A decade of cosmology with strong gravity:

What have we learnt? What did we get wrong? Where are we heading?

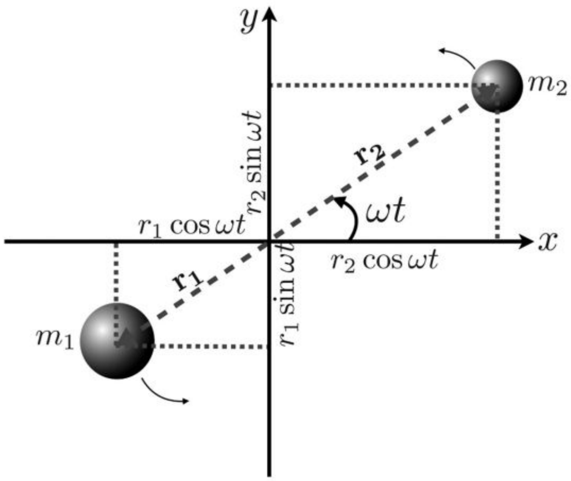
S. Mastrogiovanni
(on behalf of the LVK in some parts of this talk)

INFN
GravitySirens
Funded by the European Union
European Research Council

Autopsy of a compact binary

The GW frequency is emitted at twice the orbital frequency of the binary.

Chirp mass $\mu = \frac{(m_1 m_2)^{3/5}}{(m1 + m_2)^{1/5}}$



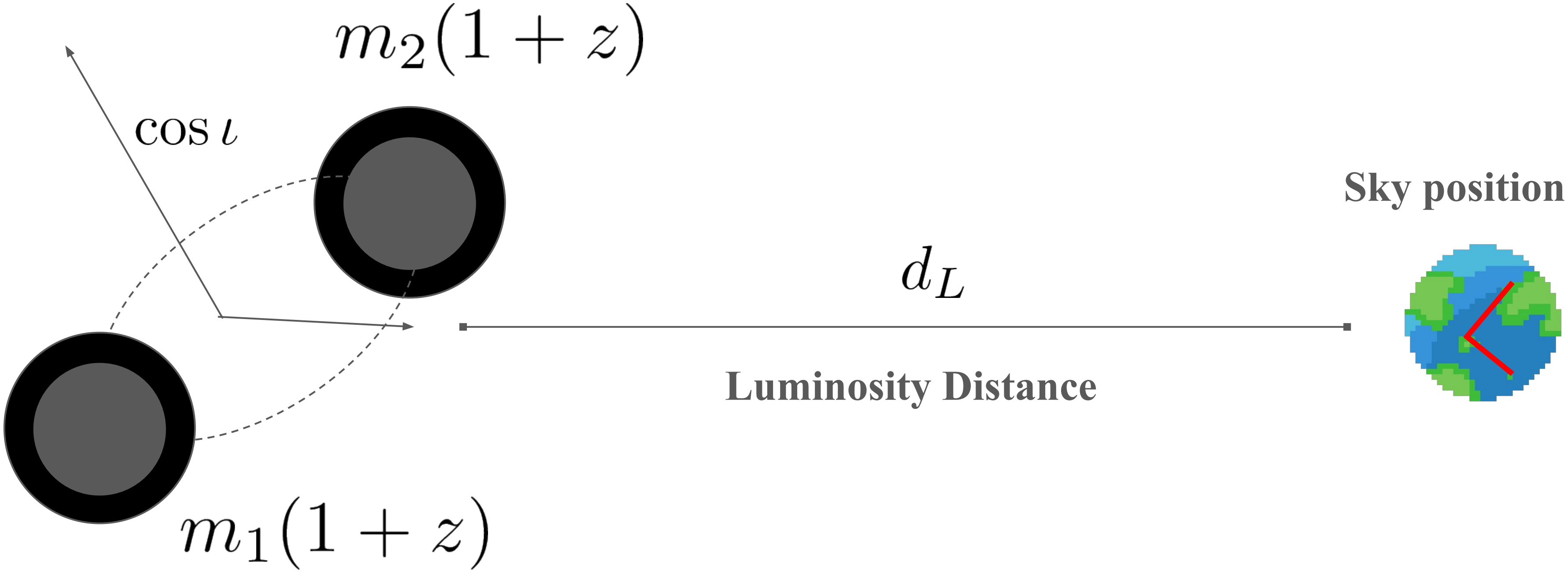
$$\frac{df_\mathrm{s}}{dt_s} = \frac{96\pi^{8/3}}{5} (G\mu)^{5/3} f_\mathrm{s}^{11/3}$$

GW frequency evolution at source

$$|h| \propto \frac{\mu_\mathrm{s}^{5/3}}{d} f_\mathrm{s}^{2/3} \sin(\phi_\mathrm{s})$$

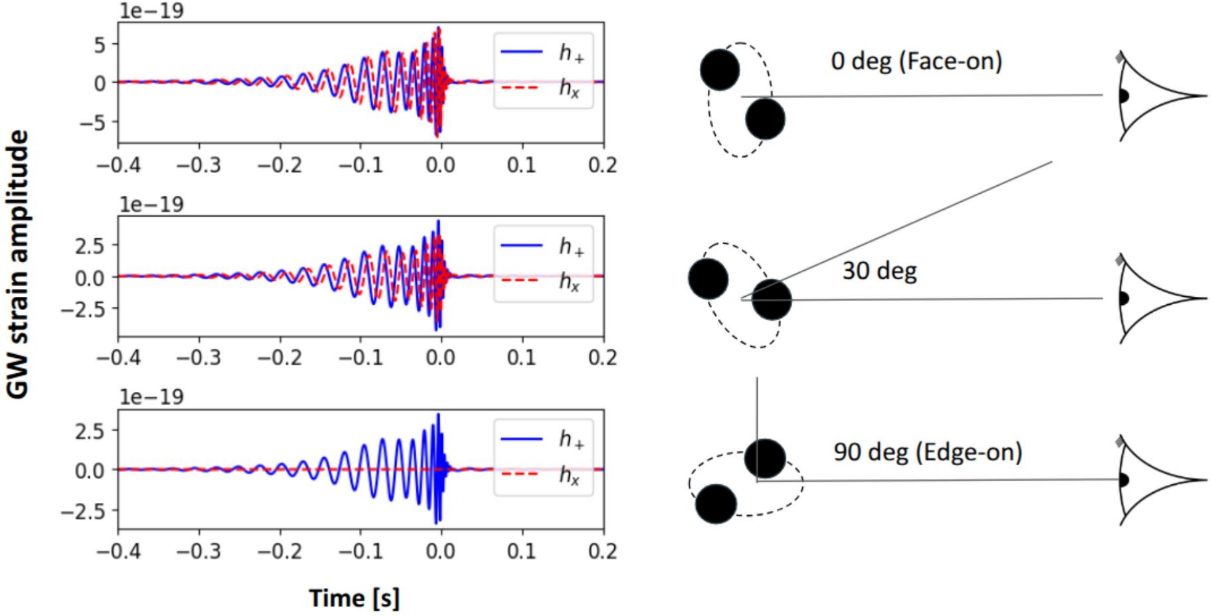
Amplitude at the source

Autopsy of a Binary: Cosmology

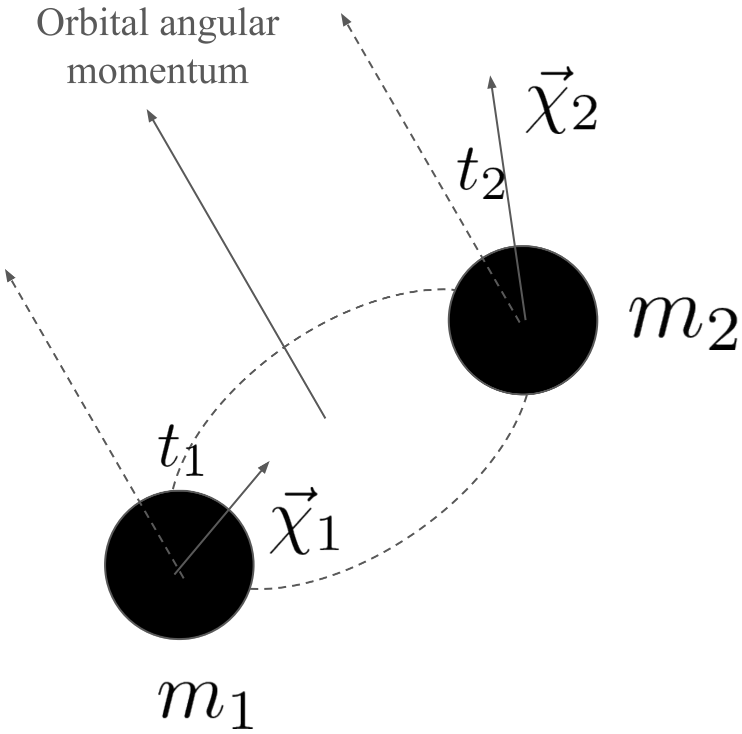


Autopsy of a compact binary

Luminosity distance of the source is typically not well measured.



Autopsy of a compact binary



$$\chi_{\rm eff} = \frac{\chi_1 \cos t_1 + q\chi_2 \cos t_2}{1+q}$$

Effective spin parameter

$$q = \frac{m_2}{m_1}$$

Mass ratio

$$\chi_{\rm p} = \max\left[\chi_1 \sin t_1;\ \left(\frac{4q+3}{3q+4}\right) q\chi_2 \sin\ t_2\right]$$

Precessing spin parameter

Propagation tests of general relativity

$$h'' + 2[1+\alpha_M(\eta)]\frac{a'}{a}h' - c_T^2\nabla^2 h = -m_g^2 c^4$$

GW friction   Propagation   Massive graviton

Dispersion relation:

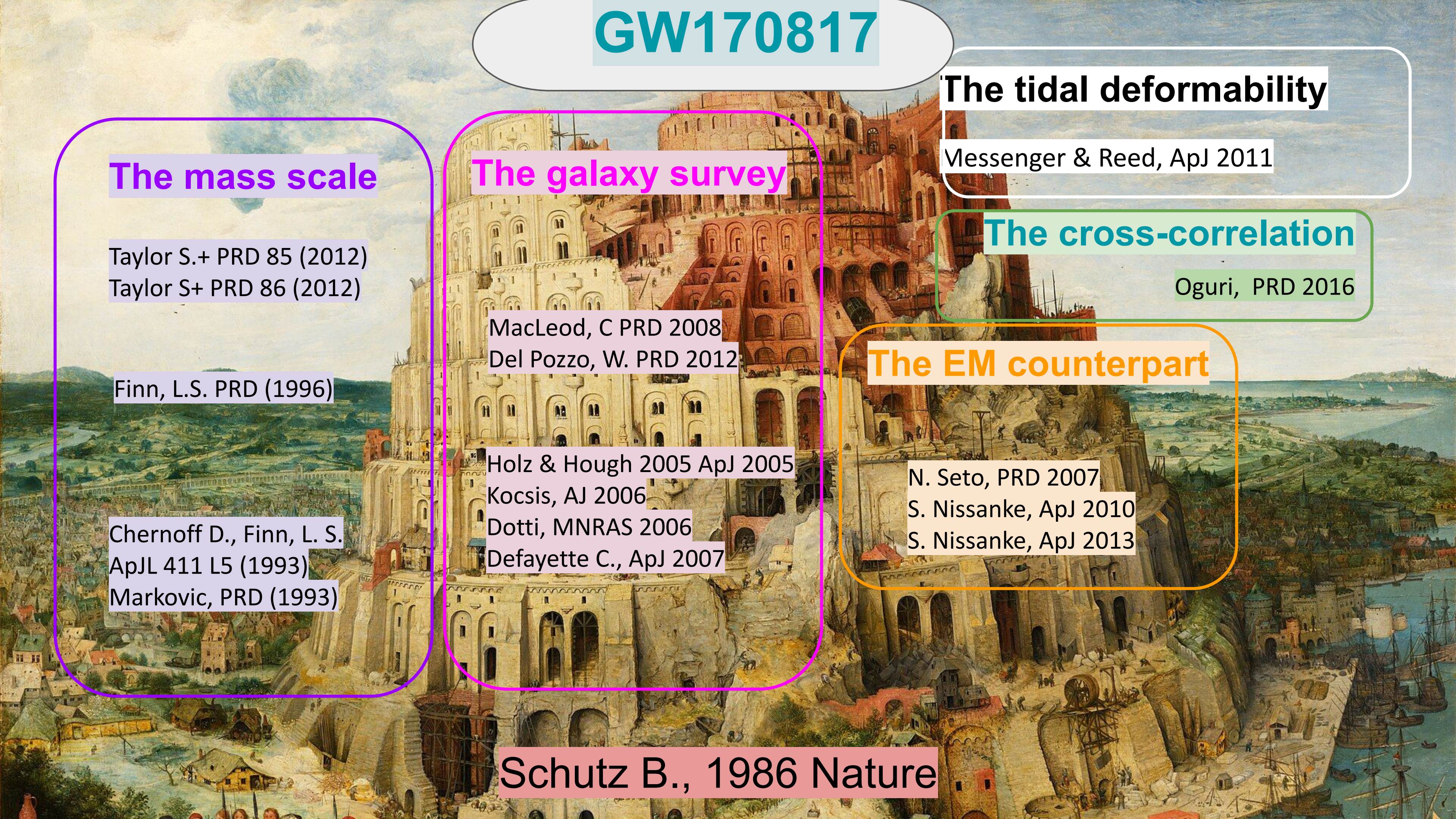
- GWs group velocity depends on the frequency.
- GWs modes arrive off-phased at the detector.
- GWs modes show a time delay w.r.t EM counterparts.

*Horava gravity, **massive gravity**, scalar tensor theories with field derivative couplings*

GW friction:

- GWs show an additional energy leakage as they travel.

extra energy dissipation terms, e.g. a running Planck mass, 4+n dimensional gravity, scalar-tensor theories



GW170817

The mass scale

Taylor S.+ PRD 85 (2012)
Taylor S+ PRD 86 (2012)

Finn, L.S. PRD (1996)

Chernoff D., Finn, L. S. ApJL 411 L5 (1993)
Markovic, PRD (1993)

The galaxy survey

MacLeod, C PRD 2008
Del Pozzo, W. PRD 2012

Holz & Hough 2005 ApJ 2005
Kocsis, AJ 2006
Dotti, MNRAS 2006
Defayette C., ApJ 2007

The tidal deformability

Messenger & Reed, ApJ 2011

The cross-correlation

Oguri, PRD 2016

The EM counterpart

N. Seto, PRD 2007
S. Nissanke, ApJ 2010
S. Nissanke, ApJ 2013

Schutz B., 1986 Nature

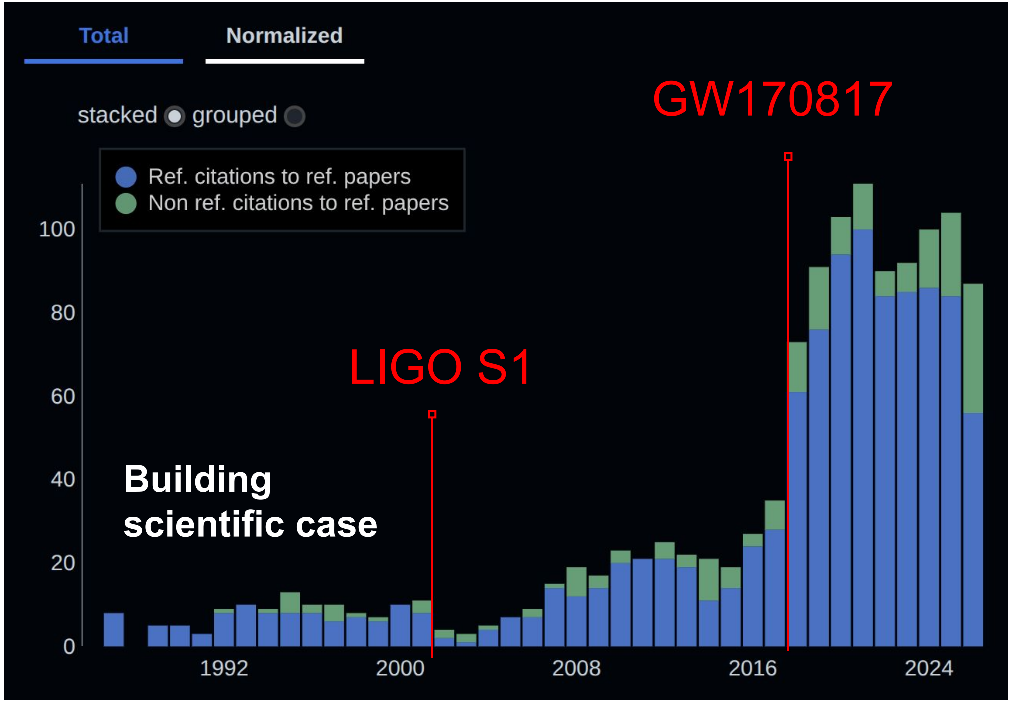
The progenitor: Schutz 1986

Schutz's seminal paper opened GW cosmology

Considered only **BNSs** at r<100 Mpc

- **Observed EM counterpart:** single bright sirens will give a H0 precision of a few percents.

- **Dark sirens:** In the average comoving volume box <100 Mpc you have ~36 clusters. Then you just need ~35 of these binaries in the worst case to give you the correct H0.



Cosmology with GWs number counts

In the early 90's Chernoff, Finn and Markovic realized that the number count of detected **BNSs** as function of redshift should depend on the Hubble parameter

$$\dot{n}(z| > \rho_0) = \widehat{\mathcal{N}_0} 4\pi \left(\frac{c}{H_0}\right)^3 \tilde{f}(z;q_0)h(z)(1+z)^2 P\left[\delta \frac{\tilde{d}_L(z;q_0)}{(1+z)^{5/6}}\right],$$

Central mass value **Hubble parameter** **Projection factor**

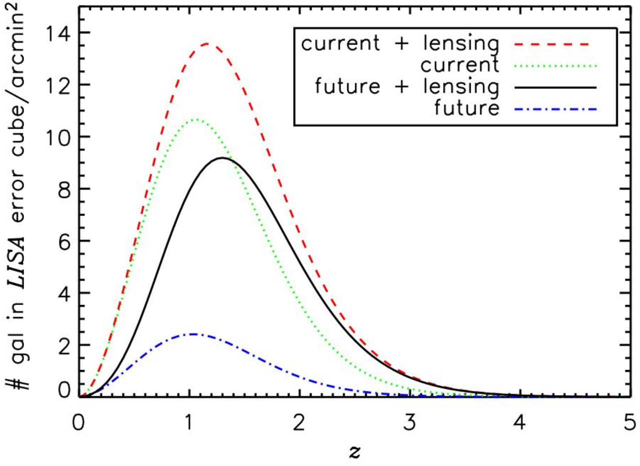
Cosmological parameters can be inferred by assuming a known mass value for **all the BNS sources.** Later studies (see Finn PRD 1996) improved these analytical prescriptions

Not much attention was given to GW cosmology for the next 10 years

Binary black holes as bright sirens

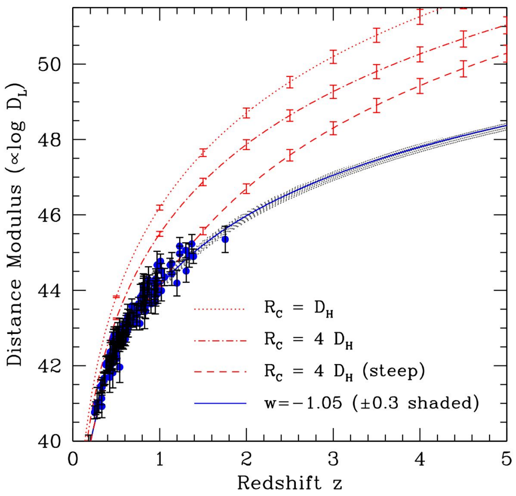
In the early 2000's massive **Binary Black Holes** detectable in LISA were being explored as possible dark and bright sirens.

Dark sirens



Holz & Hough 2005 (ApJ 2005)

Bright sirens

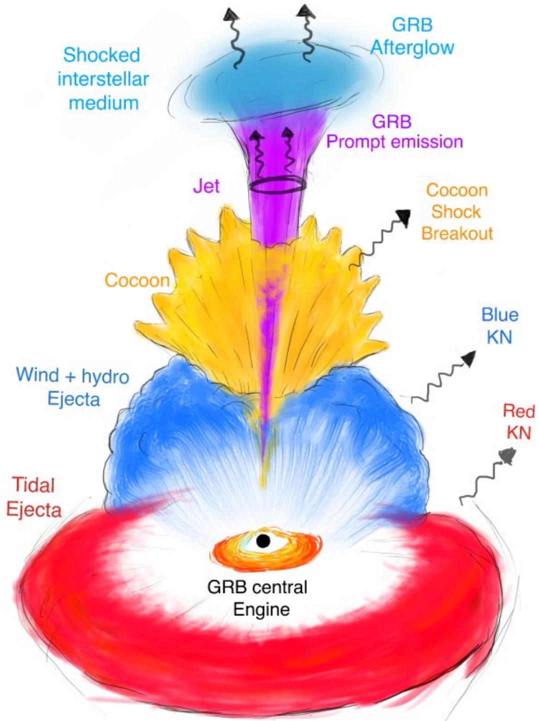


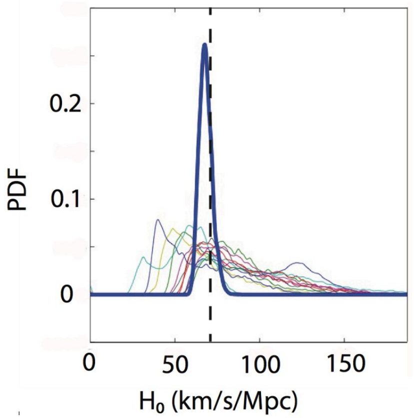
Kocsis AJ 2006
Dotti MNRAS 2006
Defayette ApJ 2007

Advancing bright sirens in the 2010

In the early 2010's several groups argued that the short gamma-ray burst (named short hard burst by then) geometry can be used to [N. Seto, PRD 2007 S. Nissanke, ApJ 2010 S. Nissanke, ApJ 2013]:

- Improve the GW inclination angle and distance measure
- Improve GW cosmology with bright sirens



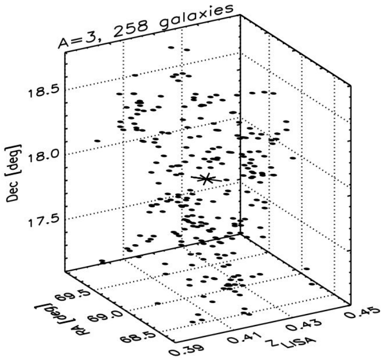


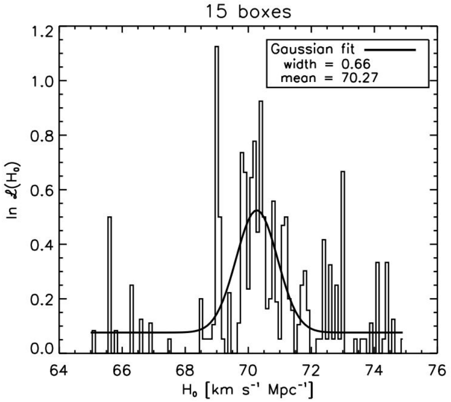
Credit: S. Ascenzi

Dark sirens and galaxy catalogs in 2010

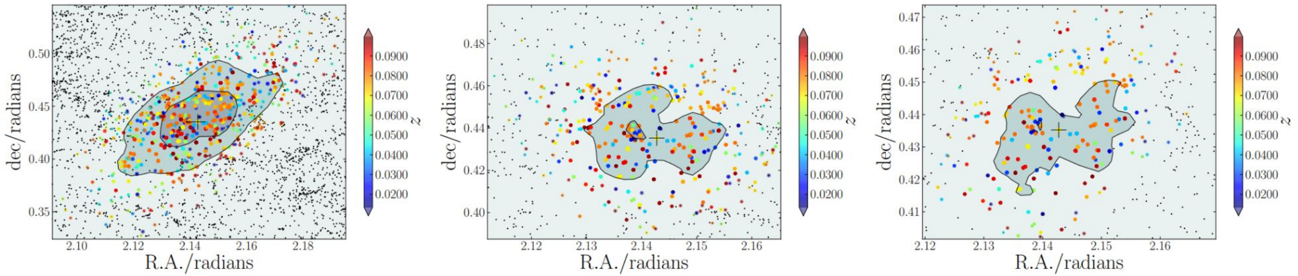
In 2010 we see a resparked interested in using binary black holes as dark sirens with galaxy catalogs for LISA and LVK

The first full Bayesian approaches with **complete galaxy catalogs** are born in these years.





MacLeod, C PRD 2008

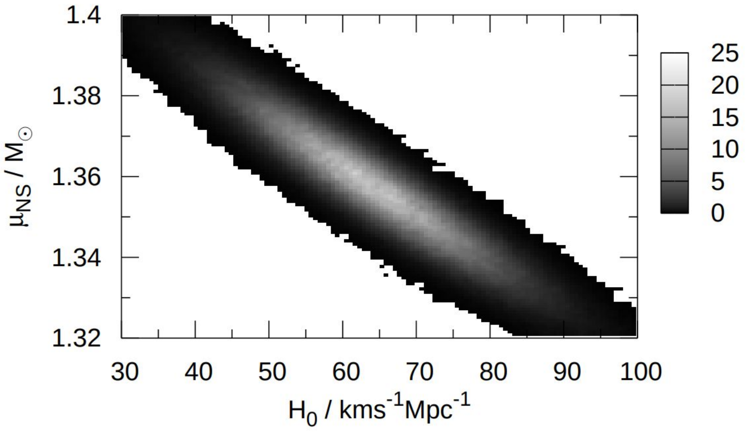


Del Pozzo, W. PRD 2012

Going from counts to a mass ladder

In 2012, Taylor S.+, PRD 85-86 (2012) extended what was conceived in Chernoff 1993. The main novelties of their work, always for BNS was:

- We can measure a distribution of redshifted masses for BNS, it is not just a number count.
- We can jointly fit for the BNS mass spectrum and the cosmological model (effectively a mass calibration)



Cross-correlating GWs with galaxies

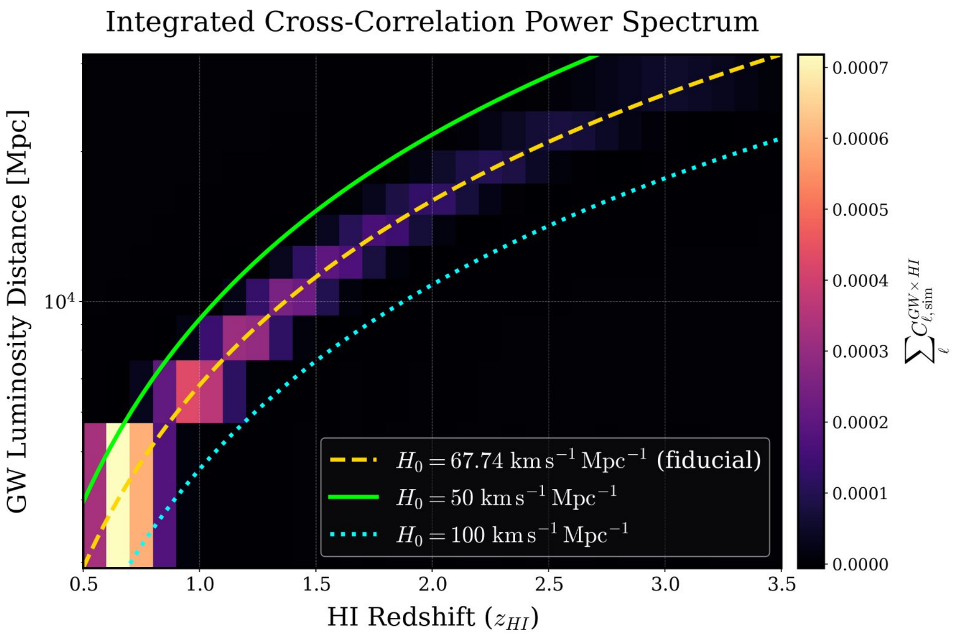
In 2016 Oguni [PRD 2016], proposed a complementary method for GW cosmology based on angular cross-correlation with large scale structures.

$$\tilde{C}_\ell^{XY}(x_i, x_j) = C_\ell^{XY}(x_i, x_j) + \mathcal{N}_\ell^{XY}(x_i, x_j)$$

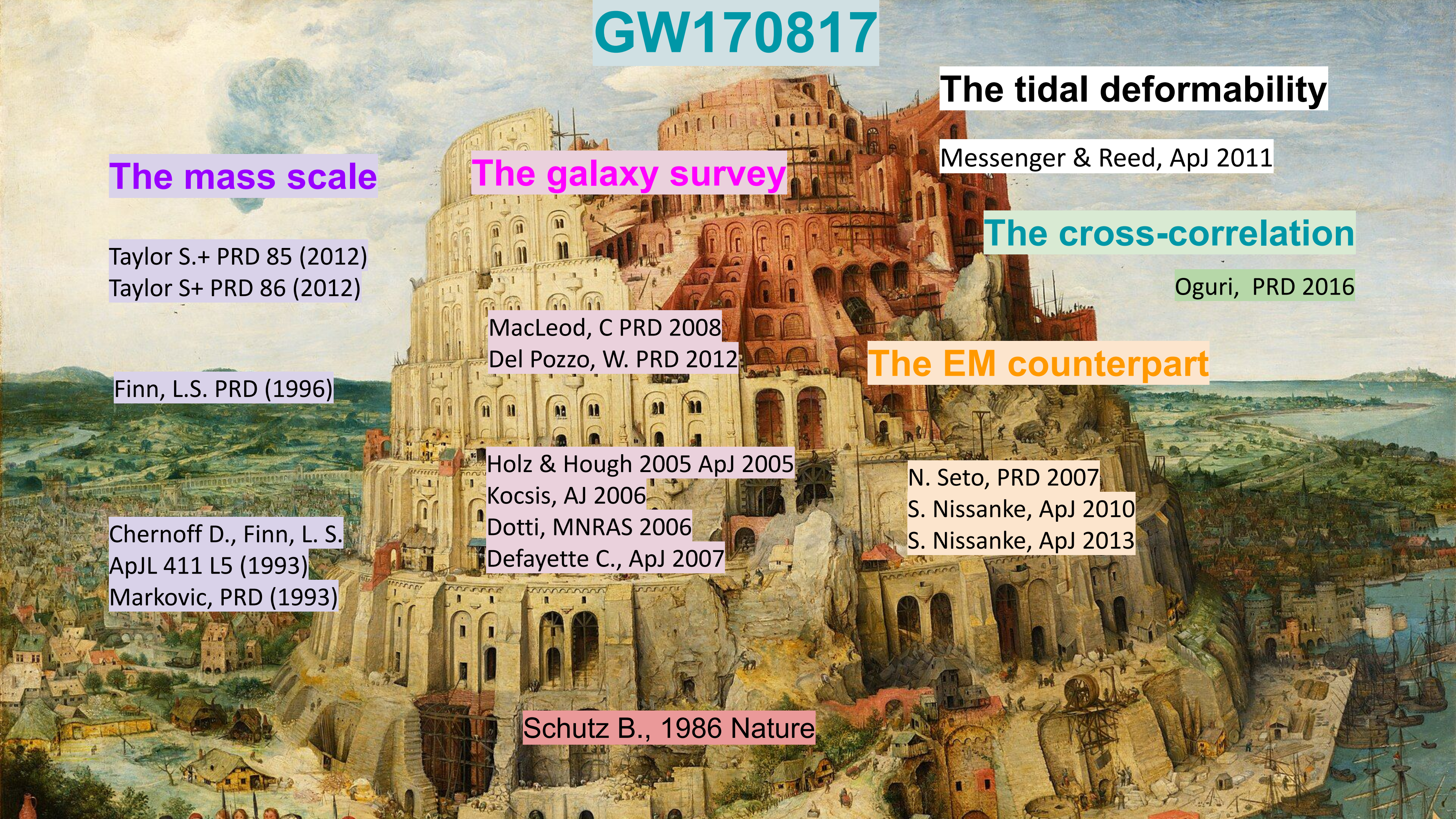
$$C_\ell^{XY}(x_i, x_j) = \frac{2}{\pi} \int \frac{dk}{k} \mathcal{T}_{\ell,X}(k, x_i) \mathcal{T}_{\ell,Y}(k, x_j) \mathcal{P}(k)$$

The basic idea is to

- Divide the GWs in luminosity distance bins
- Divide galaxies in redshift bins
- Cross-correlate the two for various cosmological models



Schultz M., in preparation


GW170817
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S. Nissanke, ApJ 2010
S. Nissanke, ApJ 2013
Chernoff D., Finn, L. S.
ApJL 411 L5 (1993)
Markovic, PRD (1993)
Schutz B., 1986 Nature

What happened on August 17th 2017

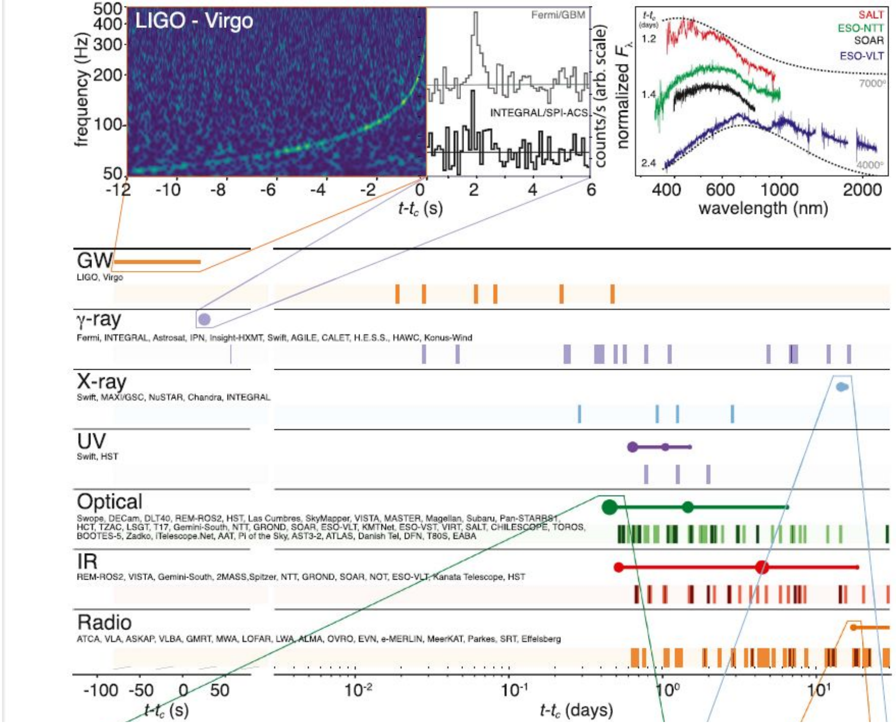
At 12:41:04 UTC a GW from the merger of two Neutron star is detected

- +2 seconds later Integral and Fermi detect a GRB.
- ~10 hrs later a kilonova emission from NGC4993 is observed.

With GW170817 we have been provided:

- Luminosity distance from GW170817.
- Redshift identification of the host galaxy from NGC4993.
- Peculiar motion of NGC4993.

Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20

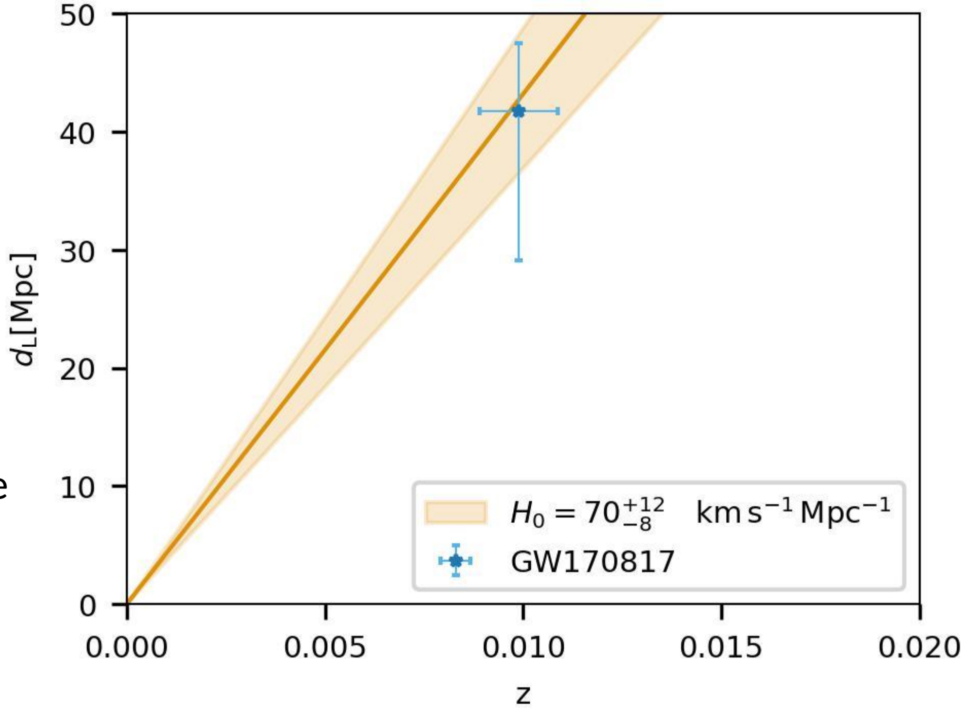


Bright sirens: GW170817

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

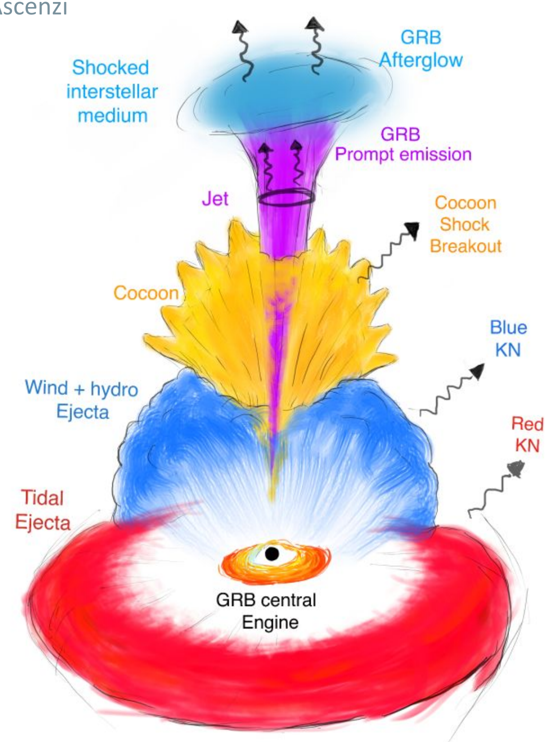
- **Short Gamma-ray burst and Kilonova:** Two associated EM counterparts allowed the identification of the source host galaxy NGC4993.

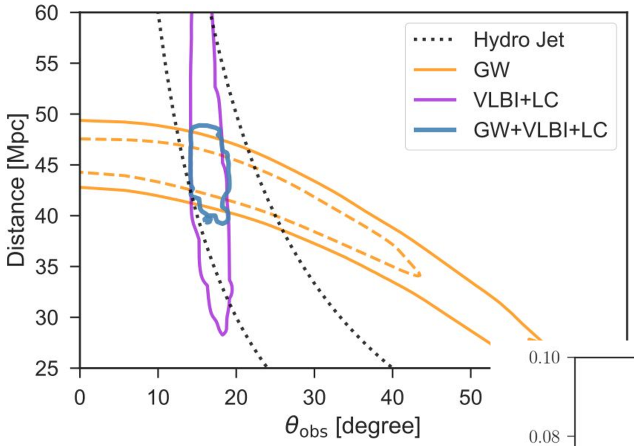
- This type of events will difficult to detect, we might expect to have 0-10 others in the next two observing runs *[SM+ A&A (2017), Patricelli+, MNRAS (2022)]*



Bright sirens: GW170817

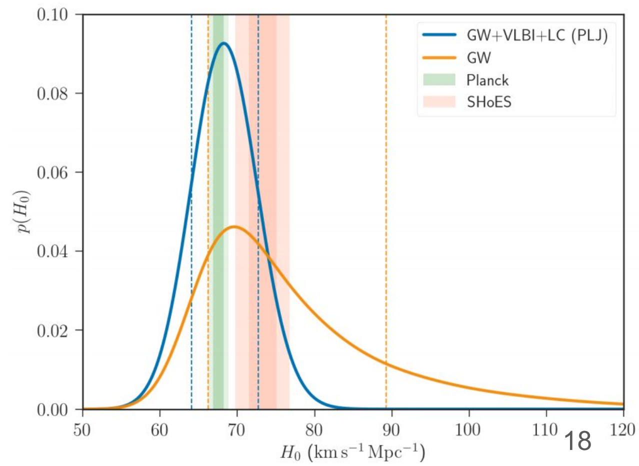
Credit: S. Ascenzi



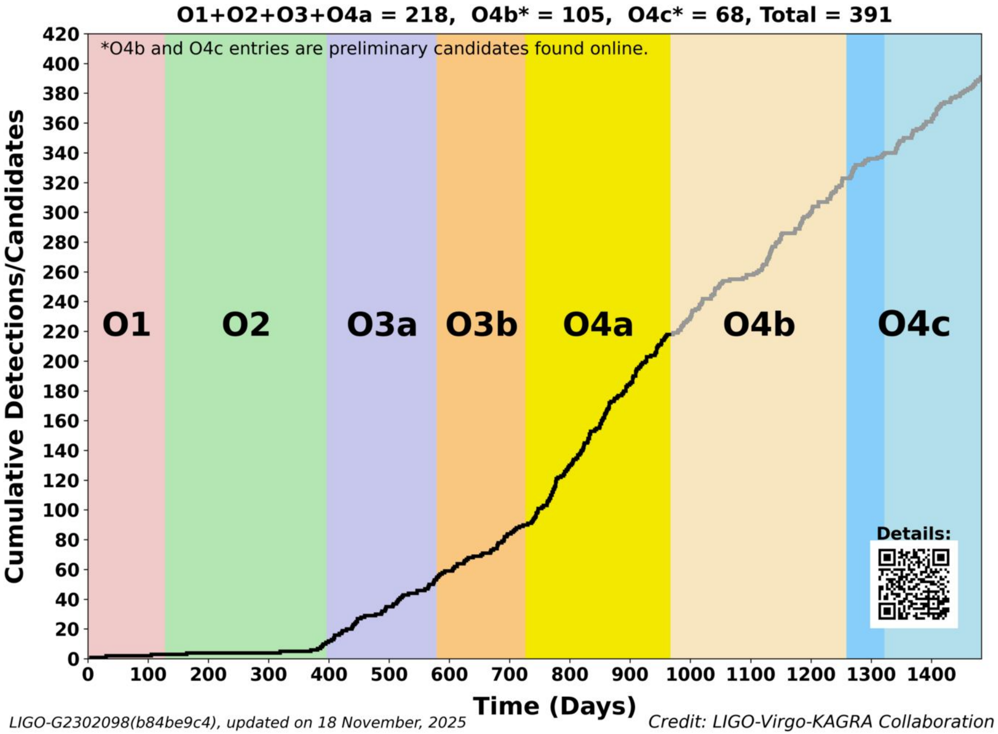


[K. Hotokezaka, Nature Astronomy, 3(2019)]

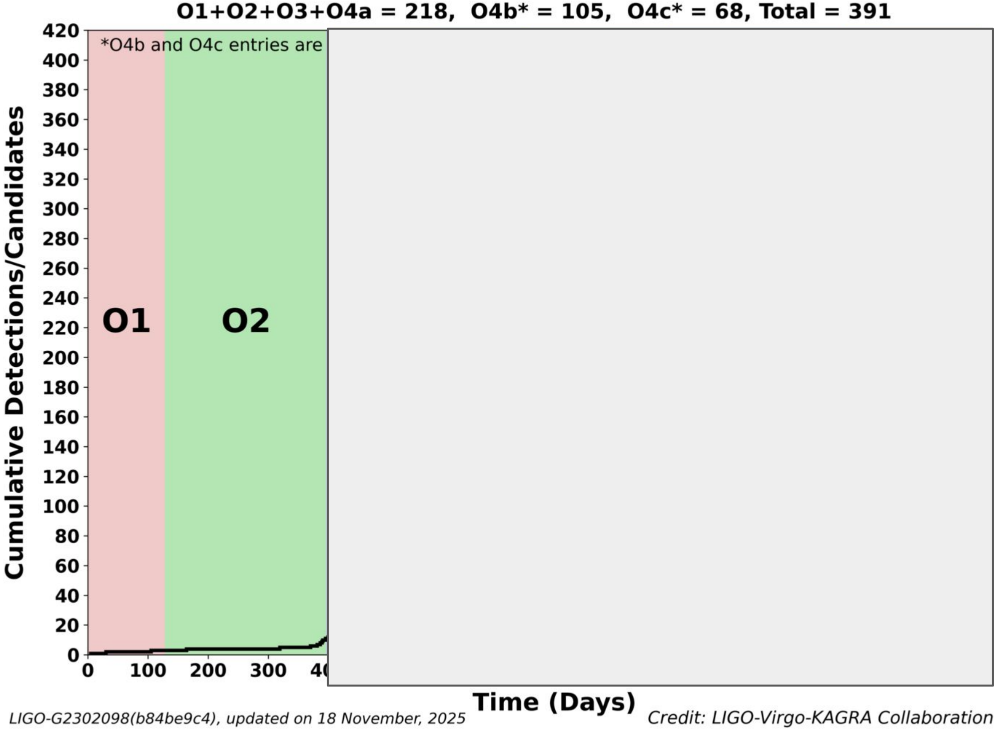
Afterglow informed cosmology



The population of GW sources



The population of GW sources

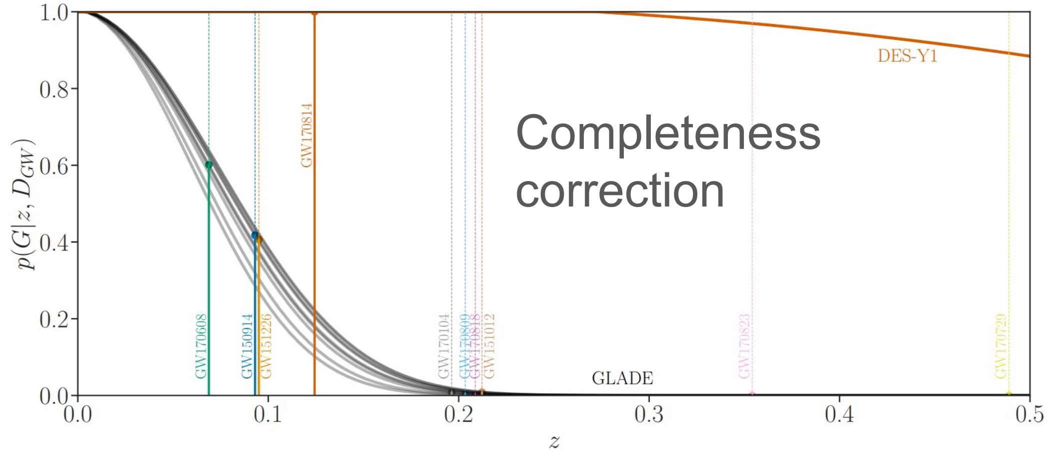


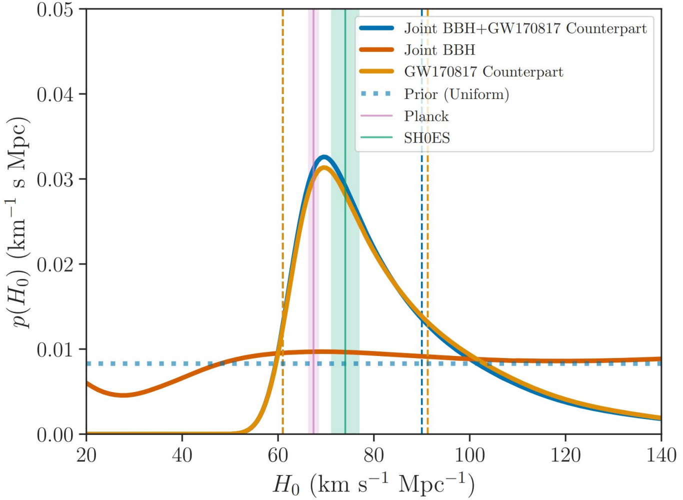
Cosmology with GWTC-1.0

At the end of O2 (2017) we had ~10 dark sirens and 1 bright siren, we used the galaxy catalog GLADE (fixing the BBH mass distribution) and we obtained a “measure” of H0. Results were pretty insensitive to the BBH mass distribution

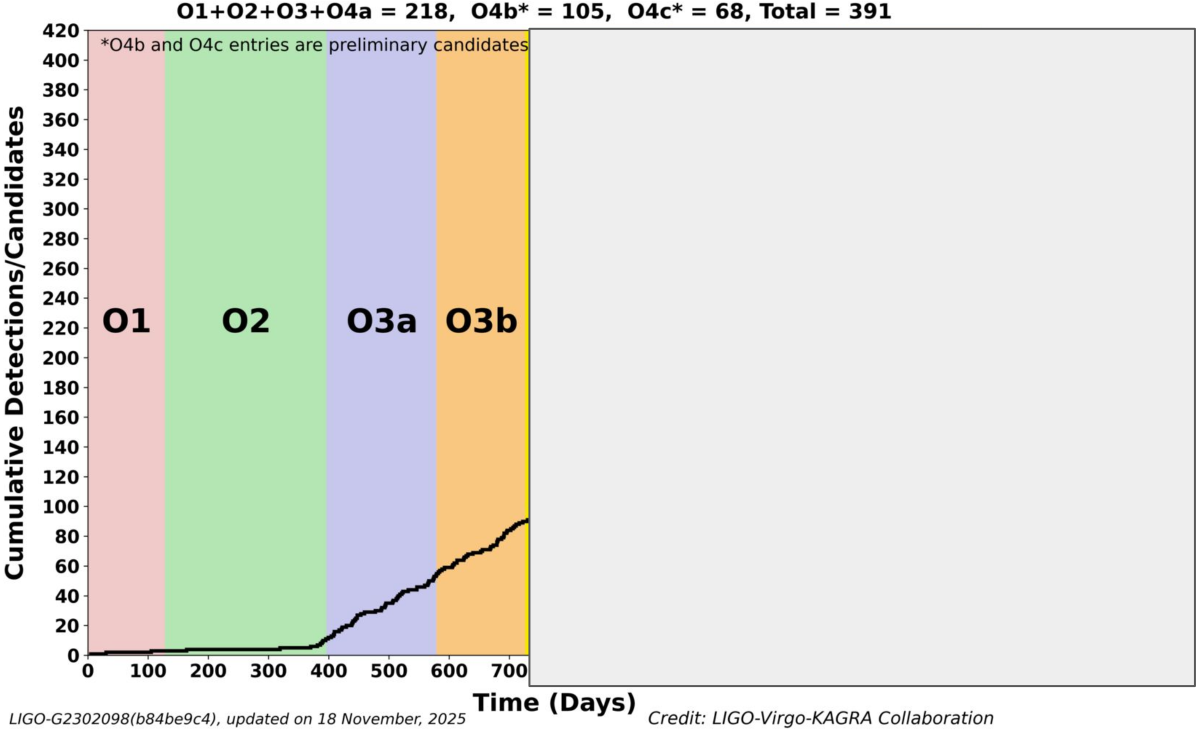
We also added the completeness correction to the galaxy catalog

LVK Astrophys J 909 Number 2 218 (2021)





The population of GW sources



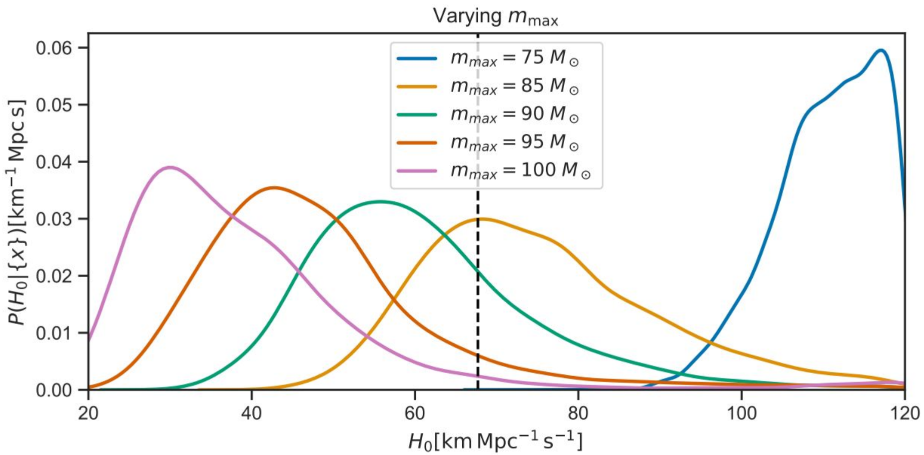
LIGO-G2302098(b84be9c4), updated on 18 November, 2025

Credit: LIGO-Virgo-KAGRA Collaboration

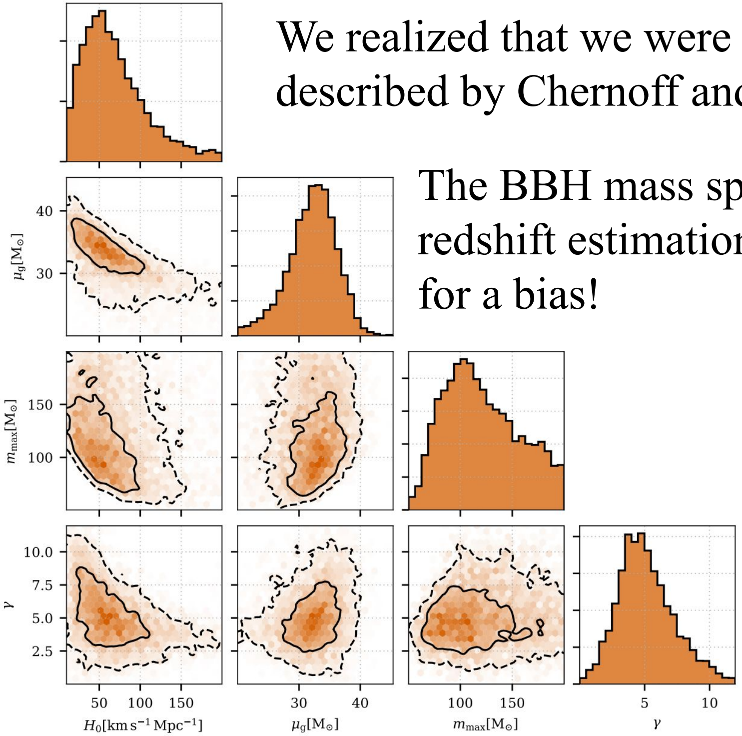
Cosmology following GWTC-3.0

At the end of O3 (2019), we were having ~50 significant dark sirens available for GW cosmology and still 1 bright siren…

But we were having problems, posteriors on H0 for dark sirens were extremely sensitive to the upper end of the BBH mass spectrum

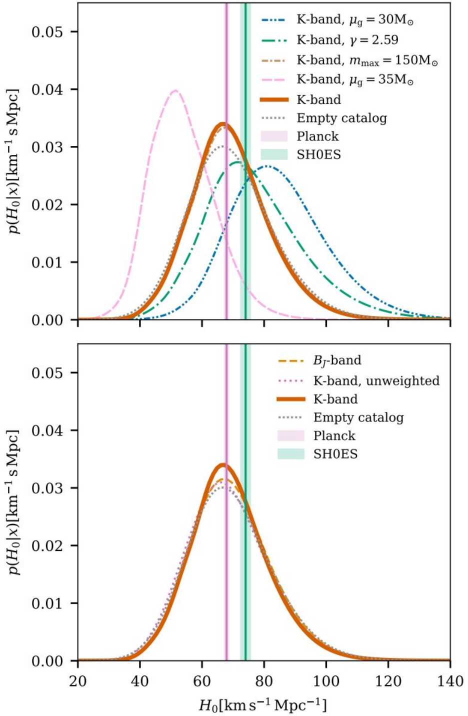


Cosmology following GWTC-3.0



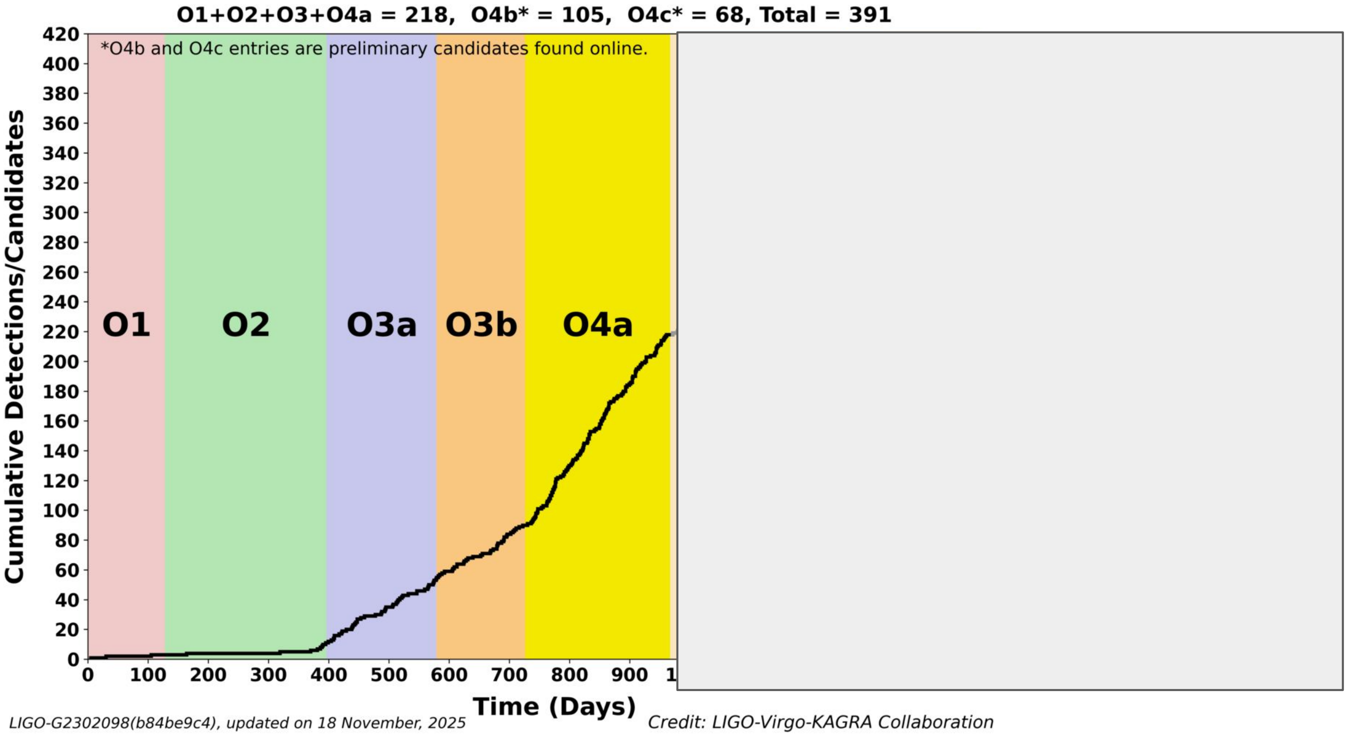
We realized that we were dealing with what was described by Chernoff and Finn in 1993 with a difference:

The BBH mass spectrum can provide statistical redshift estimation, but it is also a major issue for a bias!



R. Abbott et al 2023 ApJ 949 76

The population of GW sources

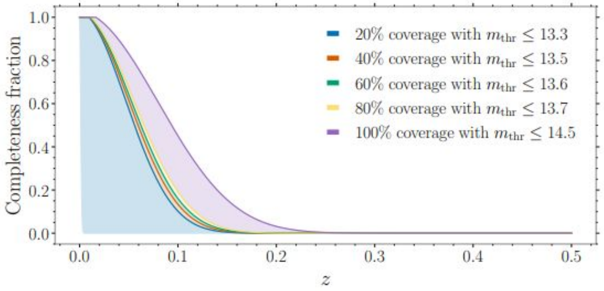


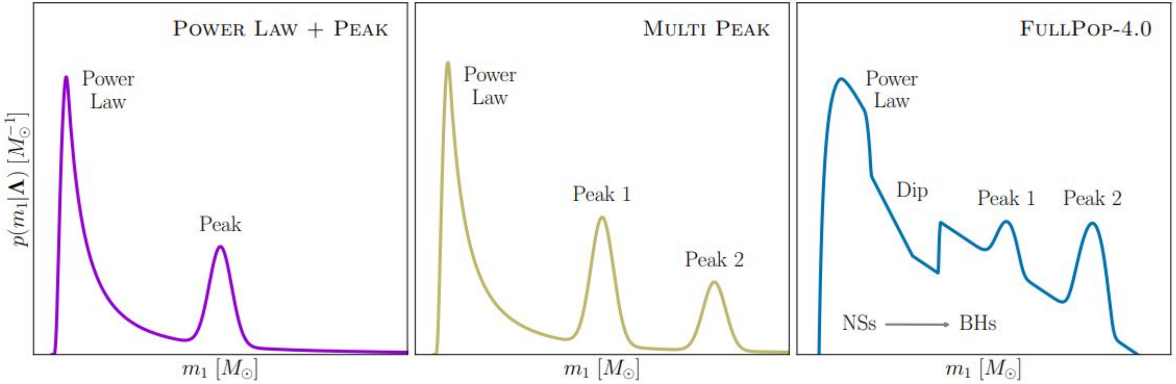
Cosmology following GWTC-4.0

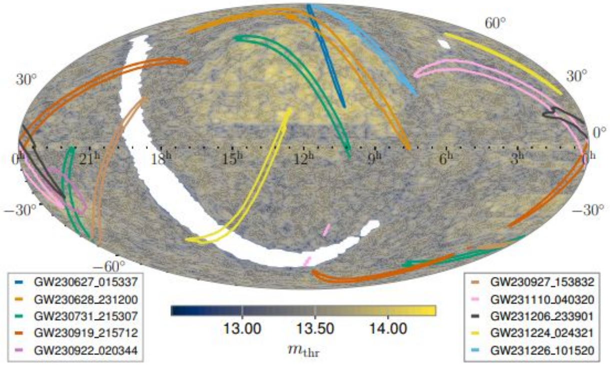
- We used the most significant GW sources (142/218) from GWTC-4 to estimate the cosmic expansion [LVK+, 2509.04348, accepted on ApJ]

- We employed three different mass models and an all-sky galaxy catalog (GLADE+).

- We merged the galaxy catalog and mass calibration into a single global fit.

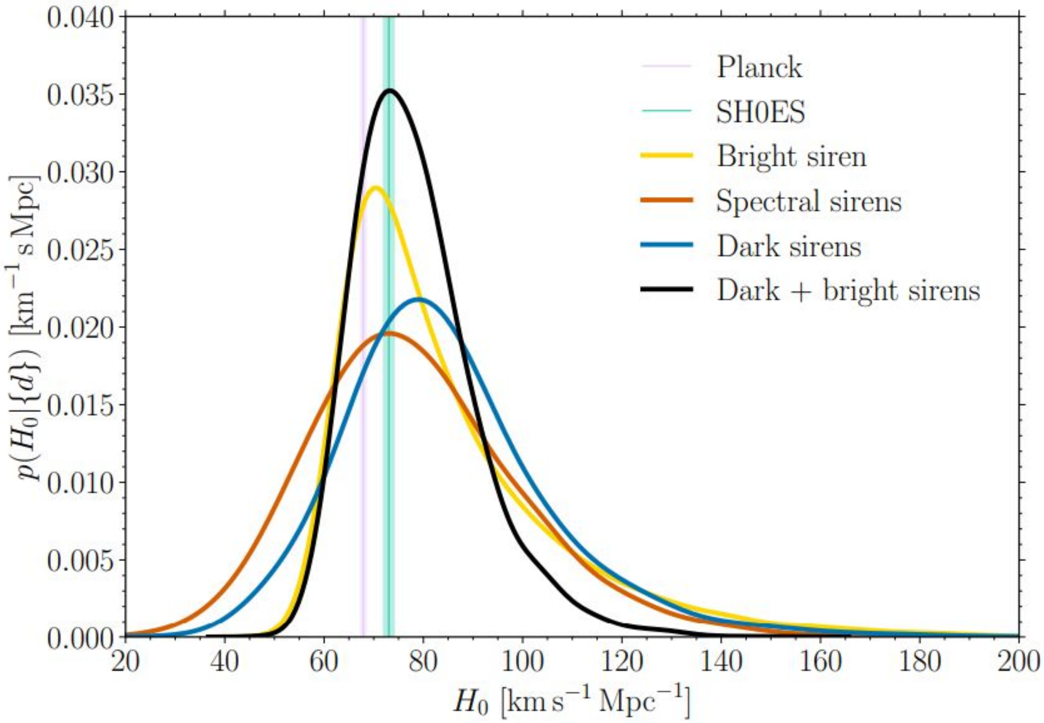






Cosmology following GWTC-4.0

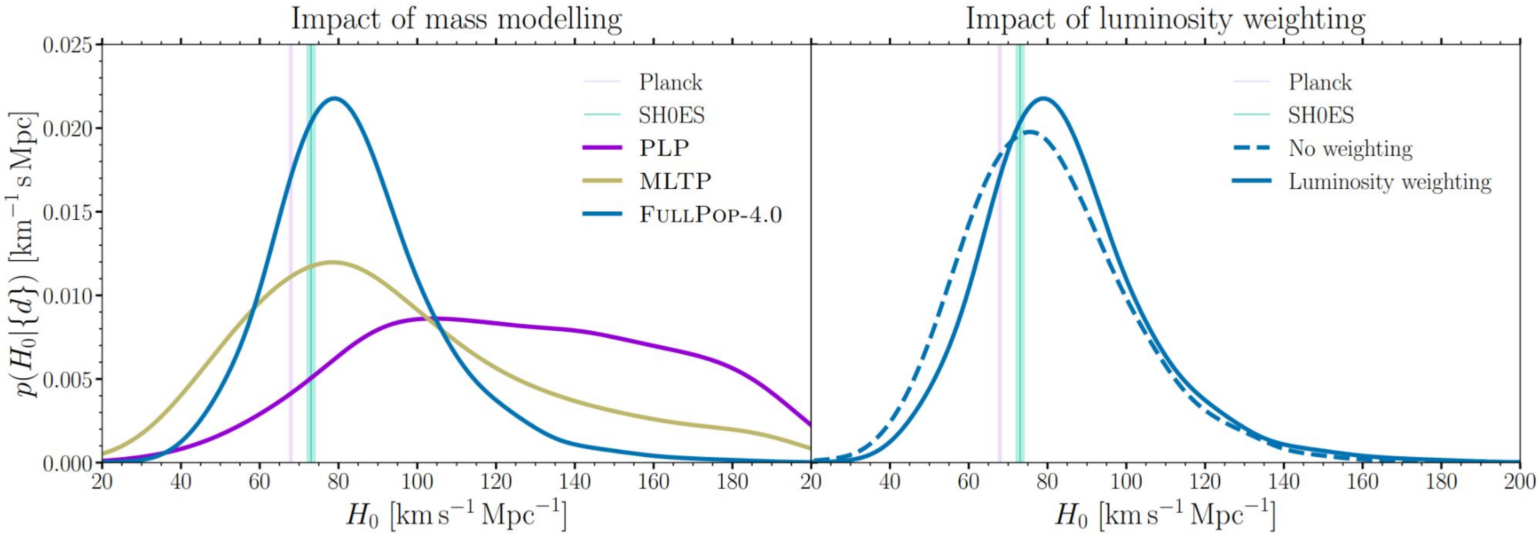
- Dark Standard sirens are not yet competitive with the precision offered by a single bright siren.
- The cosmological information is mostly coming from the BBH mass calibration and not from the galaxy catalog.
- For a FlatLCDM universe, the Hubble constant is the parameter that we can measure the best.



[LVK+, 2509.04348]

Cosmology following GWTC-4.0

Gravitational Wave Cosmology systematics are still dominated by the mass spectrum of BBHs, but we can select the model with Bayes factors



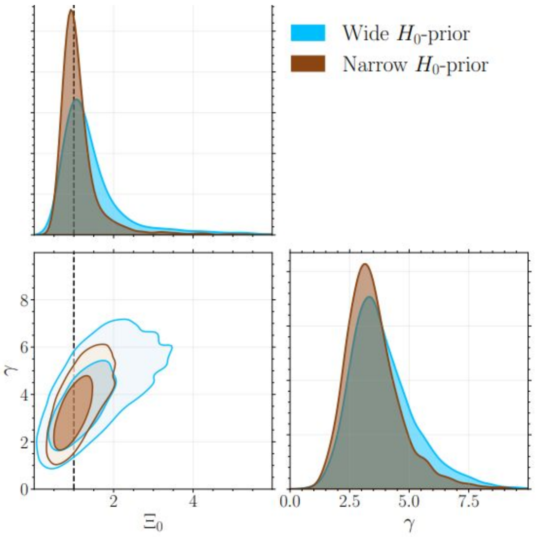
[LVK+, 2509.04348]

Cosmology following GWTC-4.0

- Binary black holes allows us to set tight constraints on modified gravity (more effective at high redshifts).
- Roughly speaking, we are providing a measure on G(source)/G(today).
- These constraints are becoming comparable with the ones obtained from LSSs [Ishak+, 2024] and CMB [Seraille+, 2024]

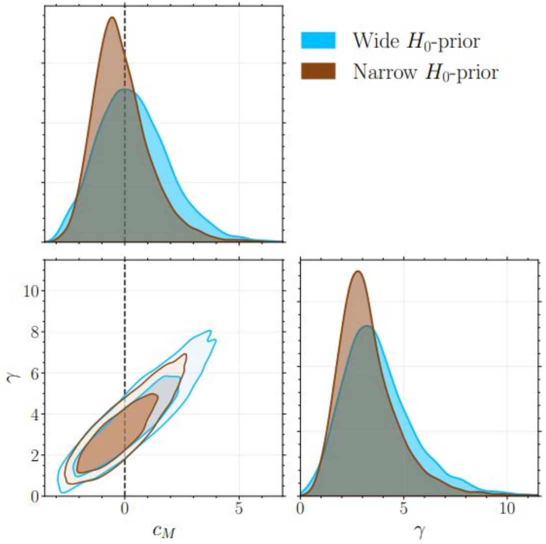
Phenomenological approach

$$D_{\rm L}^{\rm GW} = D_{\rm L}^{\rm EM}\left(\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right)$$



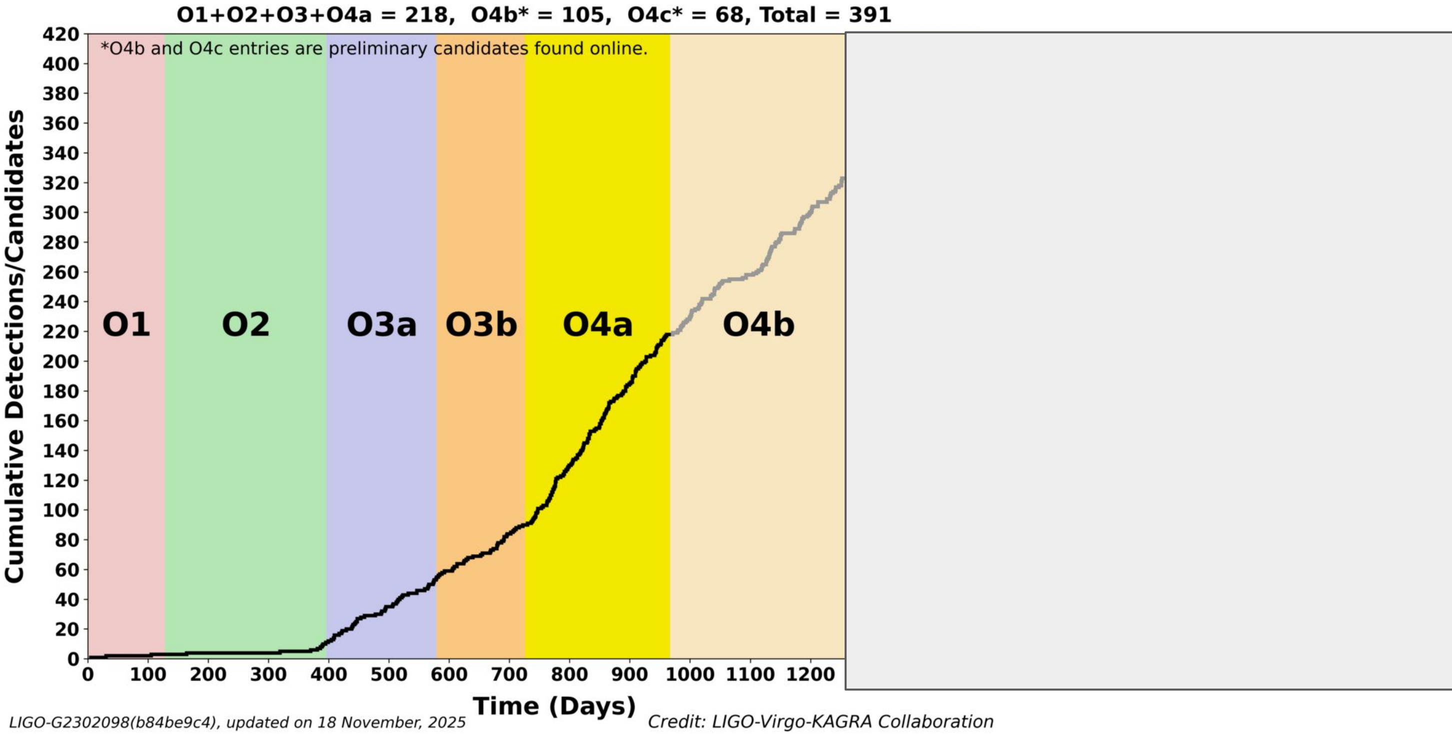
Running Planck mass

$$D_{\rm L}^{\rm GW} = D_{\rm L}^{\rm EM} \exp\left\{\frac{1}{2}\int_0^z \frac{{\rm d}z'}{1+z'}\alpha_M(z')\right\}$$



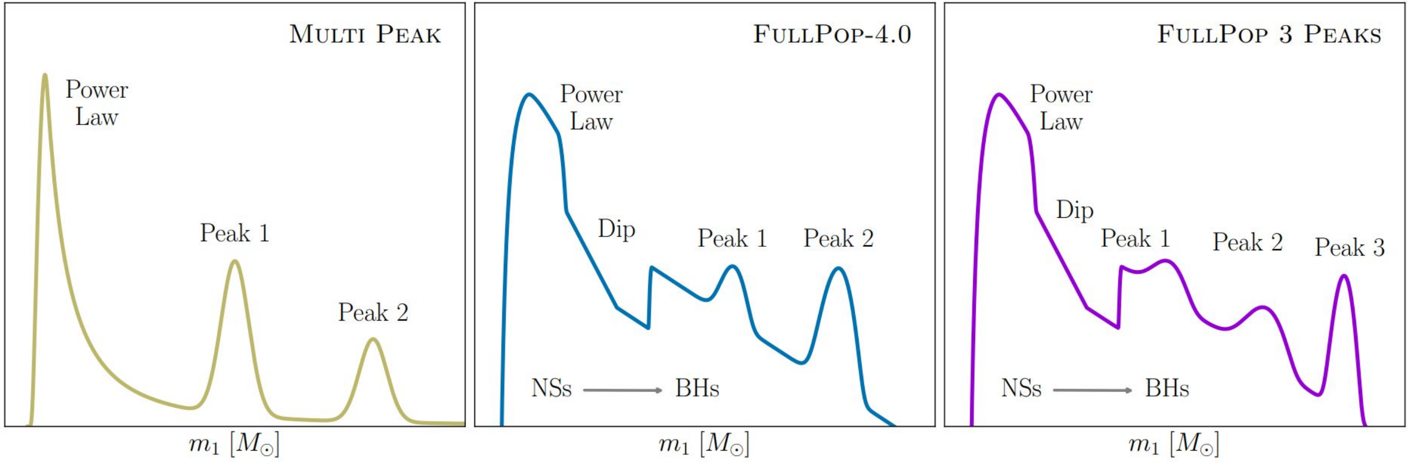
[LVK+, 2509.04348]

The population of GW sources

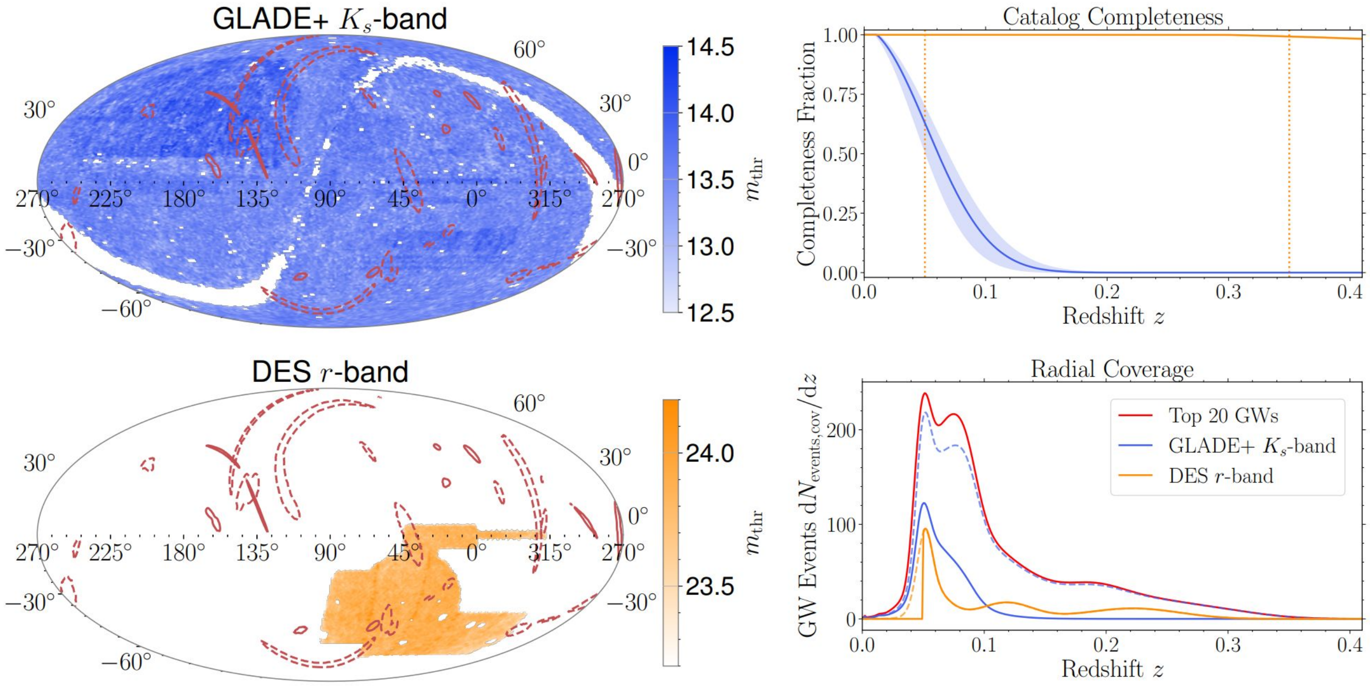


Latest results from GWTC-5.0

- We used the most significant 235 GW sources from GWTC-4 to estimate the cosmic expansion [LVK+, 2605.27227]
- We employed three different mass models and an all-sky galaxy catalog (GLADE+) as well as the Dark Energy Spectroscopic Survey Y6 (DES-Y6).

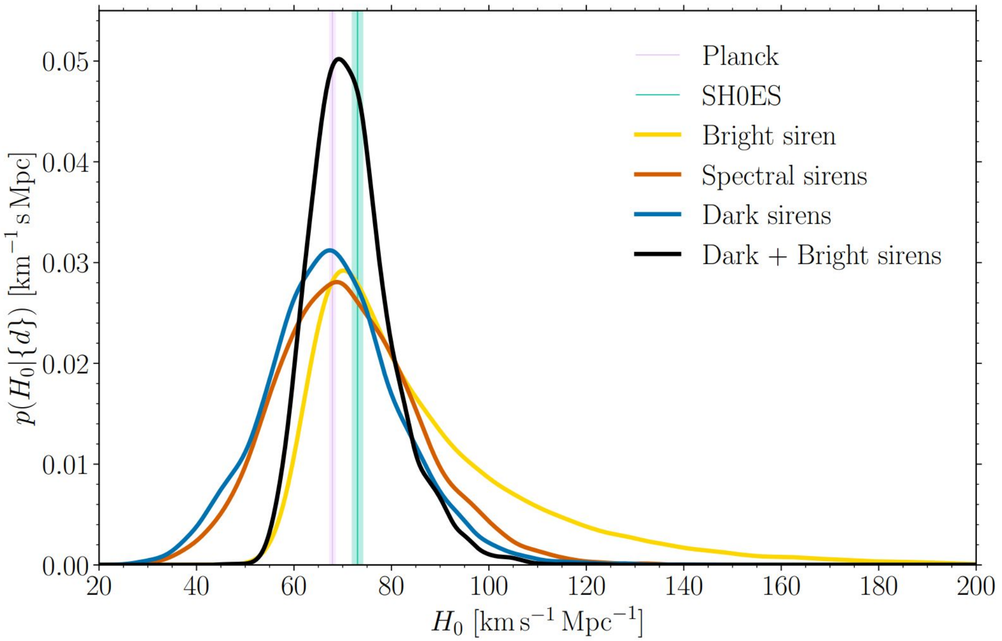


Latest results from GWTC-5.0



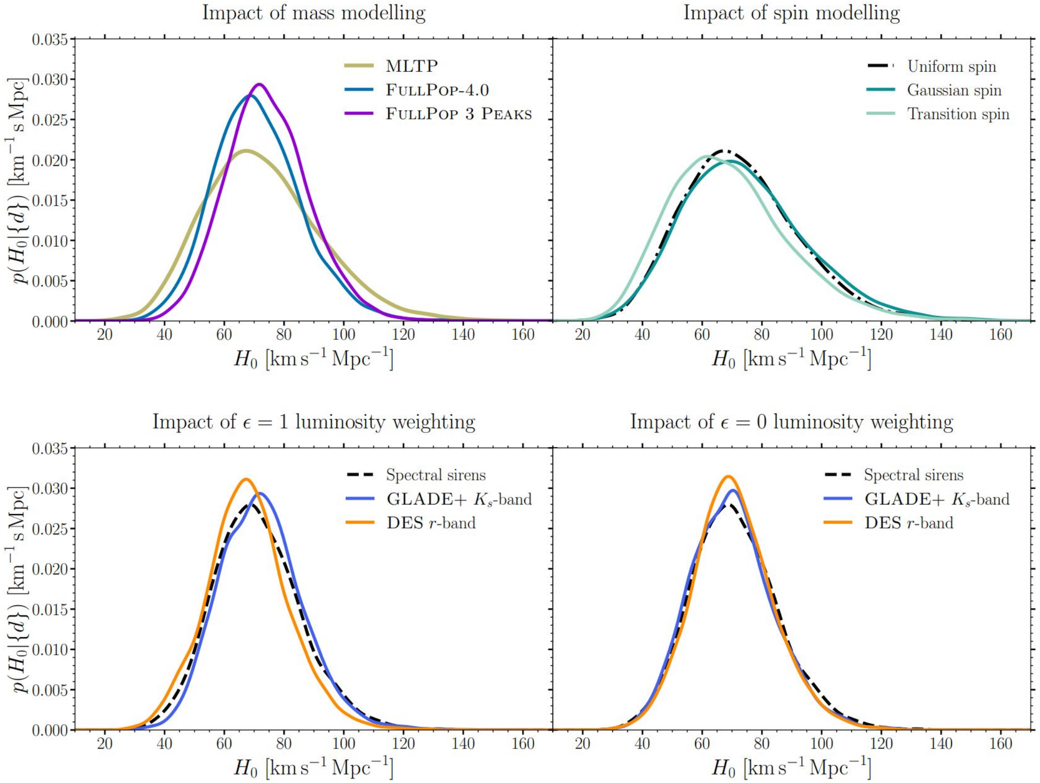
Latest results from GWTC-5.0

- Dark and Spectral sirens are now becoming as precise as the only bright siren that we have.
- Again, most of the cosmological information is coming from the calibration of the BBH mass spectrum.



[LVK+, 2509.04348]

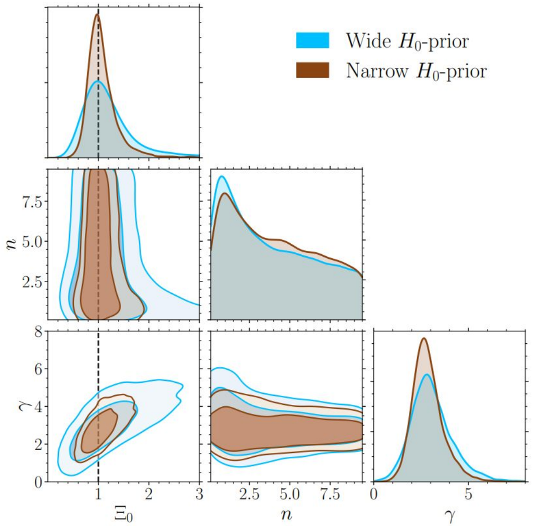
Latest results from GWTC-5.0



Latest results from GWTC-5.0

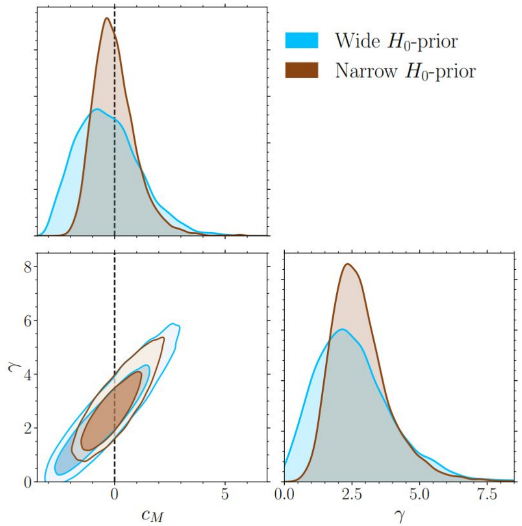
Phenomenological approach

$$D_{\rm L}^{\rm GW} = D_{\rm L}^{\rm EM}\left(\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right)$$



Running Planck mass

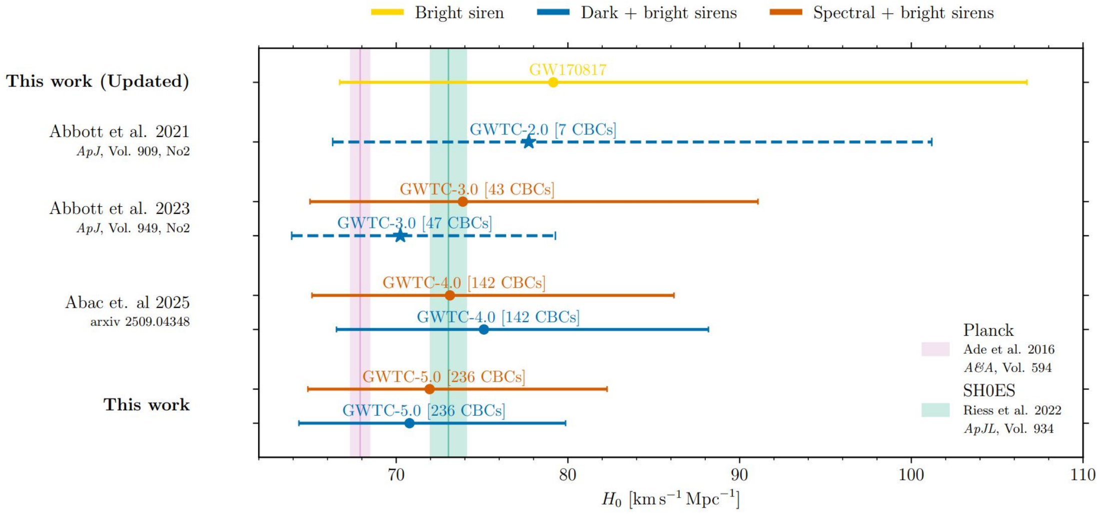
$$D_{\rm L}^{\rm GW} = D_{\rm L}^{\rm EM}\exp\left\{\frac{1}{2}\int_0^z \frac{{\rm d}z'}{1+z'}\alpha_M(z')\right\}$$

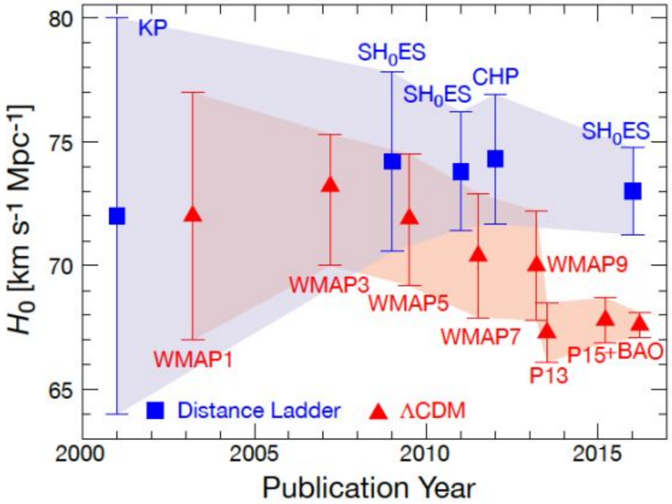


Conclusions an overall perspective

Gravitational-wave cosmology is at its beginning like supernova cosmology 20 years ago.

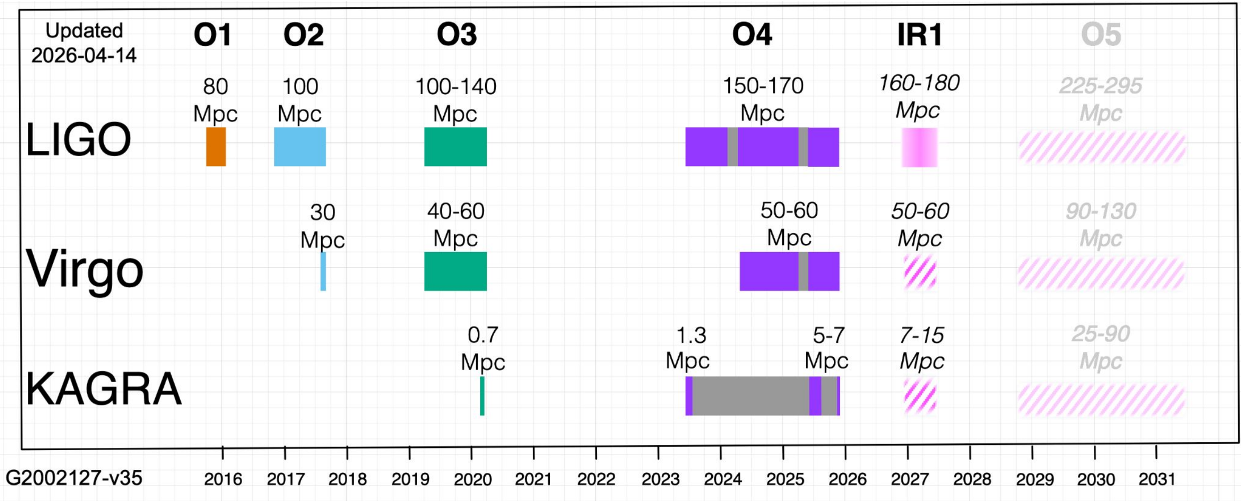
With the upcoming runs, we expect to have hundreds of GW sources that can be used to improve the precision and check for the measurement robustness



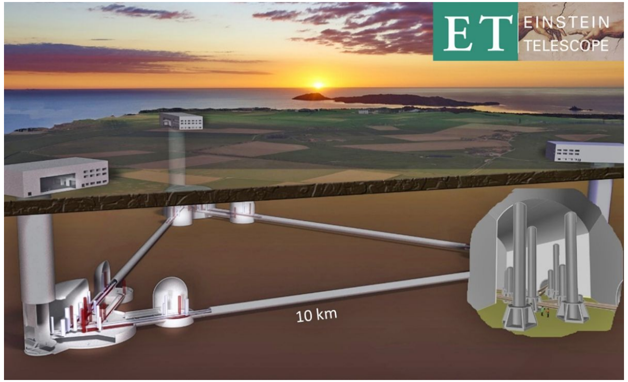


[W. Freedman, Nature Astronomy, 1, 0169 (2017)]

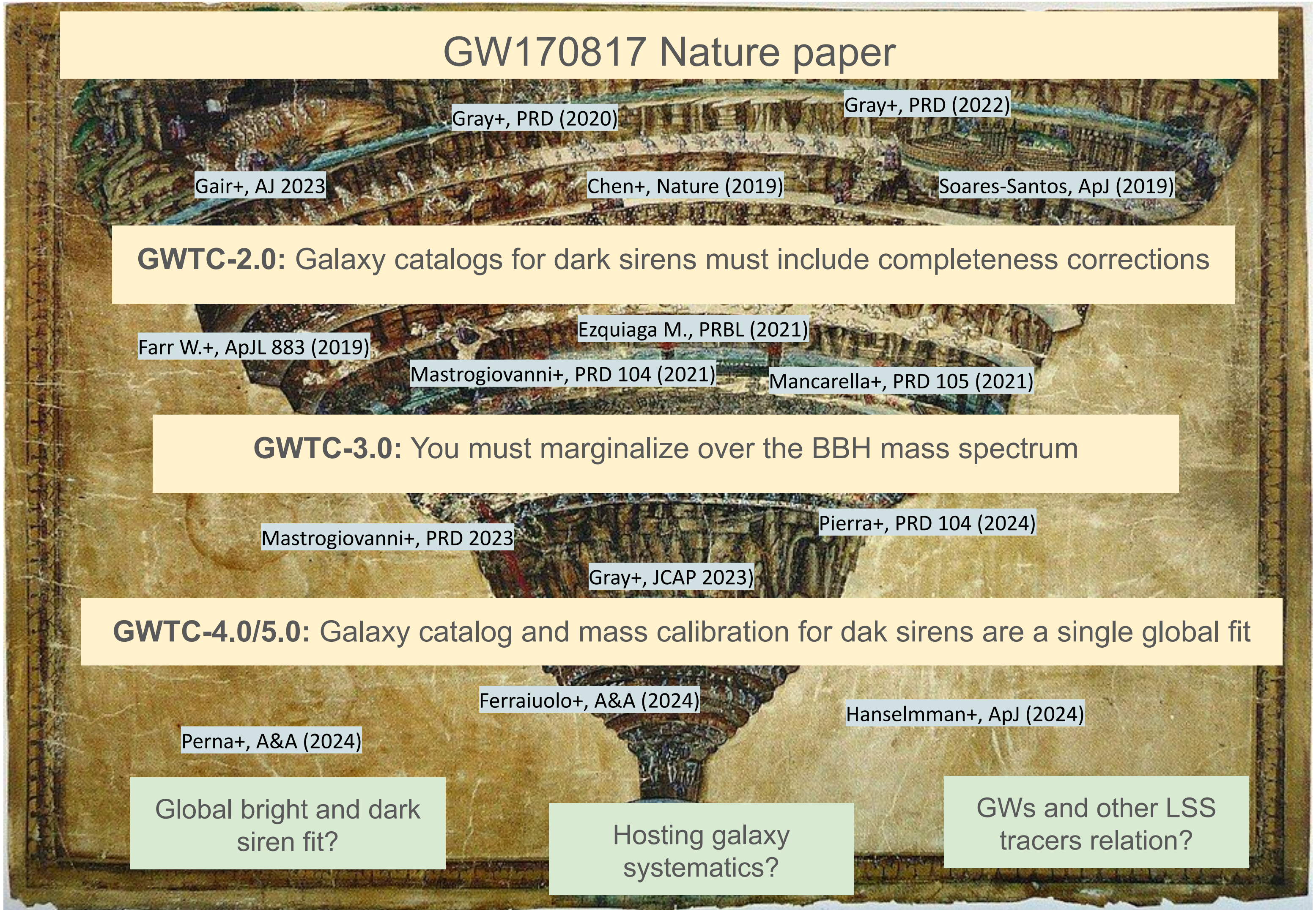
GW cosmology: the future



2035+
Einstein Telescope



[LVK observing plans]



GW170817 Nature paper

Gray+, PRD (2020)

Gray+, PRD (2022)

Gair+, AJ 2023

Chen+, Nature (2019)

Soares-Santos, ApJ (2019)

GWTC-2.0: Galaxy catalogs for dark sirens must include completeness corrections

Ezquiaga M., PRBL (2021)

Farr W.+, ApJL 883 (2019)

Mastrogiovanni+, PRD 104 (2021)

Mancarella+, PRD 105 (2021)

GWTC-3.0: You must marginalize over the BBH mass spectrum

Pierra+, PRD 104 (2024)

Mastrogiovanni+, PRD 2023

Gray+, JCAP 2023)

GWTC-4.0/5.0: Galaxy catalog and mass calibration for dak sirens are a single global fit

Ferraiuolo+, A&A (2024)

Hanselmman+, ApJ (2024)

Perna+, A&A (2024)

Global bright and dark siren fit?

Hosting galaxy systematics?

GWs and other LSS tracers relation?