

Sirens to tune the universe

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Nikhef, Amsterdam

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Plan of the talk

- Compact binaries as standard sirens
- H_0 from GW detections
- “ H_0 -statistical” method
- Systematic effects in GW measurement of H_0
- Some projections for the future

Importance of synergy!

- 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

Schutz (1986), Holz & Hughes (2005)

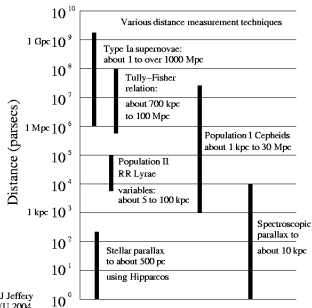
- GW from compact binaries give us a direct access to luminosity distance.

Independent measurement of phase evolution and amplitude

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

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

- Independent of the cosmic distance ladder!



$d_L \rightarrow$ cosmological parameters

Late-time expansion / acceleration parameters.

- H_0 : Hubble parameter
- Ω_m : Matter fraction
- Ω_Λ : Dark energy fraction
- $w(z)$: Dark energy equation-of-state

Redshift-distance relation:

$$d_L = c(1+z) \int^z \frac{dz'}{H(z')}, \quad H(z') = H_0 \sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda \exp \left\{ 3 \int_0^{z'} \frac{dz''}{1+z''} [1+w(z'')] \right\}}$$



Hubble parameter

Where does z come from?

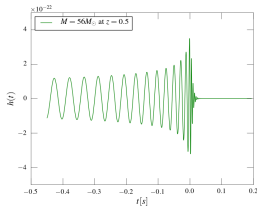
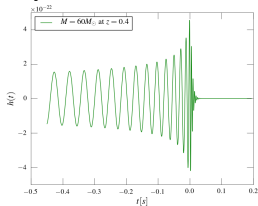
- Spectral lines!

observed "frequency"; intrinsic "frequency" at source

- Spectral lines for compact binaries?

Where does z come from?

- Binary black holes: cosmological redshift degenerate with total mass.

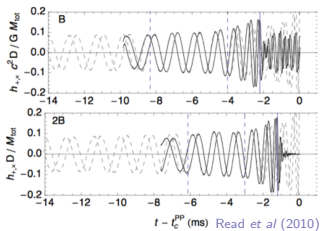


- Neutron stars: matter effects!

Break degeneracy weakly.

Relies on knowledge of NS physics.

Difficult to measure (Adv ground based).



Where does z come from?

- Astrophysics of compact binaries.

Intrinsic mass distribution of NS.

Robust features in intrinsic BBH mass distributions?

- Scale set by the cosmological constant?

Where does z come from?

- With compact binaries

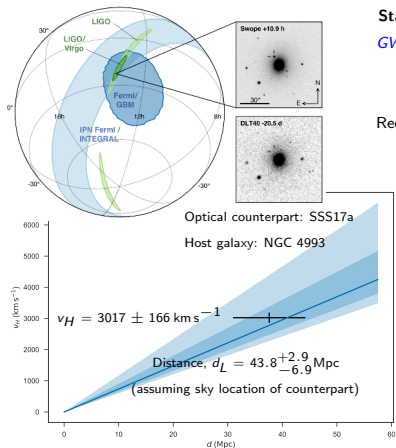
d_L directly measured

redshift difficult to measure

- Fall back on electromagnetic measurement of redshift

coincident optical counterparts; identified host galaxies

H_0 with GW170817



Independent of any distance ladder!

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

10 of 30

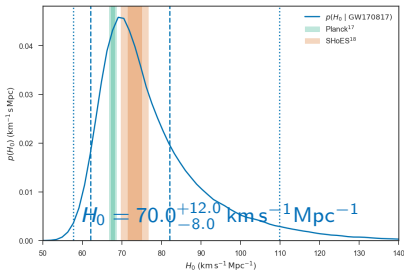
Standard siren

Schutz (1986), Holz & Hughes (2005)

GWs provided a direct measurement of the luminosity distance!

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

Recession velocity (redshift) came from host galaxy NGC 4993.

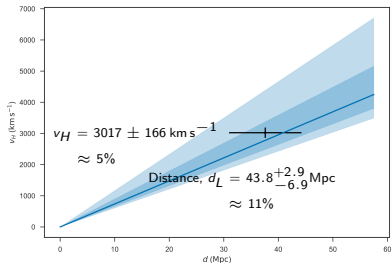


Abbott *et al.* *Nature* **551** #7678, 85-88 (2017)

H_0 with GW170817

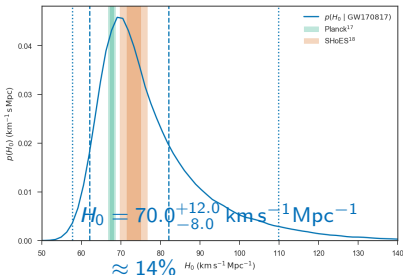
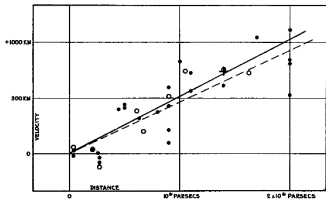
Edwin Hubble, *Proc. Nat. Acad. Sciences.* (1929)

First plot in the GW Hubble diagram:



Independent of any distance ladder!

LSC-EPO
11 of 30

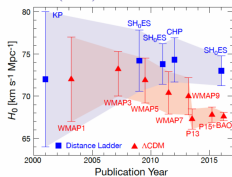


Abbott *et al.* *Nature* 551 #7678, 85-88 (2017)

State-of-the-art measurements of H_0

Two contrasting methods applied on nearby and very distant cosmological scales

Freedman (2017)



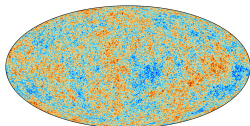
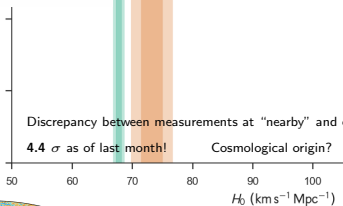
Planck $\approx 0.7\%$
SHoES $\approx 2\%$

Standard candles
Cosmic distance ladder

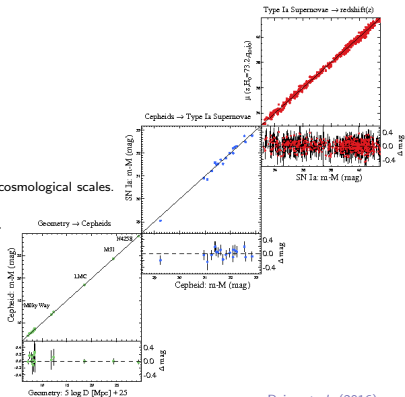
Discrepancy between measurements at "nearby" and cosmological scales.

4.4σ as of last month!

Cosmological origin?

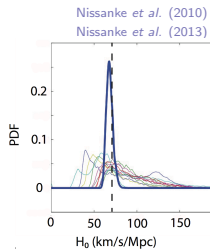


Planck collaboration (2015) + Λ -CDM

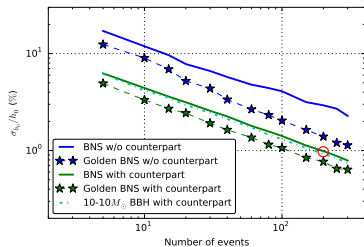


Reiss et al. (2016)

Better with more detections!



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



Chen *et al.* (2017)

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

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

Better with more detections!

GW selection effects

threshold SNR \rightarrow interferometer horizon
only nearby signals detected

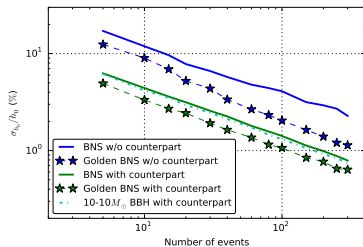
Detection efficiency (selection function):

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

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

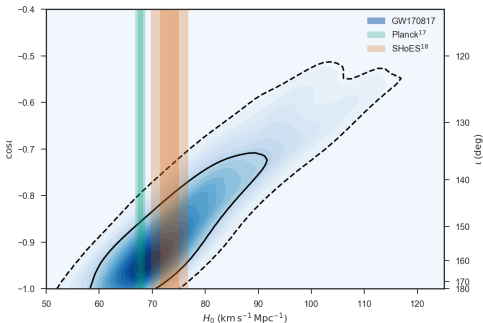
Mandel, Farr, Gair (2018); Chen *et al.* (2017)

14 of 30



Chen *et al.* (2017)

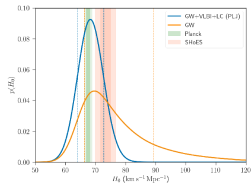
Degeneracy with inclination



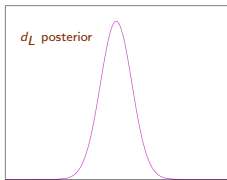
Distance-inclination degeneracy: GW amplitude from by a distant binary viewed face-on (or face-off) is similar to that of a closer binary viewed edge-on.

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

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



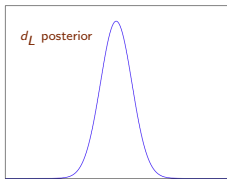
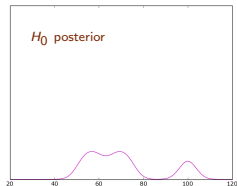
Independent events



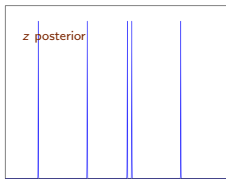
+



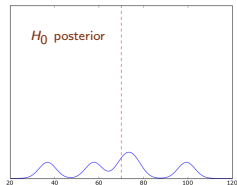
\Rightarrow



+



\Rightarrow



Different possible galaxies for single event

Multimodal H_0 posterior for each event

Combine information from all observed events \Rightarrow

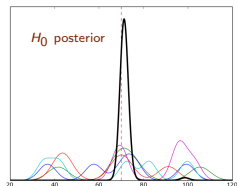


Schutz " H_0 -statistical" method

set of possible host galaxies

applicable also for **binary black holes**

Schutz (1986); Del Pozzo (2012)



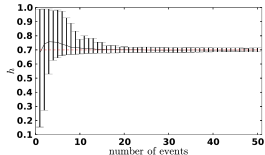
H_0 -statistical

Idea in Schutz (1986).

MacLeod and Hogan (2008) in the context of LISA.

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

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



Chen *et al.* (2017); Nair *et al.* (2018) **Selection effects!**

H_0 -statistical: completion of galaxy catalogue

Ghosh *et al.* (unpublished)

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

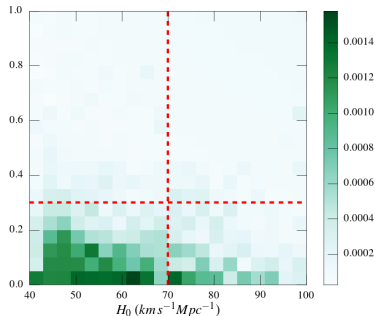
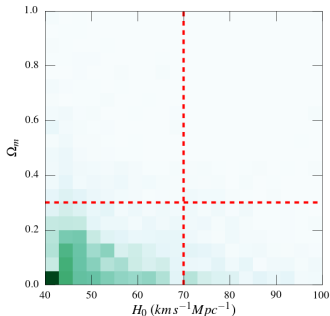
Posterior

Prior

↑
Extra pre-factor

Usual likelihood

↑
Additional term to account for missing galaxies



- Bayesian method for both “counterpart” and “statistical” analysis.

$$p(H_0 | \{x_{\text{GW}}\}, \{D_{\text{GW}}\}) \propto p(H_0) p(N_{\text{det}} | H_0) \prod_i^{N_{\text{det}}} p(x_{\text{GW}_i} | D_{\text{GW}_i}, H_0)$$

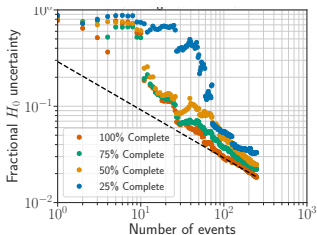
Combination of all information will give best measurement of H_0

- For “statistical”: takes into account possibility that host galaxy is not in the catalogue by modelling the catalogue with an apparent magnitude threshold.

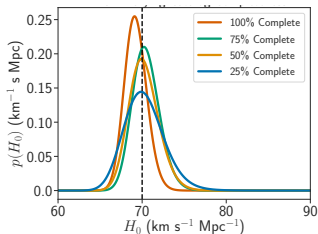
$$p(x_{\text{GW}} | D_{\text{GW}}, H_0) = \frac{p(x_{\text{GW}} | G, H_0)}{p(D_{\text{GW}} | G, H_0)} p(G | D_{\text{GW}}, H_0) + \frac{p(x_{\text{GW}} | \bar{G}, H_0)}{p(D_{\text{GW}} | \bar{G}, H_0)} p(\bar{G} | D_{\text{GW}}, H_0)$$

Denominator analogous to detection efficiency or selection function

H_0 -statistical: results on simulations



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



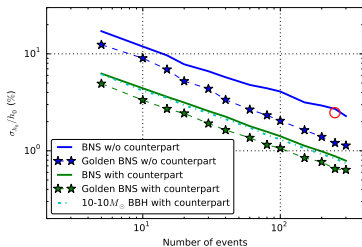
Statistical: [incomplete galaxy catalogue](#)

Account for galaxies absent in catalogue

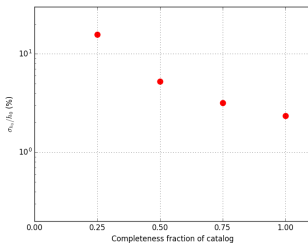
Cosmology Working Group: Ajith, Brady, Chen, Datrier, Del Pozzo, **Fishbach**, Gair, Ghosh, **Gray**, Hendry, Holz, **Magaña-Hernandez**, Messenger, **Qi**, Samajdar, **Sur**, Van Den Broeck, Veitch, . . .

H_0 -statistical: results on simulations

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



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



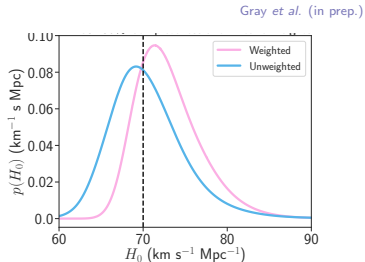
Statistical: **incomplete galaxy catalogue**

Account for galaxies absent in catalogue

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

H_0 -statistical: results on simulations

Luminosity weighting of galaxies:



B-band: star formation rate

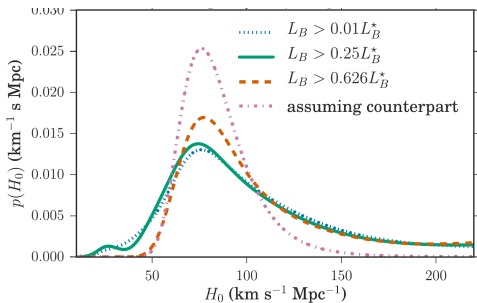
K-band: total mass

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 -statistical with GW170817

- GW170817 assuming no counterpart:

Fishbach *et al.* (2018)

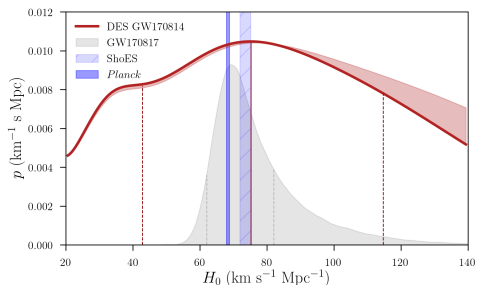


- Correcting for catalogue incompleteness
- Luminosity weighting

H_0 -statistical with GW170814

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

Soares-Santos *et al.* (2019)



- First realistic application

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)
- GW 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 ?

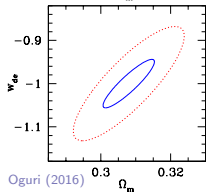
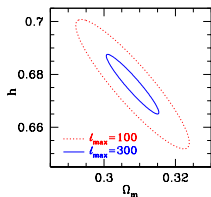
Correlations of GW/EM distributions

Angular / 3D correlation functions

GW distributions with cluster catalogues / LSS

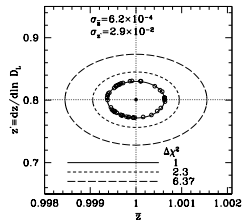
ET

BBO + Euclid / SKA



Oguri (2016)

Ω_m



Mukherjee & Wandelt(2018)

Zhang (2018)

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, . . .

Thank you!