Perspectives for cosmology with current detectors and next generation detectors

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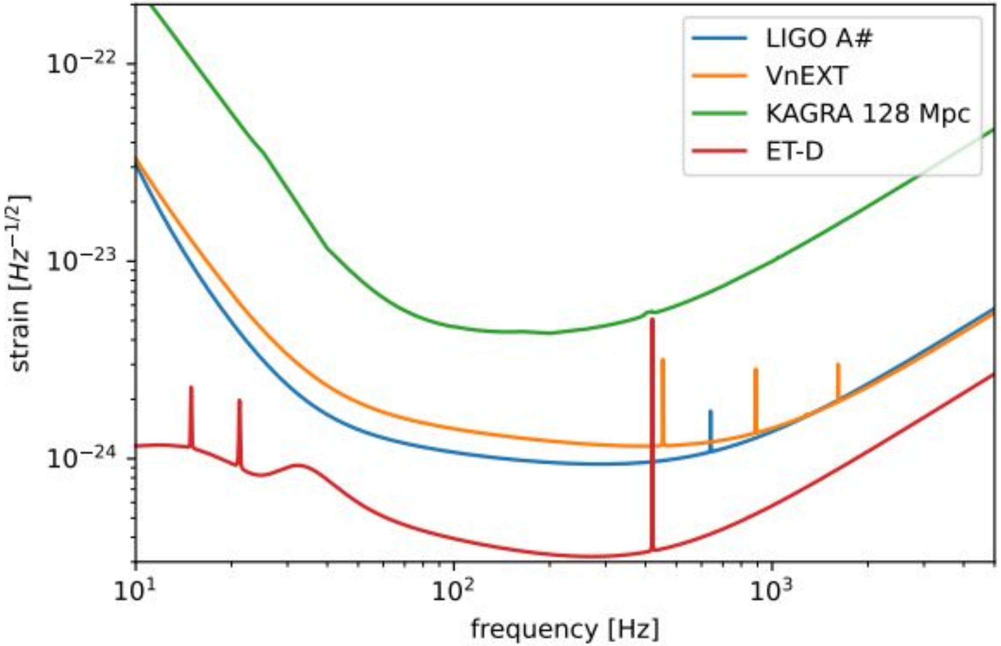
With the Virgo_nEXT Observational Science Team

GWADW 2023 Elba Island

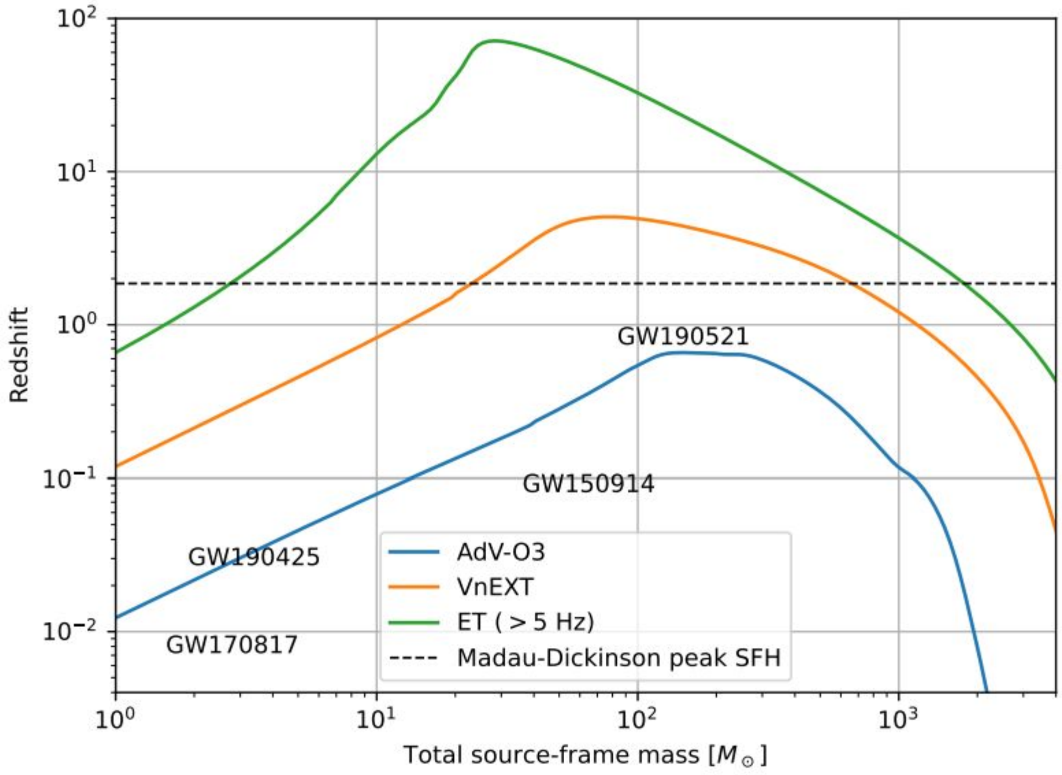
Talk based on Virgo_nEXT study: VIR-0497D-22

Beyond O5 to the next generation detectors era



VIR-0497D-22

Accessing almost all the Universe



Age of the Universe 13.8 Gyr

z= 11, 13.35 Gyr ago farthest galaxy observed

z= 8, 13.17 Gyr ago farthest GRB observed

z= 2, 10 Gyr ago Peak the Star formation rate

z= 0.3, 3.5 Gyr ago Dark Energy era

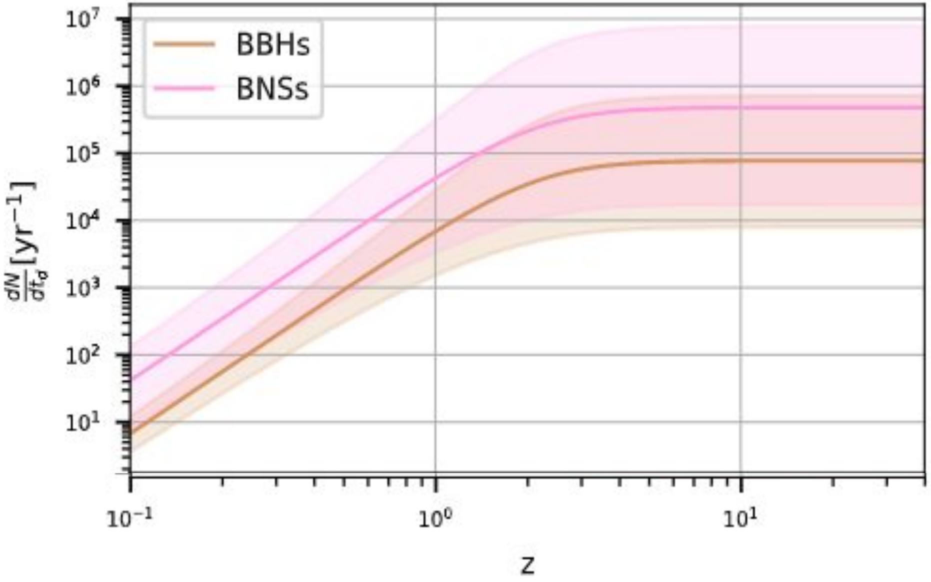
With Virgo_nEXT we will get access to the life of the first stars.

A cosmic population of compact binary coalescences

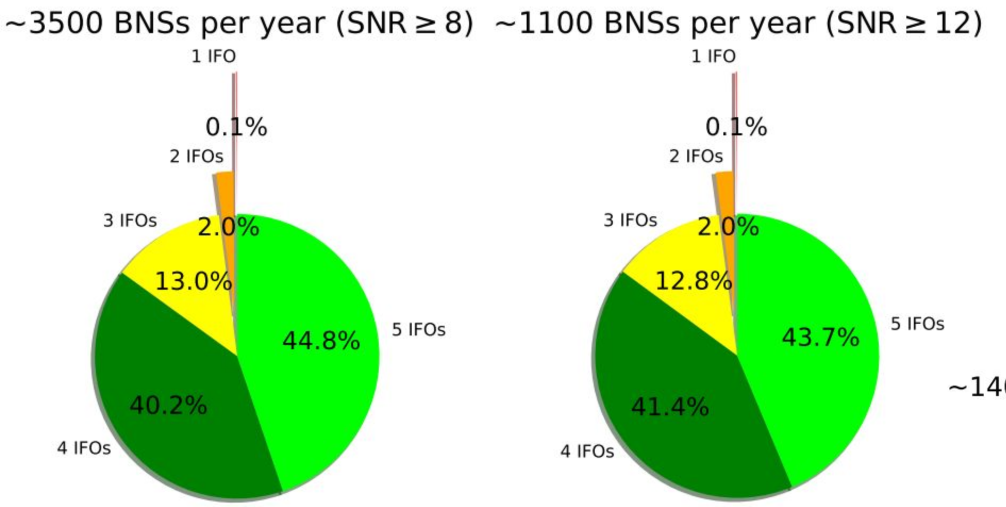
We simulate a population of binary black holes (BBHs) and binary neutron stars (BNSs) merging at cosmological scales.

- We use merger rate models based on current observations (more mergers in the younger universe).
- We use a 5 detectors network with independent 80% duty cycle.
- We use a signal-to-noise ratio (SNR) detection threshold on the network of 8 and 12.

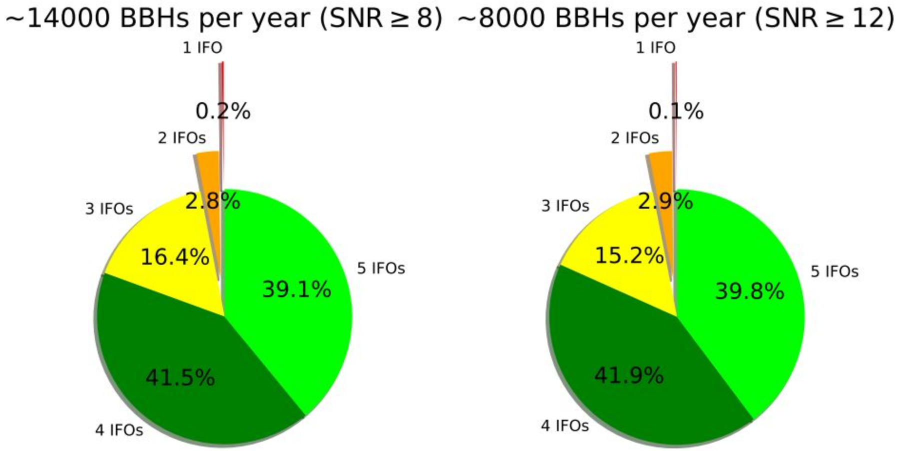
$$R(z) = 23.9 \left[\frac{\text{mergers}}{\text{Gpc}^3\text{yr}^1}\right] \frac{(1+z)^{1.66}}{1+\left(\frac{1+z}{3}\right)^6},$$



A cosmic population of compact binary coalescences



Binary Neutron Stars



Binary Black Holes

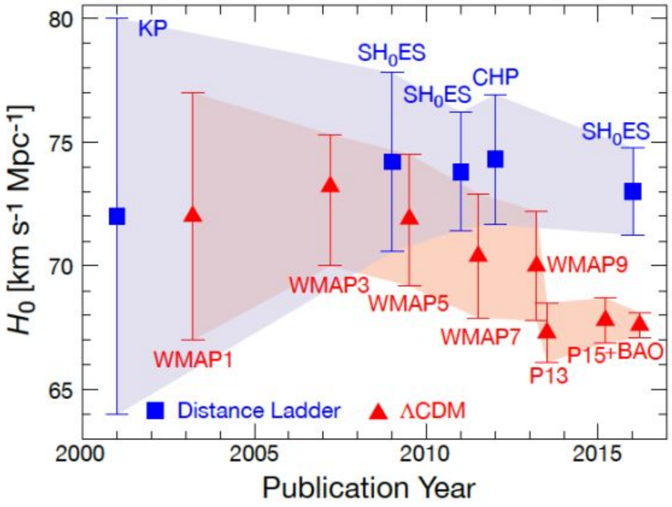
A cosmic population of compact binary coalescences

According to General Relativity, and confirmed by many observations, the Universe is expanding with 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

[W. Freedman, Nature Astronomy, 1, 0169 (2017)]

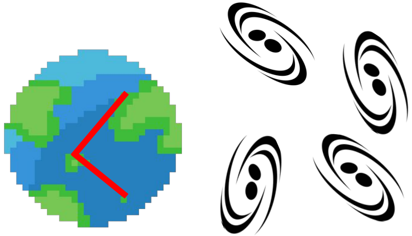


Despite its success in the standard cosmological model suffers:

- ➢ **Theoretical issues:** *What is the nature of Dark Energy?*
- ➢ **Observational issues:** *Why the measure of the Hubble constant does not agree at the level of the CMB and today?* [A. Reiss, ApJL 934 (2022)]

Gravitational Waves from cosmic distances

Source frame

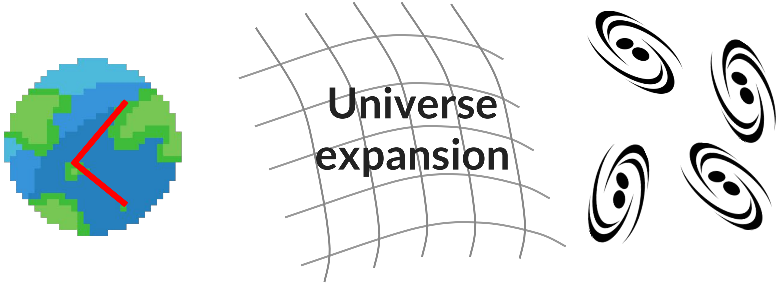


Chirp mass — Source time

$$h(t) \propto \frac{\mathcal{M}^{5/4}(t_c - t)^{-1/4}}{d} e^{\phi(t)}$$

Physical distance

Detector frame



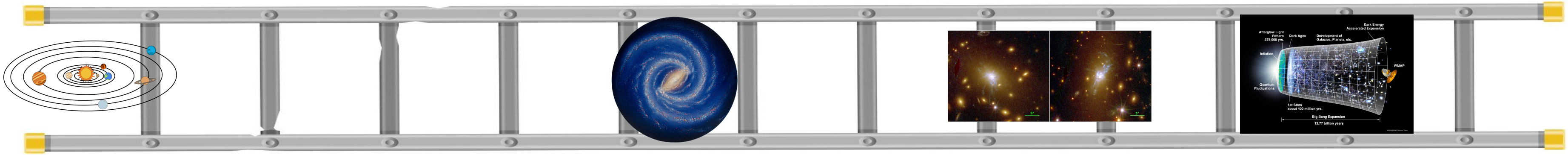
Redshifted chirp mass — Detector time

$$h(t^{\rm det}) \propto \frac{[\mathcal{M}(1+z)]^{5/4}(t_c^{\rm det} - t^{\rm det})^{-1/4}}{d_{\rm L}} e^{\phi(t)}$$

Luminosity distance

Gravitational Waves from cosmic distances

In order to measure the expansion of the Universe we need to know the source's **distance** and **recessional velocity**



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

Gravitational Waves from cosmic distances

From GWs we can not measure the source redshift (escaping velocity)

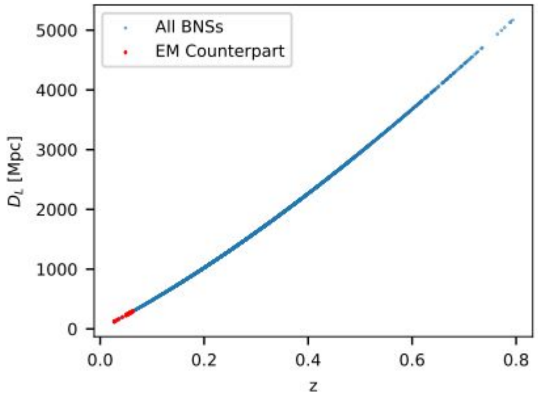
In recent years, we used several methods to assign a redshift to GW sources

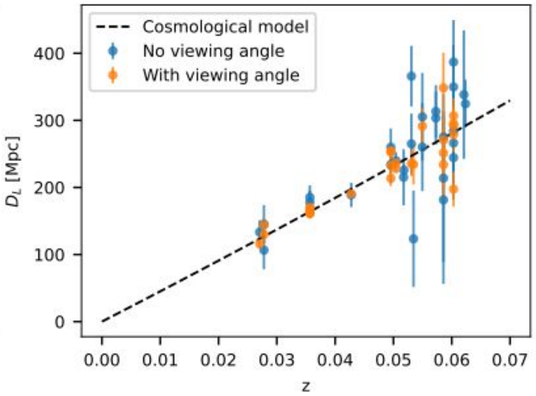
- **Bright sirens:** An associated Electromagnetic (EM) counterpart (GRB, Kilonova etc…) can provide the identification of the host galaxy.
- **Dark sirens:** Galaxy surveys can be used to identify possible hosts in the GW localization volume.
- **Spectral sirens:** Knowledge of the source-frame mass distribution can be used to assign a redshift to GW sources.

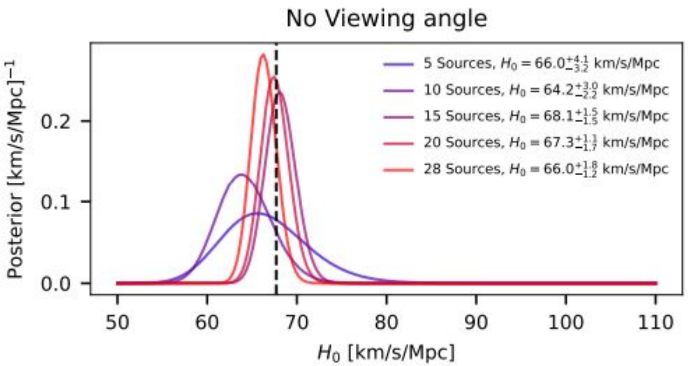
Bright standard sirens prospects

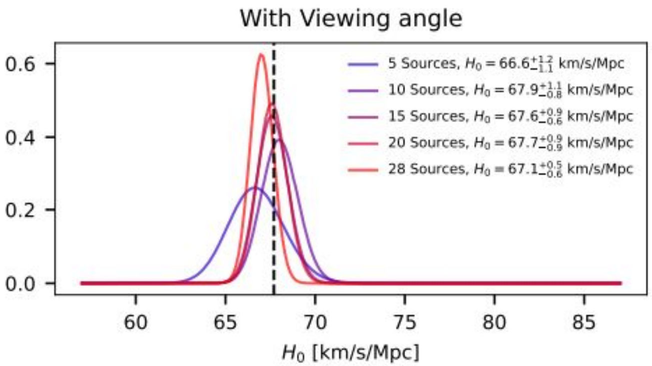
We assume that Large Field of View facilities such as Vera Rubin LSST would be able to detect the Kilonova emission up to 300 Mpc.

About 30 sources with EM counterpart





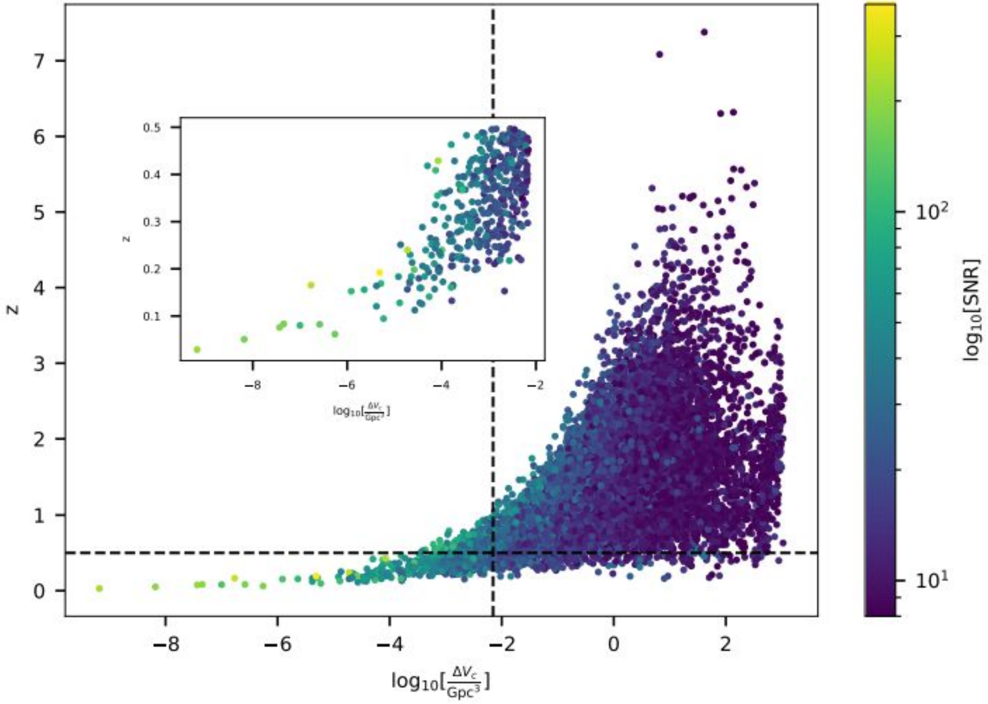




Dark sirens with galaxy catalogs

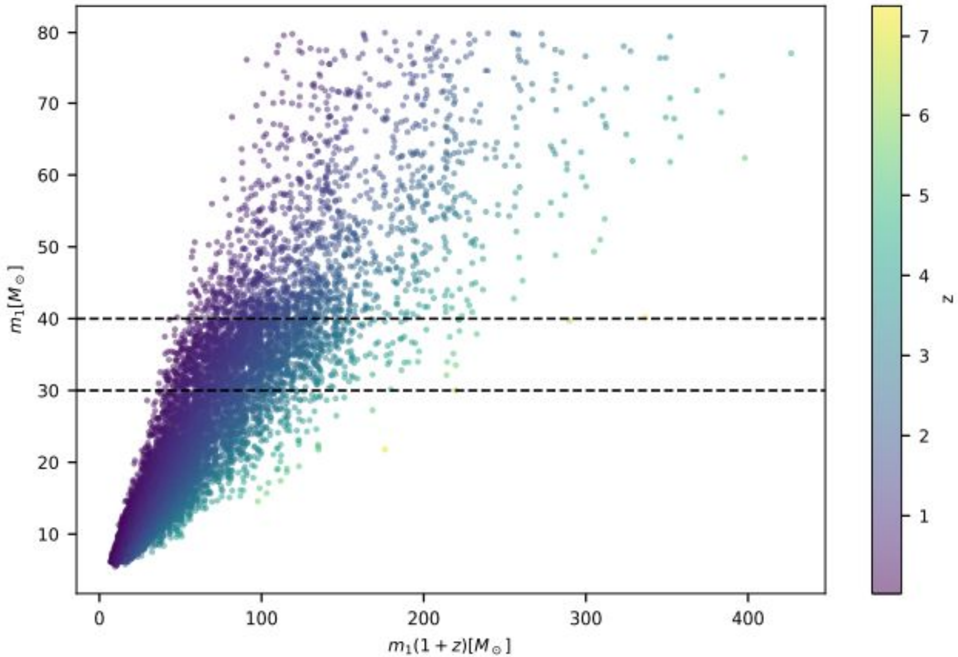
Localization is of crucial importance for the galaxy catalog method.

- 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



Spectral sirens with the source-frame mass method

- Thousands of BBHs a mass similar to 35 solar masses will be detected up to redshift 7.
- This overdensity of black holes can be exploited to obtain an implicit redshift measurement.
- The combination of all these BBHs will provide an Hubble constant measure of 3-4% precision in one year.



Conclusions

- Virgo_nEXT will bridge the current detector era with the next generation detectors era.
- We will have access to binary black holes merging at cosmic noon (the peak of star formation rate).
- We will have 3 independent methods to measure the expansion rate of the Universe (useful to cross-check systematics).
- In just one year of Virgo_nEXT we could be able to solve the Hubble constant tension

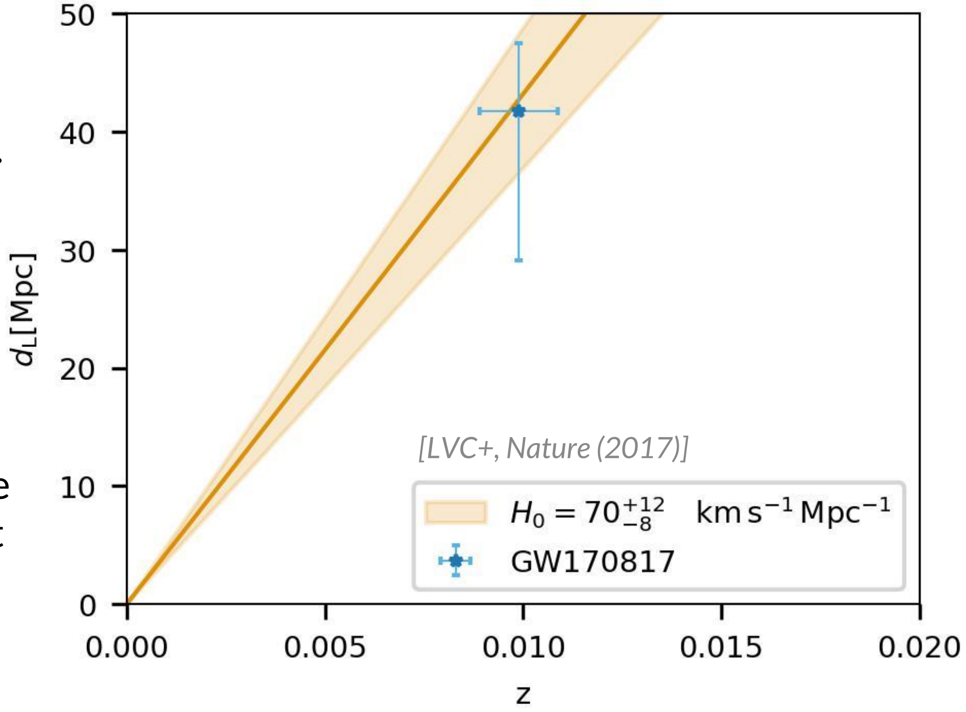
Thank you for your attention

Bright sirens: Cosmology with GW170817

- **GW170817:** A binary neutron star merger detected by LIGO and Virgo. From the GW, source distance ~ 40 Mpc *[LVK+, ApJL, 848 (2017)]*.

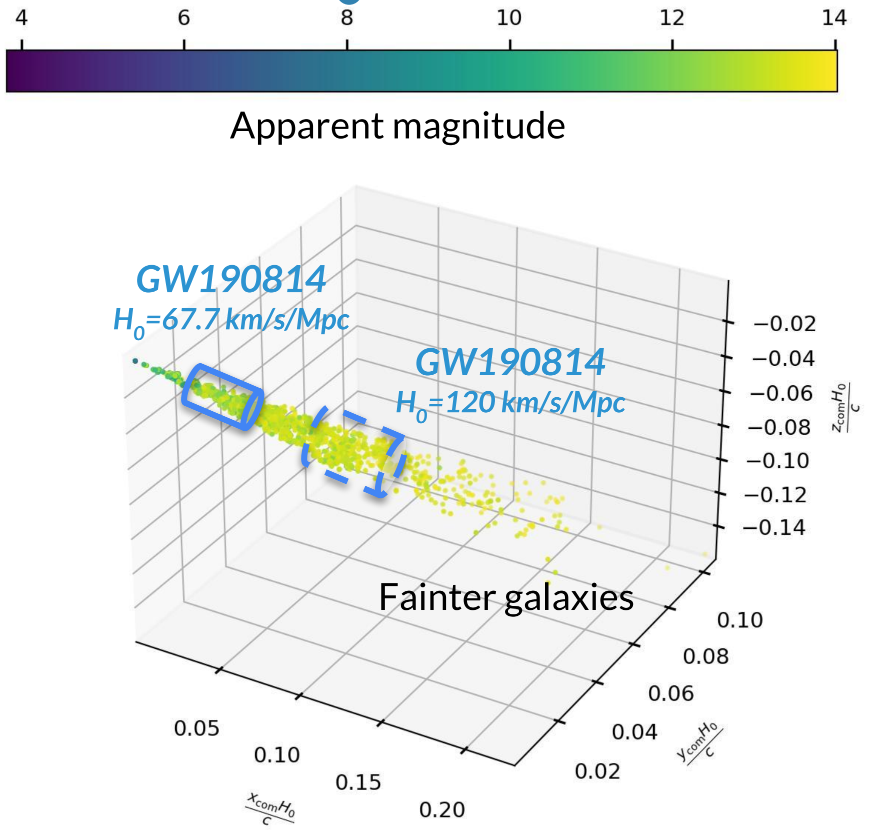
- **Short Gamma-ray burst and Kilonova:** Two associated EM counterparts allowed the identification of the source host galaxy **NGC4993**.

- This type of events will difficult to detect, we might expect to have 0-10 others in the next two observing runs *[SM+ A&A (2017), Patricelli+, MNRAS (2022)]*



[LVC+, Nature (2017)]

Dark sirens: Cosmology aided by galaxy surveys

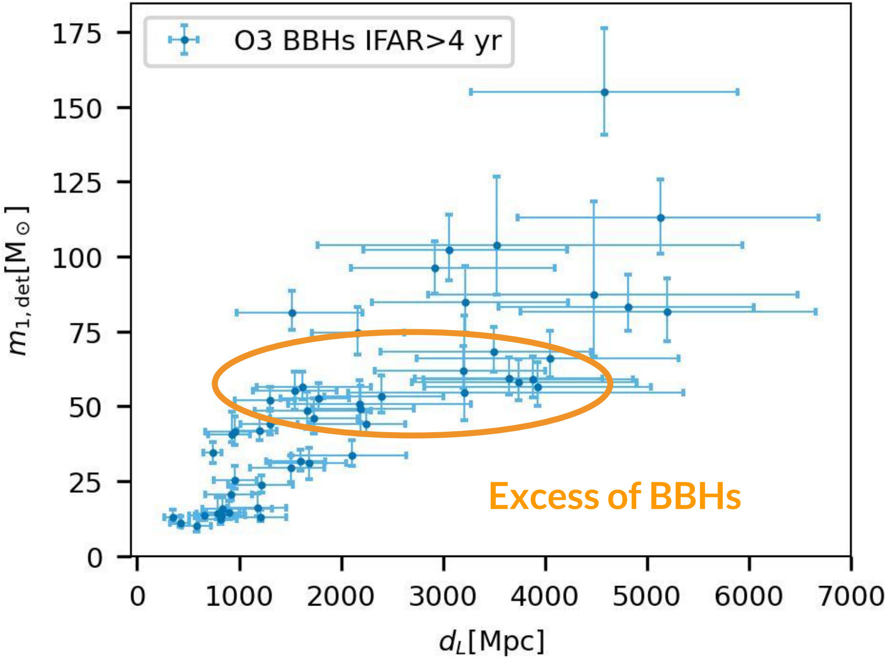


- A cosmological model has statistical support when the GW localization matched an *overdensity* of galaxies.
- Galaxy catalogs are not complete at higher redshifts, we need to apply corrections in order to now bias our analyses *[R. Gray+, PRD (2019)]*

Spectral sirens: GW-only cosmology

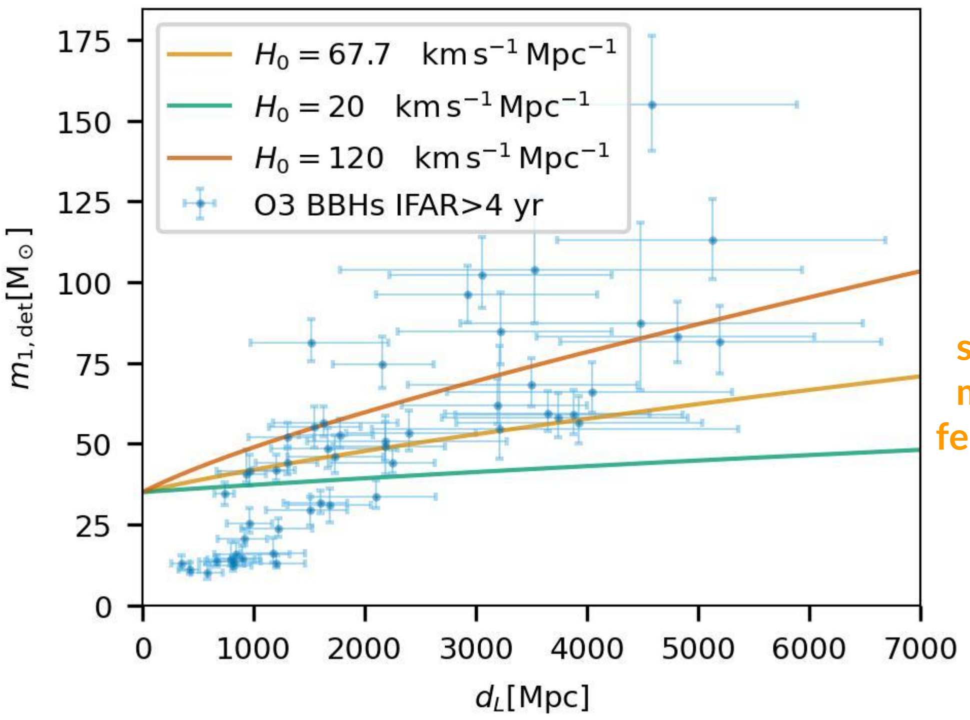
- Many GW are detected with large sky localizations and are very far (galaxy catalogs highly incomplete).
- If BBHs are *preferentially* produced at a given mass, we can exploit the mass-redshift relation to assign a redshift to the GW source *[SM+, PRD 104 (2021)]*.

$$m_{1,\mathrm{det}} = m_{1,\mathrm{s}}(1+z)$$



Spectral sirens: GW-only cosmology

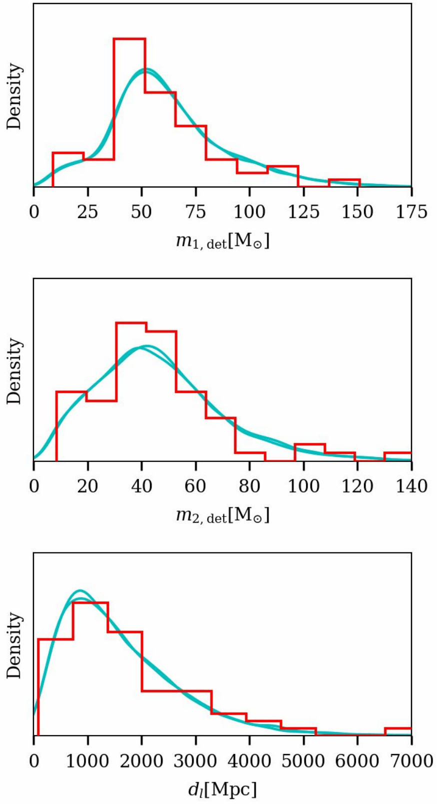
- If we assume an overdensity of BBHs produced at 35 solar masses, some “extreme” cosmologies can not fit the overdensity of BBHs.



35 solar mass feature

Spectral sirens: GW-only cosmology

Detector Frame



Cosmology

Selection biases

Simulati on

Source Frame