Cosmology with gravitational waves from compact binary coalescences

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Plan of the talk

- Overview

  Orientation and motivation

  Cosmology with gravitational waves

- LIGO-Virgo results and current directions

  Standard-siren H_0 from GW170817

  The "statistical" method

- Prospects and caveats

Cosmography

Late time cosmology!

Cf. talk by **Daniel Figueroa**

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

Nicola Tamanini

Redshift-distance relation:

$$d_L = c(1+z)\int^z \frac{dz'}{H(z')}\ , \quad H(z') = H_0\sqrt{\Omega_m(1+z')^3 + \Omega_K(1+z')^2 + \Omega_\Lambda \exp\left\{3\int_0^{z'}\frac{dz''}{1+z''}[1+w(z'')]\right\}}$$

$\uparrow$

Hubble parameter

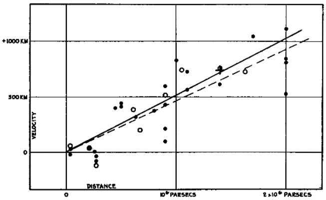
Cosmology: Hubble's law

recession velocity of a galaxy in the local universe $\longrightarrow$ $$c\,z = H_0\,d$$ $\longleftarrow$ distance to the galaxy

$\uparrow$ Hubble parameter

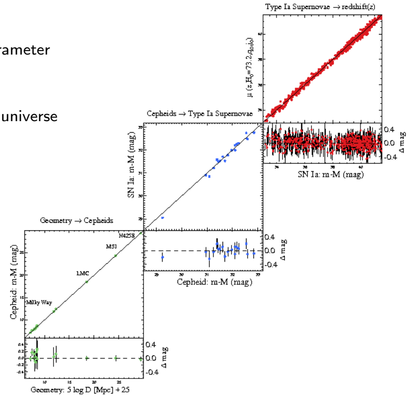
recession $\rightarrow$ stretching of spacetime itself $\rightarrow$ expansion of the universe

usually measured as a cosmological redshift $v_H = c\,z$



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

Note: significant overestimate!

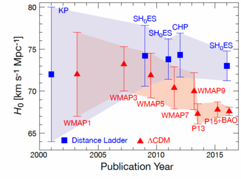


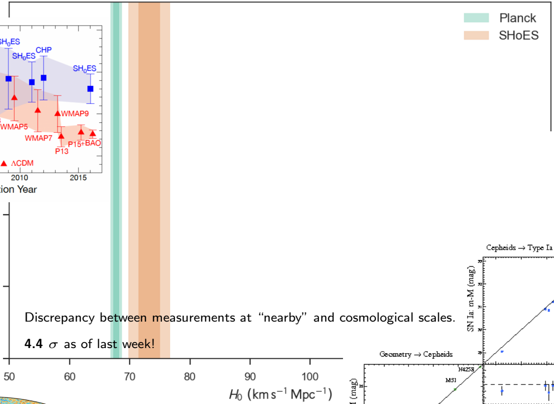
Cosmic distance ladder: Reiss *et al.* (2016)

State-of-the-art measurements of H_0

Two contrasting methods applied on nearby and very distant cosmological scales

Freedman (2017)



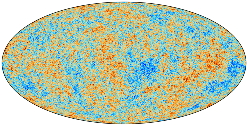


Standard candles

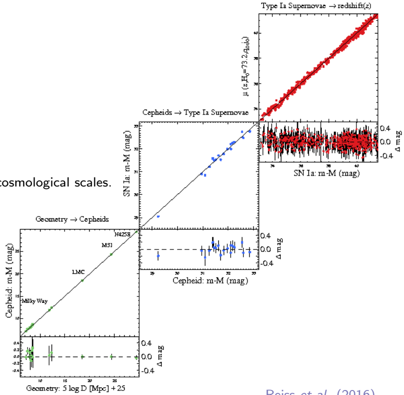
Cosmic distance ladder

Discrepancy between measurements at "nearby" and cosmological scales.

4.4 σ as of last week!



Planck collaboration (2015) + **Λ-CDM**



Reiss *et al.* (2016)

Cosmology with compact binaries

Standard siren Schutz (1986), Holz & Hughes (2005)

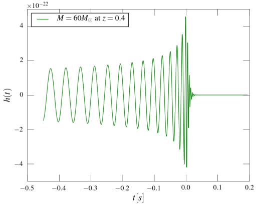
- GW from compact binaries give us a direct access to luminosity distance.

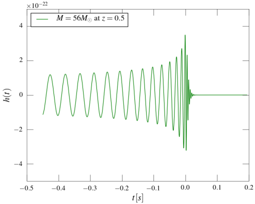
Independent measurement of phase evolution and amplitude

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

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

- Cosmological redshift (nearly) degenerate with total mass.





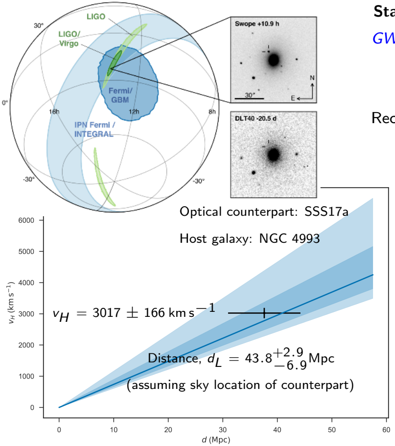
H_0 with GW170817

Standard siren Schutz (1986), Holz & Hughes (2005)

GWs provided a direct measurement of the luminosity distance!

$$v_H = H_0 d_L$$

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



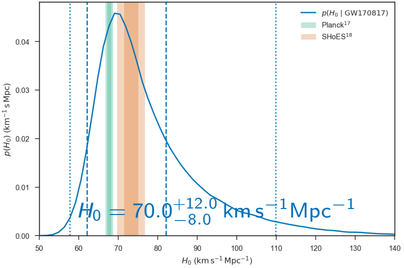
Optical counterpart: SSS17a

Host galaxy: NGC 4993

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

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

(assuming sky location of counterpart)



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

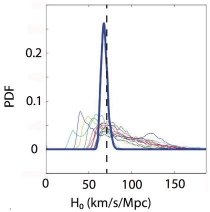
Independent of any distance ladder!

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

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

Better with more detections!

Nissanke *et al.* (2010)
Nissanke *et al.* (2013)

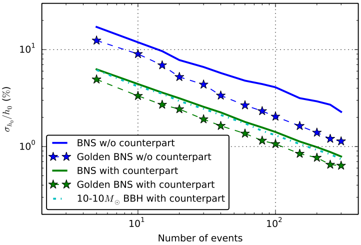


$$d_L H_0 \approx zc$$

GW selection effects

threshold SNR $\rightarrow$ interferometer horizon

only nearby signals detected



Detection efficiency (selection function):

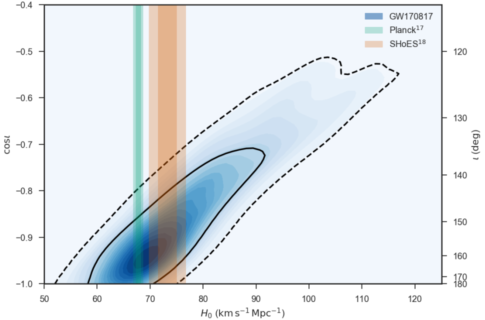
$$\mathcal{N}_{\text{eff}}(\boldsymbol{\Omega}) = \int_{\mathcal{E}_{\text{det}}} d\mathcal{E} \int d\theta \; p(\mathcal{E}\,|\,\theta, \boldsymbol{\Omega}, \mathcal{H}, \mathcal{I}) \, p(\theta\,|\,\boldsymbol{\Omega}, \mathcal{H}, \mathcal{I})$$

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

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

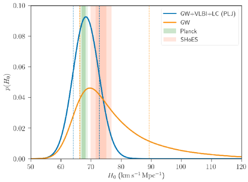
Chen *et al.* (2017)

Degeneracy with inclination

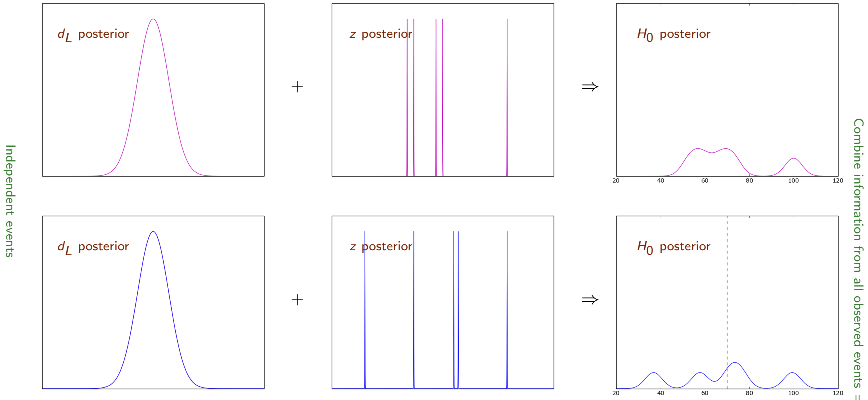


Distance-inclination degeneracy: GW amplitude from by a distant binary viewed face-on (or face-off) is similar to that of a closer binary viewed edge-on.

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

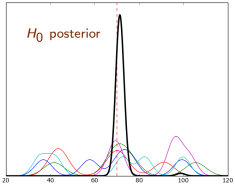


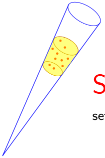
Hotokezaka *et al.* (2018): jet → **inclination** → H_0



Different possible galaxies for single event

Multimodal H_0 posterior for each event





Schutz “H_0-statistical” method

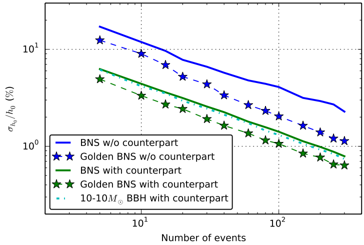
set of possible host galaxies

applicable also for **binary black holes**

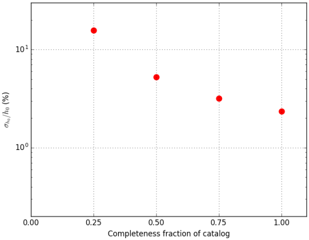
Schutz (1986); Del Pozzo (2012)

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

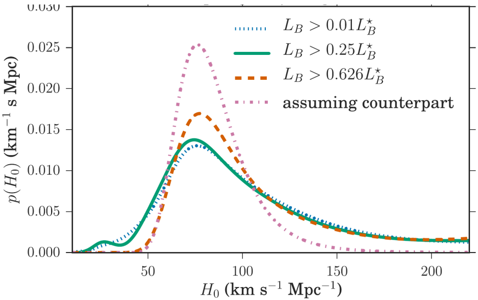
Cosmology Working Group: Ajith, Brady, Chen, Datrier, Del Pozzo, **Fishbach**, Gair, Ghosh, **Gray**, Hendry, Holz, **Magaña-Hernandez**, Messenger, **Qi**, Samajdar, **Sur**, Van Den Broeck, Veitch, . . .

H_0-statistical with GW170817

- GW170817 assuming no counterpart

Talk by **Maya Fishbach**

Fishbach *et al.* (2018)

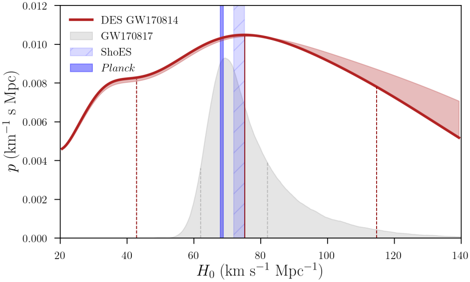


- Correcting for catalogue incompleteness
- Luminosity weighting

H_0-statistical with GW170814

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

Soares-Santos *et al.* (2019)



- First realistic application

gwcosmo codebase and LVC plans

Magaña-Hernandez, Gray, ...

- Bayesian method for both "counterpart" and "statistical" analysis.

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

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.

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

Denominator analogous to detection efficiency or selection function

- Mass distribution (and rate) assumptions enter the "selection function".

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)