

Bright and dark sirens

GW cosmology with or without EM counterparts

Archisman Ghosh

Leiden University

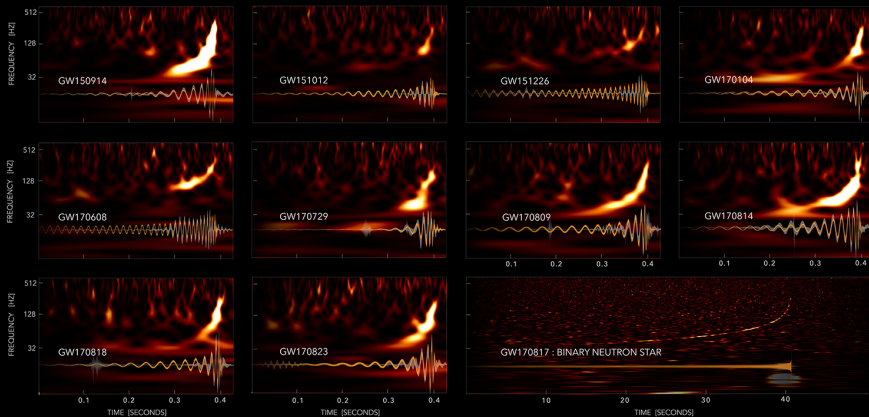
COSMO'19

RWTH Aachen University

2019 Sep 04



GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



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

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

This talk will be in the context of compact binary coalescences!

Plan of the talk

- Compact binaries as standard sirens
- H_0 measurement from current / upcoming observations

Standard siren H_0 from GW170817

Galaxy catalogue method

simulations, projections

H_0 with O1 & O2 BBHs

Systematic effects

- Concluding remarks

Towards the immediate future

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)

Independent of other measurements, in particular, the distance ladder.

Redshift-distance relation:

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

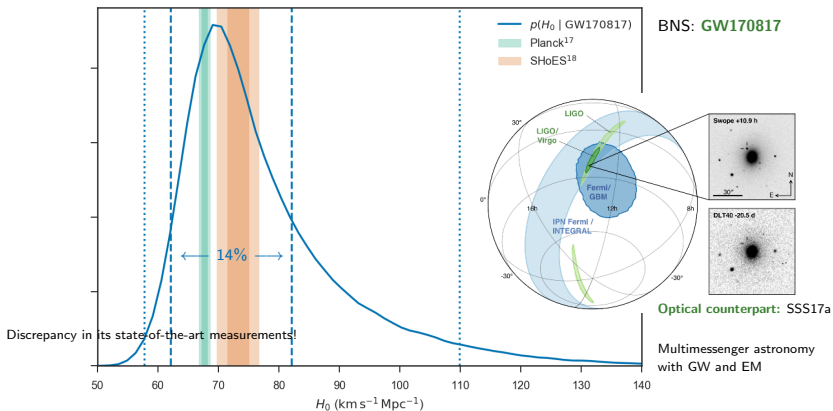
GW redshift (largely) degenerate with total mass

Where does the redshift come from?

EM for this talk

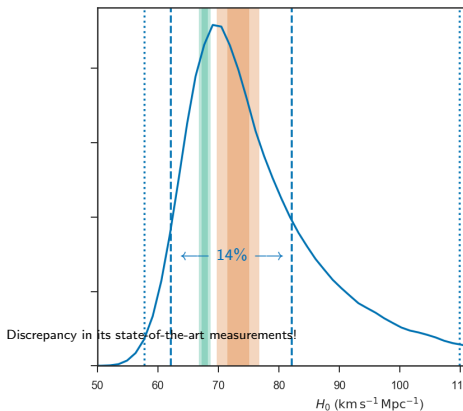
A gravitational-wave standard siren measurement of the Hubble constant

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*

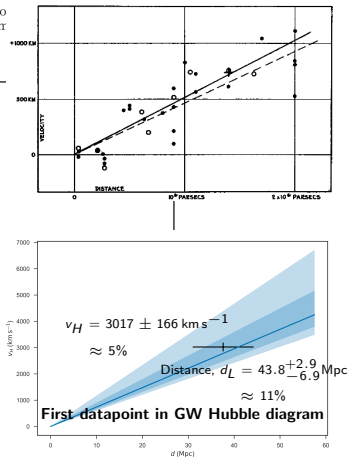


A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration*, The 1M2H Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory*, The VINROUGE Collaboration* & The MASTER Collaboration*



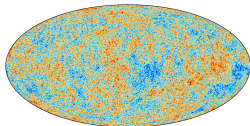
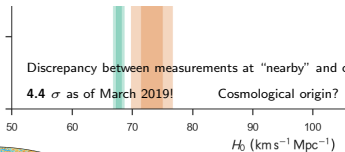
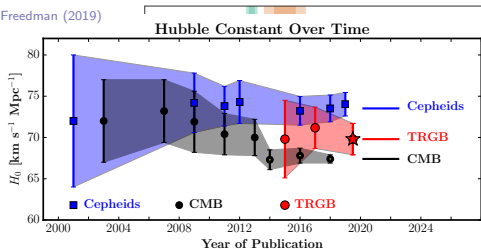
Edwin Hubble, *Proc. Nat. Acad. Sciences.* (1929)



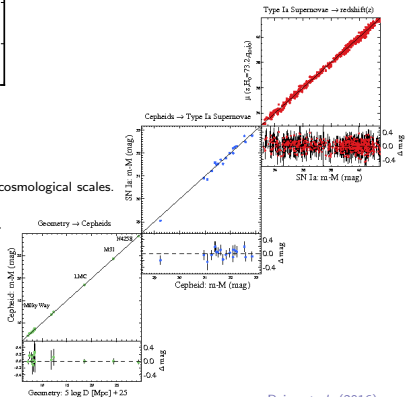
Discrepancy in state-of-the-art measurements of H_0

Two contrasting methods applied on nearby and very distant cosmological scales

Freedman (2019)



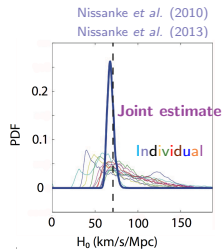
Planck collaboration (2015) + Λ -CDM



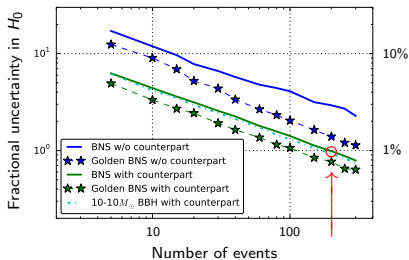
Reiss et al. (2016)

Better with more detections

Combine information from multiple similar detections.



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



Chen *et al.* (2018)

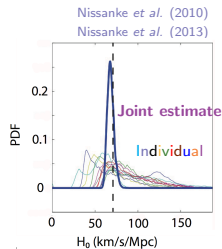
see also: Feeney *et al.* (2019)

Better with more detections

Careful of systematic effects!

GW selection effects

threshold SNR \rightarrow interferometer horizon
only nearby signals detected



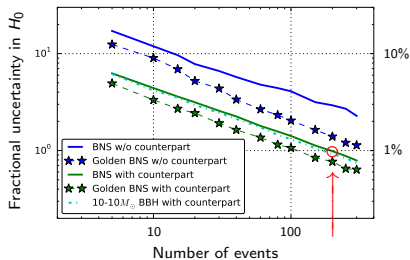
Detection efficiency (selection function):

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

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)

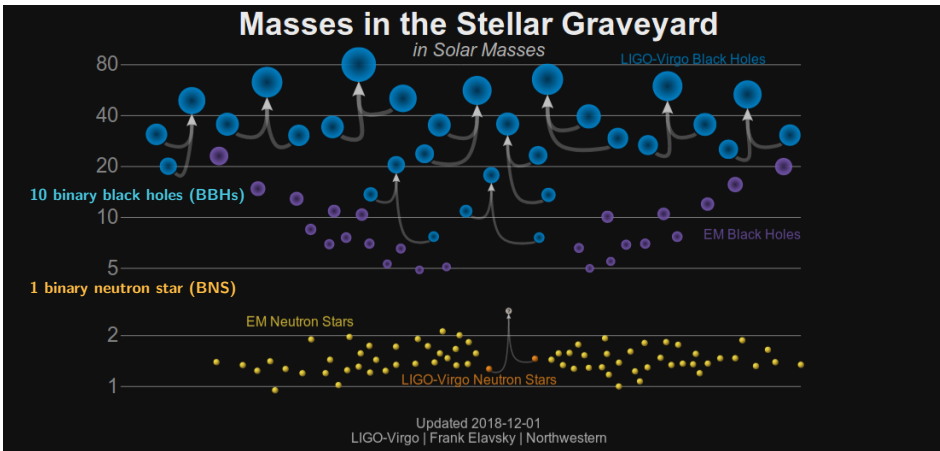


Chen et al. (2018)

see also: Feeney et al. (2019)

Gravitational-wave observations of compact binary coalescences

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



H_0 with galaxy catalogues: Schutz method

Idea in Schutz (1986).

MacLeod and Hogan (2008) in context of LISA.

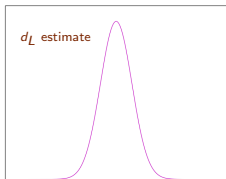
Del Pozzo (2012) Bayesian method in context of Adv-LIGO.

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

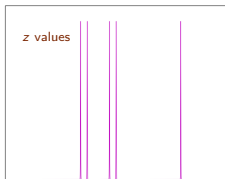
Nair *et al.* (2018)

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

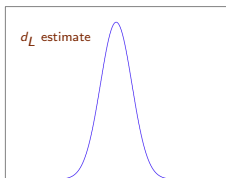
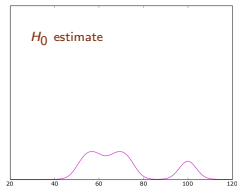
Independent events



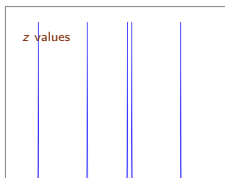
+



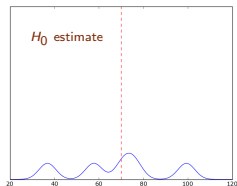
\Rightarrow



+



\Rightarrow



Different possible galaxies for single event

Multimodal H_0 estimate for each event

Combine information from all observed events \Rightarrow

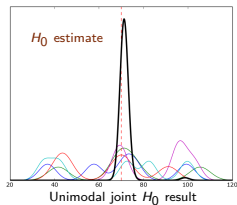


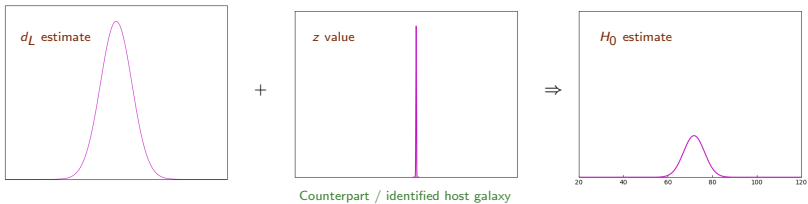
Schutz method

galaxy catalogues in absence of transient EM counterparts

applicable also for **binary black holes**

Schutz (1986)



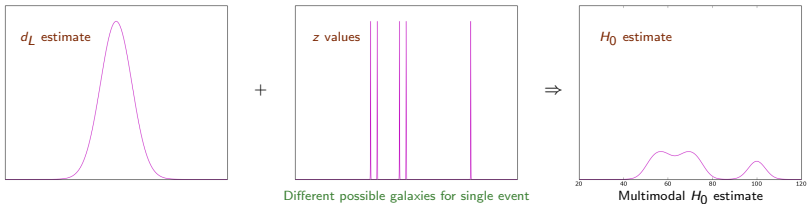


Schutz method

galaxy catalogues in absence of transient EM counterparts

applicable also for **binary black holes**

Schutz (1986)

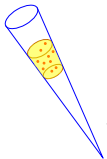
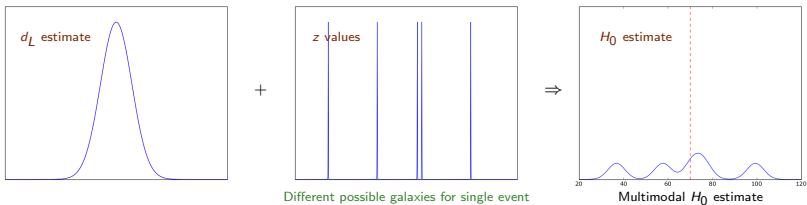


Schutz method

galaxy catalogues in absence of transient EM counterparts

applicable also for **binary black holes**

Schutz (1986)



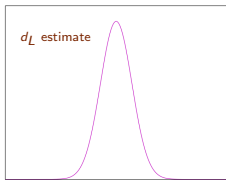
Schutz method

galaxy catalogues in absence of transient EM counterparts

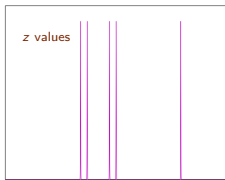
applicable also for **binary black holes**

Schutz (1986)

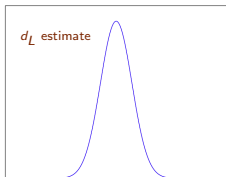
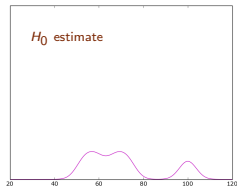
Independent events



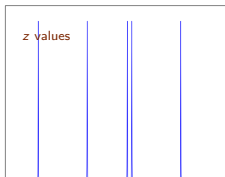
+



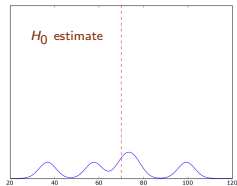
\Rightarrow



+



\Rightarrow



Different possible galaxies for single event

Multimodal H_0 estimate for each event

Combine information from all observed events \Rightarrow

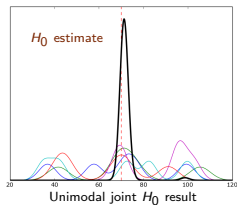


Schutz method

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)

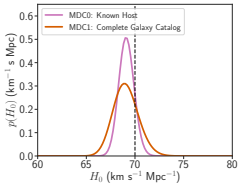
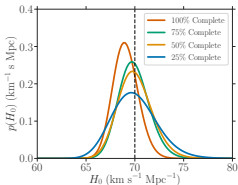
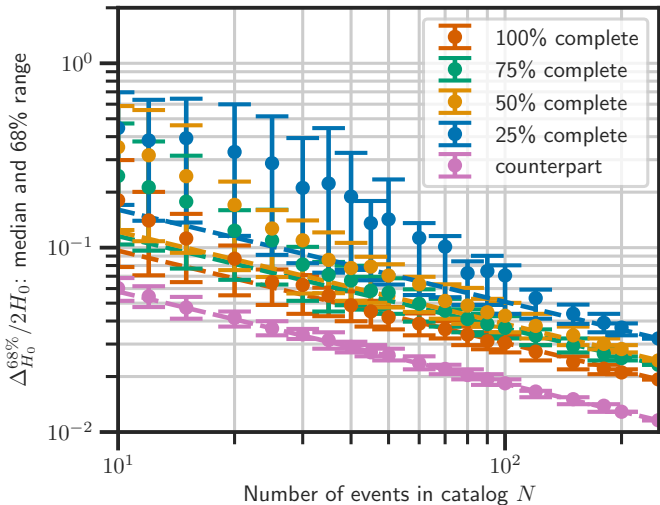
H_0 with galaxy catalogues: simulations

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



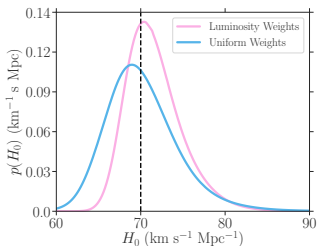
Gray et al. (2019) (with AG)

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)



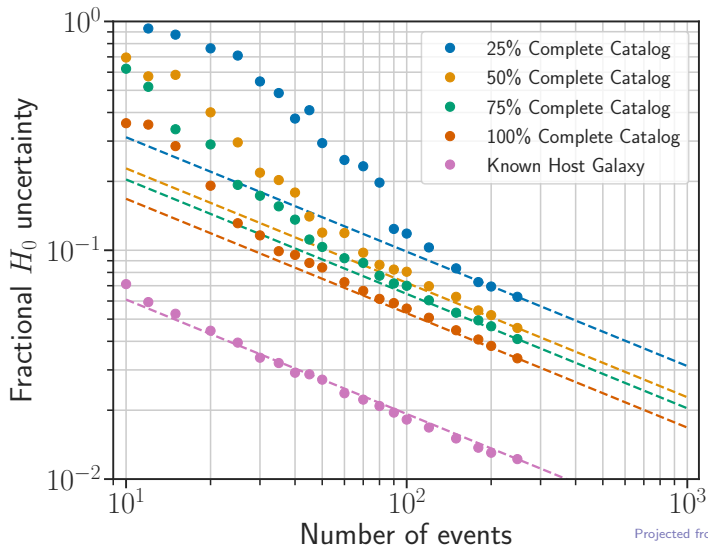
B-band: star formation rate

K-band: total mass

Clustering of galaxies: improves by ~ 2.5

Chen *et al.* (2018)

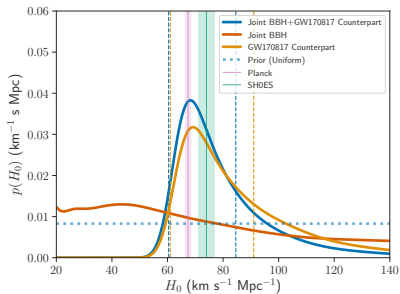
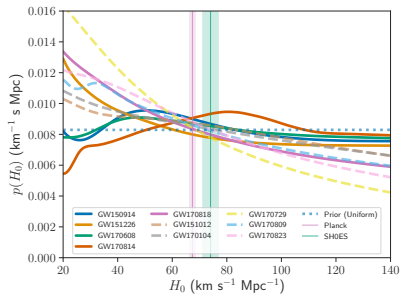
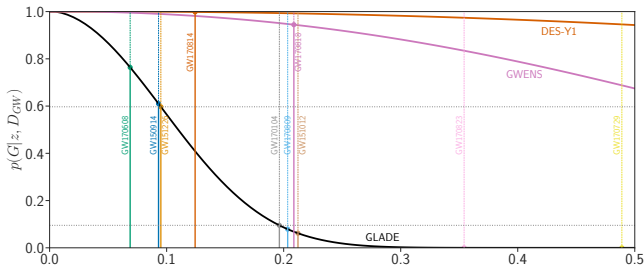
H_0 with galaxy catalogues: projections from results on simulations



Projected from Gray et al. (2019) (with AG)

H_0 from O1 & O2 detections

Abbott et al. arXiv:1908.06060



H_0 from O1 & O2 detections

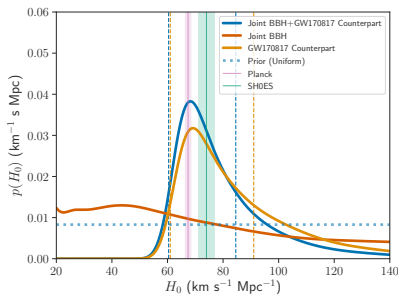
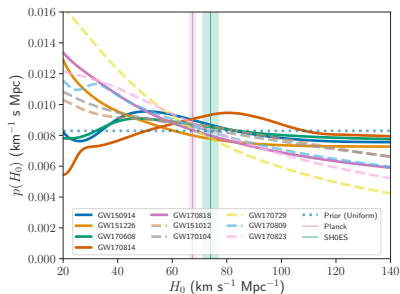
Abbott et al. arXiv:1908.06060

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

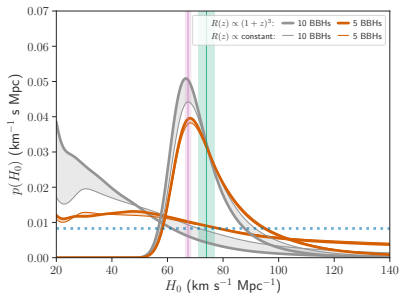
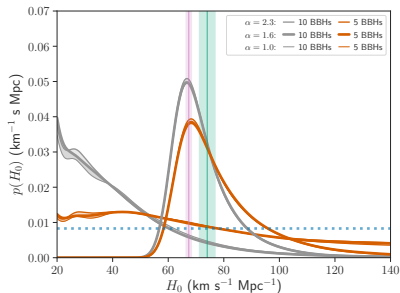
Detections with considerable catalogue support: features of galaxy catalogue

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:



Sources of systematic uncertainties

Crucial to understand and address accuracy towards a precise measurement

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

Photometric measurements of redshifts

Luminosity estimates

- Selection effects (GW and EM)

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

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

ampl. < 4%

systematic?

Towards the immediate 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 ?

Outlook

- Short term: H_0 measurement jointly with EM observations.

Systematic effects in EM and GW!

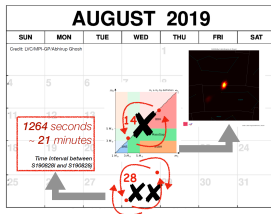
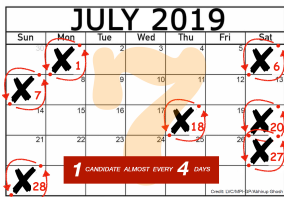
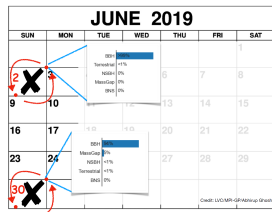
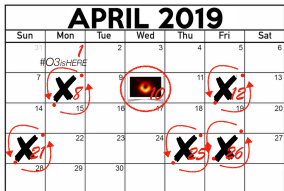
- Longer term: Other cosmological parameters

3G / LISA?

Simultaneous study of modified cosmology and gravity

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

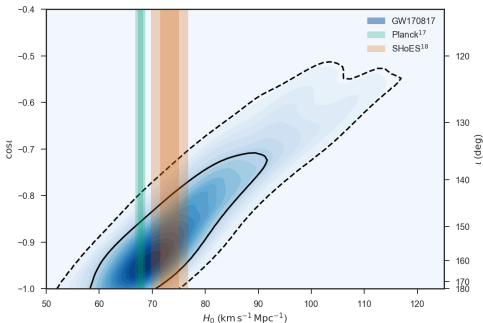
Standard candles, sirens, rulers, ...



The O3 fun has begun!

EXTRA SLIDES

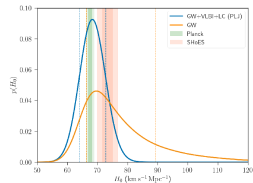
Degeneracy with inclination



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.

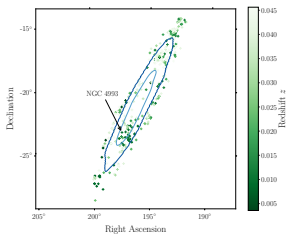
Hotokezaka *et al.* (2018): jet \rightarrow inclination $\rightarrow H_0$



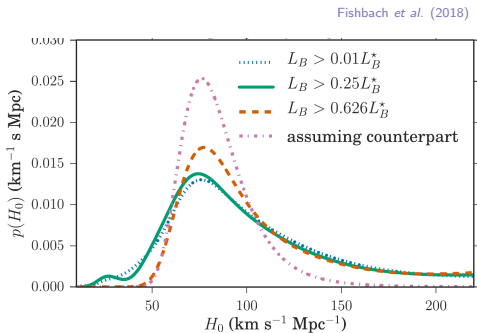
Broken with GW alone? Multiple detectors. Higher modes.

H_0 from GW170817 with GLADE catalogue

- GW170817 assuming no counterpart:

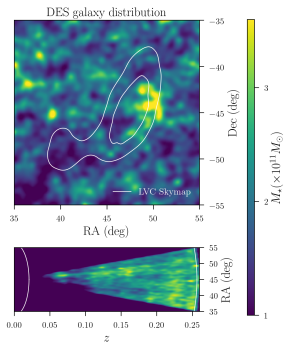


- Correcting for catalogue incompleteness
- Luminosity weighting



H_0 from GW170814 with DES catalogue

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



- **First realistic application**

