Constraining the expansion of the Universe with massive black hole binaries

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10th LISA Cosmology Working Group Workshop

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 $z \sim 2.5$

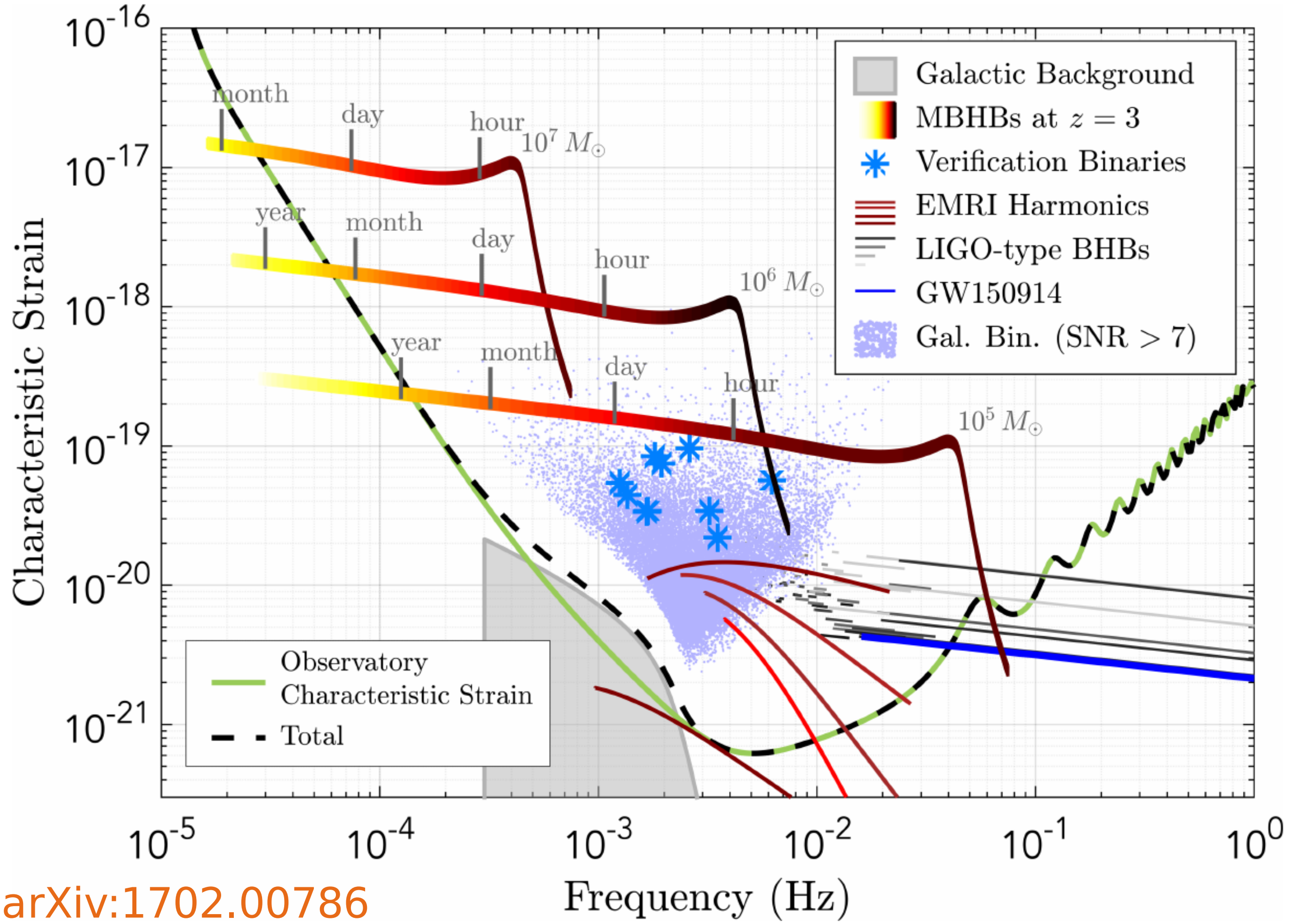
We need new models and new probes!

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**

What sources do we have with LISA ?



arXiv:1702.00786

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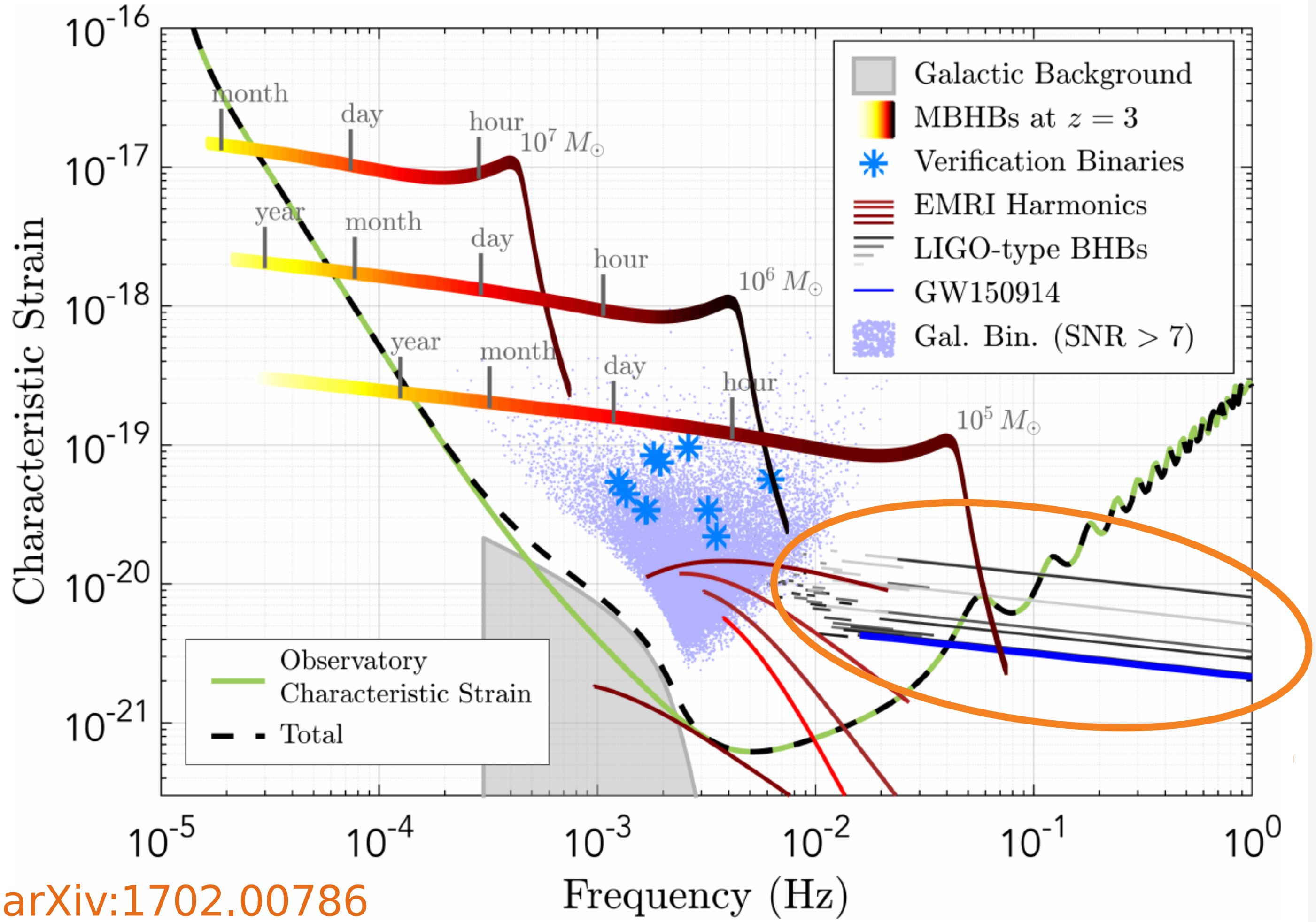

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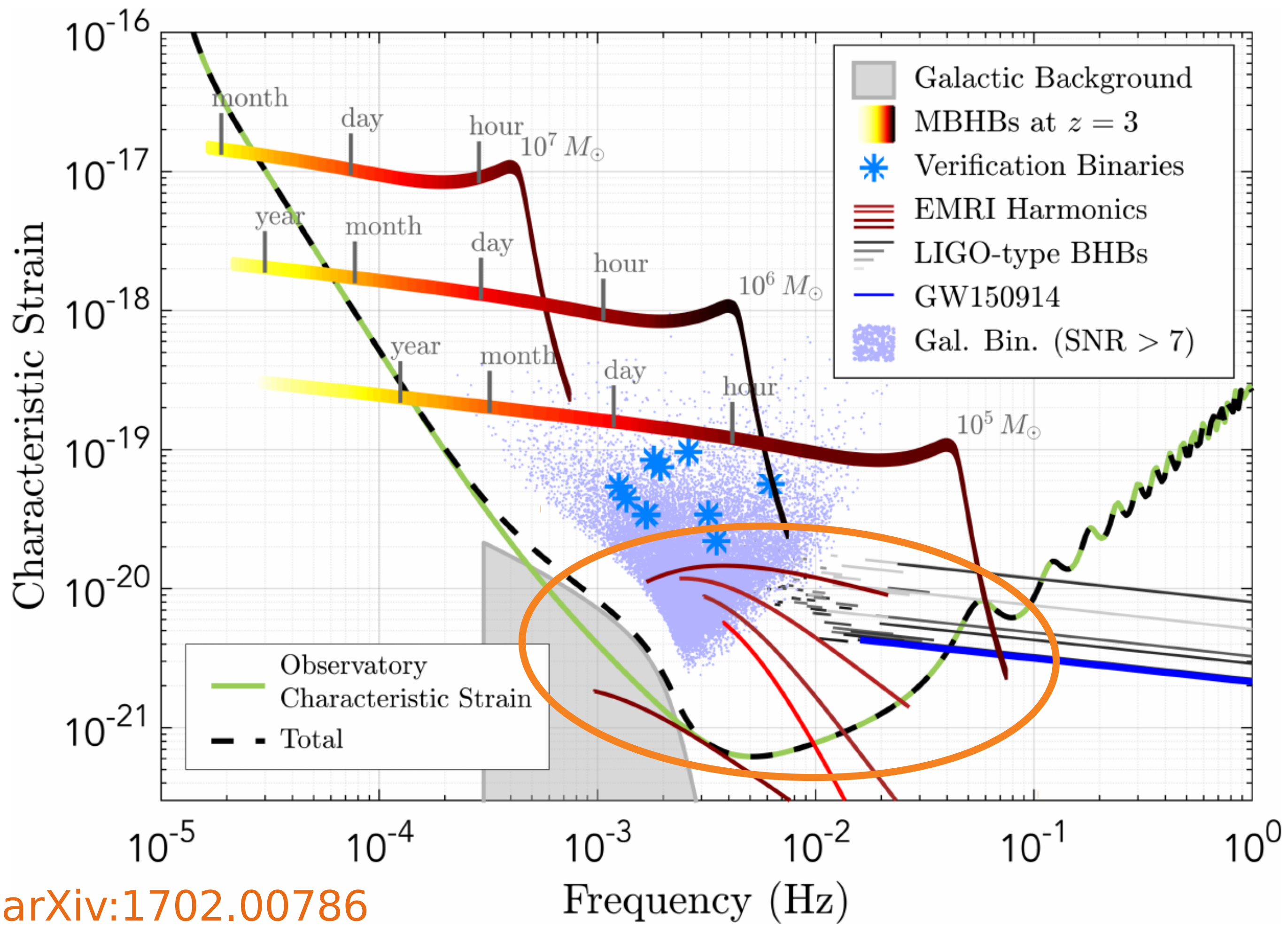

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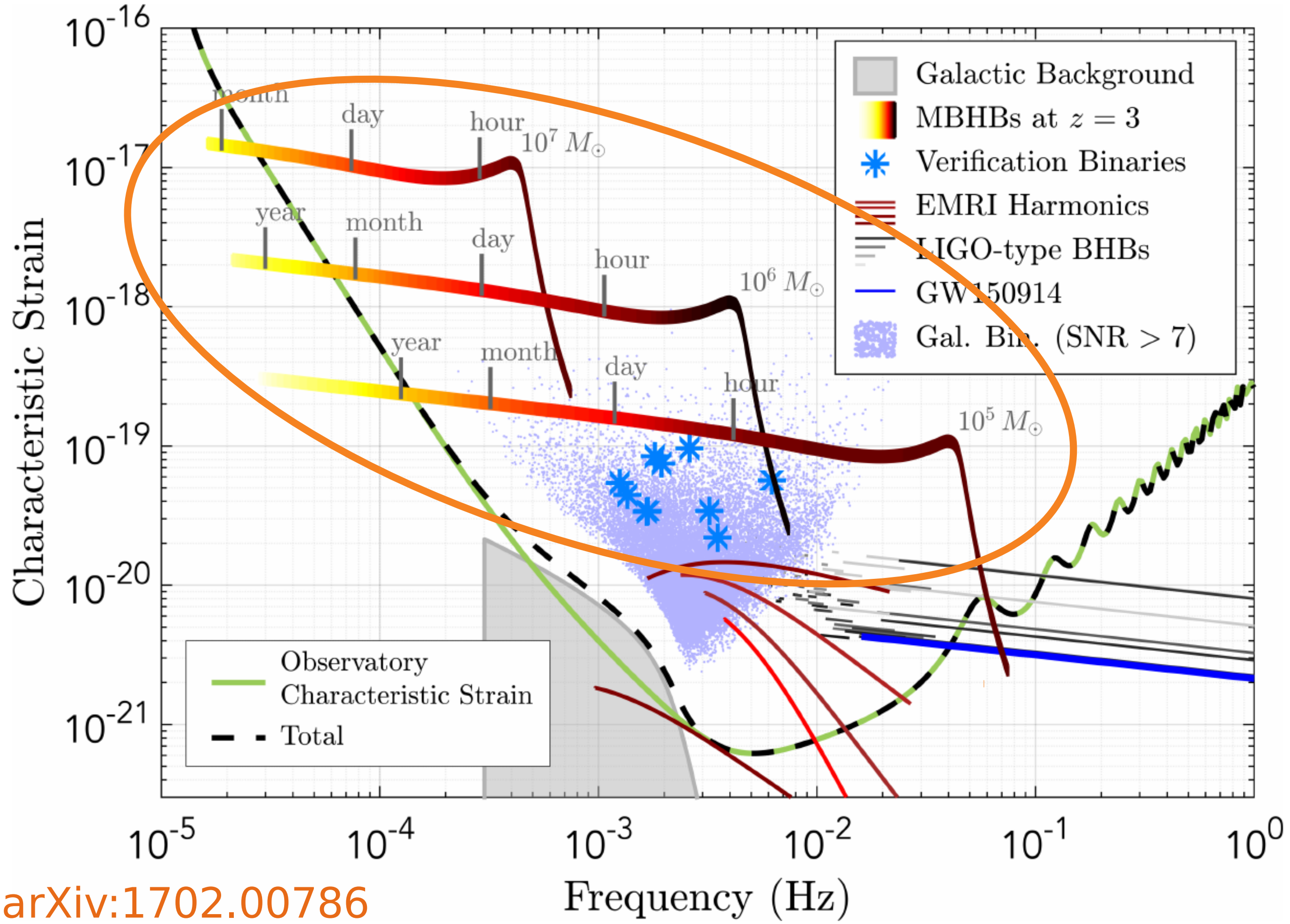

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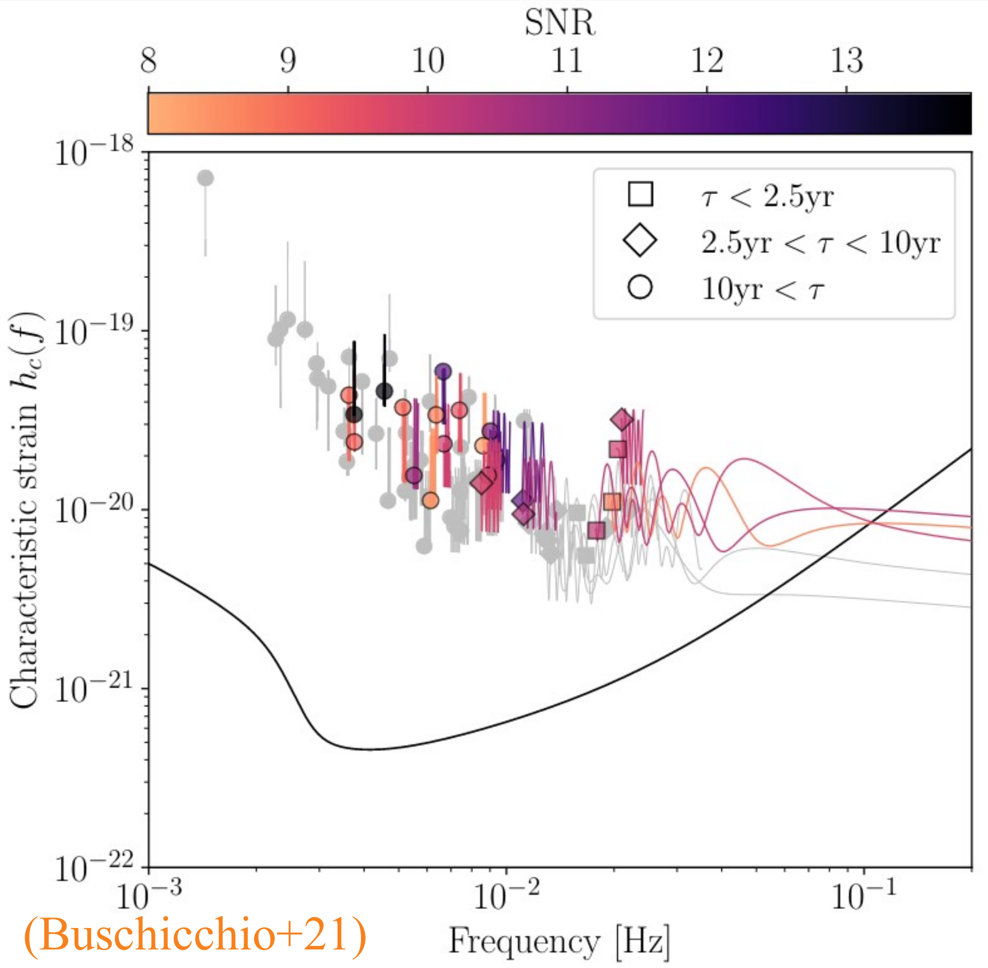
Stellar BHBs at high frequency : LISA point of view



(Buschicchio+21)

- We expect ~10 in 4 yrs and 1-2 multi-band systems during LISA

- Long-lived sources

↓

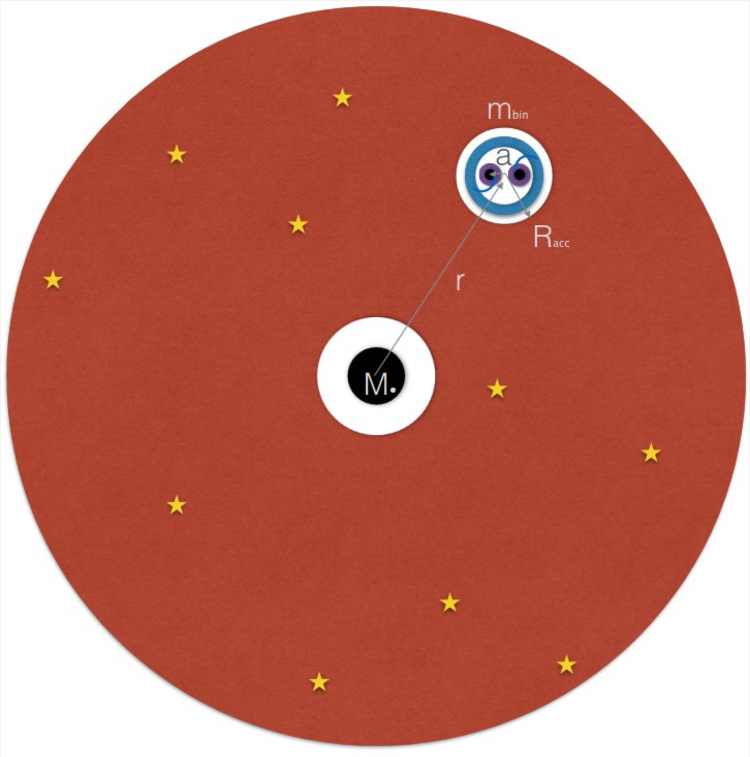
✓ Accurate sky localization (~10 deg^2)

✗ Poor d_L estimates

✓ Time to search for EM counterpart in the inspiral and Δt_{merger} ~ mins

EM counterpart to Stellar BHBs mergers

Isolated and dynamical formation channels do not predit an EM counterpart, but...



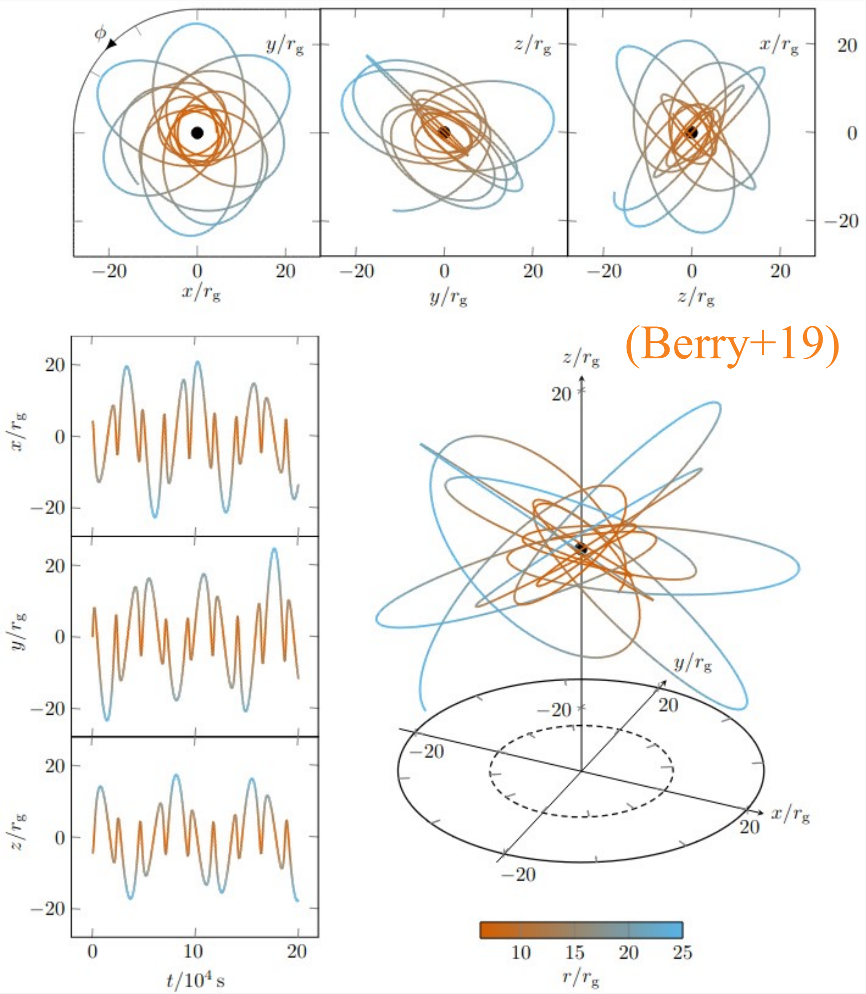
(Stone+16, Bartos+16, Caputo+20)

- ✗ Gamma-ray :
  - ➤ It requires $L \sim 10^4\ L_{edd}$
  - ➤ Might be facilitated by jet emission
- ✗ X-ray :
  - ➤ Accretion still requires $L > 10^4\ L_{edd}$
  - ➤ Remnant kicks are uncertain

✓ $L \sim 2\text{-}5 \times L_{edd}$ leaves a detectable imprint in the GW signal (Sberna+22)

EM emissions might be AGN-dominated

Extreme mass ratio inspiral in LISA



(Berry+19)

- ➤ Uncertain merger rate : ~1-10^3/yr events
- ➤ Long-lived sources as SBHBs

↓

✔ Accurate sky localization (~10 deg^2)

✗ Poor d_L estimates

- ➤ Complex data analysis procedure :
  - ✗ Overlapping signals
  - ✗ Higher harmonics

(Check Pozzoli's talk for SGWB from EMRIs)

EM counterpart from EMRIs

Two types of sources :

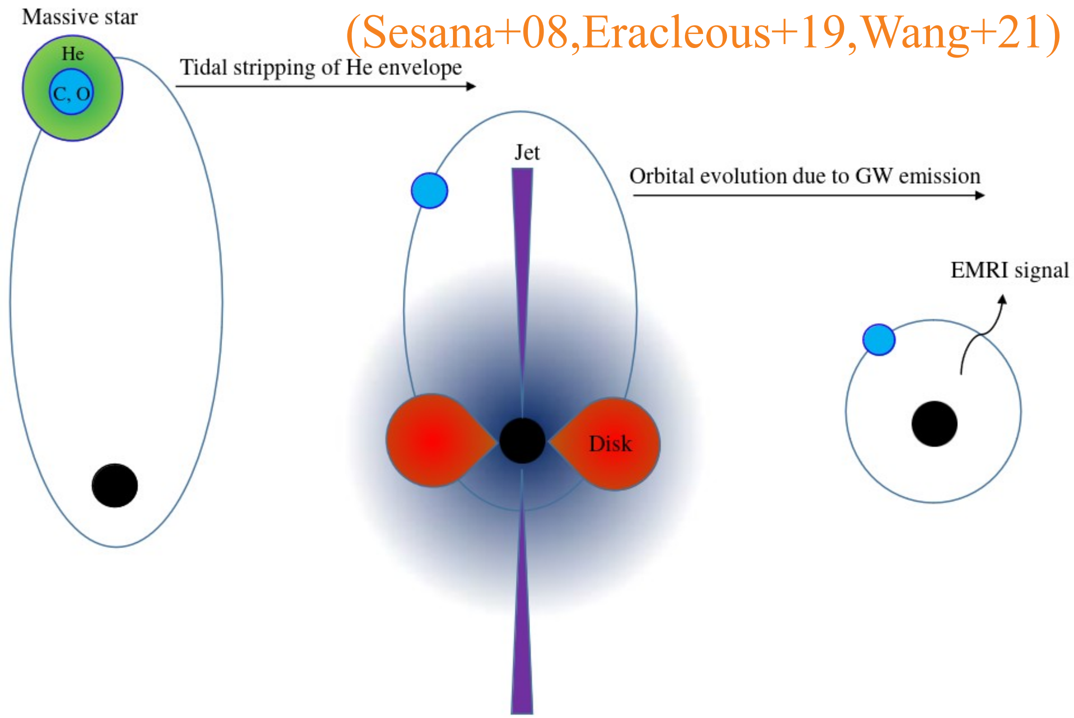
- White Dwarfs → GW signal before EM
- Massive stars → EM signal before GW

- Broad rate : 0.01-10^2 /yr
- Two horizon scales:
  - GW horizon : z~0.1
  - EM horizon : z~1

✔ Bright X-ray emission ~ 10^{44-45} erg/s

✗ For massive stars : delay of ~10-20 yrs between the two signals

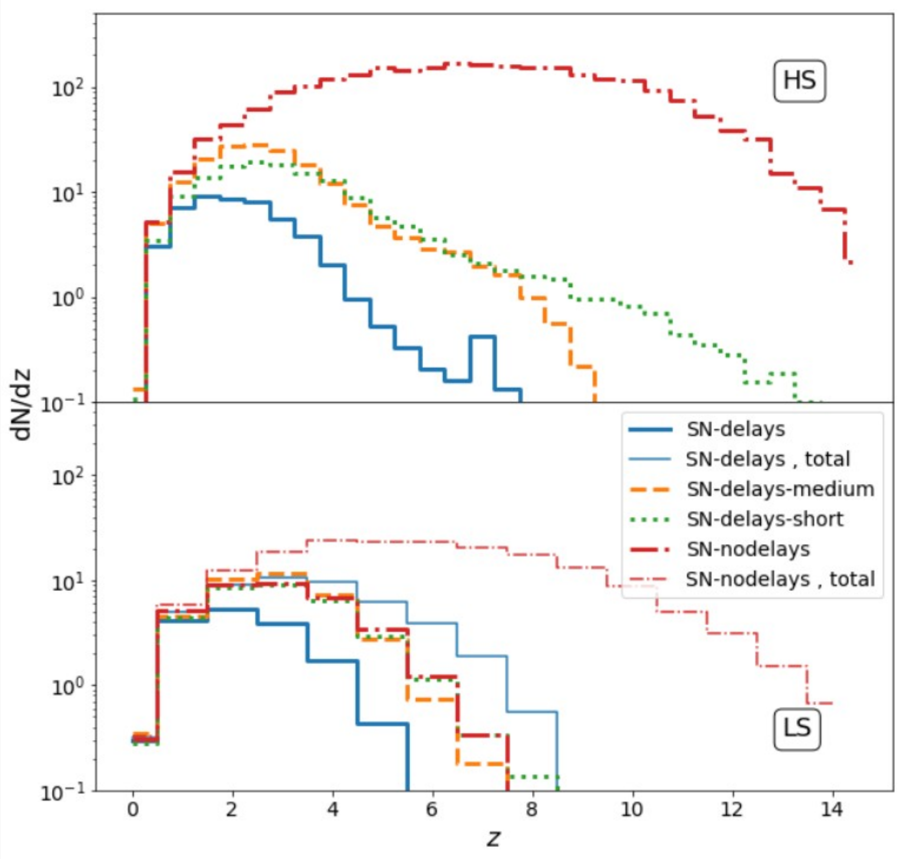
(Sesana+08,Eracleous+19,Wang+21)



Let’s move to Massive BHBs (MBHBs)

MBHB merger rates

Let's proceed with order: How many MBHB mergers do we expect?



Large uncertainties in astrophysical processes (Klein+16, Katz+19, Barausse+20):

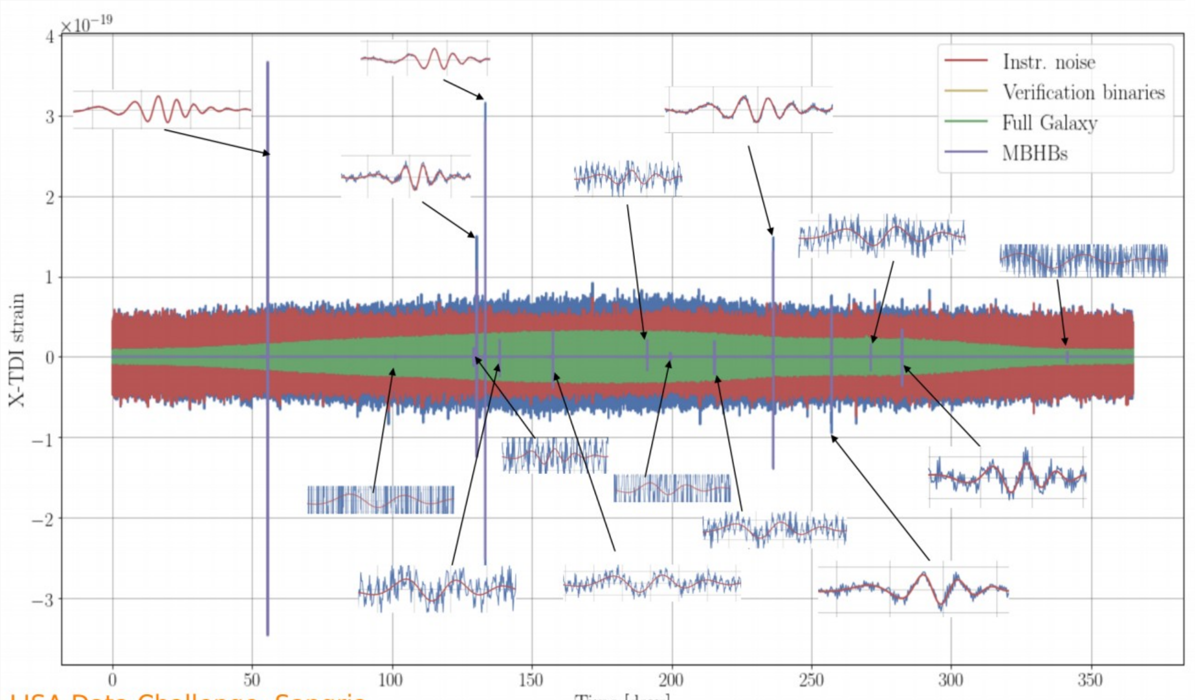
- ➤ Initial seed mass
- ➤ Time delays between galaxy and MBHB merger
- ➤ Feedback processes

Cosmological simulations predicts ~ 1/yr with $M_{BH} \sim 10^5\, M_\odot$

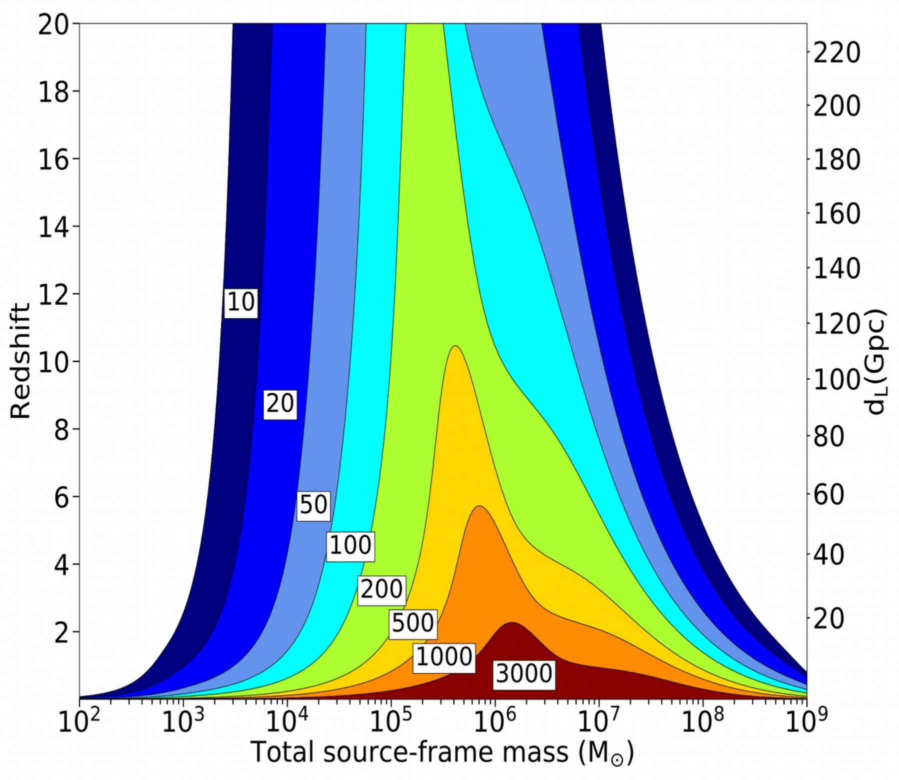
From few to several hundreads per year

How MBHBs do look like in LISA?

- ➤ Strong and long-lasting signals
- ➤ Strong overlap between signals from different sources → Global fit approach
- ➤ Detectable up to z ∼ 20



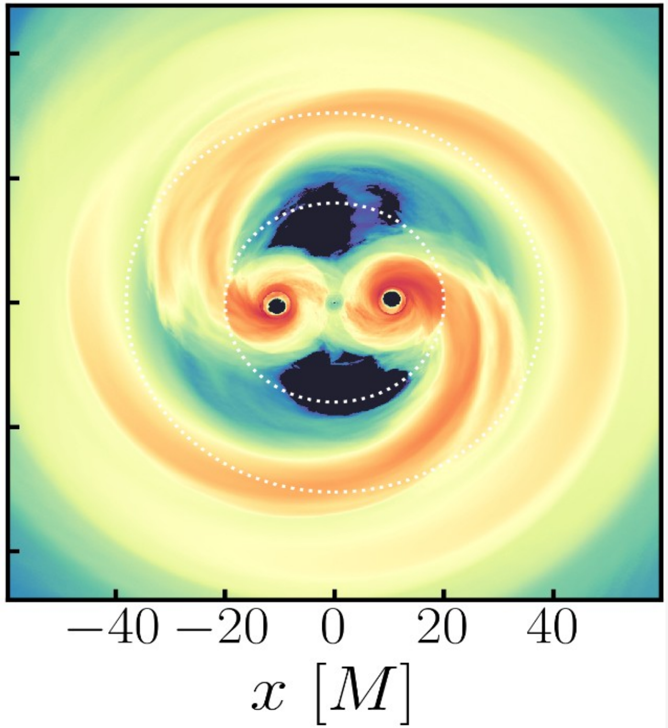
LISA Data Challenge, Sangria



What EM emission do we expect?

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

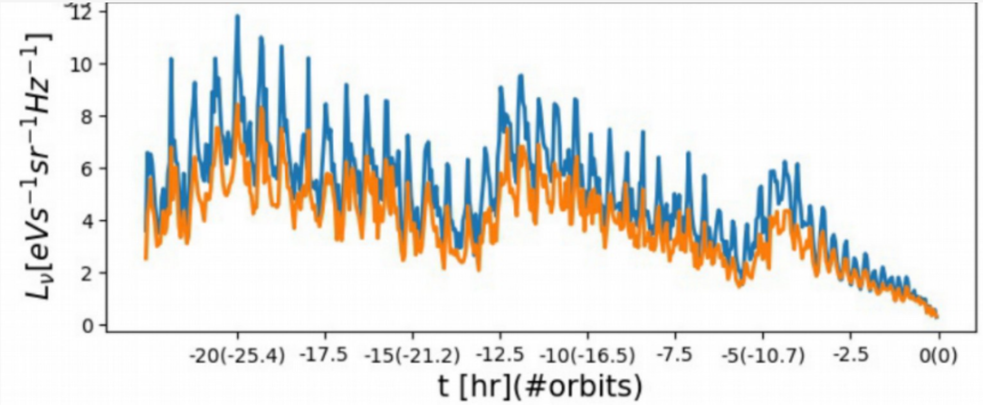
During the inspiral . . .



- ➤ The binary excavates a cavity
- ➤ Two bright minidisks around each BHs emitting in X-ray
- ➤ Gas streams flowing in the cavity
- ➤ Periodicities due to the orbital motion of the binary might be clear signatures (Dal Canton, AM +19)

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

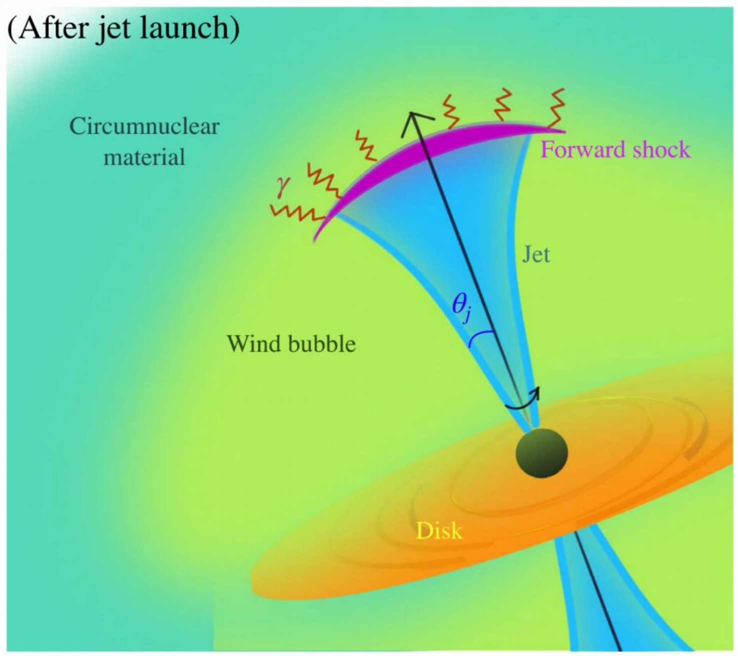
What EM emission do we expect?



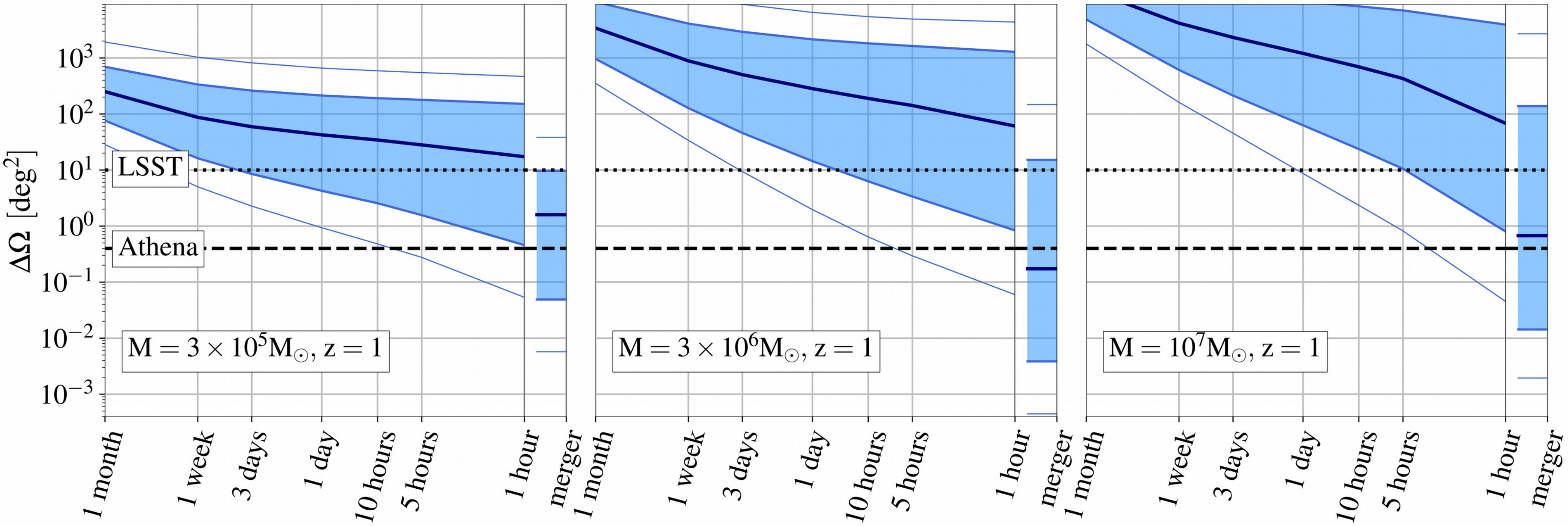
However, close at merger, minidisks might be depleated ⇒ Reduction in luminosity (Tang+18)

Post-merger signatures

- ➤ Disk-rebrightening (Rossi+10)
  - ✔ In-plane kicks for BHs with spins aligned along the orbital momentum
  - ✘ Might be to weak to be observed
- ➤ Afterglow emission (Yuan+21)
  - ✔ Broad band emission from radio to X-ray
  - ✘ Delays from days to months



LISA sky localization for systems at z = 1

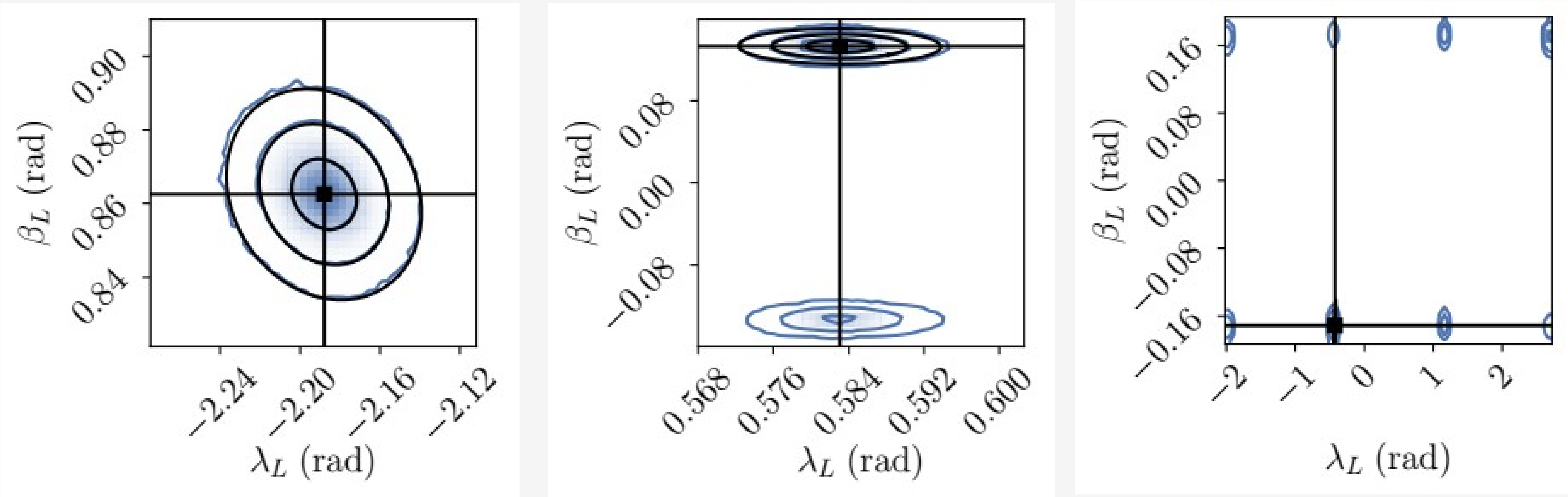


$\Delta\Omega$ ~ telescope FOV only close to merger → < 10 hrs **LSST**; → merger **Athena**

Large distributions → strong dependence from true binary position

“Multimodal” LISA events

Systems with multimodal sky posterior distribution from LISA data analysis



- Arise from LISA degeneracy pattern function
- 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

“Multimodal” LISA events

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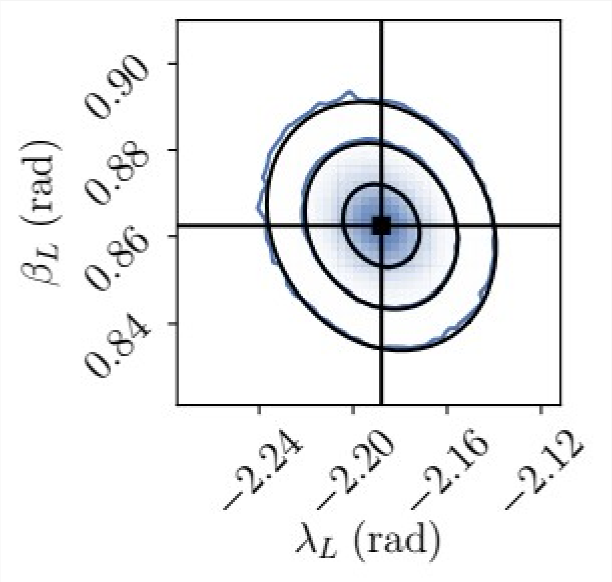

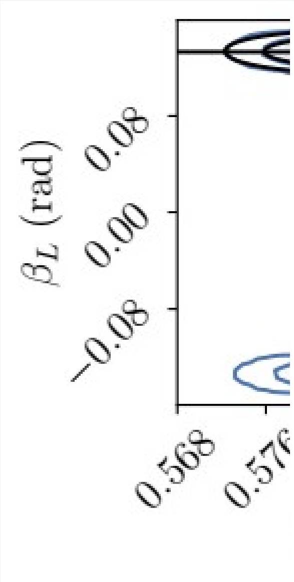

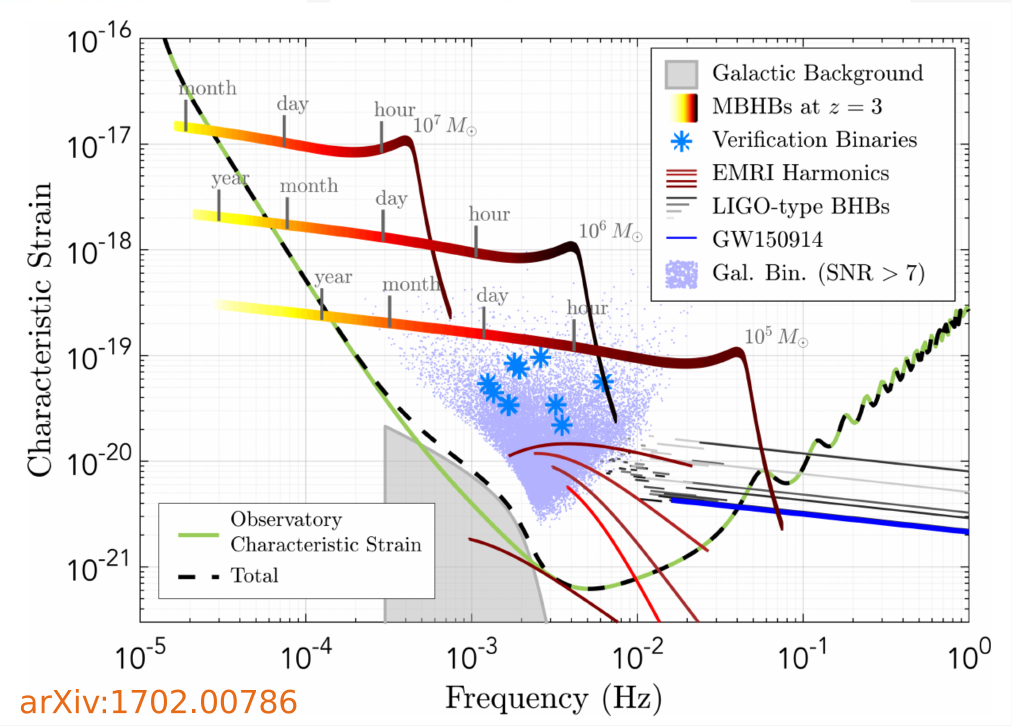

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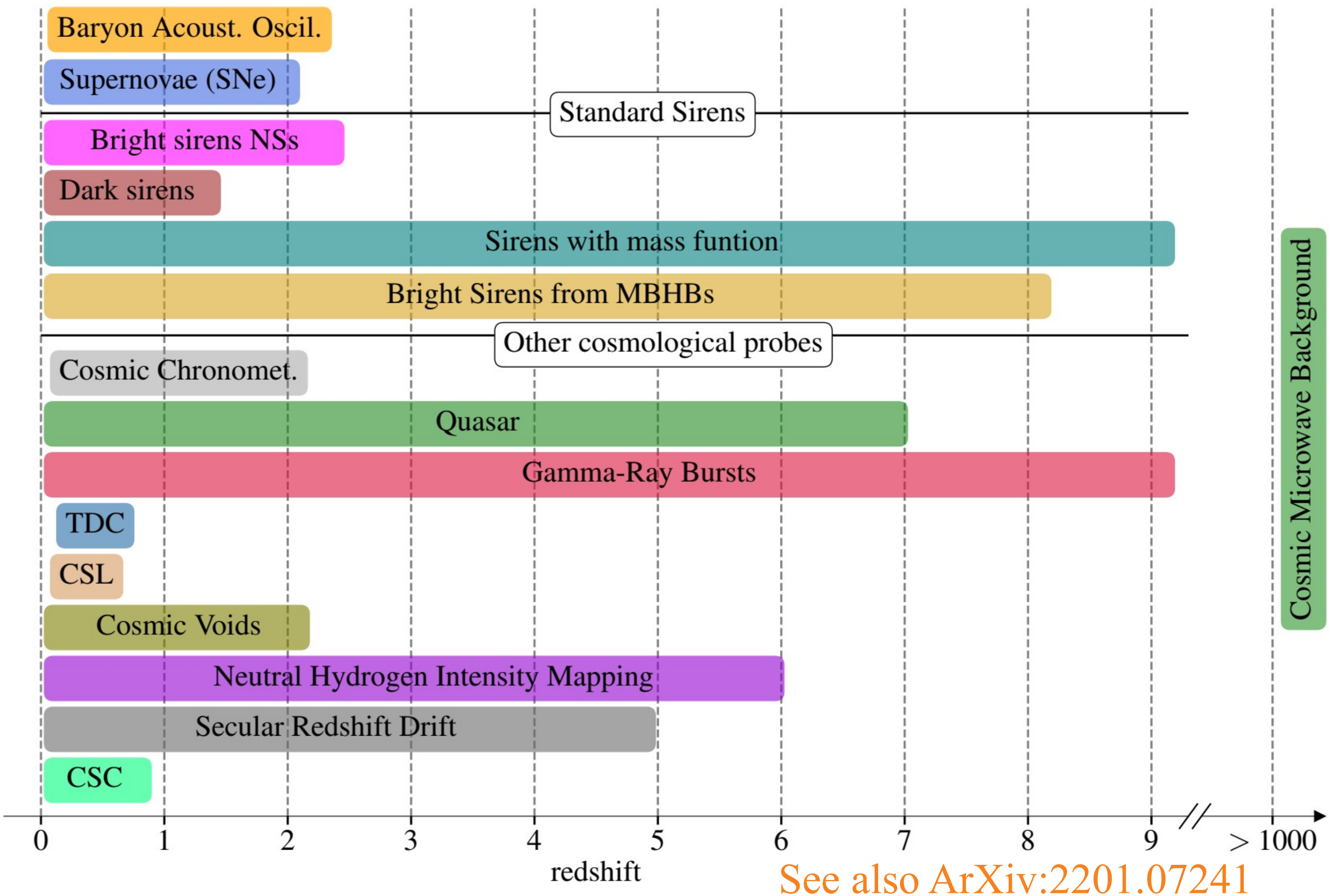
MBHBs can go up to high redshift



See also ArXiv:2201.07241

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

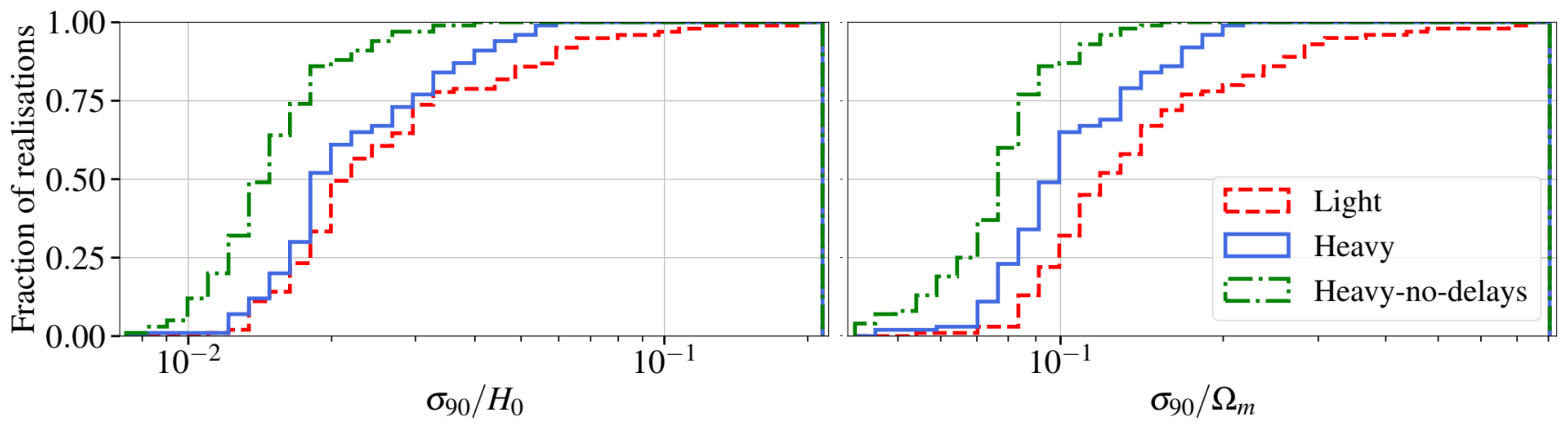
(In 4 yr)	Standard	w Obsc./Colli. radio
Light	6.4	1.6
Heavy	14.8	3.3
Heavy-no-delays	20.7	3.5

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

Prospects for H_0 and Ω_m in 10 yr

Fit: $H(z) = H_0\sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)}$
with 10yr of LISA observations

Light	Heavy	Heavy-no-delays
16	37	51.7



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

Redshift bin approach in 10 yr

$$D \equiv \frac{d_L(z)}{1+z} = c\int_0^z \frac{dz'}{H(z')}$$

$$H(z) = \left(\frac{dD}{dz}\right)^{-1}$$

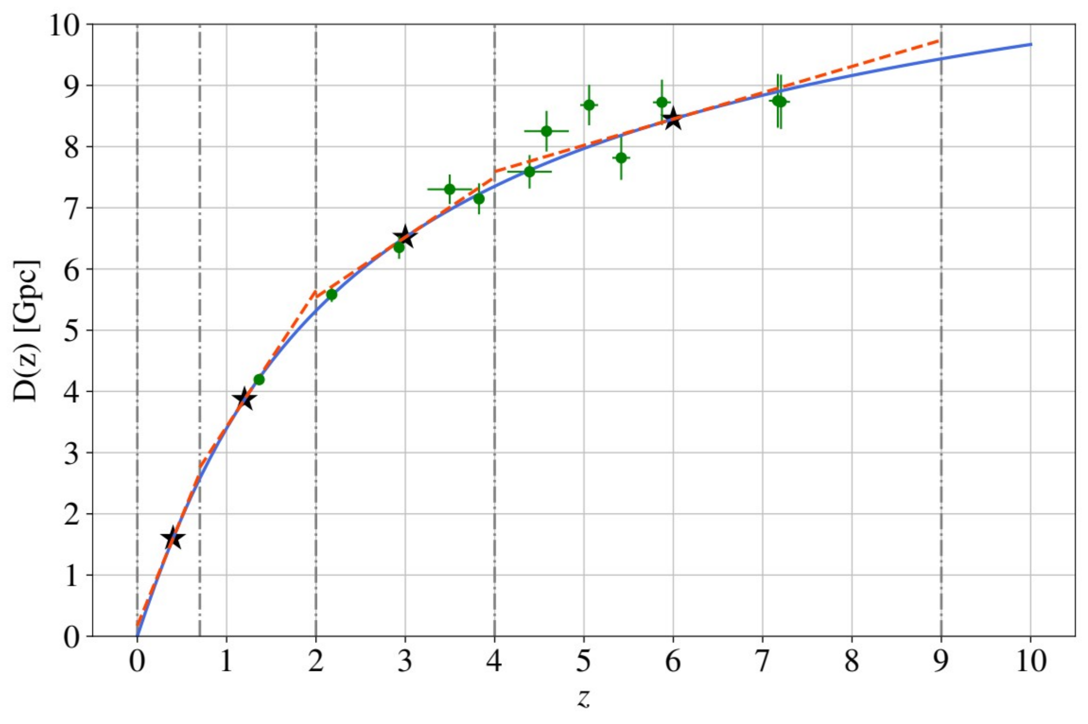
Model independent approach

(it assumes only flatness)

Trade-off between:

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

Requirement: D(z) accuracy ≤ 5%

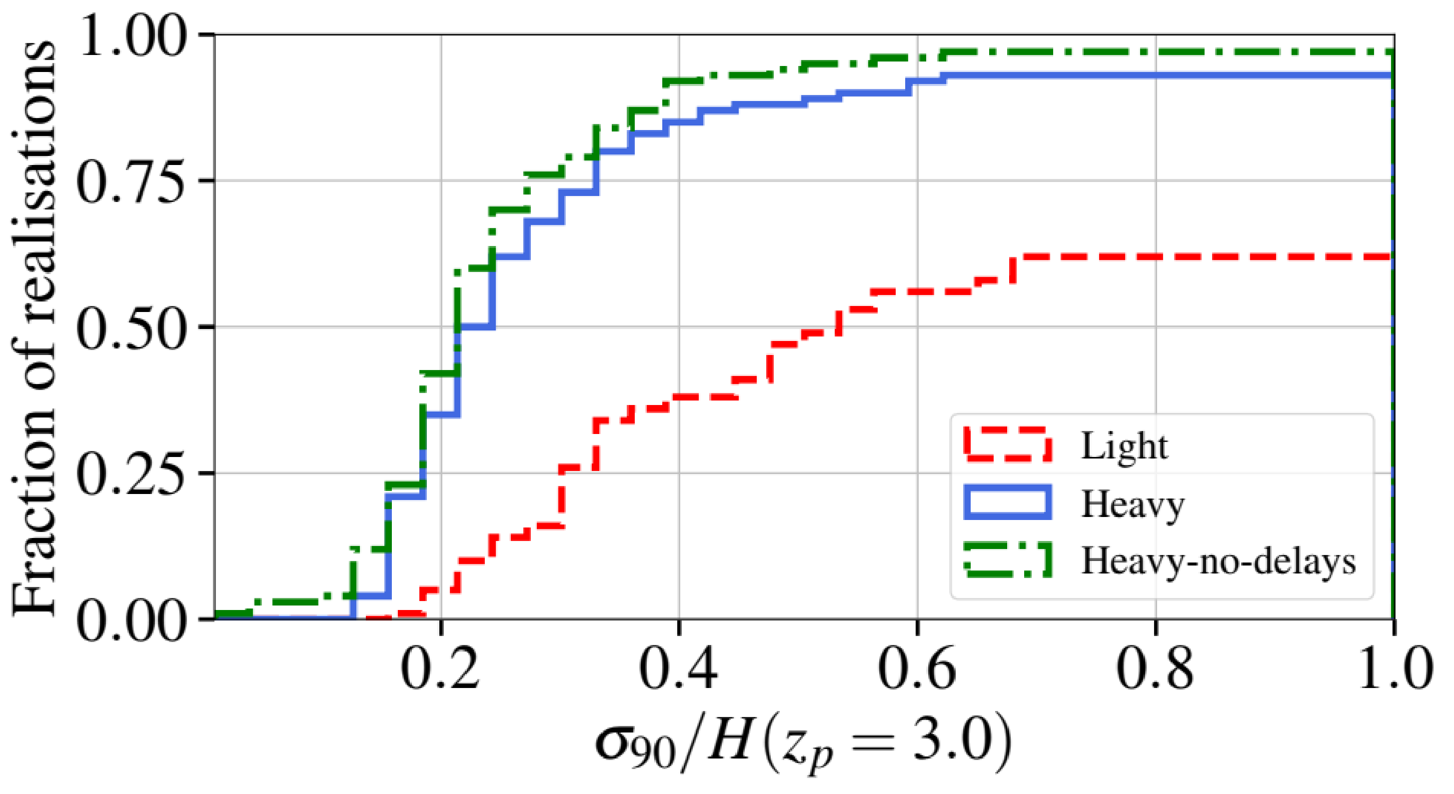


What if we do not have EMcp in a bin or if the D and z errors are too broad?

Constraining H(z) at high redshifts (Preliminary results)

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



Conclusion

Cosmology with bright sirens will be challenging

Stellar BHBs
- ✔ Granted sources from LVK
- ✔ Local cosmological measurements
- ✘ EM counterpart might be too faint

EMRIs
- ✘ Uncertainties in the merger rate
- ✔ Local cosmological measurements
- ✔ EM counterpart is similar to AGN luminosity
- ✘ Only few studies on the topic

Massive BHBs
- ✘ Uncertainties in the merger rate
- ✔ Local cosmological measurements
- ✔ High-z cosmological measurements
- ✔ Broad type of EM emission
- ✘ Our strategy depend strongly on the radio emission : we need better modeling

From the current results
- ➤ H_0 constrained to few percent in 10 yr
- ➤ Larger uncertainties on Ω_m
- ➤ Provide information on H(z) at high redshifts

Backup slides

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

ΛCDM Universe

- ΛCDM parametrization
  2-parameters model: (H_0, Ω_m)
  (see Caprini's talk)

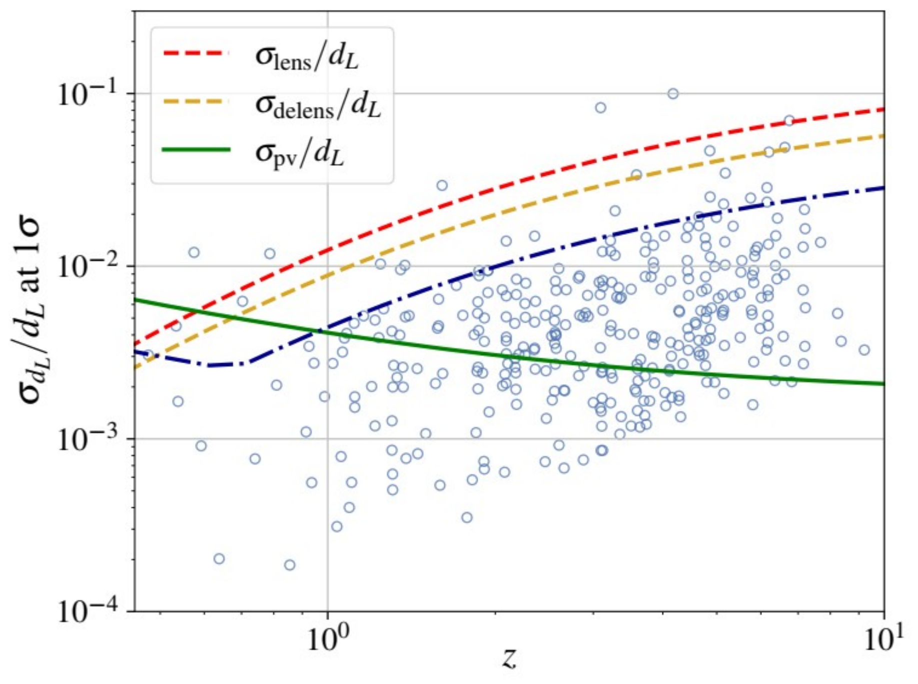
Dark energy/modified gravity

- CPL parametrization for ω(z)
  4-parameters model: (H_0, Ω_m, ω_0, ω_a)
  Phenomenological Tracker model (Bull+20)
- 4-parameters model: (ω_0, ω_∞,z_c,Δz)
  (work in progress)
- Phenomen. modified gravity (Belgacem+19)
  2-parameters model: (Ξ_0 , n)
  (see Caprini's talk)

At high redshift

- Matter-only approximation
  2-parameter models: $D(z_p)$, $H(z_p)$
  (see Caprini's talk)
- Redshift bin approach
  Model-independent
  2-parameter models: $D(z_p)$, $H(z_p)$
- Splines interpolation
  Model-independent
  Constrain at all redshifts
  (work in progress)

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.

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

ELT

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

EMcps in optical, X-ray and radio