



# Cosmology and fundamental physics from compact binary coalescences detected by the LIGO, Virgo and KAGRA collaboration

S. Mastrogiovanni

Italian Institute for Nuclear Physics

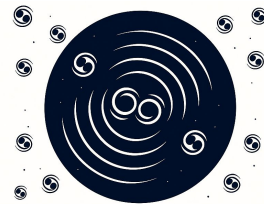
[simone.mastrogiovanni@roma1.infn.it](mailto:simone.mastrogiovanni@roma1.infn.it)



Funded by  
the European Union



European Research Council  
Established by the European Commission



GravitySirens



# The GravitySirens group



S. Mastrogiovanni  
PI



G. Pierra  
Postdoc



A. Colombo  
Postdoc



S. Ferraiuolo  
PhD candidate



L. Iampieri  
PhD candidate



A. Scarpa  
Former Master student



A. Buchicchio  
PhD candidate

# Gravitational Waves

**Gravitational Waves (GWs)** are propagating perturbations in the spacetime metric caused by time-varying mass-energy distributions

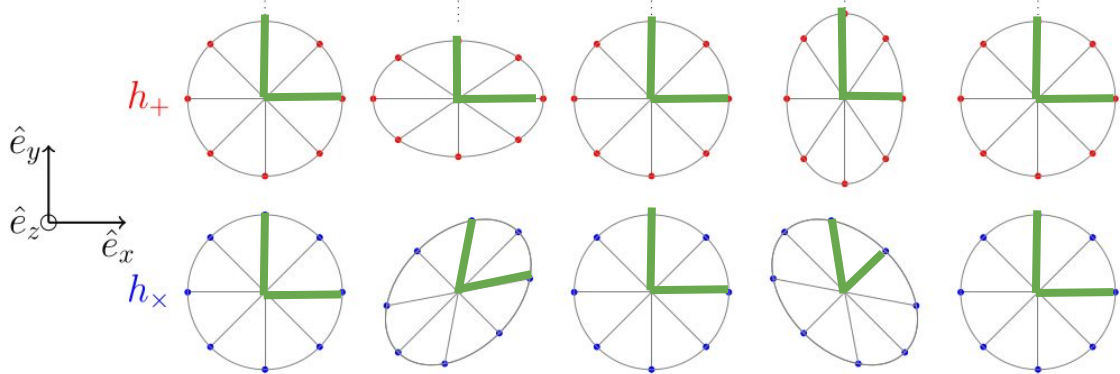
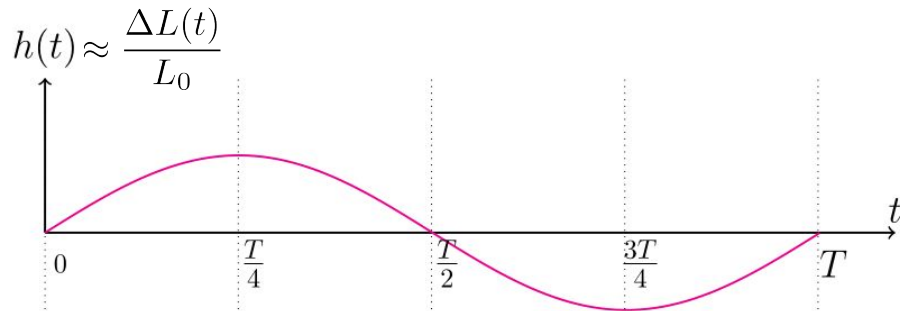
GWs changes the proper distance between two freely-falling test masses and they have two polarizations.

GW

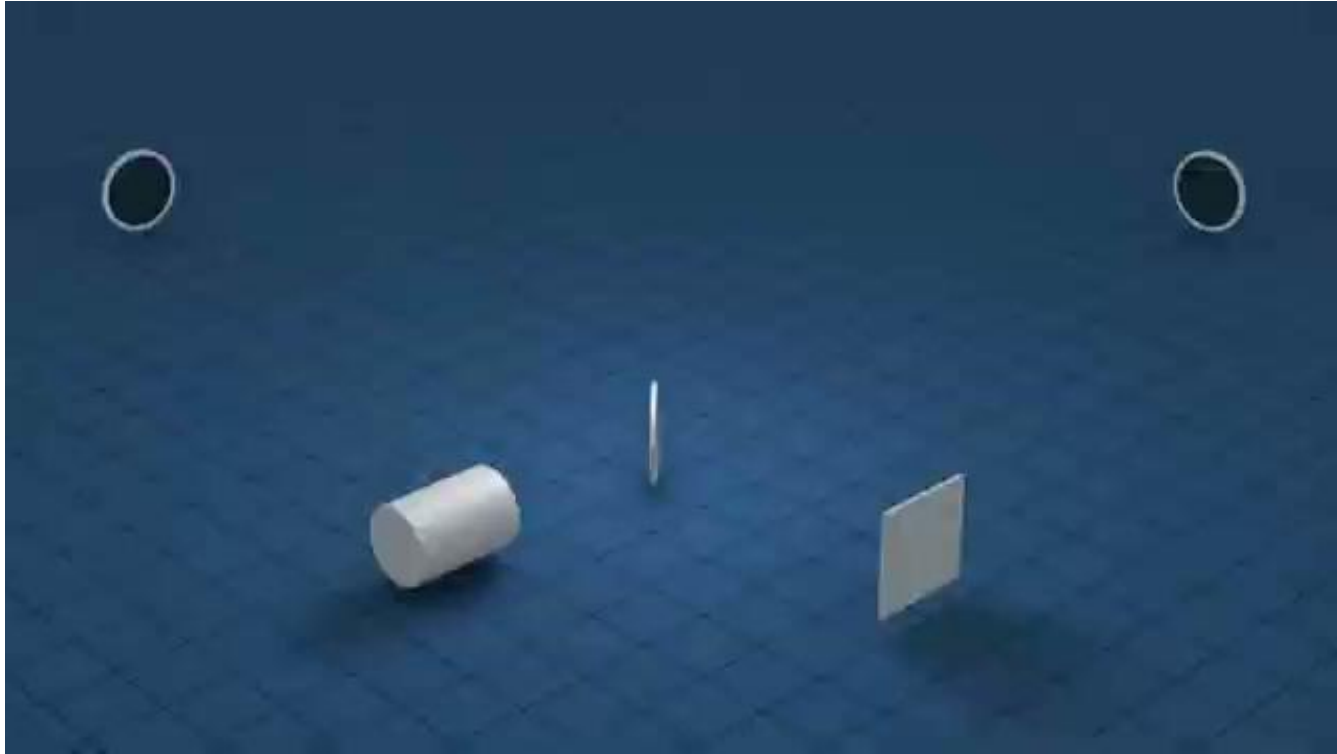
Quadrupole

$$h_{jk}^{\mathbf{TT}}(t, r) = \frac{2G}{c^4 r} \left[ \frac{d^2}{dt^2} Q_{jn}^{\mathbf{TT}} \left( t - \frac{r}{c} \right) \right]$$

$$\frac{8\pi G}{c^4} \simeq 10^{-43} \text{ kg}^{-1} \text{ m}^{-1} \text{ s}^{-2}$$



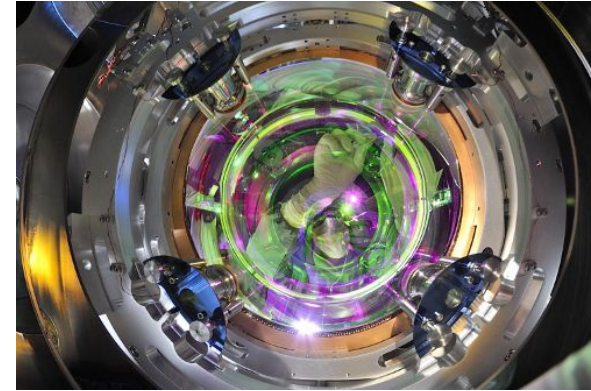
# Gravitational Waves



# Gravitational Waves



**Superattenuators for seismic isolation**

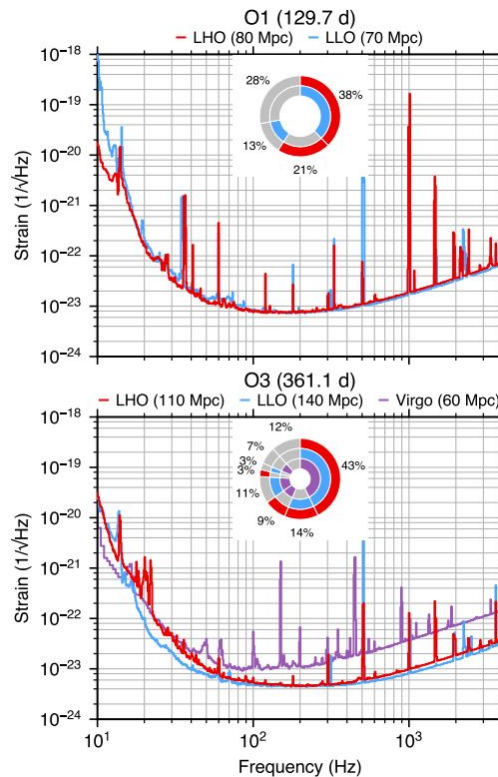


**Mirrors weight 42 kg to reduce the radiation pressure noise**

**Coatings to reach a Finesse of  $\sim 400$**

# Gravitational Waves

- The sensitivity of a GW detector is estimated with the **Power Spectral Density (PSD)**, namely the average fluctuation of the noise in a frequency range.
- LIGO, Virgo and KAGRA have progressively increased their sensitivity.
- Given the sources we are looking for, we can convert the PSD to a detection range.



LVK+ 2508.18080

# Gravitational Waves

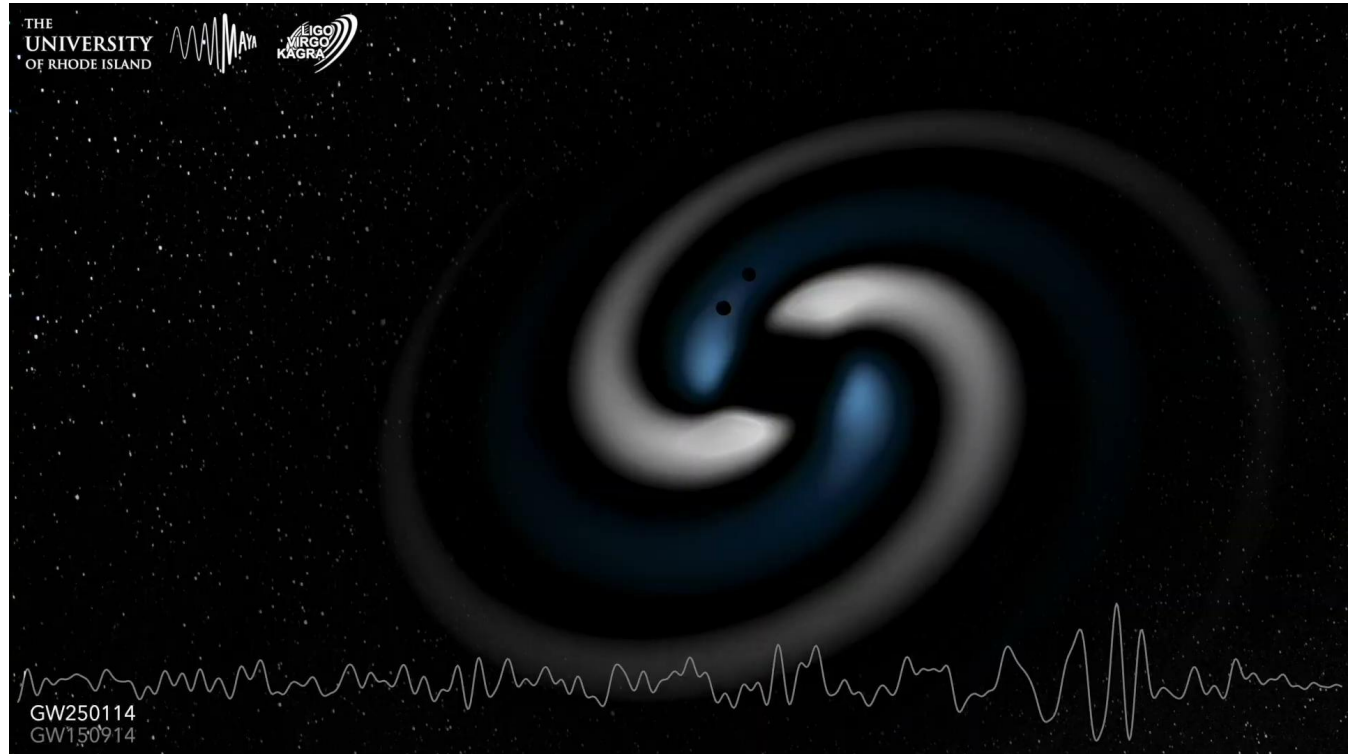


# Gravitational Waves



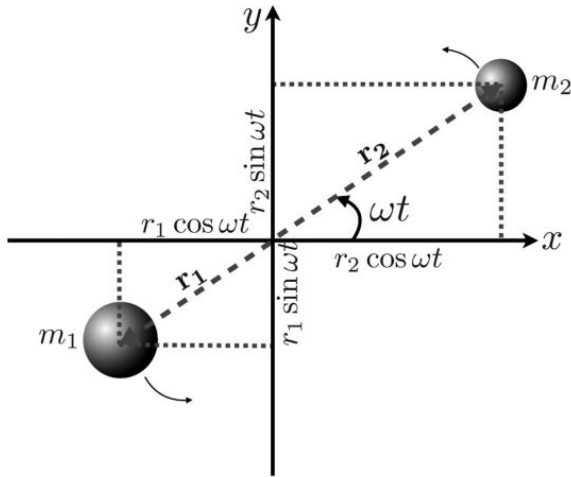
# Gravitational Waves

Here you are  
looking at the  
quadrupolar  
emission ( $l=|m|=2$ )



# Autopsy of a compact binary

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



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

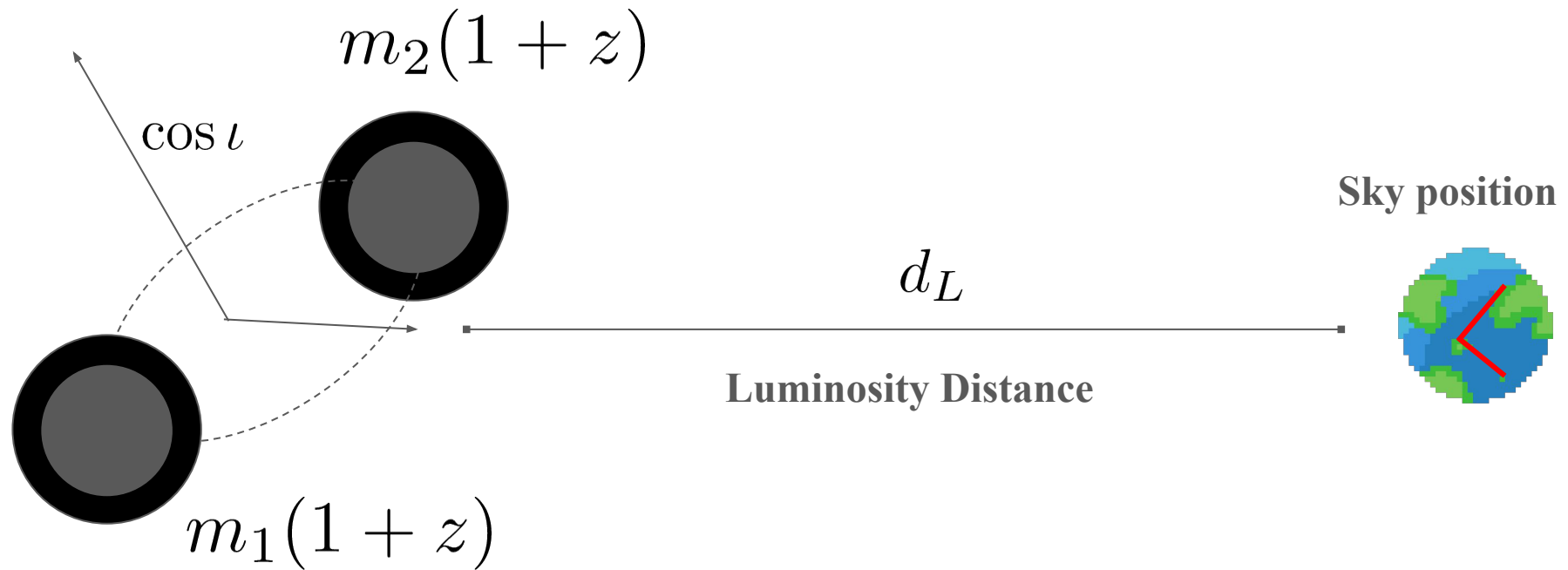
$$\frac{df_s}{dt_s} = \frac{96\pi^{8/3}}{5} (G\mu)^{5/3} f_s^{11/3}$$

GW frequency evolution at source

$$|h| \propto \frac{\mu_s^{5/3}}{d} f_s^{2/3} \sin(\phi_s)$$

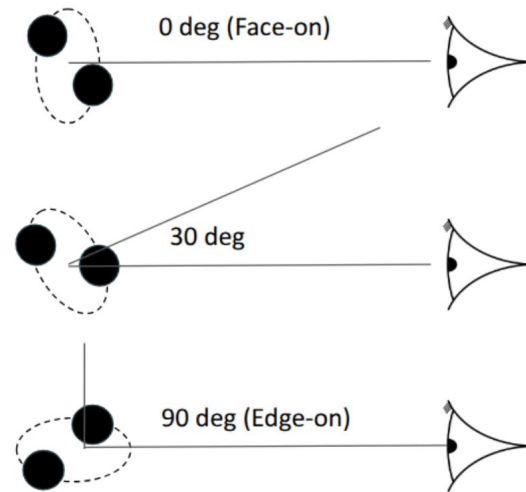
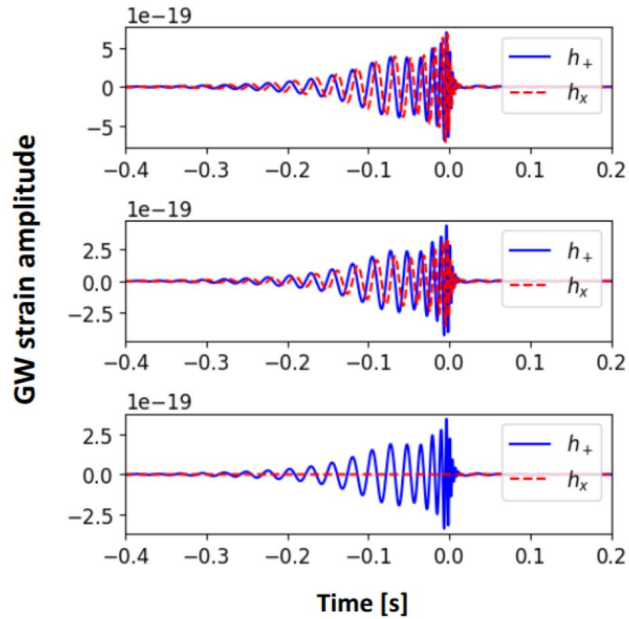
Amplitude at the source

# Autopsy of a Binary: Cosmology

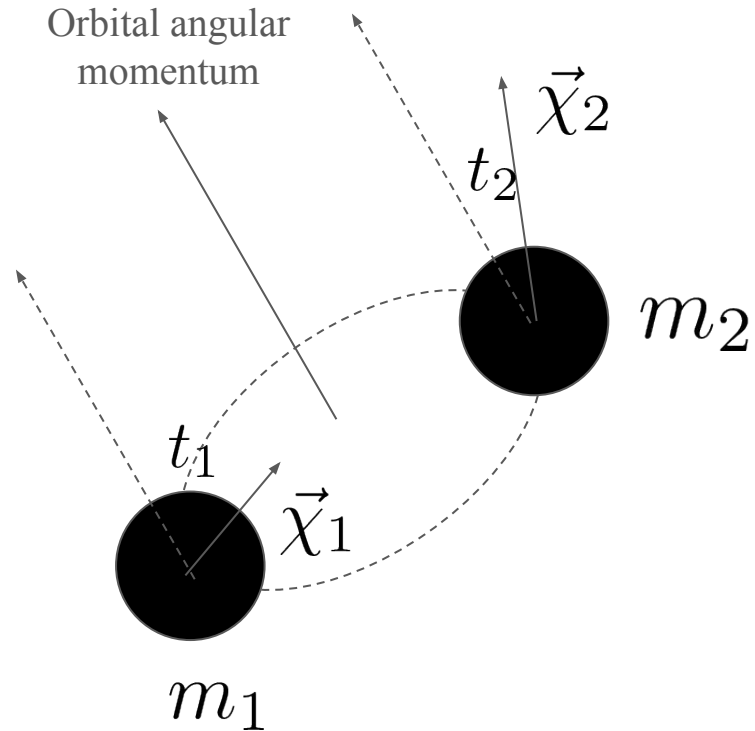


# Autopsy of a compact binary

Luminosity distance of the source is typically not well measured.



# Autopsy of a compact binary



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

**Effective spin parameter**

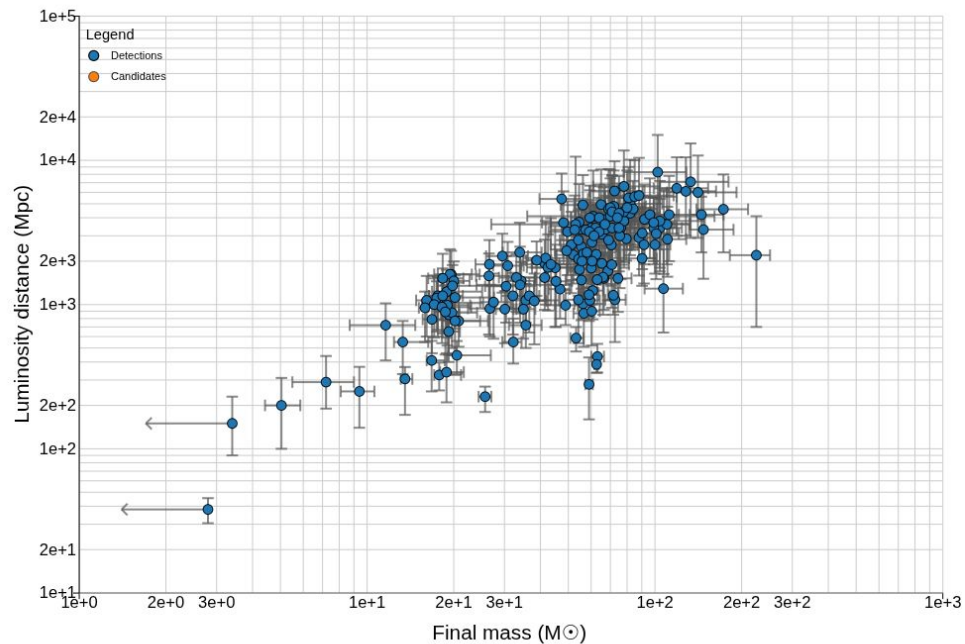
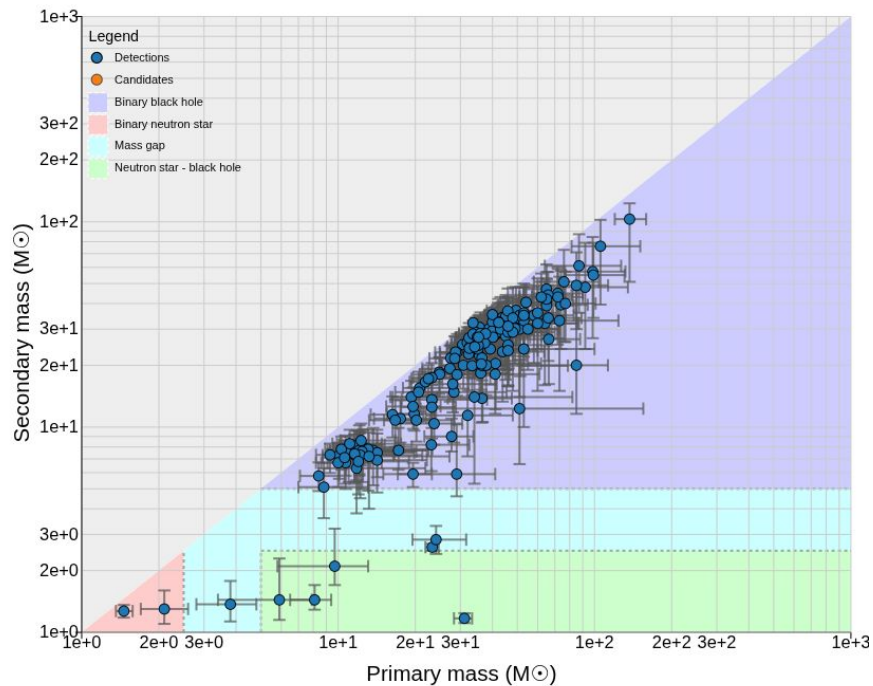
$$q = \frac{m_2}{m_1}$$

**Mass ratio**

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

**Precessing spin parameter**

# After the first, 218 comes



# 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:

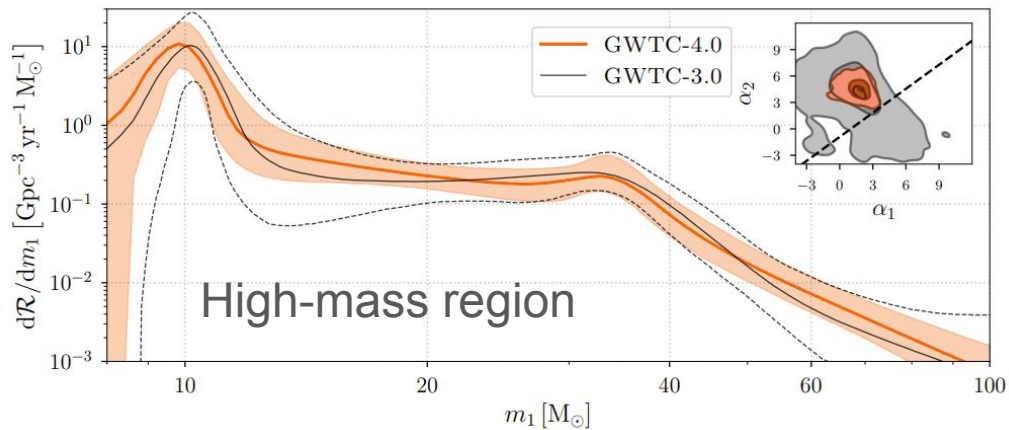
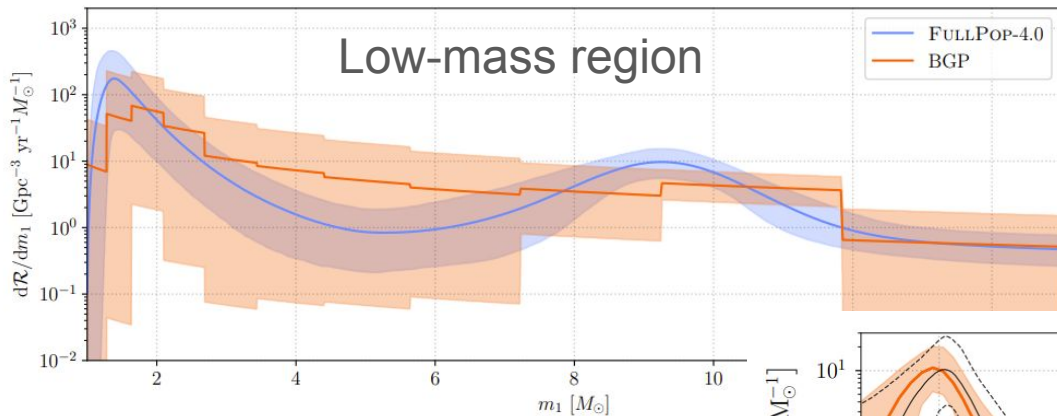
- GWs show an additional energy leakage as they travel.

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

The background of the slide is a reproduction of the painting 'The Starry Night' by the Dutch painter J.M.W. Turner. The painting depicts a night scene with a turbulent, swirling sky filled with bright, glowing stars and a crescent moon. In the foreground, a dark, jagged cypress tree stands on the left, and a small village with a prominent white church spire is visible in the distance. The overall style is characterized by visible, expressive brushstrokes and a rich, textured surface.

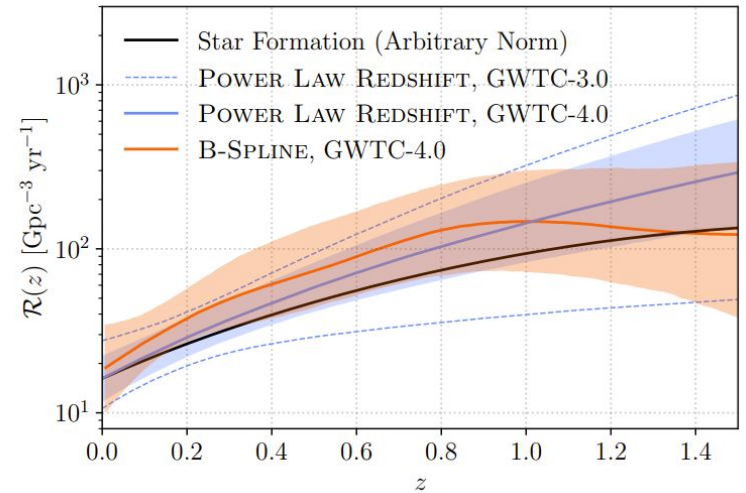
**What do we know about the population of compact objects that we are observing?**

# The mass spectrum



# The merger rate

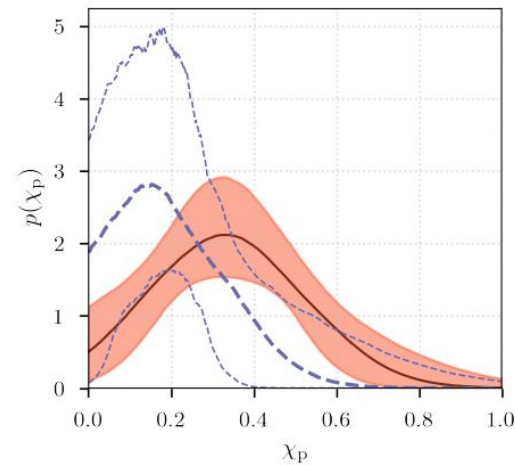
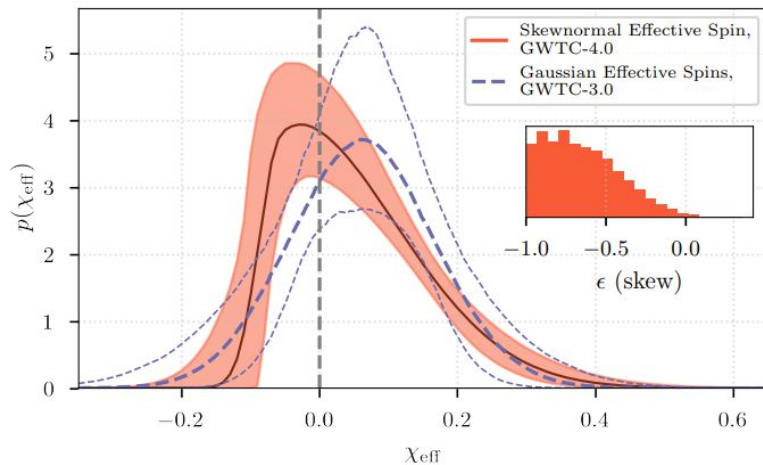
- The **BBH merger** rate today is about 20 mergers per  $\text{Gpc}^{-3} \text{yr}^{-1}$  and it evolves in cosmic time.
- The **BBH merger** rate seems to track the star formation rate.
- The rate of **BNS mergers** is weakly constrained 7.6-250  $\text{Gpc}^{-3} \text{yr}^{-1}$ , no constraint on its redshift evolution.
- The rate of **NSBH mergers** is weakly constrained 9.1-84  $\text{Gpc}^{-3} \text{yr}^{-1}$ , no constraint on its redshift evolution.



LVK 2025, arXiv: 2508.18083 (accepted on PRX)

# The spins

- Overall more support for binaries with aligned spins to the orbital angular momentum - *Hint for formation from stellar binaries with mass transfer?*
- Very likely a small fraction of the population have spins not aligned to the orbital angular momentum - *Black holes formed from dynamical capture?*



LVK 2025, arXiv: 2508.18083 (accepted on PRX)

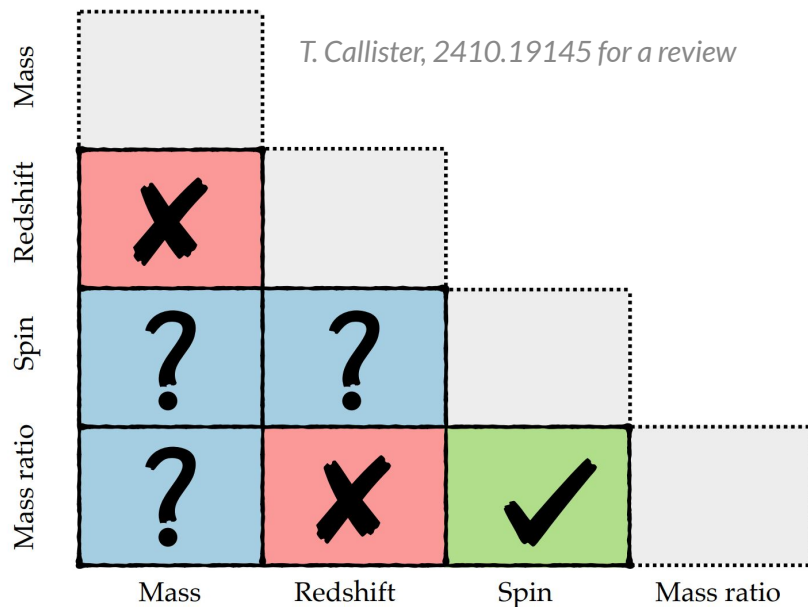
# Correlations among parameters?

- **Confident:**

- BBHs with more unequal masses have larger effective spin parameters.

- **Tentative:**

- BBHs with masses above 35 solar masses have a more rapid spin distribution ( $\sim 0.7$ ).
- The distribution of effective spin likely broadens with redshift.
- Lower mass black holes prefer an equal mass companion.



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

The background of the slide is a reproduction of the painting 'The Starry Night' by Vincent van Gogh. The painting depicts a night scene with a turbulent, swirling sky filled with bright, glowing stars and a crescent moon. In the foreground, a dark, jagged cypress tree stands on the left, and a small village with a prominent white church spire is visible in the distance. The overall style is characterized by visible, expressive brushstrokes and a rich, textured color palette.

# Cosmology with populations of gravitational waves

# 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.



# What happened on August 17th 2017

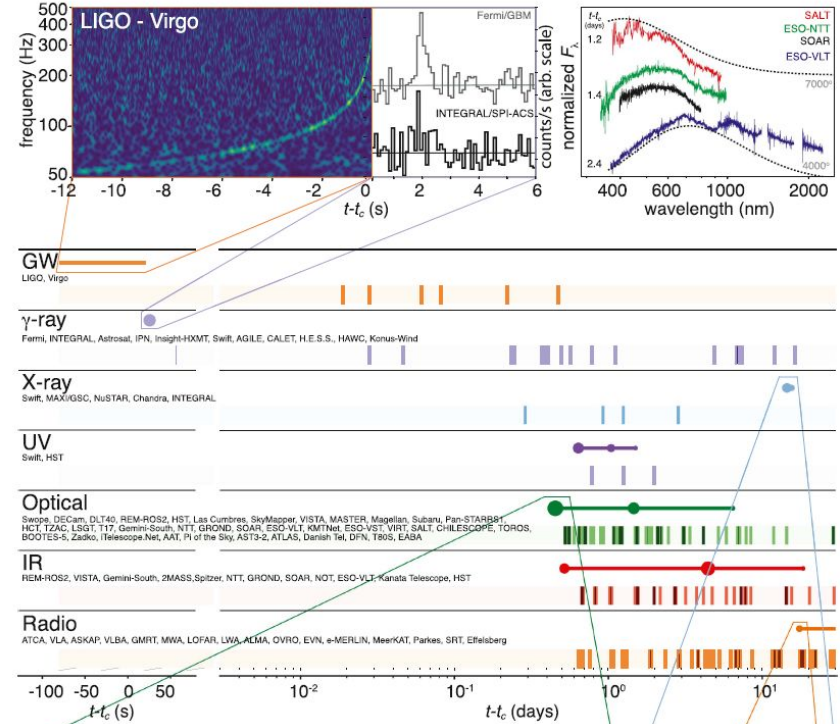
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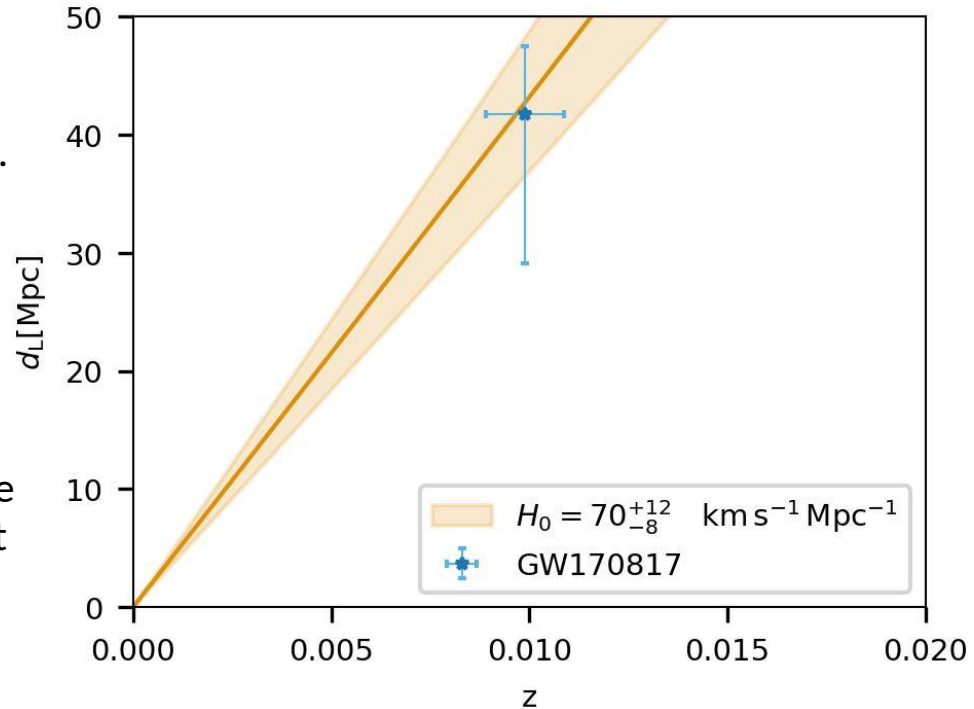
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ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20



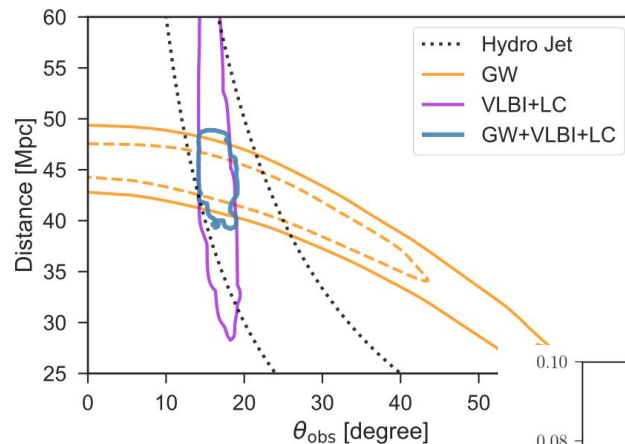
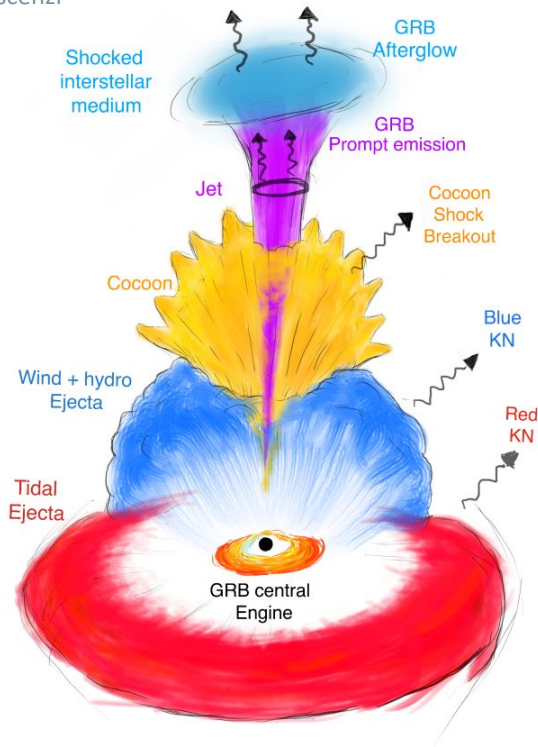
# Bright sirens: GW170817

- **GW170817:** A binary neutron star merger detected by LIGO and Virgo. From the GW, source distance  $\sim 40$  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)]



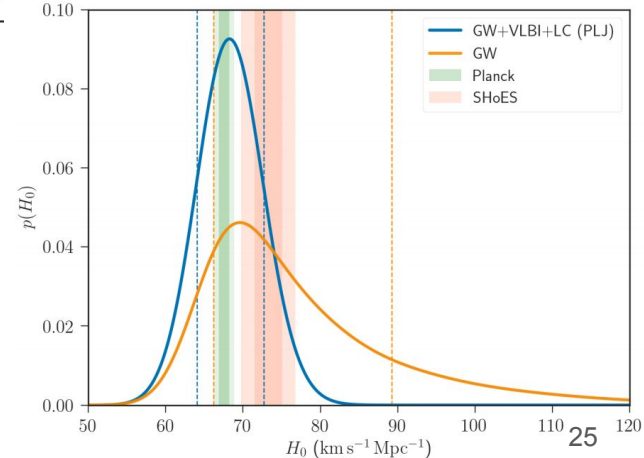
# Bright sirens: GW170817

Credit: S. Ascenzi



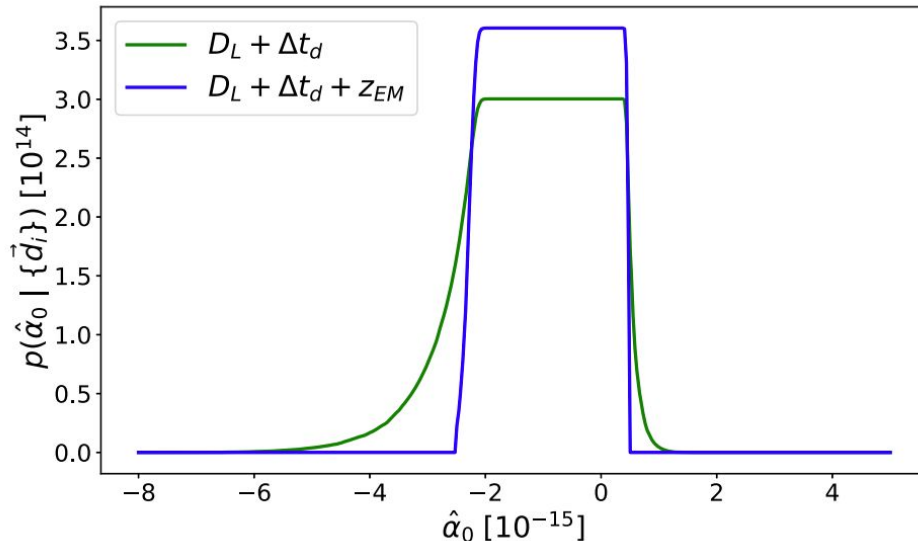
[K. Hotokezaka, Nature Astronomy, 3(2019)]

Afterglow informed cosmology



# Bright sirens: GW170817

- If we just consider that the speed of gravity has no dispersion relation, then we are able to set a constraint on the speed of gravity **with precision of  $10^{-15}$** .
- From GW170817, mass of the graviton  **$<10^{-22}$  eV/c<sup>2</sup> at 90% C.I.**



# 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)

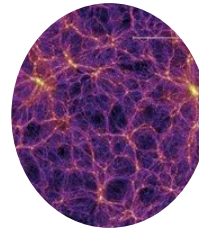
Galaxy surveys

**Catalog Sirens**



SM+, PRD 108 (2023)

Large scale  
structures (LSSs)



Namikawa PRL 116 (2016)  
Mukherjee PRD 502 (2021)

GW/EM time delay

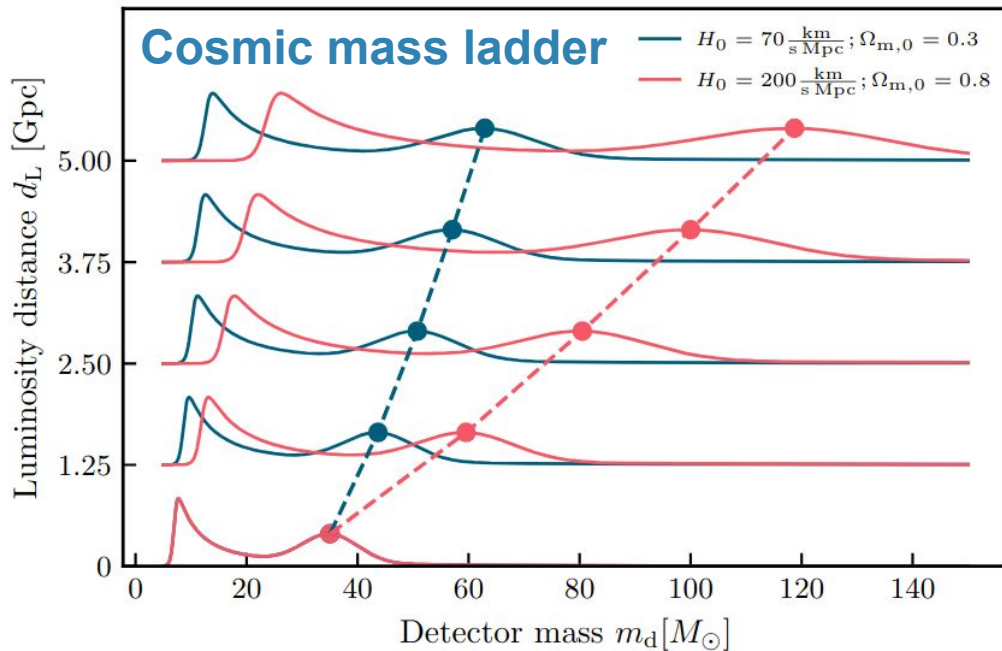
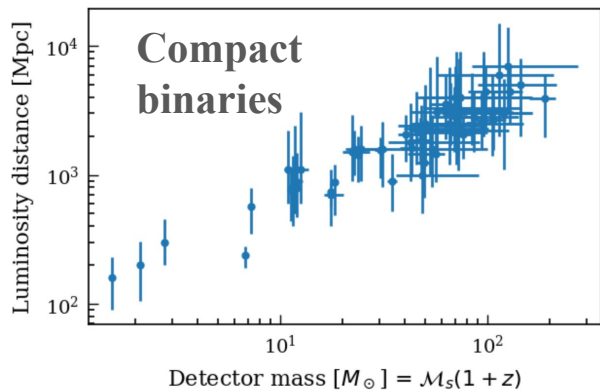
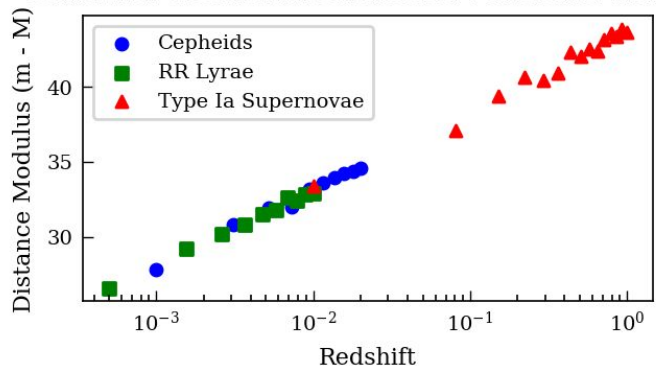
**Lagging sirens**



Iampieri L., SM PRD 2025

# Dark sirens cosmology: masses

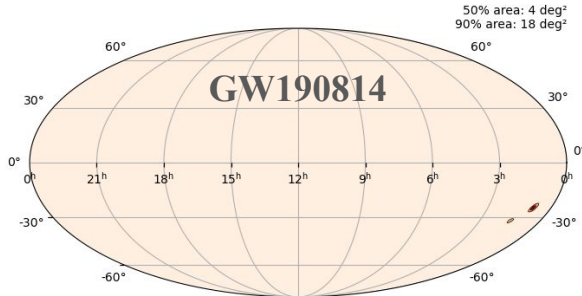
Calibration of Standard Candles as a Function of Redshift



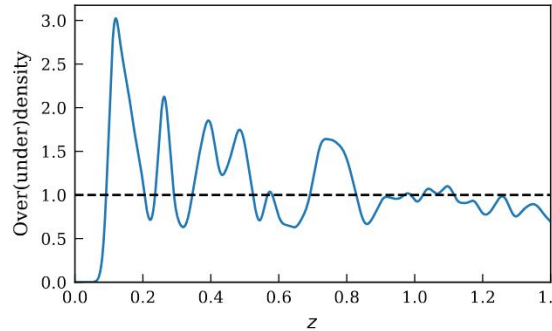
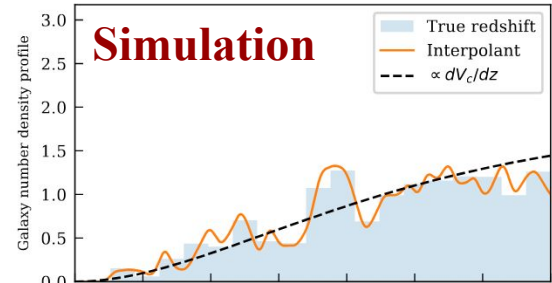
Pierra, Colombo, SM, CQG 2025

# Dark sirens cosmology: Galaxies surveys

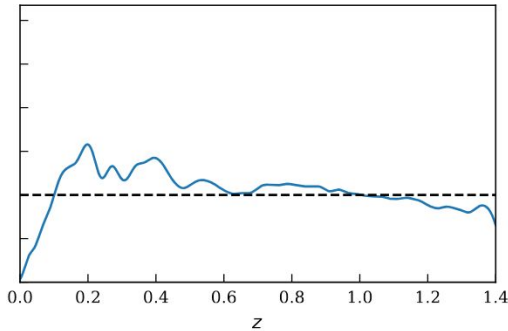
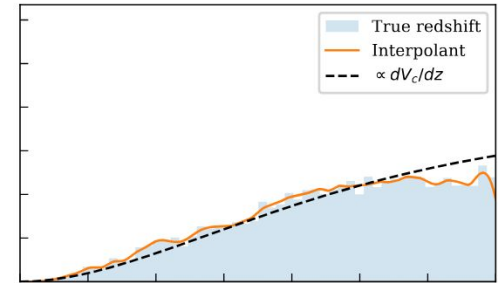
- A cosmological model has statistical support when the GW localization matched an *overdensity* of galaxies.
- Galaxy catalogs are not complete at higher redshifts, we need to apply corrections in order to now bias our analyses [R. Gray+, PRD (2019), Gair, SM, AJ (2022)].



## Light-cone 5 deg<sup>2</sup>



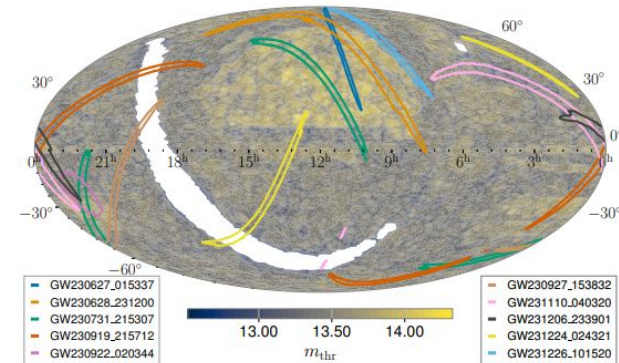
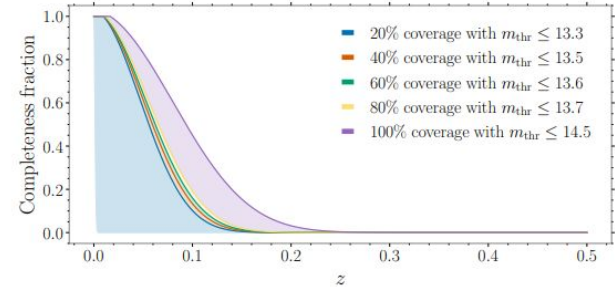
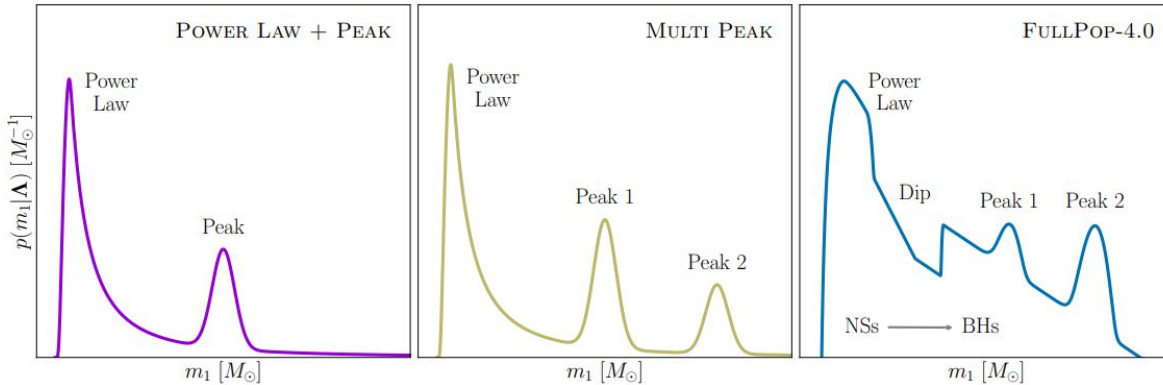
## Light-cone 10 deg<sup>2</sup>



Pierra, SM, arXiv:2507.10597

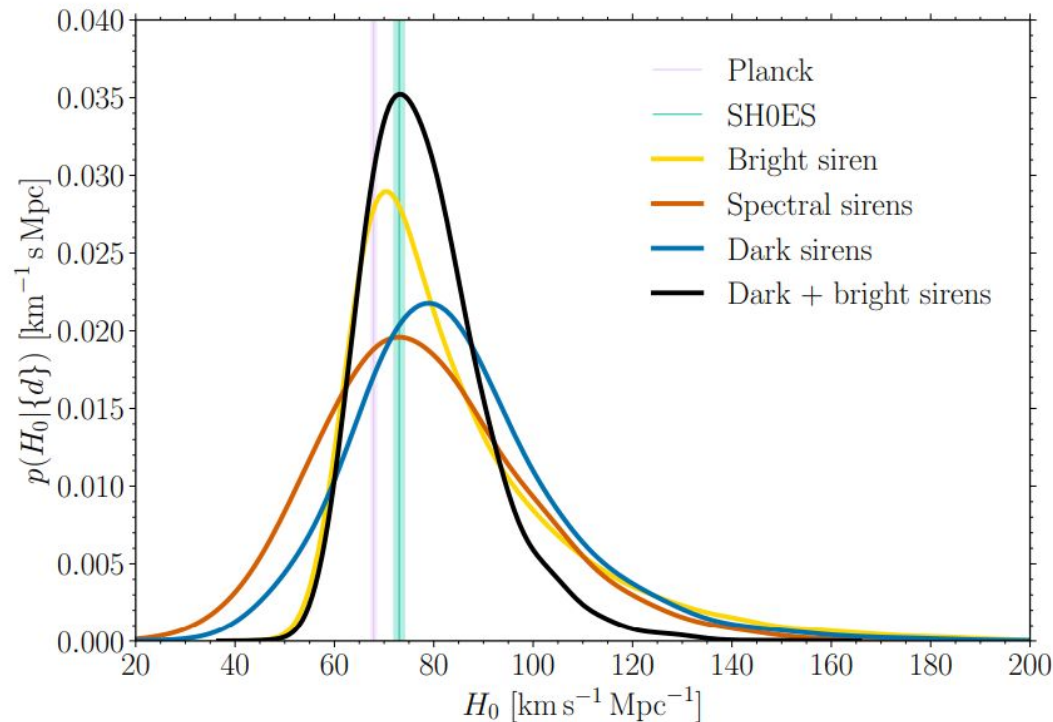
# Latest results from GWTC-4

- We used the most significant GW sources (142/218) from GWTC-4 to estimate the cosmic expansion [LVK+, 2509.04348]
- We employed three different mass models and an all-sky galaxy catalog (GLADE+)



# Latest results from GWTC-4

- 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 Flat $\Lambda$ CDM universe, the Hubble constant is the parameter that we can measure the best.



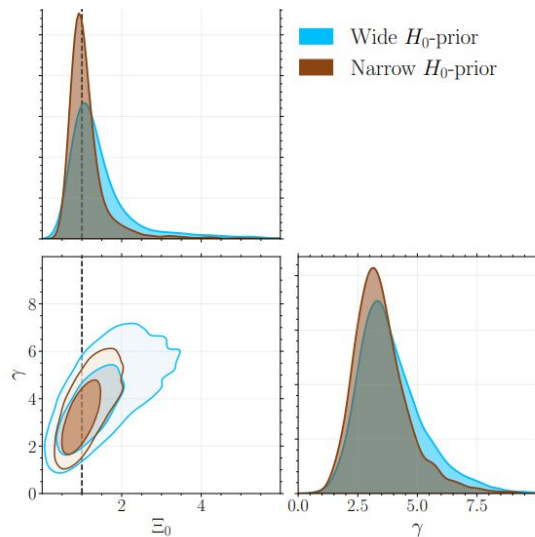
[LVK+, 2509.04348]

# Latest results from GWTC-4

- 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  $G(\text{source})/G(\text{today})$ .
- These constraints are becoming comparable with the ones obtained from LSSs [Ishak+, 2024] and CMB [Seraille+, 2024]

## Phenomenological approach

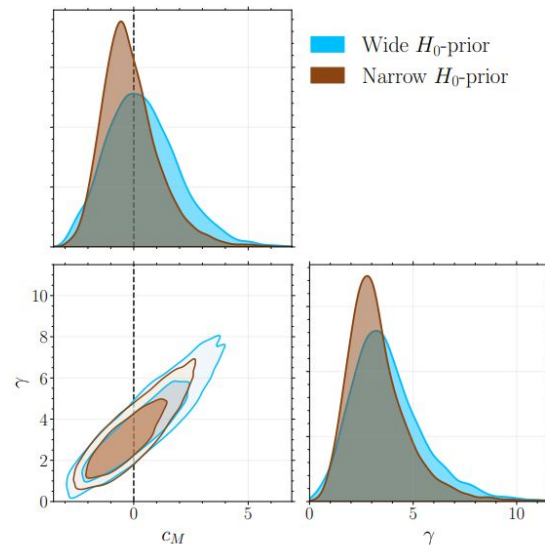
$$D_L^{\text{GW}} = D_L^{\text{EM}} \left( \Xi_0 + \frac{1 - \Xi_0}{(1+z)^n} \right)$$



[LVK+, 2509.04348]

## Running Planck mass

$$D_L^{\text{GW}} = D_L^{\text{EM}} \exp \left\{ \frac{1}{2} \int_0^z \frac{dz'}{1+z'} \alpha_M(z') \right\}$$

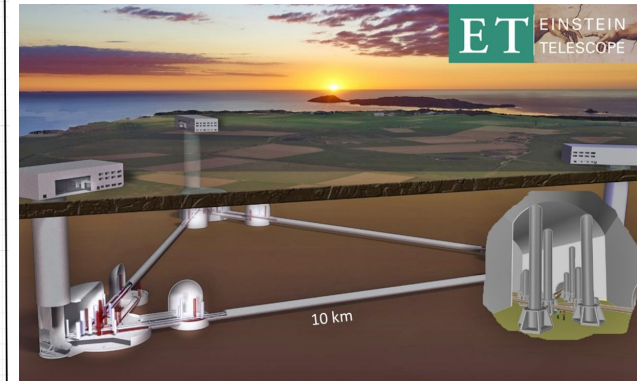
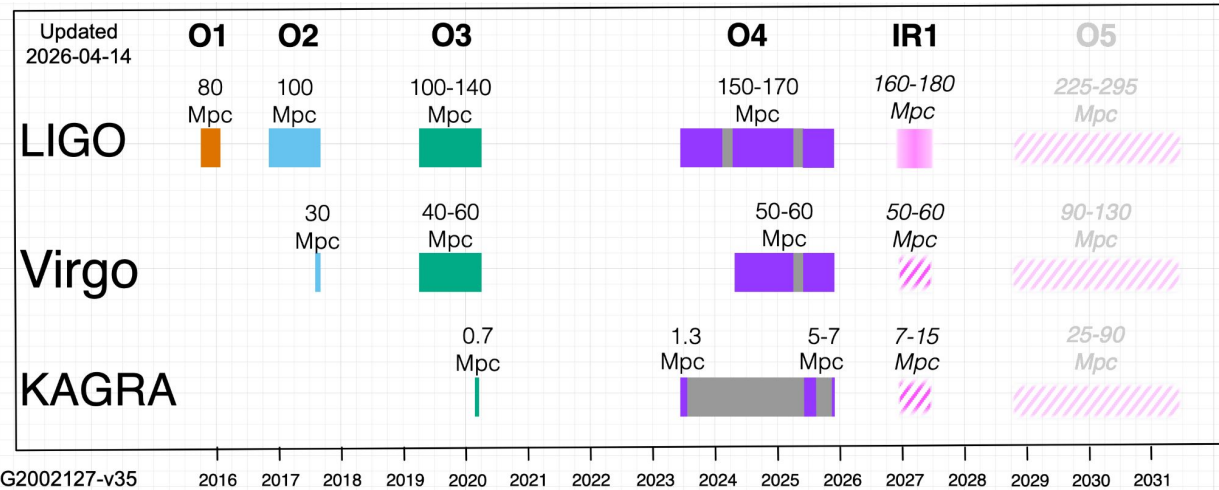


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**What could be the future of  
Gravitational wave cosmology?**

# GW cosmology: the future

## 2035+ Einstein Telescope

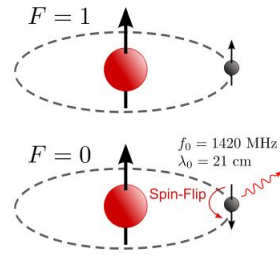


## [LVK observing plans](#)

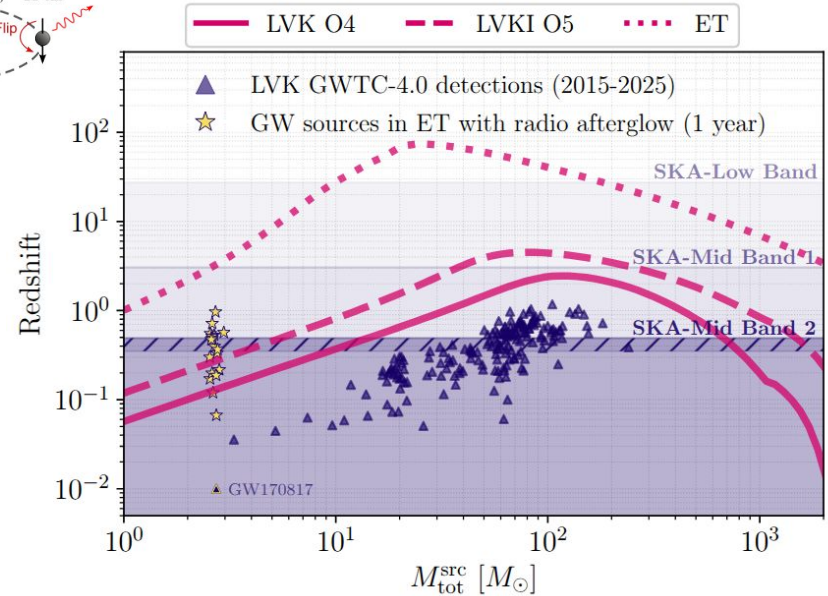
# GW cosmology: the future

The 21cm emission line of the hydrogen atom can be used to trace the neutral hydrogen (DM) in our universe.

Radio observations by SKAO can trace neutron hydrogen but also detect GRB afterglows

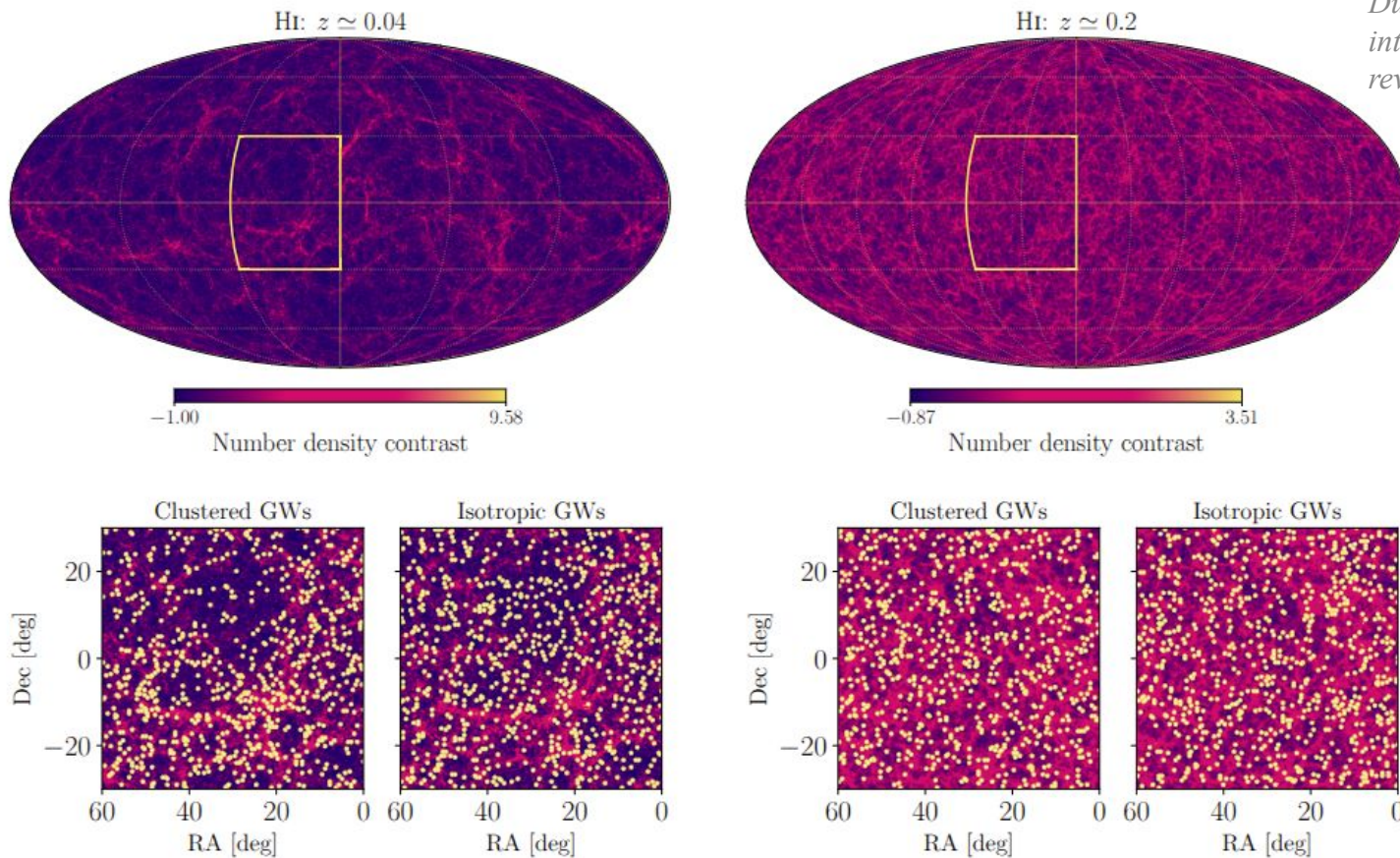


Gravitational waves in synergy with radio observations



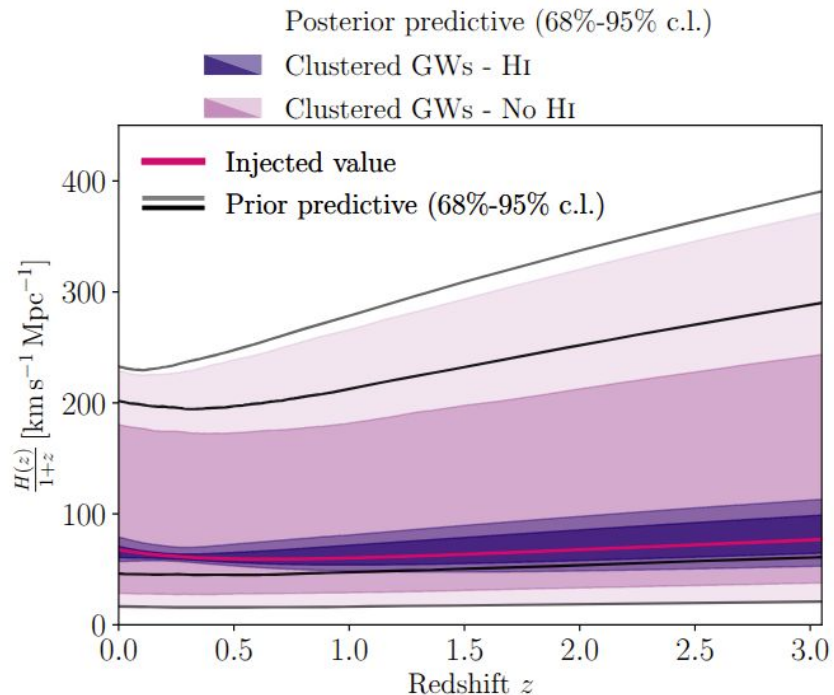
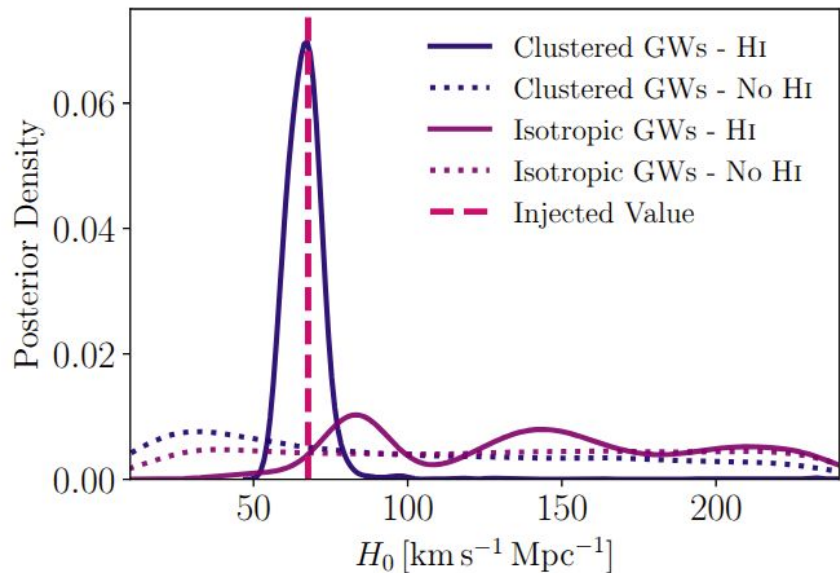
# GW cosmology: the future

*Dupletsa, SM, + Under  
internal LVK/ET  
review*



# The future in the Radio?

*Caveat: In the simulation we neglected the mass-calibration for binary black holes*

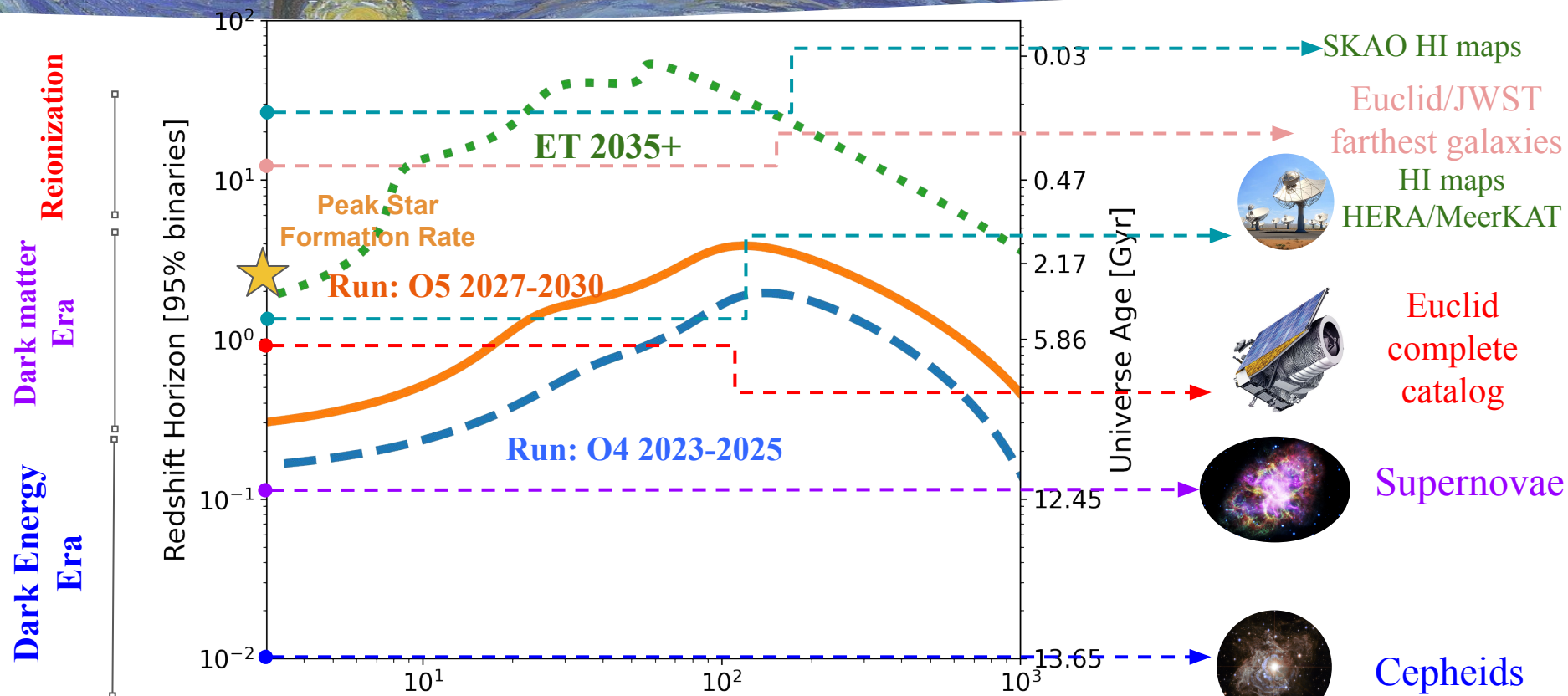


*Duplitsa, SM,+ Under internal LVK/ET review*

# Conclusions



# Resolved GW sources

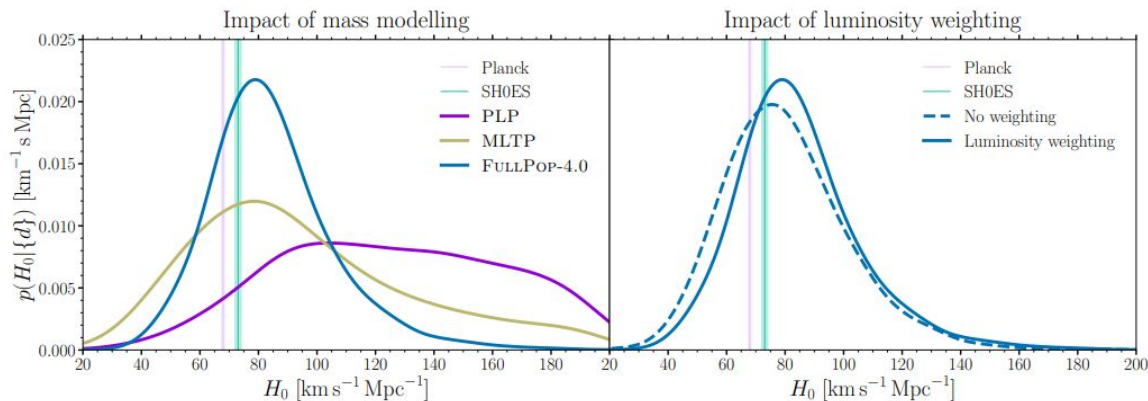
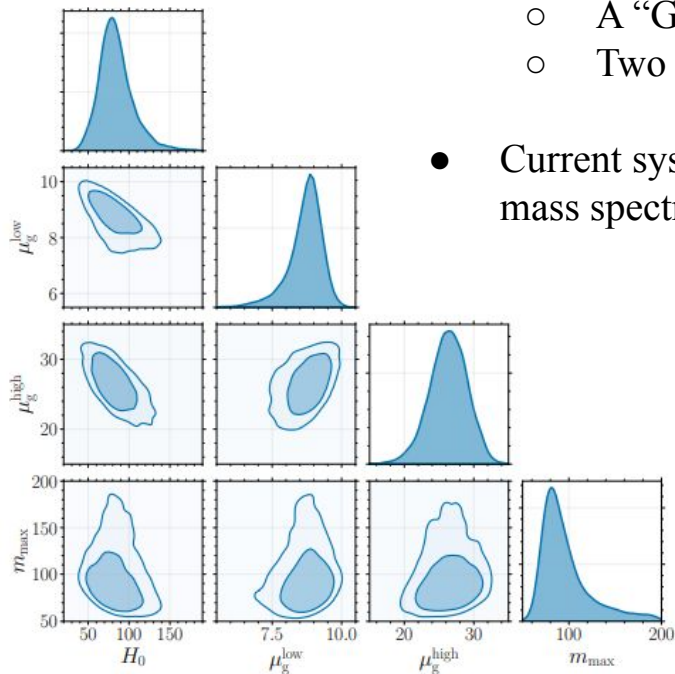


**Extra slides**



# Latest results from GWTC-4

- There are three mass scales informative on cosmology:
  - A “Gap” between neutron stars and Black holes.
  - Two local overdensities of black holes production at 8 and 30 solar masses.
- Current systematics on GW cosmology should be explored at the level of the mass spectrum model.

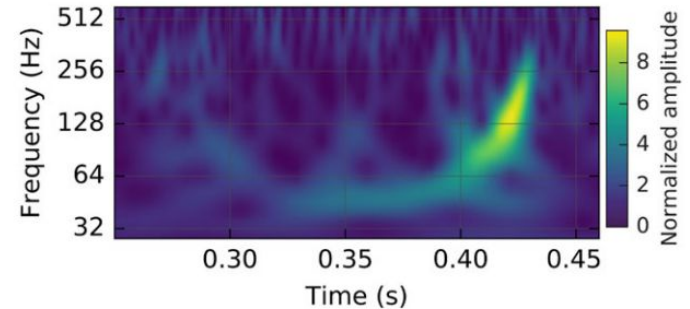
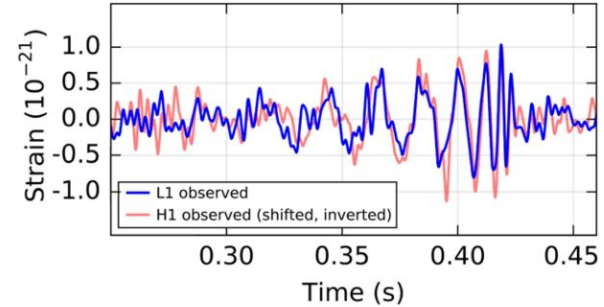


[LVK+, 2509.04348]

# GW150914 the first GW signal

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)]