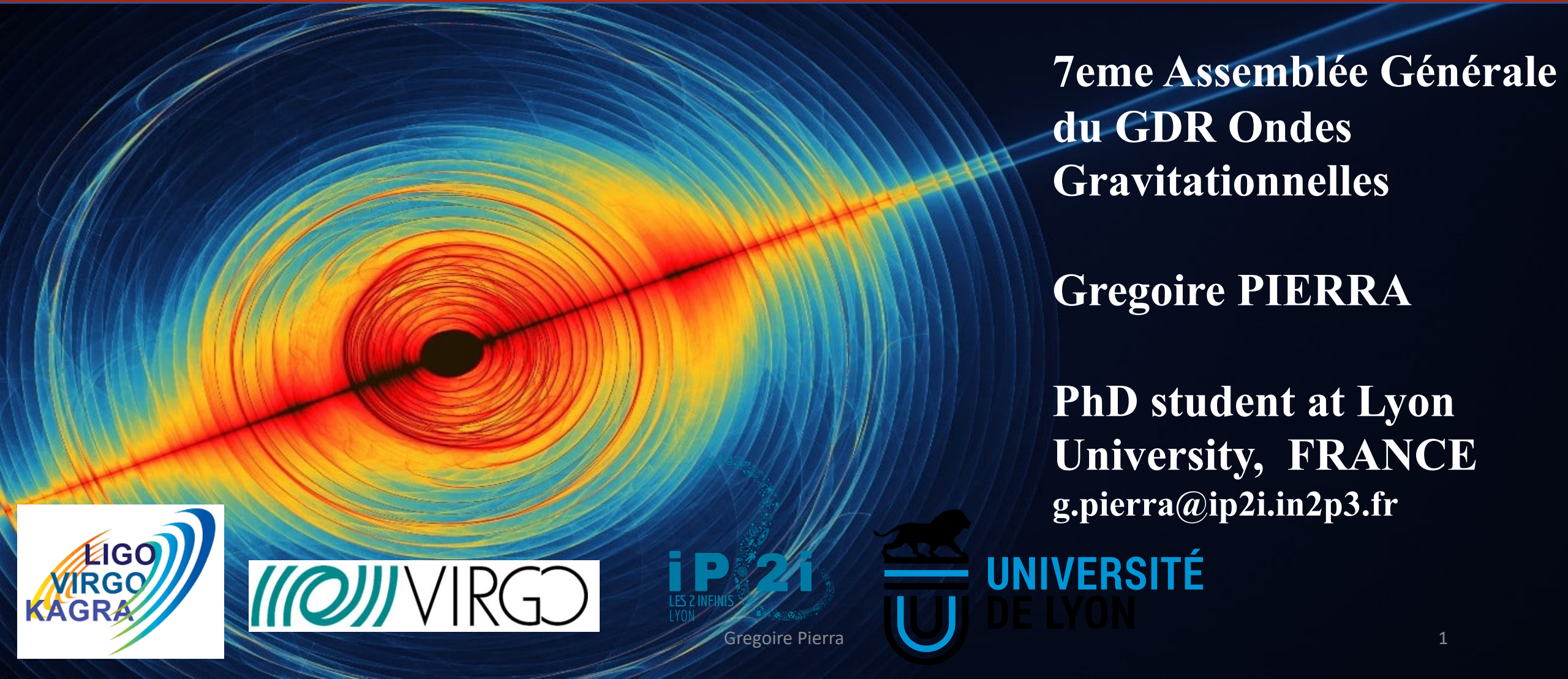
Cosmology with Dark-Sirens, a review of O3 LVK results



7eme Assemblée Générale du GDR Ondes Gravitationnelles

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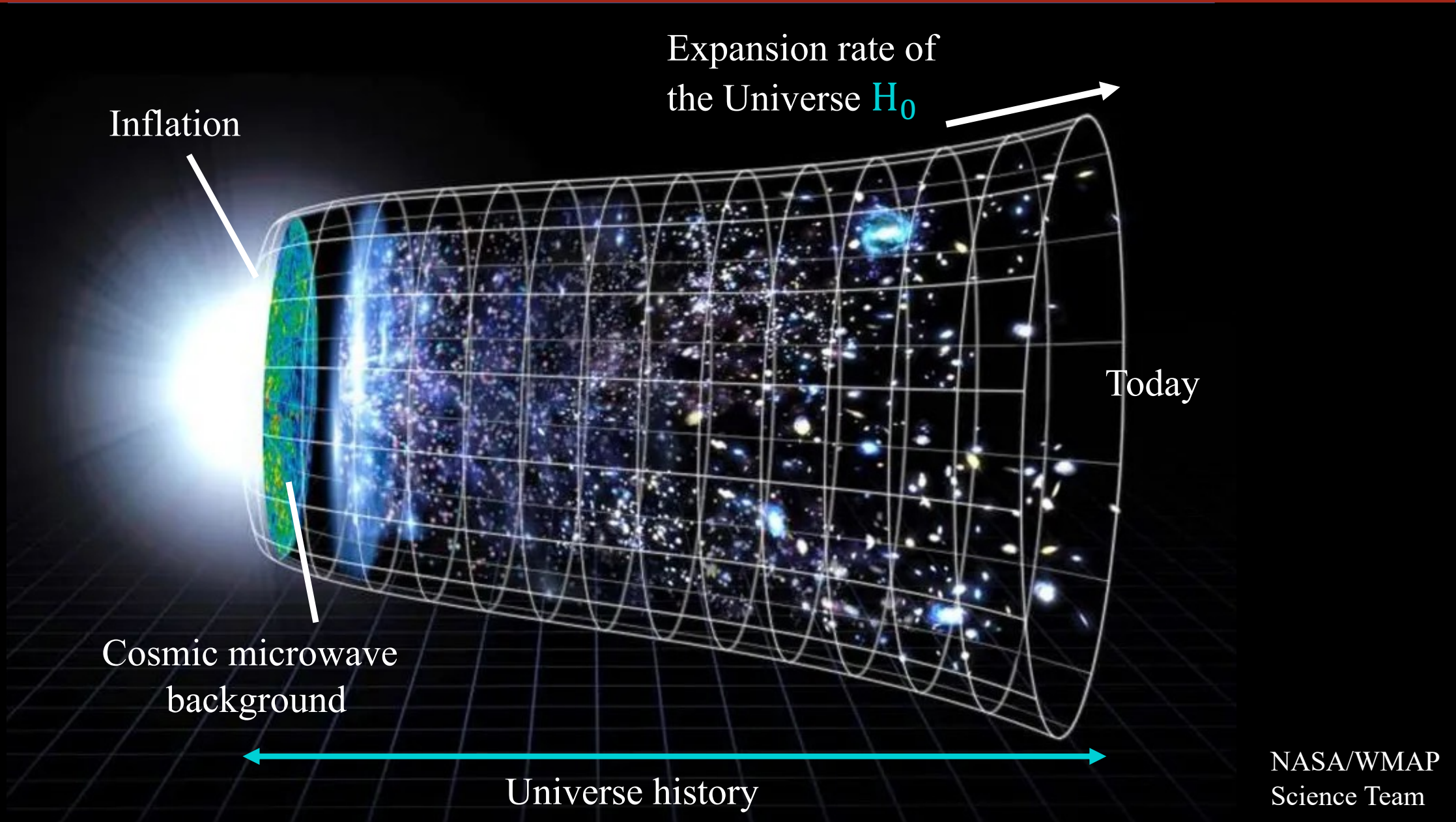
Overview

1. Introduction to the Hubble tension

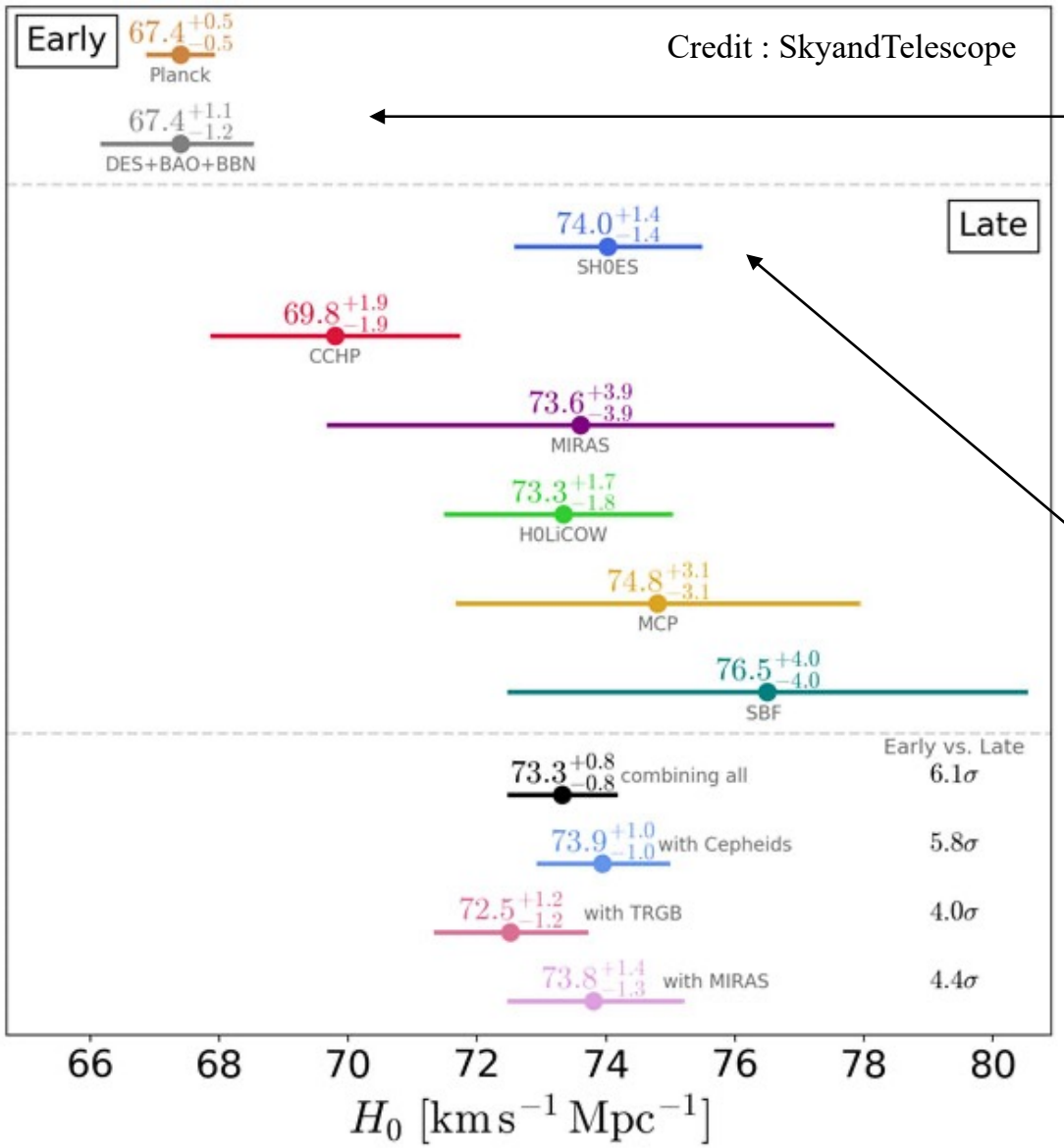
2. Cosmology with Dark Sirens
    1. Spectral Sirens
    2. Galaxy catalog

3. O3 LVK cosmology results

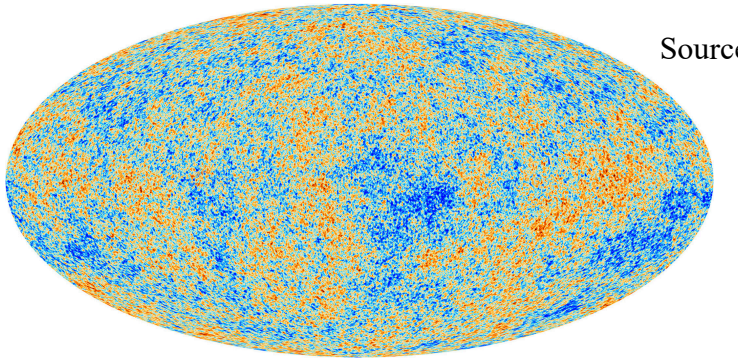
Hubble Constant



Hubble tension



Credit : SkyandTelescope



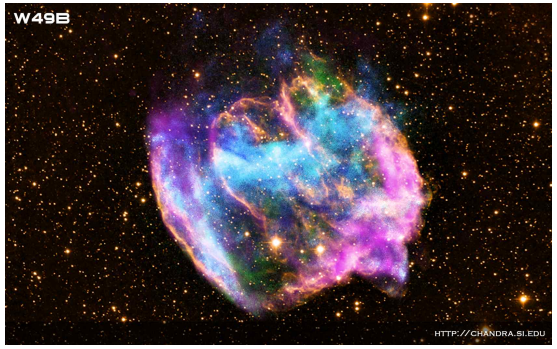
Source :WMAP

CMB measurement

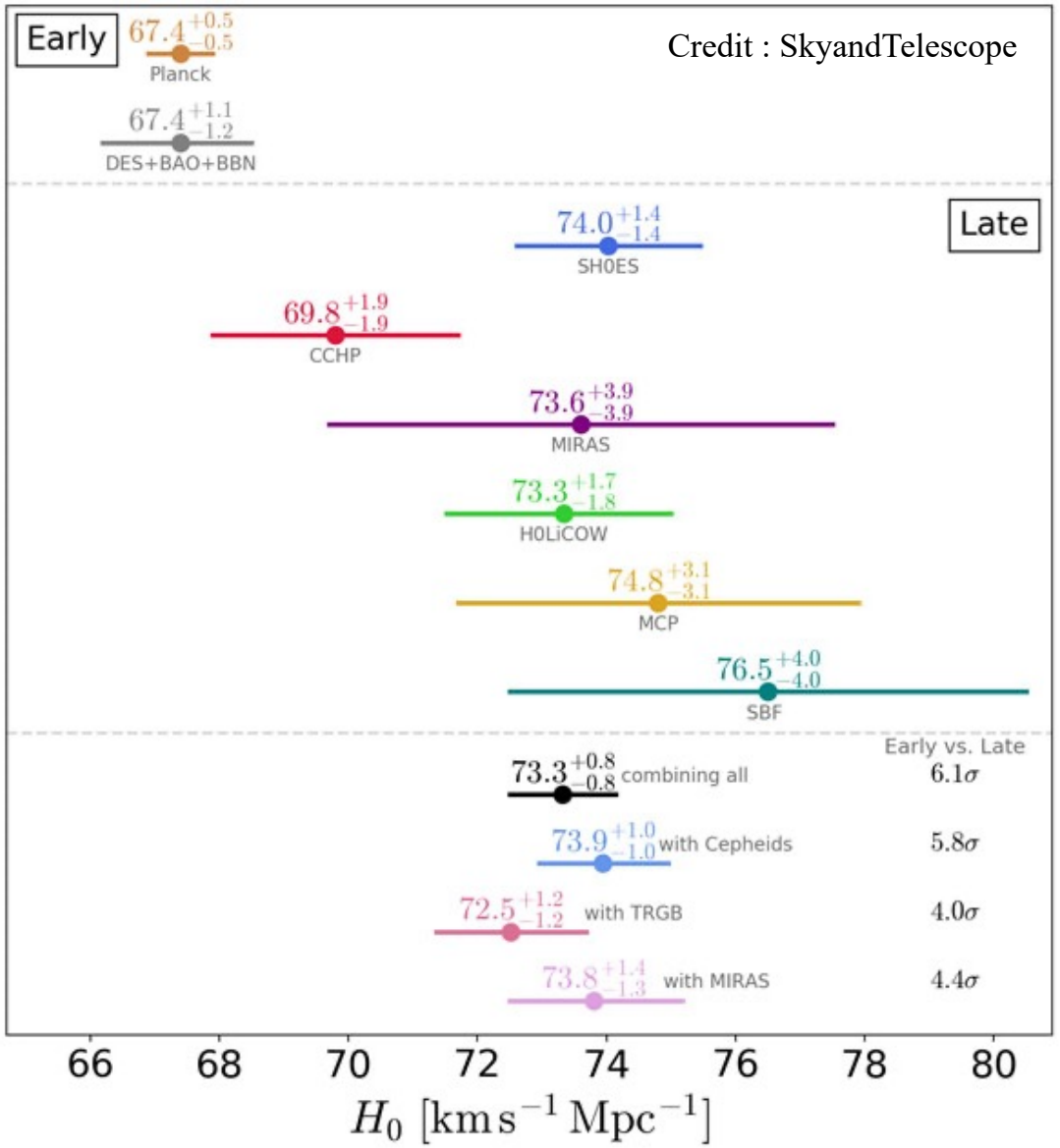
$$H_0 = 67.4^{+0.5}_{-0.5} \ [\mathrm{km.s^{-1}.Mpc^{-1}}]$$

Supernovae Ia

$$H_0 = 74.0^{+1.4}_{-1.4} \ [\mathrm{km.s^{-1}.Mpc^{-1}}]$$



Hubble tension



The importance of the Hubble tension

- Failure of the ΛCDM scenario ?
- A clue that we are missing something in our understanding of the Universe ?
- Exotic Dark energy, Dark matter ?
- Flawed measurements ?
- Some cosmic conspiration ?

This talk

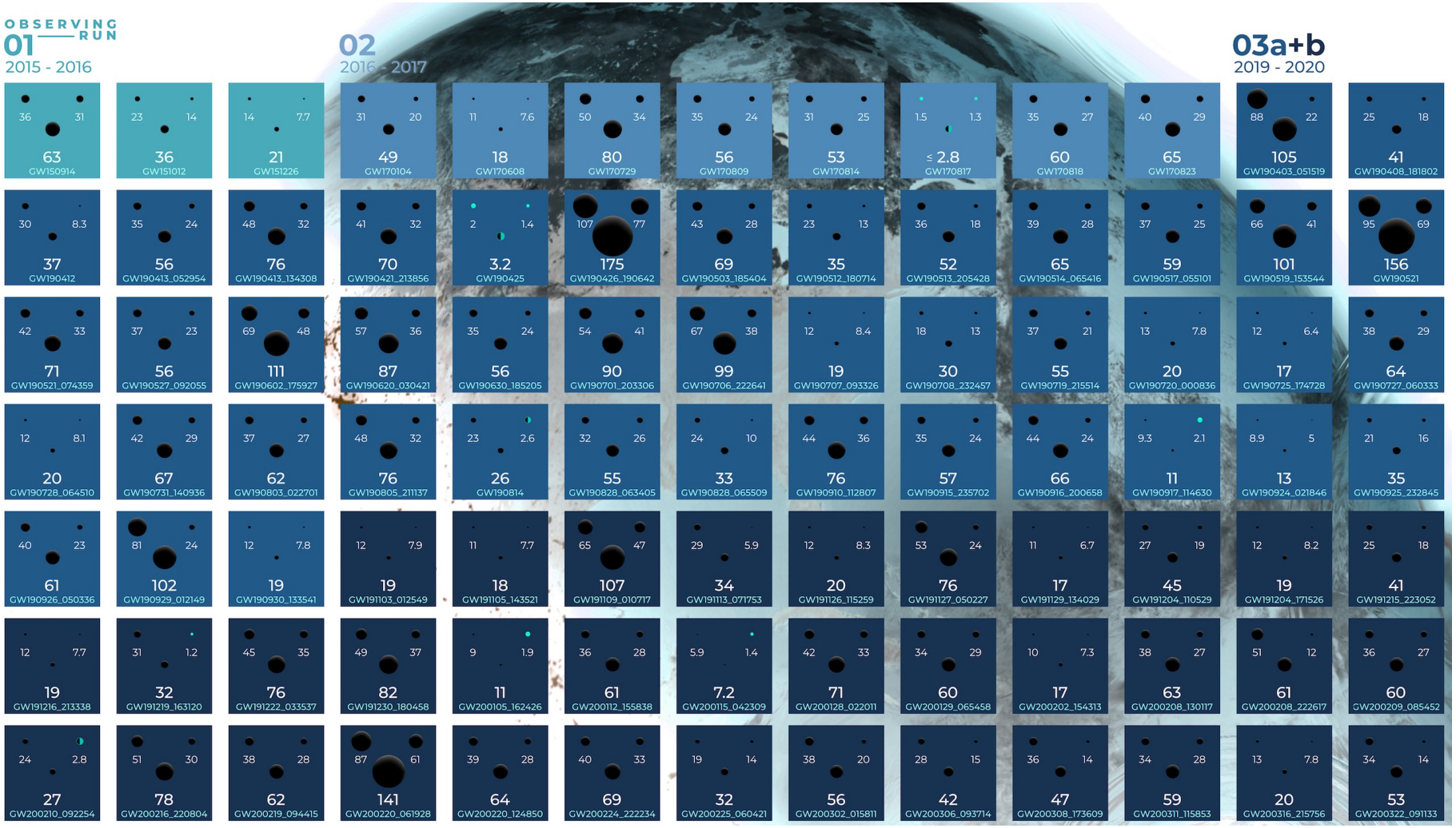
This talk

→ Approach to estimate the cosmology with GW signals

- Using Dark-Sirens only
- Looking at correlation with the BBH population parameters

→ O3 LVK cosmology results

Dark-Sirens from LVK detections



LVK Stellar graveyard

- 91 Compact binary mergers
- 90 of them are Dark-Sirens(no E.M. counterpart)

Credit : LVK collaboration

Dark Sirens for cosmology

How to access H0 with GWs ?

- The redshift z and the luminosity distance d_L of a GW source are related through cosmology

$$d_L \simeq \frac{c}{H_0} z$$

(low redshift approximation)

d_L : Directly measurable the GW signal

z : Need to be found through other methods

- Access H0 by breaking this degeneracy

- Two pipelines inside LVK :

ICAROGW

S. Mastrogiovanni et al 2023

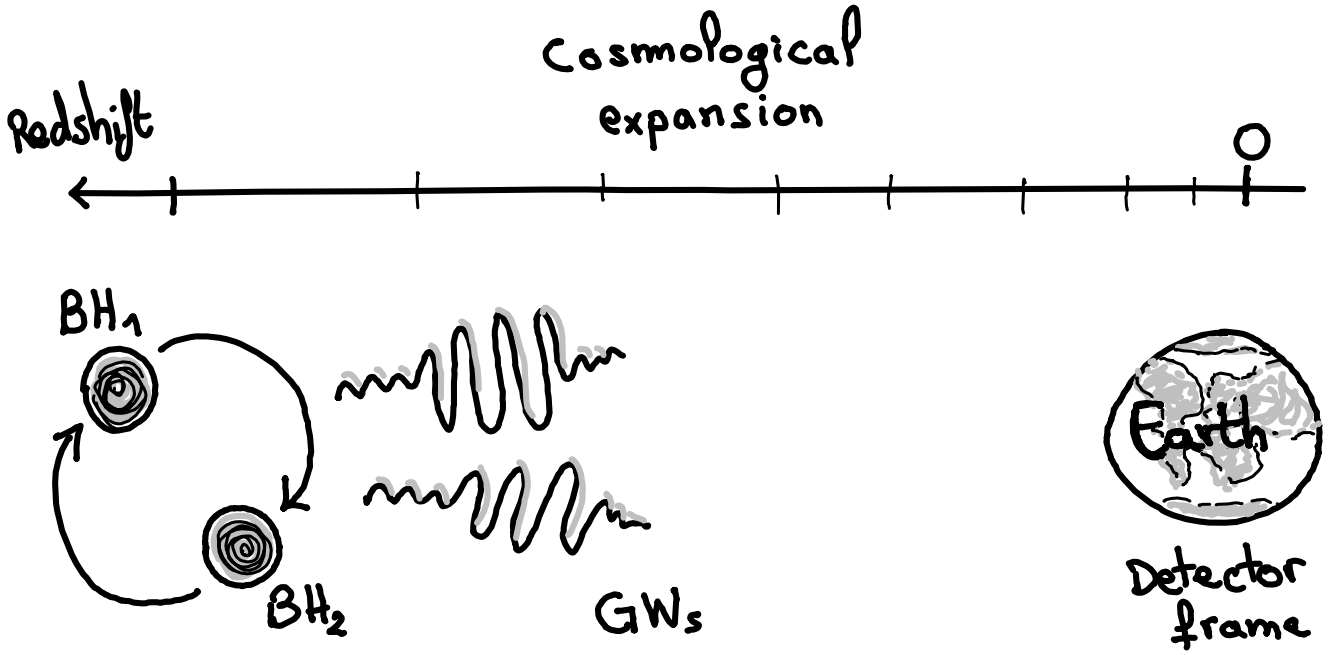
S. Mastrogiovanni et al 2023 (ICAROGW2.0)

GWCOSMO

R. Gray et al 2023

Spectral Sirens method

- Gravitational wave are redshifted by the expansion of the universe



Need to break this degeneracy in order to measure z

- Degeneracy between the detected and the source mass of BBH : $m_i^d = (1+z)m_i^s$

Spectral Sirens method

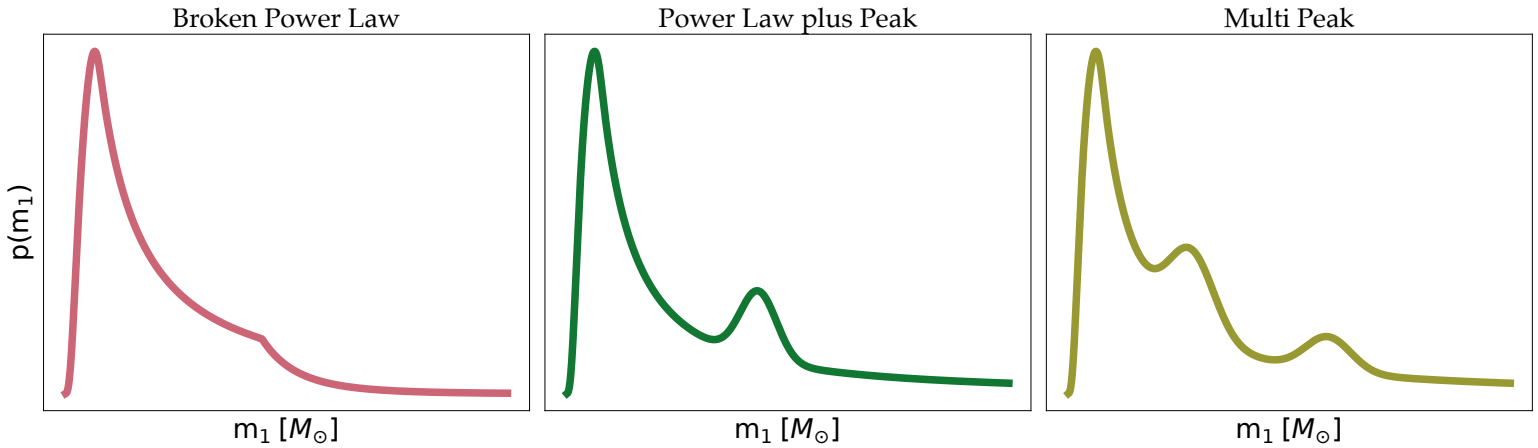
- Assumption on the source frame mass model leads to statistical measurement of the redshift

$$m^d = (1+z)m^s \rightarrow z = \frac{m^d}{m^s} - 1$$

- Joint fit of cosmological parameters and population models (*Taylor et al. 2012, Taylor and Gair 2012, Farr et al. 2019, You et al. 2020, Mancarella et al 2022, Ezquiaga et al 2022*)

Importance of population models in the cosmological inference

LVK Source frame mass models



Galaxy catalog method

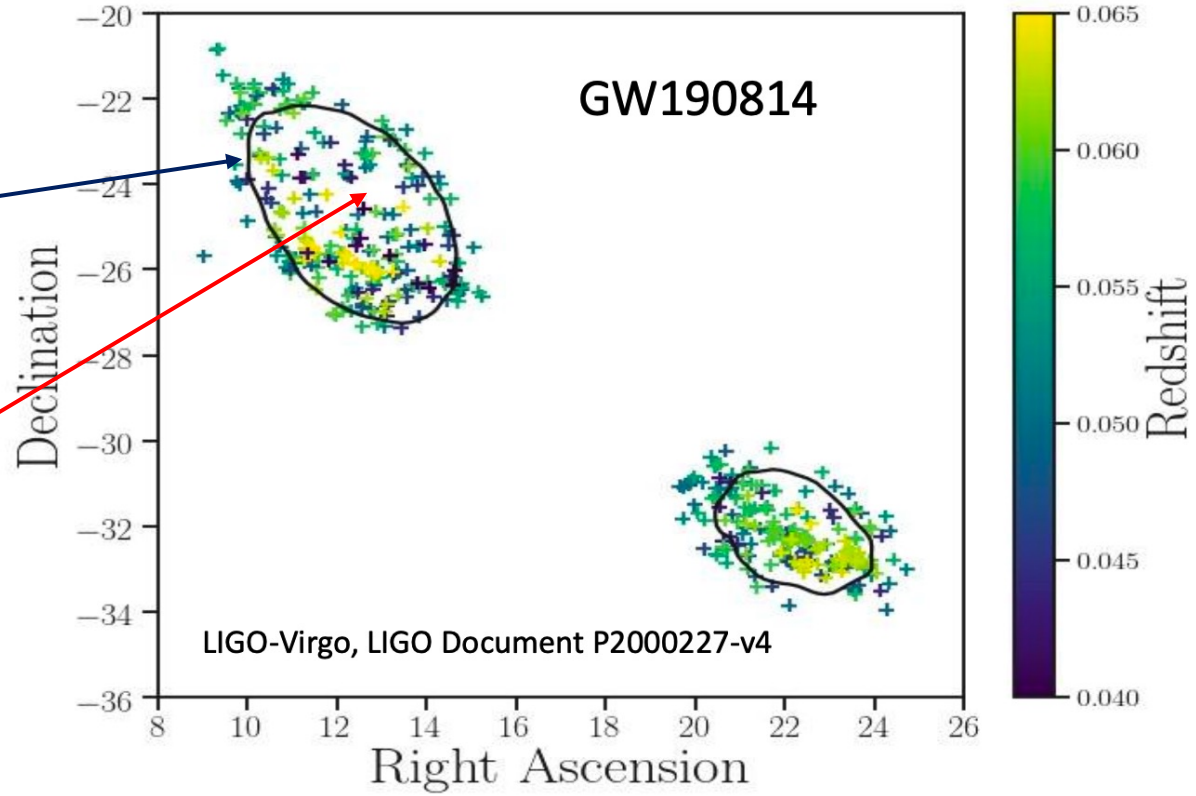
Add extra information on the redshift on the sources via galaxy catalog

GW signal

- Luminosity distance
- Sky localisation

Galaxy catalog

- Potential host of the source
- Redshift measurement

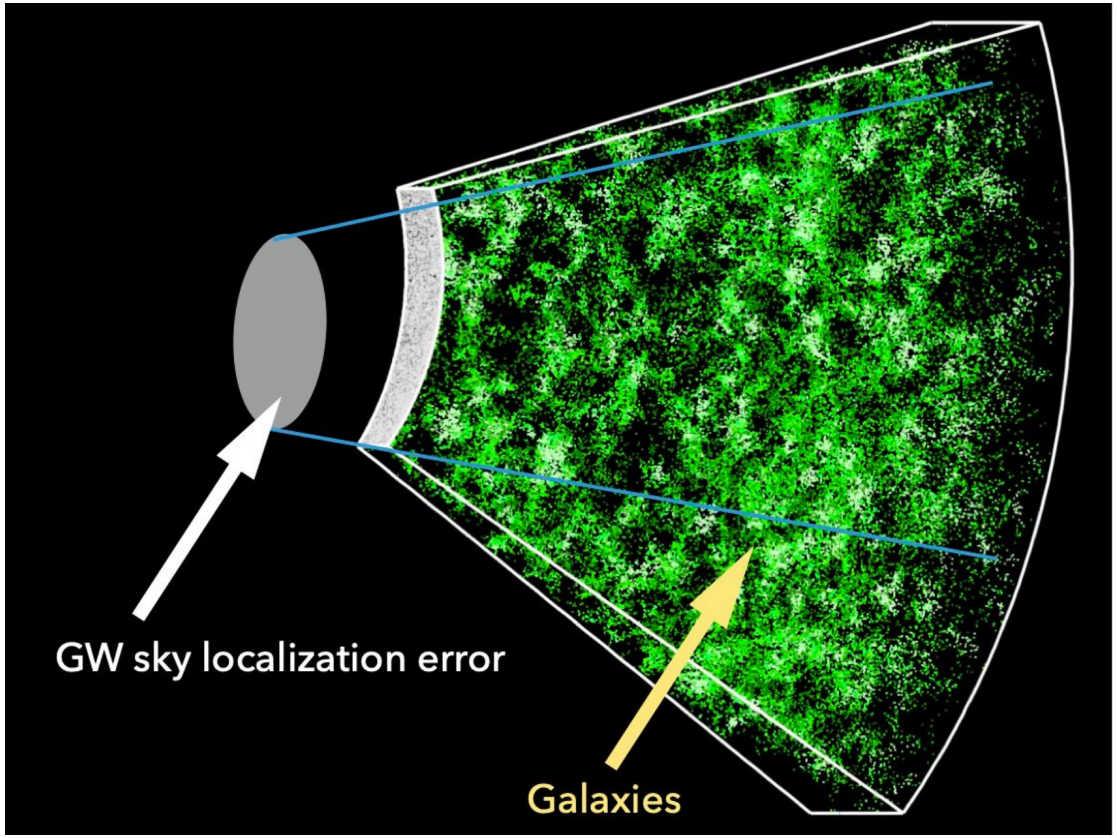


The redshift of the source is obtain statistically thanks to potential host galaxies

Galaxy catalog method

Main galaxy catalog problematics :

- Incomplete at distances where LIGO-Virgo-Kagra detects CBCs
- Unreliable redshift estimation for high-redshift galaxies
- Lot of systematics



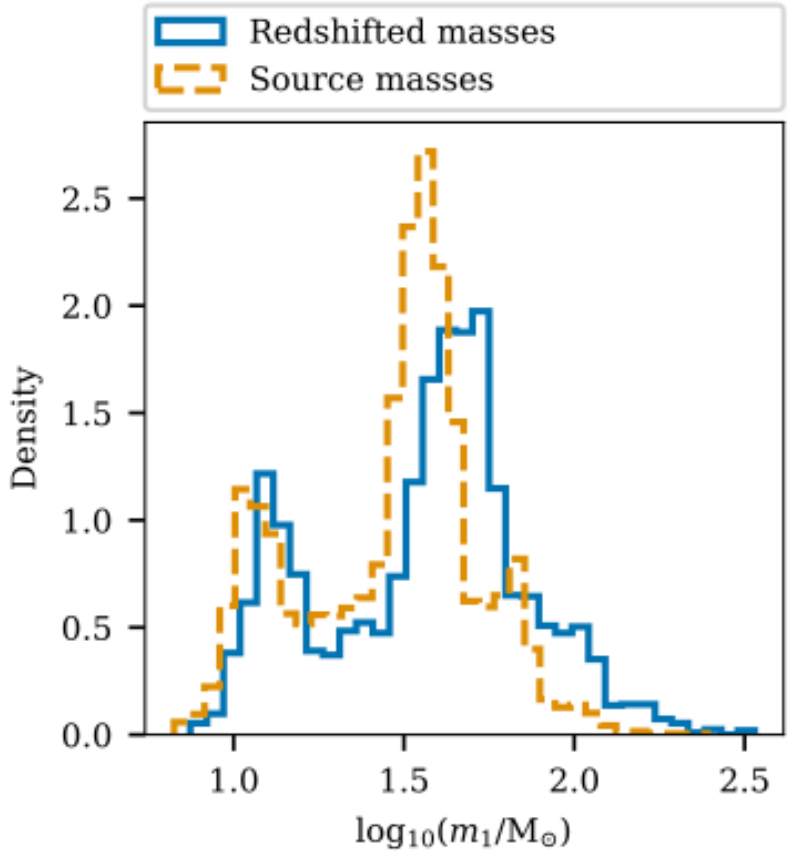
O3 LVK cosmology results

LVK cosmology paper O3 : Constraints on the cosmic expansion history from GWTC-3

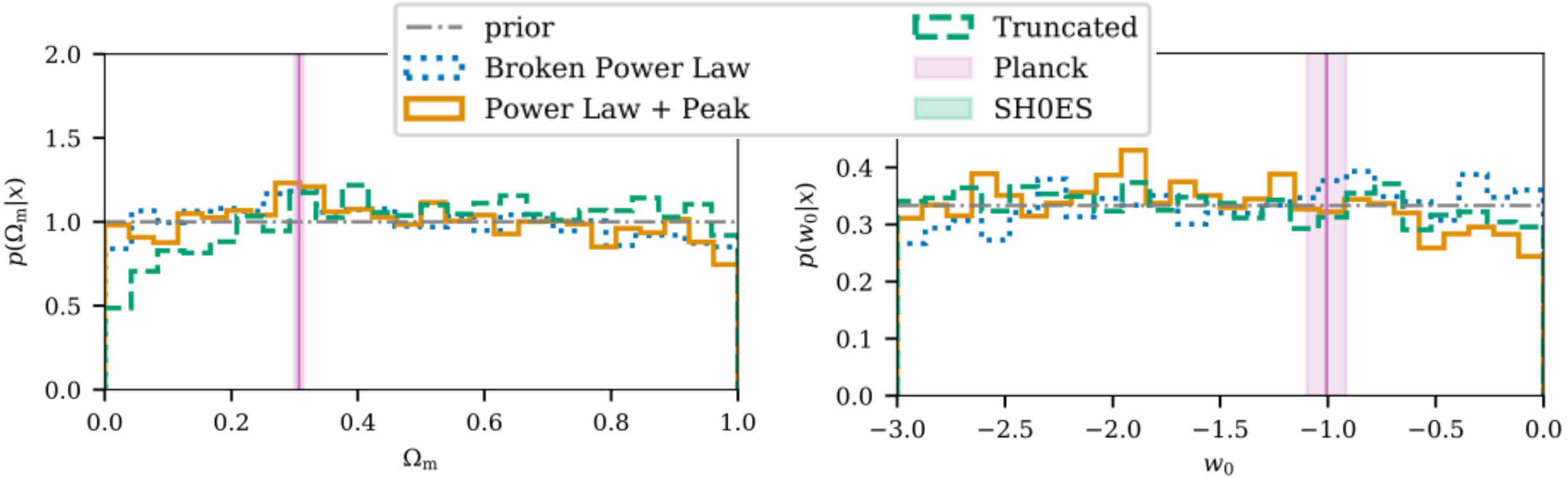
Analysis set-up :

- 42 binary black hole detections
- Cut-off to ensure astrophysical signals :
  SNR > 11 & IFAR > 4yr
- M&D merger rate model
- 2 cosmological models
- 3 mass models (sources frame)

GW190814 excluded (NSBH)

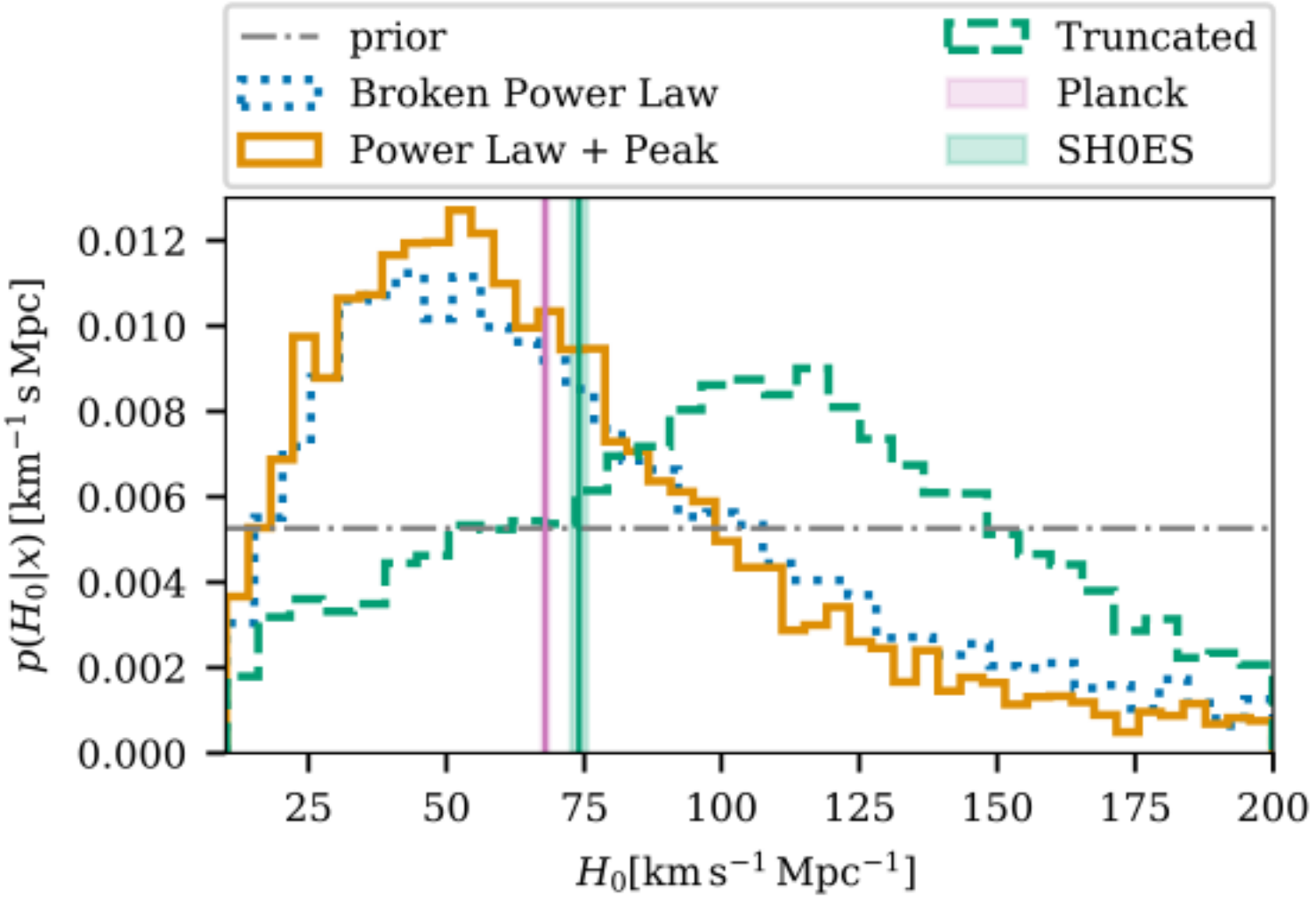


Spectral Siren results



- No constraint with the current GW detections on w_0, Ω_m
- Uninformative about the two cosmological model studied

Spectral Siren results



Best constraint with IcaroGW

- Power-Law + Peak

$$H_0 = 50^{+37}_{-30}\ \mathrm{km.s^{-1}.Mpc^{-1}}$$

- Broken Power-Law

$$H_0 = 44^{+52}_{-24}\ \mathrm{km.s^{-1}.Mpc^{-1}}$$

Spectral Siren results

No evidence in the data to support one cosmological model

- Uninformative on Ω_m and w_0
- Error on H0 too large

Mass model	$\log_{10} \mathcal{B}$
Truncated	−1.9
Power Law + Peak	0.0
Broken Power Law	−0.5

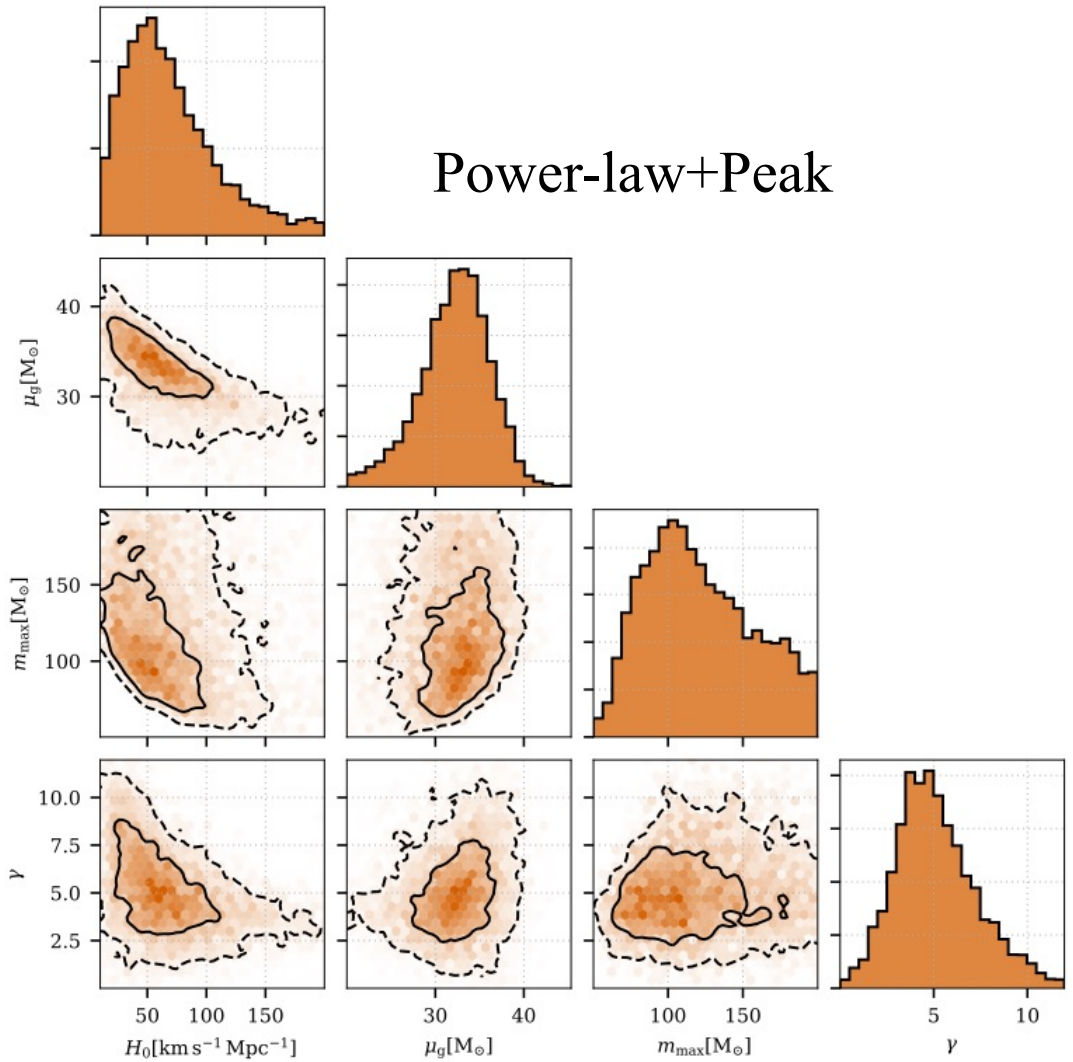
Truncated model strongly disfavoured

- By a factor ~100
- Too much structure in the mass spectrum
- Impossibility to capture the fraction of high mass events ~35 Msol

For the PLP and the BPL models :

- Ability to fit the excess of BBHs at higher masses
- Set a scale for the redshift distribution of BBHs

Spectral Siren results



- Significant correlation between the position of the peak in the source mass distribution and H0
- Constraints on H0 arise from the ability of our model to catch those sharp features in the mass spectrum
- With the PL+Peak : Exclusion of high H0 values
- With the Truncated : Support for higher values of H0, due to the impossibility to account for the structures around ~35Msol
- Results consistent with independent studies *(Mancarella et al 2022)*

Spectral Siren results

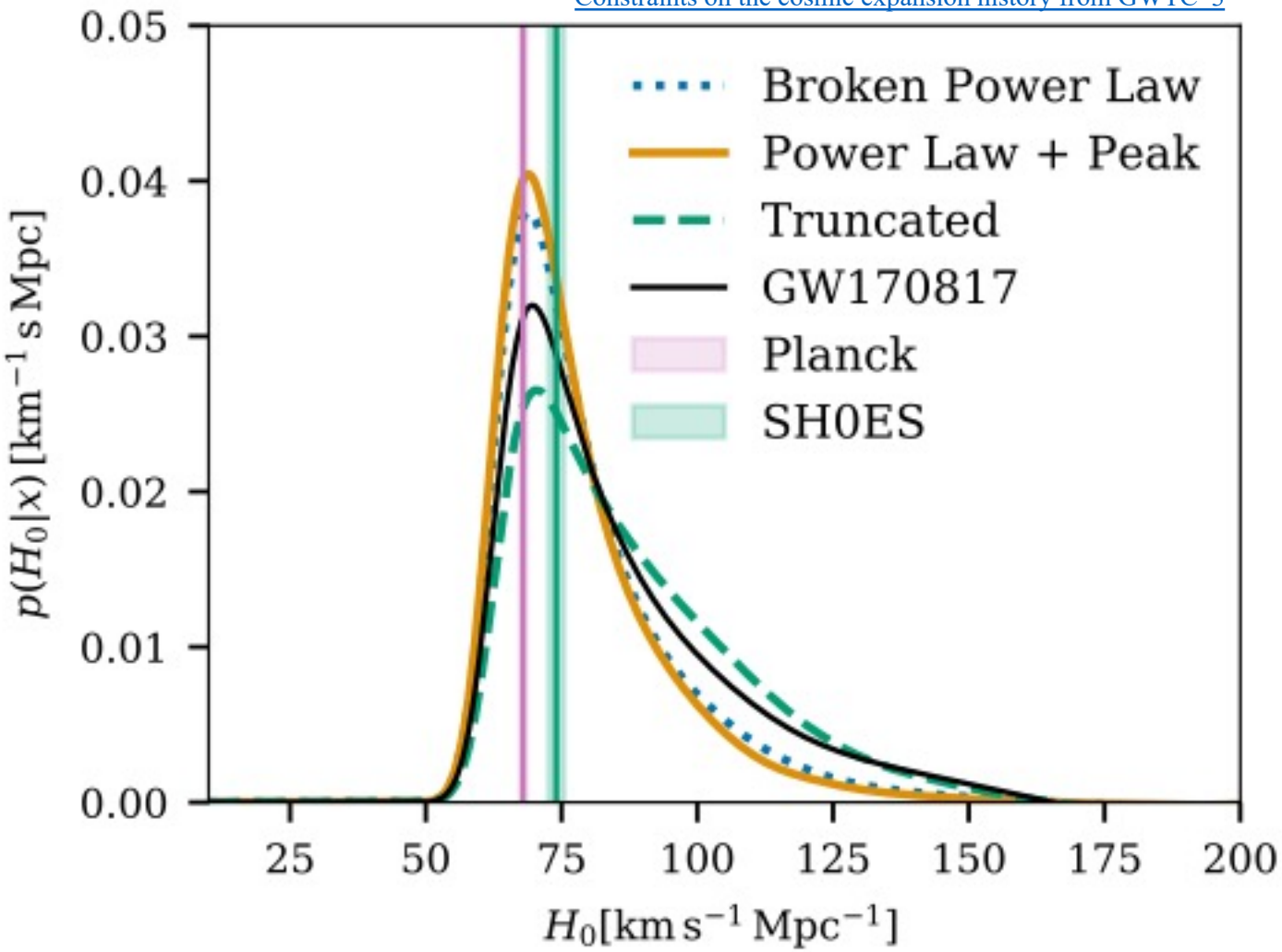
Results obtained with ICAROGW from S. Mastrogiovanni et al 2023

GWTC-3 combined with GW170817

$$H_0 = 68^{+12}_{-8}\ \mathrm{km.s^{-1}.Mpc^{-1}}$$

- 17% improvement compared to GW170817 alone
- 12% improvement compared to GWTC-2 + GW170817

Constraints on the cosmic expansion history from GWTC–3



Galaxy catalog results

Results obtained with GWcosmo from [Gray et al. 2020]

Using 47 GW detections, 42 BBH,
2 BNS, 2 NSBH and GW190814

+ Fixed pop parameters

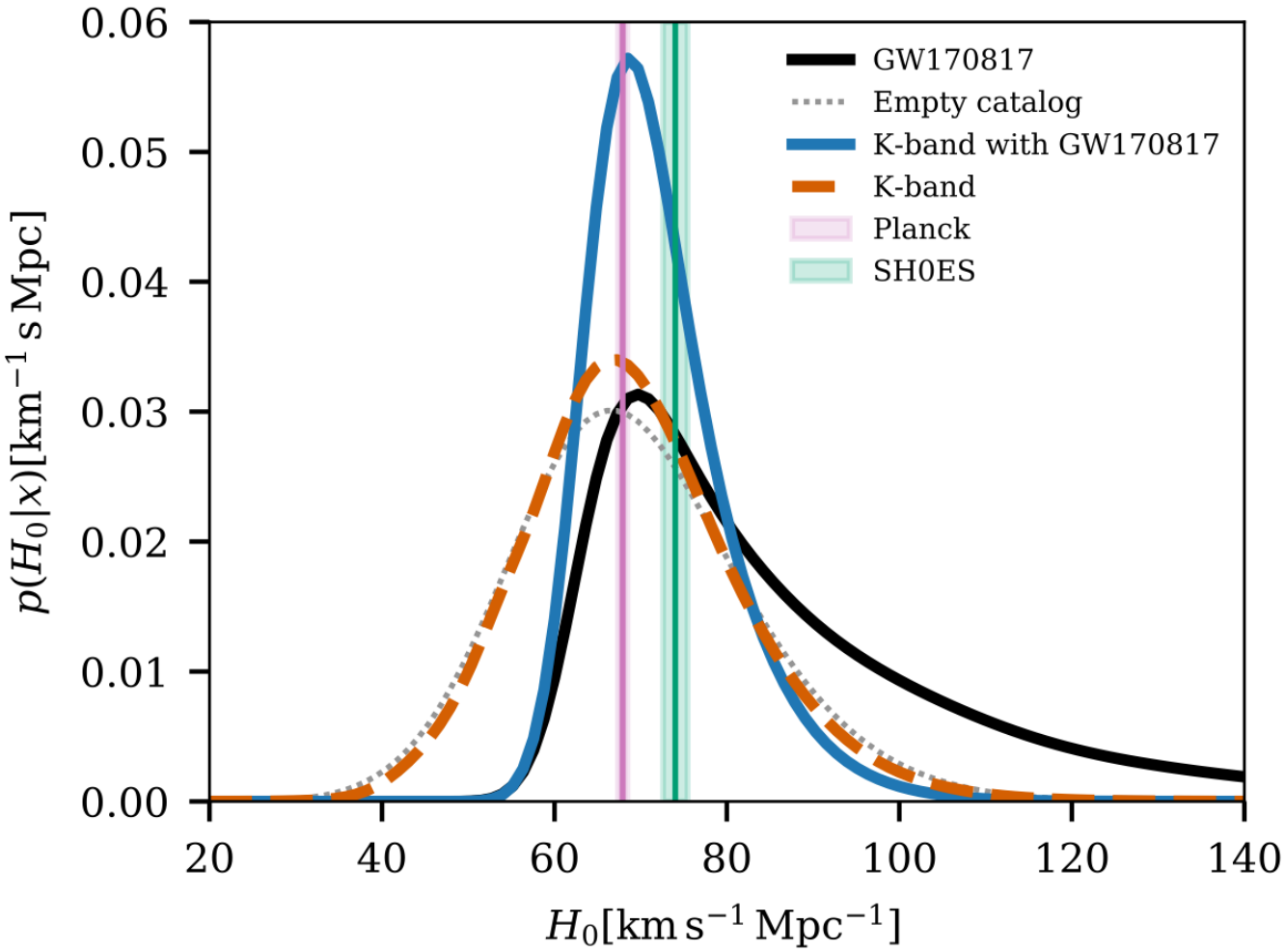
From the galaxy catalog only :

$$H_0 = 67^{+13}_{-12} \ \ km.s^{-1}.Mpc^{-1}$$

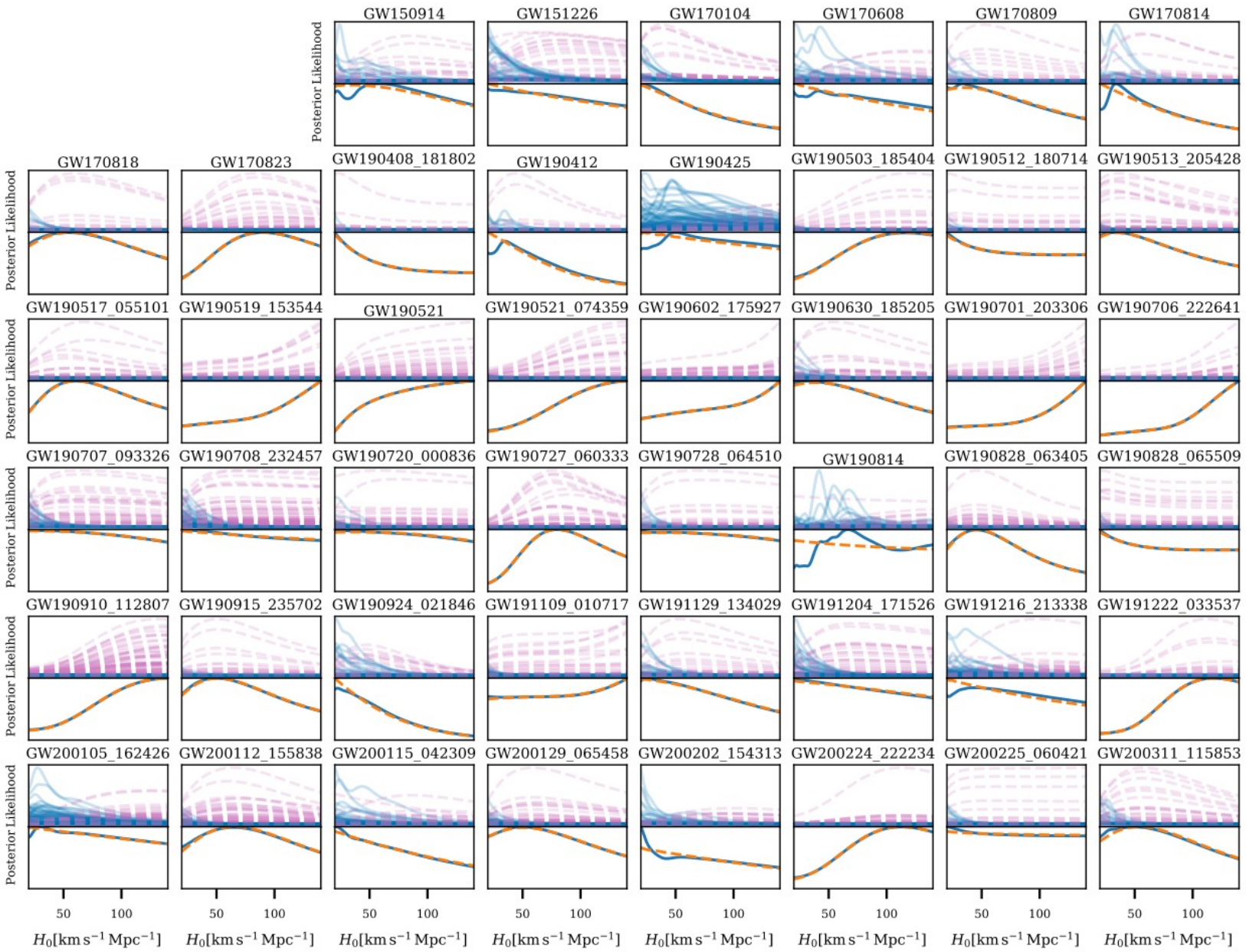
Combined with GW1708187 :

$$H_0 = 68^{+8}_{-6} \ \ km.s^{-1}.Mpc^{-1}$$

Constraints on the cosmic expansion history from GWTC–3



Event by event posteriors



Galaxy catalog

No galaxy information

- Only GW190814 shows additional information from the galaxy catalog
- Mainly driven by population assumptions

Conclusions of O3 results

- Using 42 BBH events : We inferred constraints on the cosmological parameters using IcaroGW, GWcosmo
- First analysis to jointly estimate population properties and cosmology (showing crucial correlations)
- The choice of the source mass model can impact the inferred value of the cosmological parameters
- Improved constraints on the Hubble constant :
  - Spectral Sirens + GW170817 : $H_0 = 68^{+12}_{-8} \ km.s^{-1}.Mpc^{-1}$
  - Galaxy catalog + GW170817 : $H_0 = 68^{+8}_{-6} \ km.s^{-1}.Mpc^{-1}$ (Fixed pop parameters)