Constraining cosmological parameters with massive black hole binaries

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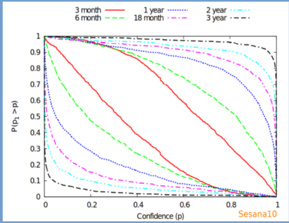
Why should we focus on MBHBs?

The importance of MBHBs

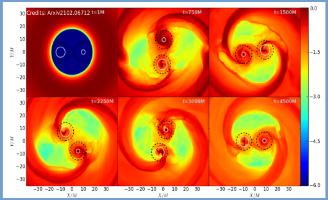
Astrophysics

Constrain MBHBs formation and evolution scenarios



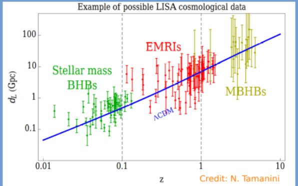
Multi-messenger

Formation of X-ray corona and jet around newly formed horizons



Cosmology

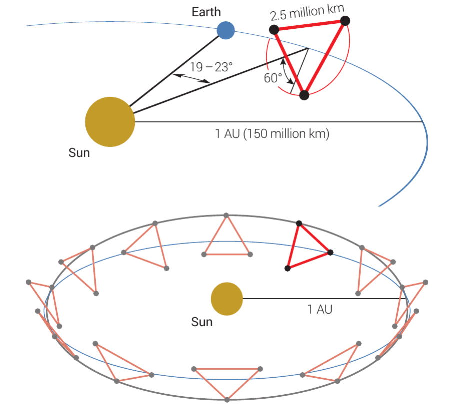
Testing the expansion rate of the Universe

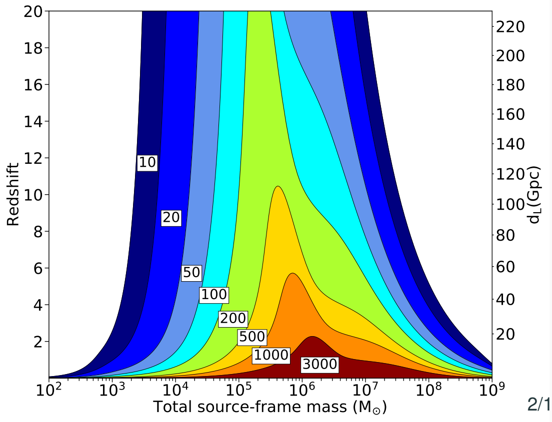


Observing the entire Universe with GWs

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)
- Successfully passed Phase A - Now in Phase B1 - Mission Adoption at end 2023





MBHBs as 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 $z \lesssim 2.5$

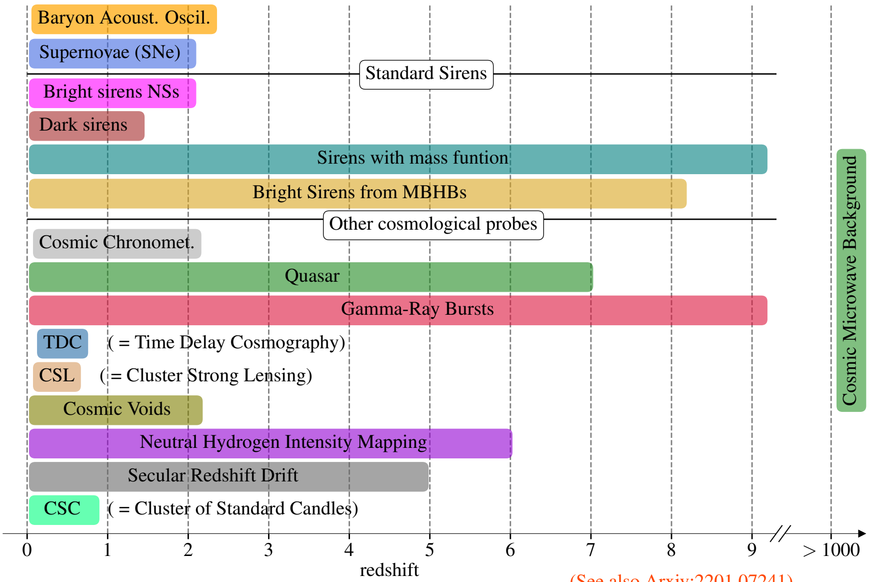
We need new models and new probes!

Standard sirens are new cosmological probes

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

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

MBHBs can go up to high redshift



(See also Arxiv:2201.07241)

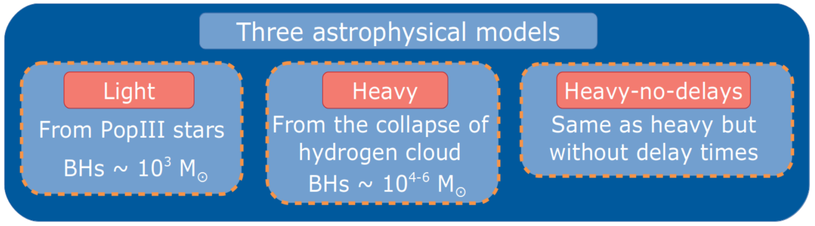
What constrains can we put on the expansion of the Universe at high redshift with bright MBHBs?

Key improvements respect to previous works (Tamanini+16)

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

Starting point

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



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 $\sim 10\,\mathrm{deg}^2$
- Identification+redshift

Radio

SKA

- FOV $\sim 10\,\mathrm{deg}^2$
- Redshift with ELT

X-ray

Athena

- FOV $\sim 0.4\,\mathrm{deg}^2$
- 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 'Standard' case

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

ΛCDM Universe

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

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)**
  4-parameters model: $(\omega_0, \omega_\infty, z_c, \Delta z)$
  (work in progress)
- **Phenomen. modified gravity (Belgacem+19)**
  2-parameters model: (Ξ_0, n)
  (see Chiara's talk)

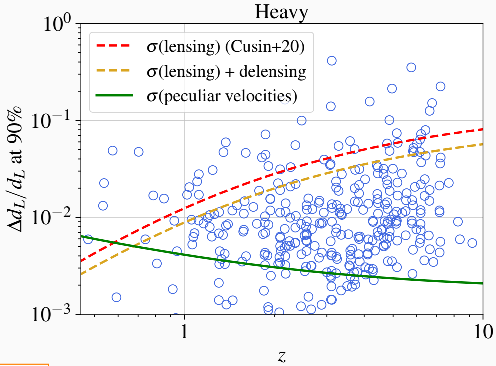
At high redshift

- **Matter-only approximation**
  2-parameter models: $D(z_p)$, $H(z_p)$
  (see Chiara'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 $\Rightarrow \frac{\Delta d_L}{d_L} < 10\%$
- Lensing relevant for $z \gtrsim 2-3$
- Peculiar velocities are negligible



Redshift measurements

LSST/Rubin Obs.

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

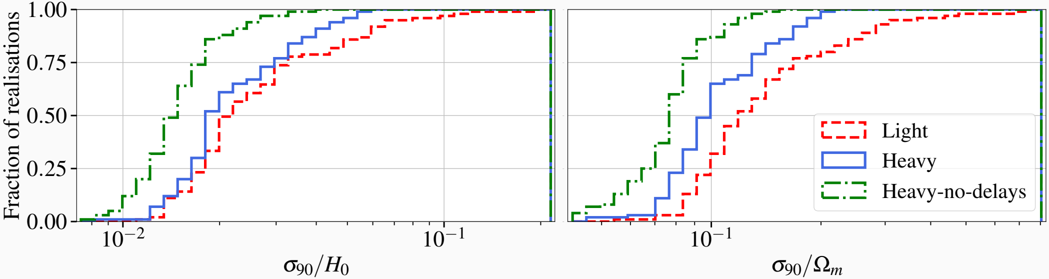
ELT

	$m_{\rm ELT} < 27.2$	$27.2 < m_{\rm ELT} < 31.3$
$z < 1$		No z measure
$1 < z < 5$	$\Delta z = 10^{-3}$	$\Delta z = 0.5$
$z > 5$		$\Delta z = 0.2$

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

If we perform the inference over $(H_0, \Omega_m, \omega_0, \omega_a)$ with $\omega(z) = \omega_0 + \omega_a \frac{z}{z+1}$
$\Rightarrow$ Poor constrains on ω_0 and no constrain on ω_a

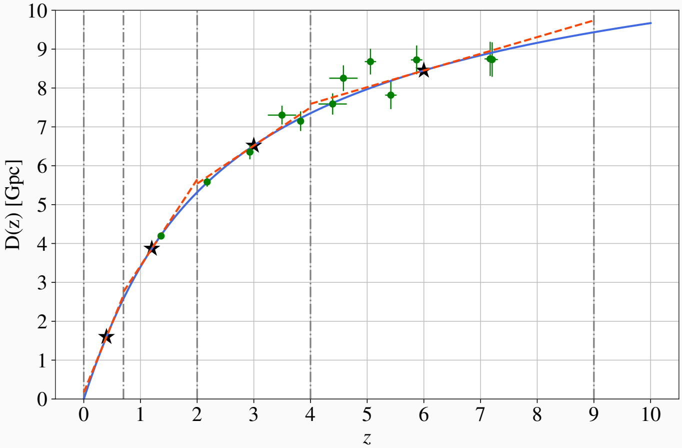
Redshift bin approach in 10 yr

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

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

Model independent approach

(it assumes only flatness)



Trade-off between:

- Bin size
- Number of EMcps in each bin

Requirement: $D(z)$ accuracy $\lesssim 5\%$

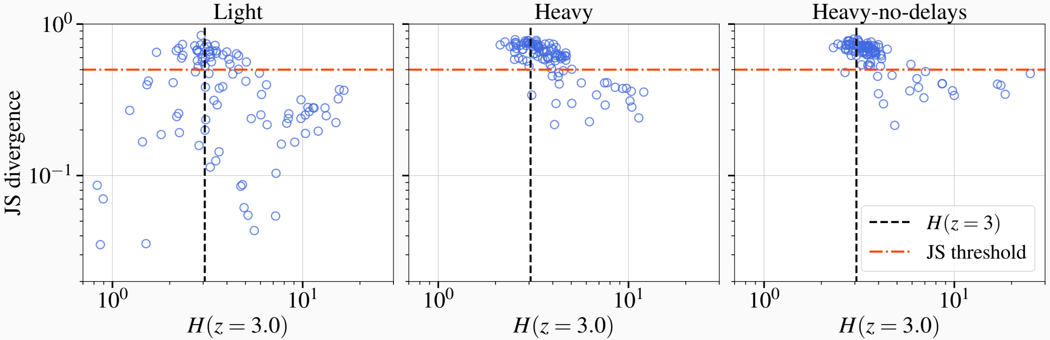
Problem: What if we do not have EMcp in a bin or if the D and z errors are too broad?

What to do with uninformative realisations?

No or few events in a bin $\Rightarrow$ The realisation is not informative $\Rightarrow$ The posterior coincides with the prior choice

Jensen-Shannon (JS) test

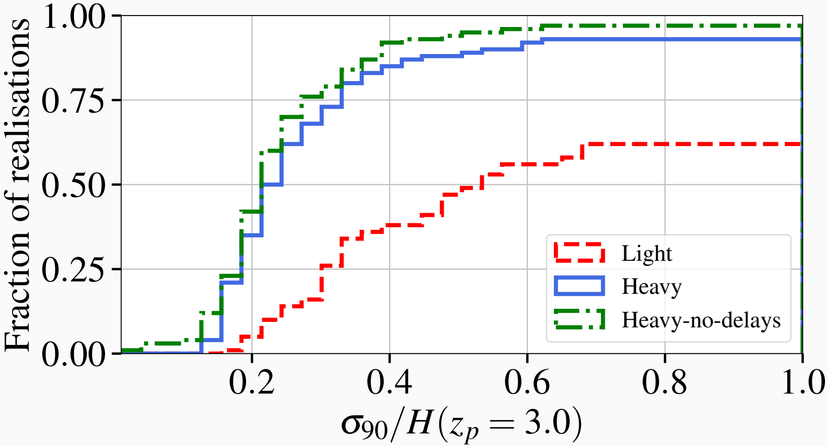
We compare the posterior and the prior distributions $\rightarrow$ JS=0 if posterior == prior; JS=1 if posterior != prior



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



Conclusions

MBHBs can probe Universe at $z \sim 2 - 7$

Current results

- H_0 can be constrained to few percent in 10 yr
- Larger uncertainties on Ω_m
- Potential to constrain $H(z)$ at high redshifts
- If we're unlucky, we might not have enough EMcps in redshift bins

Prospects for future

- Expand the analysis to all redshift bins
- Test alternative dark energy models
- Model-independent approach with splines interpolation
- Combine MBHBs with other LISA sources as stellar BHBs and EMRIs

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Thanks! Any questions?