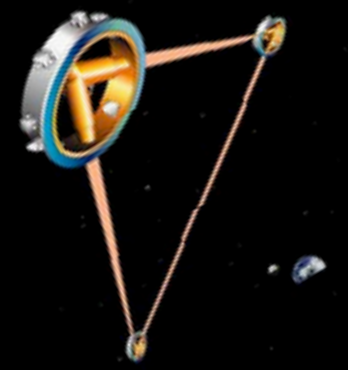
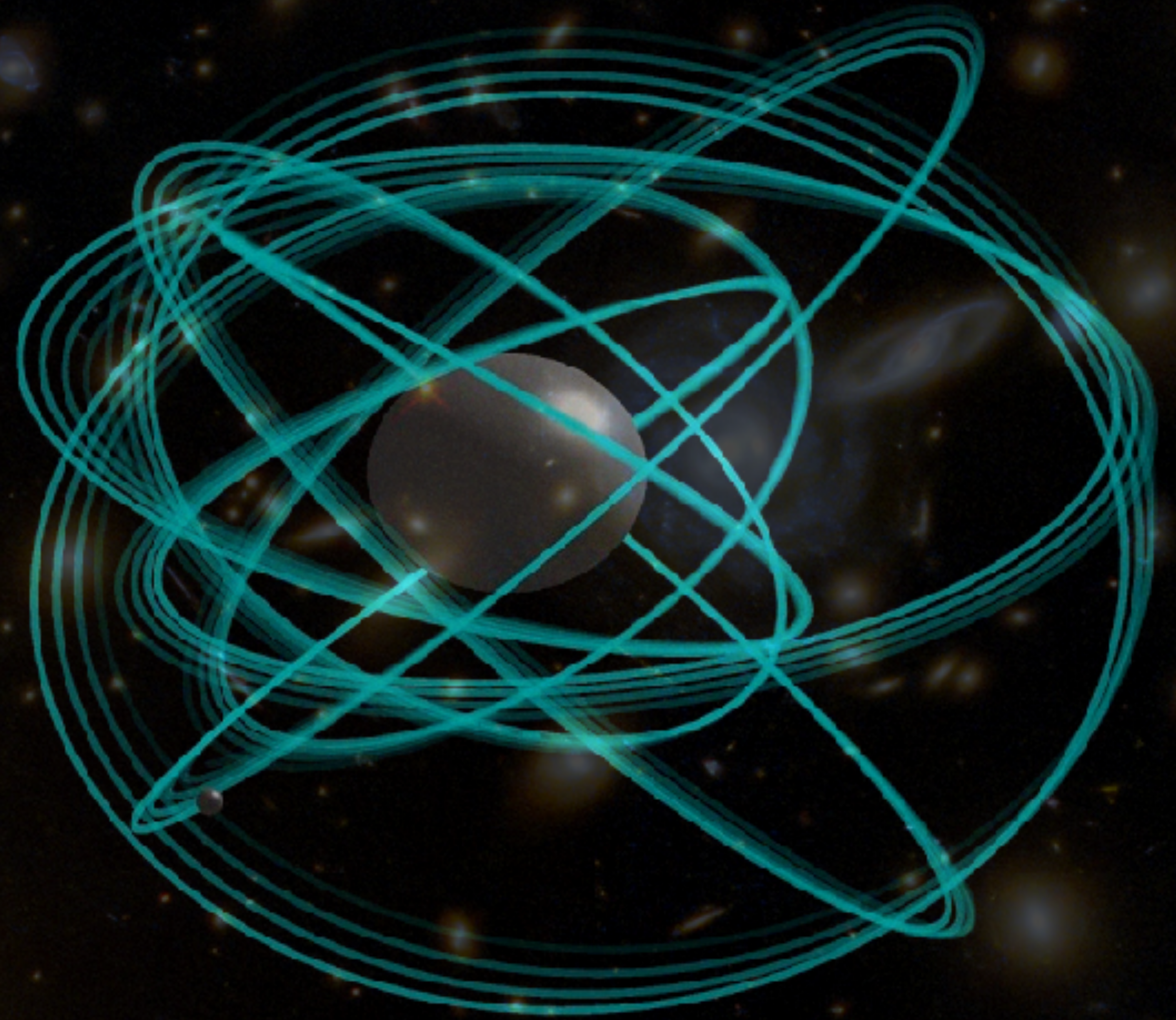
Cosmology with LISA standard sirens and their host galaxies

Orsay - 20/06/2022





Danny Laghi

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

in collaboration with:

N. Tamanini, W. Del Pozzo, A. Sesana, J. Gair, S. Babak, D. Izquierdo-Villalba

Credits: Steve Drasco/ESA-HUBBLE

UNDERSTANDING THE COSMIC EXPANSION HISTORY

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

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

- Observing astrophysical objects in a **flat FLRW metric**:

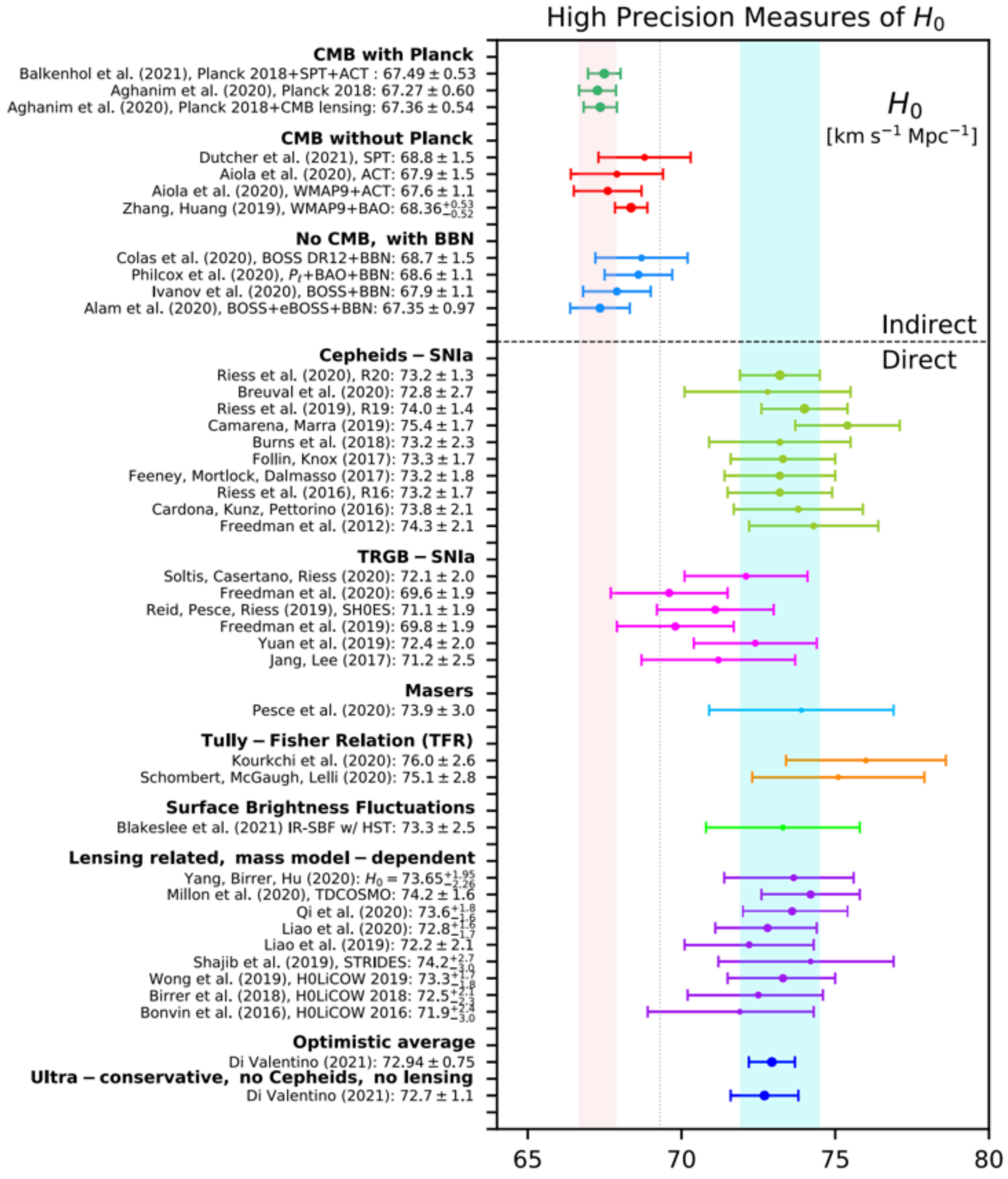
$$d_L(\Omega, z) = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w_0+w_a)} e^{-3\frac{w_a z'}{1+z'}}}}$$

MEASURING THE HUBBLE CONSTANT

- Different Hubble constant measurements do not agree with each other

- 4σ to 6σ disagreement between 'early time' vs 'late time' estimates

- Many proposals to resolve the Hubble puzzle, the matter is still under debate



Di Valentino et al., *CQG* (2021)

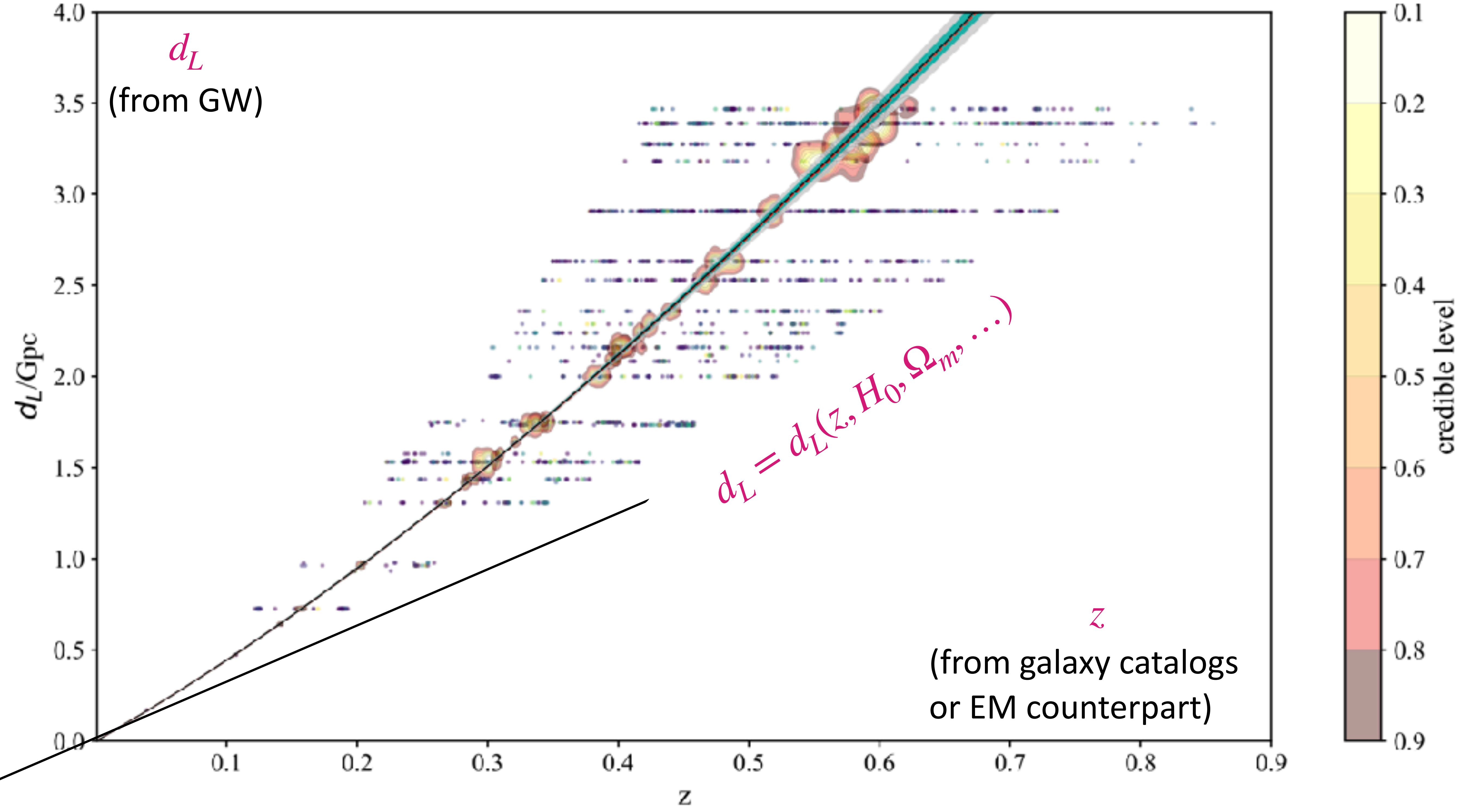
WHY GW COSMOLOGY?

Schutz, *Nature* (1986)

GWs are "**self-calibrated**": $h \sim d_L^{-1}$

- ✅ No need for distance scale ladder
- ❌ No redshift measurement from GWs

Krolak, Schutz, *GRG* (1987)



- "**Bright** standard sirens":
  - Measure **EM counterpart** of the galaxy host and obtain z
- "**Dark** standard sirens":
  - Infer z by **statistically matching** GW sky position with galaxy catalogs
  - Compute the **probability** of each galaxy to be the true host of the GW source

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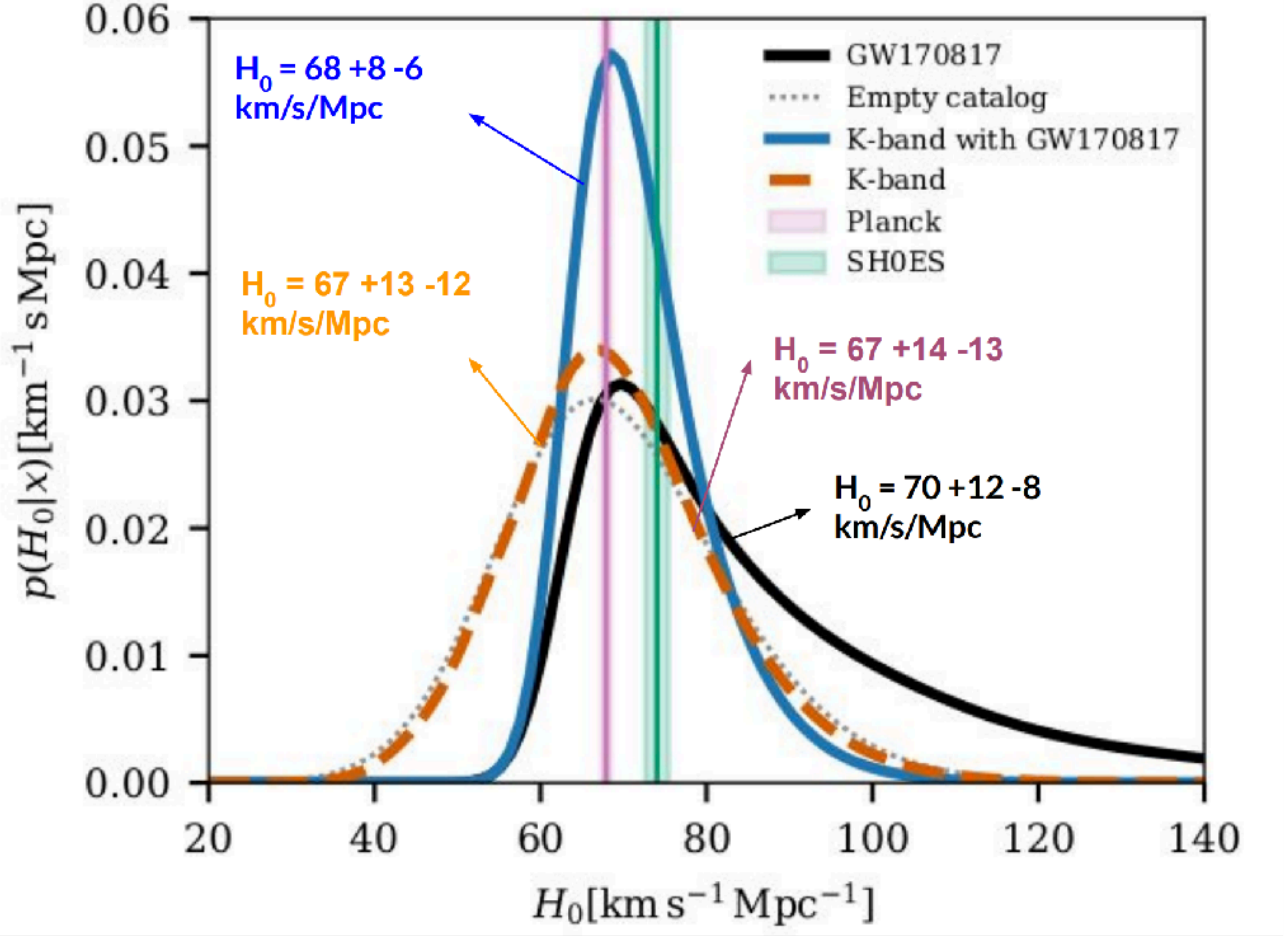
- No redshift mea

LVK, GWTC-3 cosmo paper, arXiv:2111.03604



(from galaxy catalogs)

- "Bright standard si
  - Measure E
- "Dark standard sire
  - Infer z by statistically matching GW sky position with galaxy catalogs
  - Compute the probability of each galaxy to be the true host of the GW source

LIGO-VIRGO detectors

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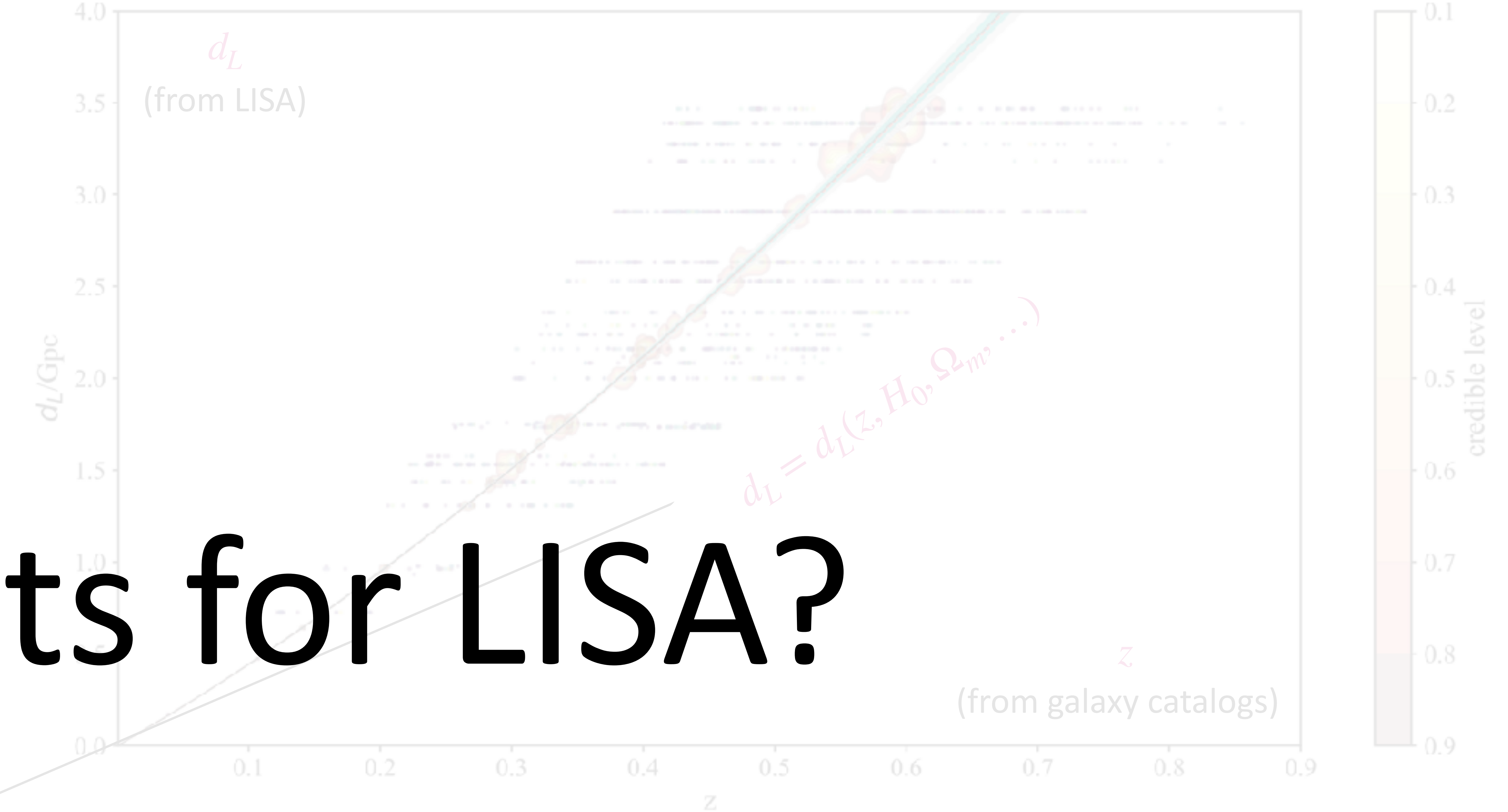

Prospects for LISA?

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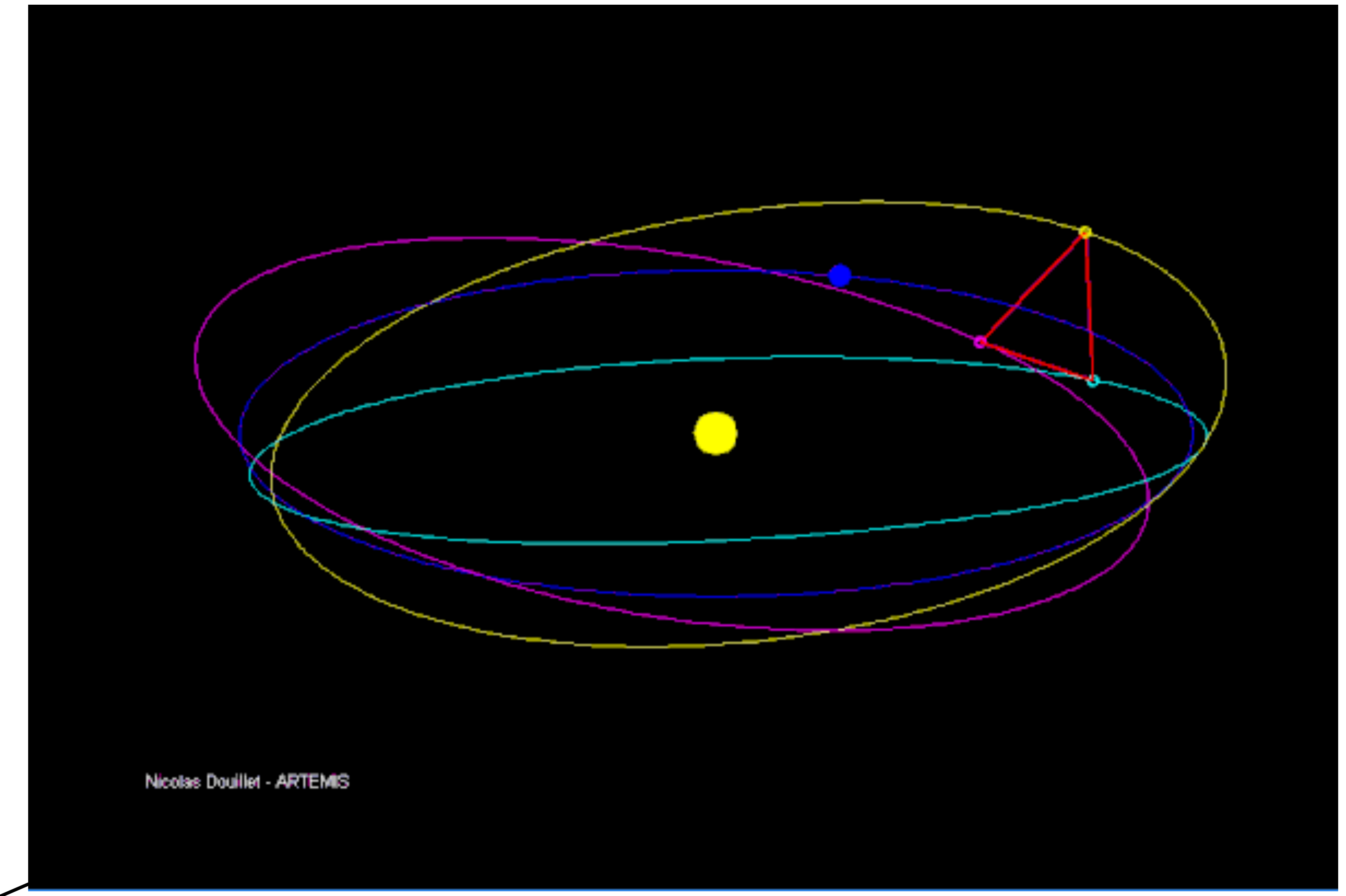
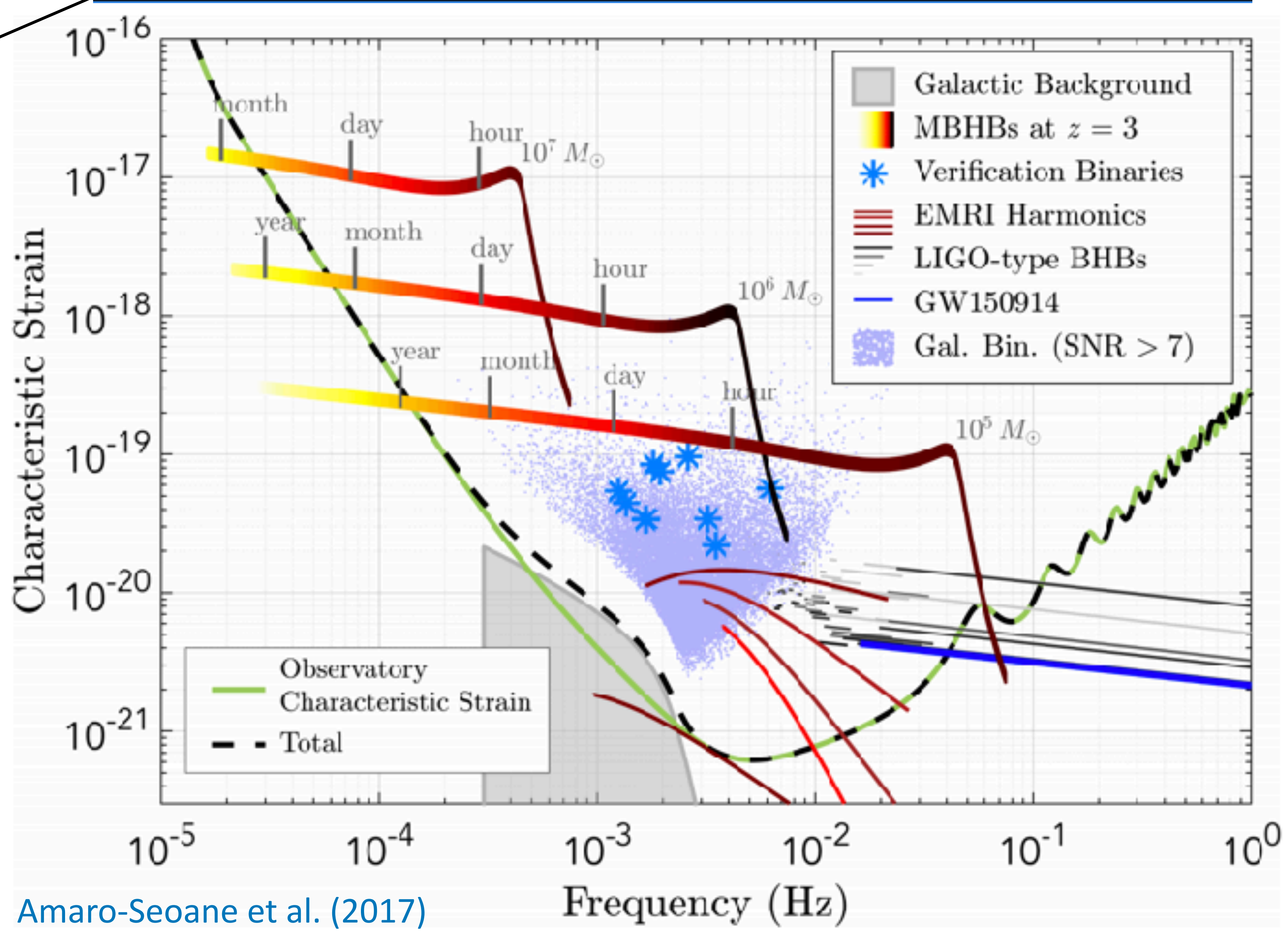
LASER INTERFEROMETER SPACE ANTENNA

- 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)

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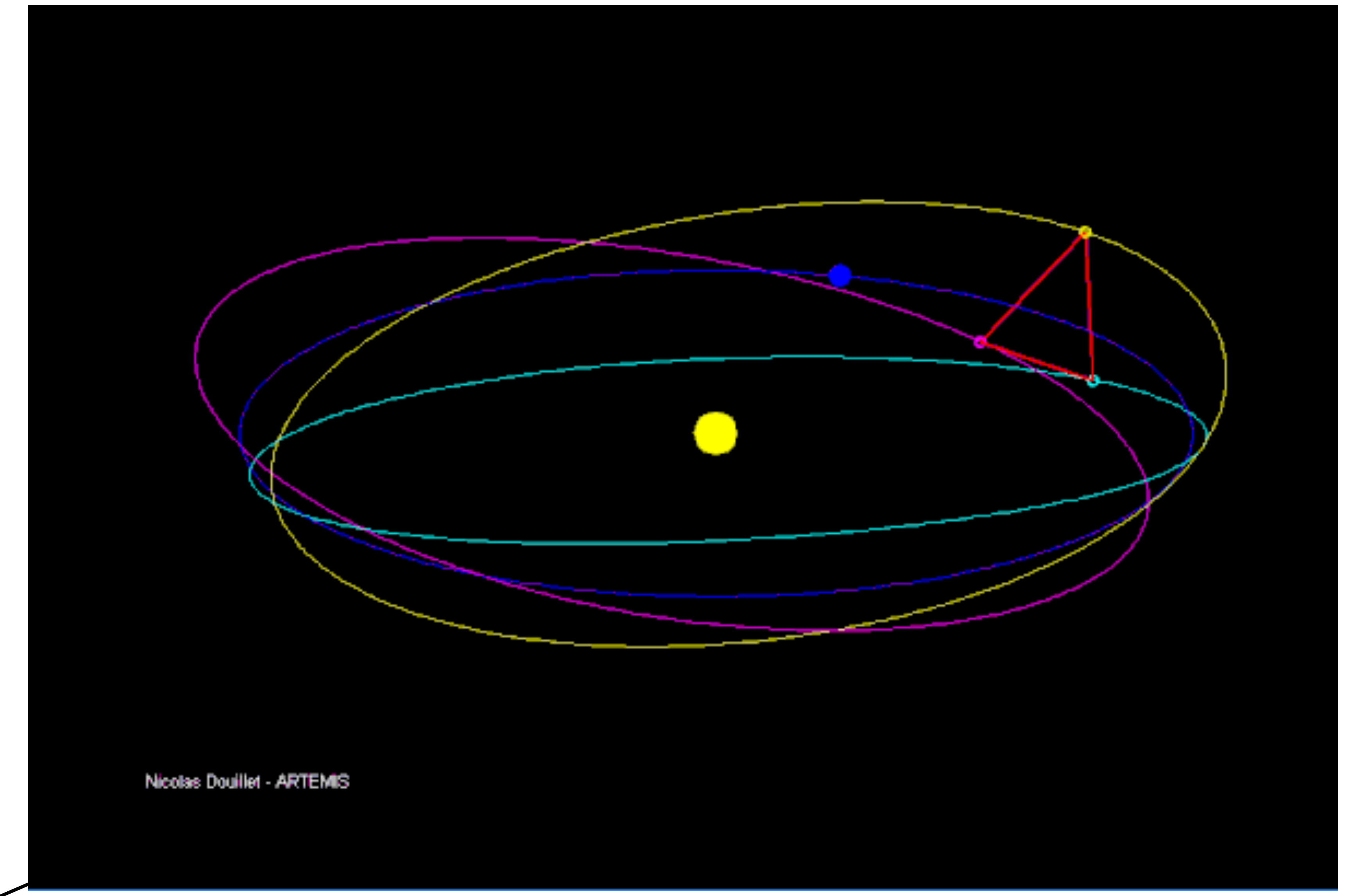
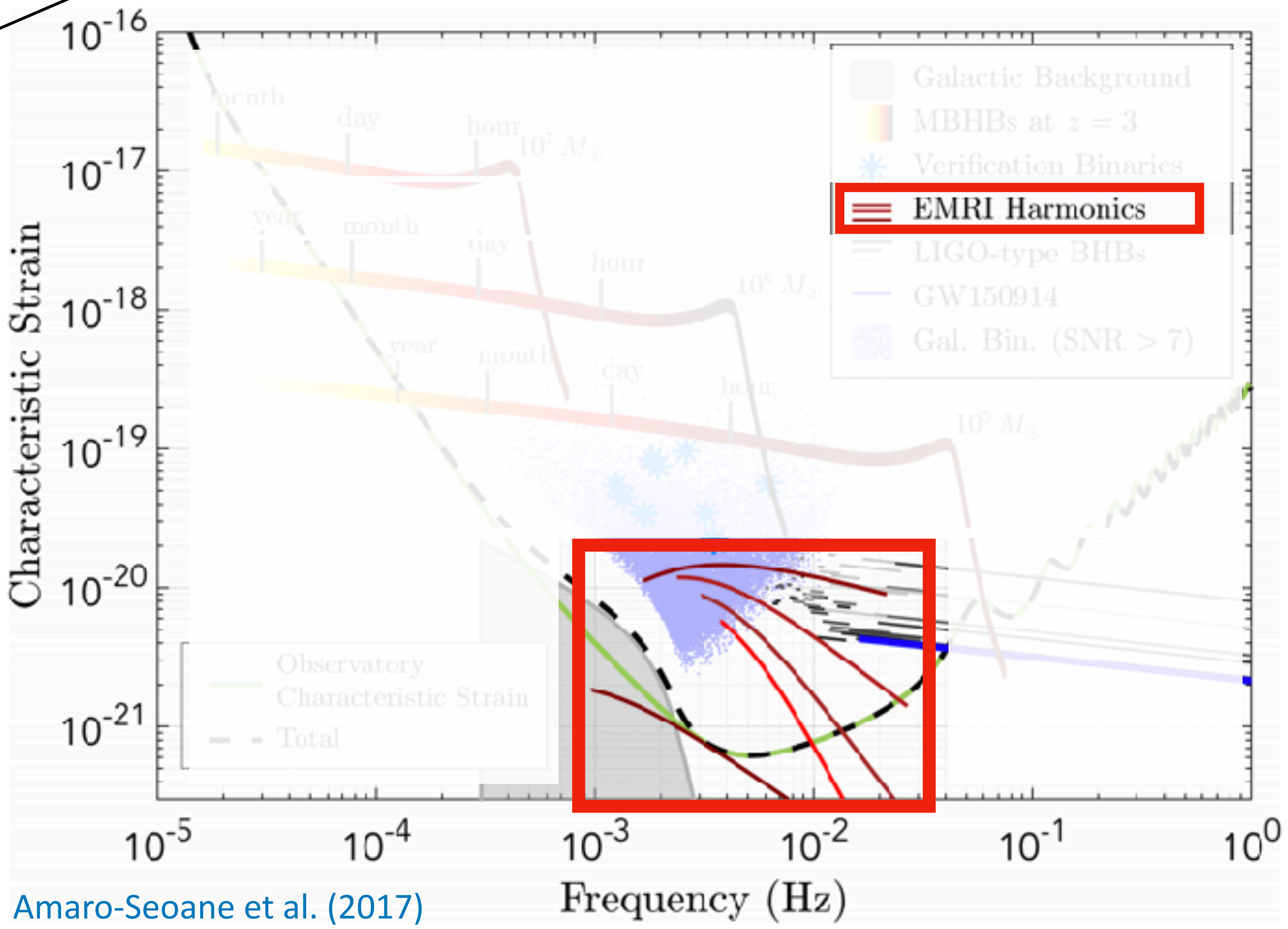




Amaro-Seoane et al. (2017)

EXTREME MASS-RATIO INSPIRALS

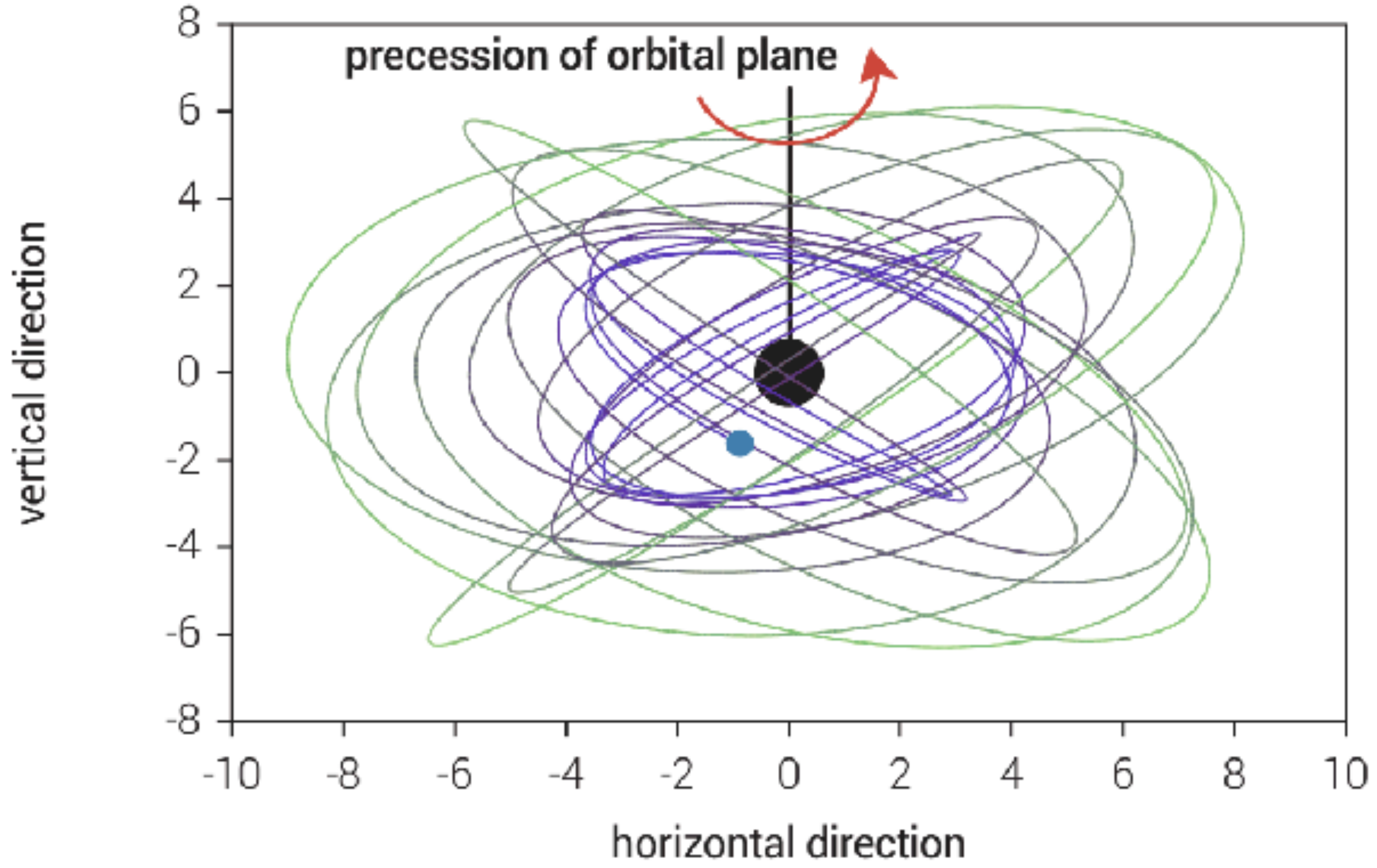
Binary systems with **mass-ratio** $q \sim 10^{-6} - 10^{-3}$

- **Massive BH** $(10^4\, M_\odot - 10^7\, M_\odot)$
- **Compact object** $(10\, M_\odot)$

Slow inspiral, $10^4 - 10^5$ orbital cycles in the final year before plunge

✅ **Extremely accurate** measurements of the system parameters

❌ No EM counterpart



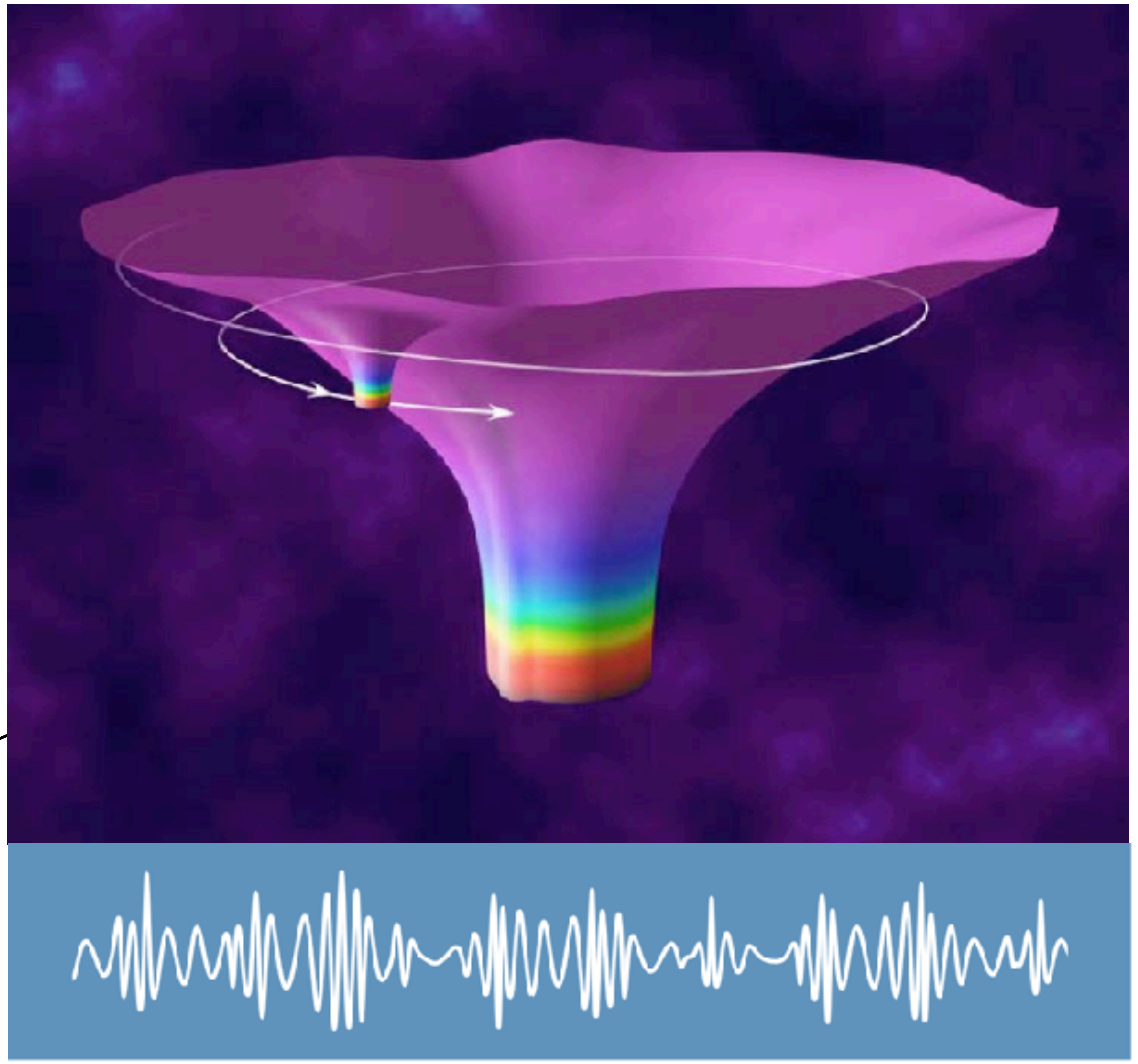


Figure 4: An artist's impression of the spacetime of an extreme-mass-ratio inspiral and a representative waveform of the expected gravitational waves. A smaller black hole orbits around a supermassive black hole. *Credit: NASA.*

eLISA White Paper, arXiv:1305.5720

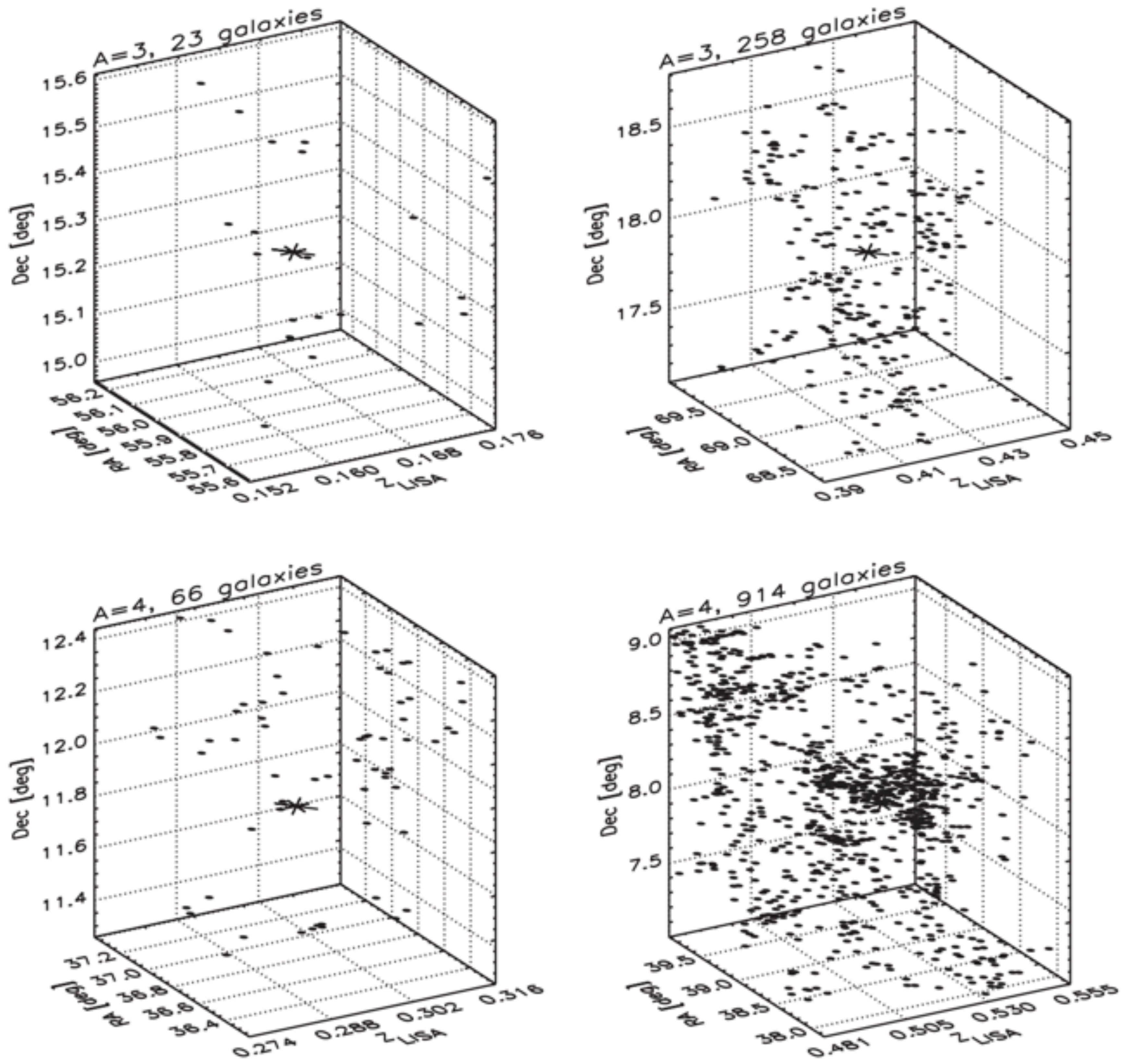
PREVIOUS STUDIES

Macleod, Hogan, *PRD* (2008):

H_0 at 1% with 20 EMRIs at $z < 0.5$

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)

EMRIs AS DARK STANDARD SIRENS

Measure
EMRI GW

Measure
galaxy redshifts

Obtain
d_L and (θ, ϕ)

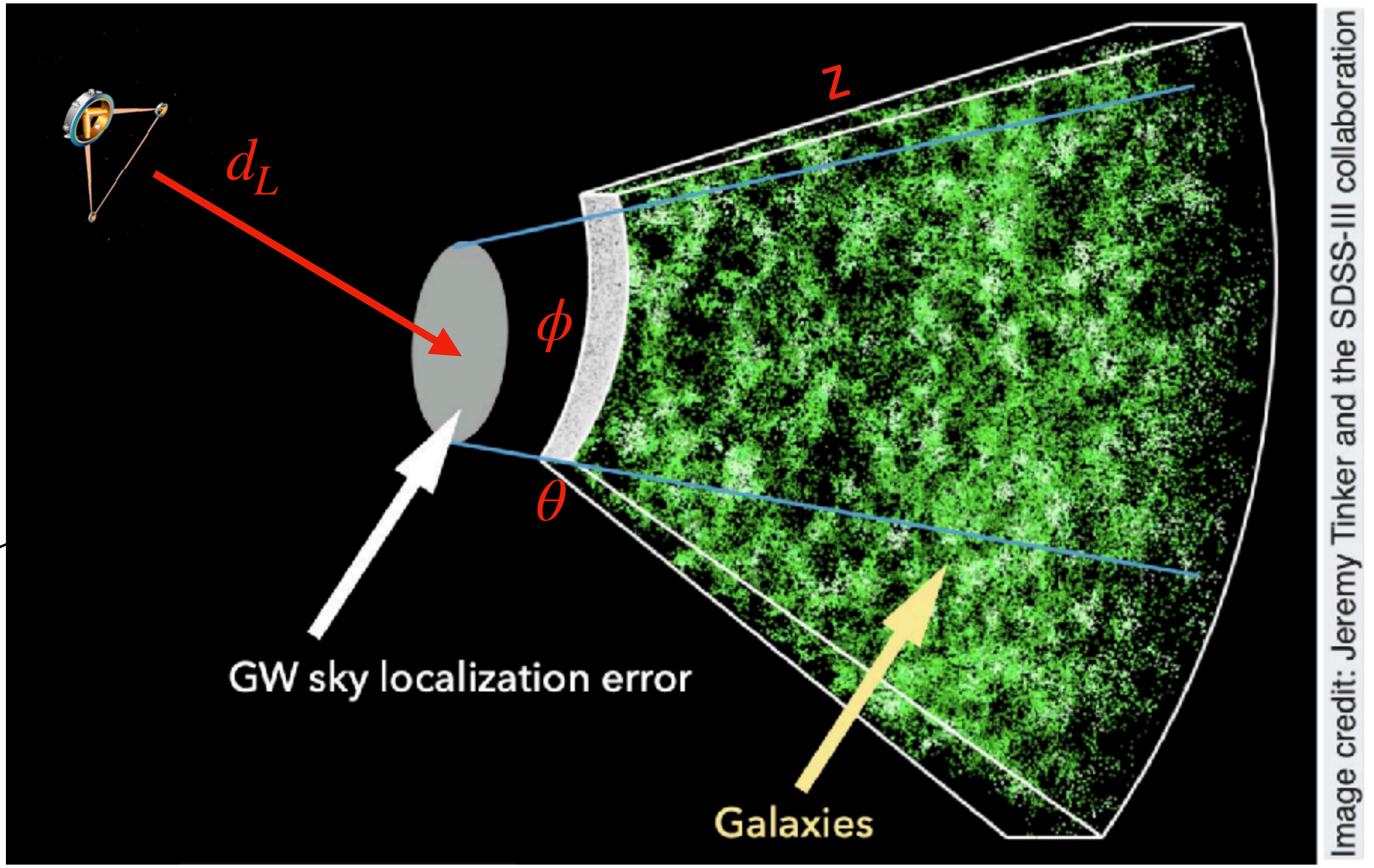
cross-match

Obtain
galaxy catalog

Estimate
EMRI redshift

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

Bayesian analysis → Measure Ω



HOW MANY EMRIs WILL WE OBSERVE?

EMRI rates span 2-3 orders of magnitudes, reflecting variations in:

- MBH population: semi-analytic models, realistic/pessimistic
- Stellar clusters distributions around MBHs
- EMRI's orbit parameters
- …

Model	Mass function	MBH spin	Cusp erosion	M–σ relation	N_p	CO mass $[M_\odot]$	EMRI rate $[\mathrm{yr}^{-1}]$ Total	Detected (AKK)	Detected (AKS)
M1	Barausse12	a98	yes	Gultekin09	10	10	1600	294	189
M2	Barausse12	a98	yes	KormendyHo13	10	10	1400	220	146
M3	Barausse12	a98	yes	GrahamScott13	10	10	2770	809	440
M4	Barausse12	a98	yes	Gultekin09	10	30	520 (620)	260	221
M5	Gair10	a98	no	Gultekin09	10	10	140	47	15
M6	Barausse12	a98	no	Gultekin09	10	10	2080	479	261
M7	Barausse12	a98	yes	Gultekin09	0	10	15800	2712	1765
M8	Barausse12	a98	yes	Gultekin09	100	10	180	35	24
M9	Barausse12	aflat	yes	Gultekin09	10	10	1530	217	177
M10	Barausse12	a0	yes	Gultekin09	10	10	1520	188	188
M11	Gair10	a0	no	Gultekin09	100	10	13	1	1
M12	Barausse12	a98	no	Gultekin09	0	10	20000	4219	2279

Babak et al., PRD (2017)

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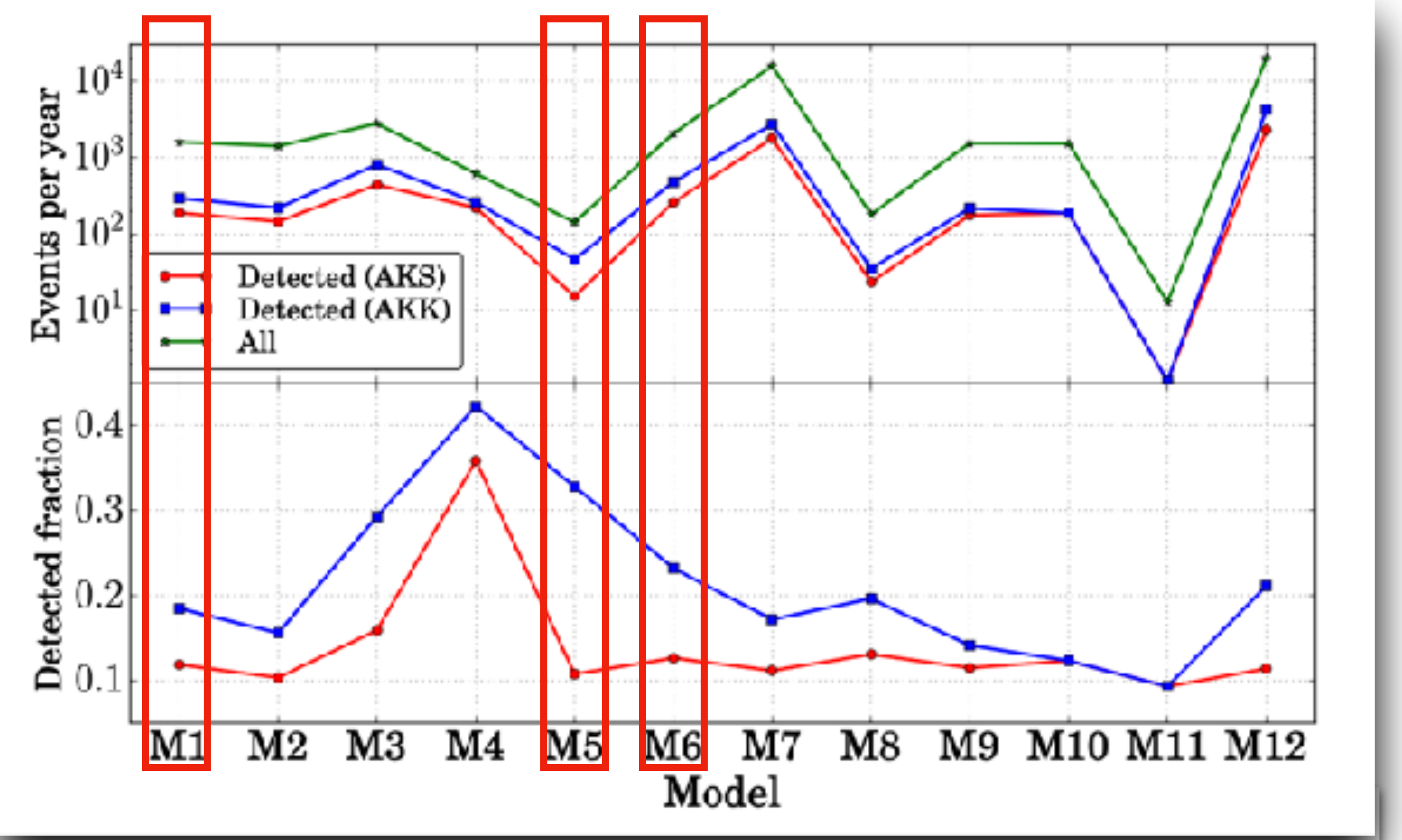

fiducial → M1
pessimistic → M5
optimistic → M6

Model	Mass function	MBH spin	Cusp erosion	M–σ relation	N_p	CO mass $[M_\odot]$	EMRI rate $[yr^{-1}]$ Total	Detected (AKK)	Detected (AKS)
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M12	Barausse12	a98	no	Gultekin09	0	10	20000	4219	2279

Babak et al., PRD (2017)

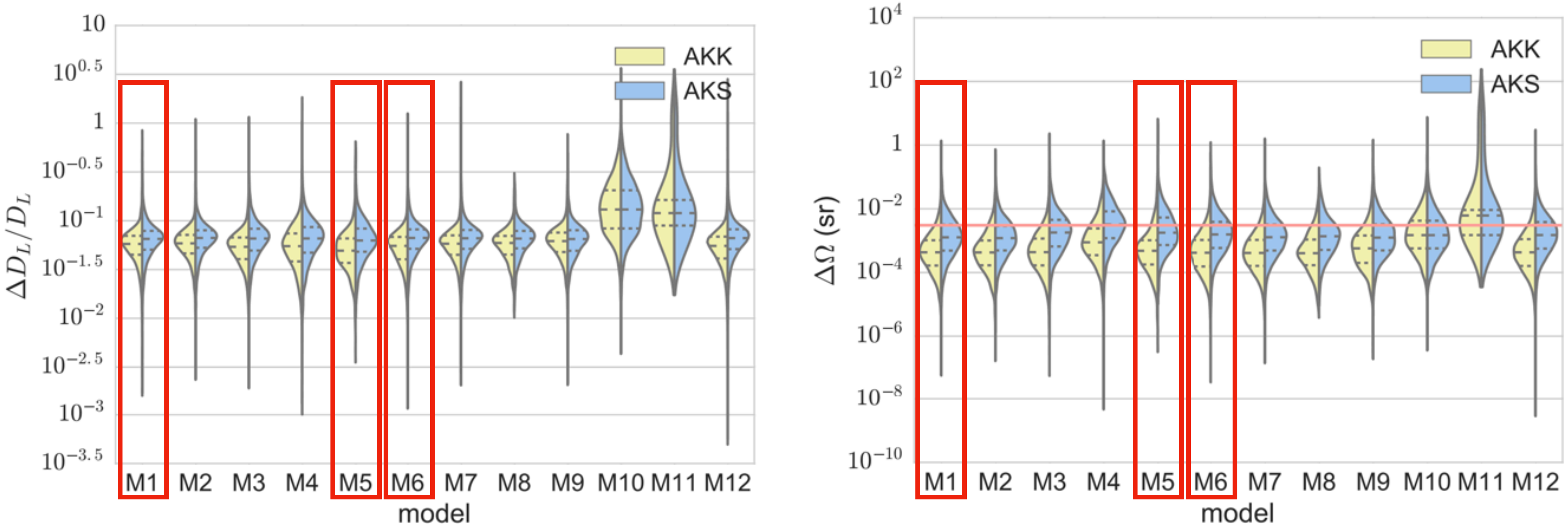
HOW WELL CAN WE LOCALIZE EMRIs?

EMRI PE: catalogs of Babak et al. provide **best** estimates and **uncertainties** for:

$$d_L \pm \sigma_{d_L} \qquad \phi \pm \sigma_\phi \qquad \theta \pm \sigma_\theta$$

$\Delta d_L / d_L \sim 10^{-1}$

$\Delta\Omega/\Omega \sim 10 \text{ deg}^2$



Babak et al., PRD (2017)

ERROR-BOXES

Flux-limited, full-sky galaxy simulations of
Henriques et al., *MNRAS* (2012)
based on the **Millennium Run**

Springel et al., *Nature* (2005)

- For a given cosmology:

$$\hat{d}_L \pm \Delta \hat{d}_L \longrightarrow z \pm \Delta z$$

- Assuming cosmological priors:

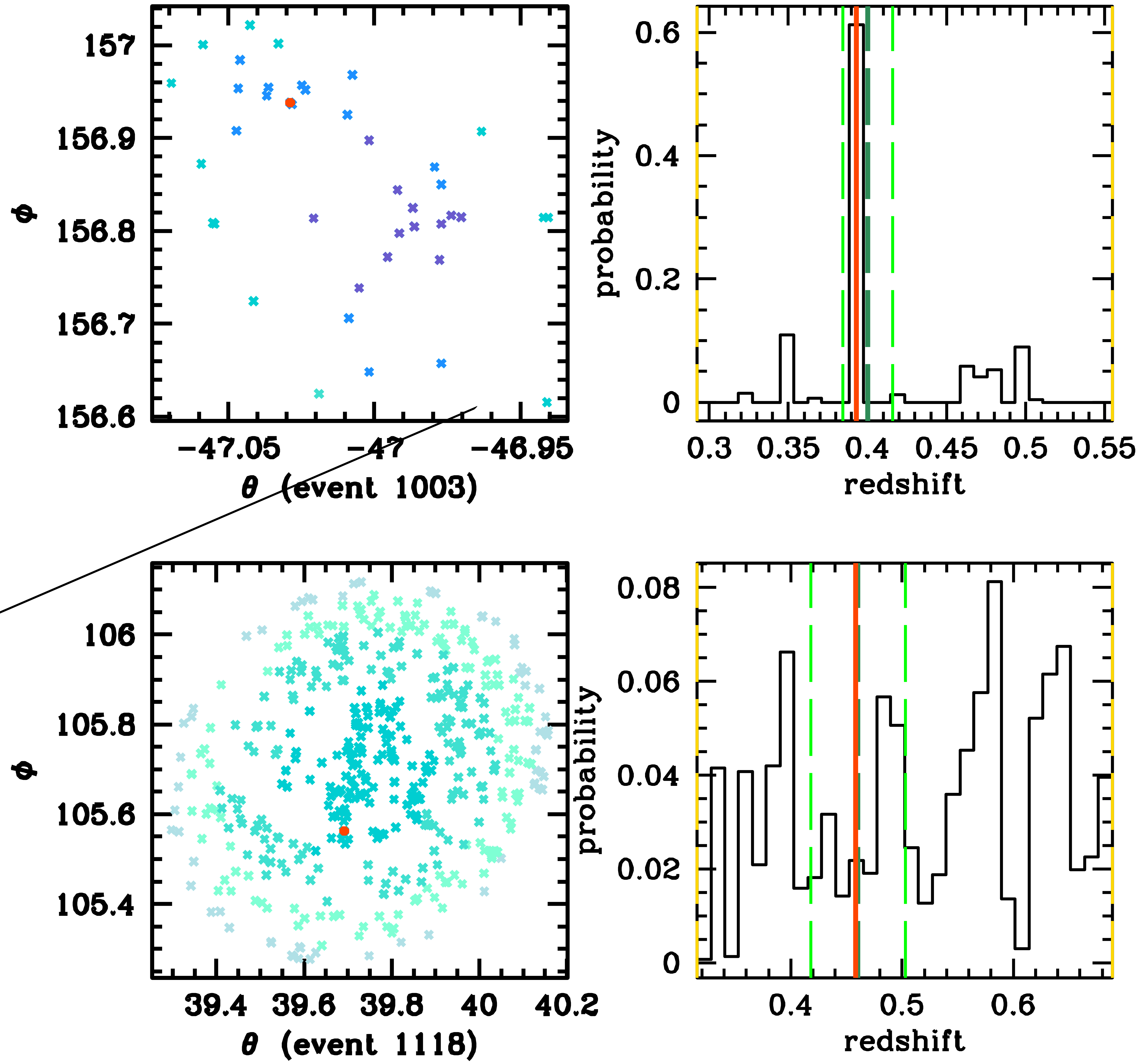
$$[z^-, z^+]$$

- Accounting for galaxy peculiar velocities:

$$[z^- - \Delta z^-_{v_p}, z^+ + \Delta z^+_{v_p}]$$

- EMRI error box:

$$\Delta\Omega_{sky} \times [z^- - \Delta z^-_{v_p}, z^+ + \Delta z^+_{v_p}]$$

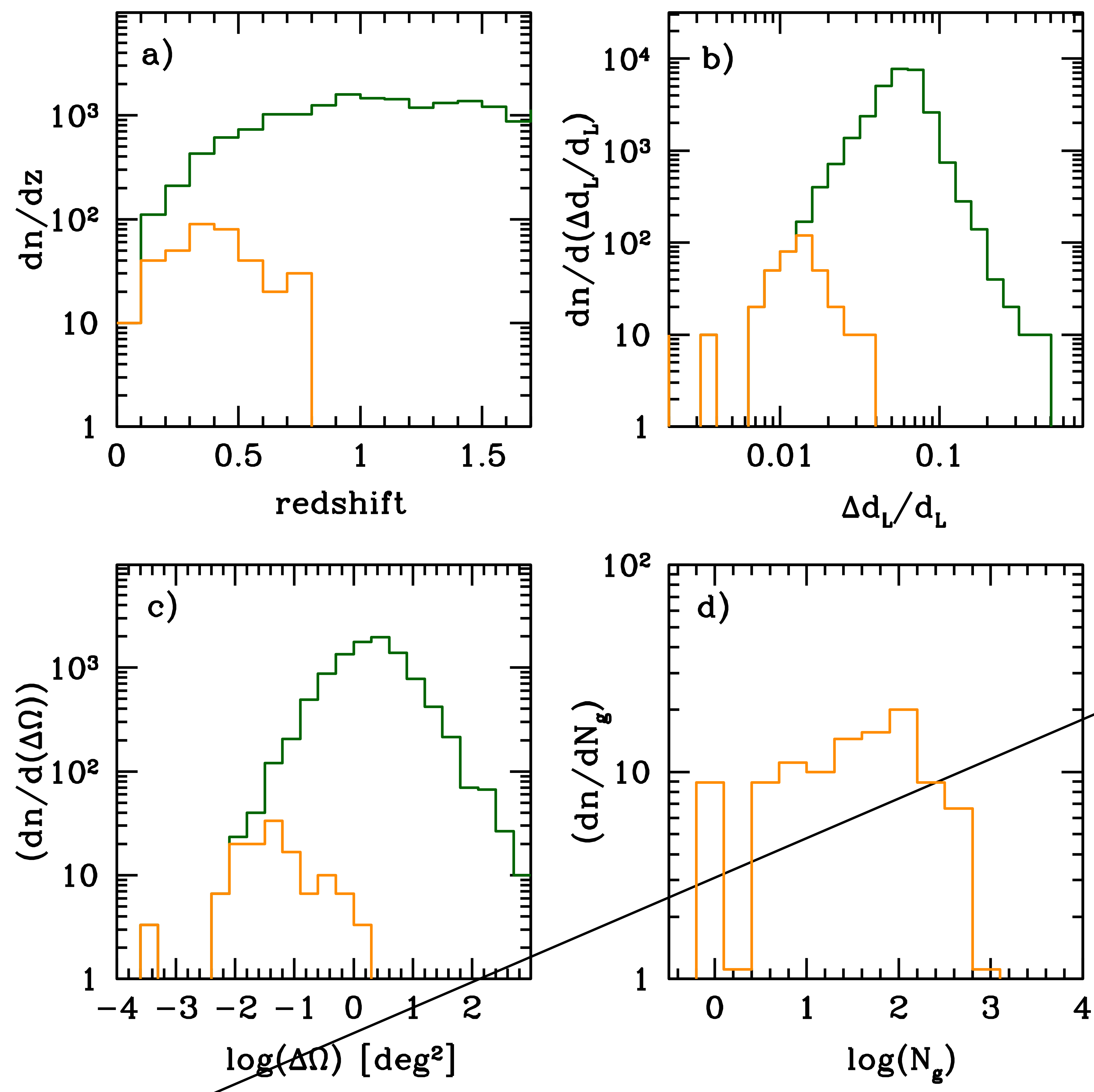


Laghi et al., *MNRAS* (2021)

SELECTING EVENTS

Green: 10yrs 3k EMRIs!

M1 model



number of candidate hosts within the 3D error volume

Laghi et al., *MNRAS* (2021)

SELECTING EVENTS

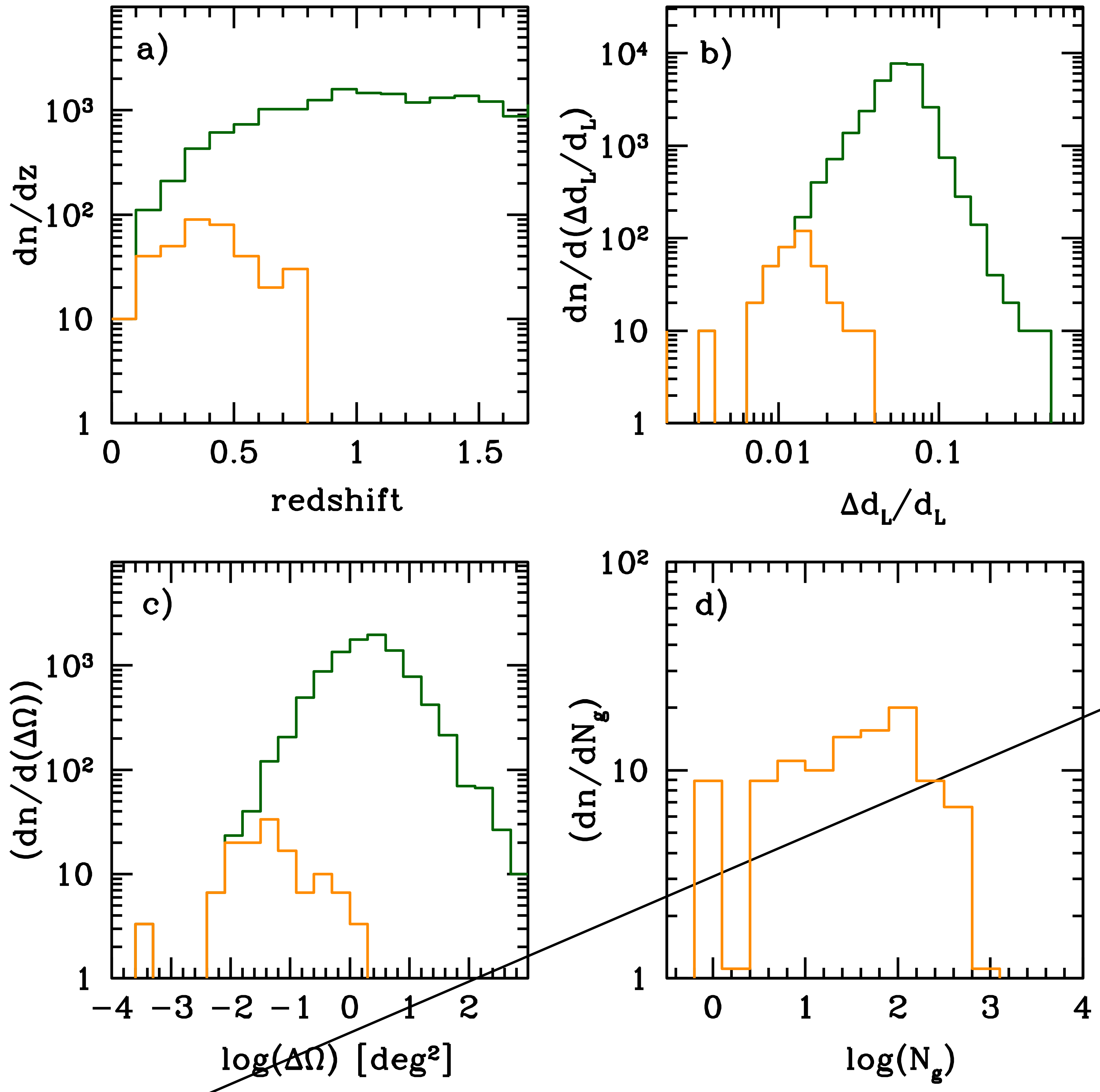
$\Delta d_L / d_L \lesssim 0.04$

$\Delta\Omega_{sky} \lesssim 2\ \mathrm{deg}^2$

Green: 10yrs 3k EMRIs!

Orange: 10yrs & SNR>100

M1 model



number of candidate hosts within the 3D error volume

Laghi et al., *MNRAS* (2021)

Require **SNR>100**:

- Well-localised, most-informative events
- Few hosts per error-box

(SNR>100)	Events
M5 (pessimistic)	O(5)
M1 (fiducial)	O(30)
M6 (optimistic)	O(70)

BAYESIAN INFERENCE

Cosmological prior

Quasi-likelihood

$$p(\Omega \,|\, D\, \mathscr{H}\, I) \;\propto\; p(\Omega \,|\, \mathscr{H}\, I)\, p(D \,|\, \Omega\, \mathscr{H}\, I)$$

D = GW data $\mathscr{H}$ = cosmological model I = any information available

BAYESIAN INFERENCE

Cosmological prior

Quasi-likelihood

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

cosmological model:

Flat FLRW metric

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

GW redshift prior:

LISA 3D error volume
+
galaxy catalog

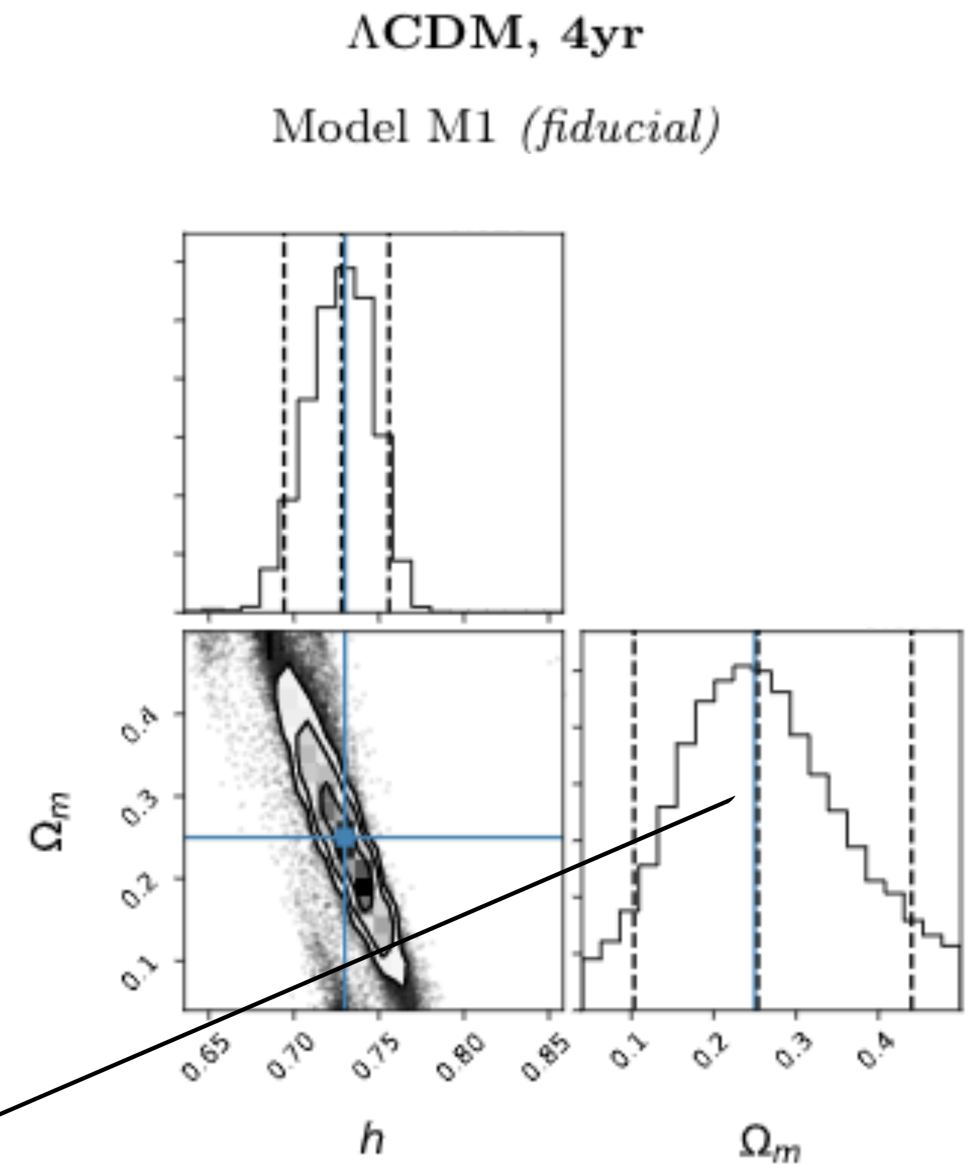
LISA likelihood:

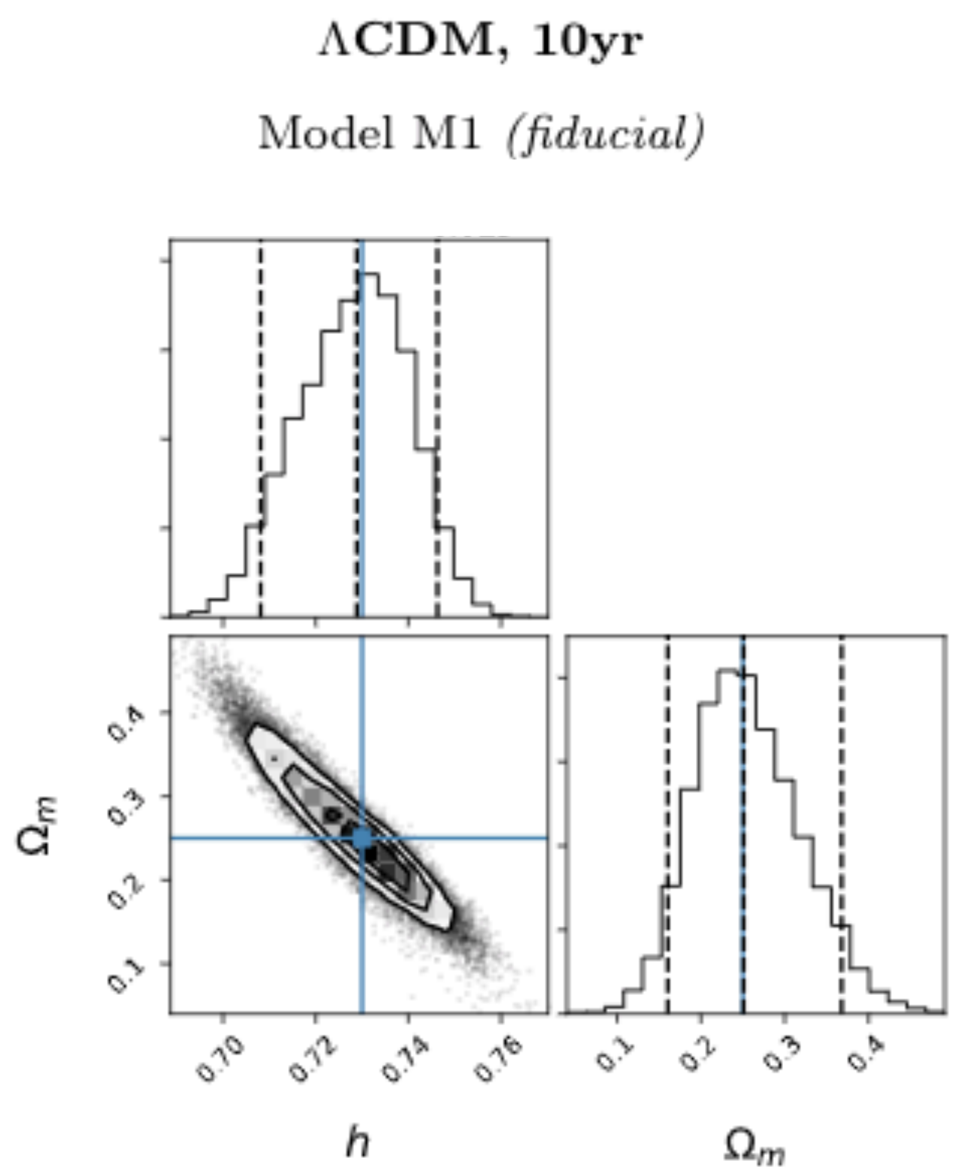
3D Gaussian distribution
(from EMRI PE)

D = GW data $\mathscr{H}$ = cosmological model I = any information available

RESULTS: ΛCDM

EMRIs will be excellent probes of H_0



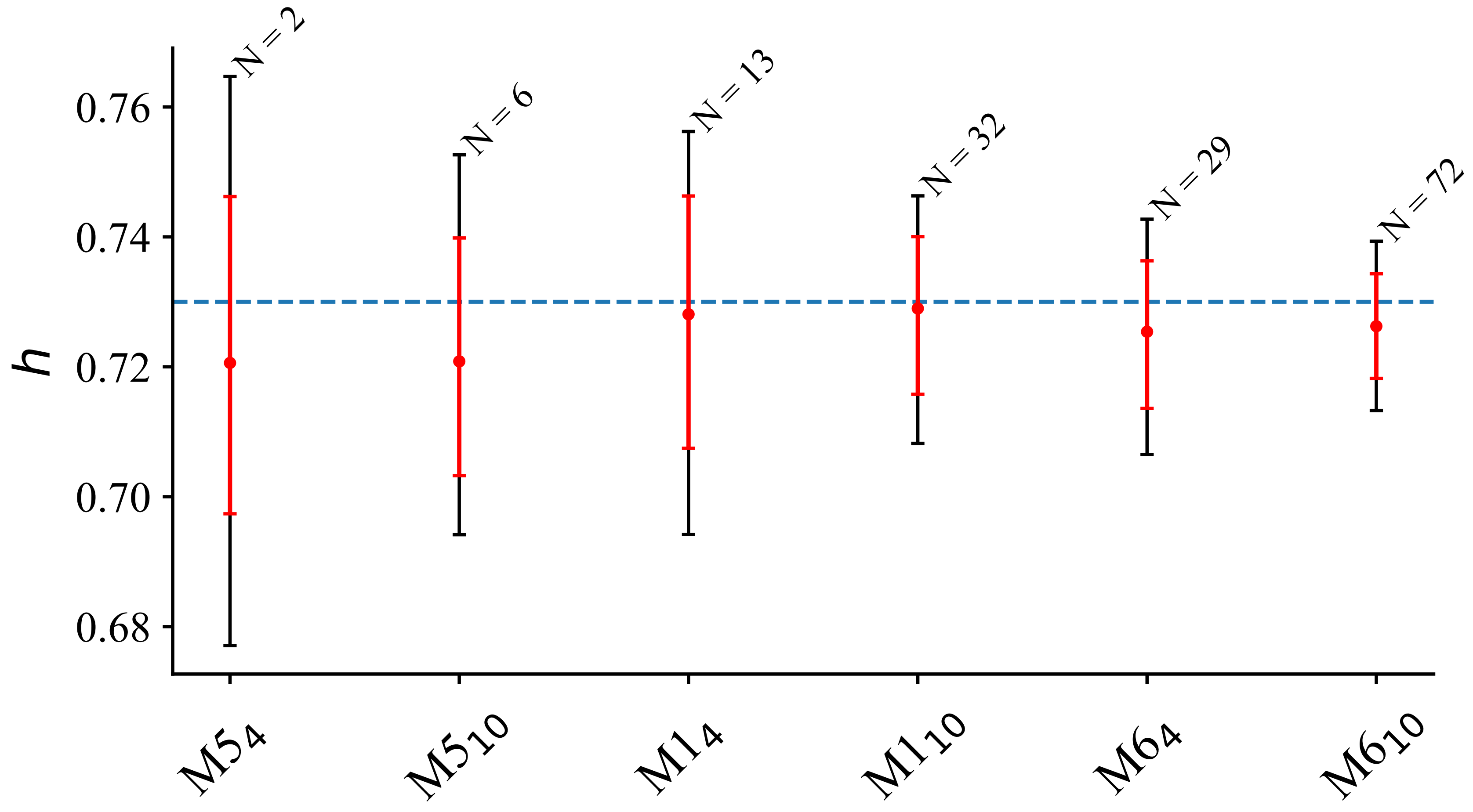


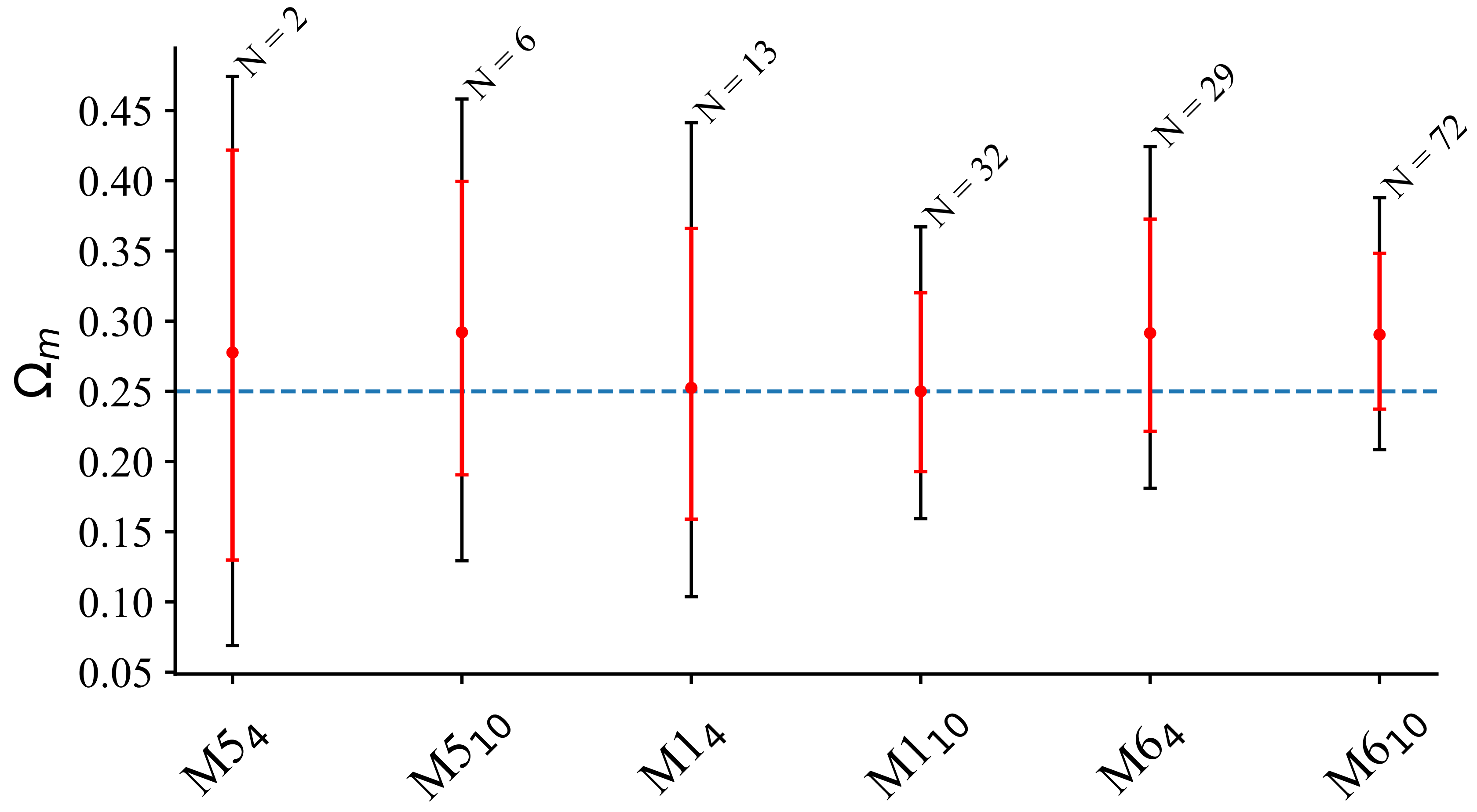
h accuracy (90% CI)

1-6%

Ω_m accuracy (90% CI)

25% at most





Analysis done with **`cosmoLISA`**

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

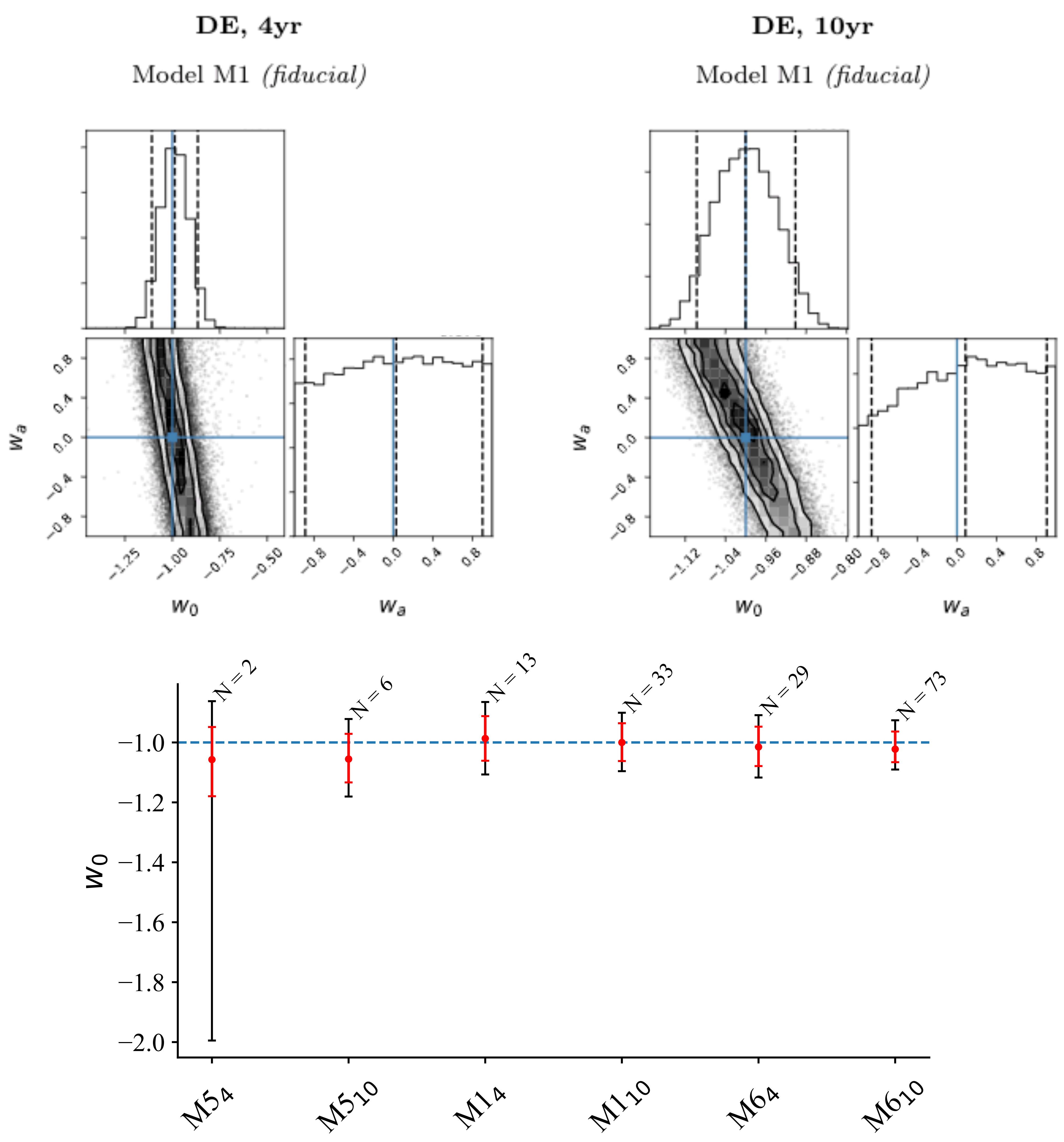
$h = H_0/100\,\mathrm{km}^{-1}\mathrm{s\,Mpc}$

RESULTS: DE

EMRIs can constrain w_0

$$w(z) = w_0 + w_a z/(1+z)$$

w_0 accuracy (90% CI)
10% at most



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Laghi et al., *MNRAS* (2021)

ANOTHER LISA CBC SOURCE: MASSIVE BLACK HOLE BINARIES

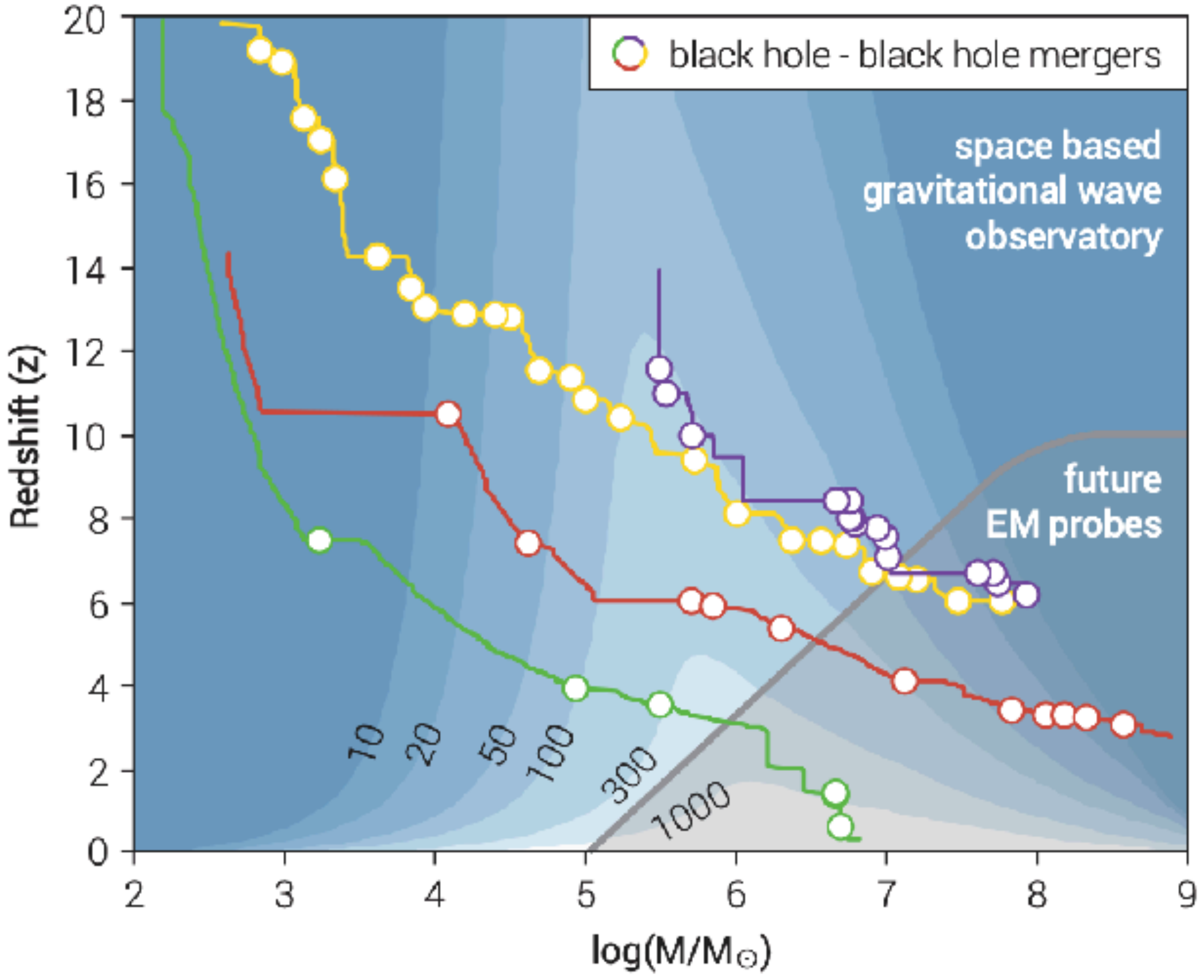


Figure 2: Constant-contour levels of the sky and polarisation angle-averaged SNR for eLISA, for equal mass non-spinning binaries as a function of their total rest frame mass, *M*, and cosmological redshift, *z*. The tracks represent the mass-redshift evolution of selected supermassive black holes: two possible evolutionary paths for a black hole powering a $z \sim 6$ QSO (starting from a massive seed, blue curve, or from a Pop III seed from a collapsed metal-free star, yellow curve); a typical $10^9\,M_\odot$ black hole in a giant elliptical galaxy (red curve); and a Milky Way-like black hole (green curve). Circles mark black hole-black hole mergers occurring along the way. These were obtained using state of the art semi-analytical merger tree models [65]. The grey transparent area in the bottom right corner roughly identifies the parameter space for which massive black holes might power phenomena that will likely be observable by future electromagnetic probes.

eLISA White Paper, arXiv:1305.5720

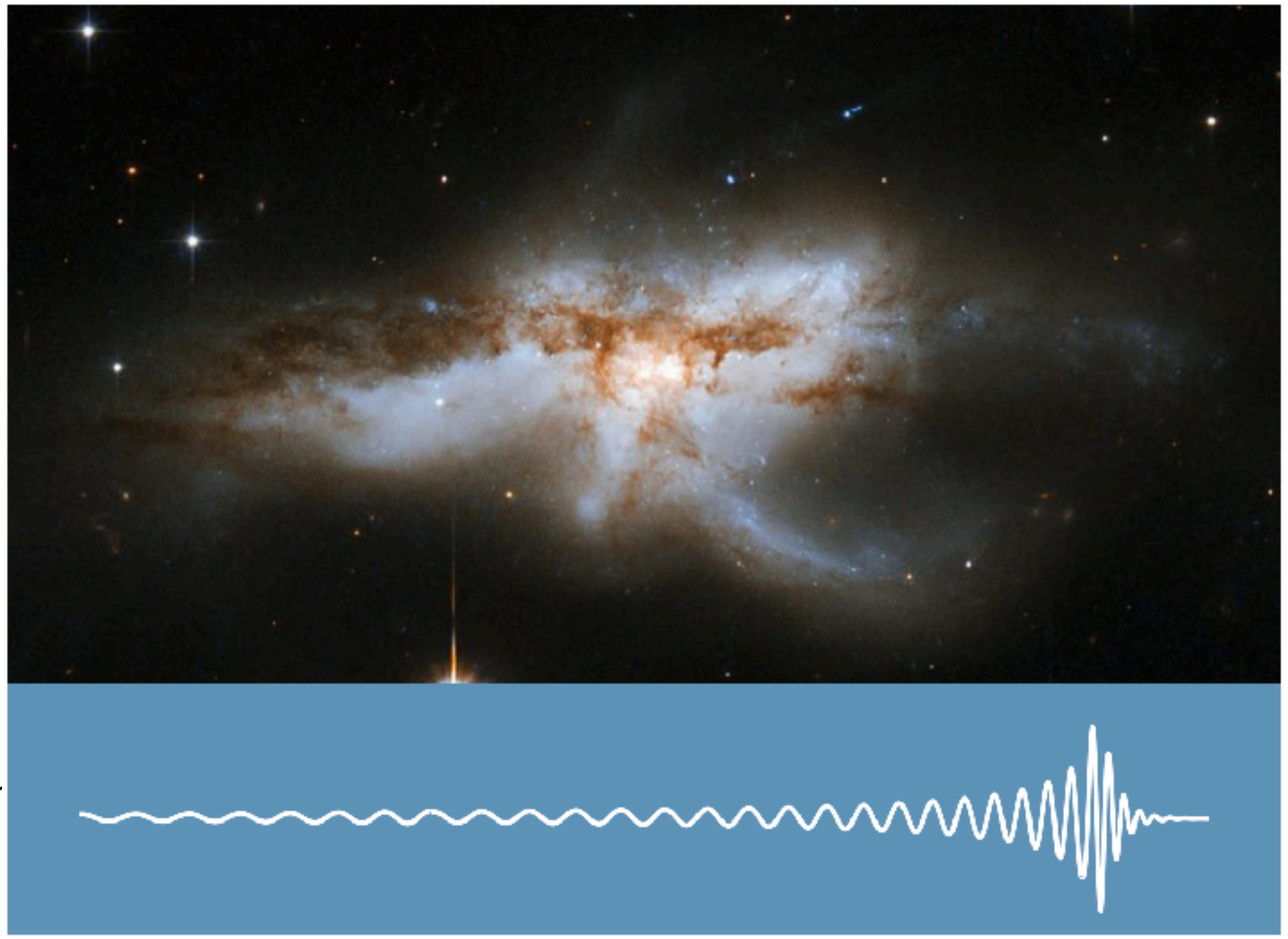


Figure 1: Merging galaxy NGC 6240 and a representative waveform of the expected gravitational waves from the coalesence of two super-massive black holes. Observations with NASA's Chandra X-ray observatory have disclosed two giant black holes inside NGC 6240. They will drift toward one another and eventually merge into a larger black hole. *Credit: NASA, ESA, the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University).*

MBHBs AS BRIGHT STANDARD SIRENS

Measure
MBHB GW

↓

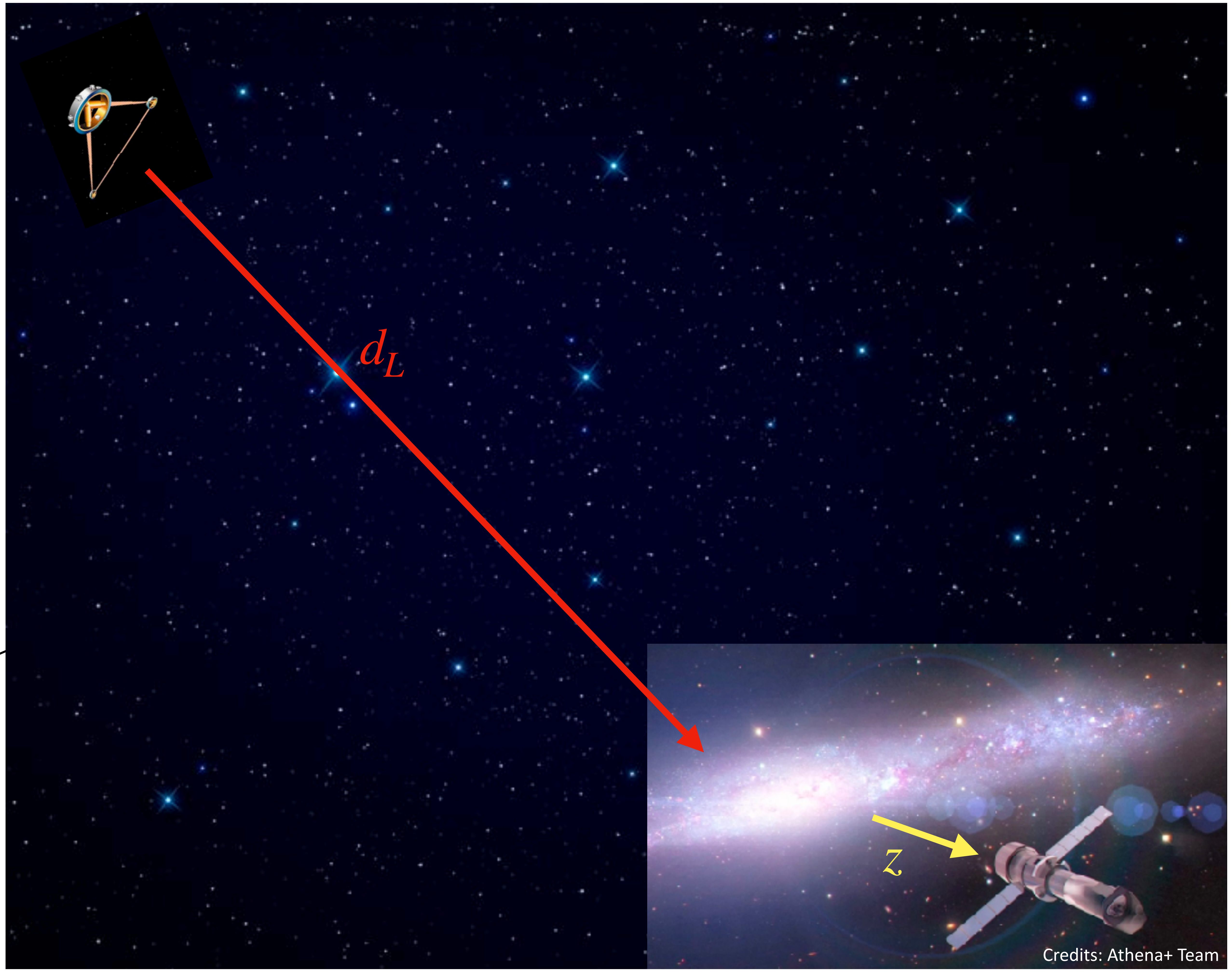
Obtain
d_L and (θ, ϕ) → Measure
EM counterpart

↓

Obtain
redshift

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

→ **Bayesian analysis** → Measure Ω

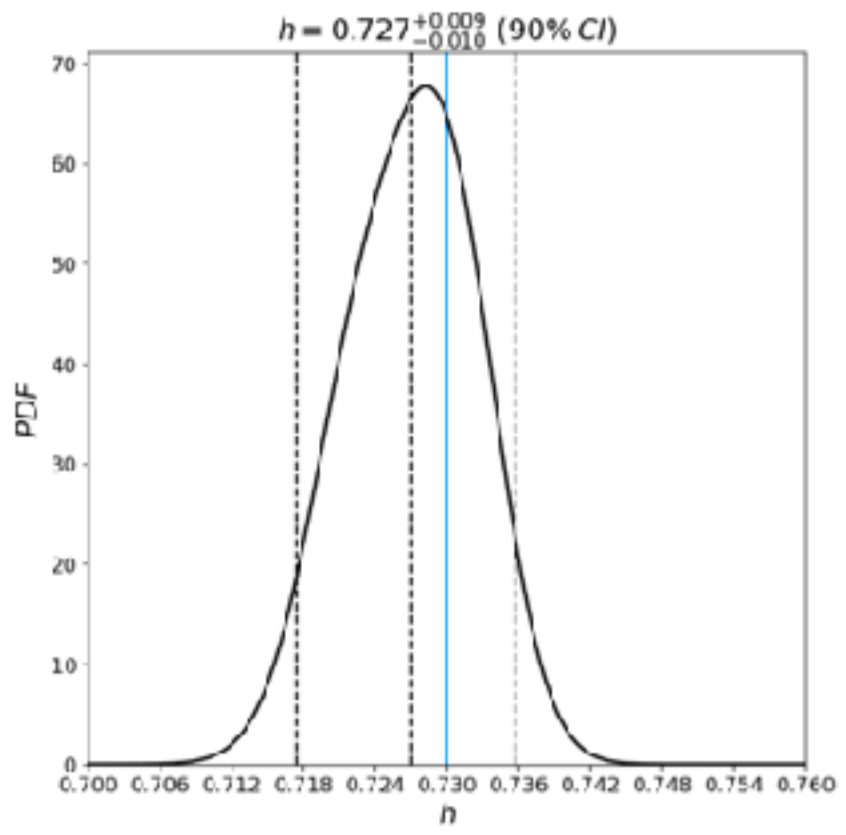


EMRIs + MBHBs FOR 10 YEARS OF OBSERVATION

Massive Black Hole Binaries with EM counterpart:

Klein et al., PRD (2015)

Tamanini et al., JCAP (2016)



(**EMRIs** & **galaxy catalog**)

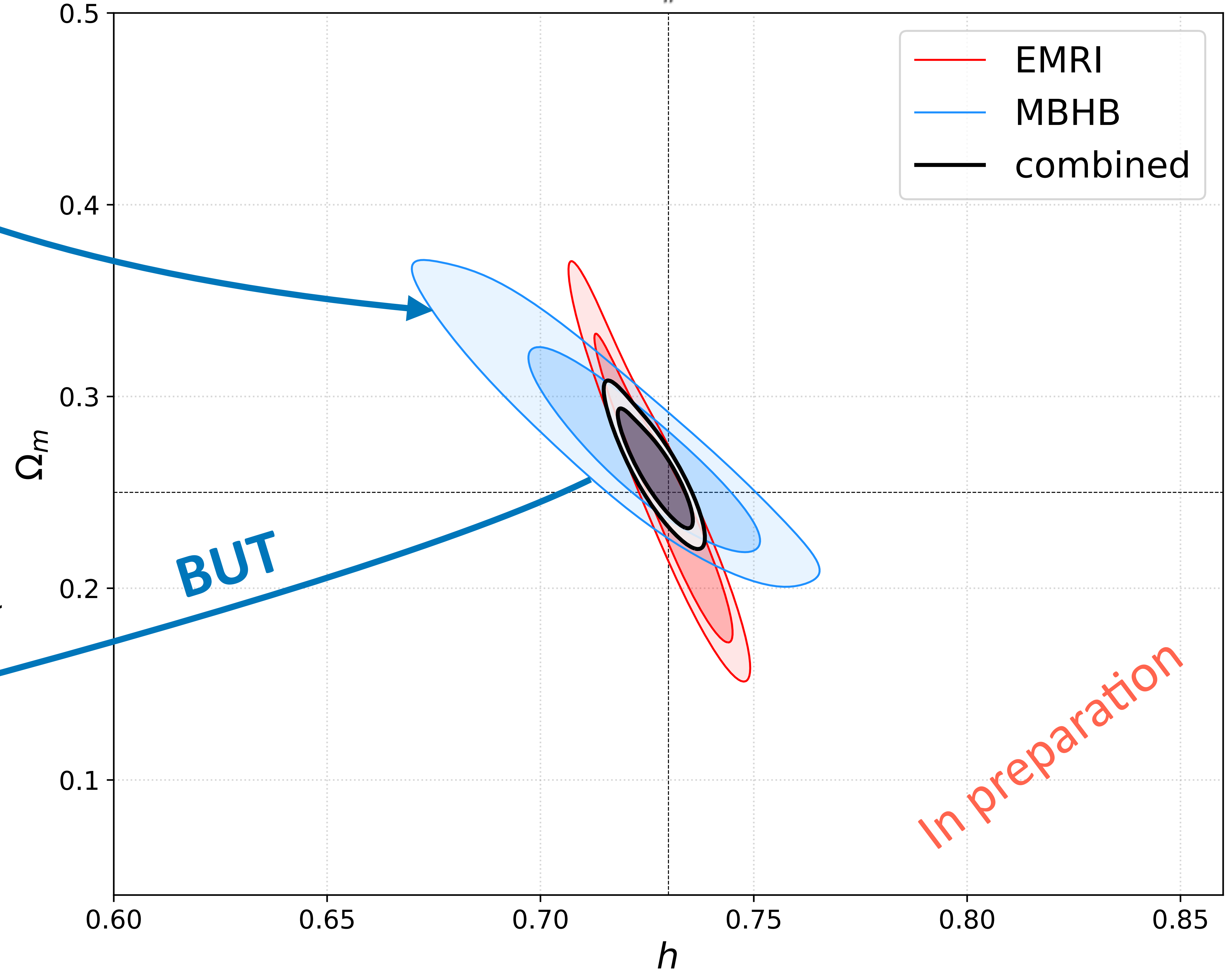
\+

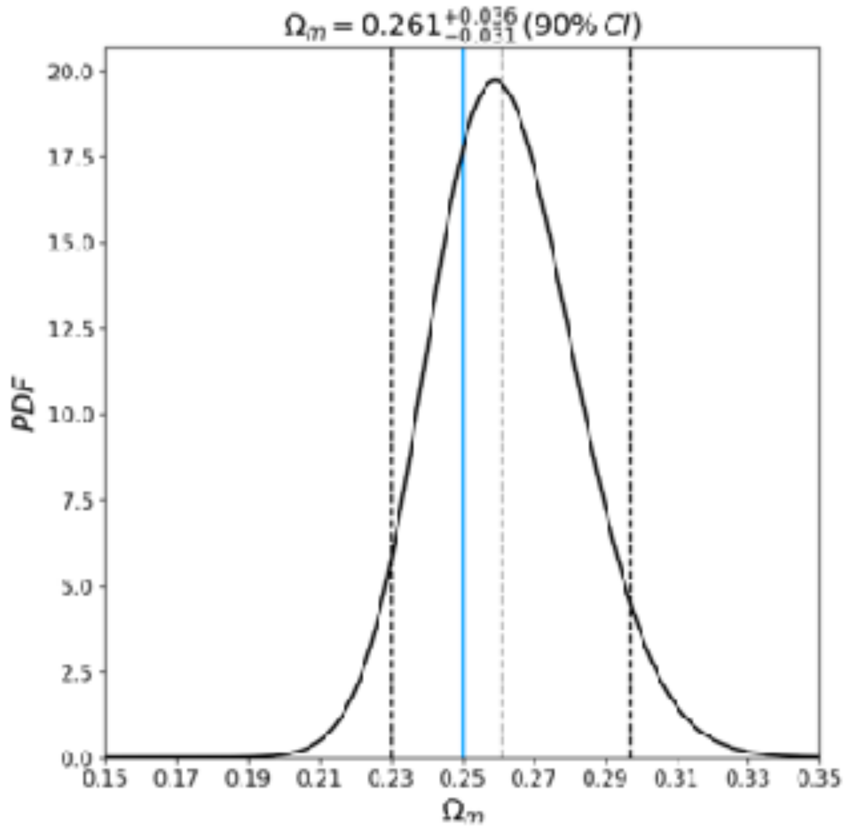
(**MBHBs** & **EM counterpart**)

=

H_0 (1%)

Ω_m (15%)





See A. Mangiagli's talk
for new MBHB rate estimates

LISA COSMOLOGICAL ENCHILADA