An Introduction to Late-time Cosmology with Gravitational Waves

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LISA CONSORTIUM

LISA School for early-career scientists - 6-17 October 2025, Les Houches

ÉCOLE DE PHYSIQUE DES HOUCHES

Standard sirens

The central question is then: how to get the GW source redshift?

Here we will consider three methods that are mostly used in current GW standard siren studies:

1. **Identification of a direct EM counterpart ("bright siren" method)**

   Requires an EM counterpart!

2. **Using spectral features in the GW mass distribution ("spectral siren" method)**

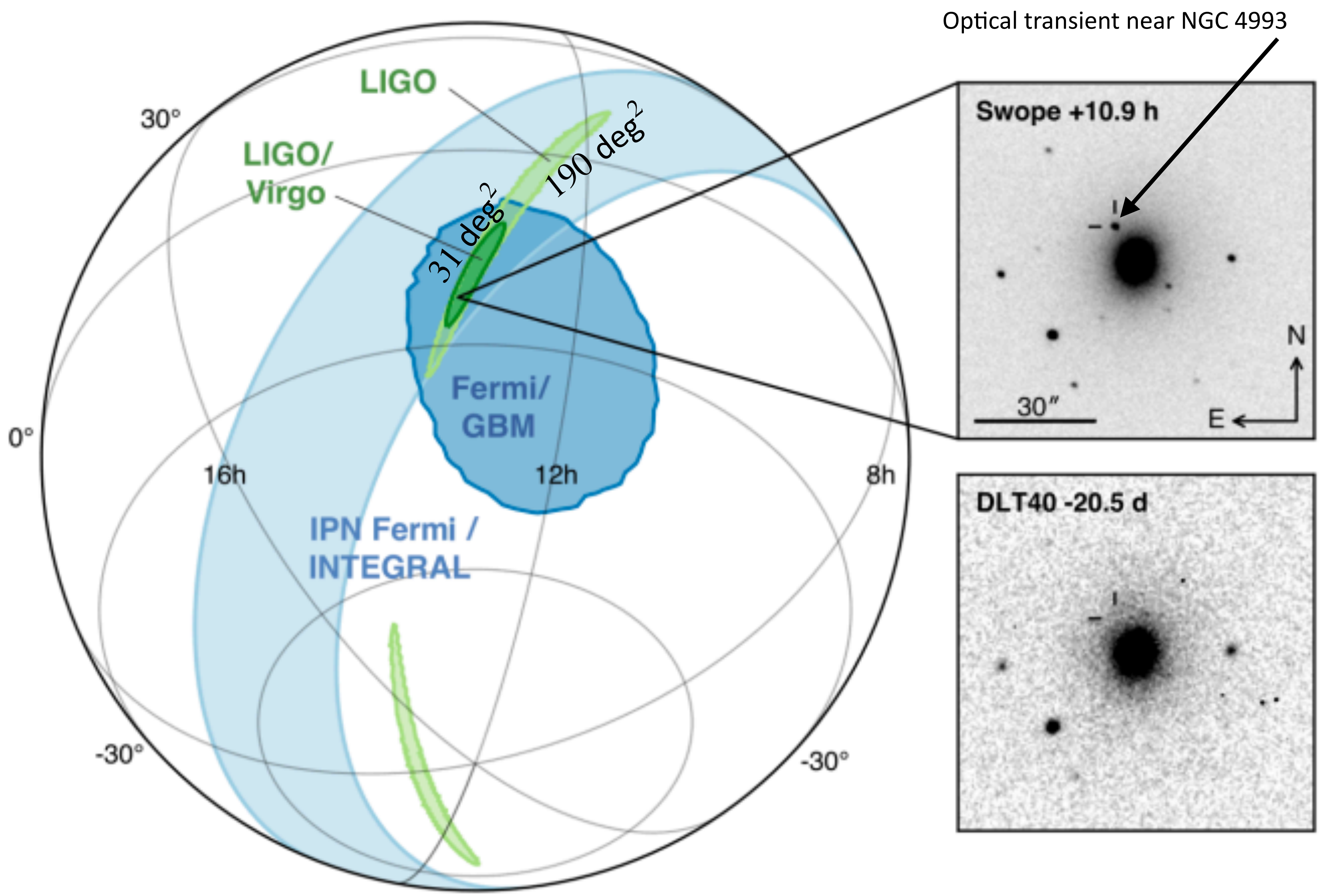
   Requires assumptions about the GW source populations!

3. **Adding redshift information coming from potential host galaxies ("dark siren" method, or "galaxy catalog" method)**

   Requires a galaxy catalog!

1. Identification of a direct EM counterpart (“bright siren” method)

GW170817



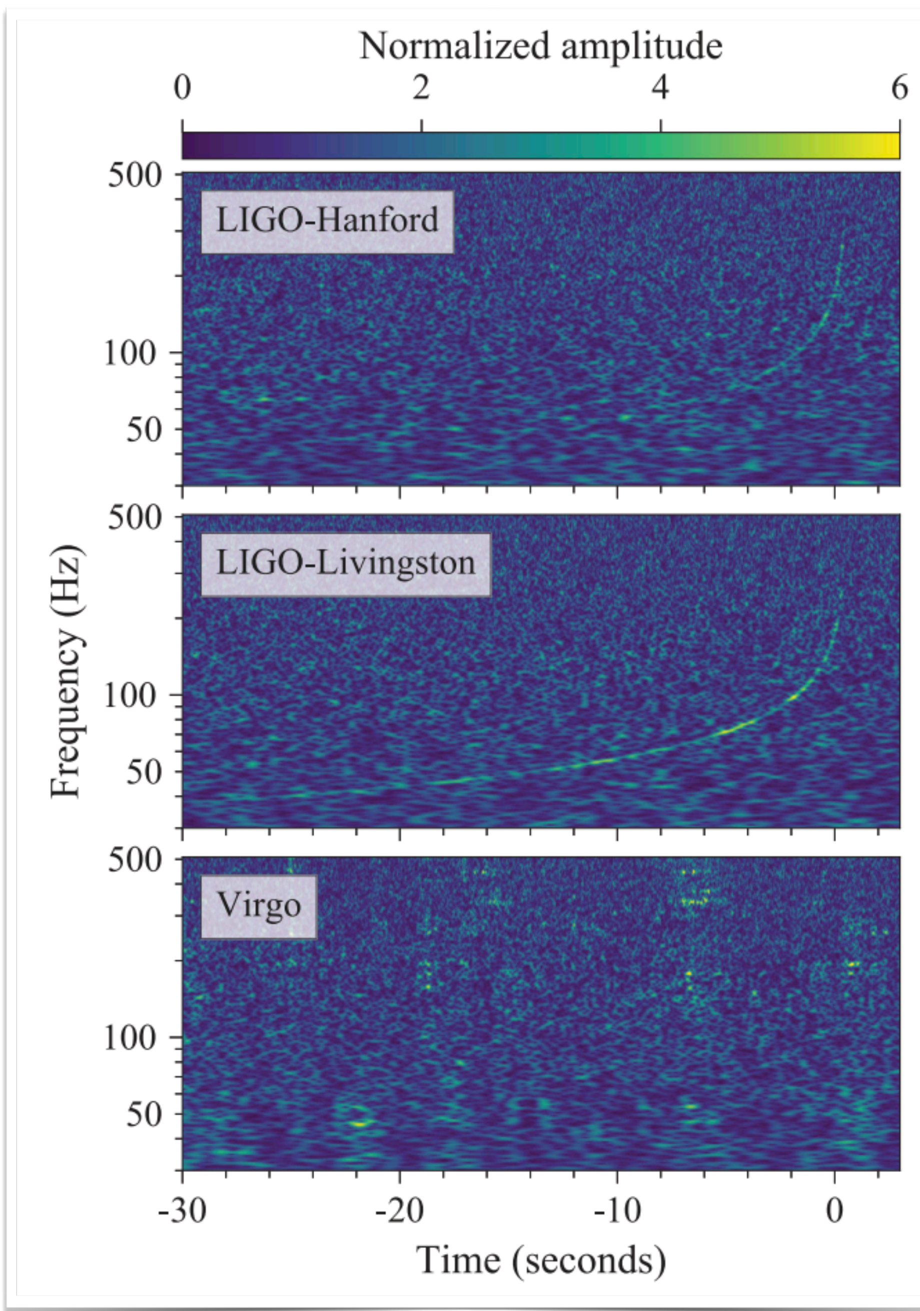
LVC et al., ApJL (2017)

Standard sirens

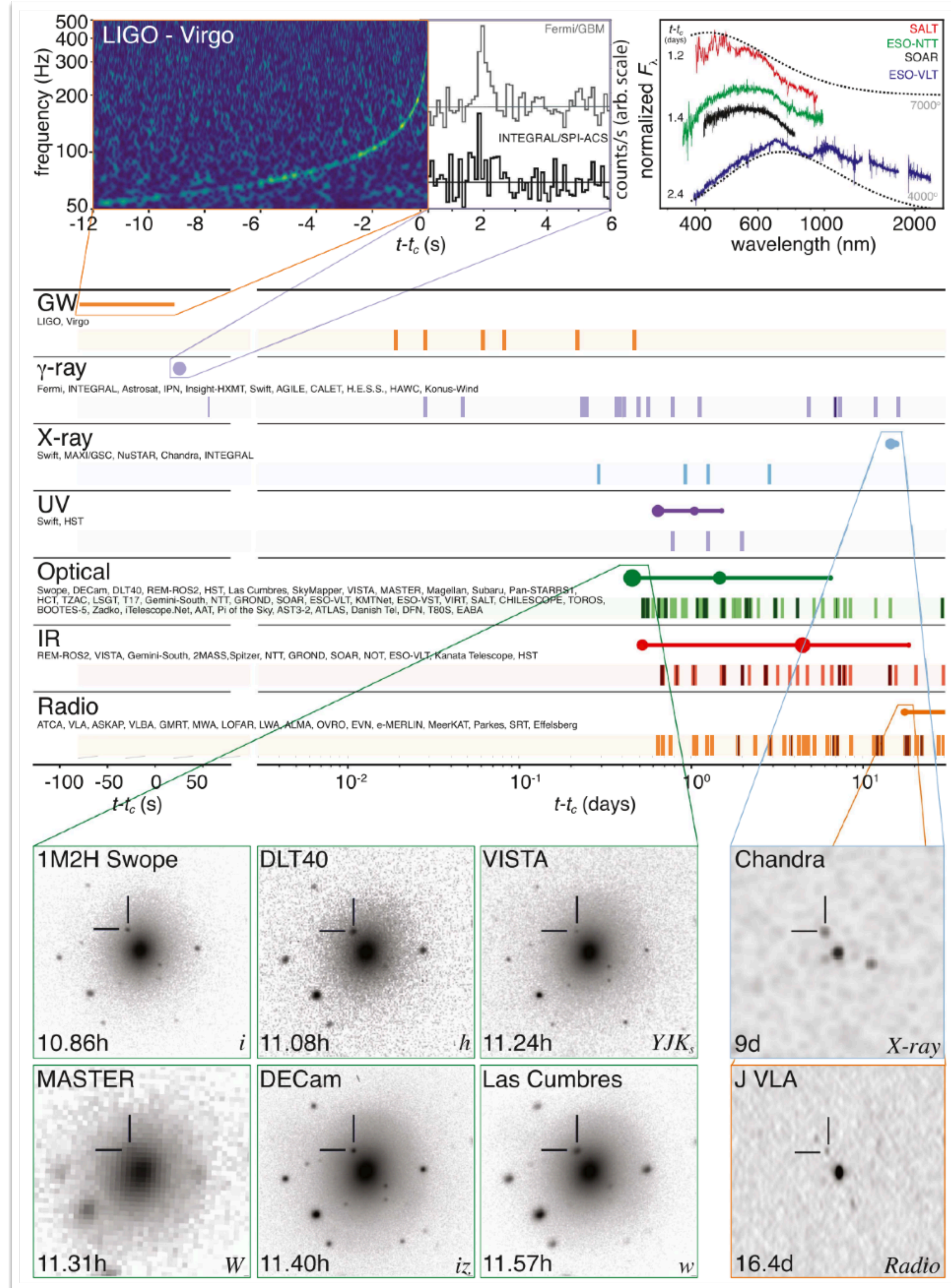
1. Identification of a direct EM counterpart (“bright siren” method)

The coincident GW-EM detection of GW170817 puts stringent constraints on the speed of GWs:

$$c_T = c^{+7\times10^{-16}}_{-3\times10^{-15}}$$



LVC, *PRL* (2017)

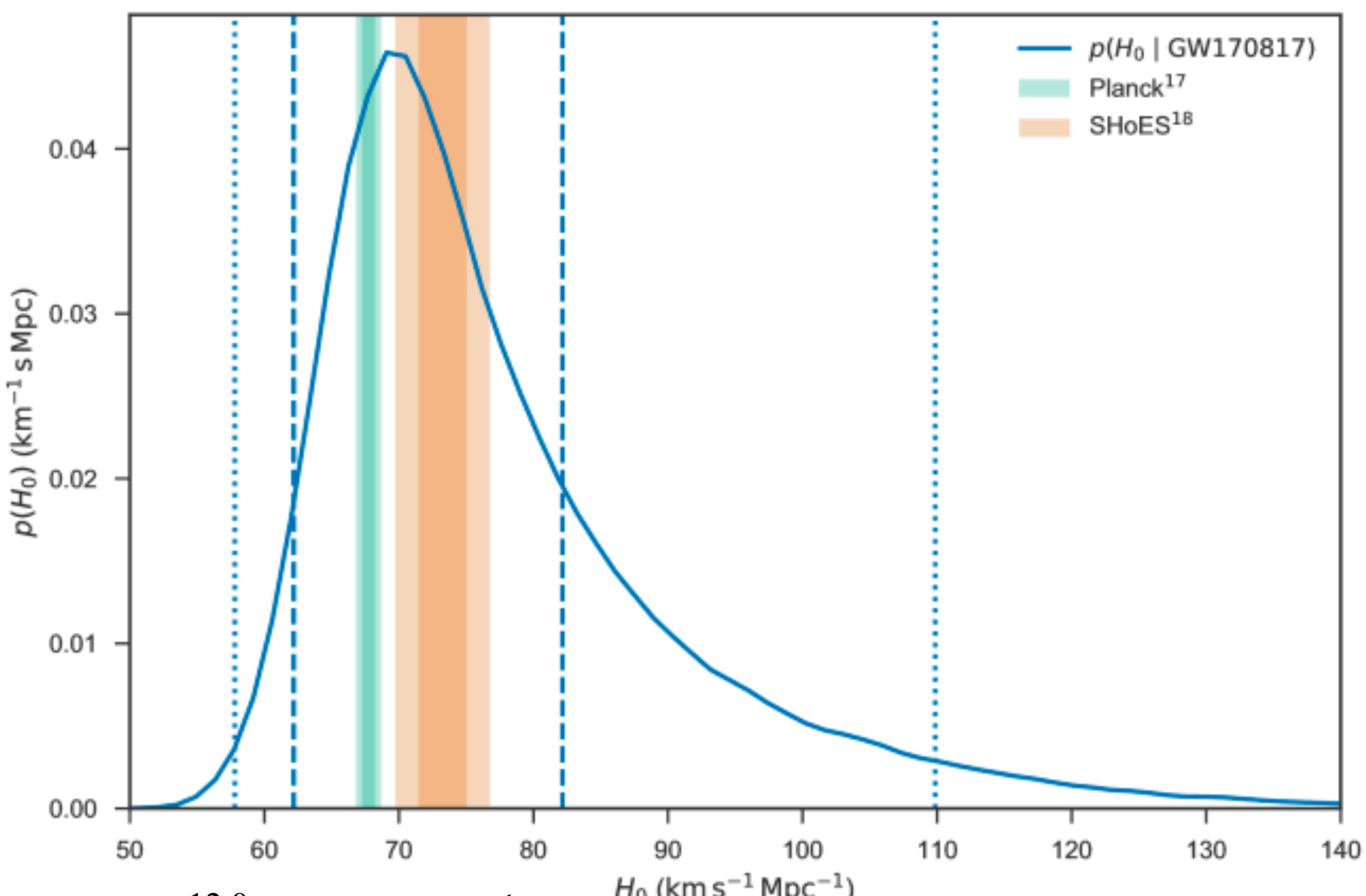


LVC et al., ApJL (2017)

Standard sirens

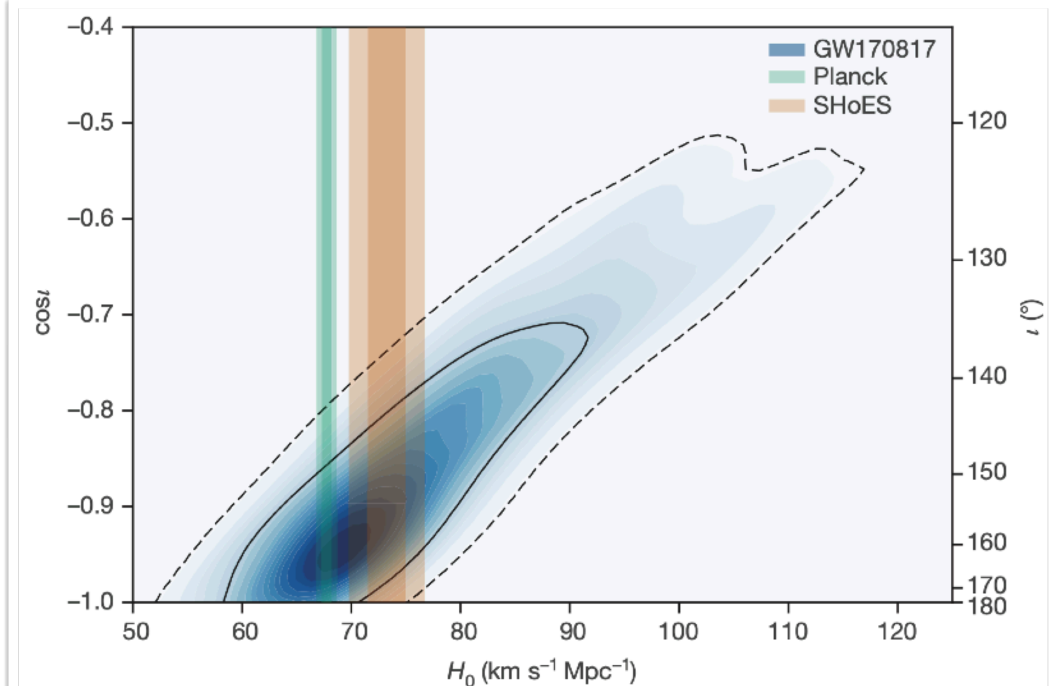
1. Identification of a direct EM counterpart (“bright siren” method)

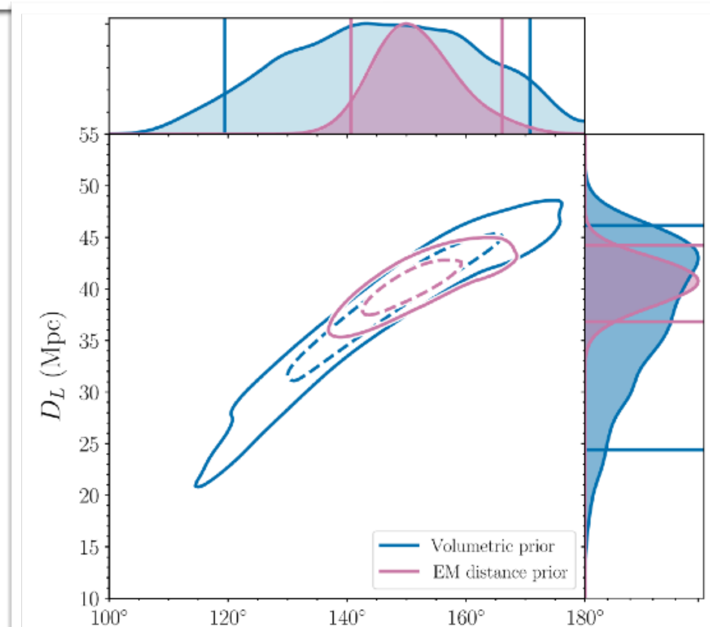
GW170817: the first bright siren measurement of H_0



$H_0 = 70^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}

LVC et al., Nature (2017)





LVC, *PRX* (2019)

Low-z event ($z \sim 0.01$): $D_\mathrm{L}(z) \simeq \dfrac{cz}{H_0}$

Results in agreement with EM constrains (CMB/SNIa)

Waiting for more EM counterparts to narrow down the H_0 posterior…

Chen et al., *Nature* (2018)

Standard sirens

2. Using spectral features in the GW mass distribution ("spectral siren" method)

$$m_i^{\mathrm{det}} = \left(1 + z(D_{\mathrm{L}}, H_0, \Omega_M)\right) m_i$$

From GWs

From phenomenological models

At a single-event level, the redshift is degenerate with the source-frame mass. However, at the population-level, features in the source-frame mass spectrum (e.g., sharp cutoff at high mass, or a peak at a specific mass) get shifted in the observed distribution

Taylor, Gair, Mandel, PRD (2012)   Farr et al., ApJL (2019)   Mastrogiovanni et al., PRD (2021)

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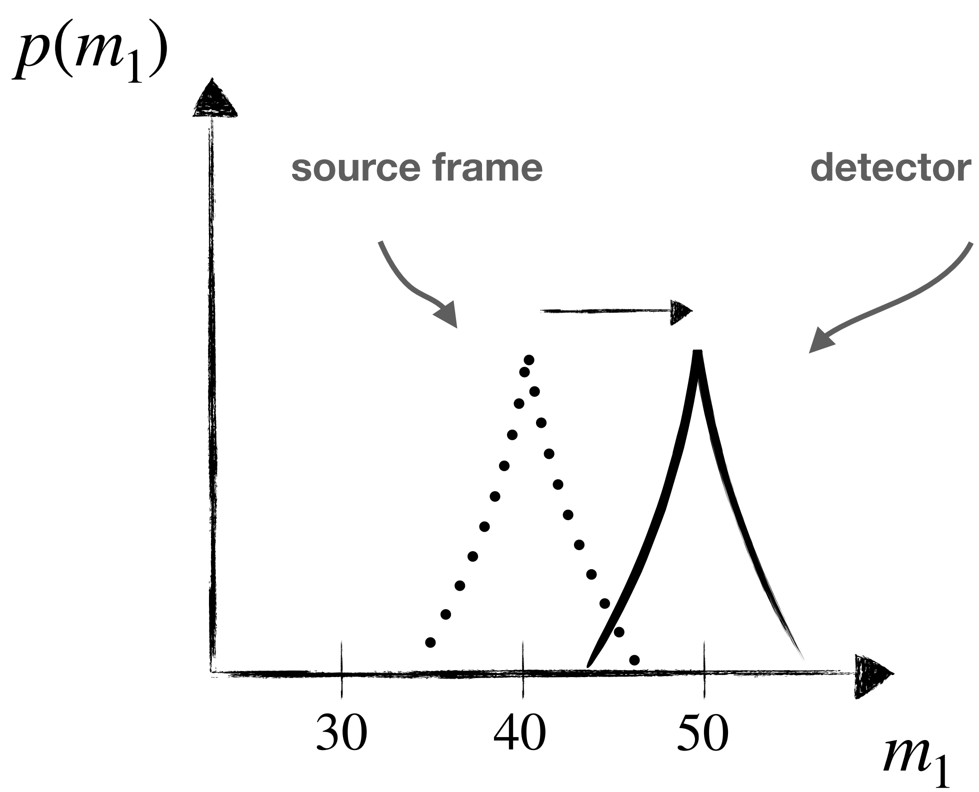
We look for "landmarks" in the mass distribution and see how far they appear shifted.

By measuring how far these features move, we can estimate the average redshift



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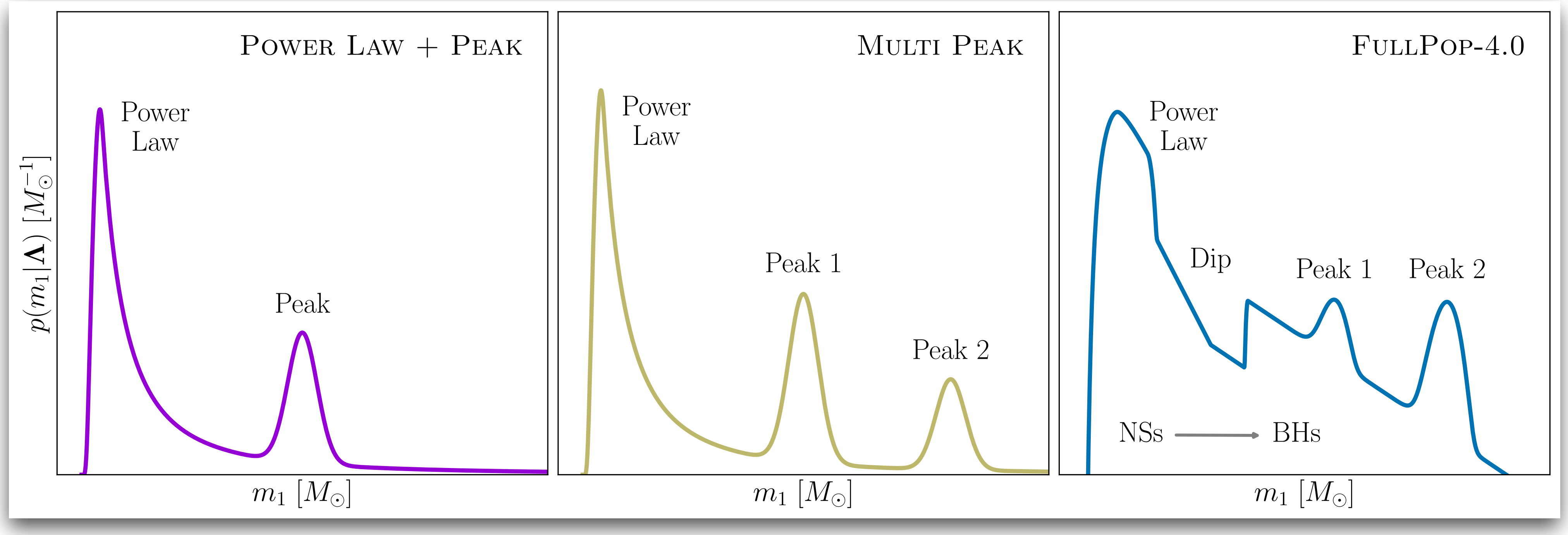
BH-only

Multipopulation (BN, NS)



LVK O4a cosmology paper, arXiv:2509.04348

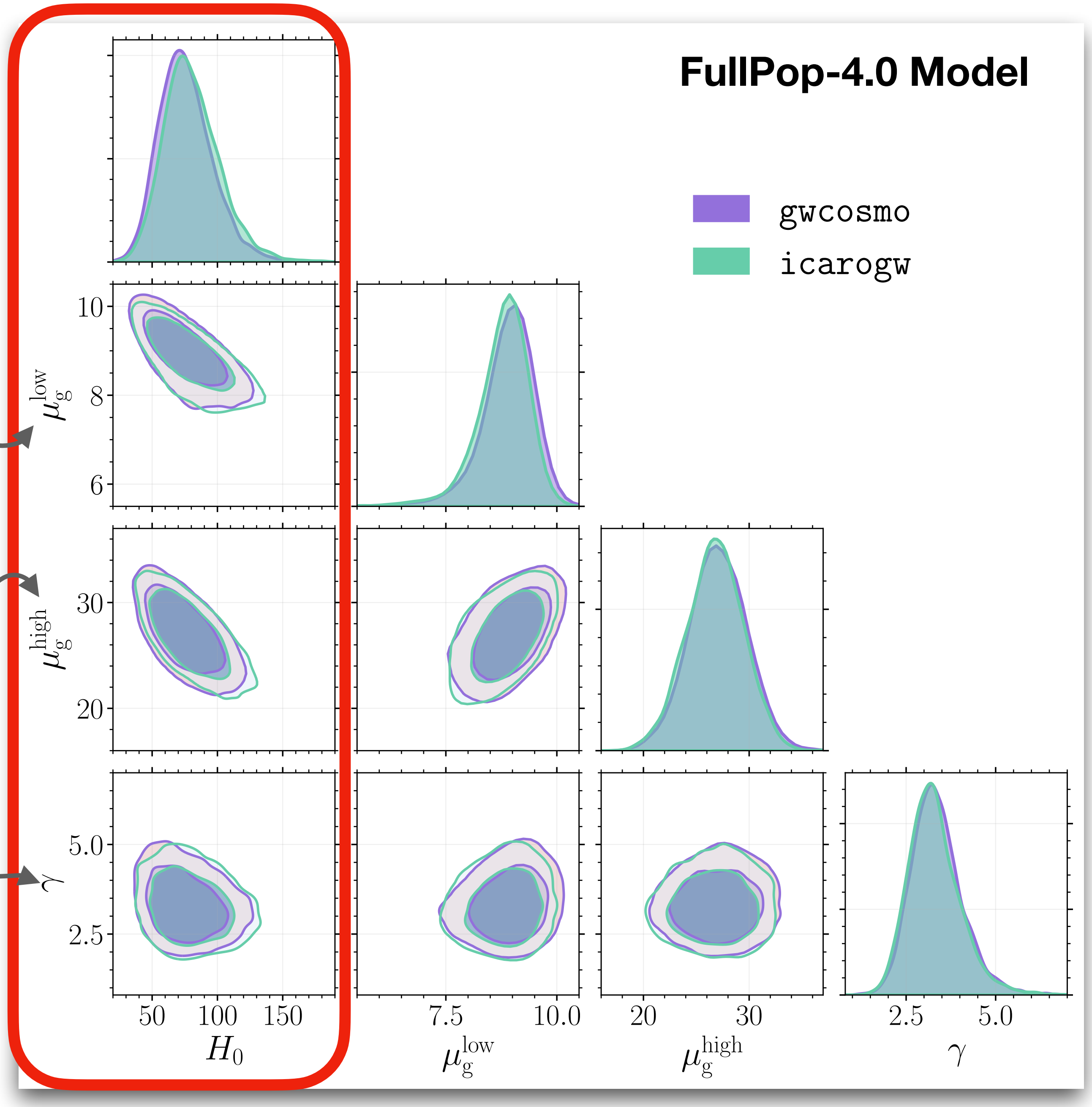
2. Using spectral features in the GW mass distribution ("spectral siren" method)

We sample both the cosmological and population parameters

Example:

position of the first (low) and second (high) peaks in the primary mass

low-z power-law slope of a Madau-Dickinson-like merger rate



Gray et al., 2020, 2022, 2023

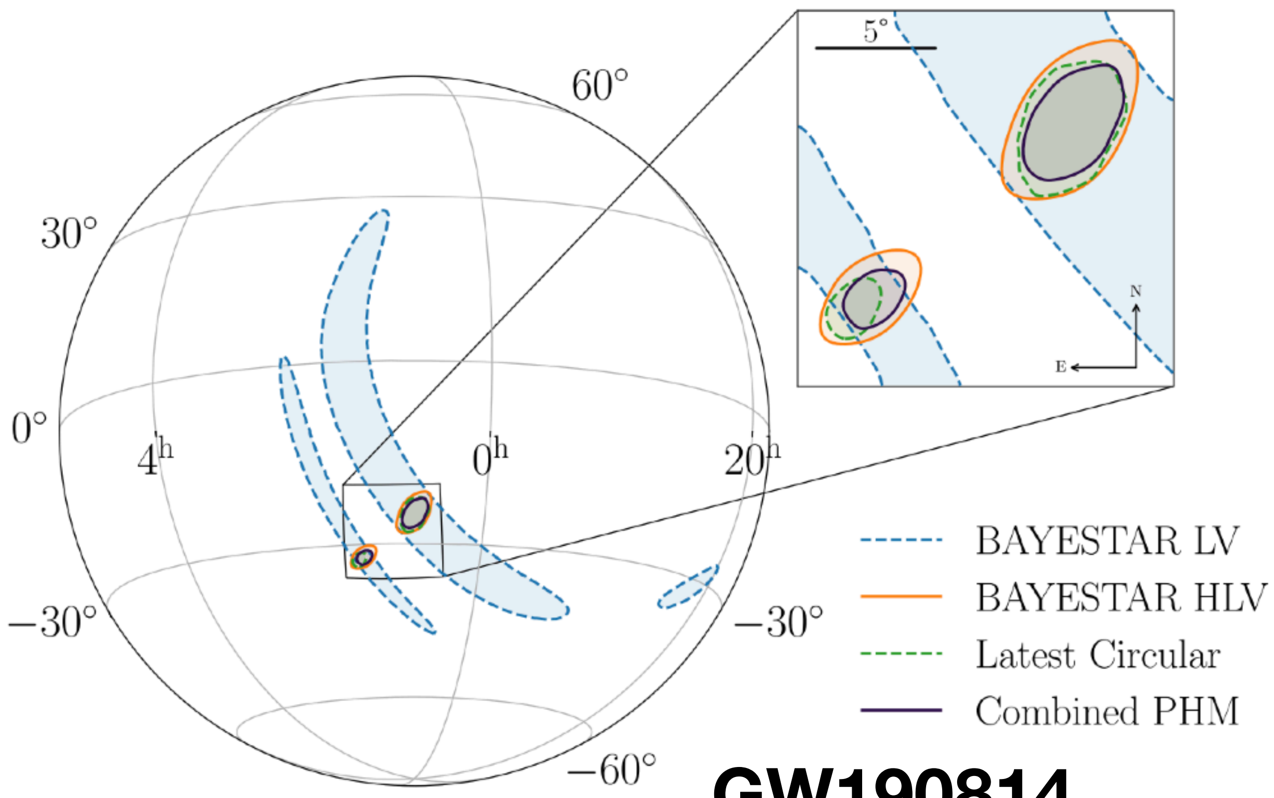
Mastrogiovanni et al., 2023, 2024

LVK O4a cosmology paper, arXiv:2509.04348

Standard sirens

3. Adding redshift information coming from potential host galaxies ("dark siren" method, or "galaxy catalog" method)

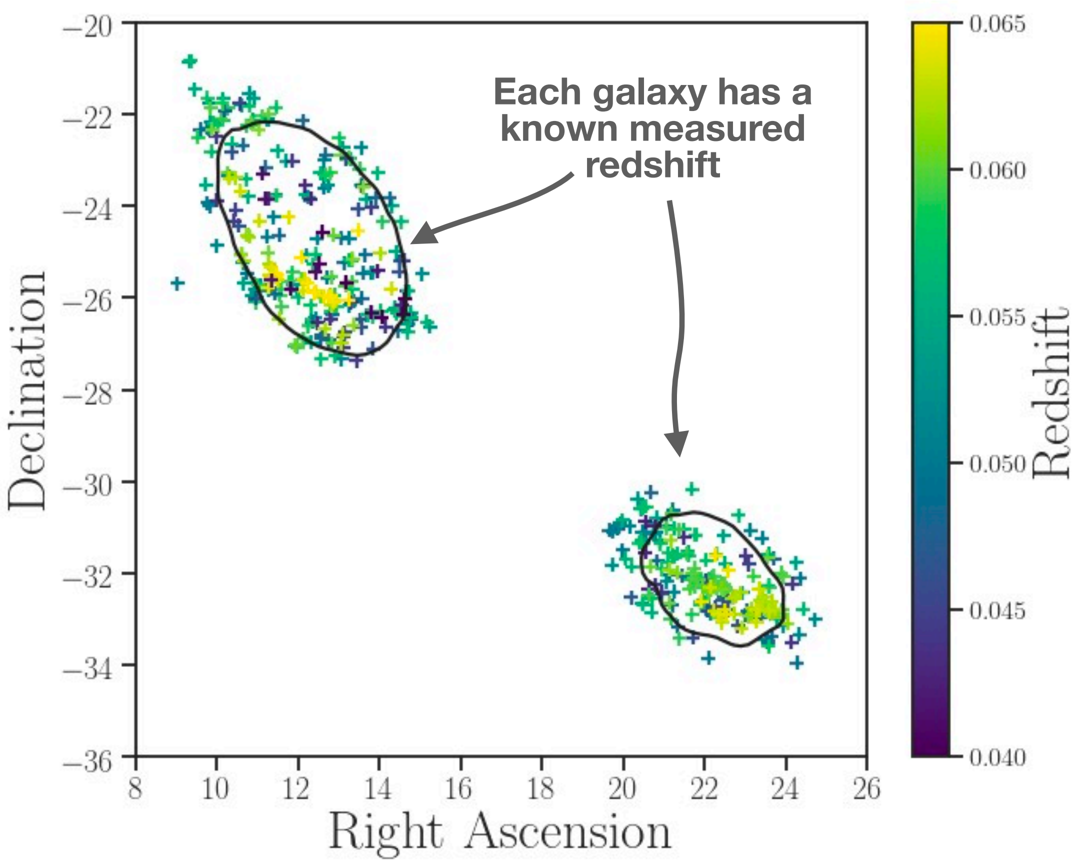
To account for the uncertainty as to which galaxy is the true host, we can marginalize over the redshifts of the galaxies that are compatible with the GW sky location



GW190814

LVK, ApJL (2020)

Glade+ galaxy catalog: Dàlya et al., *MNRAS* (2022)



LIGO-Virgo, LIGO Document P2000227-v4

Other first applications of this method: GW170817 (Fishbach et al., ApJL 2019), GW170814 (DES, LVC et al., ApJL 2019)

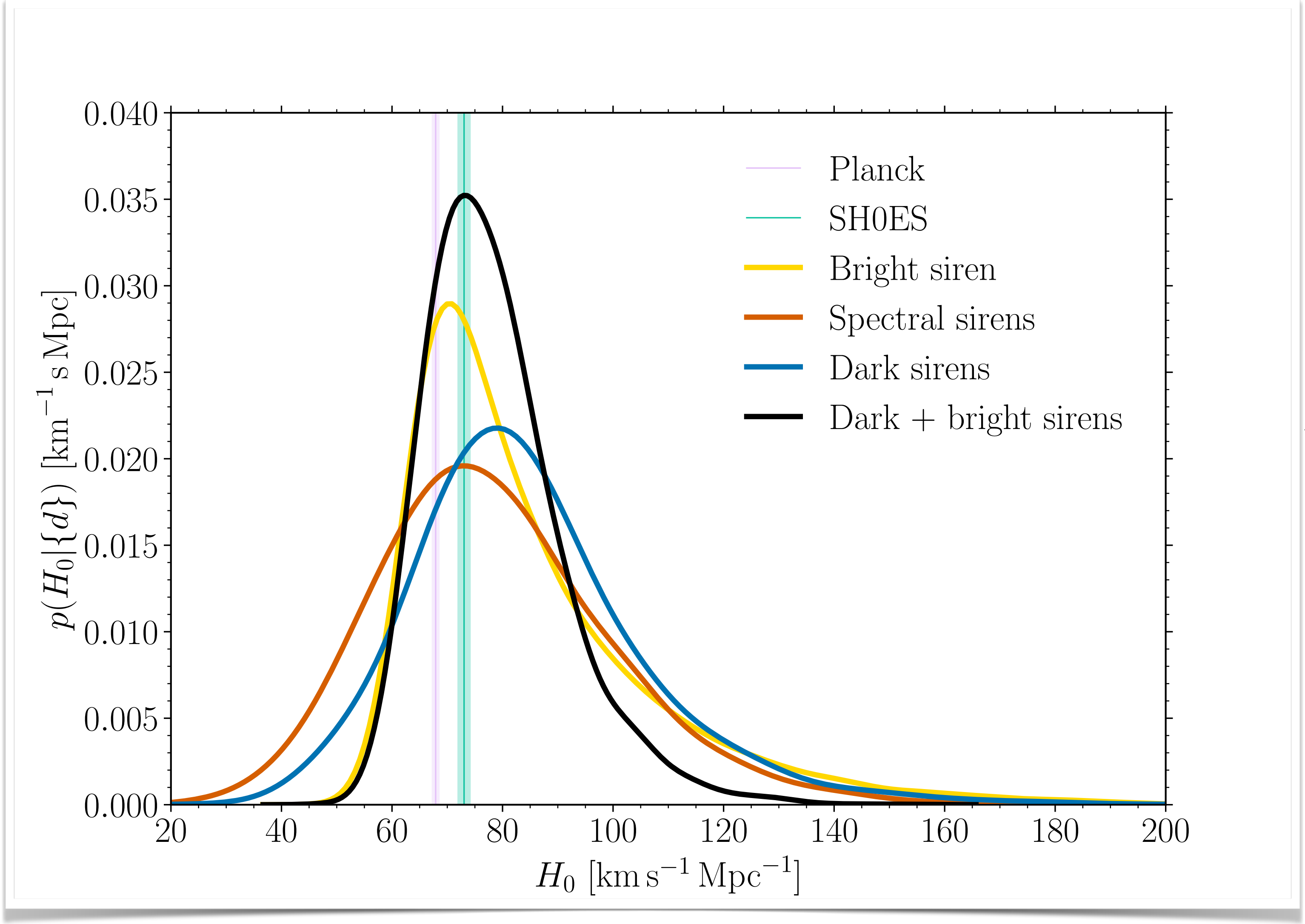
Schutz, *Nature* (1986) Del Pozzo, *PRD* (2012) Gray et al., *PRD* (2020) Finke et al., *JCAP* (2021) Palmese et al., ApJ (2023)
Mastrogiovanni et al, *PRD* (2023) Gray et al., *JCAP* (2023) LVK, arXiv:2509.04348

Standard sirens

3. Adding redshift information coming from potential host galaxies ("dark siren" method, or "galaxy catalog" method)

By combining the information from many GW events, the contributions from the true host galaxies will grow since they will all share the same H_0. Contributions from the others will statistically average out, leading to a constraint on cosmological parameters.

Example:



$H_0 = 76.4^{+23.0}_{-18.1}$ km s^{-1} Mpc^{-1}

$H_0 = 81.6^{+21.5}_{-15.9}$ km s^{-1} Mpc^{-1}

$H_0 = 76.6^{+13.0}_{-9.5}$ km s^{-1} Mpc^{-1}

(median + 68.3% CI)

LVK O4a cosmology paper, arXiv:2509.04348

Standard sirens: methods

How are these analyses done in practice? We work within the framework of hierarchical Bayesian inference in the presence of selection effects.

Mandel et al, *MNRAS* (2019)

Vitale et al., Chapter 42 in *Handbook of Gravitational Wave Astronomy*, Springer (2022) - arXiv:2007.05579

Mastrogiovanni, DL, et al, *PRD* (2023)

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For the spectral and dark siren methods, the observed GW sample is modeled as resulting from an inhomogeneous Poisson process (constant rate in detector-frame time) in the presence of selection effects. The cosmological Λ_c and population Λ_p parameters are called hyperparameters.

$$p(\Lambda \,|\, \{x\}) \propto p(\Lambda)\, L(\{x\} \,|\, \Lambda)$$

Mastrogiovanni, DL, et al, *PRD* (2023)

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$$p(\Lambda \,|\, \{x\}) \propto p(\Lambda)\, L(\{x\} \,|\, \Lambda)$$

Hyperposterior of $\Lambda = \{\Lambda_c, \Lambda_p\}$ given some observations $\{x_i\}_{i=1}^{N_{GW}}$

Hyperprior for Λ

(Hierarchical) likelihood function for the observations as a function of Λ

Mastrogiovanni, DL, et al, *PRD* (2023)

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(Hierarchical) likelihood function for the observations as a function of Λ

$$L(\{x\} \,|\, \Lambda) \propto e^{-N_{exp}} \prod_{i}^{N_{GW}} T_{obs} \int \mathrm{d}\theta_i \; L(x_i \,|\, \theta_i) \frac{\mathrm{d}N_{\mathrm{CBC}}}{\mathrm{d}\theta_i \mathrm{d}t}(\theta_i, \Lambda) \frac{1}{1+z}$$

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- $p(\Lambda \,|\, \{x\})$: Hyperposterior of $\Lambda = \{\Lambda_c, \Lambda_p\}$ given some observations $\{x_i\}_{i=1}^{N_{GW}}$
- $p(\Lambda)$: Hyperprior for Λ
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- T_{obs}: Observation time in detector-frame
- $L(x_i \,|\, \theta_i)$: GW event likelihood function
- $\frac{\mathrm{d}N_{\rm CBC}}{\mathrm{d}\theta_i \mathrm{d}t}$: Compact binary coalescence (CBC) event rate in source-frame time
- $\frac{1}{1+z}$: conversion factor from $t_{\rm o}$ to $t = t_{\rm s}$

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$$N_{exp} = T_{obs} \int \mathrm{d}\theta \; P_{det}(\theta; \Lambda) \frac{\mathrm{d}N_{\mathrm{CBC}}}{\mathrm{d}\theta \mathrm{d}t}(\theta, \Lambda) \frac{1}{1+z}$$

- $P_{det}(\theta; \Lambda)$: Probability of detecting a GW source of parameters θ given Λ

Mastrogiovanni, DL, et al, *PRD* (2023)

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What is this term?

Mastrogiovanni, DL, et al, *PRD* (2023)

Standard sirens: methods

The compact-binary-coalescence merger rate is parametrized in terms of redshift and source-frame time.

For a spectral siren analysis:

$$\frac{\mathrm{d}N_{CBC}}{d\vec{m}\,\mathrm{d}\theta\,\mathrm{d}\Omega\,\mathrm{d}z\,\mathrm{d}t} \propto \psi_{\mathrm{MD}}(z;\Lambda_p)\, p_{pop}(\vec{m},\theta\,|\,\Lambda_p)\frac{\mathrm{d}V_c}{\mathrm{d}z\mathrm{d}\Omega}(z,\Lambda_c)$$

$\vec{m} = \{m_1, m_2\}$
binary component masses

other GW parameters, e.g., spins

sky position

Mastrogiovanni, DL, et al, *PRD* (2023)

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$\vec{m} = \{m_1, m_2\}$ binary component masses

other GW parameters, e.g., spins

sky position

CBC merger rate as a function of z, usually parametrized as a Madau-Dickinson distribution

comoving volume factor

Mastrogiovanni, DL, et al, *PRD* (2023)

Standard sirens: methods

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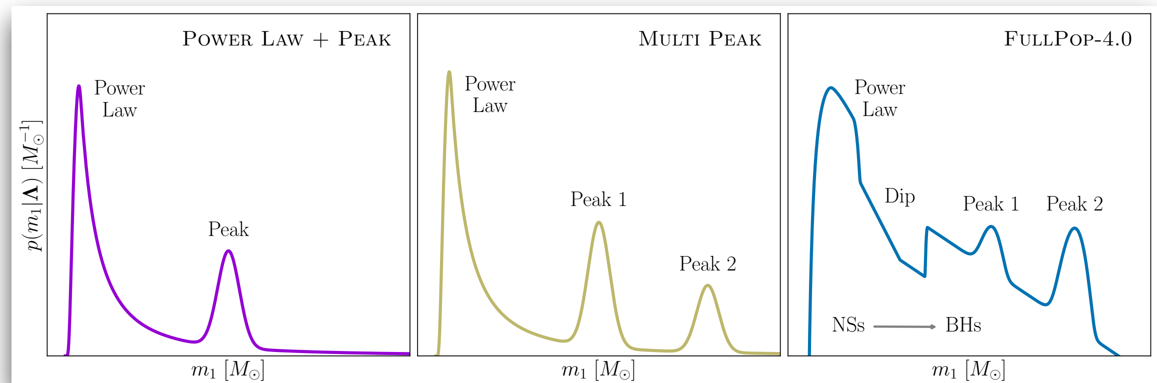

PDF describing the distribution of GW sources in masses $\vec{m}$ and other GW parameters θ

$$\frac{\mathrm{d}N_{CBC}}{d\vec{m}\,\mathrm{d}\theta\,\mathrm{d}\Omega\,\mathrm{d}z\,\mathrm{d}t} \propto \psi_{\mathrm{MD}}(z;\Lambda_p)\,p_{pop}(\vec{m},\theta\,|\,\Lambda_p)\frac{\mathrm{d}V_c}{\mathrm{d}z\,\mathrm{d}\Omega}(z,\Lambda_c)$$

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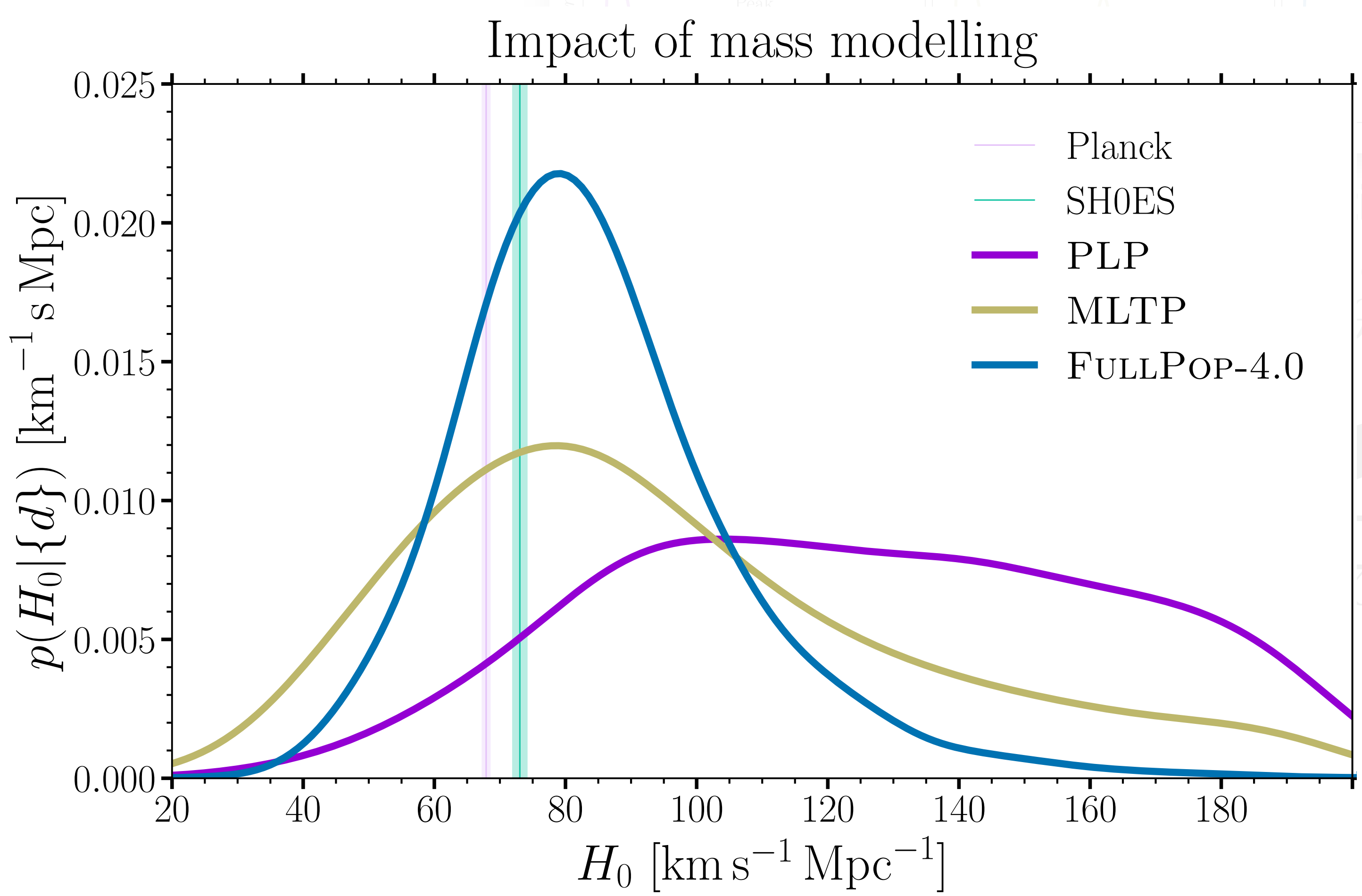
For a spectral siren analysis:

Main limitation: systematics due to the choice of a population model



LVK O4a cosmology paper, arXiv:2509.04348

Standard sirens: methods

The compact-binary-coalescence merger rate is parametrized in terms of redshift and source-frame time.

For a dark siren analysis, it's more complex! We have to build a pixelated "line-of-sight" redshift prior:

"In-catalog" term (accounts for the galaxies in your galaxy catalog)

$$\frac{\mathrm{d}N_{CBC}}{\mathrm{d}\vec{m}\mathrm{d}\theta\mathrm{d}\Omega\mathrm{d}z\mathrm{d}t} \propto \psi_{\mathrm{MD}}(z;\Lambda_p)\, p_{pop}(\vec{m},\theta\,|\,\Lambda_p) \left[\frac{1}{\Delta\Omega}\sum_j^{N_{gal}(\Omega)}\left(\frac{L}{L_*}\right)^{\epsilon} p(z\,|\,z_j,\sigma_{z,j}) + \int_{M_{thr}(z,m_{thr}(\Omega))}^{M_{max}} dM\,\mathrm{Sch}(M;\Lambda_p)\left(\frac{L}{L_*}\right)^{\epsilon}\frac{\mathrm{d}V_c}{\mathrm{d}z\mathrm{d}\Omega}\right]$$

"Out-of-catalog" term (corrects for the incompleteness of your galaxy catalog)

Absolute magnitude **Apparent magnitude** **"K-corrections"**

$$M = m + 5 - 5\log D_{\mathrm{L}}(z,\Lambda_c) - K_{corr}$$

Absolute luminosity

$$\frac{L}{L_*} = 10^{0.4(M_*-M)}$$

Mastrogiovanni, DL, et al, *PRD* (2023)

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Absolute luminosity of the galaxy over a reference galaxy luminosity

Number of galaxies in a given sky direction

Luminosity weight $\epsilon = \{0,1\}$

Galaxy redshift uncertainty model

pixel area

Threshold magnitude *above* which we are missing galaxies due to flux-limited surveys

Characteristic luminosity

Schechter (luminosity) function giving the number density of galaxies as a function of their absolute magnitudes

$$\mathbf{Sch}(M,\Lambda_p)\mathrm{d}M = \Phi(L,\Lambda_p)\mathrm{d}L$$

Absolute magnitude — Apparent magnitude — "K-corrections"

$$M = m + 5 - 5\log D_{\mathrm{L}}(z,\Lambda_c) - K_{corr}$$

Absolute luminosity

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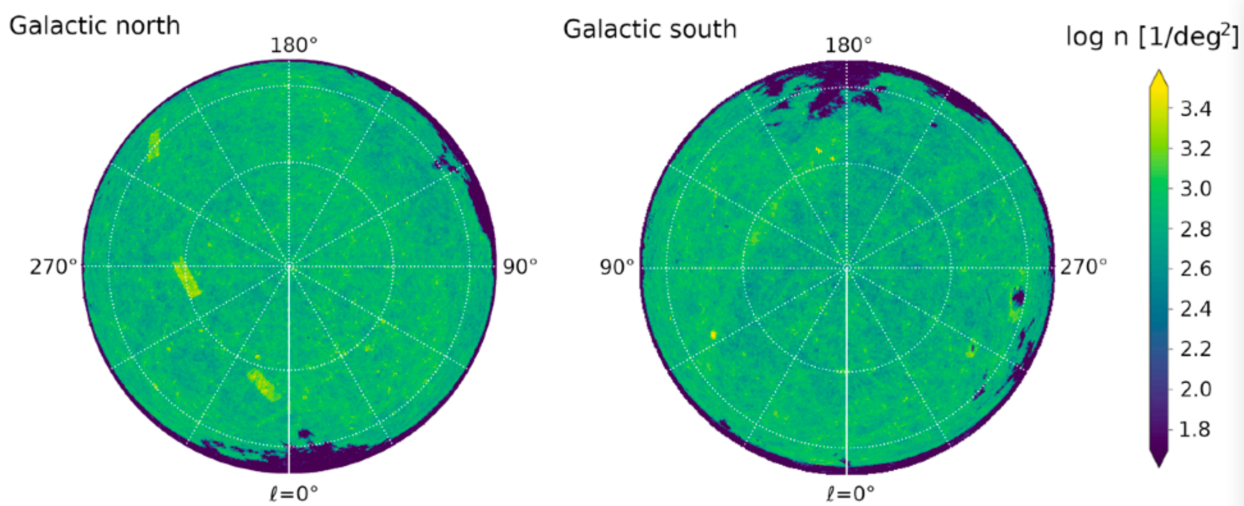
Mastrogiovanni, DL, et al, *PRD* (2023)

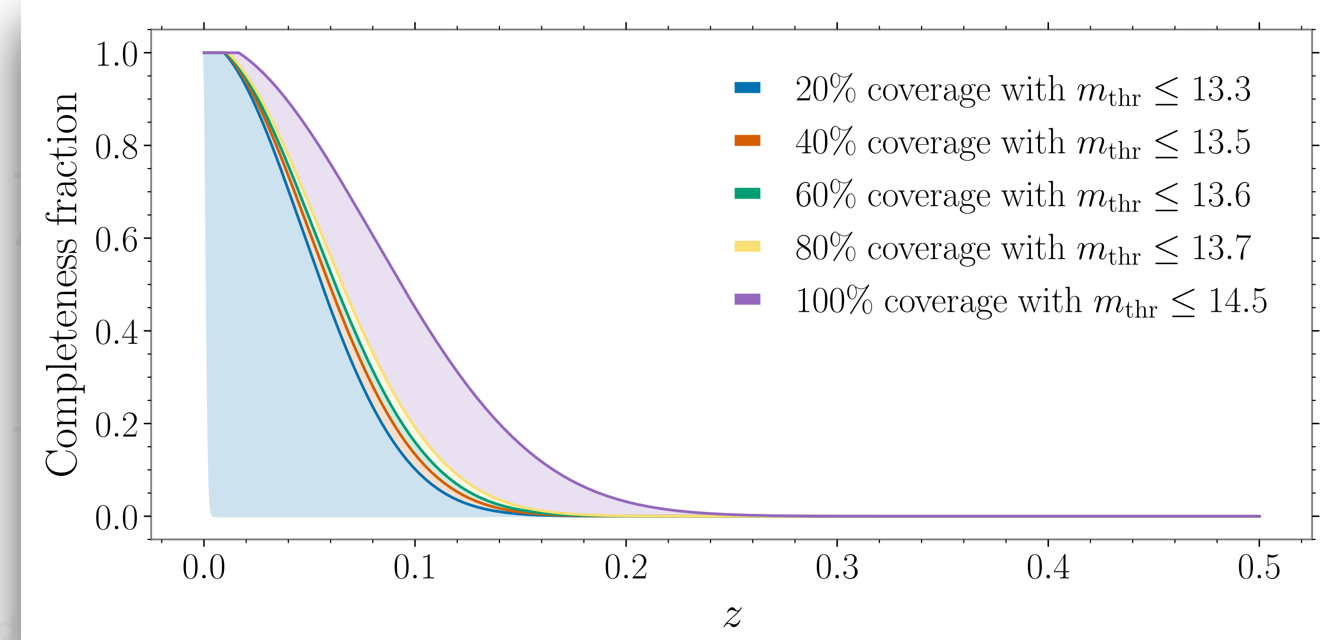
Standard sirens: methods

GLADE+: Galaxy List for the Advanced Detector Era +

Collection of **6 different surveys** (~22.5M galaxy: GWGD, 2MPZ, 2MASS XSC, HyperLEDA, WISExSCOSPZ; ~750k quasars: SDSS-DR16Q)



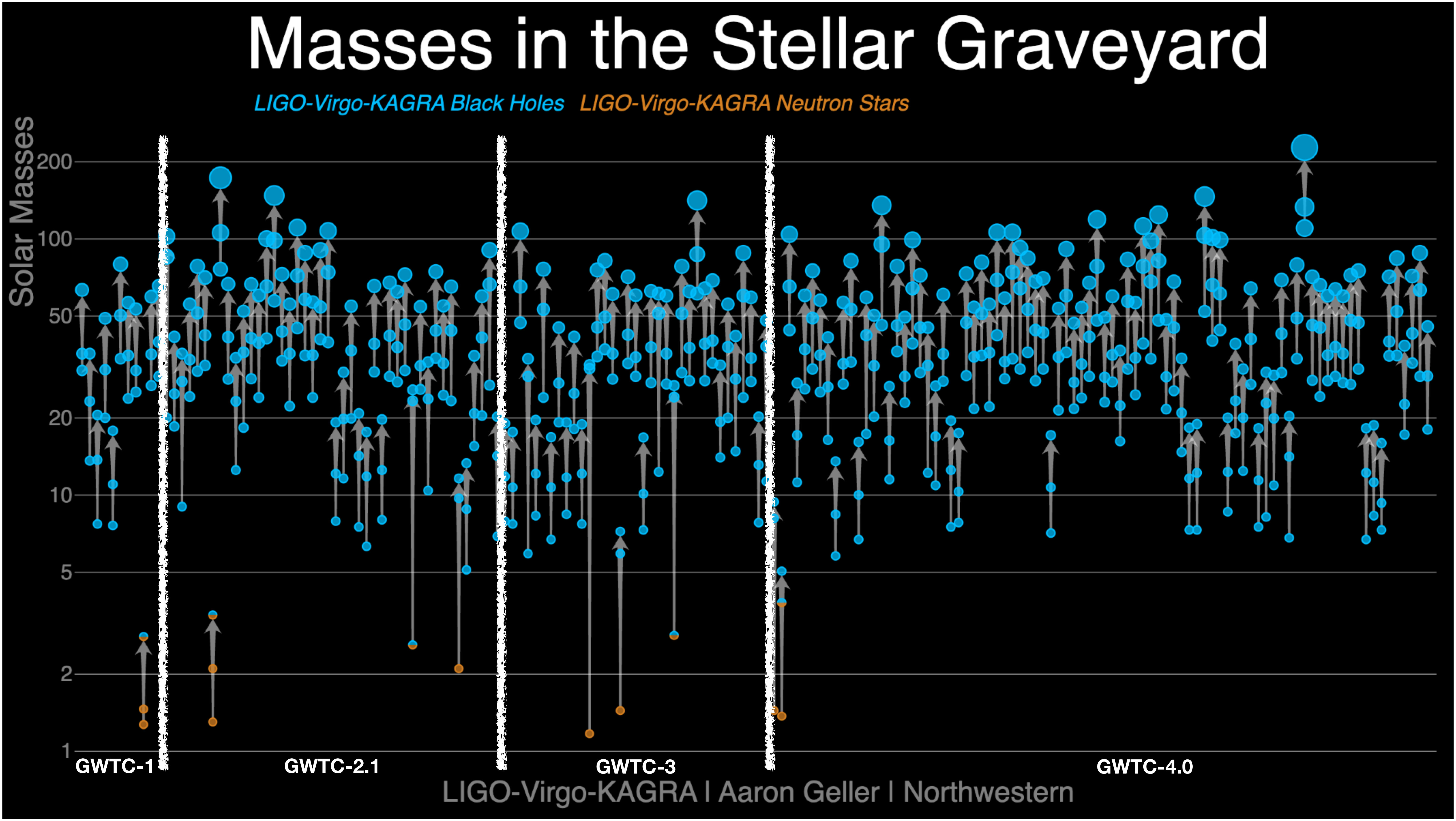
G. Dálya et al., MNRAS 514 1 (2022)



LVK O4a cosmology paper, arXiv:2509.04348

Main limitation: incompleteness of the galaxy catalog used

GWTC-4.0 is here!



GWTC-4.0 is here!

The methods we have seen have been applied to the latest GW detections

New cosmology paper with GWTC-4.0!

[LVK Collaboration, arXiv:2509.04348]

GWTC-4.0: Constraints on the Cosmic Expansion Rate and Modified Gravitational-wave Propagation

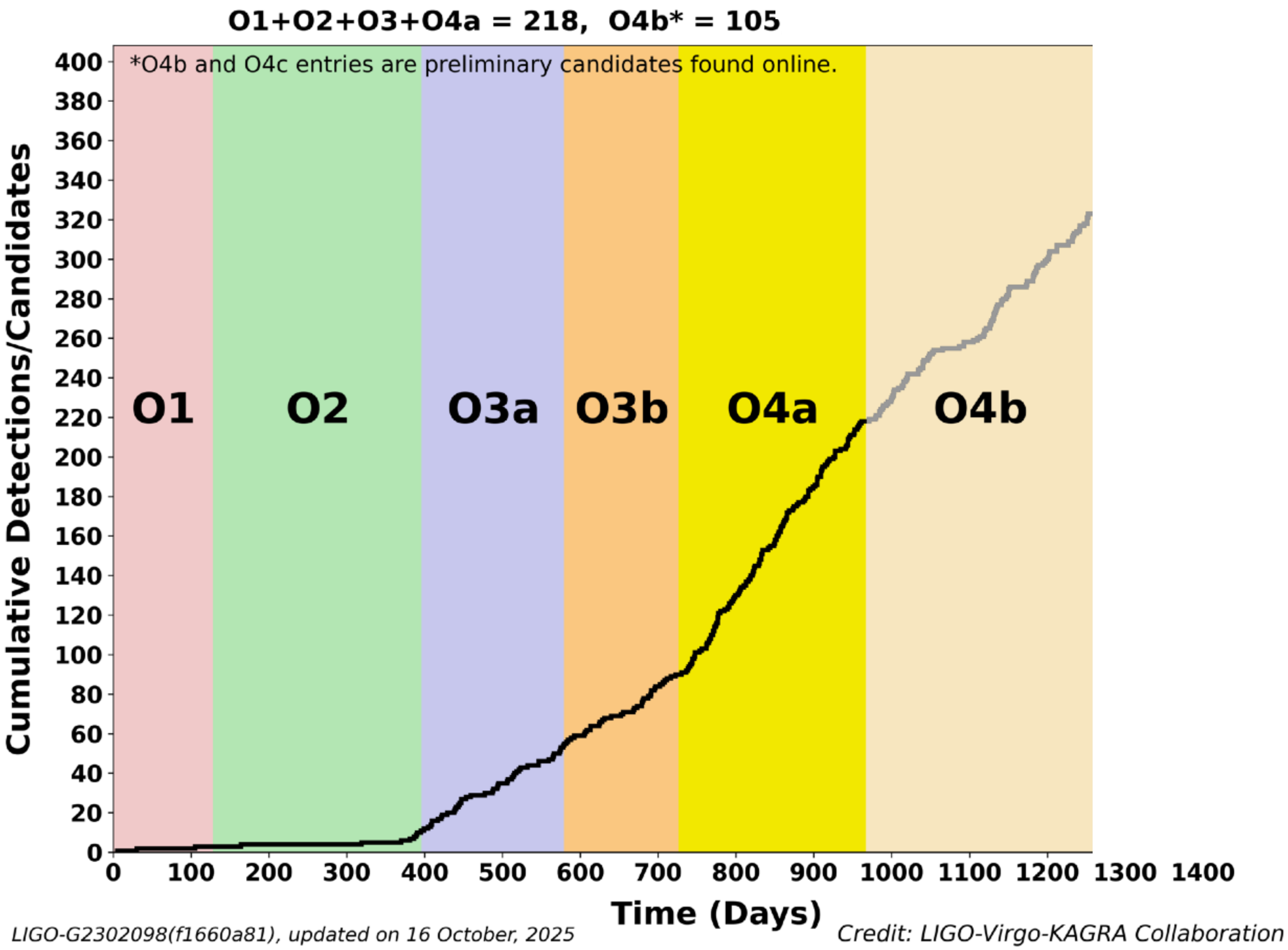
THE LIGO SCIENTIFIC COLLABORATION, THE VIRGO COLLABORATION, AND THE KAGRA COLLABORATION

ABSTRACT

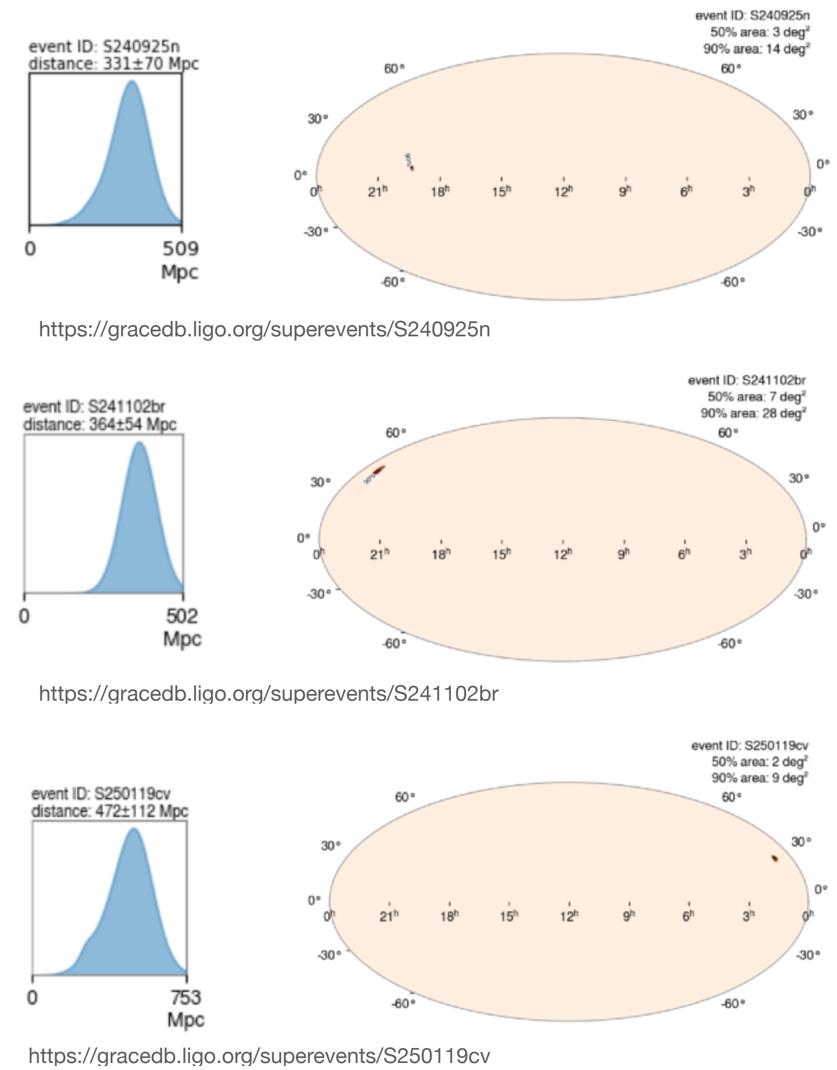
We analyze data from 142 of the 218 gravitational-wave (GW) sources in the fourth LIGO–Virgo–KAGRA Collaboration (LVK) Gravitational-Wave Transient Catalog (GWTC-4.0) to estimate the Hubble constant H_0 jointly with the population properties of merging compact binaries. We measure the luminosity distance and redshifted masses of GW sources directly; in contrast, we infer GW source redshifts statistically through i) location of features in the compact object mass spectrum and merger rate evolution, and ii) identifying potential host galaxies in the GW localization volume. Probing the relationship between source luminosity distances and redshifts obtained in this way yields constraints on cosmological parameters. We also constrain parameterized deviations from general relativity which affect GW propagation, specifically those modifying the dependence of a GW signal on the source luminosity distance. Assuming our fiducial model for the source-frame mass distribution and using GW candidates detected up to the end of the fourth observing run (O4a), together with the GLADE+ all-sky galaxy catalog, we estimate $H_0 = 76.6^{+13.0}_{-9.5}\,(76.6^{+25.2}_{-14.0})\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. This value is reported as a median with 68.3% (90%) symmetric credible interval, and includes combination with the H_0 measurement from GW170817 and its electromagnetic counterpart. Using a parametrization of modified GW propagation in terms of the magnitude parameter Ξ_0, we estimate $\Xi_0 = 1.2^{+0.8}_{-0.4}\,(1.2^{+2.4}_{-0.5})$, where $\Xi_0 = 1$ recovers the behavior of general relativity.

LIGO-Virgo-KAGRA prospects

O4b: Virgo joined the network ⇒ improved sky localization!

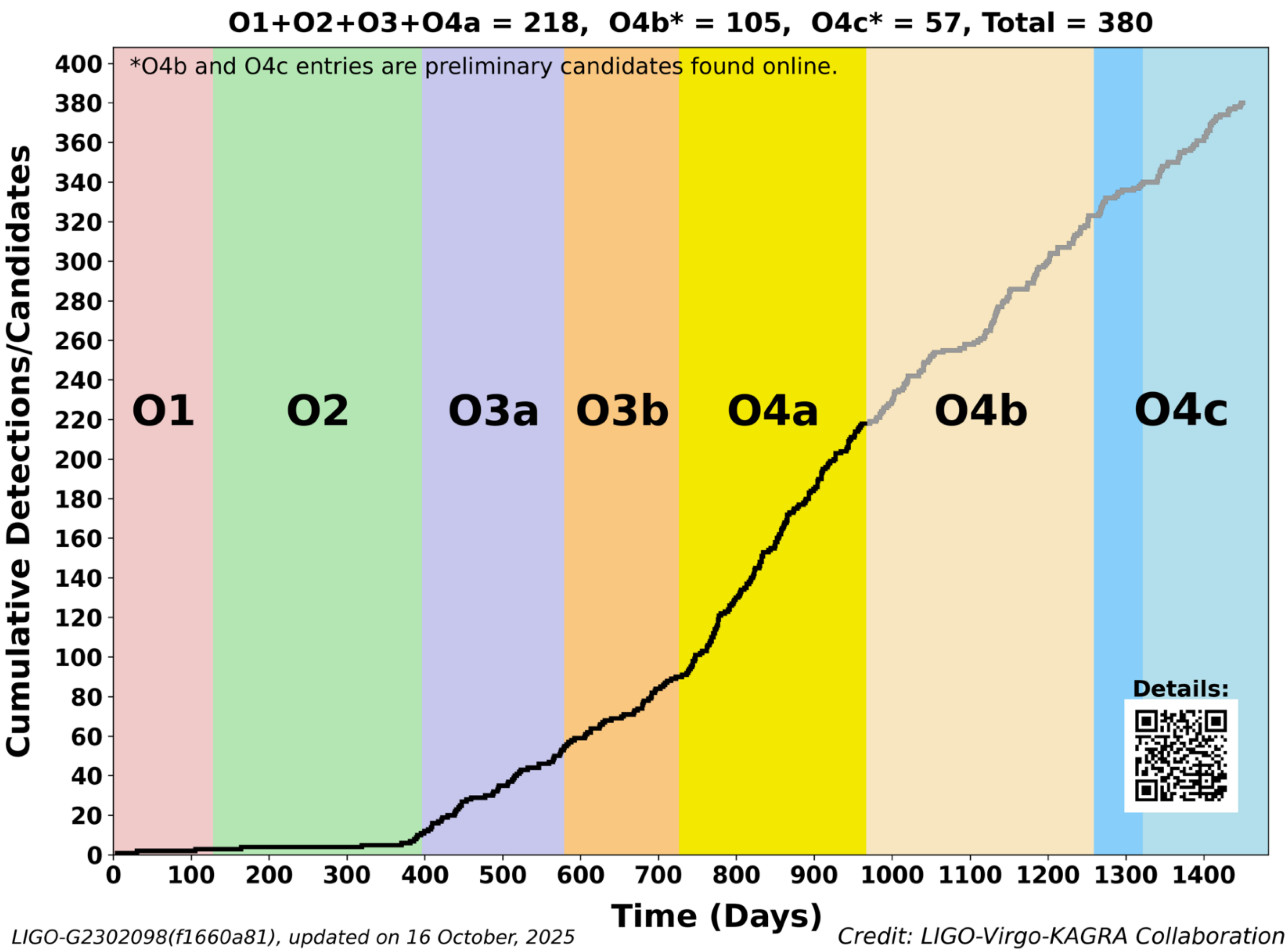


A few preliminary candidates in O4b



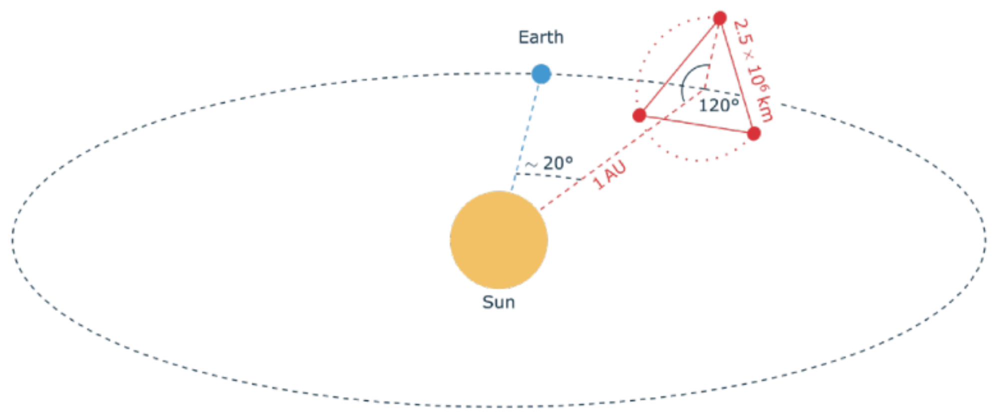
LIGO-Virgo-KAGRA prospects

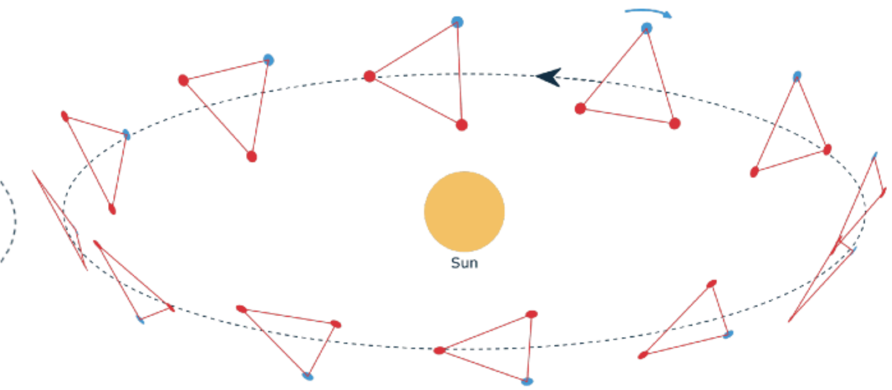
O4c: current total of 380 alerts, but ~1 month of observation still to go!

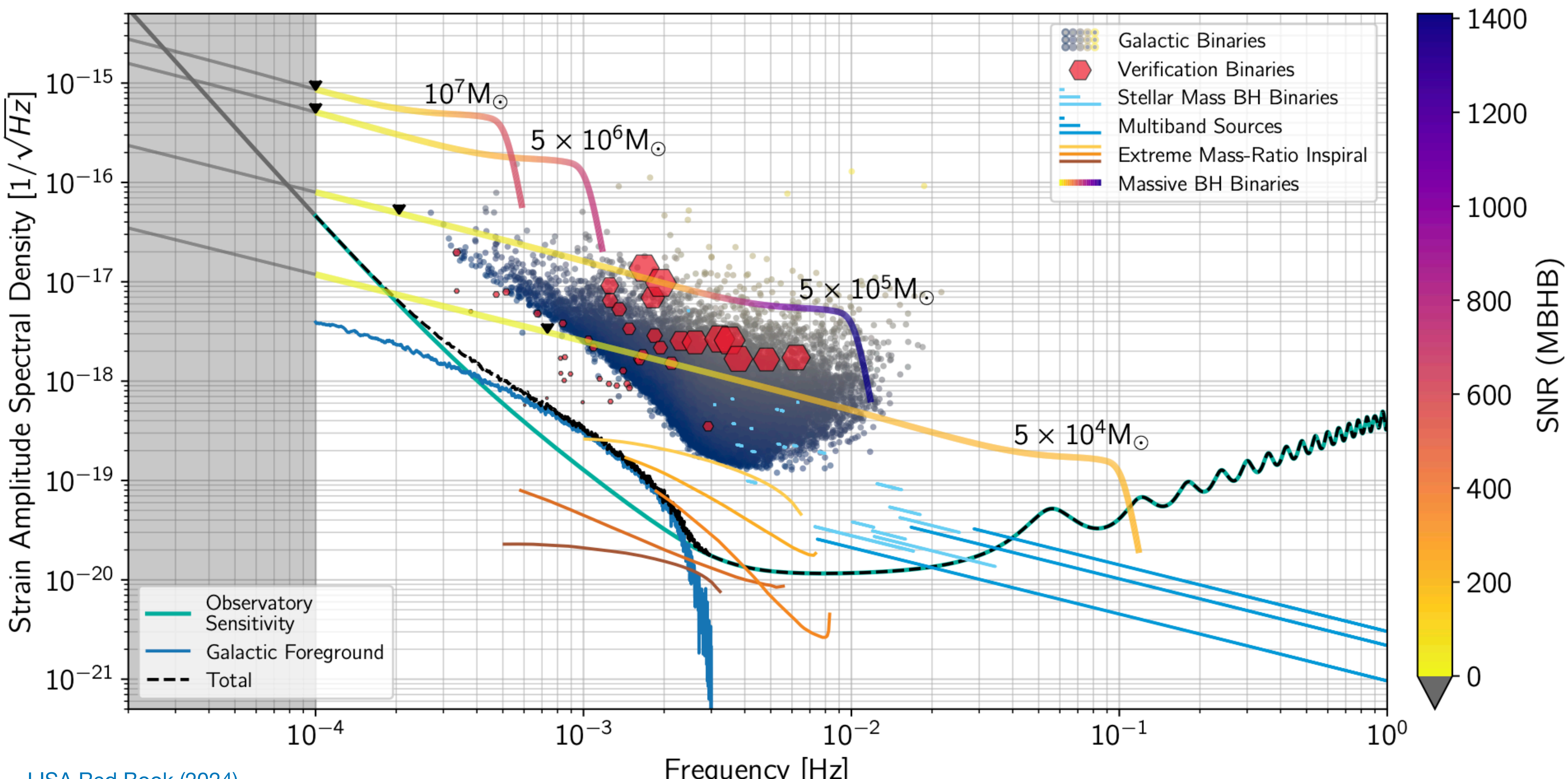


Prospects with LISA

Review on cosmology with LISA: LISA CosWG, Liv Rev. Rel. (2023) - arXiv:2204.05434





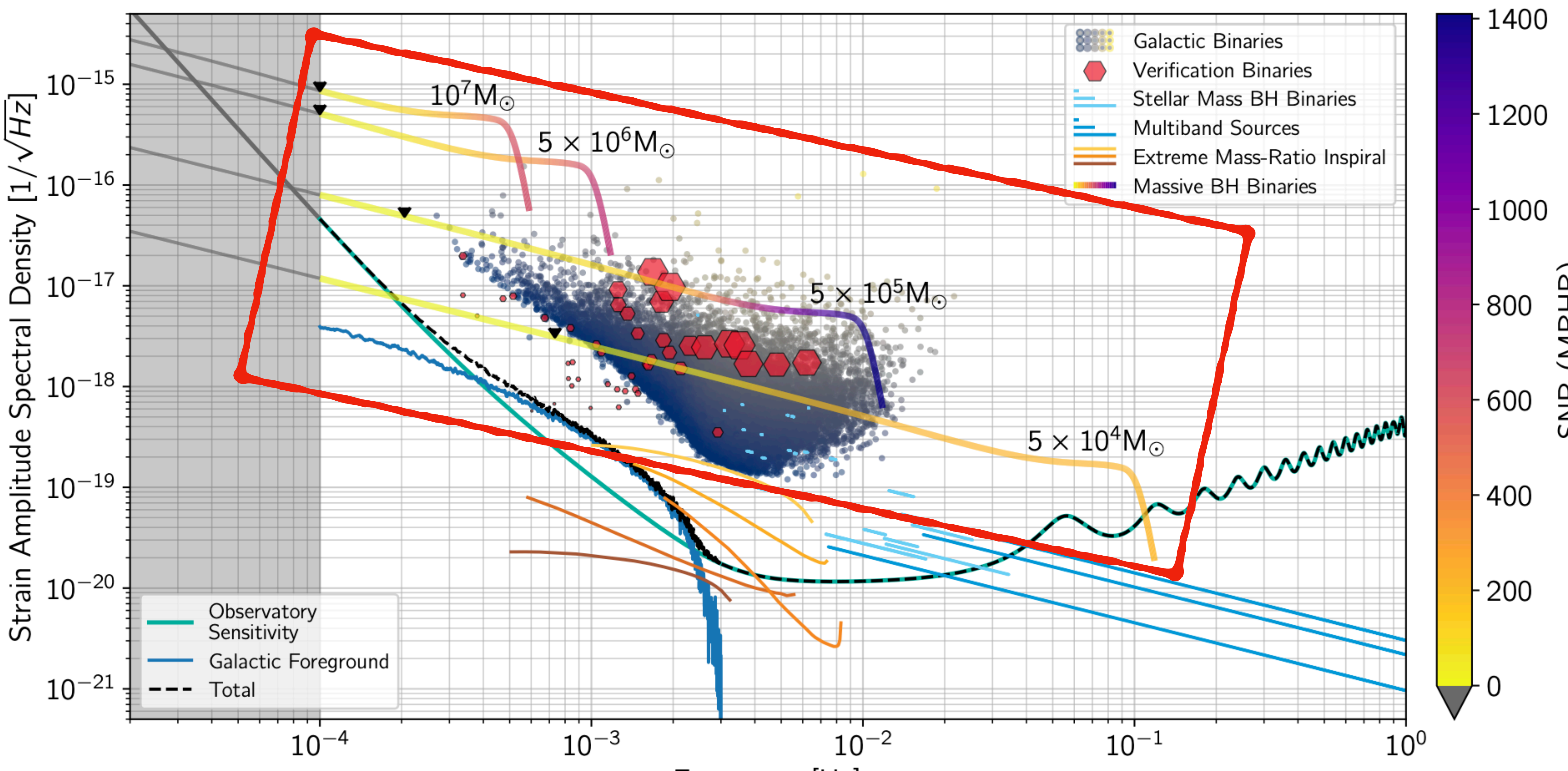


LISA Red Book (2024)

MBHBs as bright sirens

Here we will look at two promising classes of LISA standard sirens:

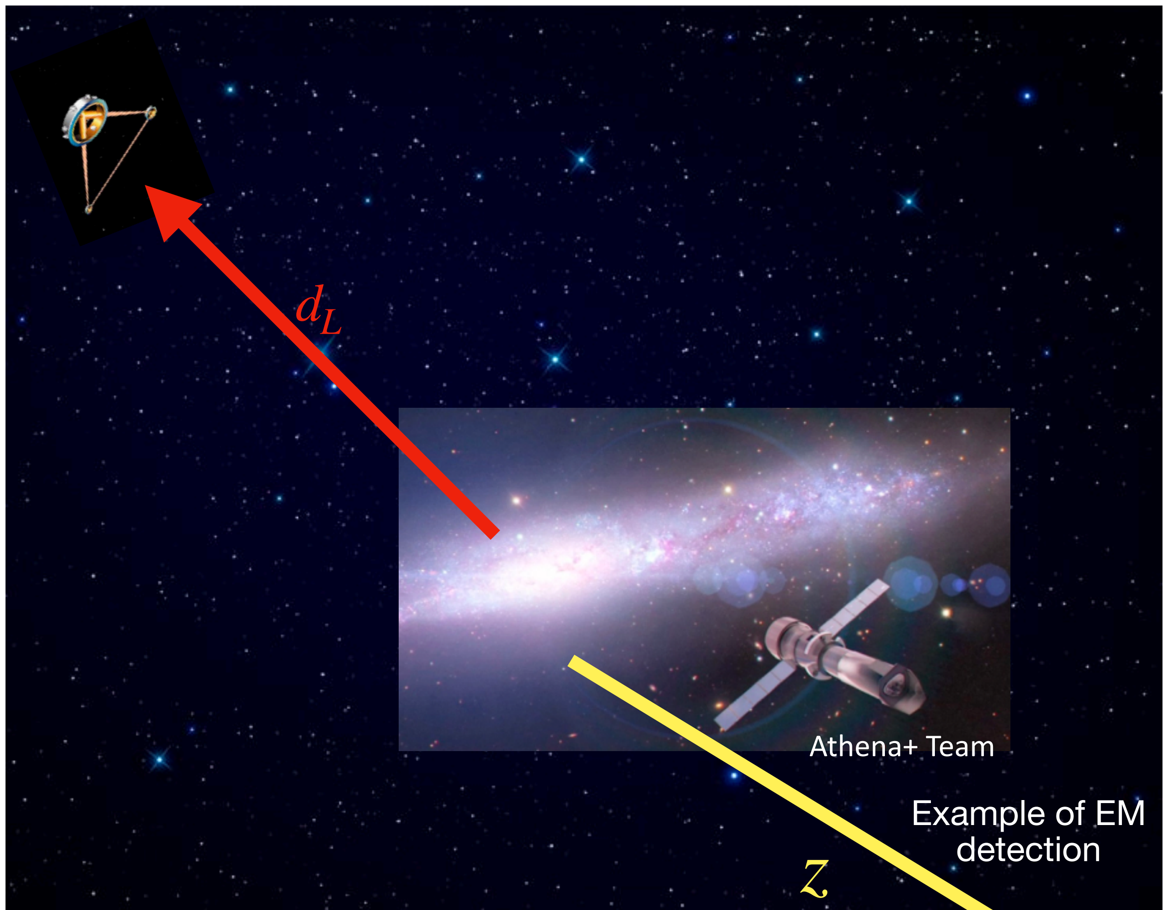
1. Massive Black Hole Binaries (MBHBs) as bright sirens

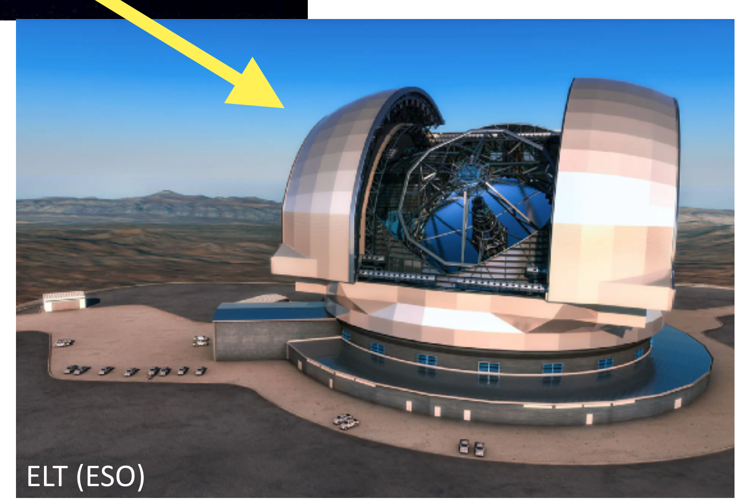


LISA Red Book (2024)

MBHBs as bright sirens

Assuming we can identify the EM counterpart and obtain the redshift:





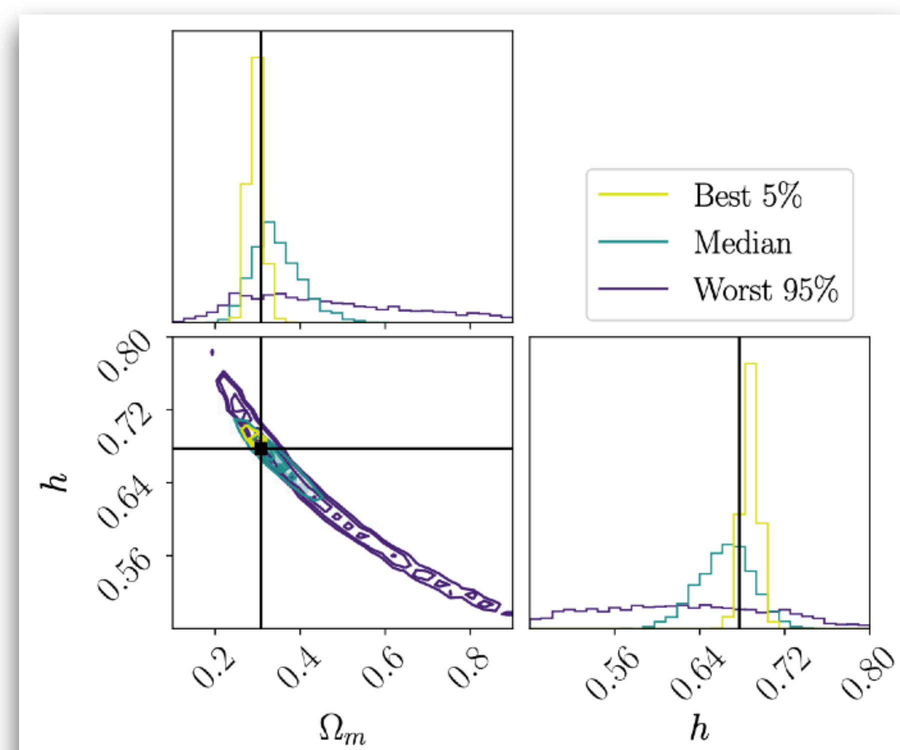
O(1-5) bright sirens per year, up to $z \lesssim 7$

Assuming good sky localization ($\Delta D_L/D_L \lesssim 0.1$ and $\Delta\Omega < 10$ deg^2):

$O(1-5)$ **bright sirens per year**

H_0 **at few-%!**

Precise high-z cosmography

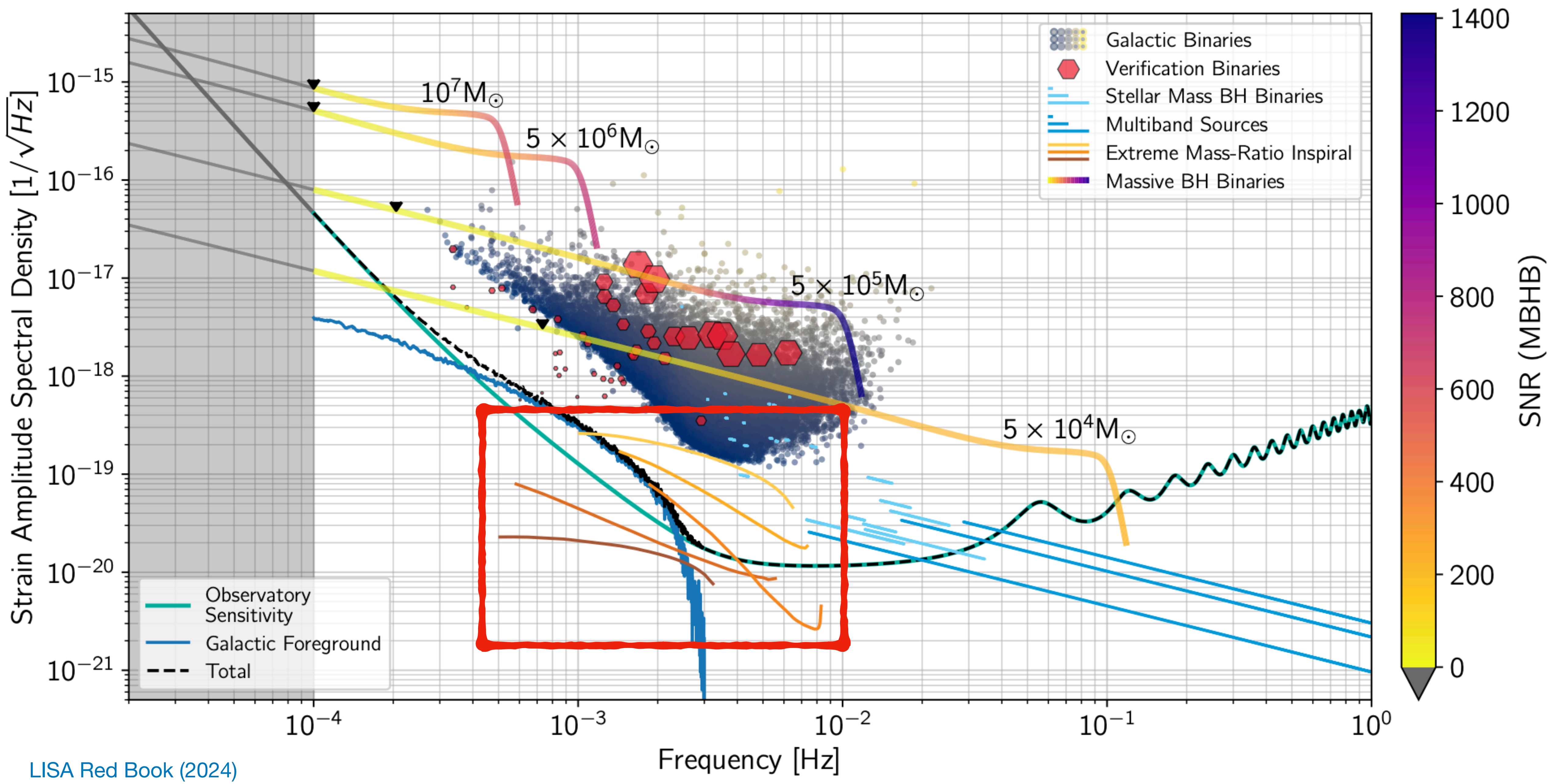


Tamanini et al., *JCAP* (2016) Mangiagli et al., *PRD* (2022) LISA CosWG, White Paper, *Liv. Rev. Rel.* (2023) Mangiagli et al, arXiv:2312.04632

EMRIs as dark sirens

Here we will look at two promising classes of LISA standard sirens:

2. Extreme Mass-Ratio Inspirals (EMRIs) as dark sirens

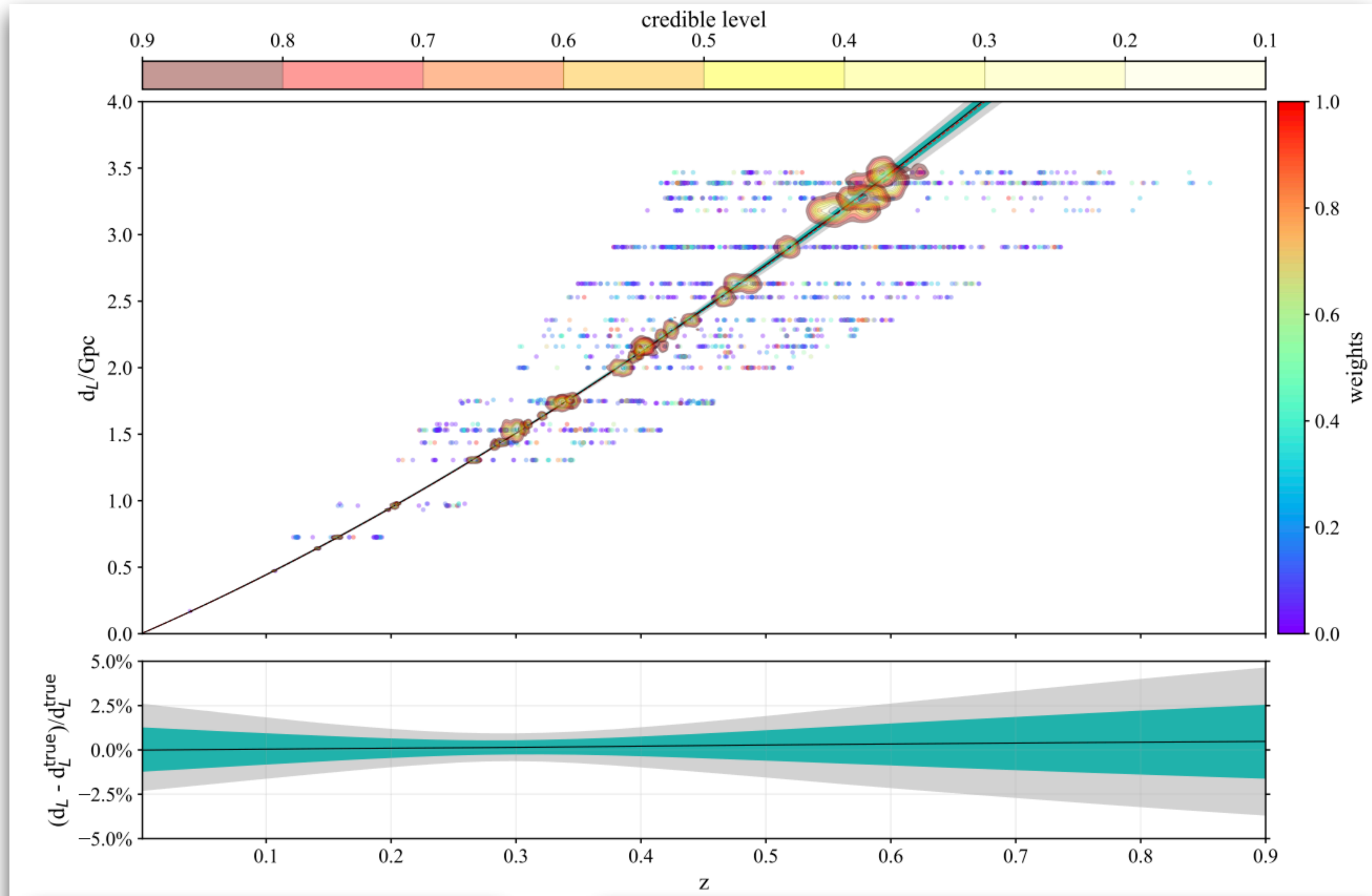


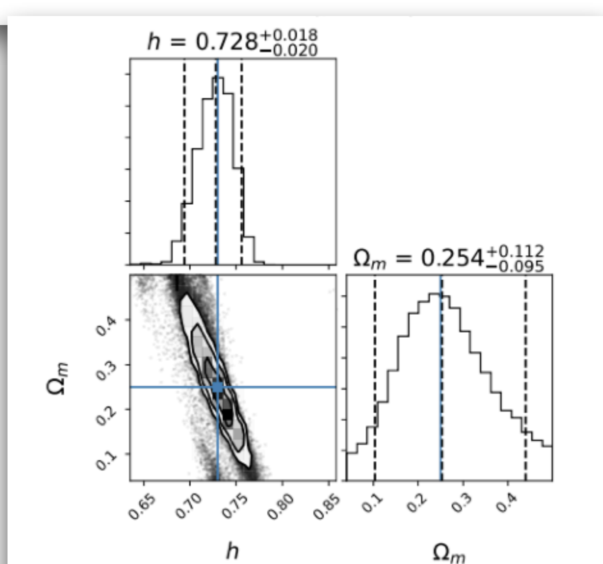
LISA Red Book (2024)

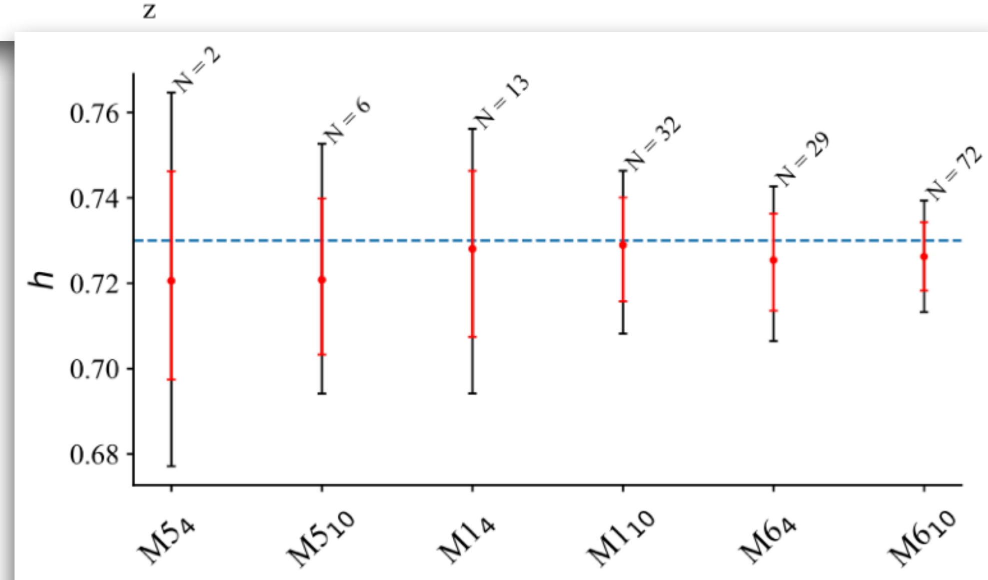
EMRIs as dark sirens

We can cross-match the EMRI sky location with galaxy catalogs

MacLeod, Hogan (2009), PRD (2008)







O(1-1000) detections per year, up to $z \lesssim 4$

No EM counterpart expected, but very god sky localization ($\Delta D_{\rm L}/D_{\rm L} \lesssim 0.1$ and $\Delta\Omega < 2$ deg^2):

$O(1-100)$ standard sirens per year

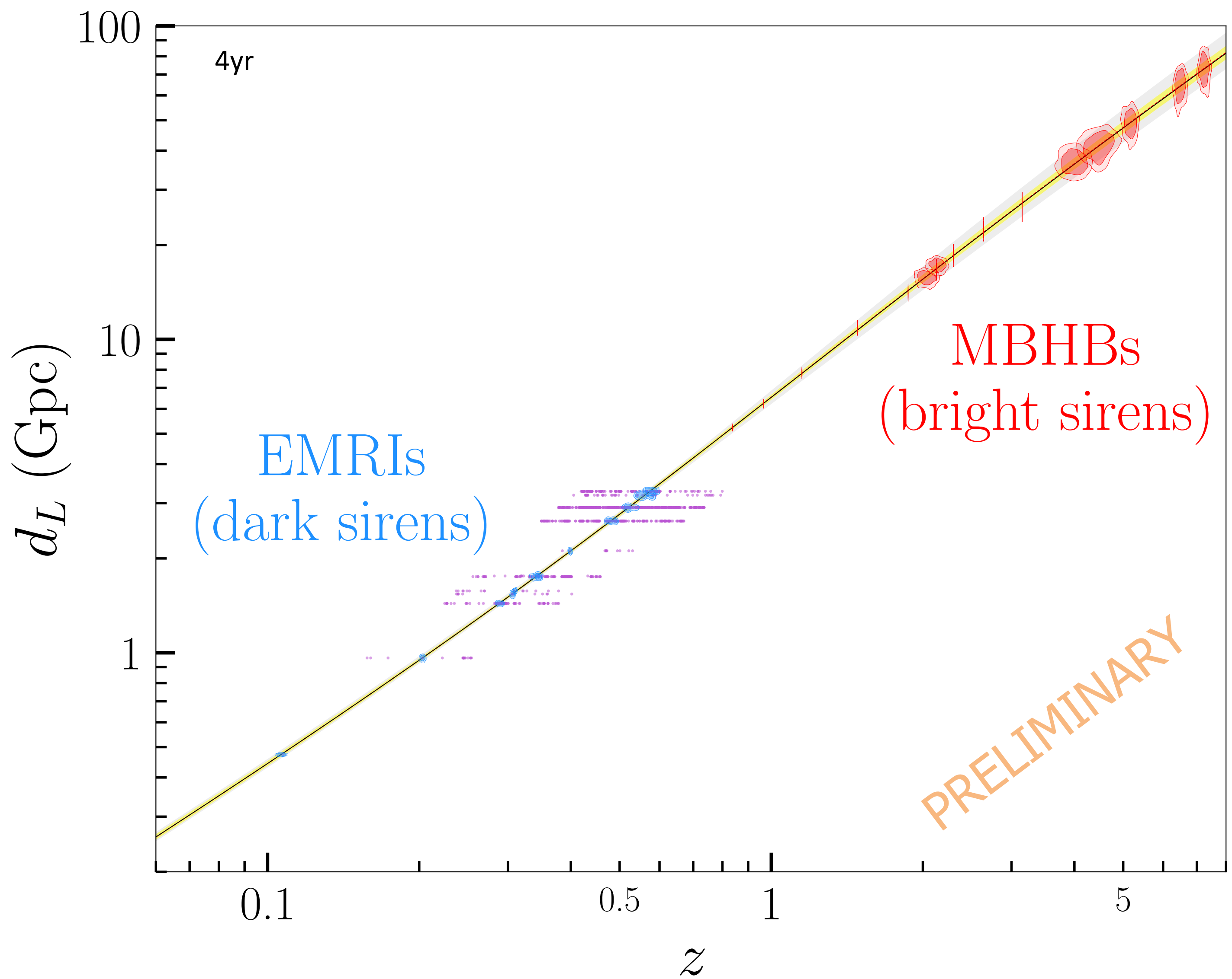
H_0 at 1-6%!

w_0 at 5-10%

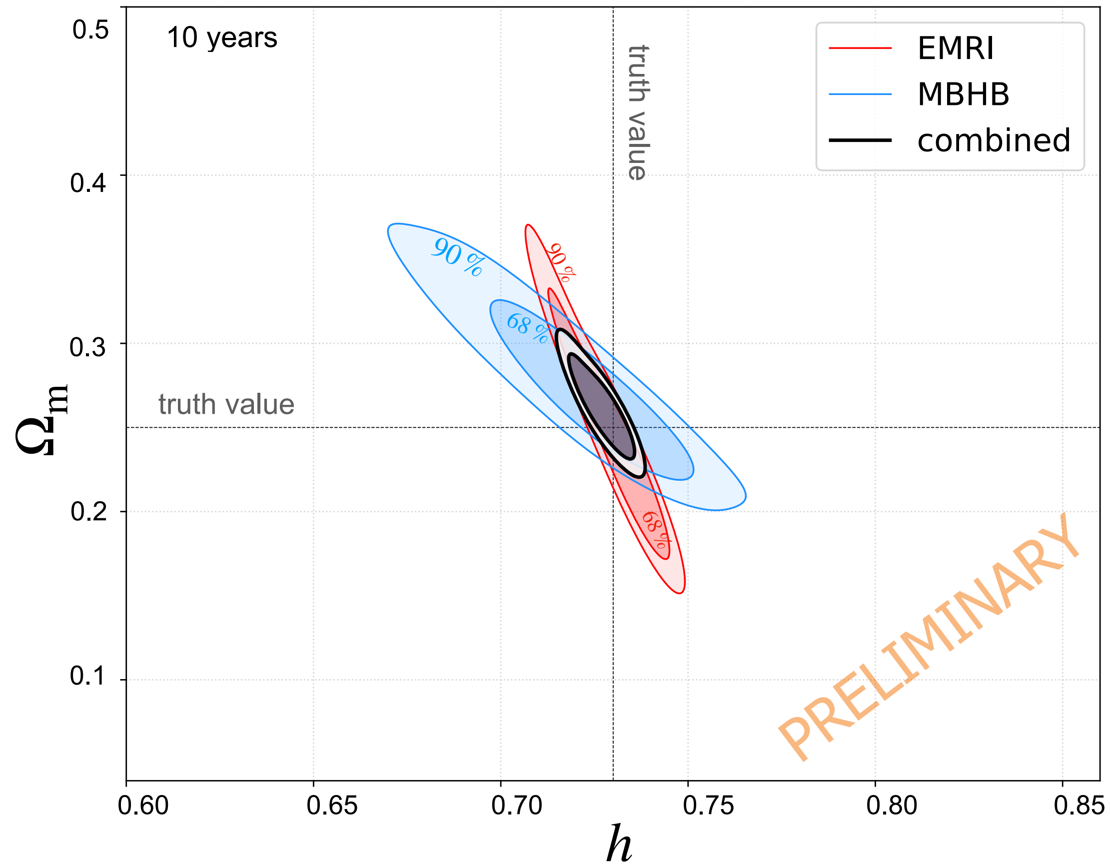
DL et al., MNRAS (2021)

LISA bright and dark sirens

We can constrain the expansion history of the universe by combining different LISA standard sirens



DL, Tamanini, et al., in preparation



H_0 at $\lesssim$1%

Ω_m at <10%