Testing cosmological models with massive black hole binaries

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Septième Assemblée Générale du GdR Ondes Gravitationnelles, 16th October 2023, LUTH

What are massive black holes (MBHs)?

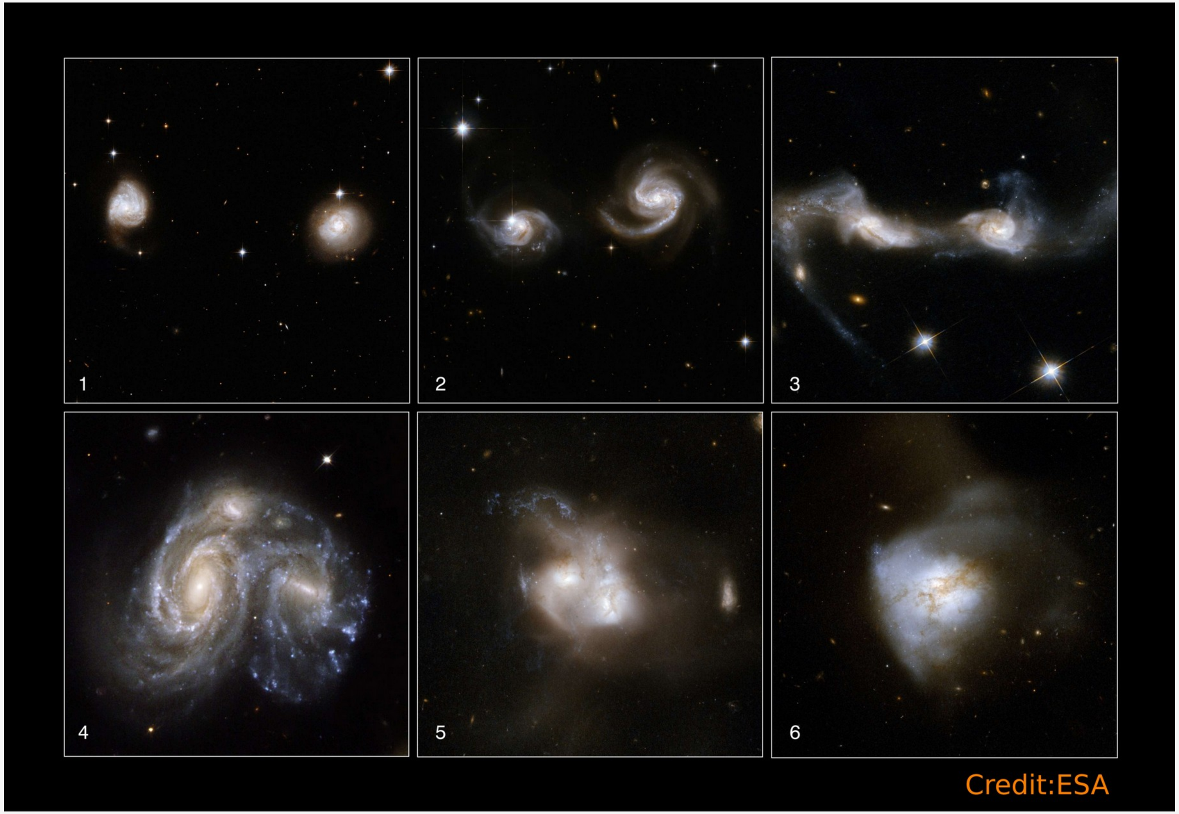
We currently believe that MBHs are hosted at the center of galaxies with masses up to $\sim 10^9 - 10^{10}\ M_\odot$

For today talk, let's focus on the interval

$$M_{BH} \sim 10^{4\text{-}7} M_\odot$$

From single MBH to binaries

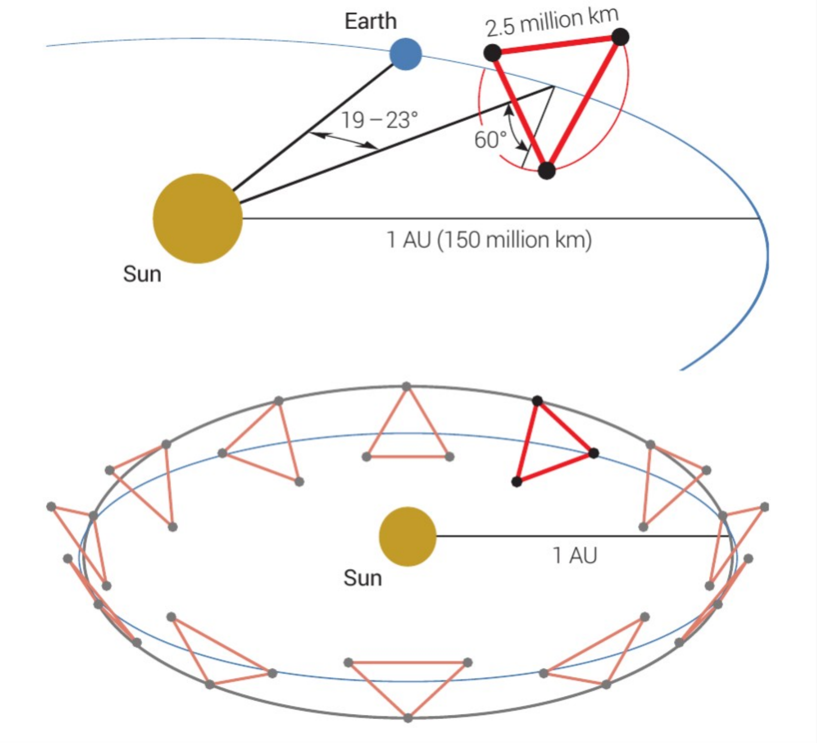
When two galaxies merge, the MBHs in their center form a binary and merge emitting gravitational waves (GWs) and electromagnetic (EM)/particles radiation

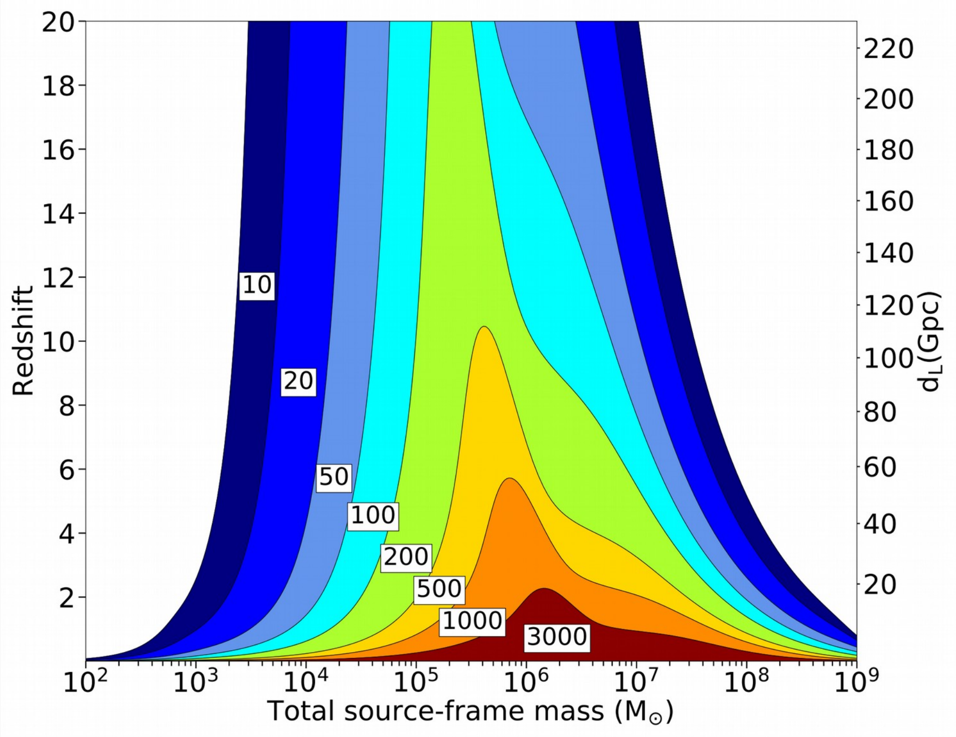


Observing the entire Universe with GWs

In mid-2030s LISA (Laser Interferometer Space Antenna) will observe the GWs from the coalescence of MBHBs in the entire Universe (ArXiv:1702.00786)

- ➤ 3rd Large class mission selected by European Space Agency (ESA)
- ➤ Now in Phase B1 - Mission adoption in January 2024





MBHBs : new cosmological probes

The Λ-Cold Dark Matter (ΛCDM) is the most common cosmological parametrization:

- ✓ Simple model with good fit to the bulk of data
- ✗ Current tensions :
  - Early Universe: Cosmic Microwave Background (CMB) observations at $z > 1000$
  - Late Universe: SNIa, lensed images at $z \sim 2.5$

We need new models and new probes!

Standard sirens are new cosmological probes

- Direct information on d_L → No calibration errors and no intrinsic scatter
- Independent from CMB or SNIa → Independent estimates

Bright sirens, i.e. **Redshift information from the EM counterpart**

Cosmology with MBHBs

What constrains can we put on the expansion of the Universe at high redshift with bright MBHBs?

Key improvements respect to previous works (Tamanini+16)

- Improve the modeling of the EM counterpart
- Bayesian analysis for GW signal (Marsat+20) → expensive but realistic
- Bayesian cosmological inference

Starting point

- Semi-analytical models: tools to construct MBHBs catalogs (Barausse+12)

Three astrophysical models

Light	Heavy	Heavy-no-delays
From PopIII stars BHs ~ 10^3 $M_\odot$	From the collapse of hydrogen cloud BHs ~ $10^{4\text{-}6}$ $M_\odot$	Same as Q3d but without delay times

Constructing the population of MBHBs with EM counterpart

In AM+2207.10678 we estimate the rate of MBHBs with a detecatable EM counterpart

Observing strategies

Optical

LSST, Rubin Obs.

- FOV ~ 10 deg^2
- Identification+redshift

Radio

SKA

- FOV ~ 10 deg^2
- Redshift with ELT

X-Ray

Athena

- FOV ~ 0.4 deg^2
- Redshift with ELT

We also explored the possibility of AGN obscuration and collimated radio emission

Number of EMcp in 4 yr

- Strong decrease with obscuaration and radio jet
- Parameter estimation selects preferentially heavy models

(In 4 yr)	Standard	w Obsc./Colli. radio
Light	6.4	1.6
Heavy	14.8	3.3
Heavy-no-delays	20.7	3.5

Here we focus on the '<u>Standard</u>' case

Overview of cosmological models in our study (AM+23, in prep.)

ΛCDM Universe

- ΛCDM parametrization
  2-parameters model: (H_0, Ω_m)

Dark energy/modified gravity

- CPL parametrization for $\omega(z)$
  4-parameters model: $(H_0, \Omega_m, \omega_0, \omega_a)$
- Phenomenological Tracker model (Bull+20)
  6-parameters model: $(H_0, \Omega_m, \omega_0, \omega_\infty, z_c, \Delta z)$
  (work in progress)
- Sign-switching Λ (Akarsu+23)
  3-parameters model: $(H_0, \Omega_m, z_\dagger)$
  (work in progress)
- Phenomen. modified gravity (Belgacem+19)
  2-parameters model: (Ξ_0, n)

At high redshift

- Redshift bins approach
  Model-independent
  2-parameter models: $d_C(z_p)$, $H(z_p)$
- Matter-only approximation
  2-parameter models: $d_C(z_p)$, $H(z_p)$
- Splines interpolation
  Model-independent
  Constrain at any redshift <6

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Matter-only approximation

Fit: $d_C(z) = d_C(z_p) + 2(1+z_p))H^{-1}(z_p)\left(1 - \frac{\sqrt{1+z_p}}{\sqrt{1+z}}\right)$

with 10yr of LISA observations

(in 4yr)	$z_p = 2,\ z > 1$	$z_p = 3,\ z > 1.5$
Light	5.3	4.4
Heavy	12.5	10.9
Heavy-no-delays	17.3	14.5

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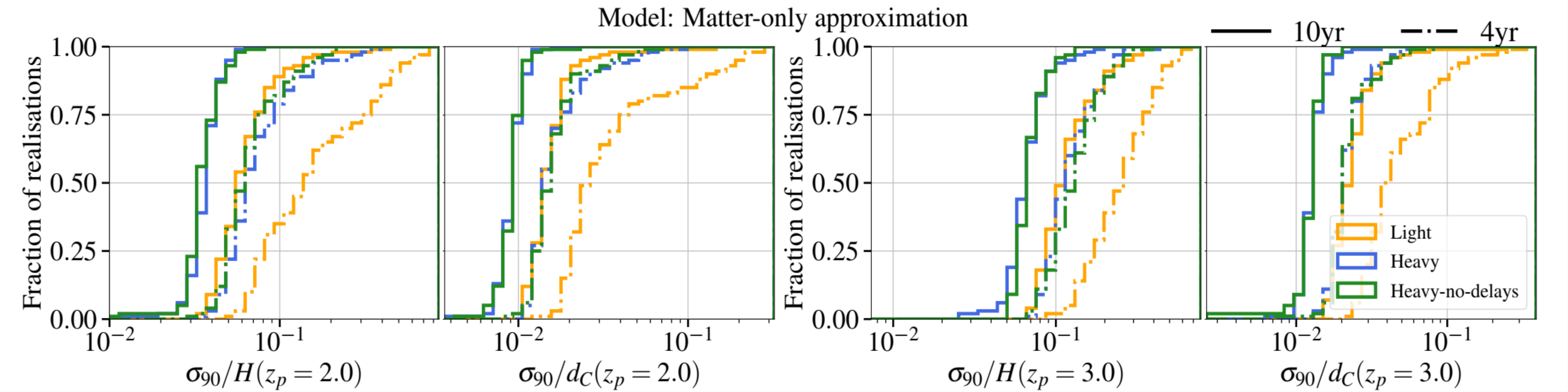

H(z=2) constrained to few percent
and H(z=3) ~10 %

Splines interpolation

Fit: Luminosity distance at 6 fixed knots redshifts at [0, 0.2, 0.7, 2, 4, 6]

with 10yr of LISA observations

Light	Heavy	Heavy-no-delays
16.0	37.0	51.7

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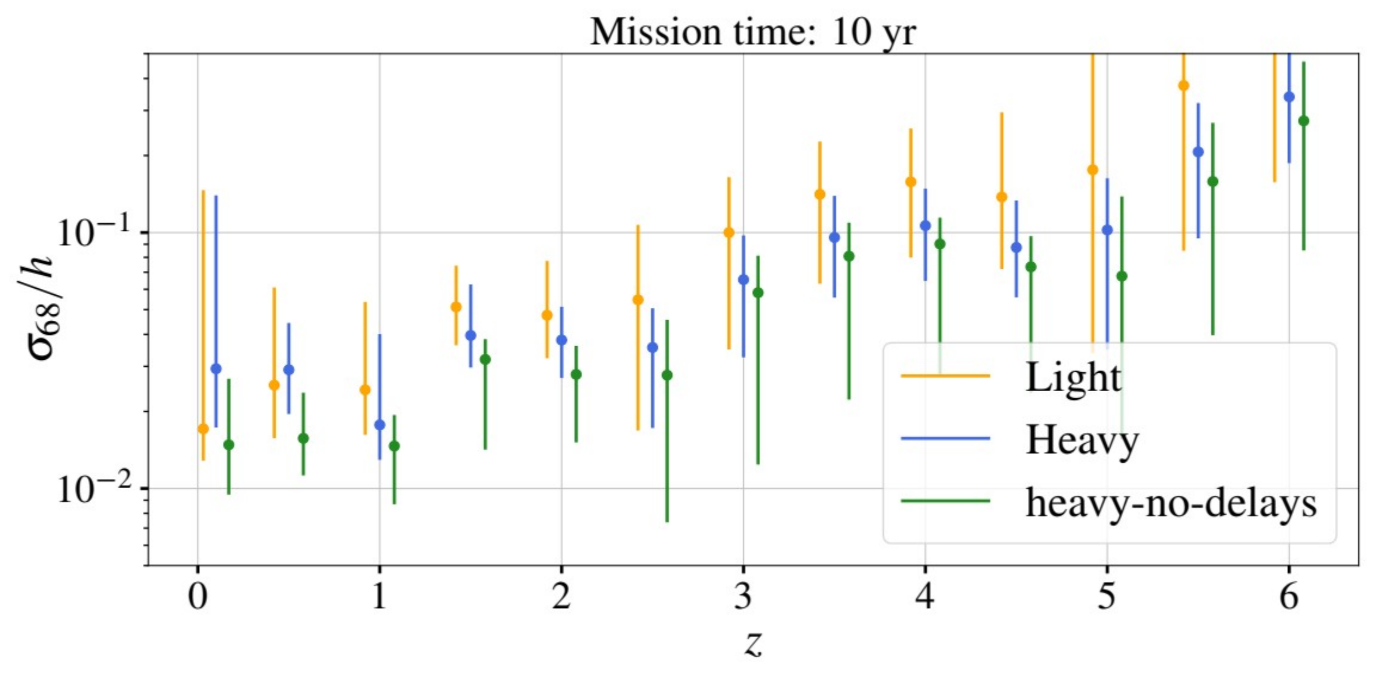

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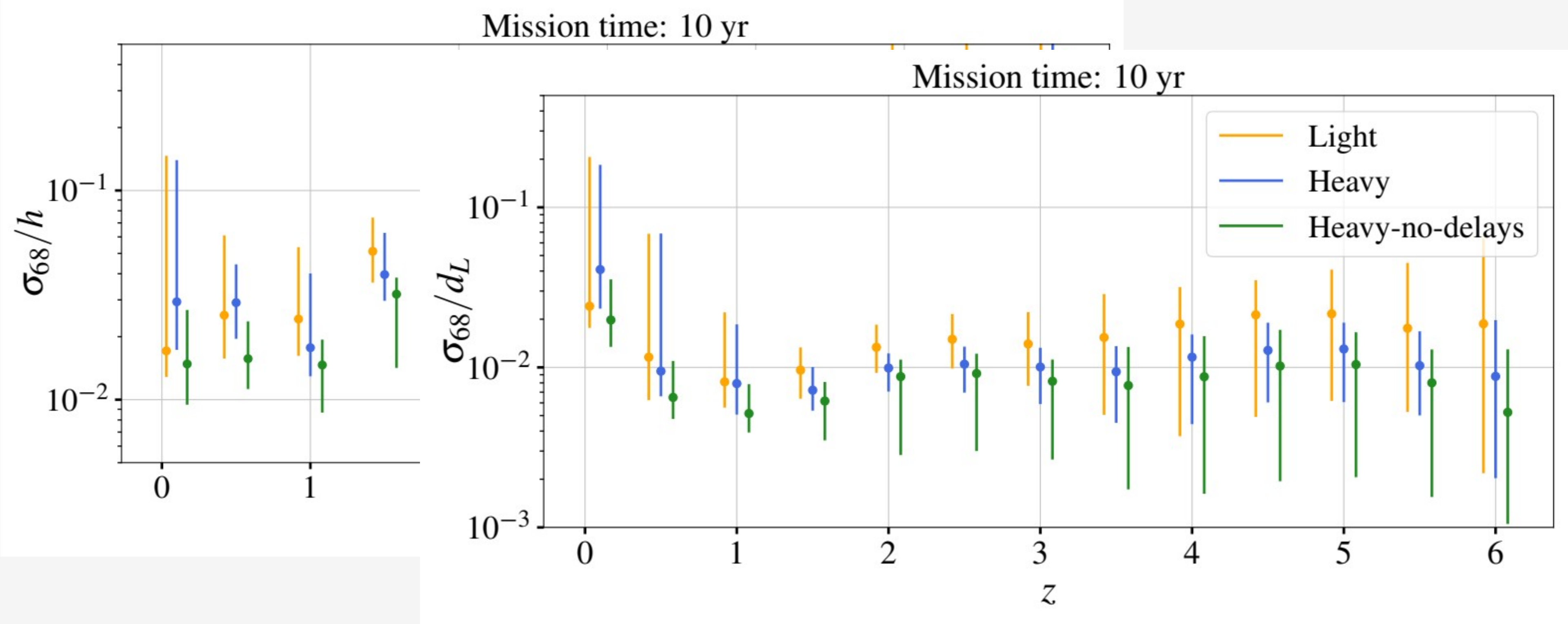


Conclusion

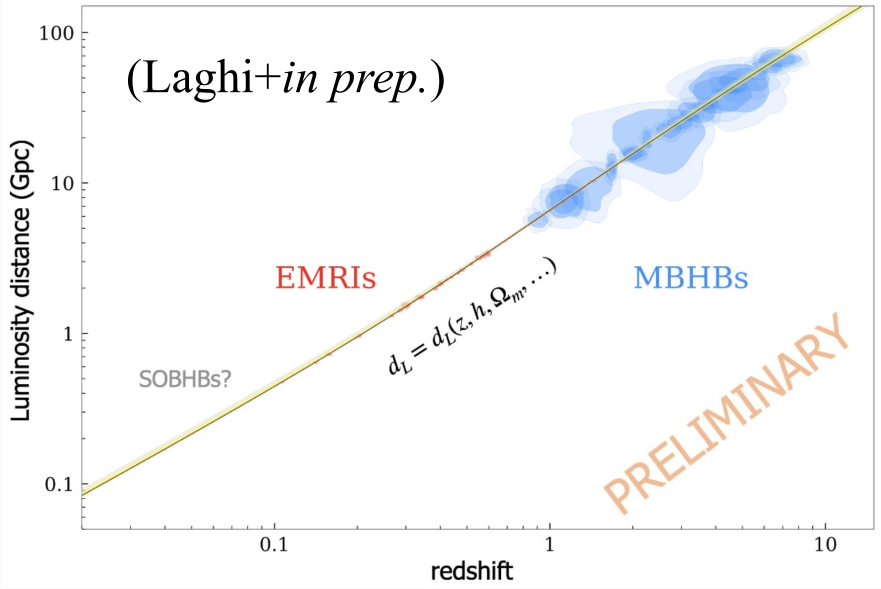
Cosmology with bright sirens will be challenging

From the current results

- ➤ Potential to constrain H(z) at high redshifts
- ➤ Information also on the comoving distance
- ➤ Strong dependence from the EM counterpart

Prospects for the future

- ➤ Need better modeling for the EM counterpart
- ➤ Combine MBHBs with other LISA sources as SOBHBs and EMRIs



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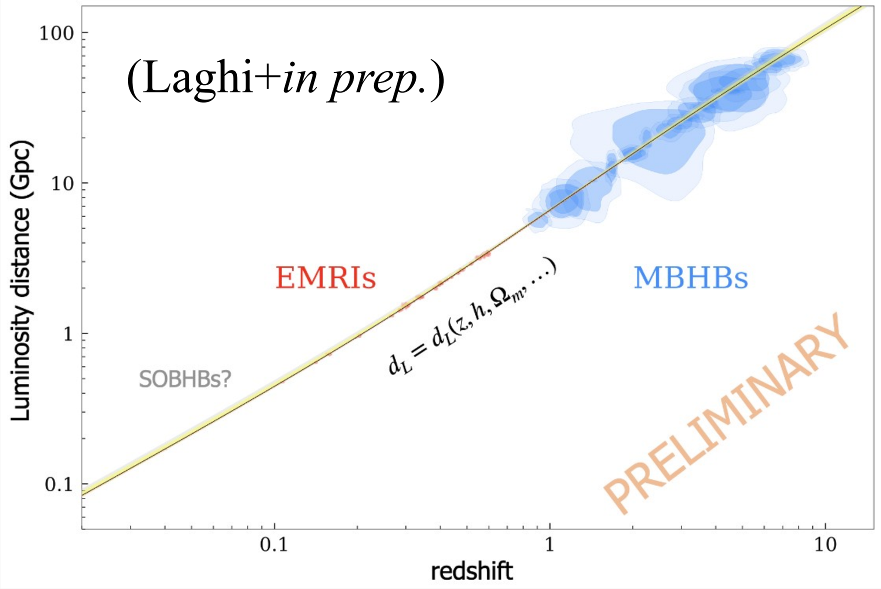
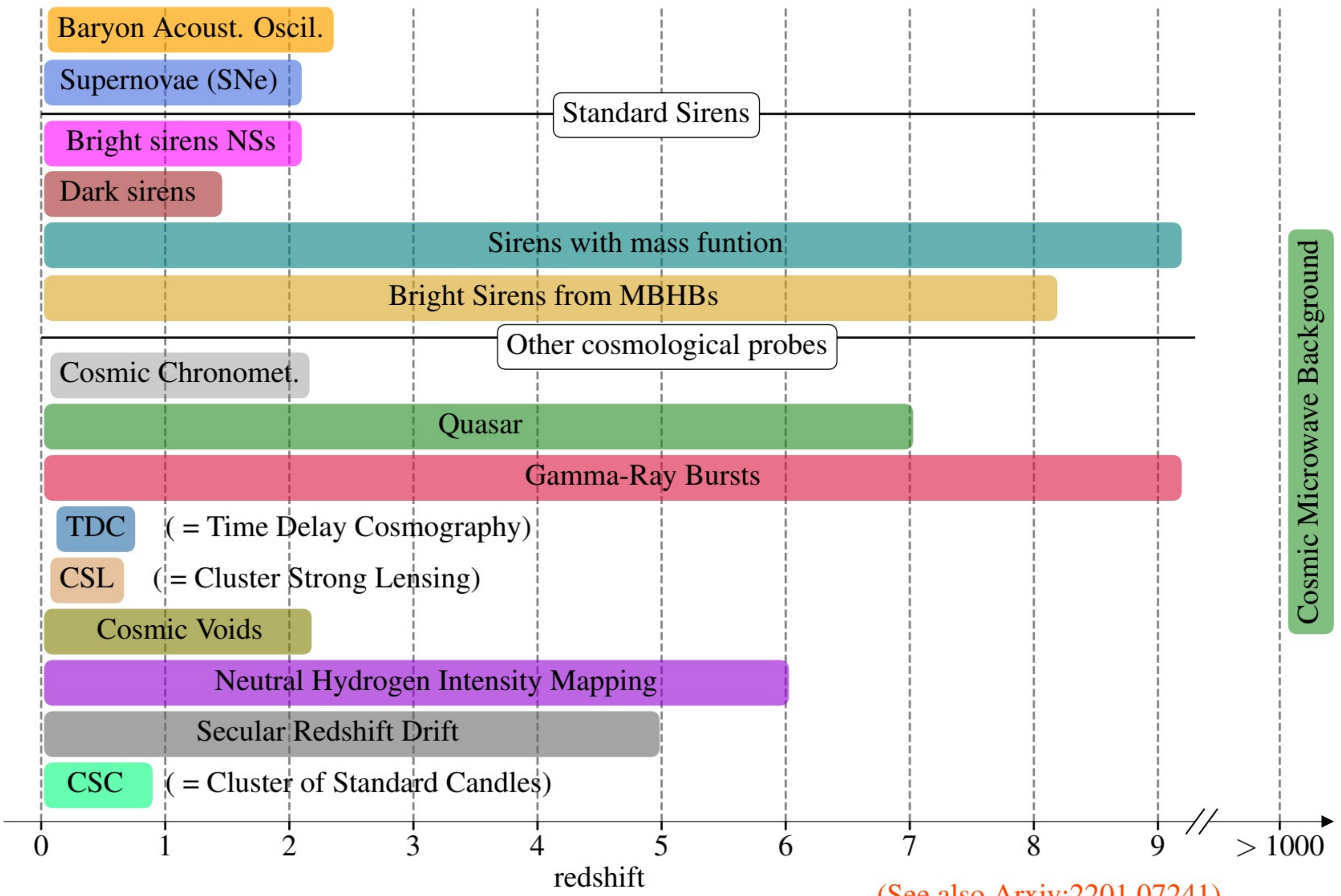


Any questions ?

Backup slides

MBHBs can go up to high redshift



(See also Arxiv:2201.07241)

Matter-only approximation and redshift bins

➤ Matter-only approximation

$$d_C(z) = d_C(z_p) + 2(1+z_p))H^{-1}(z_p)\left(1 - \frac{\sqrt{1+z_p}}{\sqrt{1+z}}\right)$$

with z_p = 2-3

We also remove EMcps at z ≤ 1-1.5

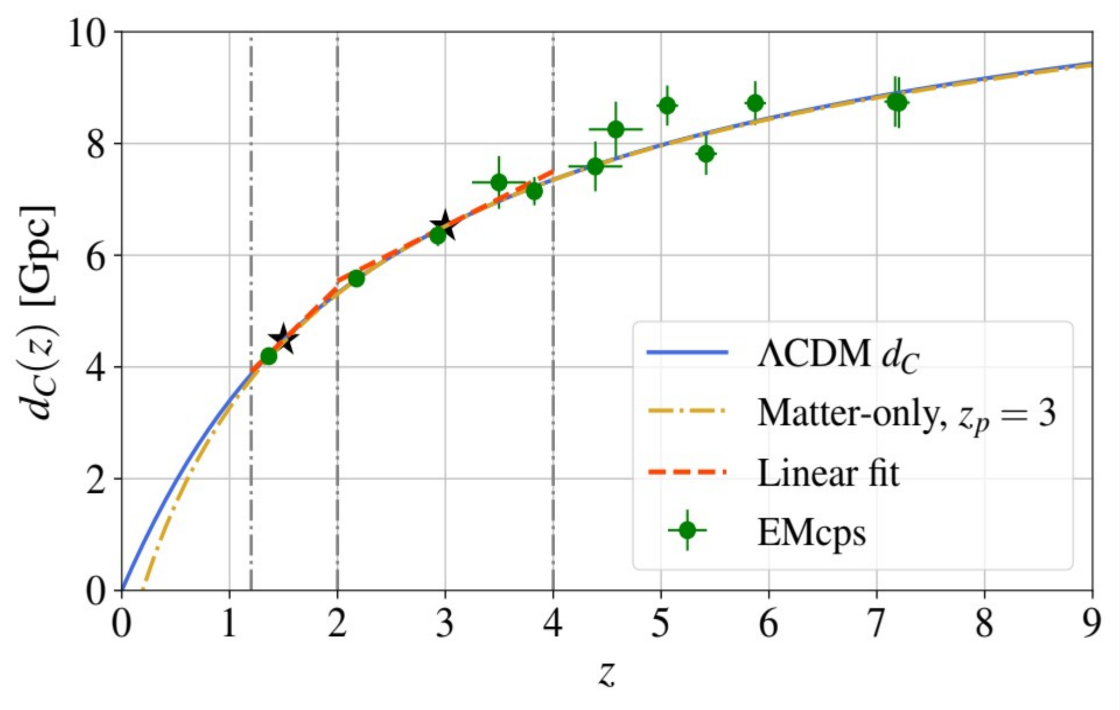
➤ Redshift bins

$$d_C(z) = c\int_0^z \frac{dz'}{H(z')} \qquad H(z) = \left(\frac{d\,d_C}{dz}\right)^{-1}$$

Trade-off between:

- ➤ Bin size
- ➤ Number of EMcps in each bin

Requirement: D(z) accuracy ≤ 5%

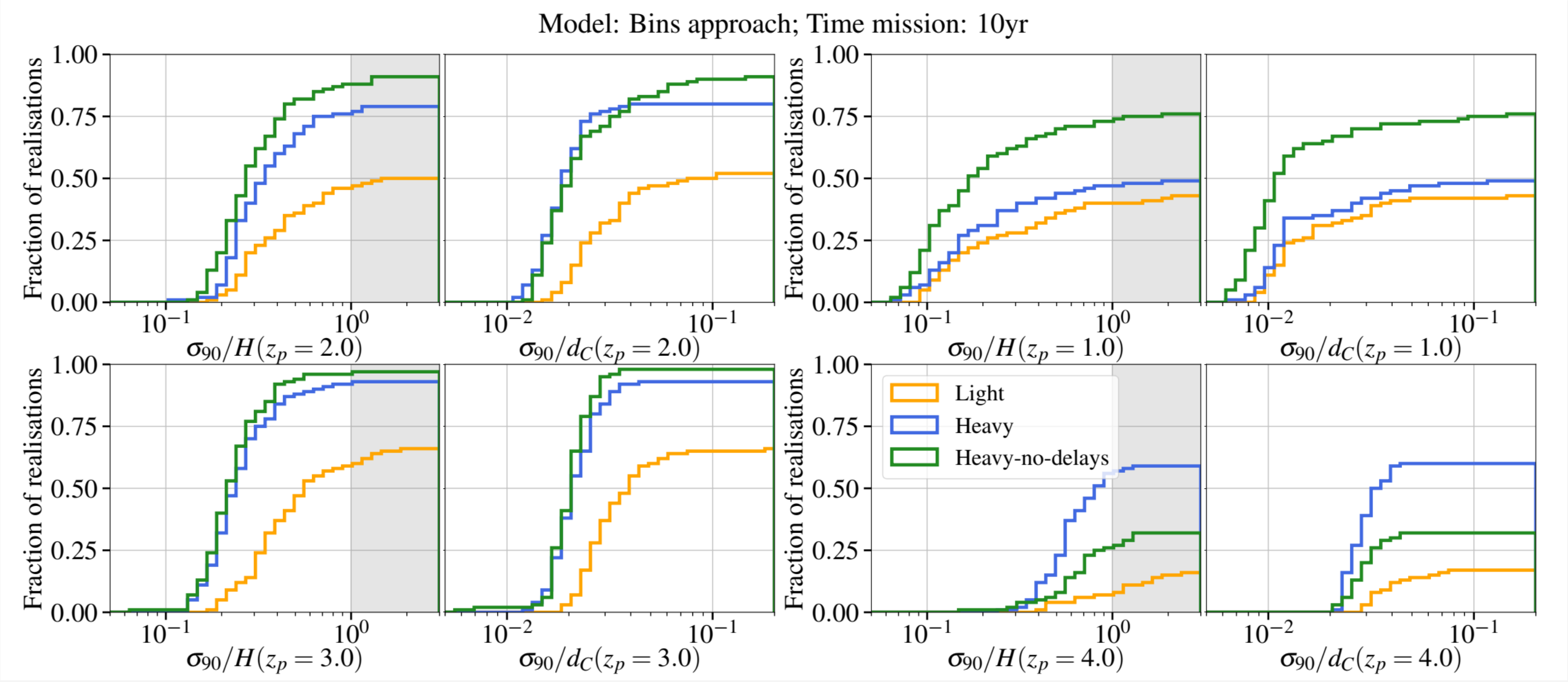


<u>Not all the redshift bins are informative</u>

Redshift bins

Fit: $D(z) = D(z_p) + H(z_p)^{-1}(z - z_p)$
with 10yr of LISA observations

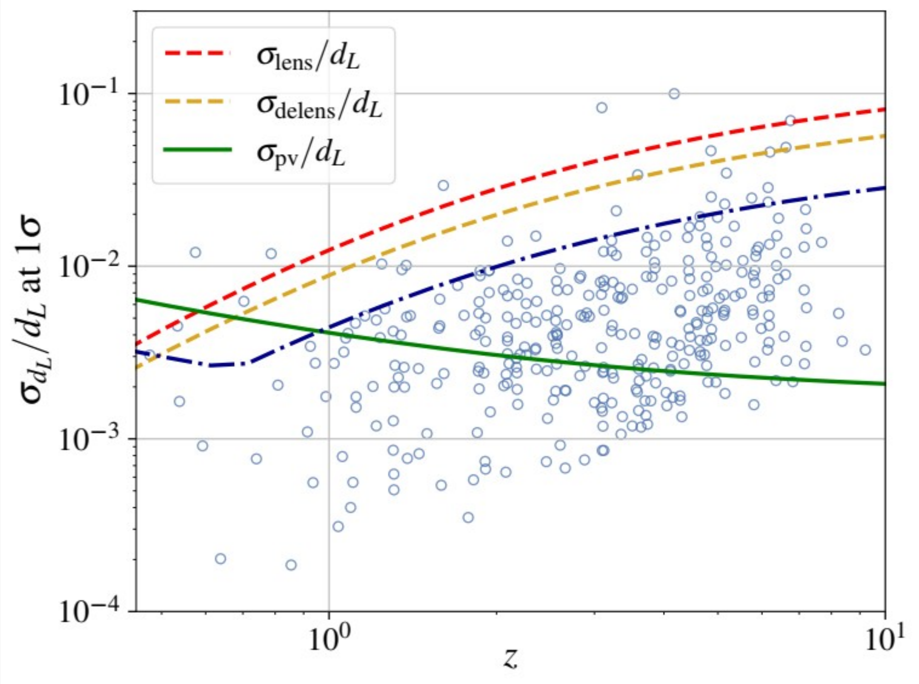
$z_p = 3$	Light	Heavy	Heavy-no-delays
$2 < z < 4$	6.1	14.6	20.7



Luminosity distance and redshift estimates

Luminosity distance

- ➤ Accurate estimate of luminosity distance → $\Delta d/d_L < 10\%$
- ➤ Lensing relevant for z > 2-3
- ➤ Peculiar velocities are negligible



Redshift measurements

LSST/Rubin Obs.

ELT

➤Photometric measurements with $\Delta z = 0.03(1 + z)$ (Laigle + 19)

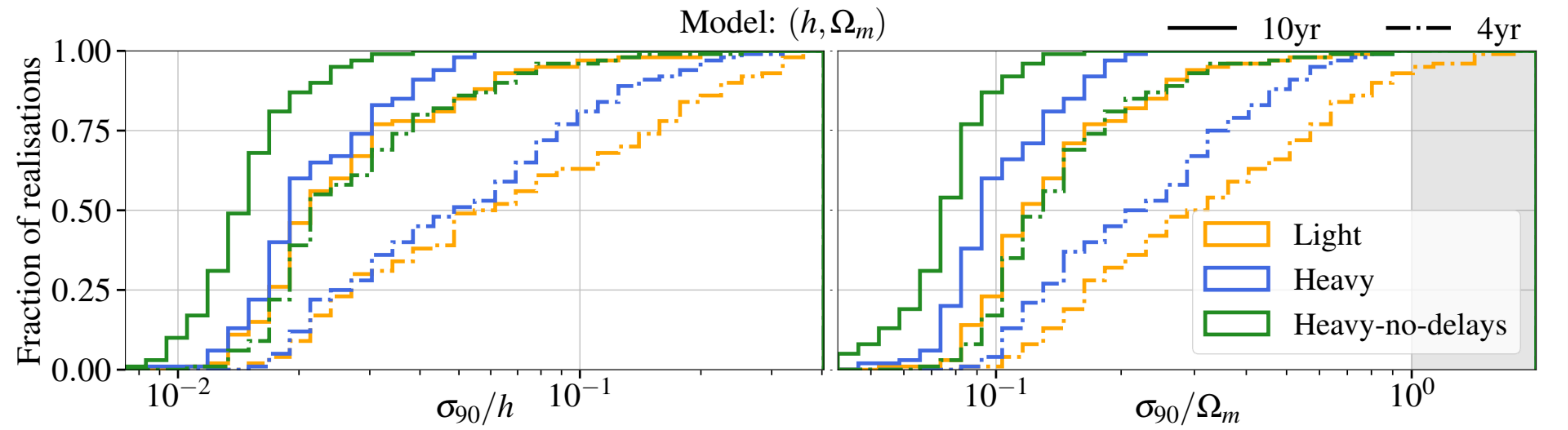
	$m_{\rm gal,ELT} < 27.2$	$27.2 < m_{\rm gal,ELT} < 31.3$
$z \leqslant 0.5$		No redshift information
$0.5 < z \leqslant 5$	$\Delta z = 10^{-3}$	$\Delta z = 0.5$
$z > 5$		$\Delta z = 0.2$

Prospects for H_0 and Ω_m

Fit: $H(z) = H_0\sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)}$

(in 4 yr)

Light	Heavy	Heavy-no-delays
6.4	14.8	20.7



H_0 can be constrained to few percent

Larger uncertainties on Ω_m

For CPL parametrization → Poor constrains on ω_0 and no constrain on ω_a

What to do with uninformative realisations?

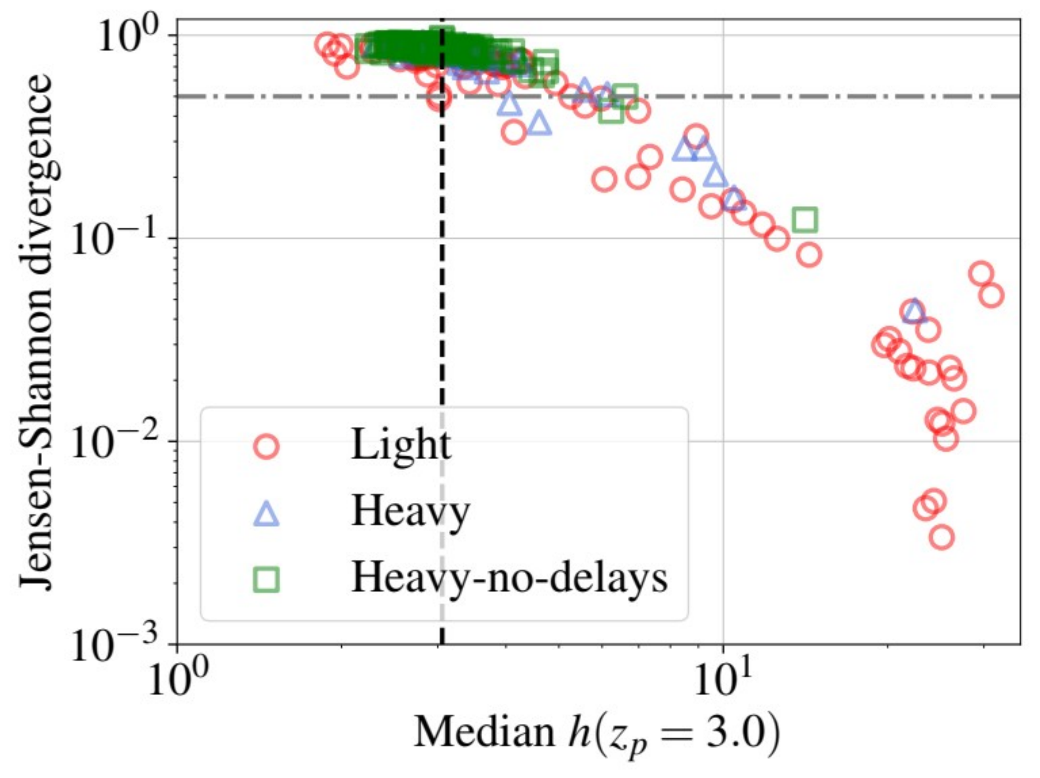
No or few events in a redshift bin → The realisation is not informative → The posterior distribution concides with the prior

Jensen-Shannon (JS) test

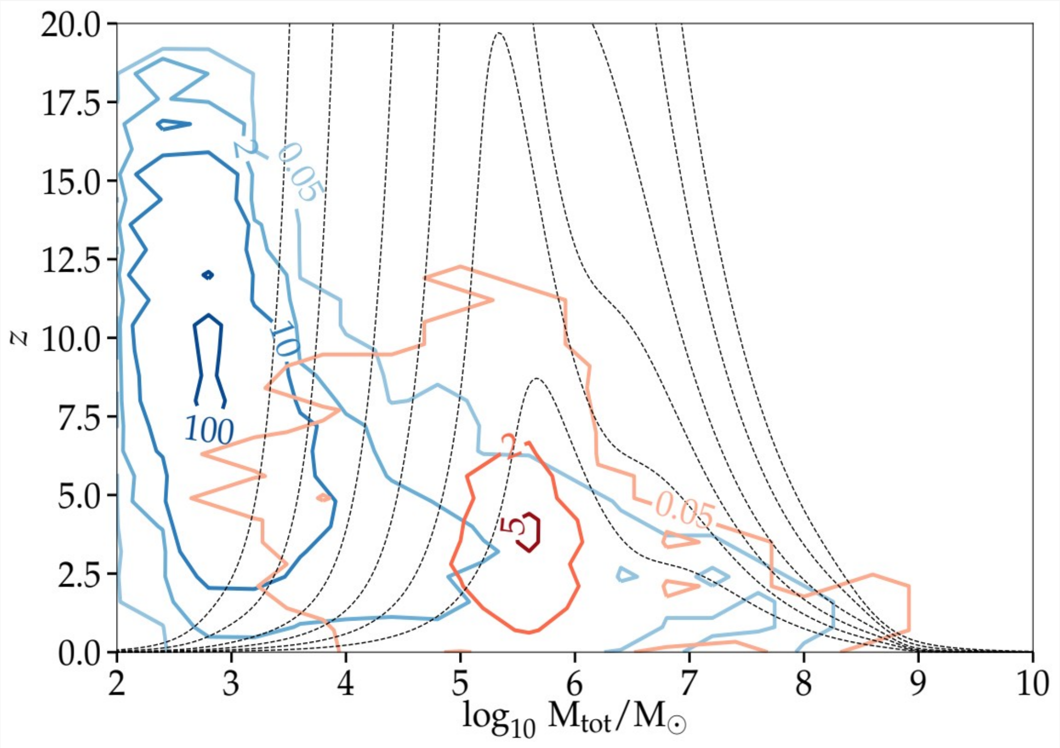
We compare the posterior and the prior distributions

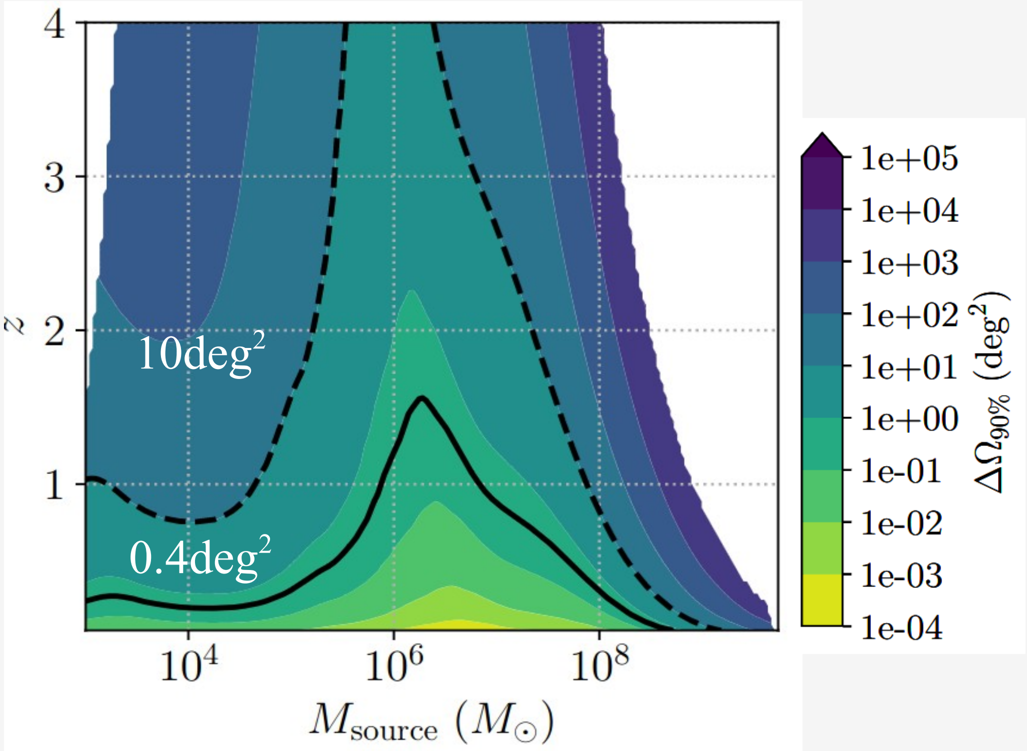
- ➤ JS=0 if posterior == prior
- ➤ JS=1 if posterior != prior

In this case, uniform prior for h(z=3) in [0.1,50]



Mass-redshift distributions and sky localization





Blue : Light seeds
Red : Heavy seeds

Contour lines: $\frac{\mathrm{d}N}{\mathrm{d}\log_{10} M_{\mathrm{tot}} \mathrm{d}z \mathrm{d}t} \times 4\mathrm{yr}$

(Marsat,..., AM+ *in prep.*)