Population and cosmological properties of compact binary coalesences detected by the LIGO, Virgo and KAGRA collaborations

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ET ITALY Einstein Telescope

VIRGO

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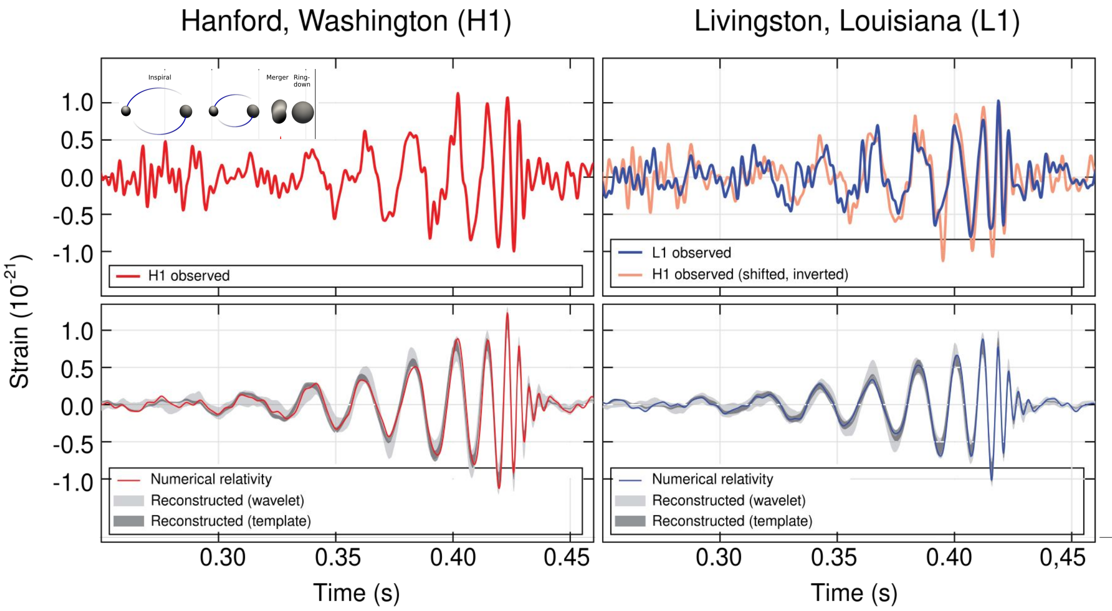
Gravitational Waves 10 years ago

Almost 10 years ago…

- The LIGO and Virgo collaborations reported the detection of a gravitational wave from a binary black hole (BBH) coalescence.
- GW150914: the merger of two almost equal mass BHs of 30 solar masses at 500 Mpc.
- **Amplitude:** Distance, inclination angle.
- **Phase:** Chirp mass

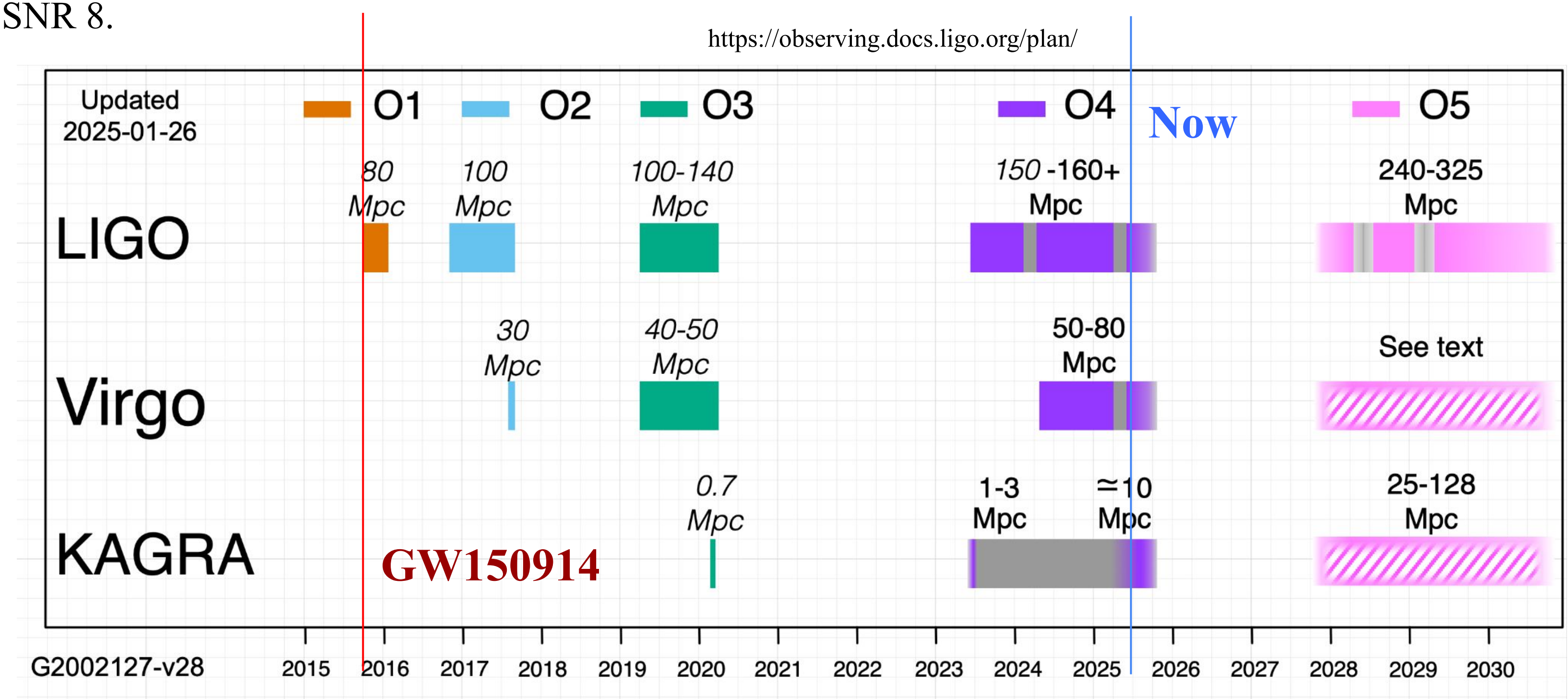


[LIGO and Virgo collaborations, Phys. Rev. Lett. 116, 061102 (2016)]

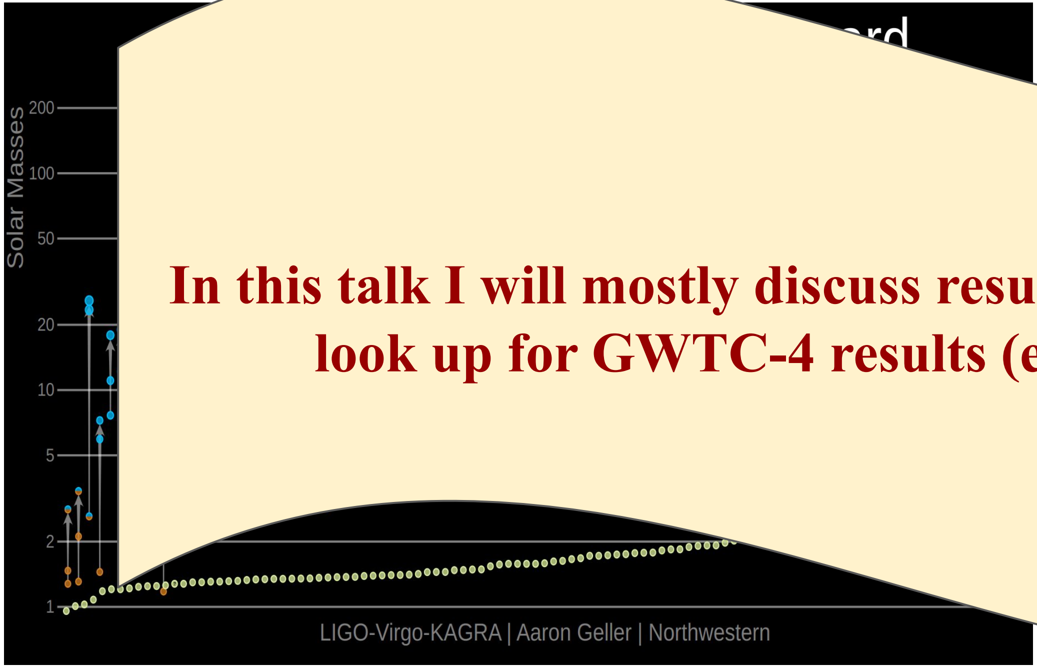
Gravitational Waves today

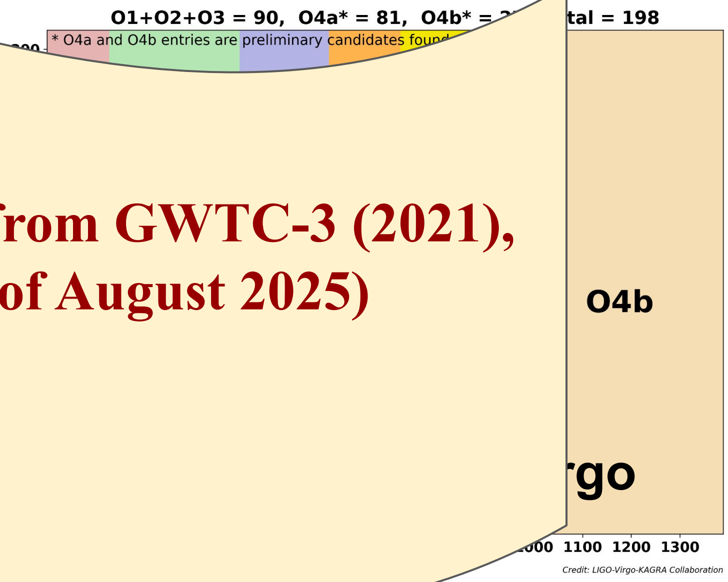
- **Horizon:** Maximum comoving distance at which you would observe a 1.4-1.4 solar masses BNS with SNR 8.

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



Gravitational Waves today





In this talk I will mostly discuss results from GWTC-3 (2021), look up for GWTC-4 results (end of August 2025)

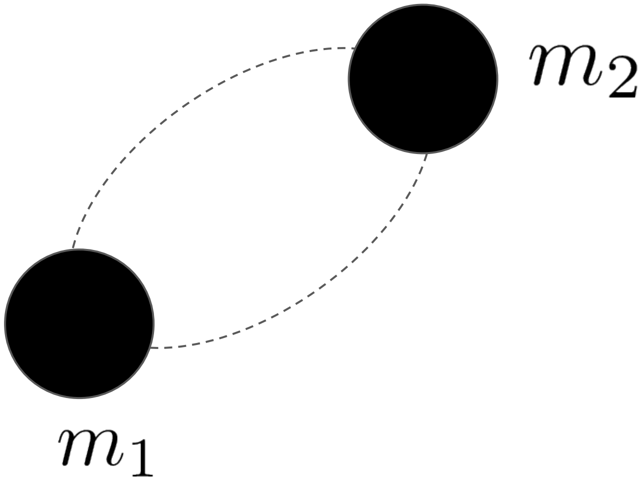
Credit: Visualization: LIGO-Virgo-KAGRA / Aaron Geller / Northwestern

Gravitational Waves today

What can we learn from these sources?

- **Astrophysical implications**
  - How compact objects are formed over cosmic time?
  - What are their possible formations channels?
- **Cosmology**
  - Can GWs at cosmological distances help us to leverage open tensions in cosmology?
  - Can we use GWs to probe modified gravity at cosmological scales?

Autopsy of a Binary



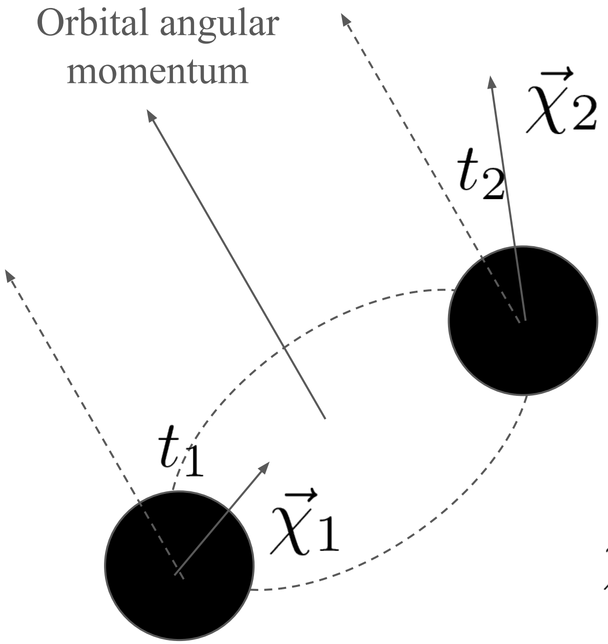
$$q = \frac{m_2}{m_1}$$

Mass ratio

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Chirp Mass

Autopsy of a Binary



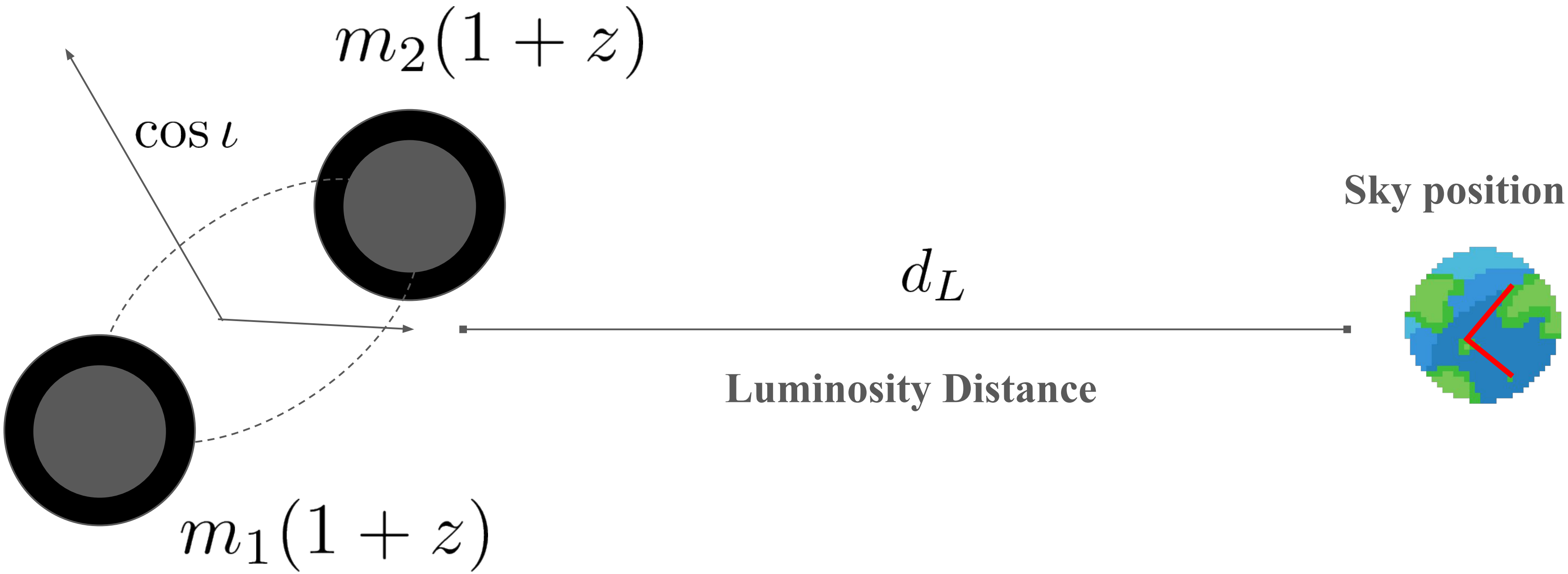
$$\chi_{\rm eff} = \frac{\chi_1 \cos t_1 + q\chi_2 \cos t_2}{1+q}$$

Effective spin parameter

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

Precessing spin parameter

Autopsy of a Binary: Cosmology

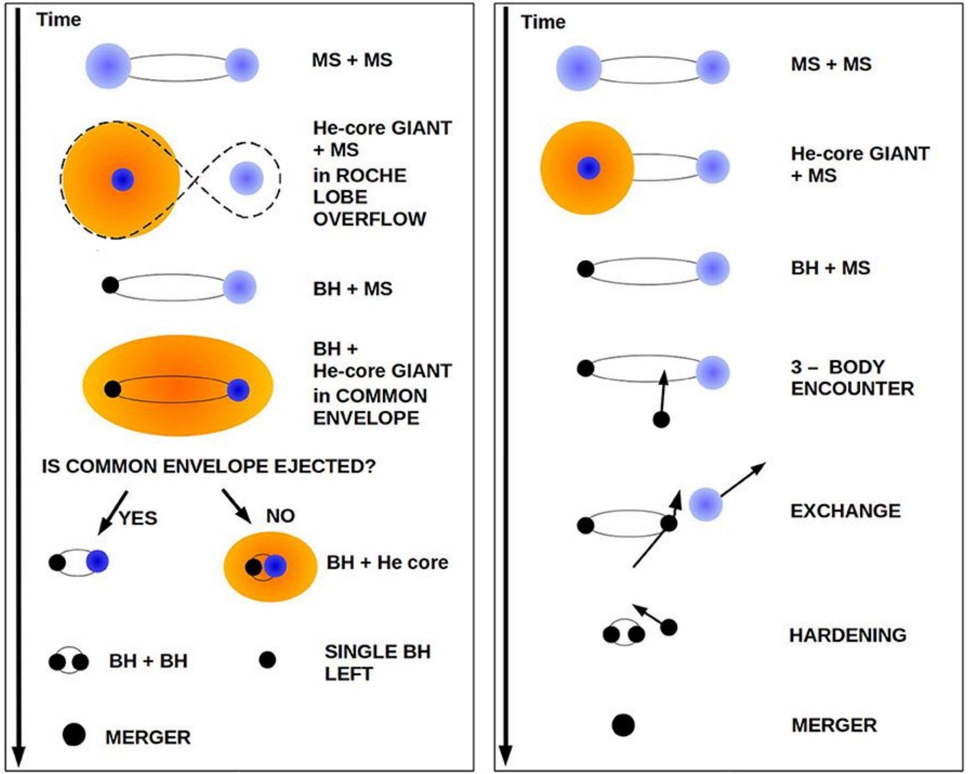


Correlations among parameters?

[Mapelli M. Handbook of Gravitational Wave Astronomy]

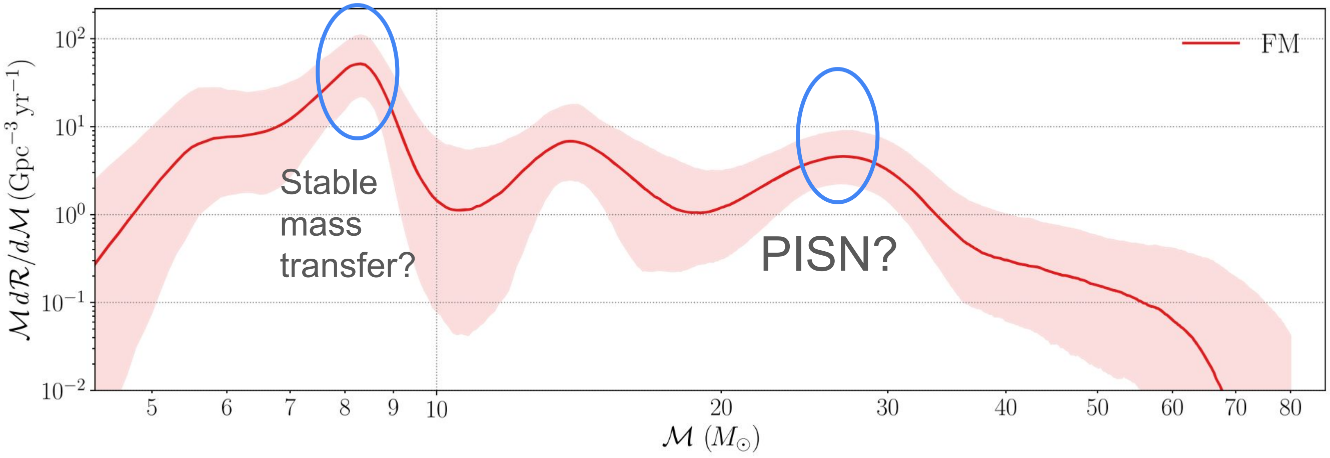
Two main formation channels:

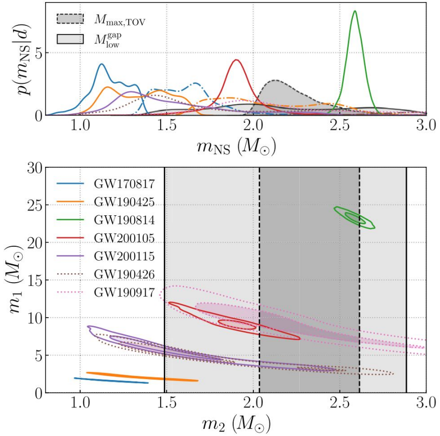
- **Isolated stellar binary evolution**
  - Formed by massive stellar binaries.
  - Low-mass (<40 solar masses) BHs with aligned spins.
  - Preference for high metallicity Milky way like galaxies
- **Dynamical formation:**
  - Formed in dense stellar environments.
  - Possibly n-th generation black holes (spin~0.7) with isotropic spins.
  - Might prefer metal-poor regions.



The mass spectrum

- The BBHs mass spectrum has at least two statistically significant overdensities.
- Equal-mass binaries are more likely to be formed.
- There are compact objects formed in the NS-BH mass gap. No significant evidence for the presence of a mass gap between NSs and BHs.





LVK, Physical Review X 13, 011048 (2023)

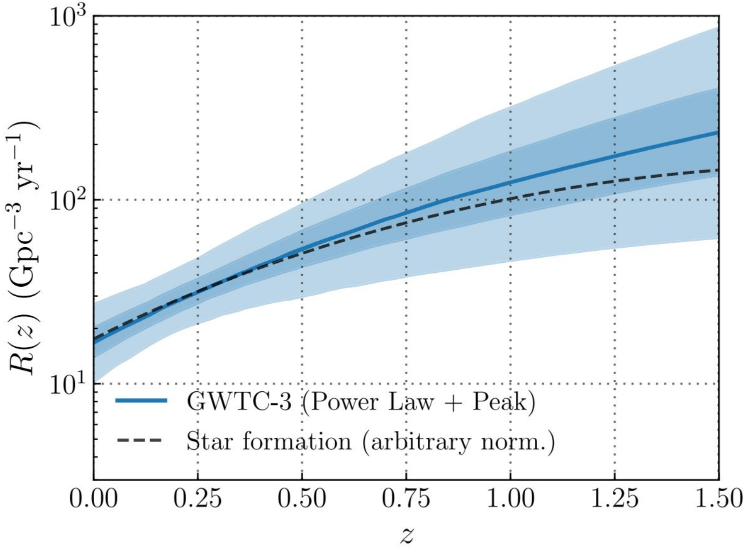
The merger rate

- The **BBH merger** rate today is about 20 mergers per Gpc^{-3} yr^{-1} and it seems to be evolving in cosmic time.

- The **BBH merger** rate seems to track the star formation rate. Although more data is needed to reach conclusive evidence.

- The rate of **BNS mergers** is weakly constrained (90% CI) 10-1700 Gpc^{-3} yr^{-1}, no constraint on its redshift evolution.

- The rate of **NSBH mergers** is weakly constrained (90% CI) 7.8-140 Gpc^{-3} yr^{-1}, no constraint on its redshift evolution.

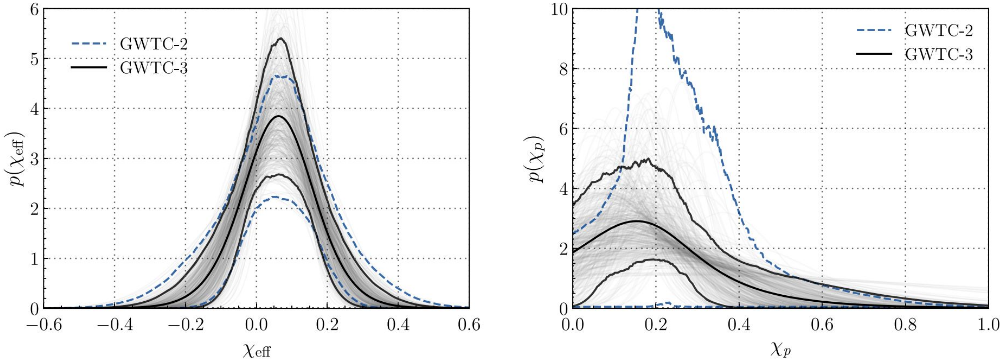


LVK, Physical Review X 13, 011048 (2023)

The spins

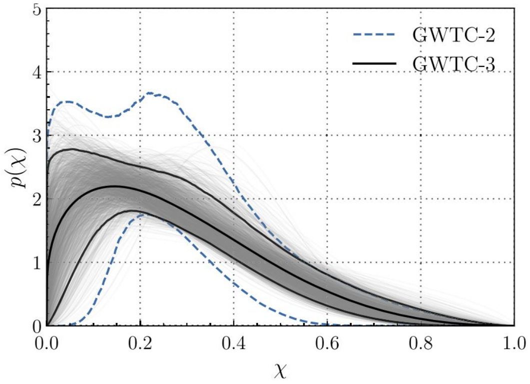
- Overall what we can say about spin distributions is still pretty poor due to our limited precision on spins determination.

- It appears that the BBHs tend to prefer to have spins slightly aligned with the orbital angular momentum.



- No evidence for a population of strongly precessing binaries (spin-induced).

- Spin magnitudes are generally small supporting values ~ 0.2

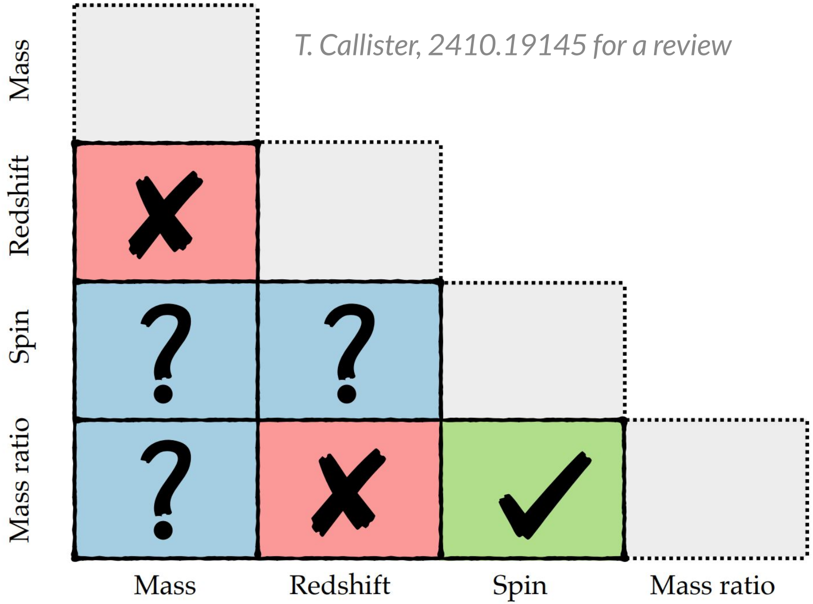


LVK, Physical Review X 13, 011048 (2023)

Correlations among parameters?

- **Confident:**
  - BBHs with more unequal massive have larger effective spin parameters.
- **Tentative:**
  - BBHs with masses above 35 solar masses have a more rapid spin distribution (~0.7).
  - The distribution of effective spin likely broadens with redshift.
  - Lower mass black holes prefers an equal mass companion.

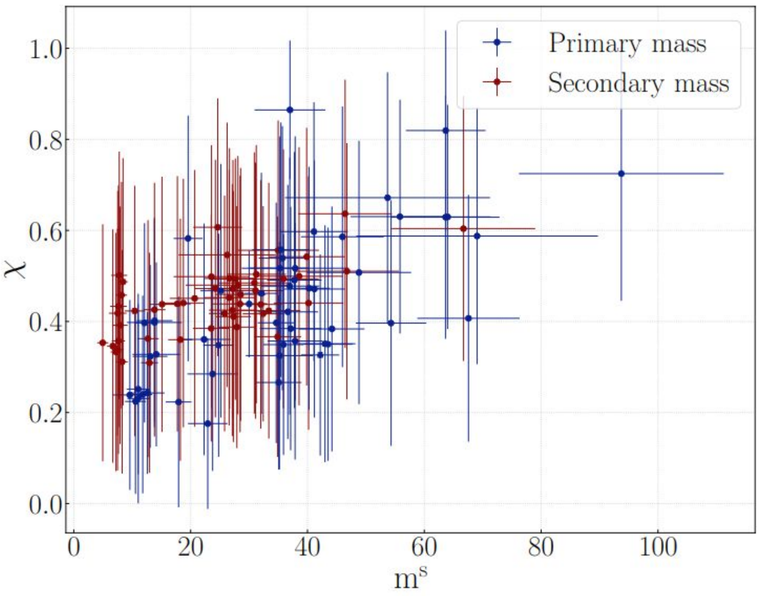
Not found: Evidence for evolution in redshift of mass spectrum and mass ratio.



T. Callister, 2410.19145 for a review

Correlations among parameters?

- The spin magnitude of Binary Black Holes is a smoking gun to distinguish astrophysical formation channels.
- Effective spin correlates with mass ratio. What about mass?
- We look at spin magnitudes correlation with mass as they are a clearer estimator for the presence of dynamically assembled mergers.
- **Is there a transition from two spin populations in terms of mass?**



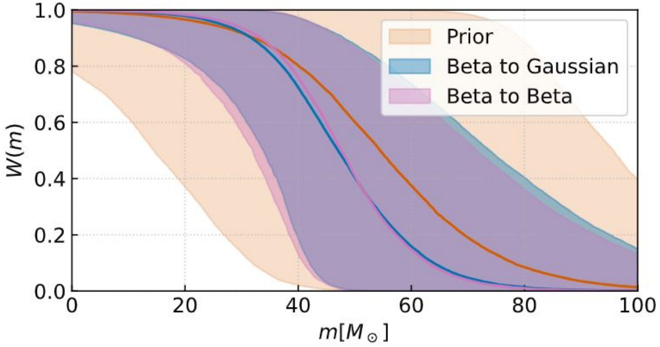
*[Pierra, **SM**, Perries A&A 692 (2024)]*

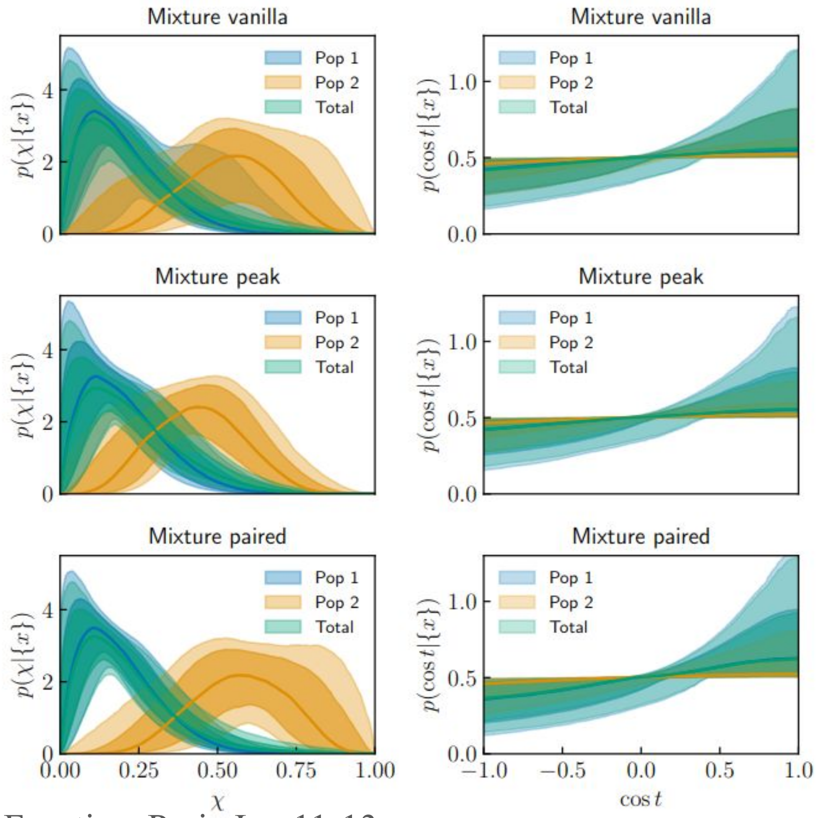
Correlations among parameters?

[Pierra, **SM**, Perries A&A 692 (2024)]

- We obtain that 98% of events is formed from a population with **low masses** (up to 40-60 solar masses) with **low spins**.

- We obtain that 2% of the population has masses **above** 40-60 solar masses and spins **supporting** 0.7. There is also a hint for a more isotropic distribution.





Cosmological tensions

- **The Hubble constant tension:** Do we really know all the engines driving the Universe expansion? [Hill et al., PRD 105 (2022)].

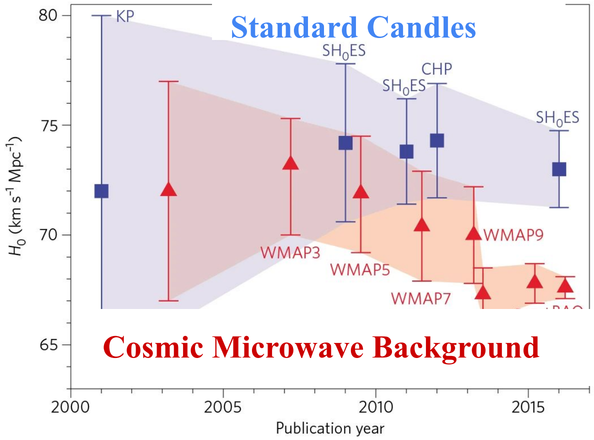
- **The nature of Dark Energy**: How does it behave? What is its Equation of state?

Limitations for current cosmic probes

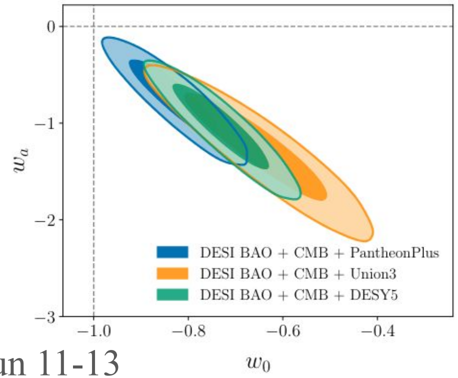
- **Standard Candles:** Only local Universe and require calibration.

- **Cosmic Microwave Background:** Only one, most of information already extracted.

W. L. Freedman, Nature Astronomy, 0121 (2017)



DESI collaboration, JCAP 02 (2025) 021



Cosmology with LVK data

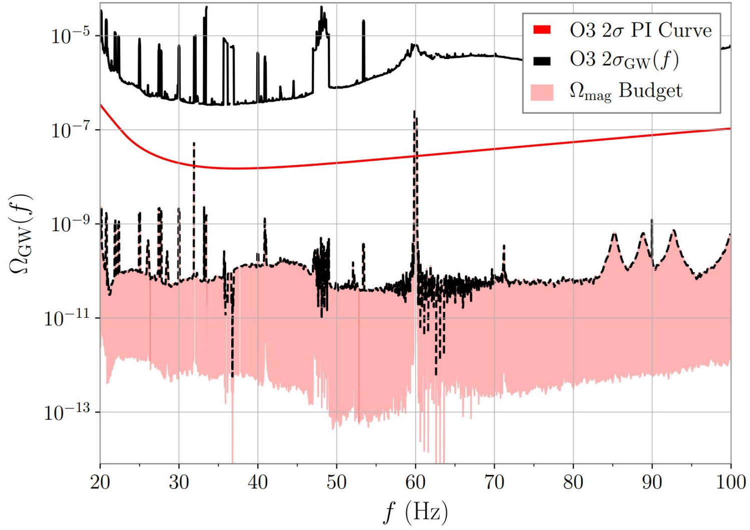
You can find two threads of "cosmological" implications with LVK data

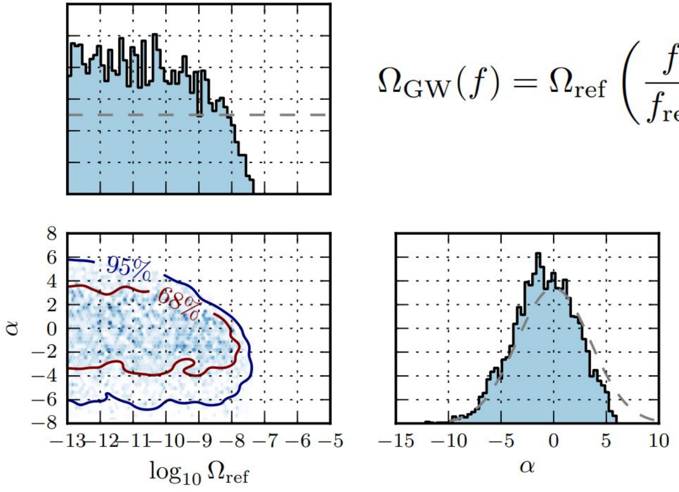
- **Upper-limits from the Stochastic GW Background:** GW energy spectrum (istropic [2101.12130] and directional [2103.08520]), implications for cosmic strings [2101.12248] and dark photons [2105.13085], upper limits on CBC merger rates and astrophysical backgrounds.

- **Constraints from resolved CBCs:** Constraints on the cosmic expansion [1710.05835, 1908.06060, 2111.03604] and population properties. [2010.14533, 2111.03634].

Stochastic GW background

We can obtain upper-limits on the GW energy density and use it to constrain your preferite theory. Upper-limit currently at the 10^{-8}.

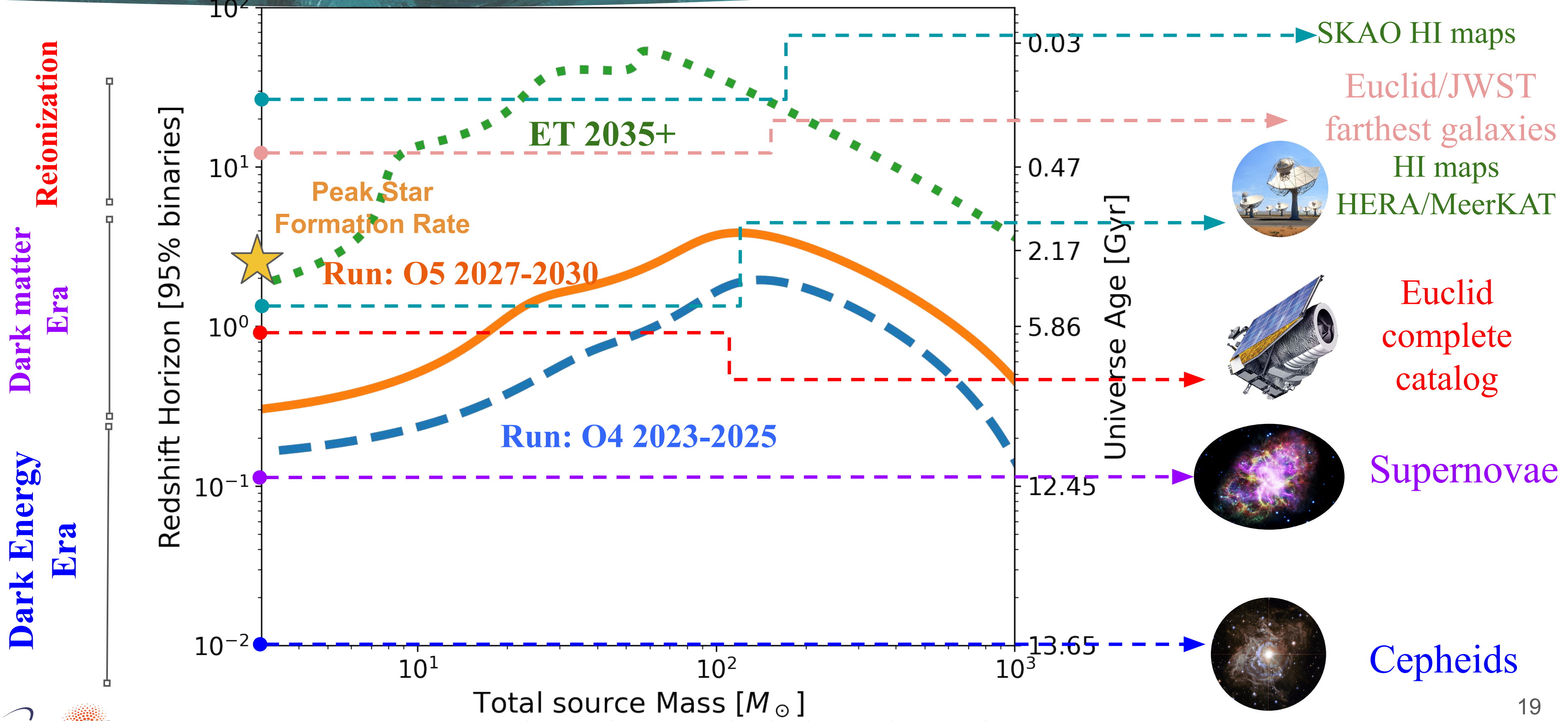




$$\Omega_{GW}(f) = \Omega_{ref}\left(\frac{f}{f_{ref}}\right)^{\alpha}$$

LVK, Phys. Rev. D 104, 022004 (2021)

Resolved GW sources



Dark sirens cosmology

Gravitational Waves (GWs) from Compact Binary Coalescences (CBCs): new cosmological sources

👍 Distance - directly provided by GWs

👎 Redshift (Escape velocity) - not provided by GWs

Black holes astrophysics

Spectral Sirens

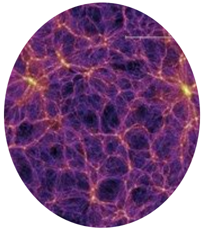
SM+, PRD 104 (2021)

Galaxy surveys

Catalog Sirens

SM+, PRD 108 (2023)

Large scale structures (LSSs)



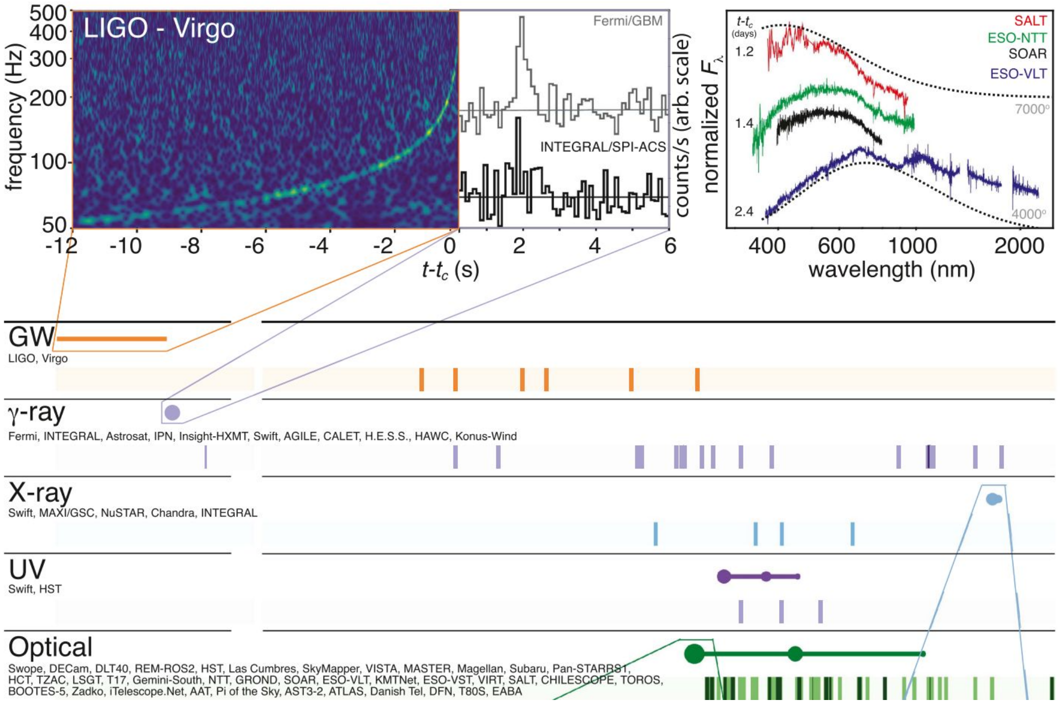
Namikawa PRL 116 (2016)

GW/EM time delay

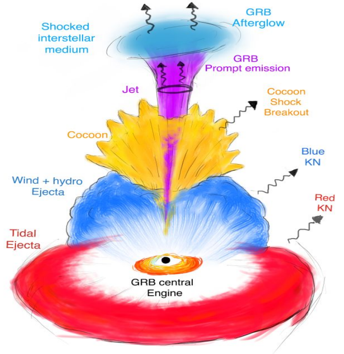
Lagging sirens

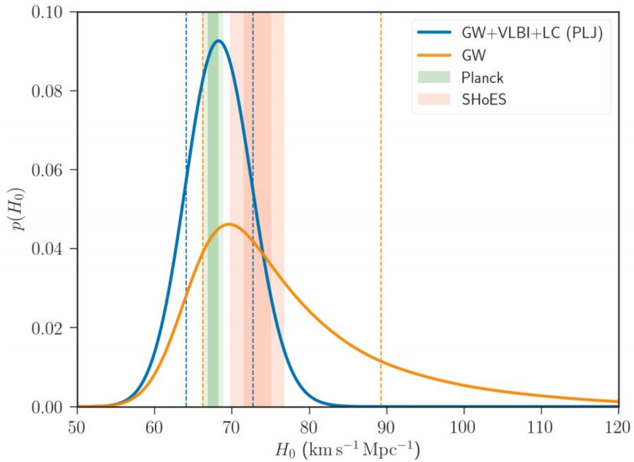
Iampieri L., **SM** PRD 2025

GW170817: The only bright sirens



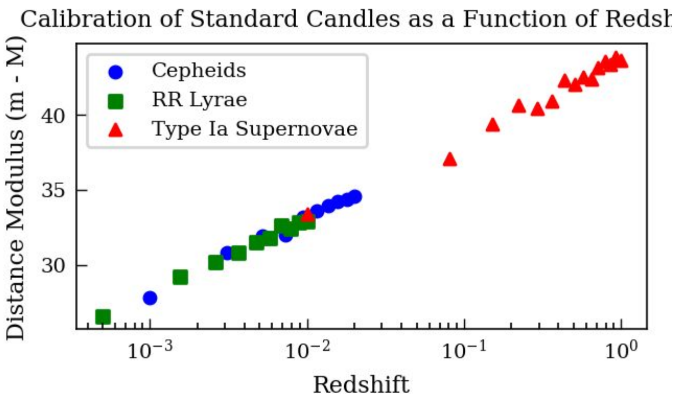
LV+ many EM observers ApJL, 848:L12, 2017

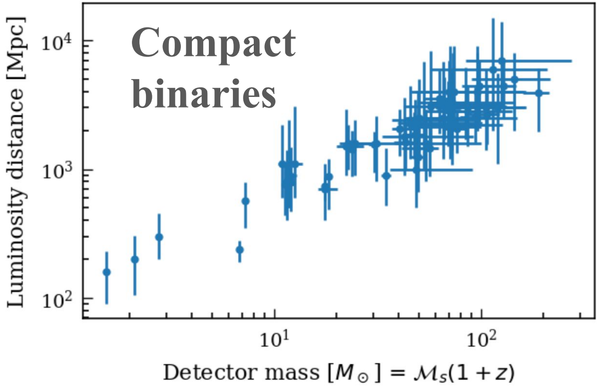




[K. Hotokezaka, Nature Astronomy, 3(2019)]

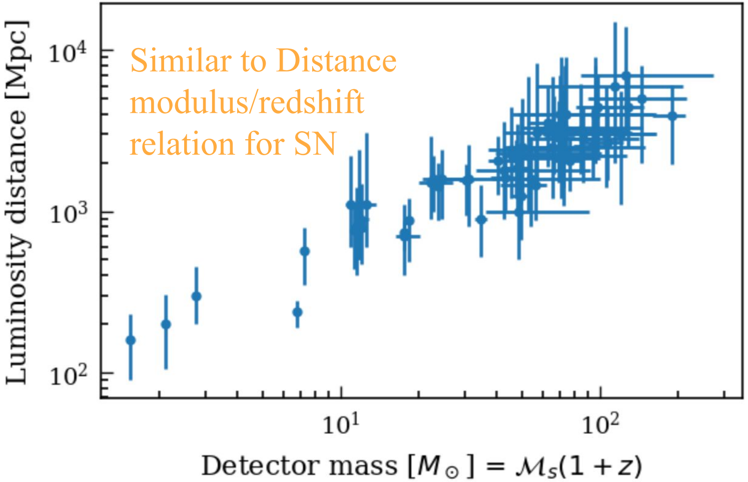
Dark sirens cosmology: Masses





Dark sirens cosmology: Masses

LVK+, Phys. Rev. X; 13(4):041039; 2023



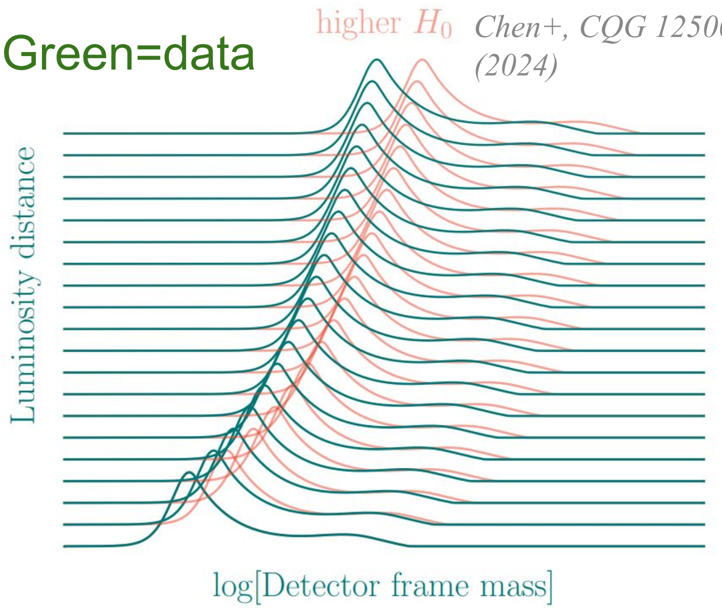
Cosmology

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

Selection bias

Green=data

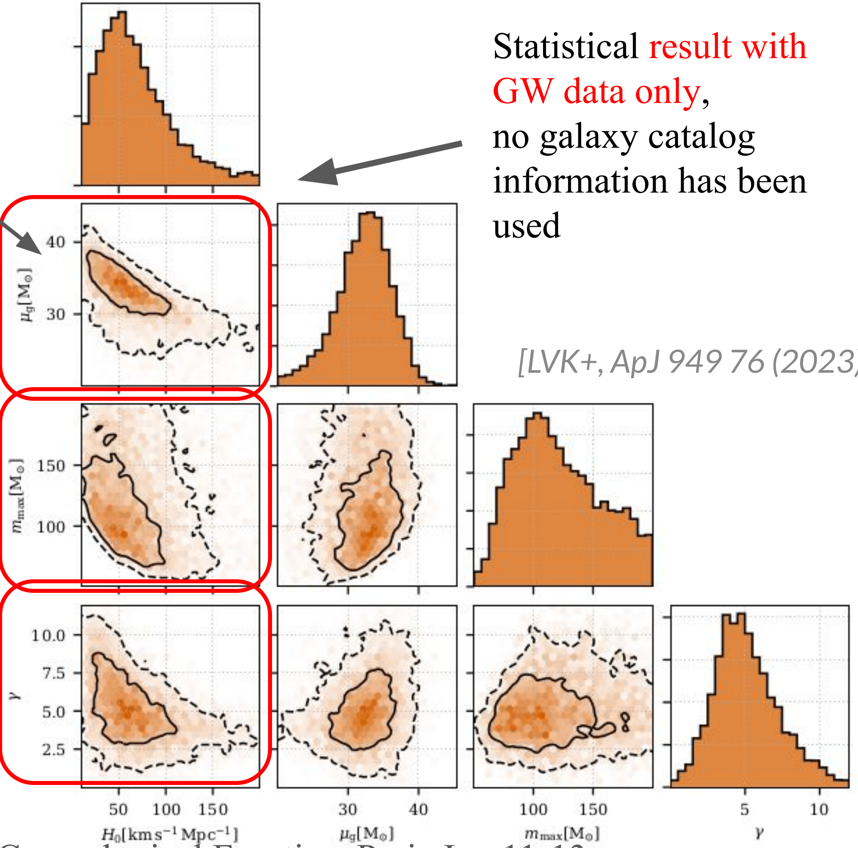
Chen+, CQG 125004 (2024)



Dark sirens cosmology: Masses

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

Population parameters that correlate with H0

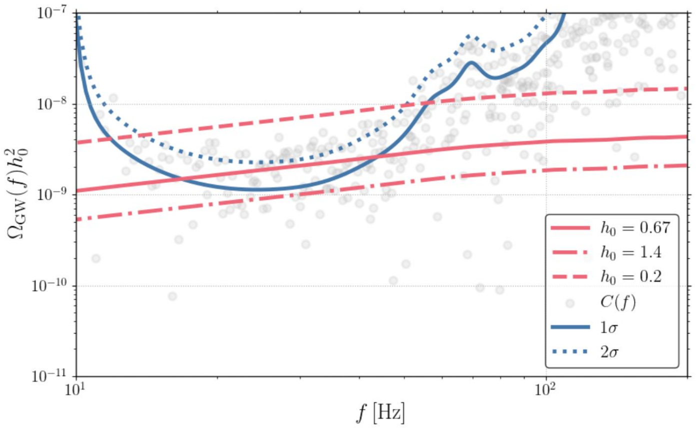


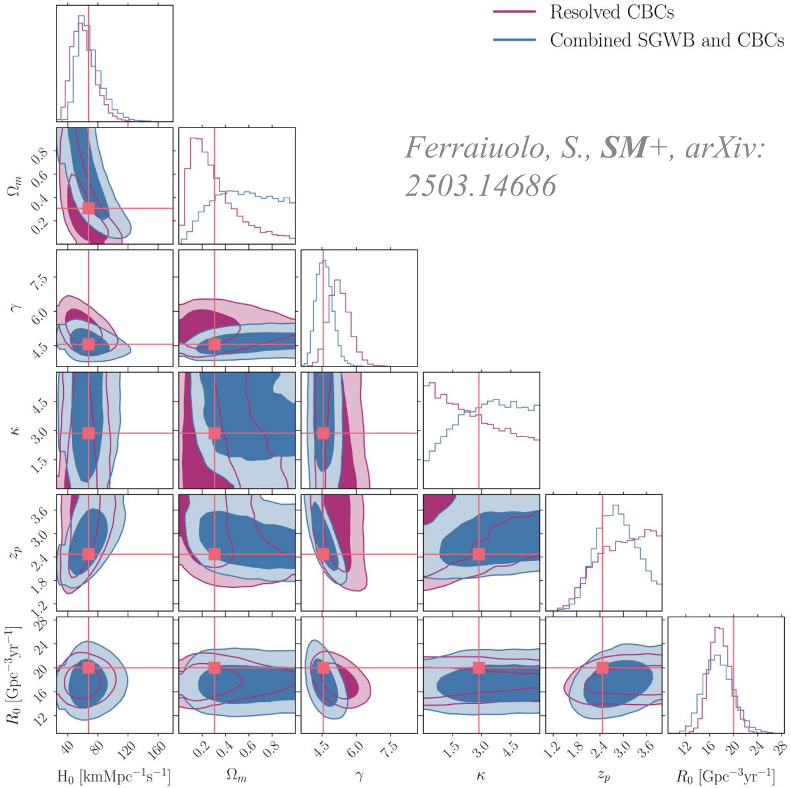
Statistical result with GW data only, no galaxy catalog information has been used

[LVK+, ApJ 949 76 (2023)]

Dark sirens cosmology: Stochastic

- The stochastic GW background from unresolved sources can improve the H_0 inference.
- We find that a 5-detector network with O5 sensitivities will be able to exclude additional regions in the $H_0/\boldsymbol{\Omega}_m$ plane.

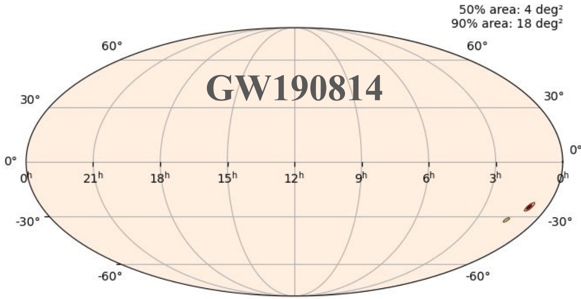


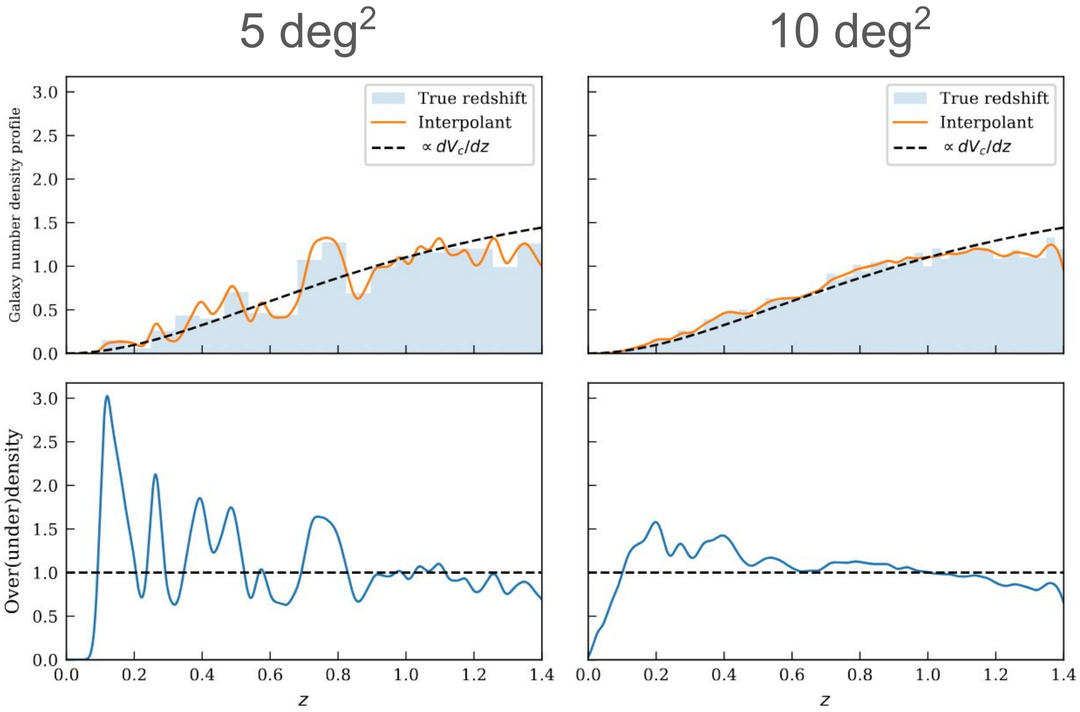


*Ferraiuolo, S., **SM**+, arXiv: 2503.14686*

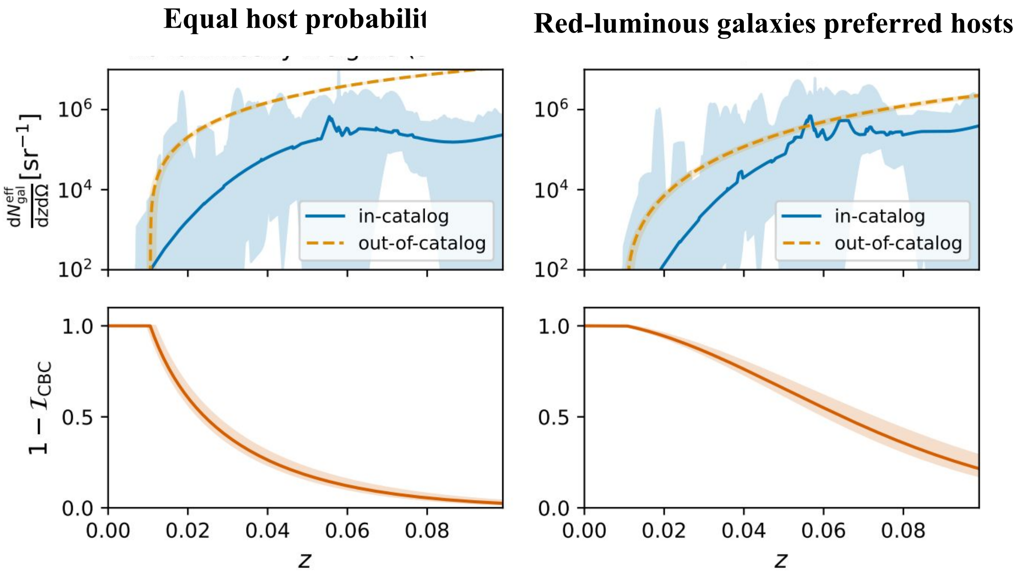
Dark sirens cosmology: Galaxies surveys

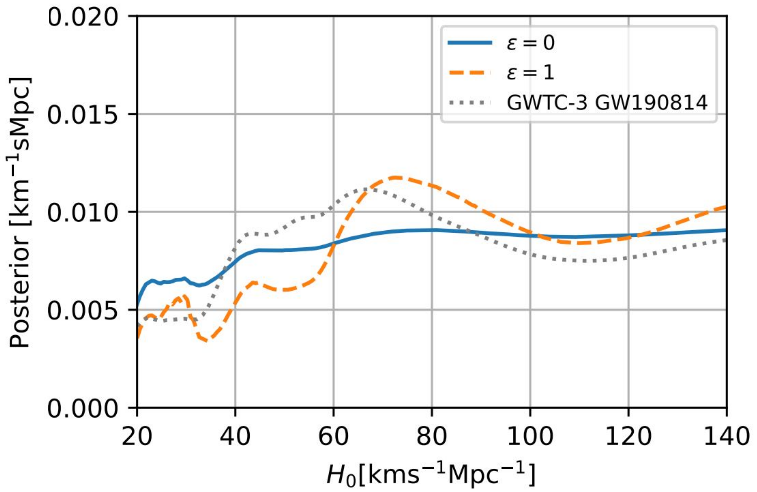
- A cosmological model has statistical support when the GW localization matched an *overdensity* of galaxies.
- Galaxy catalogs are not complete at higher redshifts, we need to apply corrections in order to now bias our analyses *[R. Gray+, PRD (2019), Gair, **SM**, AJ (2022)].*





Dark sirens cosmology: Galaxies surveys





*[**SM**+, PRD 108 (2023)]*

Dark sirens cosmology: Galaxies surveys

CBC per galaxy per year

$$\frac{dN_{\rm CBC}(\Lambda)}{dz d\vec{m} d\vec{\chi} d\Omega dt_s} = R^*_{\rm gal,0}\psi(z;\Lambda)p_{\rm pop}(\vec{m},\vec{\chi}|\Lambda)\times$$

Term similar to the vanilla rate

$$\left[\frac{dV_c}{dz d\Omega}\phi_*(H_0)\Gamma_{\rm inc}(\alpha+\epsilon+1, x_{\rm max}(M_{\rm thr}), x_{\rm min}) + \right.$$

Integral of Schecter function

Number density of galaxies per steradian (completeness correction)

$$\left.\frac{1}{\Delta\Omega}\sum_{j=1}^{N_{\rm gal}(\Omega)} f_L(M(m_j,z);\Lambda)p(z|z^j_{\rm obs},\sigma^j_{\rm z,obs})\right]$$

Number density of galaxies per steradian (catalog)

Luminosity weight

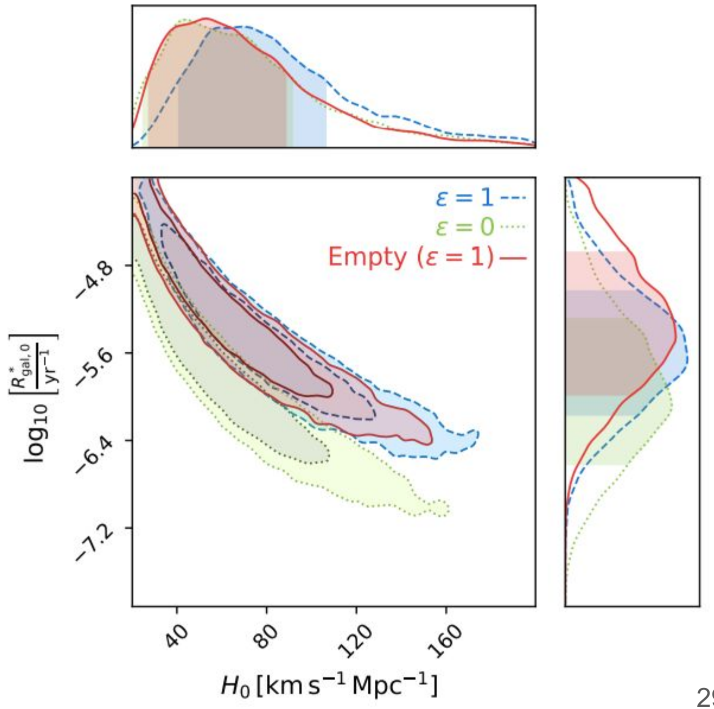
Galaxy localization in redshift

Sky pixel area

Dark sirens cosmology: Galaxies surveys

*[**SM**+, PRD 108 (2023)]*

- **Hubble constant posterior for 42 GW events with SNR>11 using galaxy catalogs and marginalizing over all population assumptions.**
- The inference is dominated by the population assumptions and not the galaxy catalog



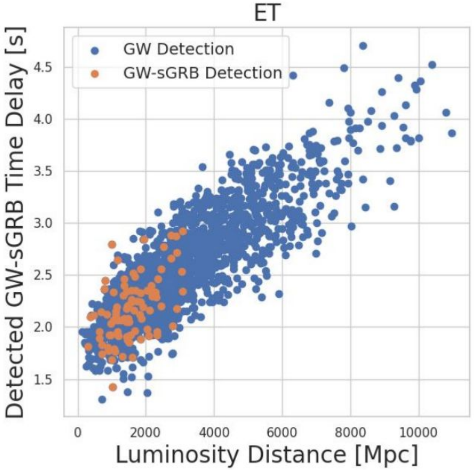
Lagging sirens: Almost multi-messenger

We can also use the observed time delay between GRBs and GWs to measure cosmology (no spec z)

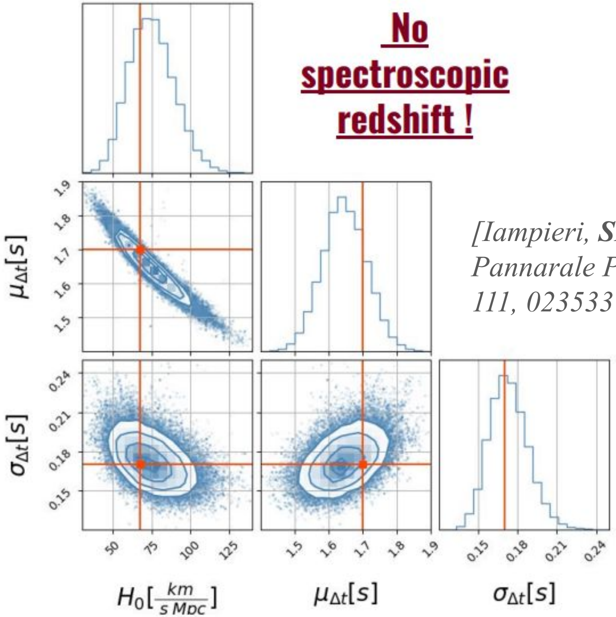
Prompt Time Delay — Speed of Gravity

$$\Delta t_d^{GW-EM} = (1+z_s)\Delta t_s^{GW-EM} + \frac{v_g - c}{c} T_l$$

Observed Time Delay — Cosmological Redshift — Lookback Time



One hundred BNS detected with ET can provide some H0 information even if the host galaxy is not identified.



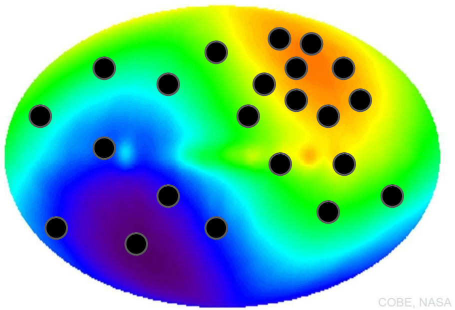
No spectroscopic redshift !

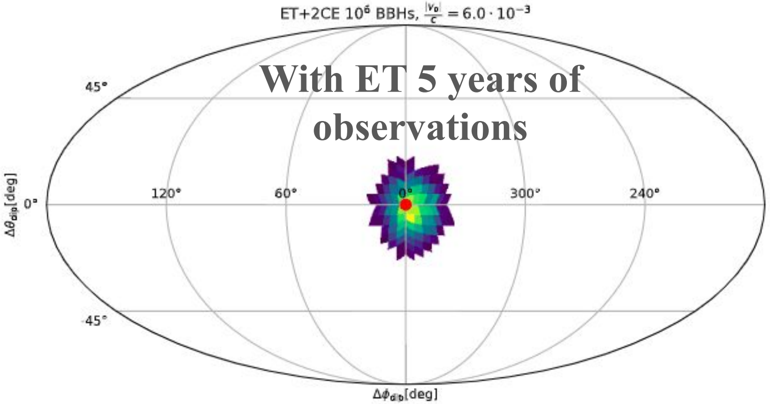
*[Iampieri, **SM**, Pannarale Phys. Rev. D 111, 023533 (2025)]*

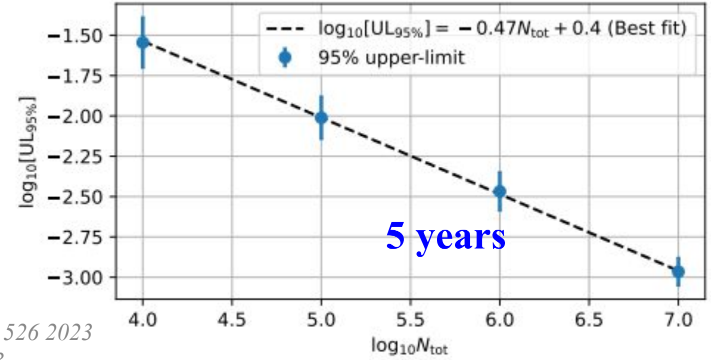
Tests of isotropy

- GW sources can also teach us more about the isotropy of the Universe.
- With 5 years of Einstein Telescope, we will be able to measure the cosmic kinematic dipole.

Apparent distribution of sources







*Grimm N, **SM,** MNRAS 526 2023*
***SM**+, MNRAS 521 2023*

Conclusions

- **Other results I did not mention (due to time)**

    - From GW170817: The speed of gravity has to be equal to the speed of light (precision 10^{-15}).
    - From the farthest BBHs: The upper limit on the mass of the graviton is 1.73×10^{-23} eV/c^2.
    - Consistency of GR between Inspiral and Merger/Ring-down at a precision of 15%.
    - No extra GW polarizations.

- Currently GW population and cosmology studies are starting to explore the question: *What are our systematics?* There is extensive literature in the past two years.

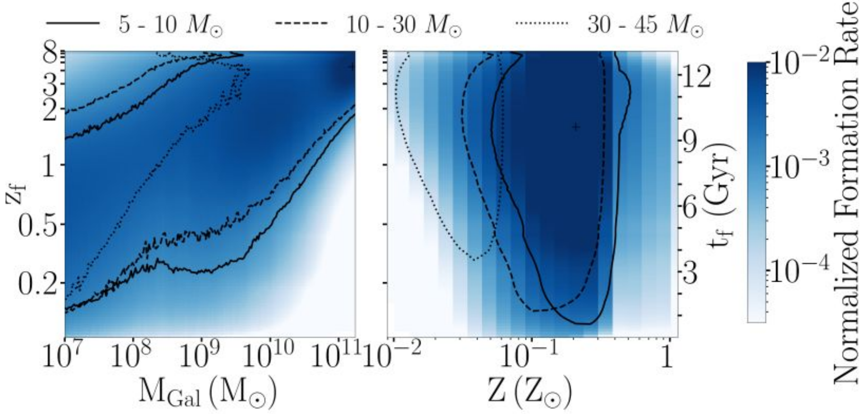
- The next data release is in August 2025: Stay tuned for some surprise. *Spoiler*: No EM counterparts or BNSs.

Back up

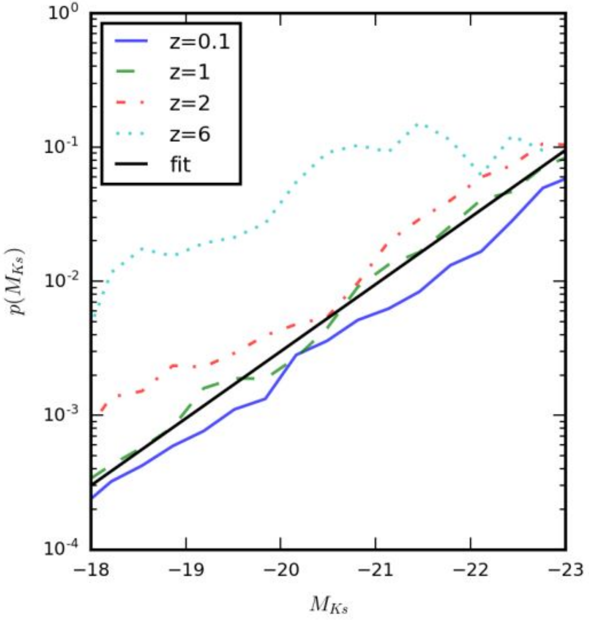
A binary formation

- Merging BBHs are more likely to be **formed** at redshift >2 and found today in massive galaxies.

- Massive galaxies, large stellar mass, larger infrared luminosity.



GW host probability



*[Perna, G., **SM** 2405.07904 (submitted A&A)]*

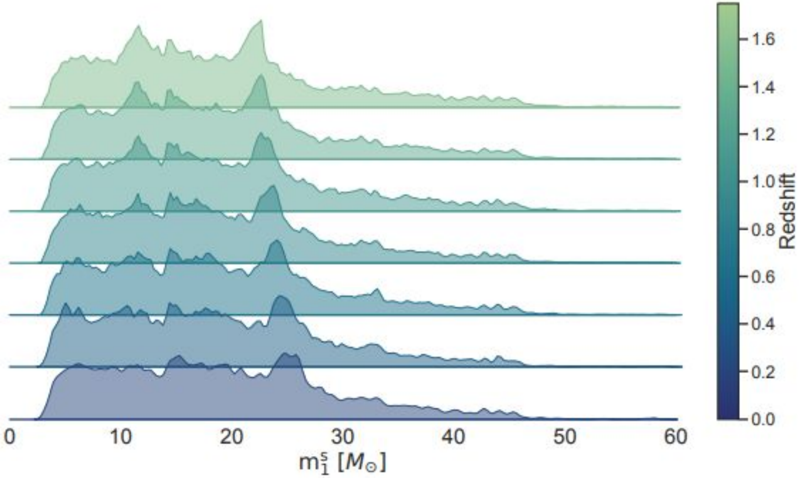
[Artale M.C+MNRAS 495 (2020)]

Spectral sirens: systematics

- We use a synthetic BBH catalog containing 4 different formation channels: isolated binaries and hierarchical mergers in young, globular and nuclear star clusters. [M. Mapelli et al MNRAS 511 (2022)]

- The BBH mass spectrum shows a mild evolution in redshift, in particular in the 10-30 solar mass region.

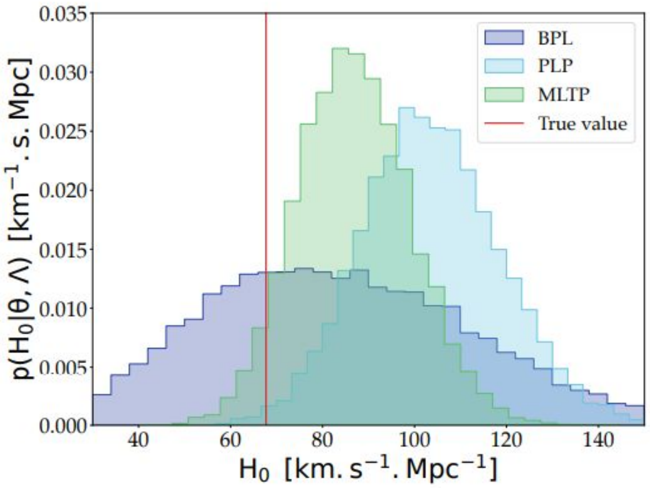
- We simulated 2000 GW detections from the BBH catalog and using simple redshift-independent mass models we inferred the value of H0.



*[G. Pierra, **SM**+, S. Perries, M. Mapelli, PRD 109 (2024)]*

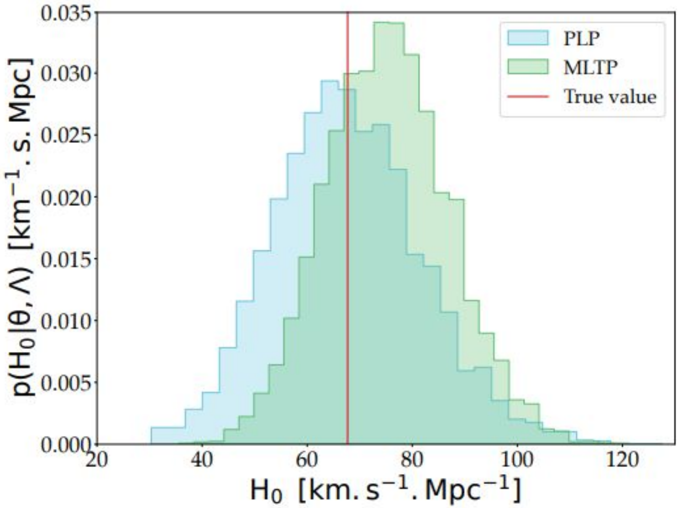
Spectral sirens: systematics

- Redshift-independent mass models with mass features are more prone to systematics when inferring H0



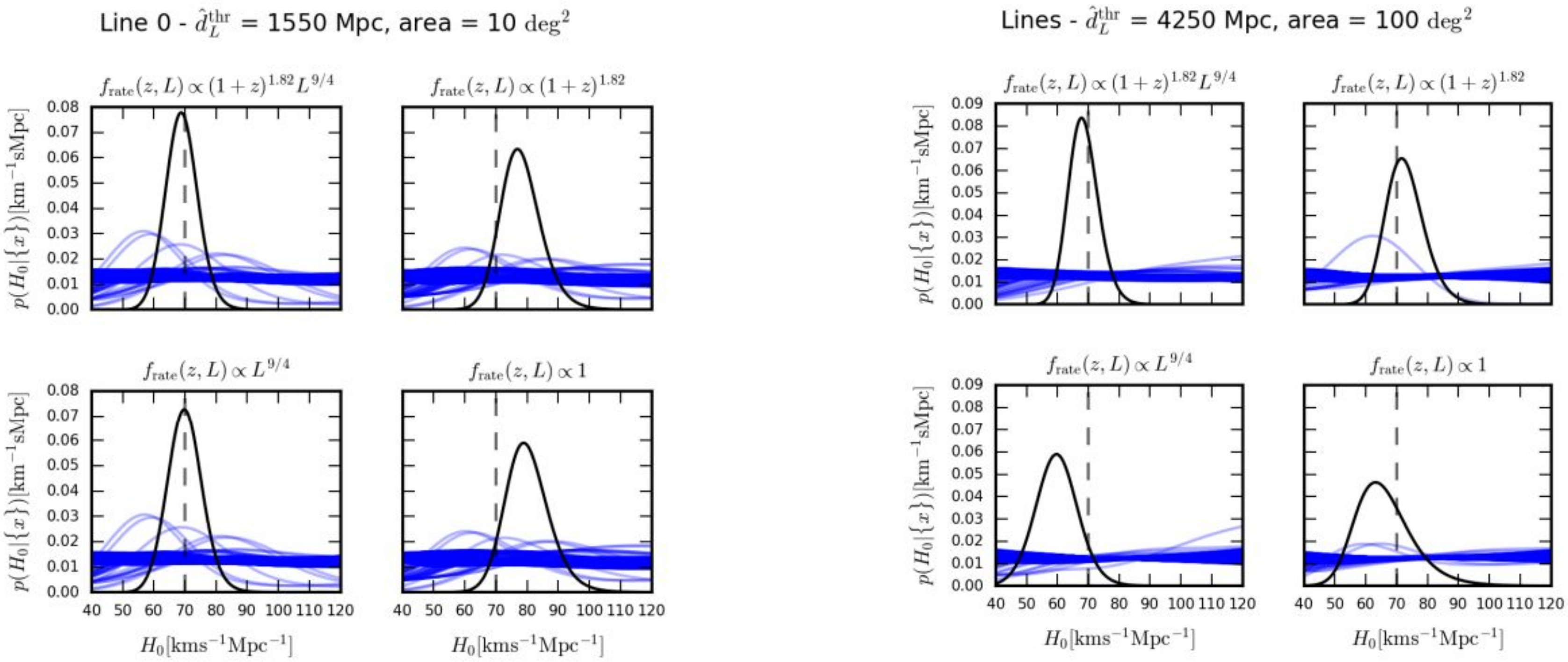
[G. Pierra, ***SM****+, S. Perries, M. Mapelli, PRD 109 (2024)]*

- The bias is removed when removing the mild redshift dependence from the mass spectrum



Catalog sirens: systematics

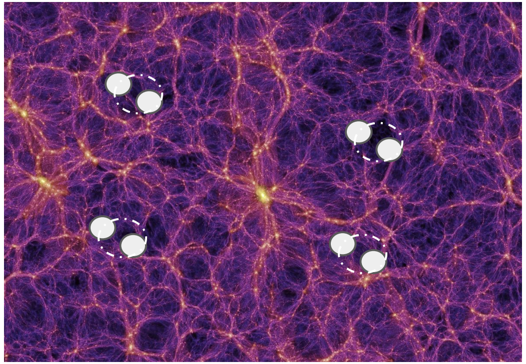
- Luminosity weights can be important for close-by GW events.



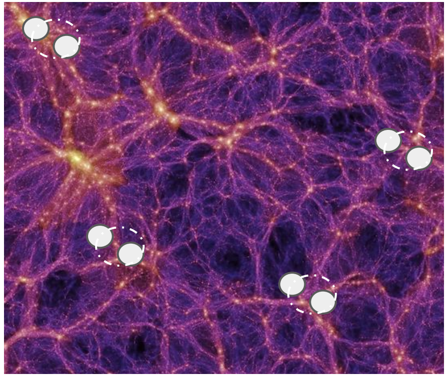
[Perna G., **SM+**, 2405.07904 (submitted A&A) **2024**]

GWs and Large scale structures

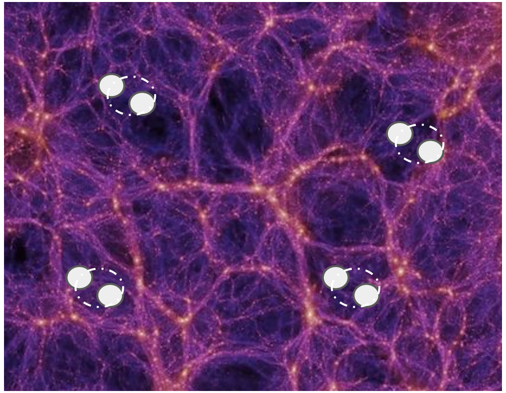
Redshift 0



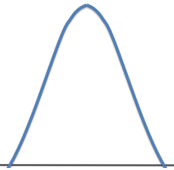
Redshift 1.5



Redshift 2



Possible redshift

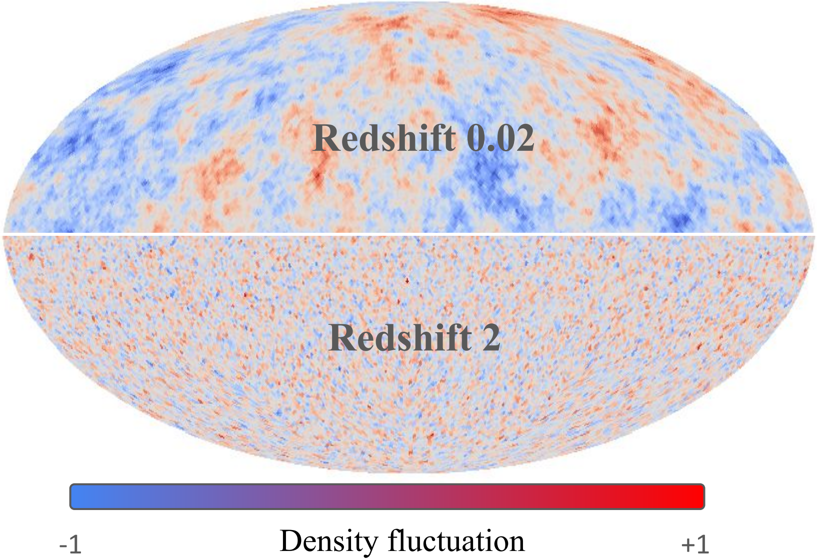


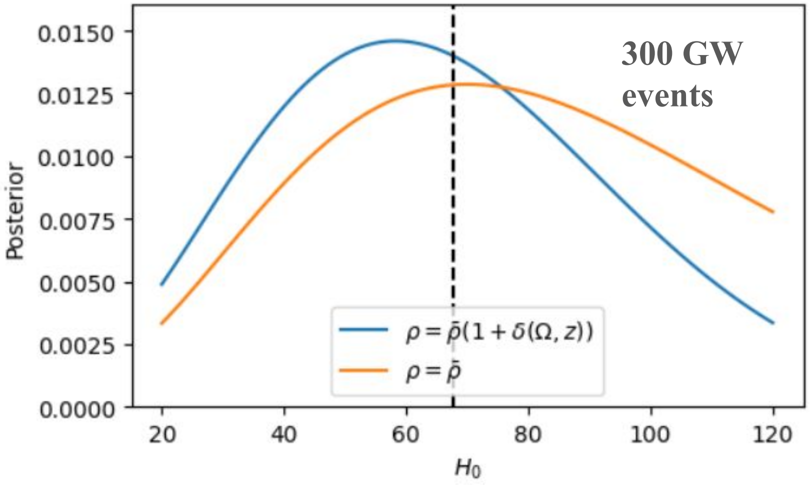
Open question: How does GW track other Large-scale structure tracers? (Mostly galaxy clusters and HI maps)

[S. Libanore et al JCAP02(2021)035, Scelfo JCAP 2020, 2022]

Radio sirens

- Radio observations of HI will provide complete complete maps of matter density up to redshift ~2.
- Density structures can be used to provide implicit redshift information for GW events.





WIP with Dupletsa, Murgia, Spinelli