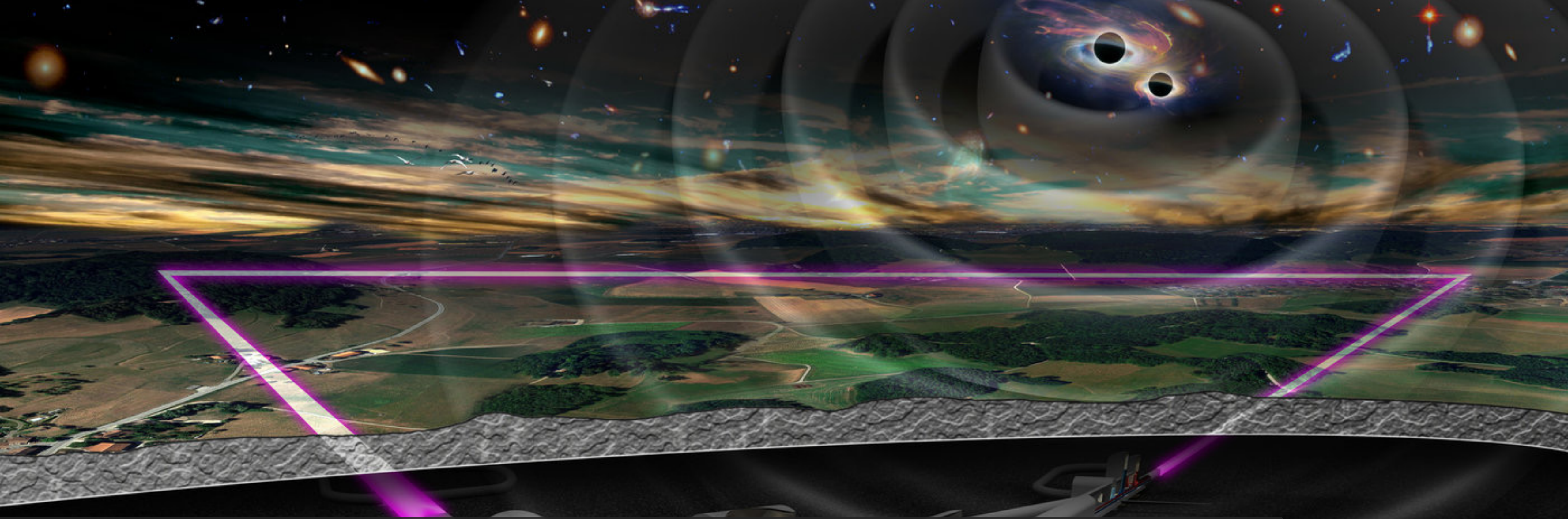


Forecasts for ΛCDM and Dark Energy models through Einstein Telescope standard sirens

Matteo Califano

Scuola Superiore Meridionale, Napoli

MC, I. de Martino, D. Vernieri, S. Capozziello Arxiv:2205.11221, MNRAS (2023) and Arxiv:2208.13999, submitted to PRD

Gravitational Waves as Standard Sirens

From the GW signal analysis, we can estimate:

PHASE evolution $\rightarrow M^z = M(1+z)$

AMPLITUDE $\rightarrow \frac{M^z}{d_L} \times f('angles') \rightarrow d_L$

Gravitational Waves as Standard Sirens

GWs from compact binaries allow for a detemination of distance!

Self-calibrated

Independent of distance ladder

Gravitational Waves as Standard Sirens

From the **Distance-redshift relation** we can extract the cosmological parameters:

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

Where can z come from?

Gravitational Waves as Standard Sirens

In our papers we consider two techniques:

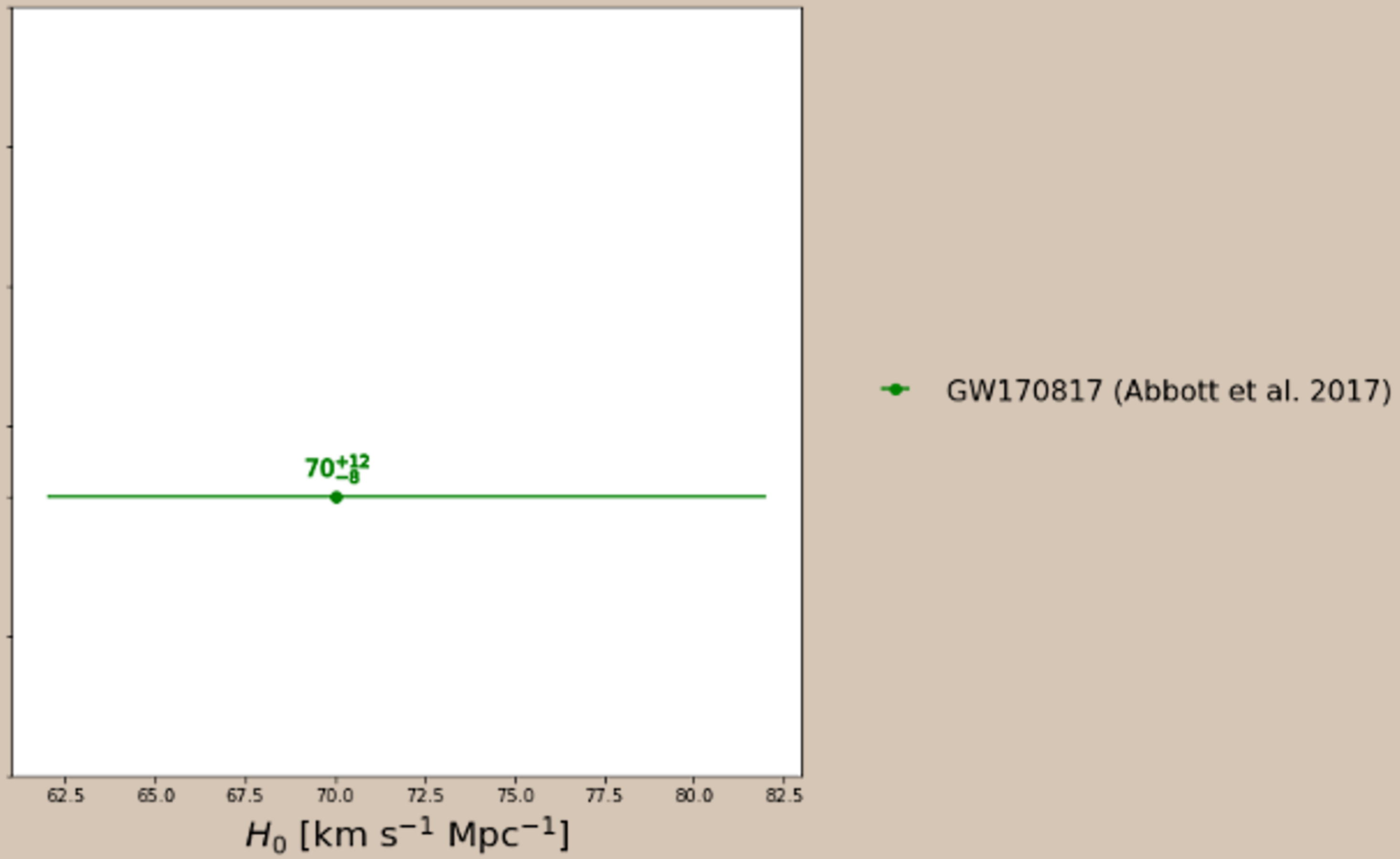
EM counterpart

PROS: accurate redshift estimation
CONS: Infrequent and rare events

Source-frame mass & Rate Evolution

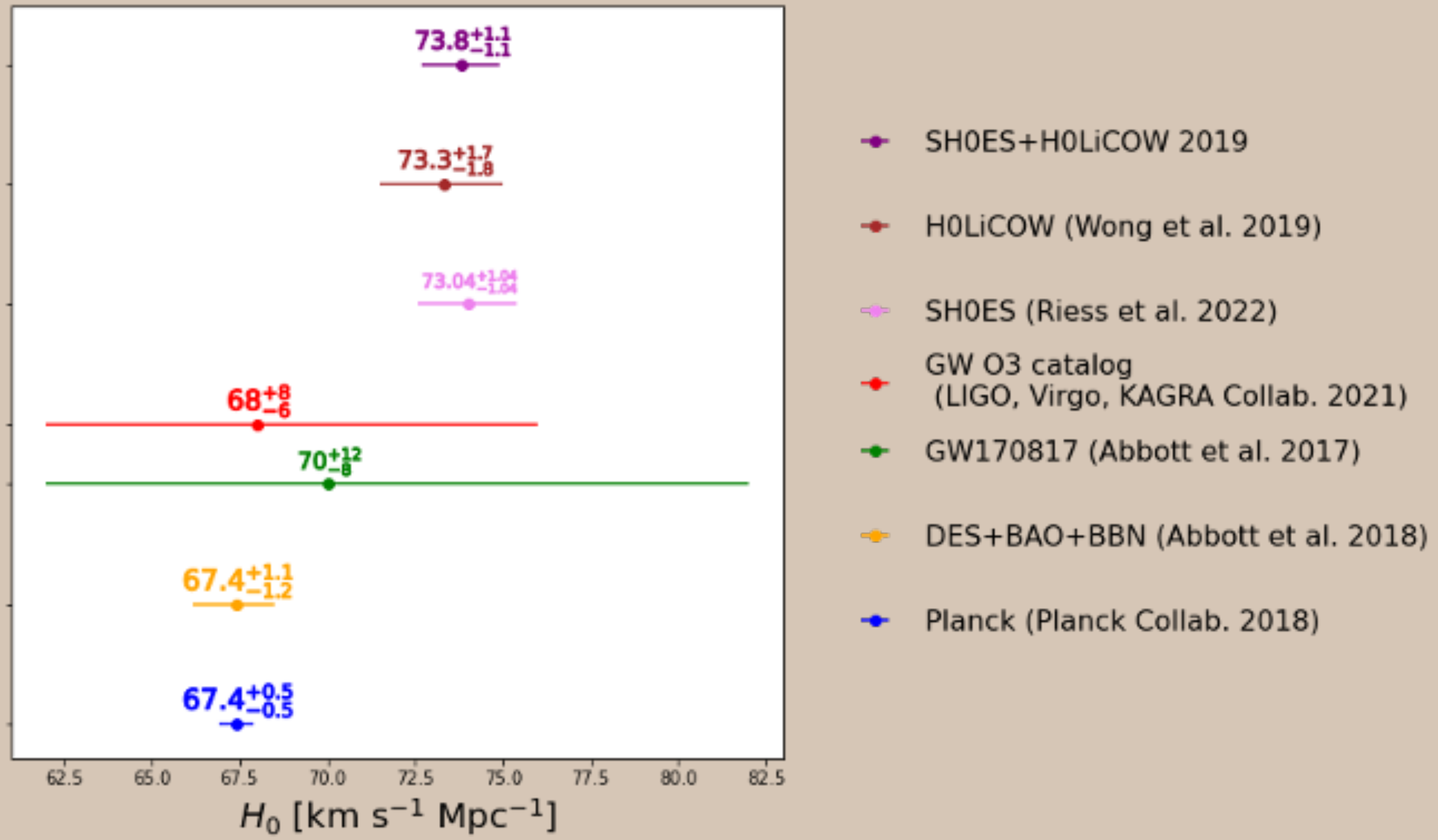
PROS: No need of EM counterpart, can fit cosmology and astrophysics together.
CONS: Needs to be driven by some astrophysical expectation.

Gravitational Waves as Standard Sirens

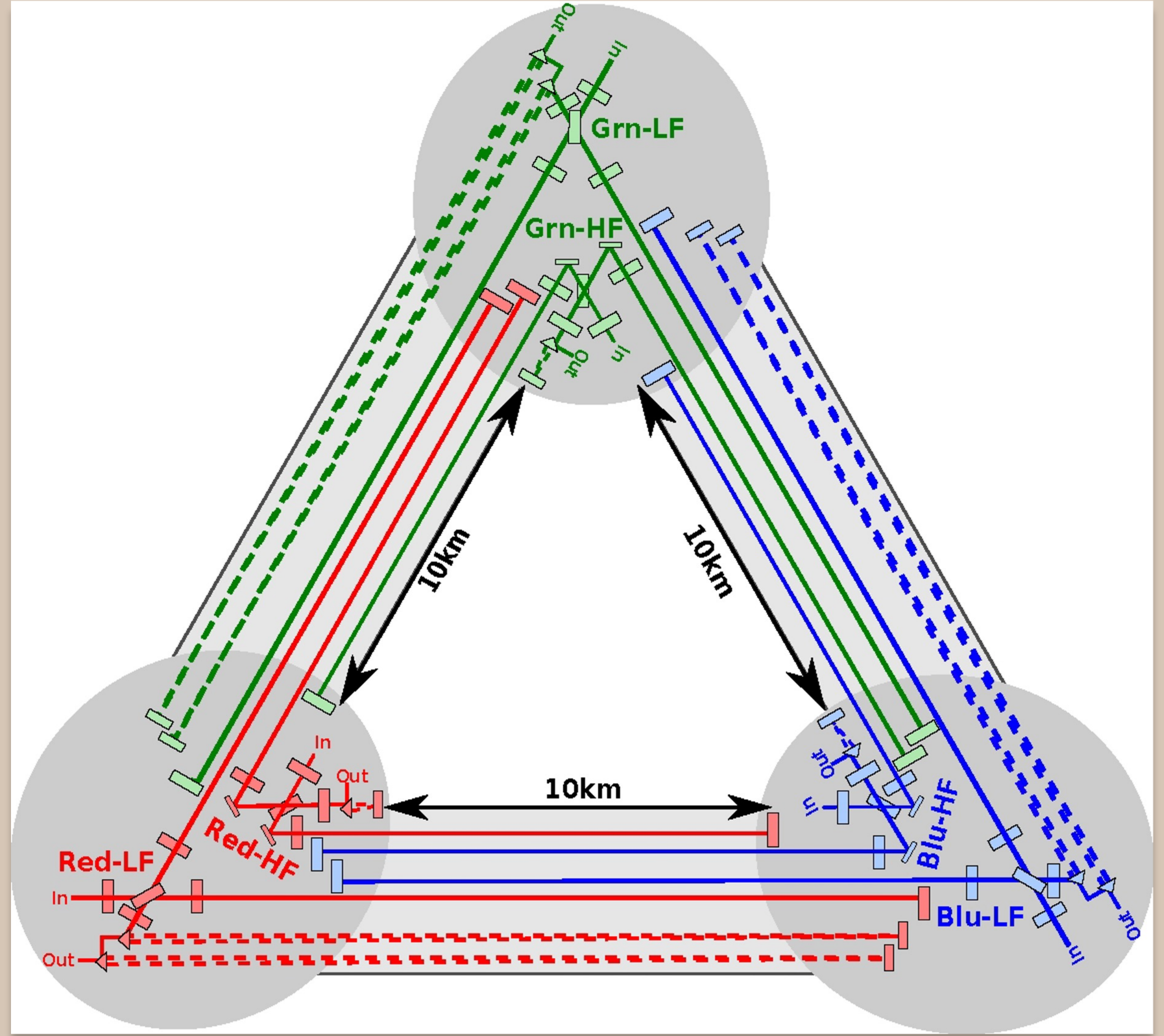


Gravitational Waves as Standard Sirens

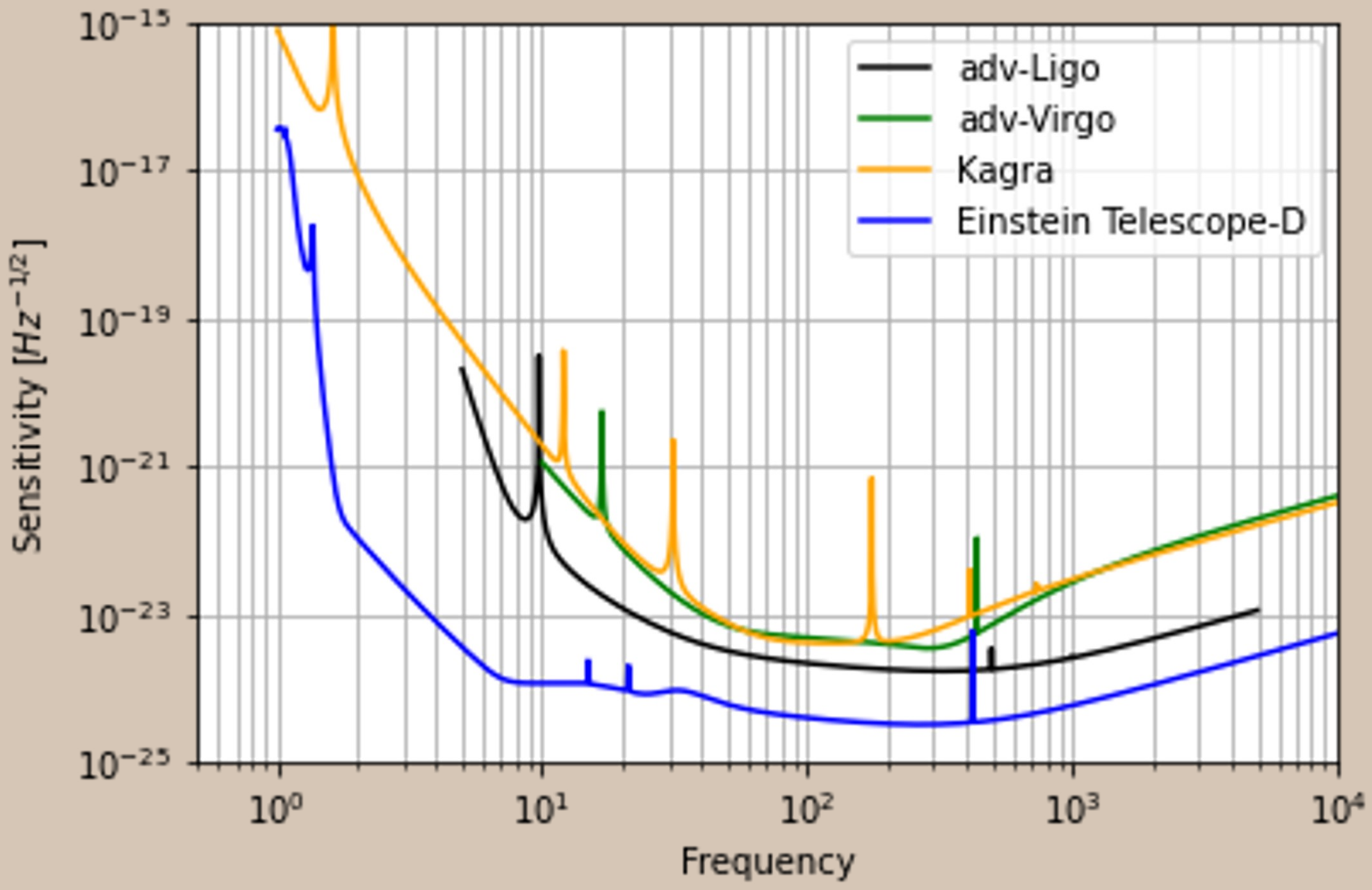
Gravitational Waves as Standard Sirens



Einstein Telescope interferometer



Einstein Telescope interferometer



Generation of mock data

We assume a fiducial cosmological model ΛCDM.

Given a cosmology the theoretical luminosity distance will be

$$d_L = \frac{c(1+z)}{H_0} \int^z \frac{dz'}{E(\Omega_i, z', \lambda)}$$

Generation of mock data

We extract the redshift from a normalized probability distribution, related to the Star Formation Rate R_f

$$p(z) = \frac{R_z(z)}{\int_0^{10} R_z(z)\, dz}, \qquad R_z(z) = \frac{R_m(z)}{1+z} \frac{dV(z)}{dz},$$

$$R_m(z) = R_0 \cdot \int_{t_{min}}^{t_{max}} R_f[t(z) - t_d]\, P(t_d)\, dt_d\,,$$

Generation of mock data

We simulate the SNR of ET for the synthetic data

$$\rho = \sqrt{\sum_i (\rho^{(i)})^2}$$

$$\rho_i^2 = \frac{5}{6} \frac{\left[G\ M_{c,obs}\right]^{\frac{5}{3}} F_i^2(\theta, \phi, \psi, i)}{c^3 \pi^{\frac{4}{3}} d_L^2(z)} \int_{f_{lower}}^{f_{max}} \frac{f^{\frac{7}{3}}}{S_{h,i}(f)} df$$

Generation of mock data

We extracted d_L from a Gaussian distribution $\mathcal{N}\left(d_L^{fid}, \sigma_{d_L}\right)$

$$\sigma_{d_L} = \sqrt{\left(\sigma_{inst}^2 + \sigma_{lens}^2 + \sigma_{pec}^2\right)}$$

$$\sigma_{instr} = \frac{2}{\rho} d_L(z)$$

$$\sigma_{lens} = F_{delens}(z)\left[0.066\left(\frac{1-(1+z)^{-0.25}}{0.25}\right)^{1.8} d_L(z)\right]$$

$$\sigma_{pec} = \left[1 + \frac{c(1+z)^2}{H(z)d_L(z)}\right]\frac{\sqrt{\langle v^2\rangle}}{c} d_L$$

Generation of mock data

Selection of EM counterpart

We estimate the flux for the coincident short GRB

$$F(\theta_V) = \frac{L(\theta_V)(1+z)}{4\pi d_L^2 k(z) b}$$

$$b = \frac{\int_{1\,keV}^{10^4 keV} EN(E)dE}{\int_{E_1}^{E_2} N(E)dE} \qquad k(z) = \frac{\int_{E_1}^{E_2} N(E)dE}{\int_{E_1(1+z)}^{E_2(1+z)} N(E)dE}$$

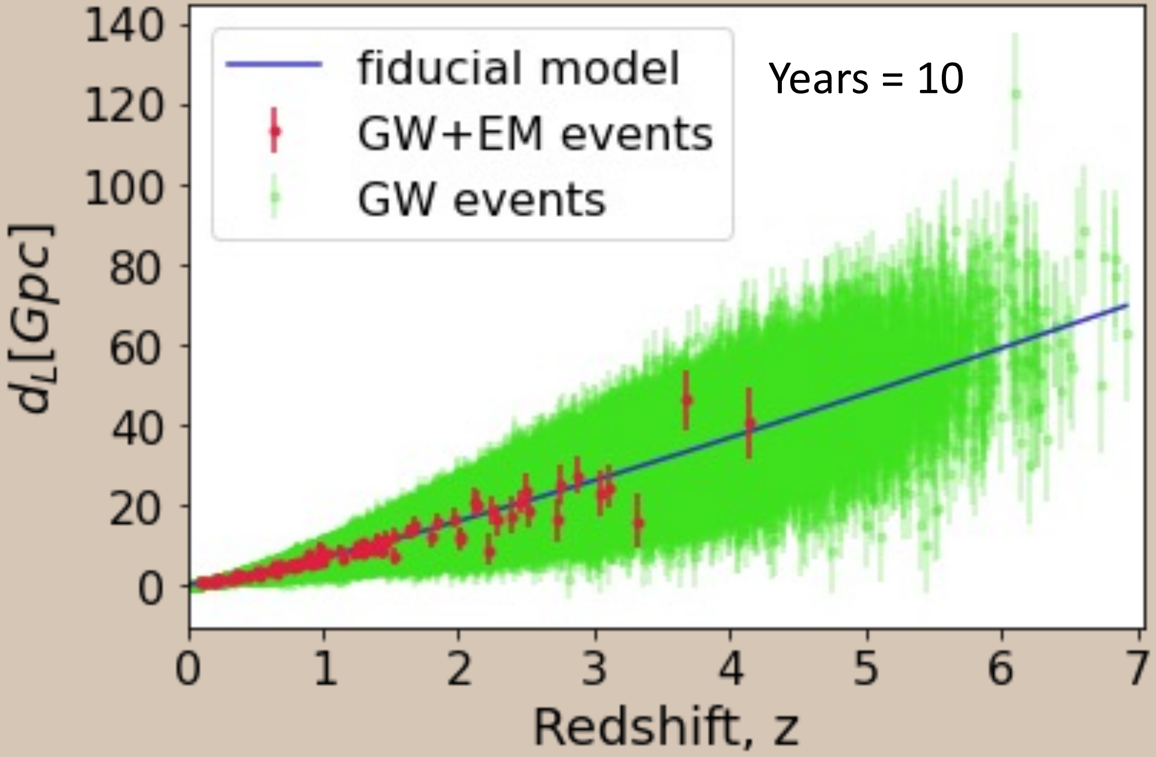
We record the combined event if $F(\theta_V) > F^{threshold} \left(= 0.2\,\frac{ph}{cm^2 s}\right)$ for THESEUS satellite.

Generation of mock data

Rate of events

Imposing a SNR threshold equal 9, we estimate a rate of GW signals of $\sim 10^4$ events /year.

We estimate a rate of combined detection with the THESEUS satellite of ~ 11 events /year.



Analysis & Results

Bright Sirens

We include in the single-event likelihood the selection effects $\rho > \rho^t$, $F(\theta_V) > F^t$

$$p(d_i|H_0, \Omega_{k,0}, \Omega_{\Lambda,0}) = \frac{\int p(d_i|D_L, H_0, \Omega_{k,0}, \Omega_{\Lambda,0}) p_{pop}(D_L|H_0, \Omega_{k,0}, \Omega_{\Lambda,0}) dD_L}{\int p_{det}(D_L, H_0, \Omega_{k,0}, \Omega_{\Lambda,0}) p_{pop}(D_L|H_0, \Omega_{k,0}, \Omega_{\Lambda,0}) dD_L}$$

$$p_{pop}(D_L|H_0, \Omega_{k,0}, \Omega_{\Lambda,0}) = \delta\left(D_L^{th}(H_0, \Omega_{k,0}, \Omega_{\Lambda,0}) - D_L\right)$$

$$p(d_i|D_L, H_0, \Omega_{k,0}, \Omega_{\Lambda,0}) \propto \exp -\frac{1}{2}\frac{(d_i - D_L)^2}{\sigma_{d_i}^2}$$

$$p_{det}(D_L, H_0, \Omega_{k,0}, \Omega_{\Lambda,0}) = \int_{\substack{\rho>\rho^t \\ F>F^t}} p(d_i|D_L, H_0, \Omega_{k,0}, \Omega_{\Lambda,0})\, dd_i$$

Analysis & Results

Dark Sirens

When we cannot extract the redshift information from electromagnetic signal, we have to marginalize the posterior over the redshift.

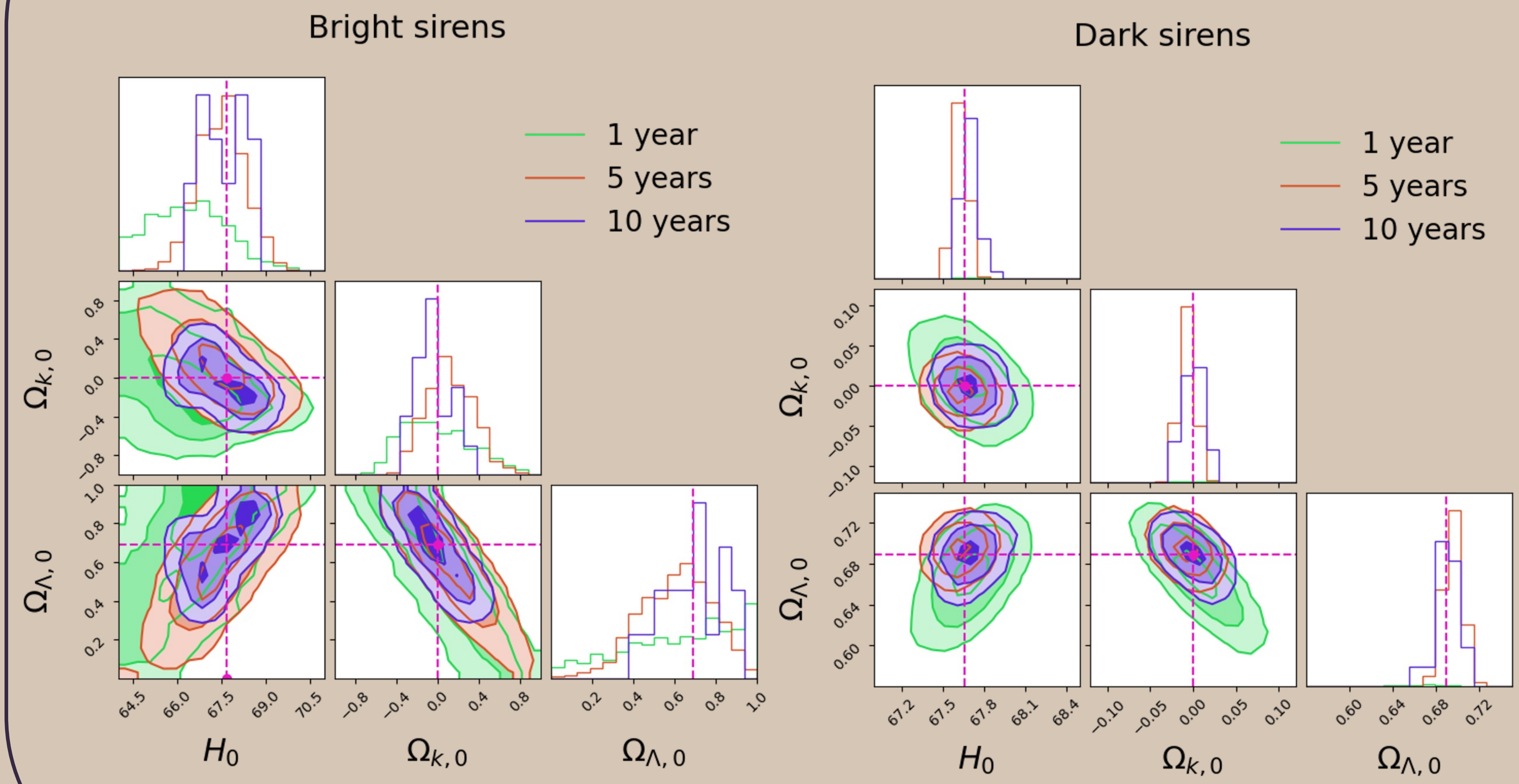
$$p(d_i|H_0, \Omega_{k,0}, \Omega_{\Lambda,0}) = \int_0^{z_{max}} p\left(d_i|d_L^{th}(z, H_0, \Omega_{k,0}, \Omega_{\Lambda,0})\right) p_{obs}(z)dz$$

Analysis & Results

Best-fit accurancy (10 years)

	Bright Sirens	Dark Sirens
$\sigma_{H_0} =$	0.78	0.04
$\sigma_{\Omega_{k,0}} =$	0.16	0.01
$\sigma_{\Omega_{\Lambda,0}} =$	0.14	0.01

KΛCDM



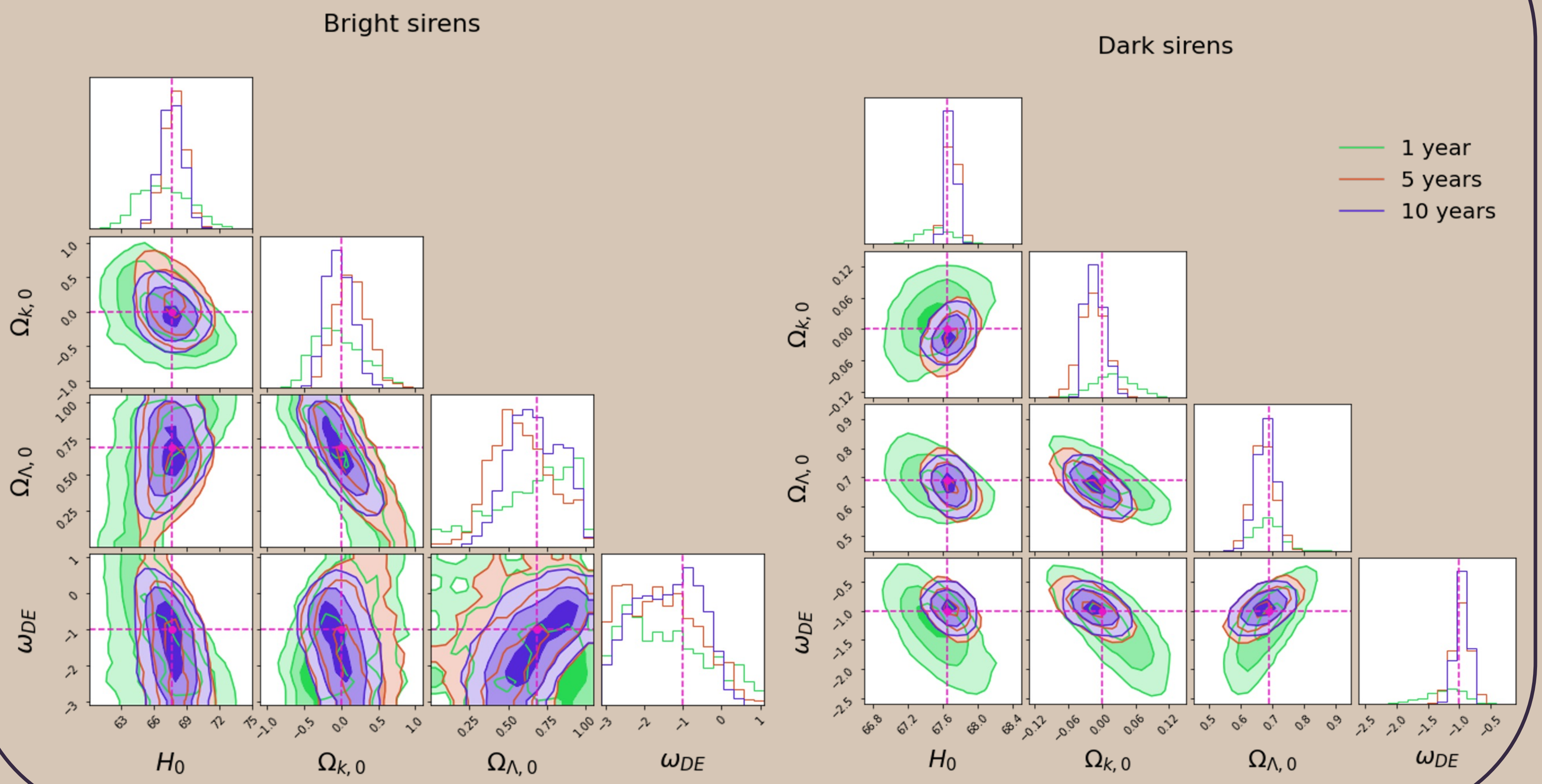
$$E^2(z) = \left(1 - \Omega_{k,0} - \Omega_{\Lambda,0}\right)(1+z)^3 + \Omega_{k,0}(1+z)^2 + \Omega_{\Lambda,0}$$

Analysis & Results

Best-fit accurancy (10 years)

	Bright Sirens	Dark Sirens
$\sigma_{H_0} =$	0.79	0.06
$\sigma_{\Omega_{k,0}} =$	0.18	0.02
$\sigma_{\Omega_{\Lambda,0}} =$	0.18	0.03
$\sigma_{\omega_{DE}} =$	0.93	0.10

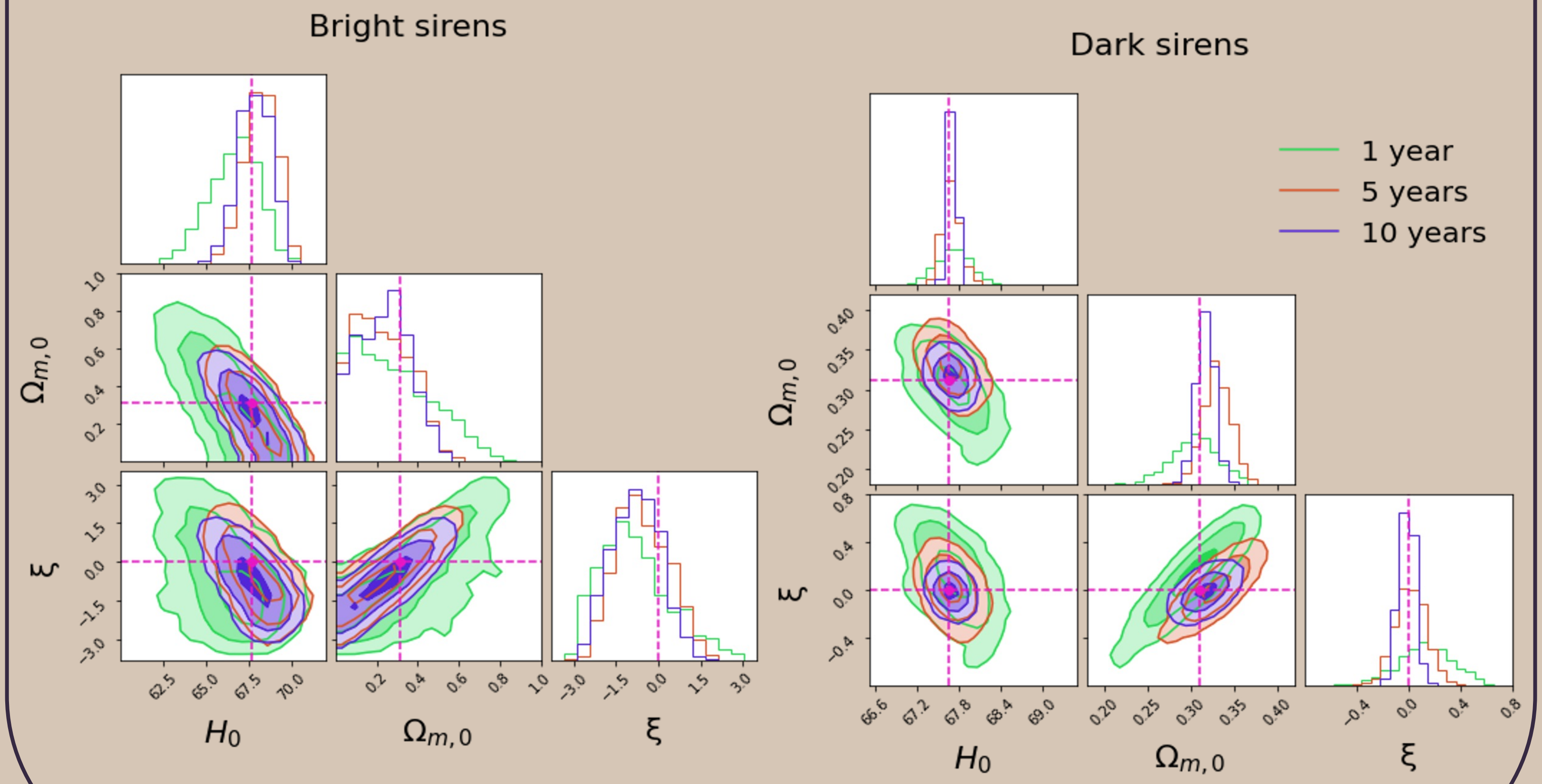
KωCDM



$$E^2(z) = \left(1 - \Omega_{k,0} - \Omega_{\Lambda,0}\right)(1+z)^3 + \Omega_{k,0}(1+z)^2 + \Omega_{\Lambda,0}(1+z)^{1+\omega_{DE}}$$

Analysis & Results

Interacting Dark Energy



Best-fit accurancy (10 years)

	Bright Sirens	Dark Sirens
$\sigma_{H_0} =$	1.03	0.05
$\sigma_{\Omega_{m,0}} =$	0.14	0.01
$\sigma_{\xi} =$	0.88	0.06

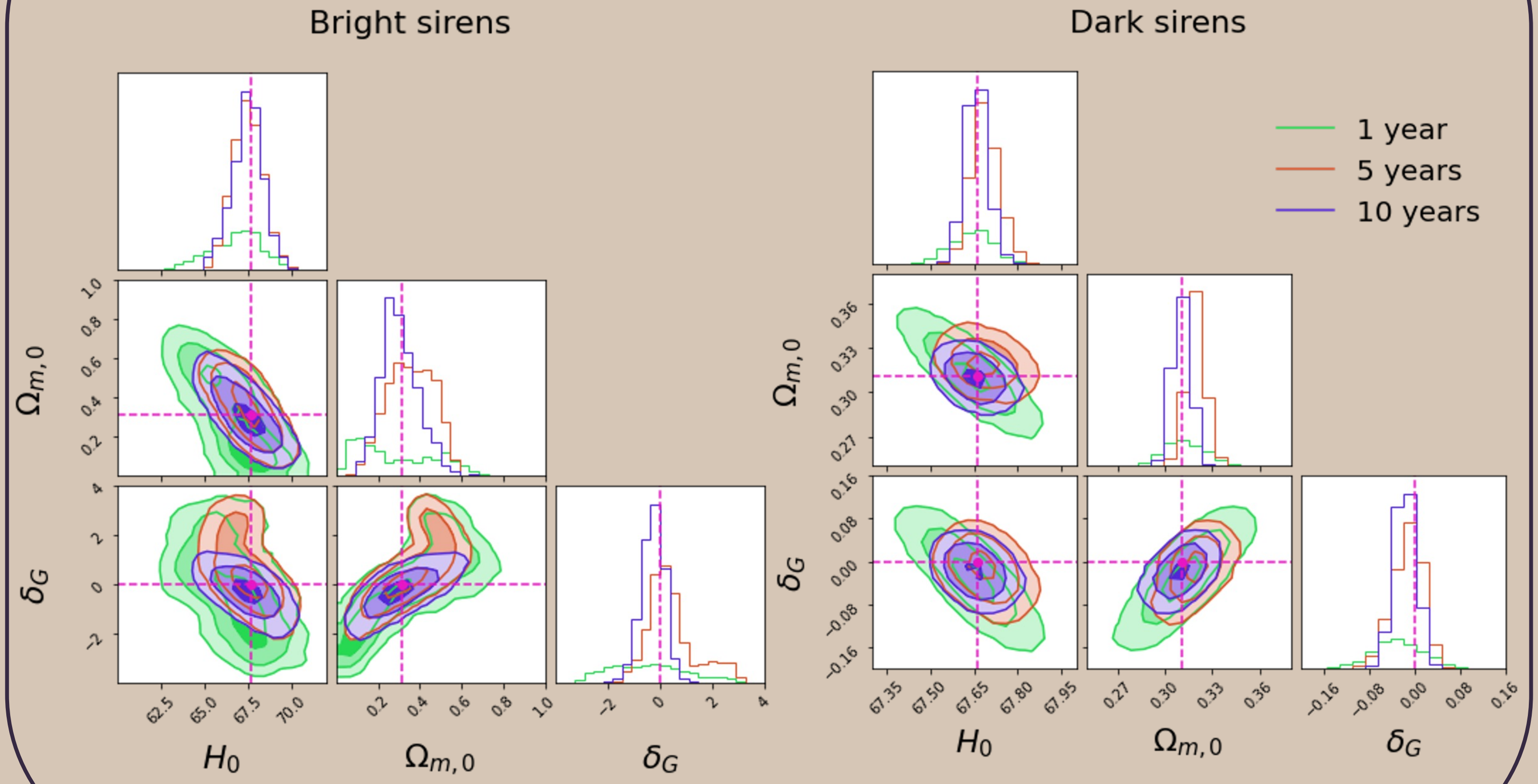
$$E^2(z) = \Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}\left[(1+z)^{3\left(1+\omega_{DE}+\frac{\xi}{3}\right)} + \frac{\xi}{3\left(\omega_{DE}+\frac{\xi}{3}\right)}\left(1-(1+z)^{3\left(\omega_{DE}+\frac{\xi}{3}\right)}\right)(1+z)^3\right]$$

Analysis & Results

Best-fit accurancy (10 years)

	Bright Sirens	Dark Sirens
$\sigma_{H_0} =$	0.95	0.04
$\sigma_{\Omega_{m,0}} =$	0.09	0.01
$\sigma_{\delta_G} =$	0.44	0.02

Time- Varying Gravitational Constant



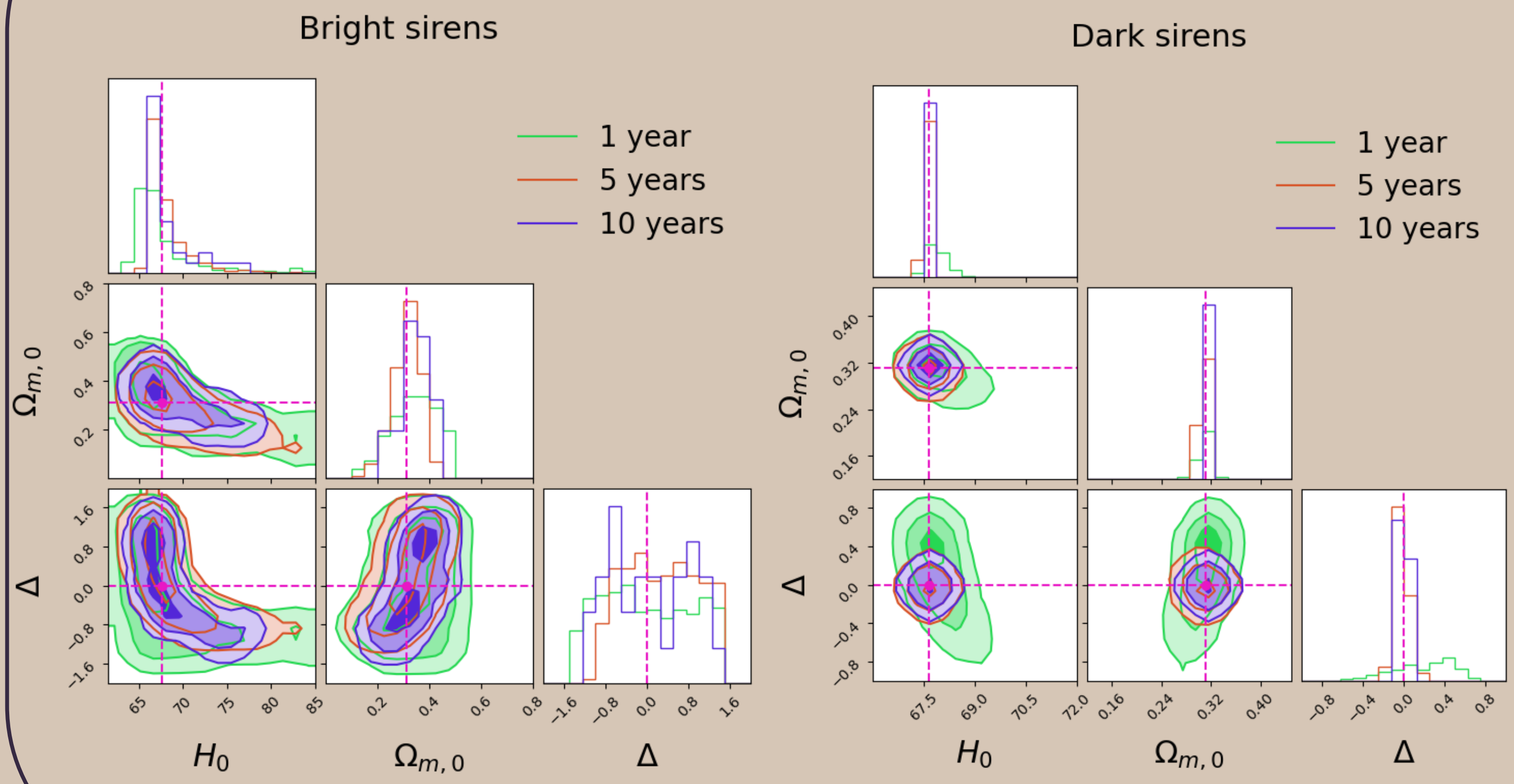
$$E^2(z) = \Omega_{m,0}(1+z)^{3-\delta_G} + \Omega_{\Lambda,0}(1+z)^{\frac{\Omega_{m,0}}{\Omega_{\Lambda,0}}\delta_g}$$

Analysis & Results

Best-fit accurancy (10 years)

	Bright Sirens	Dark Sirens
$\sigma_{H_0} =$	0.86	0.03
$\sigma_{\Omega_{m,0}} =$	0.06	0.002
$\sigma_{\Delta} =$	0.86	0.01

Emergent Dark Energy



$$E^2(z) = \Omega_{m,0}(1+z)^3 \; + \Omega_{\Lambda,0}\left[\frac{1 \; - \tanh\left(\Delta \log_{10}\left(\frac{1+z}{1+z_t}\right)\right)}{1+\tanh(\Delta \log_{10}(1+z_t))}\right]$$

Conclusions

In the analysis, we distinguish the catalogs depending on whether the redshift information comes from the GRB (Bright Sirens) or the BNS merger rate (Dark Sirens). We assume the rate is *a priori* known to follow the SFR.

We show the huge capability of ET to solve the Hubble tension independently by the theoretical framework chosen.

The ET standard sirens will represent an alternative approach to constrain the cosmological parameters and the DE models.