Probing the expansion of the universe using gravitational wave standard sirens at LISA

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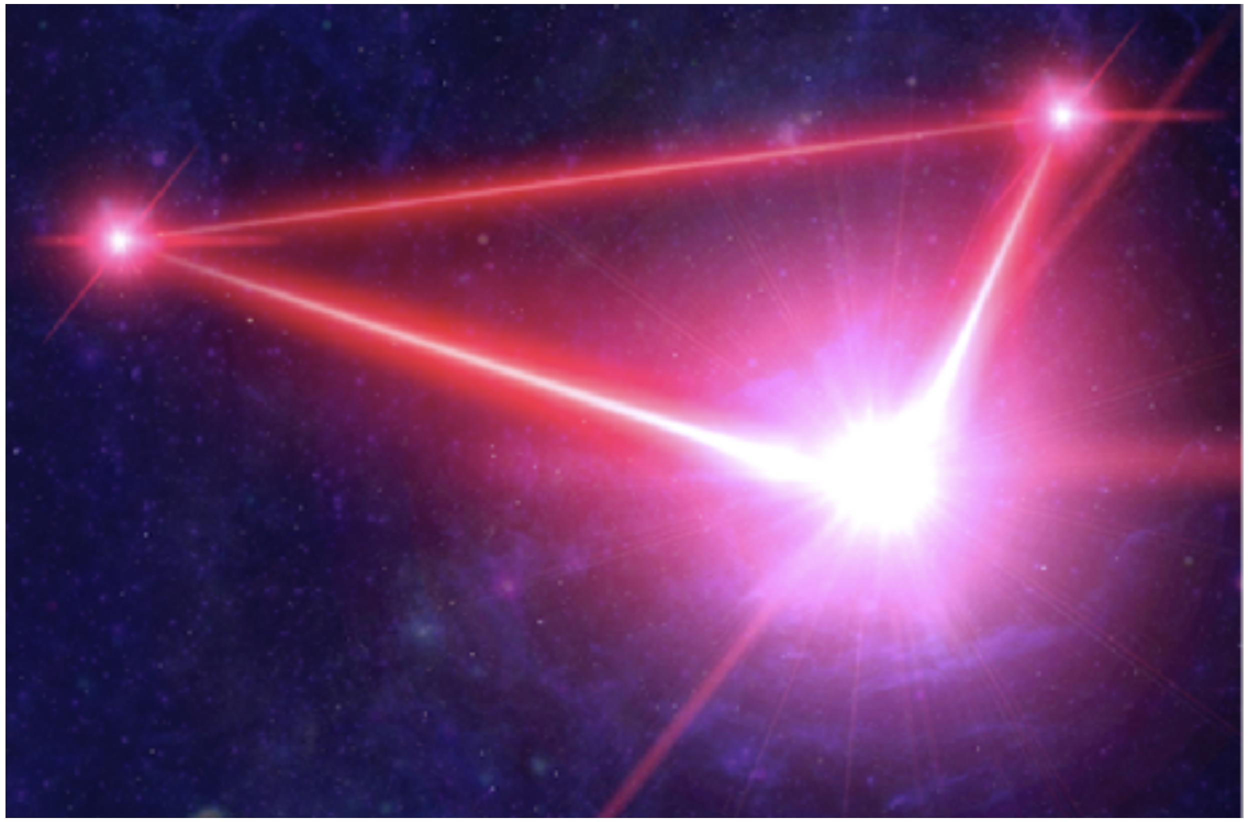
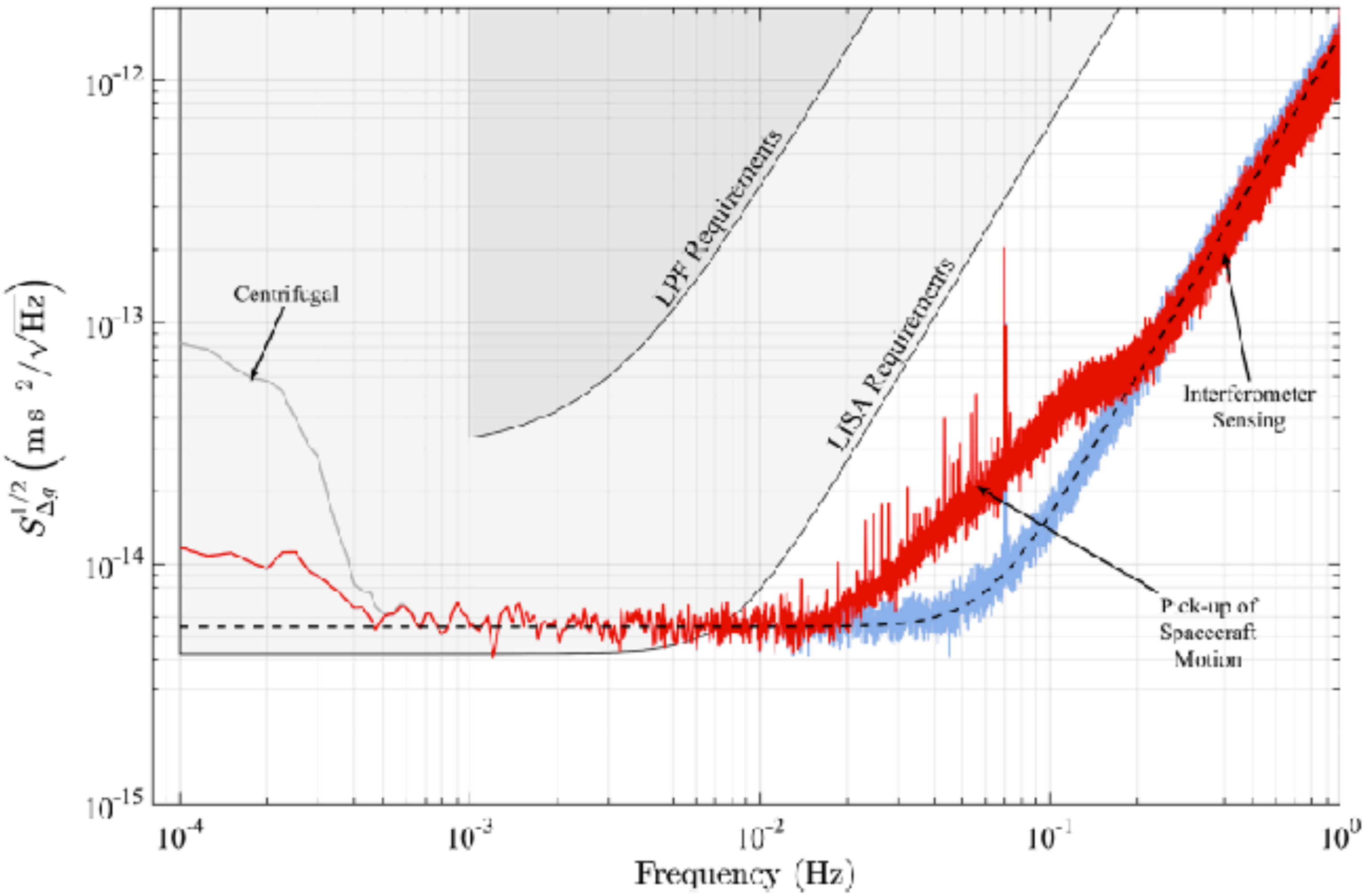


LISA
space-based interferometer performing direct GW detection

LISA Pathfinder launch Dec 2015, operations 2016-2017



one LISA arm reduced in one spaceship

<u>test the ability to put two masses in free fall</u>: measure the differential acceleration among them

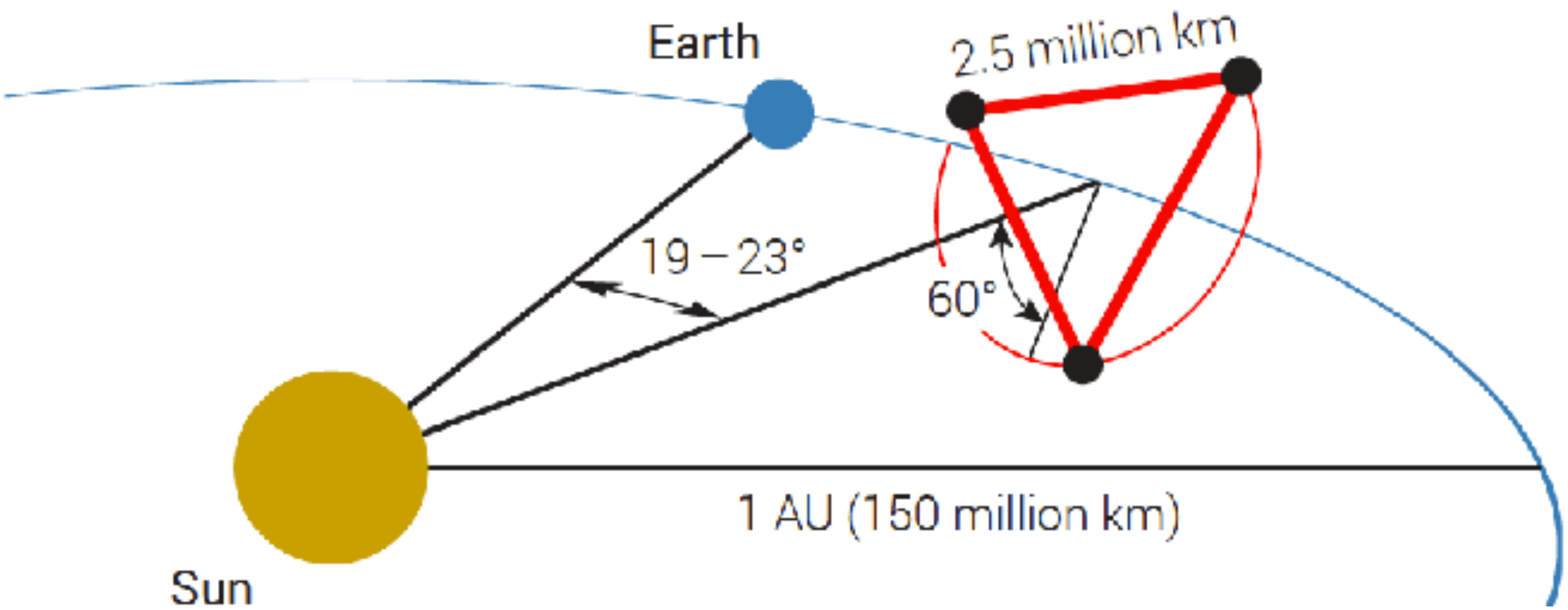
Armano et al, PRL 116, 231101 (2016)

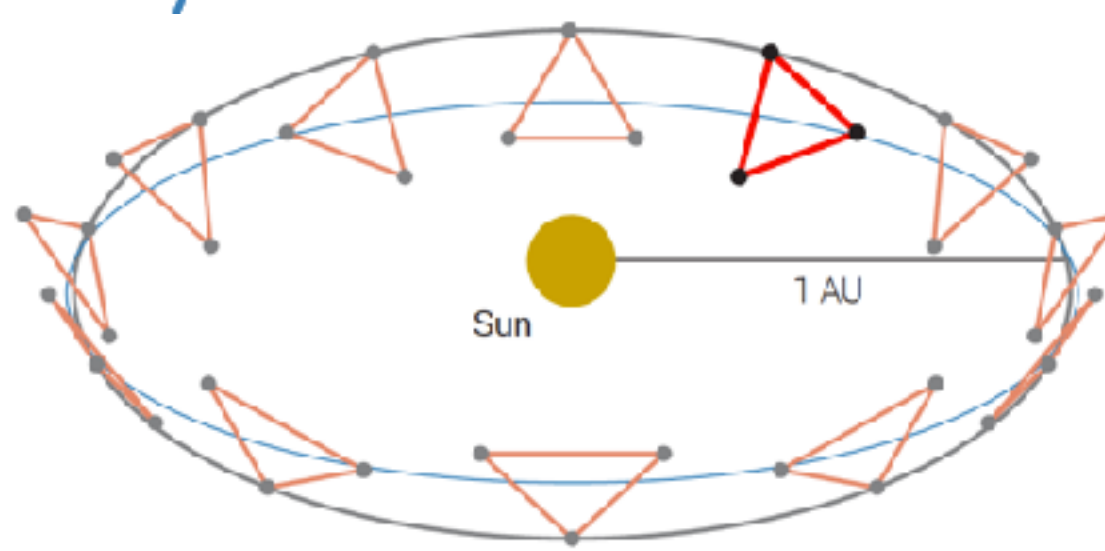
LISA chronology

- 1980s - 2011: joint NASA/ESA proposal
- 2011: NASA withdraws, ESA continues with descoped mission NGO (two arms)
- 2012: ESA selects JUICE for L1
- 2013: ESA selects LISA scientific theme for L3: "the gravitational universe"
- 2013 - 2016: studies of different configurations and refinement of the scientific case
- 25/10/2016: ESA call for mission
- 13/01/2017: LISA Consortium submits the LISA proposal (3 arms), APPROVED BY ESA
- 3/2017 - fall 2017: ESA Phase 0 study
- beginning 2018 - 2019: ESA Phase A study (with industries)
- 2019 - 2020: preparation of industrial implementation
- 2021: ESA mission adoption
- 8.5 years: mission construction
- around 2030 - 2034: launch (Ariane 6)
- nominal mission duration 4 years, tested extension up to 10 years
- cost: 1050 M€

LISA configuration

frequency range of detection: $10^{-4}\,\mathrm{Hz} < f < 1\,\mathrm{Hz}$





it is a survey instrument:

no pointing
continuous sky observation
very best angular resolution for high SNR sources: 1deg^2

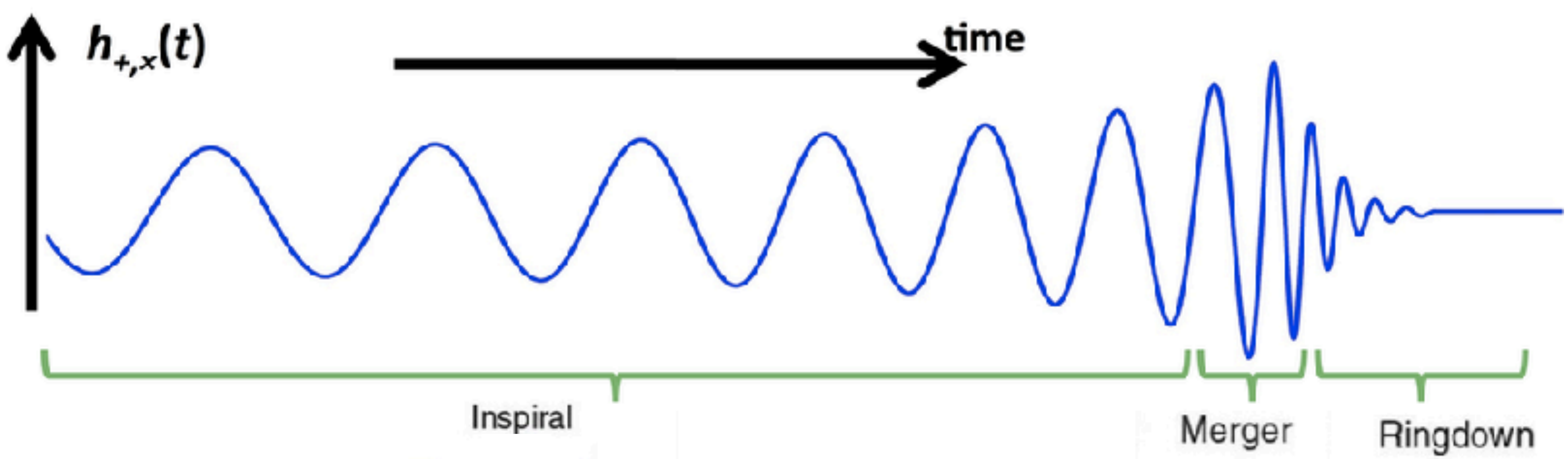
What LISA measures

1. The <u>gravitational wave strain</u> from the inspiral and merger of compact binaries : it encodes information on the binary parameters

$$h(t) \sim 2\,\frac{\Delta L}{L} \qquad\qquad \mathcal{M}_c,\ d_L,\ t_c,\ \eta,\ \Phi_c,\ \phi$$

<u>LISA target</u> :

- BH binaries, massive (high SNR) and LIGO-like
- galactic binaries
- Extreme Mass Ratio Inspirals



What LISA measures

2. the stochastic background of gravitational waves

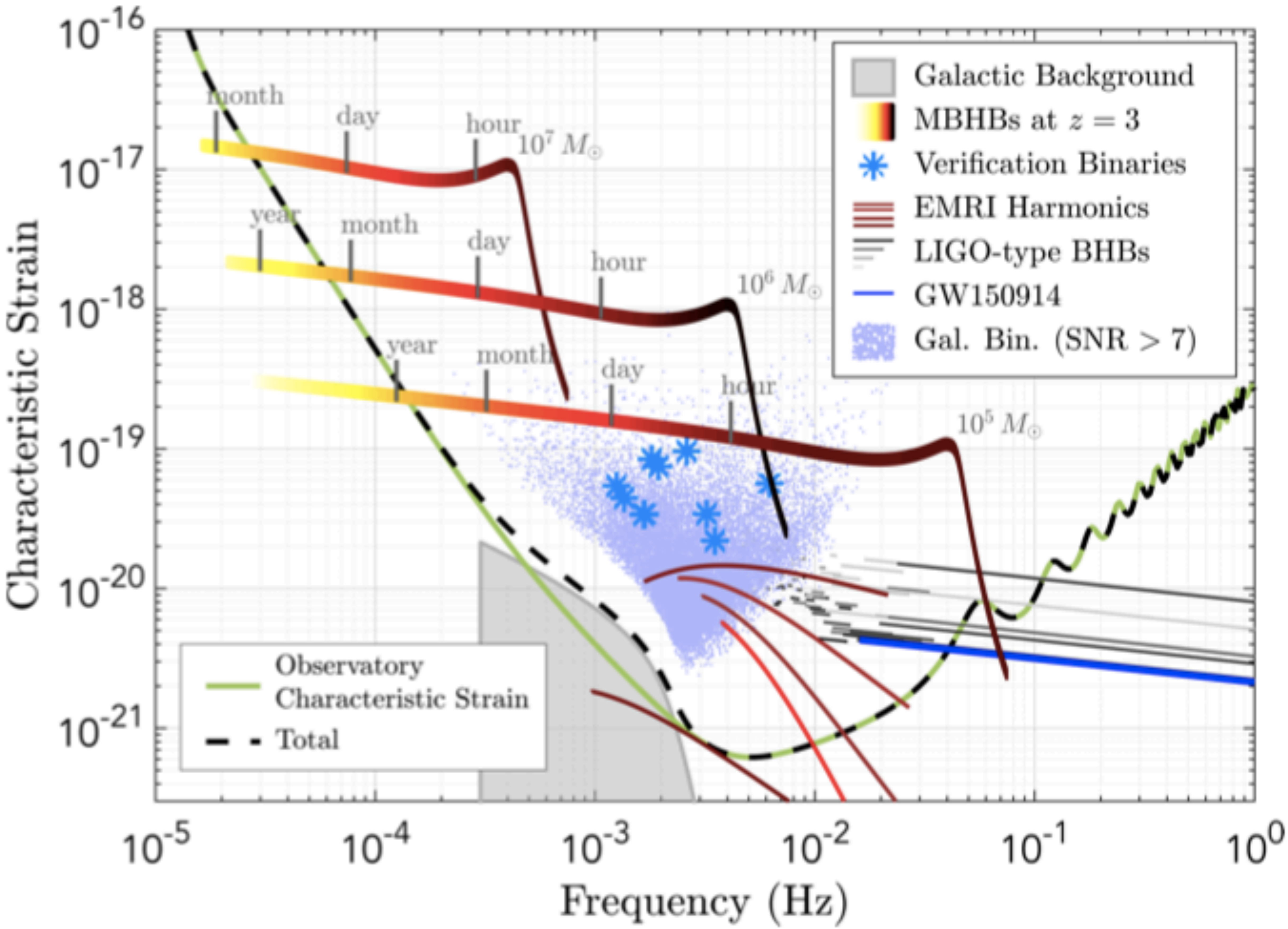
the superposition of sources that cannot be resolved individually

- binaries too numerous and with too low SNR to be identified
- signals from the early universe with too small correlation scale (typically horizon at the time of production) with respect to the detector resolution

$$\Omega_{\rm GW} = \frac{\rho_{\rm GW}}{\rho_c} = \frac{\langle \dot{h}_{ij} \dot{h}_{ij} \rangle}{32\pi G\, \rho_c} = \int \frac{\mathrm{d}f}{f} \frac{\mathrm{d}\Omega_{\rm GW}}{\mathrm{d}\ln f}$$

energy density
power spectrum

What LISA measures



LISA AND COSMOLOGY:

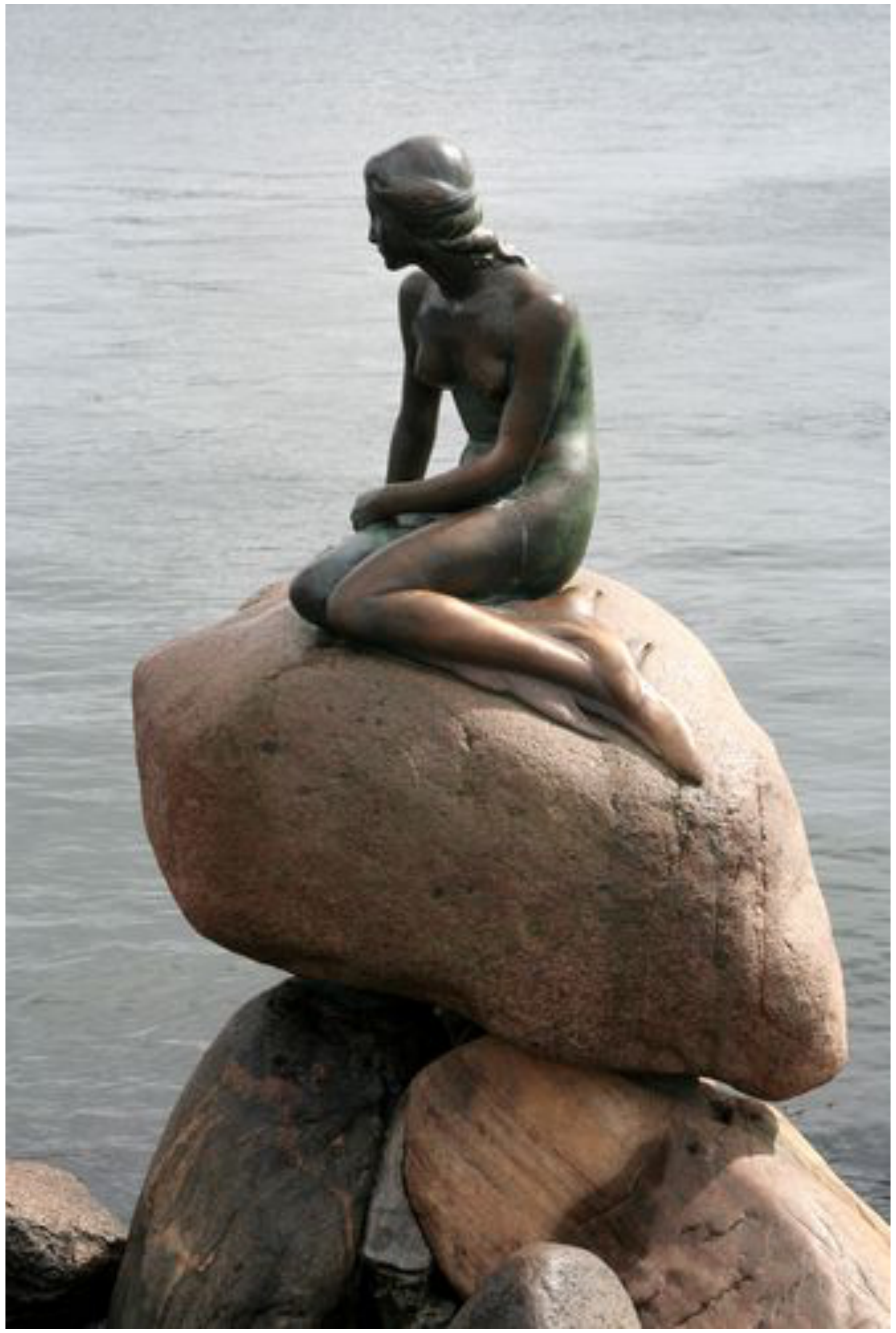
some results from the *LISA cosmology working group*
(Germano Nardini, CC)

the stochastic GW background from primordial sources: test of early universe and high energy phenomena

use of GW emission from binaries to probe the background expansion of the universe : test of acceleration

Standard sirens

GW emission by compact binaries can be used as SuperNovae Ia (standard candles) to test the content of the universe



Standard sirens

GW emission by compact binaries + redshift by an EM counterpart can be used to probe the distance-redshift relation

$$h_+(t) = \frac{4}{d_L(z)}\left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f}{c}\right)^{\frac{2}{3}}\frac{1+\cos^2\imath}{2}\cos[\Phi(t)]$$

$$h_\times(t) = \frac{4}{d_L(z)}\left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f}{c}\right)^{\frac{2}{3}}\cos\imath\,\sin[\Phi(t)]$$

$$\mathcal{M}_c = (1+z)M_c$$

redshifted chirp mass

$$d_L(H_0, \Omega_\Lambda, \Omega_M, w_0, w_a)$$

Standard sirens

GW emission by compact binaries + redshift by an EM counterpart can be used to probe the distance-redshift relation

$\boxed{\text{no distance ladder}}$

Standard sirens

GW emission by compact binaries + redshift by an EM counterpart
can be used to probe the distance-redshift relation

no distance ladder

but no redshift either!

Standard sirens

GW emission by compact binaries + redshift by an EM counterpart can be used to probe the distance-redshift relation

$$h_+(t) = \frac{4}{d_L(z)} \left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}} \left(\frac{\pi f}{c}\right)^{\frac{2}{3}} \frac{1+\cos^2\imath}{2} \cos[\Phi(t)]$$

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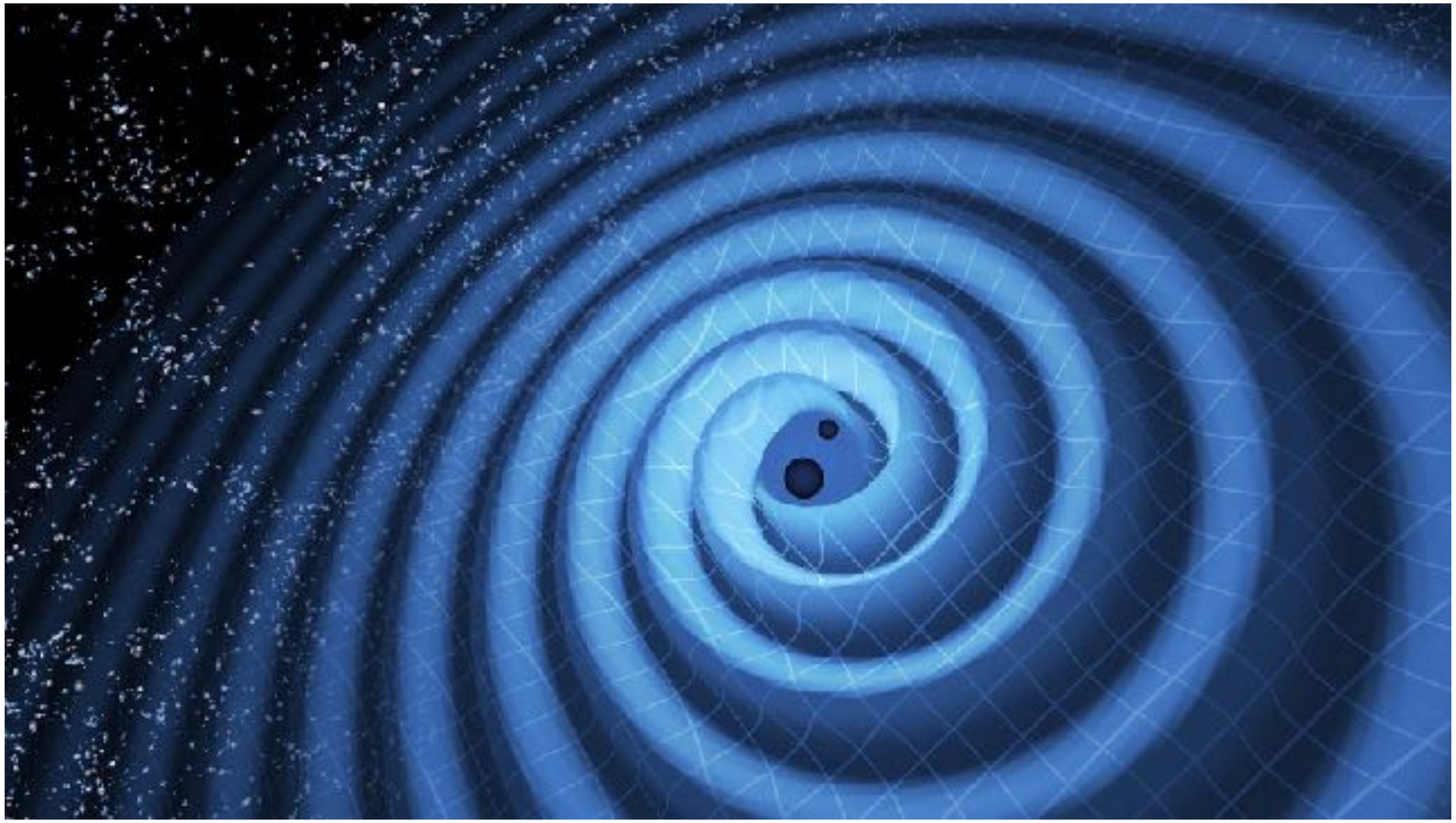
Standard sirens: analogous to SNIa, but

GW emission by BH binaries provides a direct measurement of luminosity distance up to high redshift: 😃

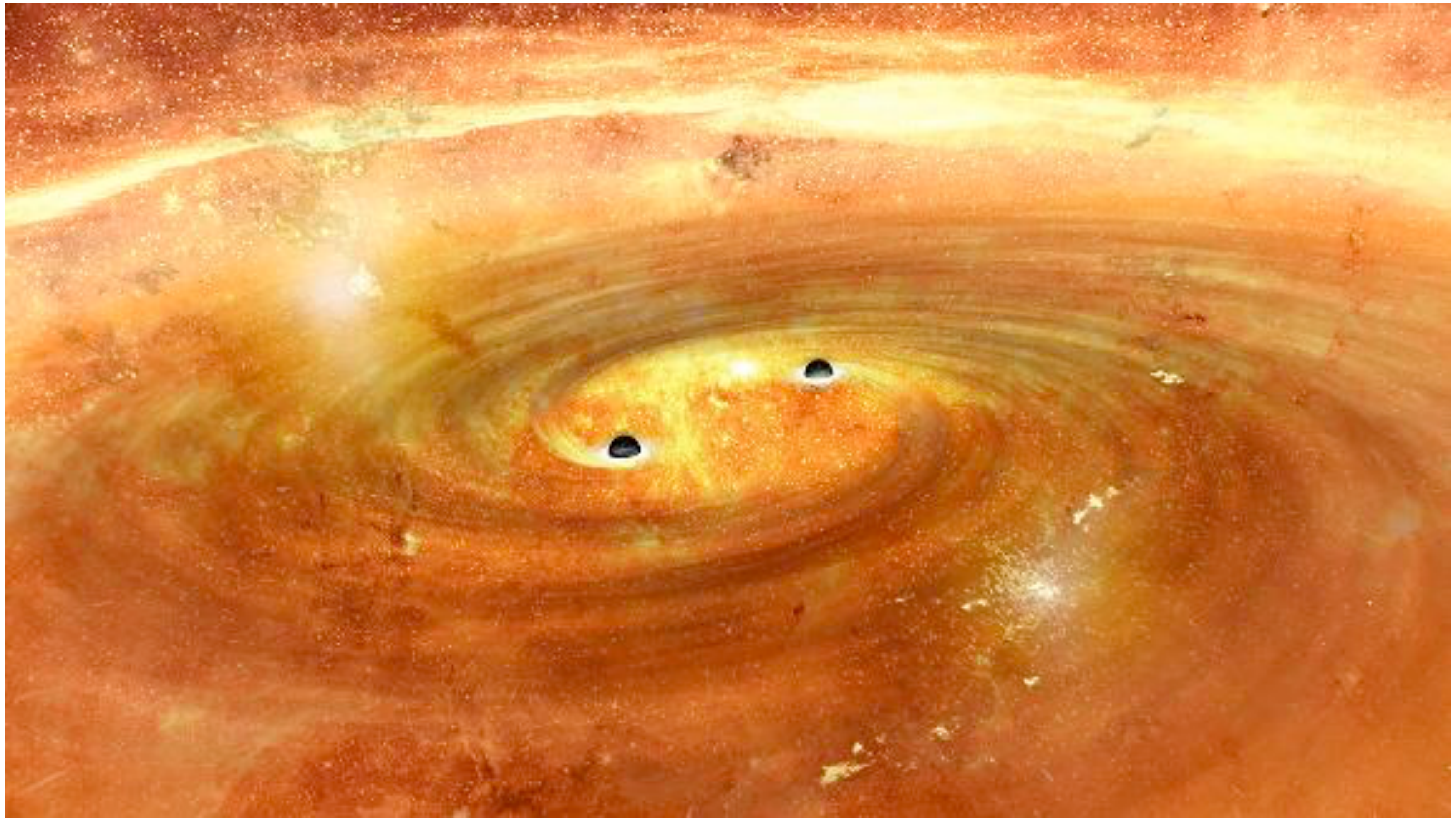


Standard sirens: analogous to SNIa, but

GW emission by BH binaries provides a direct measurement of luminosity distance up to high redshift: 😃

but

it needs to be combined with an independent measurement on the redshift : 😞



standard sirens with LISA: MBHB coalescence

- the rate and redshift distribution of MBH binary events are obtained from numerical simulations
  (three different models - PopIII, heavy seeds with delay, heavy seeds without delay)

- Fisher matrix code to calculate SNR, the error on d_L and on sky localisation from inspiral (conservative) or inspiral+merger and ringdown (optimistic)

- Select events with SNR>8 and sky localisation < 10 deg^2

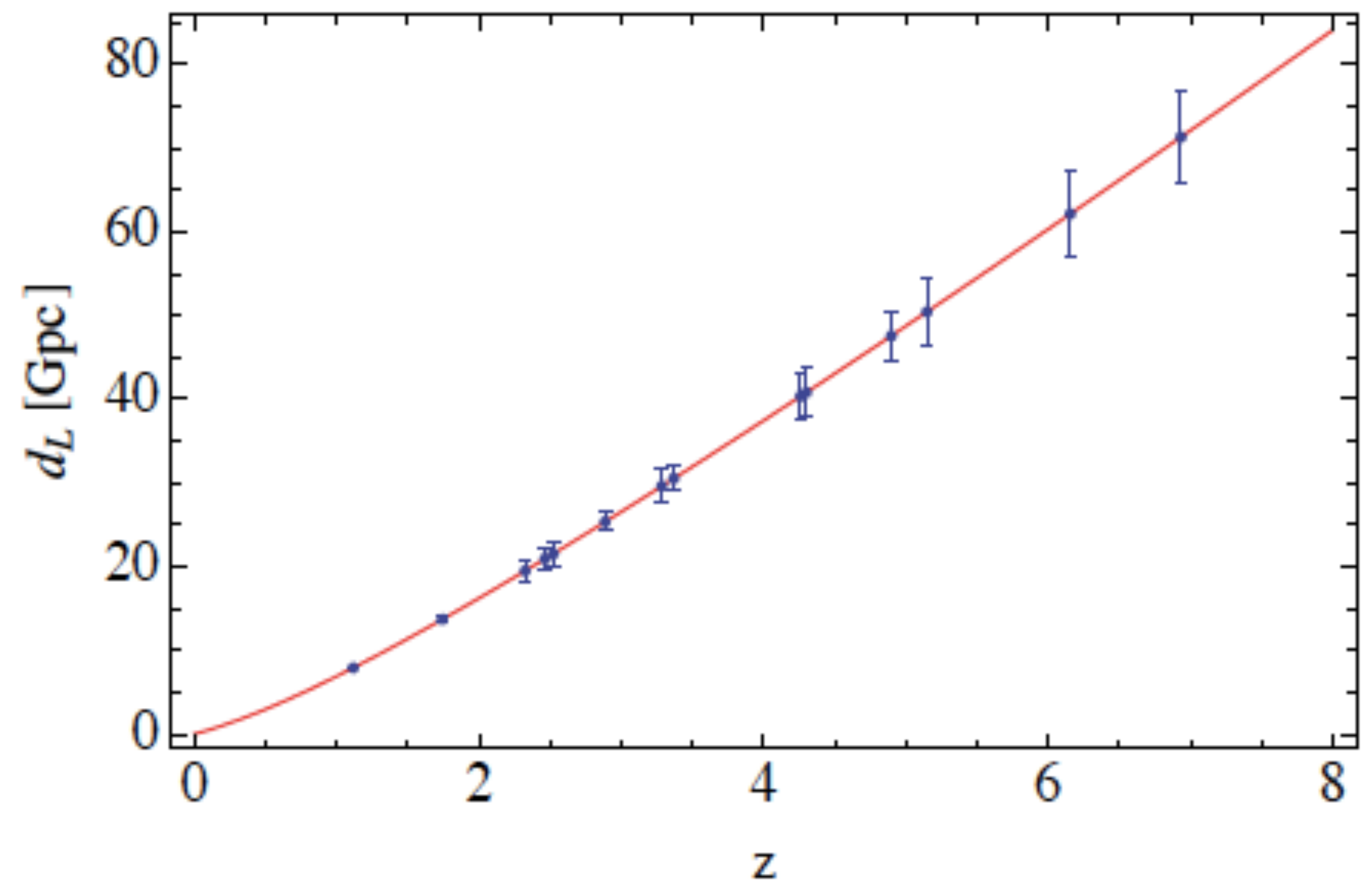
- Add weak lensing and peculiar velocities errors to d_L

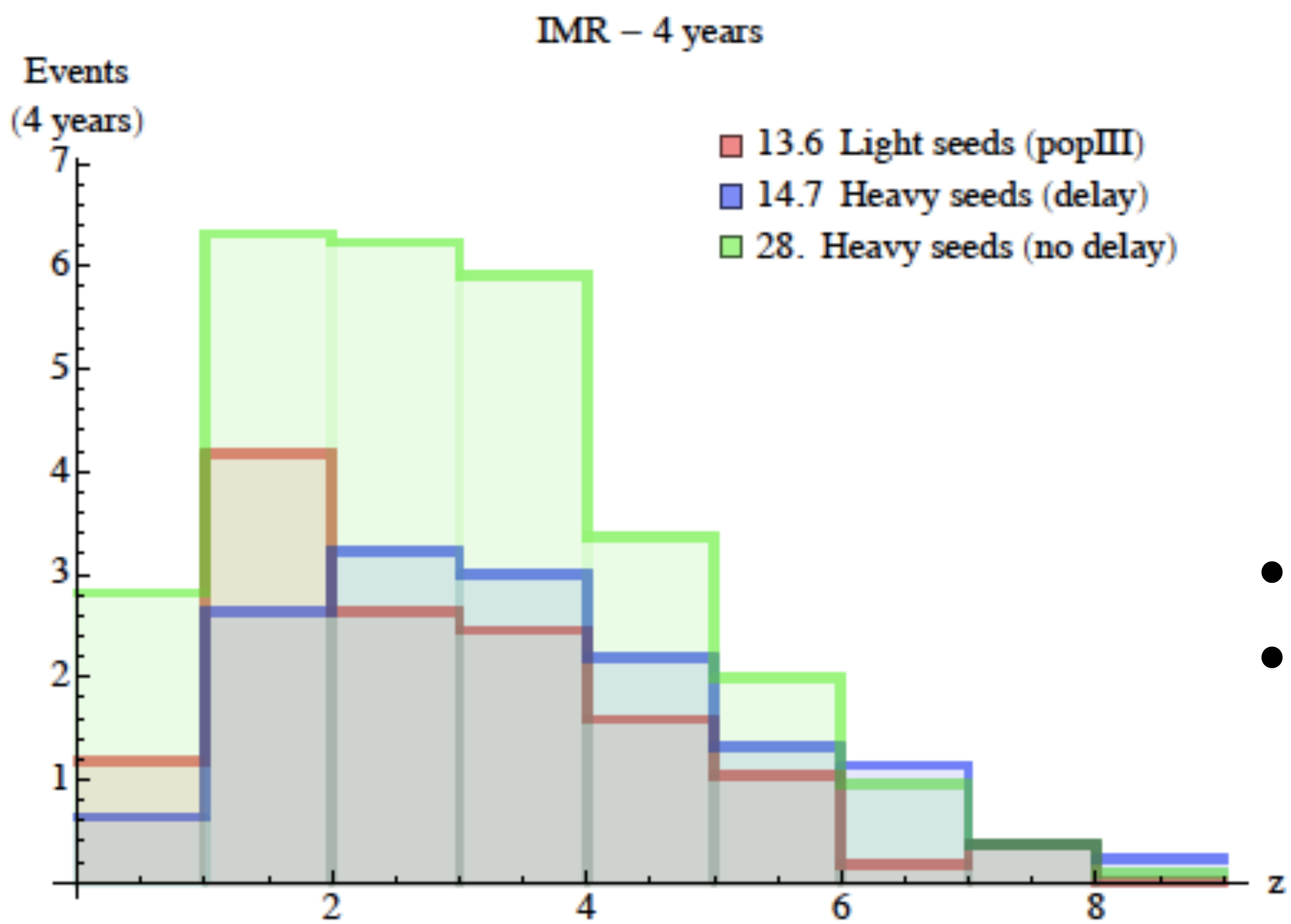
- model of the counterparts :
  - detected directly in the optical by LSST
  - detected first in the radio by SKA and then in the optical by E-ELT
  - add extra redshift error if photometric

standard sirens with LISA: MBHB coalescence

N. Tamanini et al arXiv:1601.07112

example of simulated data
with counterparts
(SKA+EELT)
and weak lensing errors





VERY FEW EVENTS AT
LOW REDSHIFT !

- where needed to probe DE (bad)
- can test expansion at high redshift (good)

standard sirens with LISA: MBHB coalescence

ΛCDM

LISA alone :

$$\Omega_M = 0.3 \pm [0.05,\ 0.03]$$
$$h = 0.67 \pm [0.02,\ 0.01]$$

<u>worst case scenario</u> regarding MBHB formation model and sky localisation

<u>best case scenario</u> regarding MBHB formation model and sky localisation

standard sirens with LISA: MBHB coalescence

ΛCDM

LISA alone :

$$\Omega_M = 0.3 \pm [0.05,\ 0.03]$$
$$h = 0.67 \pm [0.02,\ 0.01]$$

Planck alone :

$$\Omega_M = 0.308 \pm 0.0012$$
$$h = 0.678 \pm 0.009$$

most optimistic scenario for MBHB formation gives an independent measurement of the Hubble parameter to 1%

LISA FIXING Ω_M :

$$h = 0.67 \pm [0.006,\ 0.004]$$

- independent constraint
- 0.6% in best case

standard sirens with LISA: MBHB coalescence

Dynamical Dark Energy

too few events at low redshift to get a good measurement

$$w_0 = -1 \pm [0.3,\ 0.1]$$
$$w_a = 0 \pm [1.5,\ 0.8]$$

SNIa + Planck + BAO :
(Betoule et al 2014)

$$w_0 = -0.957 \pm 0.124$$
$$w_a = -0.336 \pm 0.552$$

Euclid forecast :

$$\Delta w_0 = 0.02$$
$$\Delta w_a = 0.1$$

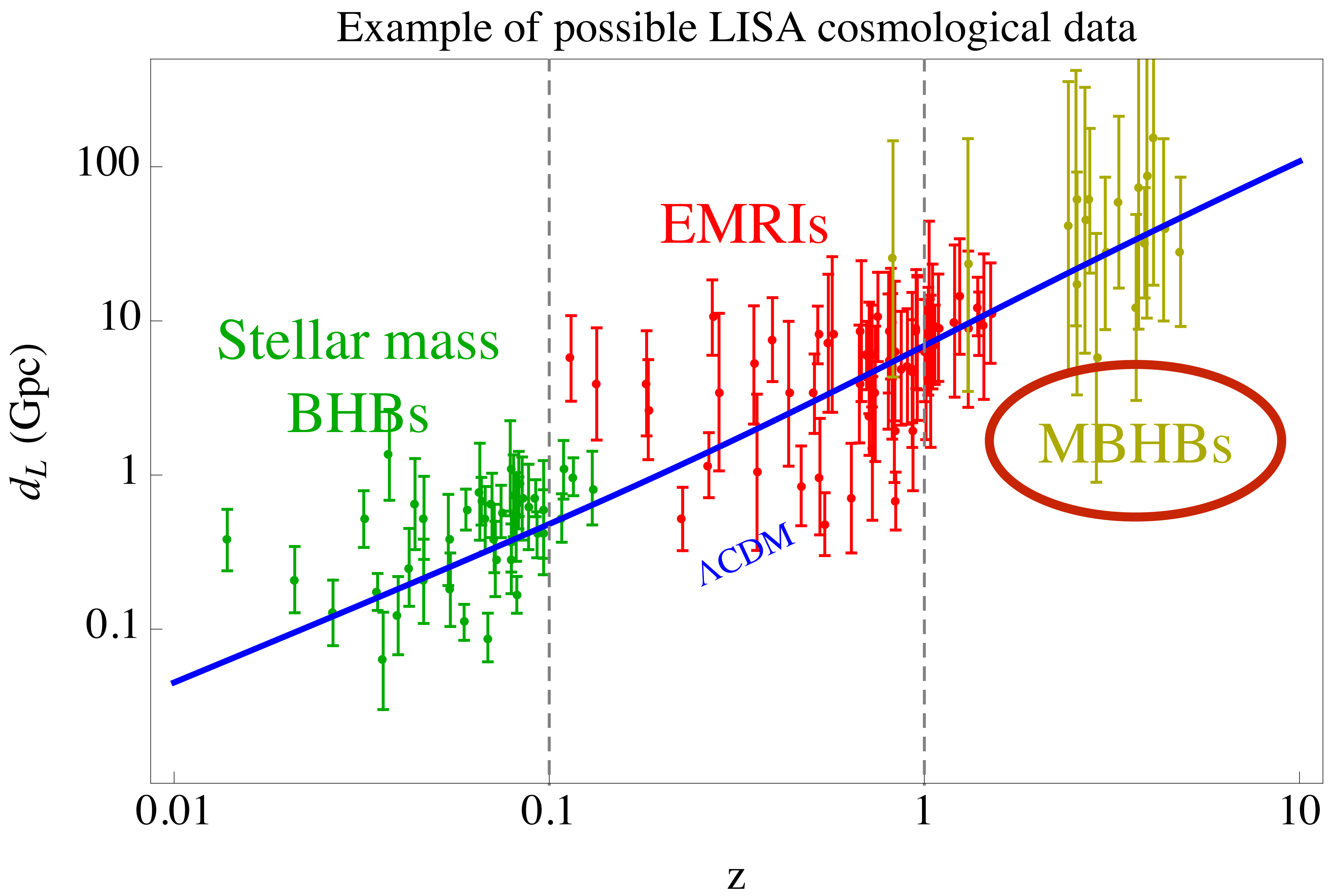
standard sirens with LISA: MBHB coalescence

Dynamical Dark Energy

too few events at low redshift to get a good measurement

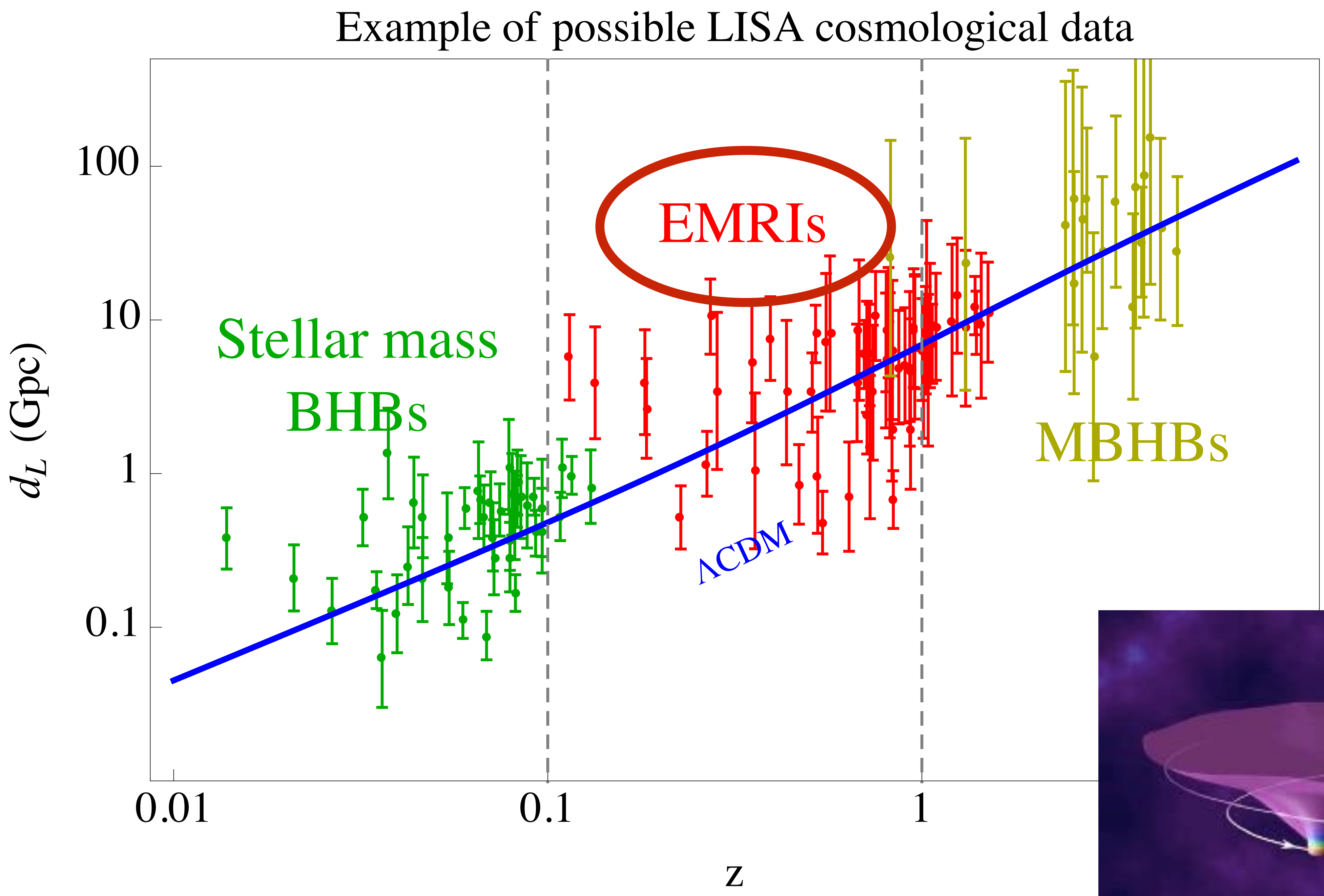
these constraints can get better using also other LISA sources

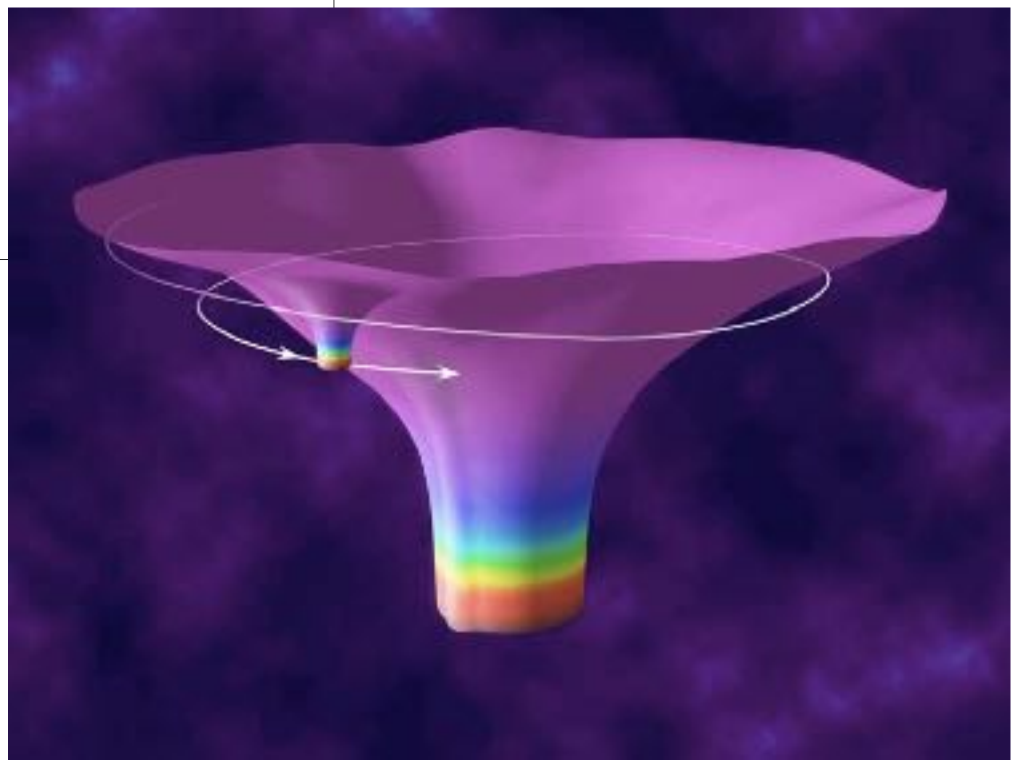
future work: use all LISA sources



credits: N. Tamanini

future work: use all LISA sources





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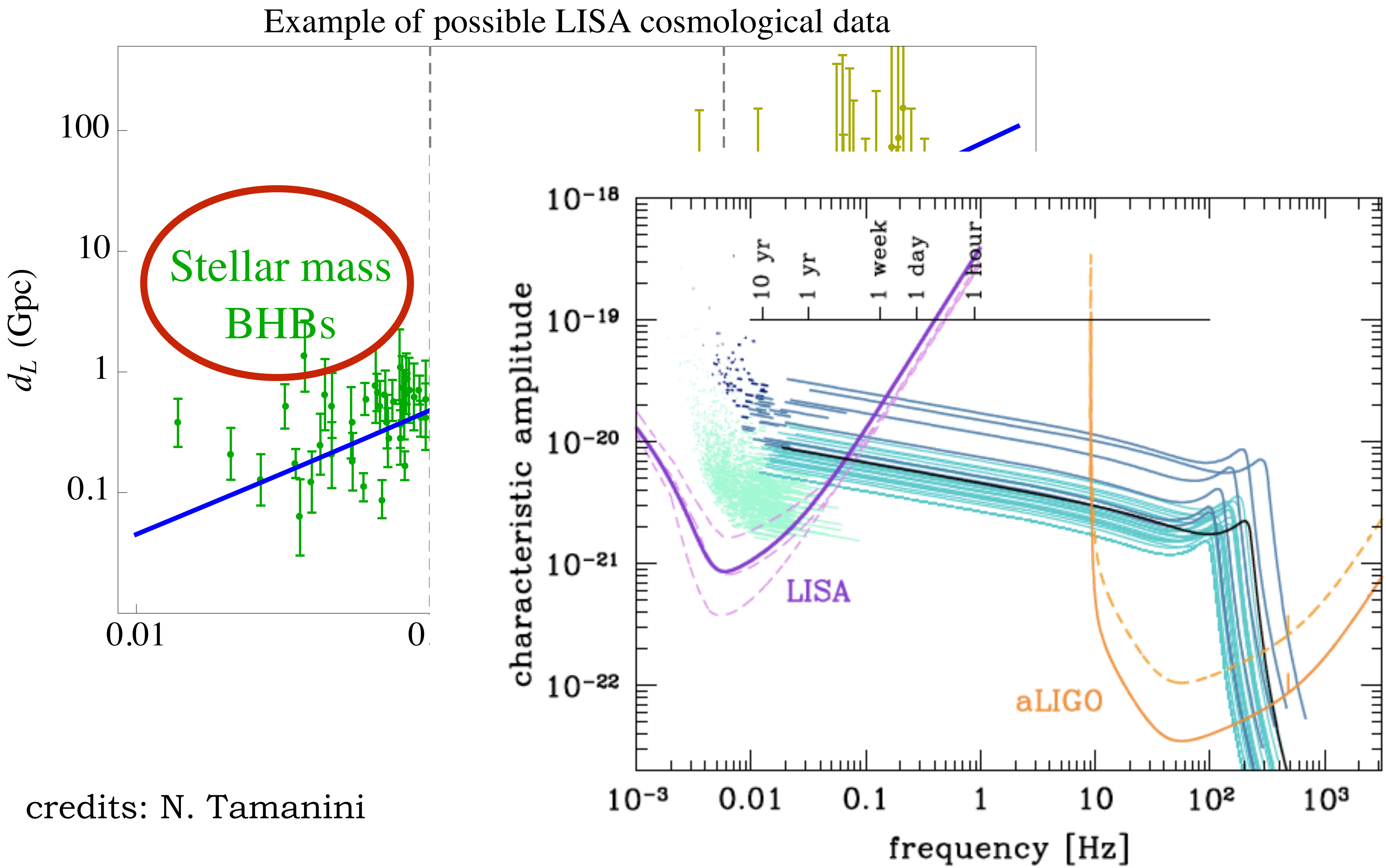

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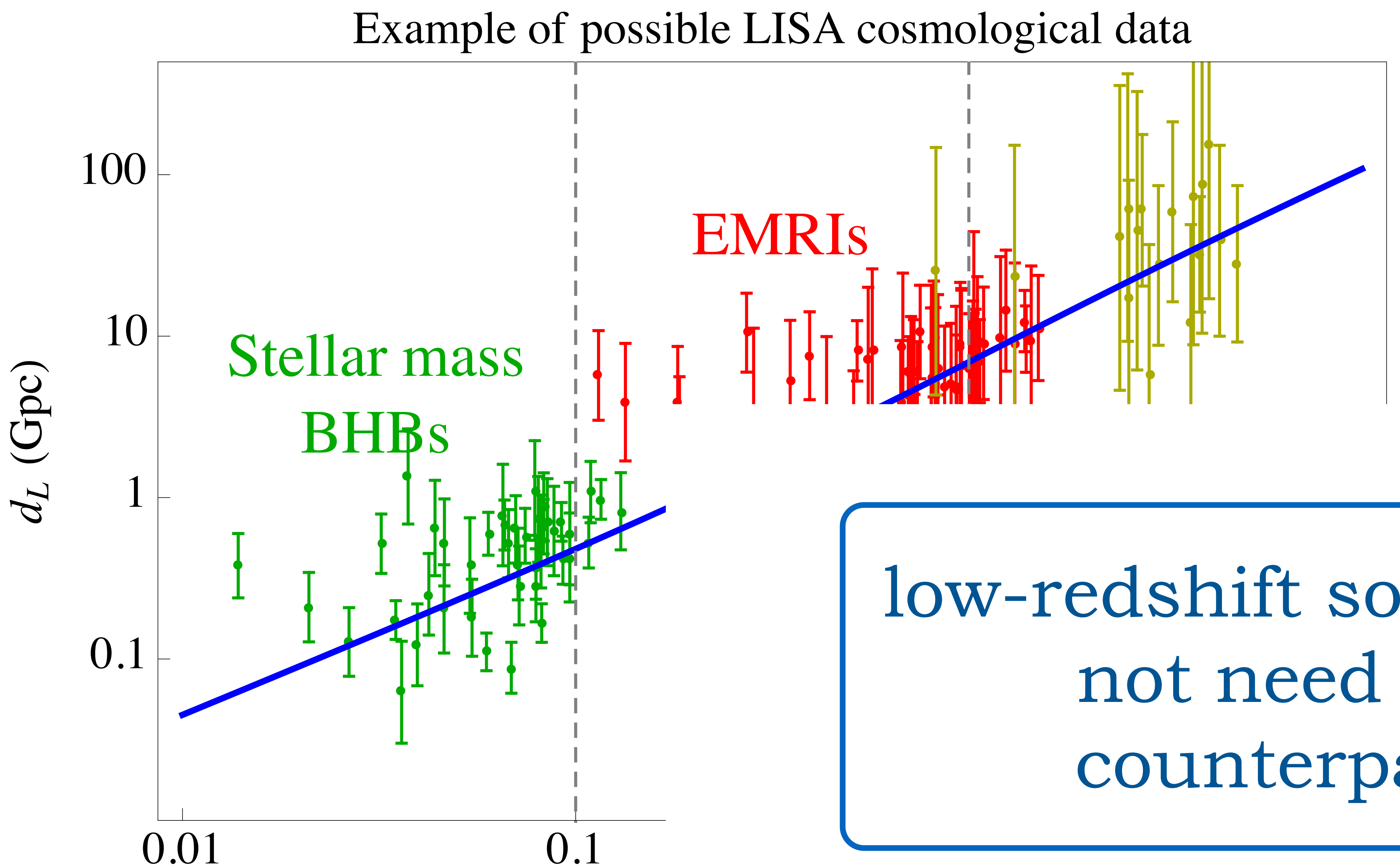
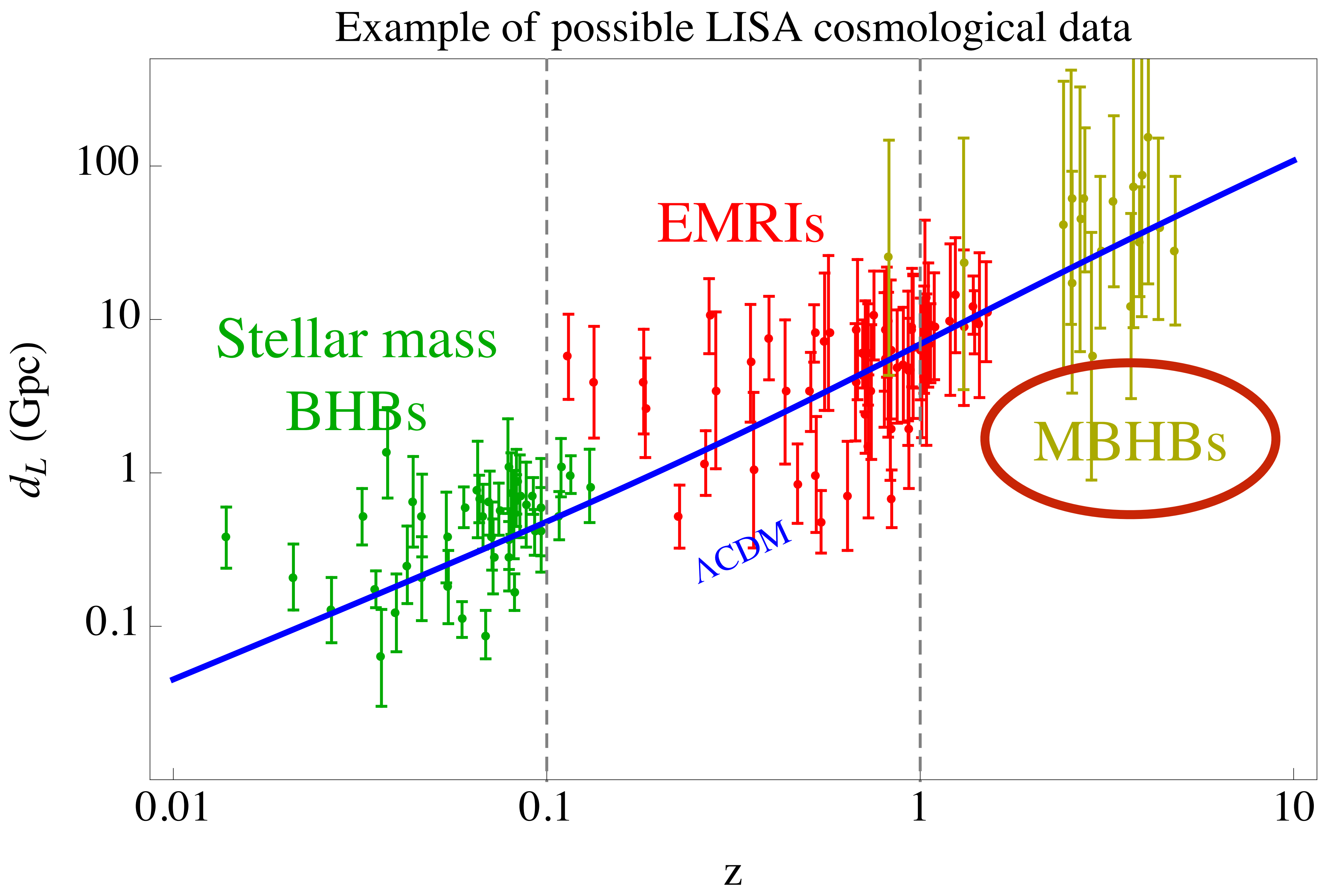


low-redshift sources do not need em counterpart!

the identification of the redshift can be done with statistical methods

credits: N. Tamanini

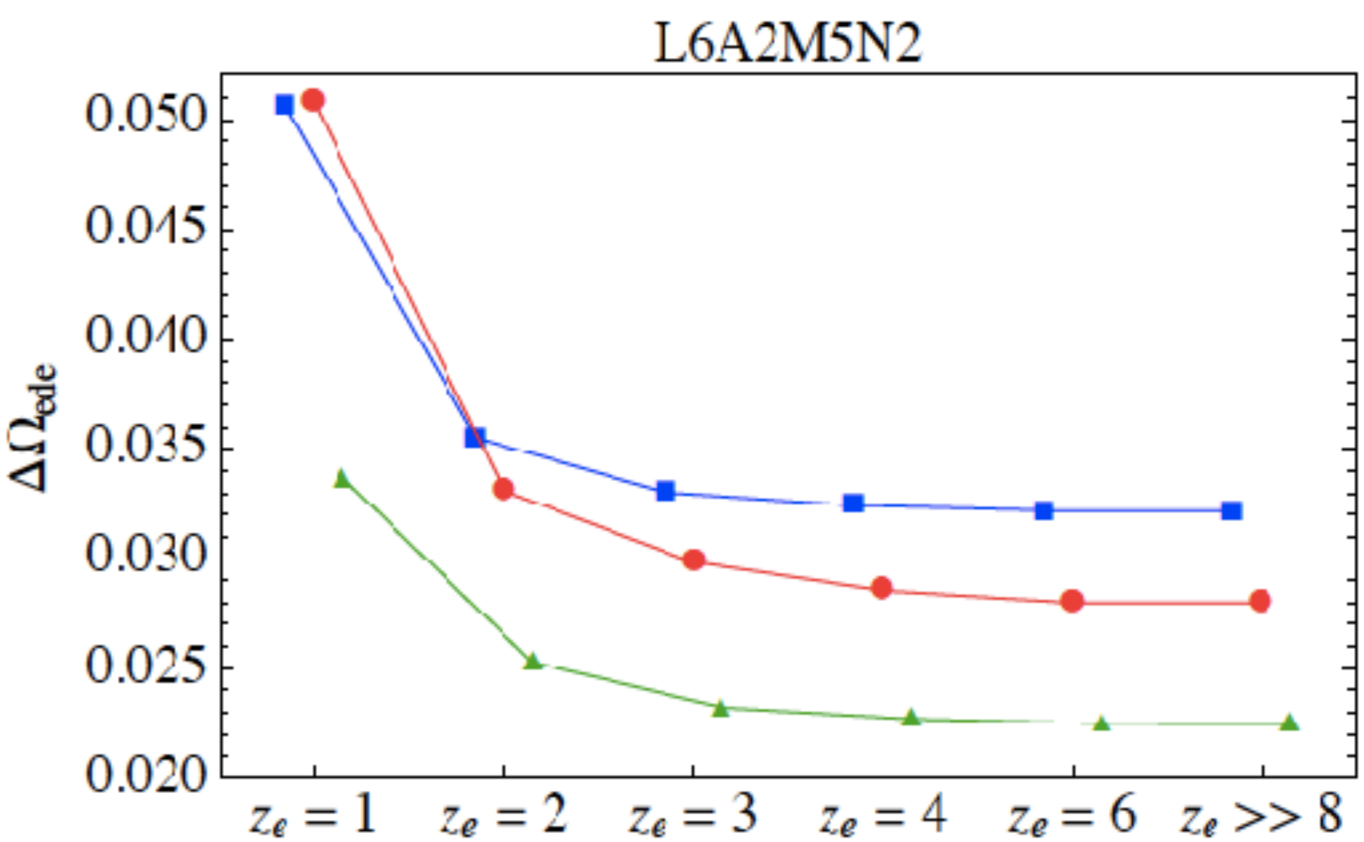
future work: use all LISA sources



credits: N. Tamanini

LISA can provide competitive constrains on models where dark energy starts to contribute at early times

Early Dark Energy



Ω_{de} fraction of dark energy at early times

z_e redshift up to which dark energy contributes

Planck alone : $\Delta\Omega_{de} = 0.0036$

but only if it contributes up to decoupling, otherwise the measurement quickly degrades

CC and N. Tamanini arXiv:1607.08755

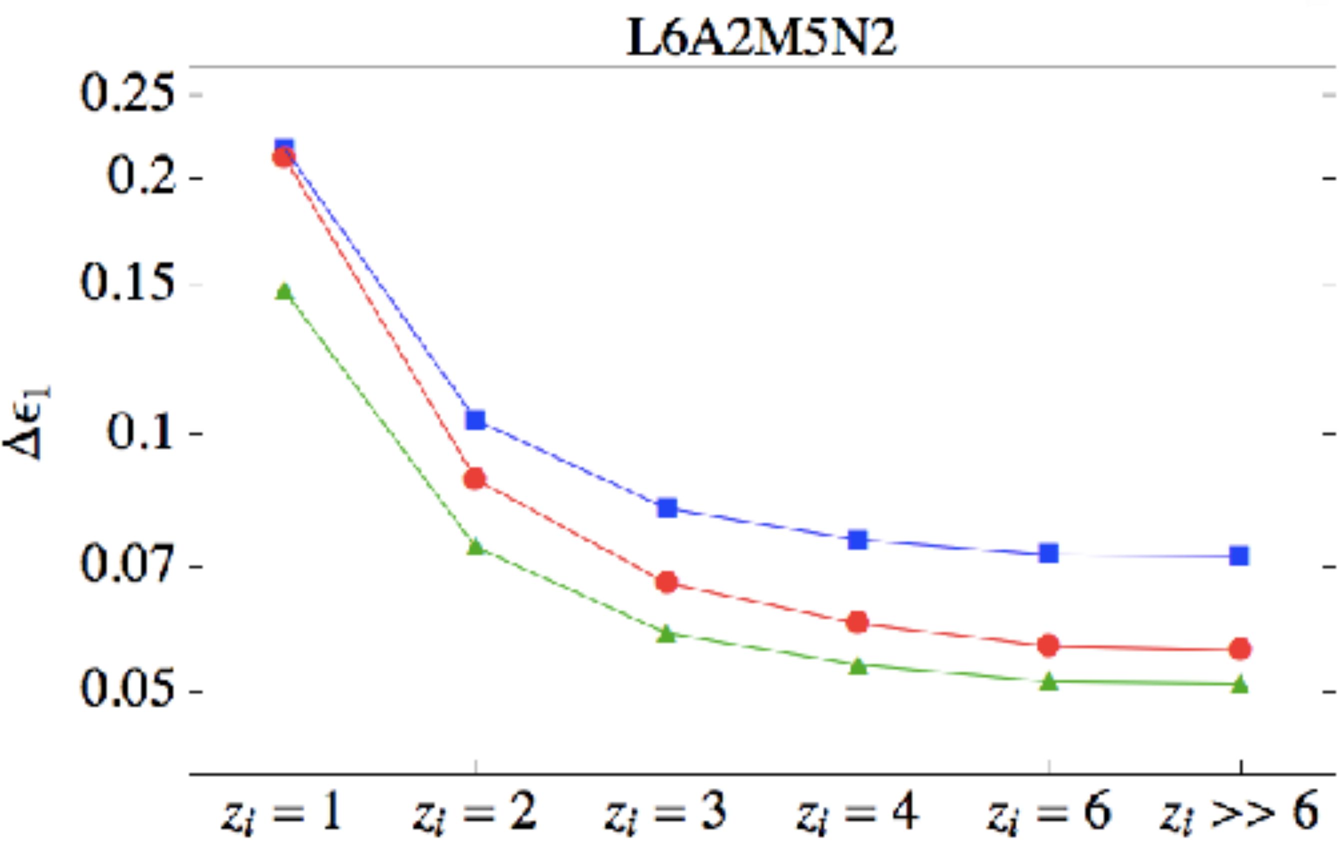
Interacting Dark Energy

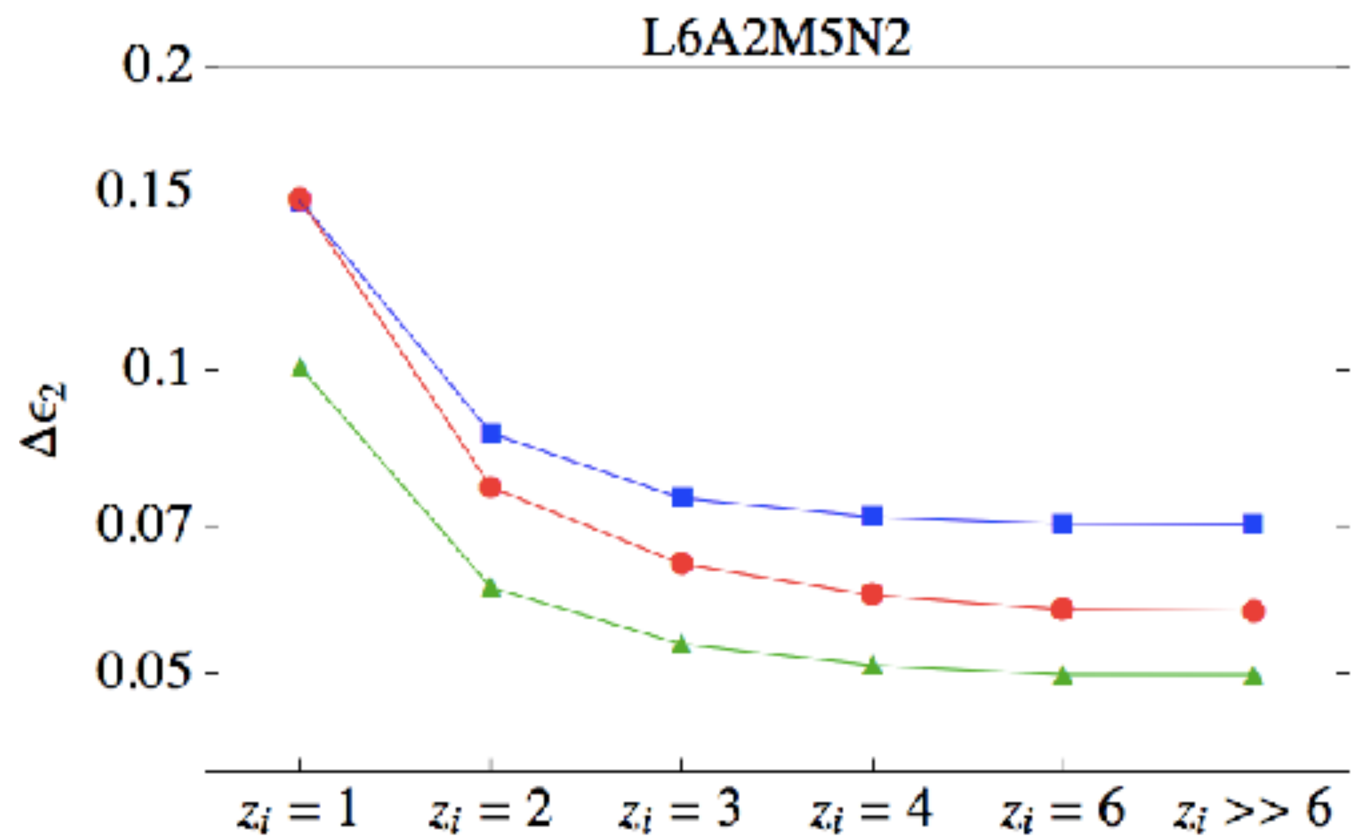
$$\dot{\rho}_{dm} + 3H\rho_{dm} = Q$$
$$\dot{\rho}_{de} + 3H(1+w_0)\rho_{de} = -Q$$

two models for the interaction

$Q = \epsilon_1 H \rho_{dm}$ and $Q = \epsilon_2 H \rho_{de}$

redshift when the interaction turns on : z_i





$$\epsilon_1 = 0.00199^{+0.00024}_{-0.00177}$$

Costa et al 2016

$$\epsilon_2 = 0.159^{+0.146}_{-0.154}$$

Murgia et al 2016

Conclusions

- GW can be a powerful mean to probe late-time background cosmology
- the measurement of the luminosity distance is clean
- in the case of LISA, using MBHB one needs an independent em counterpart to get the redshift, but one can have sources up to redshift 7
- LISA using MBHB + Planck can provide a below 1% measurement of H_0
- LISA using MBHB can also offer constraints on models where the DE starts to play a role at high redshift
- using lower redshift sources, it is possible to improve constraints on DE and get a probe of the universe acceleration fully independent on em emission