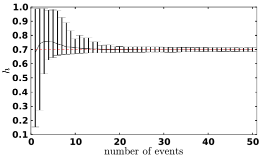




Narrow beam with potential host galaxies around optical counterpart if host galaxy not uniquely identified.

Schutz (1986)

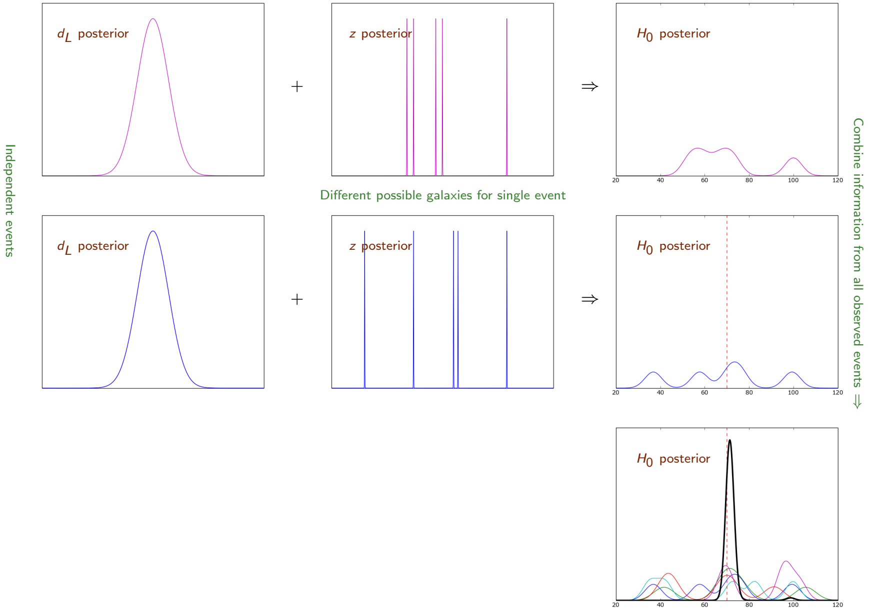
A fully statistical analysis using cross-correlation with a galaxy catalog in absence of a transient optical counterpart.



applicable also for binary black holes

extension to other cosmological parameters?

Del Pozzo (2012)



d_L posterior
z posterior
H_0 posterior
Different possible galaxies for single event
Independent events
Combine information from all observed events ⇓
20
40
60
80
100
120

H_0-statistical: selection effects

$$d_L H_0 \approx zc$$

GW selection effects

threshold SNR $\rightarrow$ interferometer horizon

only nearby signals detected

Detection efficiency:

$$\mathcal{N}_{\text{eff}}(\boldsymbol{\Omega}) = \int_{\mathcal{E}_{\text{det}}} d\mathcal{E} \int d\theta \; p(\mathcal{E}\,|\,\theta, \boldsymbol{\Omega}, \mathcal{H}, \mathcal{I})\, p(\theta\,|\,\boldsymbol{\Omega}, \mathcal{H}, \mathcal{I})$$

Abbott *et al.* Nature **551** #7678, 85-88 (2017)

Mandel, Farr, Gair (2018); Chen *et al.* (2017)

EM selection effects

depth of telescope

incomplete galaxy catalogues

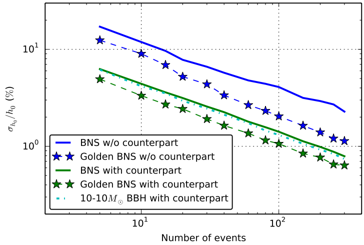
Correct for / take into account possible contribution of galaxies missing from catalogue.

Integrated method of taking into account both effects.

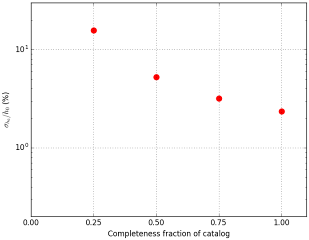
Messenger & Veitch (2013); Gray *et al.* (in prep.)

H_0-statistical: results on simulations

Chen *et al.* (2017)



Sur (2017, Masters thesis), Gray *et al.* (in prep.)



Incomplete galaxy catalogue

Ajith, Brady, Chen, Datrier, Del Pozzo, Fishbach, Gair, Ghosh, **Gray**, Hendry, Holz, **Magaña-Hernandez**, Messenger, **Qi**, Samajdar, **Sur**, Van Den Broeck, Veitch

Ongoing and future work

- Fold in probabilities of galaxies hosting the sources.

  Luminosity weighting.

  Astrophysically-motivated weighting of host galaxies?

- Going beyond H_0?

  Caveat: incompleteness of galaxy catalogues.

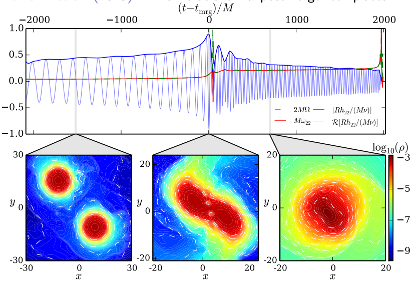
  Sources correlated with visible matter distribution?

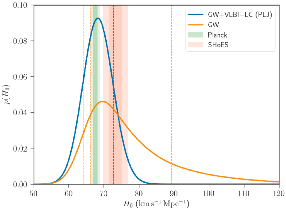
  Cluster catalogues $\Rightarrow$ probability density in redshift space?

- Cross-correlation with clustering more effective?

Synergetic multimessenger science: road to the future

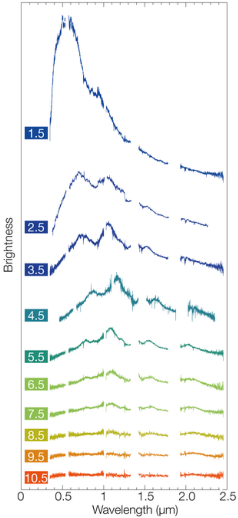
Bernuzzi *et al.* (2015): NR simulations $\longrightarrow$ postmerger templates?





GW & EM!

Kilonova $\longrightarrow$ NS-EoS?



Hotokezaka *et al.* (2018): jet $\longrightarrow$ inclination!

Pian *et al.* (2017)

THANK YOU!