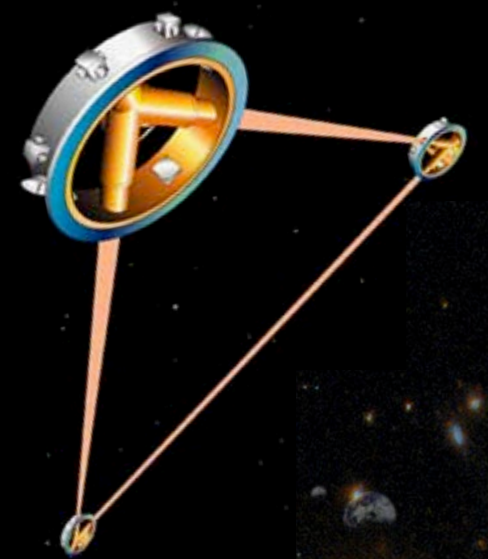
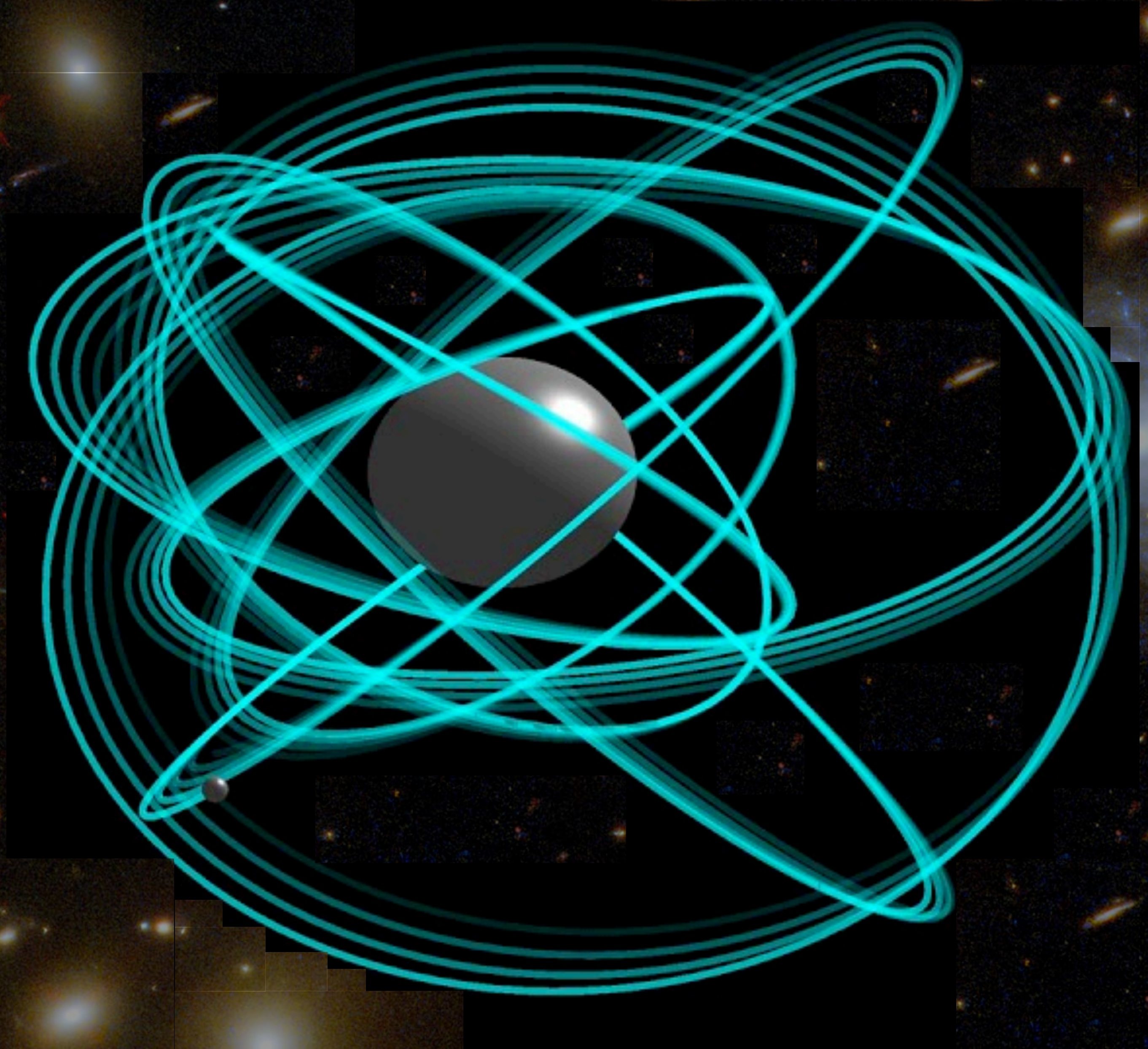
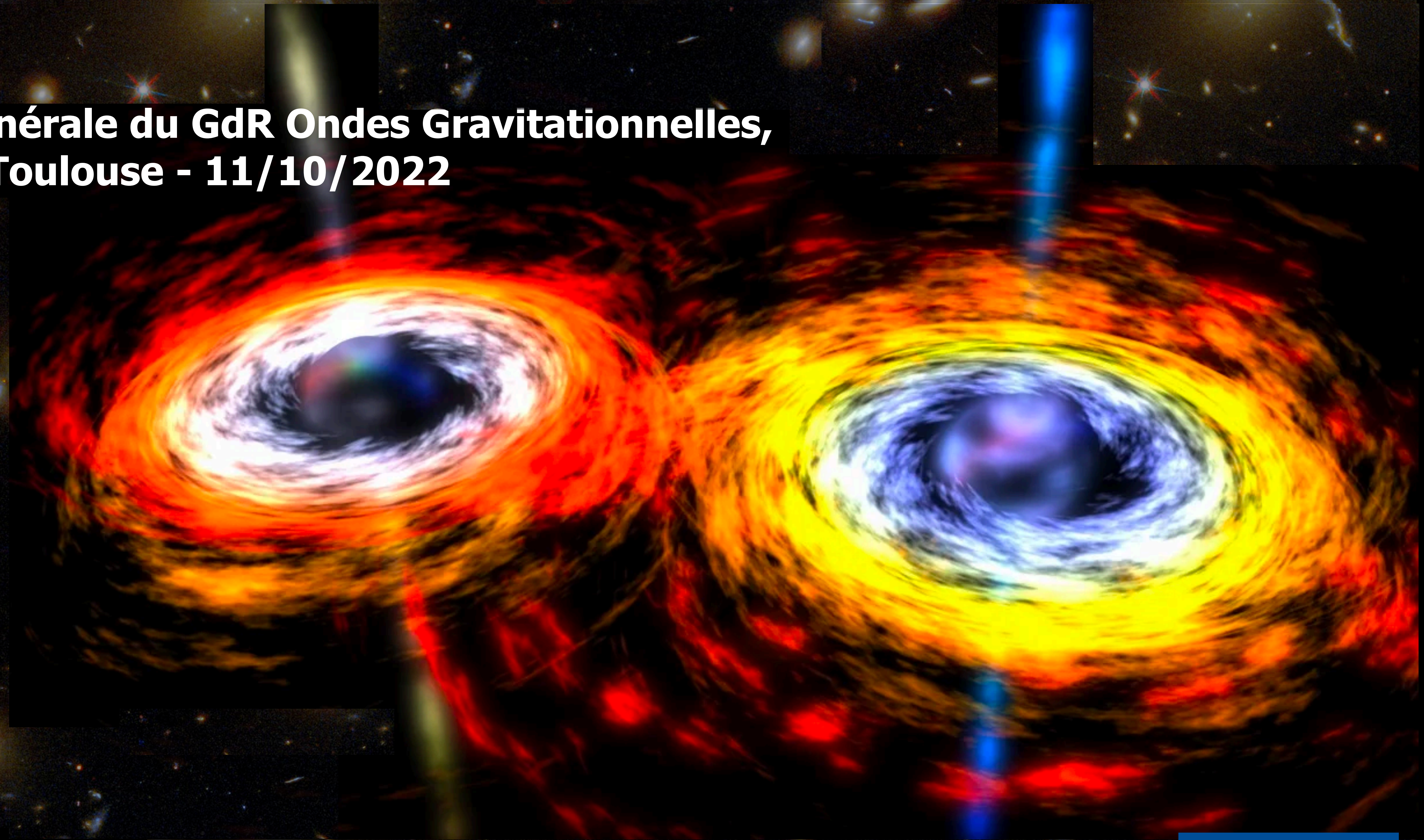
Constraining the cosmic expansion history with LISA standard sirens



Sixième Assemblée Générale du GdR Ondes Gravitationnelles,
L2IT, Toulouse - 11/10/2022





Danny Laghi

CNES Postdoctoral Fellow* @ L2IT
danny.laghi@l2it.in2p3.fr

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Credits: Steve Drasco/ESA-HUBBLE/NASA

THE COSMIC EXPANSION HISTORY

According to the standard cosmological model, we can describe the cosmic expansion history in terms of a set of **cosmological parameters**:

$$\Omega = \{H_0, \Omega_m, \Omega_\Lambda, \dots\}$$

Fundamental relation between cosmological parameters and **astrophysical observables**:

redshift

$$d_L(\Omega, z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w_0+w_a)} e^{-3\frac{w_a z'}{1+z'}}}} \quad \text{(flat FLRW)}$$

Luminosity distance

'FLRW' = Friedmann-Lemaître-Robertson-Walker

WHY GW COSMOLOGY?

Schutz, *Nature* (1986)

GWs are natural "**cosmic-rulers**":

- Any coalescing binary encodes its distance in its GW signal

✅ **No need for distance scale ladder**

Gravitation is **scale-free:**

- The mass is degenerate with the redshift in the GW signal

❌ **No redshift measurement from GWs**

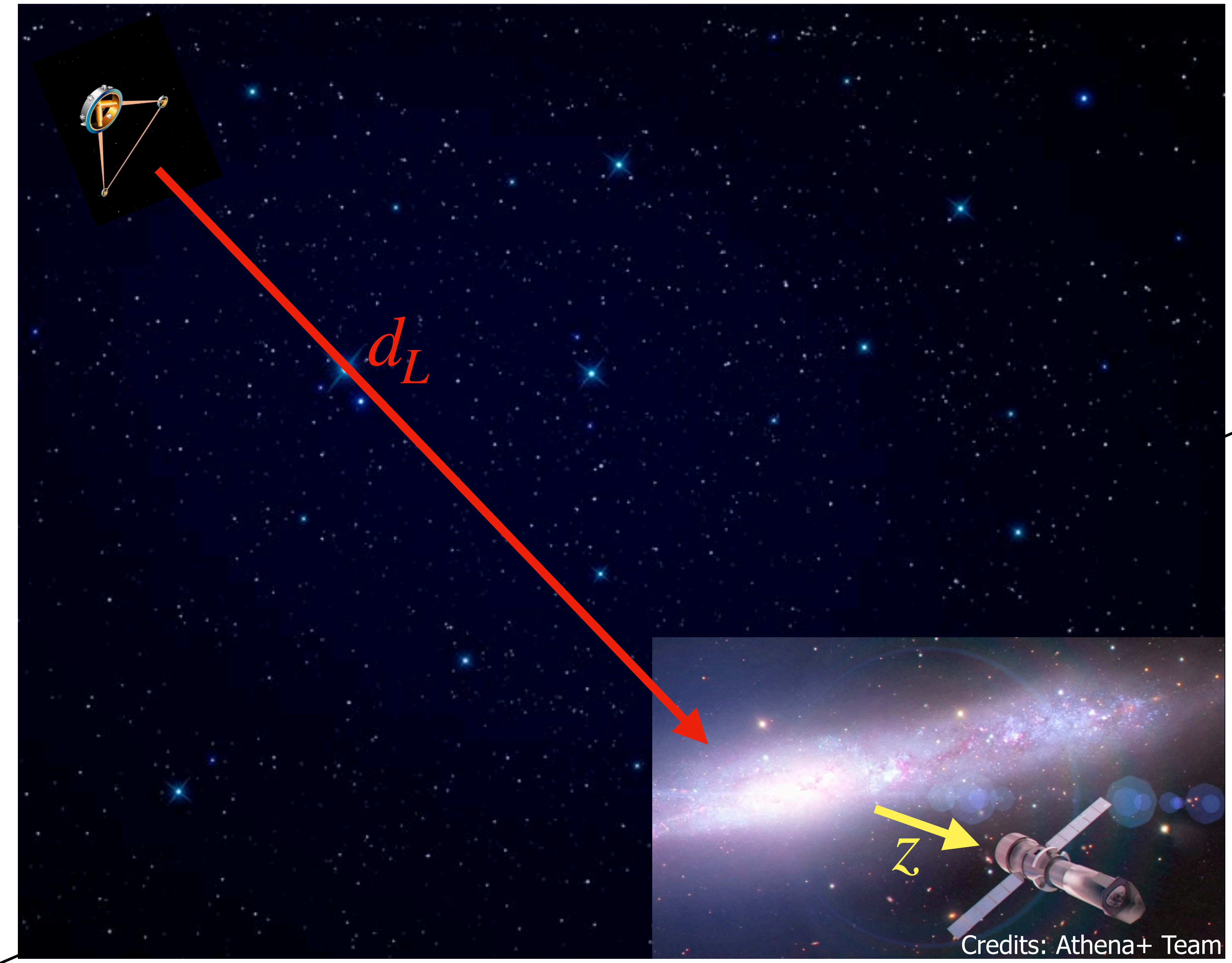
Krolak, Schutz, *GRG* (1987)

STANDARD SIRENS

Holz, Hughes, *APJ* (2005)

"**Bright** standard sirens"

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



'EM' = Electromagnetic

"**Dark** standard sirens"

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

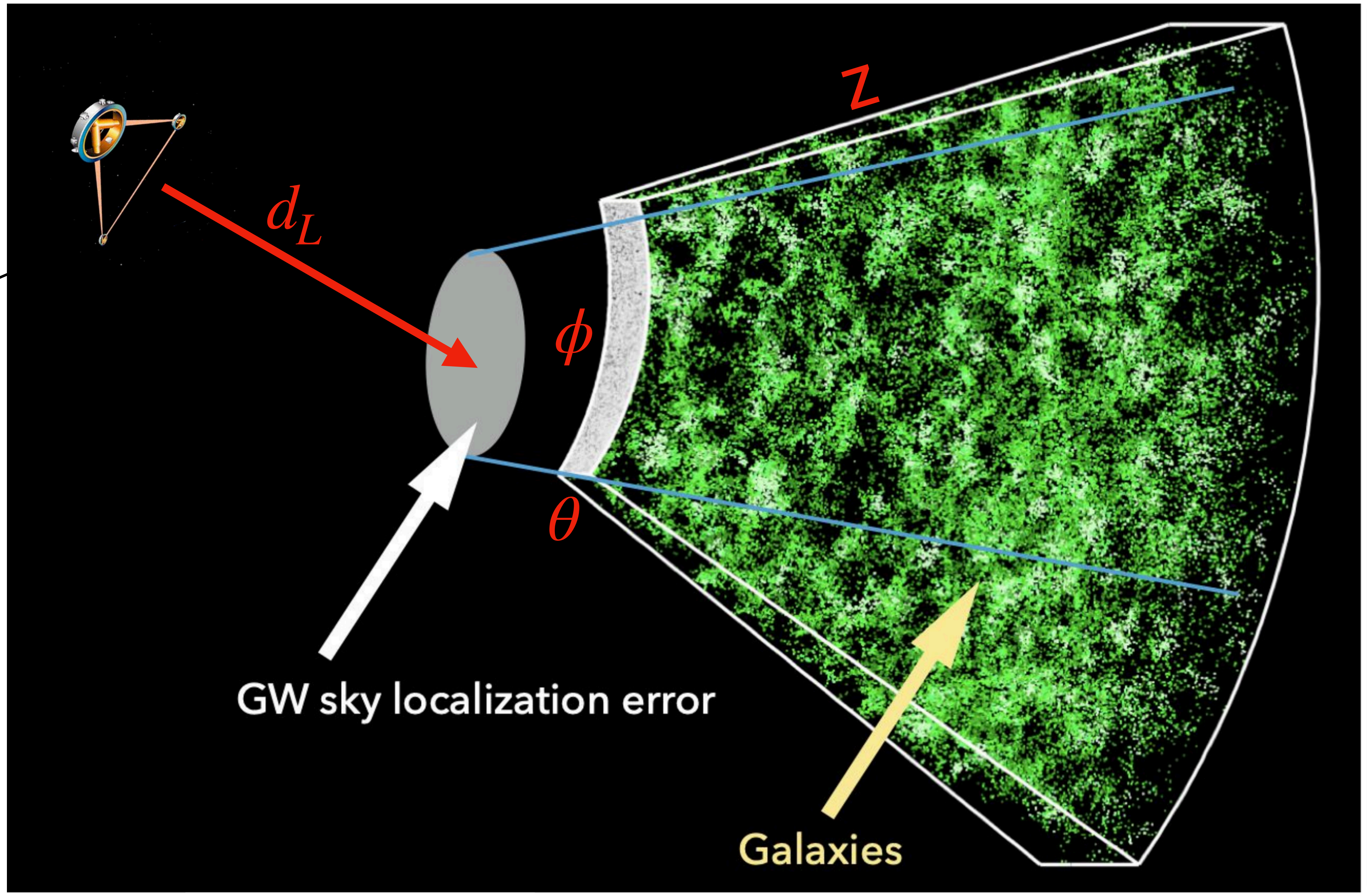
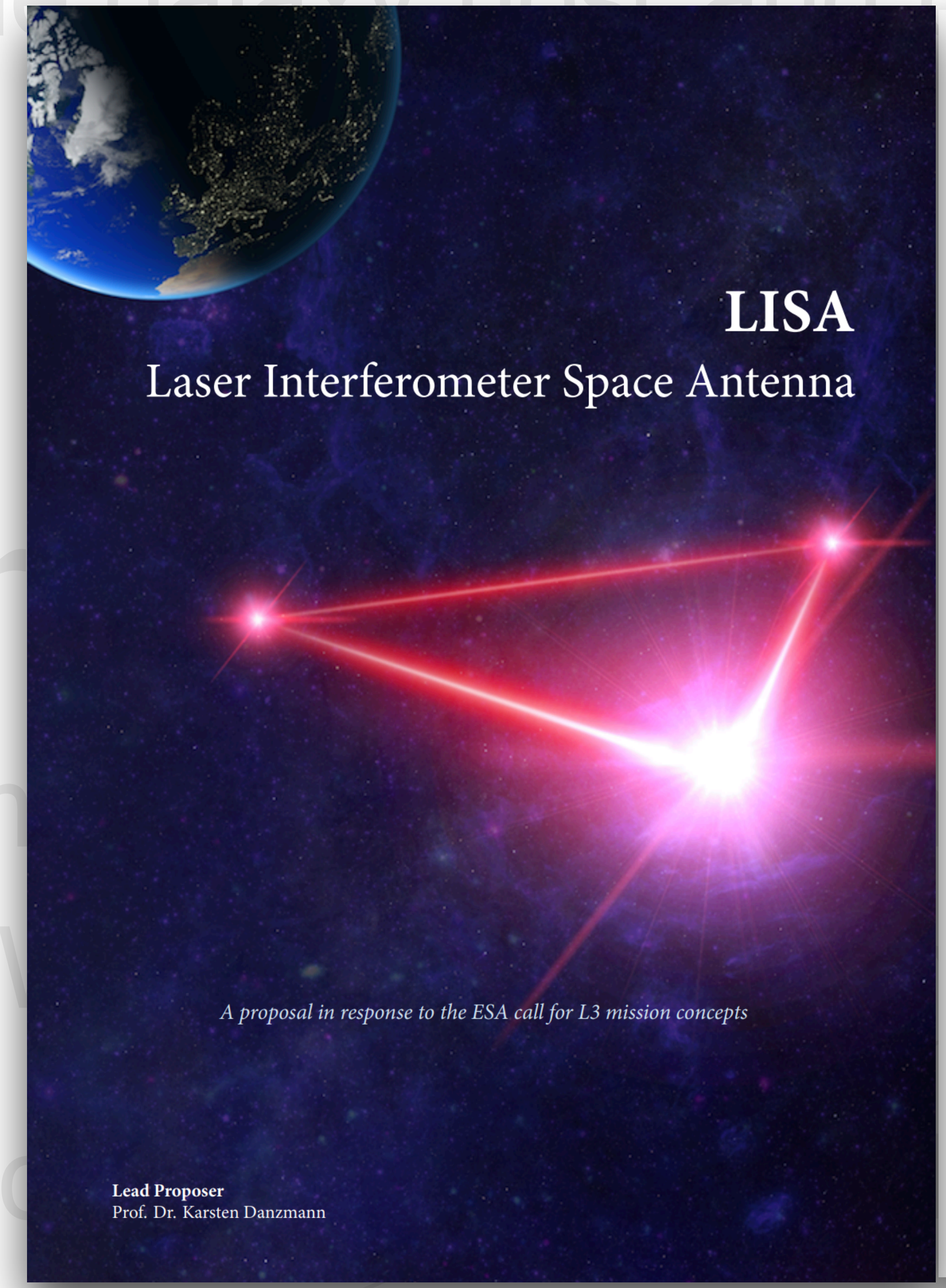


Image credit: Jeremy Tinker and the SDSS-III collaboration

Prospects for LISA?



LISA Mission Proposal: arXiv:1702.00786

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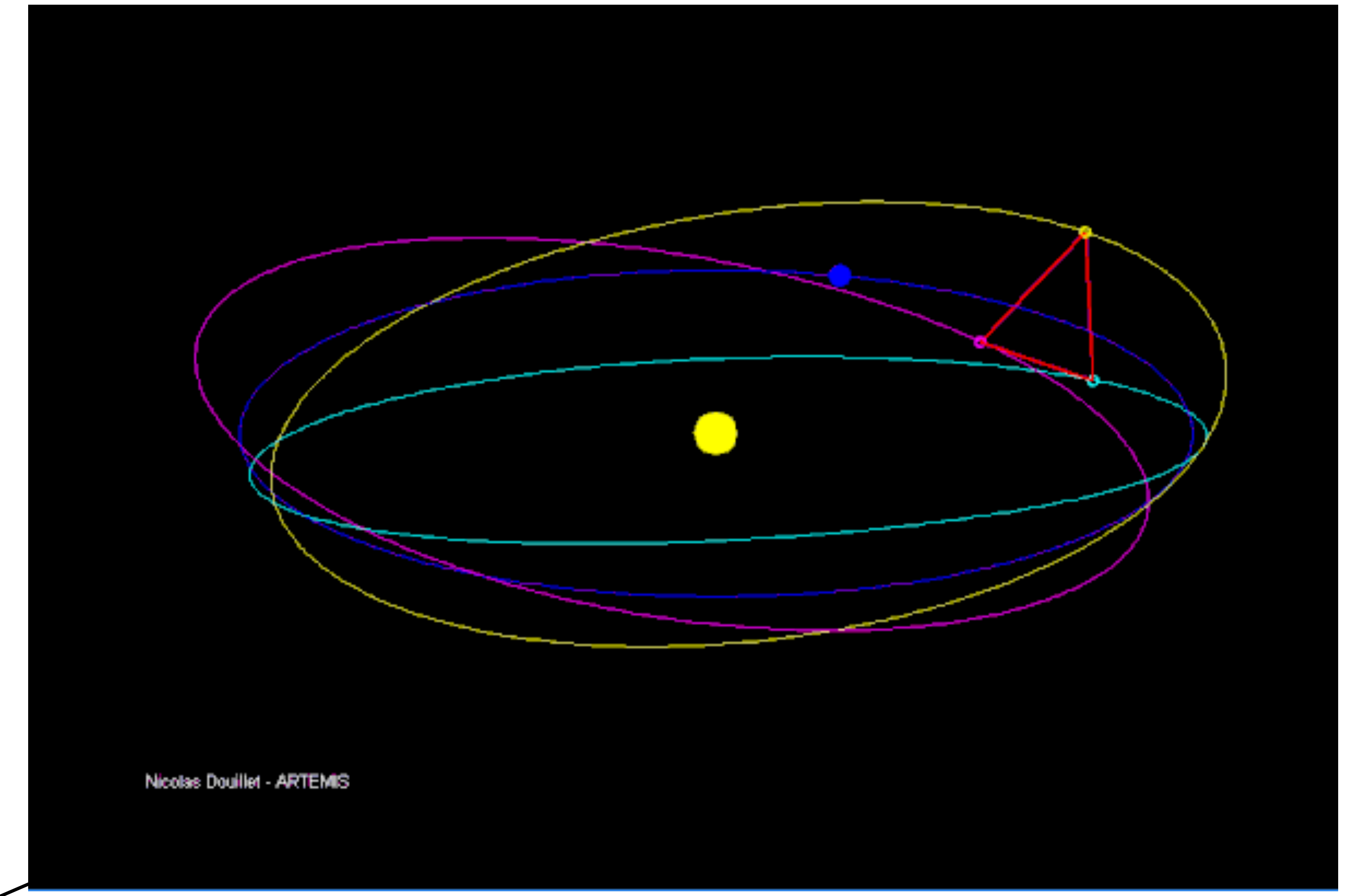
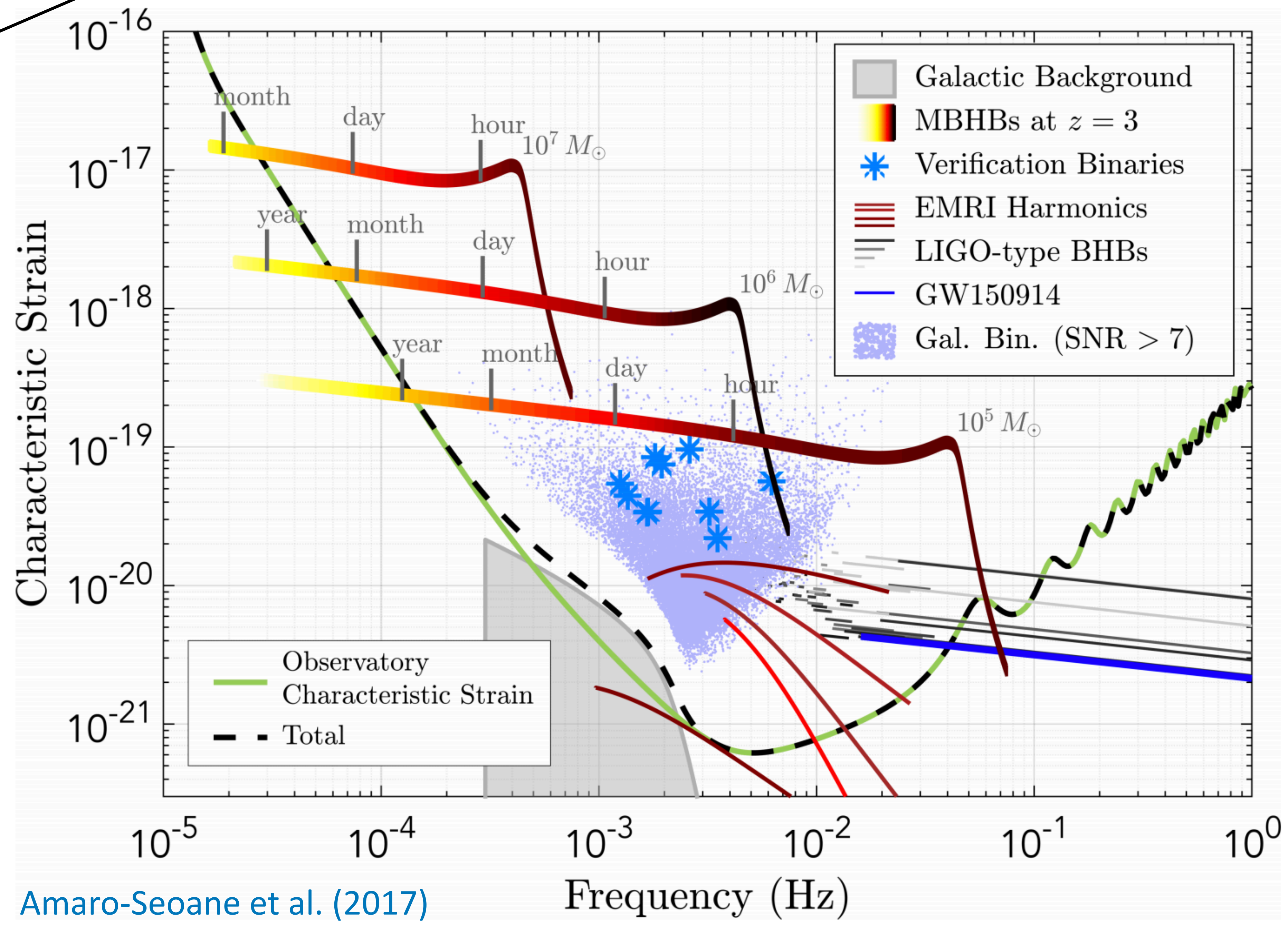
LASER INTERFEROMETER SPACE ANTENNA

- LISA will be the **first space-based** GW detector (expected launch in 2034)

- LISA will observe GWs in a yet **unexplored** frequency range ($10^{-4} - 10^{-1}$ Hz)

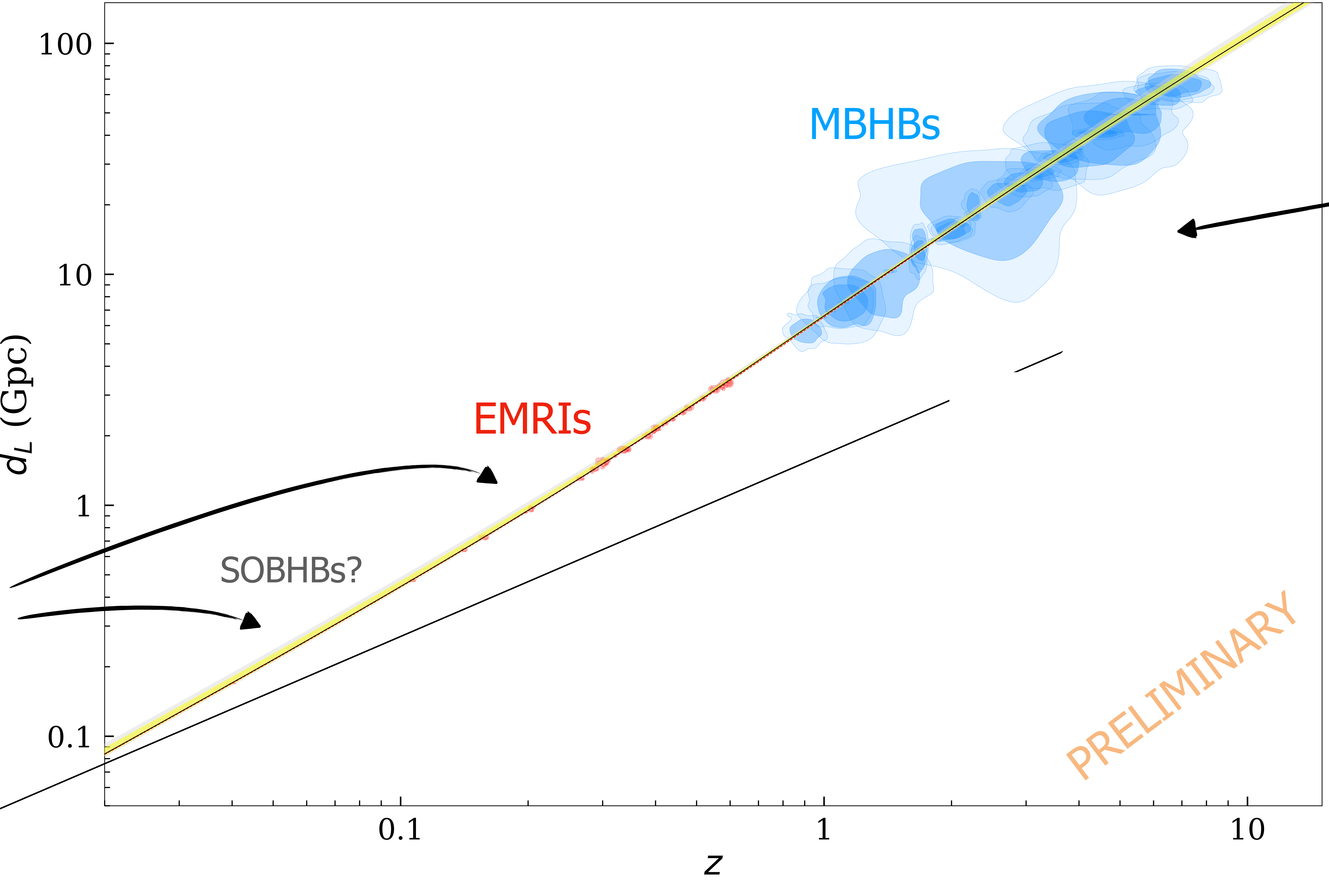
- LISA will detect **compact binary coalescences** up to very high redshift





Amaro-Seoane et al. (2017)

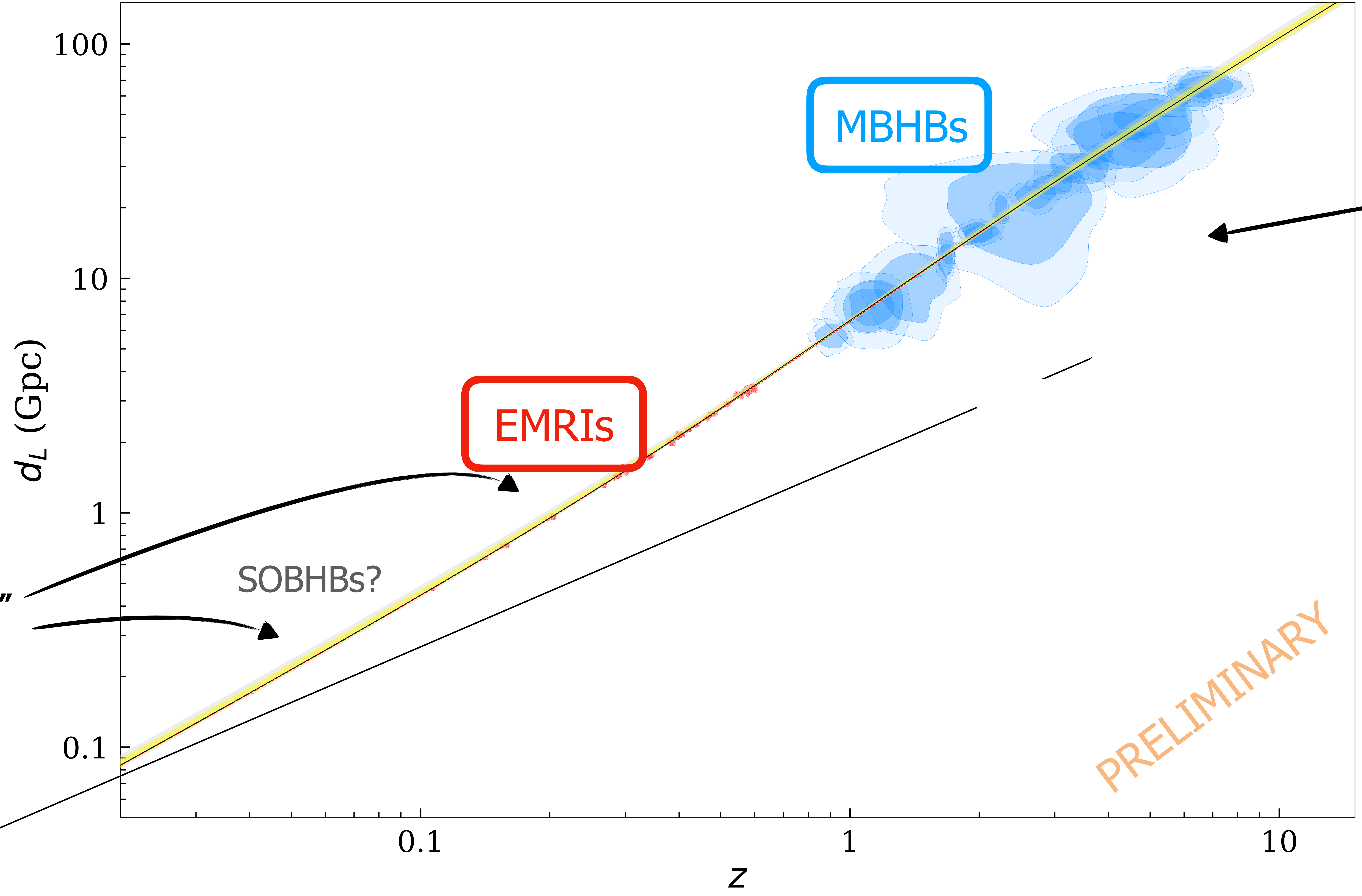
LISA COSMOLOGICAL SPECTRUM



"Bright sirens"
with
EM counterpart

"Dark sirens"
without
EM counterpart

LISA COSMOLOGICAL SPECTRUM



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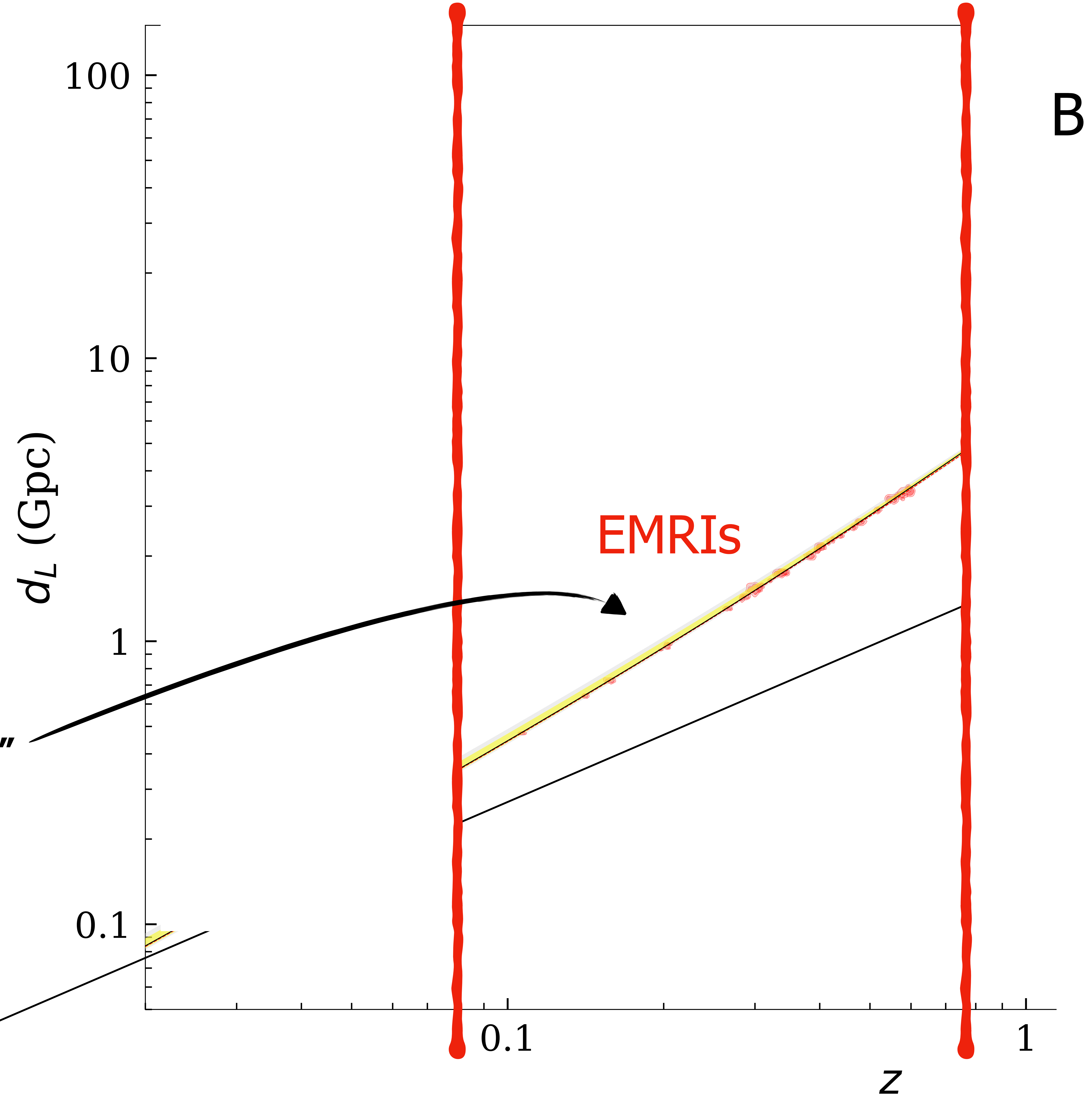
EXTREME MASS-RATIO INSPIRALS



"Dark sirens"

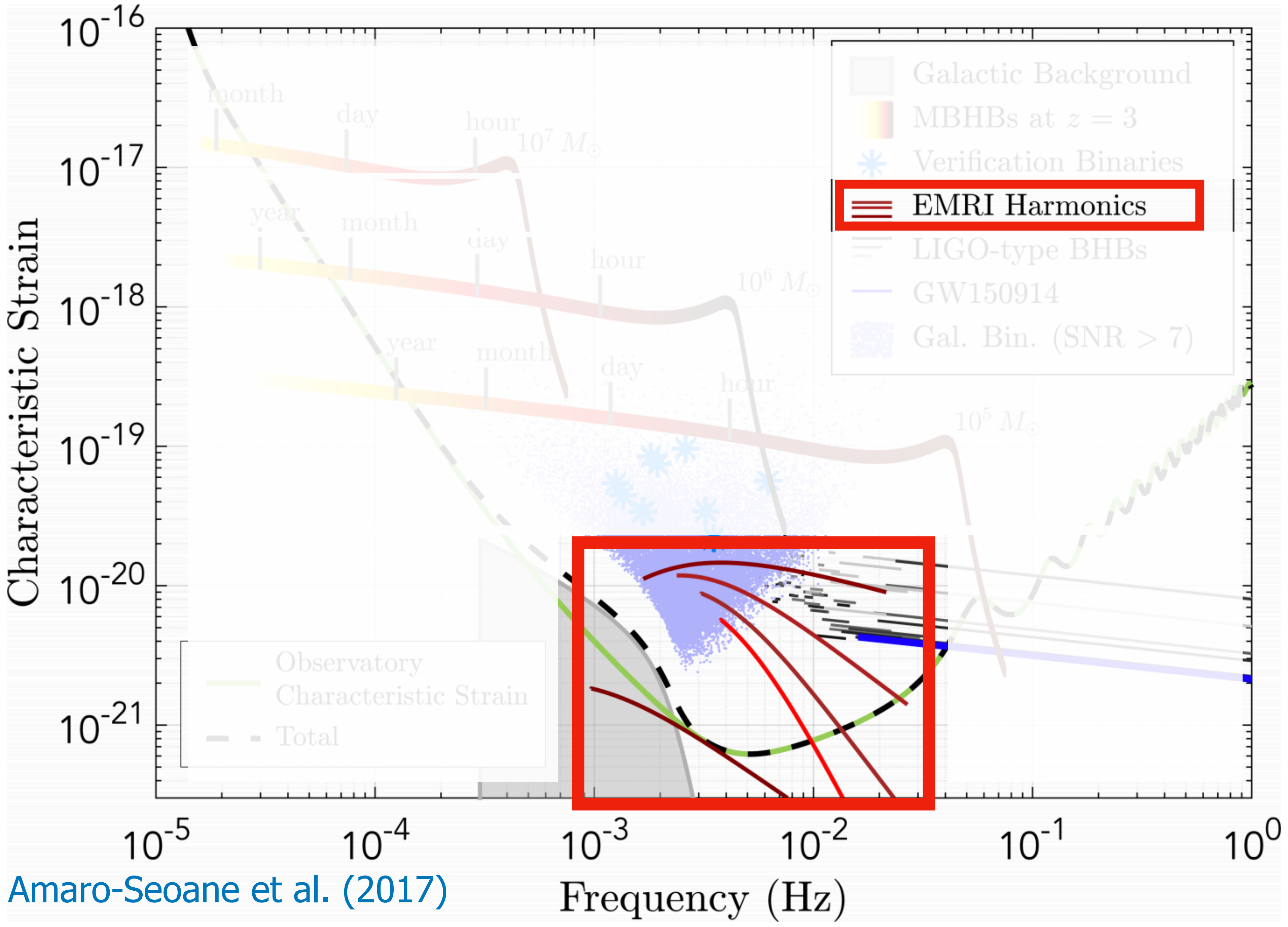
without
EM counterpart

Binary systems with **mass-ratio**

$q \sim 10^{-6} - 10^{-3}$

e.g.

$10^6\, M_\odot$ BH + $10\, M_\odot$ BH



Amaro-Seoane et al. (2017)

EMRIs AS DARK SIRENS

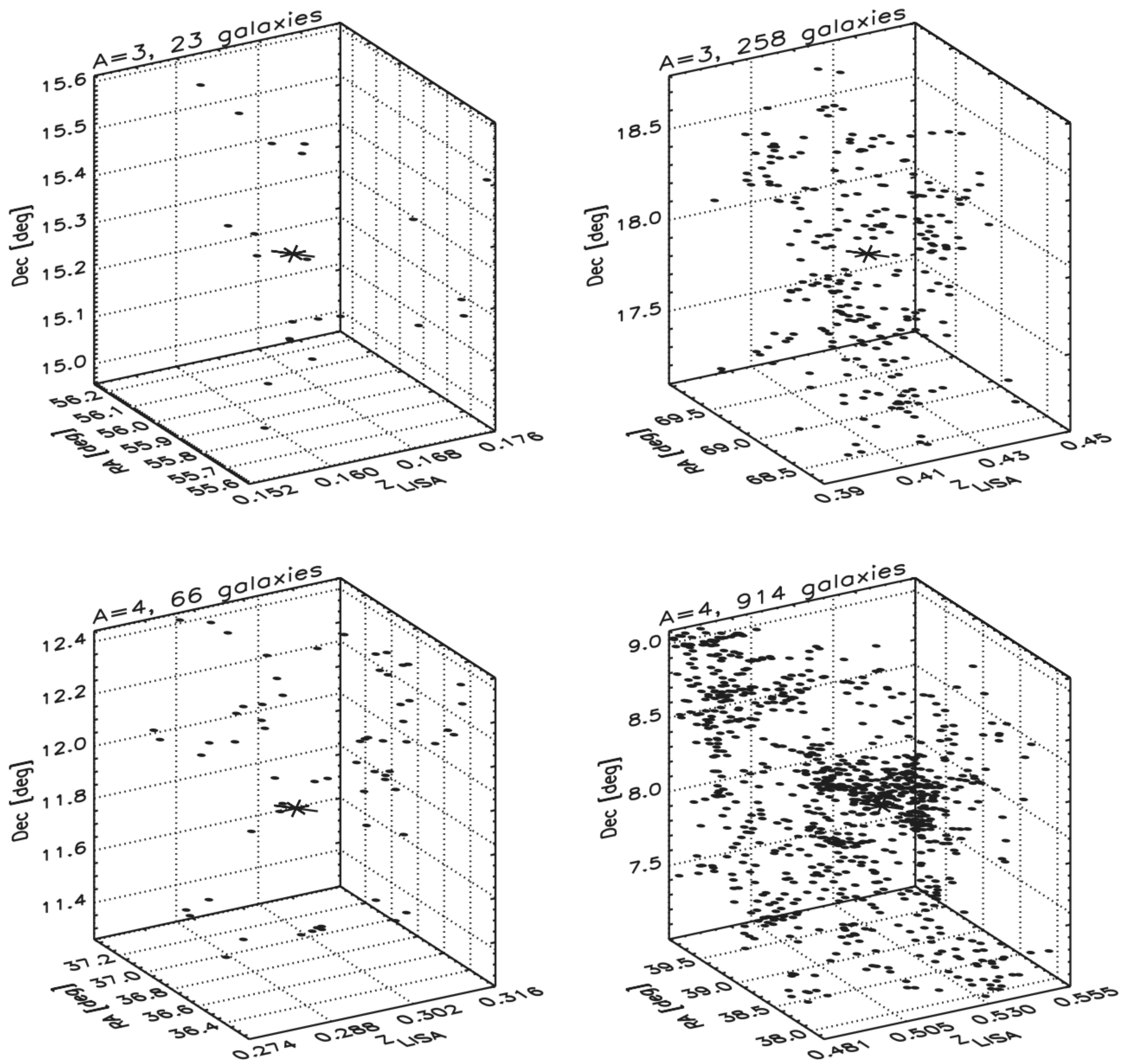
Previous studies:

Macleod, Hogan, *PRD* (2008):

H_0 at 1% with 20 EMRIs at $z < 0.5$ (68% CI)

BUT

- assume only linear cosmic expansion
- assume old 5 Gm LISA configuration
- no PE on the GW signals
- no Bayesian inference framework



Macleod, Hogan, PRD (2008)

RECENT ESTIMATES

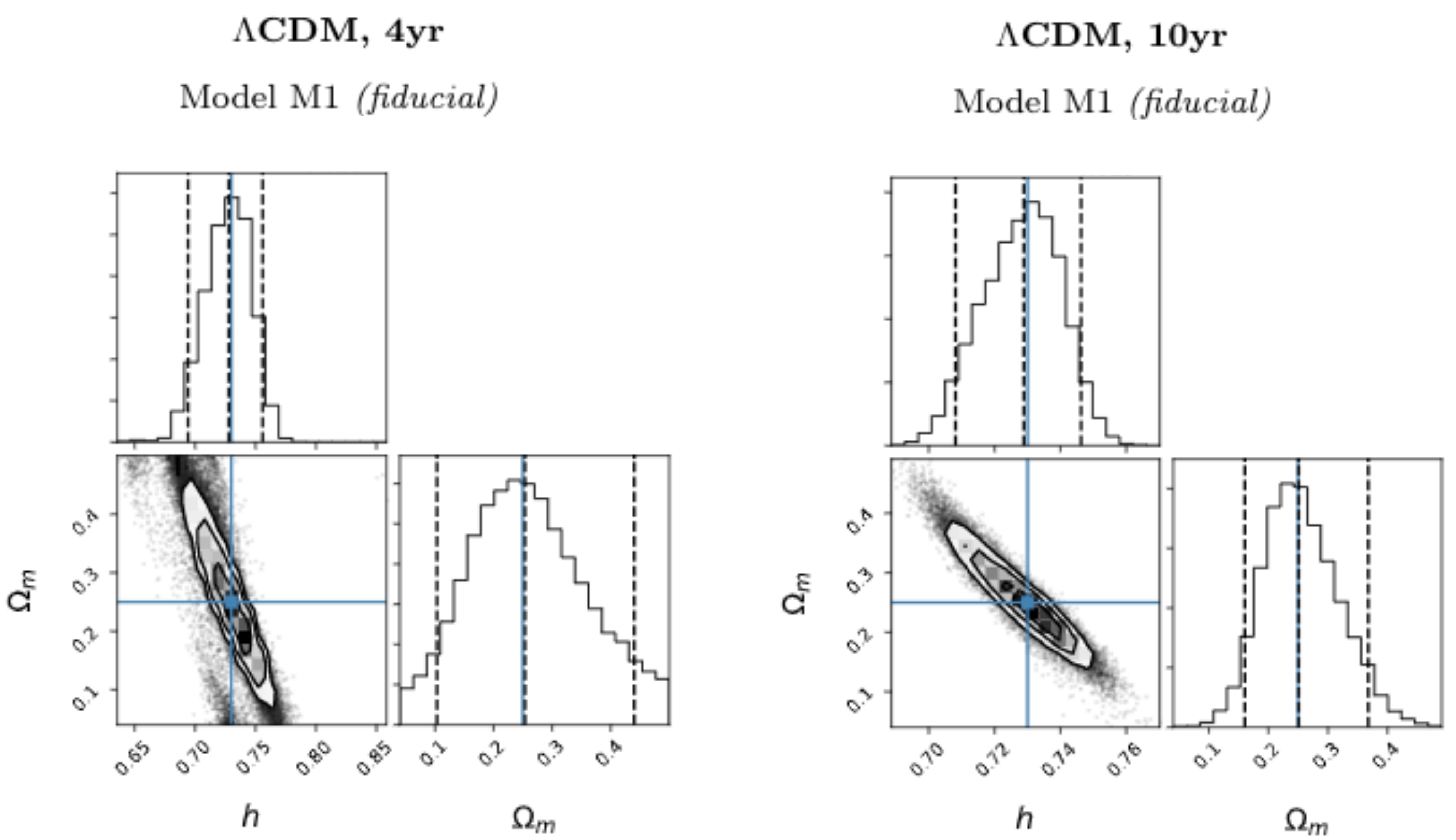
Laghi, Tamanini, Del Pozzo, Sesana,
Gair, Babak, Izquierdo-Villalba, *MNRAS* (2021)

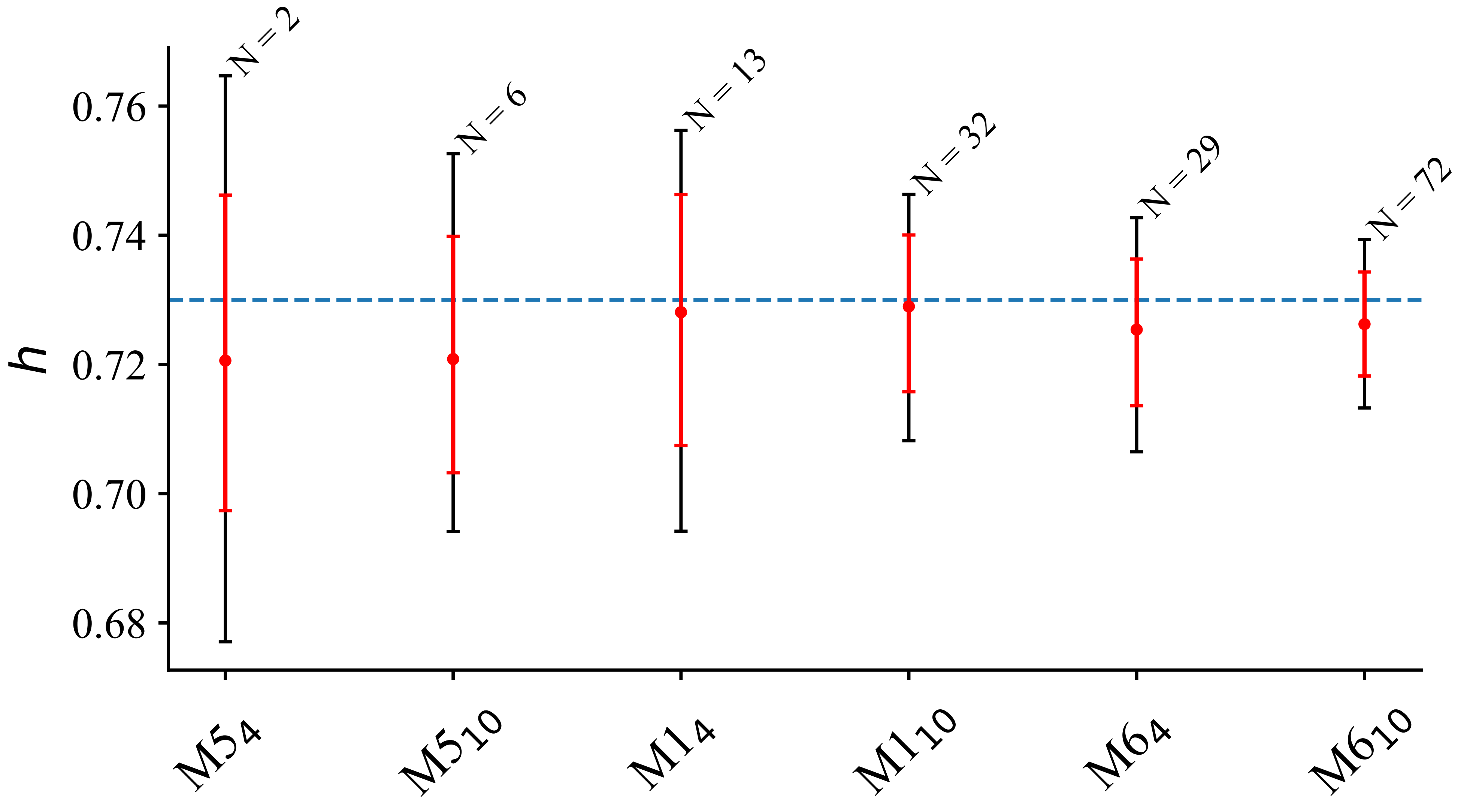
- assume full $d_L - z$ relation
- assume new 2.5 Gm LISA configuration
- EMRI PE based on catalogs of Babak et al., *PRD* (2017)
- Galaxy catalog of Henriques et al., *MNRAS* (2012)
- **Bayesian analysis** on the loudest events (done with **`cosmoLISA`**)

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

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

EMRIs are very good probes of H_0



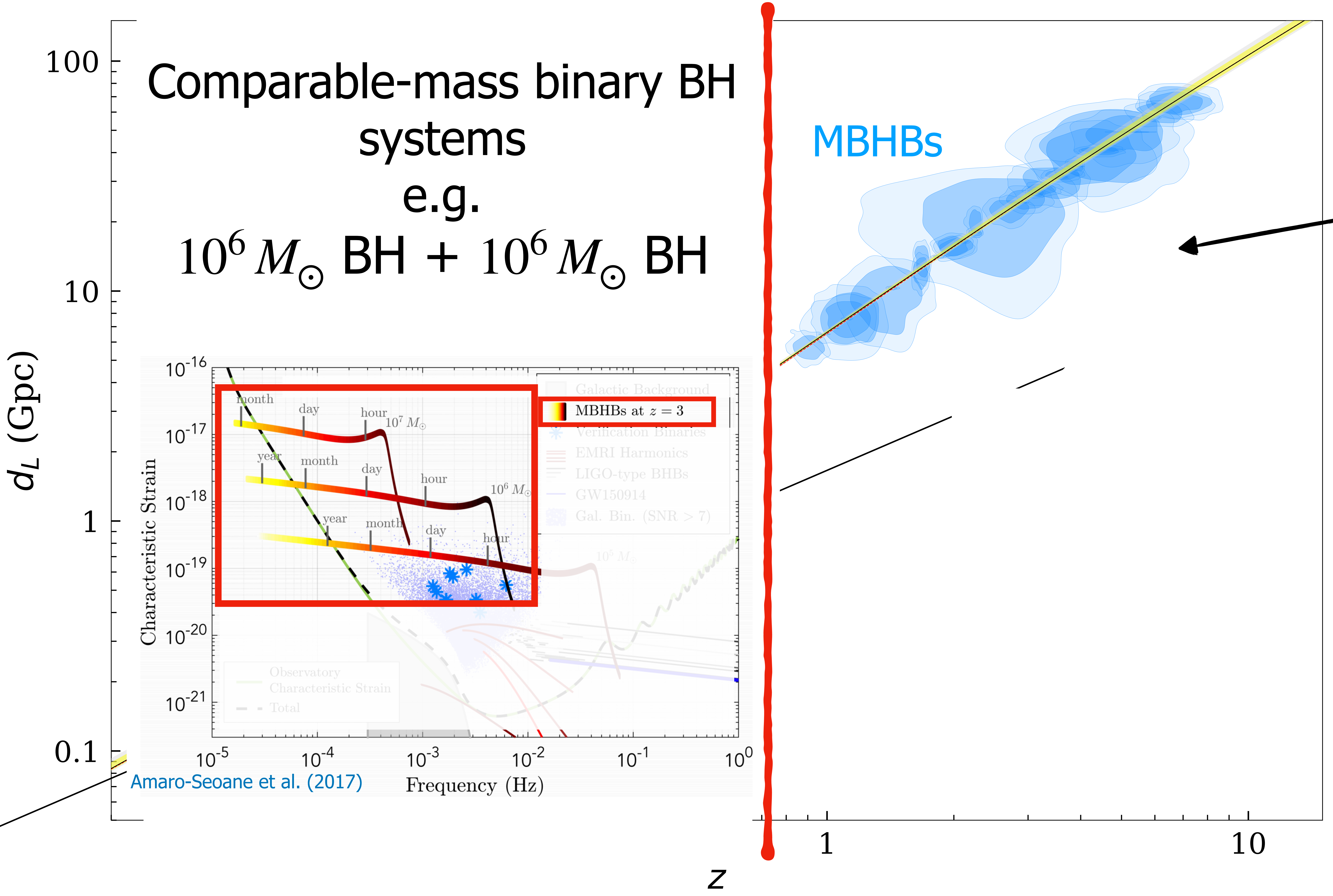


Laghi et al., *MNRAS* (2021)

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

MASSIVE BLACK HOLE BINARIES

Comparable-mass binary BH systems
e.g.
$10^6\,M_\odot$ BH + $10^6\,M_\odot$ BH



Amaro-Seoane et al. (2017)

"Bright sirens"
with
EM counterpart

MBHBs AS BRIGHT SIRENS

Recent studies (from LISA CosWG *White Paper*, arXiv:2204.05434):

Tamanini et al., *JCAP* (2016)

LISA CosWG, *JCAP* (2019)

H_0 at ~7% in a "realistic" LISA scenario (68% CI) [~4 EM counterparts per year]

BUT

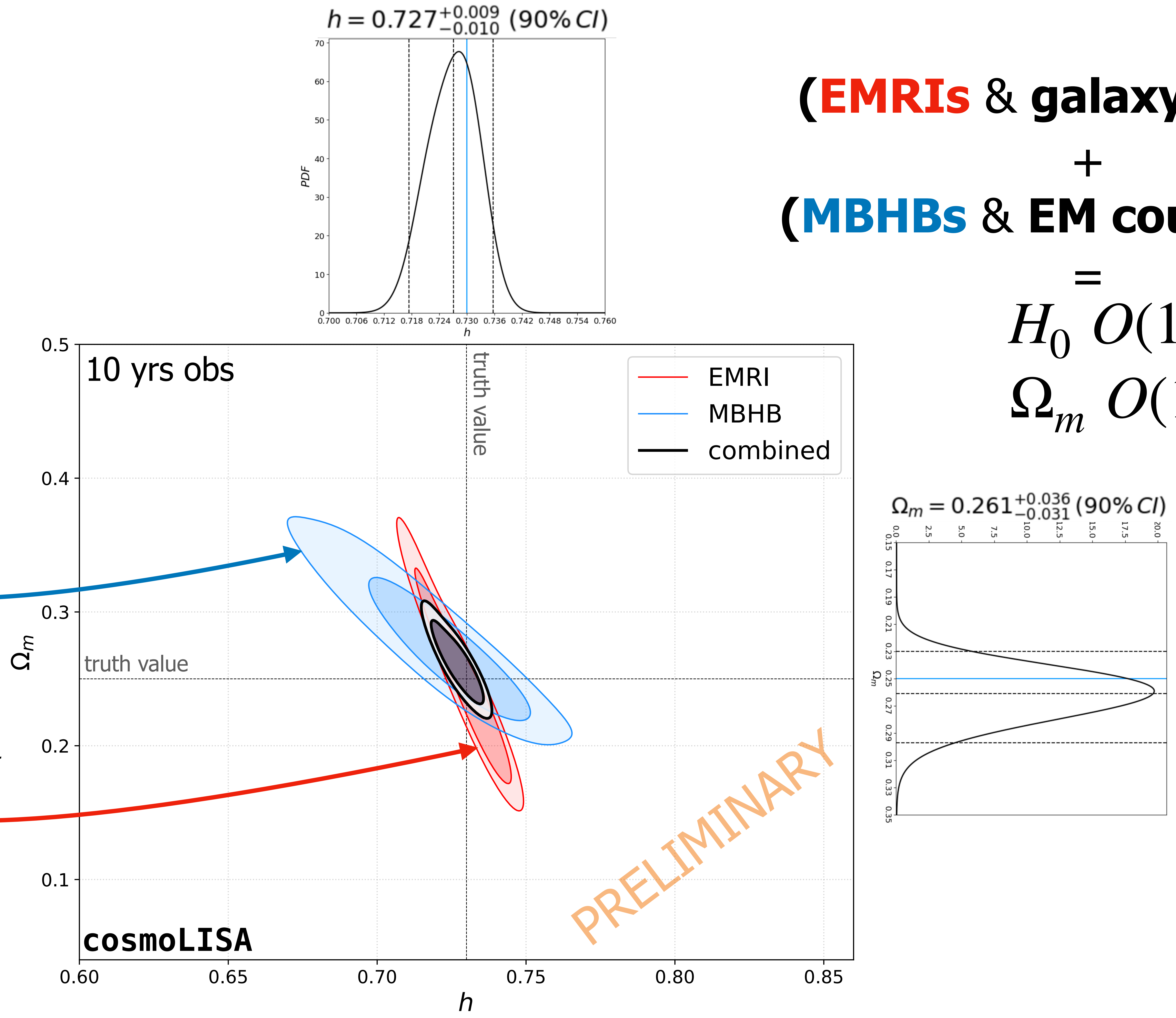
- See Mangiagli et al., arXiv:2207.10678 for updated MBHB+EM counterpart rates
- If less counterparts, more pessimistic estimates

JOINT ANALYSIS: EMRIs + MBHBs

The key is to
combine them!

MBHB catalogs with EM counterpart taken from:
Klein et al., *PRD* (2015)
Tamanini et al., *JCAP* (2016)

Laghi et al., *MNRAS* (2021)



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

OPEN CHALLENGES

- Add layers of complexity to the analysis: likelihood, catalogs etc.

- Combine them all and deliver reliable cosmological estimates