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

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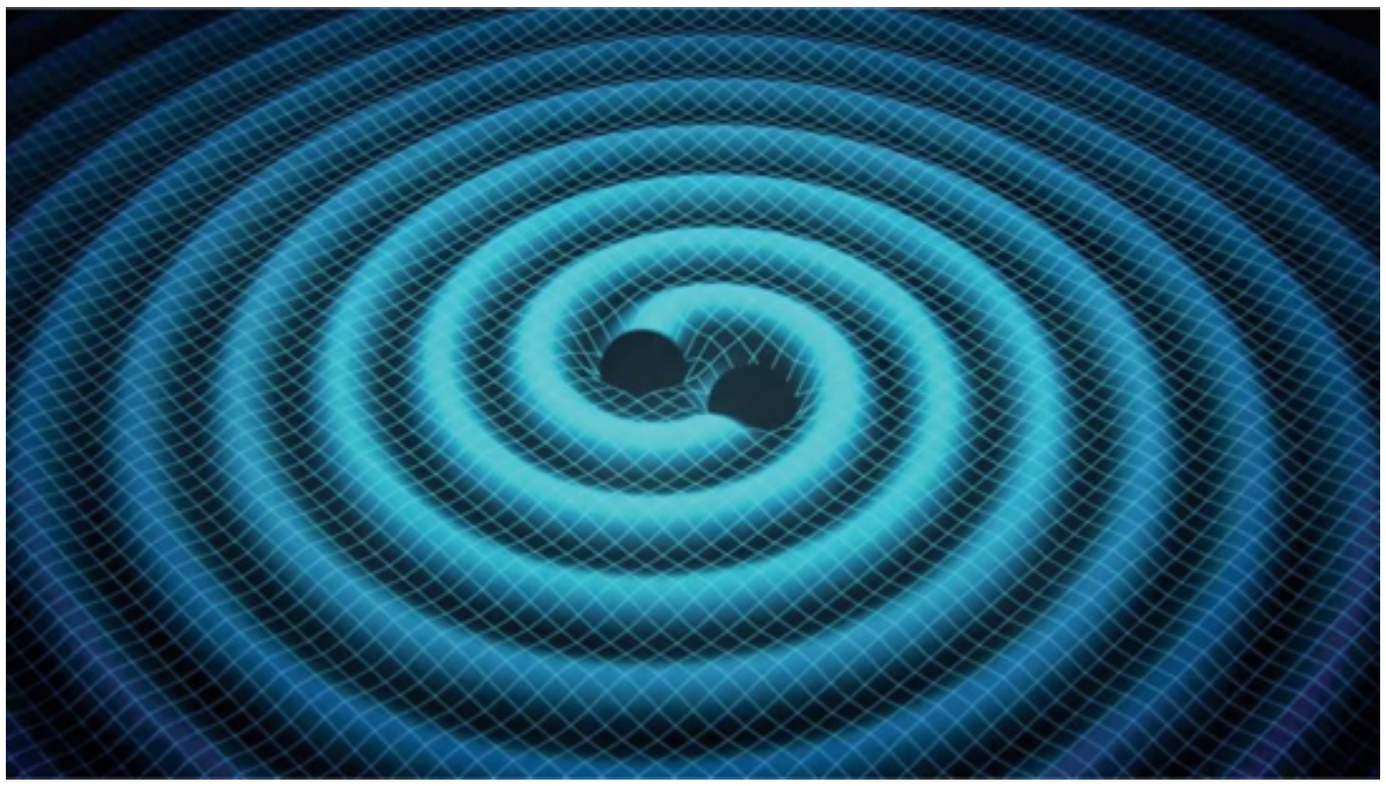
APC Paris

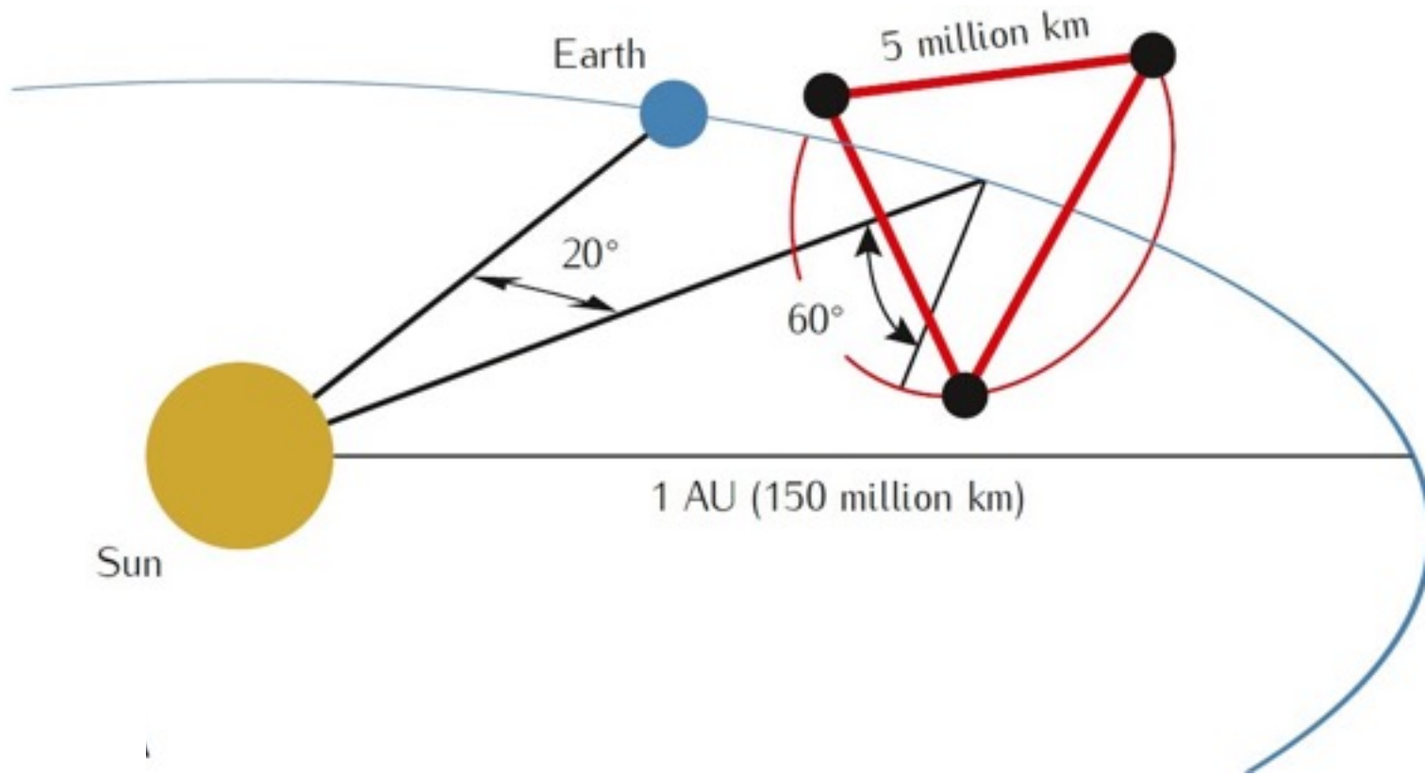


Outline

- status of (e)LISA
- can we use GW to probe the expansion of the universe? the concept of standard sirens
- new results for (e)LISA: standard sirens from massive black hole binaries
- (e)LISA potential in constraining ΛCDM and two alternative cosmology models

N. Tamanini, CC, E. Barausse, A. Sesana, A. Klein, A. Petiteau
arXiv:1601.07112
CC and N. Tamanini, arXiv:1607.08755

ESA Gravitational Wave Observatory



- ESA L3 mission (launch 2030-2034)
- launch of LISA Pathfinder on Dec 3, 2015 performing exceptionally well

- GOAT committee appointed by ESA to study the science return of several mission designs: results provided last March
- last week: XI LISA symposium in Zurich: exciting news!
- ESA call for mission will be next October
- the name goes back to LISA and NASA will actively participate

LISA observatory

www.elisascience.org

LISA mission design study for ESA GOAT committee:

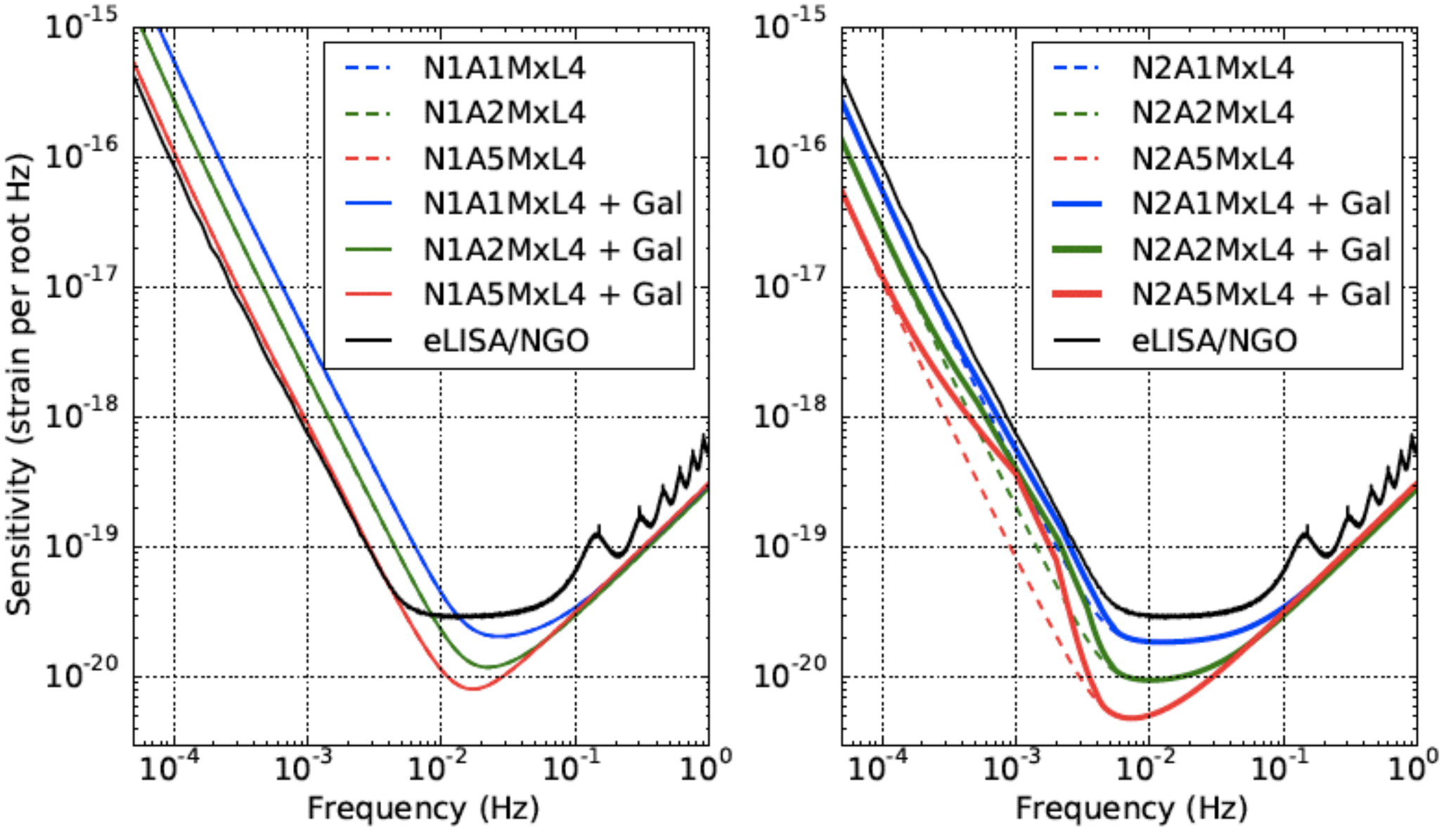
- number of laser links: 4 or 6? → Solved: 6 links
- noise level: two possibilities → Solved: pathfinder has flown!
- length of the arms: 1, 2, 5 million km? → Still open
- duration: 2 or 5 years? → Still open

working groups of the LISA consortium studied the science return of different designs
result of the ***LISA cosmology working group***

LISA observatory: sensitivity to compact binaries

targeted detection: MBH binaries with masses of order $10^{3\text{-}7}\,M_\odot$

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



A. Klein et al, arXiv1511.05581: MBH binaries

Late-time cosmology with the LISA observatory

probing the universe acceleration?

$$d_L(z) = (1+z)\,\mathcal{G}\left(\int_0^z \frac{dz'}{H(z')}\right)$$

$$H(z) = H_0\sqrt{\Omega_M\,(z+1)^3 + (1-\Omega_\Lambda-\Omega_M)\,(z+1)^2 + \Omega_\Lambda\,\exp\left[-\frac{3w_a z}{z+1}\right](z+1)^{3(1+w_0+w_a)}}$$

Late-time cosmology with the LISA observatory

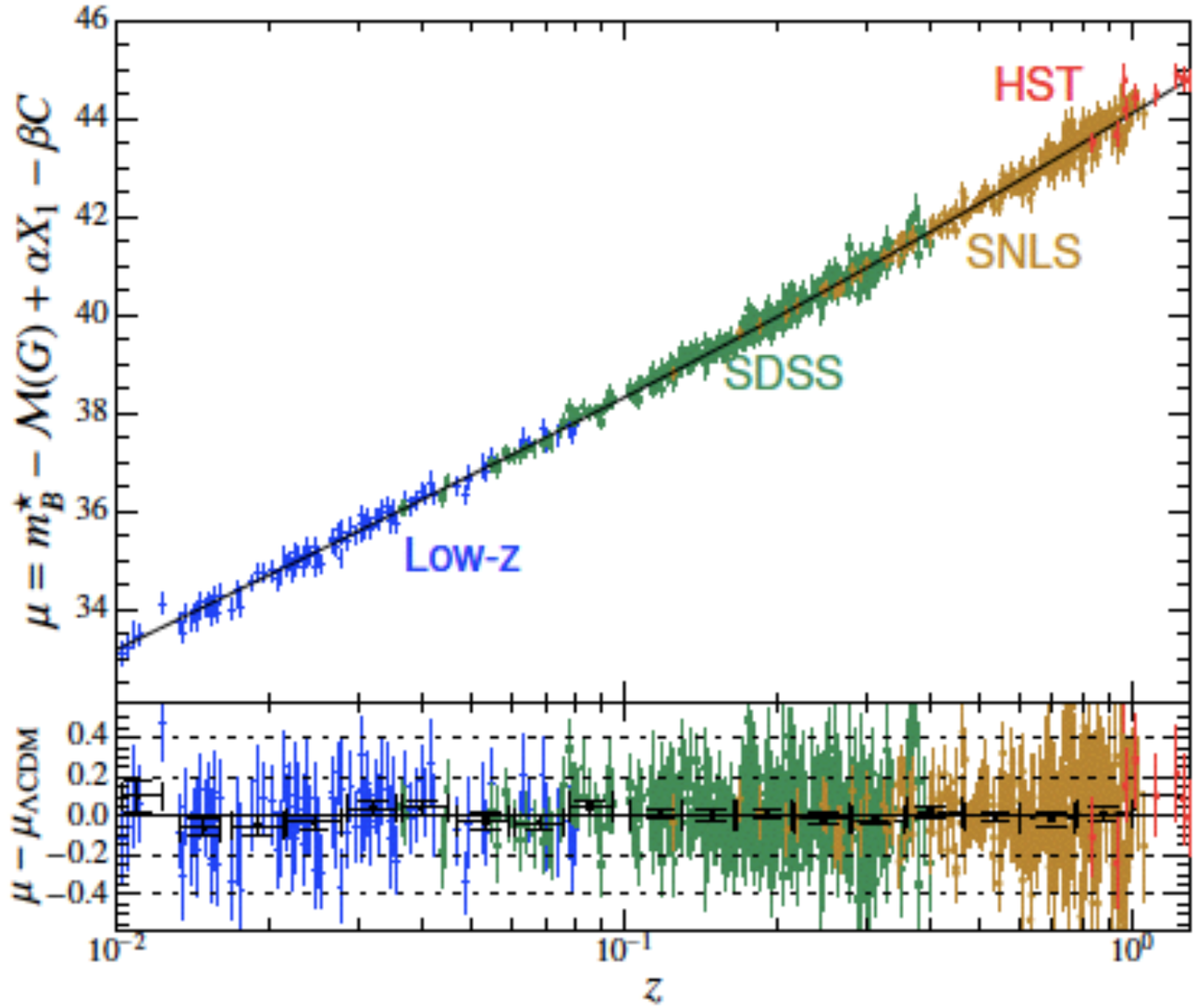
probing the universe acceleration?

$$d_L(z) = (1+z)\,\mathcal{G}\left(\int_0^z \frac{dz'}{H(z')}\right)$$

with SNIa

- easy to measure redshift
- hard to measure luminosity distance (standard candles)

Betoule et al 2014



Late-time cosmology with the LISA observatory

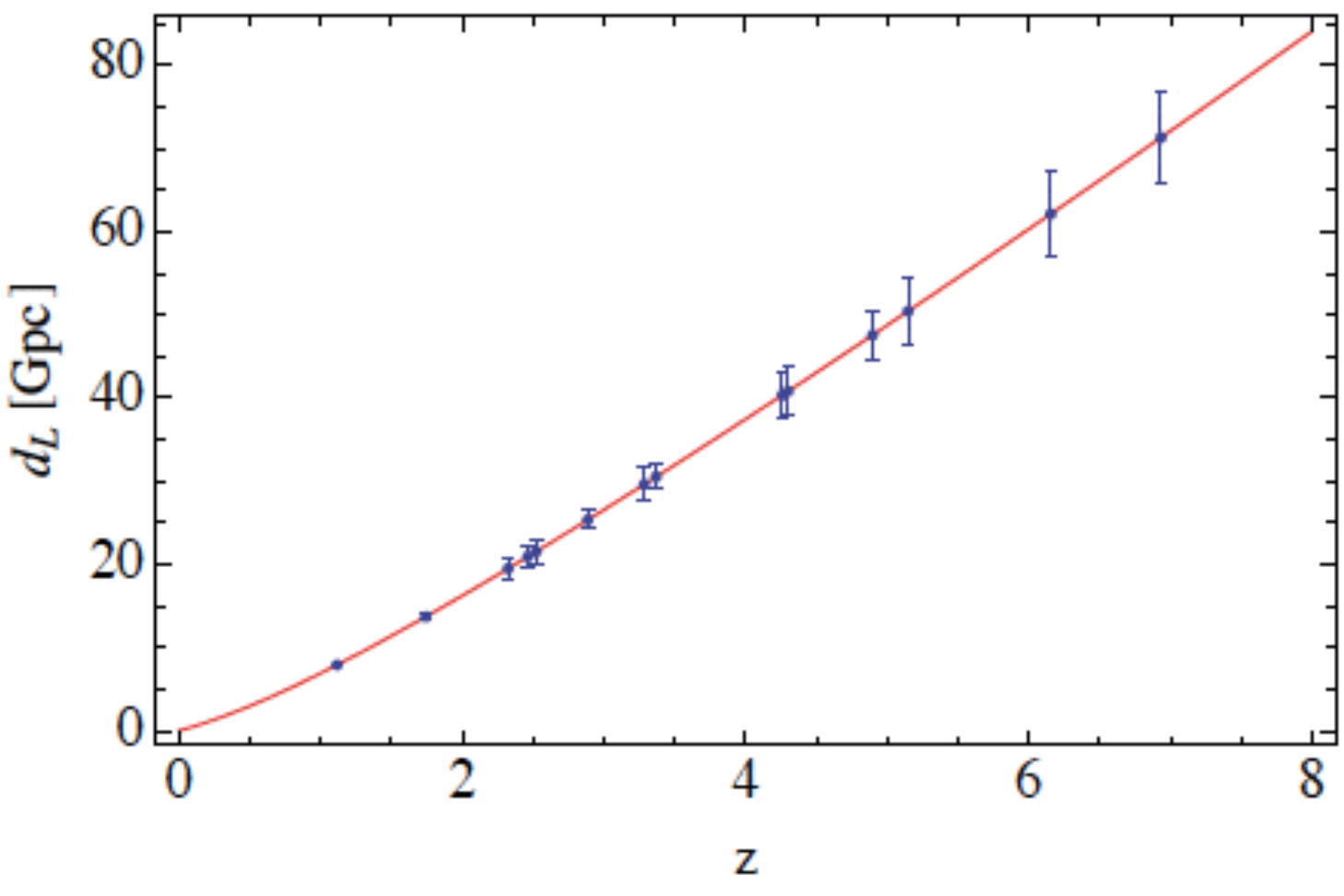
probing the universe acceleration?

$$d_L(z) = (1+z)\,\mathcal{G}\left(\int_0^z \frac{dz'}{H(z')}\right)$$

with GW from compact binaries

- easy to measure luminosity distance
- impossible to measure redshift

Tamanini et al 2015, simulated



standard sirens

GW emission by compact binaries
can be used to measure the luminosity distance

$$h_+(t) = \frac{4}{r}\left(\frac{GM_c}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f}{c}\right)^{\frac{2}{3}}\frac{1+\cos^2\iota}{2}\cos[\Phi(t)]$$

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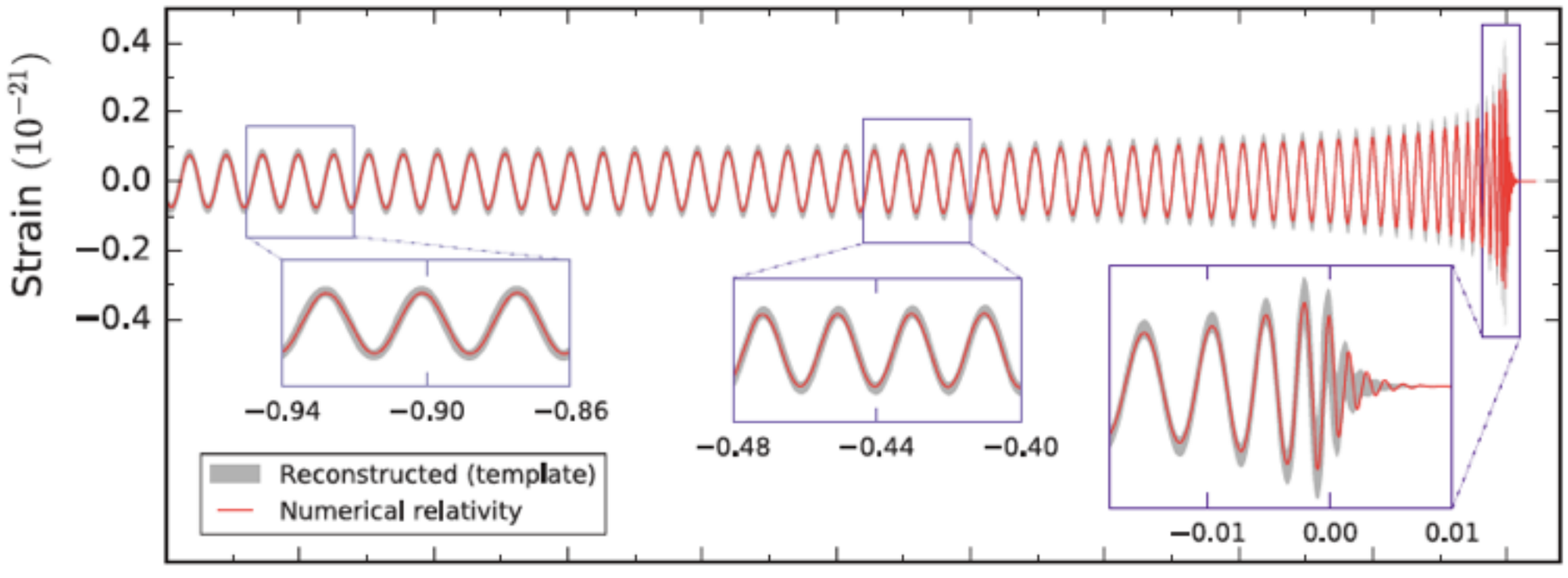

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$$h_+(t) = \frac{4}{d_L(z)} \left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}} \left(\frac{\pi f}{c}\right)^{\frac{2}{3}} \frac{1+\cos^2 \imath}{2} \cos[\Phi(t)]$$

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

redshifted chirp mass

Analogous to SNIa, but :

- direct measurement of d_L up to large redshift without calibration 😀
- need an independent (optical) measurement of the redshift 😞

standard sirens

what can we do with LISA?

- LISA can measure merging MBH binaries of $10^{3\text{-}7}\ M_\odot$ up to redshift $z \sim 10$: for these we have access to d_L

- to get the *redshift* of these sources one needs **ELECTROMAGNETIC COUNTERPARTS** (typically a jet produced at or after the merger)

- the EM counterpart is detected by a telescope pointing in the merging MBH binary direction

- how many standard sirens (MBH binary + EM counterpart) will LISA be able to detect, supplemented by some telescope?

how we tackled the problem for LISA

N. Tamanini et al, arXiv1601.07112 : standard sirens

- 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)

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

- Add weak lensing and peculiar velocities errors to d_L

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- 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

how we tackled the problem for LISA

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- model of the counterparts :
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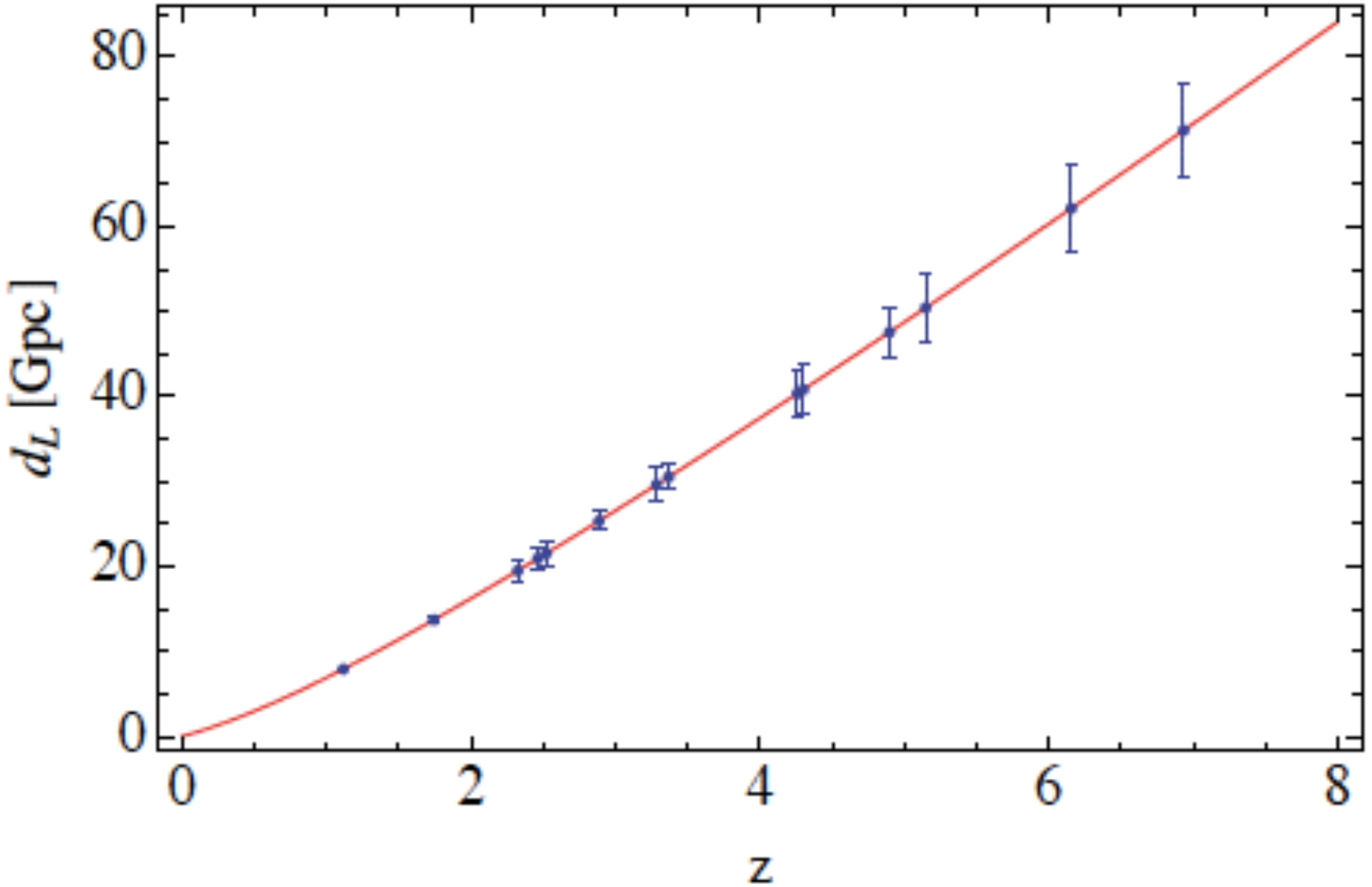
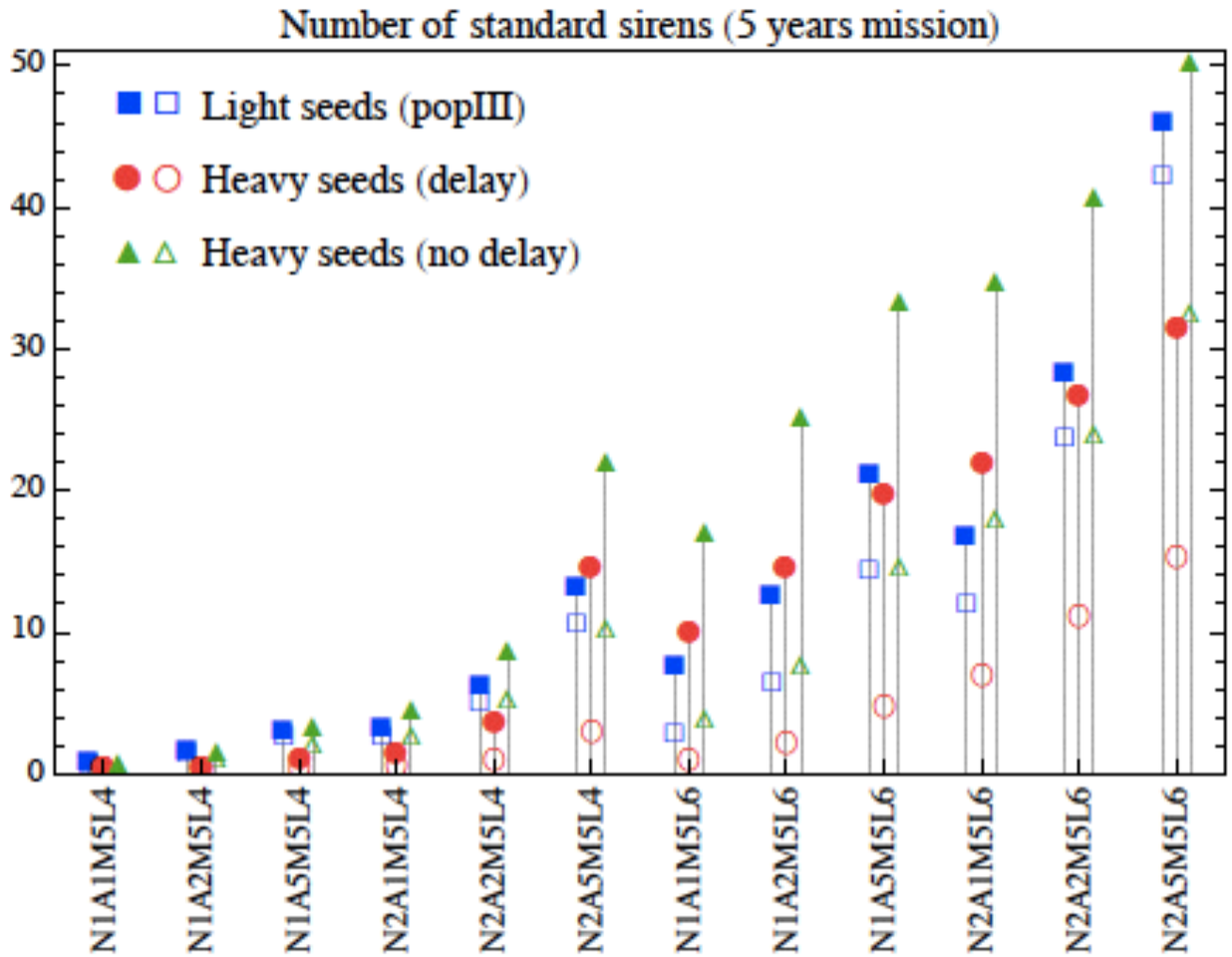
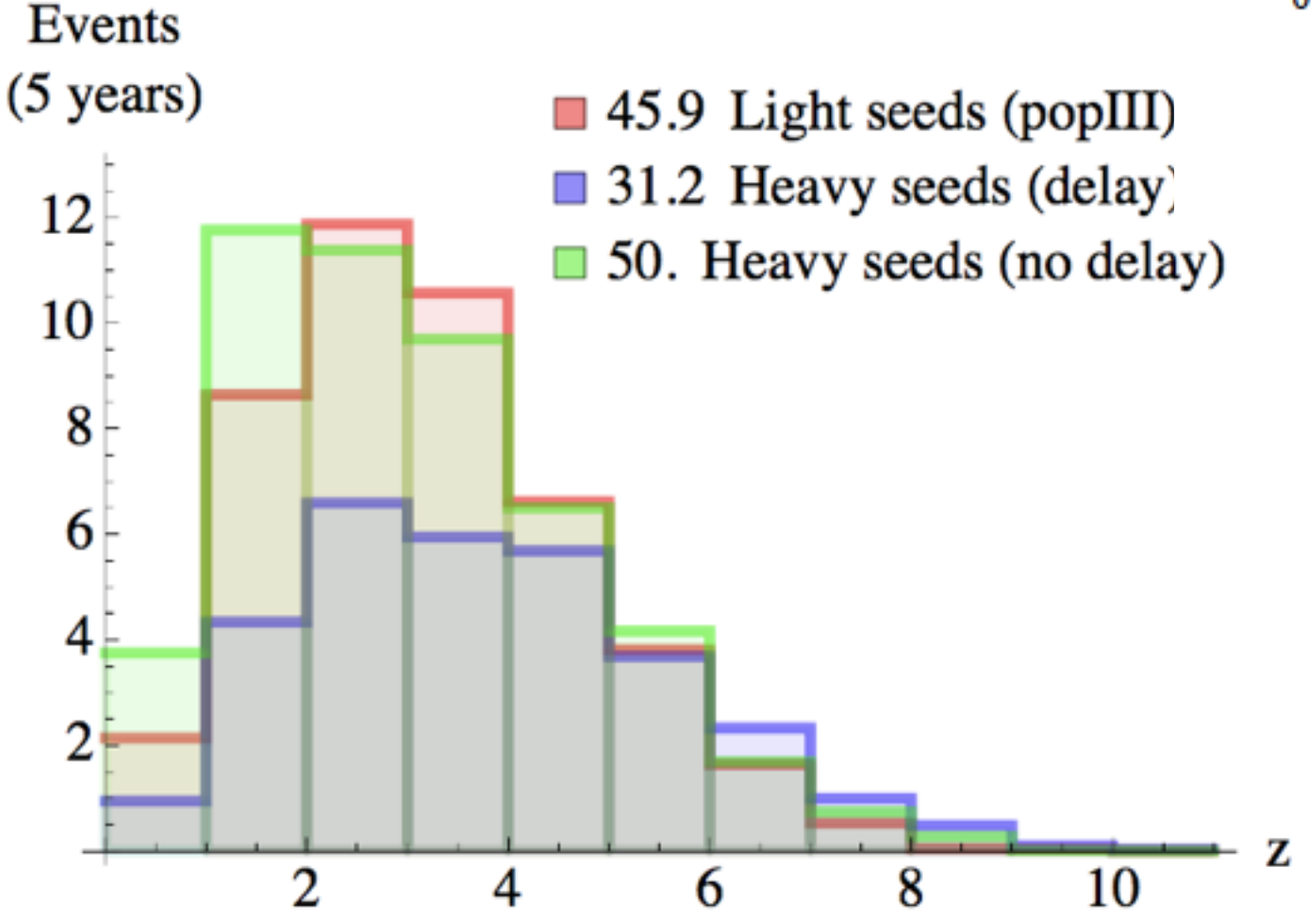
example of simulated data *with counterparts:* realistic events with weak lensing and peculiar velocity errors



number and redshift distribution of LISA standard sirens

the total number of standard sirens varies a lot with the *LISA configuration* and the *MBHB formation model*





VERY FEW EVENTS AT LOW REDSHIFT !

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

constraints on cosmological parameters with LISA

- LISA cannot constrain simultaneously the five parameters $(\Omega_M,\, \Omega_\Lambda,\, h,\, w_0,\, w_a)$

we need to choose cosmological models

constraints on cosmological parameters with LISA

- LISA cannot constrain simultaneously the five parameters $(\Omega_M,\, \Omega_\Lambda,\, h,\, w_0,\, w_a)$

Cosmological constant + curvature

$$\Omega_M = 0.3 \pm [0.22,\, 0.026]$$

$$\Omega_\Lambda = 0.7 \pm [0.54,\, 0.09]$$

$$h = 0.67 \pm [0.13,\, 0.016]$$

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worst case scenario regarding MBHB formation model and sky localisation

best case scenario regarding MBHB formation model and sky localisation

constraints on cosmological parameters with LISA

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Cosmological constant + curvature

$$\Omega_M = 0.3 \pm [0.22,\, 0.026]$$
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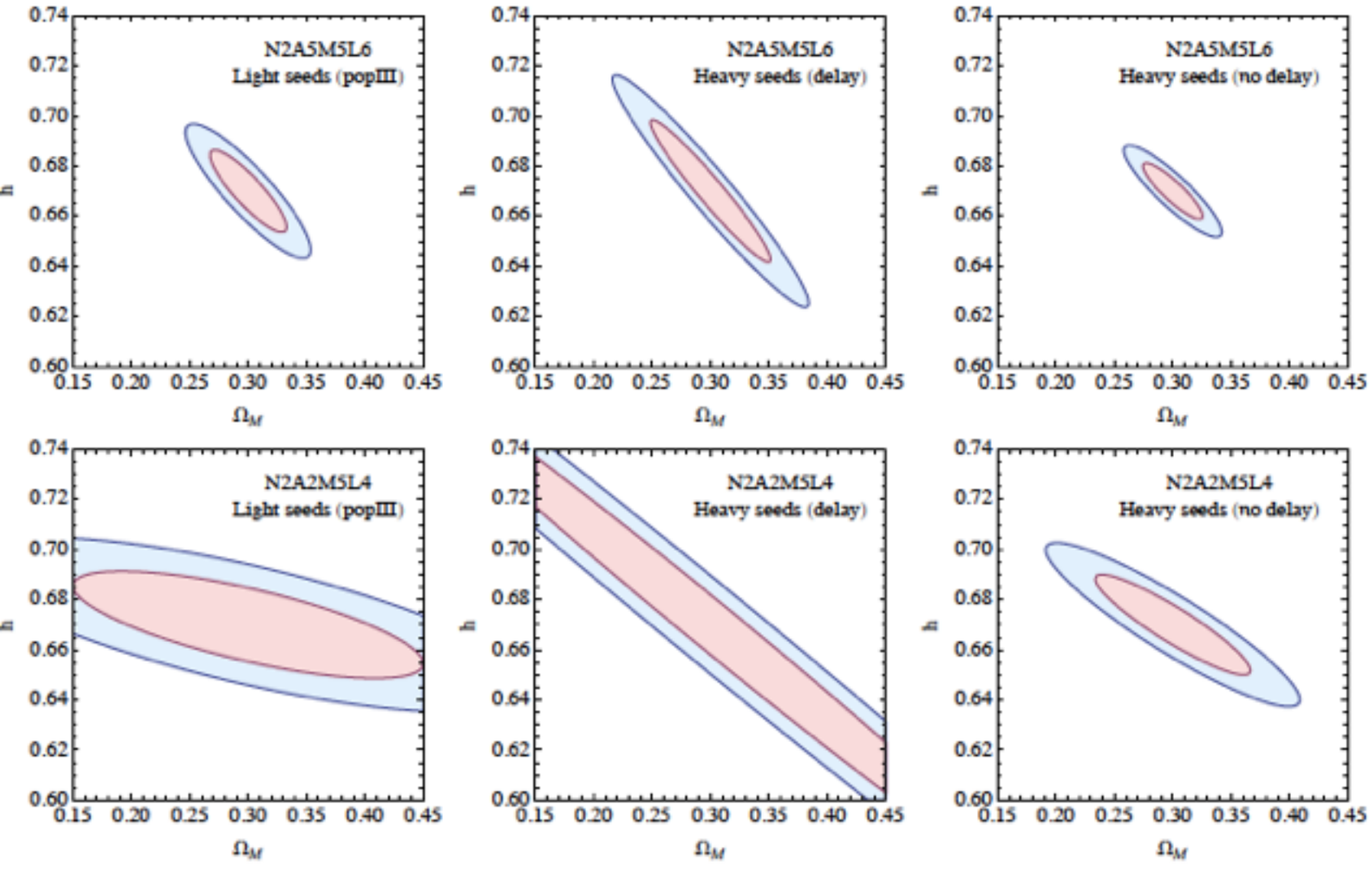
$$h = 0.67 \pm [0.13,\, 0.016]$$

best case scenario gives a 2% fully independent measurement of the Hubble parameter

SNIa + Planck + BAO (Betoule et al 2014)

$$\Omega_M = 0.305 \pm 0.01$$
$$\Omega_\Lambda = 0.693 \pm 0.01$$
$$h = 0.683 \pm 0.01$$

ΛCDM



$$\Omega_M = 0.3 \pm [0.09,\ 0.018]$$
$$h = 0.67 \pm [0.048,\ 0.008]$$

Planck alone :

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

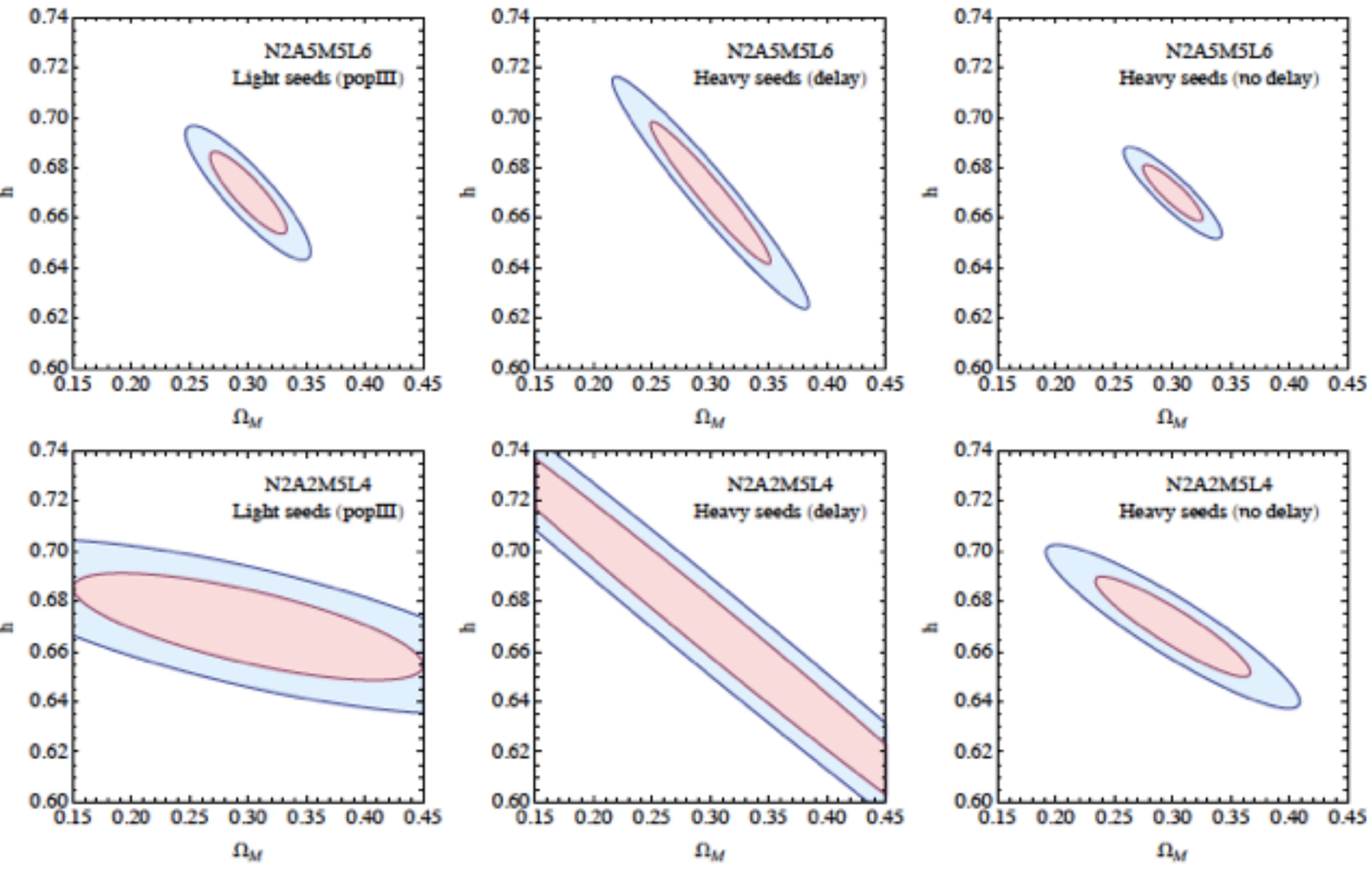
LISA fixing H_0 :

$$\Omega_M = 0.3 \pm [0.024\,, 0.0078]$$

SNIa alone : (Betoule et al 2014)

$$\Omega_M = 0.294 \pm 0.034$$

ΛCDM



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Planck alone :

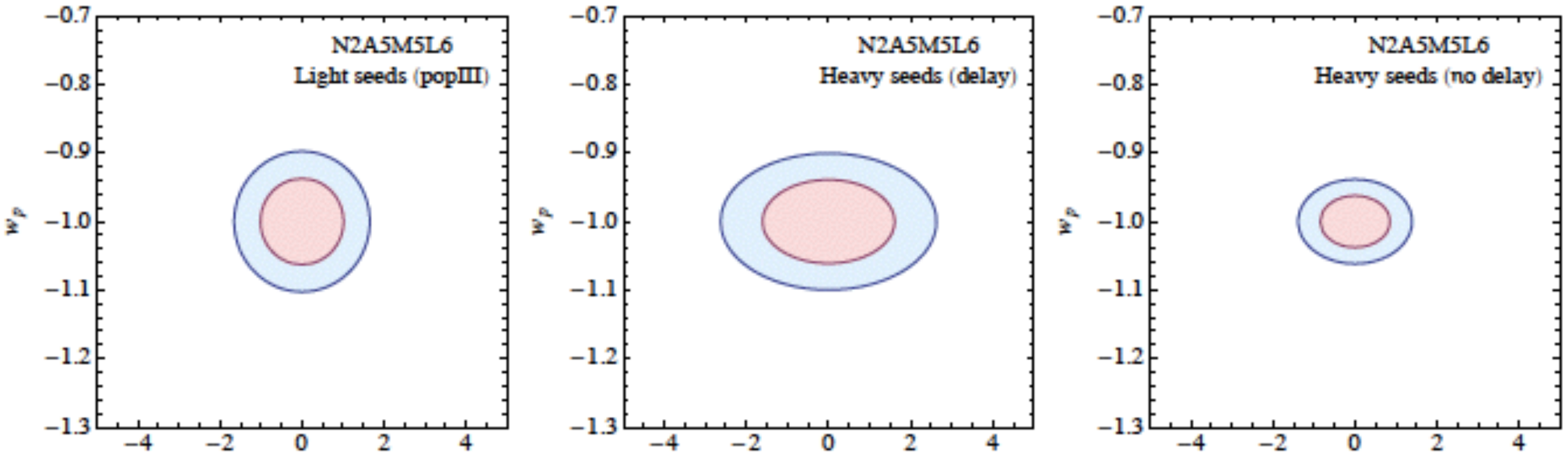
$$\Omega_M = 0.308 \pm 0.0012$$
$$h = 0.678 \pm 0.009$$

LISA fixing Ω_M :

$$h = 0.67 \pm [0.0099\,, 0.003]$$

- fully independent constraint
- comparable with Planck in *worst case scenario*
- 0.4% in *best* case

Dynamical Dark Energy



w_a

too few events at low redshift to get a good measurement

$$w_0 = -1 \pm [0.58,\ 0.1]$$

$$w_a = 0 \pm [2.78,\ 0.56]$$

N2A5M5L6			N2A2M5L4		
z_p	Δw_p	Δw_a	z_p	Δw_p	Δw_a
0.244	0.0413	0.665	0.193	0.0626	3.34
0.264	0.0401	1.06	0.239	0.0830	3.30
0.228	0.0248	0.559	0.194	0.0455	1.14

SNIa + Planck + BAO :

(Betoule et al 2014)

$$w_0 = -0.957 \pm 0.124$$

$$w_a = -0.336 \pm 0.552$$

Euclid forecast :

$$\Delta w_0 = 0.02$$

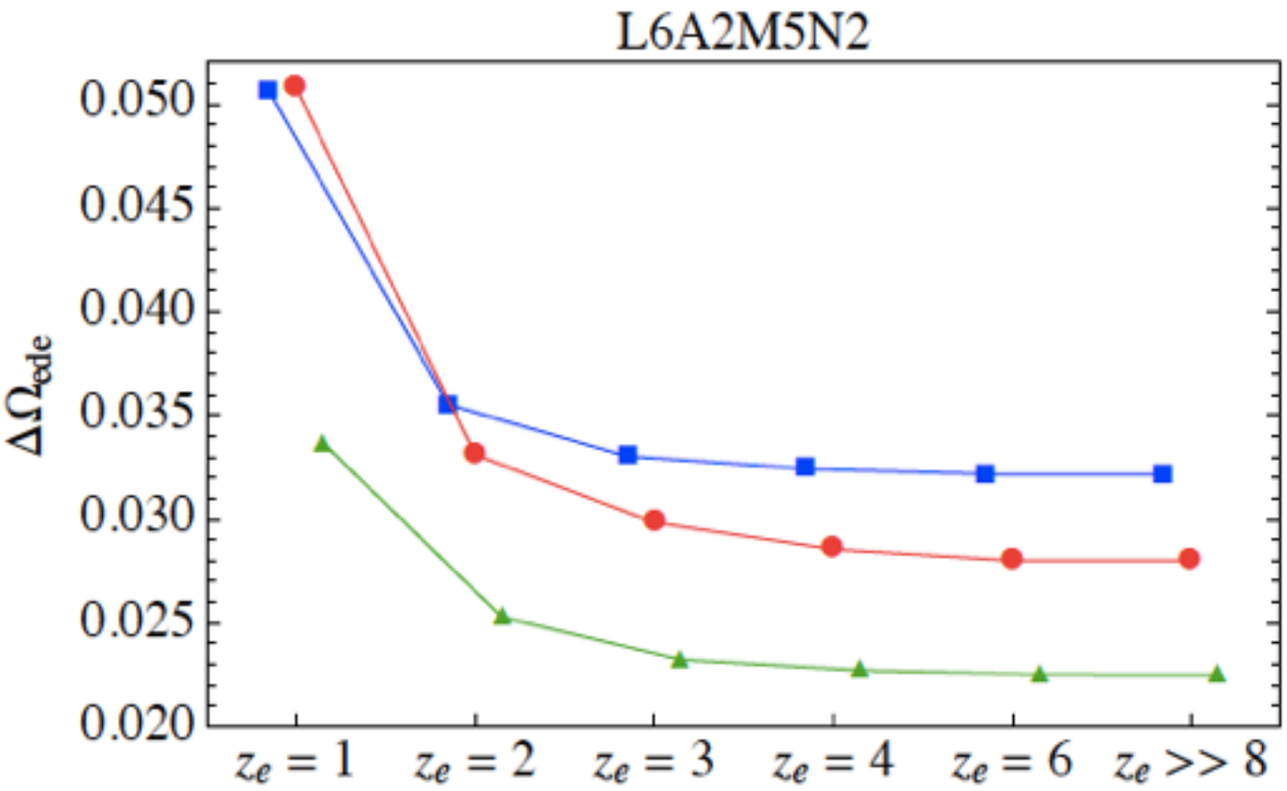
$$\Delta w_a = 0.1$$

constraints on cosmological parameters with LISA
summary of standard cosmology

- LISA will help solving the tension about the measurement of H_0 !
- it cannot provide good constraints on dynamical dark energy because most of standard sirens are at high redshift
- maybe it can be used to probe the expansion of the universe at $z \sim 6$, redshift yet unobserved?
- we analyzed two examples of more exotic dark energy models providing deviations from the ΛCDM expansion at high redshift
- *early dark energy* and *interacting dark energy* (for which there is some evidence in latest cosmological observations)

Salvatelli et al 2014, Murgia et al 2016

Early Dark Energy

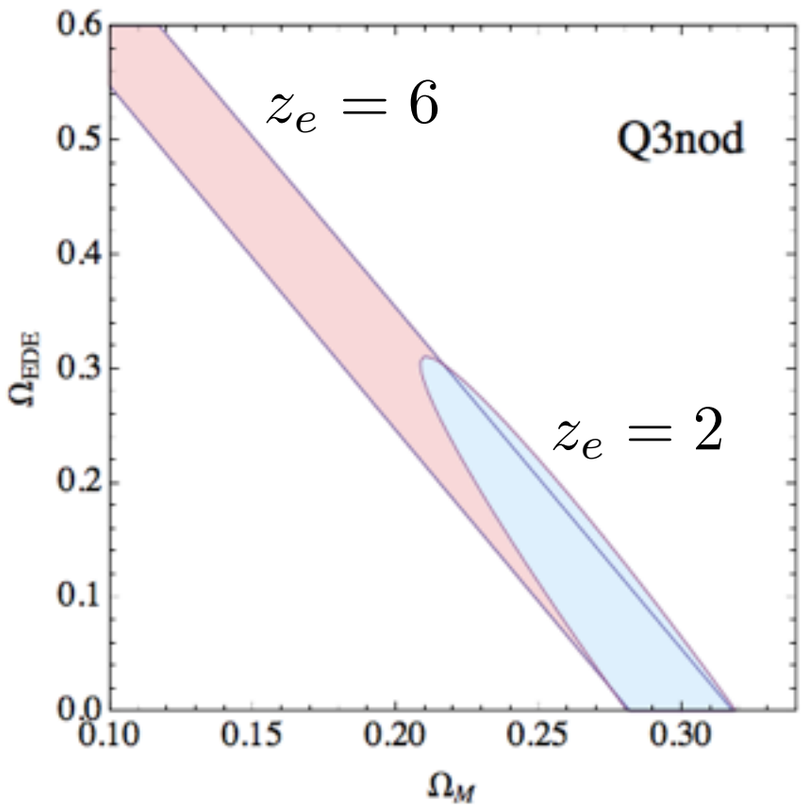


Ω_{de} fraction of dark energy at early times

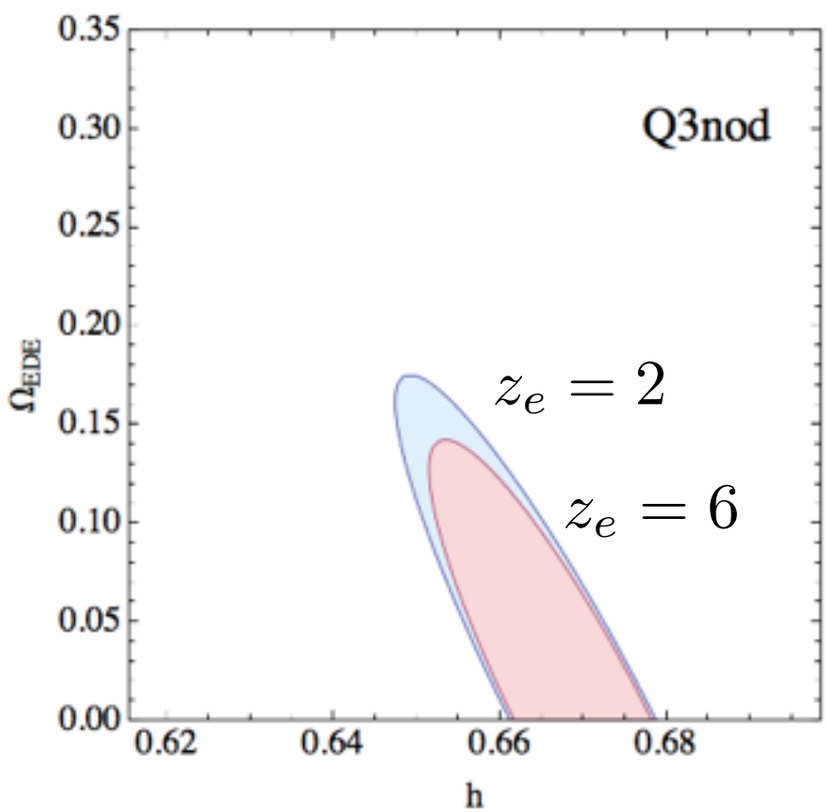
z_e redshift up to which dark energy contributes

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

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



with Ω_m better measurement at low z_e because of degeneracy: the bulk of standard sirens is at high redshift



Interacting Dark Energy

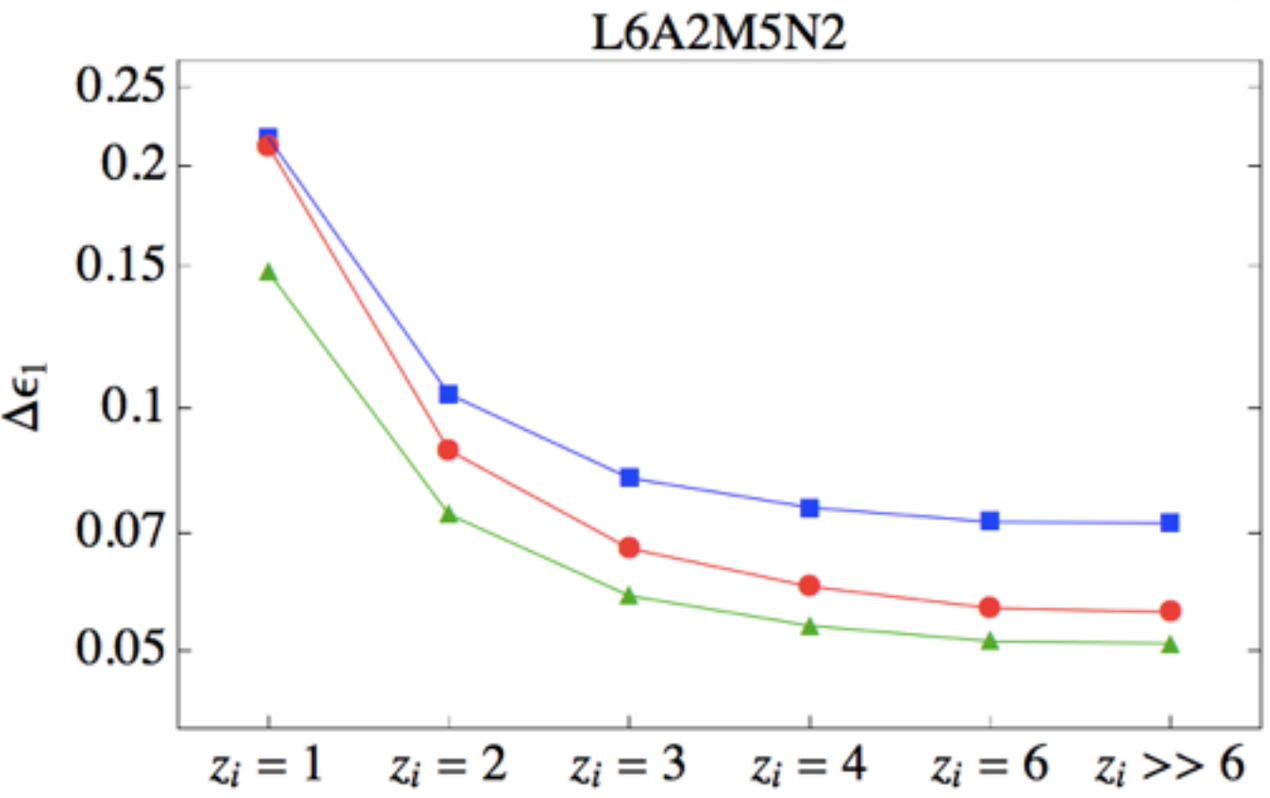
$$\dot{\rho}_{dm} + 3H\rho_{dm} = Q$$

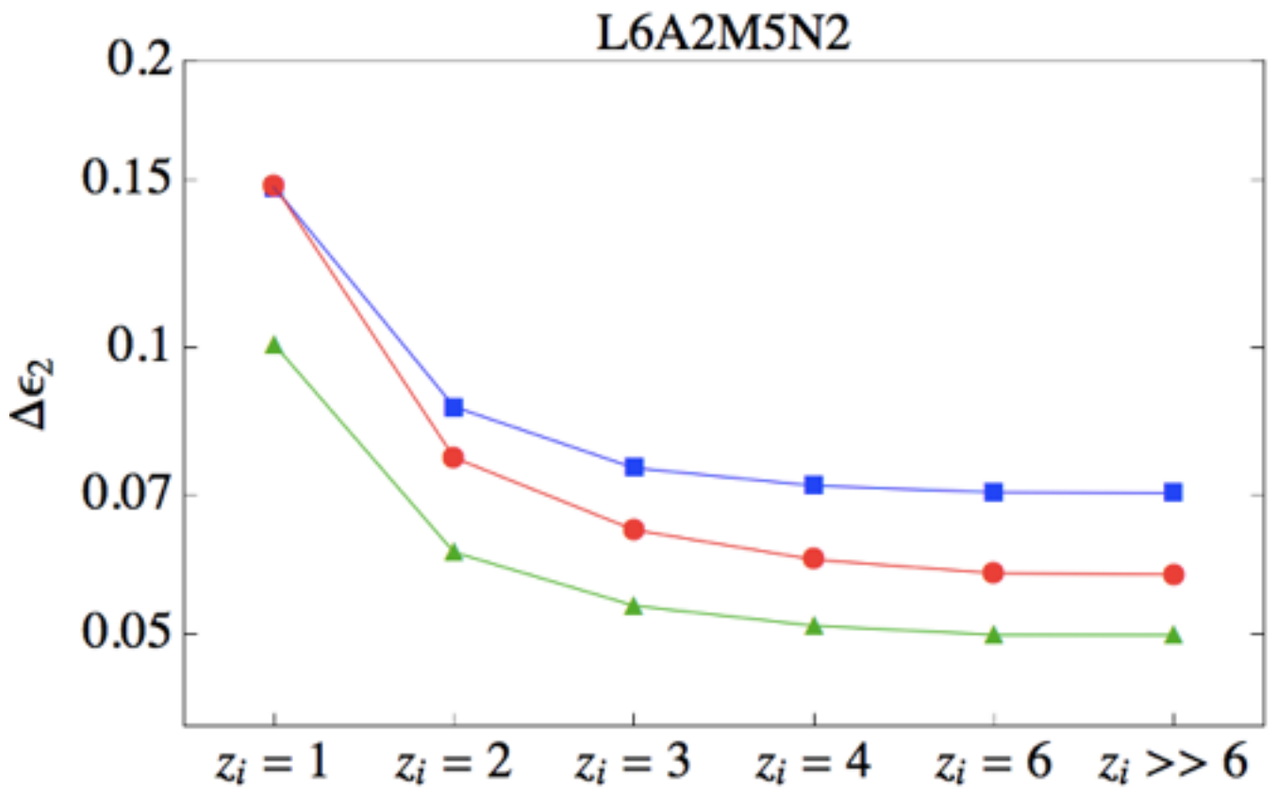
$$\dot{\rho}_{de} + 3H(1+w_0)\rho_{de} = -Q$$

two models for the interaction

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

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

we have assisted to a historical event, the LIGO/Virgo detection, which (so far) confirms GR

this opens the era of GW astronomy and cosmology :
we have a new, independent “messenger” to be added to EM emission

LISA is now on track for launch in 2030-2034

GW are revealing to be a powerful mean to probe cosmology:
this should be fully investigated and exploited!