

A decade of cosmology

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

S. Mastrogiovanni

INFN
GravitySirens
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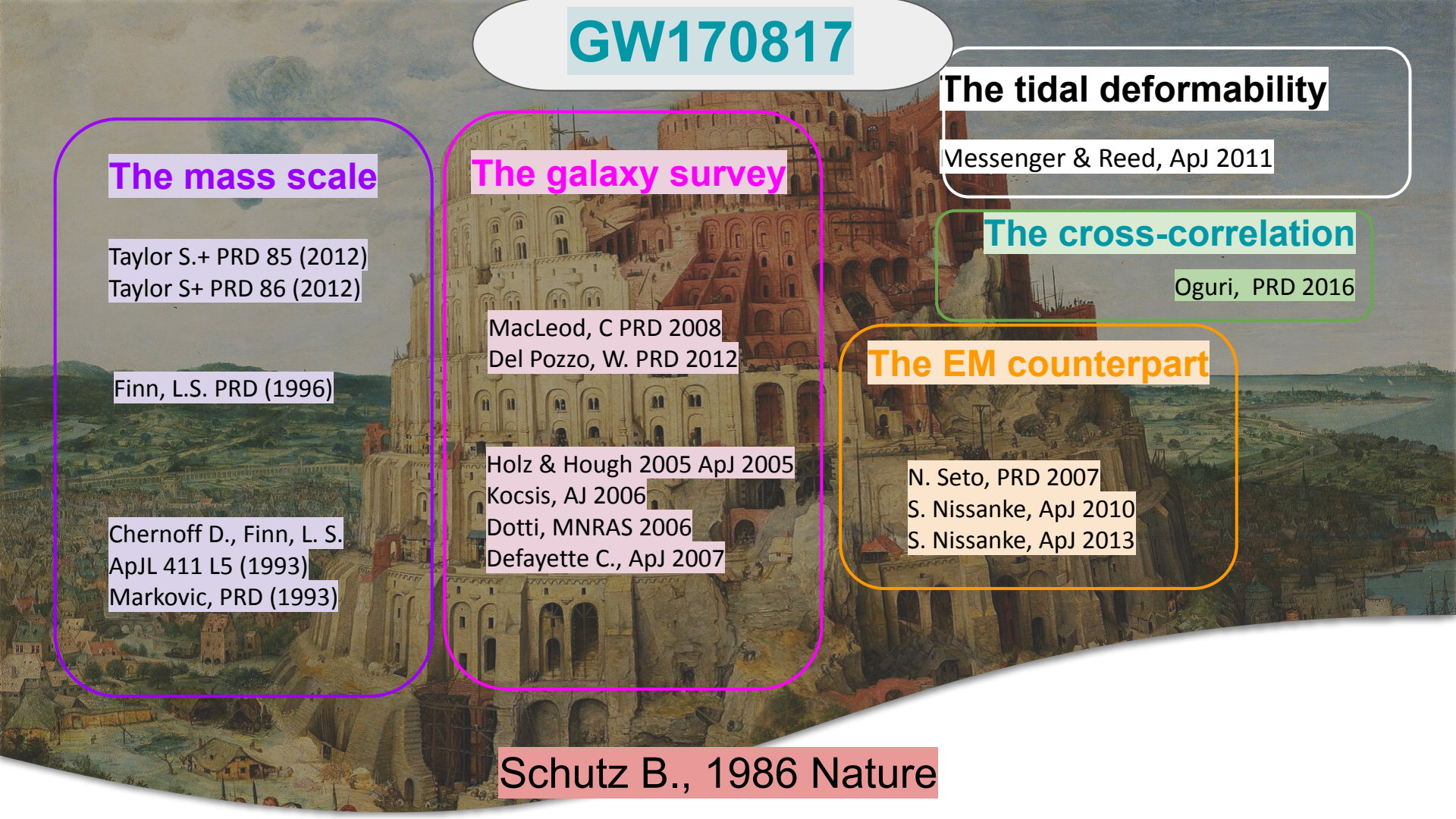
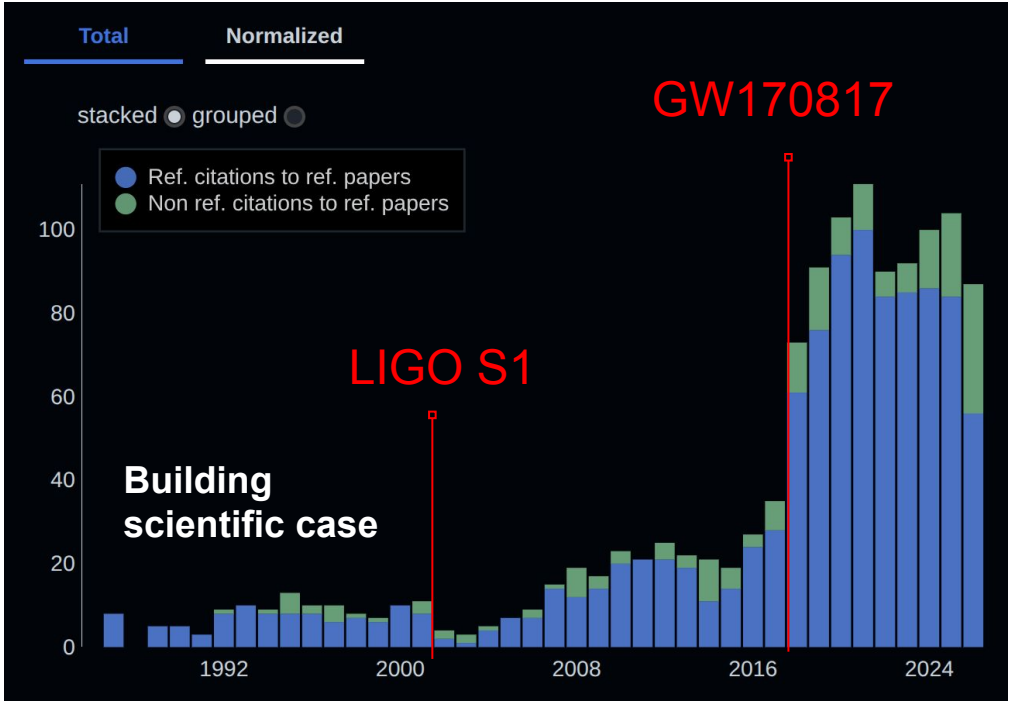

GW170817
The tidal deformability
Messenger & Reed, ApJ 2011
The mass scale
Taylor S.+ PRD 85 (2012)
Taylor S+ PRD 86 (2012)
Finn, L.S. PRD (1996)
Chernoff D., Finn, L. S.
ApJL 411 L5 (1993)
Markovic, PRD (1993)
The galaxy survey
MacLeod, C PRD 2008
Del Pozzo, W. PRD 2012
Holz & Hough 2005 ApJ 2005
Kocsis, AJ 2006
Dotti, MNRAS 2006
Defayette C., ApJ 2007
The 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**

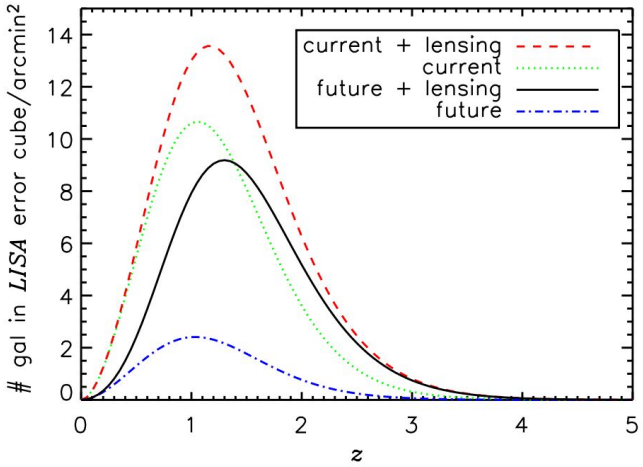
Cosmological parameters can be inferred by assuming a known mass value for **all the BNS sources.** Later studies (see Finn PRD 1996) improved these analytical prescriptions

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

Binary black holes as bright sirens

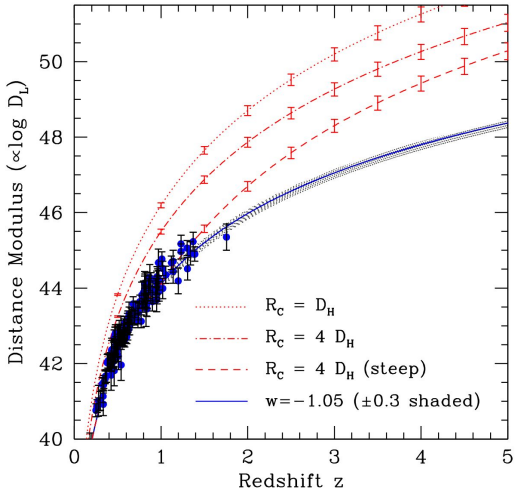
In the early 2000's massive **Binary Black Holes** detectable in LISA were being explored as possible dark and bright sirens.

Dark sirens



Holz & Hough 2005 (ApJ 2005)

Bright sirens

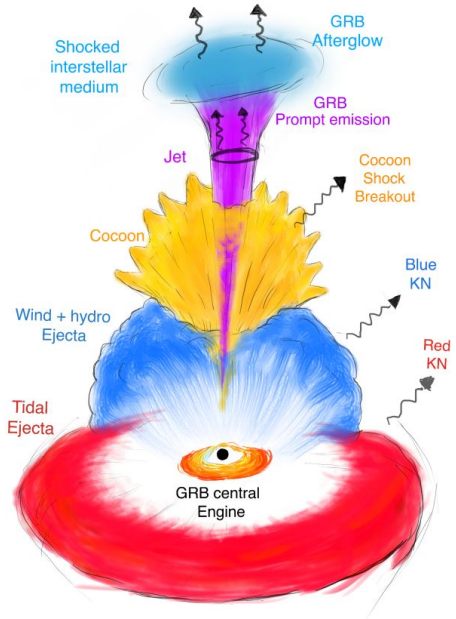


Kocsis AJ 2006
Dotti MNRAS 2006
Defayette ApJ 2007

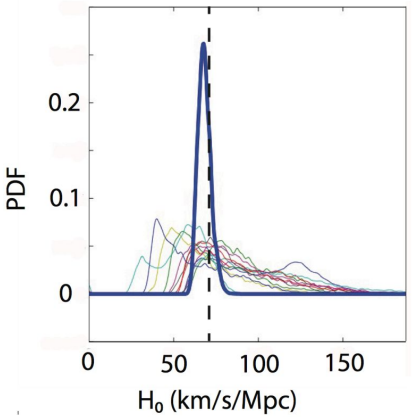
Advancing bright sirens in 2000’

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



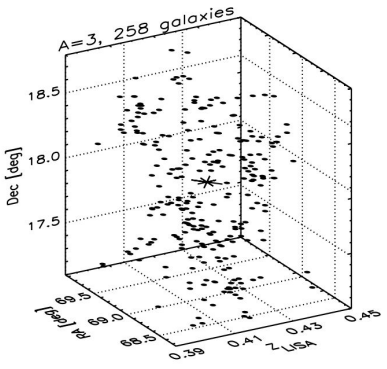
Credit: S. Ascenzi

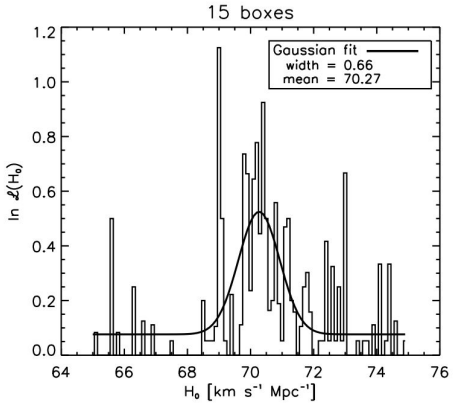


Dark sirens in 2010

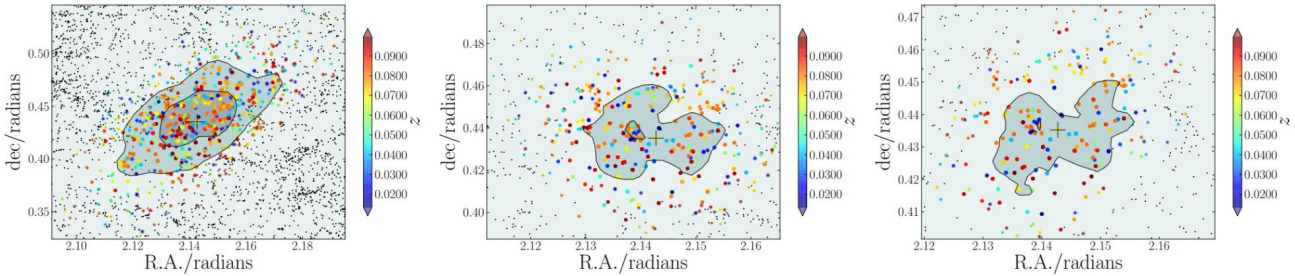
In 2010 we see a resparked interested in using binary black holes as dark sirens with galaxy catalogs for LISA and LVK

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





MacLeod, C PRD 2008

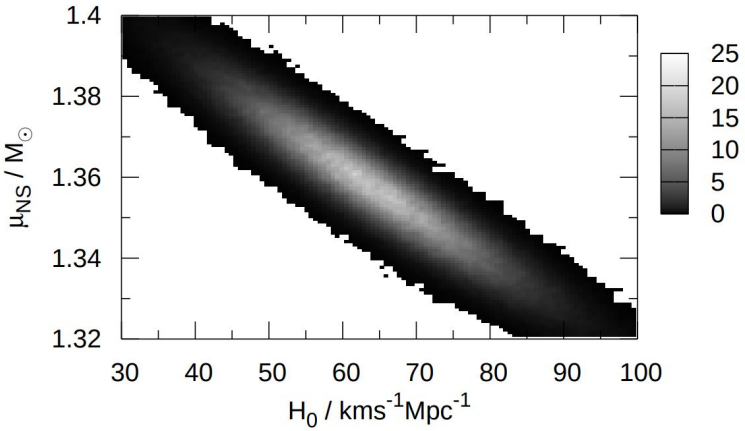


Del Pozzo, W. PRD 2012

Dark sirens and the 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-correlations with LSSs

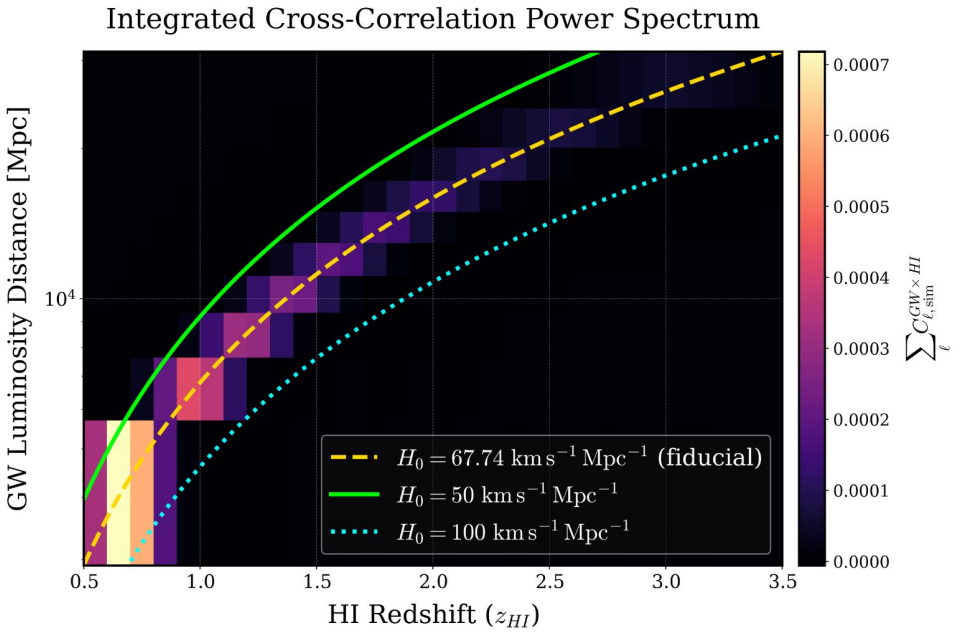
In 2016 Oguni [PRD 2016], proposed a complementary method for GW cosmology based on angular cross-correlation with large scale structures.

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

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

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



Schulz M. + 2607.26193

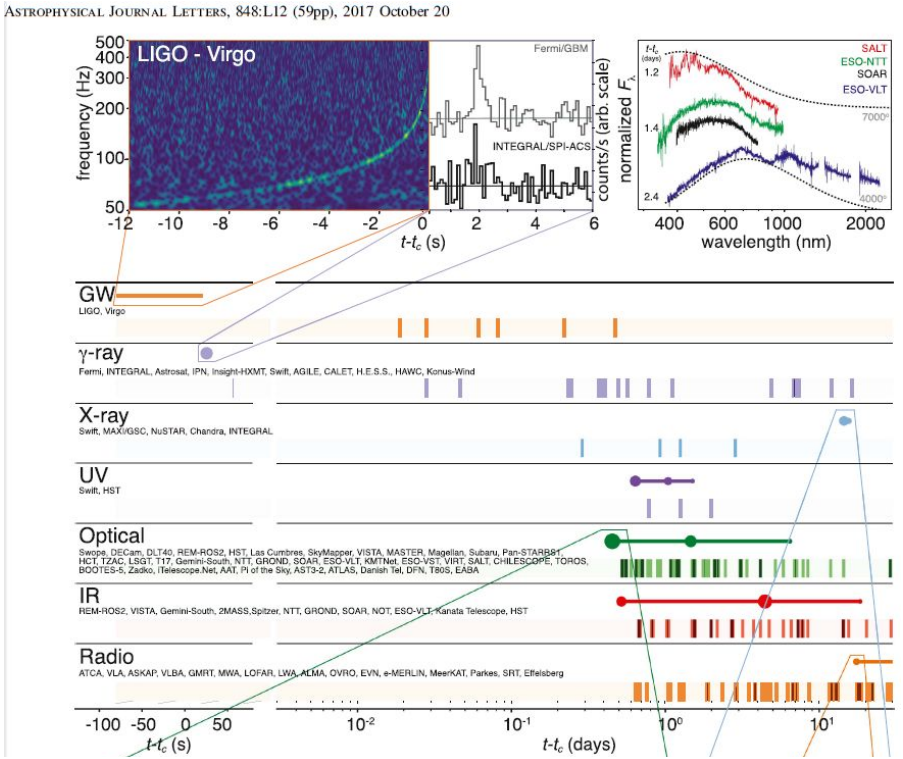
GW170817: The first bright siren

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

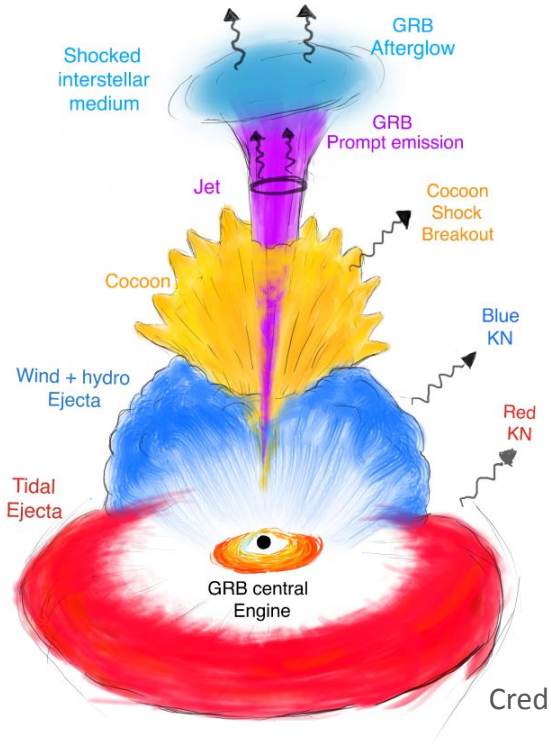
- +2 seconds later Integral and Fermi detect a GRB.
- ~10 hrs later a kilonova emission from NGC4993 is observed.

With GW170817 we have been provided:

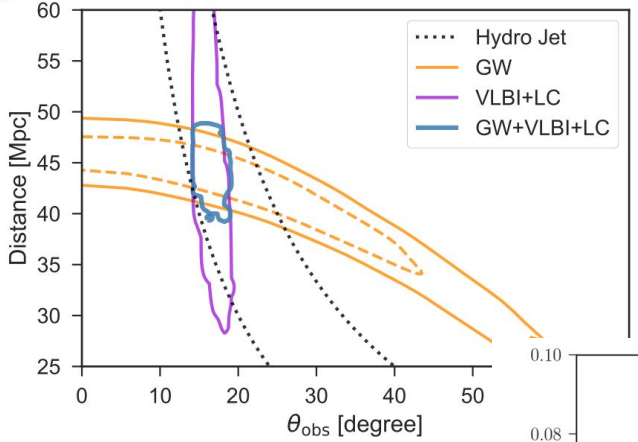
- Luminosity distance from GW170817.
- Redshift identification of the host galaxy from NGC4993.
- Peculiar motion of NGC4993.



GW170817: The first bright siren

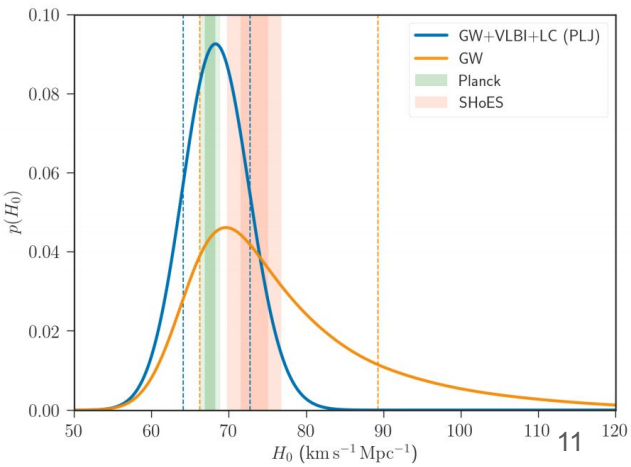


Credit: S. Ascenzi

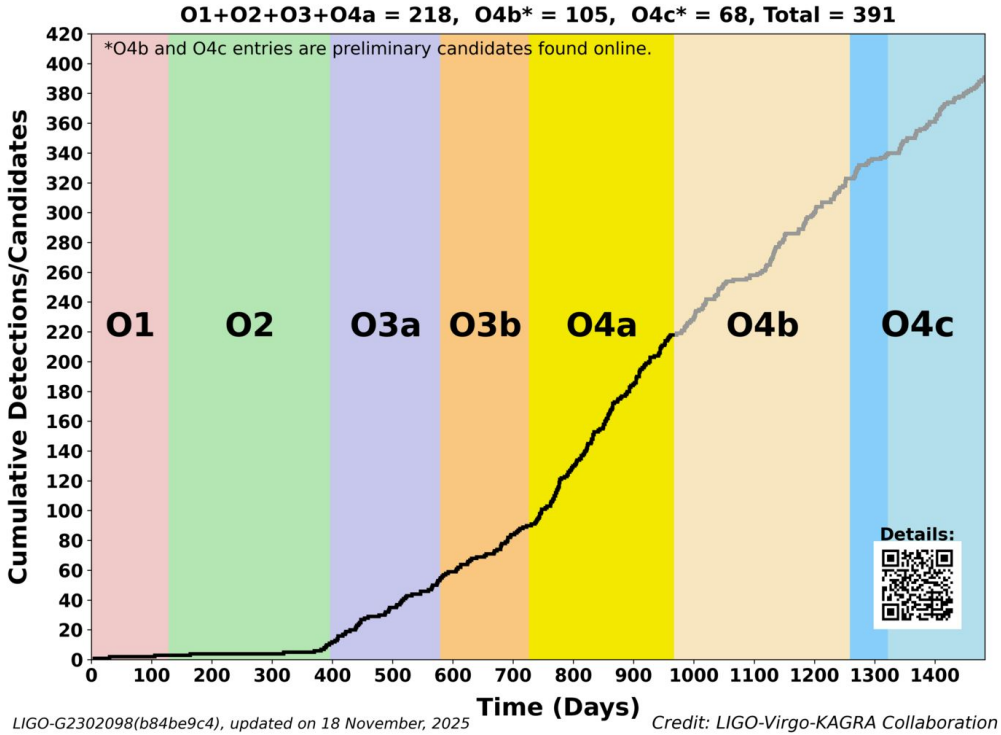


[K. Hotokezaka, Nature Astronomy, 3(2019)]

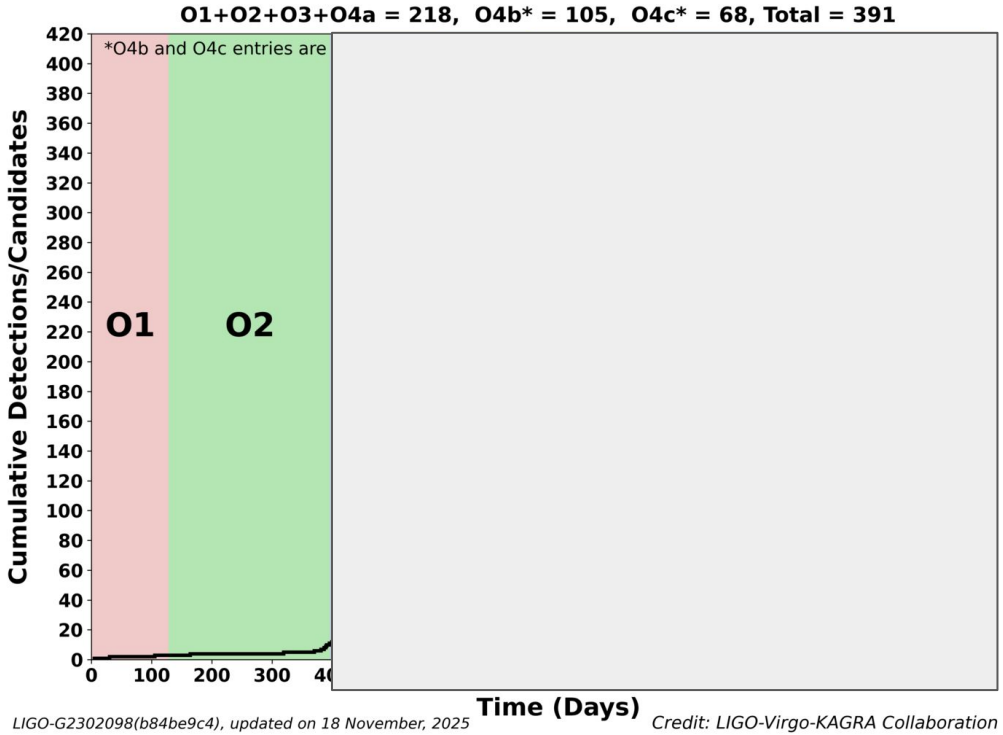
Afterglow informed cosmology



Standard sirens nowadays



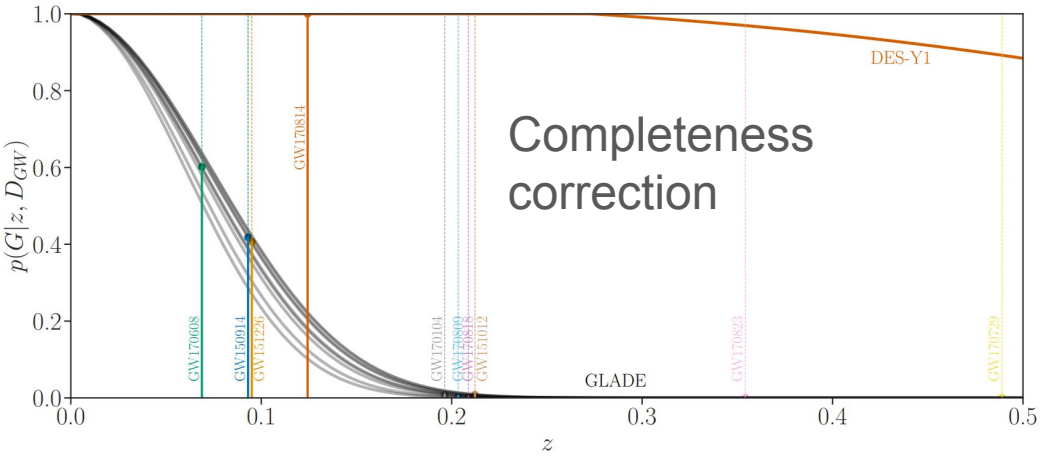
Standard sirens until the end of O2



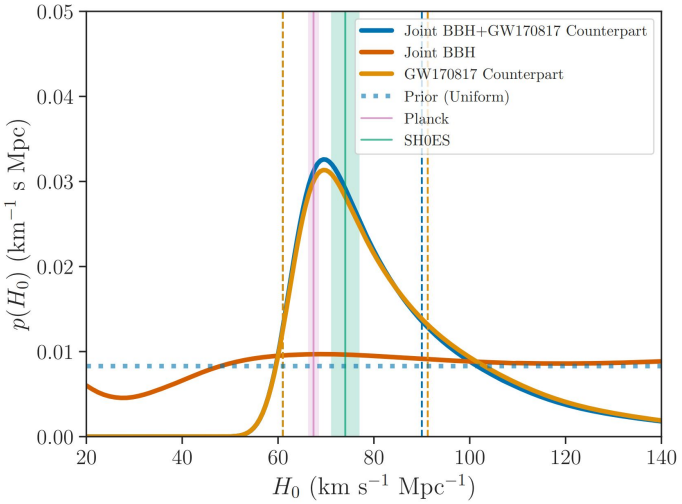
Standard sirens until the end of O2

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

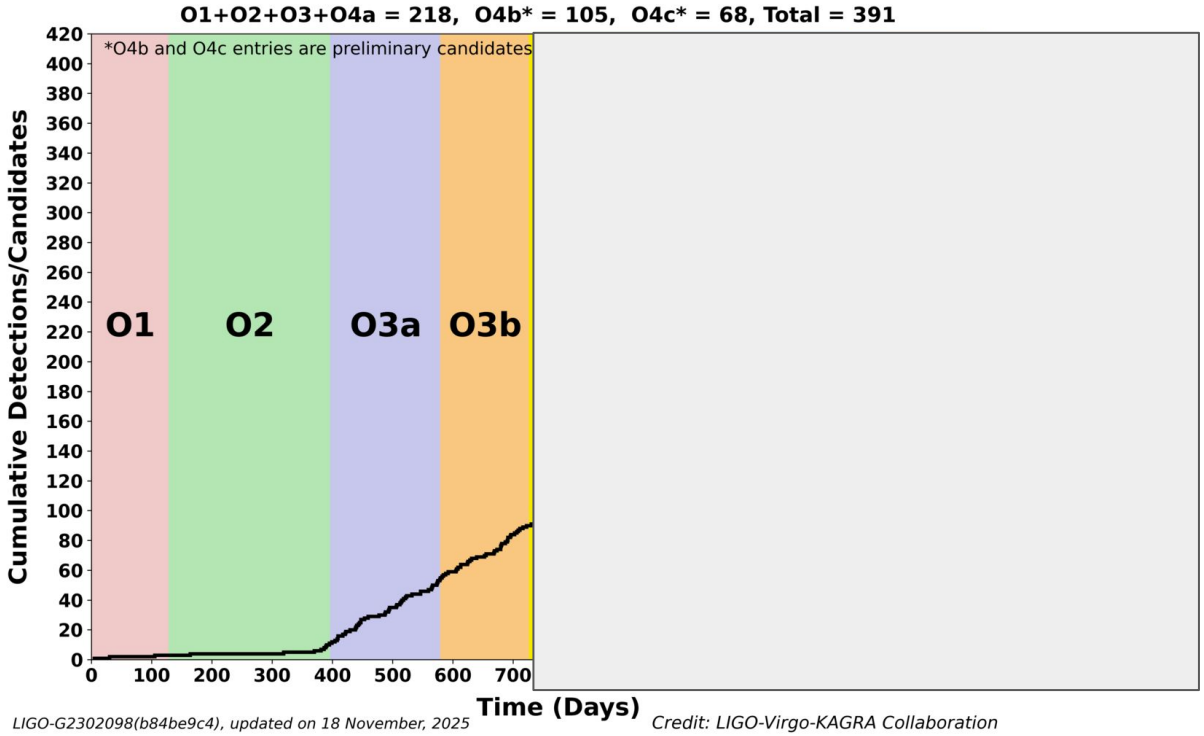
We also added the completeness correction to the galaxy catalog



LVK Astrophys J 909 Number 2 218 (2021)



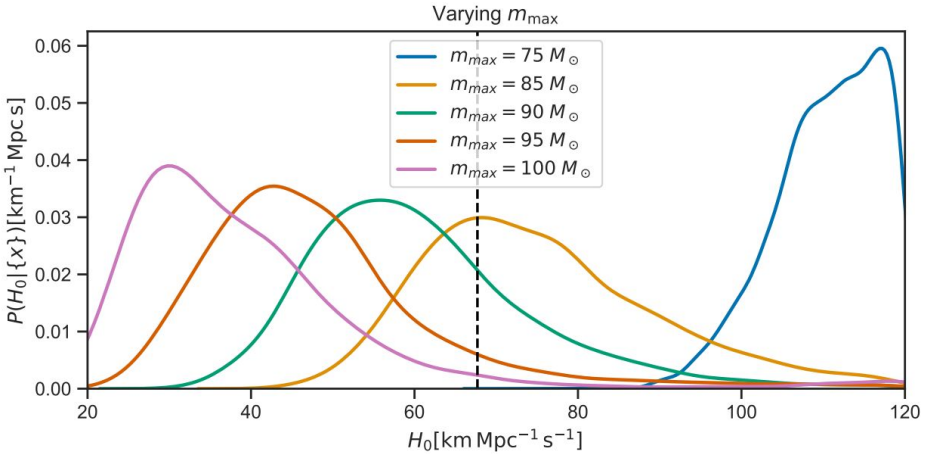
Standard sirens until the end of O3



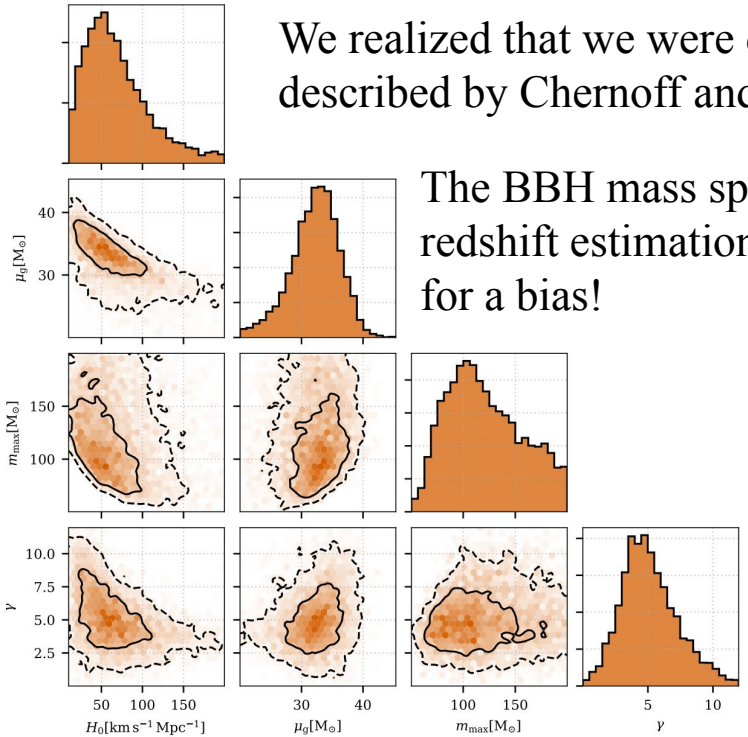
Standard sirens until the end of O3

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

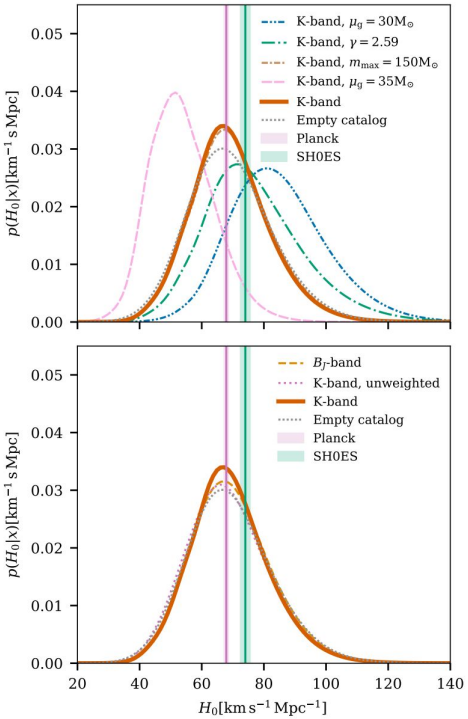


Standard sirens until the end of O3



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

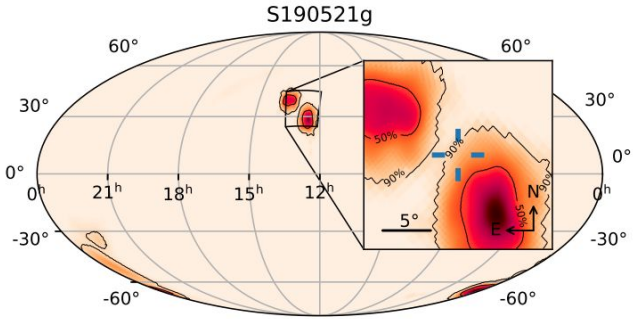
The BBH mass spectrum can provide statistical redshift estimation, but it is also a major issue for a bias!



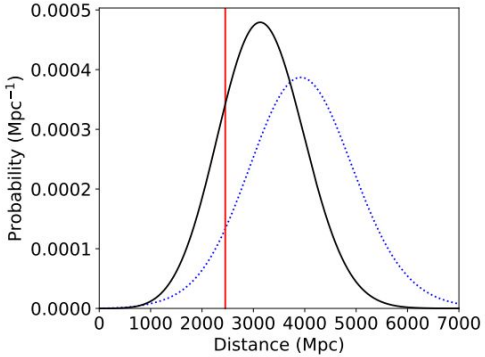
R. Abbott et al 2023 ApJ 949 76

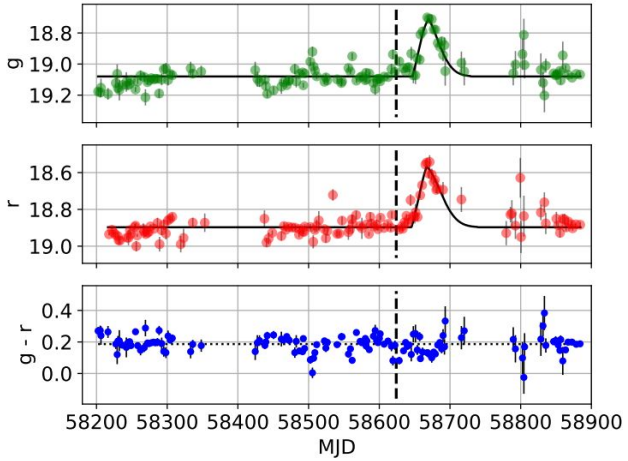
The curious case of GW190521

In 2021 the LVK reported the detection of GW190521, the most massive GW event at the time. A few months later, an association to an AGN flare was proposed.



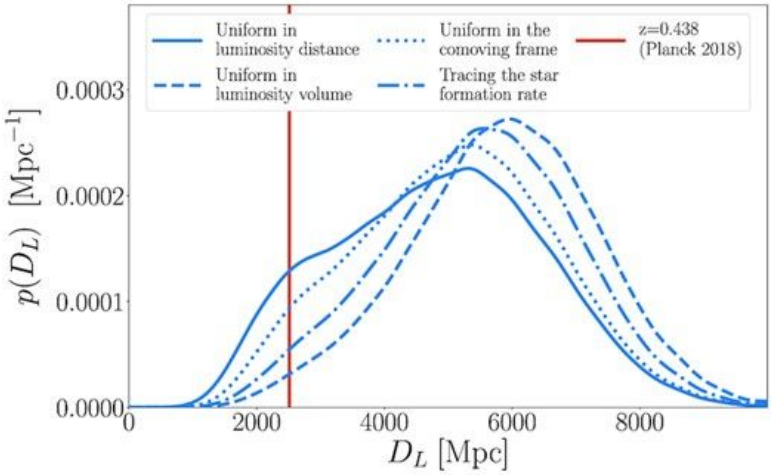
Graham Phys. Rev. Lett. 124, 251102



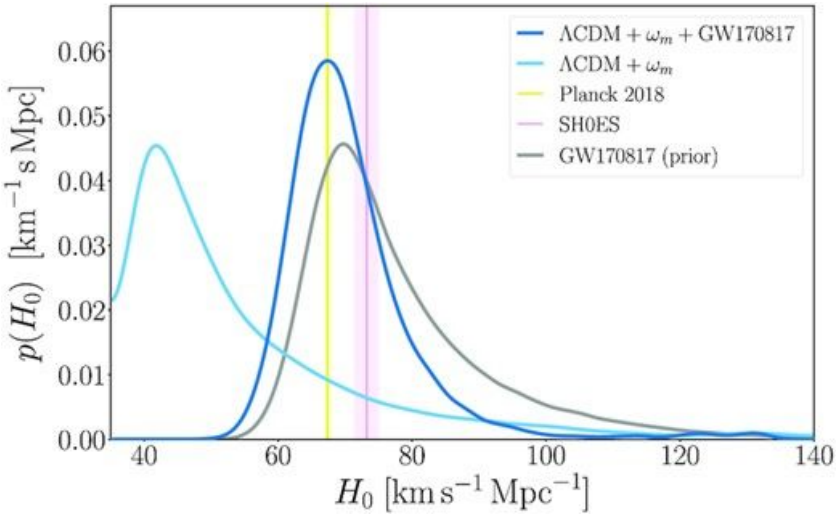


The curious case of GW190521

Although the association is not statistically strong [Ashton+, CQG 2021], it is still interesting to consider this as a bright siren.

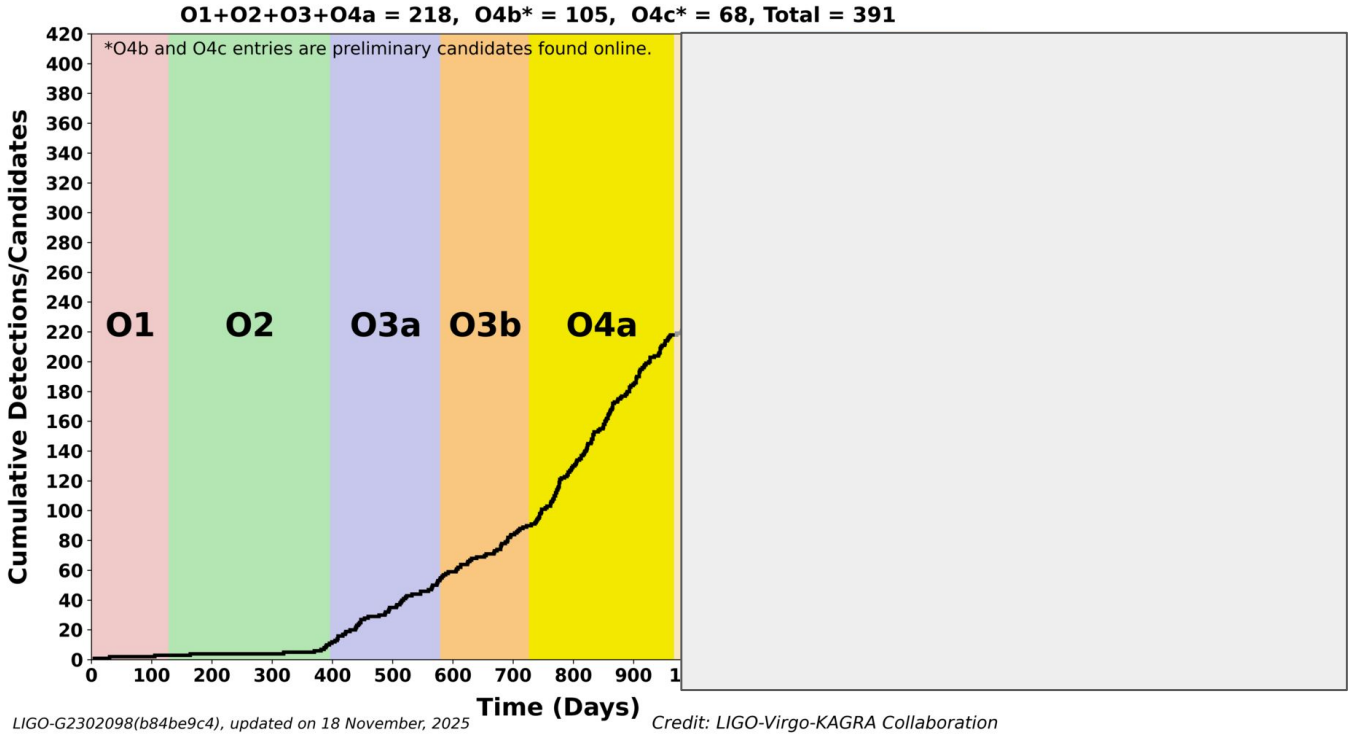


Chen+, MNRAS, 2022



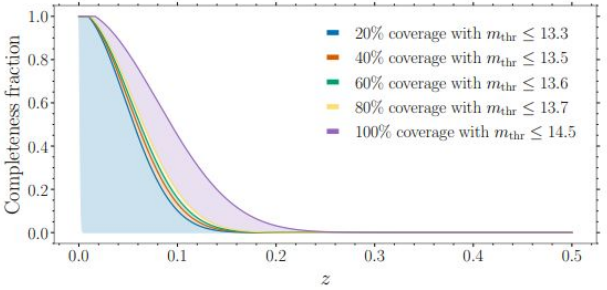
Additional methods have been developed to correct for false associations in cosmological analyses [Palmese+, ApJL 021]

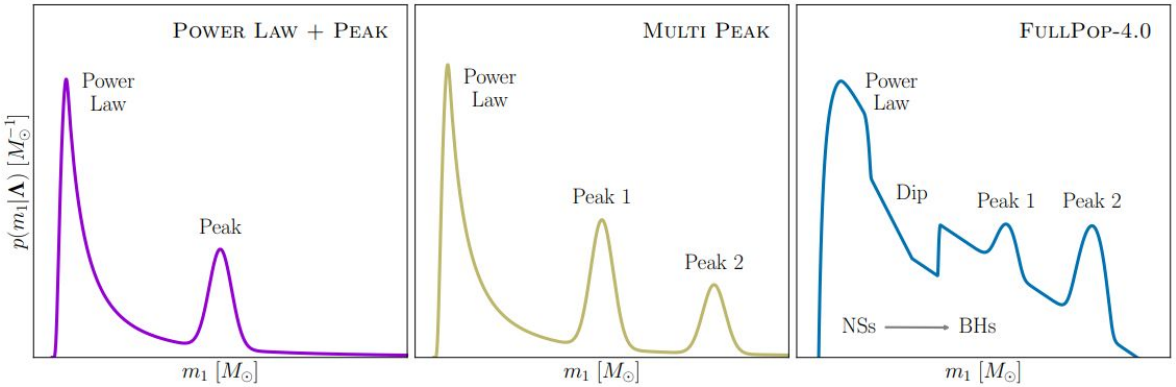
Standard sirens until the end of O4a

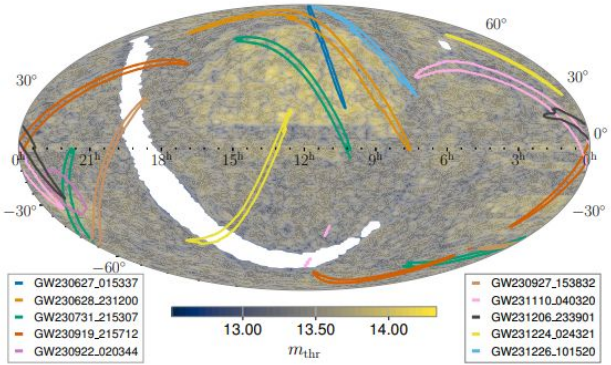


Standard sirens until the end of O4a

- We used the most significant GW sources (142/218) from GWTC-4 to estimate the cosmic expansion [LVK+, ApJL 2027]
- 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.

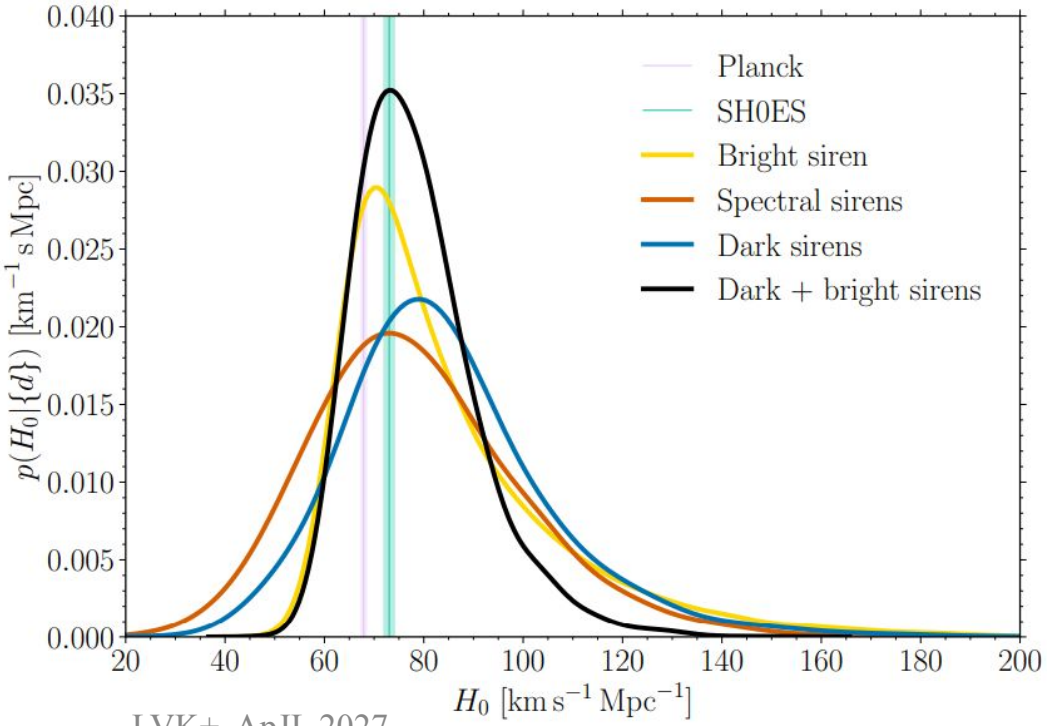






Standard sirens until the end of O4a

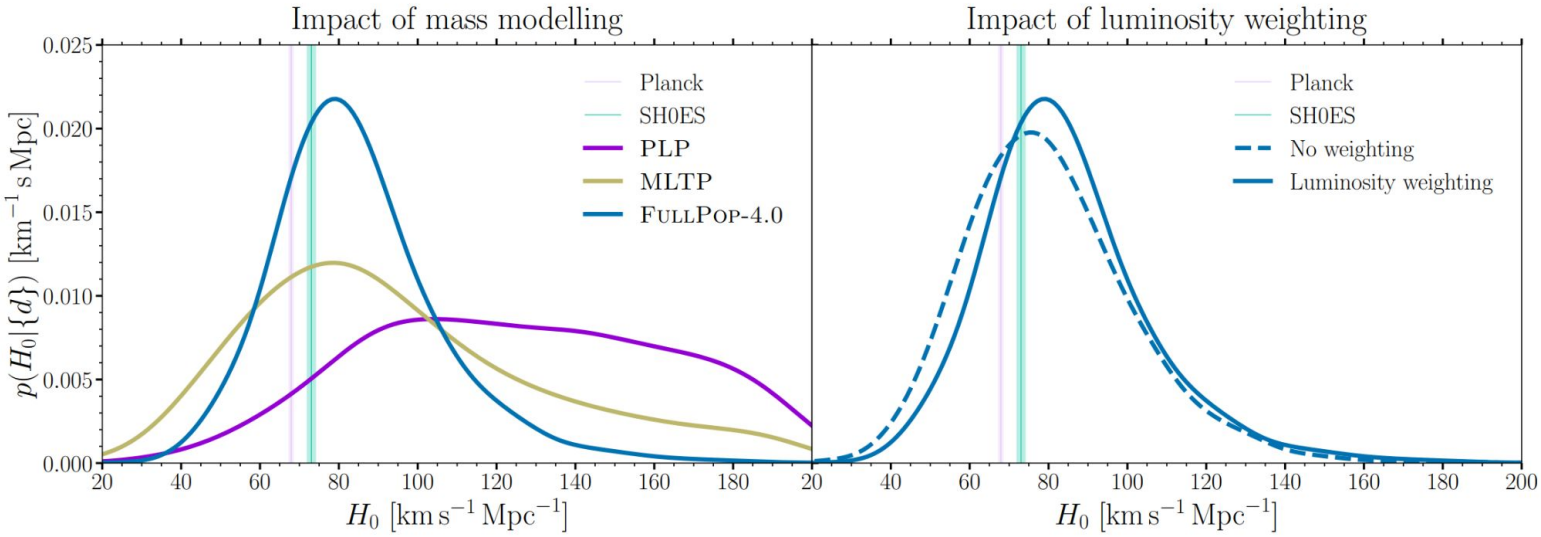
- Dark Standard sirens are not yet competitive with the precision offered by a single bright siren.
- The cosmological information is mostly coming from the BBH mass calibration and not from the galaxy catalog.
- For a FlatLCDM universe, the Hubble constant is the parameter that we can measure the best.



LVK+, ApJL 2027

Standard sirens until the end of O4a

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



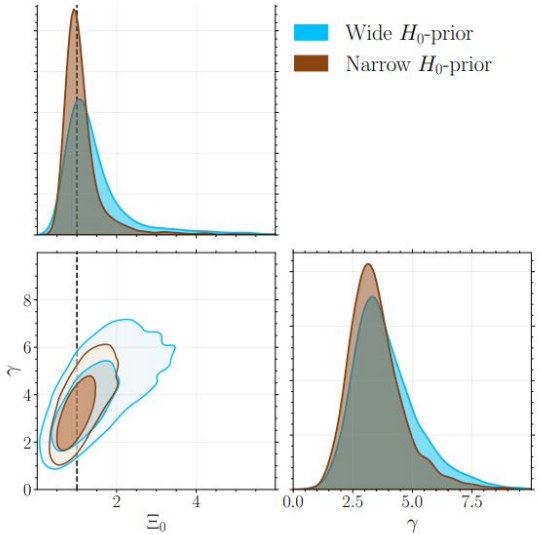
[LVK+, ApJL 2027]

Standard sirens until the end of O4a

- 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]

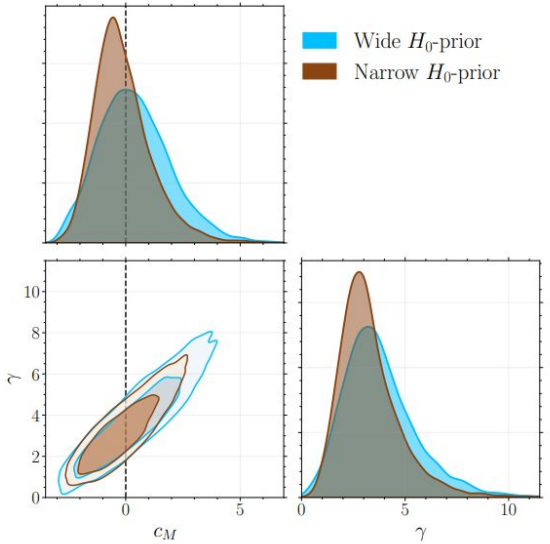
Phenomenological approach

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



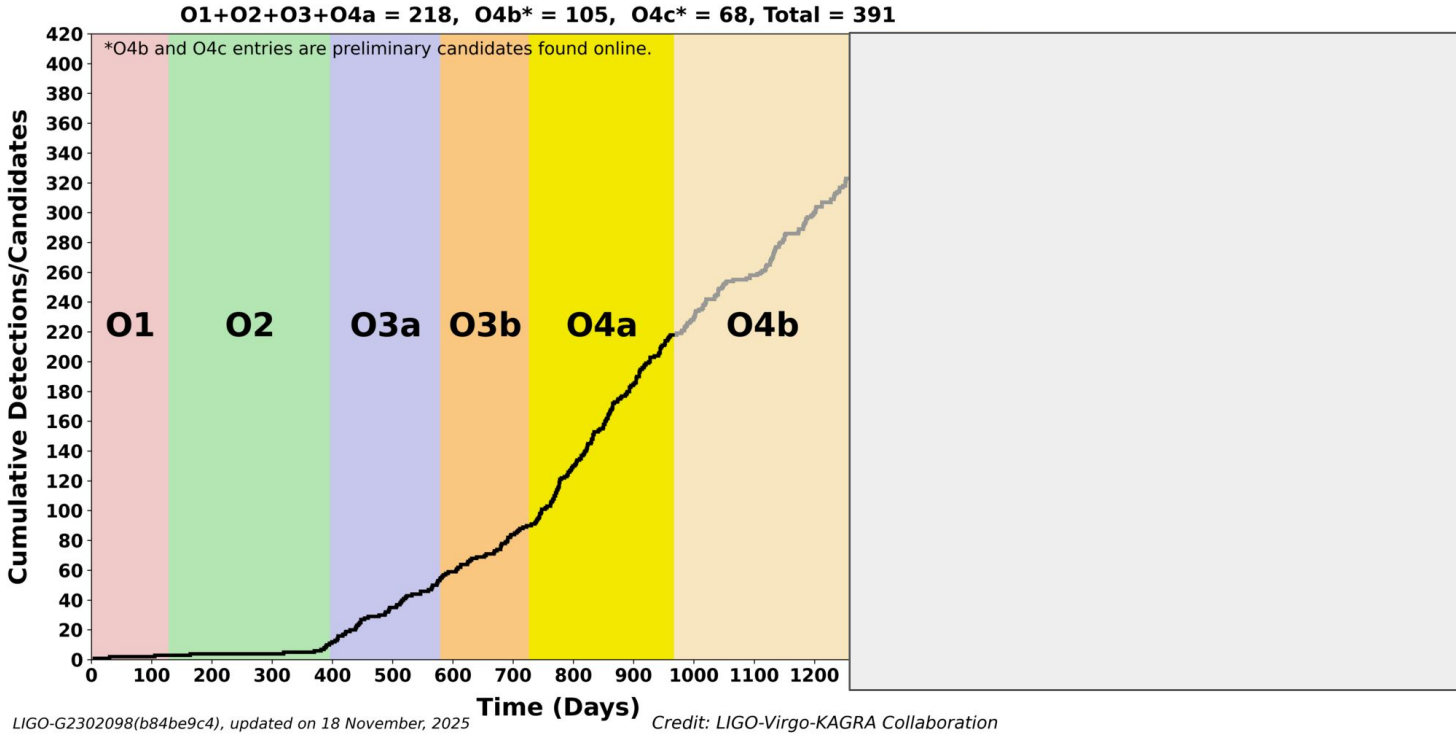
Running Planck mass

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



[LVK+, ApJL 2027]

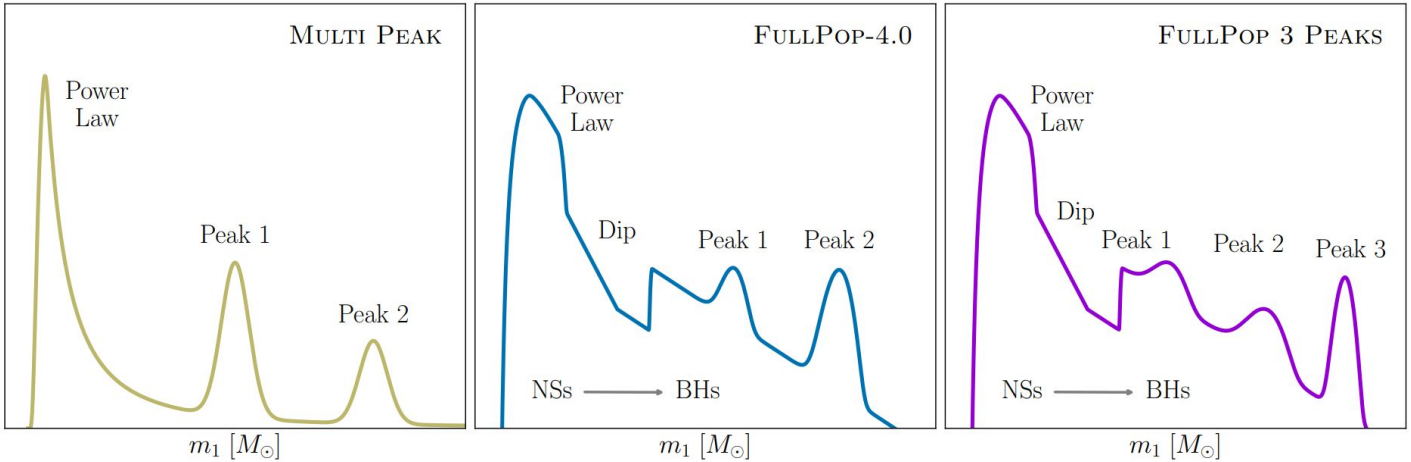
Standard sirens until the end of O4b



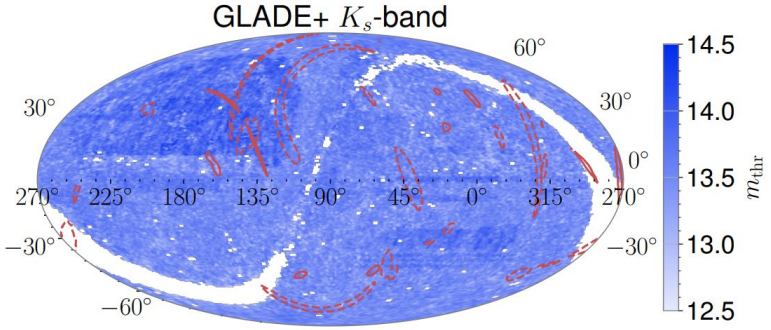
Standard sirens until the end of O4b

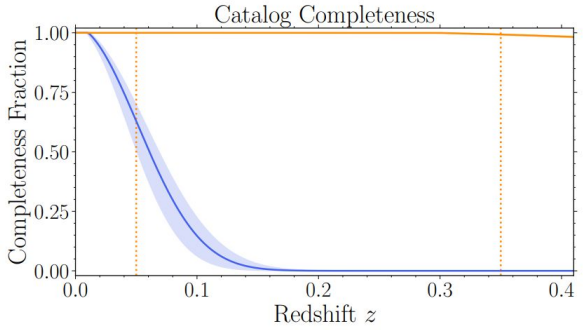
- We used the most significant 235 GW sources from GWTC-4 to estimate the cosmic expansion [LVK+, 2605.27227]

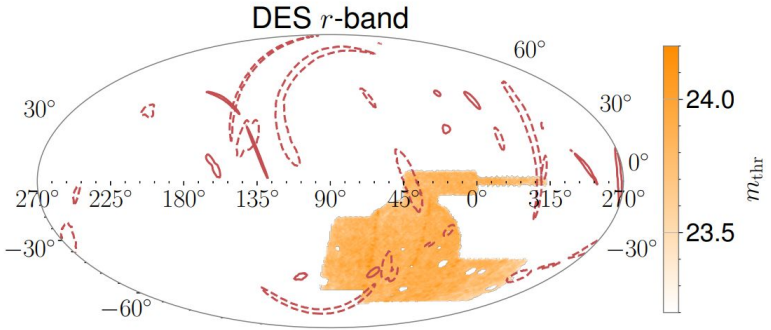
- We employed three different mass models and an all-sky galaxy catalog (GLADE+) as well as the Dark Energy Spectroscopic Survey Y6 (DES-Y6).

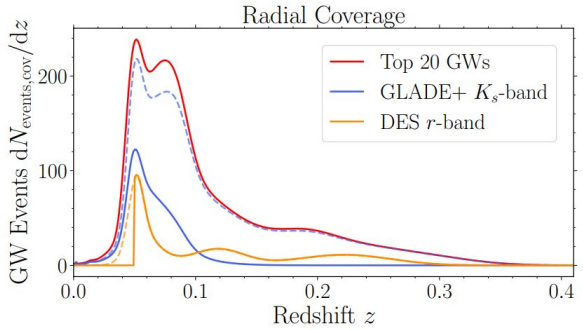


Standard sirens until the end of O4b



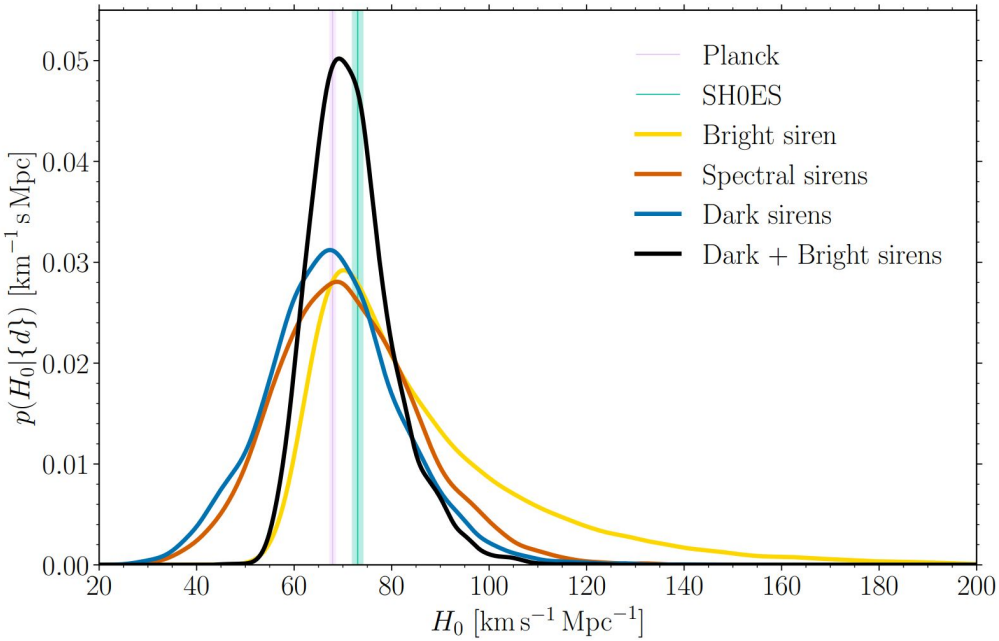






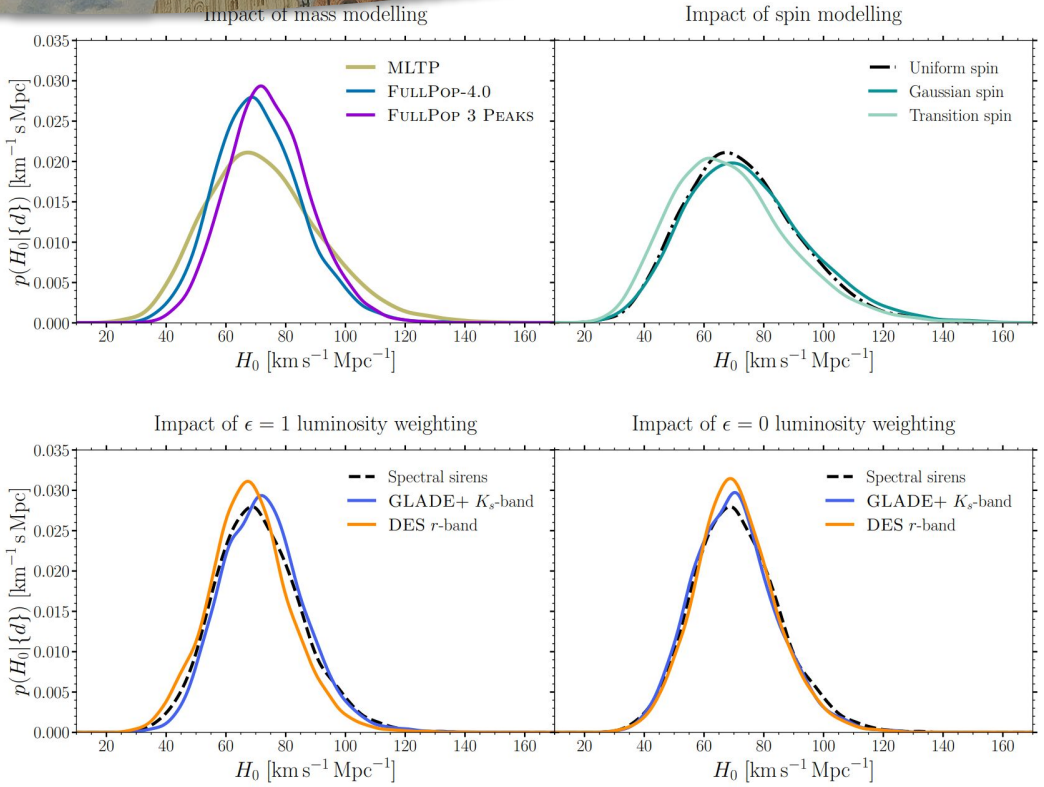
Standard sirens until the end of O4b

- 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]

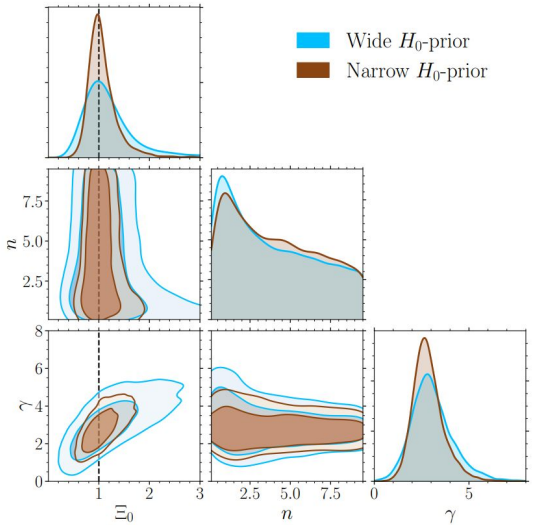
Standard sirens until the end of O4b



Standard sirens until the end of O4b

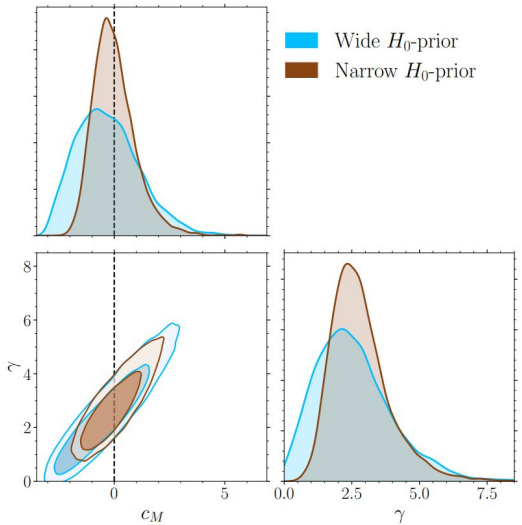
Phenomenological approach

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



Running Planck mass

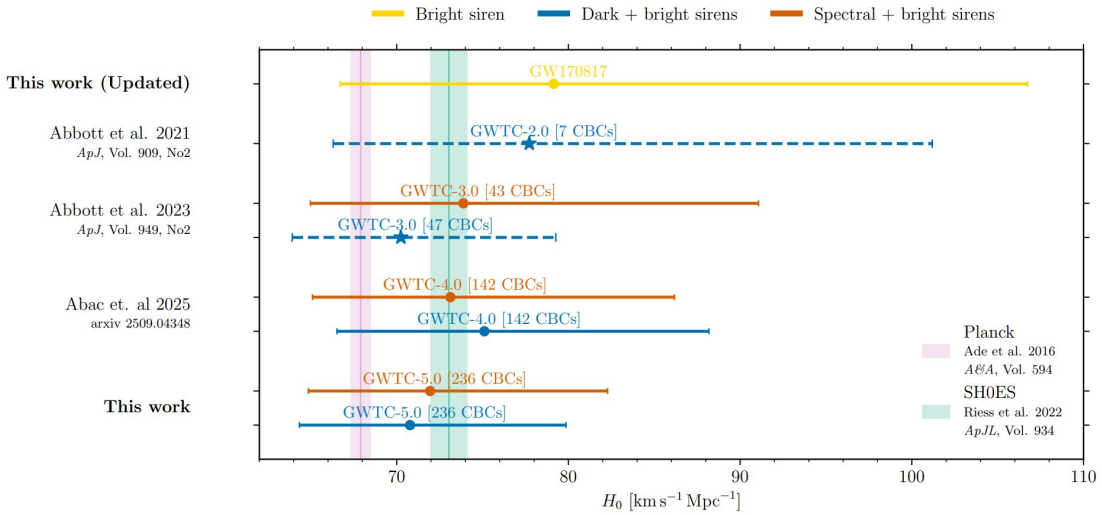
$$D_{\rm L}^{\rm GW} = D_{\rm L}^{\rm EM}\exp\left\{\frac{1}{2}\int_0^z \frac{{\rm d}z'}{1+z'}\alpha_M\left(z'\right)\right\}$$

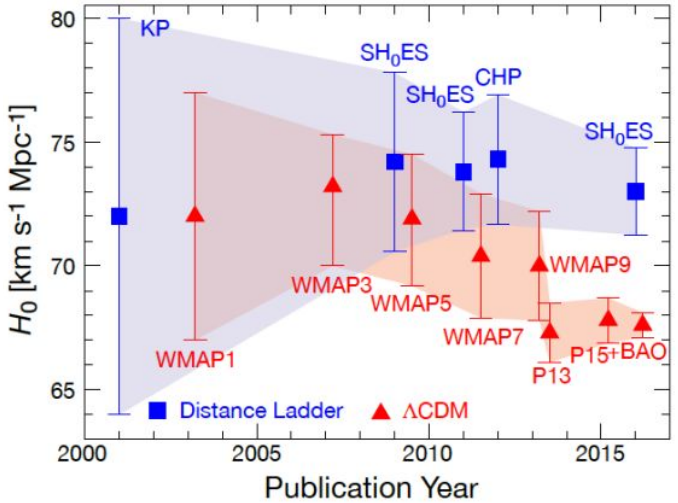


Today's snapshot

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

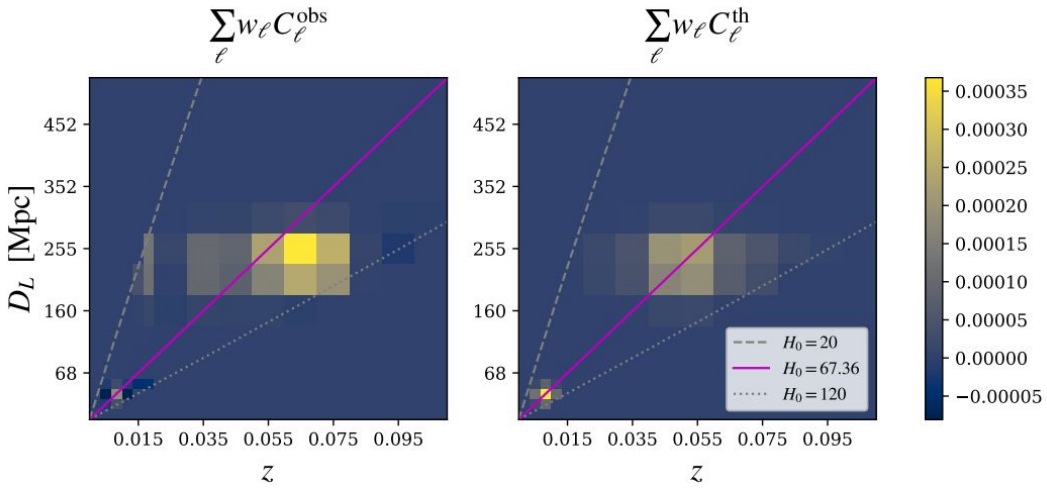




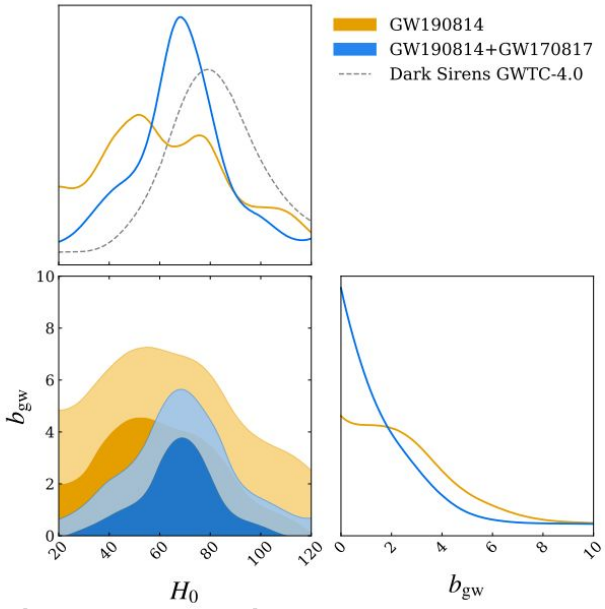
[W. Freedman, Nature Astronomy, 1, 0169 (2017)]

Recent cross-correlation results

There has been recent attempts [Mukherjee, ApJ 2024, Matos+ 2512.15380] to use cross-correlation methods for measuring the Hubble constant.



[Matos+, 2512.15380]



[Matos+, 2512.15380]

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

Perna+, A&A (2024)

Ferraiuolo+, A&A (2024)

Hanselmman+, ApJ (2024)

Global bright and dark siren fit?

Hosting galaxy systematics?

GWs and other LSS tracers relation?

Mancarella+ PRL 2024,Chen+ PRL 2024, Triscari-Benimavo'+ 2609.12053

Agapito+2026, Gray+2026

Dupletsa+2026, Schulz+2026

My personal takes

What have we learnt?

(i) We should calibrate the source-mass of compact binaries, **we are not so different from standard candles** (ii) We are improving precision for galaxy catalogs due to photometric uncertainties (iii) Bright sirens are rare, and we should be careful about their selection biases (iv) describing the CBC rate is of crucial importance.

What did we get wrong?

(i) We did not account for uncertainties in the CBC merger rate (we got a bias!) (ii) We miss modeled the galaxy luminosity functions for many surveys (iii) We trusted bright sirens that were probably not very bright.

Where are we heading?

(i) We need robust blinding strategist, as the rest of observational cosmologist (ii) We need to extract the most of any bright siren (either detected or not) (iii) We should move towards a astrophysically-motivated and flexible CBC rate model (but not so flexible) (iv) we should keep an eye on GW clustering properties.

EM cosmological data is difficult, leave it to your expert colleagues