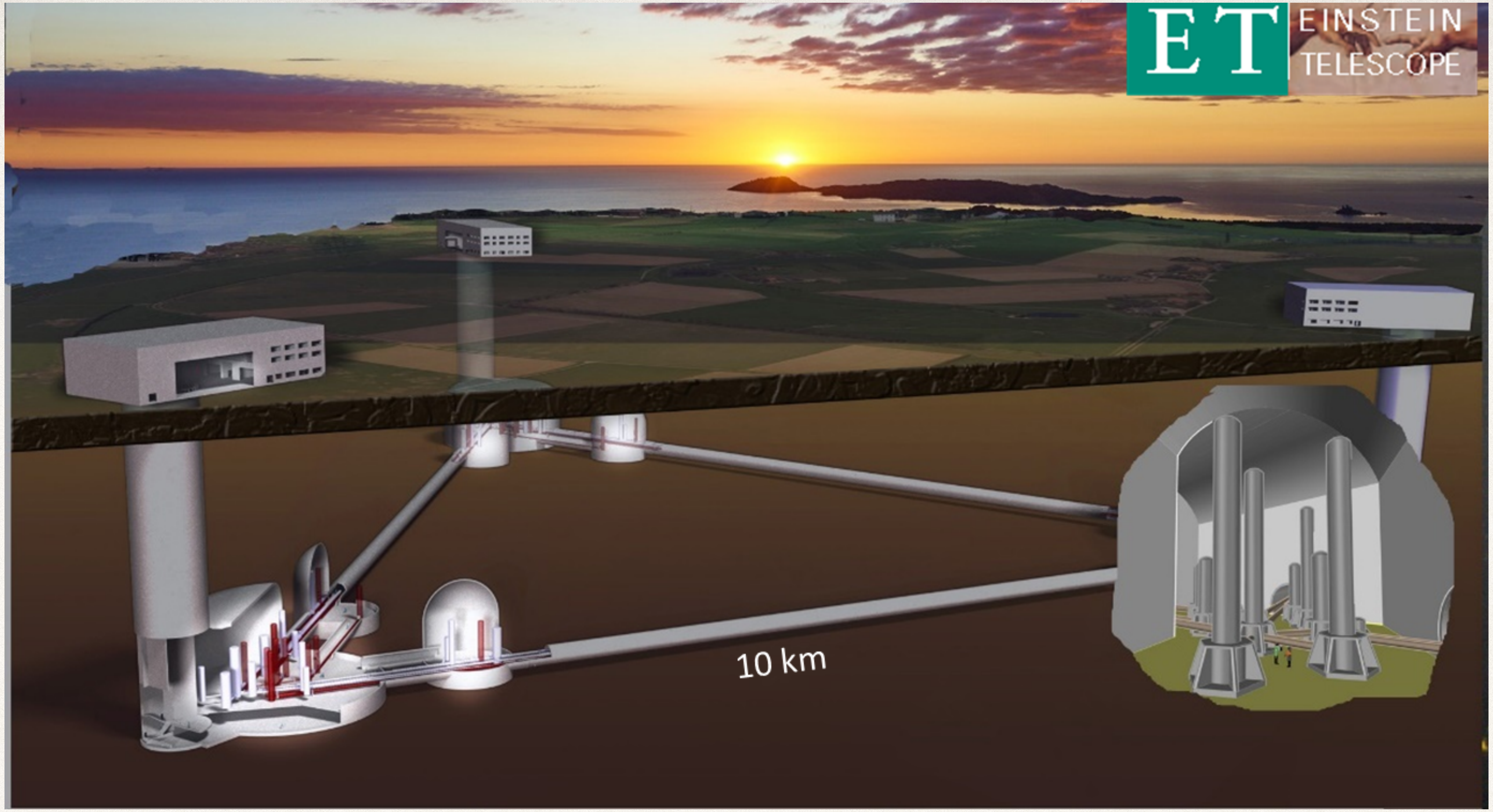

Forecasts for ΛCDM and Dark Energy models through Einstein Telescope mock data

Based on Califano, De Martino, Vernieri, Capozziello, arxiv: 2205.11221 ET-0111A-22

and arxiv: 2208.13999 ET-0188A-22

XIII ET Symposium @ Cagliari 08/05/2023

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Gravitational Waves as Standard Sirens

GW Observables

- With GWs detectors we can measure the amplitude and the phase evolution of the signal

$$h_+ = \frac{2c}{D_L}\left(\frac{G\mathcal{M}^z}{c^3}\right)^{\frac{5}{3}} f^{\frac{2}{3}}(1+\cos^2\iota)\cos 2\Phi(t) \qquad h_\times = \frac{2c}{D_L}\left(\frac{G\mathcal{M}^z}{c^3}\right)^{\frac{5}{3}} f^{\frac{2}{3}}\cos\iota\cos 2\Phi(t)$$

- From the observation, we can estimate

$$\tau_c = \frac{f}{\dot{f}}, \qquad D_L \propto \frac{c}{\left(f^2\tau_c h\right)}, \qquad \mathcal{M}^z = \frac{(1+z)(m_1 m_2)^{\frac{3}{5}}}{(m_1+m_2)^{\frac{1}{5}}} \propto f^{-\frac{11}{5}}\dot{f}^{\frac{3}{5}}$$

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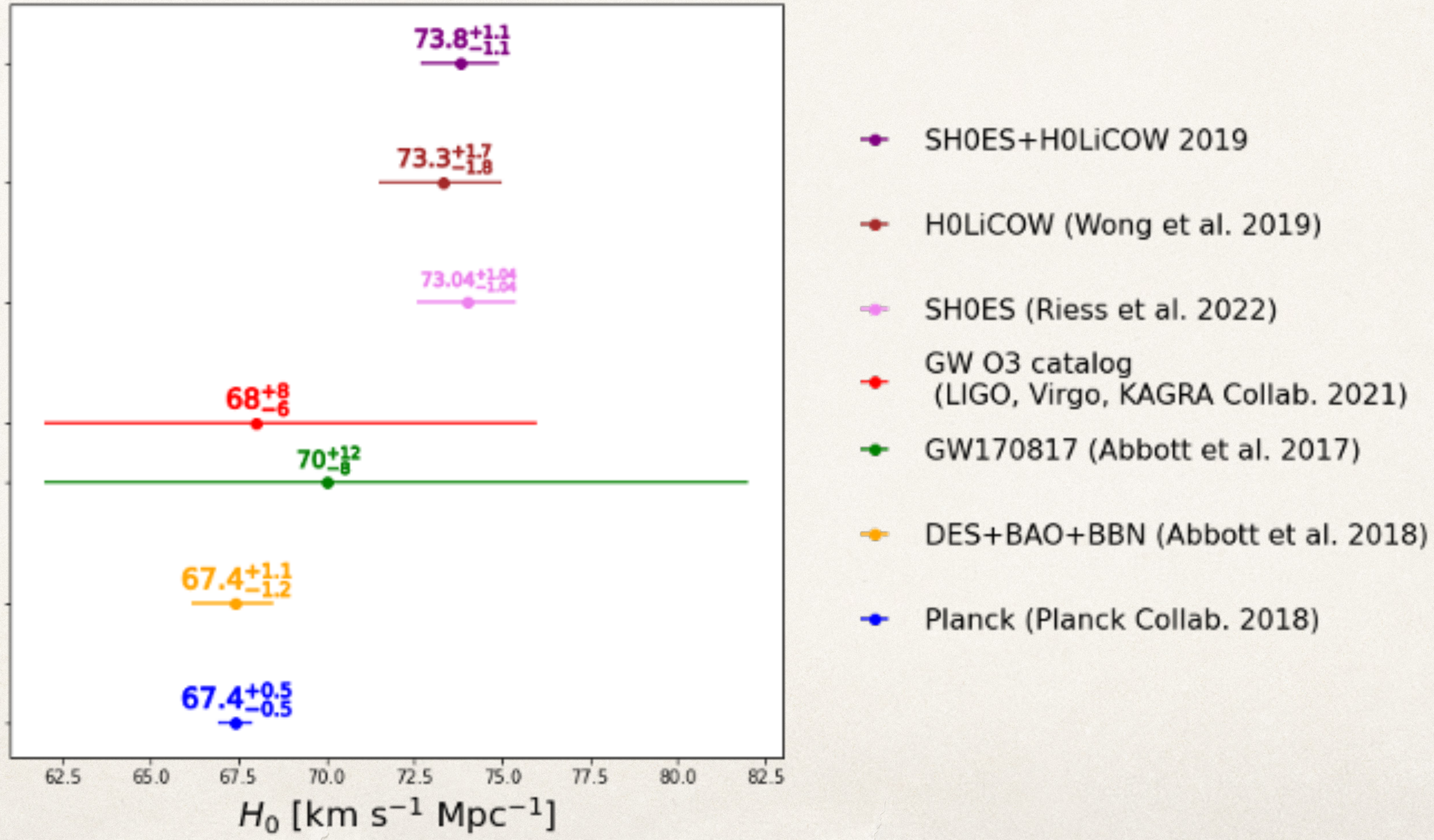
- Binary inspiral allows for a determination of the distance to the source without any reference to the cosmic distance ladder.

- GWs suffer of mass-redshift degeneracy.

H_0 tension



73.8$^{+1.1}_{-1.1}$
73.3$^{+1.7}_{-1.8}$
73.04$^{+1.04}_{-1.04}$
68$^{+8}_{-6}$
70$^{+12}_{-8}$
67.4$^{+1.1}_{-1.2}$
67.4$^{+0.5}_{-0.5}$
62.5
65.0
67.5
70.0
72.5
75.0
77.5
80.0
82.5
H_0 [km s^{-1} Mpc^{-1}]
SH0ES+H0LiCOW 2019
H0LiCOW (Wong et al. 2019)
SH0ES (Riess et al. 2022)
GW O3 catalog (LIGO, Virgo, KAGRA Collab. 2021)
GW170817 (Abbott et al. 2017)
DES+BAO+BBN (Abbott et al. 2018)
Planck (Planck Collab. 2018)

Construction of mock sources catalog

- We assume a fiducial cosmological model ΛCDM

$$\Lambda_{cosmo} = \{H_0 = 67.66 \text{ km s}^{-1} \text{ Mpc}^{-1},\ \Omega_{m,0} = 0.3111,\ \Omega_{k,0} = 0.00,\ \Omega_{\Lambda,0} = 0.6889\}$$

- Given a cosmology the theoretical luminosity distance will be

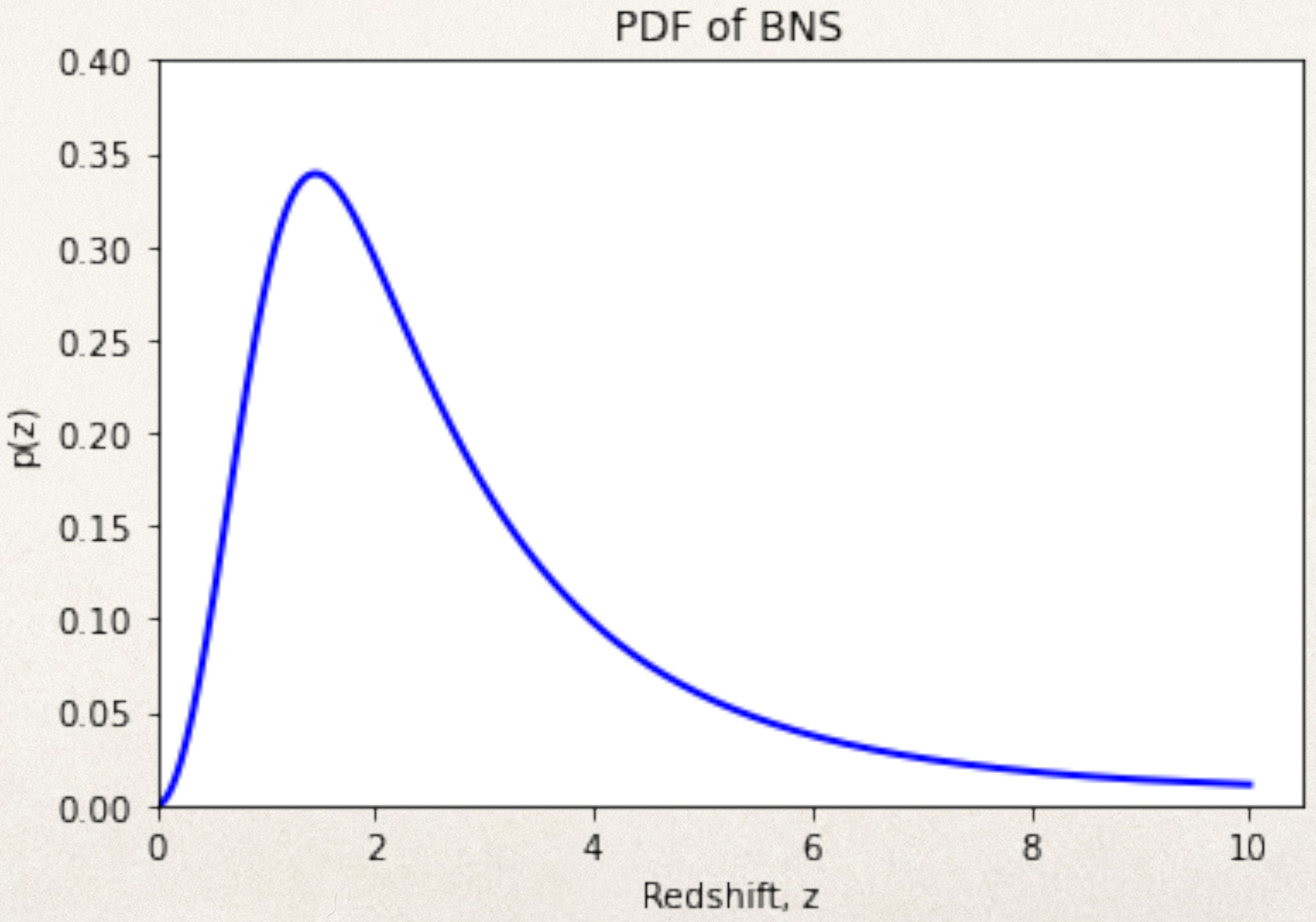
$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{E(z', \Lambda_{cosmo})}$$

- We extract the redshift from a normalized probability distribution

$$p(z) = \frac{R_z(z)}{\int_0^{10} R_z(z) dz}$$

$$R_z(z) = \frac{R_m(z)}{1+z} \frac{dV(z)}{dz}$$

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



- To generate the synthetic signals of GWs, we assume the NS mass distribution be uniform in the interval [1, 2.5] $M_{\odot}$.

- We select sky angles θ and φ from an isotropic distribution, and orientation angle ι and the polarization ψ from uniform distribution.

- We estimate the SNR ρ for the ET and we retain an event if $\rho > 9$.

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

$$\sigma_{d_L} = \sqrt{\sigma_{inst}^2 + \sigma_{lens}^2 + \sigma_{pec}^2}$$

Selection of electromagnetic counterpart

- We estimate the flux for the coincident short-GRB

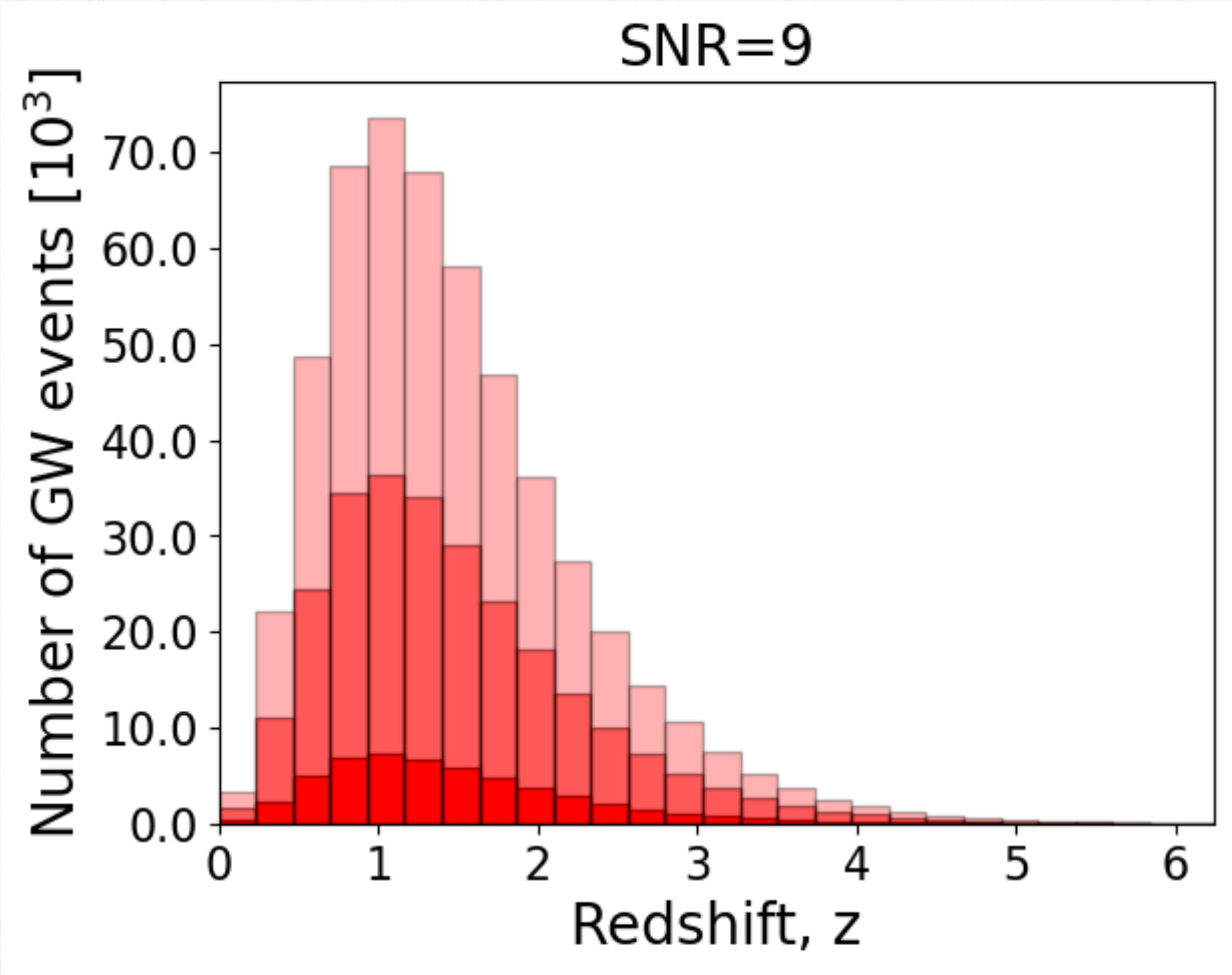
$$F\left(\theta_V\right) = \frac{L\left(\theta_V\right)(1+z)}{4\pi\, d_L^2\, k(z)\, b}$$

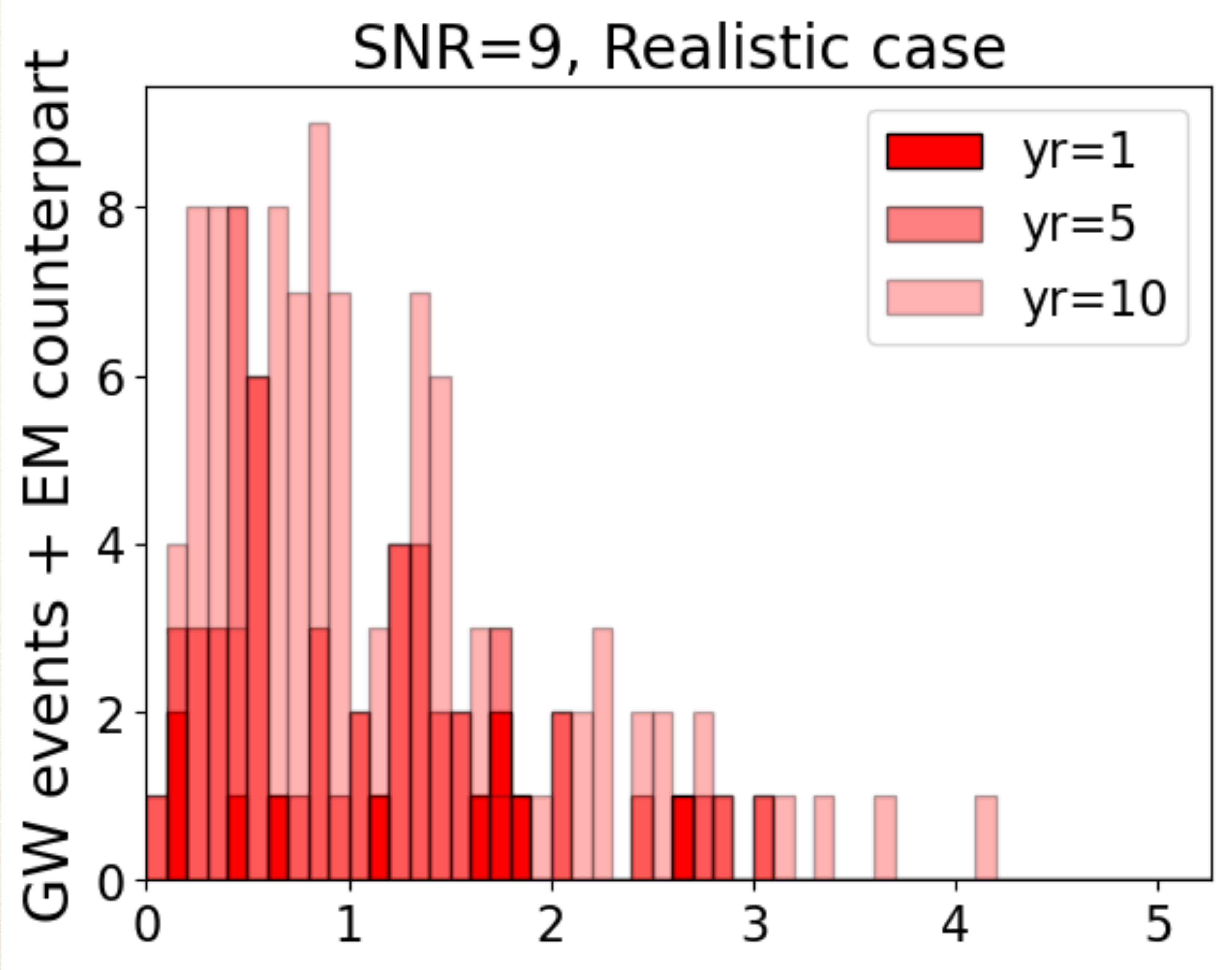
$$b = \frac{\int_{1\ keV}^{10^4 keV} E\, N(E)dE}{\int_{E_1}^{E_2} N(E)dE} \qquad k(z) = \frac{\int_{E_1}^{E_2} N(E)dE}{\int_{E_1(1+z)}^{E_2(1+z)} N(E)dE}$$

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

GW events distribution

- Imposing a SNR 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-XGIS satellite of ~ 11 events/year.





Analysis

CASE I: Bright Sirens

- We include in the single-event likelihood the selection effects $\rho > \rho_t$, $F\left(\theta_V\right) > F_t$

$$p\left(d_i | \Lambda_{cosmo}\right) = \frac{\int p\left(d_i | D_L, \Lambda_{cosmo}\right) p_{pop}\left(D_L | \Lambda_{cosmo}\right) dD_L}{\int p_{det}\left(D_L, \Lambda_{cosmo}\right) p_{pop}\left(D_L | \Lambda_{cosmo}\right) dD_L}$$

[Mandel et al. MNRAS (2019)]

$$\longrightarrow \quad p_{pop}\left(D_L | \Lambda_{cosmo}\right) = \delta\left(D_L^{th}\left(\Lambda_{cosmo}\right) - D_L\right)$$

$$\longrightarrow \quad p(d_i | D_L, \Lambda_{cosmo}) \propto \exp - \frac{1}{2} \frac{\left(d_i - D_L\right)^2}{\sigma_{d_i}^2}$$

$$\longrightarrow \quad p_{det}\left(D_L, \Lambda_{cosmo}\right) = \int_{\rho > \rho_t,\ F > F_t} p\left(d_i | D_L, \Lambda_{cosmo}\right) dd_i$$

CASE II: Dark Sirens

- When we cannot extract the redshift information from electromagnetic signal, we have to marginalise over the redshift

$$p\left(d_i \,|\, \Lambda_{cosmo}\right) = \int p\left(d_i \,|\, D_L, \Lambda_{cosmo}\right) p_{pop}\left(D_L \,|\, \Lambda_{cosmo}\right) p(z)\; dz dD_L$$

[Ding et al. JCAP (2019)]

Results

$K\Lambda CDM$	$E^2(z) = \Omega_{m,,0}(1+z)^3 + \Omega_{K,0}(1+z)^2 + \Omega_{\Lambda,0}$			
	σ_{H_0}	$\sigma_{\Omega_{K,0}}$	$\sigma_{\Omega_{\Lambda,0}}$	
Bright Sirens	0.79	0.16	0.13	
Dark Sirens	0.04	0.01	0.01	
$K\omega CDM$	$E^2(z) = \Omega_{m,,0}(1+z)^3 + \Omega_{K,0}(1+z)^2 + \Omega_{\Lambda,0}(1+z)^{3(1+\omega)}$			
	σ_{H_0}	$\sigma_{\Omega_{K,0}}$	$\sigma_{\Omega_{\Lambda,0}}$	σ_ω
Bright Sirens	0.80	0.18	0.18	0.93
Dark Sirens	0.06	0.02	0.03	0.10
Interacting DE	$E^2(z) = \Omega_{m,,0}(1+z)^3 + \Omega_{\Lambda,0}\left[(1+z)^{3(1+\omega^{eff})} + \frac{\xi}{3\omega^{eff}}(1-(1+z)^{3\omega^{eff}})(1+z)^3\right], \quad \omega^{eff} = \omega + \frac{\xi}{3}$			
	σ_{H_0}	$\sigma_{\Omega_{m,0}}$	σ_ξ	
Bright Sirens	1.03	0.14	0.88	
Dark Sirens	0.05	0.01	0.06	

Time-Varying G	$E^2(z) = \Omega_{m,,0}(1+z)^{3-\delta_G} + \Omega_{\Lambda,0}(1+z)^{\delta_G \frac{\Omega_{m,0}}{\Omega_{\Lambda,0}}}$		
	σ_{H_0}	$\sigma_{\Omega_{m,0}}$	σ_{δ_G}
Bright Sirens	0.95	0.09	0.44
Dark Sirens	0.04	0.01	0.02

Emergent DE	$E^2(z) = \Omega_{m,,0}(1+z)^3 + \Omega_{\Lambda,0}\left[\frac{1+\tanh(\Delta \log(\frac{1+z}{1+z_t}))}{1+\tanh(\Delta \log(1+z_t))}\right]$		
	σ_{H_0}	$\sigma_{\Omega_{m,0}}$	σ_{Δ}
Bright Sirens	0.86	0.06	0.86
Dark Sirens	0.03	0.02	0.01

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.

- We show the huge capability of ET to solve the Hubble tension independently by the theoretical framework chosen, achieving an accuracy on the Hubble constant less than 1%.

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

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.
- We show the huge capability of ET to solve the Hubble tension independently by the theoretical framework chosen, achieving an accuracy on the Hubble constant less than 1%.

THANK YOU!

QUESTIONS?

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

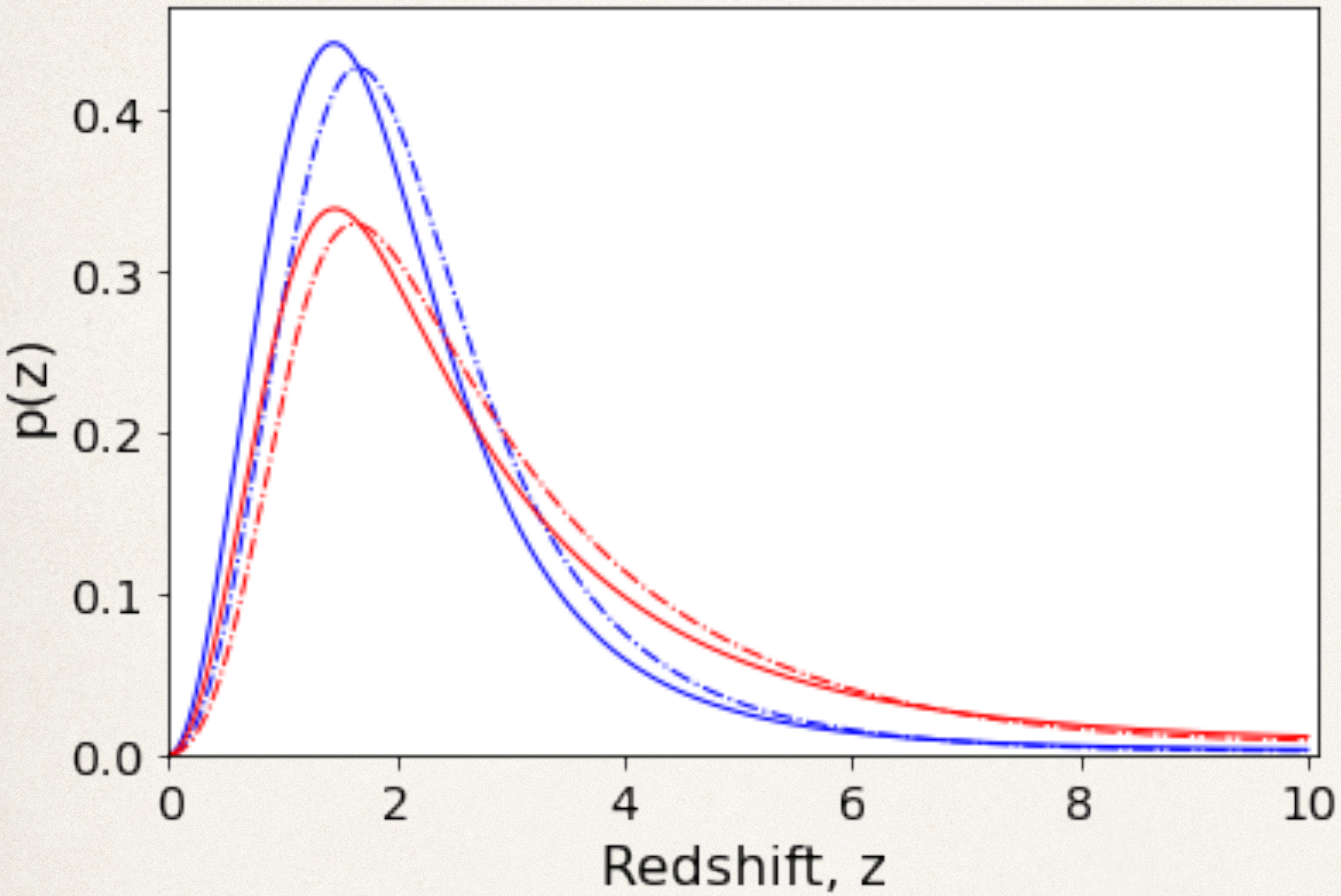
Backup slides

Open Issue: Redshift information

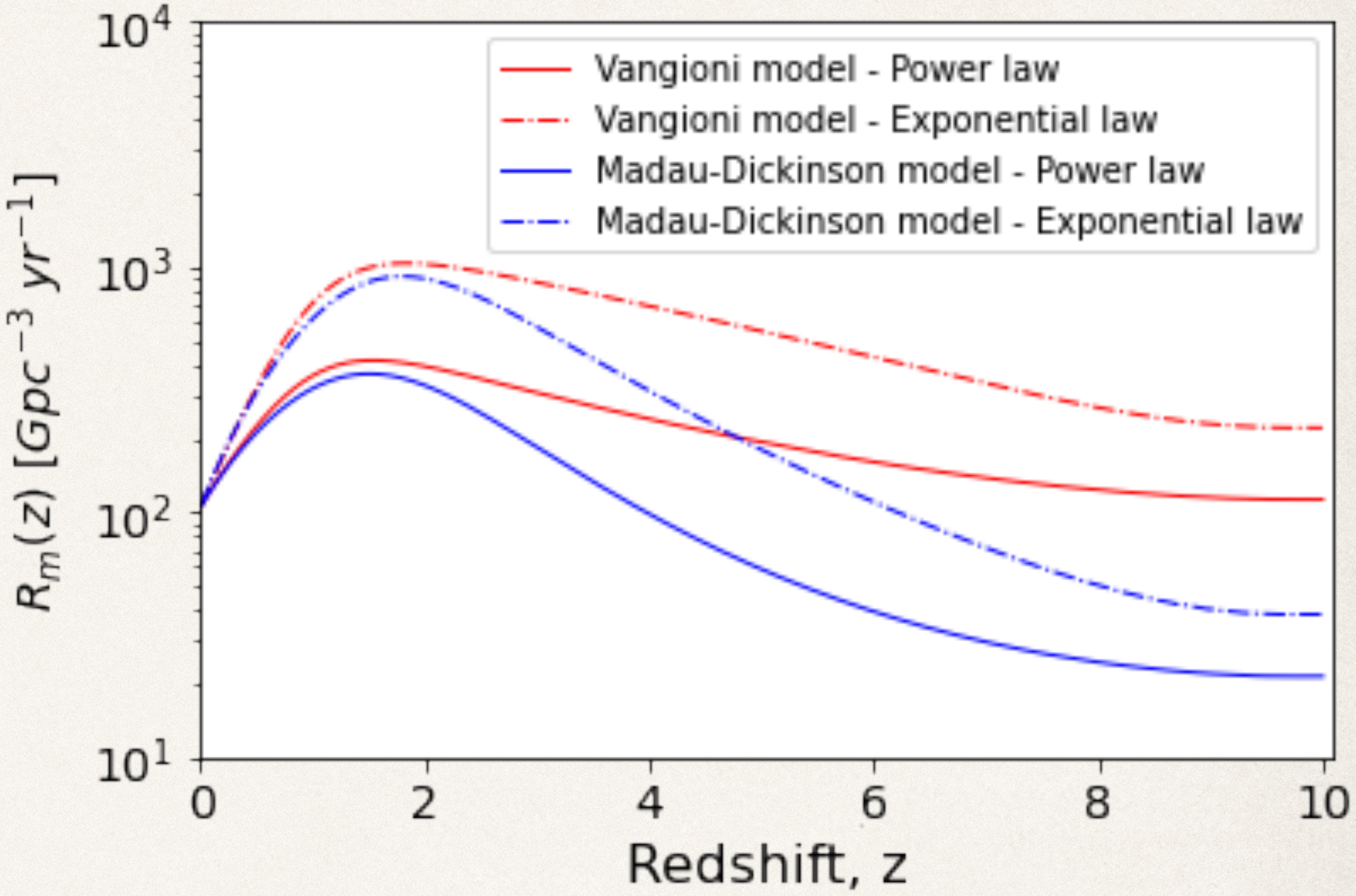
- Host galaxy identification
  [Schutz, Nature, 1986]
  - Source sky localizzation error.
  - σ_{d_L} error.
  - Overlapping sky area between GW sources and galaxy surveys.
  - The accurate redshift estimation of galaxies.
- Cross-Correlation
  [Mukherjee and Wandelt, 2018]
- Coincident short GRB
  - Only 0.1% of GW events could have a detected counterpart.
- Prior information on redshift
  - We need to assume astrophysical model for the p(z).
- Tidal deformation
  [Messenger and Read, PRL, 2012]
  - We need high precision in the signal analysis.
  - It depends on neutron star equation of state.

Impact of different assumptions

- Star Formation Rate:
  - Vangioni model, $R_f(z) = \dfrac{\nu\ a \exp(b(z - z_m))}{a - b + b \exp(a(z - z_m))}$ [Vangioni et al.,MNRAS, 2015]
  - Madau-Dickinson model, $R_f(z) = \dfrac{1 + z)^{\alpha}}{1 + \left[\frac{1+z}{C}\right]^{\beta}}$ [Madau and Dickison, ARAA,2014]
- t_d probability distribution:
  - Power law, $P(t_d) = t_d^{-1}$
  - Exponential, $P(t_d) = \tau^{-1} \exp\left(-\dfrac{t}{\tau}\right)$



p(z)
0.0
0.1
0.2
0.3
0.4
0
2
4
6
8
10
Redshift, z



$R_m(z)$ $[Gpc^{-3}\ yr^{-1}]$
10^1
10^2
10^3
10^4
0
2
4
6
8
10
Redshift, z
Vangioni model - Power law
Vangioni model - Exponential law
Madau-Dickinson model - Power law
Madau-Dickinson model - Exponential law

GW + EM events				
MODEL	**# events**	$\mathbf{H_0}$	$\mathbf{\Omega_{k,0}}$	$\mathbf{\Omega_{\Lambda,0}}$
Baseline model	332	$67.47^{+0.39}_{-0.40}$	$-0.08^{+0.08}_{-0.09}$	$0.72^{+0.07}_{-0.07}$
Model 1	603	$67.18^{+0.34}_{-0.32}$	$0.01^{+0.07}_{-0.07}$	$0.65^{+0.06}_{-0.06}$
Model 2	271	$67.48^{+0.30}_{-0.30}$	$-0.09^{+0.09}_{-0.10}$	$0.71^{+0.07}_{-0.07}$
Model 3	536	$67.20^{+0.27}_{-0.28}$	$0.01^{+0.08}_{-0.07}$	$0.65^{+0.05}_{-0.06}$
Dark Sirens				
MODEL	**# events**	$\mathbf{H_0}$	$\mathbf{\Omega_{k,0}}$	$\mathbf{\Omega_{\Lambda,0}}$
Baseline model	521552	$67.68^{+0.04}_{-0.04}$	$0.00^{+0.01}_{-0.01}$	$0.69^{+0.01}_{-0.01}$
Model 1	1143212	$67.64^{+0.04}_{-0.04}$	$0.00^{+0.01}_{-0.01}$	$0.69^{+0.01}_{-0.01}$
Model 2	443560	$67.62^{+0.05}_{-0.05}$	$0.01^{+0.01}_{-0.01}$	$0.68^{+0.01}_{-0.01}$
Model 3	966659	$67.68^{+0.04}_{-0.04}$	$-0.01^{+0.01}_{-0.01}$	$0.68^{+0.01}_{-0.01}$

Table 6: The *baseline* model adopts the *Vangioni model* for the SFR and the *power law* form of the time delay distribution; **Model 1** is based on the *Vangioni model* for the SFR and the *exponential distribution* of the time delay distribution; **Model 2** is based on the *Madau - Dickison model* for the SFR and the *power law* form of the time delay distribution; **Model 3** is based on the *Madau - Dickison model* for the SFR and the *exponential distribution* of the time delay distribution.

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

$$\sigma_{d_L} = \sqrt{\sigma_{inst}^2 + \sigma_{lens}^2 + \sigma_{pec}^2}$$

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

[Cutler and Flanagan, PRD (1994)]

[Dalal et al., PRD (2006)]

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

[Speri et al., PRD (2021)]

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

[Kocsis et al., Astrop. J. (2006)]