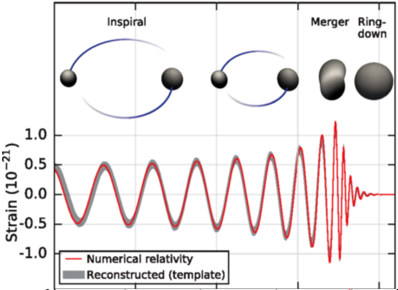
Black holes as bells and sirens

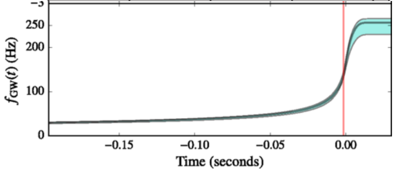
Archisman Ghosh
Nikhef, Amsterdam

Institute d'Astrophysique de Paris
2019 February 25

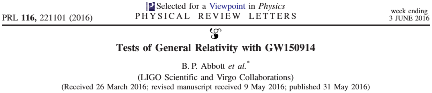
Probing strong-field gravity

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

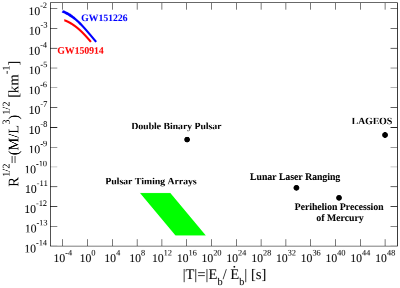
B. P. Abbott *et al.**

(LIGO Scientific and Virgo Collaborations)

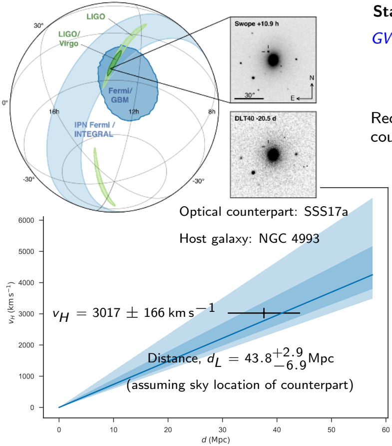
(Received 26 March 2016; revised manuscript received 9 May 2016; published 31 May 2016)

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

Yunes *et al.* (2016)



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

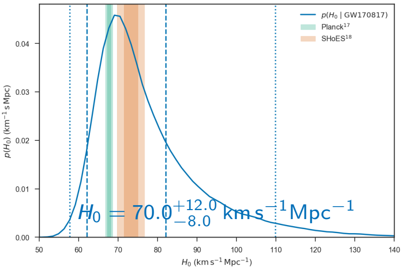
(assuming sky location of counterpart)

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.



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

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)

Plan of the talk

- Probing strong-field gravity

    The no-hair conjecture for Kerr black holes

    The inspiral-merger-ringdown consistency test

    Ringdown and a possible test of the no-hair conjecture

- Gravitational-wave cosmology

    A “statistical” method and galaxy catalogues

- Future prospects towards an integrated study

Probing strong-field gravity

The no-hair conjecture for Kerr black holes

No-hair conjecture: *A stationary black hole in Einstein's general relativity is described only by its mass and spin.*

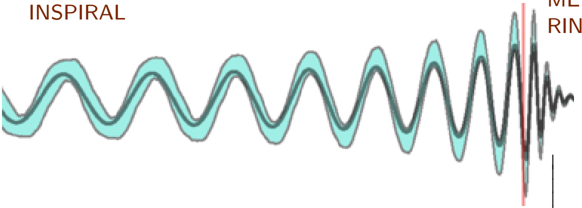
During ringdown, the quasinormal mode frequencies and damping times will depend only on the mass and spin of the remnant black hole, which can be obtained from linearized Einstein equations on Kerr background.

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

Inspiral-merger-ringdown consistency test

INSPIRAL

MERGER-
RINGDOWN



Final mass and spin

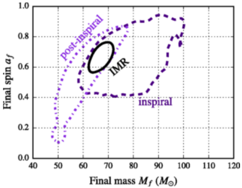
COMPARE!

NR fit

Initial masses and spins

Independent prediction of final mass and spin

Inspiral-merger-ringdown consistency test

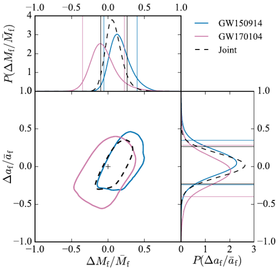


GW150914

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

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

GW150914 + GW170104

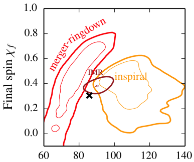


One of the first tests of GR carried out with GW150914

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

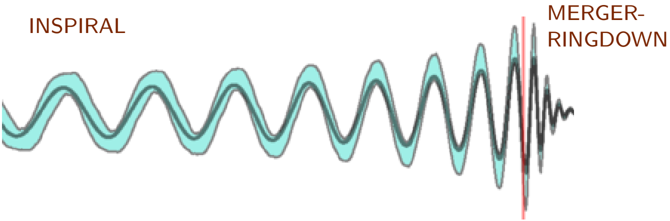
PHYSICAL REVIEW D **94**, 021101(R) (2016)

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



- Cut in frequency domain (for practical purposes).

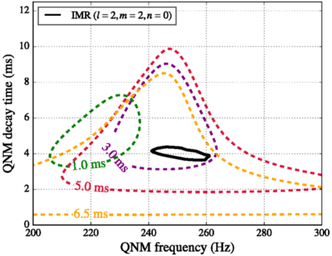
Higher harmonics

- Inclusion of non-linear regime.

Ringdown of GW150914

- Fitting with damped sinusoids.

- Linear regime.



Time after peak ampl.	SNR
1 ms	
3 ms	8.5
5 ms	6.3
6.5 ms	4.8

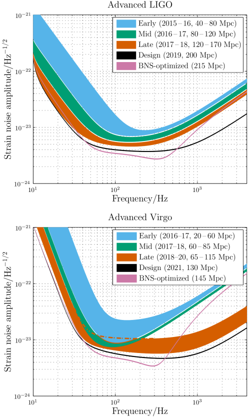
Difficult to measure leading QNM for GW150914.

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

Expected improvement in the coming years

- Additional detectors.

  Loudness scales as $\sqrt{N_{\text{detectors}}}$.



- Accuracies scale with detector sensitivity.

  For same event 3× better at design sensitivity.

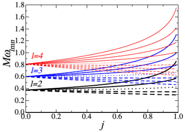
Abbott *et al.*, LLR (2016) 19:1

- Leading QNM of GW150914-like source should be clearly detectable.

Testing the no-hair conjecture with ringdown quasinormal modes

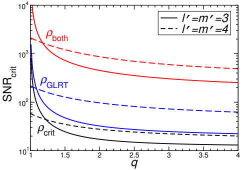
No-hair conjecture: *A stationary black hole in Einstein's general relativity is described only by its mass and spin.*

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 $\omega_{lmn}(M_f, J_f)$, $\tau_{lmn}(M_f, J_f)$.



Berti *et al.* (2007)

Detection of multiple modes desirable.

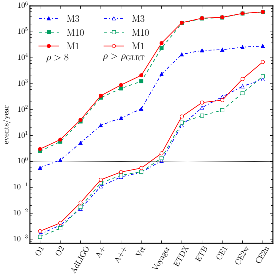
Testing the no-hair conjecture with ringdown quasinormal modes

Design sensitivity $\sim$ 3 times higher.

Need about 3× design sensitivity to isolate subleading QNM

Assume populations . . .

Single event!



Berti *et al.* (2016)

Combine information from multiple detections:

- "Coherent mode stacking" Yang *et al.* (2017)

- "TIGER-like" parameterized deformations Gossan *et al.* (2011), Meidam *et al.* (2014)

Testing the no-hair conjecture with ringdown quasinormal modes

- "TIGER-like" parameterized deformations: Gossan *et al.* (2011), Meidam *et al.* (2014)

- 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.

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

- 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)

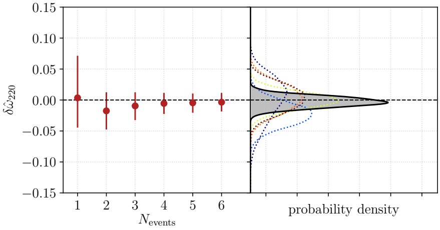
Empirical tests of the black hole no-hair conjecture using gravitational -wave observations

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]

- Start with GR templates with ringdown. Add systematic QNM deformations.

(2,2,0), (2,2,1), (2,1,0), (3,3,0), (3,3,1), (3,2,0), (4,4,0), (4,3,0), (5,5,0)
London *et al.* (2017)

- 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.

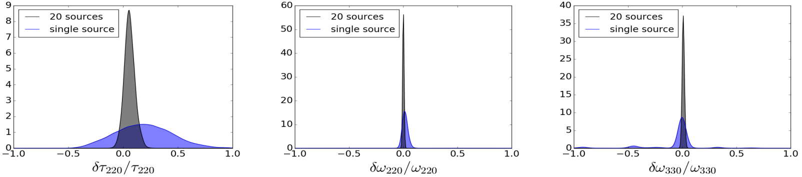


Testing the no-hair theorem with ringdown quasinormal modes

- Start with GR templates with ringdown. Add systematic QNM deformations.

(2,2,0), (2,2,1), (2,1,0), (3,3,0), (3,3,1), (3,2,0), (4,4,0), (4,3,0), (5,5,0)

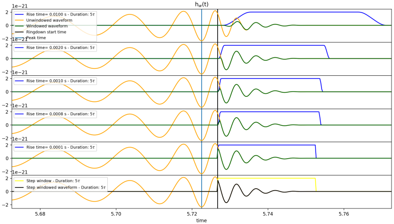
London *et al.* (2017)

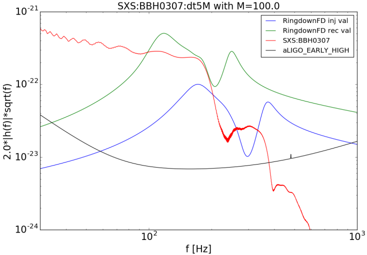


Ringdown-hunting as a sophisticated data-analysis problem

- Ringdown template occasionally tries to latch onto the pre-merger part.

- A higher mode in template may try to match leading order mode.





- Cut at appropriate time; window the data.

3ms when diameter of earth is 42ms

A “recipe” for ringdown parameter estimation

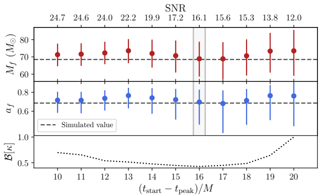
- Remove earlier detector data and search in [10M,30M] following peak of signal.

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

$$\mathcal{B}(\kappa, I) \equiv \sqrt{D_I^2(\kappa) + \det \mathbf{C}(\kappa)_I}$$

$$D_I^2(\kappa) \equiv {}^t\Delta\vec{x}(\kappa)_I \mathbf{C}^{-1}(\kappa)_I \Delta\vec{x}(\kappa)_I$$

Carullo *et al.* (2018)



Ongoing thoughts with ringdown

- Bayesian evidence for ringdown modes.

BayesWave!

- Use robust features of non-linear part of signal?

McWilliams (2018)

Fewer parameters?

Gravitational-wave cosmology

GW cosmology basics

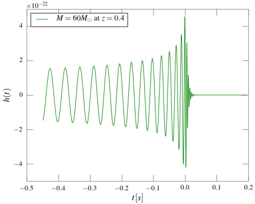
- Compact binaries give us a direct access to luminosity distance.

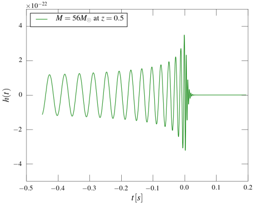
Independent measurement of phase evolution and amplitude

Phase evolution $\Rightarrow \mathcal{M}^z \equiv \mathcal{M}(1+z)$ (accurately-measured)

Amplitude $\sim \frac{\mathcal{M}^z}{d_L} \Rightarrow d_L$ (not that well-measured; degeneracy with inclination)

- Cosmological redshift (nearly) degenerate with total mass.

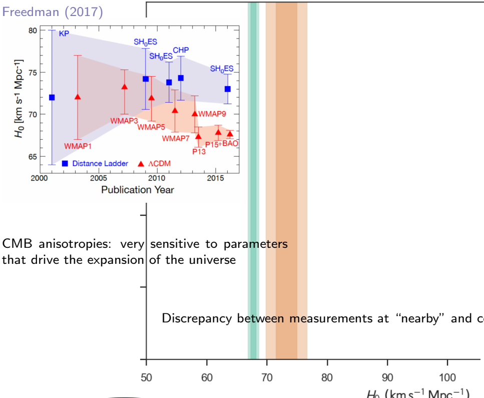




H_0 measurement with GWs: a motivation now

Two contrasting methods applied on nearby and very distant cosmological scales

Freedman (2017)

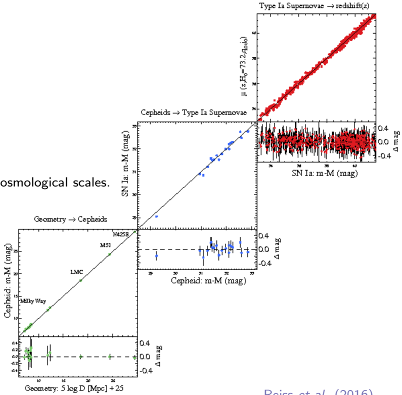


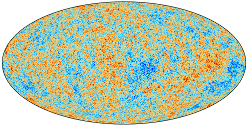
CMB anisotropies: very sensitive to parameters that drive the expansion of the universe

Discrepancy between measurements at "nearby" and cosmological scales.

Standard candles

Cosmic distance ladder





Planck collaboration (2015)

Reiss *et al.* (2016)

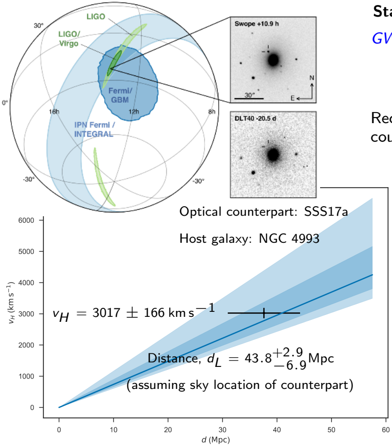
H_0 with GW170817

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.



Optical counterpart: SSS17a

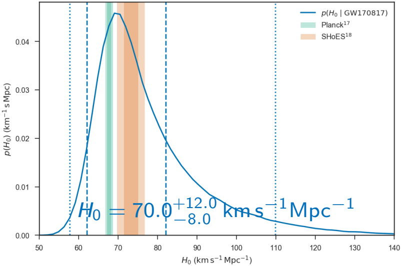
Host galaxy: NGC 4993

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

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

(assuming sky location of counterpart)

Independent of any distance ladder!



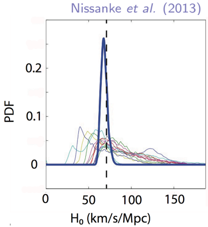
$H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$

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

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

Projections for future and caveats

$$d_L H_0 \approx zc$$


Nissanke *et al.* (2013)

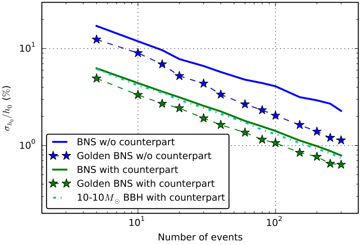
GW selection effects

threshold SNR → interferometer horizon

only nearby signals detected

Detection efficiency:

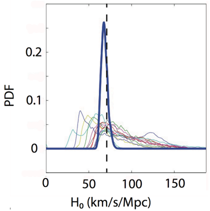
$$\mathcal{N}_{\text{eff}}(\mathbf{\Omega}) = \int_{\mathcal{E}_{\text{det}}} d\mathcal{E} \int d\theta\, p(\mathcal{E}\,|\,\theta, \mathbf{\Omega}, \mathcal{H}, \mathcal{I})\, p(\theta\,|\,\mathbf{\Omega}, \mathcal{H}, \mathcal{I})$$



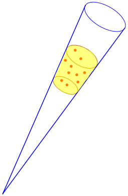
Chen *et al.* (2017)

Era of precision GW-cosmology ahead?

Nissanke *et al.* (2013)

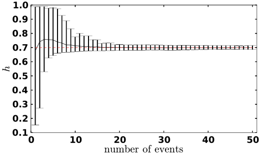


Multiple observations with transient counterparts.



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

Schutz (1986)

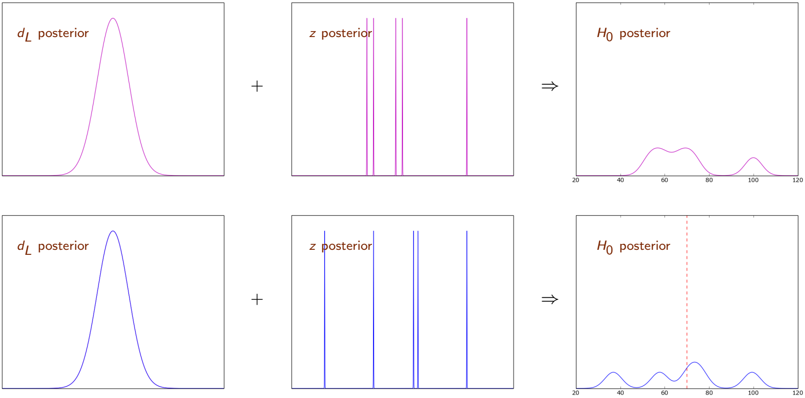


Del Pozzo (2012)

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?

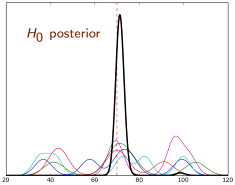


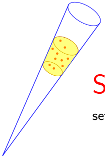
Independent events

Different possible galaxies for single event

Multimodal H_0 posterior for each event

Combine information from all observed events ⇓





Schutz “H_0-statistical” method

set of possible host galaxies

applicable also for **binary black holes**

Schutz (1986); Del Pozzo (2012)

H_0-statistical: selection effects

$$d_L H_0 \approx zc$$

GW selection effects

threshold SNR → interferometer horizon

only nearby signals detected

EM selection effects

depth of telescope

incomplete galaxy catalogues

$$p(\mathbf{\Omega}|d) = p(\mathbf{\Omega}) \left\{ \frac{N_o(\mathbf{\Omega})}{N_g(\mathbf{\Omega})} \left(\frac{1}{N_o} \sum_o \mathrm{Pos.}(D_L(z_o, \mathbf{\Omega})) \right) + \frac{N_u(\mathbf{\Omega})}{N_g(\mathbf{\Omega})} \int dz\, dM\, \Phi(M)\, \Theta(m(M, z, \mathbf{\Omega}) - m_{\mathrm{th}})\, p(z, \mathbf{\Omega}) \right\}$$

Posterior Prior ↑ Usual likelihood ↑

Extra pre-factor

Additional term to account for missing galaxies

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

Detection efficiency:

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

Integrated method of taking into account both effects.

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

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

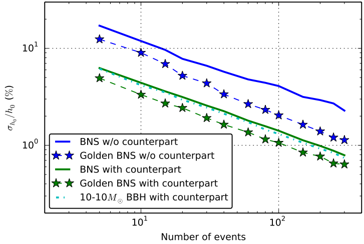
Messenger & Veitch (2013); Gray *et al.* (in prep.)

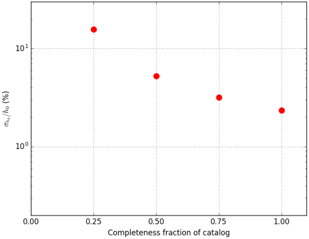
H_0-statistical: results on simulations

Masters student!

Chen *et al.* (2017): counterpart & statistical

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





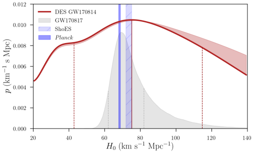
Statistical: incomplete galaxy catalogue

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

H_0: synergy between GW and EM

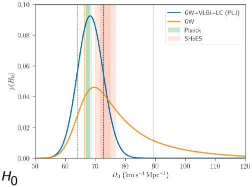
Thorough understanding of systematic effects is crucial

Soares-Santos *et al.* (2019)



- GW calibration uncertainties (GW)
- Selection effects (GW and EM)
- Uncertainties in galaxy catalogues (EM)
- Peculiar velocity flows (EM)

More information from EM follow-up observations!



Hotokezaka *et al.* (2018): jet → **inclination** → H_0

Ongoing and future work

- Fold in probabilities of galaxies hosting the sources.

  Luminosity weighting "Schechter luminosity function"

  $$P(G) \propto \Phi(M_G) = 0.4 \ln 10 \times 10^{-0.4(\alpha+1)(M_G - M_*)} e^{-10^{-0.4(M_G - M_*)}}$$

  Astrophysically-motivated weighting of host galaxies?

- Going beyond H_0?

  Caveat: incompleteness of galaxy catalogues.

  Sources correlated with visible matter distribution?

  Cluster catalogues ⇒ probability density in redshift space?

Rewind: Three roads to GW cosmology

- Electromagnetic counterparts:

  Transient counterparts

  Schutz (1986); Holz & Hughes (2005); Nissanke *et. al* (2013)

  Galaxy catalogues

  Schutz (1986); MacLeod & Hogan (2008); Del Pozzo (2012)

- Information from physics of NS:

  Mass-function — Taylor *et al.* (2012); Taylor & Gair (2012)

  Tidal deformations — Messenger & Read (2011); Del Pozzo *et al.* (2017)

- Statistical features of GW distributions. — Oguri (2016); Zhang (2018)

Integrated study?

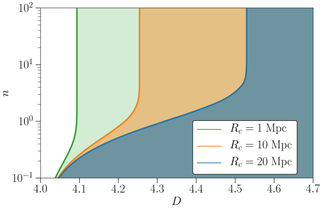
Constraints on extra dimensions from GW170817

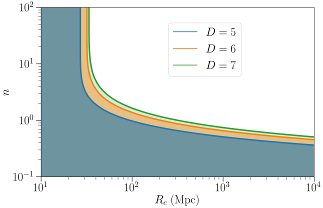
Abbott *et al.* arXiv:1811.00364 [gr-qc]

- Modified gravity models with screening mechanism.

Number of dimensions: D
Length scale: R_c
Transition steepness: n

- Expected $1/r$ fall-off of GW amplitude → constraints on extra dimensions.

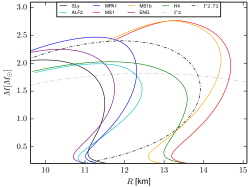


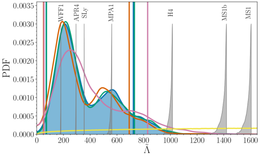


Towards synergetic multimessenger science

Dietrich *et al.* (2015): NS-EoS in vogue pre-GW170817

Kilonova light-curves for GW170817: Pian *et al.* (2017)



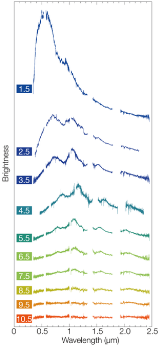


Abbott *et al.* arXiv:1805.11579 [gr-qc]

Neutron star equation-of-state

GW observations → ~~hard EoS~~

EM counterpart → ~~soft EoS~~

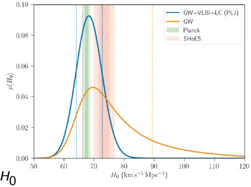


GW & EM!

Both GW & EM information lead to estimation of intrinsic as well as extrinsic parameters

GW & EM analysis performed independently

Correlated features ignored



higher GW harmonics

↓

Hotokezaka *et al.* (2018): jet → **inclination** → H_0

Merci beaucoup pour votre attention!