Gravitational waves and galaxies to constrain the Hubble constant

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“H_0 is the ultimate end-to-end test for ΛCDM”
Adam Riess, 2019

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Abstract

The rapid development of gravitational wave astronomy, along with information coming from present and future galaxy surveys, has the potential to shed light on many open questions in Astrophysics and Cosmology. The combination of gravitational wave and galaxy survey datasets is especially able to provide new and unique constraints on the dynamics of the Universe. In this work, we focus on correlating dark sirens (merging black hole binaries) with galaxy catalogs to constrain the Hubble constant H_0. More specifically, with respect to the current state of the art, we aim at proposing a more refined and effective treatment of the galaxy catalog contribution, involving also third-generation gravitational wave detectors in this very same methodology.

Hubble's observation (1929): galaxies appear to be moving away from us and their recession velocities rise with distance.

$$v_r = H(t)r \xrightarrow{t=t_0} v_r = H_0 r$$

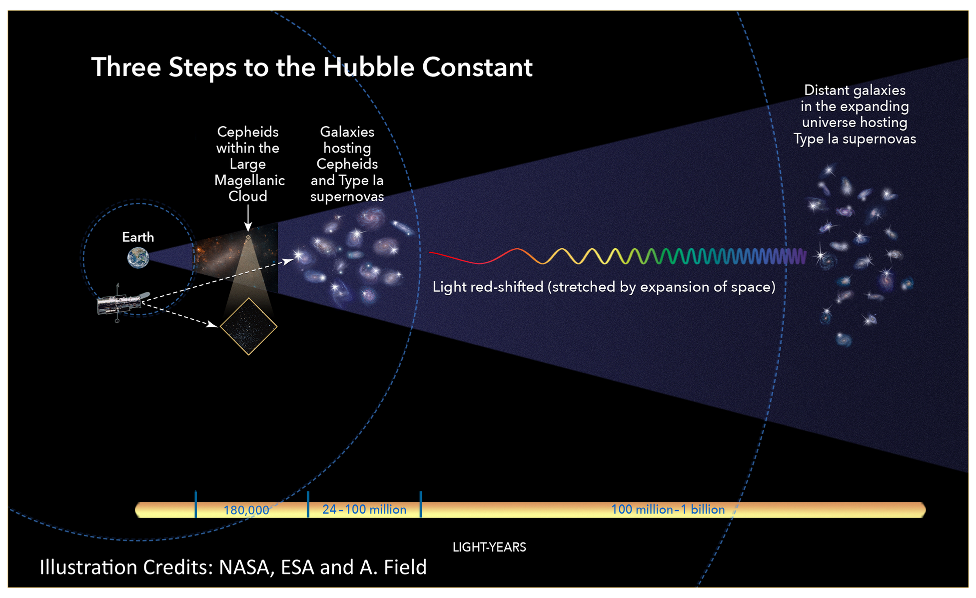


Illustration Credits: NASA, ESA and A. Field

All this is related to one of the crucial issues in nowadays Astrophysics and Cosmology:

the Hubble tension

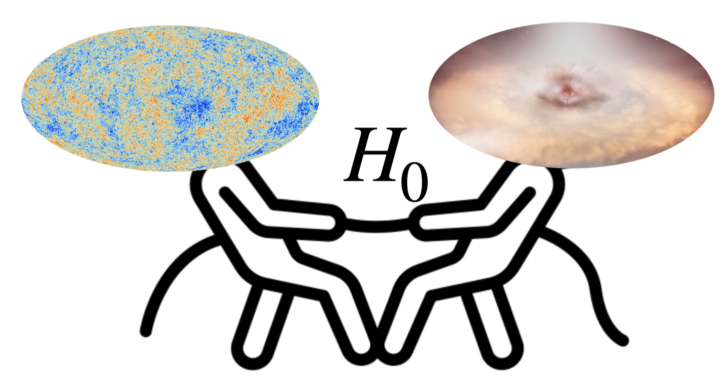
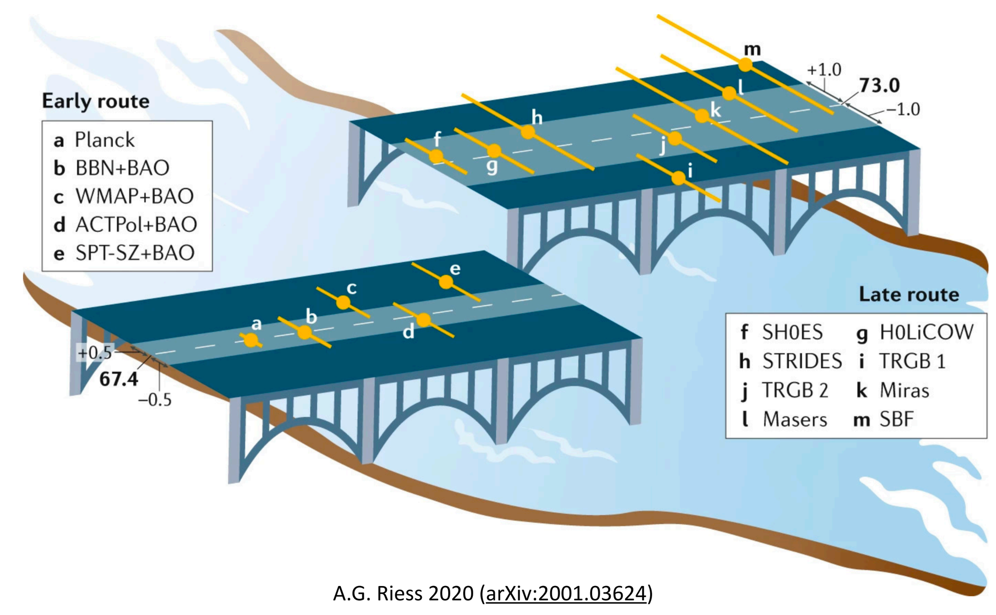


Illustration Credits: ESA, ESA/ATG medialab/C. Carreau, the Planck Collaboration

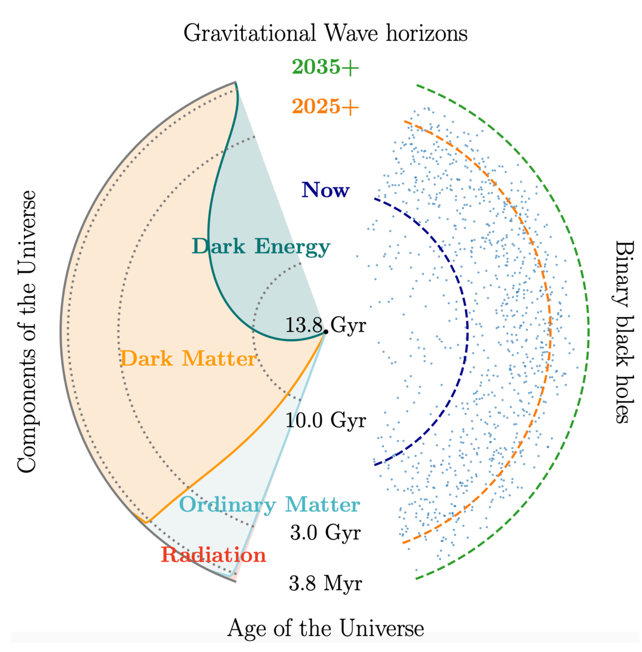


A.G. Riess 2020 (arXiv:2001.03624)

According to A.G. Riess 2020 (arXiv:2001.03624), there is a discrepancy larger than 4σ and lower than 6σ between early and late Universe measurements.

Which are the benefits from gravitational wave (GW) observations?

- independent constraints on cosmological parameters
- possibility of mapping the Universe expansion
- revealing hints of *new physics*



H.-Y. Chen *et al.* 2024 (arXiv:2402.03120)

GWs can be used as **standard sirens**:

$$h_{gw} \propto 1/d_L \quad \text{and} \quad d_L \approx \frac{cz}{H_0} \quad (z \ll 1)$$

Ok but…How to obtain the **redshift information**?

The “standard sirens” expression reminds “standard candles”, like Type 1A supernovae and cepheids:

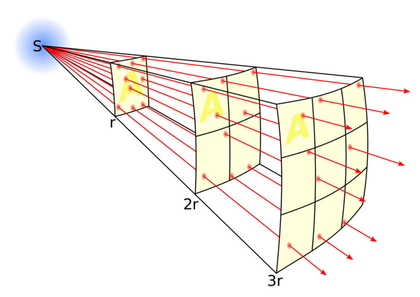
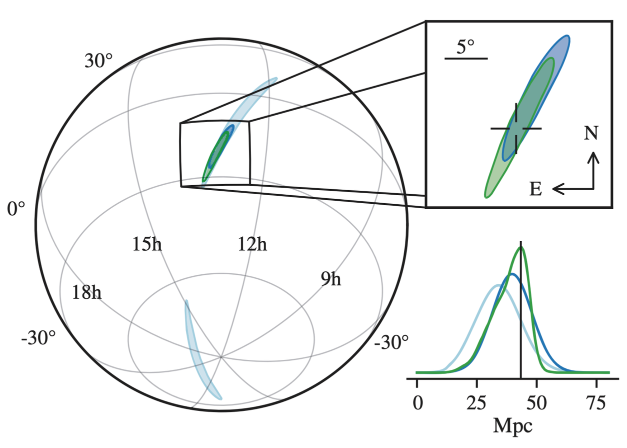


Illustration Credits: https://brilliant.org/wiki/standard-candles/

Bright sirens

- redshift from the EM counterpart of GW sources
- need of **neutron stars**
- e.g. GW170817 $\longleftrightarrow$ NGC4993

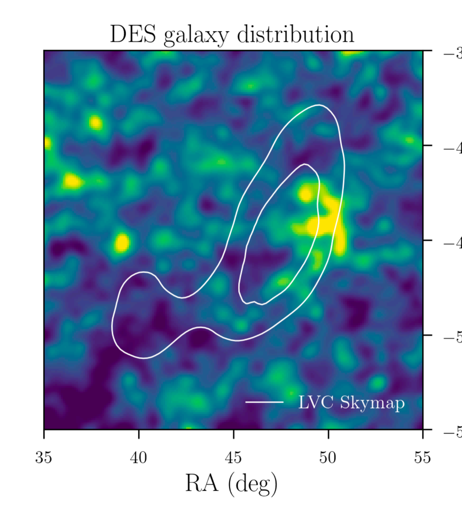


B. P. Abbot *et al.* 2017 (arXiv:1710.05832)

- **PROS**: potential improvement of sky localisation and identification of the galaxy host
- **CONS**: systems with EM counterpart seem to be much fewer than those without

Dark sirens

- using **galaxy catalogs** in the localisation region to statistically infer the redshift of the GW sources
- e.g. GW170814



M. Soares-Santos *et al.* 2019 (arXiv:1901.01540)

- **PROS**: supplies the lack of EM counterpart
- **CONS**: good localisation and completeness of galaxy catalogs are fundamental

Idea of the nowadays methodology (W. Del Pozzo *et al.* 2018 and B. P. Abbott *et al.* 2021)

- set of GW observations $\mathbf{e}$, each with $d_{L_i} \pm \Delta d_{L_i}$
- set of cosmological parameters $H \equiv H_0, \Omega_m, \ldots$ unknown within a prior range: $d_{L_i} \pm \Delta d_{L_i} \longrightarrow z_i \pm \Delta z_i$
- $j = 1,\ldots,m_i$ possibile galaxy hosts in each Δz_i

$$p(H\,|\,\mathbf{e}, I) \propto p(H\,|\,I)p(\mathbf{e}\,|\,H, I)$$

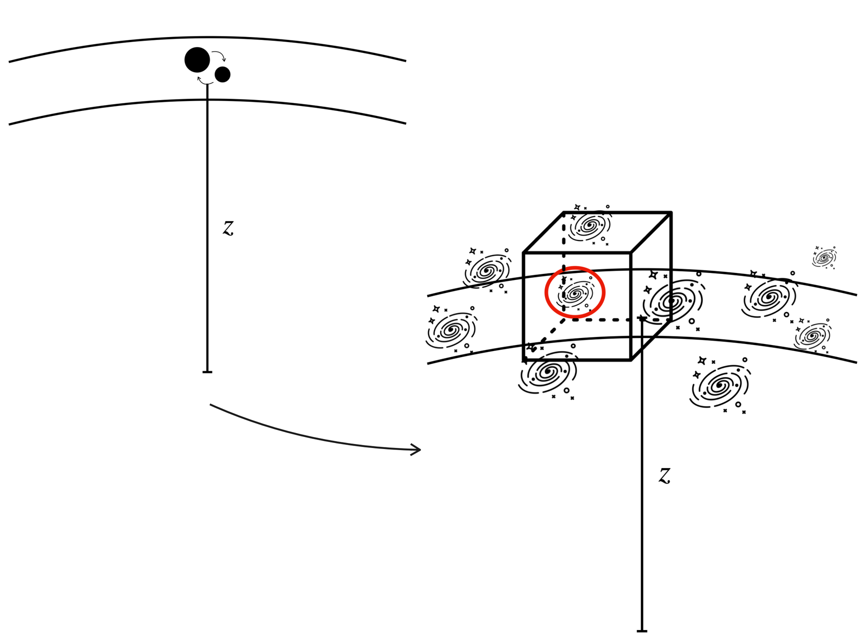
with

$$p(\mathbf{e}\,|\,H, I) = \prod_{i=1}^{n} p(e_i\,|\,H, I)(\Delta\Omega_i, z_{\max}(\Delta d_{L_i}, v_p), z_{\min}(\Delta d_{L_i}, v_p), \ldots)$$

$I =$ background information

Ingredients for the numerical evaluation:

- population of GW sources defining $\mathbf{e}$
- $\Delta\Omega_i$ and Δd_{L_i} defining the error box of e_i
- the ensemble of galaxies $g_{i,1}, \ldots, g_{i,m}$ in each error box



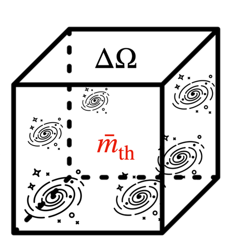
Focus on the likelihood calculation

$$p(e_i\,|\,H, I) = p(e_i\,|\,G, H, I)p(G\,|\,H, I) + p(e_i\,|\,\bar{G}, H, I)p(\bar{G}\,|\,H, I) \propto p(s\,|\,M(z_j, m_j, H)),\ \bar{m}_{\rm th}$$

- $p(s\,|\,M(z_j, m_j, H_0)) \propto \begin{cases} \text{constant} & \text{if unweighted} \\ L(M_j(H_0)) & \text{if luminosity weighted} \end{cases}$

The probability of a galaxy hosting a GW event depends only on the intrinsic **luminosity** of the galaxy.

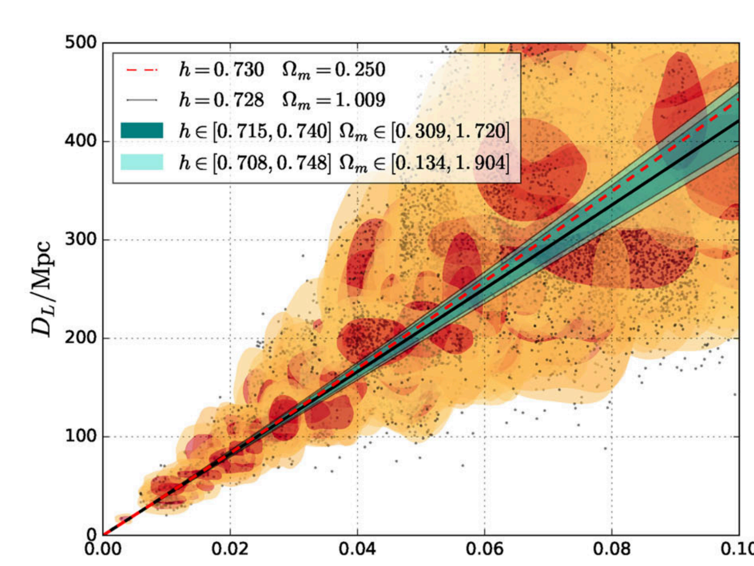
- Δz



$$\bar{m}_{\rm th} = \frac{1}{N_{\rm gal}} \sum_{j=1}^{N_{\rm gal}} m_{{\rm th}_j}$$

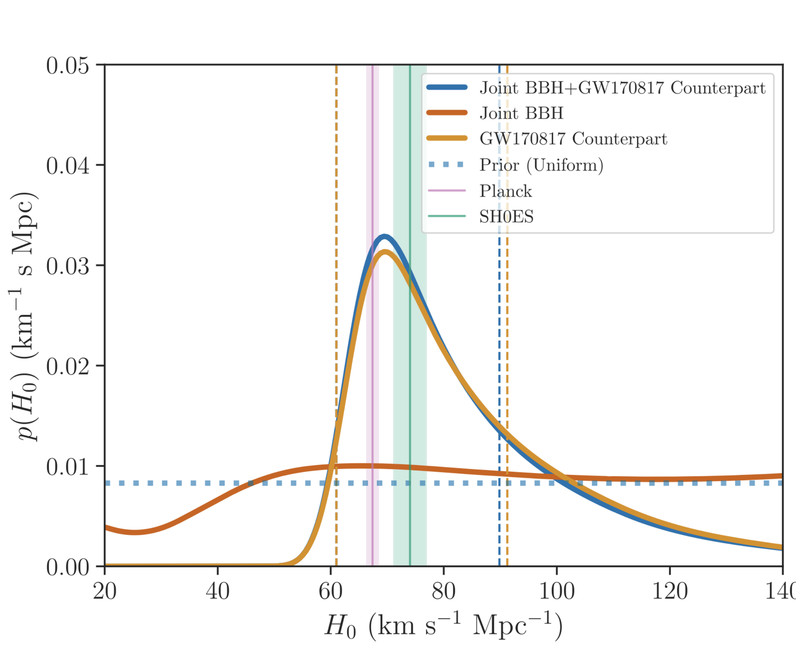
The **completeness** of a galaxy catalog is characterized by $\bar{m}_{\rm th}$.

B. P. Abbott *et al.* 2021 (arXiv:1908.06060)



W. Del Pozzo *et al.* 2018 (arXiv:1703.01300)

B. P. Abbott *et al.* 2021 (arXiv:1908.06060) discovered that from the detections of 10 BBHs +1 BNS merger during O1 and O2 of **aLIGO and Virgo**:



$$H_0 = 69^{+16}_{-8}\ \text{km s}^{-1}\ \text{Mpc}^{-1}$$

(68.3% highest density posterior interval)

A factor 1.04 better than with GW170817 only:

$$H_0 = 69^{+17}_{-8}\ \text{km s}^{-1}\ \text{Mpc}^{-1}$$

Take-home message

- this is **valid statistical methodology** that circumvents the need of direct EM counterparts to the GW events to constrain H_0;
- a deeper investigation of this approach is encouraged by the **increasing number of GW detections** and, moreover, by the fact that it provides new local **independent measurements**.

Future developments

- there is room for a detailed and effective **characterization of galaxy properties**. This is a key point in order to achieve a proper modelling;
- the analysis has to be extended to **3G GW interferometers** which will be crucial for the next astrophysical and cosmological breakthroughs.

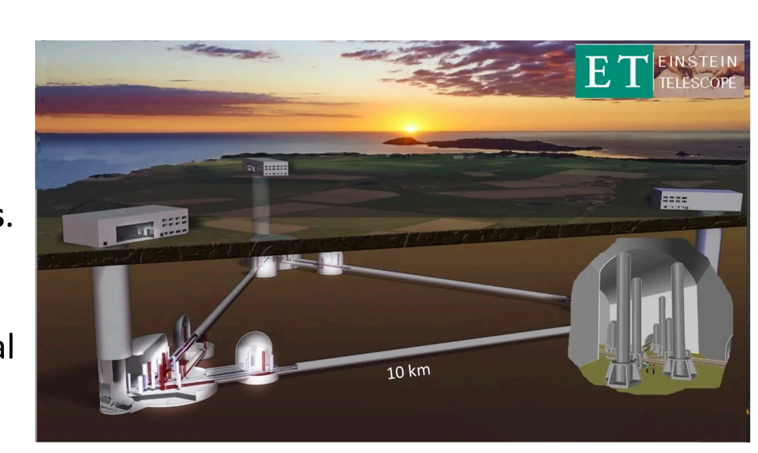


Illustration Credits: EGO Collaboration

Selected references

- W. Del Pozzo, A. Sesana and A. Klein, *Stellar binary black holes in the LISA band: a new class of standard sirens*, Mont. Not. Roy. Astron. Soc. **475** (2018) 3 [arXiv:1703.01300]
- B.P. Abbott *et al* 2021, *A Gravitational-wave Measurement of the Hubble Constant Following the Second Observing Run of Advanced LIGO and Virgo*, Astrophys. J. **909** (2021) 218 [arXiv:1908.06060]
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