Cosmology with Dark Sirens and Large Scale Structures cross-correlations

Based on Sala, Cuoco, Lesgourgues, Rafail-Revis, Valbusa dall'Armi, Casas, ArXiv:2510.08699 and

Calore, Cuoco, Regimbau, Sachdev and Serpico, Phys.Rev.Res. 2 (2020), ArXiv: 2002.02466

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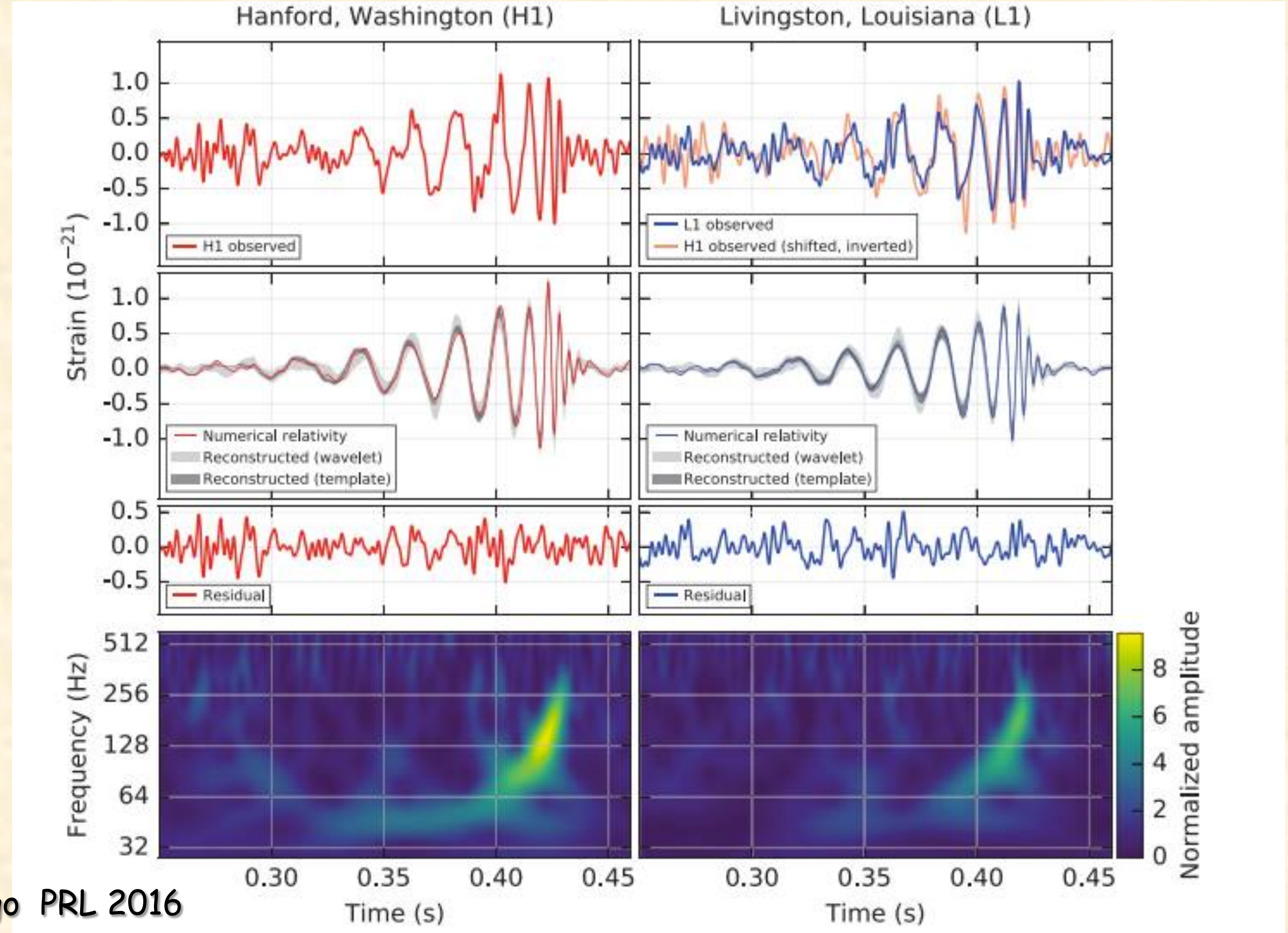
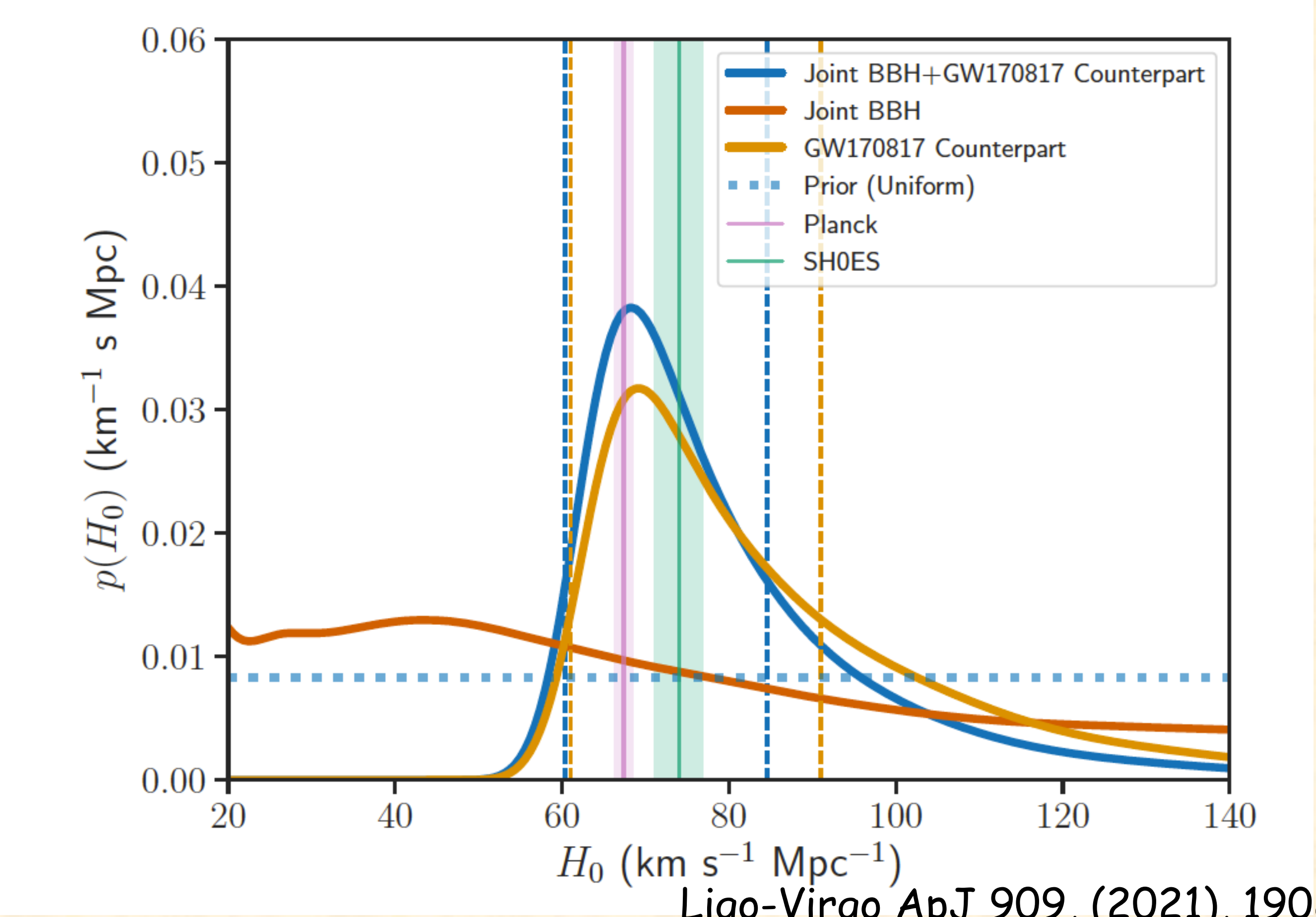
Gravitational Waves

- The detection of GWs by Ligo-Virgo opened a new window on the Universe (14 Sept. 2015, 10 yrs ago!)



Ligo –Virgo PRL 2016

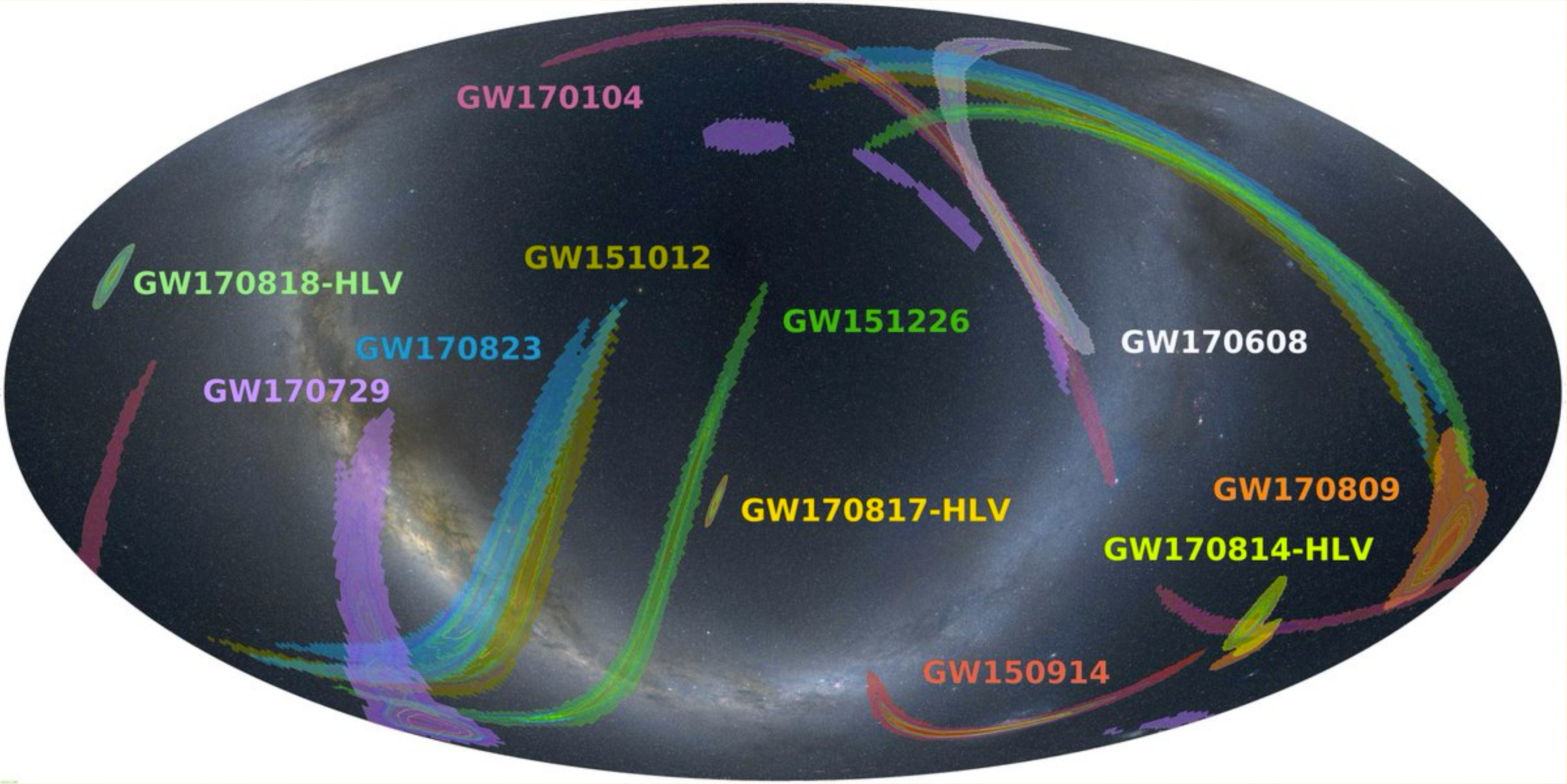
Standard Sirens



Ligo-Virgo ApJ 909, (2021), 1908.06060

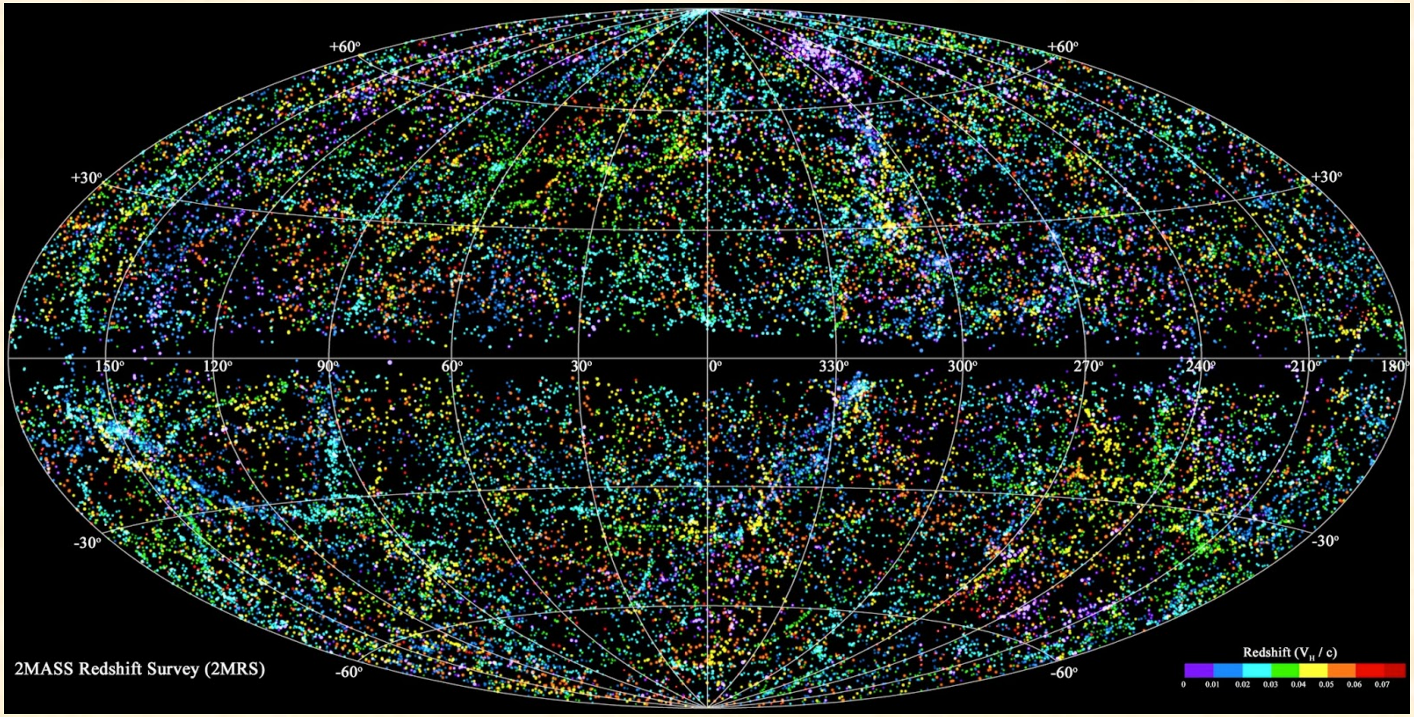
- GWs are standard Sirens: they give you the luminosity distance of the object
- An independent measurement of z (from counterpart) is generally needed (bright siren)
- In the case of Dark Sirens different techniques can be used

Map of GWs



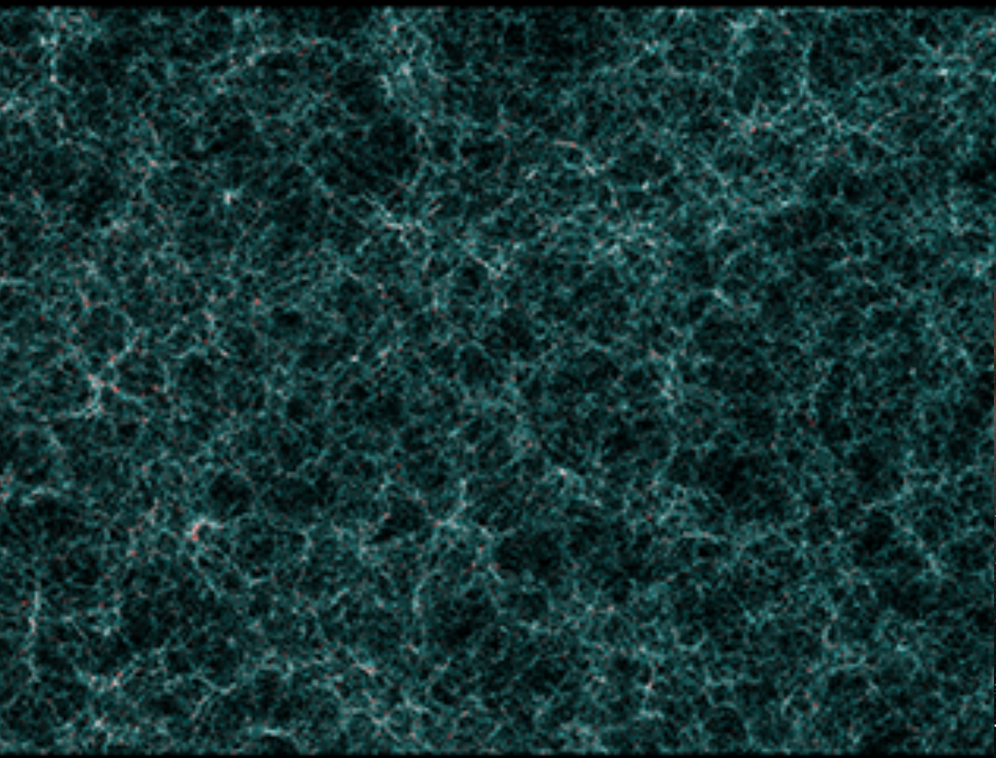
- In the next years number of detections and precision of localization will grow
- Auto-correlation statistics: very sensitive to the available statistic and angular precision
- Cross-correlation: exploit information from galaxy catalogs. More robust. Also less sensitive to the statistics and angular resolution

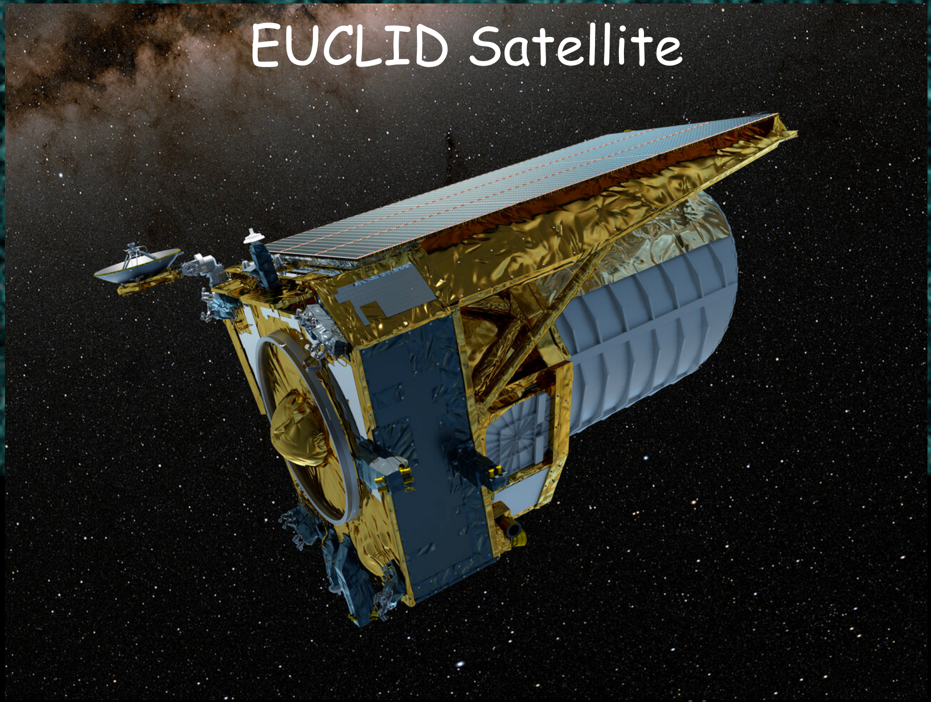
Large Scale Structures



2MASS Galaxy Catalog

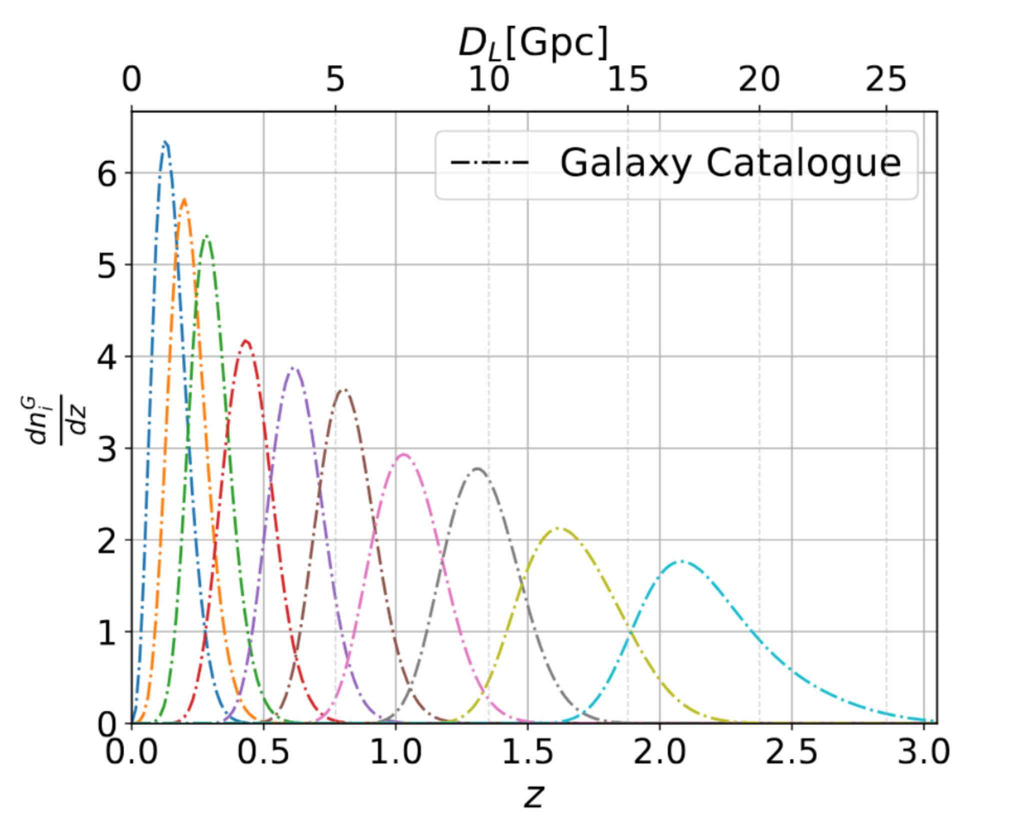
Large Scale Structures





Credits ESA

Galaxy Tomography



- An Euclid-like galaxy catalog is used. With about 10^9 galaxies with photometric z errors of about 5%
- Galaxies are divided into 10 z bins, and photometric errors are considered

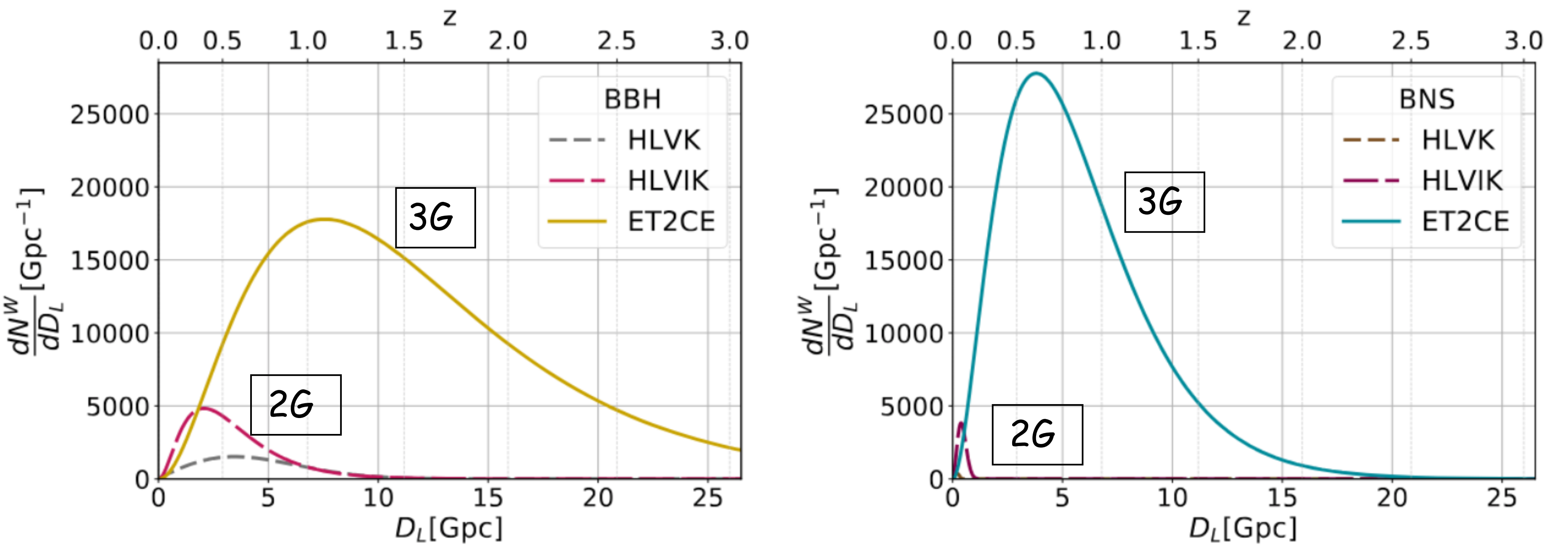
GW-LSS forecast

- Considering 3 cases:
  - HLVK design sensitivity (~10000 BBH Events in 10 yr)
  - HLVIK design sensitivity (~20000 BBH Events in 10 yr)
  - 3G: Einstein Telescope+ 2xCosmic Explorer ($3x10^5$ BBH events up to z~5)

- Expected angular resolutions of the order ~0.1-1 deg

Sala, Cuoco, Lesgourgues, Rafail-Revis, Valbusa dall'Armi and Casas, ArXiv:2510.08699
Calore, Cuoco, Regimbau, Sachdev and Serpico, Phys.Rev.Res. 2 (2020), ArXiv: 2002.02466

GW-LSS forecast



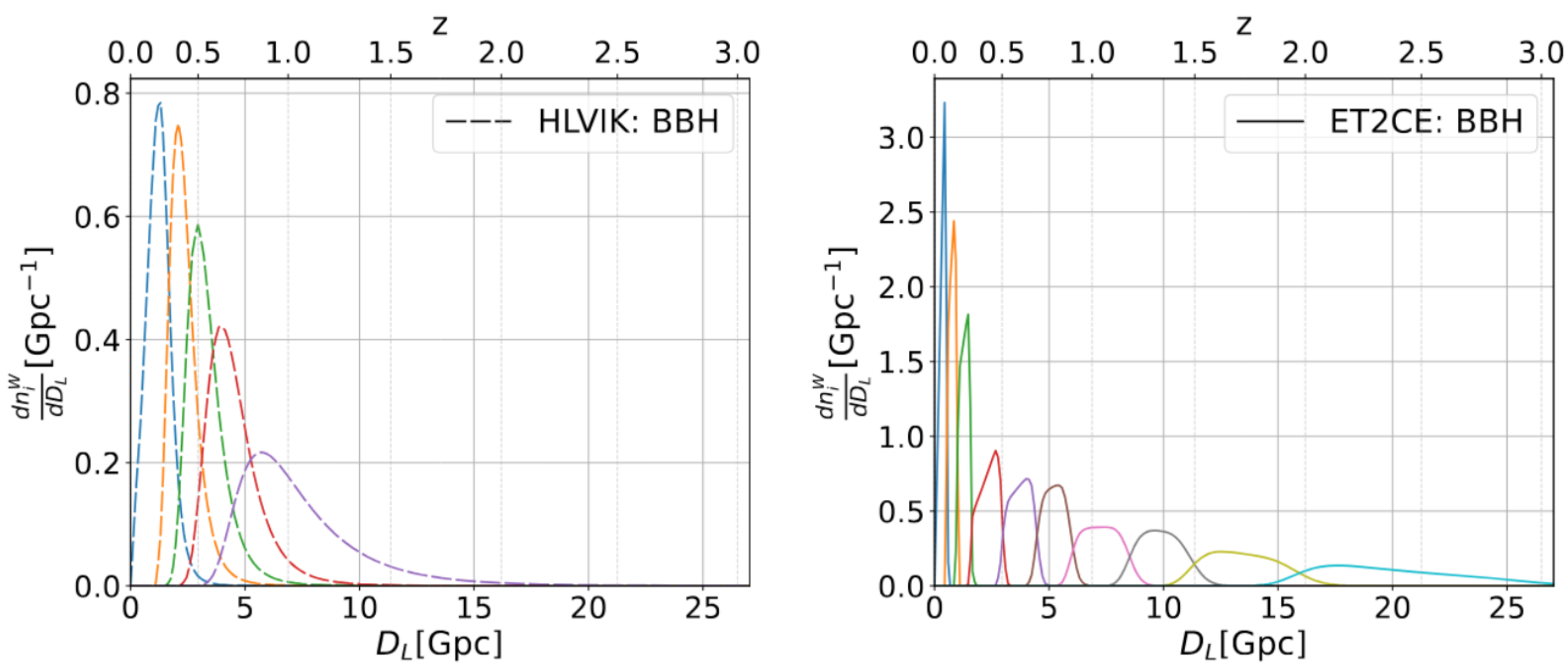
(a) Detectable BBH number density

(b) Detectable BNS number density

- The simulation gives the z and D_L distributions for the observable GW events and for the 3 sub-classes BBHs, BNSs,
- 2G will detect events up to z~0.6, while 3G up z~5

Detector	Source	# events
HLVK	BBH	9159
	BNS	86
HLVIK	BBH	20289
	BNS	1874
ET2CE	BBH	262596
	BNS	198257

Darks Sirens distributions



(a) HLVIK binned distribution

(b) ET2CE binned distribution

- We use 10 bins for the 3G case, and only 5 bins for the 2G case, due to the limited statistics available

Theoretical predictions

Angular Power Spectrum of GW-LSS cross-correlation

$$C^{A_iB_j}(\ell) = \int_{z_{\min}}^{z_{\max}} dz \frac{W^{A_i}(z)W^{B_j}(z)}{H(z)r^2(z)} \times P_{\delta\delta}\left[k = \frac{\ell+1/2}{r(z)}, z\right]$$

Expected Covariance on the Angular Power Spectrum

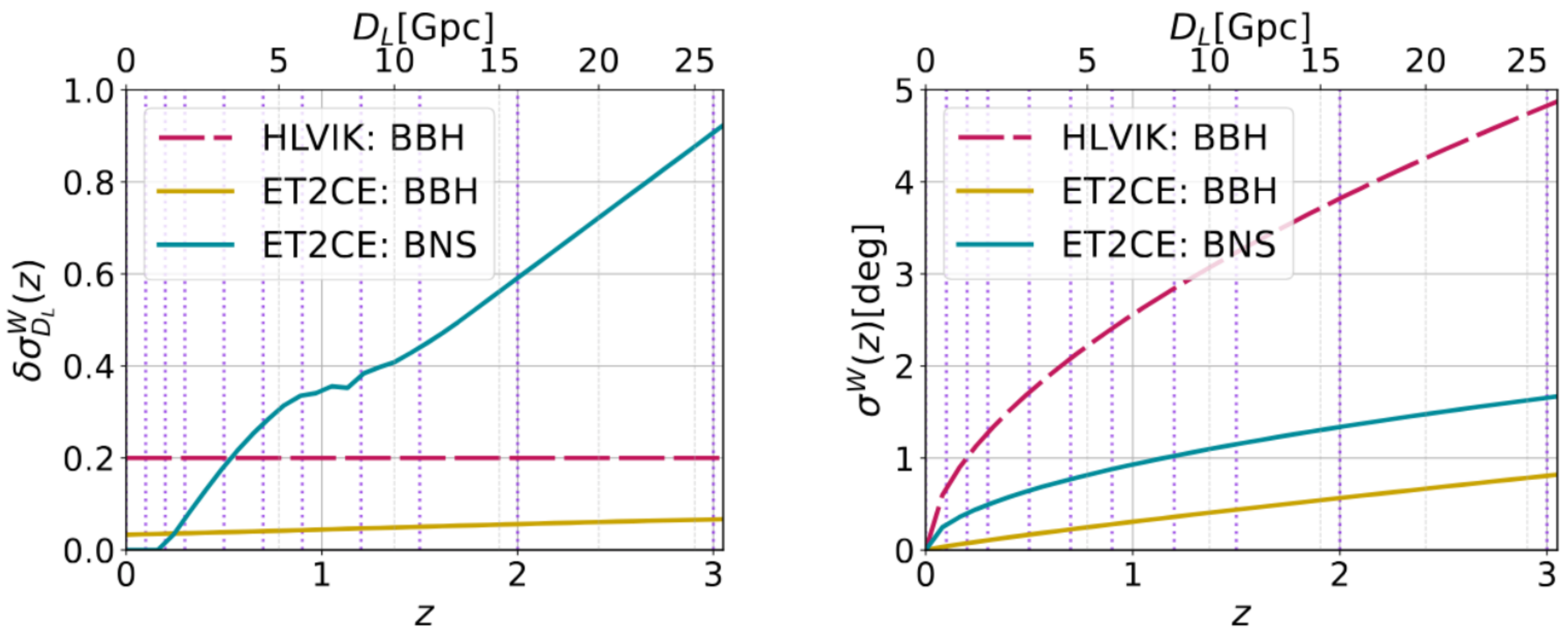
$$\begin{aligned}\mathrm{Cov}\left[\vec{T}_\ell(\vec{\theta}), \vec{T}_{\ell'}(\vec{\theta})\right] &= \mathrm{Cov}\left[C^{A_iB_j}(\ell), C^{C_kD_n}(\ell')\right] \\ &= \frac{\delta_{\ell\ell'}}{(2\ell+1)f_{\rm fov}\Delta\ell}\Big[\left(C^{A_iC_k}(\ell)+N^{A_iC_k}(\ell)\right)\left(C^{B_jD_n}(\ell)+N^{B_jD_n}(\ell)\right)+ \\ &+ \left(C^{A_iD_n}(\ell)+N^{A_iD_n}(\ell)\right)\left(C^{B_jC_k}(\ell)+N^{B_jC_k}(\ell)\right)\Big], \qquad (4.4)\end{aligned}$$

Noise and beam window

$$N^{A_iB_j}(\ell) = \frac{4\pi f^A_{\rm fov}}{N^{A_i}} \frac{\delta_{A_iB_j}}{(\mathcal{W}^{A_i}(\ell))^2}$$

$$\mathcal{W}^{A_i}(\ell) = \exp\left(-\frac{(\sigma^{A_i})^2\ \ell^2}{2}\right)$$

Angular and D_L resolution



(a) Luminosity distance relative error.

(b) Angular localisation error.

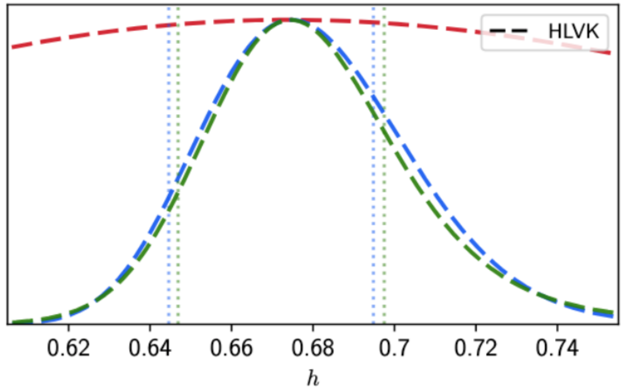
- We performed a series of simulations of GW events with the GWFAST code to determine the angular resolution and the luminosity distance resolution.

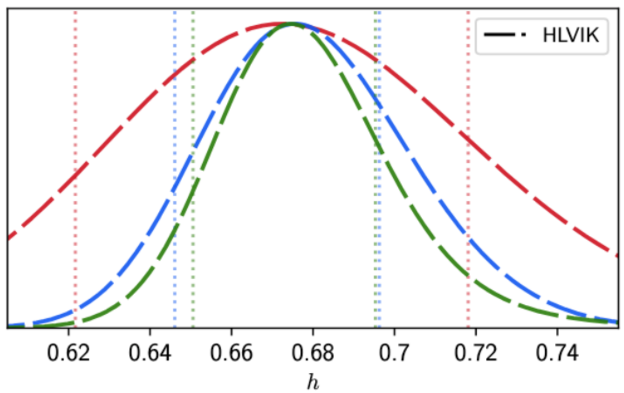
- BBH are typically better reconstructed than BNS and have better localization and distance determination.

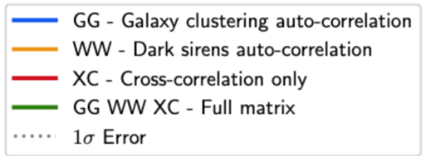
- For close-by events resolutions up to 0.1 deg are achieved. Resolutions of ~1 deg are typical.

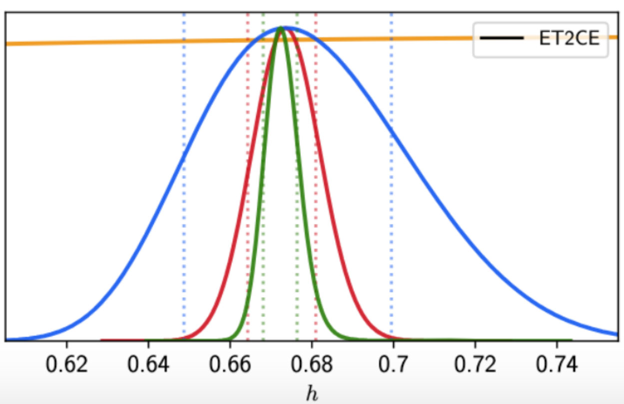
Results H0

- We perform a cosmological forecast with MCMC scans of the full likelihood.
- We assume a fiducial model with H_0=67.4 km s^{-1} Mpc^{-1}



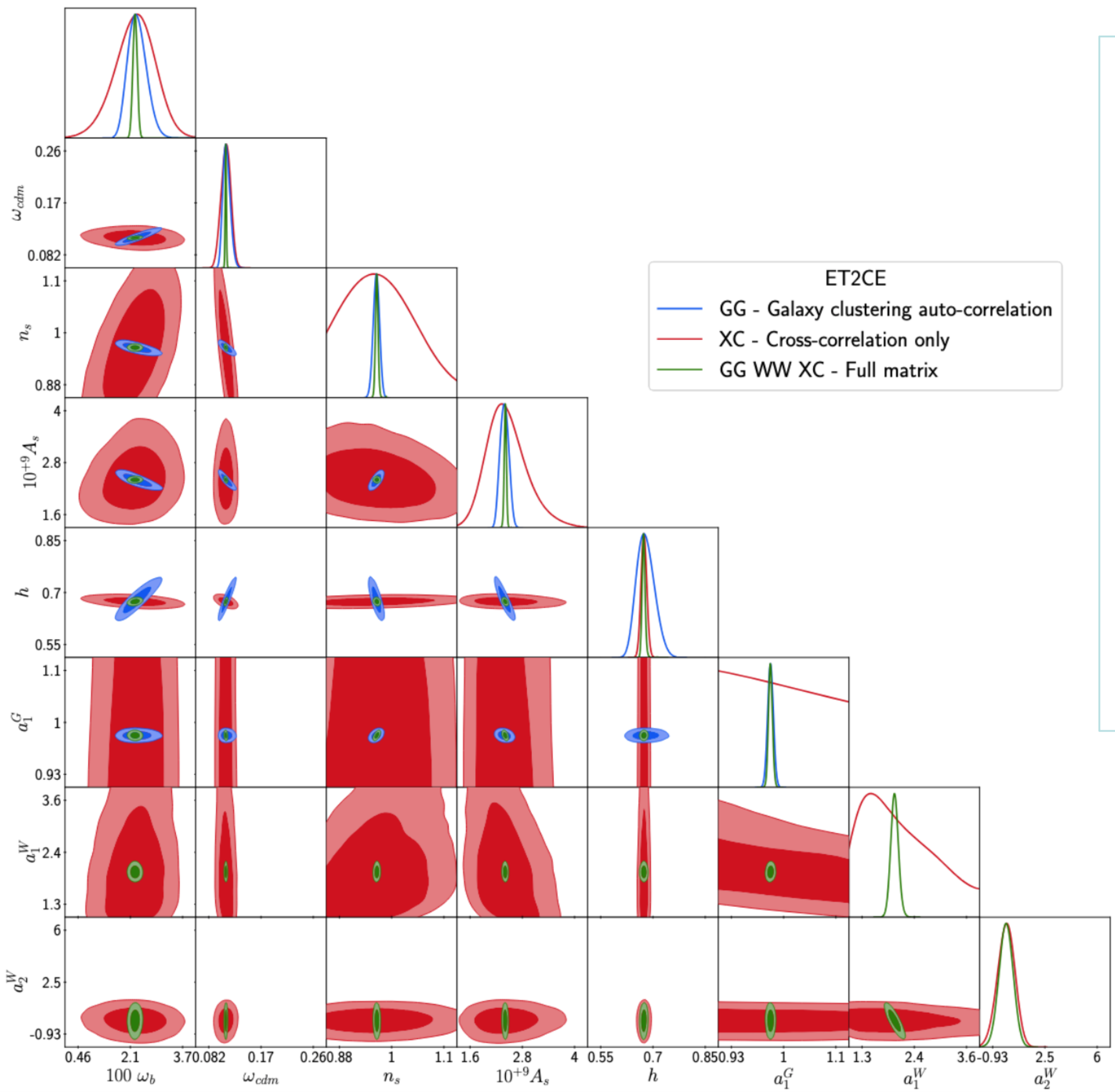






Detector	**Contribution**	H_0 **bestfit**$^{+1\sigma}_{-1\sigma}$ [km s^{-1} Mpc^{-1}]
Galaxy Catalogue	GG	$67.4^{+2.3}_{-2.8}$
HLVK	XC Full matrix	$67.3^{+15.2}_{-24.2}$ $67.6^{+2.2}_{-2.9}$
HLVIK	XC Full matrix	$67.3^{+4.5}_{-5.2}$ $67.5^{+2.0}_{-2.5}$
ET2CE	XC Full matrix	$67.3^{+0.8}_{-0.9}$ $67.2^{+0.5}_{-0.4}$

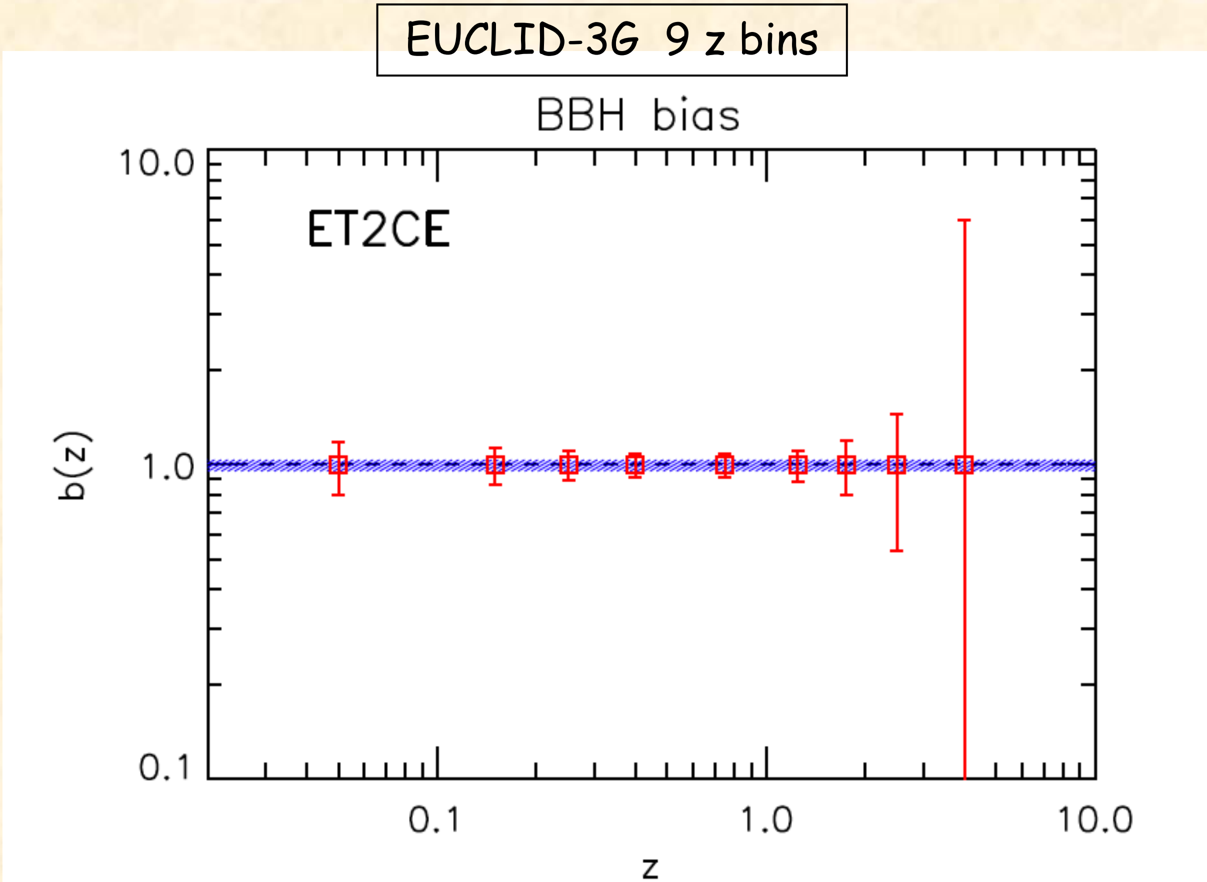
Results: Cosmological parameters



- There is a strong complementarity between galaxy auto-correlation information and GW-galaxy cross-correlation for basically all the cosmological parameters

- When both information is used constraints become several times stronger than any of the two probes alone.

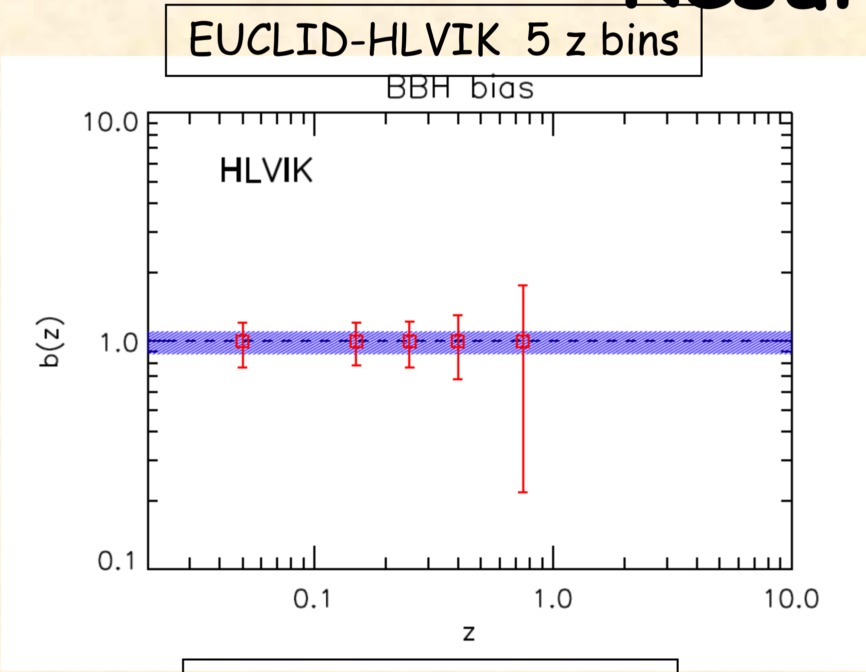
Results: bias

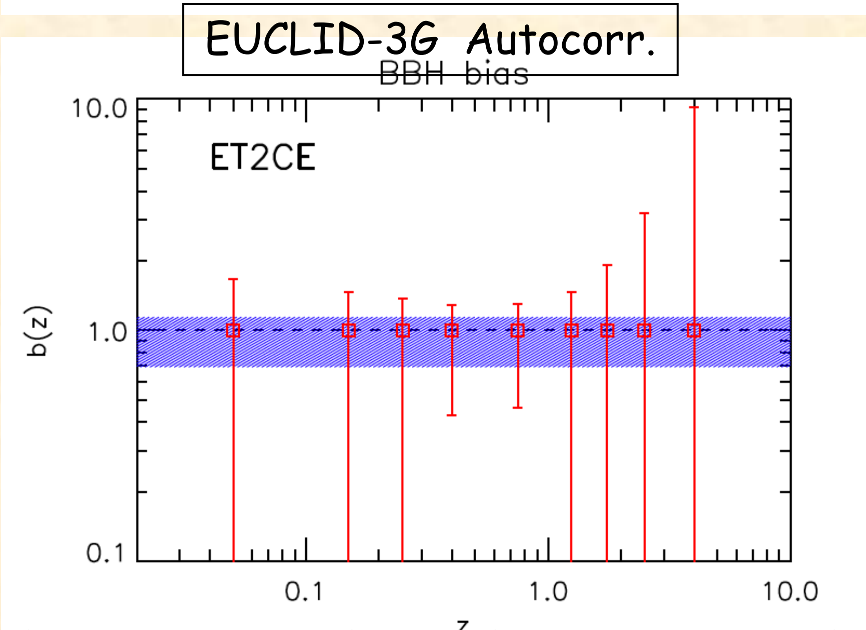


Calore, Cuoco, Regimbau, Sachdev and Serpico, Phys.Rev.Res. 2 (2020), ArXiv: 2002.02466

- Combining 3G and future galaxy surveys it possible to determine the bias as function of z at about 10% precision, which should be enough to distinguish the primordial BHs case from the astro BHs case

Results: bias





- Already with the current generation the bias can be measured reasonable well giving discrimination capabilities
- Results from GW autocorrelation only are poor. The extra information from correlation with galaxies dramatically enhance the discrimination power.

Calore, Cuoco, Regimbau, Sachdev and Serpico, Phys.Rev.Res. 2 (2020), ArXiv: 2002.02466

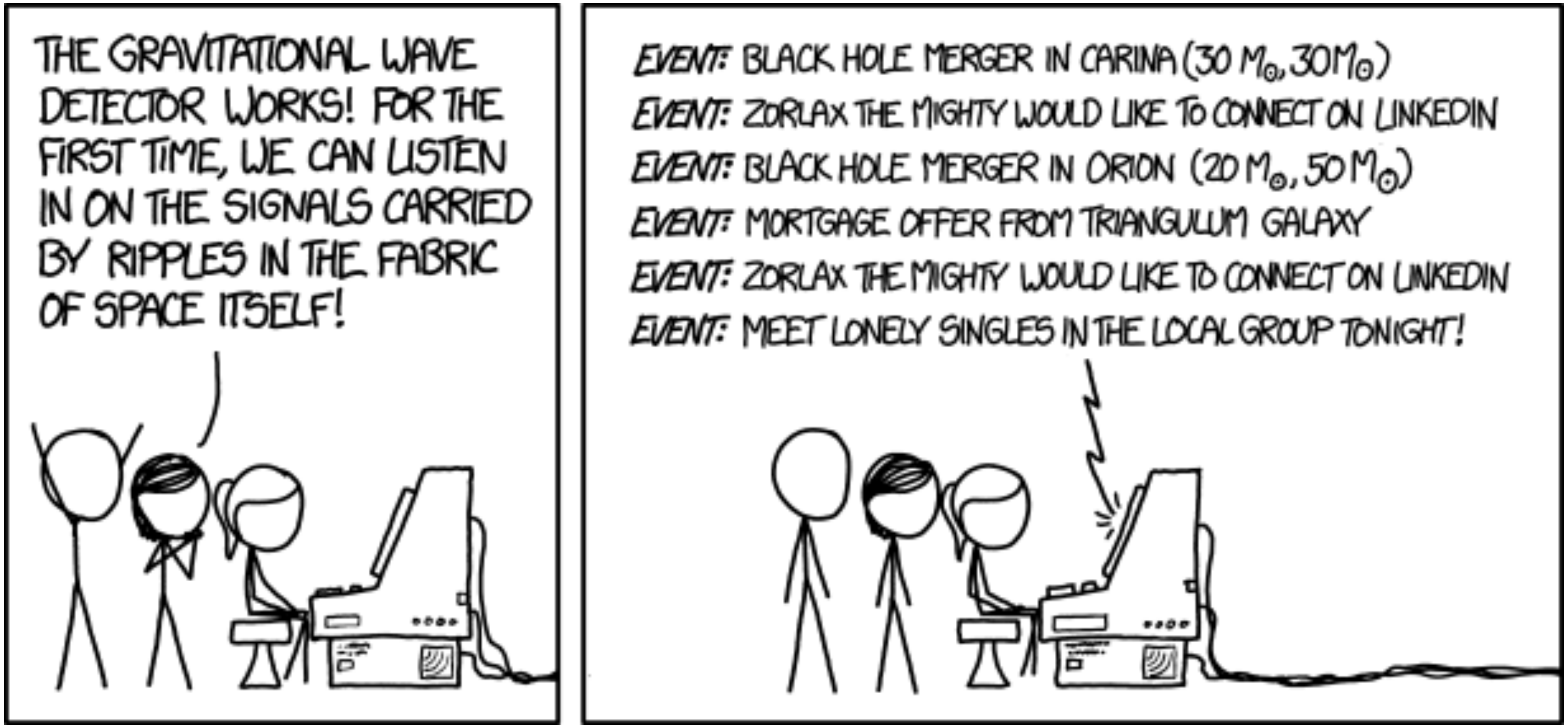
Conclusions

- Cross-correlation with LSS is a promising tool to perform cosmology with Dark Sirens

- 10yr data taking of the next (3G) generation instruments will have a sensitivity of 0.5% to H0

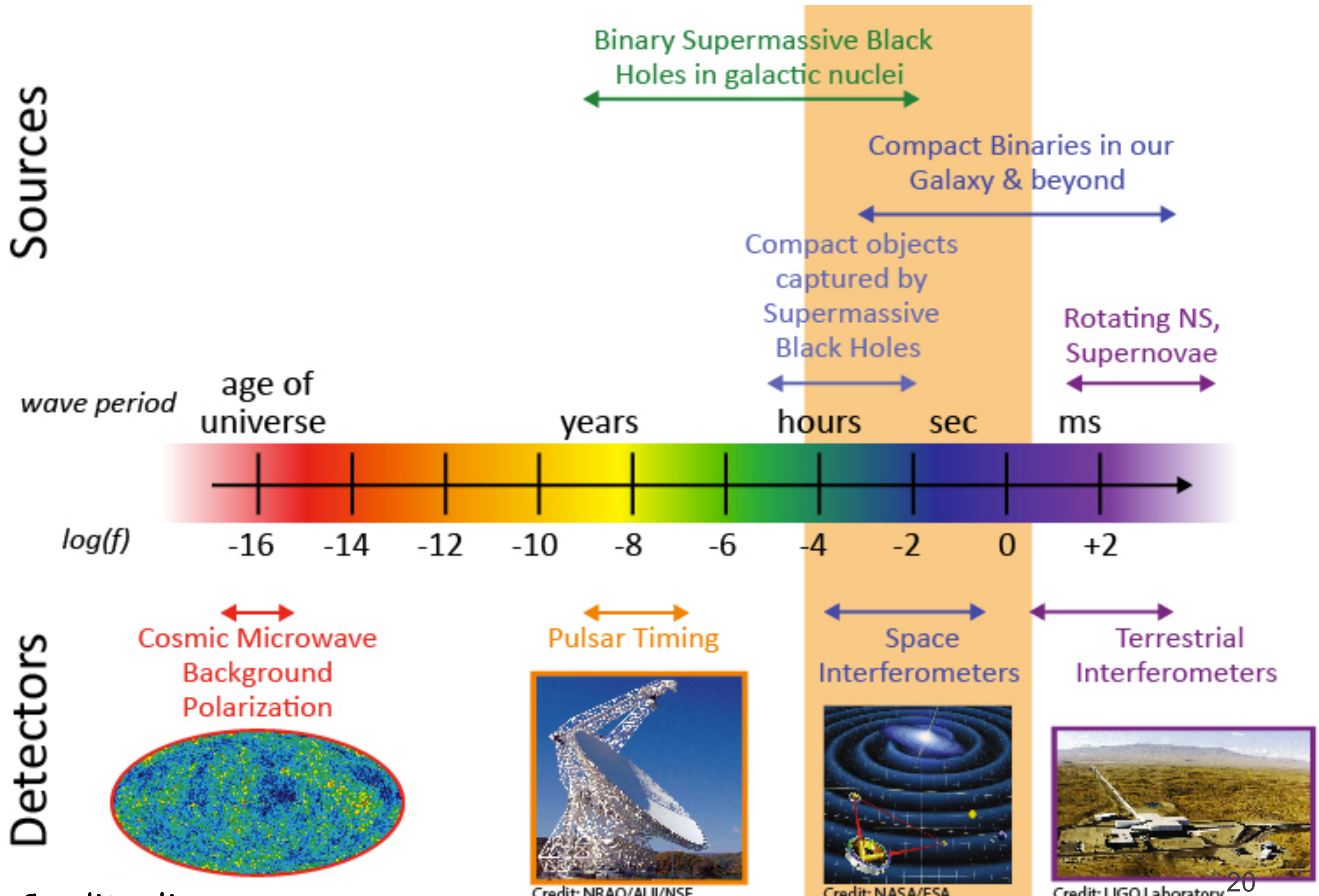
- GW biases will be measured to better than 10%, allowing to the test the fraction of primordial BHs.

Backup slides



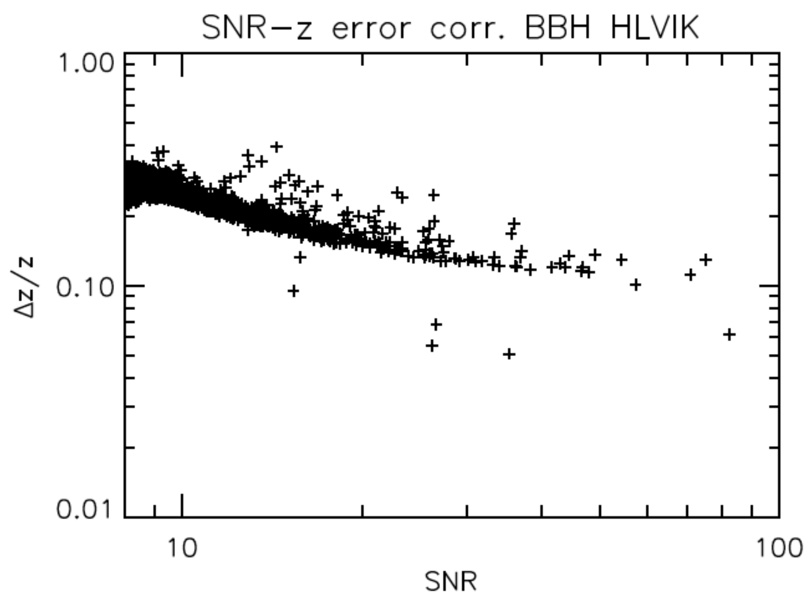
Credits: xkdc

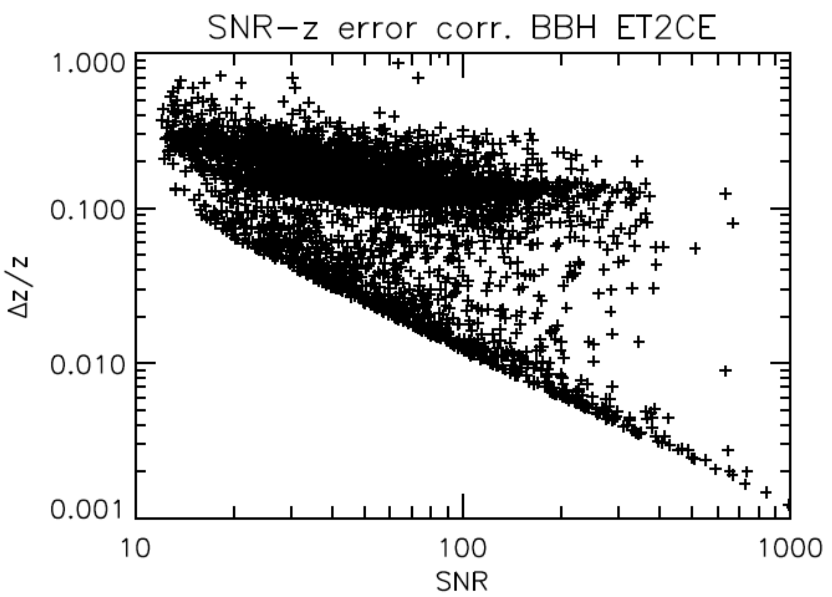
The Gravitational Wave Spectrum



Credits: lisa.nasa.gov

Redshift resolution





- Redshift resolution typically of the order of 20%
- For some very well reconstructed event can go down to 1% or 0.1%