Huitième Assemblée Générale du GdR Ondes Gravitationnelles @Aix-Marseille University Oct 15, 2024

# Probing Cosmic Expansion with Gravitational Wave-Large Scale Structure Correlations

Sayantani Bera University of the Balearic Islands, Spain

# Motivation



| AB SERVINA             |                         |                       |                        |                       |                        |                        |                        |                        |                      |                       |                         |                         |
|------------------------|-------------------------|-----------------------|------------------------|-----------------------|------------------------|------------------------|------------------------|------------------------|----------------------|-----------------------|-------------------------|-------------------------|
| 2015 - 2016            | 202                     |                       | 02                     |                       | -                      | 10                     | -                      | 1                      |                      |                       | 03a+0                   |                         |
|                        | a. 4                    | ii. 17                | : .:                   | 11 7.6                |                        | 1                      |                        | i i                    |                      | 5 •<br>3 •            | 2                       | 8                       |
| 63                     | 36                      | 21                    | 49<br>GWT0004          | 18<br>CHITTOLOG       | BO                     | 56<br>CHATCHER         | 53<br>CHATTERIN        | = 2.8<br>OVERNORT      | 60<br>ENV/70818      | 65<br>CWINDRED        | 105<br>Gwmo-ol opsm     | 41<br>CW190400, 199800  |
| 10 AL                  | 85 . N                  |                       |                        | 1.1                   |                        | 43 pH                  | 20 U                   |                        | 39 28                |                       | 2 . :                   | ;                       |
| 37<br>CW/H0402         | 56<br>CW190413_052954   | 76<br>CWTRD#3.154308  | 70                     | 3.2<br>CHATHER        | 175<br>CW104-3E 190642 | 69<br>CW100000.005404  | 35<br>cwitecs2_180714  | 52<br>CHARGES 205428   | 65                   | 59<br>CW100577.056101 | 101<br>CW/900598_953044 | 156<br>Civr90520        |
|                        |                         |                       | : :                    | 35 25                 | 54 . A                 |                        | 12 84                  | 10 13                  | A7 21                | 15 7.8                | 12 64                   |                         |
| 71<br>GW190521.074889  | 56<br>CHANGONET CHOOSES |                       | 87<br>GW/HOG20.010421  | 56                    | 90<br>CW190701, 201306 | 99<br>GW190706, 2236-1 | 19<br>                 | 30<br>GWTROTOR_250487  | 55<br>CW100770.20054 | 20<br>CHANGE 20       | 17<br>CHARGE THAT 28    | 64                      |
|                        |                         |                       |                        | 23 26                 |                        | 24                     |                        | 35 26                  | · - 24               | 10 E                  |                         |                         |
| 20<br>CW190728, 064549 | 67<br>CW19078, 140834   | 62<br>owneeds.cozner  | 76<br>CM180805_28187   | 26<br>CWTHORM         | 55<br>CW190628.062405  | 33<br>CM/100628_065009 | 76<br>CW190800_352807  | 57<br>CW/96085_292762  | 66                   | 11                    | 13<br>CW190504_075846   | 35<br>GW100025.212545   |
| 49                     |                         | 12 78                 | 12 79                  | n 77                  |                        | 29 59                  | 12 85                  | 51 JA                  | n 47                 | 27                    | 12 112                  | 25 B                    |
| ଗ<br>                  | 102<br>GW190928-05149   | 19<br>ownesso.sssea   | 19<br>CW19103_002449   | 18<br>CWMPOLISED      | 107<br>CW19109.010711  | 34<br>owners.ormss     | 20<br>CW19502, TE250   | 76<br>CW19727.090221   | 17<br>CW19129L154029 | 45<br>GW190204-310529 | 19<br>CW19204_77524     | 41<br>CW/96296 223092   |
| 10 . 77                | a ii                    |                       | -                      |                       | 30 20                  |                        | 4 n                    | 54 29                  | 10 73                |                       |                         | ж                       |
| 19<br>cwneze, 20258    | 32<br>CW195219.143220   | 76<br>CW195222_053537 | 82<br>CW190200_180-458 | 11<br>GW200008_863+26 | 61<br>CW200112, 00838  | 7.2<br>CW200115_042309 | 71<br>GW200128, 022011 | 60<br>CW20003.045458   | 17<br>GW200302.84303 | 63<br>CW300308_73017  | 61<br>CM2000000_222007  | 60<br>58/200000.0404-02 |
| 24 2.8                 | 9 . D                   | ÷                     |                        | 29 28                 | 40                     | 19 14                  | 34                     | 24 15                  |                      | 34 20                 | 12 7.8                  | 34 . 14                 |
| 27<br>CW20000 040254   | 78<br>CW2001%_220804    | 62<br>(W000278,094405 | 141<br>CM200020 04909  | 64<br>GW300220,124850 | 69<br>0000000-00004    | 32<br>CW200225.040421  | 56<br>GW206302,01881   | 42<br>CW200306, 091794 | 47<br>CHOODEDH_TTRES | 59<br>CW20030L75663   | 20                      | 53<br>CW200182.00103    |



Experimental de la construcción de Nancemente estado de la construcción de la consequencia de la construcción de la consequencia de la construcción de la consequencia de la construcción de la construcció





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  $\iota$ : inclination angle  $\Phi(t)$ : Accumulated phase

# **Measuring Ho with "standard sirens"**



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

 $d_L \sim cz/H_0$  low redshift

- Luminosity distance GW observation
- Redshift Electromagnetic counterpart

Thus an independent estimate of H<sub>0</sub> is possible







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**



Measurement of H<sub>0</sub> with ~ 15% accuracy at 68.3% confidence

# **Inferring Housing population statistics**



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<sub>0</sub> distribution for each potential host (gwcosmo)
   Schutz(1986)

#### **Constraints from GWTC-3**







Method 2 : Galaxy Catalogue technique (gwcosmo)

Abbott et al. (2023)

#### **An alternative approach:** The Large Scale Structures





Image: ESA

#### The Millennium simulation (z=0)



Image: SDSS

# Measures of clustering: Density Contrast and cross-correlation

$$\delta(\mathbf{x}) \sim \frac{\rho(\mathbf{x})}{\bar{\rho}} - 1$$
$$\xi(\mathbf{x}, \mathbf{x}') \sim \langle \delta(\mathbf{x}) \delta(\mathbf{x}')$$



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



Clustering ~ N/N -1 L : Clustering length

# 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

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



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



# 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:

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

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

## Hubble-Lemaitre diagram : 500 events



SB, Rana, More, Bose (2020)

#### An event-by-event analysis

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

For each GW event, the posterior is obtained by marginalizing over localization uncertainties **d**gw

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

$$egin{aligned} P(H_0 \mid \{oldsymbol{d}_{ ext{strain}}\}, \{oldsymbol{d}_g^{ ext{obs}}\}) & \propto P(H_0) \prod_i \mathcal{L}(oldsymbol{d}_{ ext{strain}_i}, oldsymbol{d}_{g_i}^{ ext{obs}} \mid H_0) \ & \propto P(H_0) \prod_i \int \mathcal{L}(oldsymbol{d}_{ ext{strain}_i}, oldsymbol{d}_{g_i}^{ ext{obs}} \mid H_0, oldsymbol{d}_{ ext{gw}}) P(oldsymbol{d}_{ ext{gw}}) doldsymbol{d}_{ ext{gw}}) \end{aligned}$$



-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<sub>0</sub> = 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

This work was supported by the Universitat de les Illes Balears (UIB); the Spanish Agencia Estatal de Investigación grants PID2022-138626NB-IOO, RED2022-134204-E, RED2022-134411-T, funded by MICIU/AEI/10.13039/501100011033 and the ERDF/EU; and the Comunitat Autònoma de les Illes Balears through the Servei de Recerca i Desenvolupament and the Conselleria d'Educació i Universitats with funds from the Tourist Stay Tax Law (PDR2020/11

- ITS2017-006), from the European Union - NextGenerationEU/PRTR-C17.I1 (SINCO2022/6719) and from the European Union - European Regional Development Fund (ERDF) (SINCO2022/18146).



NISTERIO E CIENCIA, INNOVACIÓN UNIVERSIDADES



#### AGENCIA ESTATAL DE INVESTIGACIÓN





Cofinanciado por la Unión Europea





FONDO EUROPEO DE DESARROLLO REGIONAL "Una manera de hacer Europa"



Conselleria d'Economia, Hisenda i Innovació





#### Extra Slides

#### Waveform simulation: inputs

| Detectors  | Sensitivity    | Injection Parameters  |         |                         |  |
|------------|----------------|---|---------|-------------------------|--|
| Detectors  | Sensitivity    | Injection ParamParametersDistribution $m_{1,2}$ uniform $\chi_{1,2}$ uniform $\phi_{12}$ , $\phi_{jl}$ uniform $\cos \theta_{1,2}$ , $\cos \iota$ uniform $\psi$ , $\phi_c$ Fixed | Limits  |                         |  |
| Livingston | Advanced LIGO  | $m_{1,2}$   | uniform | $[10, 35] M_{\odot}$    |  |
| Hanford    | Advanced LIGO  | $\chi_{1,2}$<br>$\phi_{12}, \phi_{il}$  | uniform | [0, 0.8]<br>$[0, 2\pi)$ |  |
|            |                | $\cos \theta_{1,2}$ , $\cos \iota$  | uniform | [-1, 1)                 |  |
| Virgo      | Advanced Virgo | $\psi \;,  \phi_{ m c}$   | Fixed   | 0                       |  |

<u>Detection criteria</u>: 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



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

# **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<sub>0</sub> = 70 km/s/Mpc gives an average redshift of the GW sources in each bin (black vertical line)

### Hubble-Lemaitre diagram : 50 events



#### **Constraints from the three samples**

| Constraints on $H_0$ |                       |   |  |  |  |  |  |  |
|----------------------|-----------------------|---|--|--|--|--|--|--|
| No. of GW events     | Max $d_{\rm L}$ (Mpc) | Injected $H_0$ (km s <sup>-1</sup><br>Mpc <sup>-1</sup> ) | $\begin{array}{c} \text{Constraints on } H_0 \\ (\text{km s}^{-1} \text{ Mpc}^{-1}) \end{array}$ |  |  |  |  |  |
| 5100                 | 1400                  | 70  | $70.22^{+1.09}_{-1.18}$  |  |  |  |  |  |
| 500                  | 900                   | 70  | $70.26^{+1.47}_{-1.40}$  |  |  |  |  |  |
| 50                   | 900                   | 70  | $72.24_{-6.05}^{+5.98}$  |  |  |  |  |  |

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  $\theta_{max}$  or less in the actual catalog and in a randomly distributed catalog.

#### Angular cross-correlation estimator

$$w(\leq \theta_{\max}) = \frac{n_{\mathrm{D}_1\mathrm{D}_2}(\leq \theta_{\max})}{n_{\mathrm{R}_1\mathrm{R}_2}(\leq \theta_{\max})} - 1$$

D<sub>1</sub>, D<sub>2</sub>: Data catalogs R<sub>1</sub>, R<sub>2</sub>: Random catalogs