Late-time cosmology with eLISA

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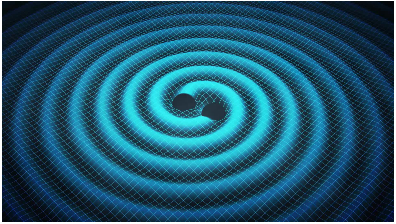
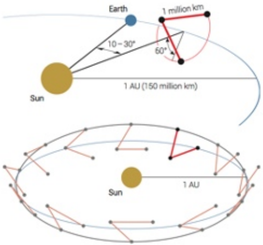
Plan of the talk

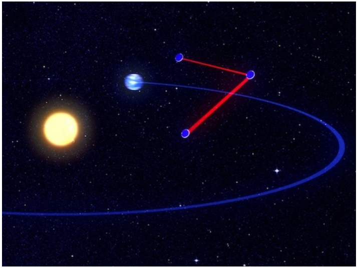
- eLISA and standard sirens
- Measuring distances (GWs)
- Measuring redshifts (EM waves)
- Forecasting eLISA accuracy for cosmology
- Comparison with present constraints



eLISA in one slide

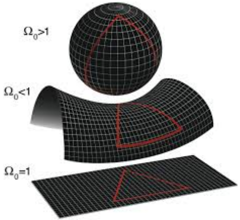
- Proposed space-based laser interferometer orbiting around the Sun in triangular formation
- Final design still under discussion:
  - 4 or 6 links (L4, L6)
  - 1 to 5 $\times 10^6$ Km arms (A1, A2, A5)
  - LISA pathfinder low frequencies acceleration noise (N2) or 10 times worse (N1)

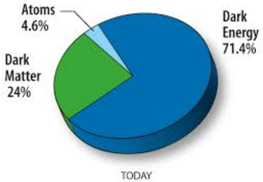


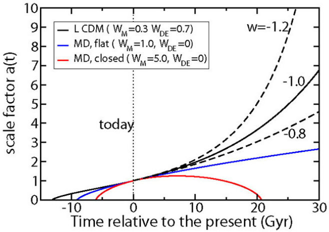


Cosmology with eLISA

- How can eLISA be used to probe late-time cosmology?
- What kind of information can we obtain?







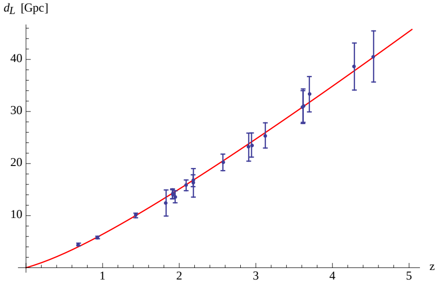
Evolution history of the universe

Map the late-time expansion using the **distance to redshift relation**:

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

- z is the **redshift** (gives size of the Universe at time of emission)
- d_L is the **luminosity distance** (gives time of emission: $t = d_L/c$)
- $H(z)$ is the **Hubble rate** (contains the cosmological parameters/information)
- The function $\mathcal{G}$ depends on the **spatial geometry**

Fitting the distance to redshift relation



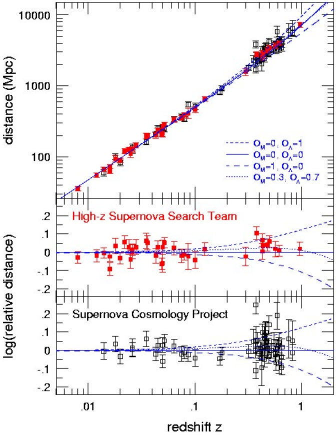
$$d_L(z) = (1+z)\,\mathcal{G}\left(\int_0^z \frac{dz'}{H(z')}\right)$$

- Fit the data with the theory
- Find constraints on the cosmological parameters

Exactly as for EM waves

Need independent measures of d_L and z to constrains the cosmological parameters in $H(z)$:

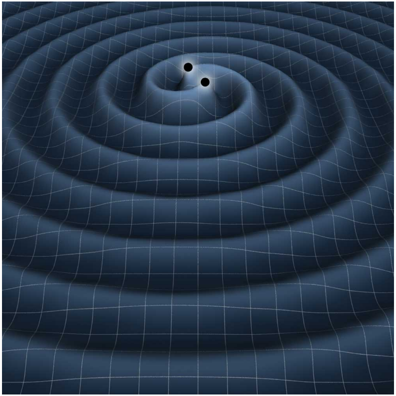
- **Measuring** **redshift** **is easy**: compare EM spectra
- **Measuring** **distance** **is hard**: need objects of known luminosity (**standard candles**) or objects of known length (**standard rulers**)



Mapping the evolution with GWs

Again need independent measures of d_L and z, but observing GWs (which is hard by itself) turns the problem around:

- **Measuring distance is easy**: from well-modeled sources of GWs (**standard sirens**)
- **Measuring redshift is hard**: need EM counterpart or other independent method



What is a standard siren?

Theoretically **well-modeled source of GWs**:
stellar binaries, neutron stars binaries, black holes binaries, ...

Expected in-spiral wave-form at observer (strongest harmonic):

$$h(t) = \frac{M_z^{5/3} f(t)^{2/3}}{d_L} F(\mathrm{angles}) \cos(\Phi(t))$$

- dimensionless strain $h(t)$
- GW phase $\Phi(t)$ and frequency $f(t) = (1/2\pi) d\Phi/dt$
- position and orientation dependence $F(\mathrm{angles})$
- redshifted chirp mass $M_z = (1+z)\frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$

What is a standard siren good for?

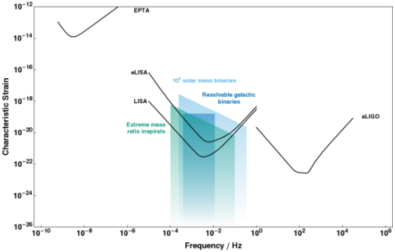
$$h(t) = \frac{M_z^{5/3} f(t)^{2/3}}{d_L} F(\text{angles}) \cos(\Phi(t))$$

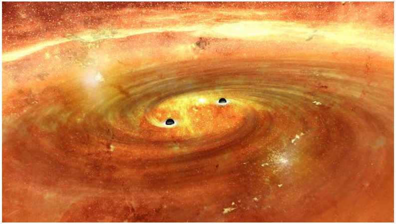
- **Direct measure of distance** d_L (and direction)
- But no independent information on **redshift** z
- **Gravitation is scale-free**: Wave-form from a local binary ($z = 0$) with masses (m_1, m_2) is indistinguishable from wave-form of a binary at redshift z with masses $\left(\frac{m_1}{1+z}, \frac{m_2}{1+z}\right)$

$\Rightarrow$ Need independent measurement of **redshift** for cosmology

What standard sirens will eLISA hear?

- Good mass coverage in range $10^4 - 10^7\ M_\odot$
  - **SMBBHs**
- Can detect sources up to $z \sim 10$–15
- Can determine sky location up to 1–10 $\deg^2$
- Can determine d_L with great accuracy: up to $\sim$1%



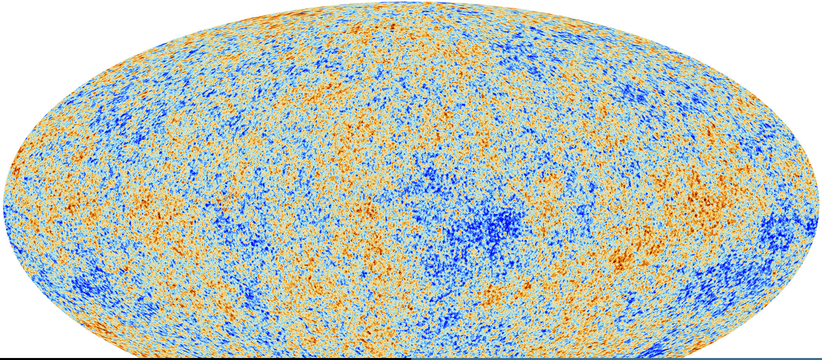


Accuracy on d_L

What is the accuracy on the **distance** d_L?

- Depends on the detector (specific eLISA design)
- Might improve once an EM counterpart has been observed
- Degrades due to inhomogeneities of the Universe
  - e.g. weak-lensing

$\Rightarrow$ need to characterize the **effects of inhomogeneities**



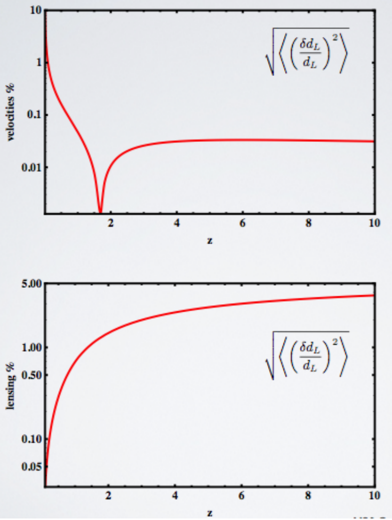
The error induced on d_L

The dominant contributions on d_L due to inhomogeneities are:

- At small redshift: **peculiar velocities**
- At high redshift: **lensing** (dominant for eLISA)

Other effects:

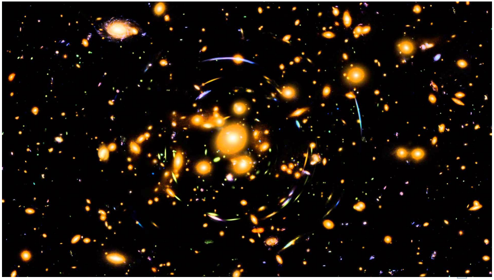
- Change of position in the sky
- Change of observed orientation



Two ways of overcome lensing

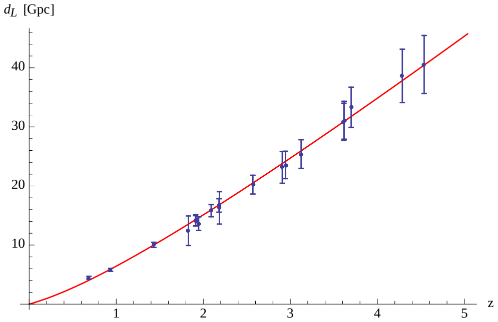
There are mainly two ways to reduce the error due to weak-lensing:

- **De-lensing**
  - Case-by-case reconstruction
  - Weak-lensing maps
- **Statistics**
  - For a sufficient numbers of source, one can average away the effects of lensing



What about redshift?

From GW sources we thus obtain the y-coordinates of our data (luminosity distance).



How do we find the coordinates on the x-axis (redshift)?

How to measure redshift?

- Need good sky location accuracy from eLISA
- Need to identify the **hosting galaxy** with an **EM counterpart** (large uncertainties for SMBBHs)
  - Optical
  - Radio
  - X-rays

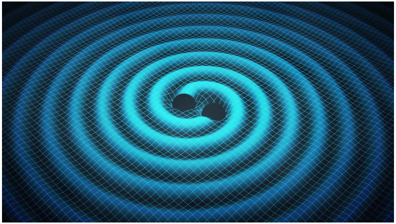
- Redshift measured only from **optical light**
  - Spectroscopically

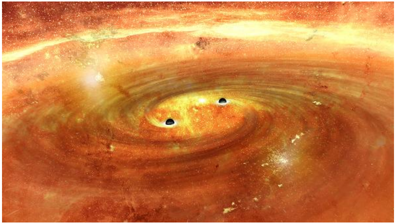
    (low magnitude high accuracy)
  - Photometrically

    (high magnitude low accuracy)

The big issue

- How many standard sirens will be detected by eLISA?





- How many SMBBHs are out there?
- For how many it will be possible to observe a counterpart?

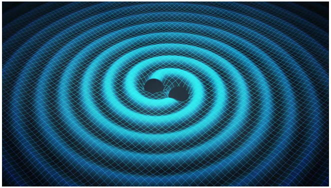
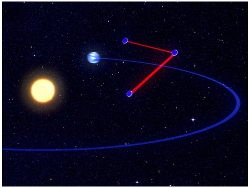
Our work

- We are trying to answer all these questions

  (in collaboration with E. Barausse, C. Caprini, A. Klein, A. Petiteau, A. Sesana)
- Focus on **5 years** eLISA mission
  (the more the better for cosmology)
- Realistic approach
  - Likely SMBBH merger rate (though large uncertainties)
  - Detection of EM counterparts using future telescopes
- All results that follows are **work in progress**

Detecting GWs with eLISA

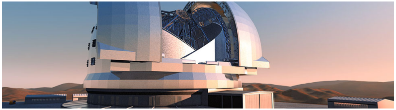
- Start from simulating SMBBHs merger events using **3 different astrophysical models**
  - Light seeds formation (popIII)
  - Heavy seeds formation (with delay)
  - Heavy seeds formation (without delay)
- Compute for how many of these a GW signal will be **detected by eLISA** (SNR>8)
- Among these select the ones with a **good sky location accuracy** ($\Delta\Omega < 10\,\mathrm{deg}^2$)

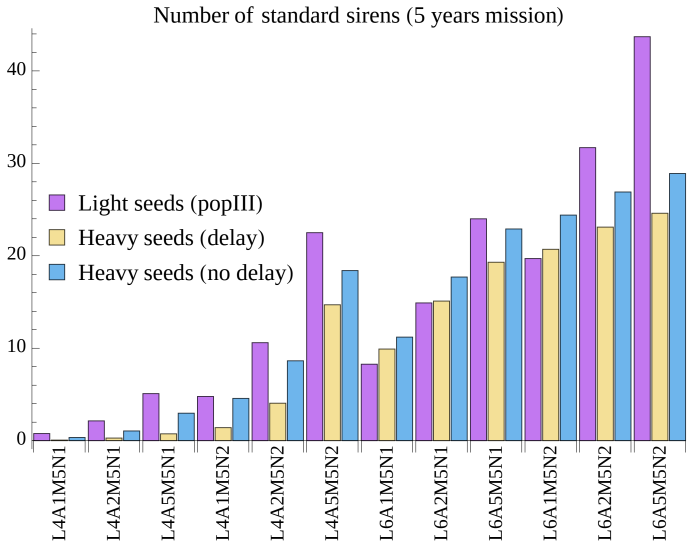
Detecting the counterparts

To detect the EM counterpart of an eLISA event sufficiently localized in the sky we use the combination SKA + E-ELT

- **SKA** detects a first radio emission from the BHs and pinpoints the source in the sky
- **E-ELT** will then focus in that direction to measure an optical counterpart from which the redshift of the source can be measured either
  - Spectroscopically or Photometrically



Standard sirens with eLISA



Cosmology

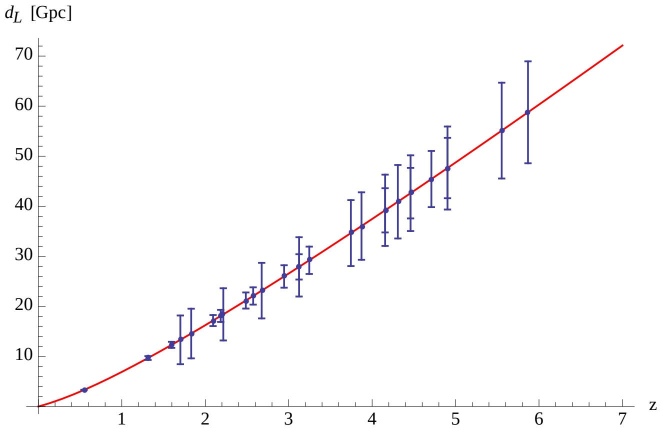
Fit the data with a 5 parameters $\theta_i = (\Omega_M, \Omega_\Lambda, h, w_0, w_a)$ **cosmological model** giving

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

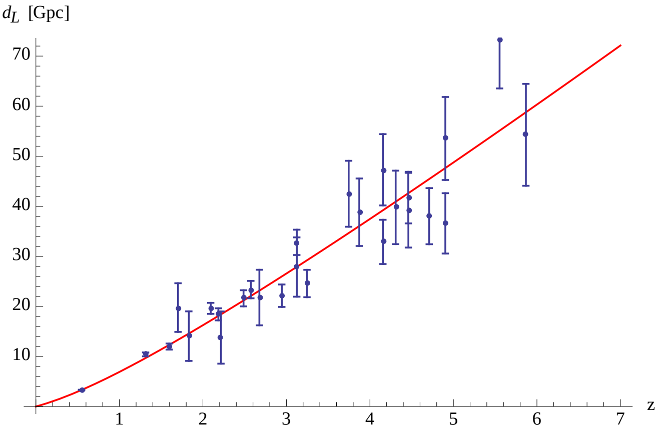
entering the distance to redshift relation

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

Example of simulated data



Example of possible real data



Fisher matrices and FoMs

Compute the **Fisher matrix** as

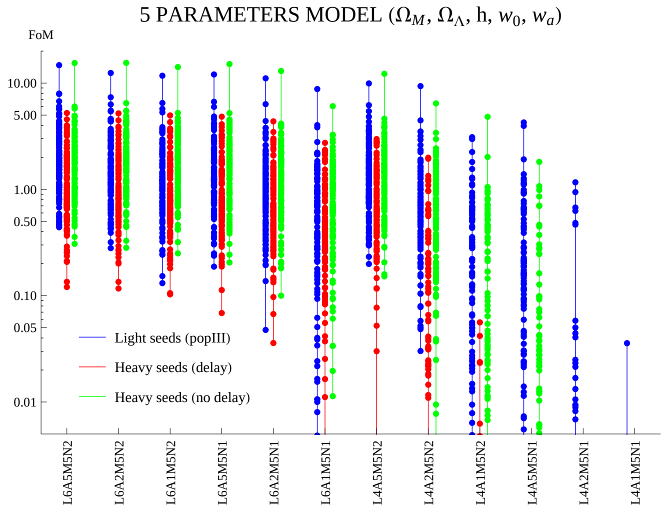
$$F_{ij} = \sum_n \frac{1}{\sigma_n^2} \left.\frac{\partial d_L(z_n)}{\partial \theta_i}\right|_{\rm fid} \left.\frac{\partial d_L(z_n)}{\partial \theta_j}\right|_{\rm fid}$$

Define a **figure of merit** (FoM) as

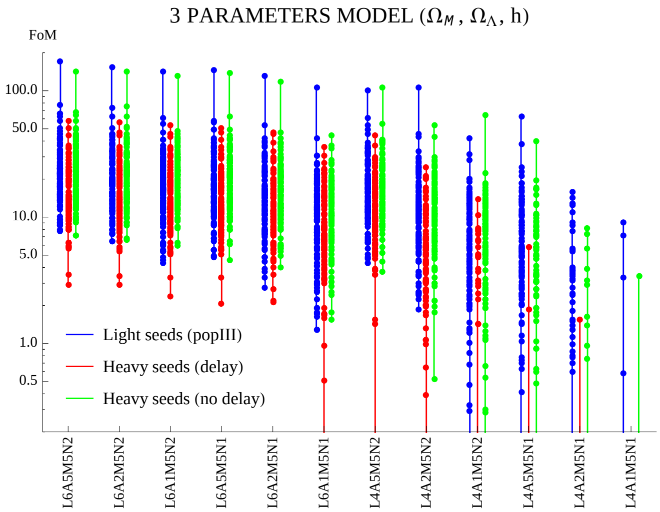
$$\mathrm{FoM} = \det(F_{ij})^{\frac{1}{2N}}$$

As an estimate for the average standard 1σ **error** on the parameter one can take $1/\mathrm{FoM}$

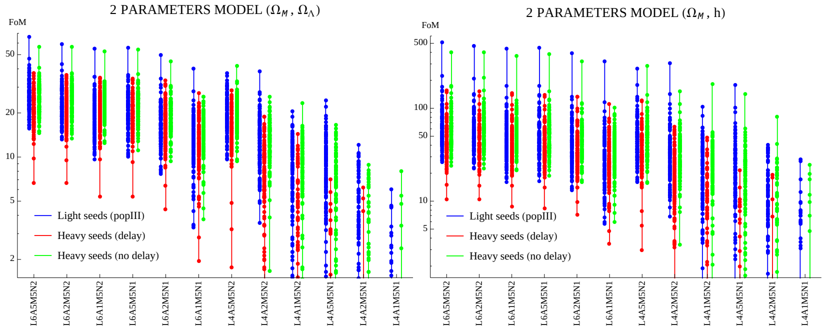
FoMs for 5 parameters cosmology



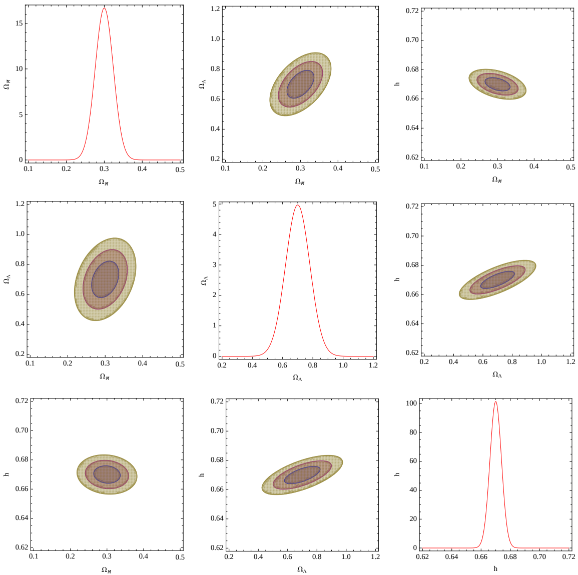
FoMs for 3 parameters cosmology



FoMs for 2 parameters cosmology



Contour plots for L6A5M5N2 (HS - no delay)



Standard 1σ errors for L6A5M5N2

$\Delta\Omega_M$	$\Delta\Omega_\Lambda$	Δh	Δw_0	Δw_a
0.525 1.02 0.596	1.27 2.21 1.45	0.00776 0.0873 0.0108	1.14 1.28 1.27	7.11 17.5 8.15
0.0205 0.0374 0.0239	0.0757 0.147 0.0803	0.00295 0.0194 0.00393		
0.0204 0.0229 0.0238	0.0584 0.0813 0.0613			
0.0201 0.0312 0.0227		0.00228 0.0107 0.00300		
	0.0741 0.123 0.0762	0.00293 0.0119 0.00391		
			0.102 0.215 0.114	0.650 1.16 0.727

Expected constraints by eLISA (L6A5M5N2)

- Bad constraints for **5 parameters** cosmology due to degeneracy between $(\Omega_M, \Omega_\Lambda, h)$ and (w_0, w_a)
- Good constraints for **3 parameters** cosmology:
  - Comparable to present constraints for Ω_M and Ω_Λ:

$$\Omega_M = 0.30 \pm 0.03 \qquad \Omega_\Lambda = 0.70 \pm 0.08$$

  - Slightly better than present constraints for h

$$h = 0.670 \pm 0.004 \quad (H_0 = 67 \pm 0.4\,\mathrm{km/s/Mpc})$$

- Good measure of the **Hubble constant**

Comparing with CMB

Expected from eLISA (L6A5M5N2):

$$\begin{cases} \Omega_M = 0.30 \pm 0.02 \\ \Omega_\Lambda = 0.70 \pm 0.02 \\ H_0 = 67.0 \pm 0.3\,\mathrm{km/s/Mpc} \end{cases}$$

From today CMB [Planck2015]:

$$\begin{cases} \Omega_M = 0.3121 \pm 0.0087 \\ \Omega_\Lambda = 0.6879 \pm 0.0087 \\ H_0 = 67.51 \pm 0.64\,\mathrm{km/s/Mpc} \end{cases}$$

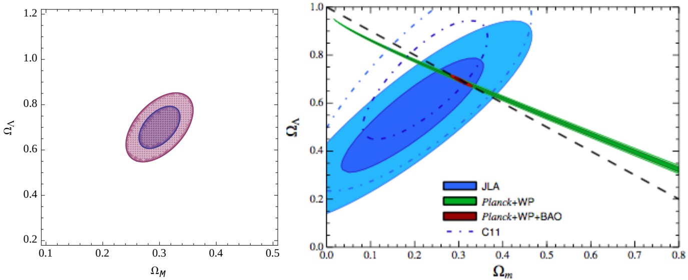
Comparing with Supernovae

Expected from eLISA (L6A5M5N2):

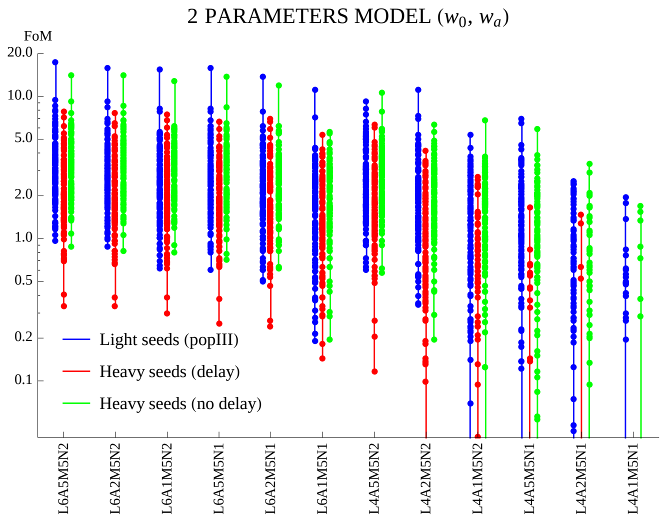
$$\Omega_M = 0.30 \pm 0.02 \qquad \Omega_\Lambda = 0.70 \pm 0.08$$

From today SNe [Betoule *et al* (2014)]:

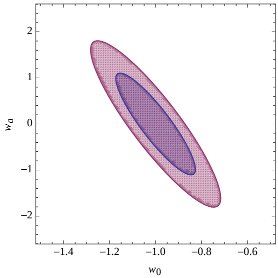
$$\Omega_M = 0.289 \pm 0.018 \qquad \text{(fixing curvature)}$$

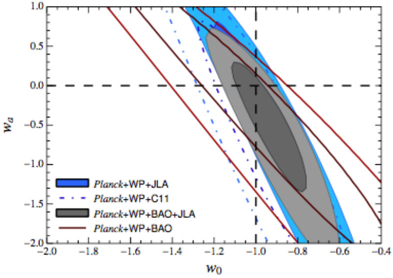


What about dark energy?



Contour plots for dark energy





$$w_0 = -1.0 \pm 0.1 \qquad w_a = 0.0 \pm 0.8$$

- Depends on the few data at low redshift ($\lesssim 1$)
- Comparable with combined present constraints (SNe+Planck+BAO) [Betoule *et al* (2014)], but not with future probes (e.g. Euclid)
- Possible high redshift addendum to supernovae data

Conclusions

- SMBBHs are excellent **distance** indicators up to $z \sim 7$
- Need good eLISA configuration to reduce sky location error (6L or best of L4)
- Need identification of EM counterparts for measuring **redshift**
- Systematic-free (no calibration needed) sources
- New cosmological measurements independent from EM

Conclusions

With eLISA we can measure (5 years mission):

- Ω_M and Ω_Λ up to few % accuracy
- H_0 up to less than 1% accuracy
- Dark energy EoS with low accuracy (though comparable to present SNe)

In other words:

- Good probe of **matter dominated era** at high-z (Ω_M, Ω_Λ, H_0)
- Not-so-good probe of **dark energy dominated era** at low-z (w_0, w_a)

Further work

- Combine eLISA expected results with other probes (CMB, Supernovae, BAO, ...)
- Consider other astrophysical models of SMBBH merger rate
- Find further realistic ways to detect counterparts (use other telescopes/EM emissions)
- Analyse alternative cosmological models (modify gravity, interacting DE-DM, ...)

THANK YOU!