

# Cosmology with Standard Sirens

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**AAPCOS-2020**

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2020 January 07

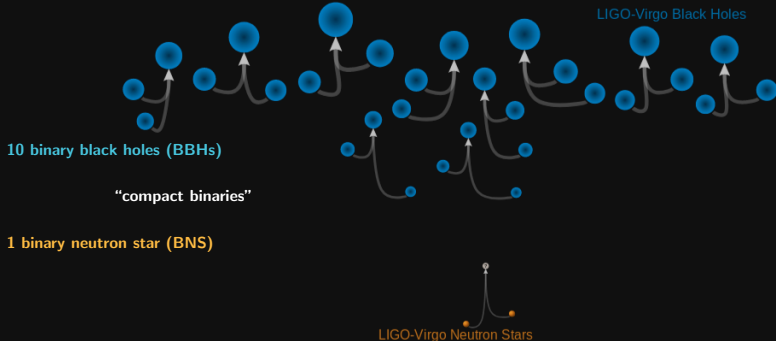


# Gravitational-wave observations

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

**O1:** 2015 Sep – 2016 Jan

**O2:** 2016 Dec – 2017 Aug



Updated 2018-12-01  
LIGO-Virgo | Frank Elavsky | Northwestern

## Gravitational-wave observations

Ongoing third observing run of Advanced LIGO-Virgo ...

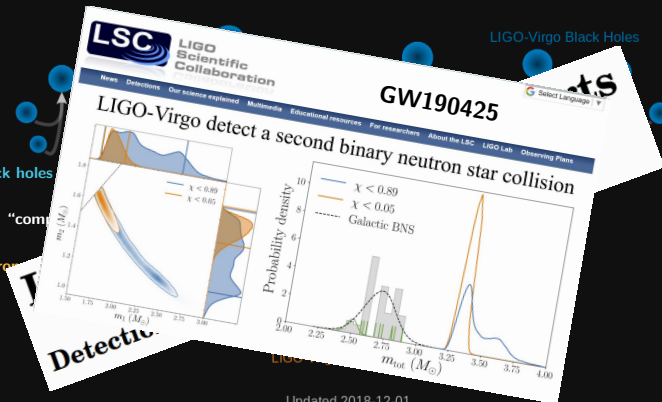
O3: 2019 Apr –  
(improved sensitivity with each run)



# Gravitational-wave observations

Ongoing third observing run of Advanced LIGO-Virgo ...

O3: 2019 Apr –  
(improved sensitivity with each run)



10 binary black holes

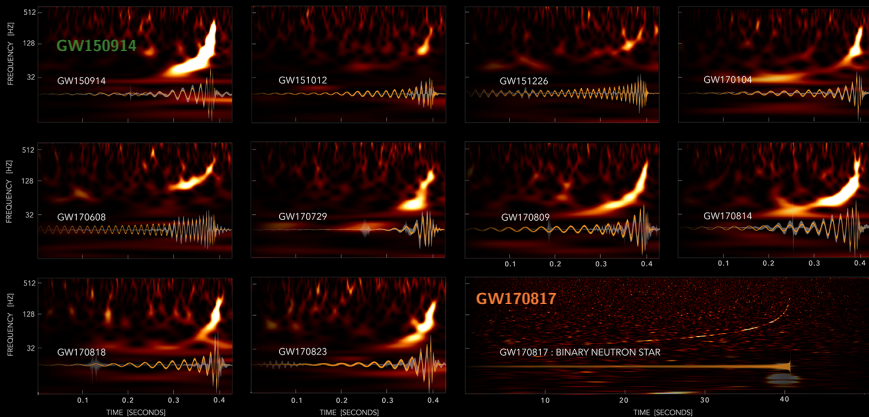
"com

1 binary neutron

Detecti...

Updated 2018-12-01  
LIGO-Virgo | Frank Elavsky | Northwestern

# 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

11 detections

exciting science

~ 40 publications

> 16,000 citations

This talk:

gravitational-wave cosmology: **standard sirens**

## Plan of this talk

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

Standard siren  $H_0$  from GW170817

Galaxy catalogue method

simulations, projections

- Concluding remarks / 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 the cosmic distance ladder!

## $d_L \rightarrow$ cosmological parameters

Redshift-distance relation:

Late-time expansion / acceleration parameters

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



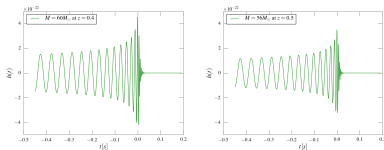
Hubble constant

Where does  $z$  come from?

## Where does $z$ come from?

- Spectral lines!

observed "frequency"; intrinsic "frequency" at source



- Spectral lines for compact binaries?

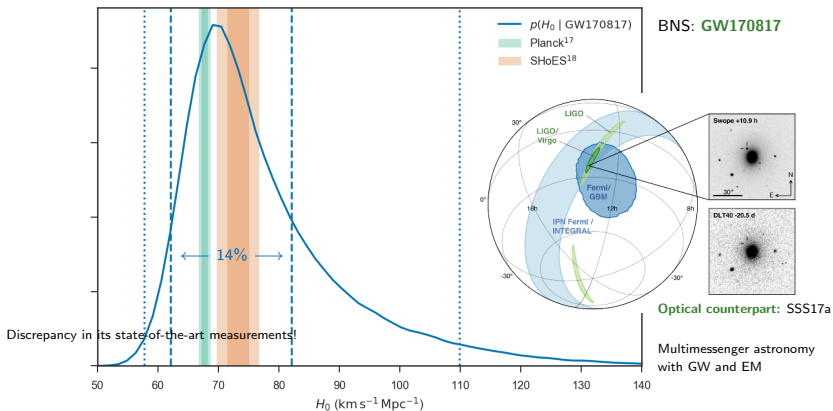
For BBH, features totally degenerate with total mass

For BNS, degeneracy only weakly broken

Need to fall back on EM for  $z$ !

# A gravitational-wave standard siren measurement of the Hubble constant

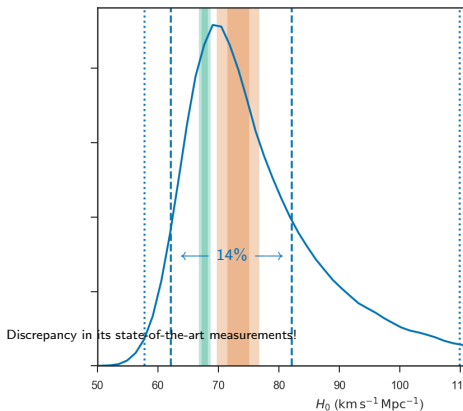
The LIGO Scientific Collaboration and The Virgo Collaboration\*, The 1M2H Collaboration\*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration\*, The DLT40 Collaboration\*, The Las Cumbres Observatory Collaboration\*, The VINROUGE Collaboration\* & The MASTER Collaboration\*



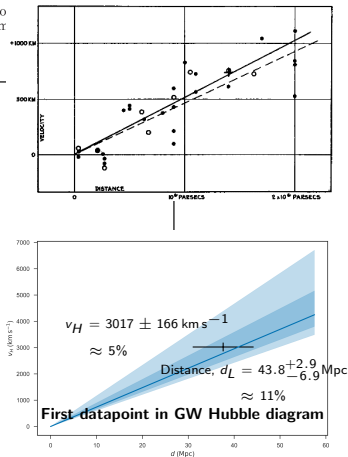


# A gravitational-wave standard siren measurement of the Hubble constant

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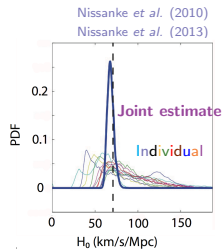


Edwin Hubble, *Proc. Nat. Acad. Sciences.* (1929)

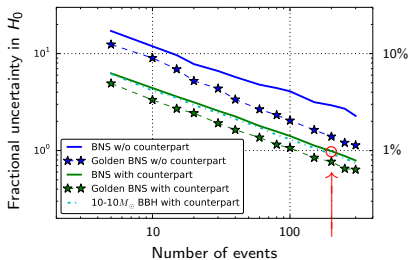


## Better with more detections

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)

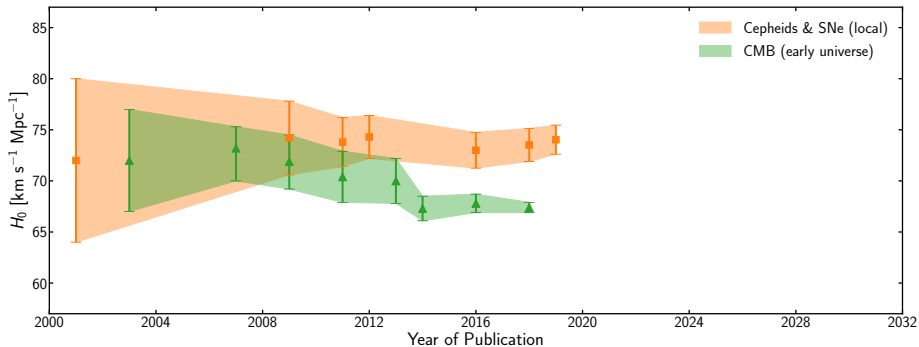
## The $H_0$ tension

Two ways of measuring  $H_0$ :

- **Local:** distance-redshift; relies on calibration via “distance ladder”
- **Early universe:** from CMB fluctuations; extrapolated via cosmological model

# The $H_0$ tension

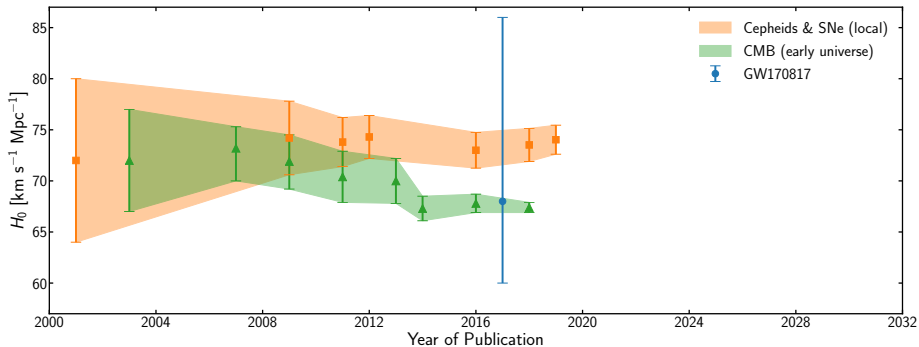
Two ways of measuring  $H_0$ :



- **Local:** distance-redshift; relies on calibration via “distance ladder”
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A major cosmological problem?

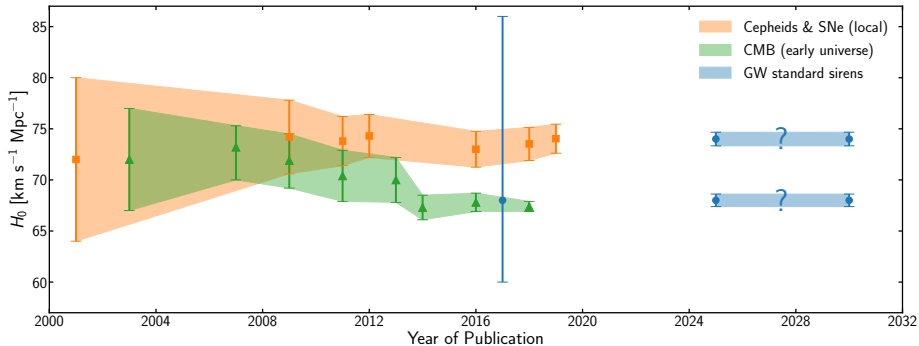
## The $H_0$ tension



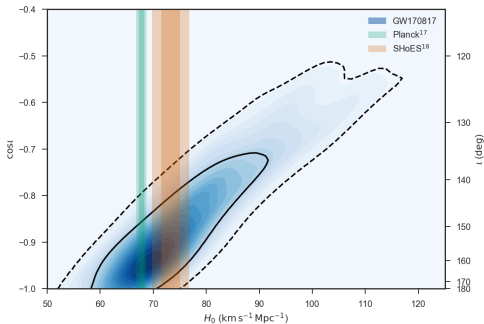
- **Standard sirens:** Independent of the “distance ladder” or cosmological model.

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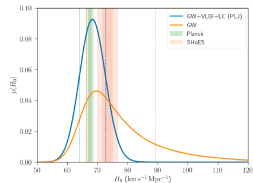
## Degeneracy with inclination



LVC: Abbott+ 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.

What if a transient EM counterpart is not observed?

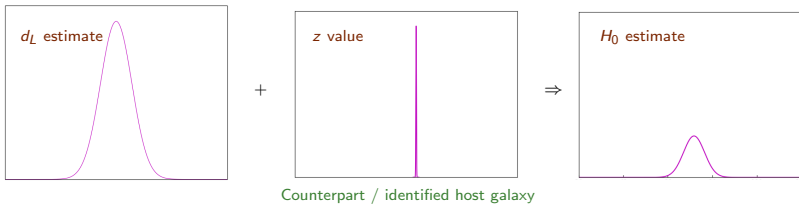
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## Schutz method

galaxy catalogues in absence of transient EM counterparts

applicable also for **binary black holes**

Schutz (1986)

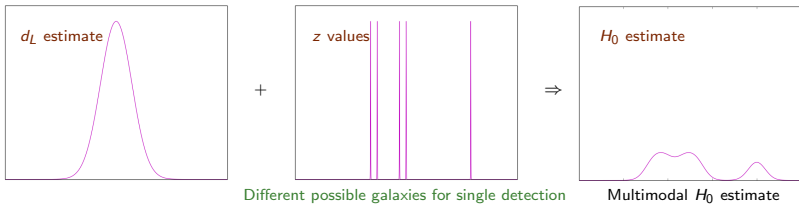


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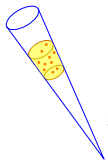
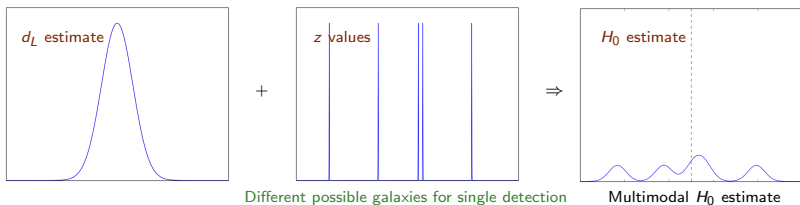
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Schutz (1986)

A **different** detection:



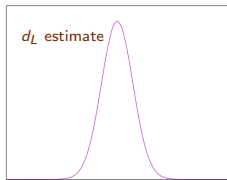
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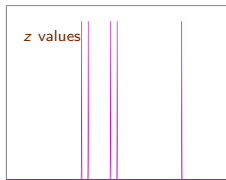
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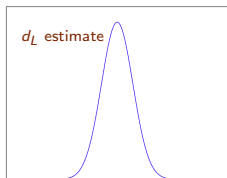
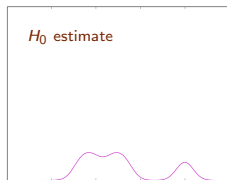
Independent detections



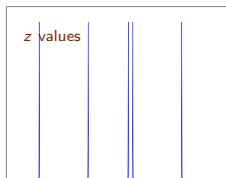
+



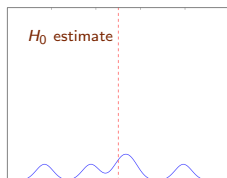
$\Rightarrow$



+



$\Rightarrow$



Different possible galaxies for single detection

Multimodal  $H_0$  estimate for each detection

Combine information from all observed detections  $\Rightarrow$

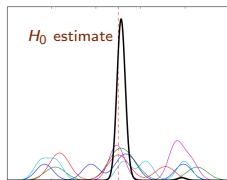


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Unimodal joint  $H_0$  result

With great statistical power comes great systematic responsibility!

# Systematic effects: selection effects

## GW selection effects

limited sensitivity of GW detector

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+ Nature **551** #7678, 85-88 (2017); **Ankan Sur** masters thesis

Mandel, Farr, Gair 2018; Chen+ 2018; Mortlock+ 2018 Messenger & Veitch (2013); Gray+ arXiv:1908.06050 (with **AG**)

# $H_0$ with galaxy catalogues: the complete story

## GW selection effects

limited sensitivity of GW detector  
only nearby signals detected

## EM selection effects

limited sensitivity of EM 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)

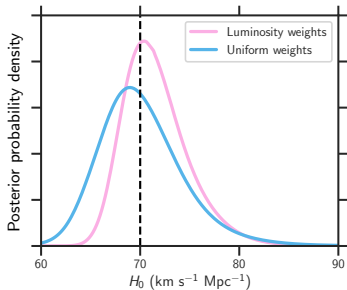
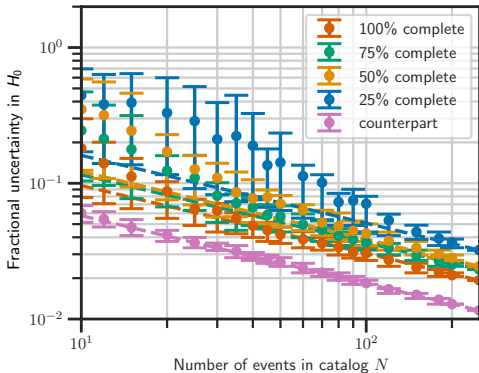
Integrated method of taking into account both effects  
in `gwcosmo` codebase by LVC cosmology group led by **AG**

Gray+ arXiv:1908.06050 (with **AG**)

# $H_0$ with galaxy catalogues: results on simulations

Gray+ arXiv:1908.06050

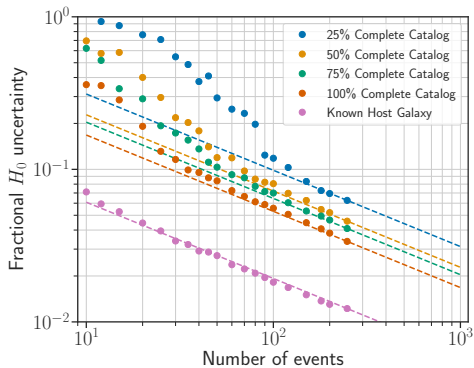
("mock data challenge" by the LVC cosmology group led by AG)



**Luminosity weighting of galaxies:**  
brighter galaxies more likely hosts

improves precision by  $\sim 1.3$

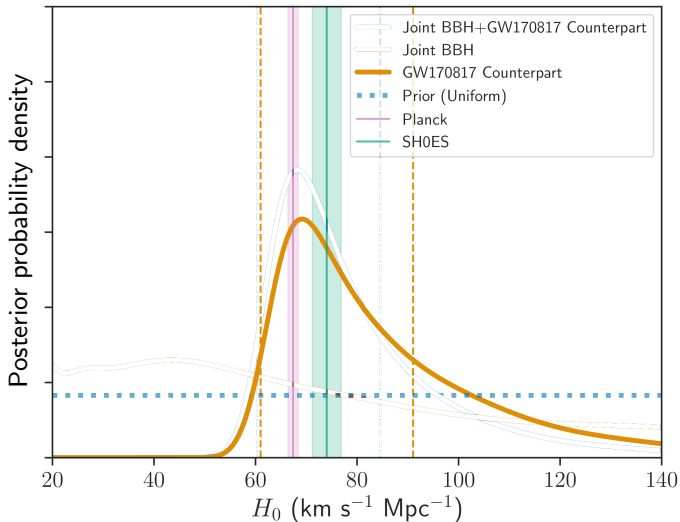
## $H_0$ with galaxy catalogues: projections from results on simulations



Projected from Gray+ arXiv:1908.06050 (with AG)

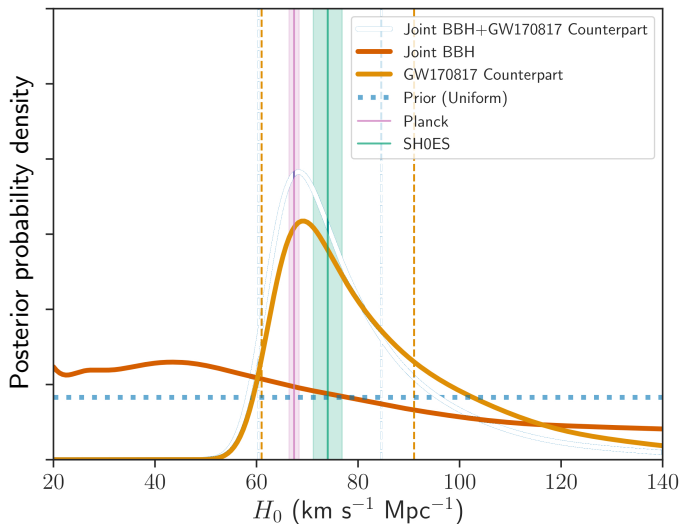
# $H_0$ with galaxy catalogues: results on LIGO-Virgo detections

LVC: Abbott+ arXiv:1908.06060 (with AG as PWT lead)



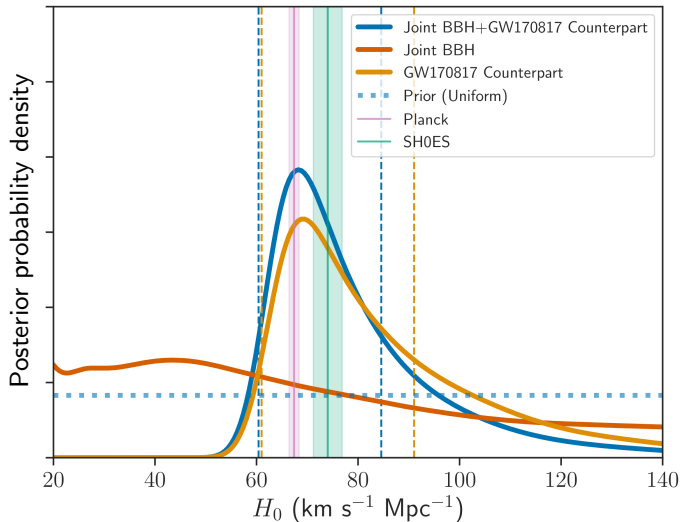
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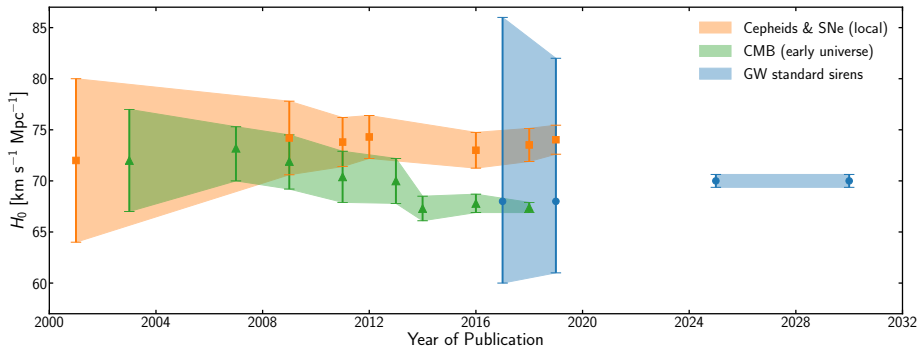


## $H_0$ with galaxy catalogues: results on LIGO-Virgo detections

LVC: Abbott+ arXiv:1908.06060 (with AG as PWT lead)



## $H_0$ with galaxy catalogues: results on LIGO-Virgo detections



## A compendium of possible sources of systematics

- Peculiar velocity flows for nearby detections

- Uncertainties in galaxy catalogues (EM)

Photometric measurements of redshifts

Estimates of luminosities for weighting

- Selection effects (GW and EM)

Catalogue completeness ✓

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

- Waveform systematic effects (GW)

- Detector calibration uncertainties (GW)

ampl. < 4%

systematic?

## GW cosmology: moving forward

- Astrophysically-motivated weighting of host galaxies
- Galaxy clustering: move over from galaxy catalogues to cluster catalogues  
Cluster cat + astrophysics  $\Rightarrow$  probability density of mergers in redshift space  
**merger density catalogues**

*Beyond  $H_0$ ?*

- Cross-correlations of GW and EM

3G: Cosmic Explorer, Einstein Telescope

## GW cosmology: other prospects

- Information from physics / astrophysics of NS: ET
  - Mass distributions *Taylor et al. (2012); Taylor & Gair (2012)*
  - Internal physics (tidal deformations) *Messenger & Read (2011); Del Pozzo et al. (2017)*
  
- GW lensing?
  - Time delays, cross-correlations . . .

## Summary and Outlook

- A new window to the observable universe!

Tip of the iceberg!

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

Systematic effects in EM and GW!

- Longer term:  $h(z)$  – cosmological parameters / modified gravity?

Multimessenger / GW-only avenues

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

Standard candles, sirens, rulers, ...

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

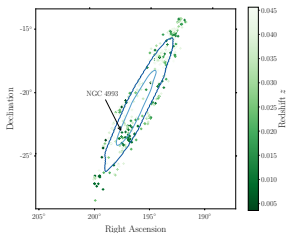
THANK YOU!

*I strongly condemn the brutal violence on students and scholars  
in academic campuses across the country.*

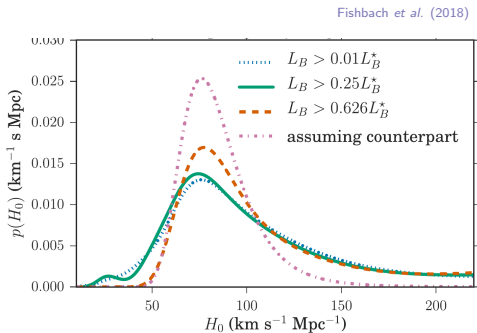
EXTRA SLIDES

## $H_0$ from GW170817 with GLADE catalogue

- GW170817 assuming no counterpart:

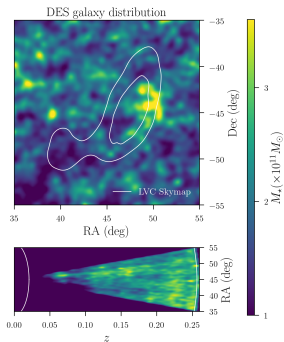


- Correcting for catalogue incompleteness
- Luminosity weighting

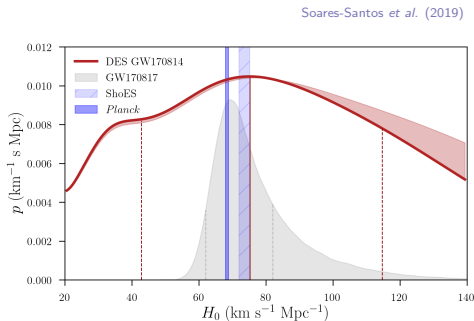


## $H_0$ from GW170814 with DES catalogue

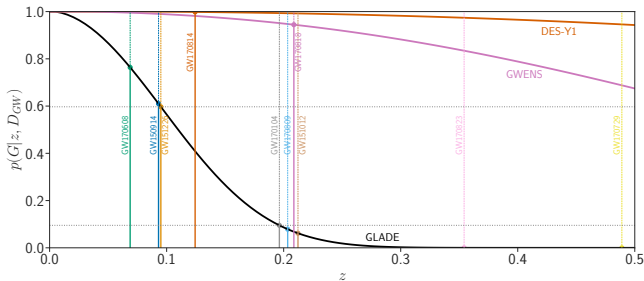
- **DES Y3 “gold” catalogue:** thoroughly surveyed GW170814 sky region.



- **First realistic application**



## $H_0$ from O1 & O2 detections



Try to find public catalogues with support for O1 & O2 detections:

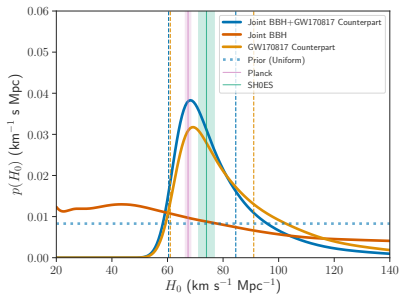
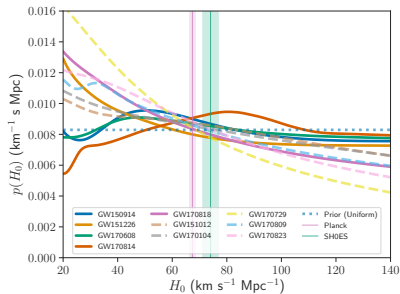
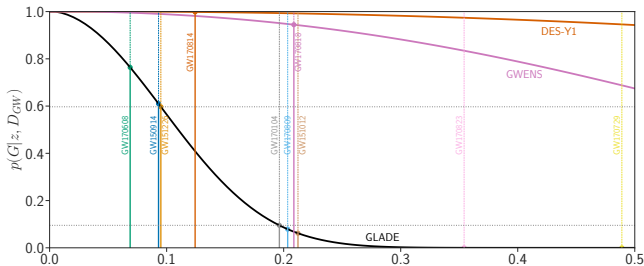
**DES-Y1** for GW170814

SDSS-based **GWENS** for GW170818

**GLADE** (compiled from GWGC, 2MPZ, 2MASS XSC, HyperLEDA, SDSS-DR12Q)

# $H_0$ from O1 & O2 detections

Abbott *et al.* arXiv:1908.06060



# $H_0$ from O1 & O2 detections

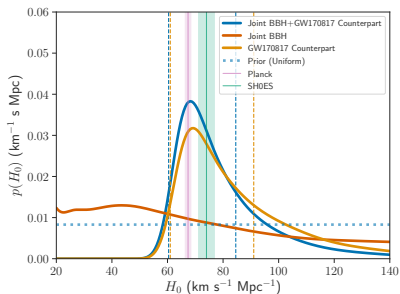
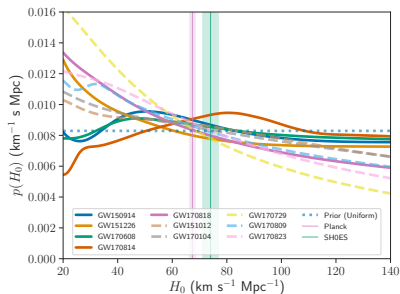
Abbott et al. arXiv:1908.06060

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:

