Huitième Assemblée Générale du GdR Ondes Gravitationnelles @Aix-Marseille University

Oct 15, 2024

Probing Cosmic Expansion with Gravitational Wave-Large Scale Structure Correlations

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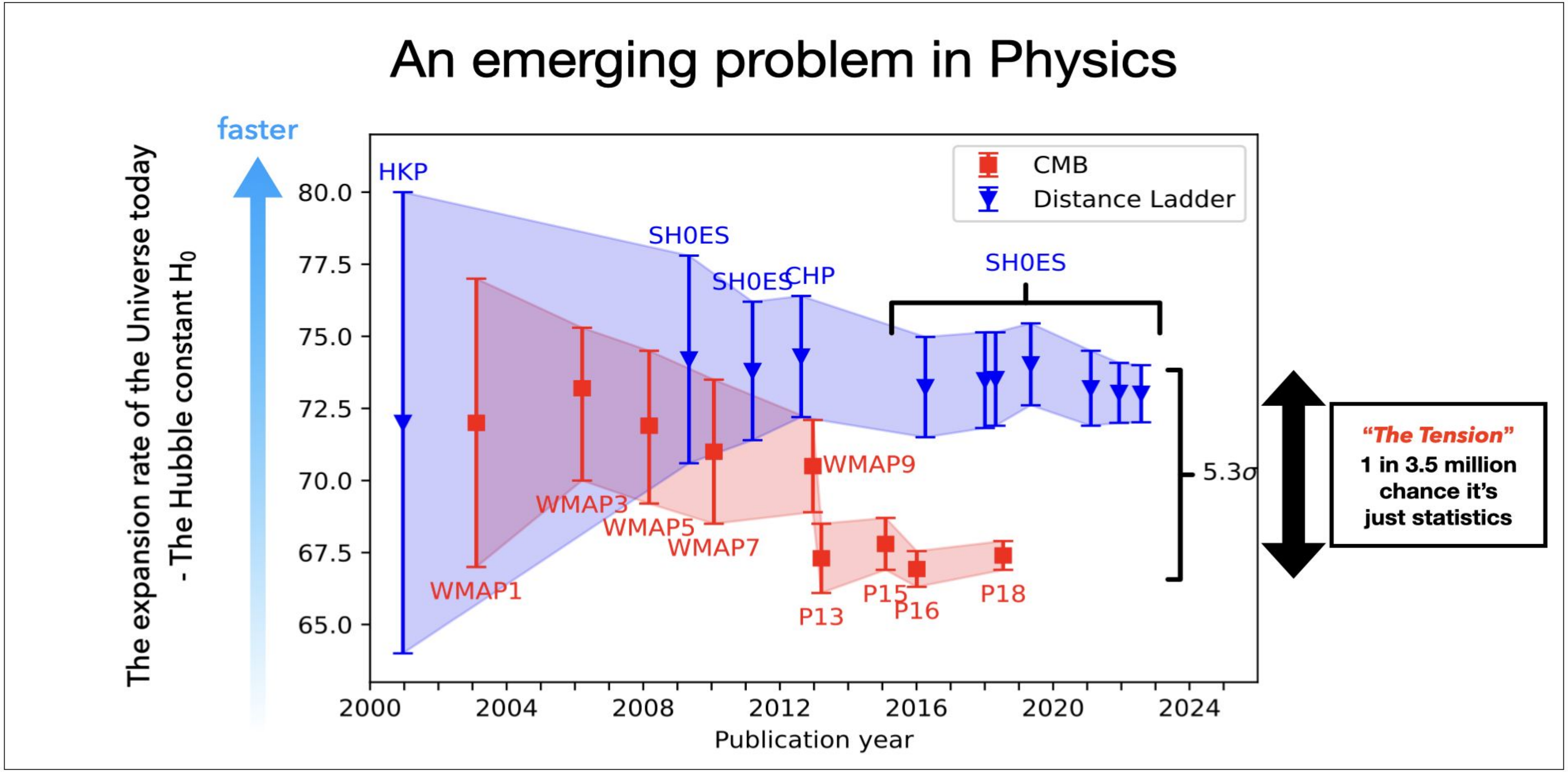
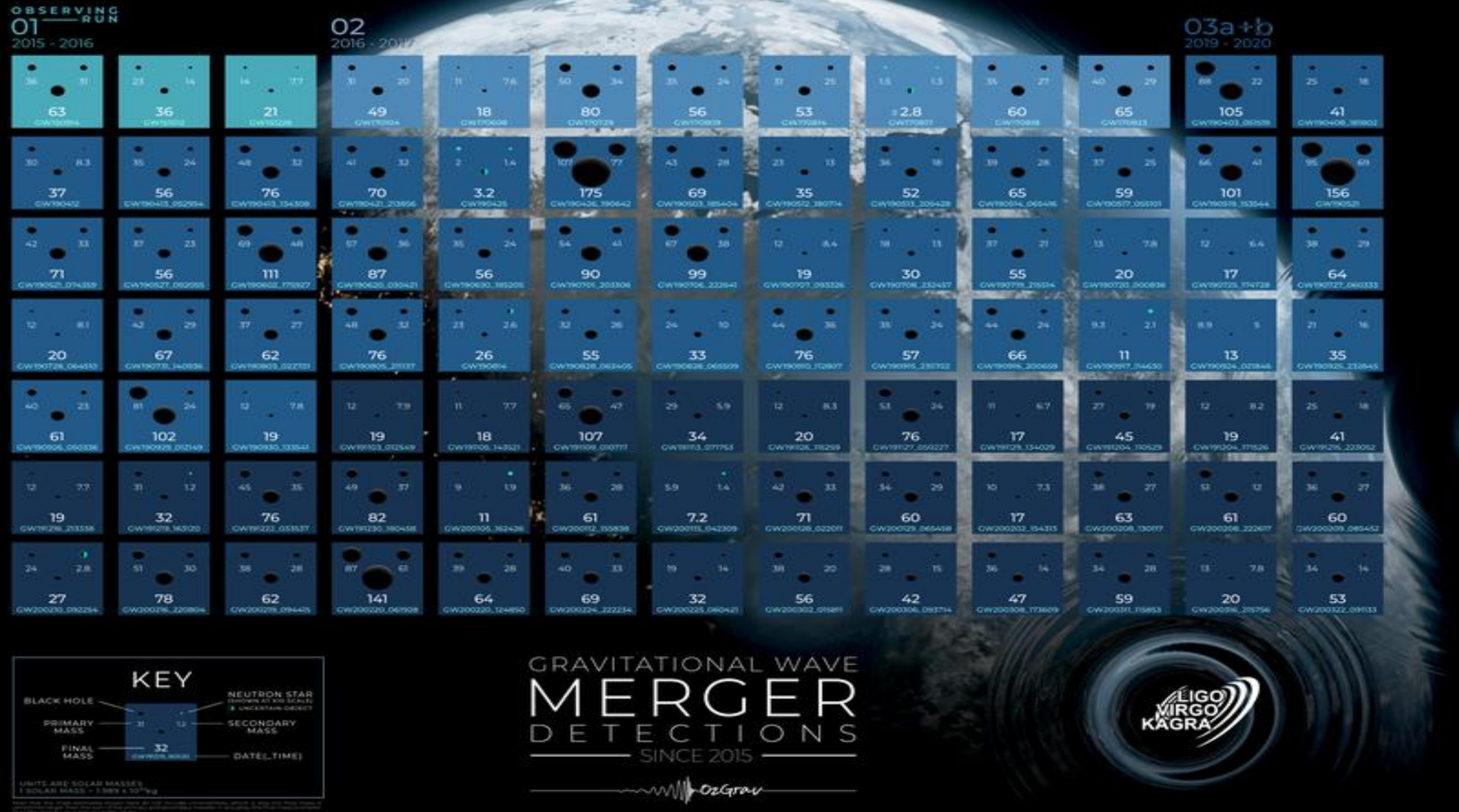
University of the Balearic Islands, Spain

Courtesy: NanoGrav

Motivation

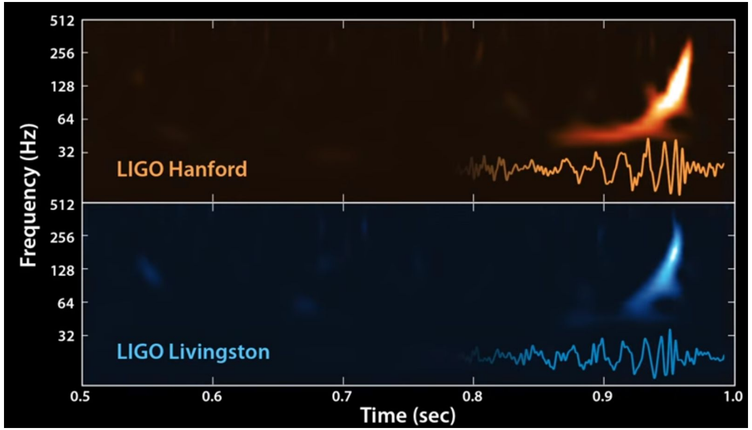
Image: *D'arcy Kenworthy*





Credit: Carl Knox (OzGrav, Swinburne University of Technology)

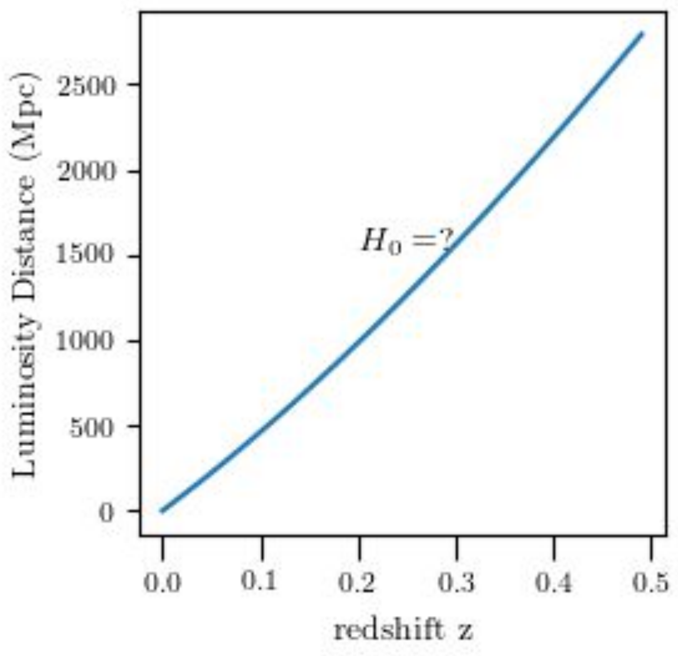
Distance measurement from Gravitational Waves



$$h(t) = \frac{M_z^{5/3} f(t)^{2/3}}{d_L} F(\iota, \theta) \cos(\Phi(t))$$

M_z: Redshifted chirp mass
ι: inclination angle
$\Phi(t)$: Accumulated phase

Measuring H_0 with "standard sirens"



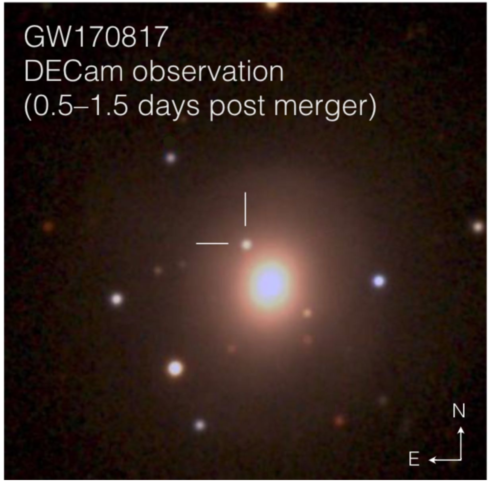
- ❑ Luminosity distance - redshift curve depends on the value of the Hubble parameter H_0

$d_L \sim cz/H_0$ low redshift

- ❑ Luminosity distance - GW observation
- ❑ Redshift - Electromagnetic counterpart

Thus an independent estimate of H_0 is possible

GW170817



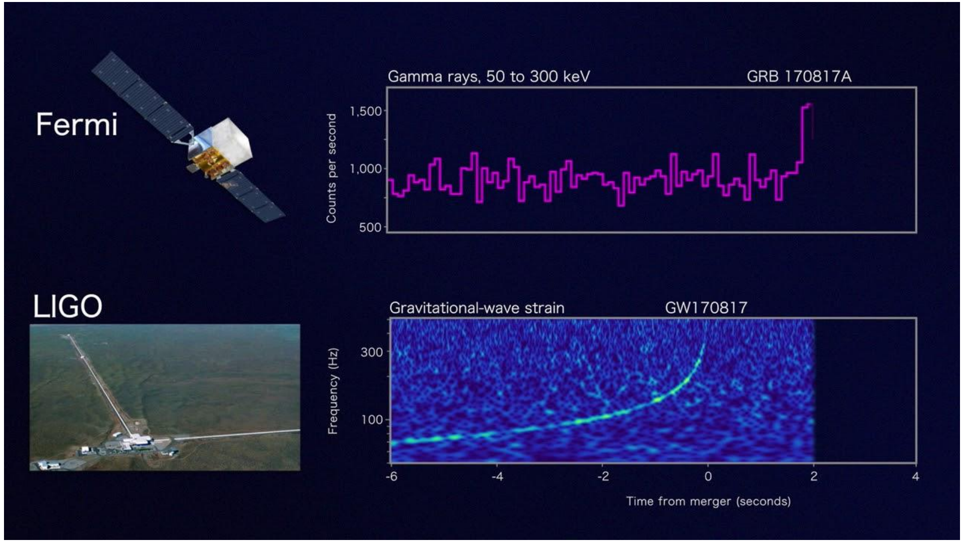
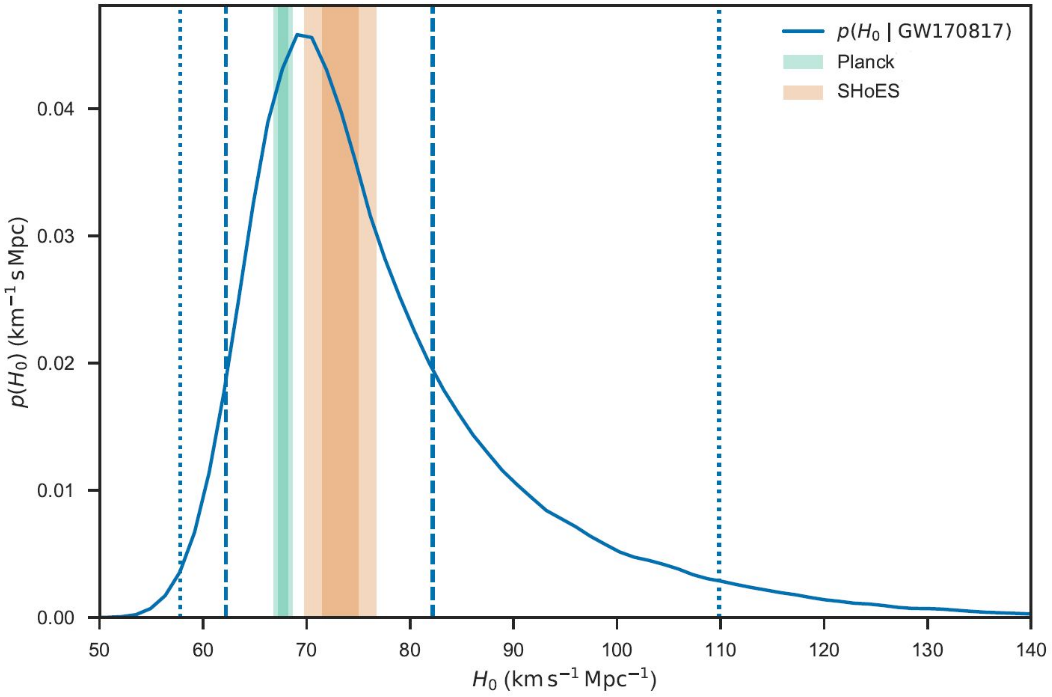


Image: https://www.ligo.org

- The only GW event detected along with a GRB: **GRB 170817A**
- Luminosity distance ~ **40 Mpc**
- Host identification : **NGC 4993**

For the majority of the detected events, host identification is not possible

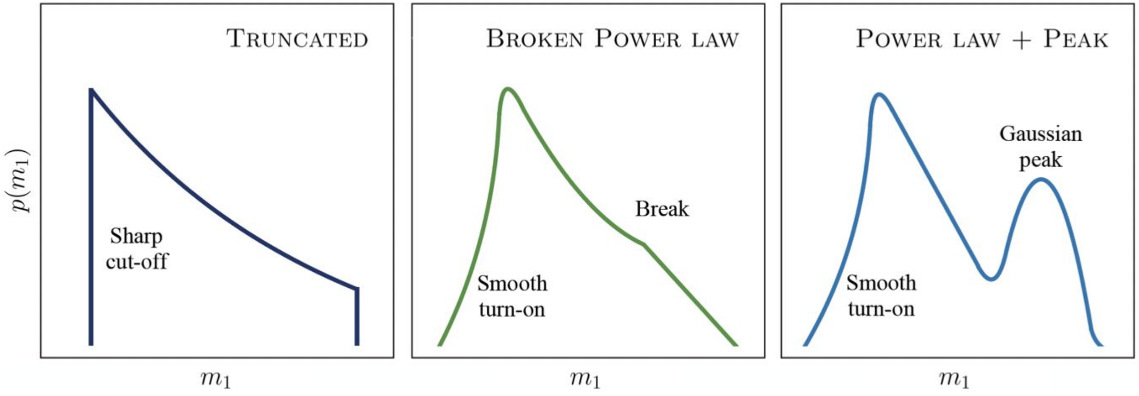
Constraints on Hubble constant from GW170817



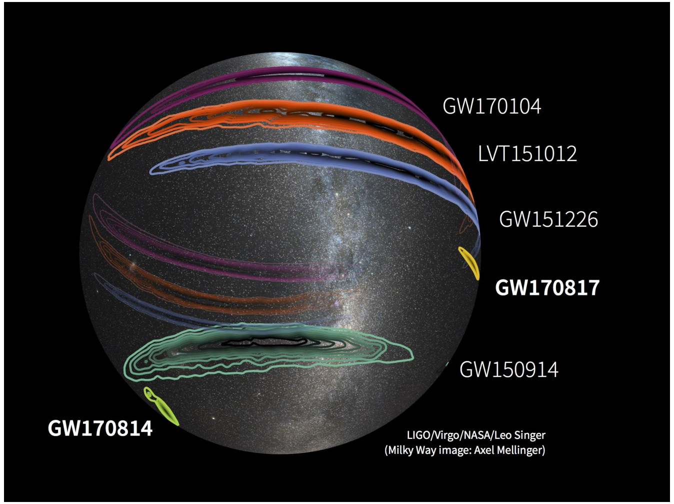
Abbott et. al. (2017)

Measurement of H_0 with ~ 15% accuracy at 68.3% confidence

Inferring H_0 using population statistics



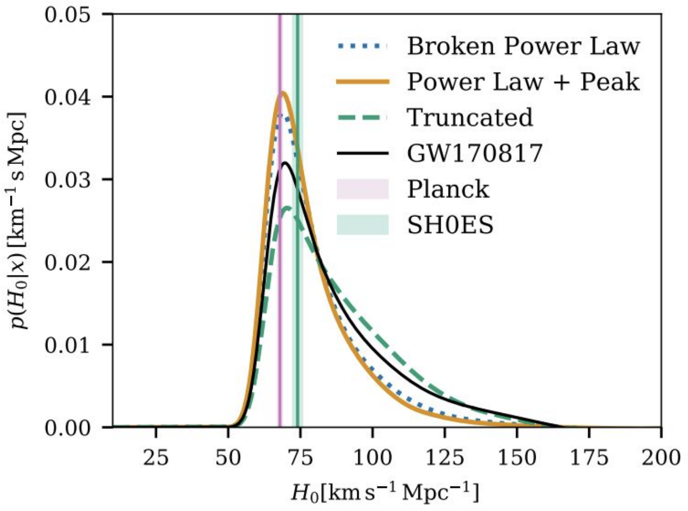
Abbott et al. (2021)



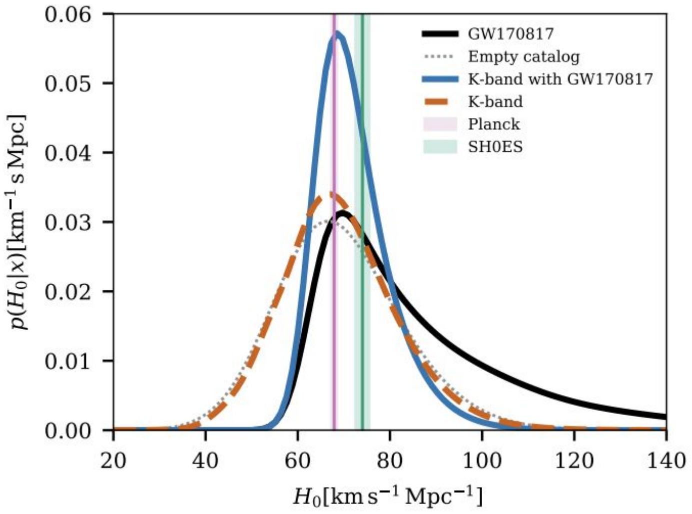
Credit : Leo Singer

- Map an astrophysically motivated source mass distribution to the detector frame - thus extract the redshift distribution (icarogw) Abbott et al. (2023)
- Consider galaxies (with known redshifts) in the localization region as potential hosts and compute H_0 distribution for each potential host (gwcosmo) Schutz(1986)

Constraints from GWTC-3



Method 1: Spectral Siren technique (icarogw)



Method 2 : Galaxy Catalogue technique (gwcosmo)

Abbott et al. (2023)

An alternative approach: *The Large Scale Structures*

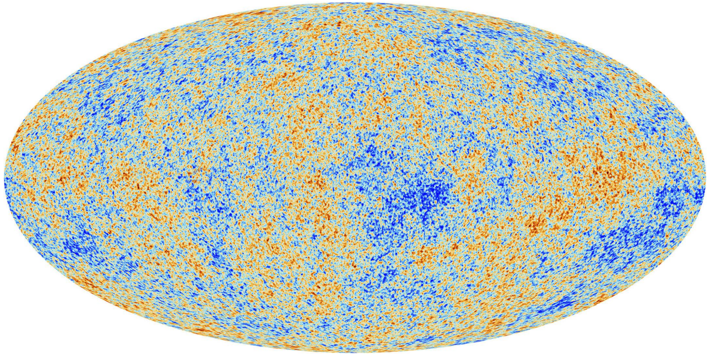


Image: ESA

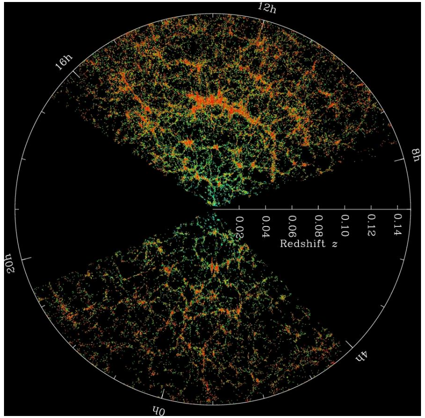


Image: SDSS

The Millennium simulation (z=0)

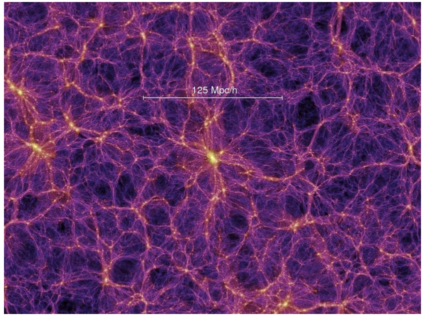


Image: https://wwwmpa.mpa-garching.mpg.de

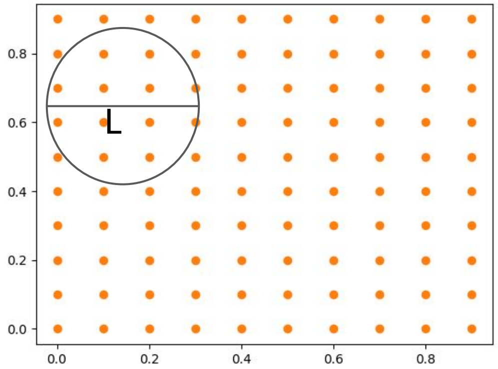
Measures of clustering: Density Contrast and cross-correlation

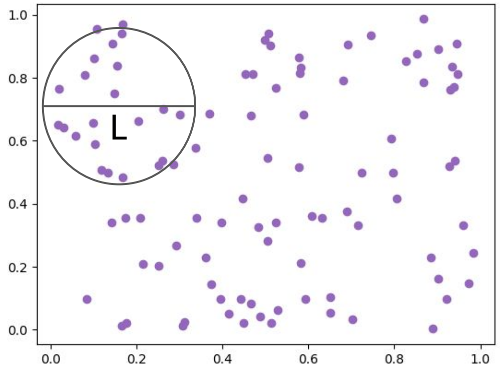
$$\delta(\mathbf{x}) \sim \frac{\rho(\mathbf{x})}{\bar{\rho}} - 1$$

$$\xi(\mathbf{x}, \mathbf{x}') \sim \langle \delta(\mathbf{x}) \delta(\mathbf{x}') \rangle$$

Angular cross-correlation

$$w(\theta, \theta') \sim \langle \delta(\theta) \delta(\theta') \rangle$$





Clustering ~ N/$\mathcal{N}$ -1
L : Clustering length

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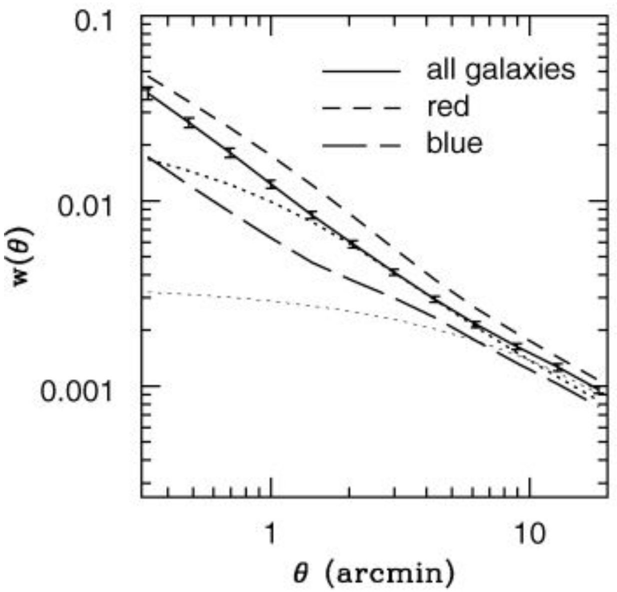


Jain, Scranton, Sheth (2003)

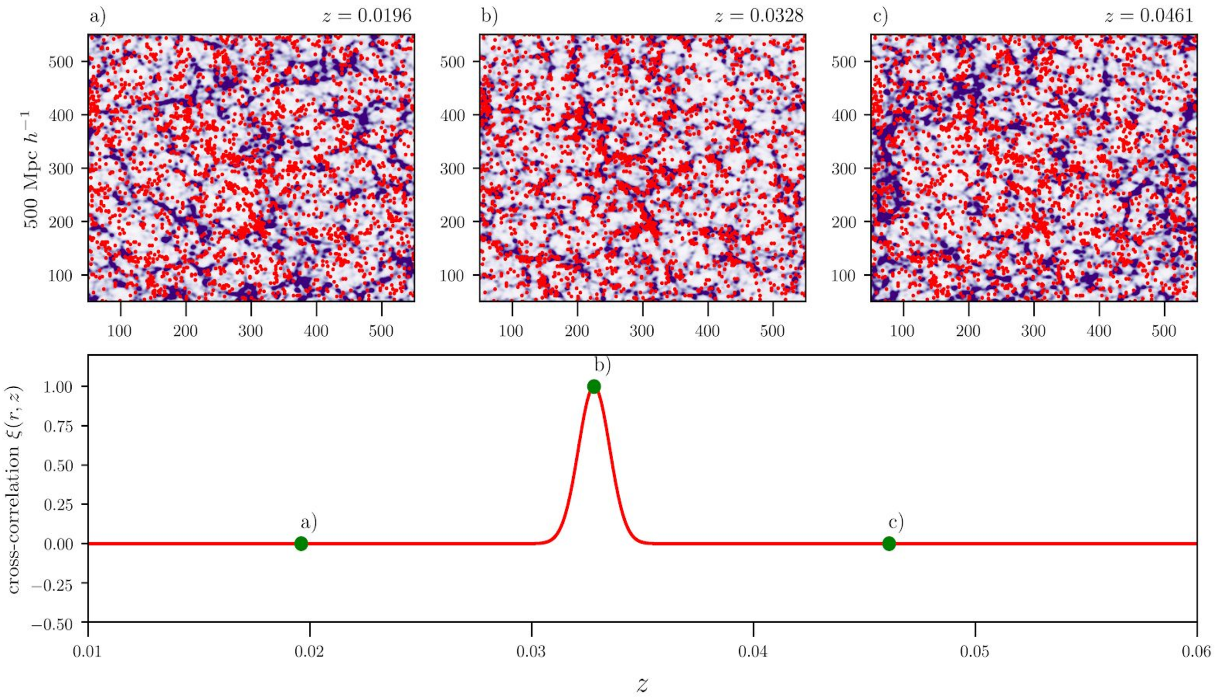
Inferring redshift from LSS distribution

Red : BBH sources at a fixed unknown redshift

Blue: Galaxy distribution at different redshift slices

The BBH distribution is a part of the same large scale structure as the galaxies.

Cross-correlation of the two distributions provide a redshift estimate for the unknown BBH population

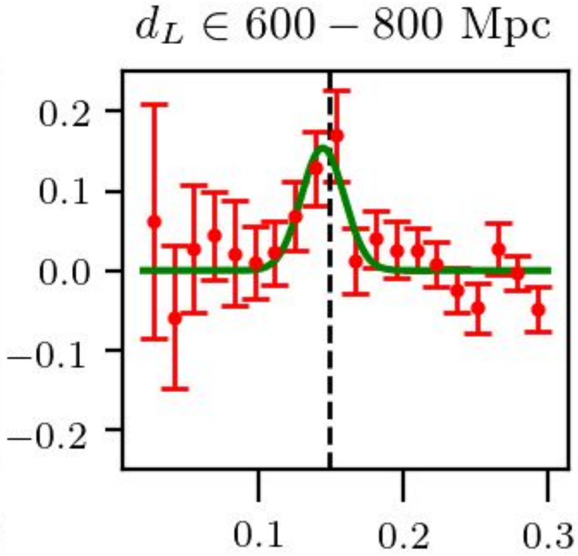


Newman (2008), Oguri (2016)

A realistic Simulation of the catalogs

- ❏ The true locations of the GW events are sampled from the dark matter distribution of a cosmological N-body simulation (Big-MultiDark Planck)
- ❏ Massive dark matter halos act as galaxy markers in our simulation.
- ❏ Realistic simulation of the GW events and parameter estimations run using BILBY: A free Bayesian Inference library for GW (Ashton et al. 2019)
- ❏ 3 detector network (Advanced Ligo L +H + Advanced Virgo): combined SNR threshold of 8

Modelling the cross-correlation

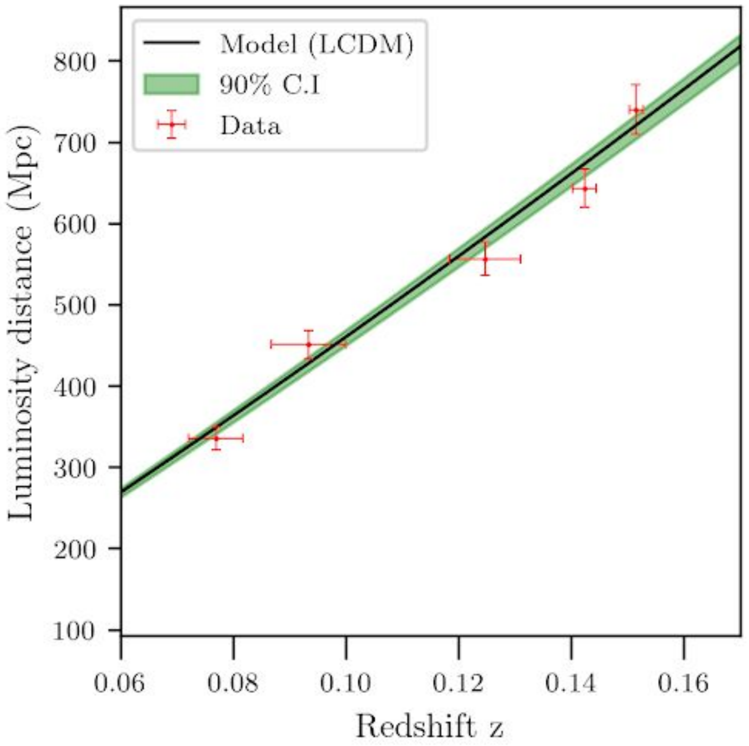


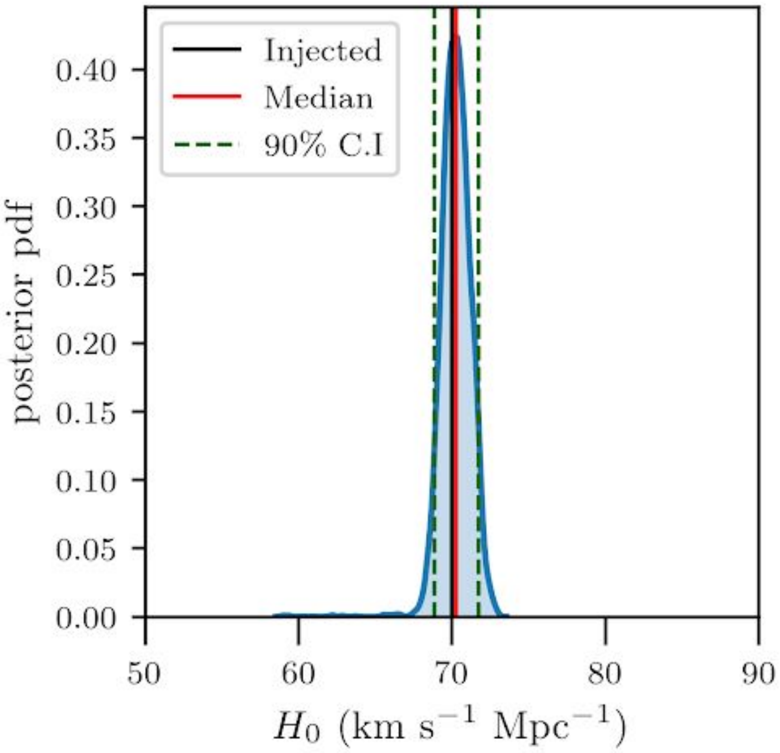
Assume power law three-dimensional cross-correlation function:

$$\xi_{\mathrm{gw,g}}(r) = \left[\frac{r}{r_0}\right]^{-\gamma}$$

$$w(\leq \theta_{\mathrm{max}}, z, z') \propto \exp\left[-\frac{(z-z')^2}{2\sigma_z^2}\right]$$

Hubble-Lemaitre diagram : 500 events





SB, Rana, More, Bose (2020)

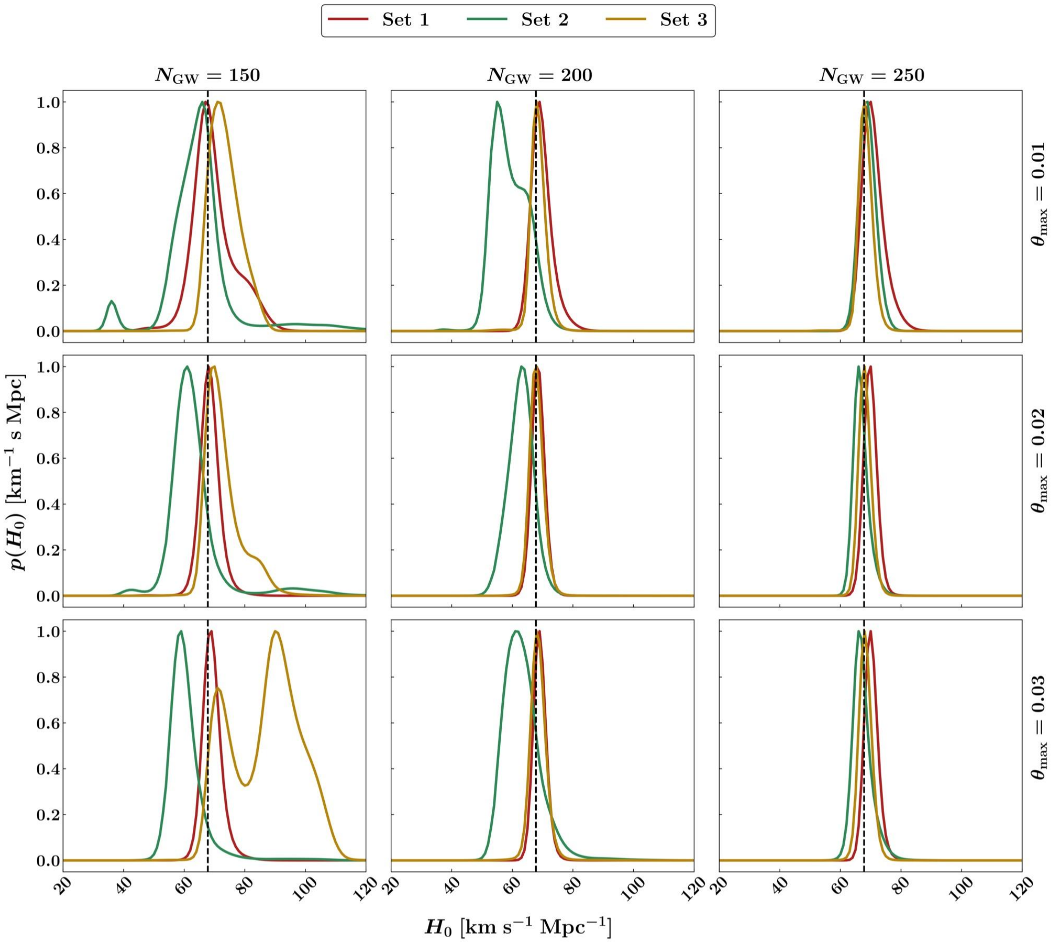
An event-by-event analysis

$$p(H_0 \mid \boldsymbol{d}_{\text{strain}}, \boldsymbol{d}_g^{\text{obs}}) = \int p(H_0, \boldsymbol{d}_{\text{gw}} \mid \boldsymbol{d}_{\text{strain}}, \boldsymbol{d}_g^{\text{obs}}) d\boldsymbol{d}_{\text{gw}}$$
$$\propto \int \mathcal{L}(\boldsymbol{d}_{\text{strain}}, \boldsymbol{d}_{\text{g}}^{\text{obs}} | H_0, \boldsymbol{d}_{\text{gw}}) P(H_0, \boldsymbol{d}_{\text{gw}}) d\boldsymbol{d}_{\text{gw}}$$

➡ For each GW event, the posterior is obtained by marginalizing over localization uncertainties $\boldsymbol{d}_{\text{gw}}$

Assuming independent probability distributions, the single-event posteriors can be combined as :

$$P(H_0 \mid \{\boldsymbol{d}_{\text{strain}}\}, \{\boldsymbol{d}_g^{\text{obs}}\}) \propto P(H_0) \prod_i \mathcal{L}(\boldsymbol{d}_{\text{strain}_i}, \boldsymbol{d}_{g_i}^{\text{obs}} | H_0)$$
$$\propto P(H_0) \prod_i \int \mathcal{L}(\boldsymbol{d}_{\text{strain}_i}, \boldsymbol{d}_{g_i}^{\text{obs}} | H_0, \boldsymbol{d}_{\text{gw}}) P(\boldsymbol{d}_{\text{gw}}) d\boldsymbol{d}_{\text{gw}}$$



-Set 1,2,3 : Different realizations of randomly generated events upto 1000 Mpc, SNR>12

-Dependence on **sample size** and **correlation scale**

-Injected value of H_0 = 67 km/s/Mpc

Ghosh, More, **SB**, Bose (arXiv: 2312.16305)

Take-Home Message

Incorporating information from large-scale structure correlations is **crucial** to a more robust inference of the background cosmology

Take-Home Message

Incorporating information from large-scale structure correlations is crucial to a more robust inference of the background cosmology

- With 3G gravitational wave detectors such as Einstein Telescope, Cosmic Explorer and space based LISA, the future looks promising.

- Euclid will map the large-scale structures in the universe very accurately up to high redshifts.

ACKNOWLEDGMENTS

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Extra Slides

Waveform simulation: inputs

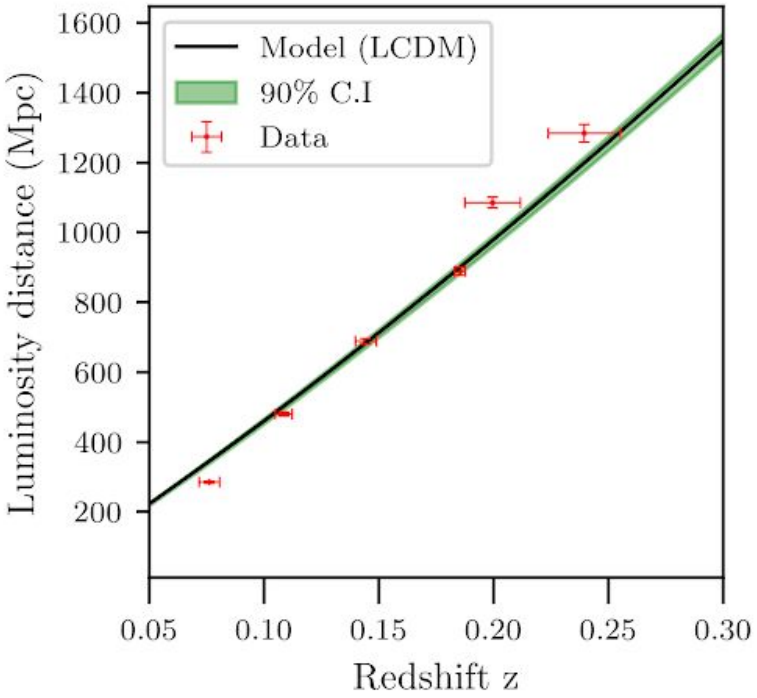
Detectors	Sensitivity
Livingston	Advanced LIGO
Hanford	Advanced LIGO
Virgo	Advanced Virgo

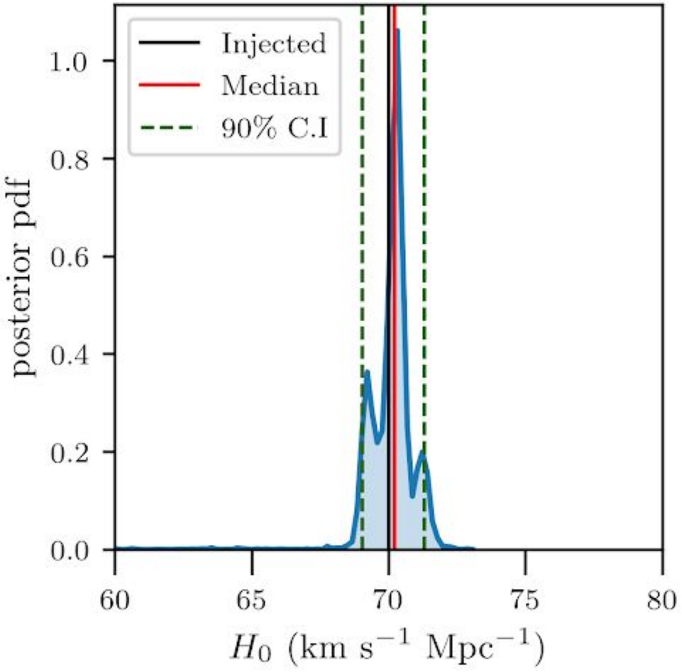
Injection Parameters		
Parameters	Distribution	Limits
$m_{1,2}$	uniform	[10, 35] $M_\odot$
$\chi_{1,2}$	uniform	[0, 0.8]
ϕ_{12} , ϕ_{jl}	uniform	[0, 2π)
$\cos\theta_{1,2}$, $\cos\iota$	uniform	[-1, 1)
ψ , ϕ_c	Fixed	0

Detection criteria: At least two of the detectors SNR above a threshold value of 5 each, the third an SNR greater than 2.5, and network SNR of greater than 8.

Hubble-Lemaitre diagram : 5000 events

Red points: d_L inferred from BBH merger waveforms, redshift from cross-correlations

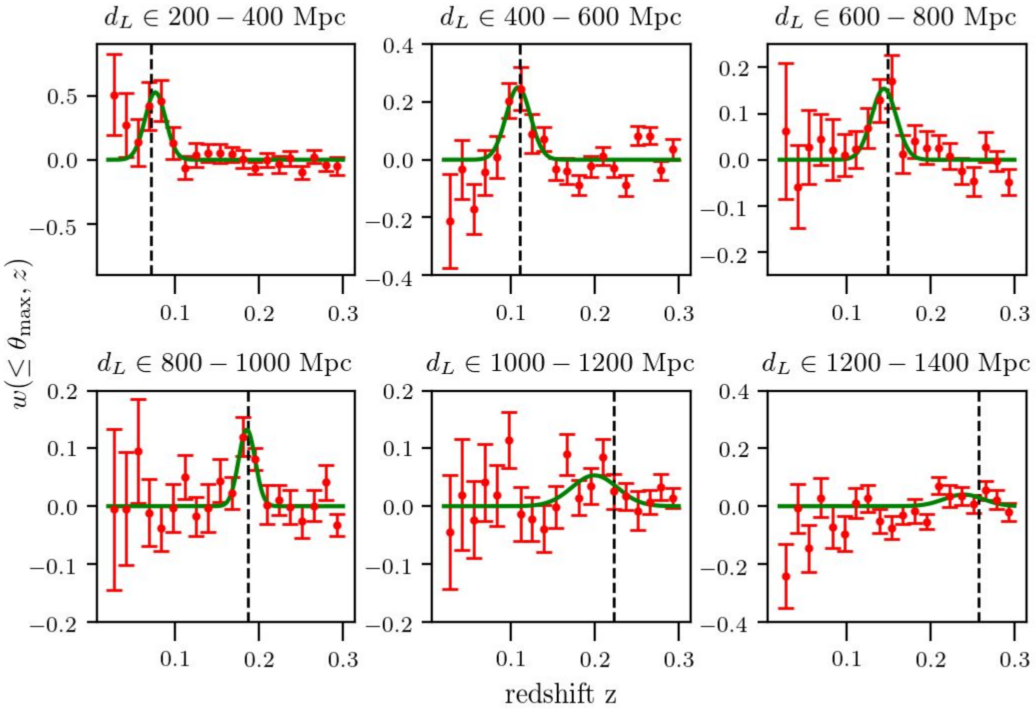




Black solid line: the true value of H_0 in the simulation
Dashed lines: 90 percent credible interval

SB, Rana, More, Bose (2020)

Redshift from angular cross-correlation

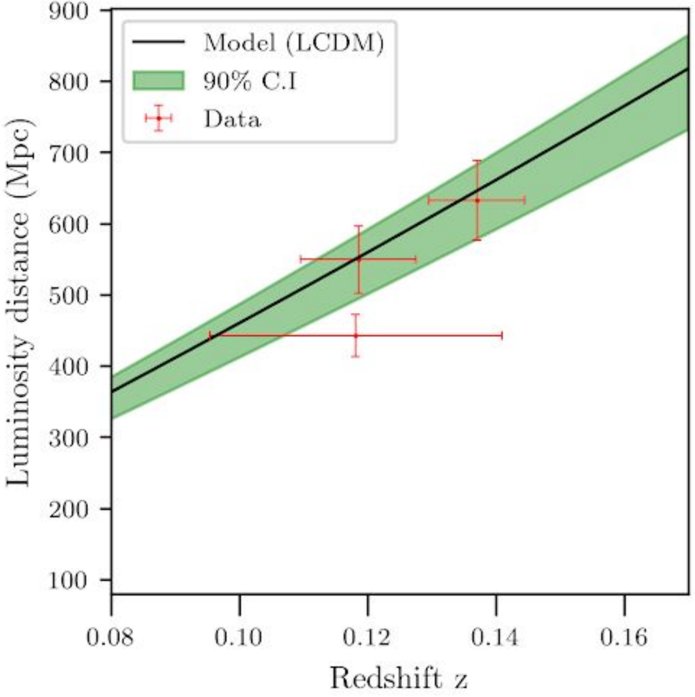


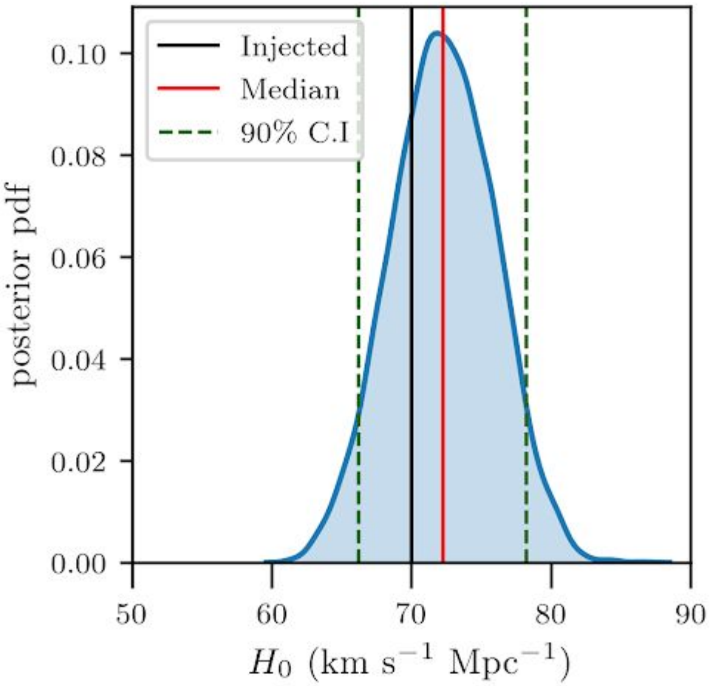
- 5000 BBH mergers divided into 6 bins in the inferred luminosity distances
- The mock galaxies are divided into 20 redshift bins

- Red points are the measured cross-correlations with error bars, peaking at the correct redshift
- The injected value of H_0 = 70 km/s/Mpc gives an average redshift of the GW sources in each bin (black vertical line)

SB, Rana, More, Bose (2020)

Hubble-Lemaitre diagram : 50 events





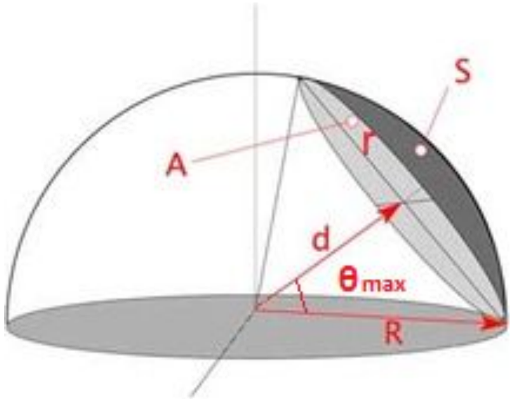
SB, Rana, More, Bose (2020)

Constraints from the three samples

Constraints on H_0			
No. of GW events	Max d_L (Mpc)	Injected H_0 (km s^{-1} Mpc^{-1})	Constraints on H_0 (km s^{-1} Mpc^{-1})
5100	1400	70	$70.22^{+1.09}_{-1.18}$
500	900	70	$70.26^{+1.47}_{-1.40}$
50	900	70	$72.24^{+5.98}_{-6.05}$

The error bars signify 90% credible interval around the the median of H0 posterior

Angular Cross-correlation Estimator



We count the number of galaxy-BBH pairs which have an angular separation θ_{max} or less in the actual catalog and in a randomly distributed catalog.

Angular cross-correlation estimator

$$w(\leq \theta_{\mathrm{max}}) = \frac{n_{\mathrm{D_1D_2}}(\leq \theta_{\mathrm{max}})}{n_{\mathrm{R_1R_2}}(\leq \theta_{\mathrm{max}})} - 1$$

D_1, D_2 : Data catalogs
R_1, R_2 : Random catalogs