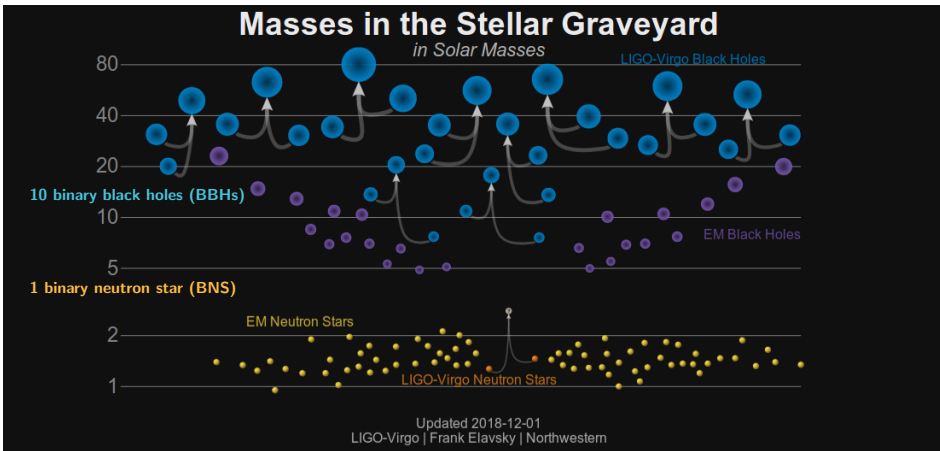
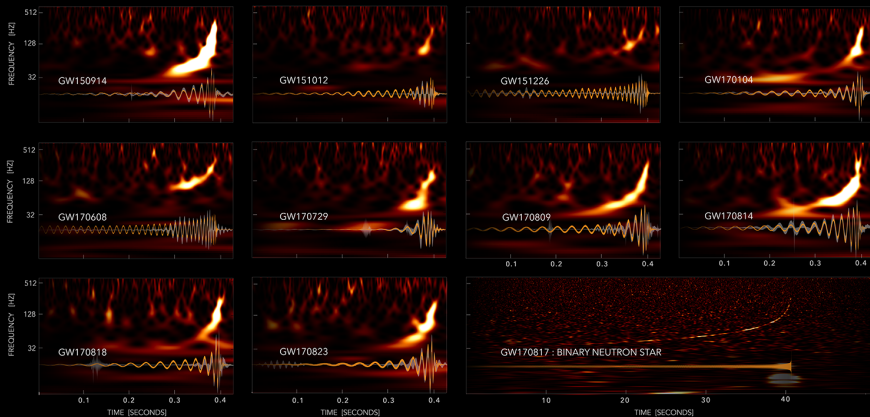


Gravitational-wave observations of **compact binary coalescences**

Following two observing runs of Advanced LIGO-Virgo ...



GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



LIGO-VIRGO DATA: [HTTPS://DOI.ORG/10.7935/B2H3-HH23](https://doi.org/10.7935/b2h3-hh23)

WAVELET (UNMODELED)

EINSTEIN'S THEORY

IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH

11 detections

exciting science

~ 40 publications

> 16,000 citations

My expertise: **probing strong-field gravity**

gravitational-wave cosmology

Plan of the talk

- Compact binaries as standard sirens
- H_0 measurement as immediate deliverable

Standard siren H_0 from GW170817

Galaxy catalogue method

simulations, O1 & O2 BBHs

- What we need for the future?

Importance of systematic effects

Required synergy

GW / EM / instrumentation

- Outlook

Compact binaries as standard sirens

Schutz (1986), Holz & Hughes (2005)

- GW from compact binaries give us a direct access to luminosity distance.

Independent measurement of phase evolution and amplitude

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

"redshifted chirp mass"

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

"luminosity distance" (degenerate with inclination)

Compact binaries as standard sirens

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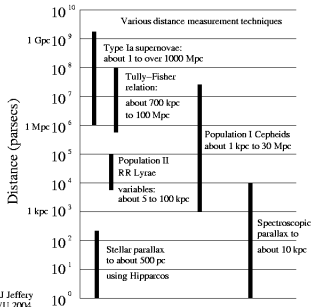
Phase evolution $\Rightarrow \mathcal{M}^z \equiv \mathcal{M}(1+z)$

"redshifted chirp mass"

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

"luminosity distance" (degenerate with inclination)

- Independent of the cosmic distance ladder!



$d_L \rightarrow$ cosmological parameters

Redshift-distance relation:

Late-time expansion / acceleration parameters

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



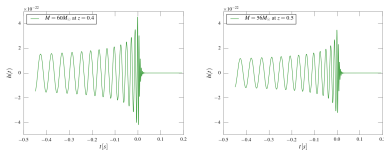
Hubble constant

Where does z come from?

Where does z come from?

- Spectral lines!

observed "frequency"; intrinsic "frequency" at source



- Spectral lines for compact binaries?

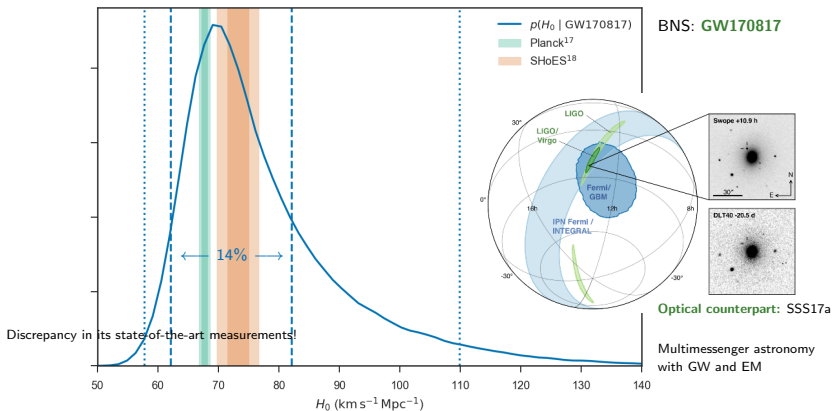
For BBH, features totally degenerate with total mass

For BNS, degeneracy only weakly broken

Need to fall back on EM for z !

A gravitational-wave standard siren measurement of the Hubble constant

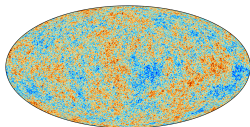
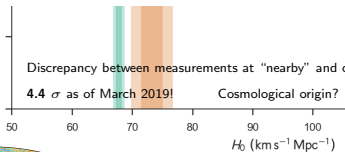
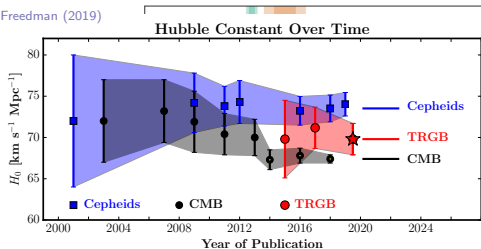
The LIGO Scientific Collaboration and The Virgo Collaboration*, The 1M2H Collaboration*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory Collaboration*, The VINROUGE Collaboration* & The MASTER Collaboration*



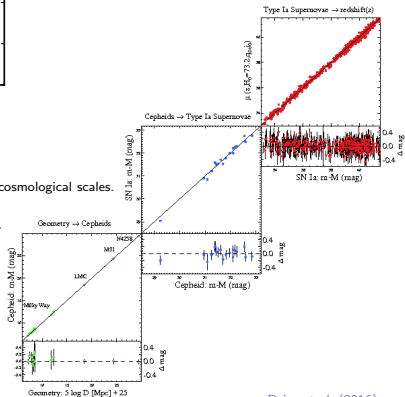
Discrepancy in state-of-the-art measurements of H_0 !

Two contrasting methods applied on nearby and very distant cosmological scales

Freedman (2019)



Planck collaboration (2015) + Λ -CDM



Reiss et al. (2016)

H_0 with GW170817

Standard siren

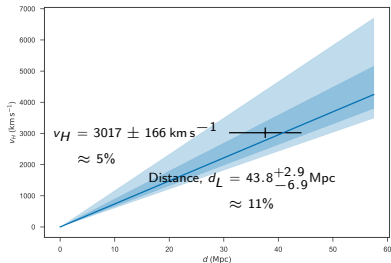
Independent of any distance ladder

GWs provided a direct measurement of the luminosity distance!

$$v_H \equiv zc \approx H_0 d_L$$

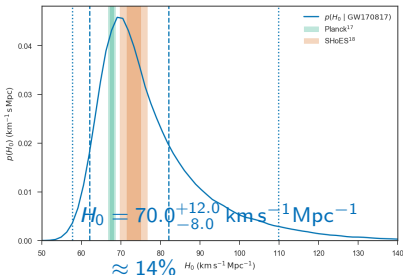
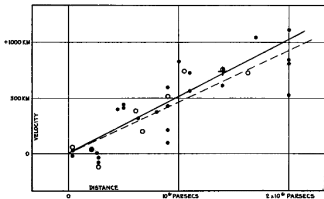
Redshift (recession velocity) came from host galaxy NGC 4993.

First plot in the GW Hubble diagram:



LSC-EPO

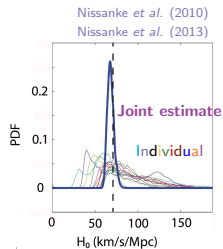
Edwin Hubble, *Proc. Nat. Acad. Sciences.* (1929)



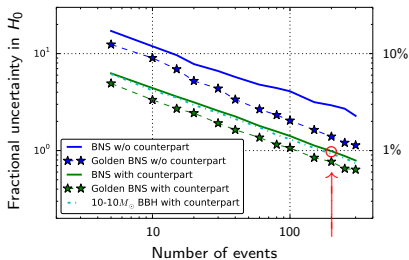
Abbott et al. *Nature* 551 #7678, 85-88 (2017)

Better with more detections

Combine information from multiple similar detections.



Precision: $\sigma_{H_0}/H_0 \sim 1/\sqrt{N}$



Chen *et al.* (2018)

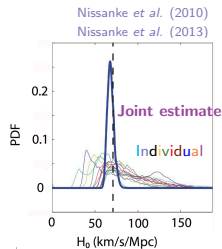
see also: Feeney *et al.* (2019)

Better with more detections

Careful of systematic effects!

GW selection effects

threshold SNR \rightarrow interferometer horizon
only nearby signals detected



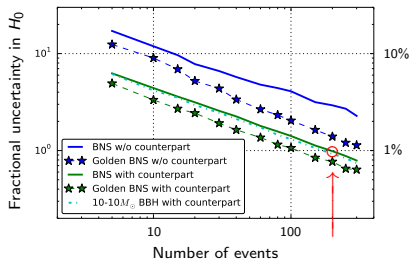
Detection efficiency (selection function):

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

Integrate over all **detectable data sets**

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

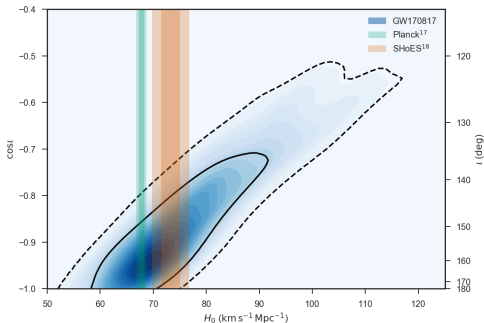
Mandel, Farr, Gair (2018); Chen *et al.* (2018); Mortlock *et al.* (2018)



Chen *et al.* (2018)

see also: Feeney *et al.* (2019)

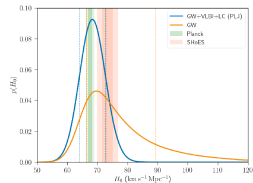
Degeneracy with inclination



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

Distance-inclination degeneracy: GW amplitude from by a distant binary viewed face-on (or face-off) is similar to that of a closer binary viewed edge-on.

Hotokezaka *et al.* (2018): jet \rightarrow inclination $\rightarrow H_0$



Broken with GW alone? Multiple detectors. Higher modes.

H_0 with galaxy catalogues: Schutz method

Idea in Schutz (1986).

MacLeod and Hogan (2008) in context of LISA.

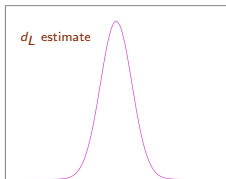
Del Pozzo (2012) Bayesian method in context of Adv-LIGO.

aLIGO-Virgo; 30 CBCs to $z = 0.1$ + SDSS $\Rightarrow H_0$ to $\sim 5\%$

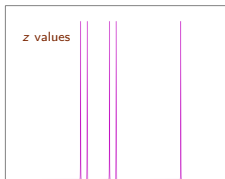
Nair *et al.* (2018)

Chen *et al.* (2018); Fishbach *et al.* (2018); Gray *et al.* (2019) (with AG)

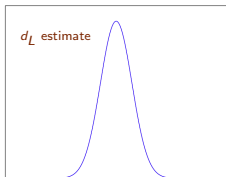
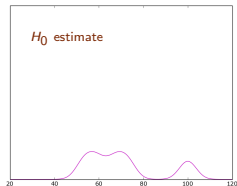
Independent events



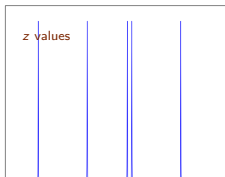
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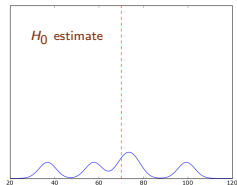
⇒



+



⇒



Different possible galaxies for single event

Multimodal H_0 estimate for each event

Combine information from all observed events ⇒

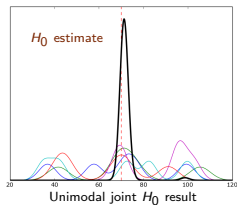


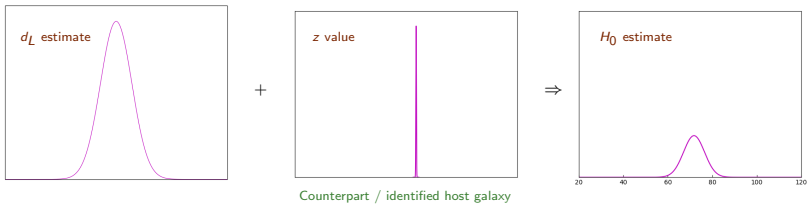
Schutz method

galaxy catalogues in absence of transient EM counterparts

applicable also for **binary black holes**

Schutz (1986)



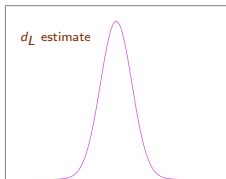


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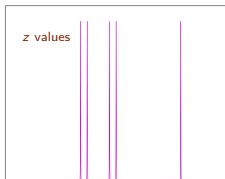
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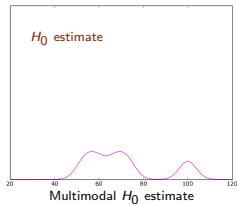


+



Different possible galaxies for single event

\Rightarrow

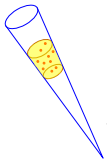
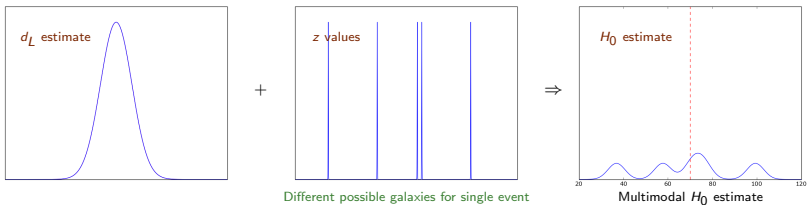


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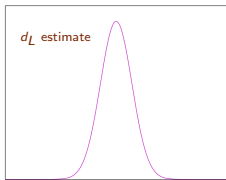
Schutz method

galaxy catalogues in absence of transient EM counterparts

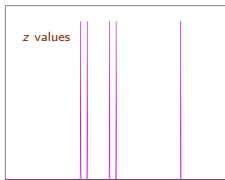
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Schutz (1986)

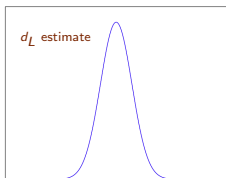
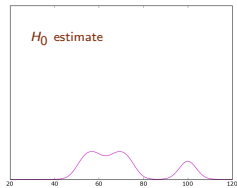
Independent events



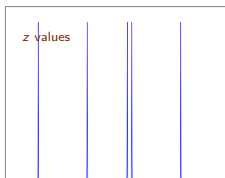
+



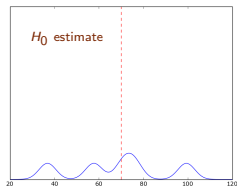
\Rightarrow



+



\Rightarrow



Different possible galaxies for single event

Multimodal H_0 estimate for each event

Combine information from all observed events \Rightarrow

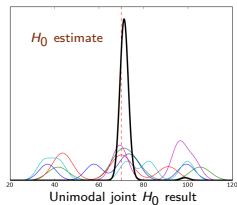


Schutz method

galaxy catalogues in absence of transient EM counterparts

applicable also for **binary black holes**

Schutz (1986)



H_0 with galaxy catalogues: the complete story

GW selection effects

threshold SNR \rightarrow interferometer horizon
only nearby signals detected

EM selection effects

depth of telescope
incomplete galaxy catalogues

$$p(x_{\text{GW}}|D_{\text{GW}}, H_0) = \frac{p(x_{\text{GW}}|G, H_0)}{p(D_{\text{GW}}|G, H_0)} p(G|D_{\text{GW}}, H_0) + \frac{p(x_{\text{GW}}|\bar{G}, H_0)}{p(D_{\text{GW}}|\bar{G}, H_0)} p(\bar{G}|D_{\text{GW}}, H_0)$$

in-catalogue

out-of-catalogue

Detection efficiency (selection function):

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

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

Integrate over all detectable data sets

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

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

Integrated method of taking into account both effects.

Messenger & Veitch (2013); Gray *et al.* (2019) (with AG)

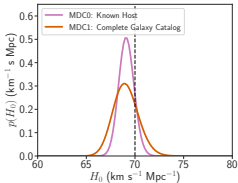
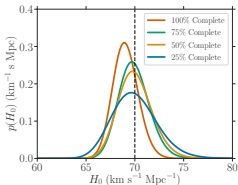
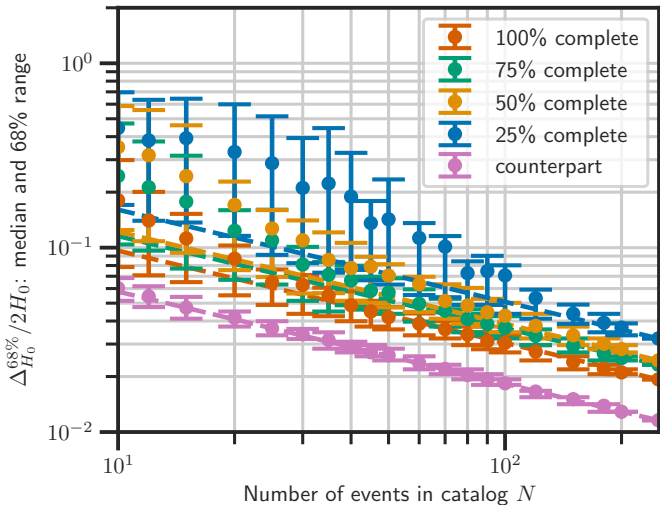
H_0 with galaxy catalogues: simulations

Gray et al. (2019) (with AG)

A few key features from the “mock data challenge”:

- Performed at BNS distances
- With galaxy catalogs about 35 times sparse / 3 times dense
- $\mathcal{O}(10 - 100)$ galaxies per event
- Redshift uncertainties, clustering ignored

H_0 with galaxy catalogues: results on simulations



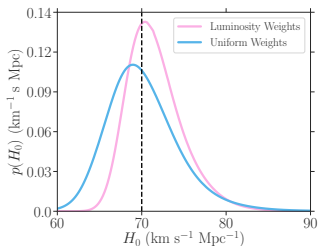
Gray et al. (2019) (with AG)

H_0 with galaxy catalogues: results on simulations

Luminosity weighting of galaxies: improves by ~ 1.3

Brighter (visible) galaxies are more likely hosts

Gray *et al.* (2019) (with AG)



B-band: star formation rate

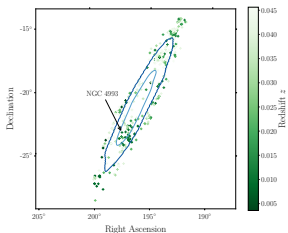
K-band: total mass

Clustering of galaxies: improves by ~ 2.5

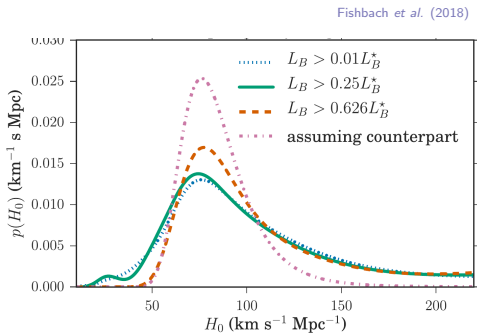
Chen *et al.* (2018)

H_0 from GW170817 with GLADE catalogue

- GW170817 assuming no counterpart:

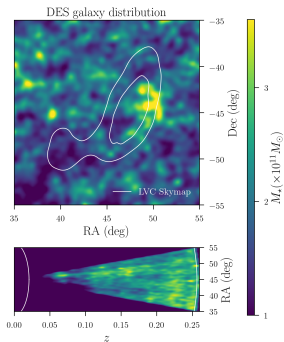


- Correcting for catalogue incompleteness
- Luminosity weighting

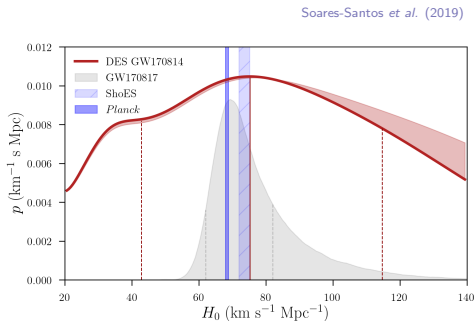


H_0 from GW170814 with DES catalogue

- **DES Y3 “gold” catalogue:** thoroughly surveyed GW170814 sky region.

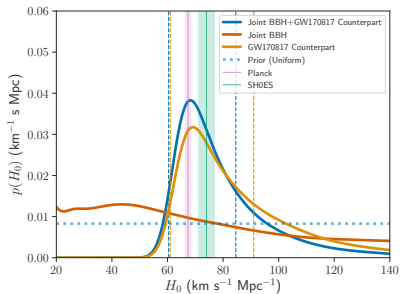
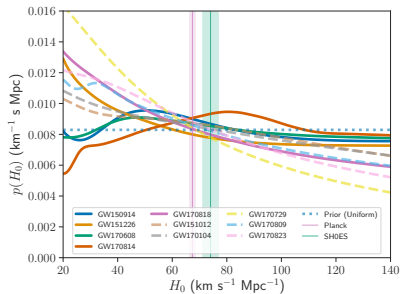
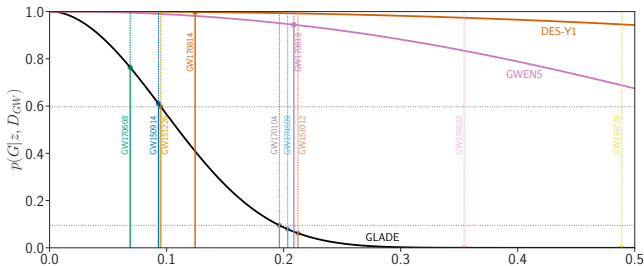


- **First realistic application**



H_0 from O1 & O2 detections

Abbott *et al.* arXiv:1908.06060



H_0 from O1 & O2 detections

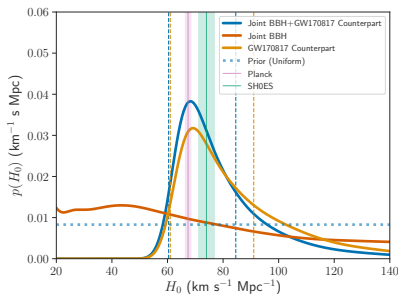
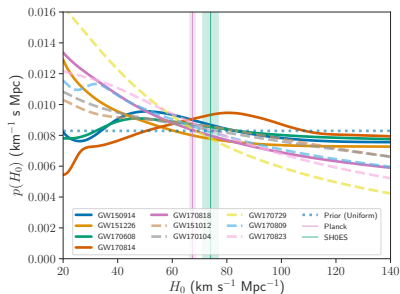
Abbott et al. arXiv:1908.06060

Detections with considerable catalogue support: features of galaxy catalogue

Detections with relatively empty catalogues: features of population assumptions

Detection efficiency in the denominator:

Depends on population parameters – mass distribution, rate evolution.



H_0 from O1 & O2 detections

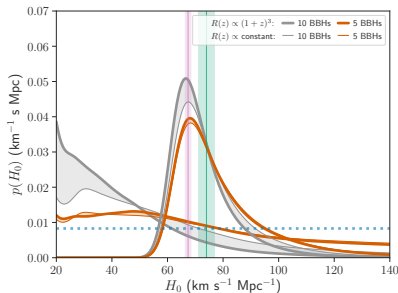
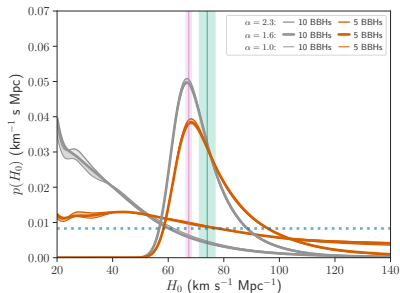
Detections with considerable catalogue support: features of galaxy catalogue

Detections with relatively empty catalogues: features of population assumptions

Detection efficiency in the denominator:

Depends on population parameters – mass distribution, rate evolution.

Perform robustness studies with varying assumptions:



Towards a precise and accurate GW measurement of H_0

Thorough understanding of systematic effects is crucial

- Peculiar velocity flows (EM)
- Uncertainties in galaxy catalogues (EM)

Photometric measurements of redshifts

Estimates of luminosities for weighting

- Selection effects (GW and EM)

Population properties: mass distribution, rate evolution, ...

Catalogue completeness

- Waveform systematic effects (GW)
- Detector calibration uncertainties (GW)

ampl. < 4%

systematic?

H_0 -statistical: towards the future

- Fold in probabilities of regions hosting the sources

Luminosity weighting: use luminosity as a proxy for mass and rate distribution

Astrophysically-motivated weighting of host galaxies

- Galaxy clustering

Sources correlated with visible matter distribution: **clustering of galaxies**

Cluster catalogues \Rightarrow probability density of mergers in redshift space

Construct **merger density catalogues**

Beyond H_0 ?

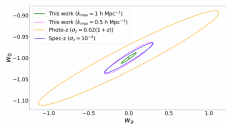
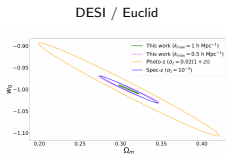
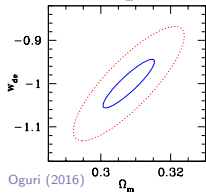
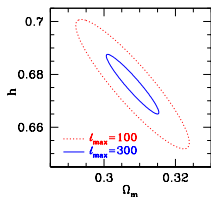
Correlations of GW/EM distributions

Angular / 3D correlation functions

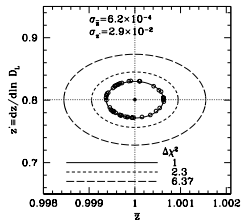
GW distributions with cluster catalogues / LSS

ET

BBO + Euclid / SKA



Mukherjee & Wandelt (2018)



Zhang (2018)

Vijaykumar+ (in progress)

Cosmology without EM

- Information from physics of NS:

ET

Mass-function

Taylor et al. (2012); Taylor & Gair (2012)

Tidal deformations

Messenger & Read (2011); Del Pozzo et al. (2017)

Multiband: BBO/DECIGO

- Effect of cosmological constant over evolution of binary!

Nishizawa (2012)

Outlook

- Short-term: H_0 measurement jointly with EM observations.

Systematic effects in EM and GW!

- More interaction between bi/multimessenger communities!

Cosmology from kilonova models?

- GW sources as rungs of the distant ladder: nearby and distant.

Standard candles, sirens, rulers, ...

[Gupta et al. \(2019\): GW as SNe calibrators](#)

APRIL 2019

| Sun | Mon | Tue | Wed | Thu | Fri | Sat |
|-----------------|------------|-----|--|-------------|-------------|-----|
| 31 #O3isHERE | 1 | 2 | 3 | 4 | 5 | 6 |
| 7 | 8 X | 9 | 10  | 11 | 12 X | 13 |
| 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 21 X | 22 | 23 | 24 | 25 X | 26 X | 27 |
| 28 | 29 | 30 | | | | |

MAY 2019

Credit: LVC/MPI-GPI/Abhirup Ghosh

| SUN | MON | TUE | WED | THU | FRI | SAT |
|-------------|-------------|-------------|---|-----|-------------|-----|
| | | | 1 | 2 | 3 X | 4 |
| 5 | 6 | 7 | 8 | 9 | 10 X | 11 |
| 12 X | 13 X | 14 | 15 | 16 | 17 X | 18 |
| 19 X | 20 | 21 X | 22 | 23 | 24 | 25 |
| 26 | 27 | 28 X | 29  | 30 | 31 | |

JUNE 2019

| SUN | MON | TUE | WED | THU | FRI | SAT |
|-------------|-----|-----|-----|-----|-----|-----|
| | | | | | | 1 |
| 2 X | 3 | 4 | 5 | 6 | 7 | 8 |
| 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| 23 | 24 | 25 | 26 | 27 | 28 | 29 |
| 30 X | | | | | | |

BBH 0%

Terrestrial <1%

NSBH 0%

MassGap 0%

BNS 0%

BBH 0%

MassGap 0%

NSBH <1%

Terrestrial <1%

BNS 0%

Credit: LVC/MPI-GPI/Abhirup Ghosh

JULY 2019

| Sun | Mon | Tue | Wed | Thu | Fri | Sat |
|-------------|------------|-----|-----|-------------|-----|-------------|
| 30 | 1 X | 2 | 3 | 4 | 5 | 6 X |
| 7 X | 8 | 9 | 10 | 11 | 12 | 13 |
| 14 | 15 | 16 | 17 | 18 X | 19 | 20 X |
| 21 | 22 | 23 | 24 | 25 | 26 | 27 X |
| 28 X | | | | | | |

1 CANDIDATE ALMOST EVERY **4** DAYS

Credit: LVC/MPI-GPI/Abhirup Ghosh