Constraining Cosmological Parameters: Euclid and Cross-Correlation with Gravitational Waves

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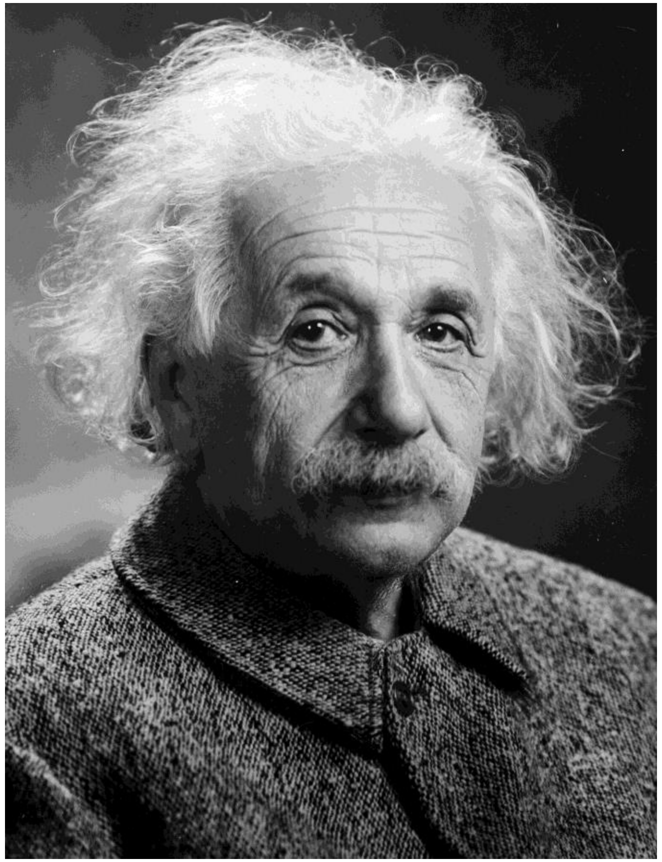
Gravitational Waves

Perturbations of the space-time metric that propagate in the universe, predicted by Einstein

Current situation:
LIGO-Virgo-KAGRA (LVK) collaboration with ~200 signals



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Current situation:
LIGO-Virgo-KAGRA (LVK) collaboration with ~200 signals

Next generation detectors:
Einstein Telescope (ET) and Cosmic Explorer (CE)
→ ***10^5 - 10^6 events per year***

Real revolution for this field... and not only

Important application for ***cosmology***

Importance of GW

$$h \sim \frac{M_z^{5/3} f_{obs}^{2/3}}{d_L}$$

M_z: detector frame mass $\longrightarrow M_z = M_c(1+z)$

d_L: luminosity distance

$\downarrow$

$$d_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{(1-\Omega_m) + \Omega_m(1+z')^3}} \approx \frac{z}{H_0}$$

Hubble law
in local universe

Direct measurement of the ***Luminosity Distance*** of the source

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Direct measurement of the ***Luminosity Distance*** of the source

Problem: mass-redshift degeneracy

$\longrightarrow$ Galaxy (z) + Gravitational Wave (d_L) = Hubble constant

Bright Sirens

Measure the redshift ***directly*** from the ***Electromagnetic counterpart*** of the GW signal:

- ***Short Gamma-ray Burst***: collimated emission ~seconds after the merger
- ***Kilonova emission***: isotropic emission from the radioactive decay of heavy nuclei

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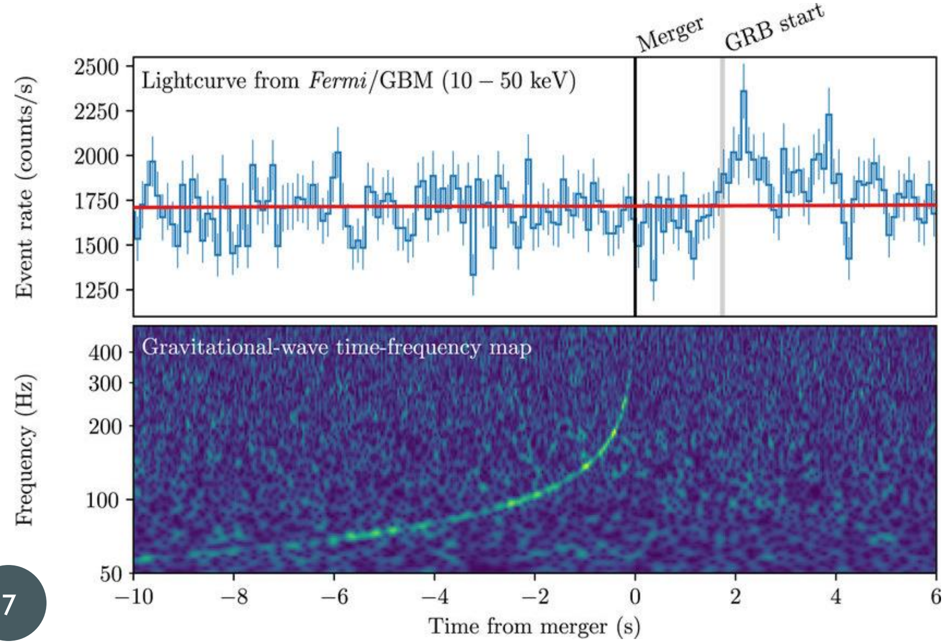
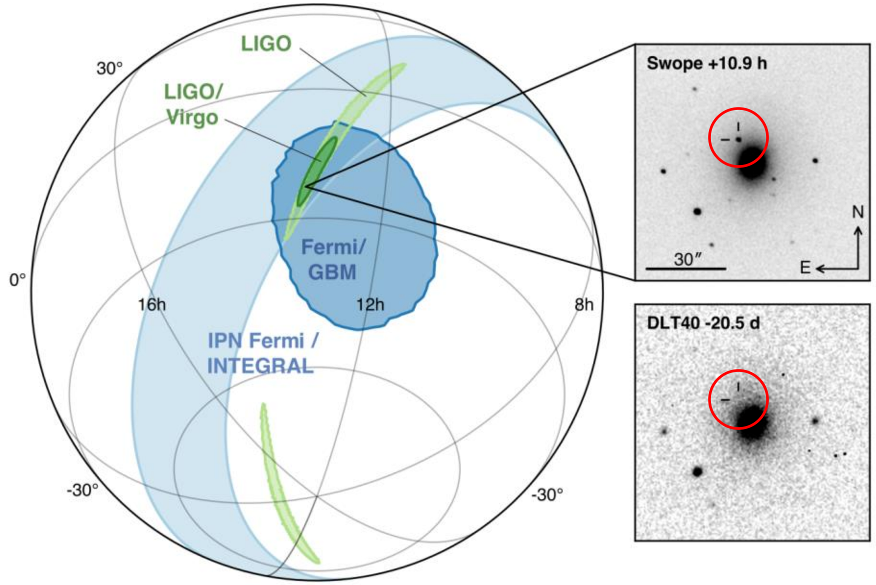
But only one signal

GW170817



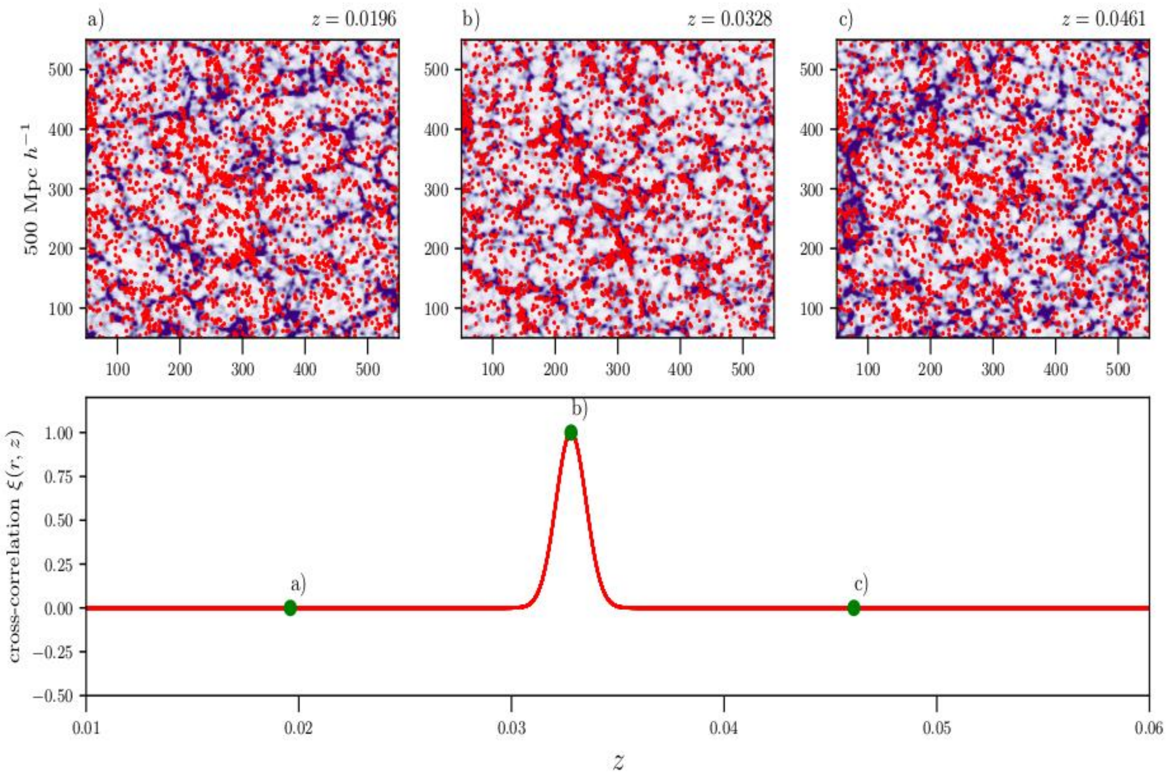


Cross-Correlation Idea

Tracer of the ***same*** cosmic density field:

Galaxy in ***redshift***, Gravitational Waves in ***luminosity distance***

Right cosmology here!



Credit: *Bera et al, 2020*

Cross-Correlation Idea

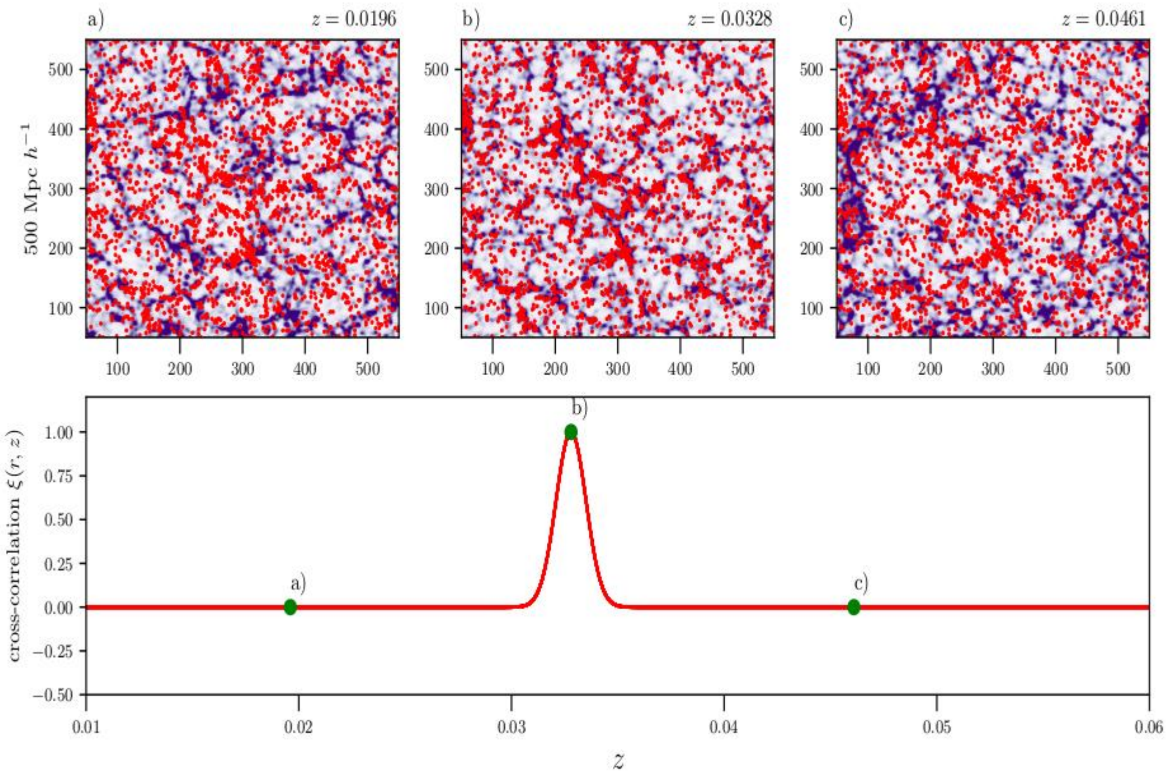
Tracer of the ***same*** cosmic density field:

Galaxy in ***redshift***, Gravitational Waves in ***luminosity distance***

Correct overlap ***only*** in the presence of the ***right cosmology!***

Cosmological information from the ***maxima of the correlation***

Right cosmology here!



Credit: *Bera et al, 2020*

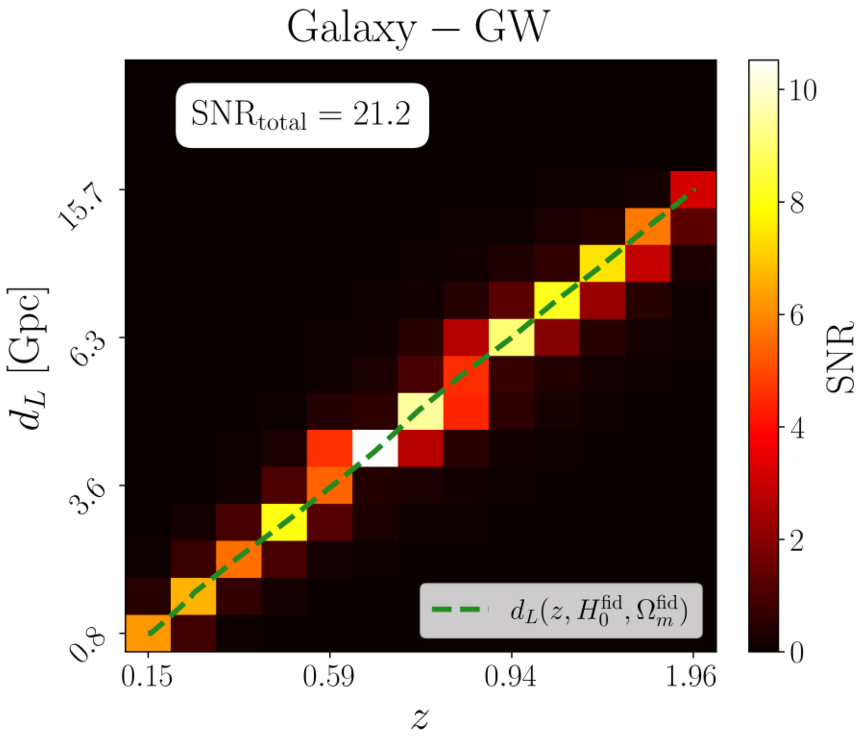
Angular Power Spectrum

Observable: ***fluctuations of the number of objects,*** in a given direction, ***in redshift and distance space***

$$\Delta^X(\mathbf{n}, x) = \frac{N^X(\mathbf{n}, x) - \langle N^X \rangle(x)}{\langle N^X \rangle(x)}$$

x: redshift *or* luminosity distance

Tomographic Angular Power Spectrum



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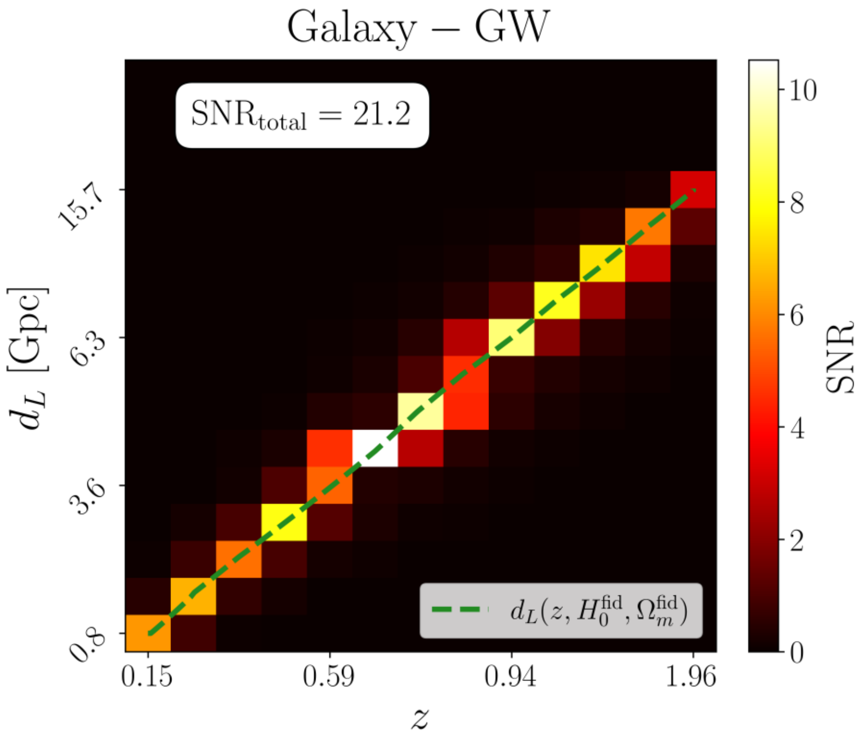
1. Split the distributions in ***distance and redshift bins***
2. Compute the ***correlation between different bins***

Maximum of the correlation around the ***fiducial cosmology***

Tomographic Angular Power Spectrum



Investigated Scenario

Fisher analysis with ***5 + redshift bins + distance bins = 34*** total parameters

$$\{H_0, \Omega_m, \Omega_b, A_s, n_s, b_{g_1,\ldots,g_i}, b_{GW_1,\ldots,GW_j}\}$$

ET in ***two L-shaped*** detectors and ***triangular*** configuration + ***2 Cosmic Explorer***

+

Euclid Photometric Survey

- ***Forecast the constraining power*** of this technique, focusing on H_0 and Ω_m
- Impact of the ***correlation*** between H_0 and Ω_m with the nuisance parameters (***galaxy and GW bias***) and the other cosmological quantities (***Power spectrum***)

Results – Relative Errors

Parameter	Total	Galaxy	GW	Cross
H_0	1.2	15.2	64	8.2
Ω_m	6.1	8.2	$\gg 100$	64.5
$\Omega_b h^2$	7.0	23.3	$\gg 100$	> 100
A_s	8.2	18.1	$\gg 100$	> 100
n_s	4.2	10.8	$\gg 100$	72
b_{GW} bin 1-5	40	/	$\gg 100$	> 100
b_{GW} bin 6-10	35	/	$\gg 100$	> 100
b_{GW} bin 11-16	> 100	/	$\gg 100$	> 100

- ***Percent level*** constraint on H_0 and few percent on Ω_m by ***combining the two tracers***

- ***Leading contribution*** to the ***Hubble Constant*** constraint from the ***cross-correlation***

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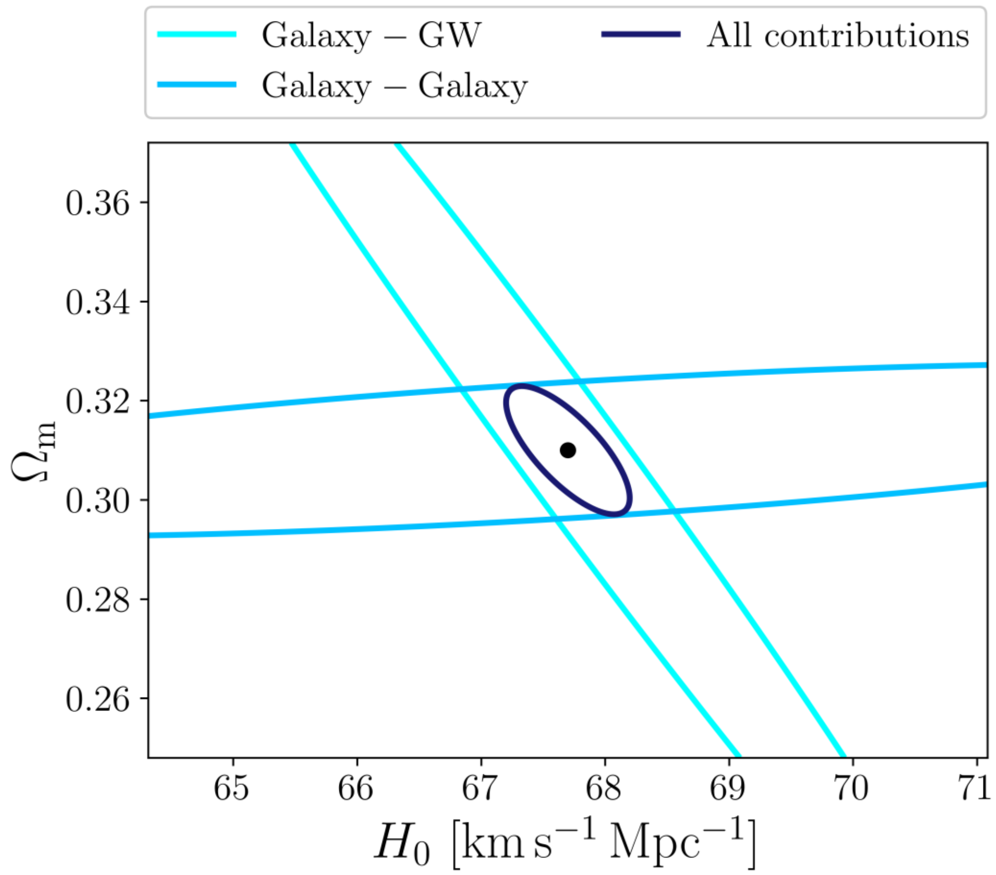
Broad ***measurement*** of the ***Gravitational-wave bias*** combining all the contributions

Results – Correlation

Great ***precision improvement*** from the combination of Galaxy and GW due to ***different correlation directions***:

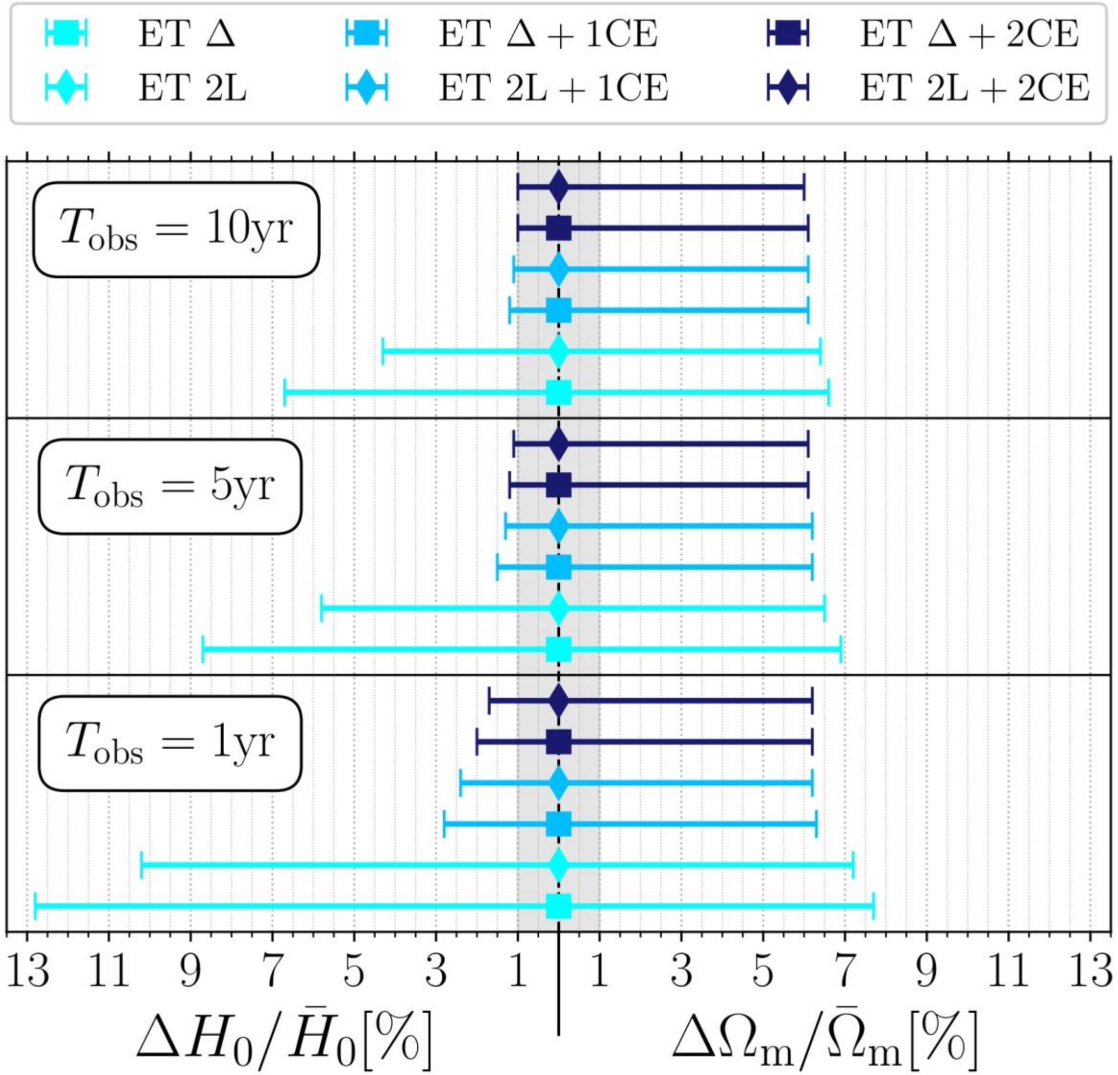
- ***Percent level*** constraint on $\boldsymbol{H_0}$
- ***Constraint*** on all the ***other parameters improved*** by consequence



All the ***cosmological parameters*** are measured with good accuracy:

Complete and independent cosmological probe

GW Detector



Good performance within ***5 yr observation***. ET-only remains weak, while adding CE greatly boosts performance

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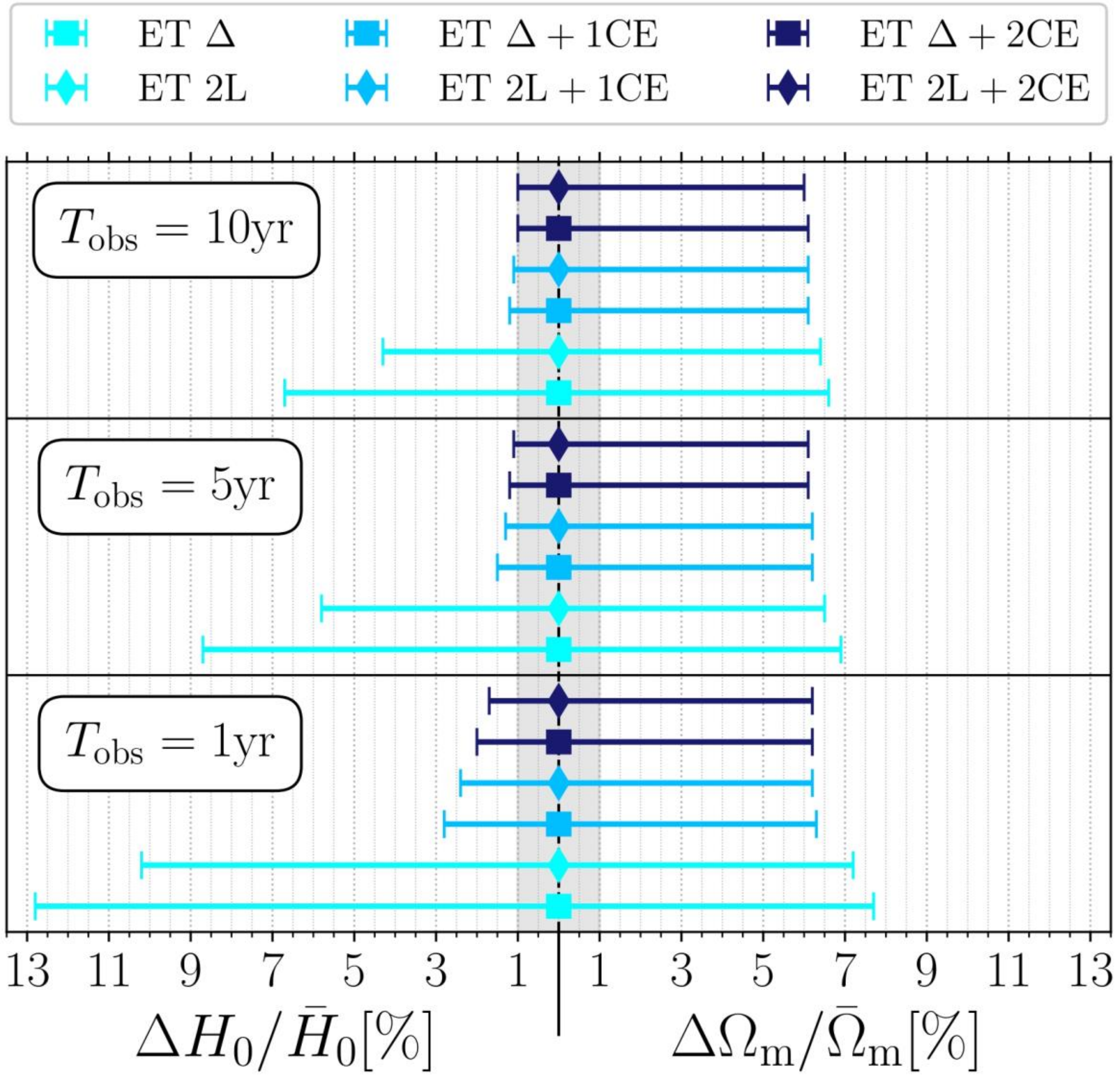


Good performance within ***5 yr observation***. ET-only remains weak, while adding CE greatly boosts performance

At least one CE seems necessary to achieve ***percent level on H_0***

ET alone limits. Constraints stay poor, with only modest gains from cross-correlation, ***limited by sky localization***

Summary

1. ***GW x gal*** tomographic angular correlation ***very promising probe***
    - ***Percent-level constraint on H_0*** and ***great precision on Ω_m***
    - ***All the cosmological parameters*** measured with ***good accuracy***
2. ***Cross-correlation*** → ***leading term*** to the constraint of the ***Hubble constant***
3. ***GW bias***: broad ***measurement*** of the bias after ***10 observation years***

The ***Cross-correlation*** represent a ***complete and independent cosmological probe***, providing good results for a large set of parameters

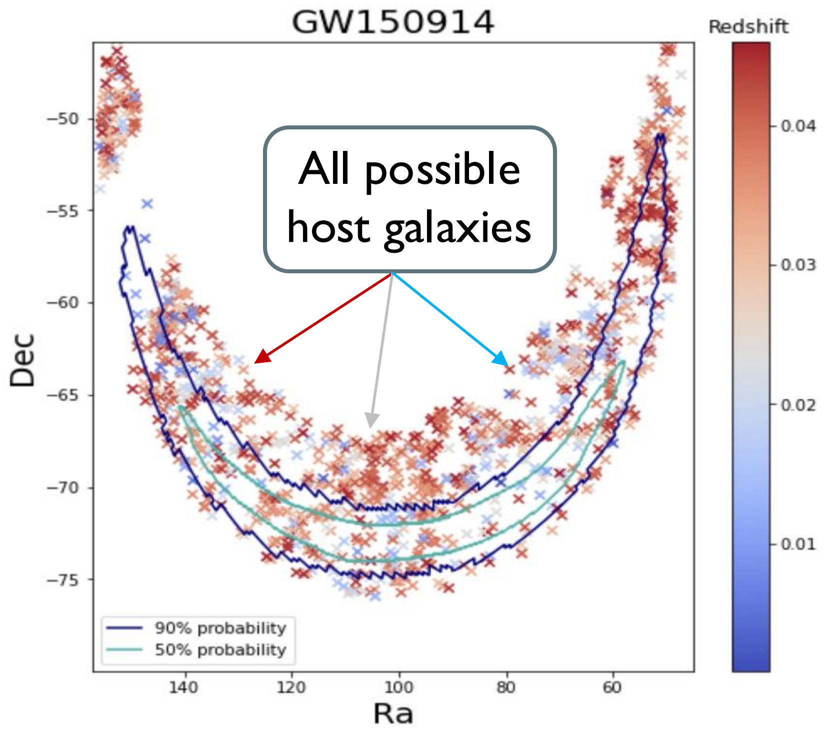
The results presented are based on arXiv:2504.10482

Thank you for your attention!

Dark Sirens

No Electromagnetic counterpart of the GW signal:

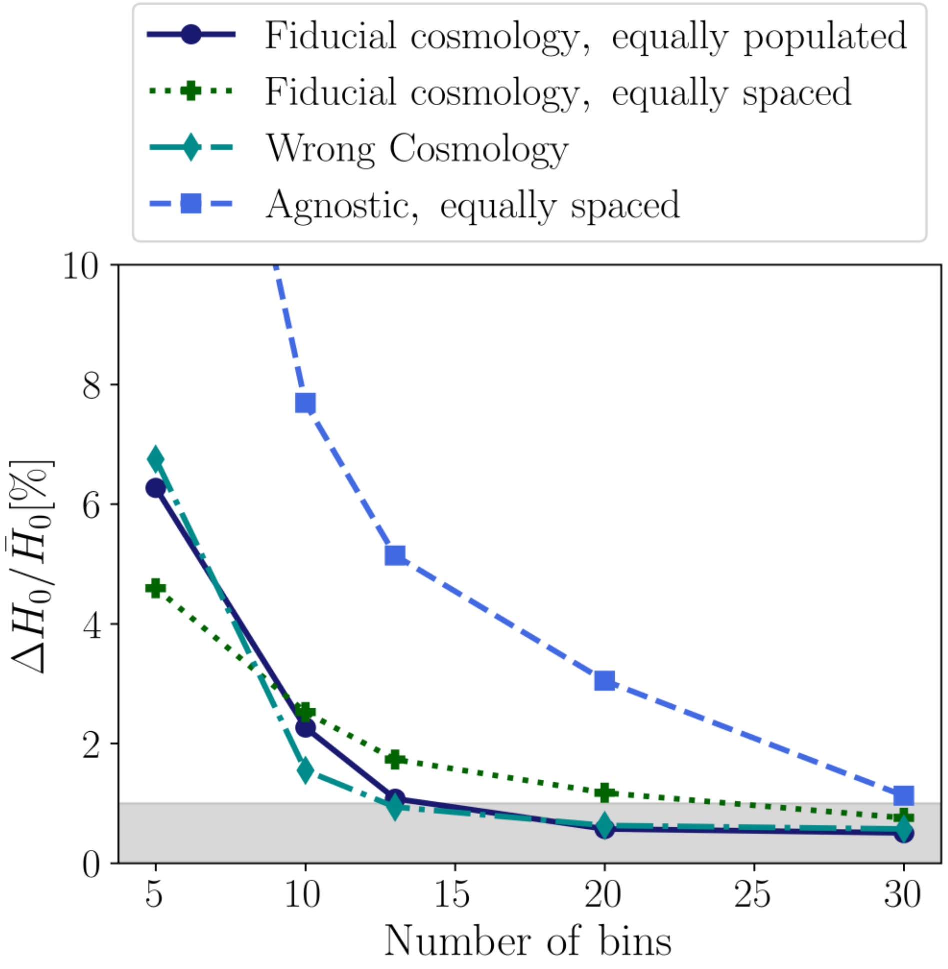
- ***Statistical association*** of the host galaxy, ***event-per-event***
- Combine ***multiple events*** to ***average out*** all the ***wrong association***



Some problems to consider

The ***completeness of the galaxy catalogue*** can bias a lot our estimation

Binning Strategy

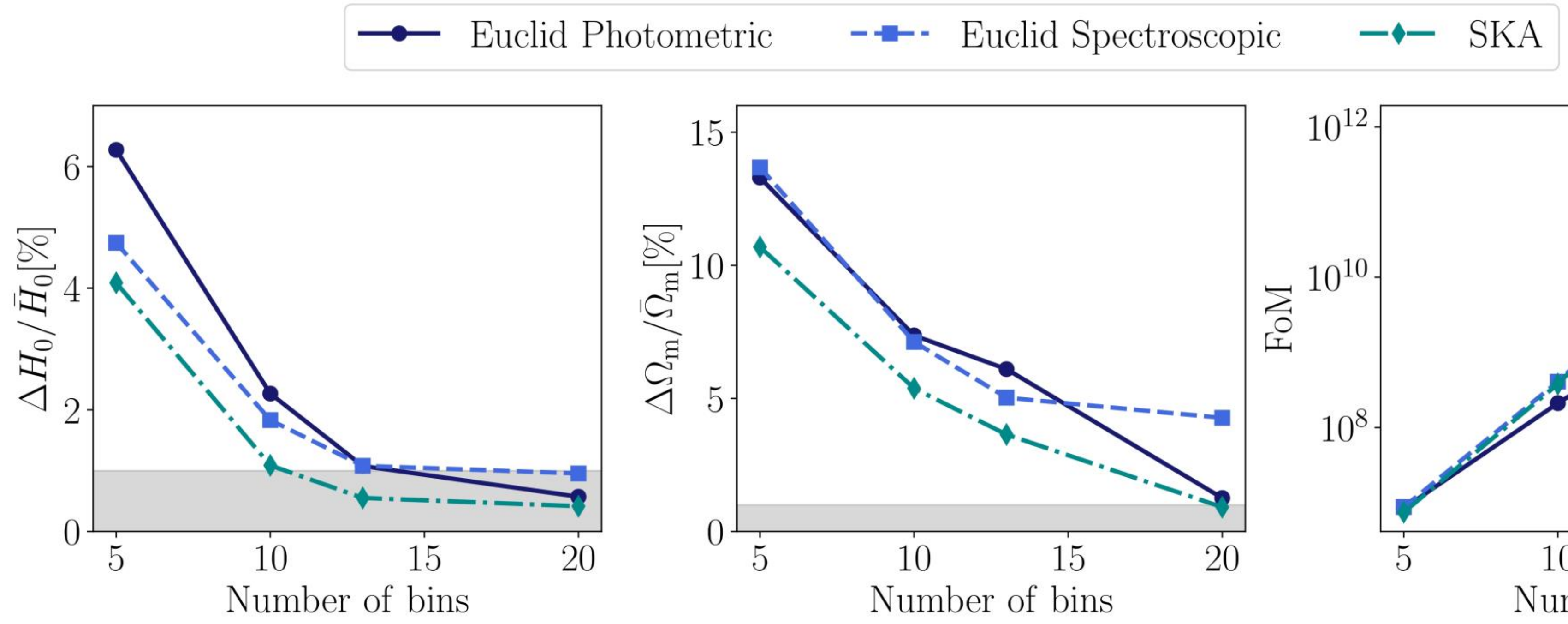


Equally populated bins converted with fiducial cosmology provides ***most information***

Wrong cosmology: comparable statistical results

Agnostic, equally spaced: robust against cosmology assumptions but ***requires many bins*** (~30) to reach ***comparable performance***

Galaxy Survey



Spectroscopic surveys (Euclid, SKA) reach ***similar precision*** as Euclid photometric, but not significantly better

SKA constraining power is ***limited by*** the worse ***overlap with GW catalogs***, reducing binning gains

Spectroscopic surveys saturate earlier (≲20 bins) due to ***shot noise*** and ***overlap*** limitations

Clustering Term

Window function in redshift and luminosity distance
Mapping between the two spaces

$$C_\ell^{\mathrm{GW-gal}}(z_i, d_{L,j}) = \int_0^\infty \mathrm{d}z \, \boxed{w^{\mathrm{gal}}(z, z_i)} \, \boxed{w^{\mathrm{GW}}(d_L(z,\lambda), d_{L,j})} \, \frac{\mathrm{d}d_L}{\mathrm{d}z}(z,\lambda) \, \frac{H(z)}{c\,\chi(z)^2}$$

$$\times \boxed{b_{\mathrm{GW}}(z) \; b_{\mathrm{gal}}(z)} \, \boxed{P\left(\frac{\ell}{\chi(z)}, z\right)}$$

Galaxy and GW bias

Primordial power spectrum