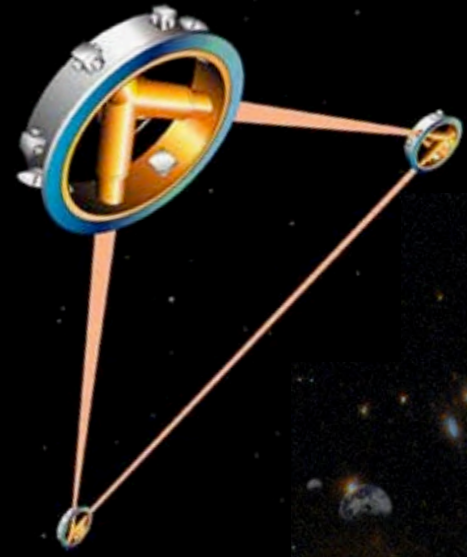


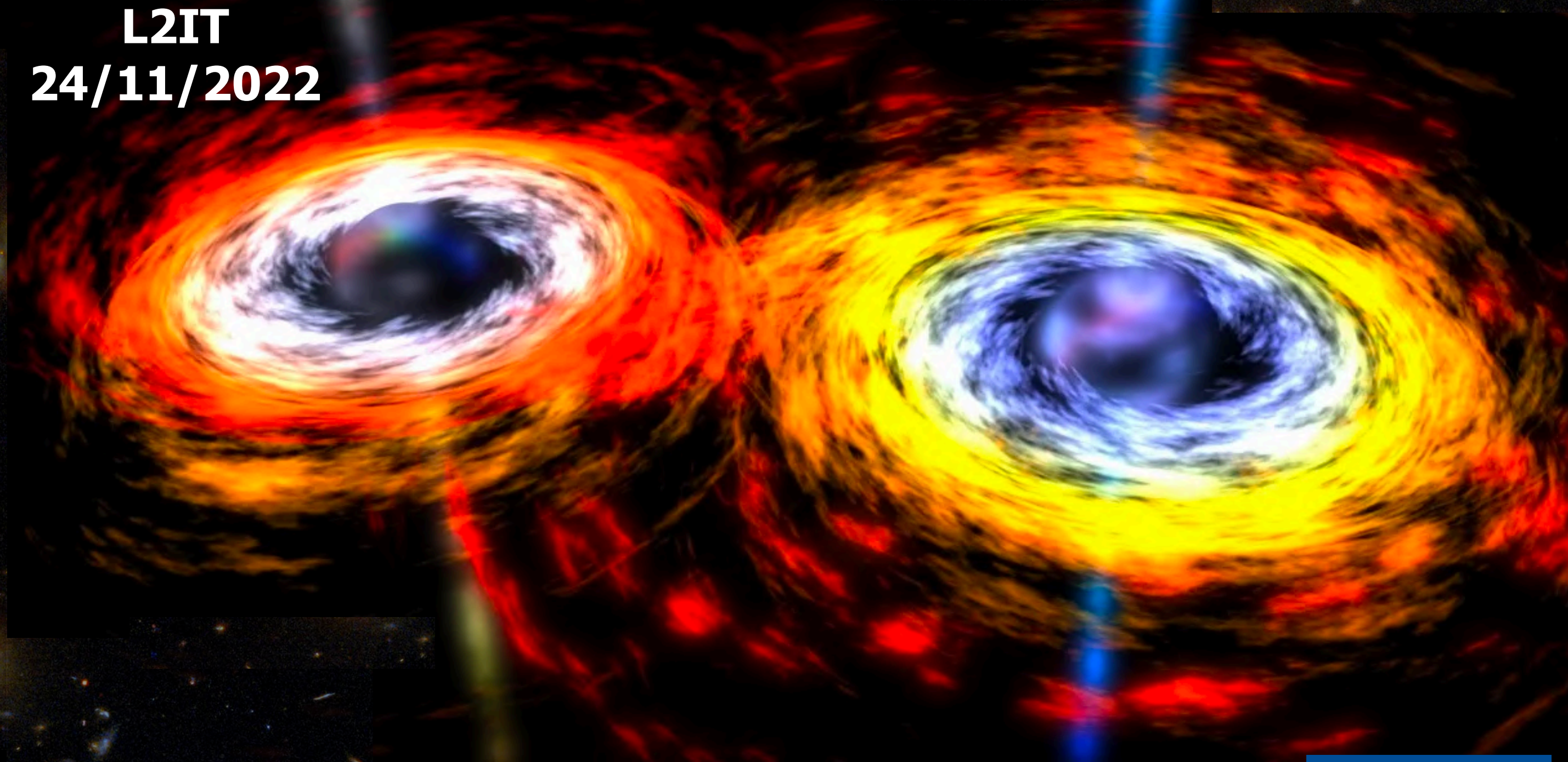
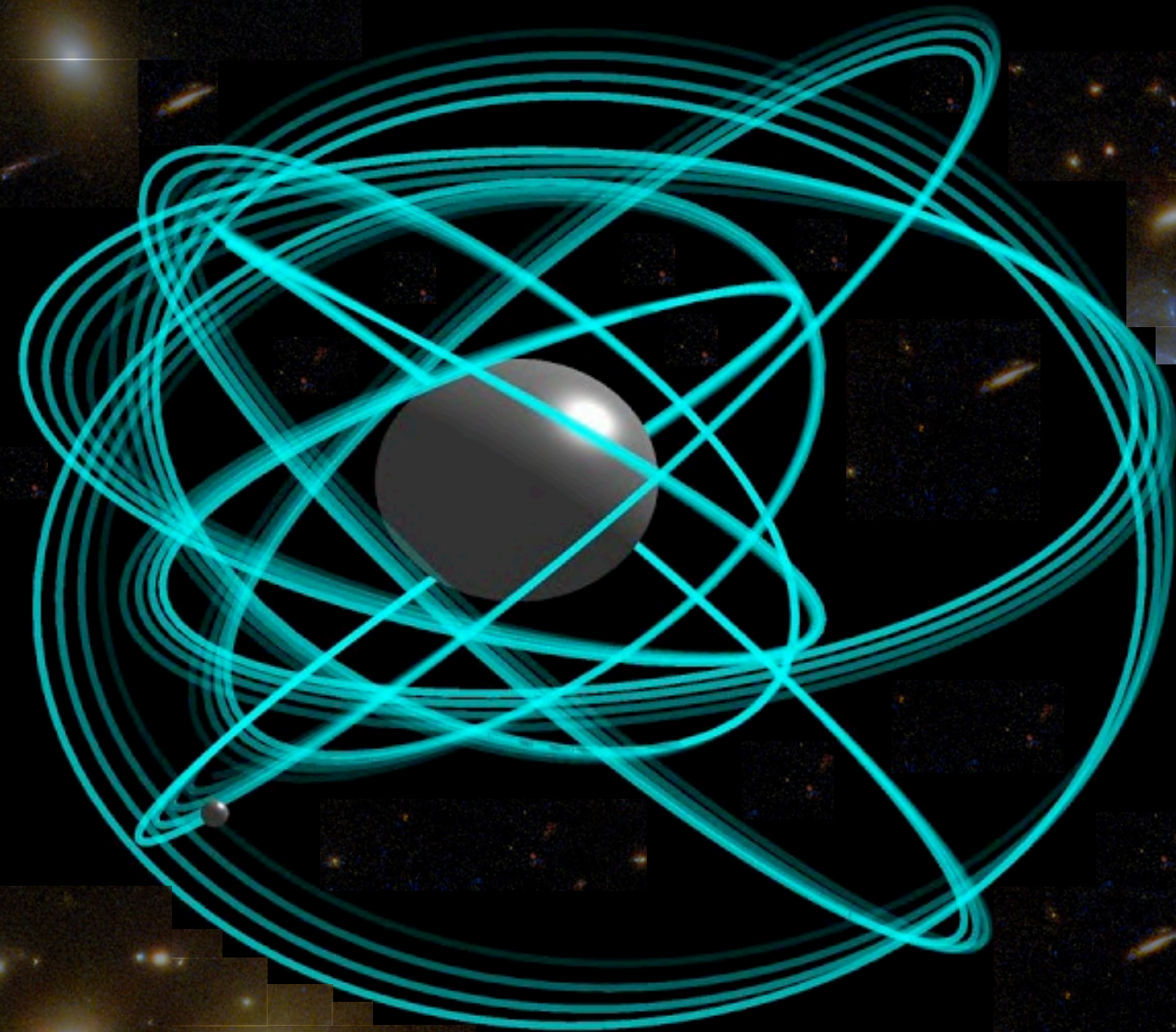
Bayesian inference methods in cosmology with LISA standard sirens



LISA Data Analysis: from classical methods to machine learning

L2IT

24/11/2022



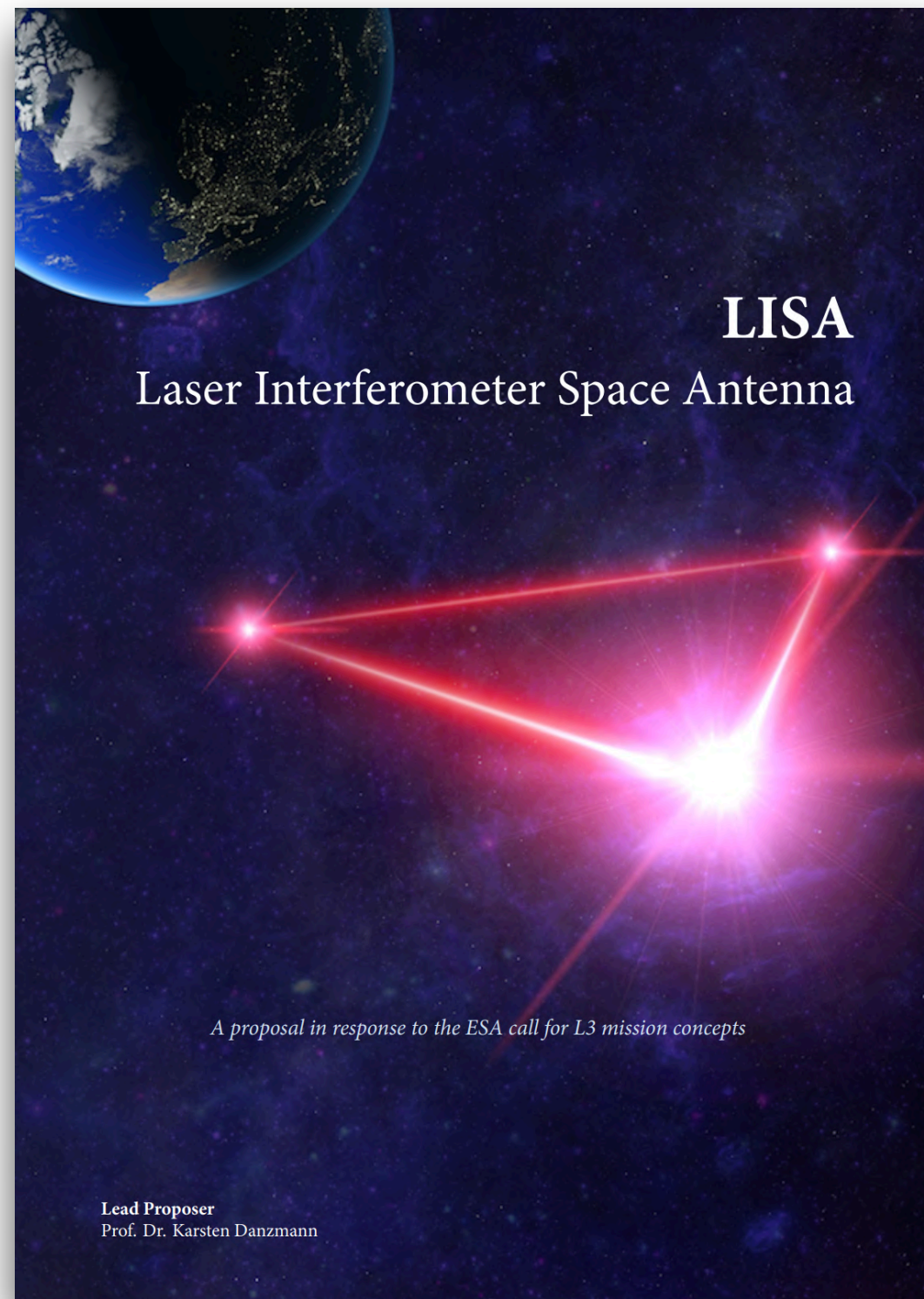
Danny Laghi

CNES Postdoctoral Fellow*

Laboratoire des 2 Infinis - Toulouse

danny.laghi@l2it.in2p3.fr





LISA Mission Proposal: arXiv:1702.00786

Contents

1	Introduction	6
2	Science performance	7
2.1	SO1: Study the formation and evolution of compact binary stars in the Milky Way Galaxy.	8
2.2	SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages	8
2.3	SO3: Probe the dynamics of dense nuclear clusters using EMRIs	10
2.4	SO4: Understand the astrophysics of stellar origin black holes	11
2.5	SO5: Explore the fundamental nature of gravity and black holes	11
2.6	SO6: Probe the rate of expansion of the Universe	12
2.7	SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics	12
2.8	SO8: Search for GW bursts and unforeseen sources	13
2.9	Summary	13

Measure the **cosmological parameters** $\Omega = \{H_0, \Omega_m, \Omega_\Lambda, \dots\}$

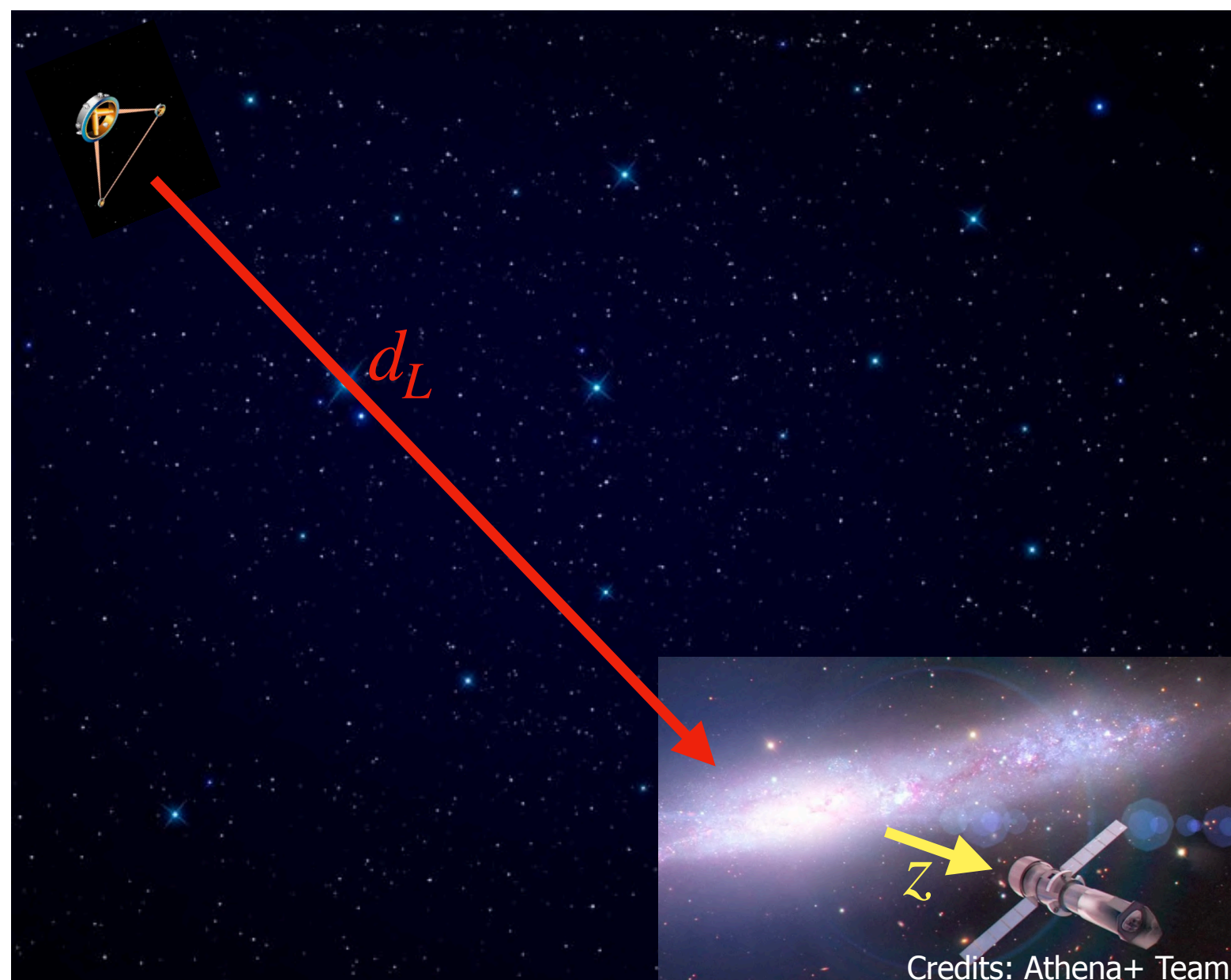
STANDARD SIRENS

$$d_L(\Omega, z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + 1 - \Omega_m}} \quad (\text{flat FLRW})$$

Holz, Hughes, *APJ* (2005)

“Bright standard sirens”

Measure **EM counterpart** of the galaxy host and obtain z



Luminosity distance
From the GW signal!

redshift
Not in the GW signal!

“Dark standard sirens”

Infer z by **statistically matching** GW sky position with galaxy catalogs

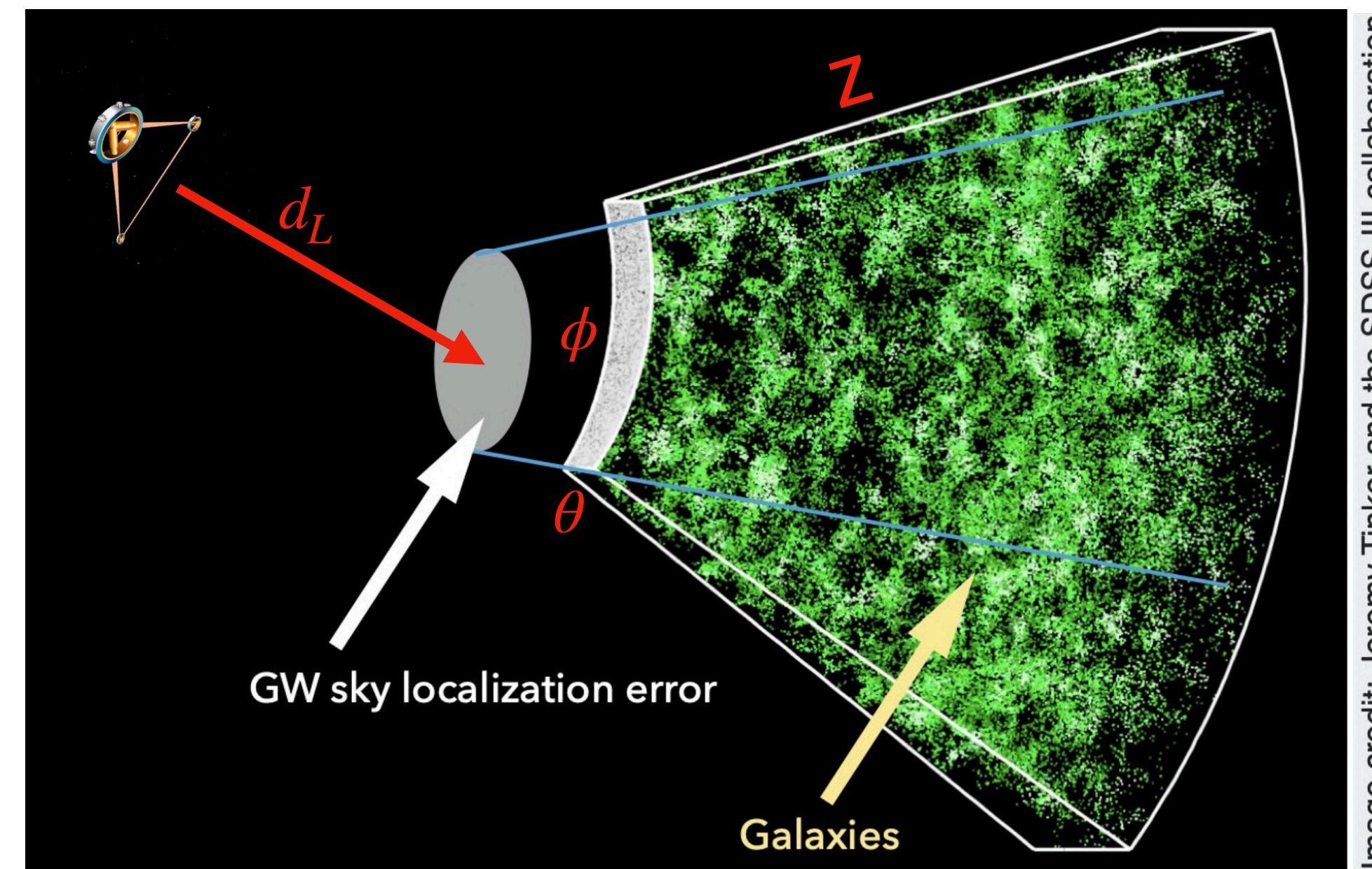


Image credit: Jeremy Tinker and the SDSS-III collaboration

COSMOLOGICAL INFERENCE SCHEME

cosmological model:

$$d_L(\Omega, z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}$$

GW redshift prior:

$$p(z_{GW} | \Omega, \mathcal{H}) \propto \sum_{j=1}^{N_{g,i}} w_j \exp \left[-\frac{1}{2} \left(\frac{z_j - z_{GW}}{\sigma_{z_j}} \right)^2 \right]$$

$$w_j = \left(\int dd_L \mathcal{N}(\hat{\Theta}, \Sigma) \right) \Big|_{(\cos \theta_j, \phi_j)}$$

LISA likelihood:

$$p(D_i | d_L, z_{GW}, \mathcal{H}) = \mathcal{N}(\hat{\Theta}, \Sigma)$$

$$\Theta = \{d_L, \cos \theta_{GW}, \phi_{GW}\}$$

$$p(\Omega | D, \mathcal{H}) \propto p(\Omega | \mathcal{H}) \prod_{i=1}^N p(D_i | \Omega, \mathcal{H})$$

Posterior

Prior

Quasi-likelihood

Nested sampling
[CPNest]

Del Pozzo, Laghi [github.com/wdpozzo/cosmolisa] **cosmoLISA**

COSMOLOGICAL INFERENCE SCHEME

cosmological model:

$$d_L(\Omega, z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}$$

GW redshift prior:

$$p(z_{GW} | \Omega, \mathcal{H}) \propto \sum_{j=1}^{N_{g,i}} w_j \exp \left[-\frac{1}{2} \left(\frac{z_j - z_{GW}}{\sigma_{z_j}} \right)^2 \right]$$

$$w_j = \left(\int dd_L \mathcal{N}(\hat{\Theta}, \Sigma) \right) \Big|_{(\cos \theta_j, \phi_j)}$$

LISA likelihood:

$$p(D_i | d_L, z_{GW}, \mathcal{H}) = \mathcal{N}(\hat{\Theta}, \Sigma)$$

$$\Theta = \{d_L, \cos \theta_{GW}, \phi_{GW}\}$$

$$p(\Omega | D, \mathcal{H}) \propto p(\Omega | \mathcal{H}) \prod_{i=1}^N p(D_i | \Omega, \mathcal{H})$$

Posterior

Nested sampling
[CPNest]

Applicable as well to multi-band/3G observations

Muttoni, Mangiagli, Sesana, DL+, PRD (2022): ET+LISA

Muttoni, DL, Tamanini, Marsat+ (in preparation): 3G

Del Pozzo, Laghi [github.com/wdpozzo/cosmolisa]

cosmoLISA

EMRIs AS DARK SIRENS

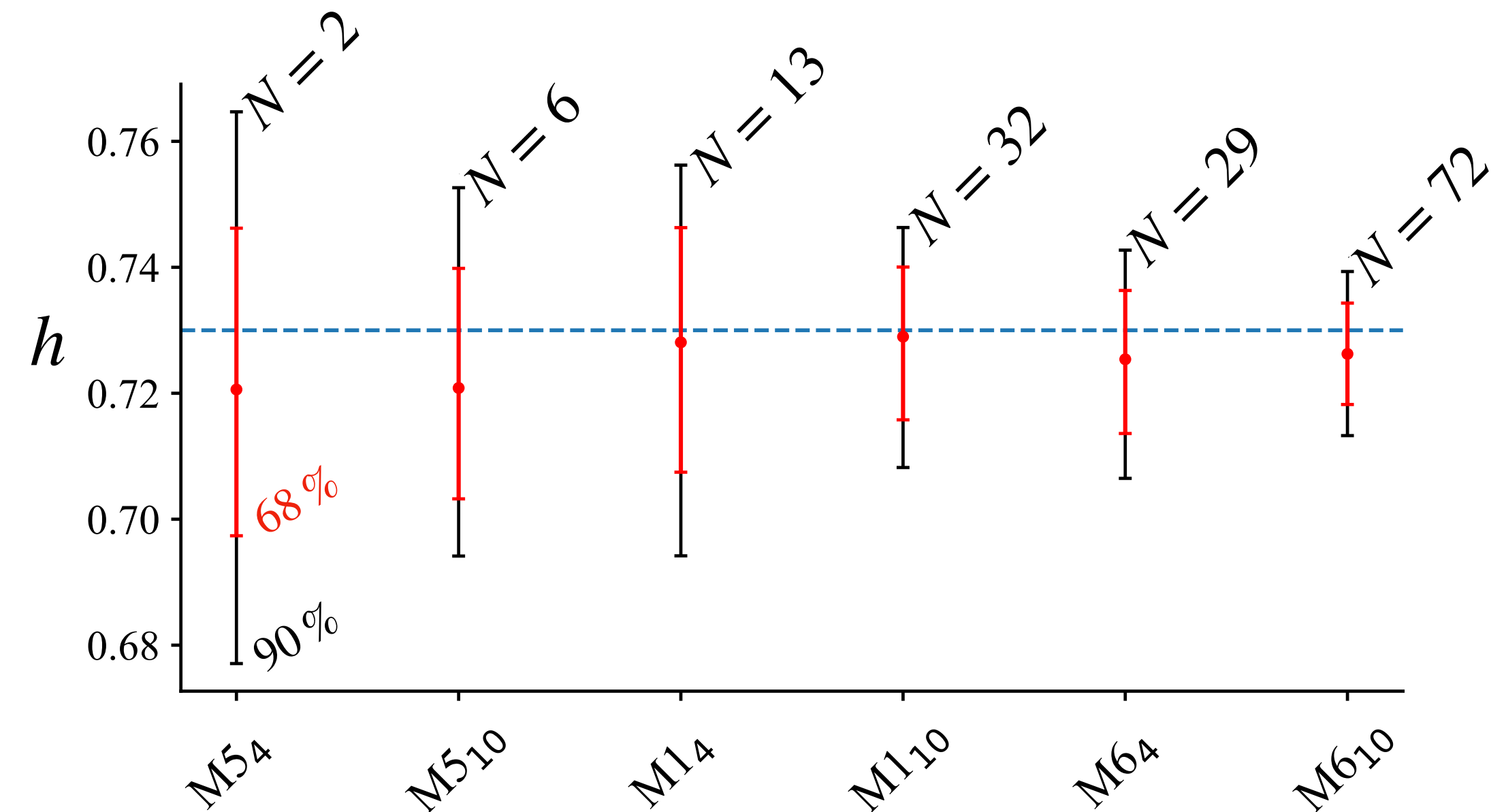
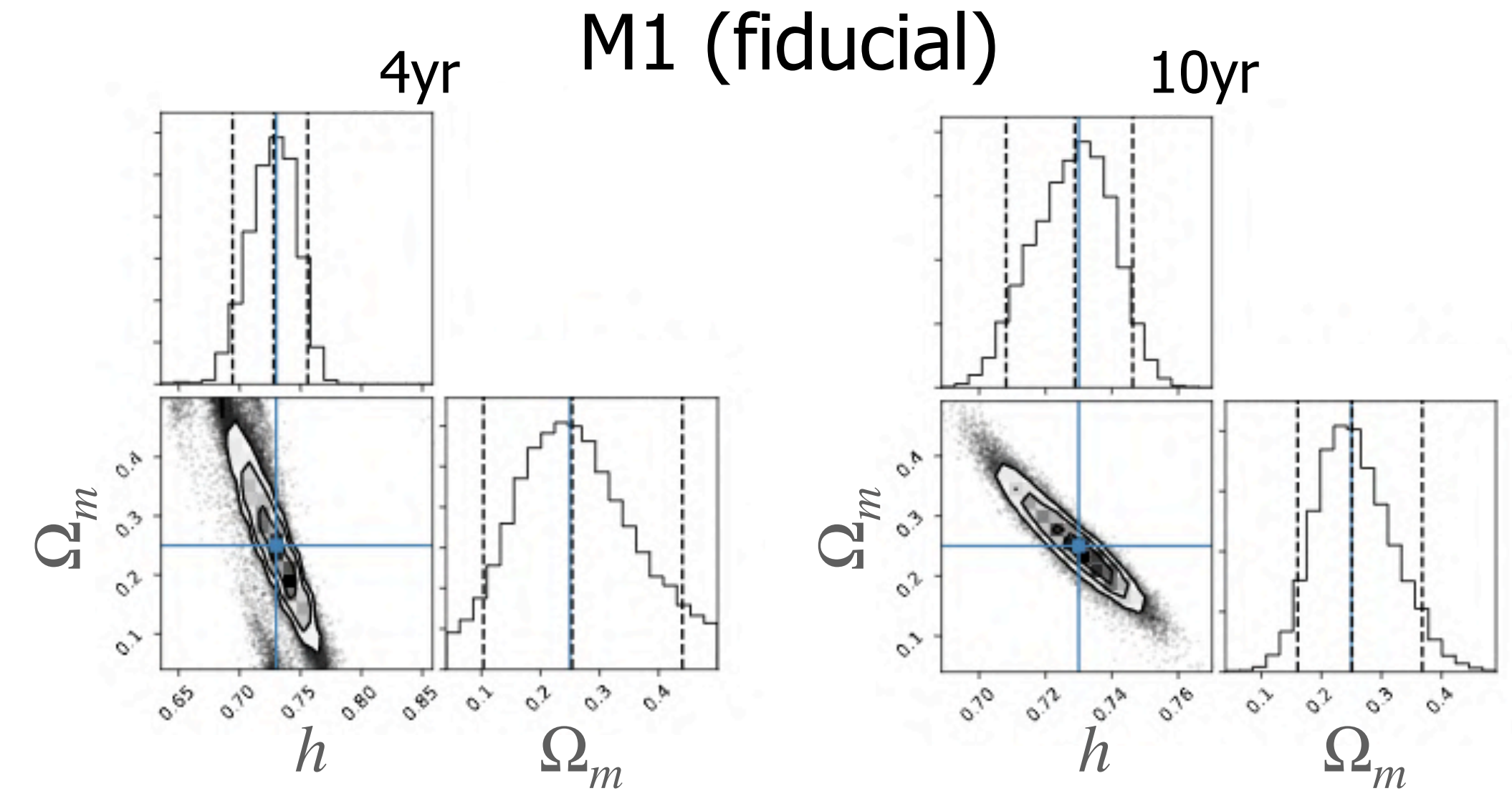
$$h = H_0/100 \text{ km}^{-1} \text{ s Mpc}$$

- EMRI PE based on catalogs of Babak+, *PRD* (2017)
- +
 - Galaxy catalog of Henriques+, *MNRAS* (2012)
- +
 - **Bayesian cosmological inference** on the loudest events (done with **cosmoLISA**)

=

H_0 at 1-6% accuracy (90% CI)

EMRIs are very good probes of H_0



EMRIs to probe modified gravity?

Liu, DL, Tamanini+ (in preparation)

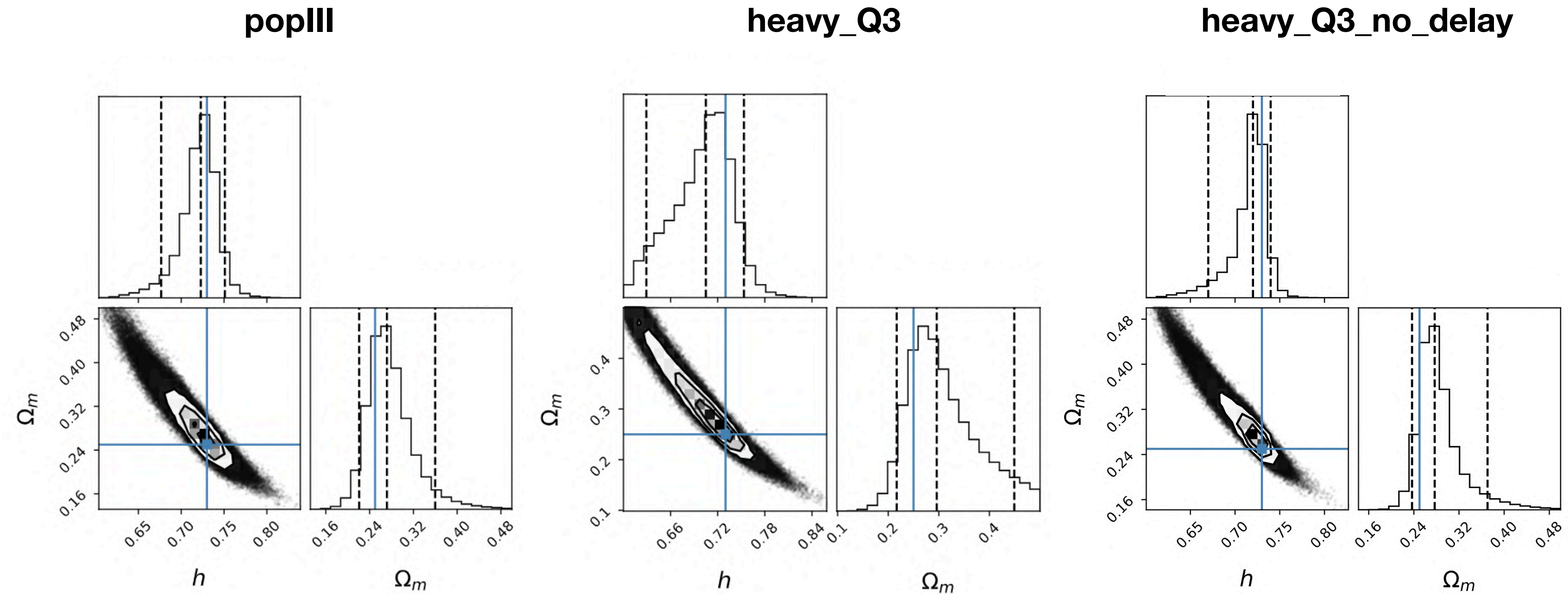
MBHBs AS BRIGHT SIRENS

- MBHB PE based on [Klein+, PRD \(2015\)](#)
- EM counterpart models of [Tamanini+, JCAP \(2016\)](#)

H_0 at 5-10% (90% CI)

Ω_m down to 25% (90% CI)

10 years of observations



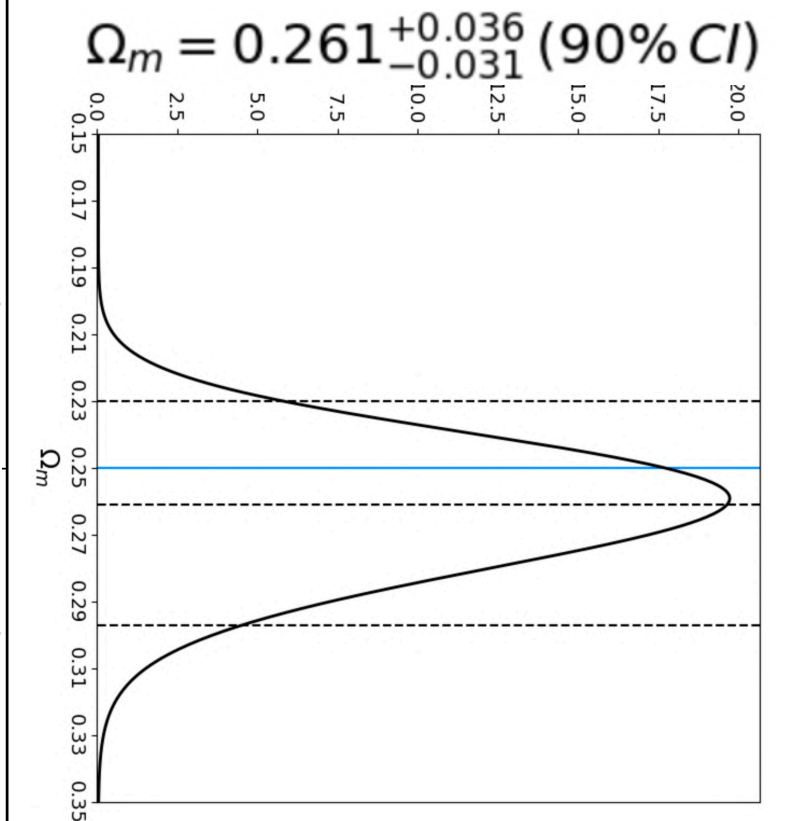
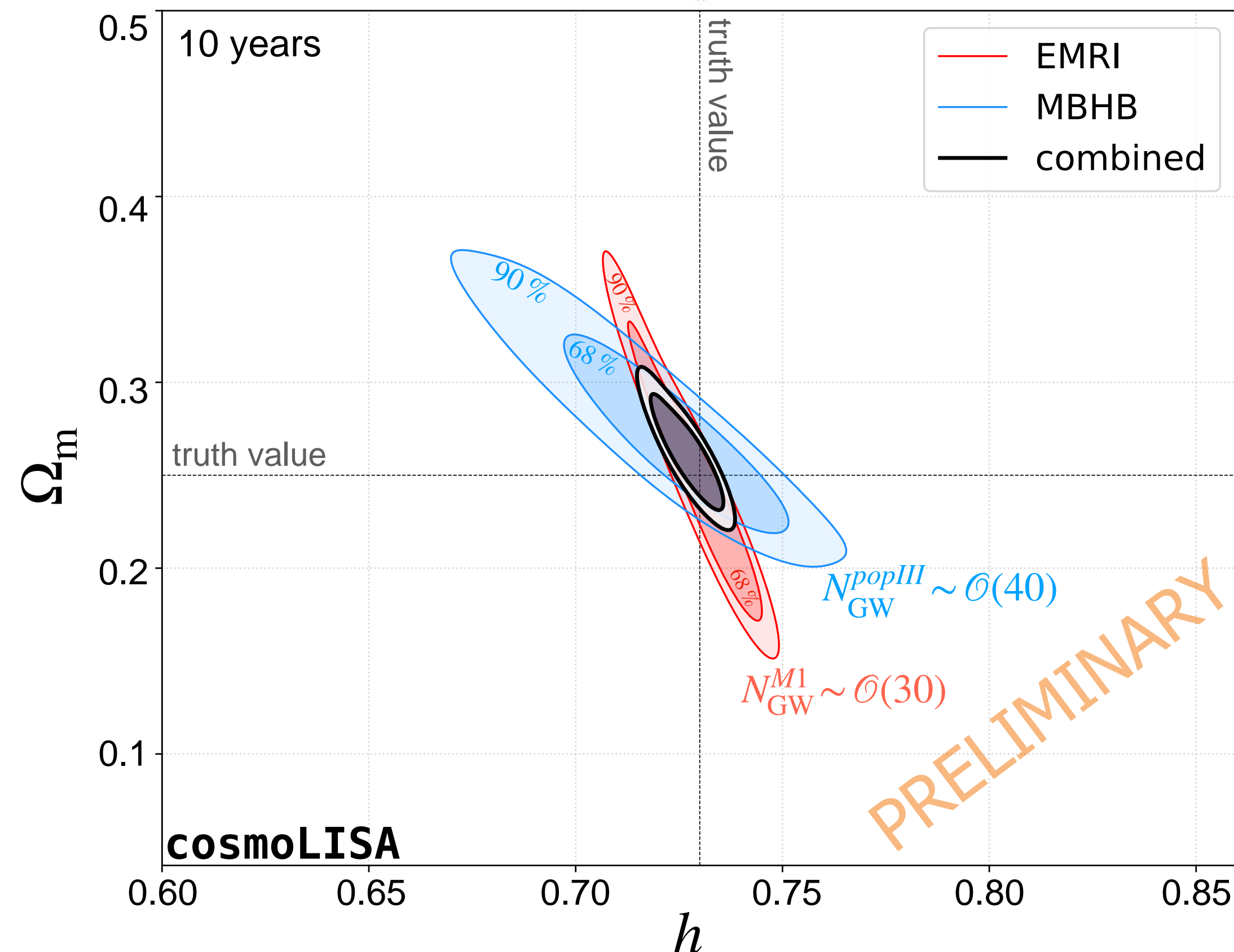
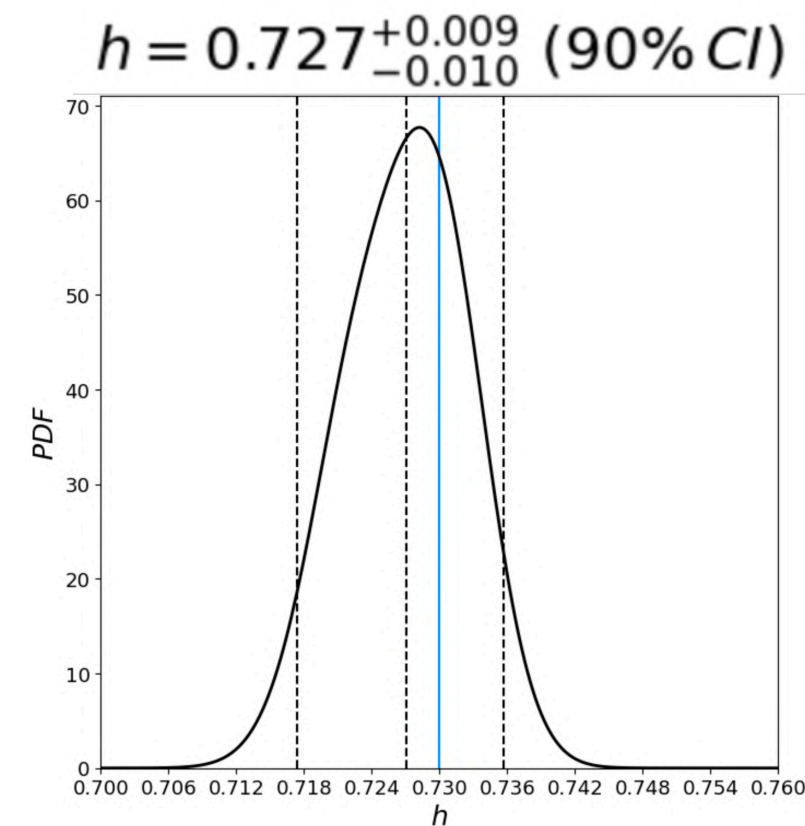
PRELIMINARY [cosmoLISA]

Currently analysing the updated MBHB+EM counterpart catalogs from [Mangiagli+, arXiv:2207.10678](#): **stay tuned!**

JOINT ANALYSIS: EMRIs + MBHBs

The key is to
combine them!

(**EMRIs** & galaxy catalog)
+
(**MBHBs** & EM counterpart)
=
 $H_0 \ O(1\%)$
 $\Omega_m \ O(15\%)$



LISA COSMOLOGICAL SPECTRUM

