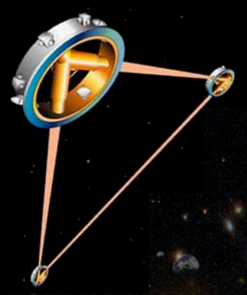
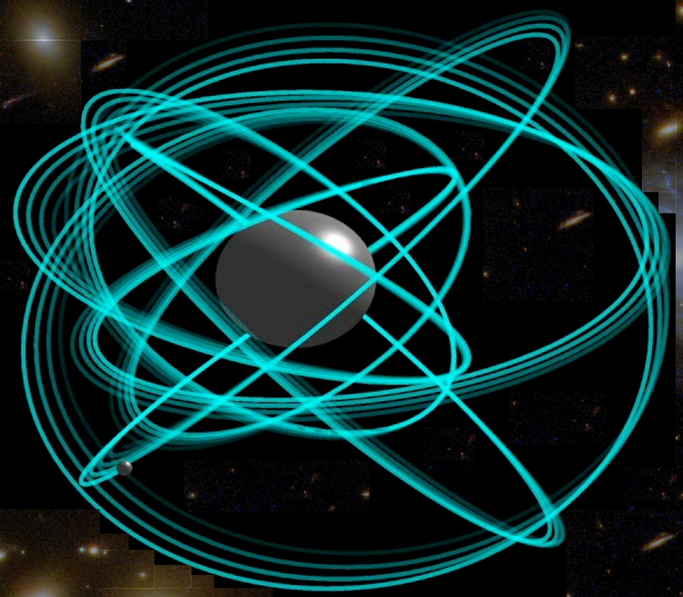
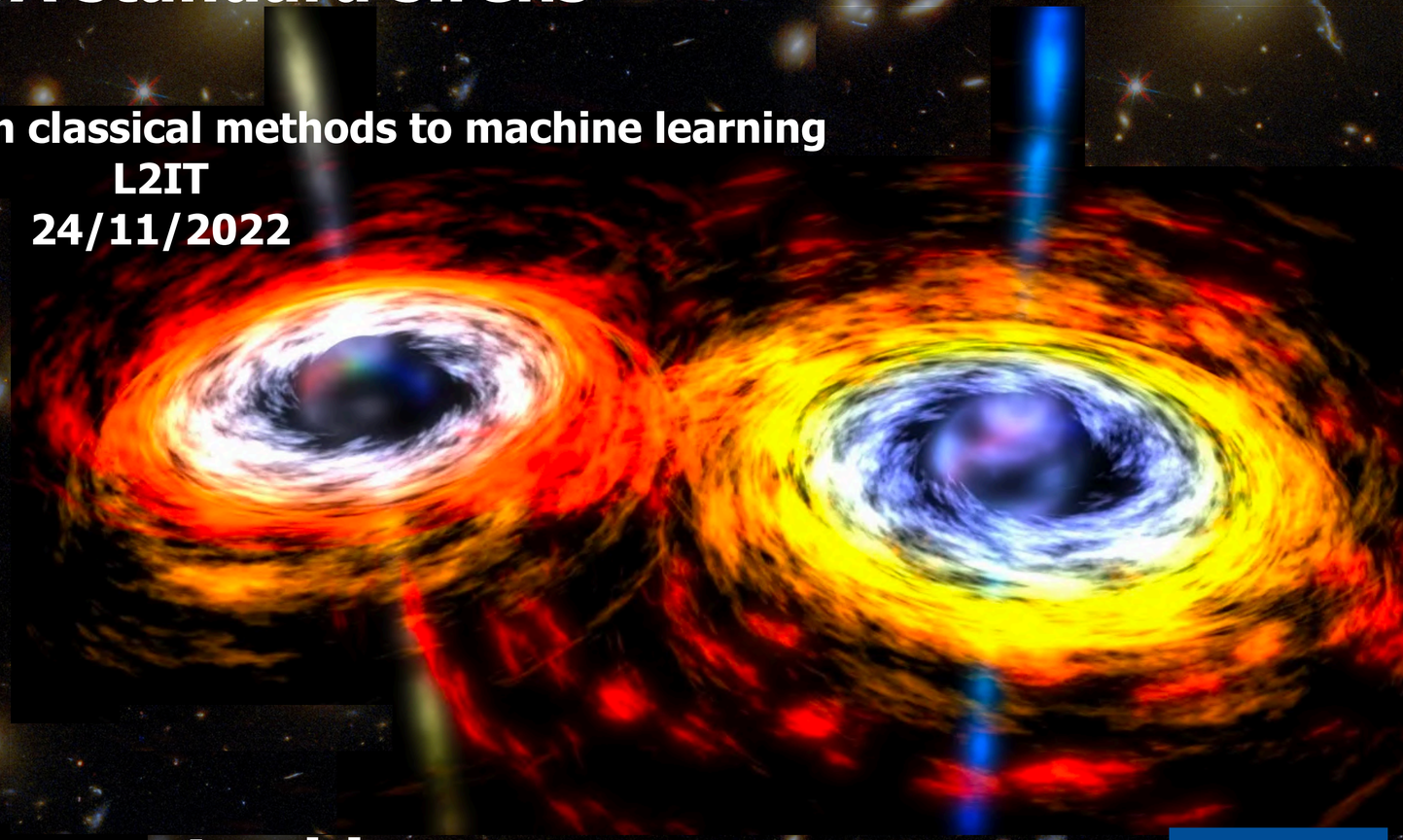
Bayesian inference methods in cosmology with LISA standard sirens



LISA Data Analysis: from classical methods to machine learning
L2IT
24/11/2022





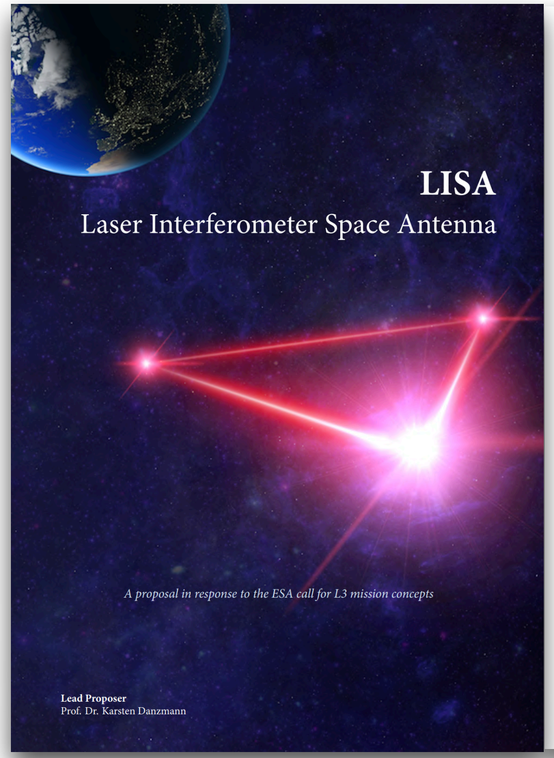
Danny Laghi

CNES Postdoctoral Fellow⋆

Laboratoire des 2 Infinis - Toulouse
danny.laghi@l2it.in2p3.fr

⋆ **This research is directly supported by the CNES**

Credits: Steve Drasco/ESA-HUBBLE/NASA



LISA Mission Proposal: arXiv:1702.00786

Contents

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

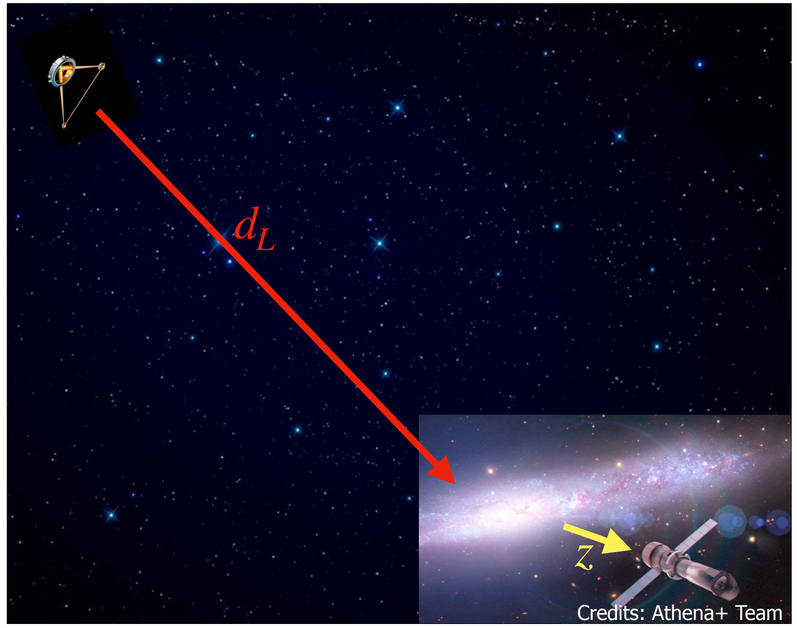
STANDARD SIRENS

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

Holz, Hughes, *APJ* (2005)

"**Bright** standard sirens"

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

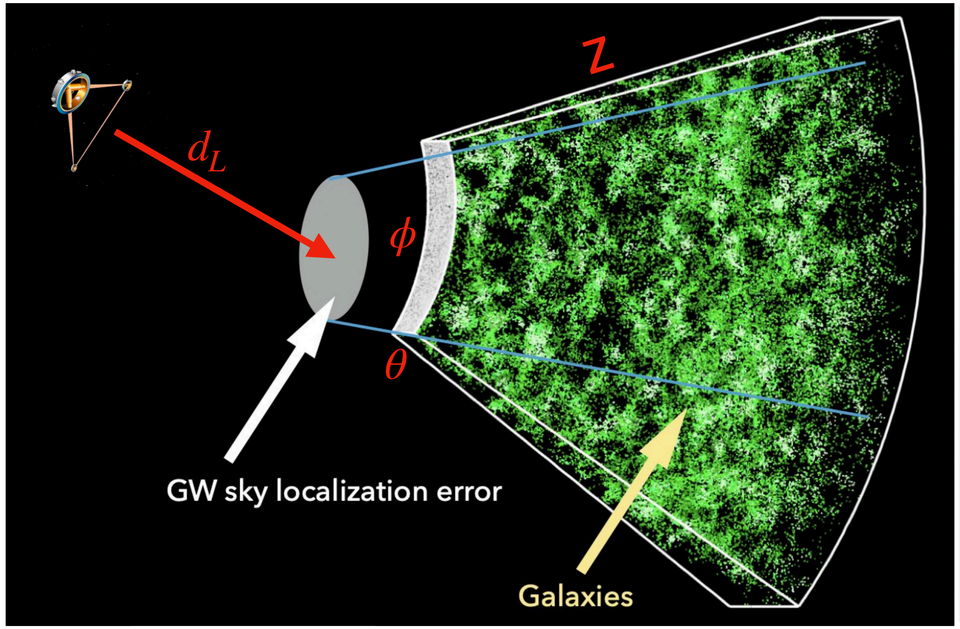


Luminosity distance
From the GW signal!

redshift
Not in the GW signal!

"**Dark** standard sirens"

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



COSMOLOGICAL INFERENCE SCHEME

GW redshift prior:

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

cosmological model:

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

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

LISA likelihood:

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

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

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

Posterior ← Nested sampling **[CPNest]** ← **Prior**, **Quasi-likelihood**

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

COSMOLOGICAL INFERENCE SCHEME

GW redshift prior:

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

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

cosmological model:

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

LISA likelihood:

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

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

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

Posterior

Nested s… [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

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

- EMRI PE based on catalogs of Babak+, *PRD* (2017)

+

- Galaxy catalog of Henriques+, *MNRAS* (2012)

+

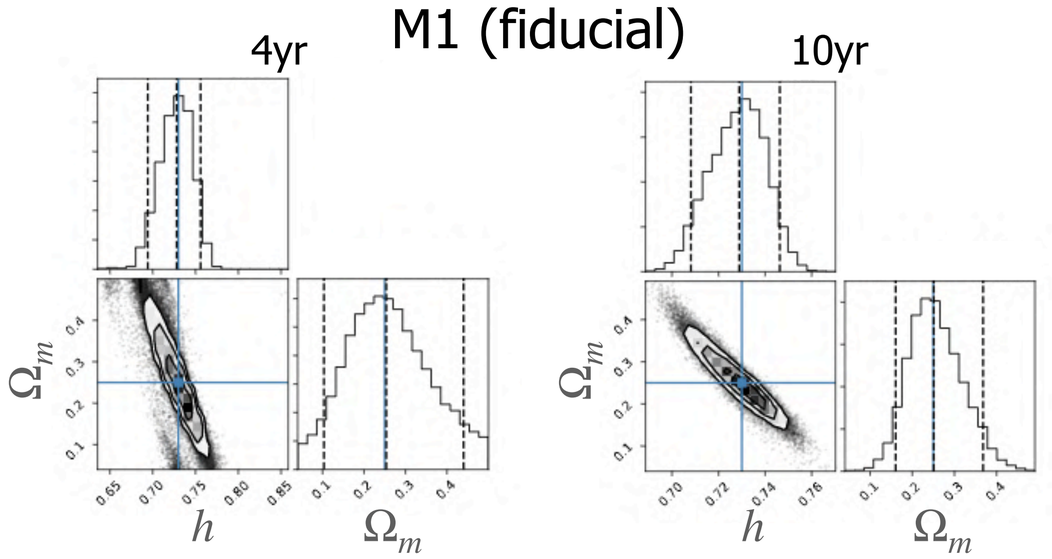
- **Bayesian cosmological inference** on the loudest events (done with **`cosmoLISA`**)

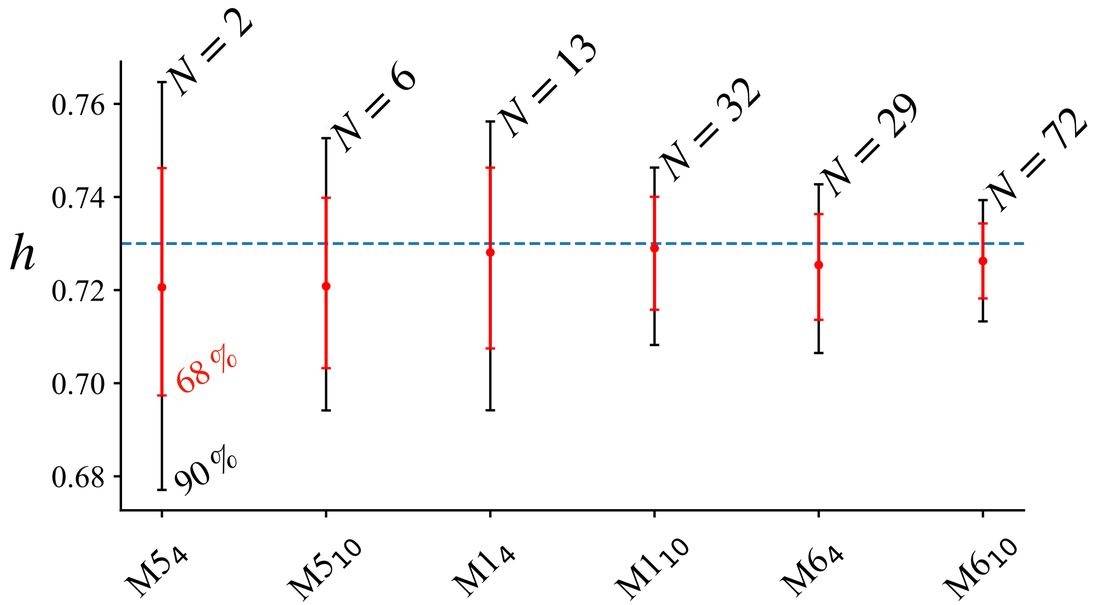
=

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)





Laghi, Tamanini, Del Pozzo, Sesana, Gair, Babak, Izquierdo-Villalba, *MNRAS* (2021)

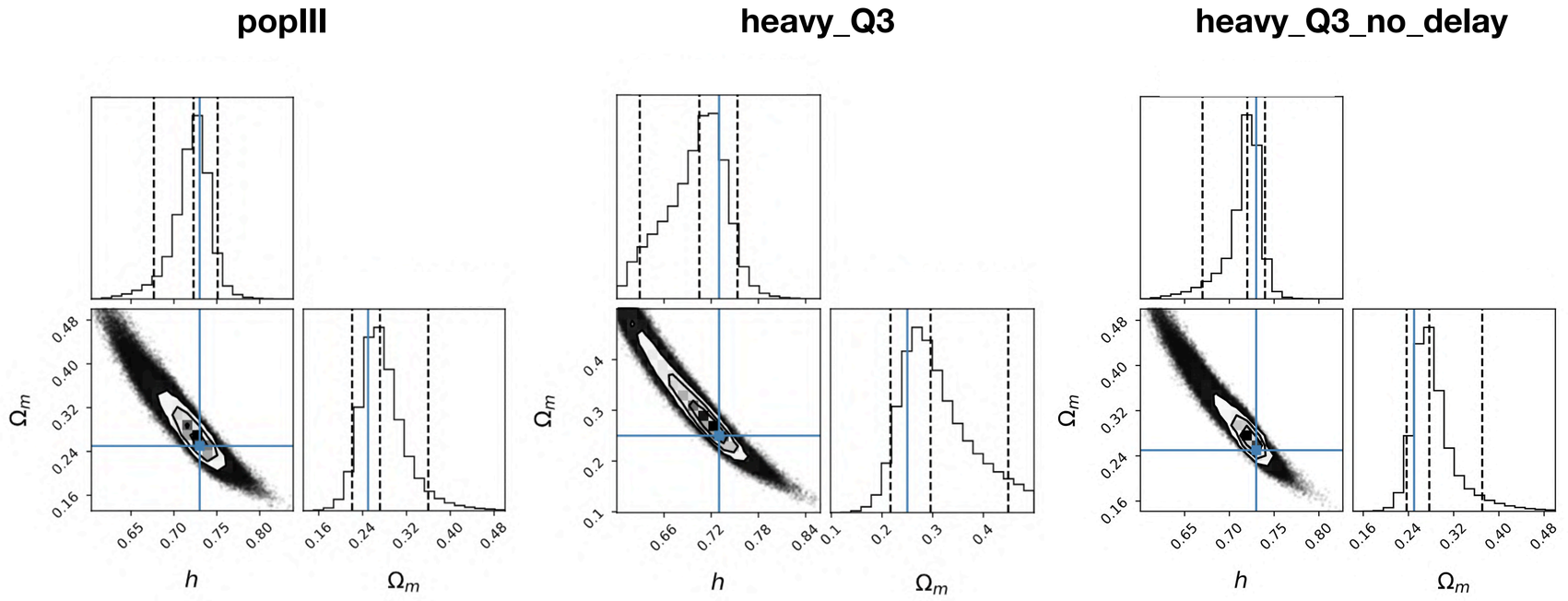
MBHBs AS BRIGHT SIRENS

- 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

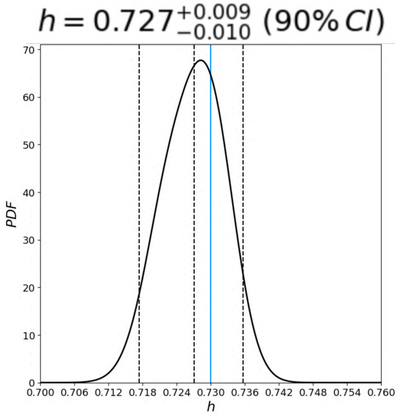


PRELIMINARY [cosmoLISA]

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)

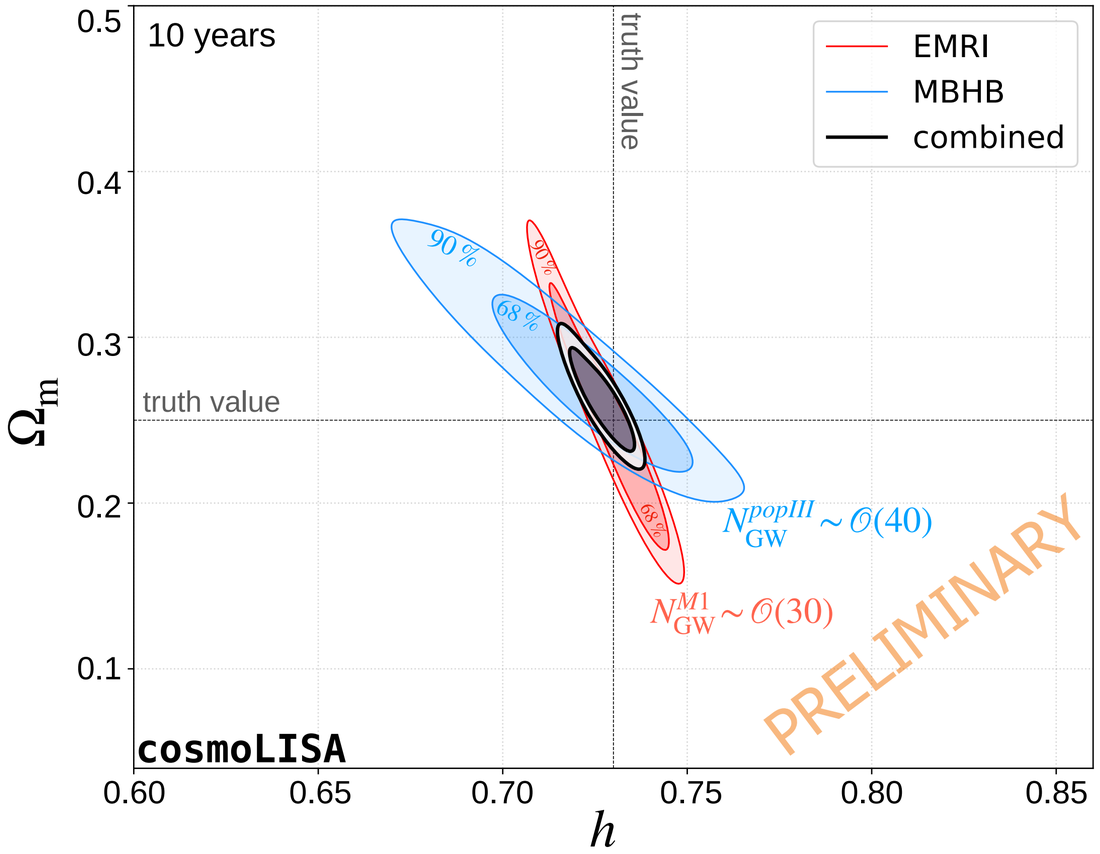
+

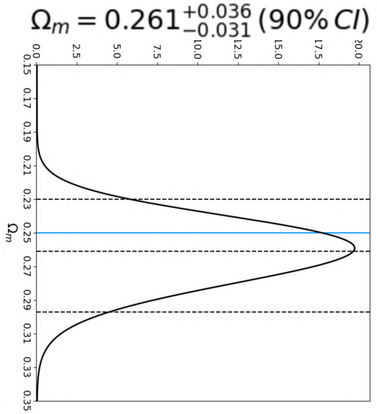
(MBHBs & EM counterpart)

=

H_0 $O(1\%)$

Ω_m $O(15\%)$





LISA COSMOLOGICAL SPECTRUM