# Late-time cosmology with eLISA

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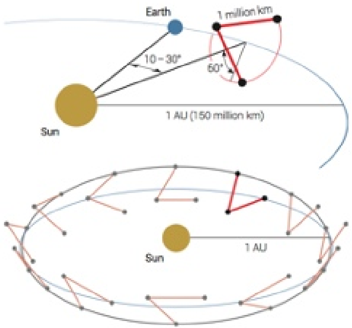
# eLISA in one slide

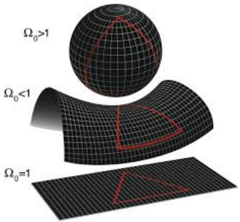


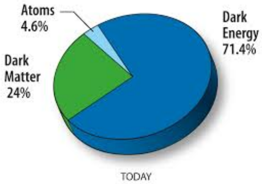
For more information see talk on Friday

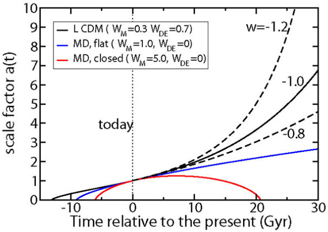
- Proposed space-based laser interferometer
- ESA L3 mission (2034): "the gravitational universe"
- Final design under discussion:
  - 4 or 6 links (2/3 arms)
  - 1 to $5 \times 10^6$ Km arms
  - Expected noise
- Main target sources: SMBHBs with $10^4 - 10^7 M_\odot$

# Cosmology with eLISA

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







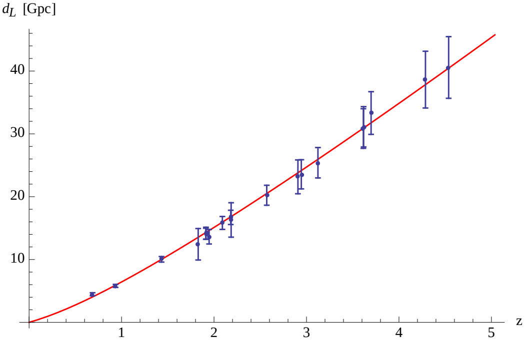
# Evolution history of the universe

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

$$\boxed{d_L(z) = \frac{c}{H_0}\frac{1+z}{\sqrt{\Omega_k}}\sinh\left[\sqrt{\Omega_k}\int_0^z \frac{H_0}{H(z')}dz'\right]}$$

- $z$ 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)

# Fitting the distance-redshift relation



- Need independent measures of:
  1. **Distance** ($d_L$)
  2. **Errors** on $d_L$
  3. **Redshift** ($z$)
- Fit the data with the theory and find constraints
- Exactly as for SNIa

# 1. Measuring distances with GWs

Directly from the measured **waveform**:

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

With EM waves:

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

With GW:

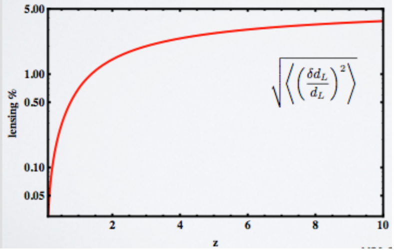
- **Measuring distance is easy**: directly from the **waveform** (**standard sirens**)
- **Measuring redshift is hard**: need EM counterpart

# 2. 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:

- **Peculiar velocities** (low redshifts)
- **Weak-lensing** (high redshifts)



# 3. How to measure redshift?

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

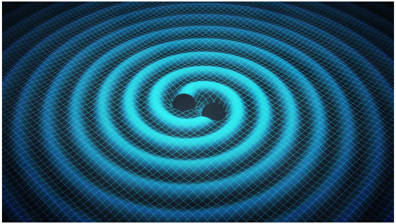
- Redshift measured only from **optical light**
  - Spectroscopically

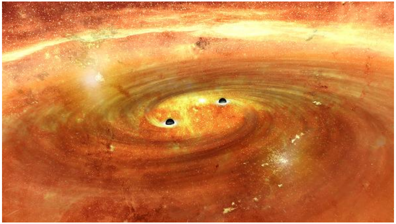
    (low magnitude high accuracy)
  - Photometrically

    (high magnitude low accuracy)

# The big issue

- How many **standard sirens** will be detected by eLISA?





- How many SMBHBs are out there (main target sources of eLISA)?
- For how many it will be possible to observe a counterpart?

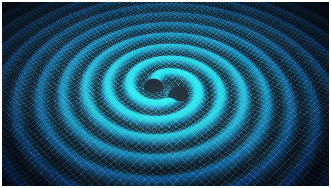
# Our work

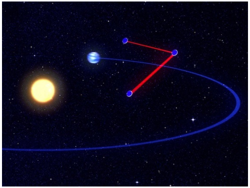
- We are trying to answer all these questions

  (in collaboration with E. Barausse, C. Caprini, A. Klein, A. Petiteau, A. Sesana)
- Focus on **5 years** eLISA mission
  (the longer the better for cosmology)
- **Realistic approach**:
  - SMBBH merger rates from simulations
  - Simple model of EM emissions from SMBBH
  - Observation of EM counterpart and measurement of redshift using future telescopes designs
- Work in progress: the results that follow are preliminary

# Detecting GWs with eLISA

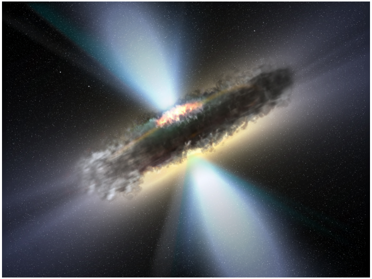
- Start from simulating SMBBHs merger events using **3 different astrophysical models** [arXiv:1511.05581]
  - Light seeds formation (popIII)
  - Heavy seeds formation (with delay)
  - Heavy seeds formation (without delay)
- Compute for how many of these a GW signal will be **detected by eLISA** (SNR>8)
- Among these select the ones with a **good sky location accuracy** ($\Delta\Omega < 10\,\mathrm{deg}^2$)





# Modelling the EM counterpart

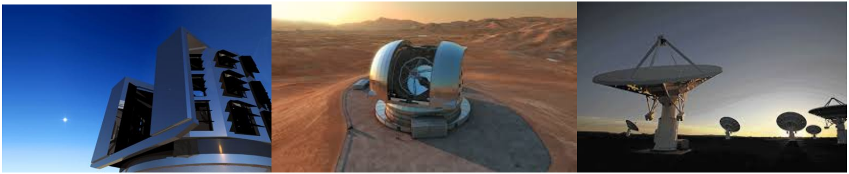
- We generally consider two mechanisms of EM emission at merger (based on [Palenzuela et al, arXiv:1005.1067]):
  - A quasar-like luminosity **flare** (optical)
  - Magnetic field induced **flare** and **jet** (radio)
- Magnitude of EM emission computed using data from simulations of SMBBHs and galactic evolution



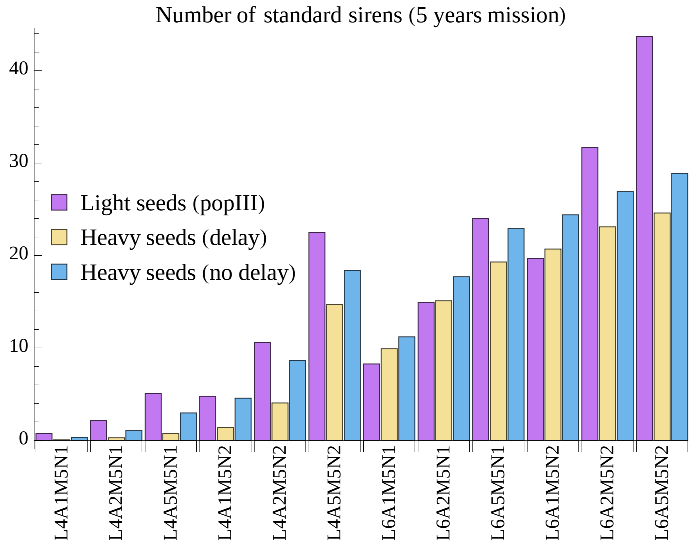
# Detecting the counterparts

To detect the **EM counterpart** of an eLISA event sufficiently localized in the sky we use the following two methods:

- **LSST**: direct detection of optical counterpart
- **SKA + E-ELT**: first use SKA to detect a radio emission from the BHs and pinpoint the hosting galaxy in the sky, then aim E-ELT in that direction to measure the redshift from a possible optical counterpart 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

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

entering the distance-redshift relation

$$\boxed{d_L(z) = \frac{c}{H_0} \frac{1+z}{\sqrt{\Omega_k}} \sinh\left[ \sqrt{\Omega_k} \int_0^z \frac{H_0}{H(z')} dz' \right]}$$

# Cosmological models

- Impossible to constrain all 5 parameters simultaneously
- Like other probes (e.g. SNe): difficult to constrain 5 parameters without combining with other datasets
- Consider cosmological models with less parameters:
  - **Cosmological constant + curvature**:
    - 3 parameters $(\Omega_M, \Omega_\Lambda, h)$
    - fix $w_0 = -1$ & $w_a = 0$
  - $\Lambda$**CDM**:
    - 2 parameters $(\Omega_M, h)$
    - fix $\Omega_M + \Omega_\Lambda = 1$, $w_0 = -1$ & $w_a = 0$
  - **Dynamical dark energy**:
    - 2 parameters $(w_0, w_a)$
    - $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ & $h = 0.67$

# Fisher matrices and FoMs

Compute the **Fisher matrix** as

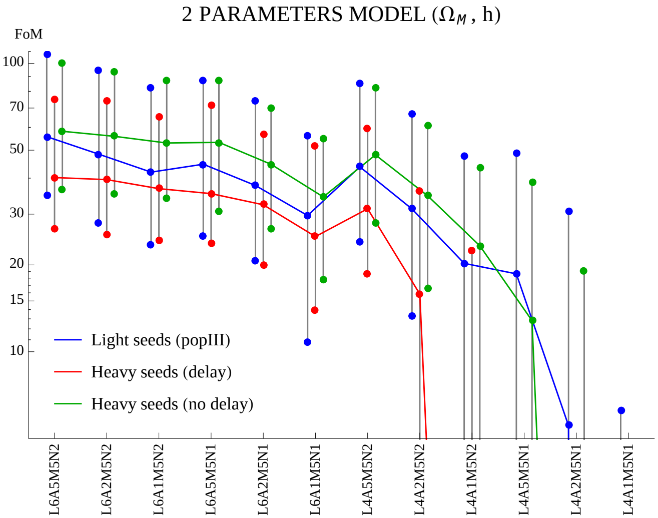
$$F_{ij} = \sum_n \frac{1}{\sigma_n^2} \left.\frac{\partial d_L(z_n)}{\partial \theta_i}\right|_{\rm fid} \left.\frac{\partial d_L(z_n)}{\partial \theta_j}\right|_{\rm fid}$$

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

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

as a useful tool to compare the constraining power of different eLISA configuration

# FoMs for ΛCDM



# Estimated constraints with eLISA

For $\Lambda$**CDM + curvature** cosmology:

L6A5M5N2: $$\begin{cases} \Delta\Omega_M \simeq 0.1 \\ \Delta\Omega_\Lambda \simeq 0.3 \\ \Delta h \simeq 0.07 \end{cases}$$

L4A2M5N2: $$\begin{cases} \Delta\Omega_M \simeq 0.2 \\ \Delta\Omega_\Lambda \simeq 0.8 \\ \Delta h \simeq 0.15 \end{cases}$$

For $\Lambda$**CDM**:

L6A5M5N2: $$\begin{cases} \Delta\Omega_M \simeq 0.04 \\ \Delta h \simeq 0.02 \end{cases}$$

L4A2M5N2: $$\begin{cases} \Delta\Omega_M \simeq 0.09 \\ \Delta h \simeq 0.03 \end{cases}$$

For **dark energy**:

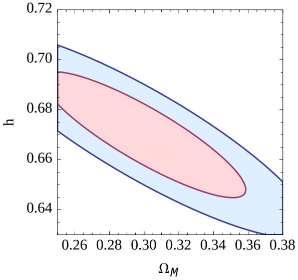
L6A5M5N2: $$\begin{cases} \Delta w_0 \simeq 0.3 \\ \Delta w_a \simeq 1.6 \end{cases}$$

L4A2M5N2: $$\begin{cases} \Delta w_0 \simeq 0.5 \\ \Delta w_a \simeq 2.9 \end{cases}$$

# Comparing with CMB

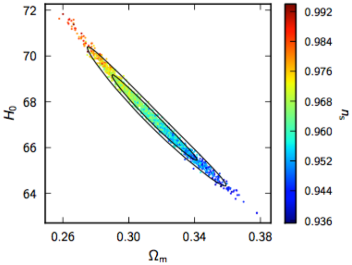
From L6A5M5N2 with ΛCDM:

$$\begin{cases} \Omega_M = 0.30 \pm 0.04 \\ \Omega_\Lambda = 0.70 \pm 0.04 \\ H_0 = 67 \pm 3\,\mathrm{km/s/Mpc} \end{cases}$$



From today CMB [Planck2015]:

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



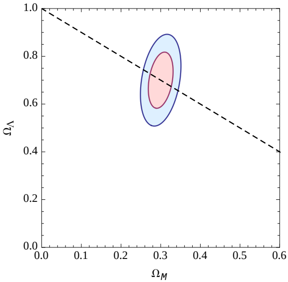
# Comparing with Supernovae (ΛCDM)

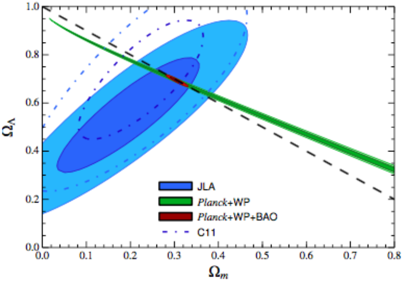
Expected from L6A5M5N2 (fixing $H_0$ & curvature):

$$\Omega_M = 0.30 \pm 0.019$$

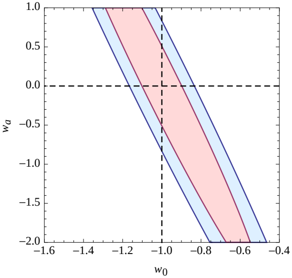
From today SNe (fixing $H_0$ & curvature) [Betoule *et al* (2014)]:

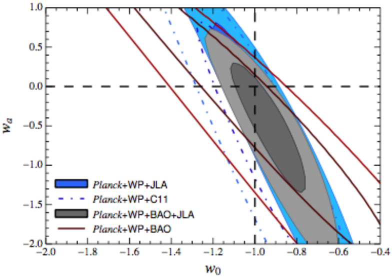
$$\Omega_M = 0.289 \pm 0.018$$





# Comparing with Supernovae (dark energy)





Expected from L6A5M5N2:

(fixing $\Omega_M, \Omega_\Lambda, h$)

$$w_0 = -1.0 \pm 0.3$$
$$w_a = 0.0 \pm 1.6$$

From CMB + SNe + BAO:

[Betoule *et al* (2014)]

$$w_0 = -1.073 \pm 0.146$$
$$w_a = -0.066 \pm 0.563$$

# Summary of cosmological constraints

**Curvature & energy content**:

- At best $\Delta\Omega_\Lambda$ and $\Delta\Omega_M$ within 10%
- Comparable to present SNe, but worse than CMB

**Local expansion**:

- At best $H_0$ within 5%
- Slightly worse than present CMB constraints

**Dark energy EoS**:

- At best $\Delta w_0$ within 30% and $\Delta w_a \sim 1.6$
- Comparable with present SNe
- Slightly worse than all present constraints combined

# Conclusions

- SMBBHs can be used as excellent **standard sirens**
  - Systematic-free measures of **distance** (no calibration needed as for SNe)
- Need low **sky location error**
  - L6 much better than L4
- Need to identify EM counterparts for measuring **redshift**
  - Will depend on capacities of future telescopes and magnitude of EM emission
- **Low accuracy** not comparable with future probes, **but**
  - New cosmological information from GWs (not EM only)
  - First direct probe of expansion at ultra-high redshifts (up to $z \sim 8$)