Testing cosmology with massive black hole binaries

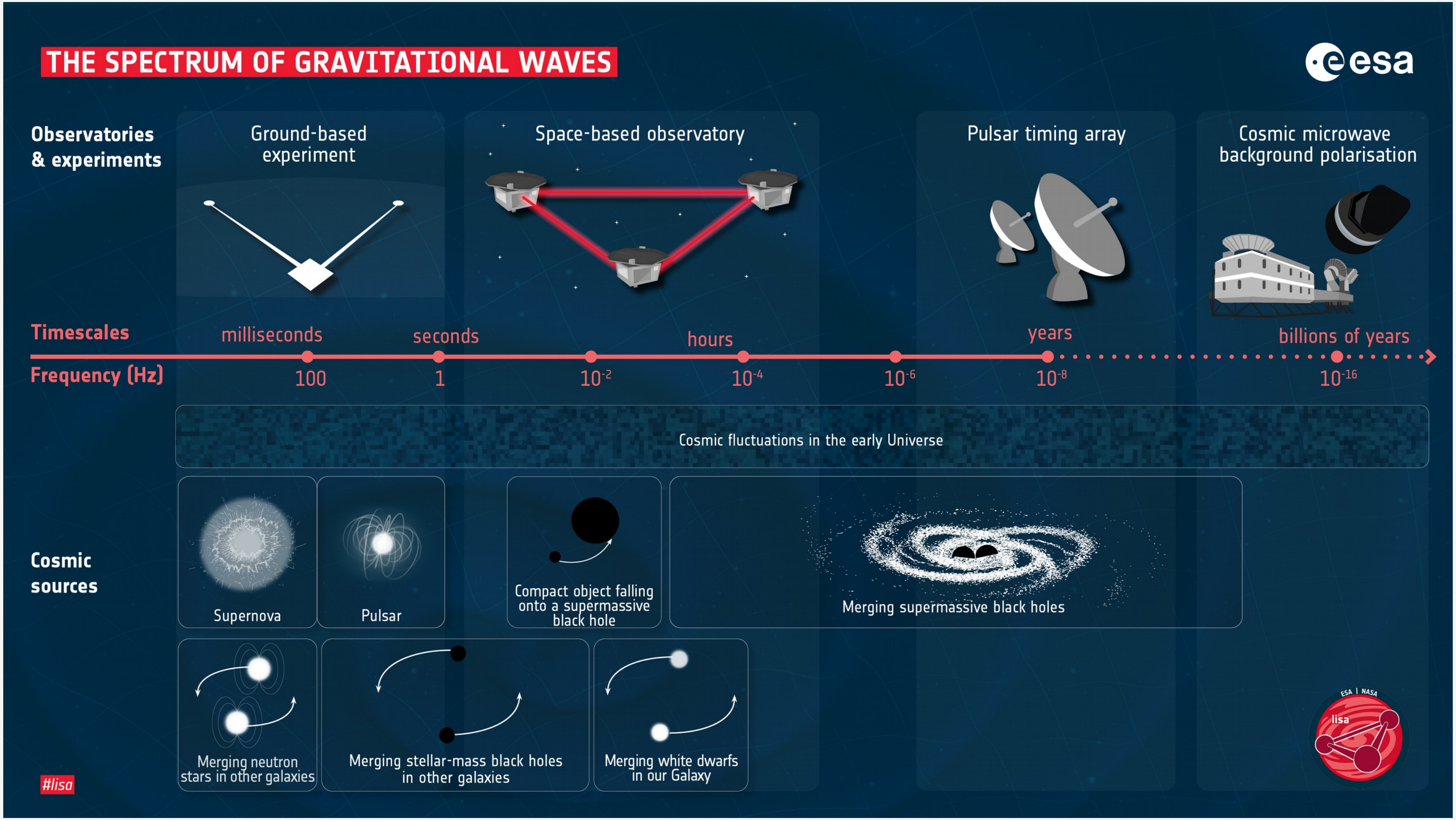
Alberto Mangiagli
Marie Curie Fellow

Astroparticule et Cosmologie (APC), Paris

Collaborators: Chiara Caprini, Sylvain Marsat, Nicola Tamanini, Marta Volonteri, Susanna Vergani, Lorenzo Speri, Henri Inchauspé

Gravity and Cosmology 2024, Yukawa Institute for Theoretical Physics, Kyoto University

Overview


THE SPECTRUM OF GRAVITATIONAL WAVES
esa
Observatories & experiments
Ground-based experiment
Space-based observatory
Pulsar timing array
Cosmic microwave background polarisation
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
10-2
10-4
10-6
10-8
10-16
Cosmic fluctuations in the early Universe
Cosmic sources
Supernova
Pulsar
Compact object falling onto a supermassive black hole
Merging supermassive black holes
Merging neutron stars in other galaxies
Merging stellar-mass black holes in other galaxies
Merging white dwarfs in our Galaxy
#lisa
ESA | NASA
lisa

Introduction

What are massive black holes (MBHs)?

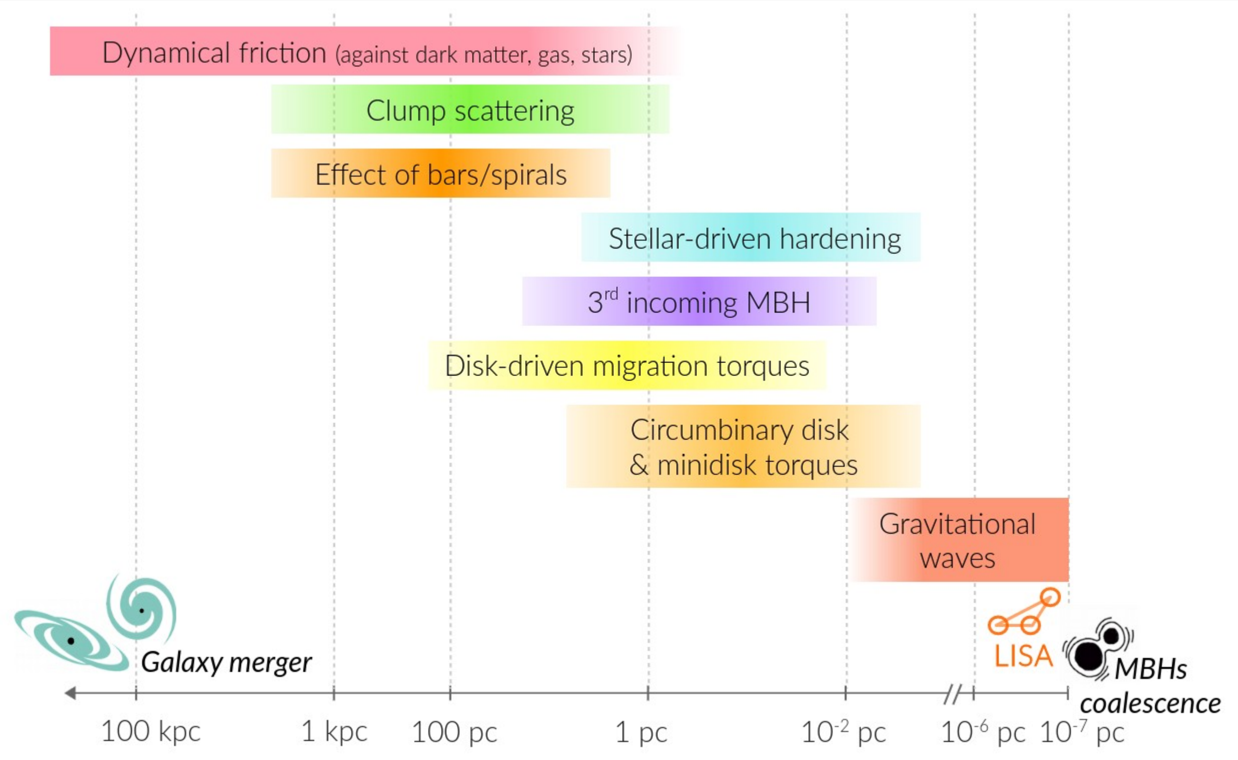
We currently believe that MBHs are hosted at the center of galaxies with masses up to $\sim 10^9 - 10^{10}\ M_\odot$

For today talk, let's focus on the interval

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

From galaxy mergers to MBH mergers

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



Courtesy of Elisa Bortolas

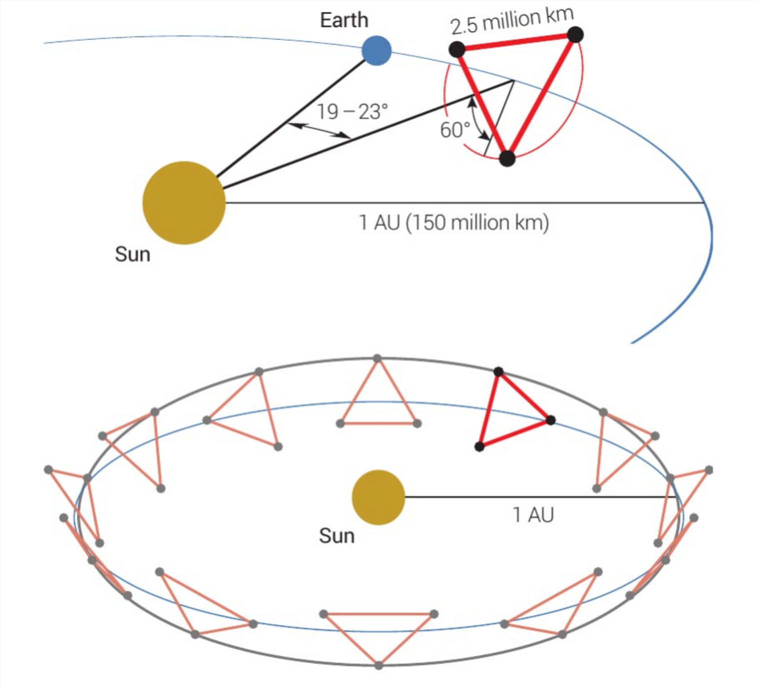
Large uncertainties in the formation and evolution processes :

- ➤ Seed mechanisms ?
- ➤ Accretion ?
- ➤ Time delays ?

(For reviews : Volonteri+10, Mayer+13, De Rosa+19, arXiv:2203.06016)

Observing the entire Universe with GWs

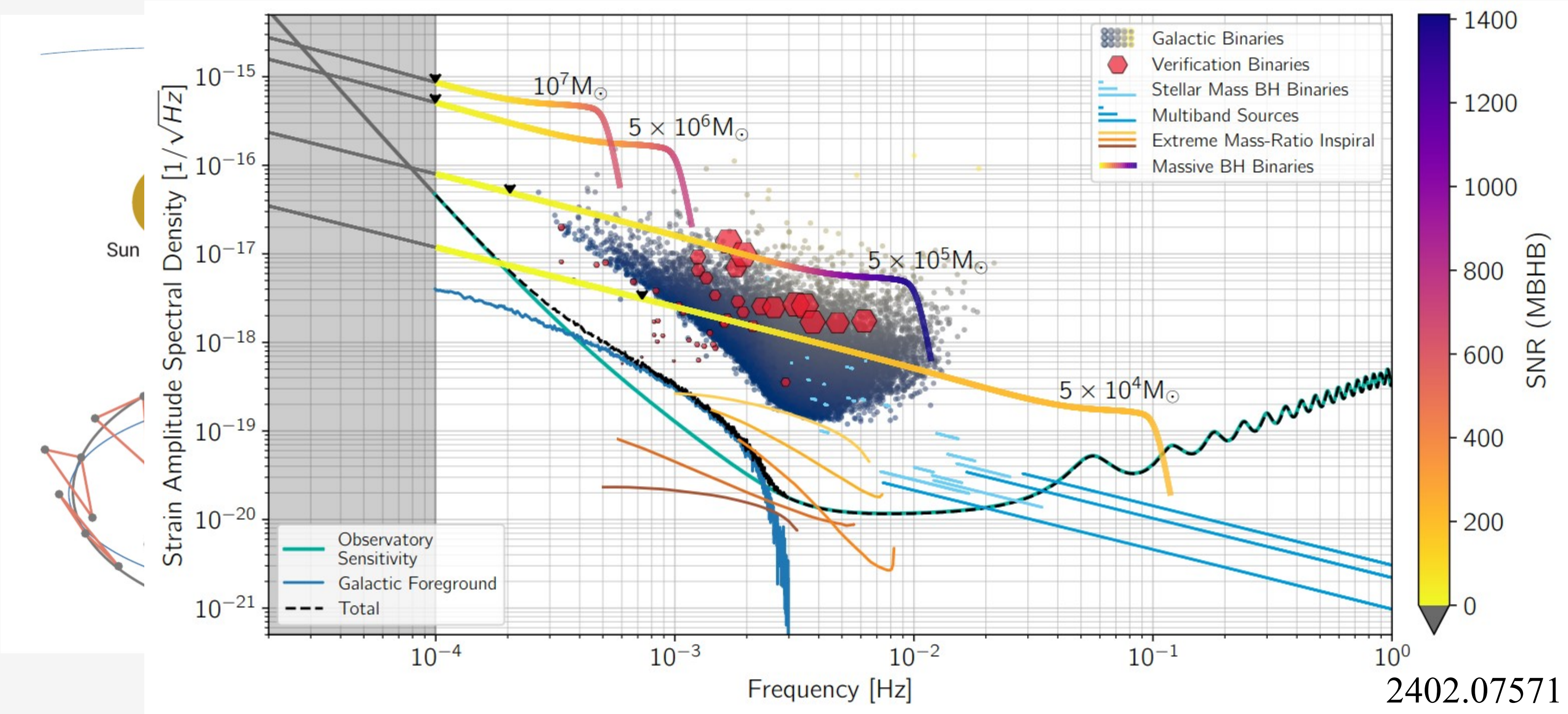
In late-2030s LISA (Laser Interferometer Space Antenna) will observe the GWs from the coalescence of MBHBs in the entire Universe



And there is more...

Observing the entire Universe with GWs

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

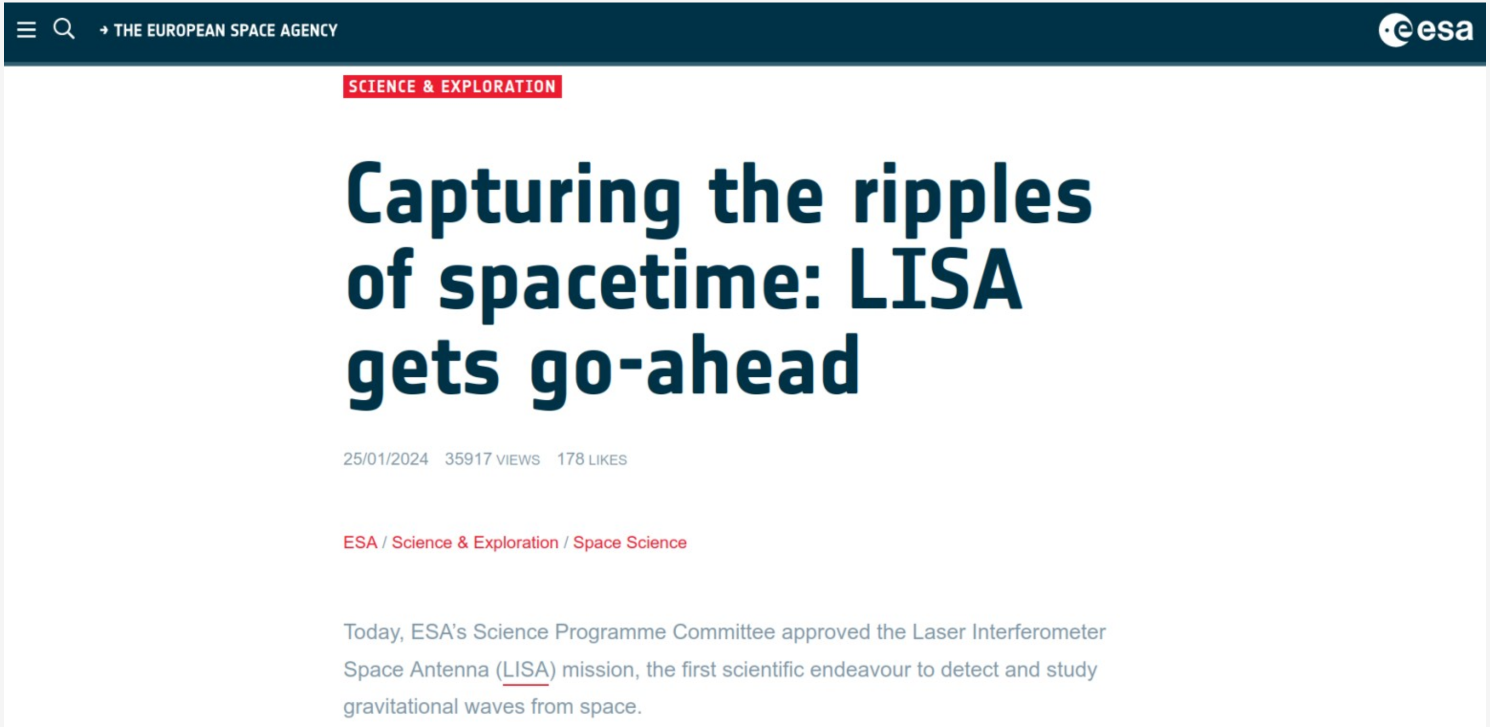


2402.07571

And there is more...

Observing the entire Universe with GWs

ESA (European Space Agency) adopted LISA on January 25th 2024 with a budget of €1.7 billion


→ THE EUROPEAN SPACE AGENCY

esa

SCIENCE & EXPLORATION

Capturing the ripples of spacetime: LISA gets go-ahead

25/01/2024 35917 VIEWS 178 LIKES

ESA / Science & Exploration / Space Science

Today, ESA's Science Programme Committee approved the Laser Interferometer Space Antenna (LISA) mission, the first scientific endeavour to detect and study gravitational waves from space.

LISA is under construction and will soon be a fundamental asset for GW physics

Massive Black Hole Binaries

Testing cosmology with MBHBs

How many multimessenger (GW+EM) MBHB events do we expect ?

ArXiv:2207.10678

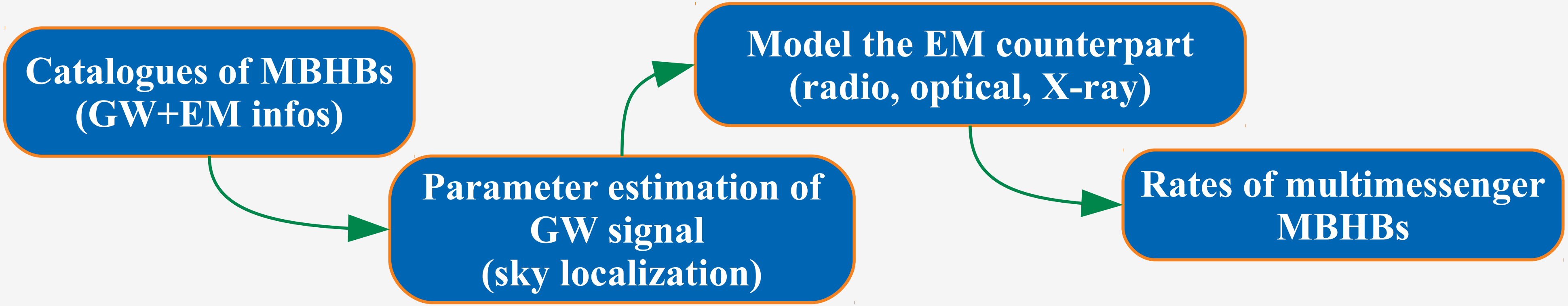
- Interactions between the MBHB and the circumbinary disk before&after the merger

What constraints we can put on the expansion of the Universe at $2 \leq z \leq 6$?

ArXiv:2312.04632

- $h \propto \frac{1}{d_L} \rightarrow$ No calibration errors and no intrinsic scatter
- Independent estimates from CMB/SNIa
- Redshift from the EM counterpart (‘*bright sirens*’)

<u>What do we need :</u>



Catalogues of MBHBs

Three astrophysical models

(Barausse+12 and updates)

Light

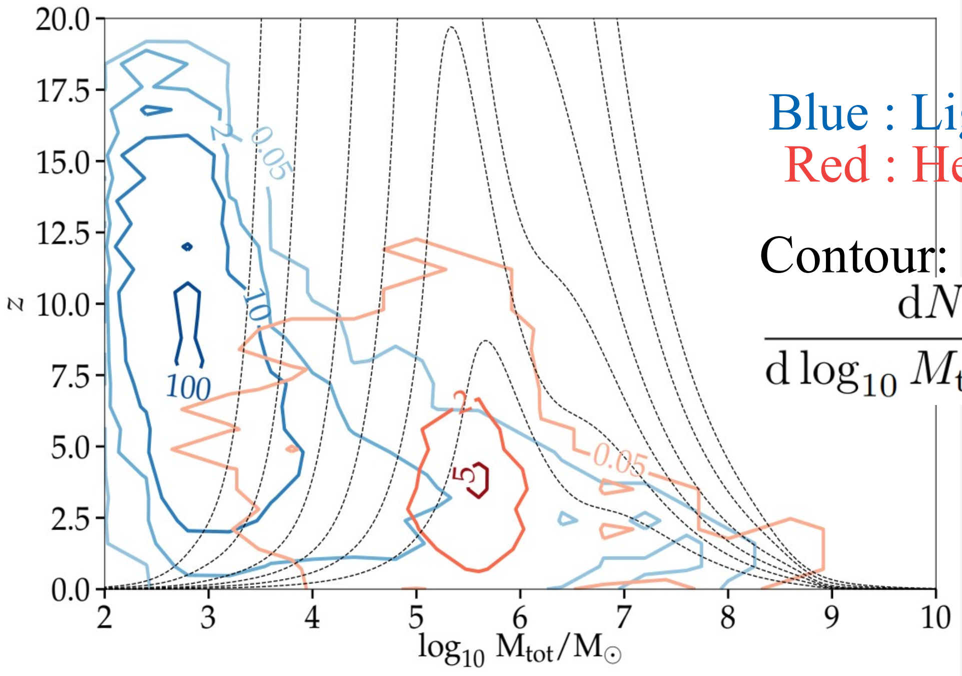
Remnants of PopIII stars
BHs ~ 10^3 $M_\odot$

Heavy

Collapse of hydrogen clouds
BHs ~ 10^{4-6} $M_\odot$

Heavy-no-delays

Same as Q3d but without delay times



Blue : Light model
Red : Heavy model

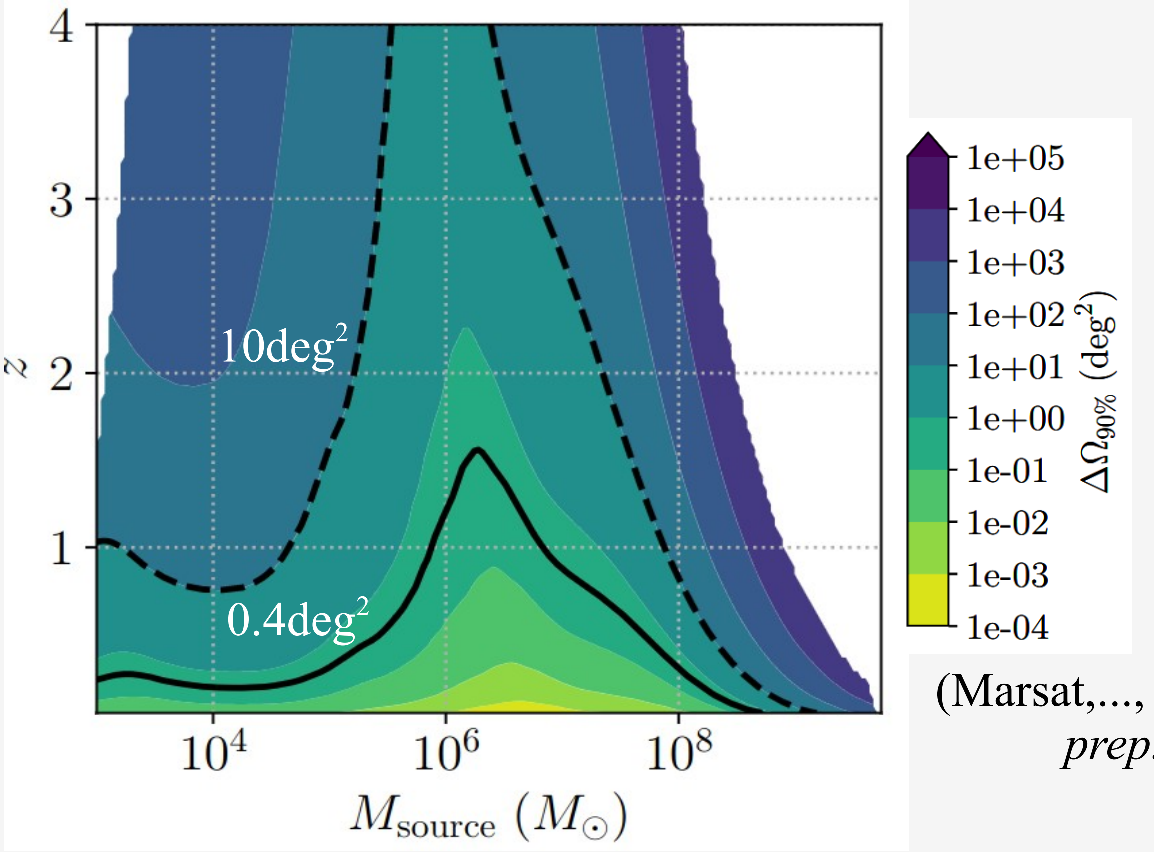
Contour:

$$\frac{dN}{d\log_{10} M_{tot} dz dt} \times 4yr$$

	Total catalogue	SNR > 10
Light	690.9	129.3
Heavy	30.7	30.4
Heavy-no-delays	475.5	471.1

Parameter estimation of the GW signal with fisher

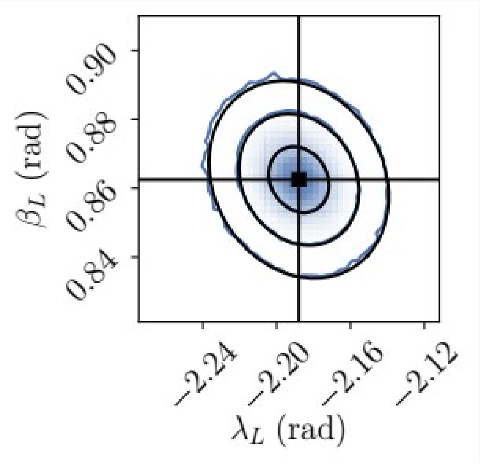
Sky localisation is a crucial quantity for multimessenger and
GW observatories must tell to EM telescopes were to point in the sky.



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

Parameter estimation of the GW signal with MCMC

We simulate 90 yr of data for each astrophysical model and perform the parameter estimation with a Bayesian code (*lisabeta*, Marsat+20)

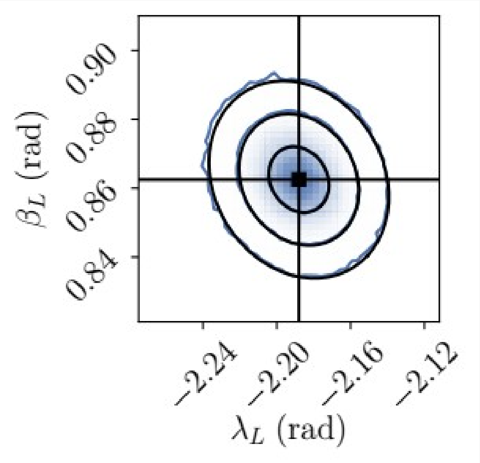


Technical part:

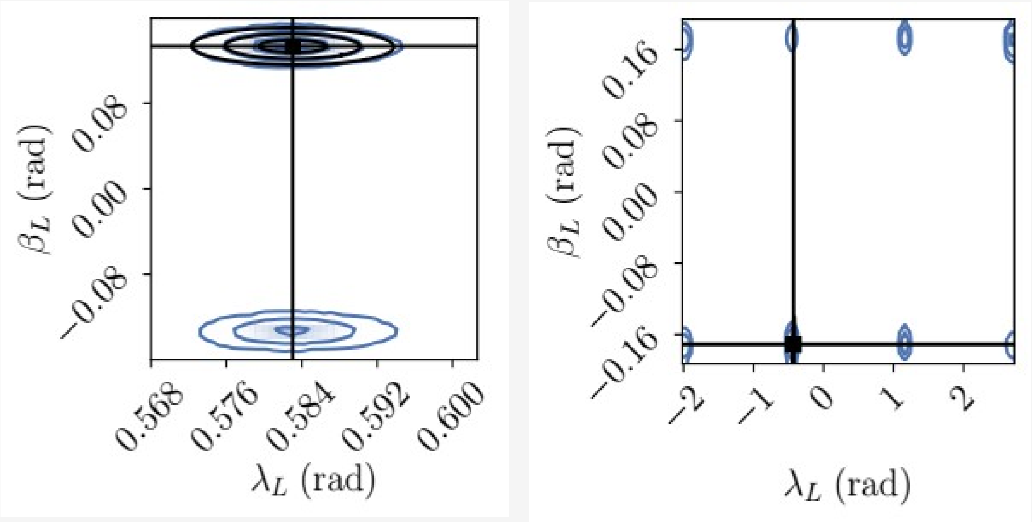
- PhenomHM
- 2.5yr resolved galactic background
- Fisher inizialitazion
- Only MBHBs (i.e. no global fit)
- SciRDv1

Parameter estimation of the GW signal with MCMC

We simulate 90 yr of data for each astrophysical model and perform the parameter estimation with a Bayesian code (*lisabeta*, Marsat+20)



<u>Multimodal events</u>



Technical part:
- PhenomHM
- 2.5yr resolved galactic background
- Fisher inizialitazion
- Only MBHBs (i.e. no global fit)
- SciRDv1

Degeneracies can be broken with :
- Orbital motion of the detector for f~10^{-4} Hz
- High frequency response of the detector for f~10^{-3} -10^{-2} Hz

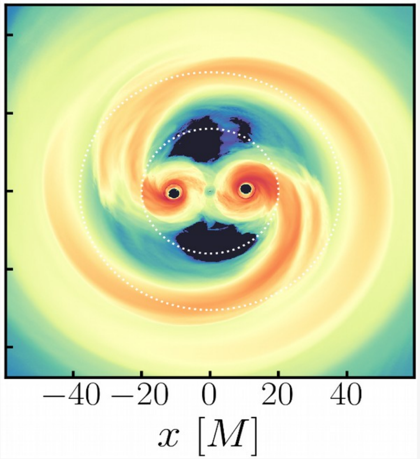
(see also Marsat+20,Baibhav+20)

EM counterpart to MBHB mergers

What type of EM emission do we expect from MBHBs ?

- No transient AGN-like emission has been associated unambiguously to a MBHBs
- Uncertainties on BH of 10^4–10^7 $M_\odot$ concerning bolometric correction, obscuration, spectra ...

<u>Before the merger</u>

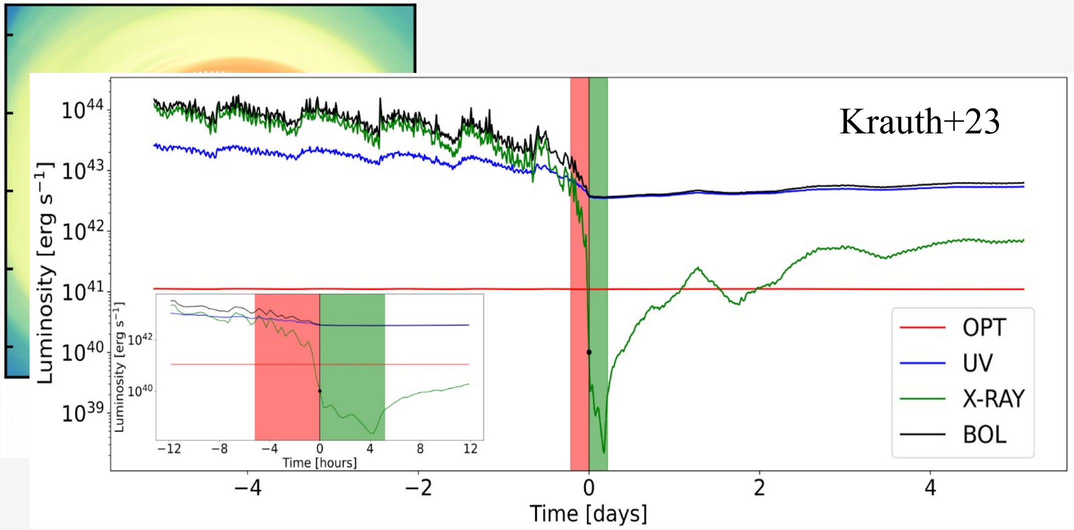


(Bowen+18, Haiman+17, Tang+18, Nobel+21,Combi+22, Cattorini+22, Gutiérrez+22 …)

What type of EM emission do we expect from MBHBs ?

- No transient AGN-like emission has been associated unambiguously to a MBHBs
- Uncertainties on BH of 10^4–10^7 $M_\odot$ concerning bolometric correction, obscuration, spectra ...

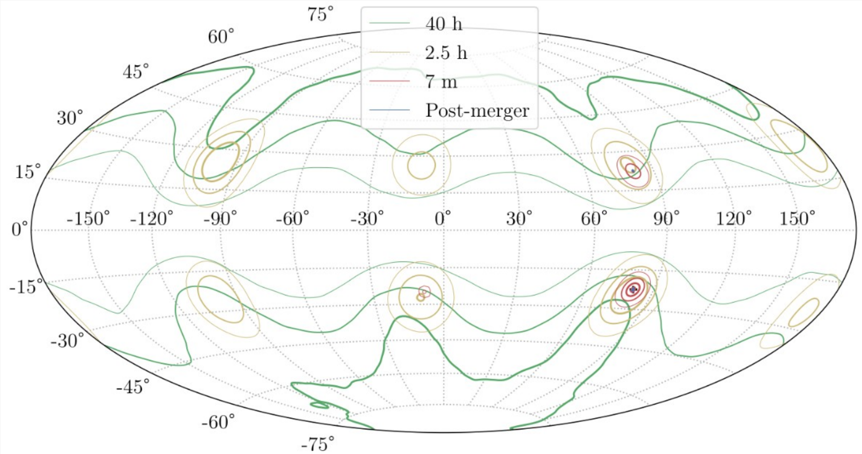
<u>Before the merger</u>



Both modulation and drop are unique hints of the presence of an underlying MBHB
(Dal Canton, AM+19)

Main caveats:

- Sky localization is strongly multimodal during the inspiral



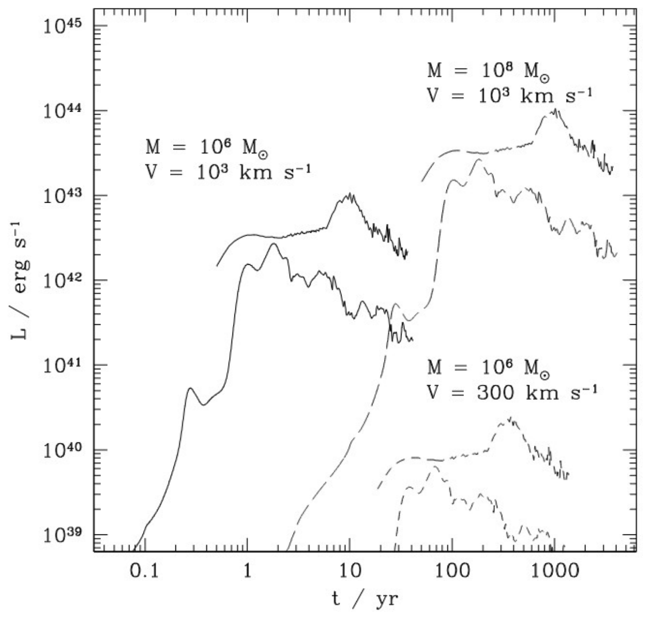
- Periodicity requires long exposure time

What type of EM emission do we expect from MBHBs ?

- No transient AGN-like emission has been associated unambiguously to a MBHBs
- Uncertainties on BH of $10^5-10^7\ M_\odot$ concerning bolometric correction, obscuration, spectra ...

<u>After the merger</u>

BH kick in the circumbinary disk



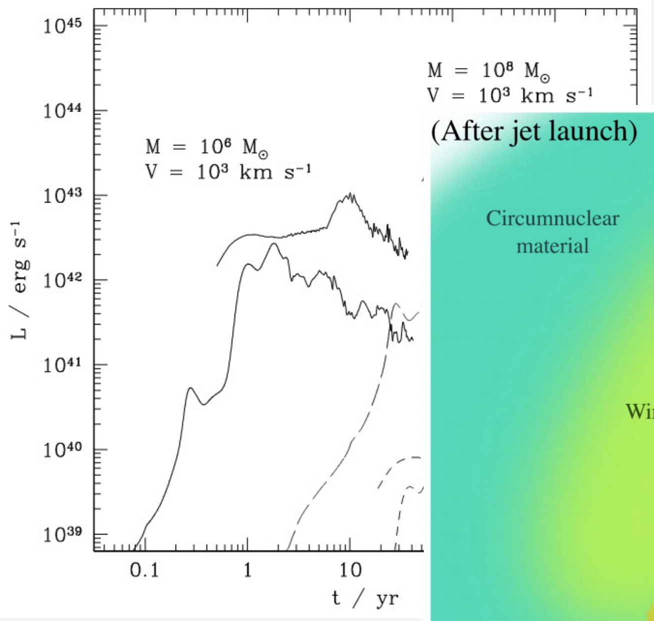
Rossi+10

What type of EM emission do we expect from MBHBs ?

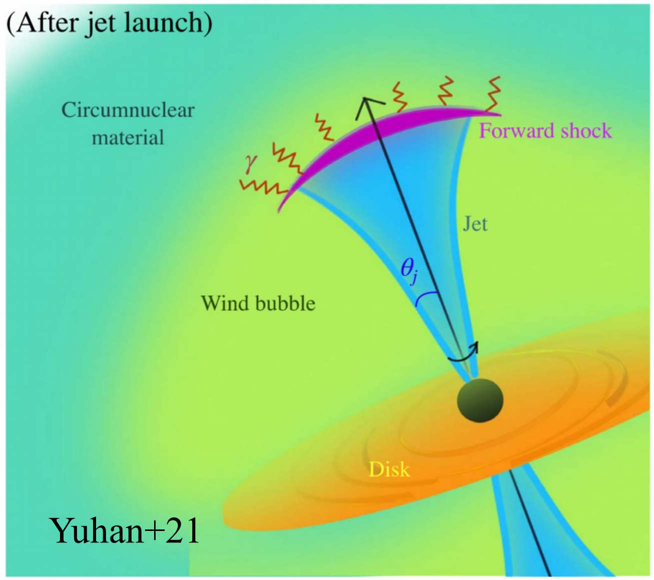
- No transient AGN-like emission has been associated unambiguously to a MBHBs
- Uncertainties on BH of $10^5 - 10^7$ $M_\odot$ concerning bolometric correction, obscuration, spectra ...

<u>After the merger</u>

BH kick in the circumbinary disk



Afterglow emission

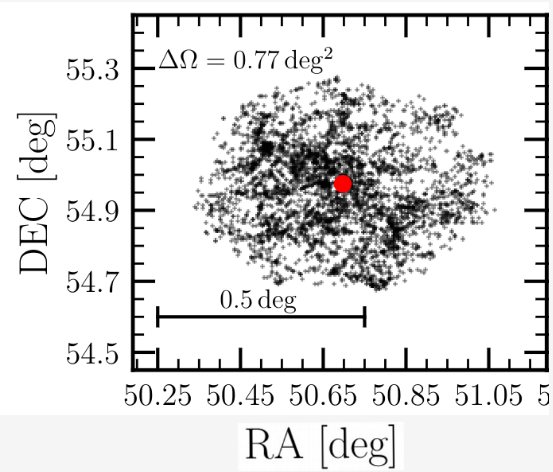


Yuhan+21

Main caveats:

- EM emerges weeks/months after the merger
- Identification: $\geq 10^2$ potential hosts in LISA error box

<u>Detection ≠ Identification</u>



$M_{tot} = 3 \times 10^6 M_\odot$
z=2

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

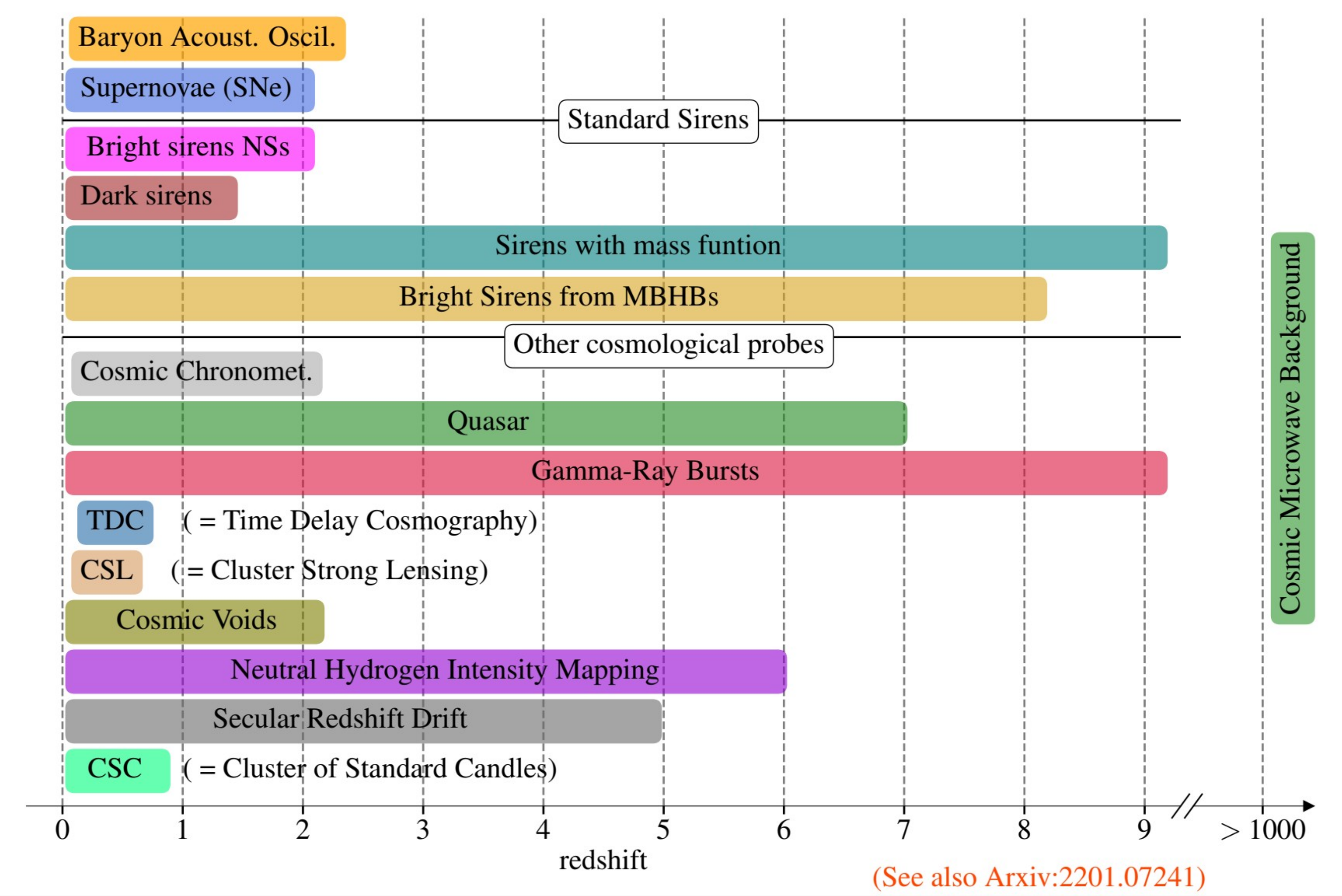
- Strong decrease with obscuaration and radio jet
- Parameter estimation selects preferentially heavy
- Multimodal events do not contribute

(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

Testing cosmology with MBHBs

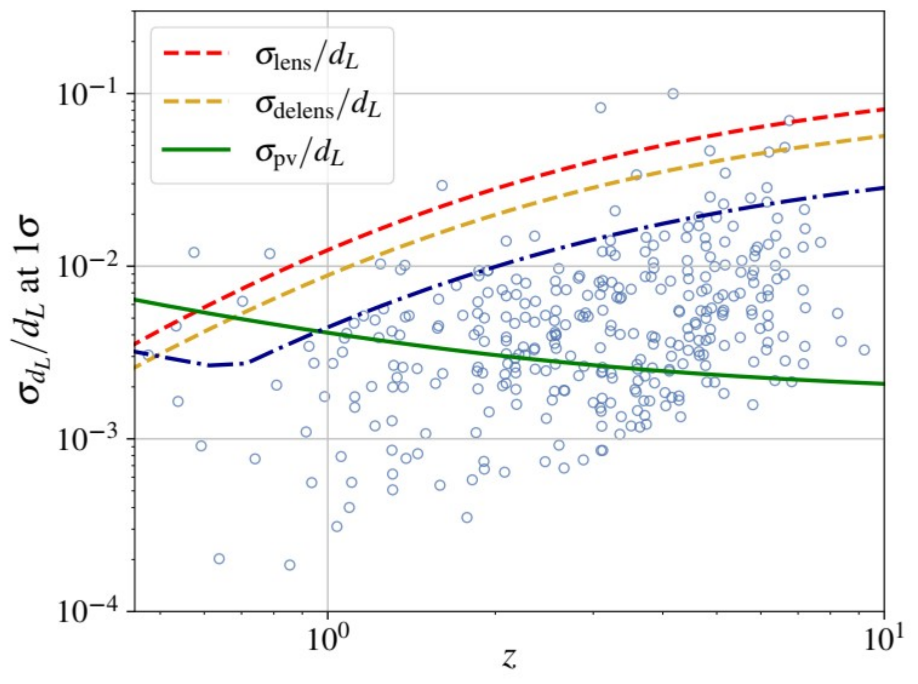
MBHBs can go up to high redshift



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
$0.5 < z \leqslant 5$	$\Delta z = 10^{-3}$	$\Delta z = 0.5$
$z > 5$		$\Delta z = 0.2$

Tested cosmological models in ArXiv:2312.04632

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, Ω_m, ω_0, ω_a)
- Phenomen. modified gravity (Belgacem+19)
  2-parameters model: (Ξ_0, n)

Modified matter

- Matter deviation with $\omega_m = \beta$
  3-parameters model: (H_0, Ω_m, β)

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

Tested cosmological models in ArXiv:2312.04632

ΛCDM Universe

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

Dark energy/modified gravity

- CPL parametrization for $\omega(z)$
  4-parameters model: $(H_0, \Omega_m, \omega_0, \omega_a)$
- Phenomen. modified gravity (Belgacem+19)
  2-parameters model: (Ξ_0, n)

Modified matter

- Matter deviation with $\omega_m = \beta$
  3-parameters model: (H_0, Ω_m, β)

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

Matter-only approximation

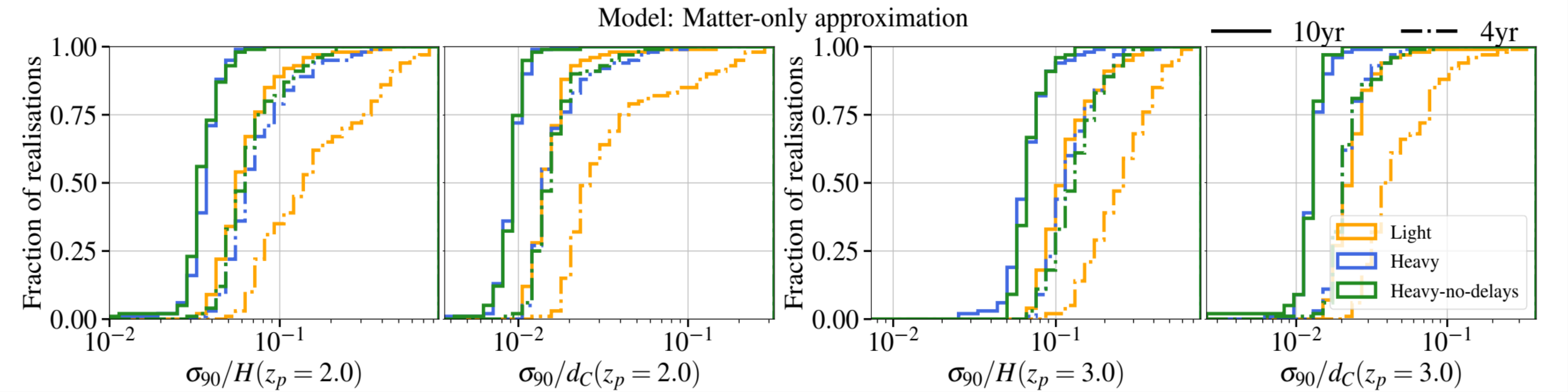
Fit: $d_C(z) = d_C(z_p)+2(1+z_p))H^{-1}(z_p)\left(1-\frac{\sqrt{1+z_p}}{\sqrt{1+z}}\right)$

(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

Matter-only approximation

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

(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



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

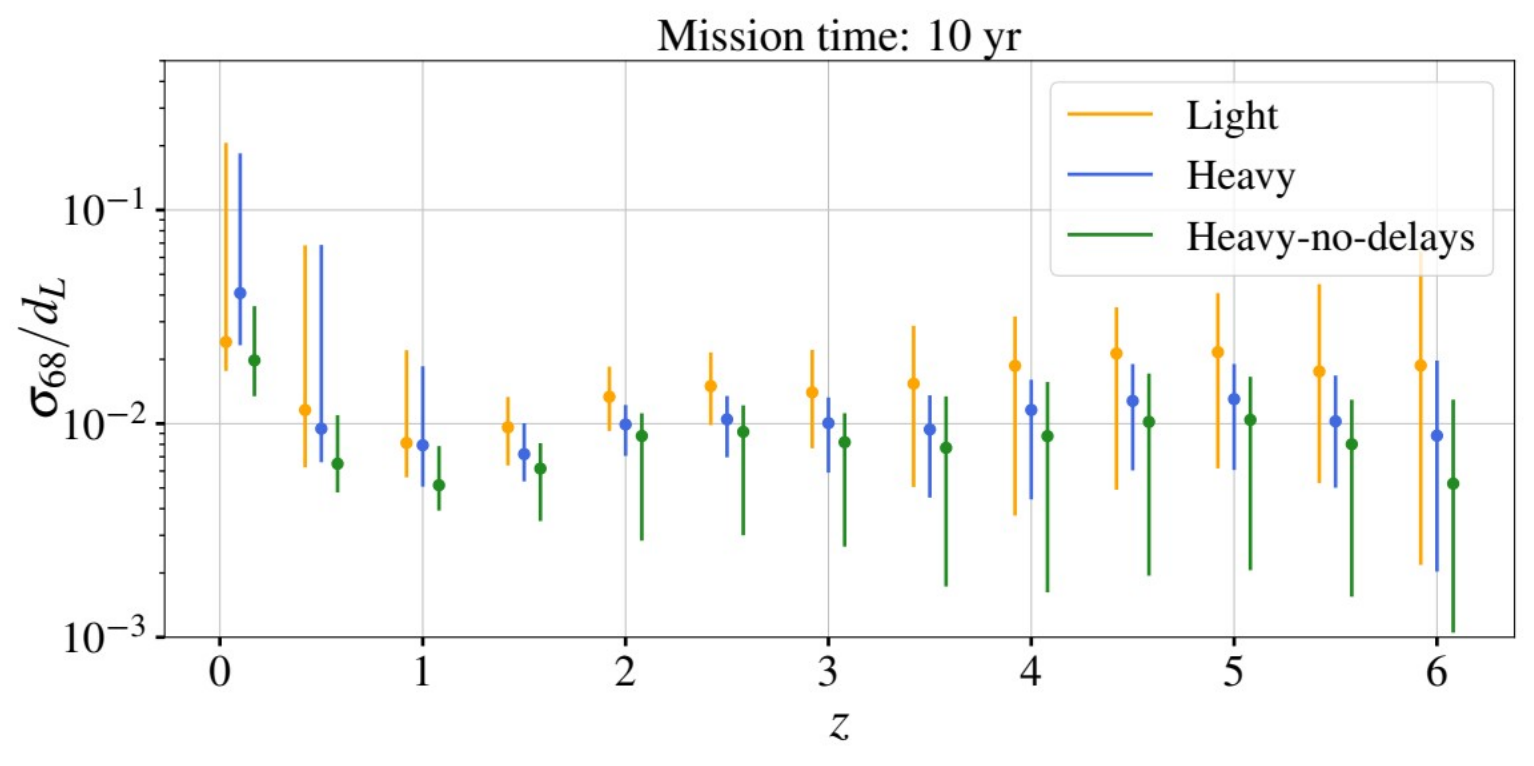
Light	Heavy	Heavy-no-delays
16.0	37.0	51.7

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



Conclusion

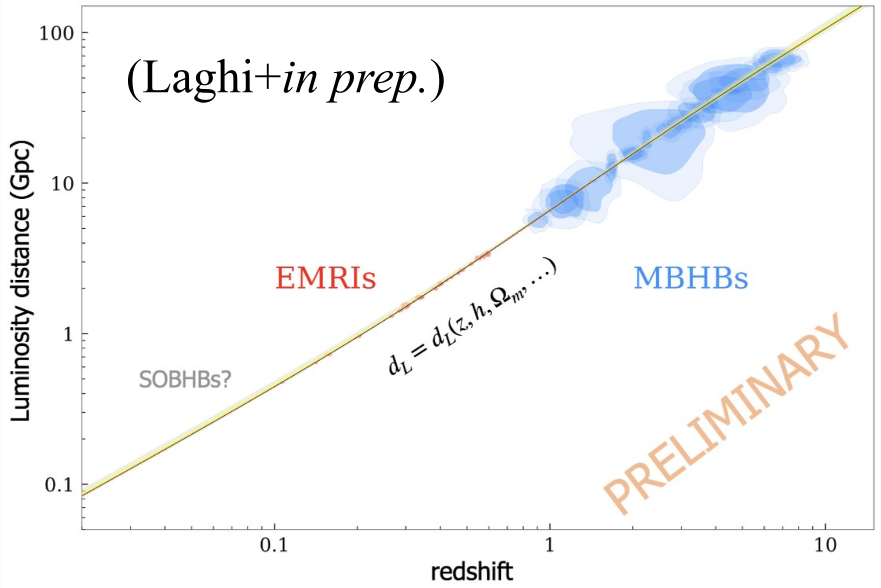
Cosmology with bright sirens will be challenging

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 and planning of observing campaigns

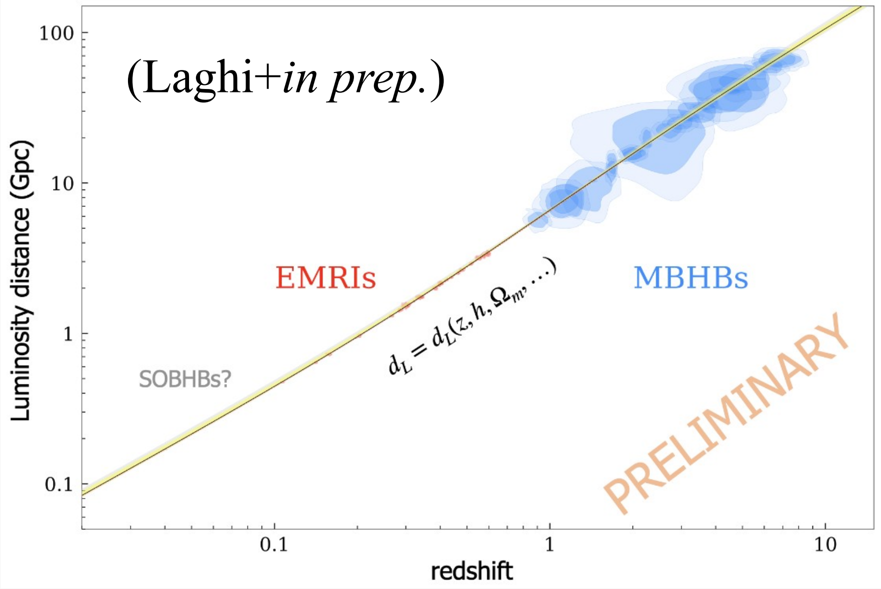
➤ Combine MBHBs with other LISA sources as SOBHBs and EMRIs

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 and planning of observing campaigns
- ➤ Combine MBHBs with other LISA sources as SOBHBs and EMRIs

Any questions ?

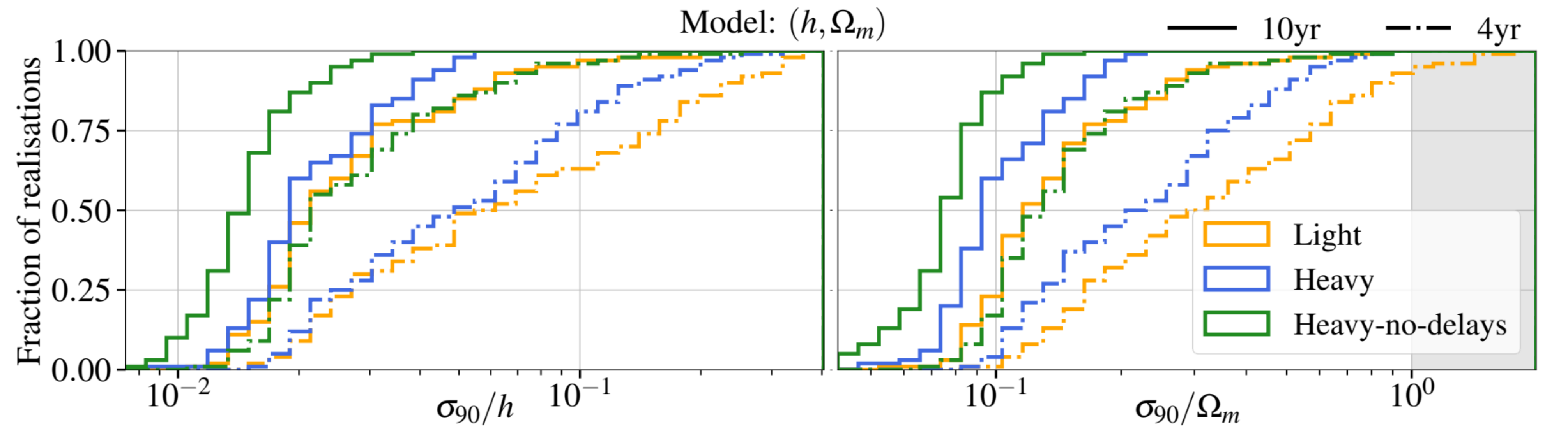
Backup slides

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

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 $z \leq$ 1-1.5

- Redshift bins

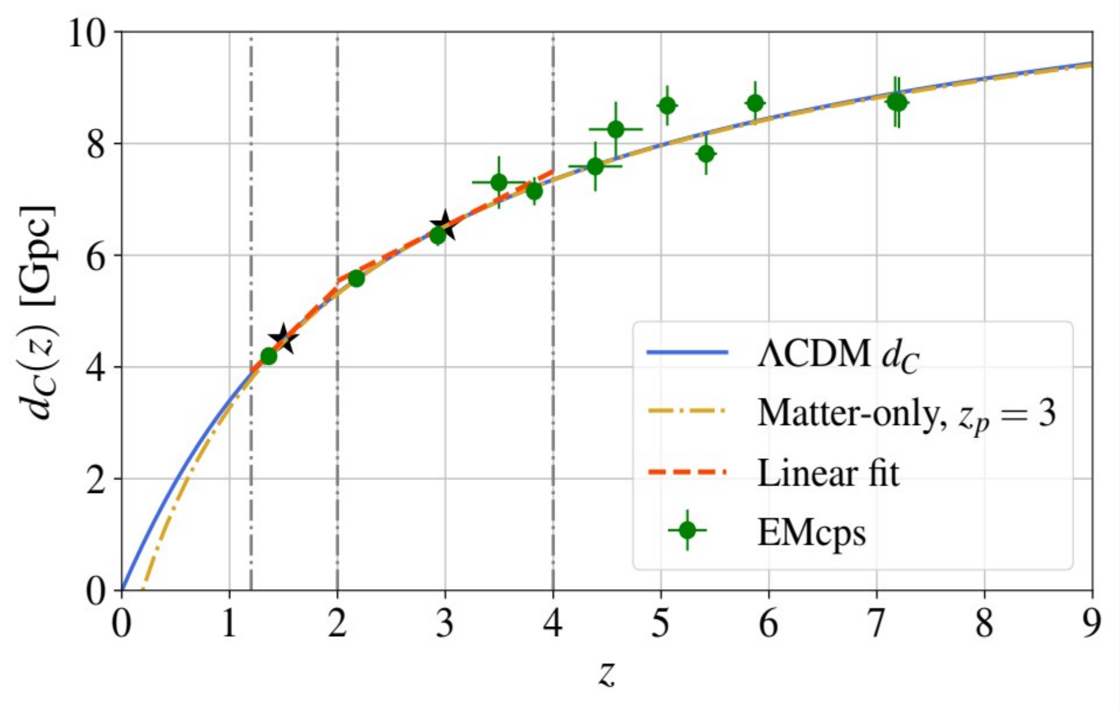
$$d_C(z) = c\int_0^z \frac{dz'}{H(z')} \qquad H(z) = \left(\frac{d\,d_C}{dz}\right)^{-1}$$

Trade-off between:

- Bin size
- Number of EMcps in each bin

Requirement: D(z) accuracy ≤ 5%

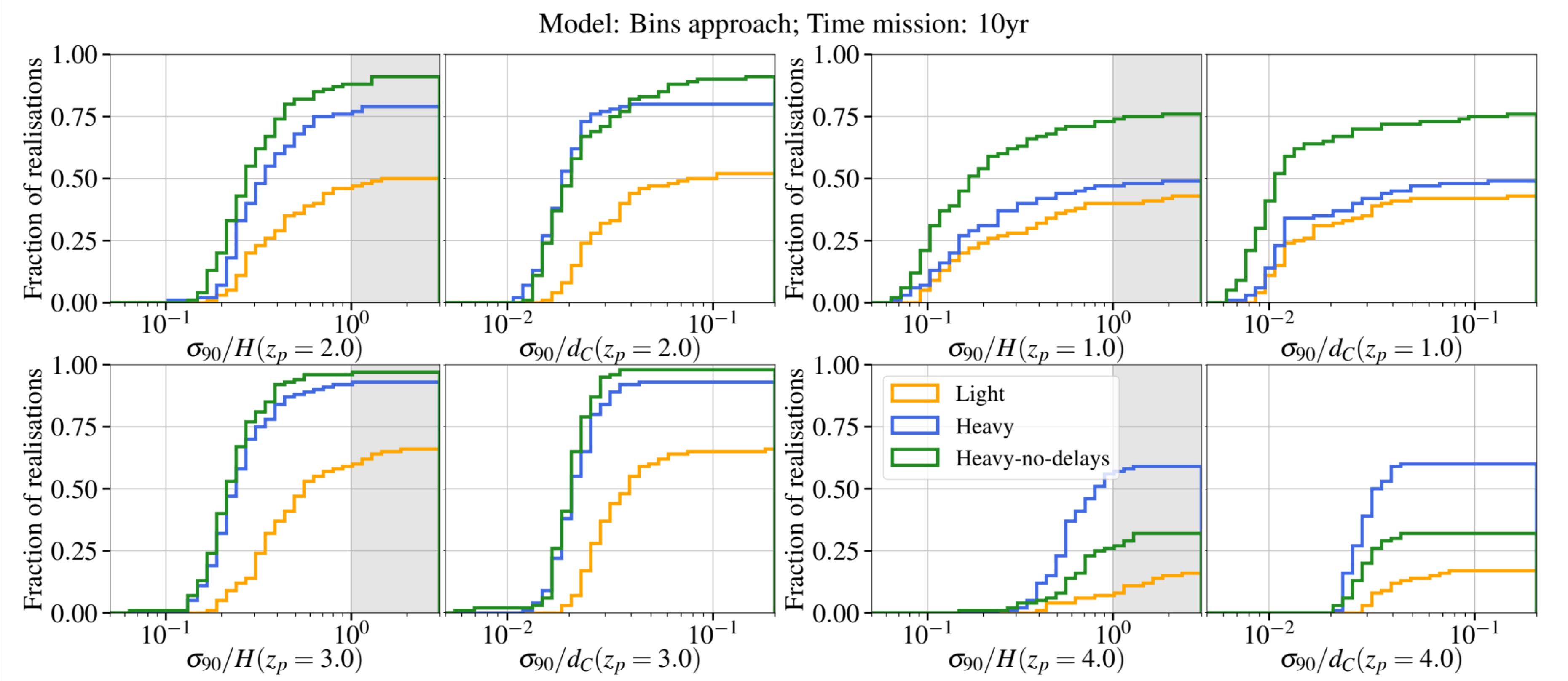
<u>Not all the redshift bins are informative</u>



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



What to do with uninformative realisations?

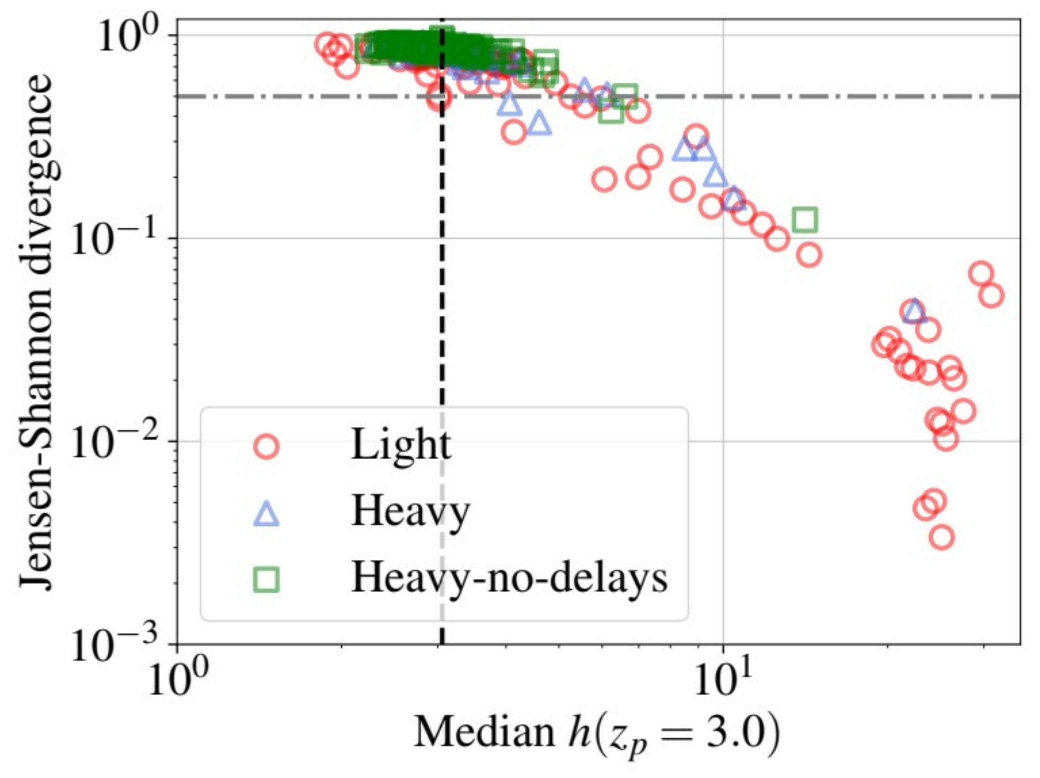
No or few events in a redshift bin → The realisation is not informative → The posterior distribution concides with the prior

Jensen-Shannon (JS) test

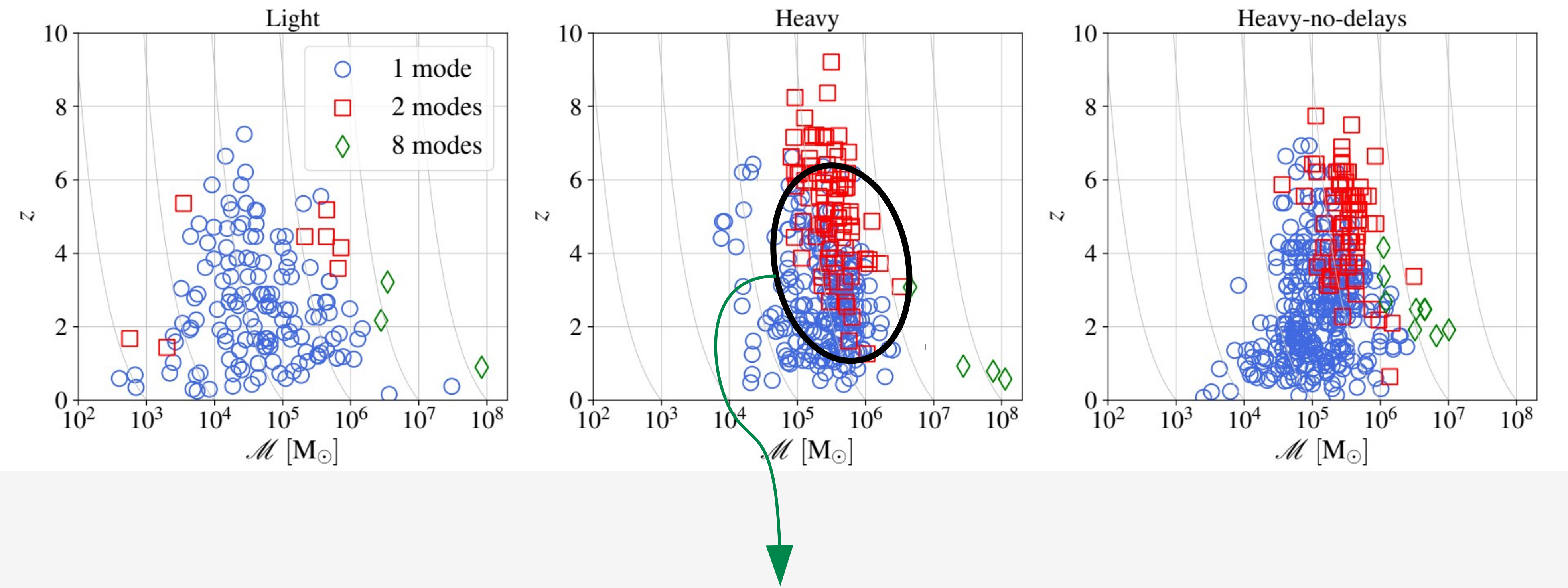
We compare the posterior and the prior distributions

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

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



Multimodality in the parameter space



Two systems with the same chirp mass and redshift might present different behaviour : multimodality depends also on extrinsic parameters !

Constructing the population of MBHBs with EM counterpart

Observing strategies

ArXiv:2207.10678

Optical

Rubin Observatory

X-Ray

Athena

$$L_{\rm bol} = \min\left(\epsilon_{\rm rad}\dot{M}_{\rm acc}c^2, L_{\rm Edd}\right)$$

(Shen+20)

$$L_{\rm opt} = 0.1 L_{\rm bol}$$

$$L_{\rm X} = \frac{L_{\rm bol}}{c_1\left(\frac{L_{\rm bol}}{10^{10}L_\odot}\right)^{k_1} + c_2\left(\frac{L_{\rm bol}}{10^{10}L_\odot}\right)^{k_2}}$$

- $\Delta\Omega <$ 10 deg^2
- $m_{\rm lim,\,opt} \sim 27.5$

- $\Delta\Omega <$ 0.4 deg^2
- $F_{\rm lim,\,X} \sim 3\times10^{-17}$ erg/s/cm^2

Radio

SKA

(Meier01)

$$L_{\rm radio} = L_{\rm flare} + L_{\rm jet}$$

- $\Delta\Omega <$ 10 deg^2
- $F_{\rm lim,\,radio} \sim 1\,\mu$Jy

We focus on two scenarios

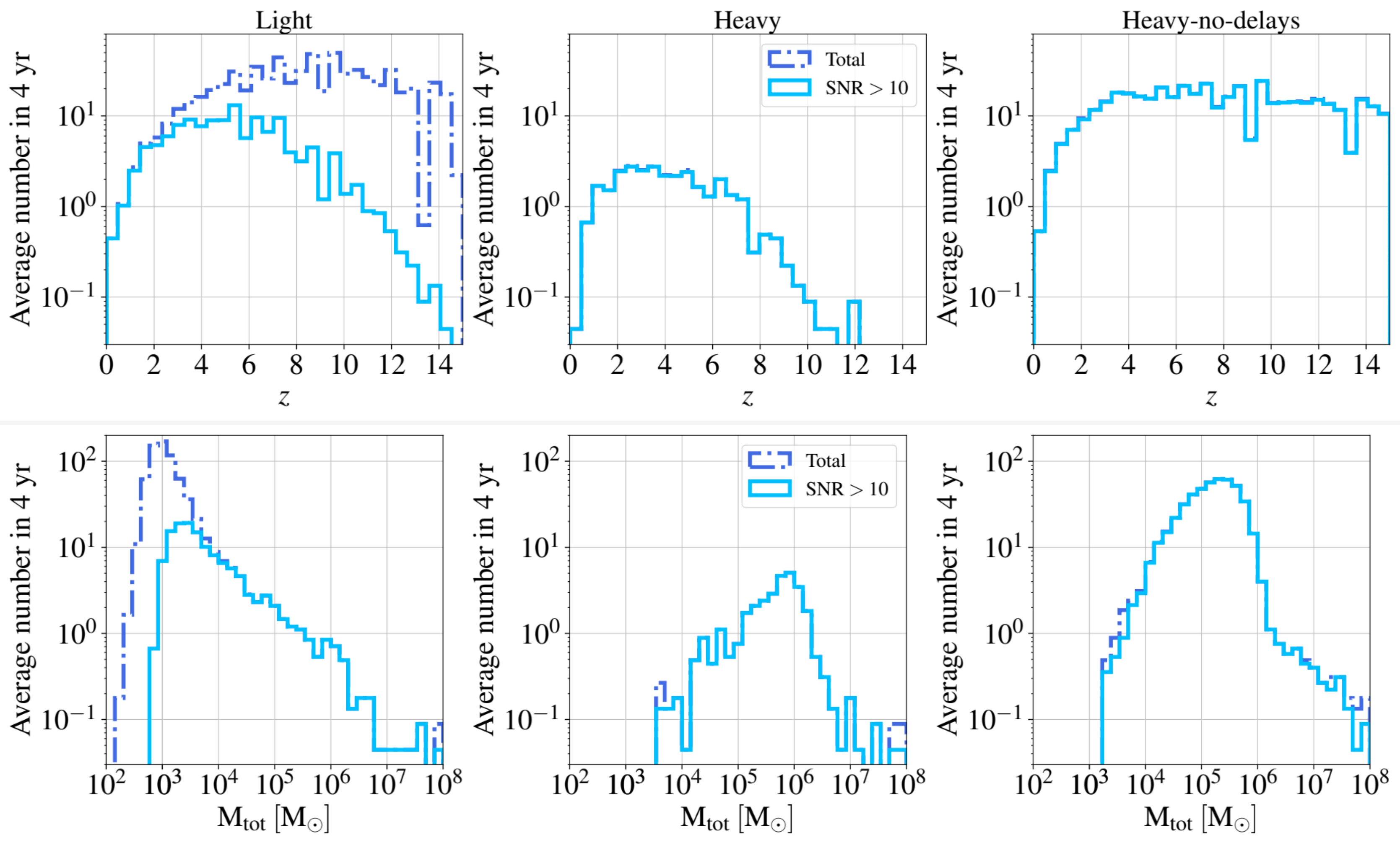
Maximising

- No AGN obscuration
- Isotropic radio emission

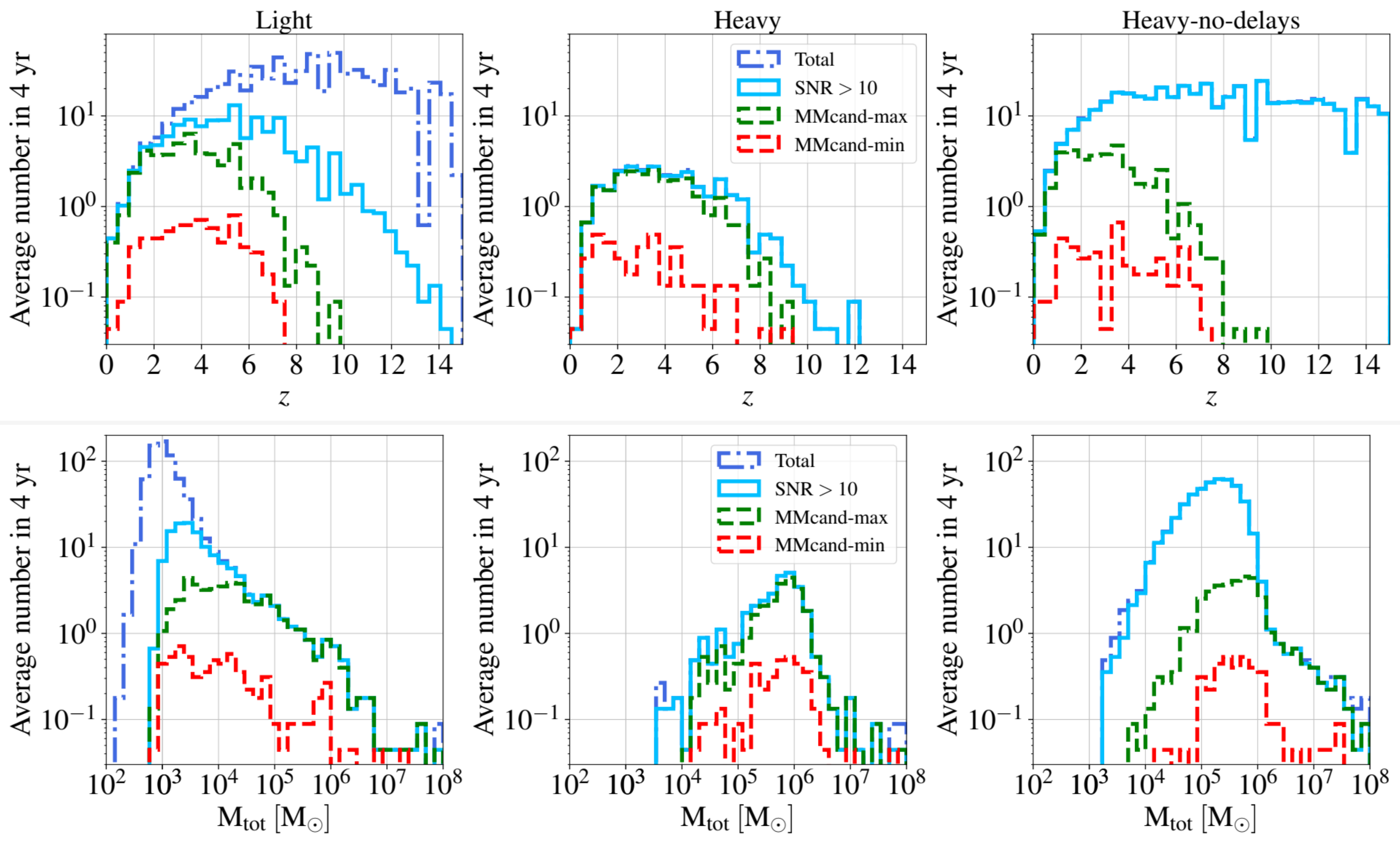
Minimising

- AGN obscuration included (Ueda+14, Gnedin+07)
- Collimated radio emission (Cohen+06)

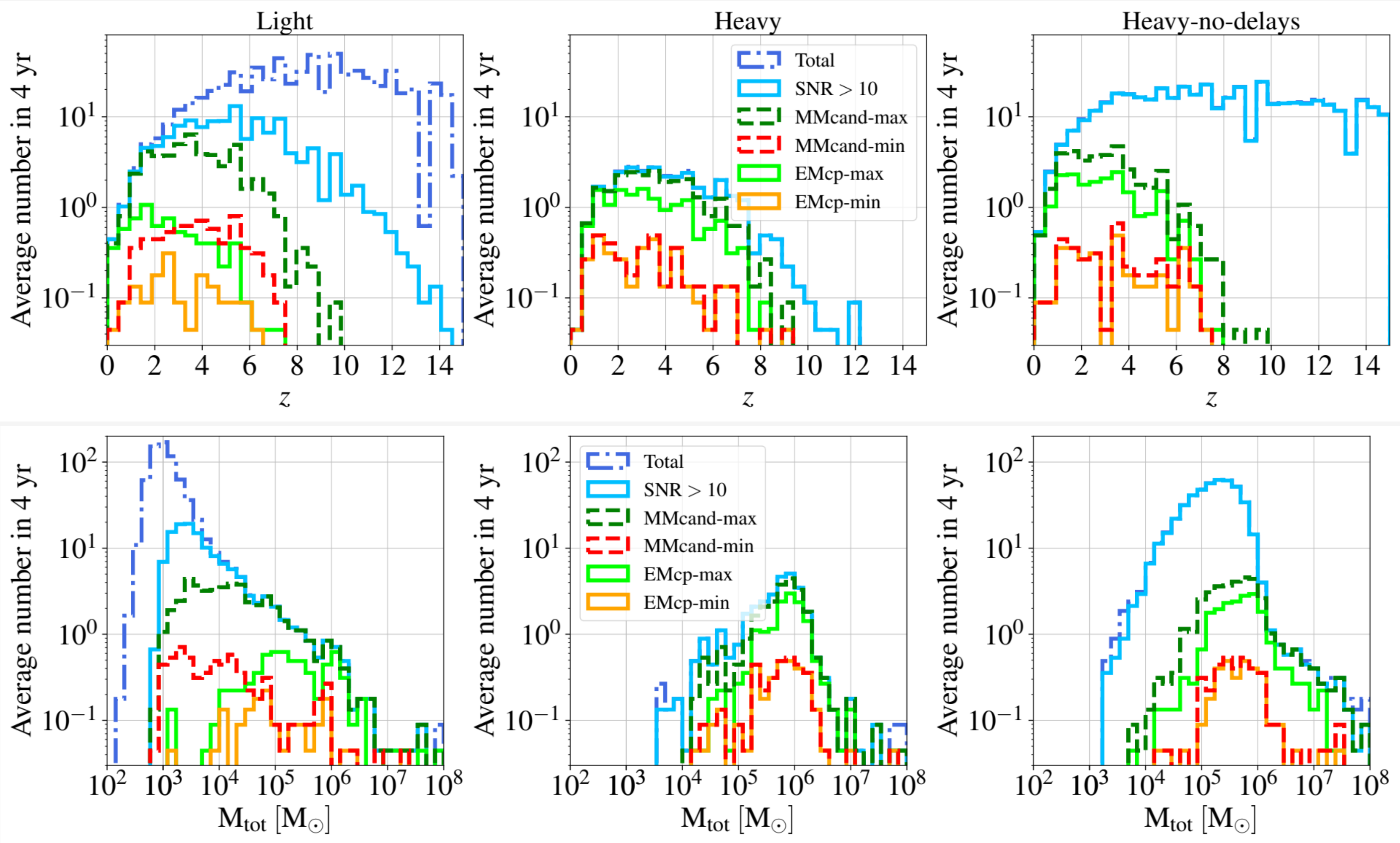
Redshift and total mass distributions



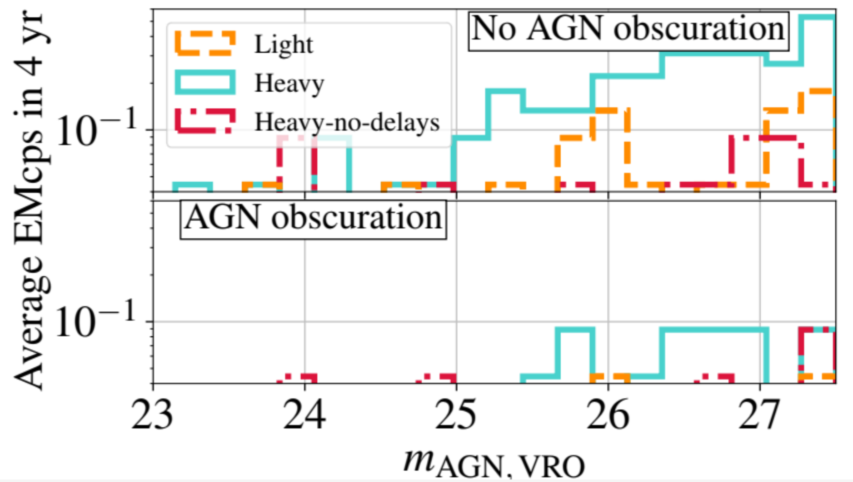
Redshift and total mass distributions

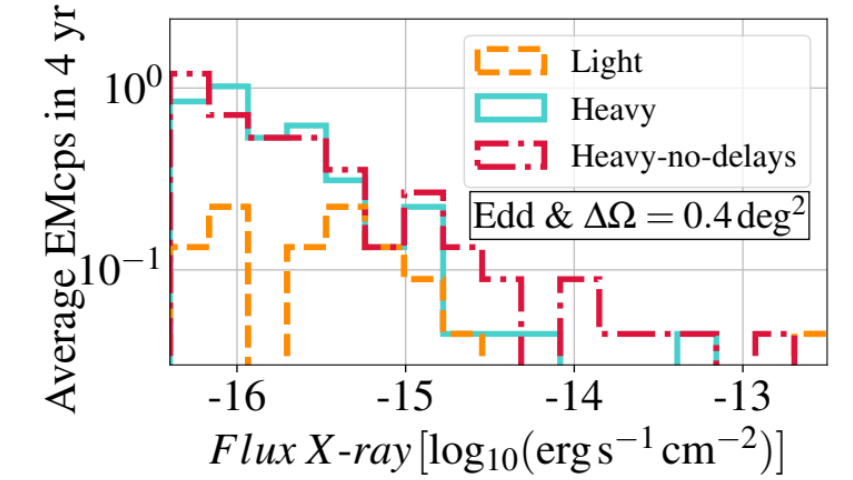


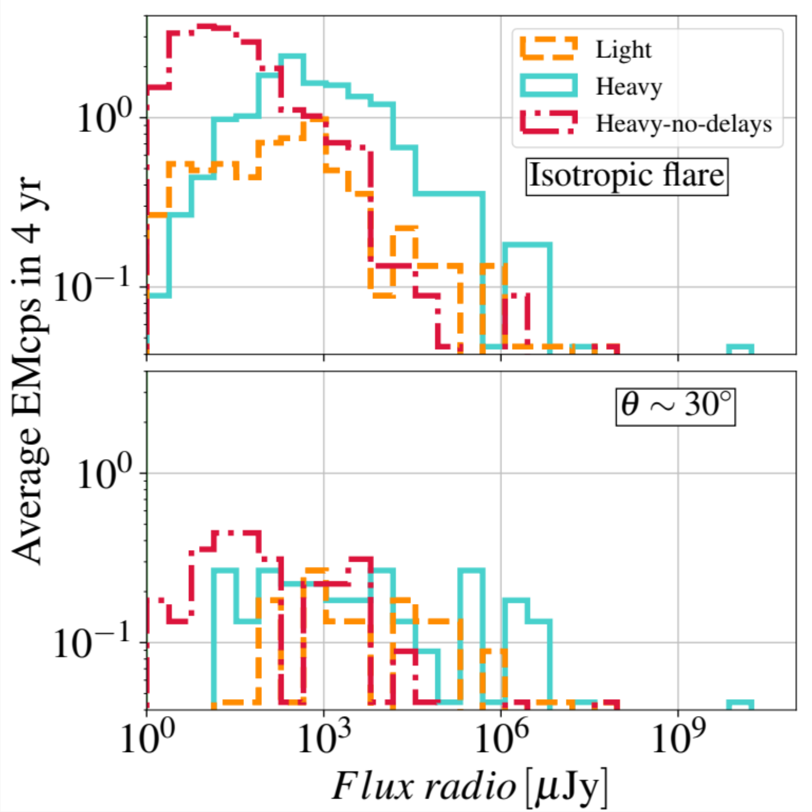
Redshift and total mass distributions



EMcps in optical, X-ray and radio







LISA sources are intrinsically faint !

EMcps in 4 yr

(In 4 yr)	LSST, VRO	SKA+ELT			Athena+ELT		
		Isotropic	$\theta \sim 30°$	$\theta \sim 6°$	Catalog $F_{\mathrm{X,\,lim}}$ = 4e-17	Eddington $F_{\mathrm{X,\,lim}}$ = 4e-17	
	$\Delta\Omega = 10\,\mathrm{deg}^2$				$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 0.4\,\mathrm{deg}^2$	
No-obsc.	0.84	6.4	1.51	0.04	0.49	1.02	Light
	3.07	14.8	2.71	0.04	2.67	3.87	Heavy
	0.53	20.3	3.2	0.04	0.58	4.4	Heavy-no-delays
Obsc.	0.13	6.4	1.51	0.04	0.04	0.13	Light
	0.75	14.8	2.71	0.04	0.22	0.18	Heavy
	0.35	20.3	3.2	0.04	0.18	0.27	Heavy-no-delays

- ➤ Dramatic decrease with obscuaration and radio jet
- ➤ Parameter estimation selects preferentially heavy

(In 4 yr)	Maximising	Minimising
Light	6.4	1.6
Heavy	14.8	3.3
Heavy-no-delays	20.7	3.5