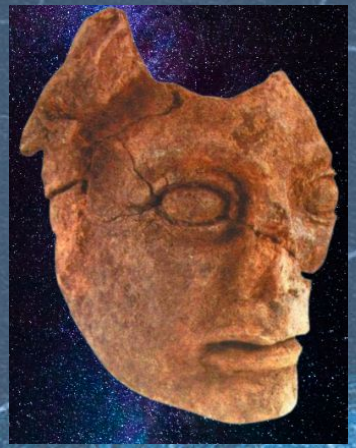
Implications of Binary Black Hole mergers for cosmology



S. Mastrogiovanni

Vulcano Workshop 2022 - Sept 26th Elba Island

A pedagogic introduction: SM, D. Steer, "*Handbook of Gravitational Wave Astronomy*" (2022)
A recent review: SM+, "Cosmology with Gravitational Waves, A review" (2022)
The last LVK results: LVK, "Constraints on the cosmic expansion history from GWTC-3" (2021).

Image credit: L. Relli - INFN

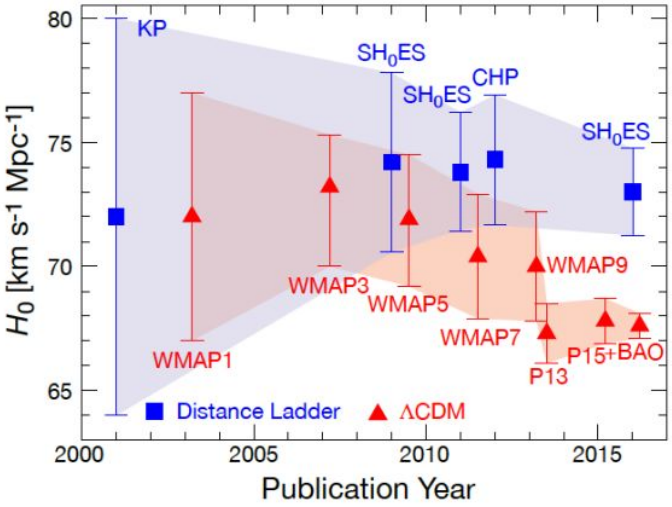
The standard cosmological model?

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)]

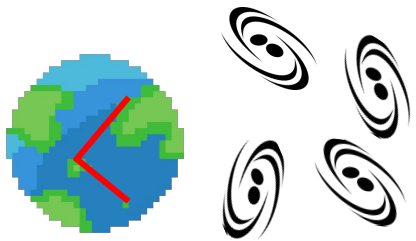


Despite its success in the standard cosmological model suffers:

- **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

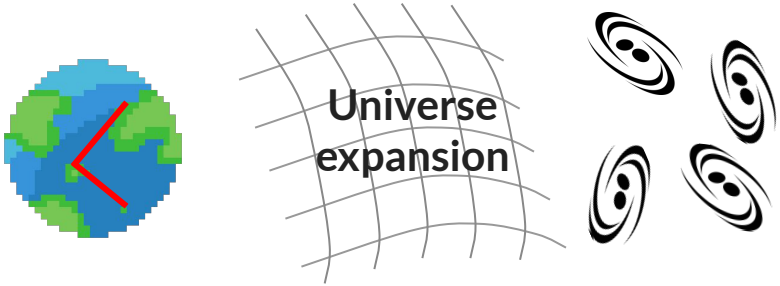


Chirp mass Source time

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

Physical distance

Detector frame



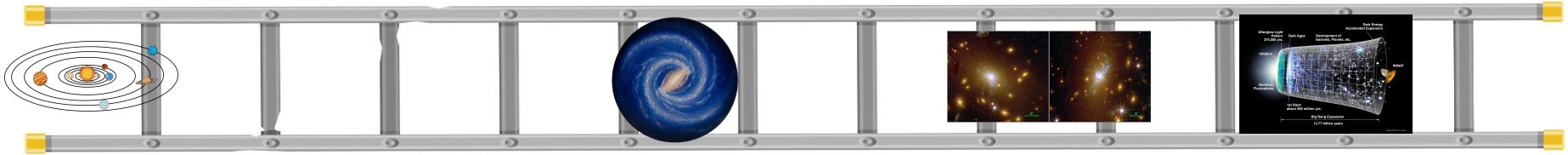
Redshifted chirp mass Detector time

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

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
- Cepheids
- Parallax
- Type Ia Supernovae

Distances with GW observations

- Compact binary coalescenses

Gravitational Waves from cosmic distances

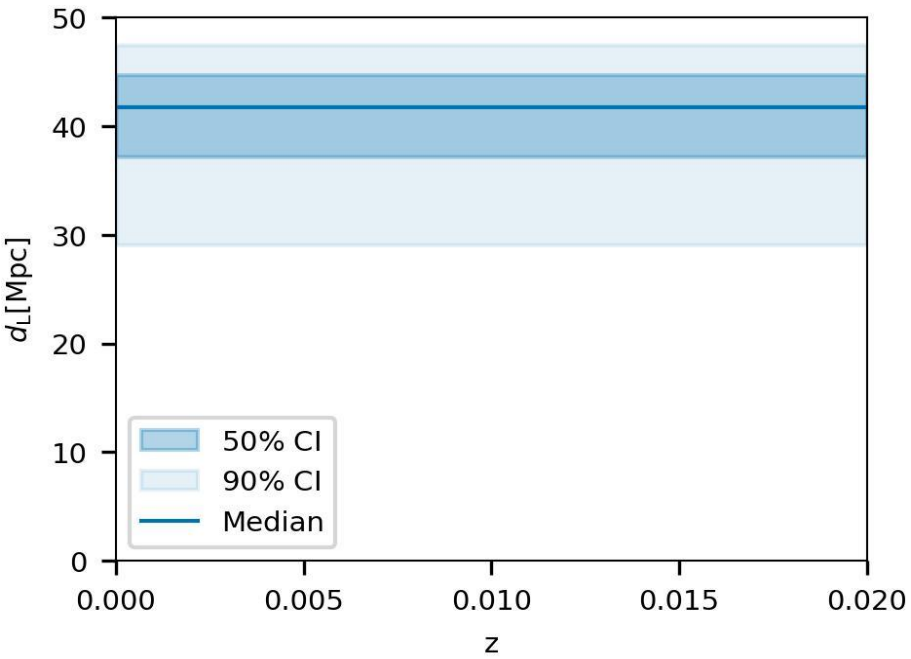
From GWs we can not measure the source redshift (escaping velocity)

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 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)]*.



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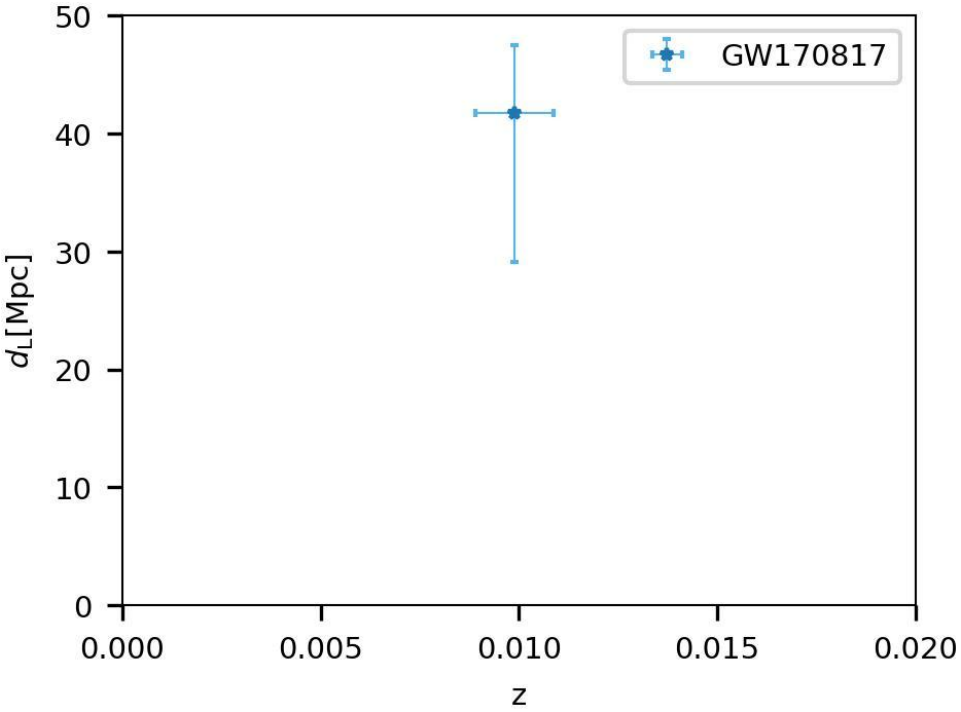
- **Short Gamma-ray burst and Kilonova:** Two associated EM counterparts allowed the identification of the source host galaxy NGC4993.



Bright sirens: Cosmology with GW170817

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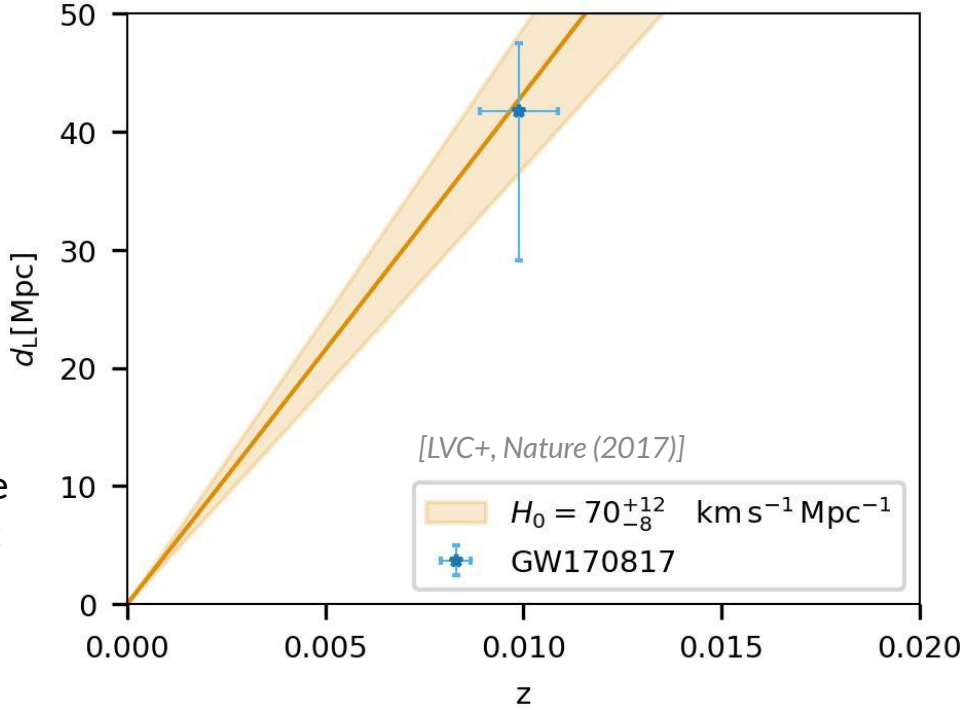
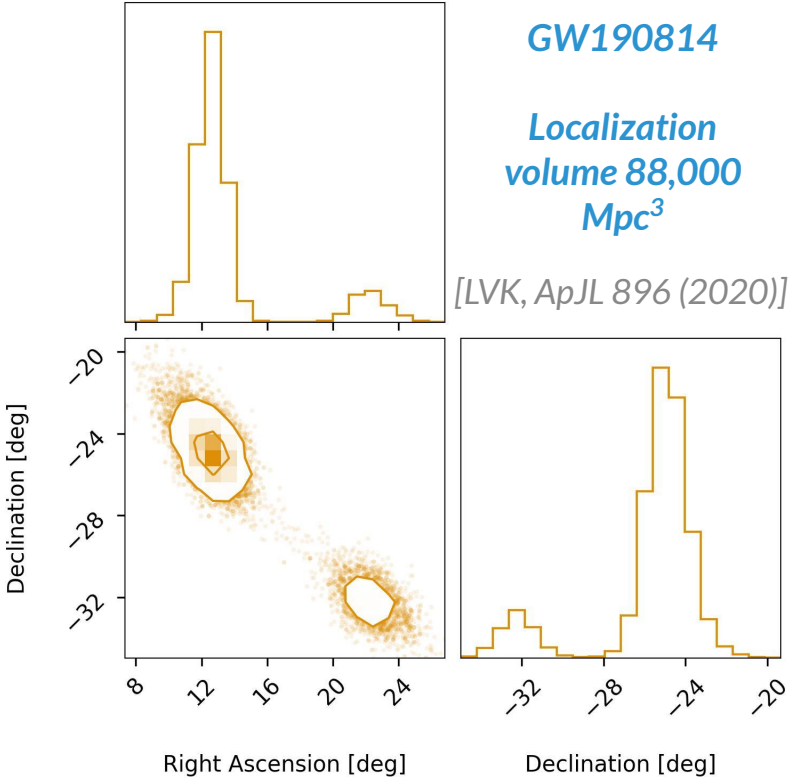
- **Short Gamma-ray burst and Kilonova:** Two associated EM counterparts allowed the identification of the source host galaxy NGC4993.
- This type of events will difficult to detect, we might expect to have 0-10 others in the next two observing runs *[SM+ A&A (2017), Patricelli+, MNRAS (2022)]*



Dark sirens: Cosmology aided by galaxy surveys

- In the case that the GW is not observed with EM counterpart, we can use galaxy catalogs to identify possible galaxy hosts *[Schutz, Nature 1986]*.
- Galaxy surveys will provide possible redshifts.
- GW will provide luminosity distance.
- Best localized events provide better constraints for cosmology.

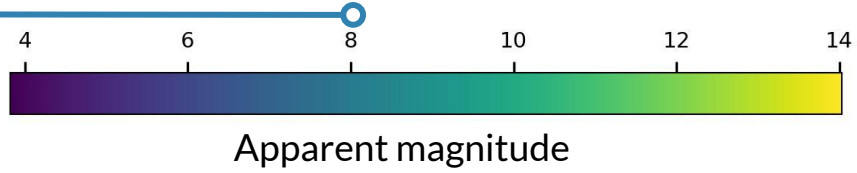


GW190814

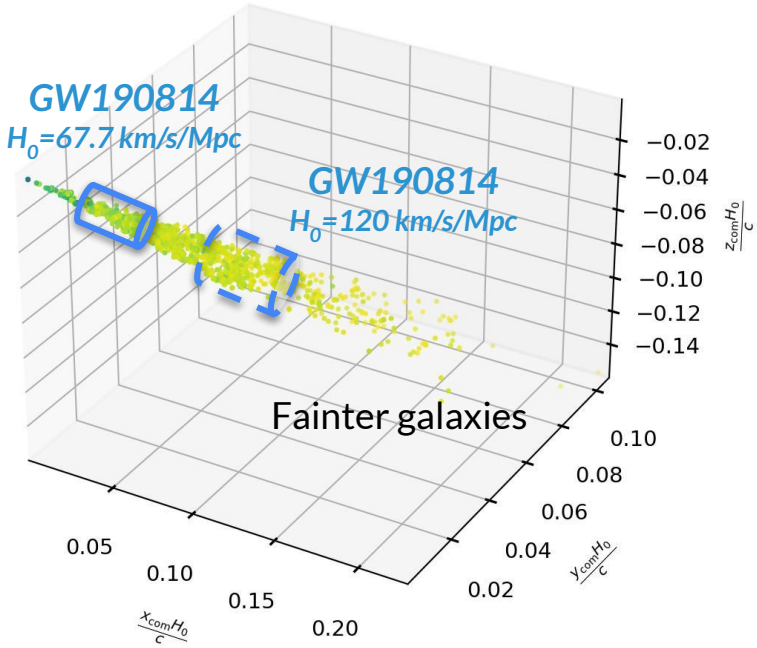
Localization volume 88,000 Mpc^3

[LVK, ApJL 896 (2020)]

Dark sirens: Cosmology aided by galaxy surveys



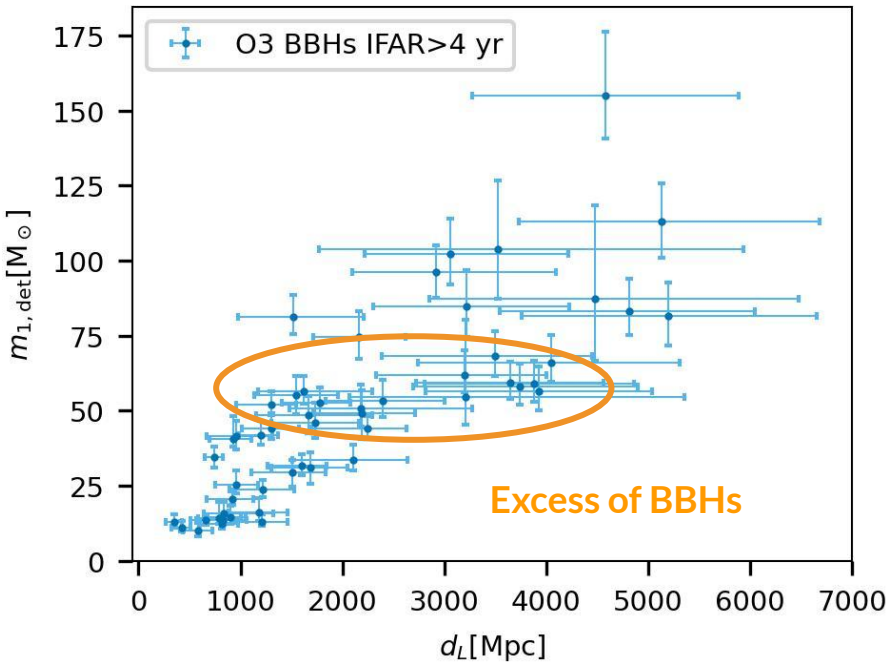
- A cosmological model has statistical support when the GW localization matched an *overdensity* of galaxies.
- Galaxy catalogs are not complete at higher redshifts, we need to apply corrections in order to now bias our analyses *[R. Gray+, PRD (2019)]*



Spectral sirens: GW-only cosmology

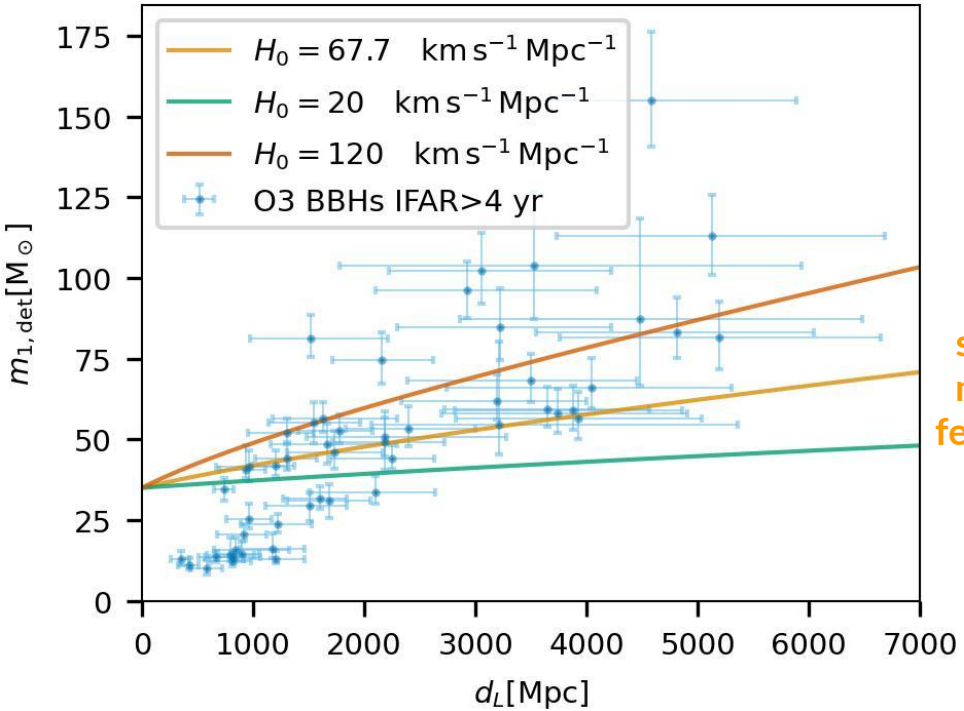
- Many GW are detected with large sky localizations and are very far (galaxy catalogs highly incomplete).
- If BBHs are *preferentially* produced at a given mass, we can exploit the mass-redshift relation to assign a redshift to the GW source *[SM+, PRD 104 (2021)]*.

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



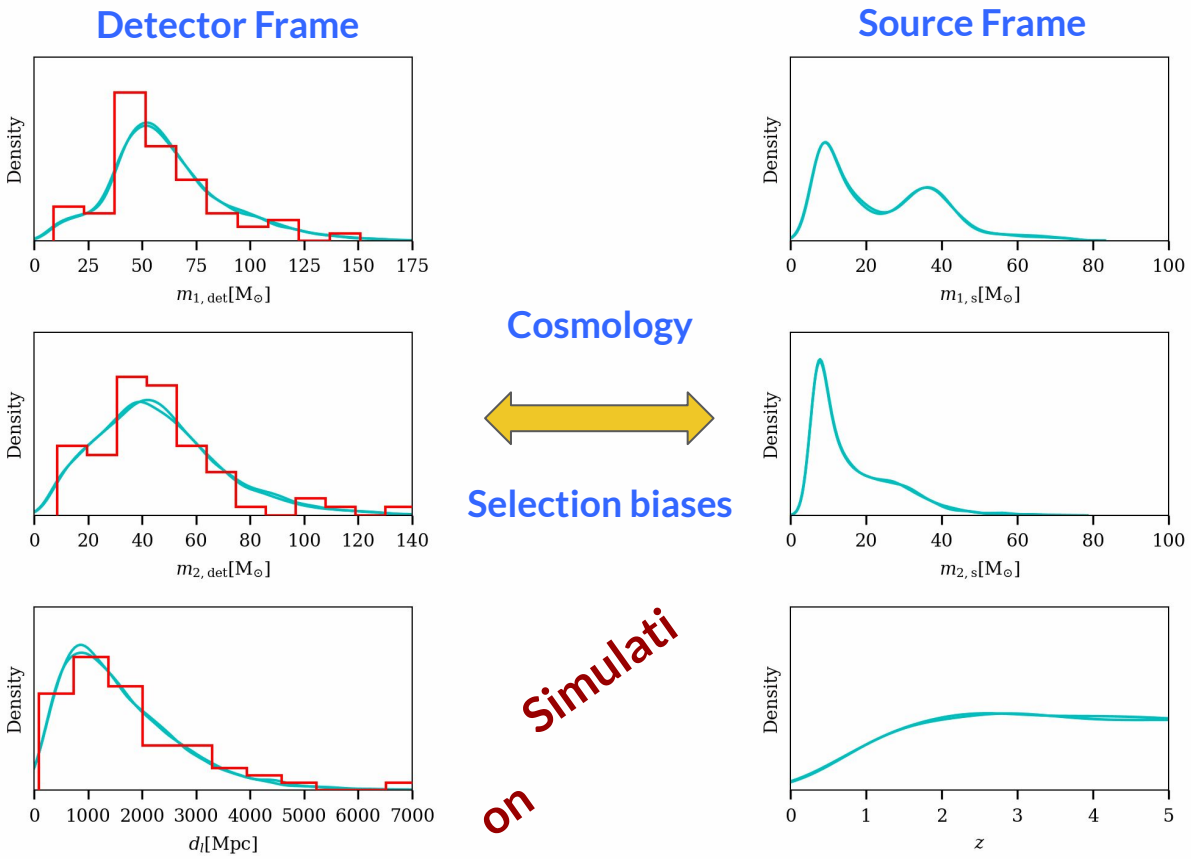
Spectral sirens: GW-only cosmology

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



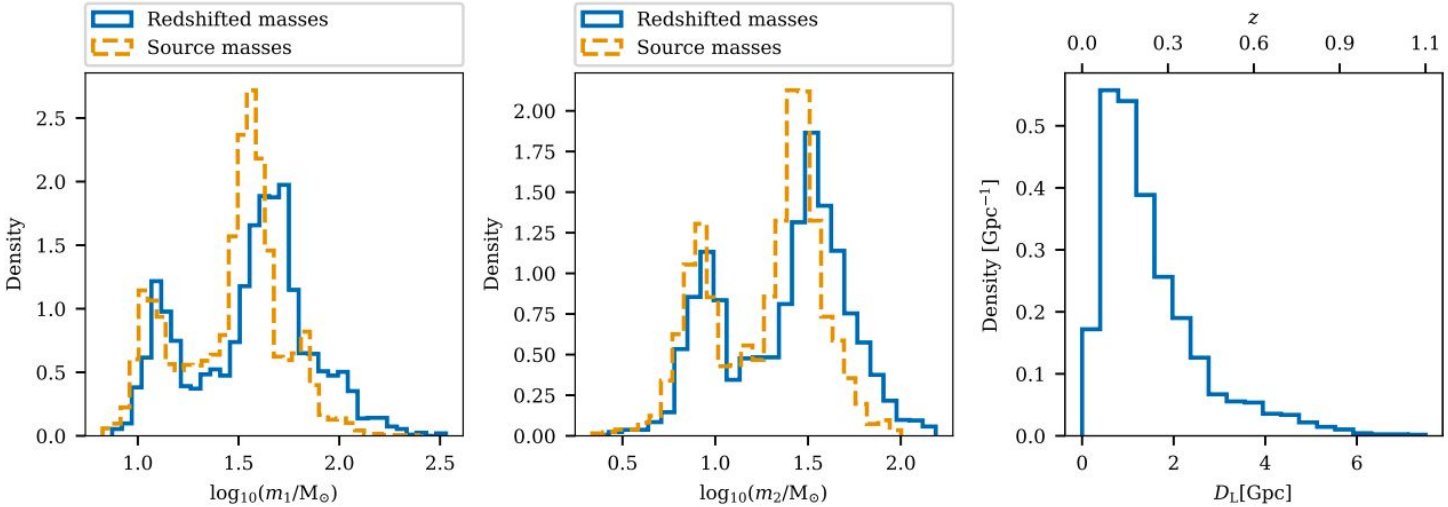
35 solar mass feature

Spectral sirens: GW-only cosmology



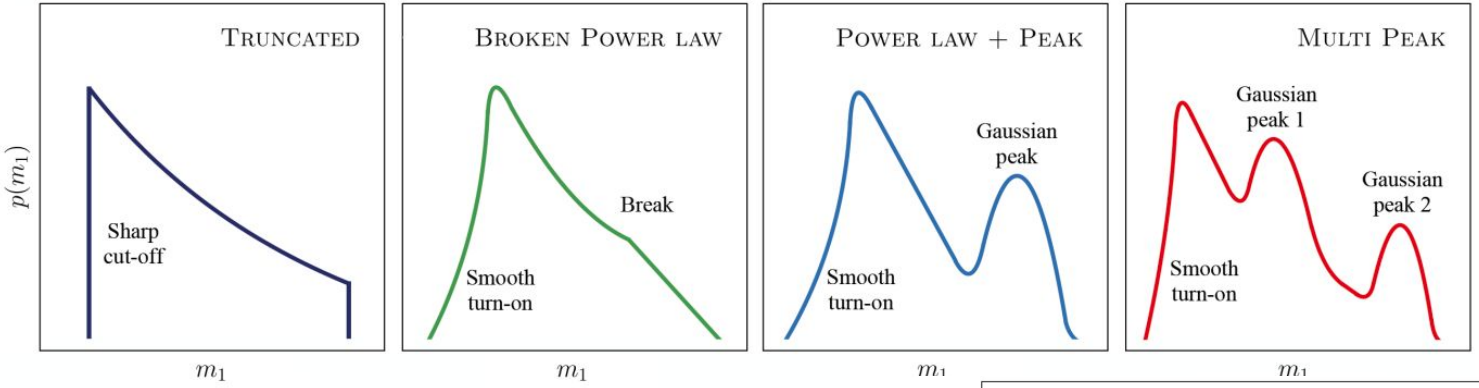
GW cosmology after GWTC-3

- **During O1 (~4 months):**
  - 3 confident BBHs
- **During O2 (~8 months):**
  - 7 confident BBHs
  - 1 confident BNS+EM counterpart
- **During O3 (~12 months):**
  - 1 consistent with BNS masses (GW190425)
  - 4 events compatible with NSBH masses
  - 2 events compatible with BNS masses
  - ~80 confident BBHs.
  - Tentative EM counterpart from GW190521

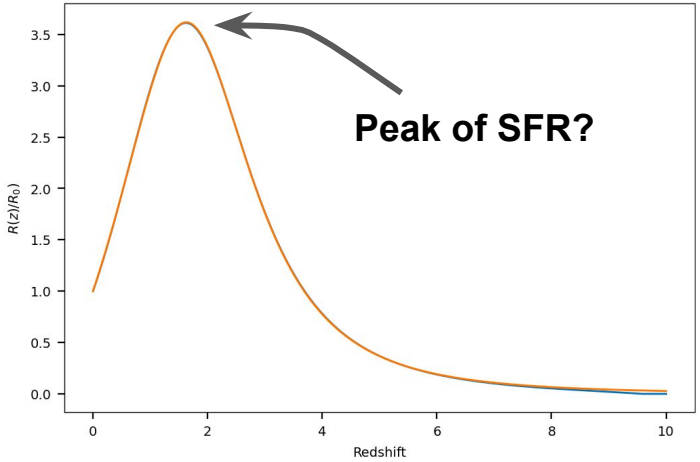


See also Tab 1 from 2111.03604

GW cosmology after GWTC-3: Spectral sirens



- Several mass models include various scales to describe stellar processes *[LVK+ 2021 ApJL 913 L7]*.
- As a consequence, the masses of GW observations are redshifted by the expansion of the Universe *[Ye+ PRD 104 2021]*.



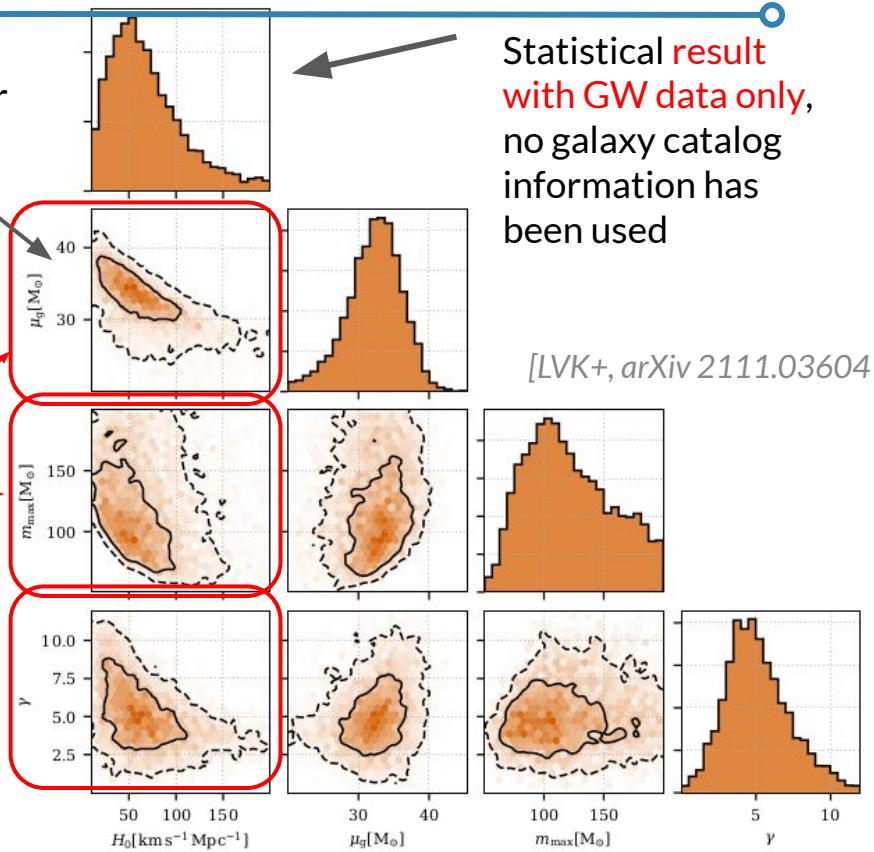
GW cosmology after GWTC-3: Spectral sirens

The excess of BBHs around 35 solar masses sets a scale for the redshift and provides constraints on H0.

Statistical result with GW data only, no galaxy catalog information has been used

[LVK+, arXiv 2111.03604 (Accepted ApJ)]

Population parameters that correlate with H0



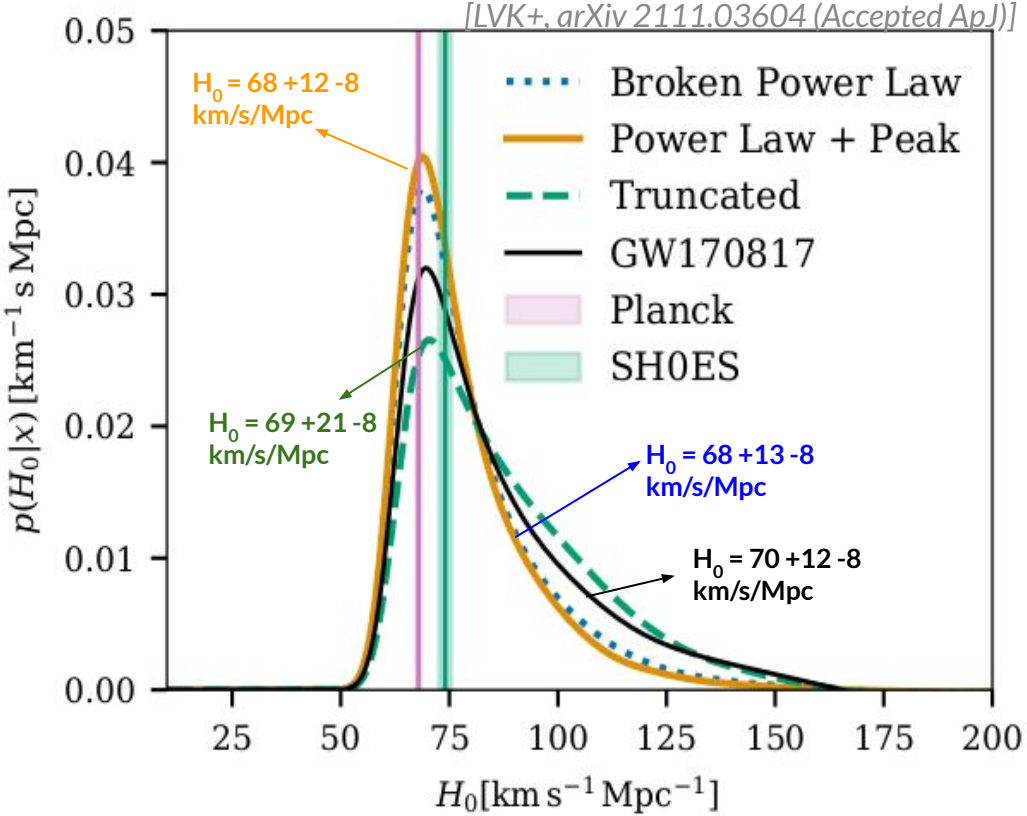
Posteriors of H_0, mu of the Gaussian peak, maximum mass of

GW cosmology after GWTC-3: Spectral sirens

The only EM information is the counterpart of GW170817

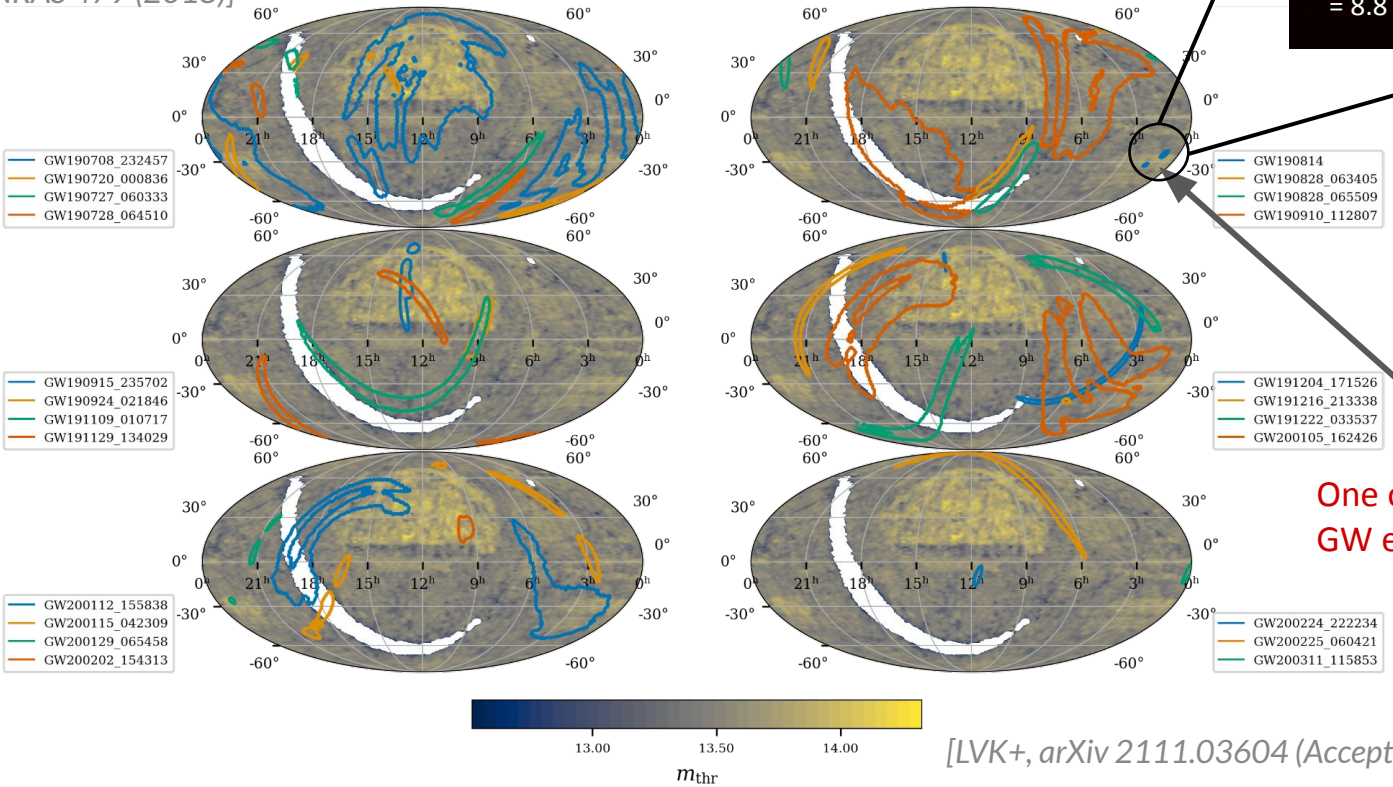
H_0 posterior of the 3 mass models combined with GW170817 posterior

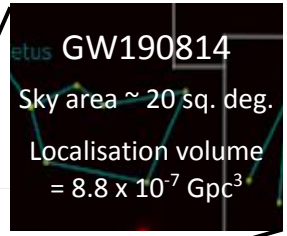
[LVK+, arXiv 2111.03604 (Accepted ApJ)]



GW cosmology after GWTC-3: Dark sirens

[Dalya+, MNRAS 479 (2018)]





One of the highly localised GW events

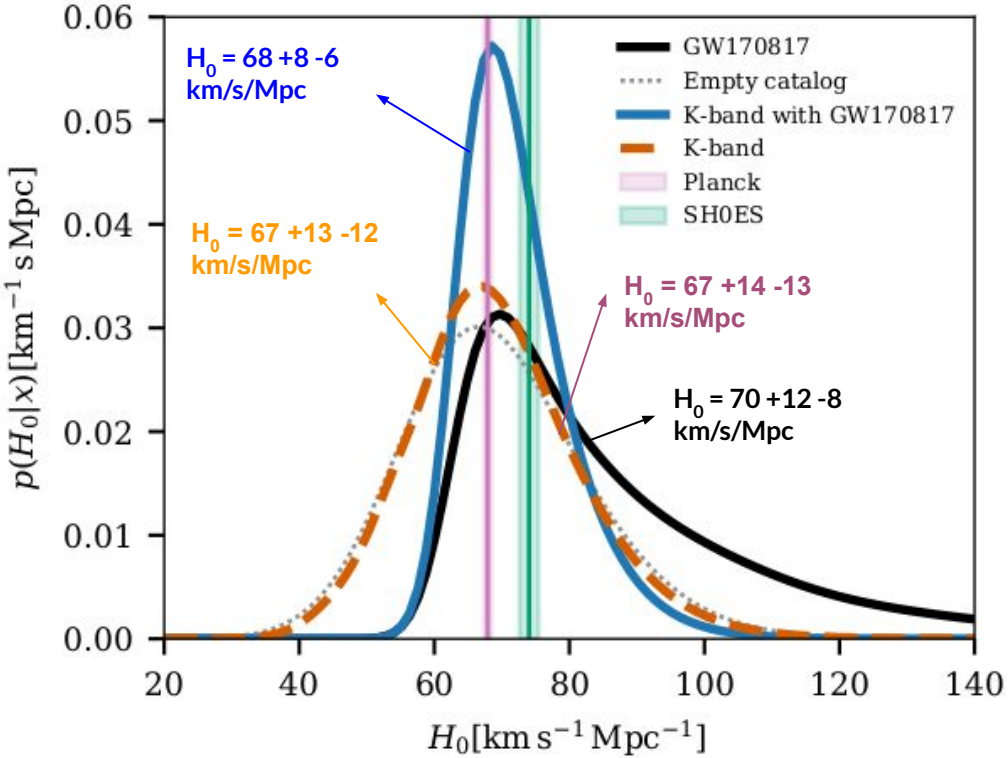
[LVK+, arXiv 2111.03604 (Accepted ApJ)]

GW cosmology after GWTC-3: Dark sirens

Main result of the paper showing various H0 posteriors.

We select the K-band for the luminosities of galaxies and the preferred mass model (powerlaw+Gaussian peak)

[LVK+, arXiv 2111.03604 (Accepted ApJ)]

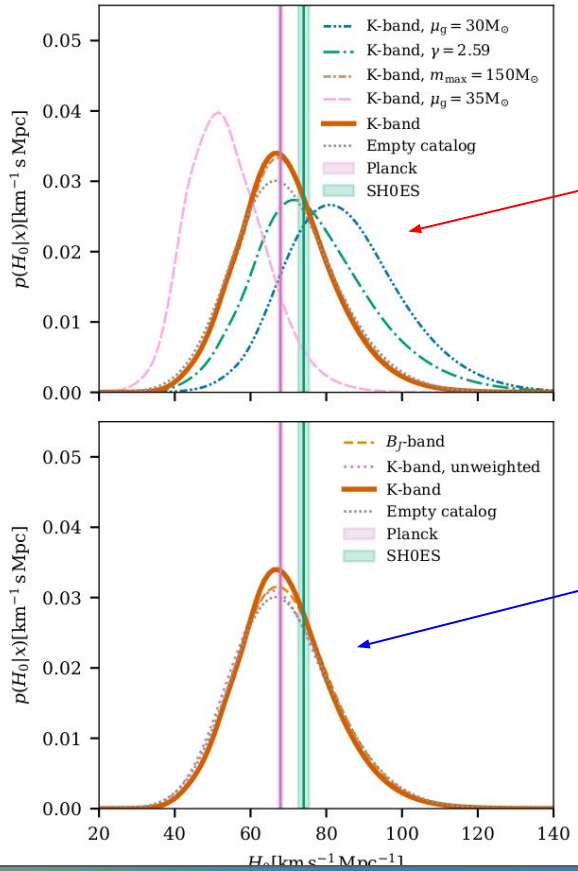


GW cosmology after GWTC-3: Dark sirens

Systematic plot showing the H0 different posteriors when **varying**:

1) **population parameters** (top plot)

2) **galaxy catalog parameters** (bottom plot)



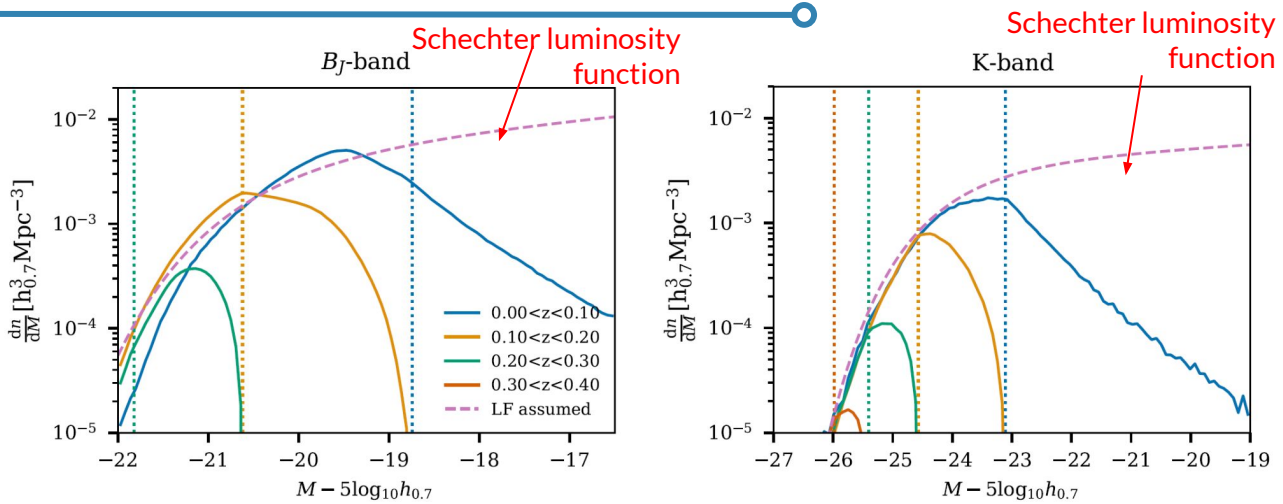
Varying certain population parameters affects the H0 posterior significantly

Varying galaxy catalog parameters affects the H0 posterior only marginally

GW cosmology after GWTC-3: Dark sirens

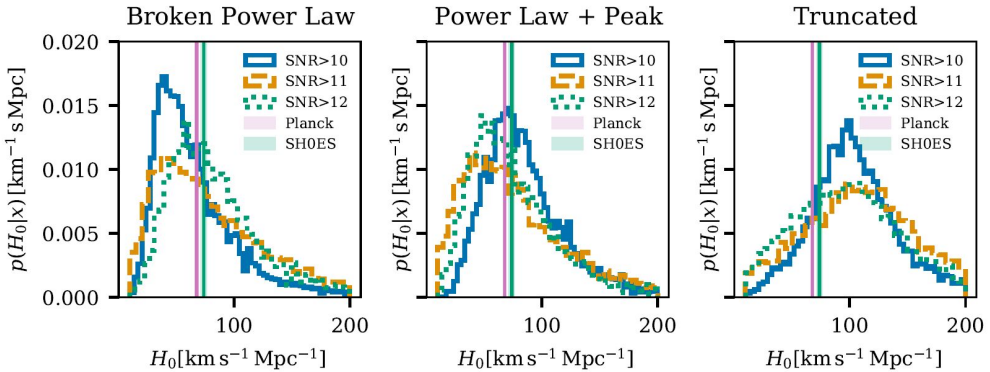
Observed vs **predicted** abs mag distributions, binned by redshift

Motivates choice of K-band for our main results



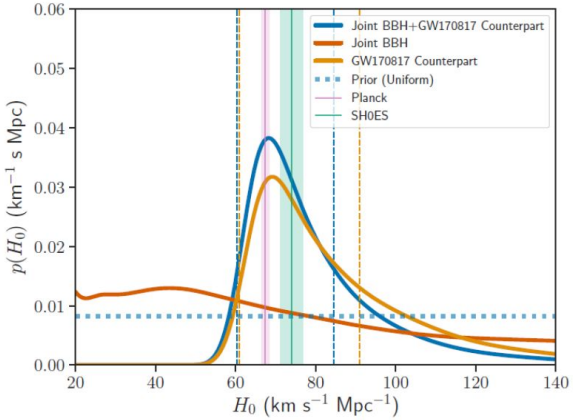
Changing SNR cut produces **consistent H_0 posteriors.**

Population excess at ~ **35** $M_\odot$ observed for each SNR cut



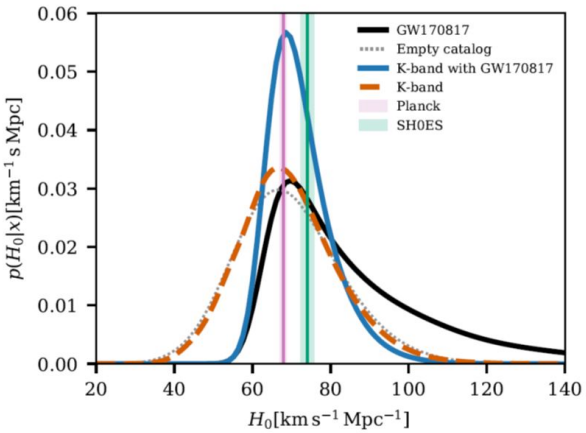
GW cosmology after GWTC-3: Conclusions

Using GWTC-1



+30 GW events

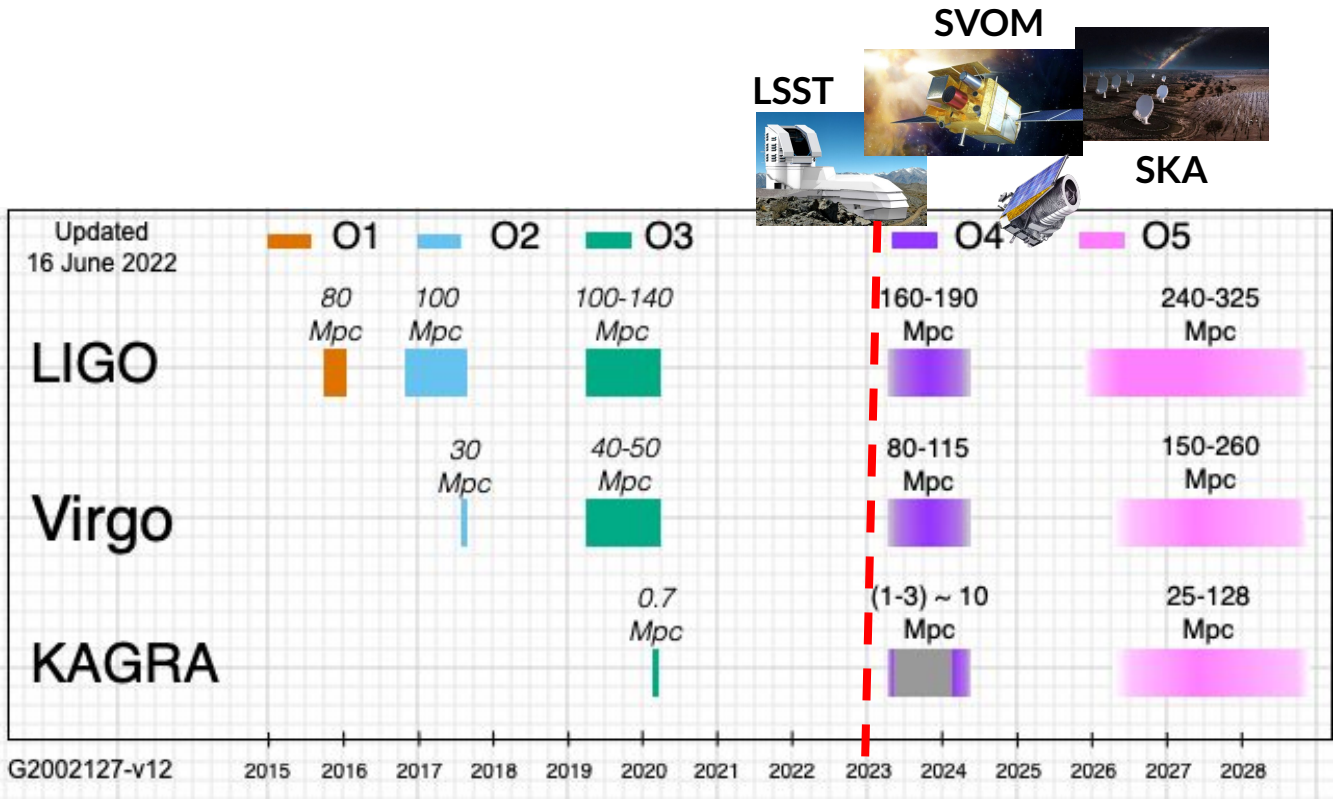
Using GWTC-3



Key messages:

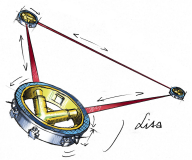
- H_0 constraint still driven by the bright siren GW170817, but **dark sirens are already making a significant difference**.
- Without **very good sky localizations**, results are sensitive to BH population model parameters.
- For **O4 and beyond**: higher GW event rates - plus deeper galaxy surveys and improved (cosmo+pop) modelling

GW cosmology after GWTC-3: Conclusions

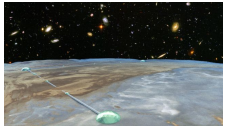


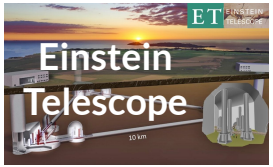
https://observing.docs.ligo.org/plan/

LISA



Cosmic Explorer



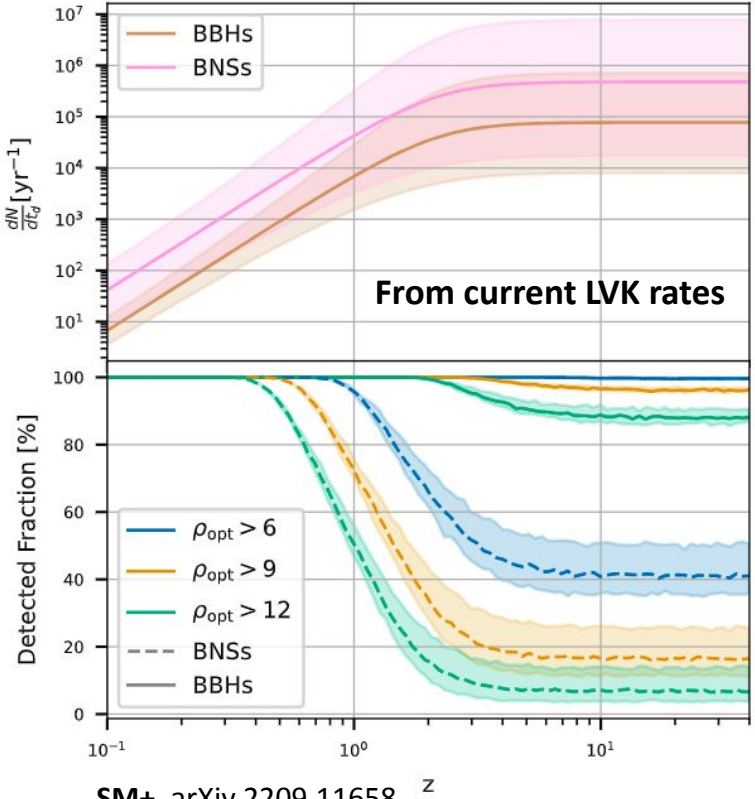


2035+

GW cosmology after GWTC-3: Conclusions

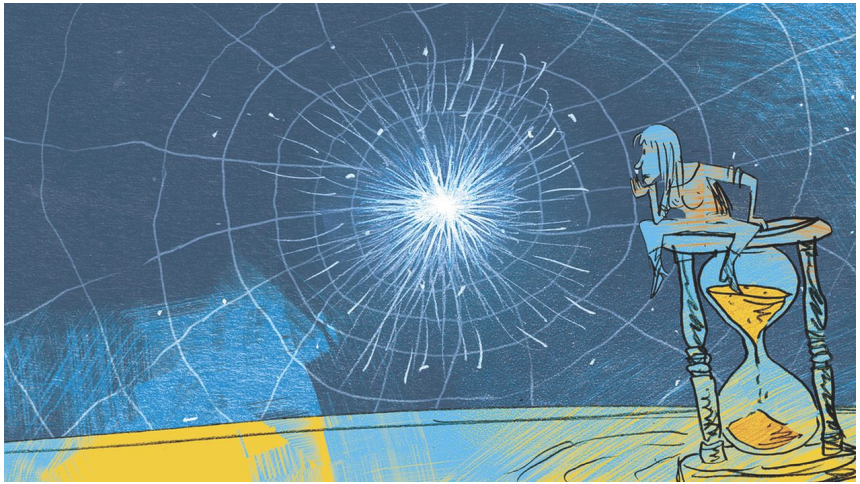
The era of 3G detectors is going to be absolutely amazing:

- Potentially no selection bias for BBHs, almost 100000 detections per year.
- Some selection bias for BNSs, but we are almost complete up to redshift 0.5.



SM+, arXiv 2209.11658

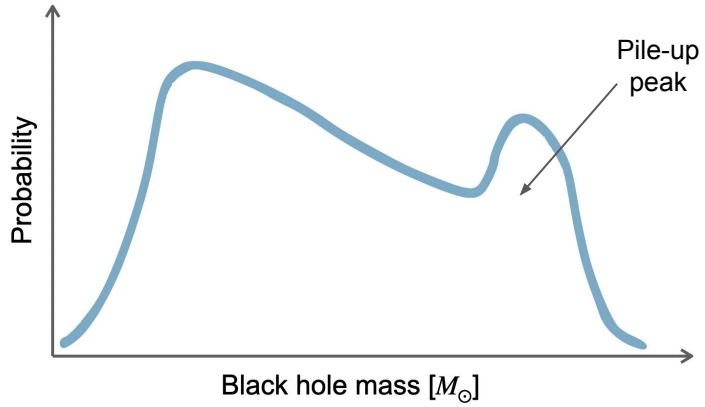
Thank you for your attention

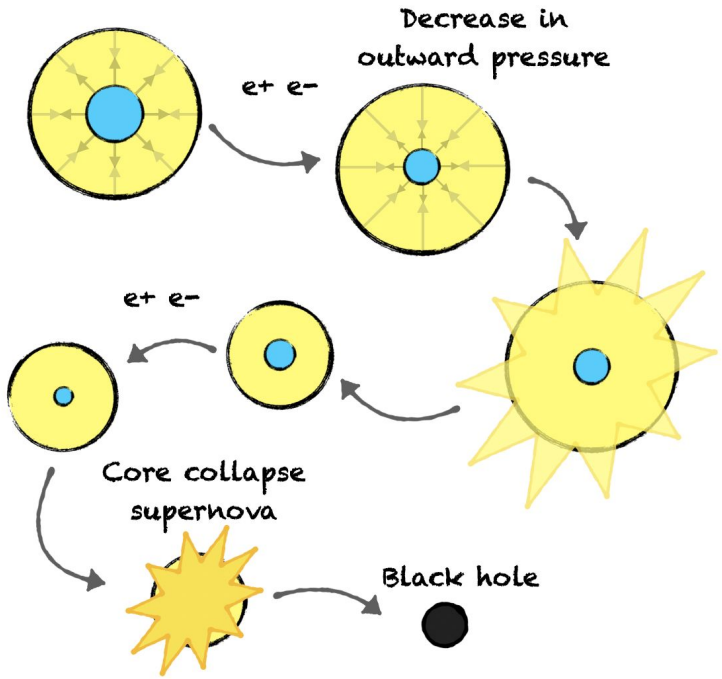


Pulsational pair instability

Credit: LVK BBHs population webinar 2021

- Massive stars shed mass in ‘pulses’.
- Produce stars of similar mass, which collapse to form black holes around ~ 35 to 45 $M_\odot$





Stars of masses $\sim 80M_\odot \rightarrow 130M_\odot$ at ZAMS

GW cosmology after GWTC-3: Conclusions

Data Analysis (e.g. Bayesian inference)

Star formation rate

- Is the mass spectrum evolving, for what kind of sources?
- Do spins prefer some mass ranges?
- Will eccentricity introduce a preference for some mass ranges?
- Does the spin distribution evolves with redshift?

Astrophysical formation channels

Universe expansion

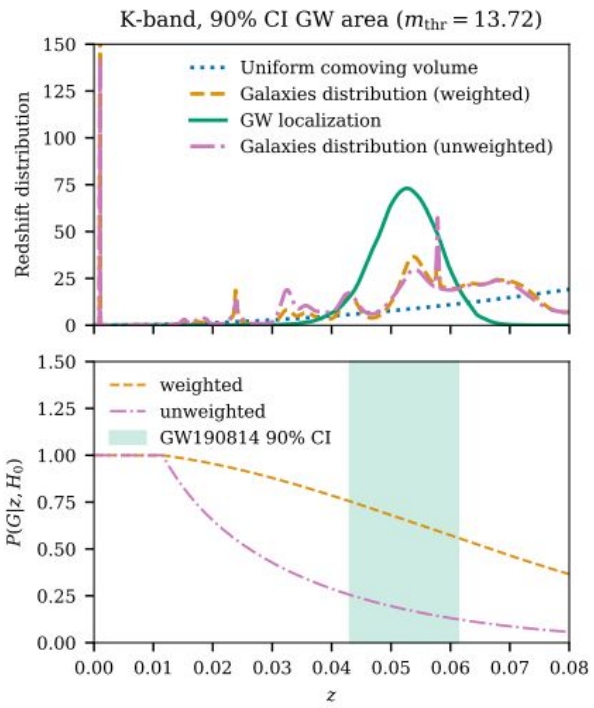
- Do we need to take into account the Universe clustering properties?
- When I will need to worry about weak and strong lensing?
- Are there deviations from GR?

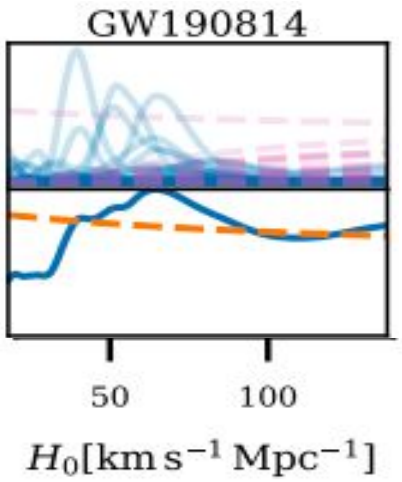
- Do I need to worry about calibration?
- Until what extent I should believe the waveform approximants?
- How do I evaluate selection biases using injections for ET and CE?

GW190814

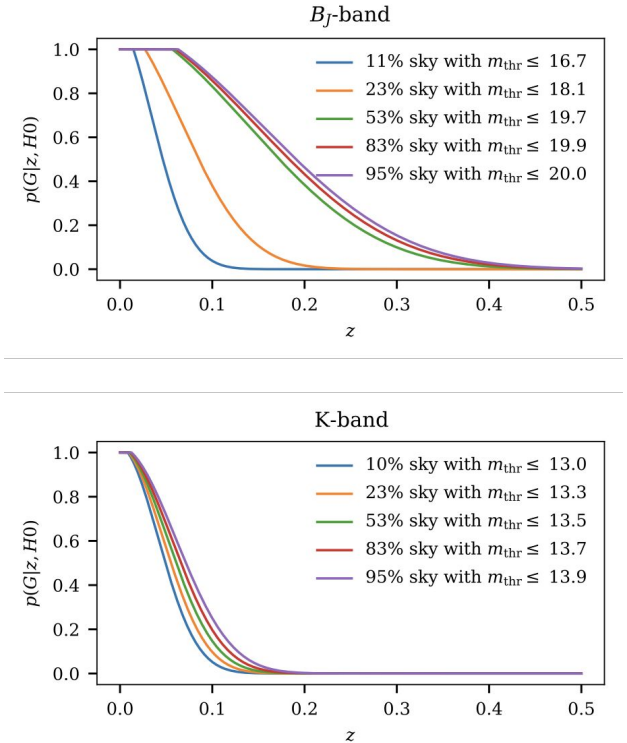
- The best localized event from O1, O2 and O3 without EM counterpart is GW190814.

- Apart from G190814, GLADE+ is highly incomplete for most of the GW events considered.

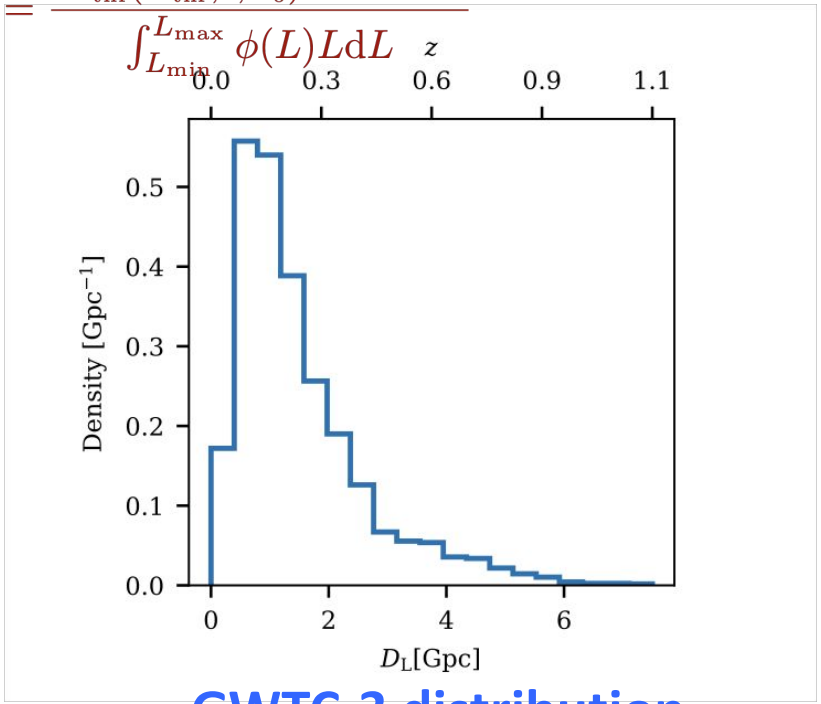




Galaxy catalog completeness: Fraction of galaxies with absolute magnitude brighter than a magnitude threshold



$$P(G|z, H_0) = \frac{\int_{L_{\rm thr}(m_{\rm thr}, z, H_0)}^{L_{\rm max}} \phi(L) L \mathrm{d}L}{\int_{L_{\rm min}}^{L_{\rm max}} \phi(L) L \mathrm{d}L}$$



GWTC-3 distribution