Late-time cosmology with gravitational waves

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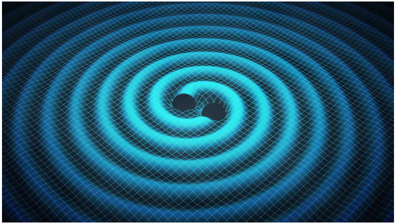
Plan of the talk

- Cosmology with standard sirens
- EM counterparts
- Inhomogeneities and lensing effects
- Late-time cosmology with eLISA



Evolution history of the universe

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

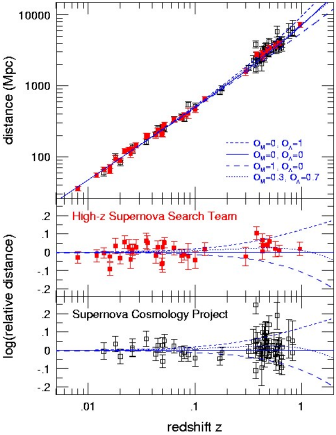
$$\boxed{d_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}}$$

- 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)

Mapping the evolution with EM waves

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

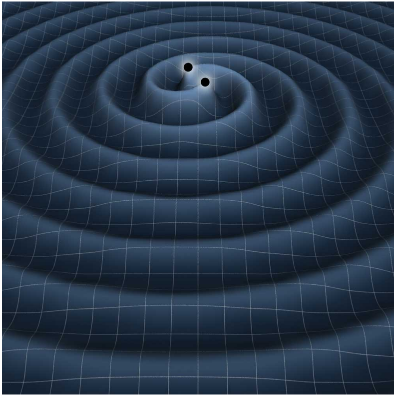
- **Measuring redshift is easy**: compare EM spectra
- **Measuring distance is hard**: need objects of known luminosity (**standard candles**) or objects of known length (**standard rulers**)



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):

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

- 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?

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

- **Direct measure of distance** d_L
- 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

How to measure redshift?

Main way:

- Find an EM counterpart
  - Optical (supernovae, pulsars)
  - GRBs
  - Radio or X-rays (SMBBHs)

Alternative ways (still under development):

- Breaking the mass degeneracy with merger and ring-down models
  - Need well-known neutron star physics (LIGO/Virgo, ET)
- Direct cosmological effects on GW propagation
  - Might be negligible for eLISA (good for BBO)

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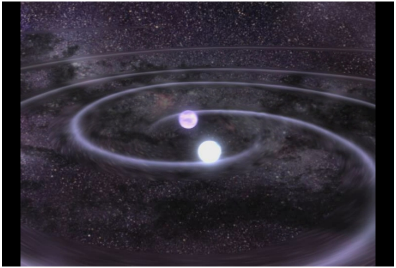
EM counterparts

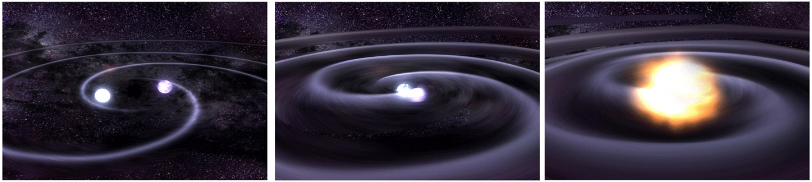
Possible standard sirens with EM counterparts can be:

- Stellar-mass ($\gtrsim M_\odot$) binaries (LIGO/Virgo)
  - Supernovae and pulsars
- Super-massive ($\gg M_\odot$) black holes binaries (eLISA)
  - Large uncertainties on emitted EM spectrum



How to detect a counterpart?

- Need good sky location accuracy from the GW detector (e.g. $\lesssim 10$ deg^2)
- Need good follow-up EM surveys to identify the source
  - Look for supernovae and pulsars (LIGO/Virgo)
  - Look for hosting galaxy (eLISA)
- Use statistics and prior knowledge
- In general look for something that goes bang



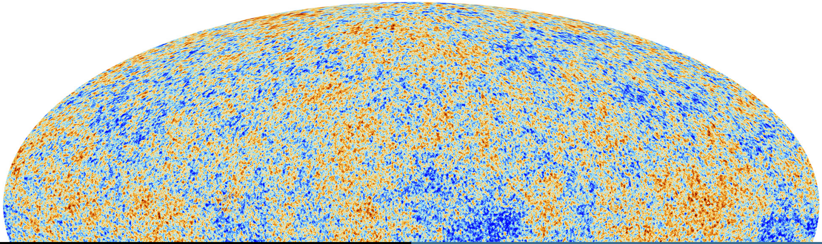
Accuracy on d_L

Once a counterpart has been detected, the **redshift** of the source can be determined with great accuracy.

But what is the accuracy on the **distance** d_L?

- Depends on the detector
- 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**



Propagation in isotropic universe

Wave-form at the **source** (Minkowski spacetime):

$$h_s(t) = \frac{M_c^{5/3} f_s(t)^{2/3}}{r} F(\mathrm{angles}) \cos(\Phi_s(t))$$

Propagation in a **FRW metric** $ds^2 = a^2(\eta)\,(-d\eta^2 + dx^2)$:

$$f_s \mapsto f_o = \frac{f_s}{1+z} \qquad \Phi_o = \Phi_s \qquad \frac{1}{r} \mapsto \frac{1+z}{d_L}$$

At the **observer** thus:

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

The effect of structures: redshift

In an inhomogeneous universe we have

$$ds^2 = a^2(\eta)\left[-\left(1+2\Psi(\eta,x)\right)d\eta^2 + \left(1-2\Phi(\eta,x)\right)dx^2\right]$$

The **redshift** is perturbed

$$1+z = \frac{a_o}{a_s}\Bigg[\underbrace{(\mathbf{v}_s - \mathbf{v}_o)\cdot\hat{\mathrm{n}}}_{\text{Doppler}} + \underbrace{\Psi_o - \Psi_s}_{\text{Gravitational redshift}} - \underbrace{\int_0^{r_s} dr(\dot{\Psi}+\dot{\Phi})}_{\text{Integrated Sachs-Wolfe}}\Bigg]$$

The effect of structures: d_L

The inhomogeneities perturb also the **luminosity distance**:

$$d_L = (1+z_s) r_s \left\{ 1 + \frac{1}{\mathcal{H}_s r_s} \mathbf{v}_o \cdot \hat{\mathrm{n}} + \left(1 - \frac{1}{\mathcal{H}_s r_s}\right) \mathbf{v}_s \cdot \hat{\mathrm{n}} \right.$$

Doppler

$$+ \left(1 - \frac{1}{\mathcal{H}_s r_s}\right) \Psi_o - \left(2 - \frac{1}{\mathcal{H}_s r_s}\right) \Psi_s$$

Gravitational potential

Time delay

$$+ \frac{2}{r_s} \int_0^{r_s} dr \Psi - 2 \left(1 - \frac{1}{\mathcal{H}_s r_s}\right) \int_0^{r_s} dr \dot{\Psi}$$

$$\left. - \int_0^{r_s} dr \frac{r_s - r}{r_s \, r} \Delta_\perp \Psi \right\}$$

Integrated Sachs-Wolfe

Lensing

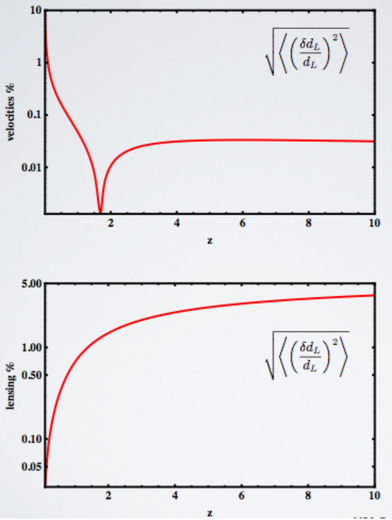
The error induced on d_L

The dominant contributions on d_L due to inhomogeneities are:

- At small redshift: **peculiar velocities**
- At high redshift: **lensing**

Other effects:

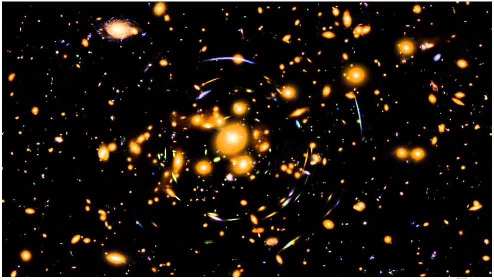
- Change of position in the sky
- Change of observed orientation



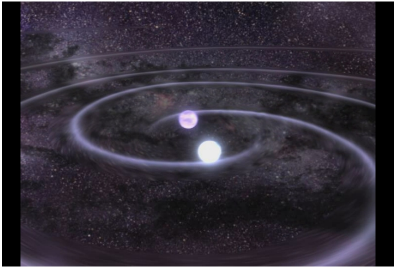
Two ways of overcome lensing

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

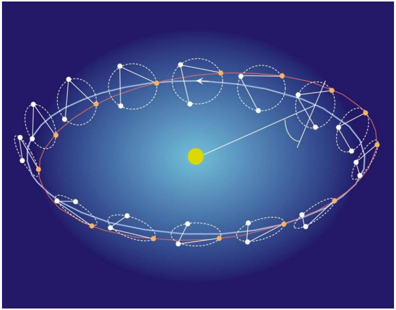


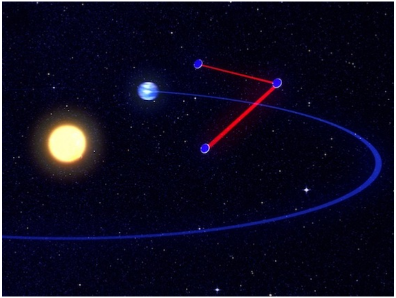
The Big Issue



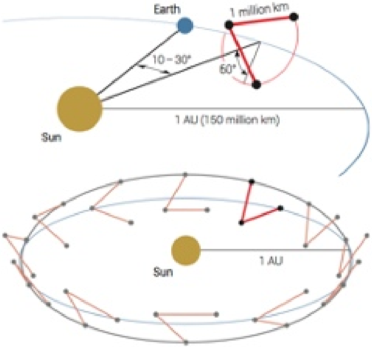
- How many standard sirens will be detected?
- Of how many GW sources will a counterpart be observed?

The case of eLISA





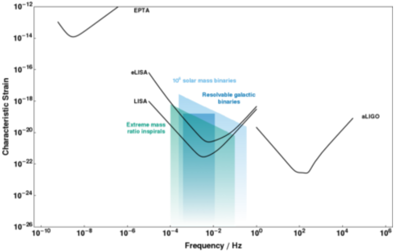
eLISA in one slide

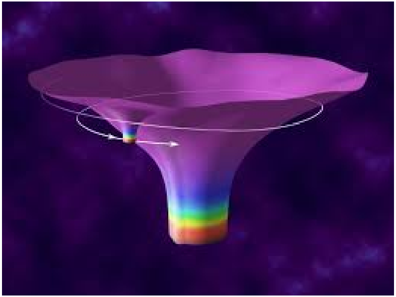


- Proposed space-based laser interferometer orbiting around the Sun
- 4 or 6 links
- 1 to 5×10^6 Km arms
- For more information see Pierre's talk on Thursday!

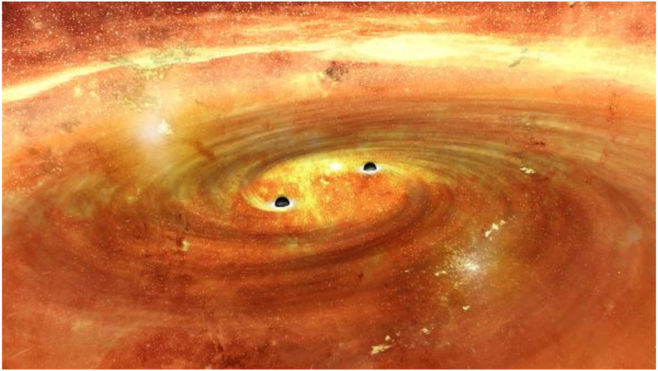
What will eLISA hear?

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



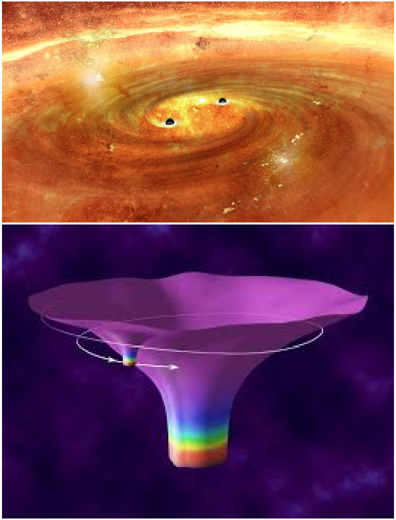


How many sources for eLISA?



- How many of these “babies” are out there?
- For how many it will be possible to observe a counterpart?

How many SMBBHs?

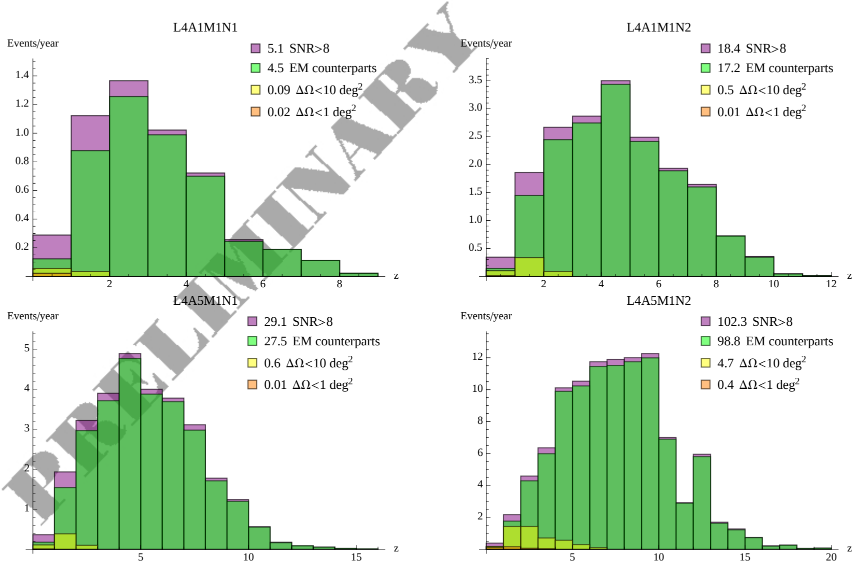


- We don't know
- Lots of approaches: mostly based on putting BHs into (galaxies put into) dark matter halos from cosmological N-body simulations
- Lots of uncertainties: BH formation, BH seed masses, galaxy evolution and mergers, BH accretion, ...

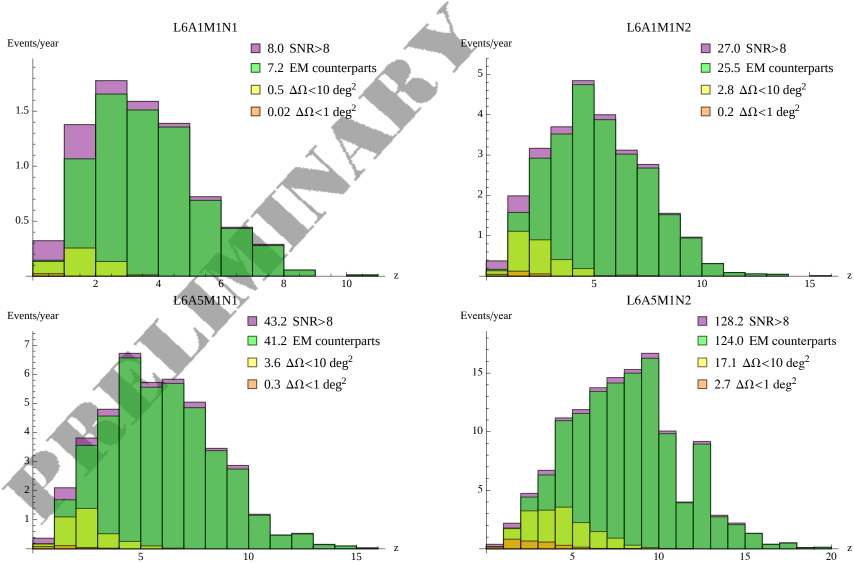
Some preliminary results

- Everything that follows is work in progress
- All results are **preliminary**
- In what follows
  - Will use one of the most promising models of SMBBHs production and evolution (popIII)
  - Will show how many sources will eLISA detect
  - Will determine how many of these will have a counterpart
  - Will use these standard sirens to do cosmology

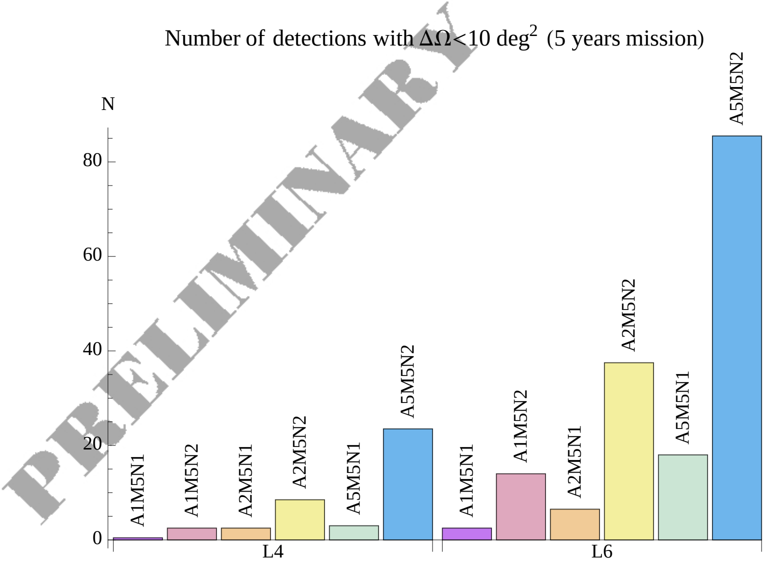
Standard sirens for eLISA (4 links)



Standard sirens for eLISA (6 links)

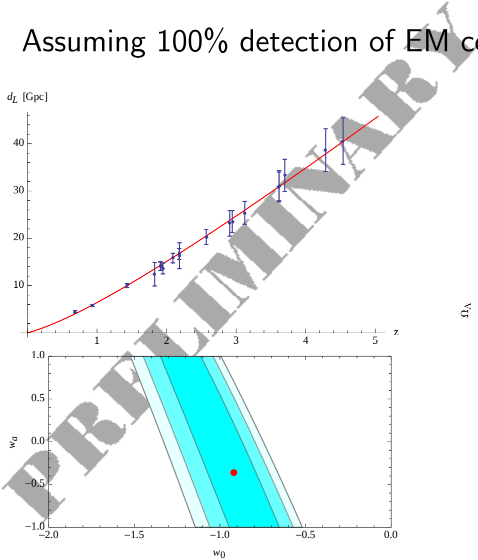


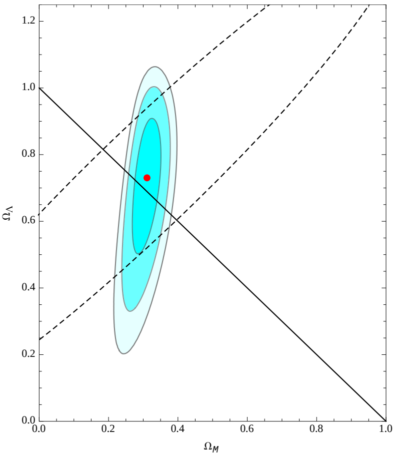
Comparing possible eLISA configurations



Example: L4A5M5N2 (best with L4)

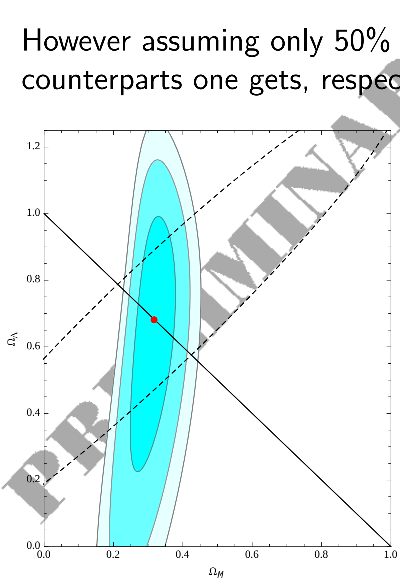
Assuming 100% detection of EM counterparts:

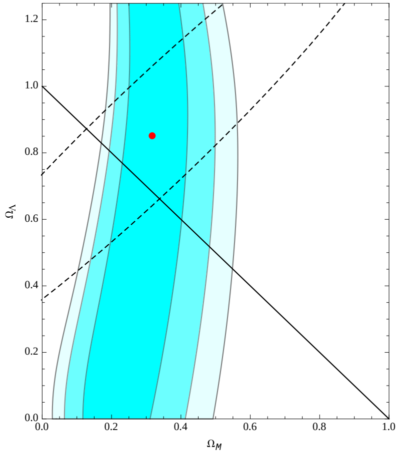




Example: L4A5M5N2 (best with L4)

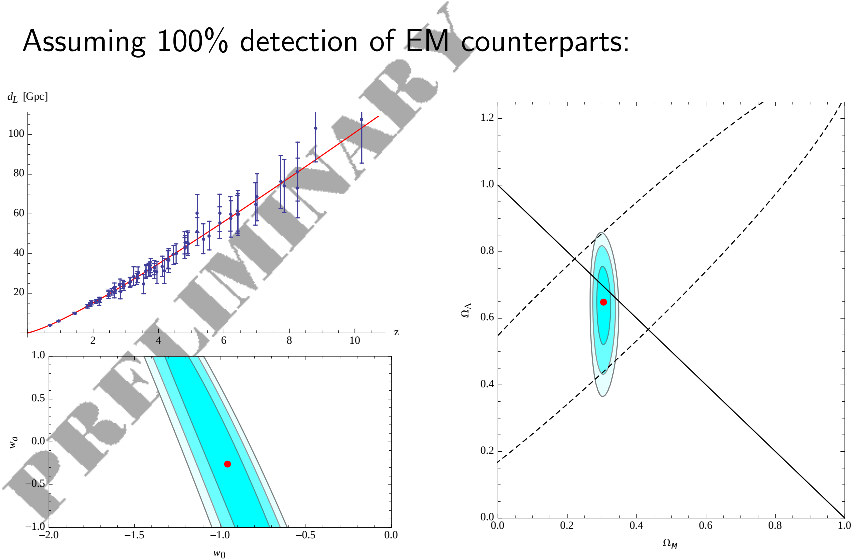
However assuming only 50% or 10% detection of EM counterparts one gets, respectively:





Example: L6A5M5N2 (best with L6)

Assuming 100% detection of EM counterparts:



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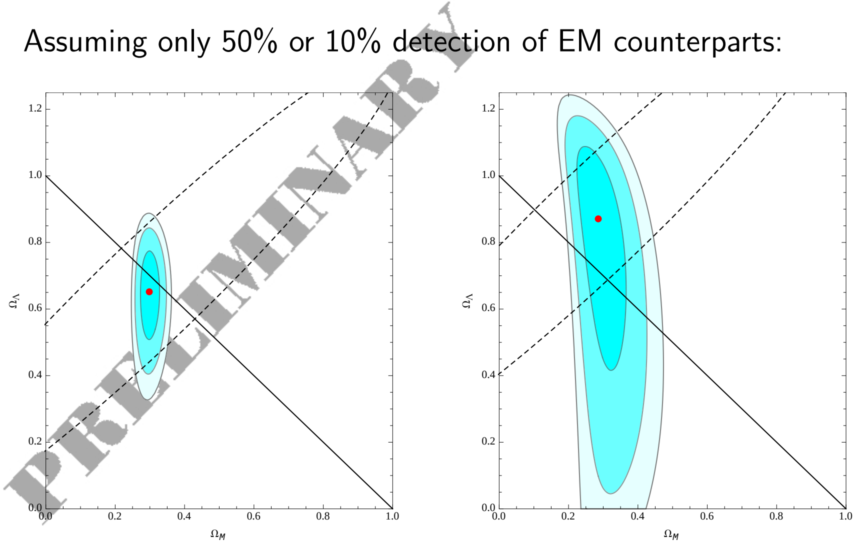

Cosmology with eLISA

- SMBBHs are excellent standard sirens up to $z \sim 10$, though still large uncertainties on numbers and emitted EM spectrum
- Need good eLISA configuration to reduce sky location error (best of L4 or 6L)
- Need good EM surveys for observations of many counterparts
- Independent and systematic-free constraints on all cosmological parameters

Conclusion

- Stellar-mass binaries and SMBBHs can be used as **standard sirens**
  - Clean and powerful **distance** indicators
  - EM counterpart needed for **redshift**
  - Sufficient statistics needed to overcome lensing
  - Systematic-free if compared to other probes
- New cosmological measurements independent from EM

$E\nu\chi\alpha\rho\iota\sigma\tau\acute{\omega}$!