Cosmology with dark sirens gravitational waves and galaxy catalogs

Attempting to solve the Hubble constant tension

Sarah Ferraiuolo, PhD Seminar, 22/05/2024

Outline

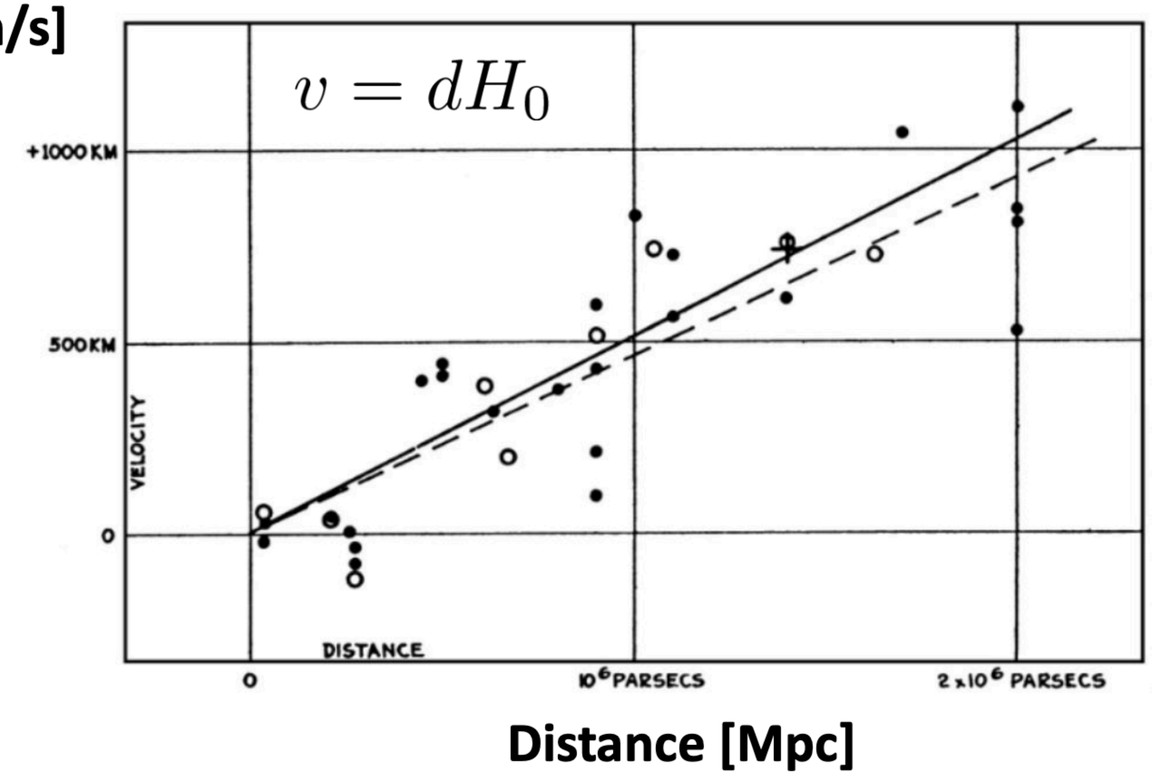
- The Standard Cosmological Model
- Hubble Tension
- Standard Sirens and Dark Sirens
- Latest Result with GWTC3
- 3G detector future prospective

The Standard Cosmological Model

For almost 100 years, we have been measuring the expansion of the Universe

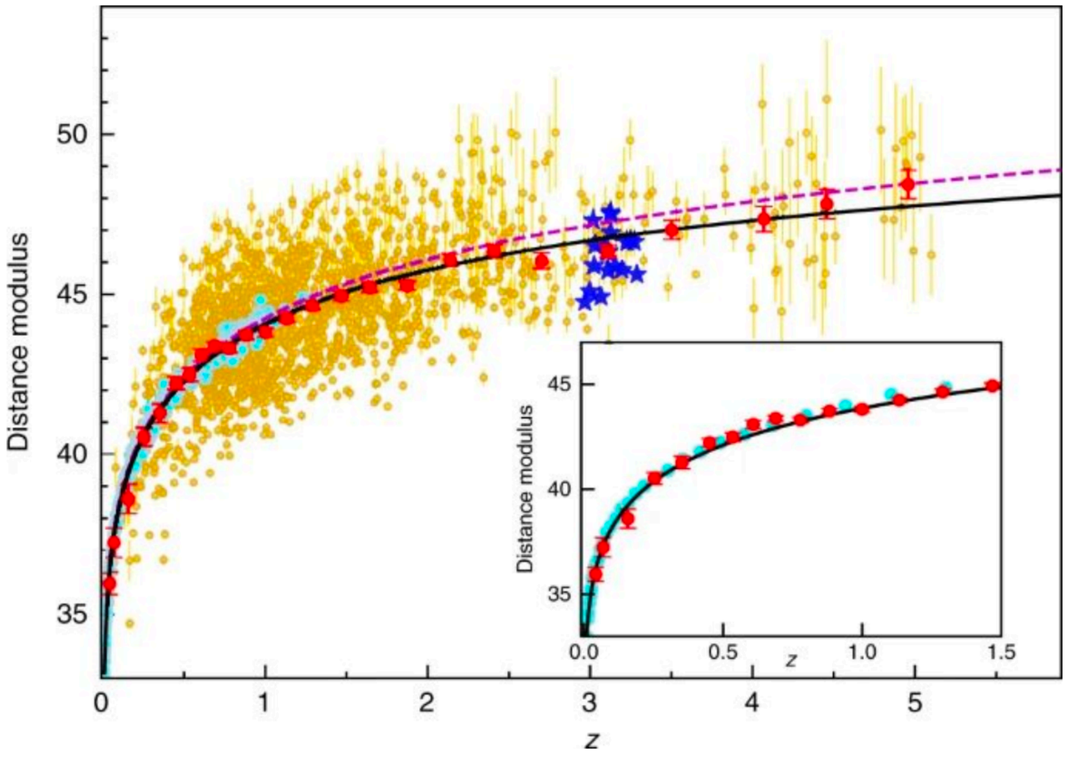
Velocity [km/s]

[E. Hubble 1929]



Distance [Mpc]

[G. Risalti et al, Nature 2023]



The Standard Cosmological Model

According to General Relativity, and confirmed by many observations, the Universe is expanding at a rate described by

$$\frac{H(z)}{H_0} = \sqrt{\Omega_{m,0}(1+z)^3 + \Omega_\Lambda + \Omega_r(1+z)^4 + \Omega_k(1+z)^2}$$

Hubble Constant — Dark Matter — Dark Energy — Radiation — Curvature

Critical density

$$\rho_c = \frac{3H_0}{8\pi G}$$

The Cosmic expansion offers us many potential discoveries:

- *What are the energy species living in our Universe?*
- *Is General Relativity valid on cosmological scales?*
- *What are the average critical densities of the Universe?*

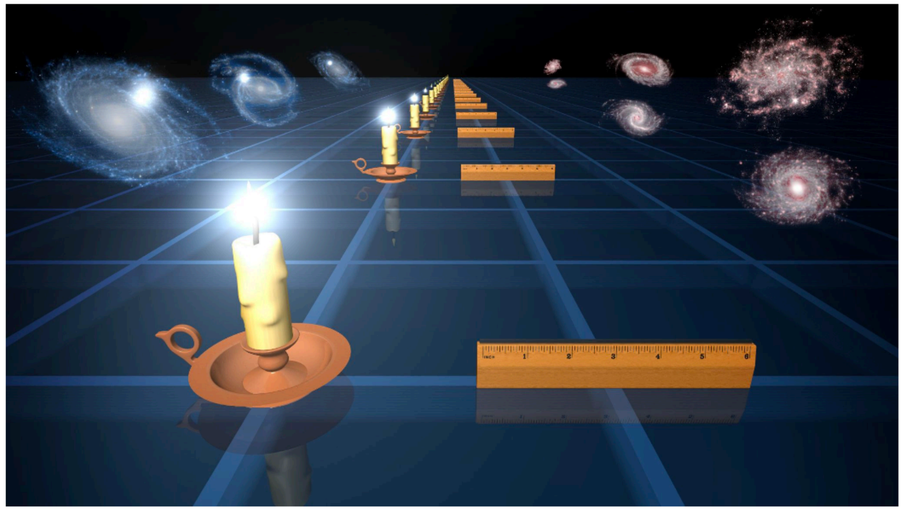
Energy density

$$\Omega_X = \frac{\rho_X}{\rho_c}$$

How have been measuring the Universe expansion?

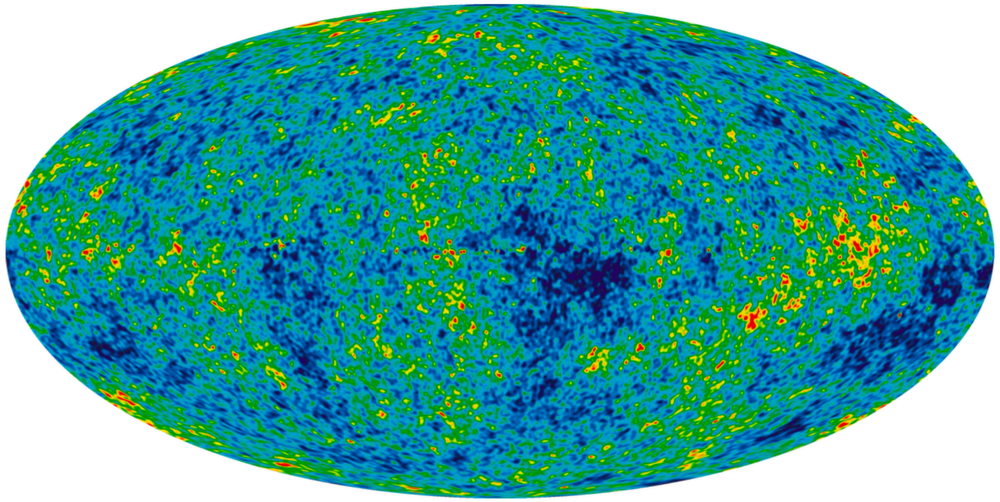
… So far

Direct (Standards Candles)



- Cepheids, Supernovae Type IA, Active Galactic nuclei, Kilonovae and short Gamma-ray Burst
- **Issues:** Requires complex astrophysical calibration

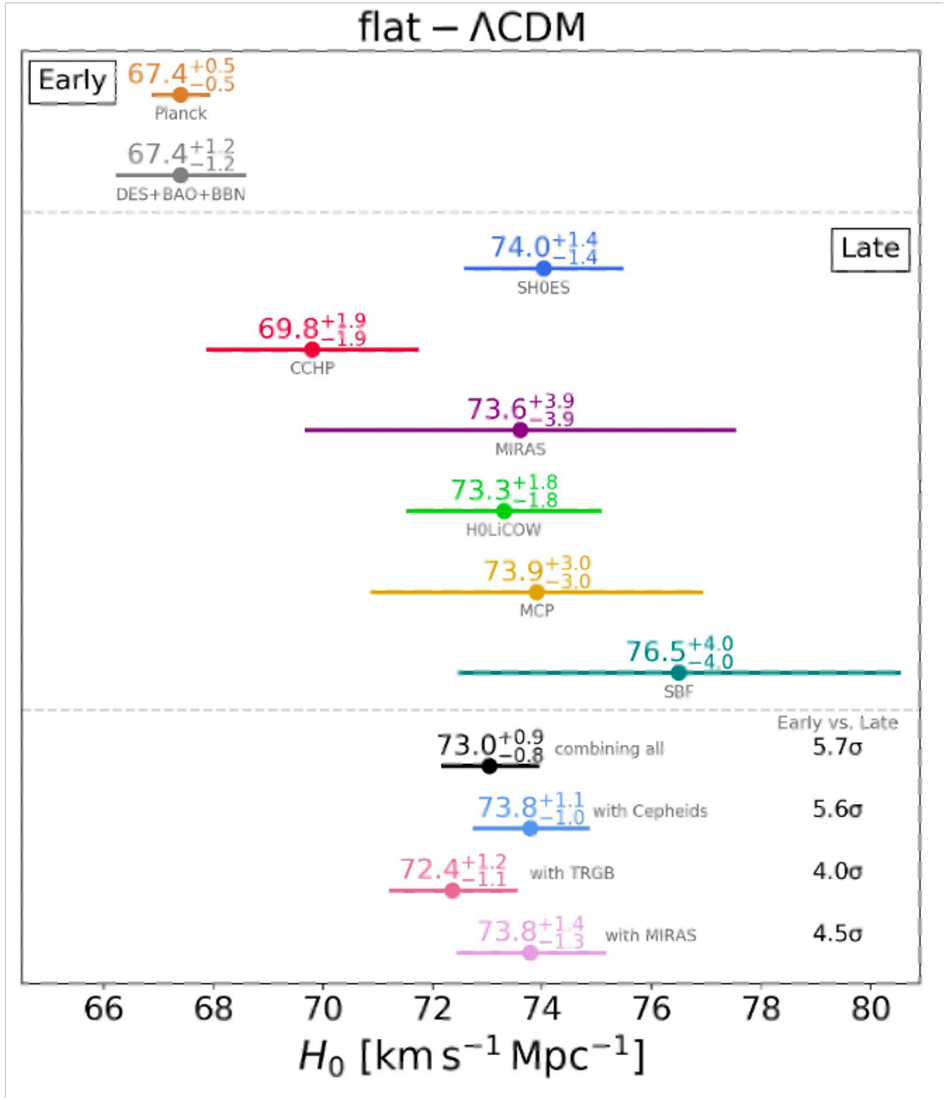
Indirect (Standars Candles)



- Cosmic Microwave Background temperature fluctuations, Baryonic nucleosynthesis
- **Issues:** Cosmic variance (a single Universe)

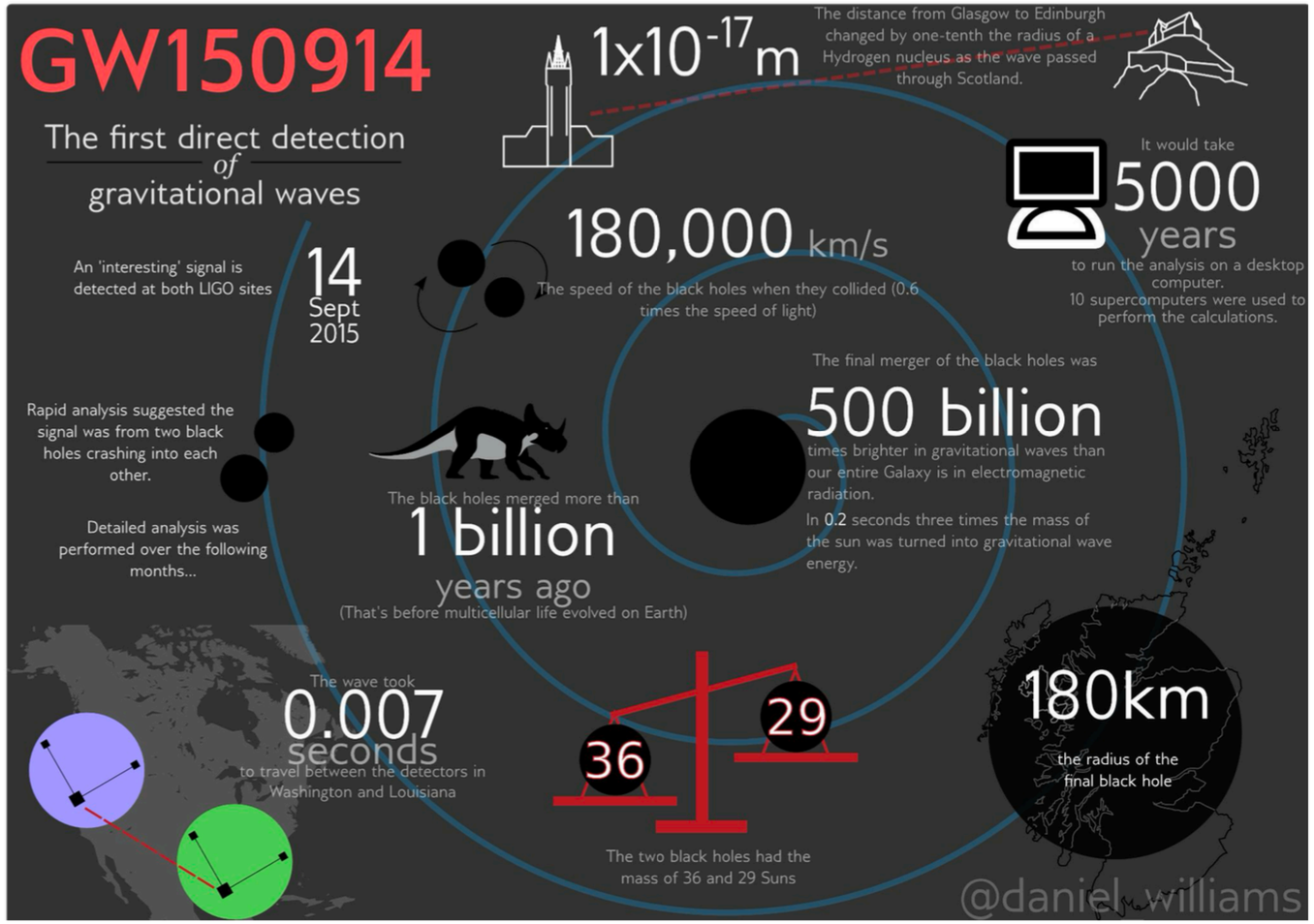
Hubble constant tension

- There is a tension between direct and indirect measurements of the Hubble constant.
- Although in-depth studies for hidden systematics the tension has not been yet alleviated.
- We are required to directly measure the Universe expansion in all the observable Universe.



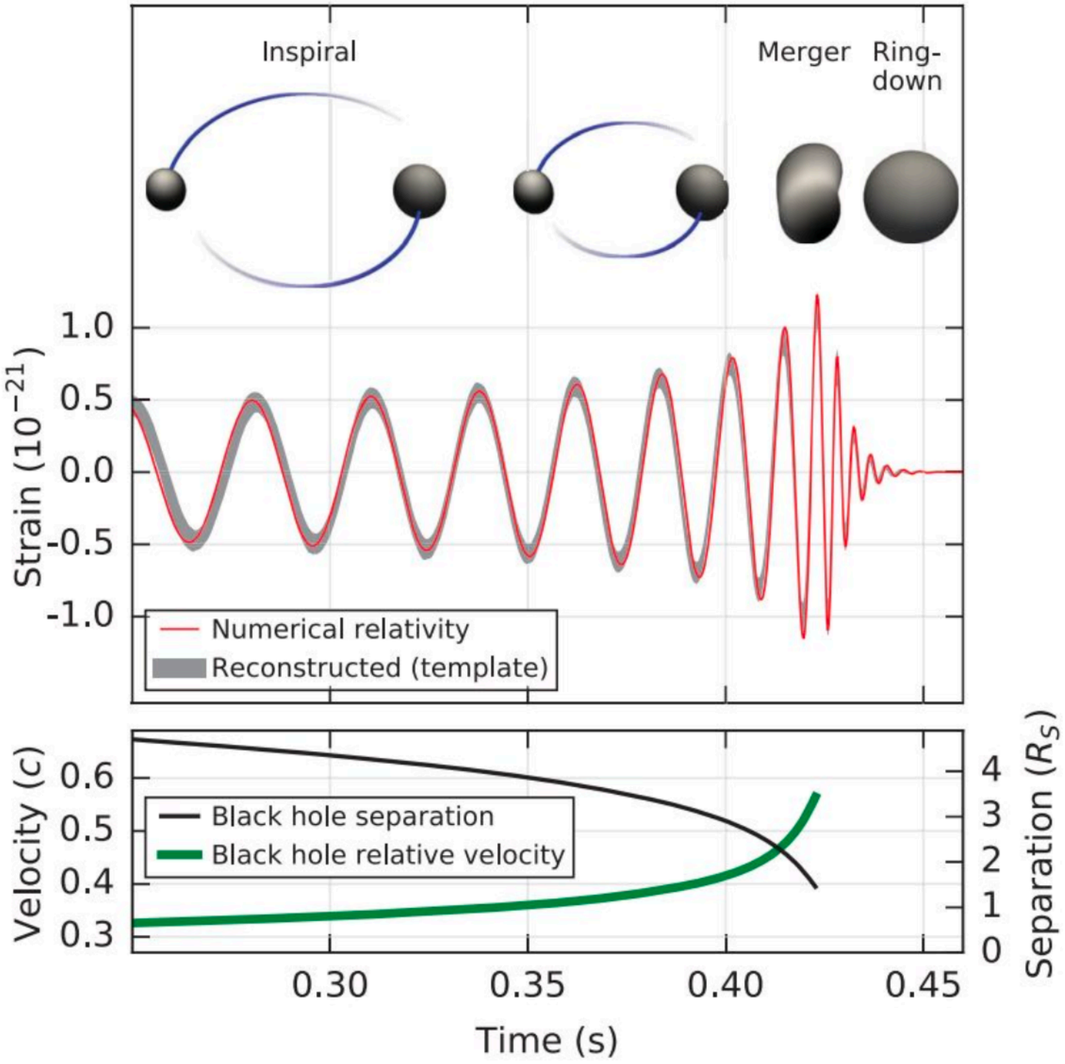
Verde, L., Treu, T. & Riess, A.G. Tensions between the early and late Universe. *Nat Astron* **3,** 891–895 (2019).

Gravitational Waves



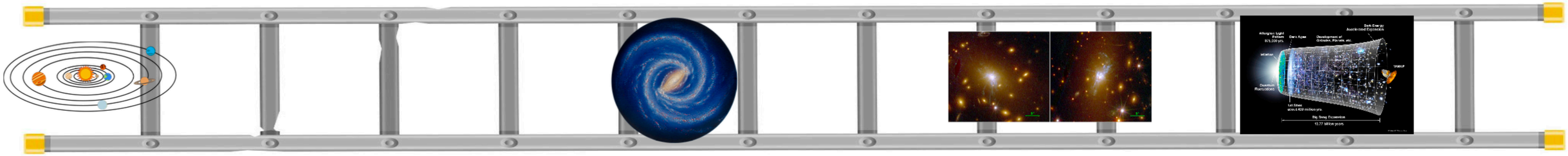
Credit: LVK EPO and Outreach groups

B. P. Abbott et al. PRL 116, 061102 (2016)



Hubble constant tension

Why use gravitational waves for cosmology



1 AU 1 pc 100 pc 1 kpc 100 kpc 1 Mpc 100 Mpc 1 Gpc 10 Gpc

Distances with Electromagnetic observations

Radar

Parallax

Cepheids

Type Ia Supernovae

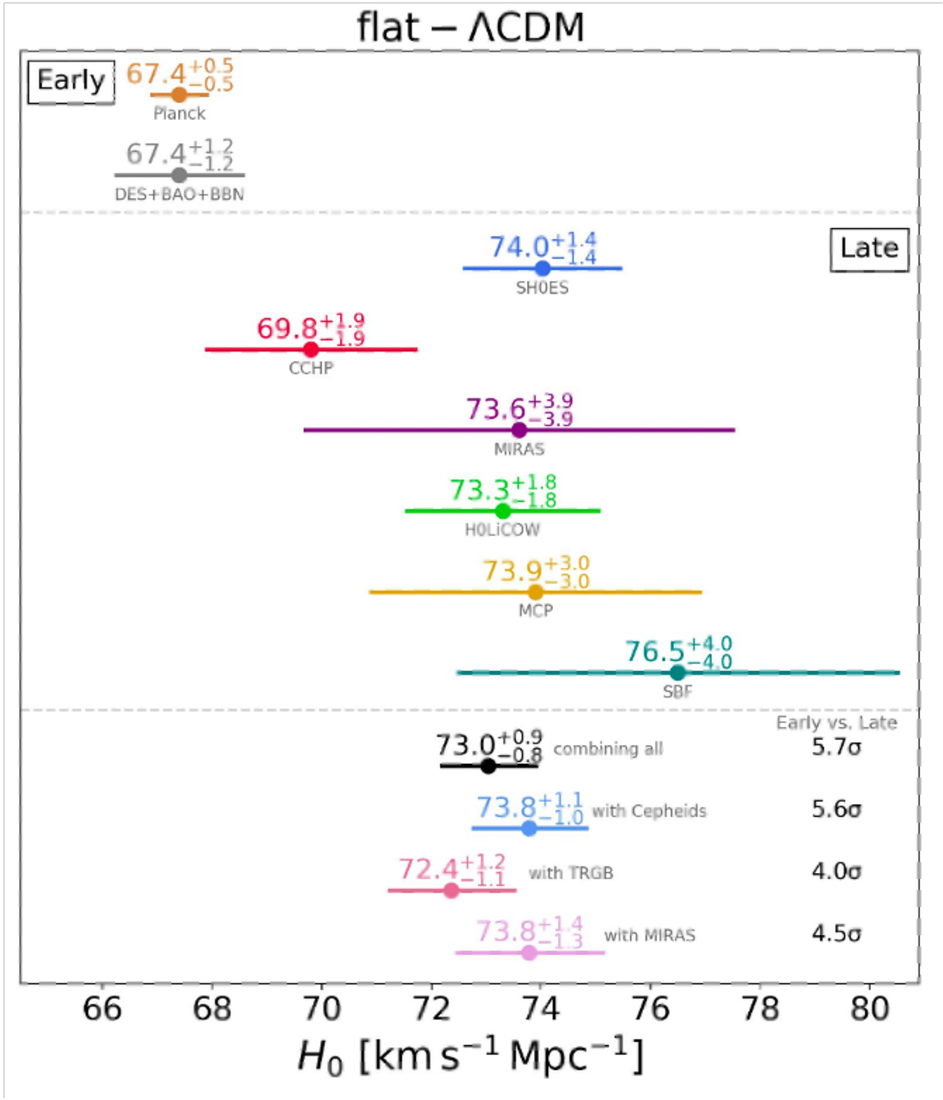
Distances with GW observations

Compact binary coalescenses

Hubble constant tension

Why use gravitational waves for cosmology

- $cz \approx H_0 d_L$



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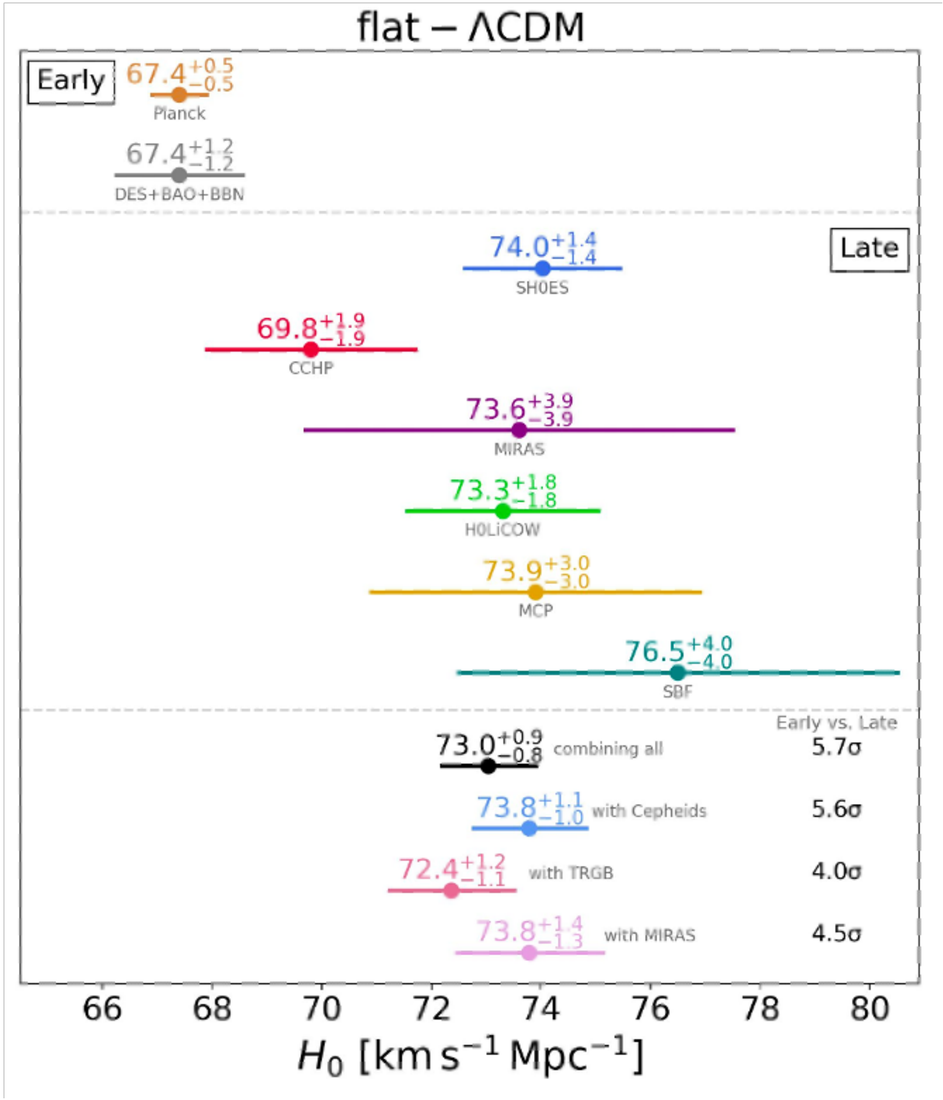
Hubble constant tension

Why use gravitational waves for cosmology

- $cz \approx H_0 d_L$

Luminosity distance: directly measurable from the amplitude of the gravitational wave signal

- $h(t) = A(M_z, d_L, t)e^{i\Phi(M_z,t)}$



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Hubble constant tension

Why use gravitational waves for cosmology

Redshift: degenerate with mass in the GW signal. Must be found through other methods

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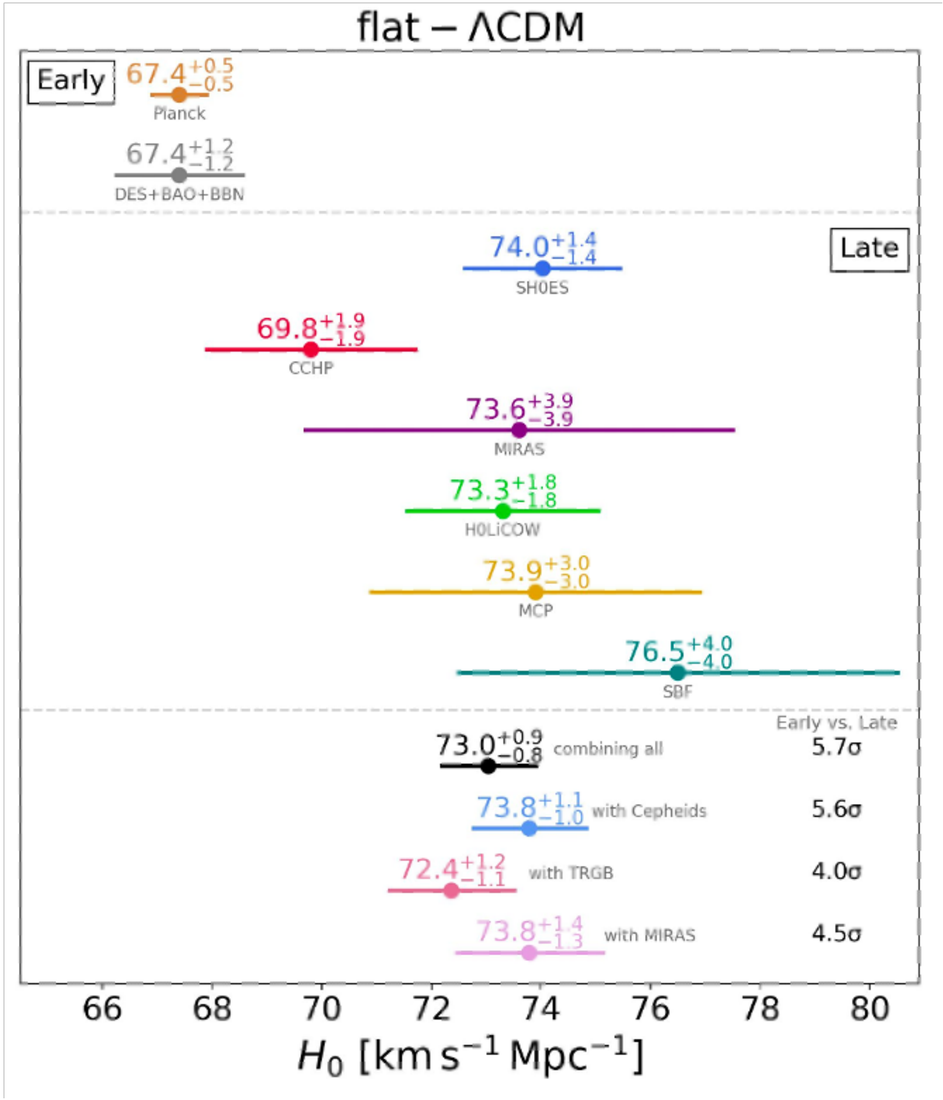

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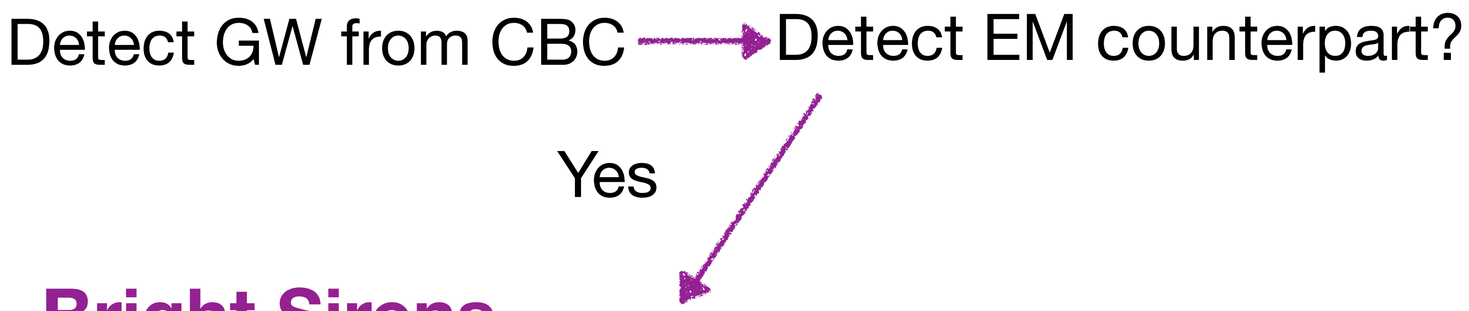
Cosmological Analysis With Standar Sirens

Detect GW from CBC → Detect EM counterpart?

Cosmological Analysis With Standar Sirens



Bright Sirens

- An EM counterpart is observed and used to obtain the host galaxy's redshift
- E.g. GW170817 and NGC4993

Cosmological Analysis With Standar Sirens

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No → **Dark Sirens**

- No EM counterpart was observed. Galaxy surveys are used to provide redshift estimates for potential host galaxies → **the galaxy catalog method**

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Measure H_0

Cosmological Analysis With Standar Sirens

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Yes

No

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Dark Sirens

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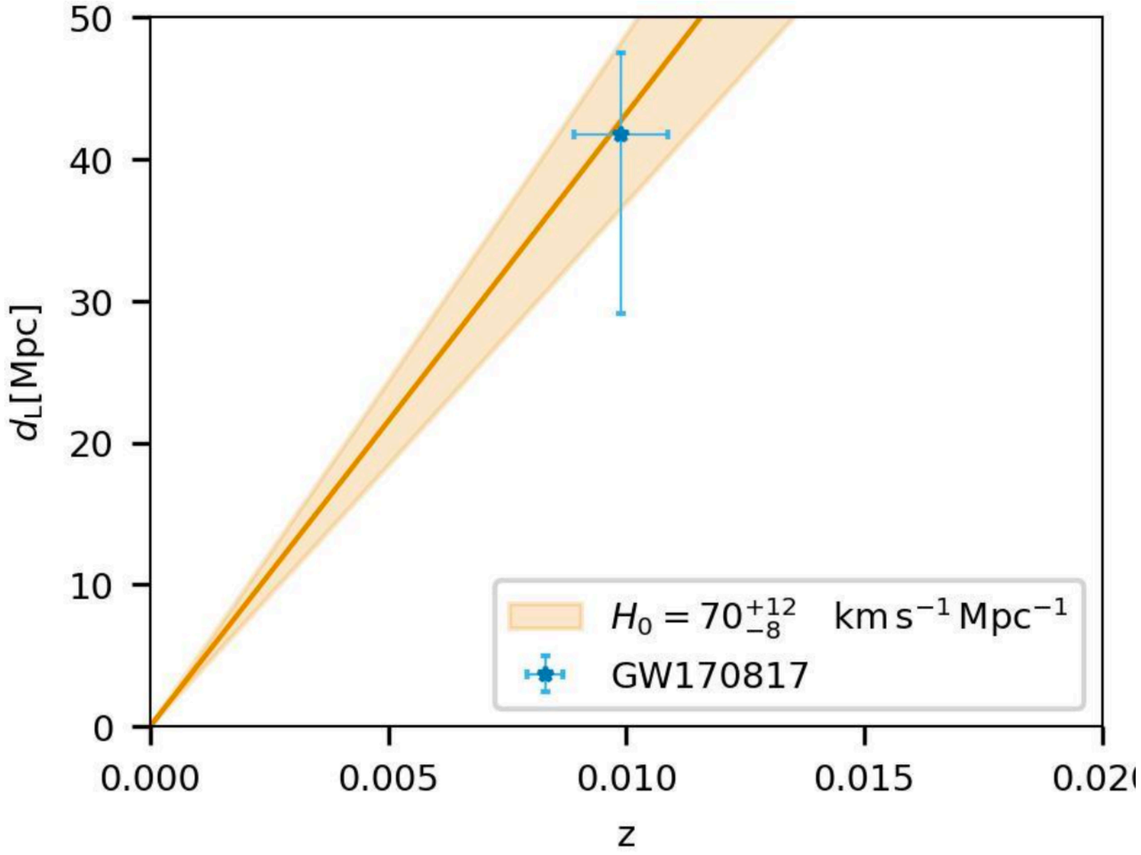
Measure H_0 →

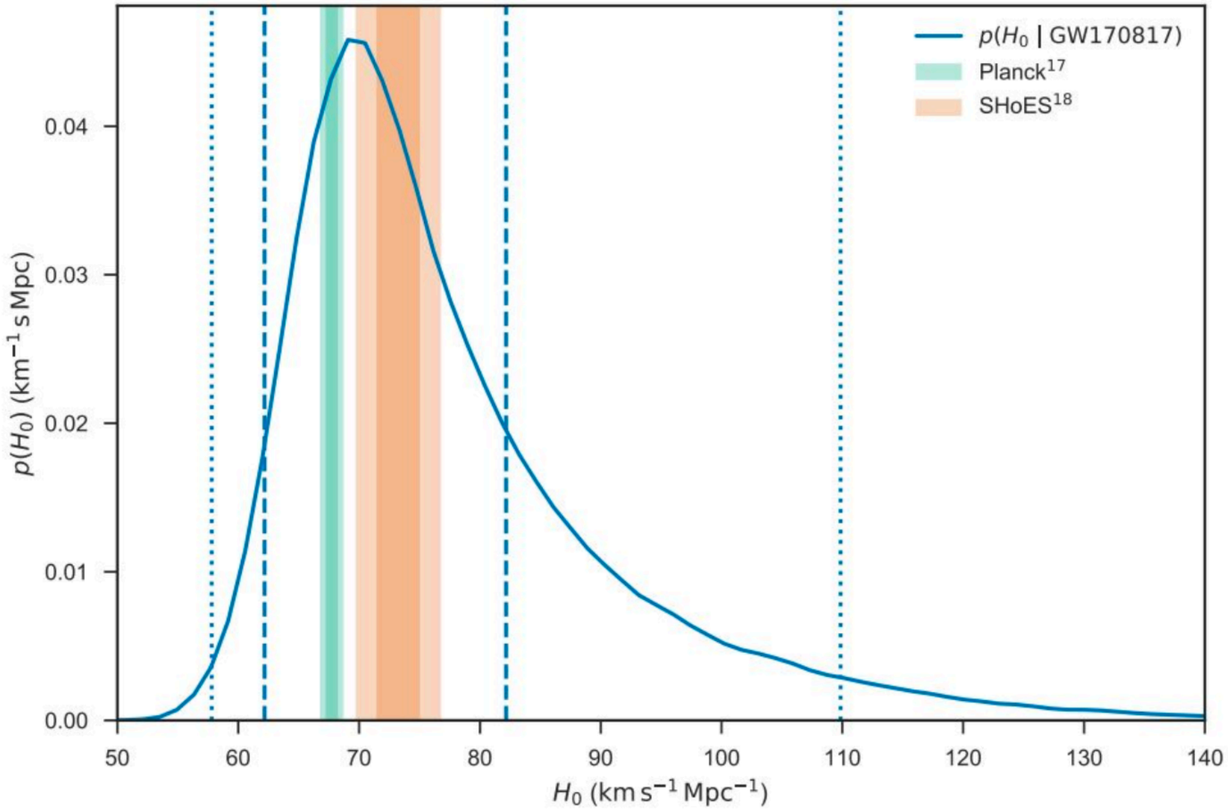
Correct for GW selection effect

Compensate for galaxy catalogue incompleteness

Bright sirens

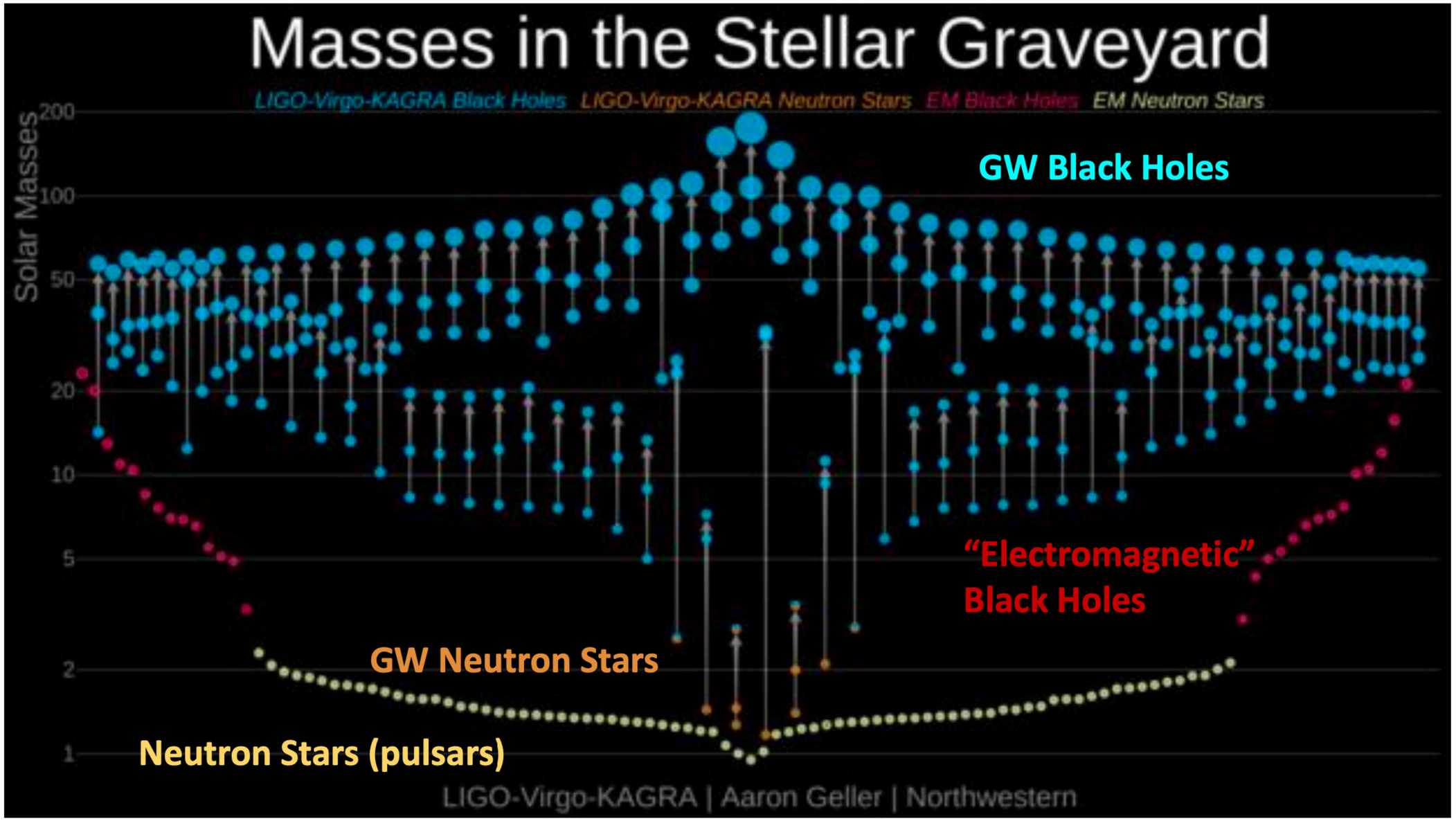
Cosmology with GW170817





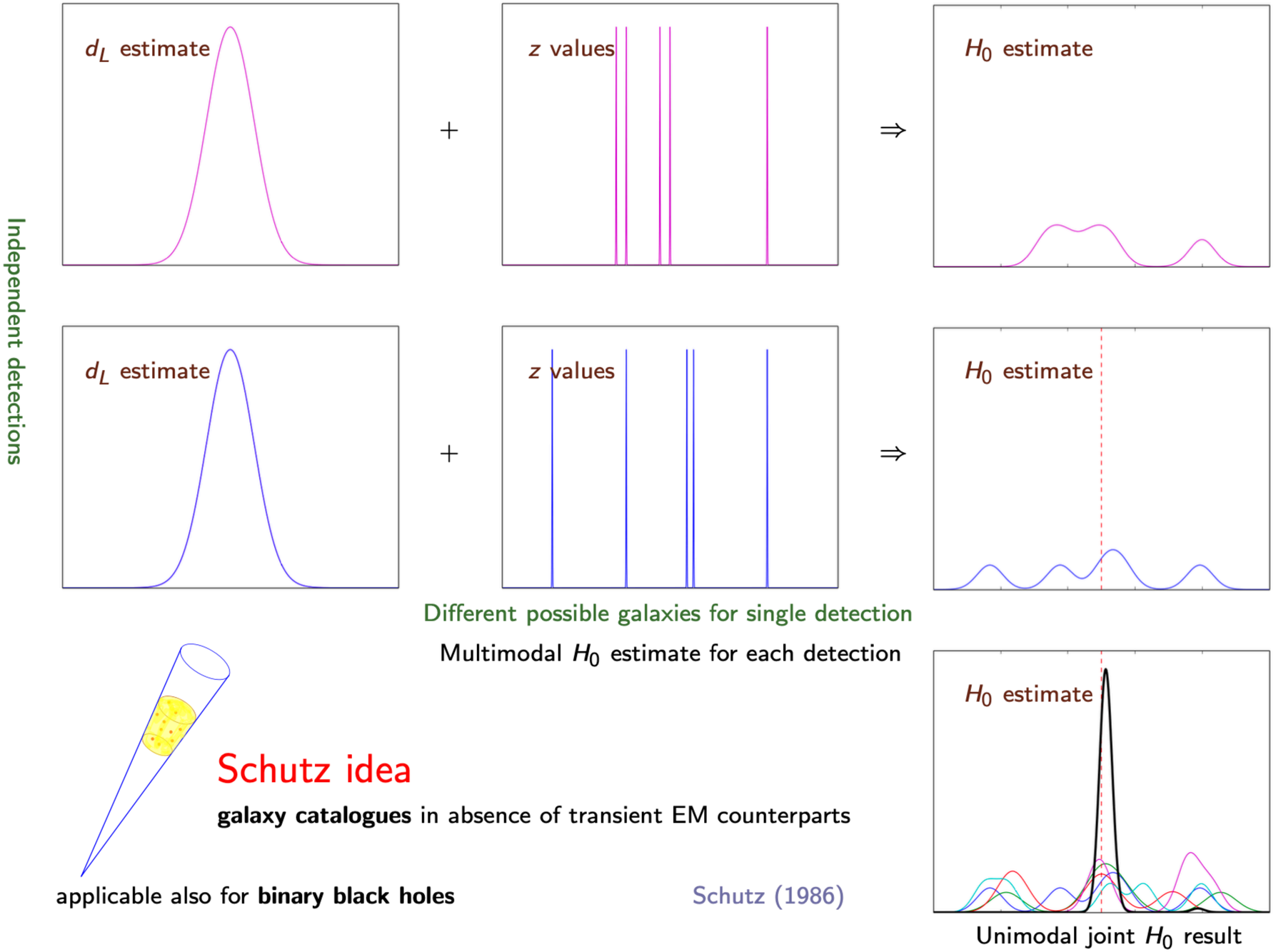
[LVC+, Nature (2017)]

Dark Sirens


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
GW Black Holes
"Electromagnetic" Black Holes
GW Neutron Stars
Neutron Stars (pulsars)
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Dark Sirens

Cosmology aided by Galaxy Survey



Schutz idea

galaxy catalogues in absence of transient EM counterparts

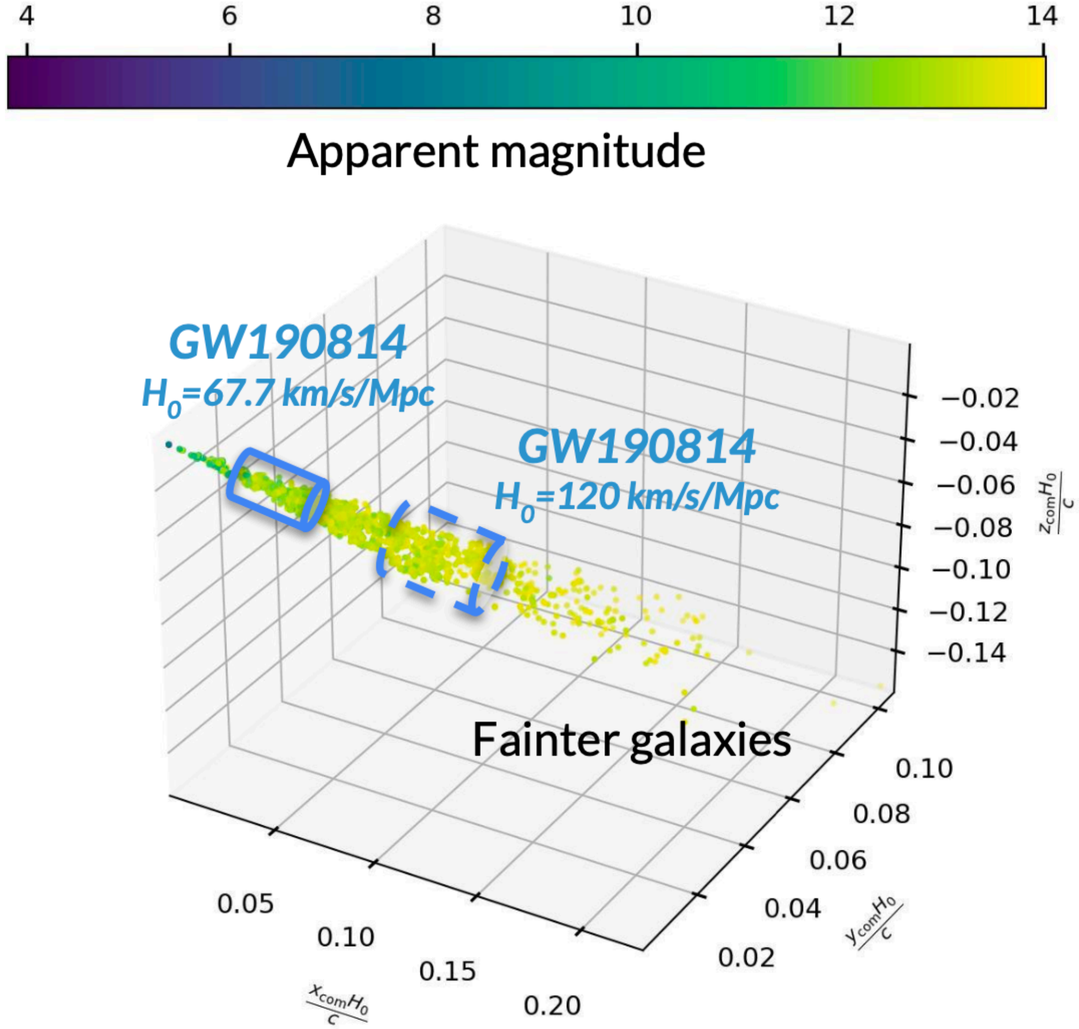
applicable also for **binary black holes**

Schutz (1986)

Dark Sirens

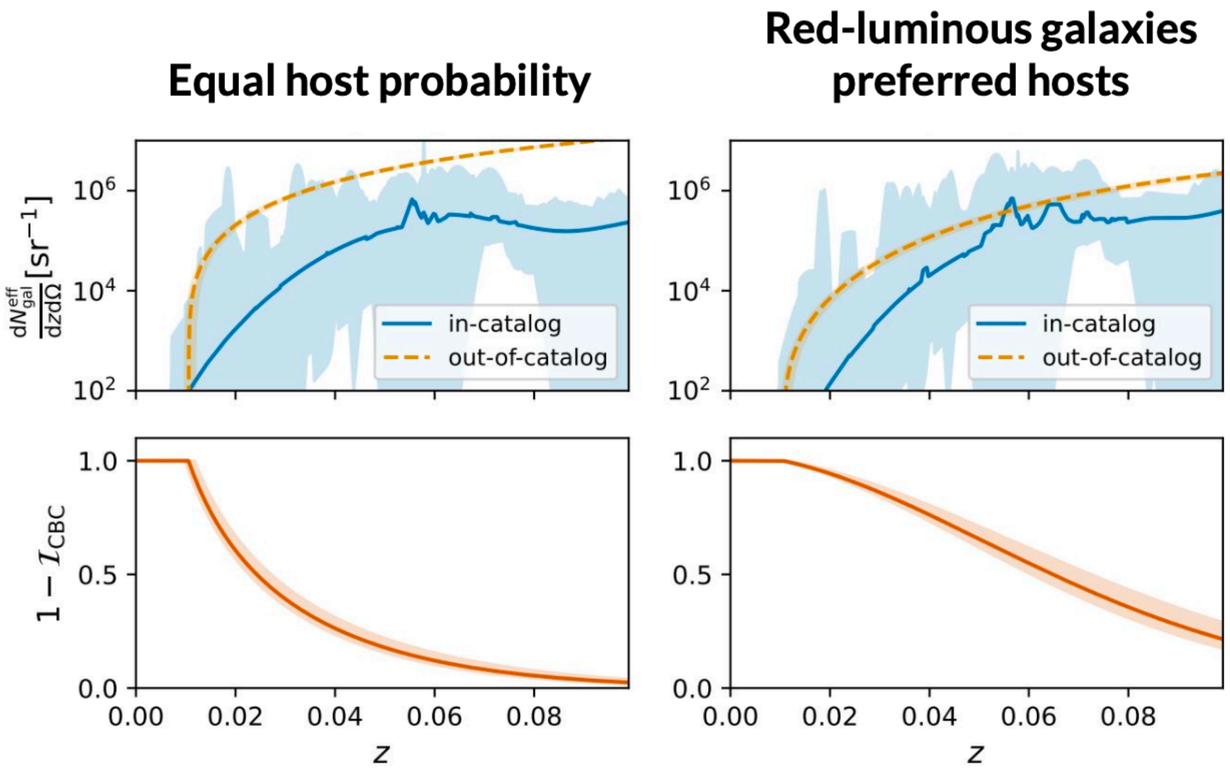
Cosmology aided by Galaxy Survey

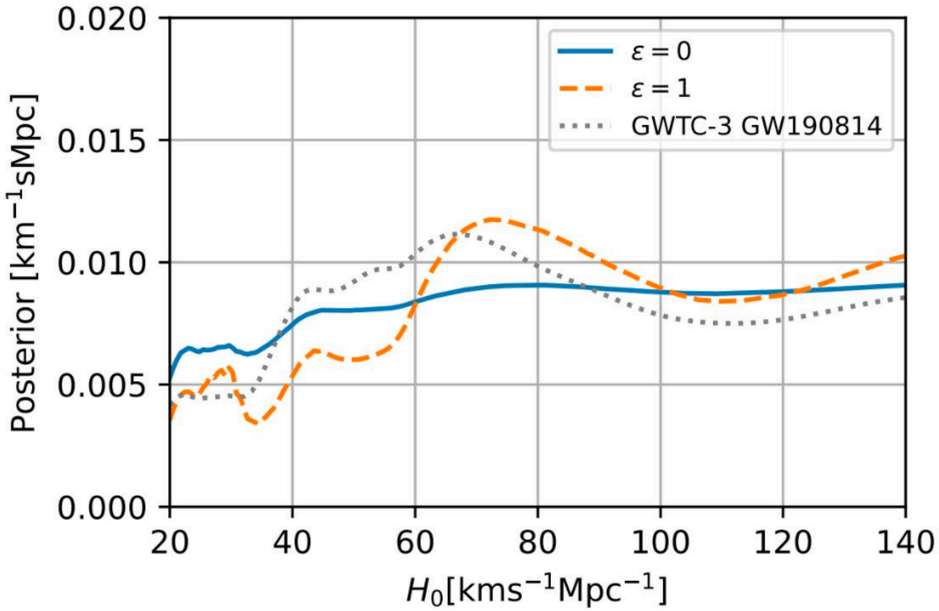
- A cosmological model has statistical support when the GW localization matches an *overdensity* of galaxies.
- Best localized events provide better constraints for cosmology.
- Galaxy catalogs are not complete at higher redshifts, we need to apply corrections to not bias our analyses
- ***Open question:*** *How does galaxy properties correlate with CBC hosting?*
  - *Two main actors: Star Formation rate and total stellar mass*



Dark Sirens

Cosmology aided by Galaxy Survey



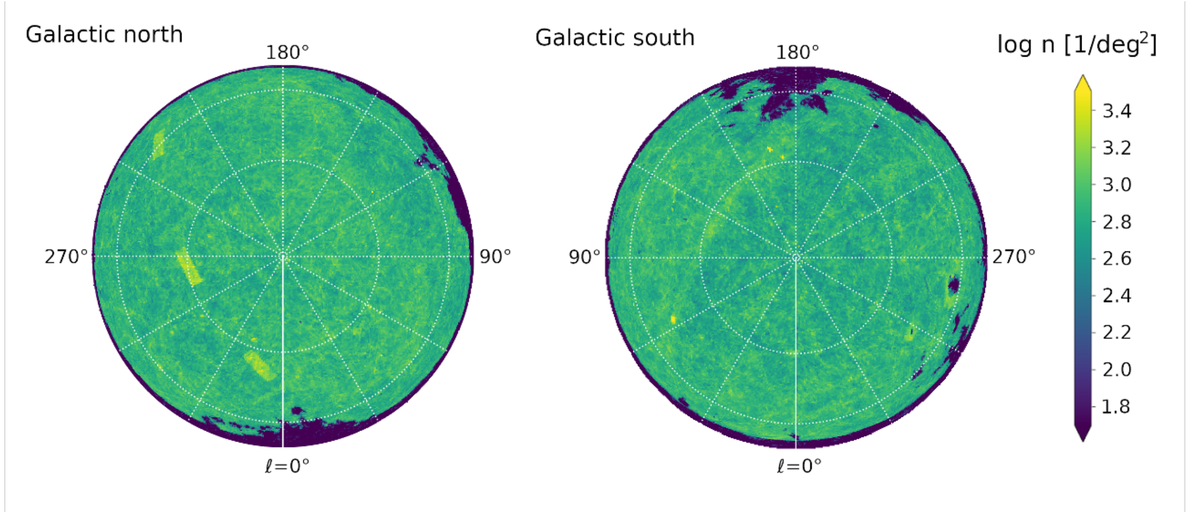


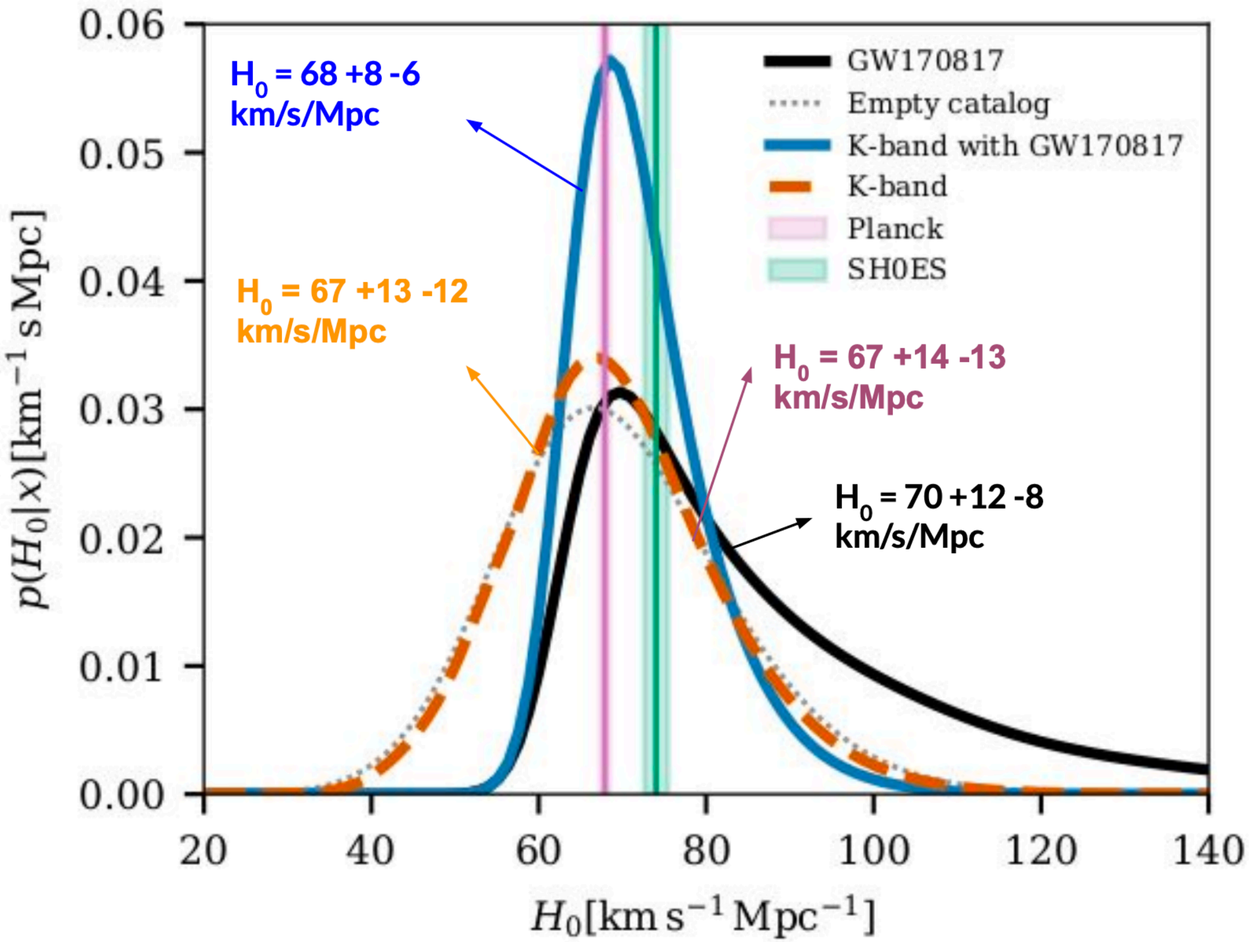
GW hosting models will have an important impact on cosmology

Dark Sirens

GWTC-3 Results

Results from 47 compact binaries (42 BBH, 2 NSBH, 2 BNS, 1 asymmetric mass binary) with SNRs > 11, with the GLADE+ galaxy catalog. The population mass distributions are fixed.

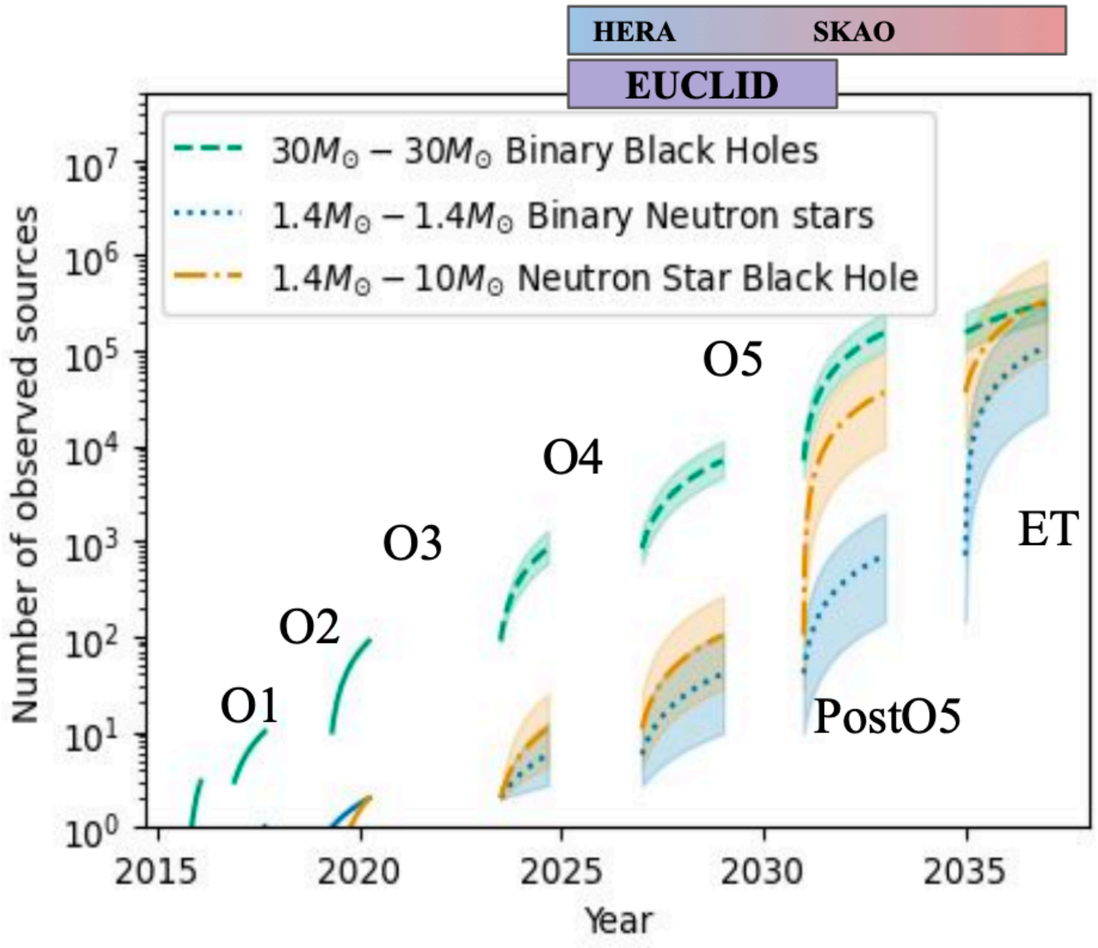


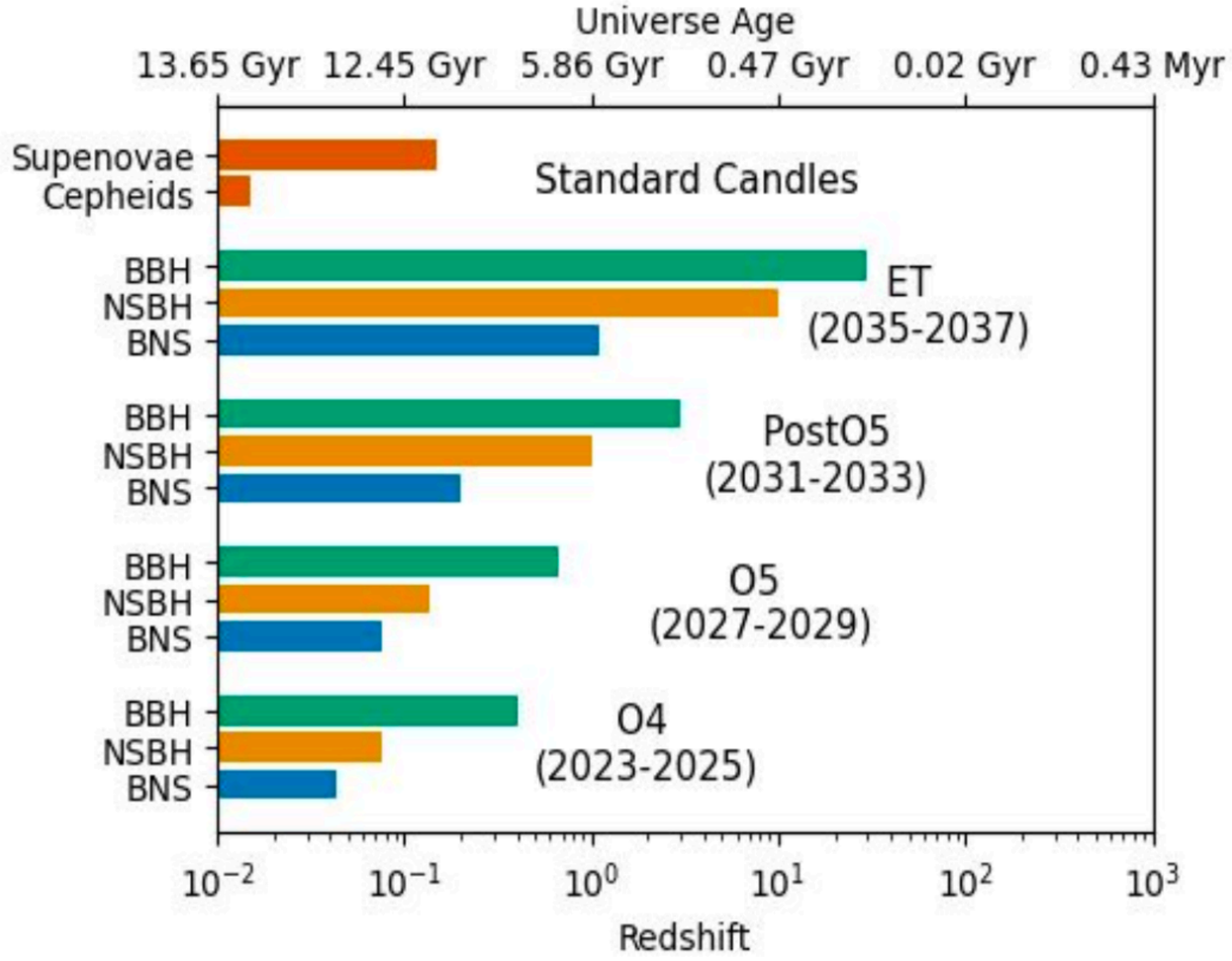


"Constraints on the cosmic expansion history from GWTC-3", The LIGO Scientific, Virgo and KAGRA collaborations

What is next for GW cosmology?

Moving forward with ground-based GW detectors





What is next for GW cosmology?

Dark sirens with 3rd Generation GW detectors

Localization is of crucial importance for the galaxy catalog method.

- About 3000 dark sirens will be localized better than GW190814.
  - ~5 dark sirens will be so well localized to have ~1 galaxy in their localization volume.
  - ~100 dark sirens will have less than 1000 galaxies in their localization paper.
  - With one year of observation, constraint on H0 at the 5% precision

Conclusions

- Gravitational Wave sources are rapidly becoming important cosmic tracers.
- Compact binary coalescences potentially give us access to the study of the cosmic expansion from today up to a few Myrs after the Big Bang.
- GWs are standard candles, however, to achieve precision and accurate cosmology they still need some astrophysical calibration.

Thank you for your attention!