# Cosmology With Dark Sirens In Light Of Upcoming Galaxy Surveys data and New Generation Interferometers (a ETxEuclid – like analysis)

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"The Dawn of Gravitational Wave Cosmology", Benasque Science Center, May 7th, 2025

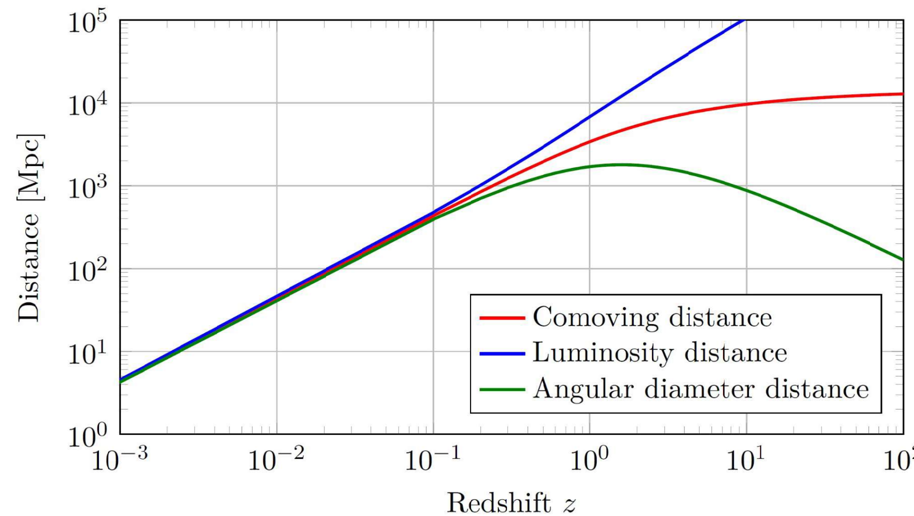
# GWs and Luminosity Distance to constrain cosmology

## Two polarization modes

$$\tilde{h}_+(f) = A\, e^{i\Psi_+(f)} \frac{c}{\boxed{D_L}} \left(\frac{G\mathcal{M}}{c^3}\right)^{5/6} \frac{1}{f_d^{7/6}} \left(\frac{1+\cos^2\iota}{2}\right)$$

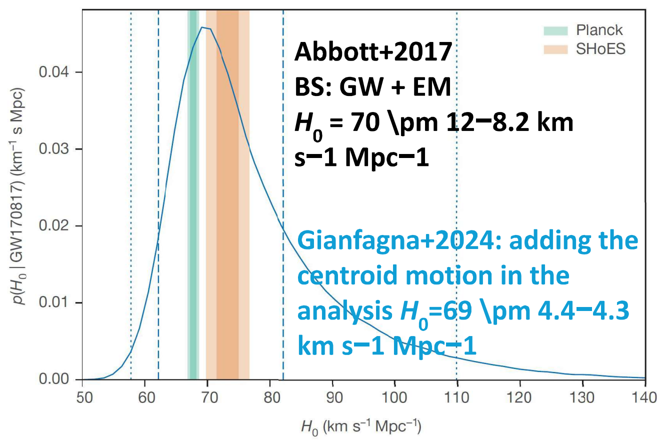
$$\tilde{h}_\times(f) = A\, e^{i\Psi_\times(f)} \frac{c}{\boxed{D_L}} \left(\frac{G\mathcal{M}}{c^3}\right)^{5/6} \frac{1}{f_d^{7/6}} \cos\iota$$

$$\mathcal{M} = M_c(1+z) \qquad M_c \stackrel{\text{def}}{=} \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} \qquad f_d = \frac{f}{1+z}$$




$$D_L(z) = (1+z)\int_0^z \frac{c\, dz'}{H_0\sqrt{\Omega_m(1+z')^3 + \Omega_r(1+z')^4 + \Omega_{\text{DE}} \exp\left(3\int_0^{z'} \frac{1+w(z'')}{1+z''}\, dz''\right)}}$$

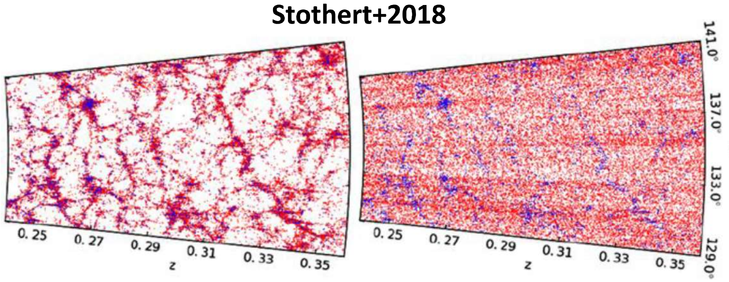
# Dark sirens and galaxy catalogues: current $H_0$ measurements



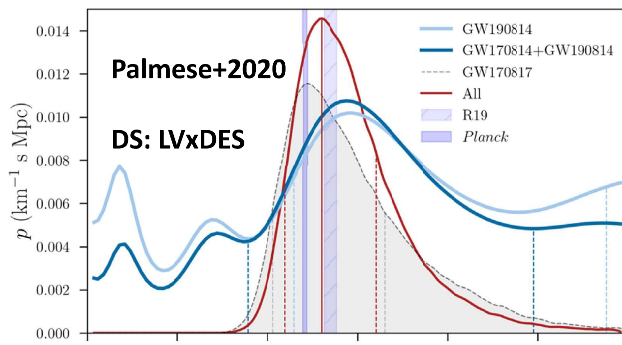

**Abbott+2017**
**BS: GW + EM**
**$H_0$ = 70 \pm 12−8.2 km s−1 Mpc−1**

**Gianfagna+2024: adding the centroid motion in the analysis $H_0$=69 \pm 4.4−4.3 km s−1 Mpc−1**

**Stothert+2018**

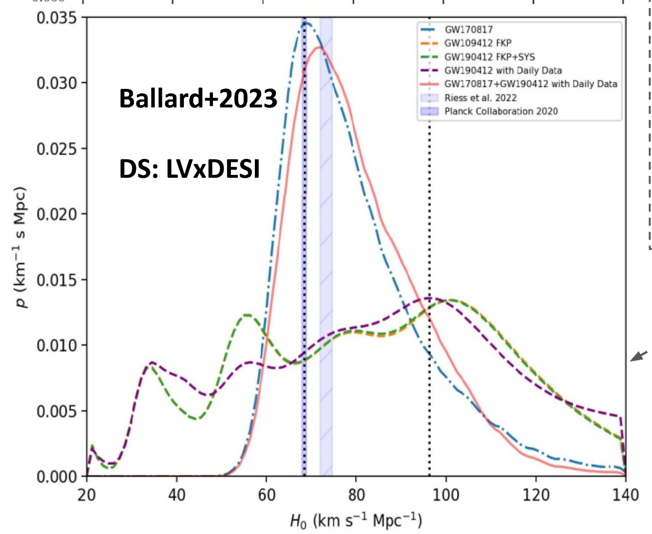



**spectro-z** **photo-z**




**Palmese+2020**
**DS: LVxDES**

**$H_0$ = 72 \pm 12−8.2 km s−1 Mpc−1**

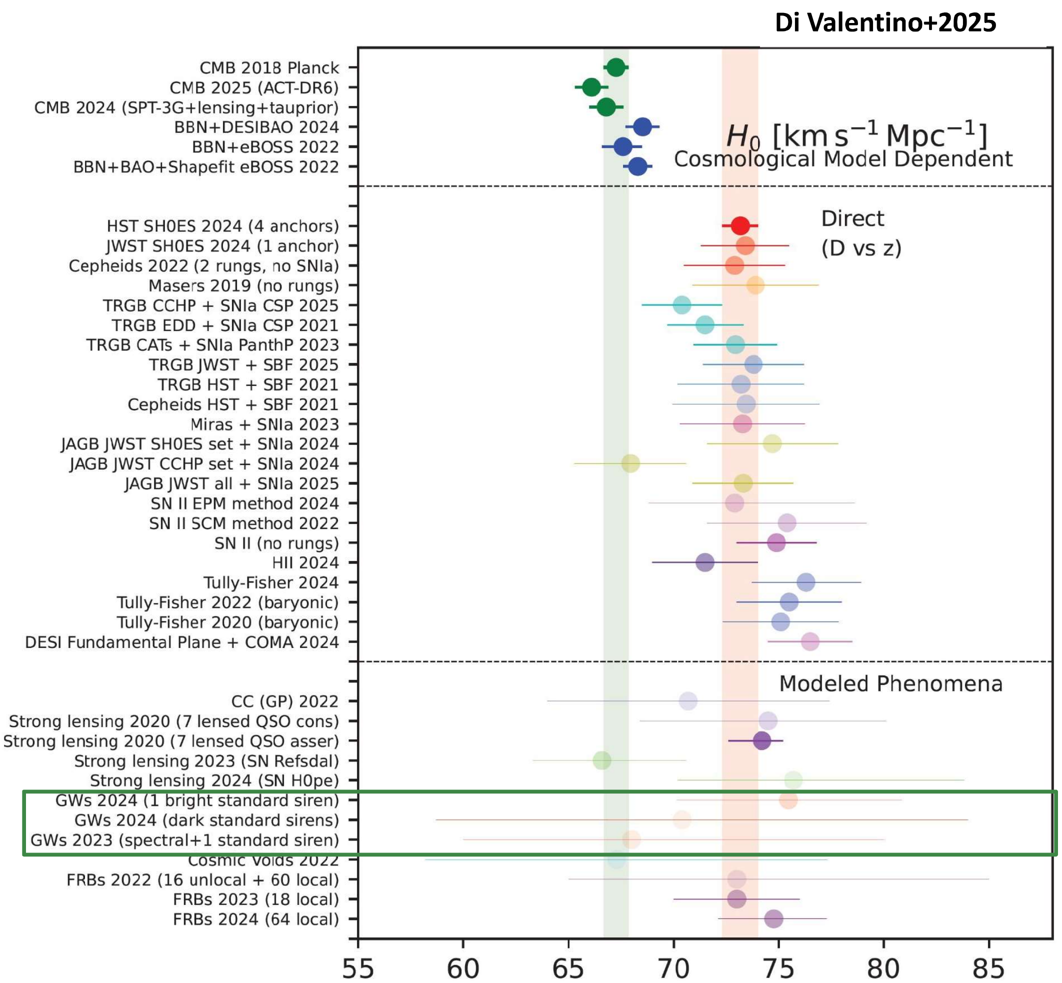



**Ballard+2023**
**DS: LVxDESI**

If we are unable to find an EM counterpart, we can use a statistical approach taking advantage of measurements of the redshift distribution of populations of potential host galaxies

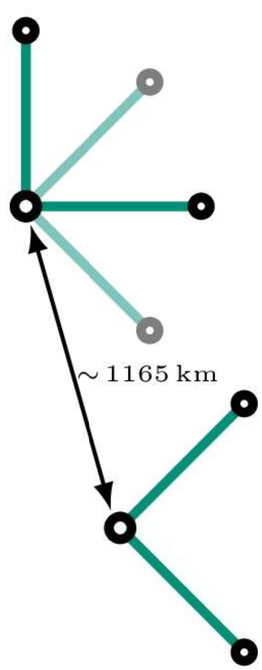
**$H_0$ = 77.96 \pm 23.0−5.03 km s−1 Mpc−1**

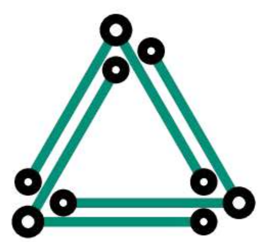
# The Hubble Tension: recent measurements

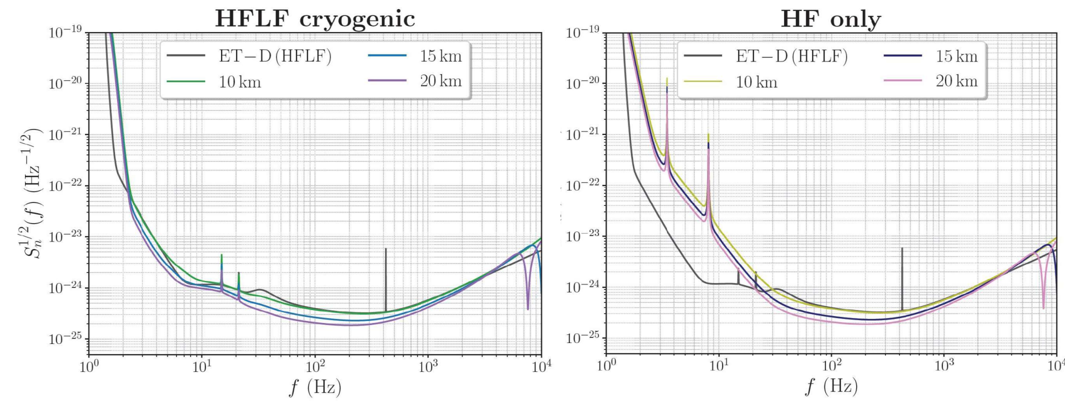


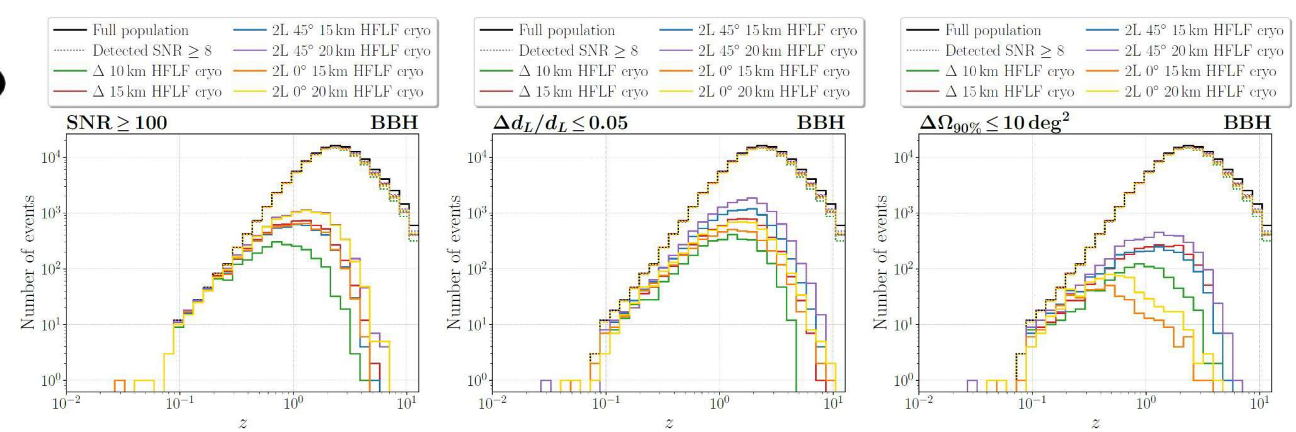
# The Einstein Telescope

Branchesi+2023



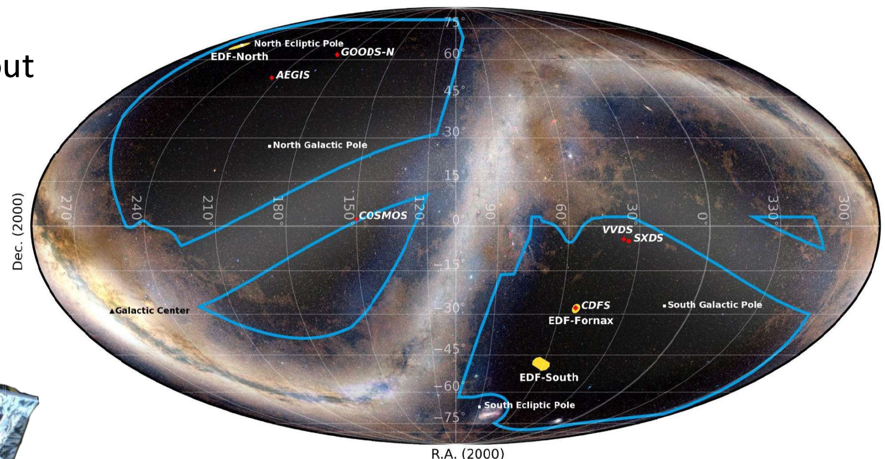





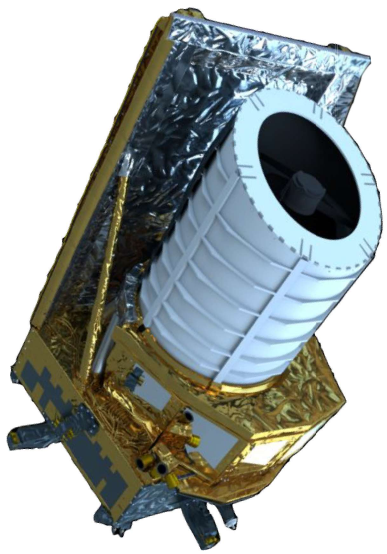



# The Euclid Wide Survey

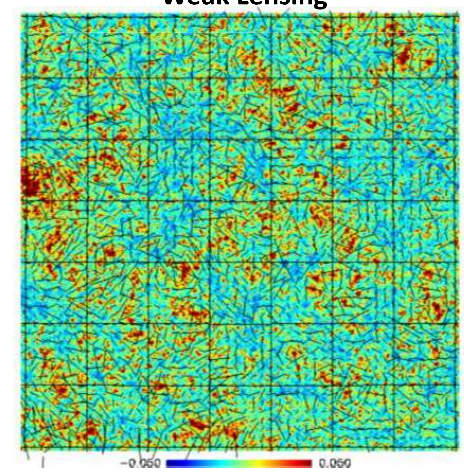
DR3 survey covers about 14,000 $deg^2$



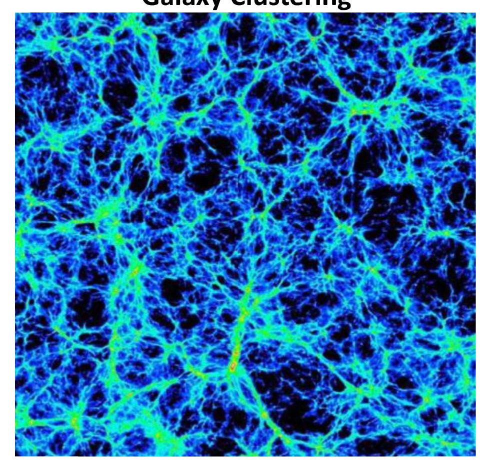

Blue borders enclose the 16 000 $deg^2$ region of interest that contains the Wide Survey. The Euclid Deep Fields are shown in yellow and the auxiliary fields with red marks (not to scale) (Mellier+2024)



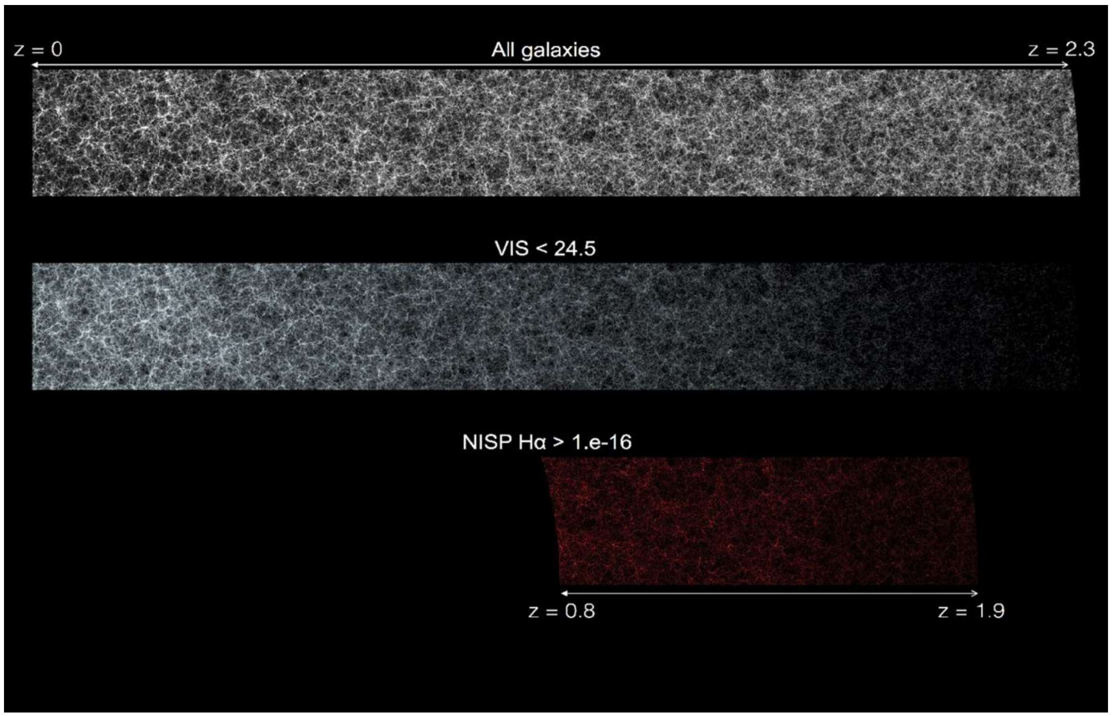
Weak Lensing




Galaxy Clustering



# The Euclid Flagship galaxy catalogue




This shows the first "Flagship" Simulation used in this work, a light cone going from z=0 to z=2.3.
It was run with L=3.7 $h^{-1}$Gpc, 2 trillion DM part, $M_p$=2.4 $10^9$ $M_{sun}$

Galaxies are added using HOD to match what we know about the distribution of galaxies. The mock has ray traced lensing maps so that combined analyses of clustering and weak lensing can be done.

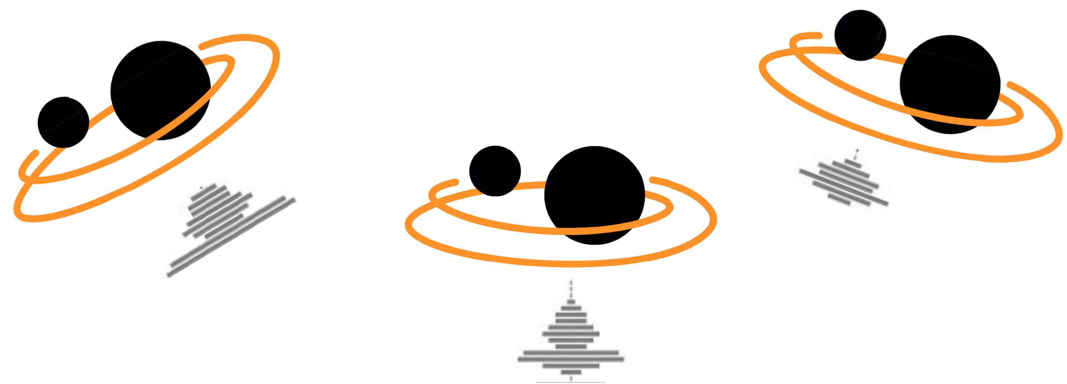
# Estimating $H_0$ from the interplay of ET-like and Euclid-Like data: the "Cross cOrrelation with Dark sirEns" (CODE) pipeline

**(Ciancarella et al. in prep)**

# CODE: Hierarchical Bayesian Inference

The Hierarchical Bayesian framework can be used every time the quantity we are looking for is not directly in the data, but regulates the distribution of the data.

We measure the distance of the DS, that is governed by the hyper-parameter $H_0$



Single events

$D_{L1}(z,H_0) + D_{L2}(z,H_0)) + D_{L3}(z,H_0) + \ldots$
$+P(z)$

Posterior on Hyper-parameter

$P(H_0)$

# CODE: Hierarchical Bayesian Inference

The Hubble constant does not regulate each individual event, but is an hyper-parameter in the data.

$$P\left(H_0|\{D_{GW}\}\right) = \frac{\mathcal{L}\left(\{D_{GW}\}|\, H_0\right)\Pi(H_0)}{P\left(\{D_{GW}\}\right)}$$

$$\mathcal{L}\left(\{D^i_{GW}\}|H_0\right) = \frac{1}{\beta(H_0)} \int d\theta \, \underbrace{\mathcal{L}_i(\theta, H_0)}_{\text{likelihood}} \overbrace{\Pi(\theta|H_0)}^{\text{prior}}$$

$$\mathcal{L}_i(\theta, H_0) = \mathcal{L}_i(z, \Omega, H_0) = \rho_i(\Omega) \frac{\mathcal{N}_i(\Omega)}{\sqrt{2\pi}\sigma_i(\Omega)} e^{-\frac{(d_L(z,H_0)-\mu_i(\Omega))^2}{2\sigma_i^2(\Omega)}}$$

$$\Pi(z, \Omega) = p_{gal}(z, \Omega) = \frac{\sum_{\alpha=1}^{N} \omega_\alpha \delta(z - z_\alpha)\delta(\Omega - \Omega_\alpha)}{\sum_{\alpha=1}^{N} \omega_\alpha}$$

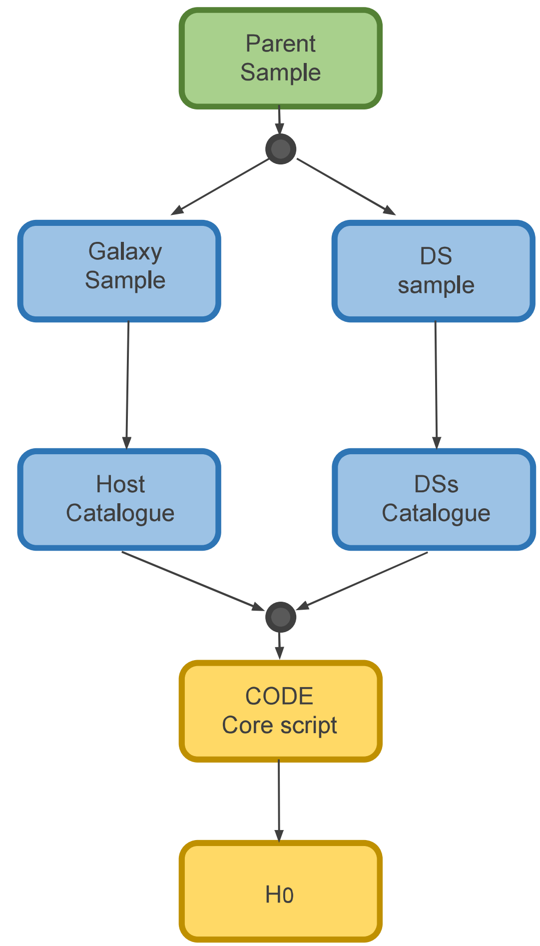
**can be replaced by the actual spectro-z or photo-z distribution**

# CODE: Pipeline Overview

The **first part** produces mock data.

The **second part** is the "input" stage. The main product of this section is the extrinsic DS catalogue.

The **third part** is the core script that computes the posterior.




**Ciancarella+ in prep.**

# Code: Likelihood

Some properties:

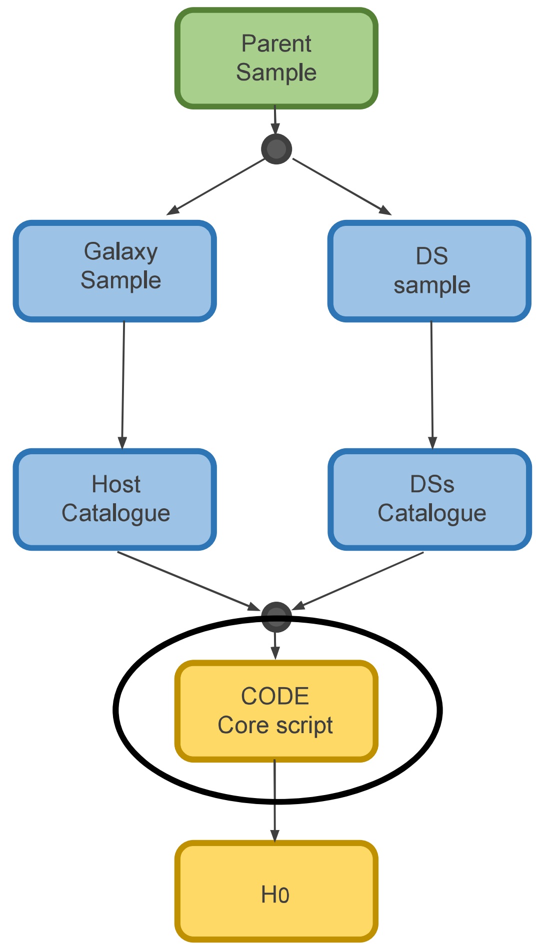
$$\mathcal{L}\left(\{D^i_{GW}\}|H_0\right) = \frac{1}{\beta(H_0)} \int d\theta \underbrace{\mathcal{L}_i(\theta, H_0)}_{\text{likelihood}} \overbrace{\Pi(\theta|H_0)}^{\text{prior}}$$

$$\beta(H_0) = \int_{\mathcal{D}} P_{det}[Dl(z, H_0), \Omega, \theta'] P_{cal}(z, \Omega) P_{\theta'}(\theta') d\theta' dz d\Omega$$

**Uniform universe case**

$$\beta(H_0, z_{max}, z_{min}) = \frac{\mathcal{V}_c(H_0, z_{max}, z_{min})}{\mathcal{V}_c(H_0, z_{\mathcal{R}})}$$

The $\boldsymbol{\beta}$ normalization takes into account selection effects.




**Ciancarella+ in prep.**

# CODE: Hierarchical Bayesian Inference

Assumptions:

- DS events are uncorrelated.
- Gaussian likelihood.
- Volume Uniform Coalescence Rate.
- Spectroscopic redshifts errors for the galaxy sample (delta-Dirac assumption).
- Mass Distribution does not evolves with time (to be updated).

$$\mathcal{L}\left(\{D_{GW}\}|\, H_0\right) = \prod_{i=1}^{N_{obs}} \mathcal{L}\left(\{D^i_{GW}\}|\, H_0\right)$$

$$\rho_i(\Omega)\frac{\mathcal{N}_i(\Omega)}{\sqrt{2\pi}\sigma_i(\Omega)} e^{-\frac{(d_L(z,H_0)-\mu_i(\Omega))^2}{2\sigma_i^2(\Omega)}}$$

$$\Pi(z,\Omega) = p_{gal}(z,\Omega) :$$

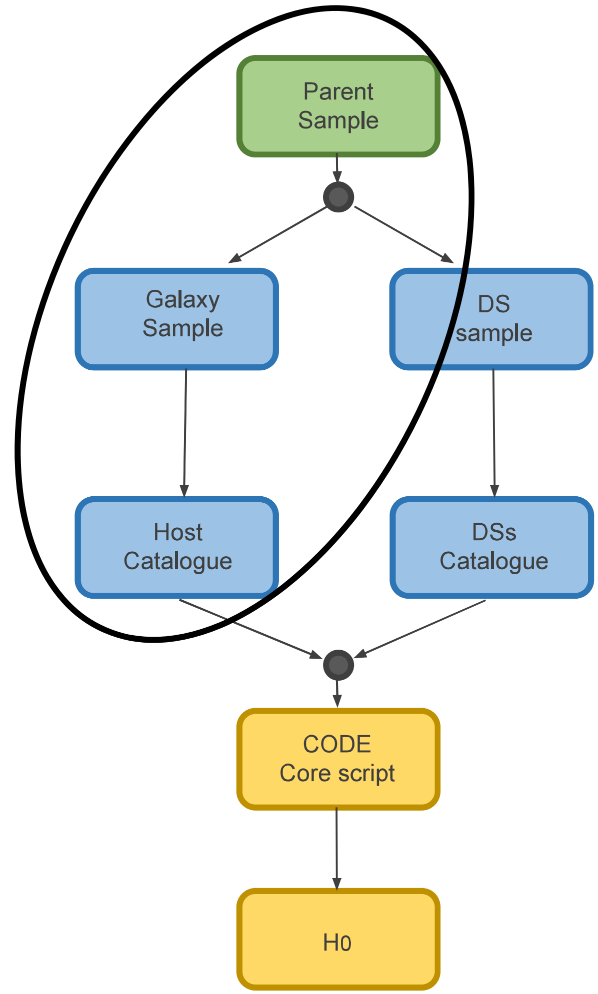
$$p_{gal}(z,\Omega) = \frac{\sum_{\alpha=1}^{N} \omega_\alpha \delta(z-z_\alpha)\delta(\Omega-\Omega_\alpha)}{\sum_{\alpha=1}^{N}\omega_\alpha}$$

# CODE: Pipeline Overview

Starting from a "Parent Sample", two hosts catalogues are used:

- **EUCLID Flagship-1 spectro-catalogue**: is obtained by selecting H-alpha galaxies with flux $>2x10^{16}$ cgs

- **Uniform Universe**: is a purposely sparse sample of random galaxies, mainly for tests. The sample is extracted from a more dense, uniform in comoving volume, parent catalogue and covers the same footprint and n(z) of the Flagship-1 spectro-sample.




Ciancarella+ in prep.

# CODE: mock ET-like DS catalogue generation

1) **Intrinsic DS catalogue:**

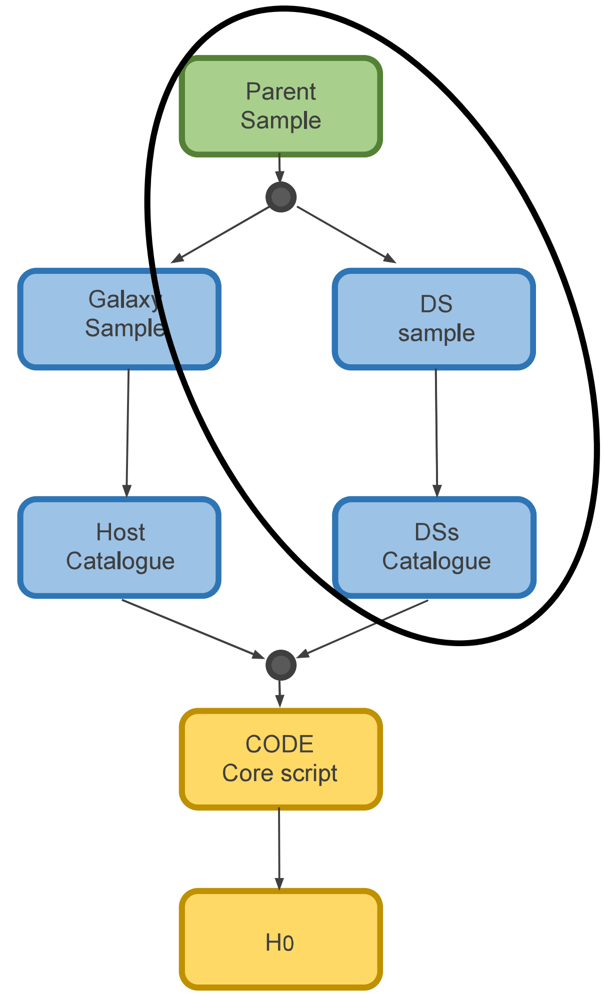
we use the true universe DS distribution (from hydro-sims or semi-analytic models) and assign to each DS the intrinsic parameters (chirp mass, symmetric mass ratio, $D_L$, angular positions, orbital plane inclination, polarisation, coalescence time, coalescence phase, BH spins) extracted from corresponding distributions.

2) **Extrinsic DS catalogue:**

we choose a waveform (IMRPhenomHM waveform (Husa+2015)) depending from the intrinsic parameters and the ET interferometer. Then we use GWFAST(Iacovelli+2022) to compute the SNR and parameter covariances for each DS

2) **Observed DS positions:**

we choose an SNR threshold and each observed DS is placed at the best-fit position from the maximisation of the multivariate distribution obtained using the GWFAST covariance.




**Ciancarella+ in prep.**

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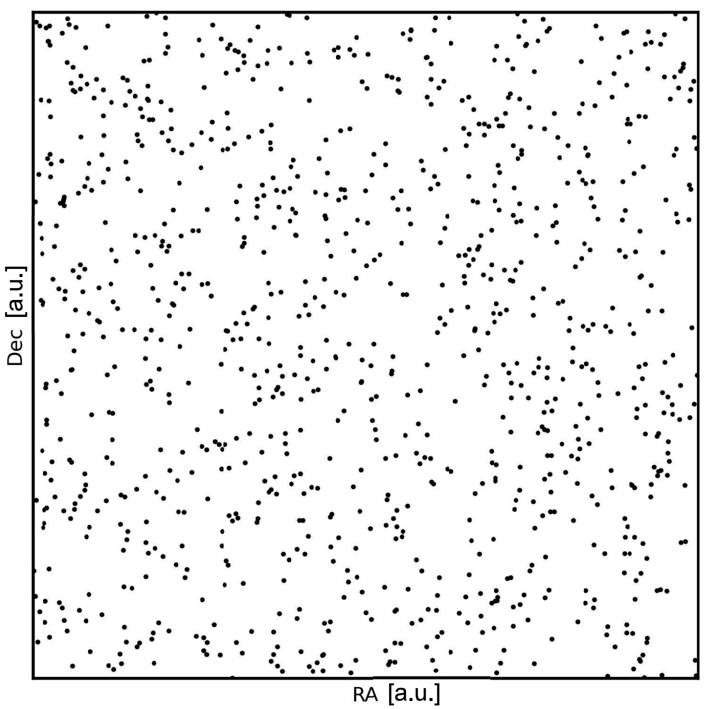
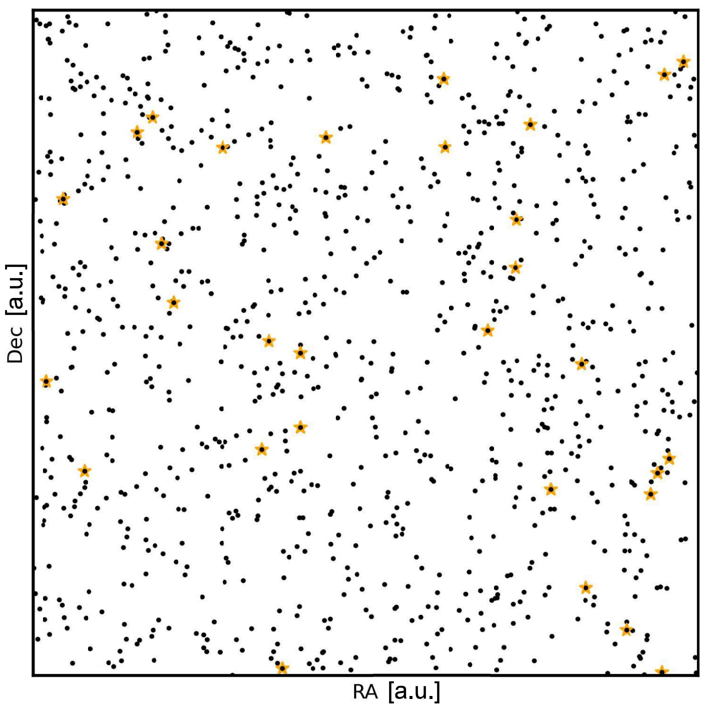



**1.** Distribution of galaxies from the light cone outputs of Flagship-1 spectro-catalogue

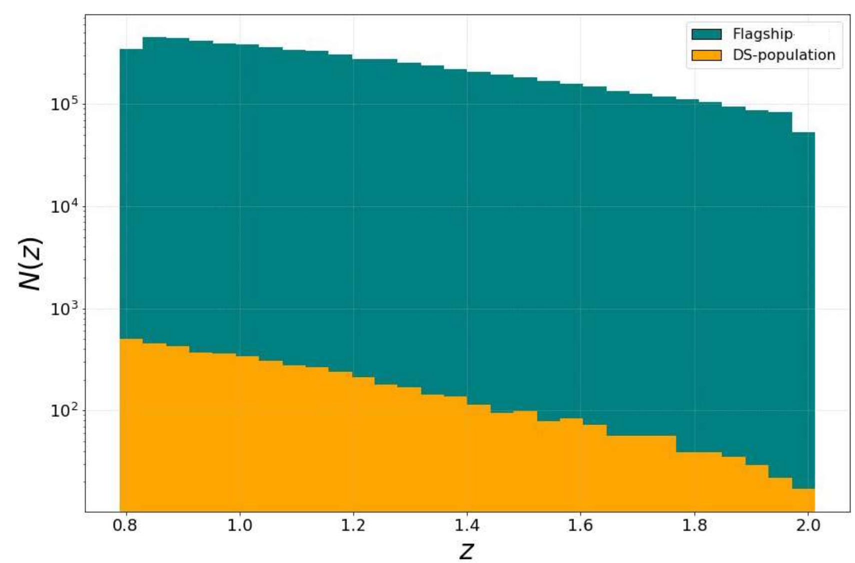
**Ciancarella+ in prep.**

# CODE: mock ET-like DS catalogue generation



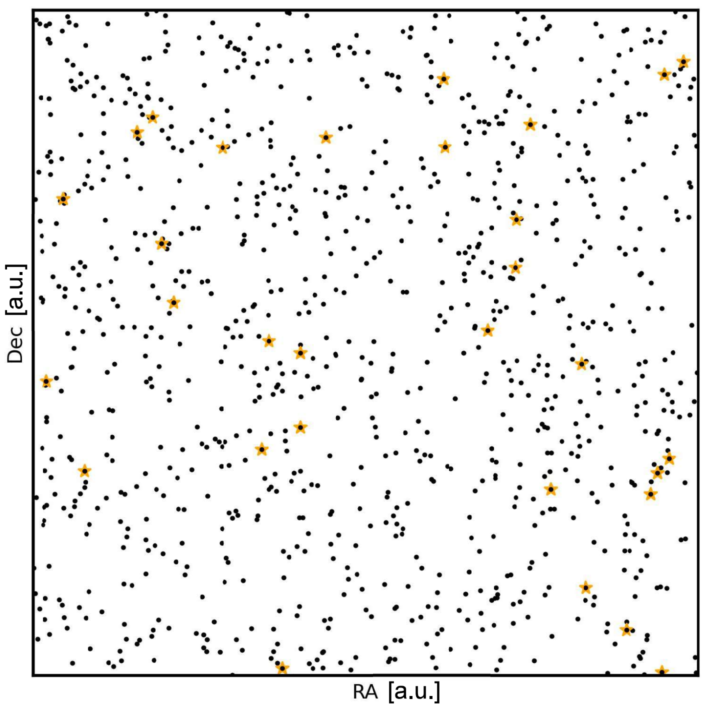

**1.** Distribution of galaxies from the light cone outputs of Flagship-1 spectro-catalogue

**2.** Stochastic selection of host galaxies of GW events for BBH




**Ciancarella+ in prep.**

# CODE: mock ET-like DS catalogue generation

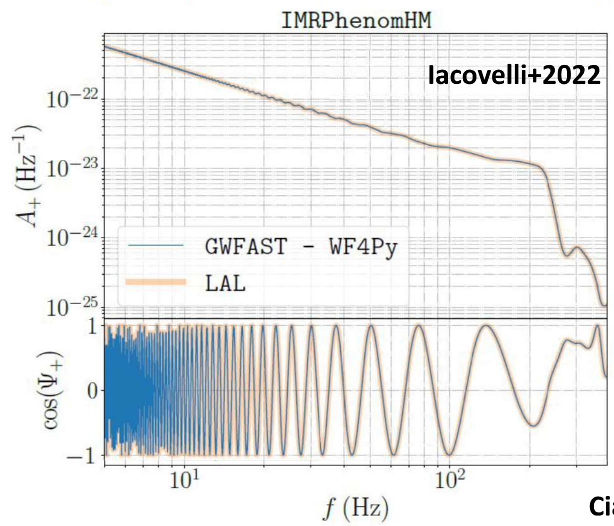



**1.** Distribution of galaxies from the light cone outputs of Flagship-1 spectro-catalogue

**2.** Stochastic selection of host galaxies of GW events for BBH

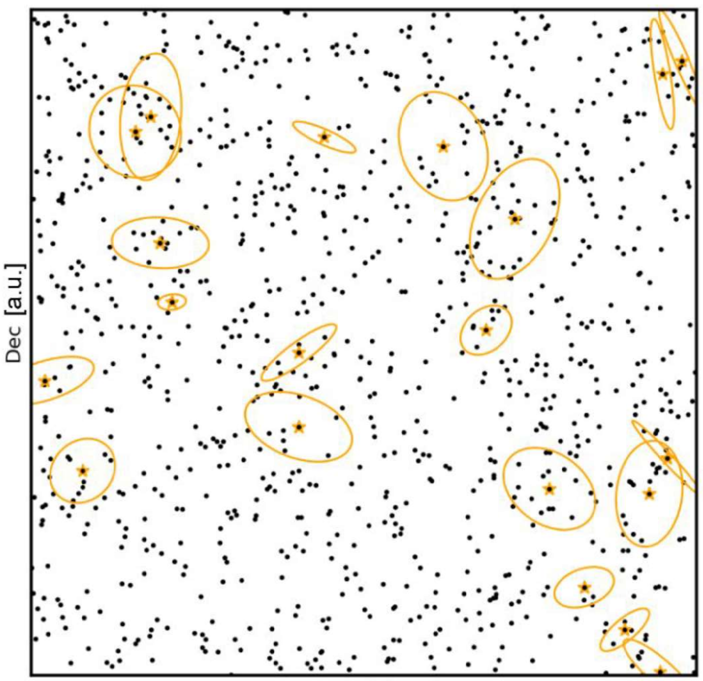
**3.** Stochastic generation of the parameters of the IMRPhenomHM waveform model

$$\boldsymbol{\theta} = \{\mathcal{M}_c,\ \eta,\ D_L,\ \theta,\ \phi,\ \iota,\ \psi,\ t_c,\ \Phi_c,\ \chi_1,\ \chi_2\}$$




Ciancarella+ in prep.

# CODE: mock ET-like DS catalogue generation




**1.** Distribution of galaxies from the light cone outputs of Flagship-1 spectro-catalogue

**2.** Stochastic selection of host galaxies of GW events for BBH

**3.** Stochastic generation of the parameters of the IMRPhenomHM waveform model

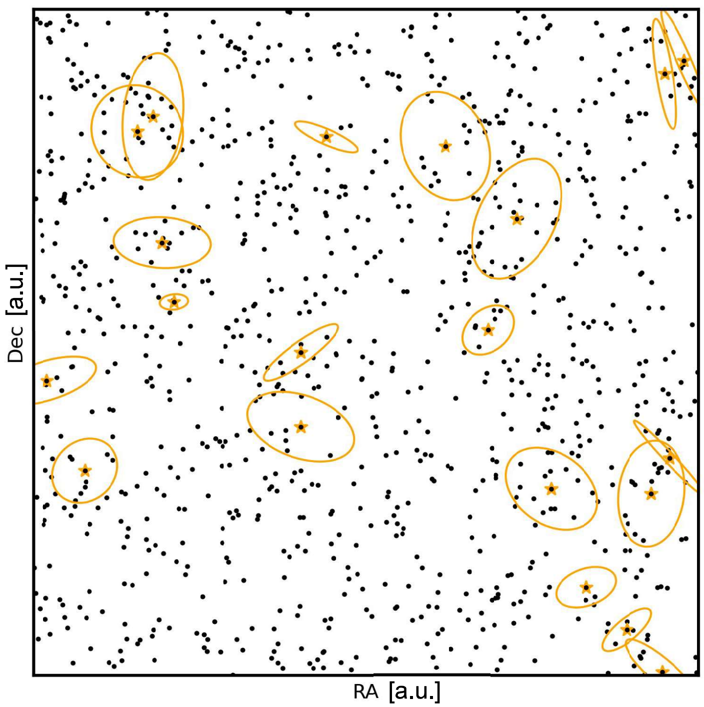
**4.** Computation of the SNR and the uncertainties on the parameters of the waveform model using GWFAST

$$\Gamma_{ij}^{k} = 4 \int \mathrm{d}f \, \frac{\partial_i h \, \partial_j h^\star}{S_n(f)} \qquad \mathcal{C}_{ij}^{k} = (\Gamma_{ij}^{-1})^k$$

$$\mathcal{C}_{ij,\,\mathrm{marg}}^{k} \stackrel{\mathrm{def}}{=} \begin{pmatrix} (\Gamma_{D_L D_L}^{-1})^k & (\Gamma_{D_L \hat{\boldsymbol{n}}}^{-1})^k \\ (\Gamma_{D_L \hat{\boldsymbol{n}}}^{-1})^k & (\Gamma_{\hat{\boldsymbol{n}}\hat{\boldsymbol{n}}}^{-1})^k \end{pmatrix}$$

**Ciancarella+ in prep.**

# CODE: mock ET-like DS catalogue generation

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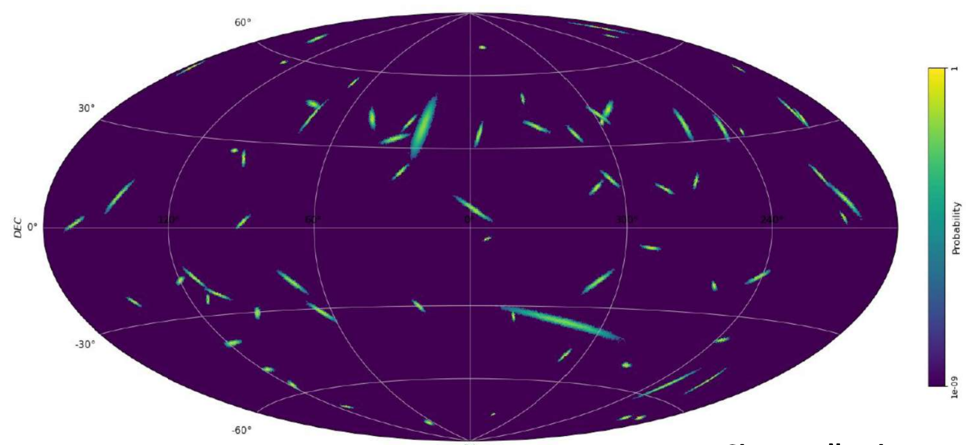


**Ciancarella+ in prep.**

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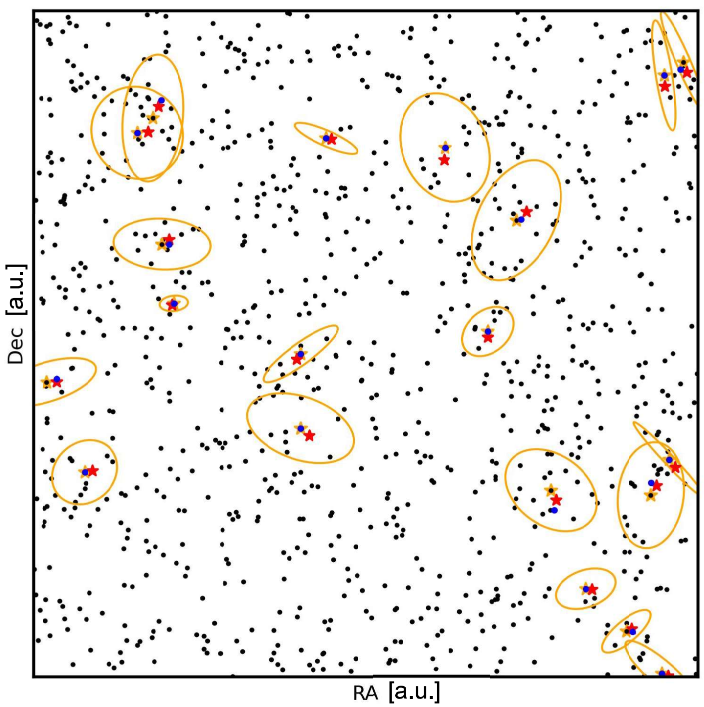



**1.** Distribution of galaxies from the light cone outputs of Flagship-1 spectro-catalogue

**2.** Stochastic selection of host galaxies of GW events for BBH

**3.** Stochastic generation of the parameters of the IMRPhenomHM waveform model

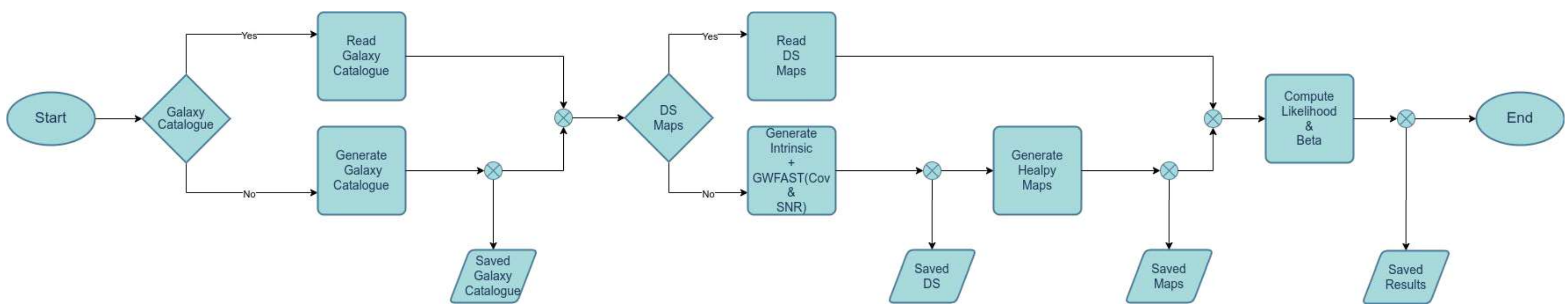
**4.** Computation of the SNR and the uncertainties on the parameters of the waveform model using GWFAST.

**5.** ET-like GW event catalog construction using the best fit of the multivariate distribution.

$$\mathcal{N}_k(\boldsymbol{\mu}^k,\, \boldsymbol{\mathcal{C}}_k) = \frac{1}{\sqrt{(2\pi)^3 \det(\boldsymbol{\mathcal{C}}_k)}} \exp\left[-\frac{1}{2}\left(\mathbf{x}-\boldsymbol{\mu}^k\right)\boldsymbol{\mathcal{C}}_k^{-1}\left(\mathbf{x}-\boldsymbol{\mu}^k\right)^T\right]$$

**Ciancarella+ in prep.**

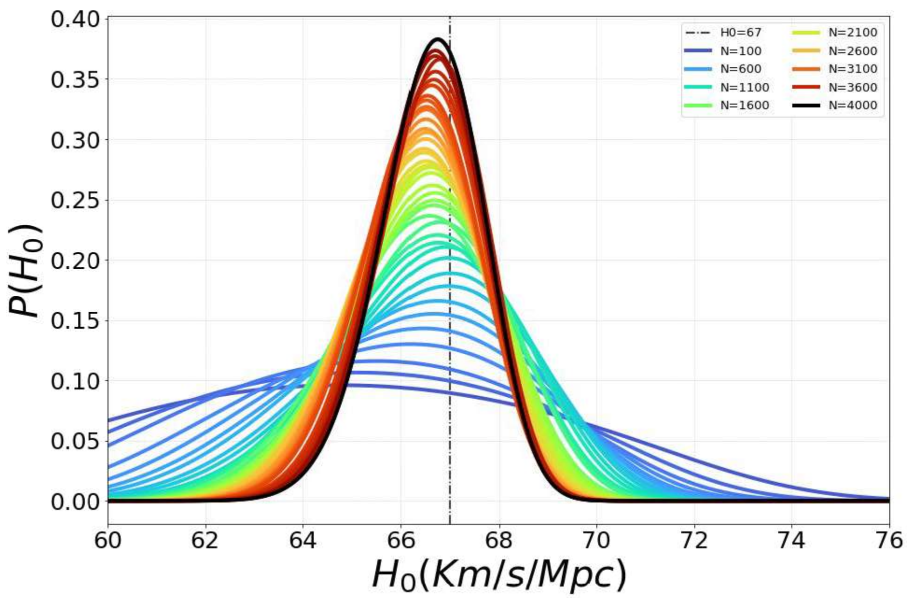
# CODE: Detailed Flowchart

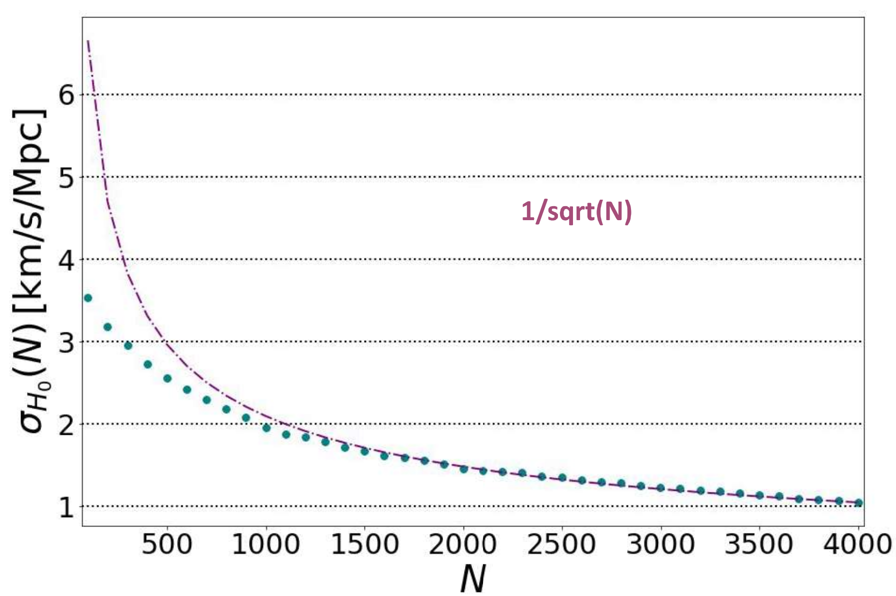



Ciancarella+ in prep.

# CODE results: Error VS Number of Events

This run shows the behaviour of the $H_0$ standard deviation with respect to the number of observed DS.
The dash dotted line is the error on $H_0$ assuming a Poissonian error: since the posterior is far from a Gaussian for a low number of events $N$, the error behaves differently from 1/sqrt($N$), but converges to it for $N$ large.

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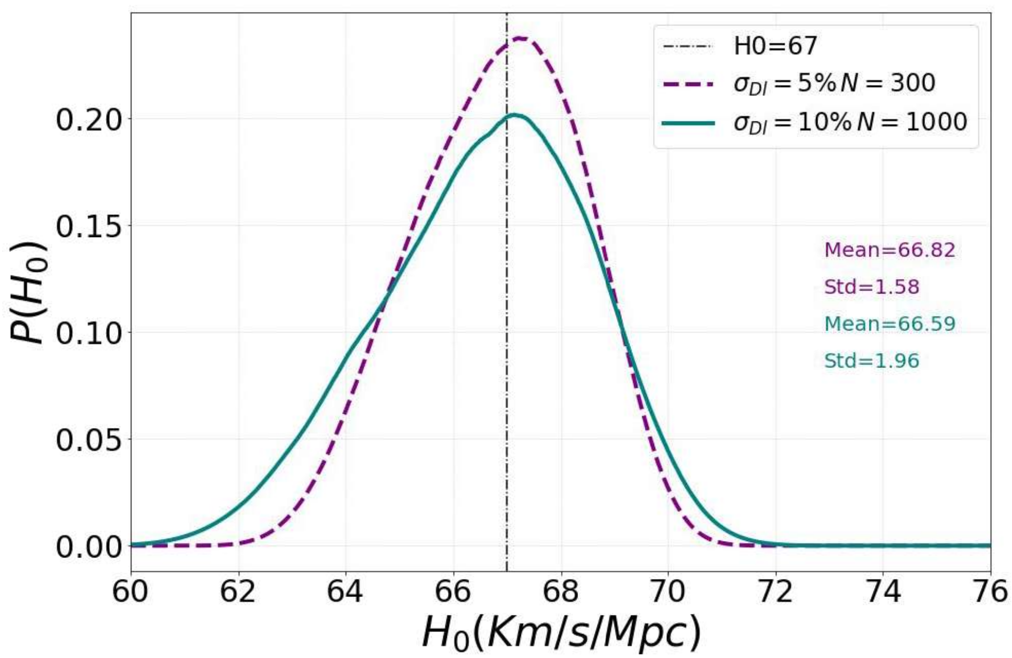
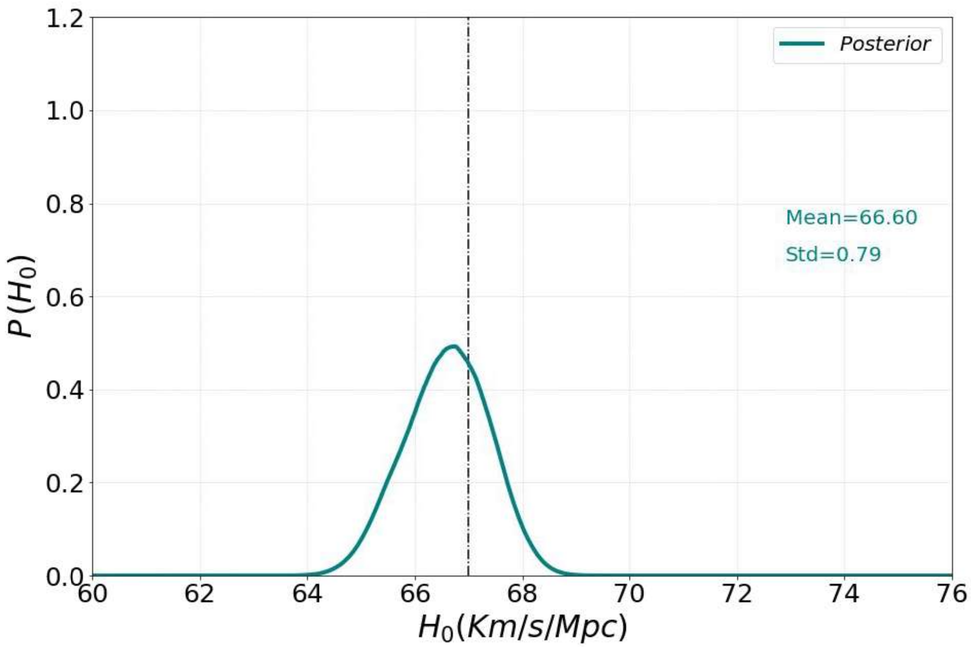
# CODE results: gold events




A sample of *gold* events, i.e. well localised both in distance and in the sky, works much better even if sparser.

**Ciancarella+ in prep.**

# CODE results: neglecting galaxy clustering

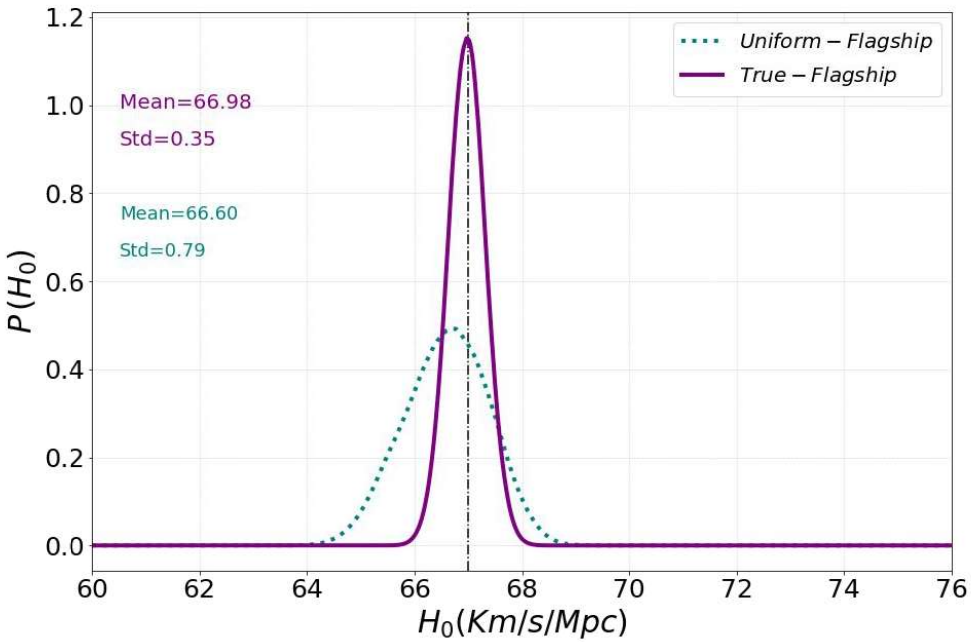



From ET are expected about 200 to 400 gold events per year inside the spectro-Euclid lightcone. Over 5 years of data taking, this means 1000 to 2000 events with uncertainty on $D_L$ of 5% or less.

**Neglecting clustering:** we select a realistic sample of 2000 gold events, and correlate them with a uniform host catalogue with the same number density and selection function of the Euclid spectro-sample.

**Ciancarella+ in prep.**

# CODE results: including galaxy clustering




**Switching on clustering:** we use Flagship, meaning that the host catalogue preserve the clustering properties expected in a real situation.

The result clearly shows the relevance of the clustering properties and the level of accuracy that can be reached by combining ET and spectro-Euclid.

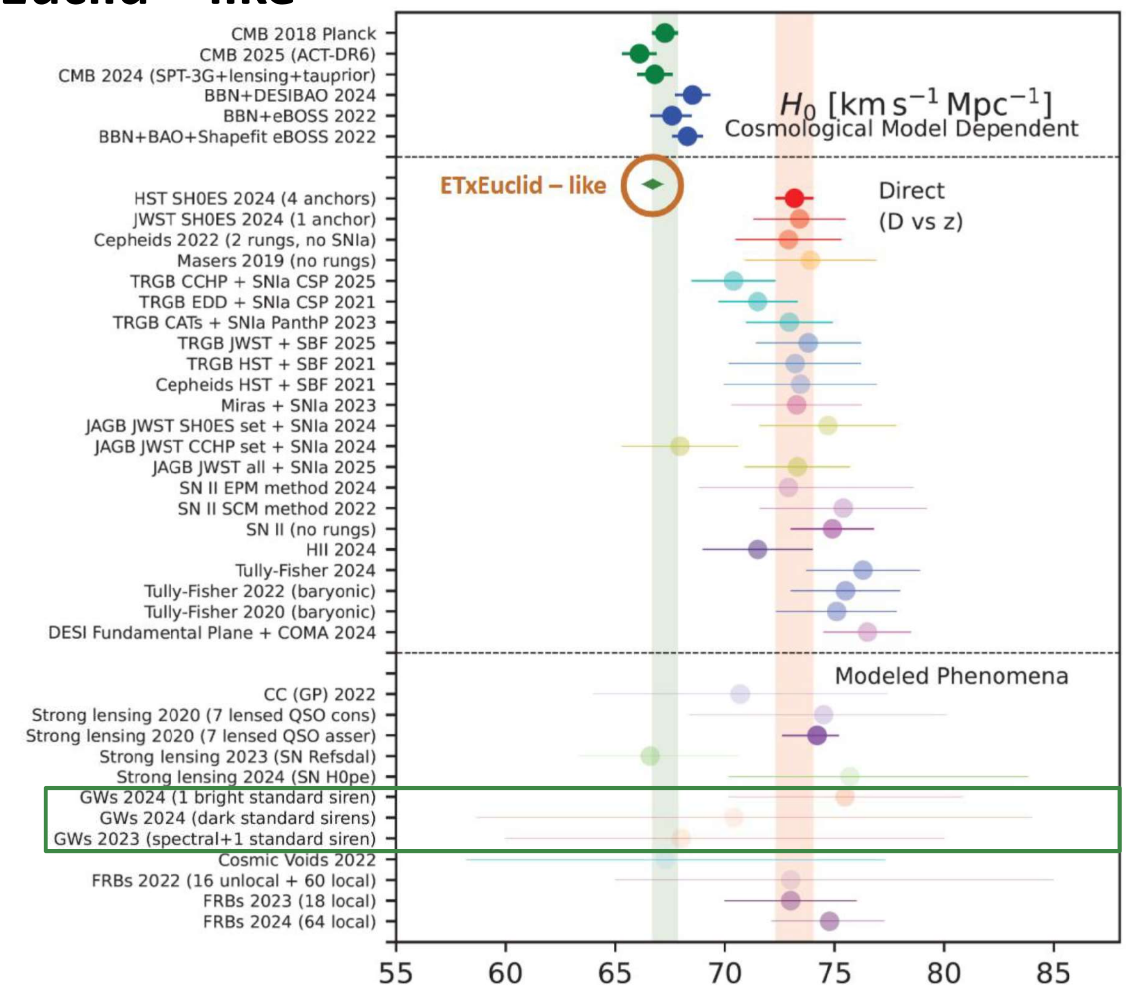
**Ciancarella+ in prep.**

# CODE results: 5 Years of ETxEuclid – like

Using 5 years of ET-like and *spectroscopic* Euclid-like data can lead to a **determination of $H_0$ with a precision between 1% to 0.5%.**

*Note*: estimation using only events with $\sigma(D_L)$=5% and a fixed localization area of 20deg$^2$

**Next step:**
Mass and redshift distributions from mock hydro-catalogues




Ciancarella+ in prep.

# Synthetic maps of the perturbed GW luminosity distance and cross-correlations with LSS probes through the DEMNUni simulations

**(Picciolini, CC et al. in prep)**

# DEMNUni simulations and catalogues

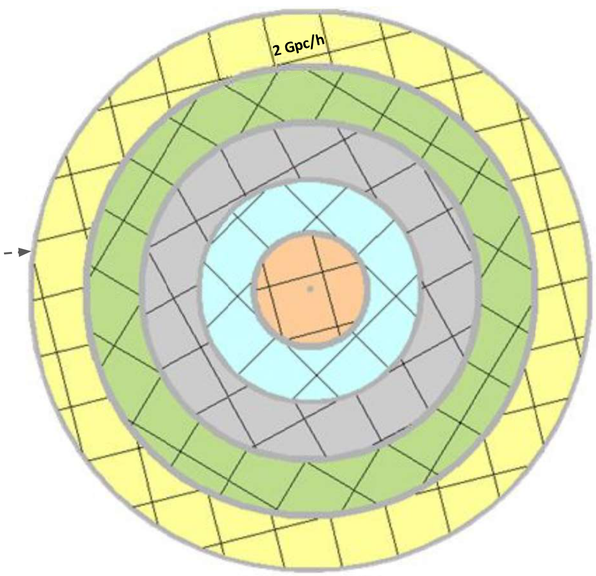
**Dark Energy and Massive Neutrino Universe (DEMNUni)** (Carbone+2016; Parimbelli,CC+2022)

- Comoving volume of $(2\ h^{-1}\,\mathrm{Gpc})^3$
- 2x$2048^3$ CDM particles (x2 with massive neutrinos)
- 63 output logarithmically equispaced in the scale factor
- Planck-2013 baseline-cosmology + 15 $M_\nu$-$w_0$-$w_a$ combinations

$$\{\Omega_{dm}, \Omega_b, \Omega_\Lambda, n_s, \sigma_8, H_0\} = \{0.27, 0.05, 0.68, 0.96, 0.83, 67\,\mathrm{Km/s/Mpc}\}$$

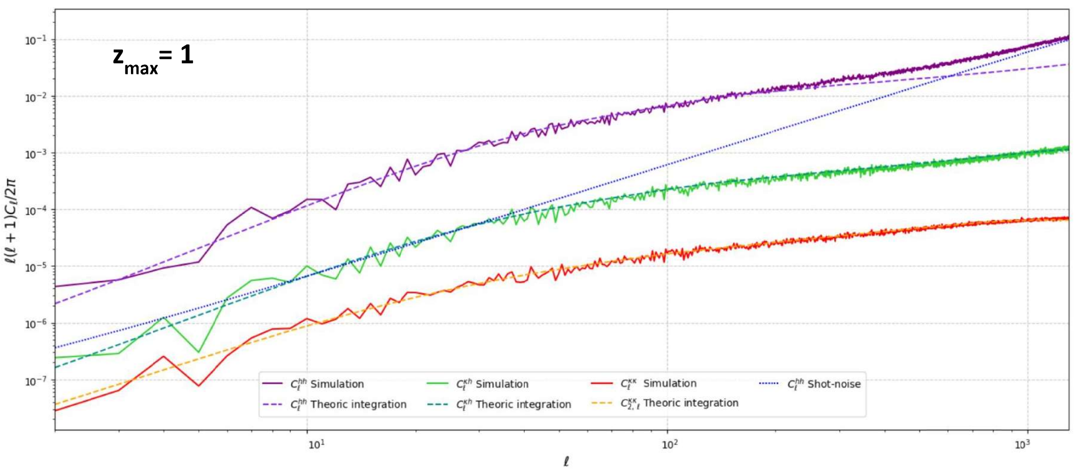
**DEMNUni Full-Sky Lightcones**

- Full sky **halo catalogs** (position and velocities)
- Full sky **convergence maps**

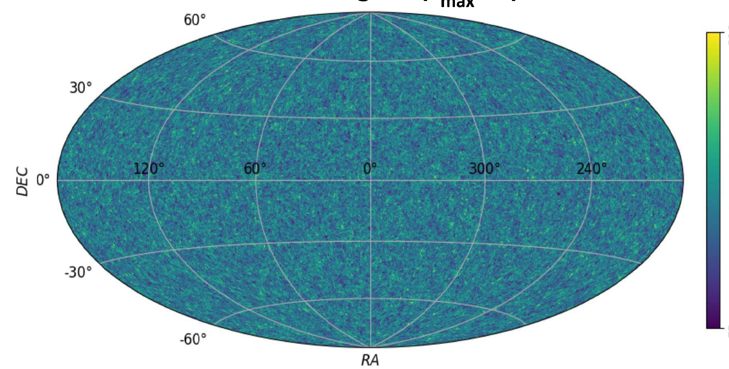


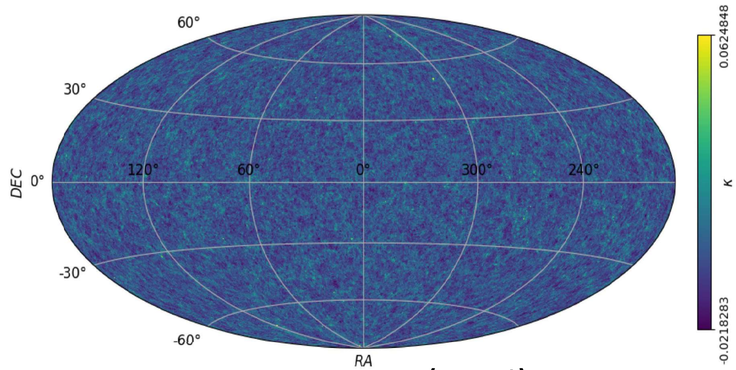

**DEMNUni comoving- box staking**

# DEMNUni LCDM angular power spectra and halo velocity distributions



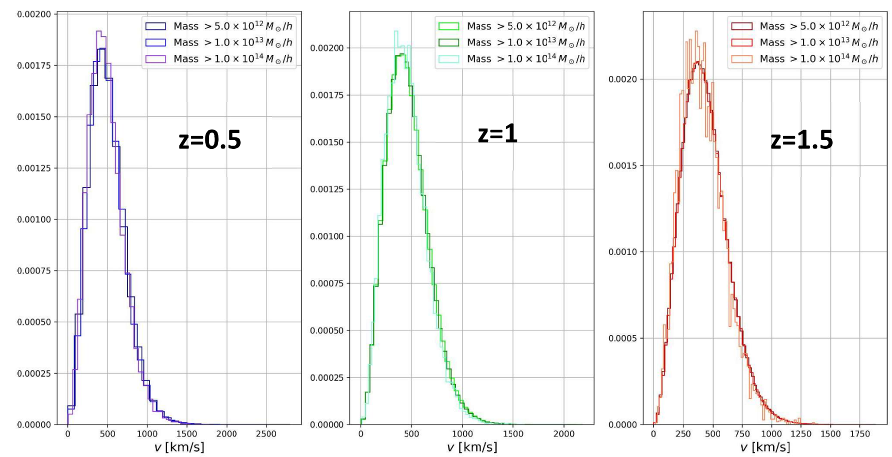

halo catalogues ($z_{max}$ = 1)



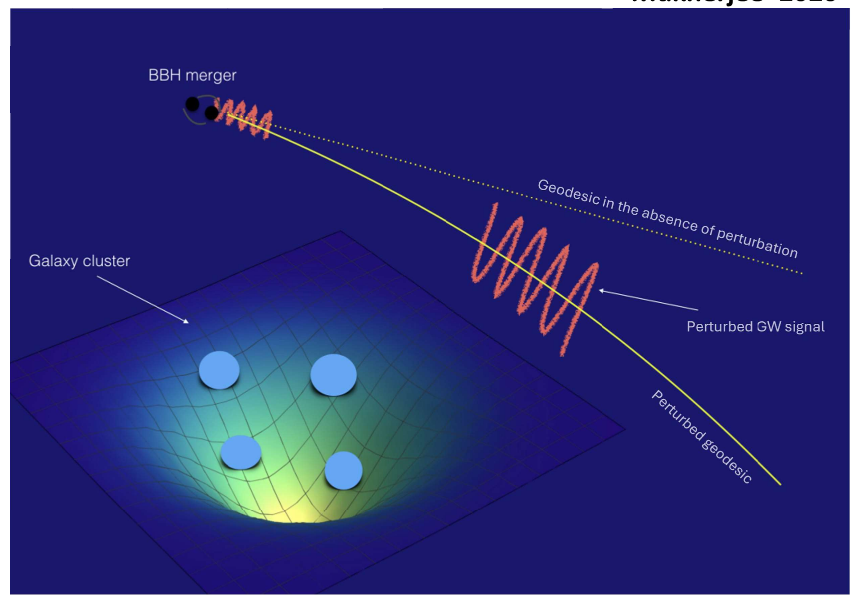

convergence maps ($z_{max}$ = 1)

halo velocity distribution



# Perturbed Gravitational Waves Luminosity Distance

Mukherjee+2020




**Perturbed FLRW metric**

$$ds^2 = a^2(\eta)\left[-(1+2\Phi)\,d\eta^2 + \delta_{ij}(1-2\Psi)\,dx^i dx^j\right]$$

The perturbed expression of the $D_L$ is obtained by mapping the GW geodesic from the unperturbed FLRW Frame to the Real Frame, where perturbations distort the **amplitude** and **path** of the signal:

$$\frac{\Delta \mathcal{D}_L}{\bar{\mathcal{D}}_L} \sim -\kappa + \left(1 - \frac{1}{\mathcal{H}\bar{\chi}}\right) v_{\parallel} + \frac{1}{\mathcal{H}\bar{\chi}}\Phi - 2\left(1 - \frac{1}{\mathcal{H}\bar{\chi}}\right) I - (\Phi + \Psi) + \frac{T}{\bar{\chi}}$$

Bertacca+2019

WLM (orange: $-\kappa$) · Doppler (green: $\left(1 - \frac{1}{\mathcal{H}\bar{\chi}}\right) v_{\parallel}$) · SW, ISW, volume, Shapiro time delay (blue: remaining terms)

# Project: motivation and pipeline

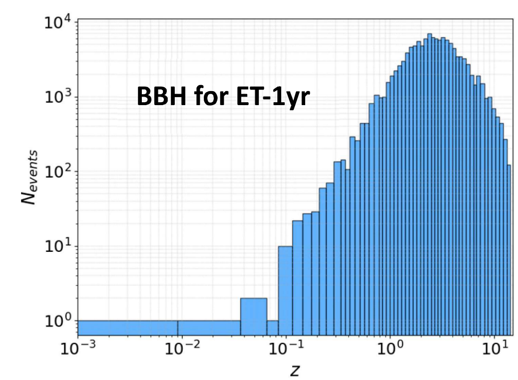
## Motivation

The unperturbed $D_L$ is required to **infer cosmological parameters**, but we need accurate knowledge of LSS perturbations in order to estimate the anisotropic $D_L$ and *reconstruct the unperturbed isotropic* $D_L$

If the unperturbed GW $D_L$ is known, the perturbed GW $D_L$ can be considered as an *independent probe* of **convergence** or source **velocity**

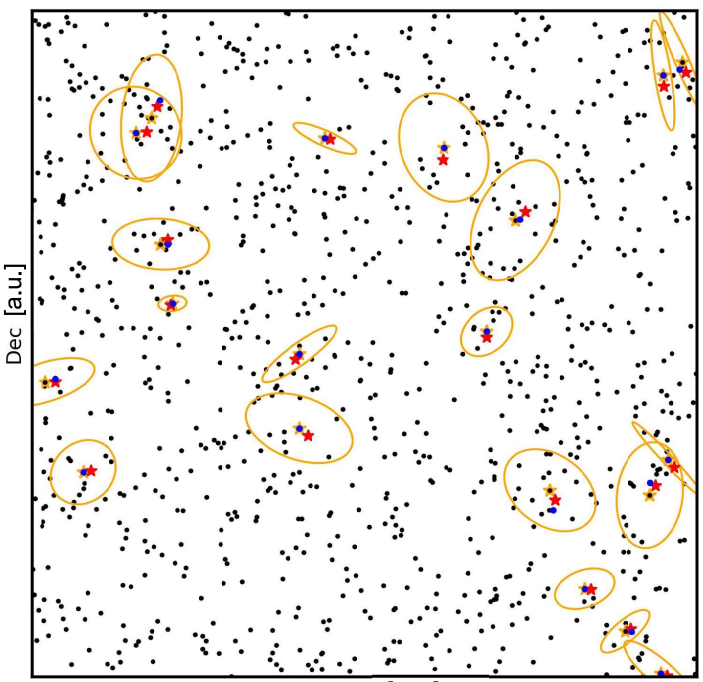
## Pipeline

We use the **DEMNUni simulations** to test the possibility of reconstructing convergence and velocity maps from the **perturbed** $D_L$ measured in a **mock catalogue of GW events** from BBH mergers expected form the Einstein Telescope.




**Picciolini+ in prep.**

# DEMNUni ET-like DS catalogue




**1.** Distribution of DM halos from the lightcone outputs of DEMNUNi simulations.

**2.** Stochastic selection of host halos for GW events from BBH systems, based on the redshift distribution provided by the mock catalog of Branchesi+2023.

**3.** Stochastic generation of the parameters of the IMRPhenomHM waveform model

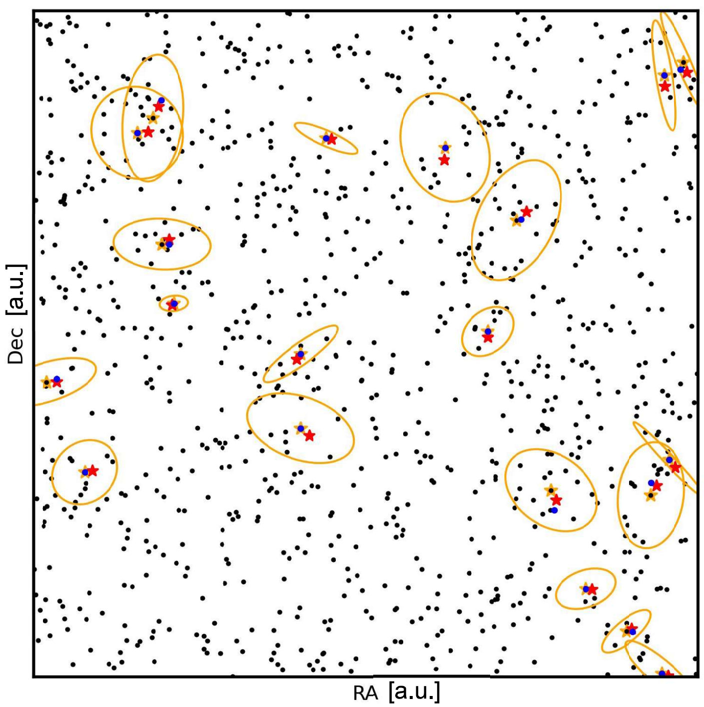
**4.** Computation of the SNR and the uncertainties on the parameters of the waveform model using GWFAST.

**5.** ET-like GW event catalog construction via stochastic sampling around the positions from step 2.

$$\mathcal{N}_k(\boldsymbol{\mu}^k, \boldsymbol{\mathcal{C}}_k) = \frac{1}{\sqrt{(2\pi)^3 \det(\boldsymbol{\mathcal{C}}_k)}} \exp\left[-\frac{1}{2}\left(\mathbf{x} - \boldsymbol{\mu}^k\right) \boldsymbol{\mathcal{C}}_k^{-1} \left(\mathbf{x} - \boldsymbol{\mu}^k\right)^T\right]$$

**Picciolini+ in prep.**

# DEMNUni ET-like DS catalogue

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**6.** Assigning new GW events to the nearest halos in the DEMNUni 3D catalogs.

**Picciolini+ in prep.**

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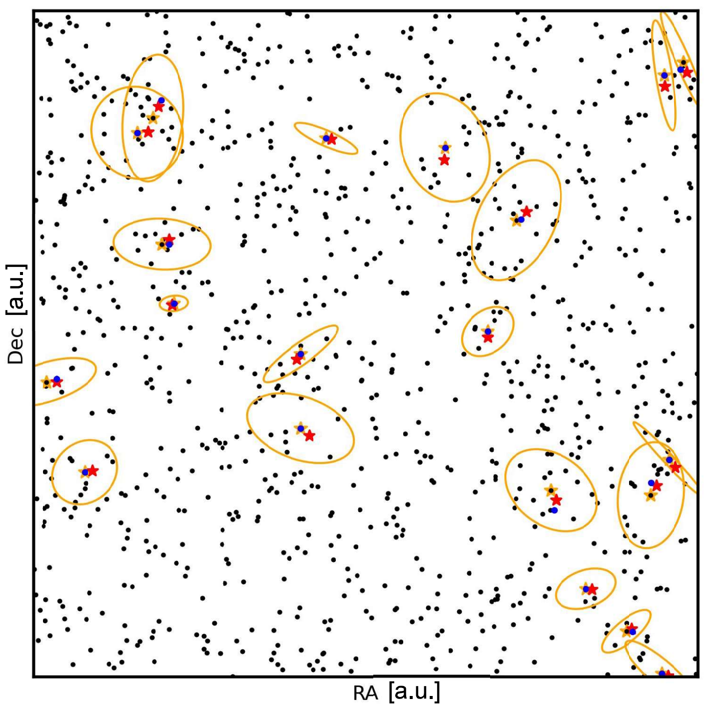


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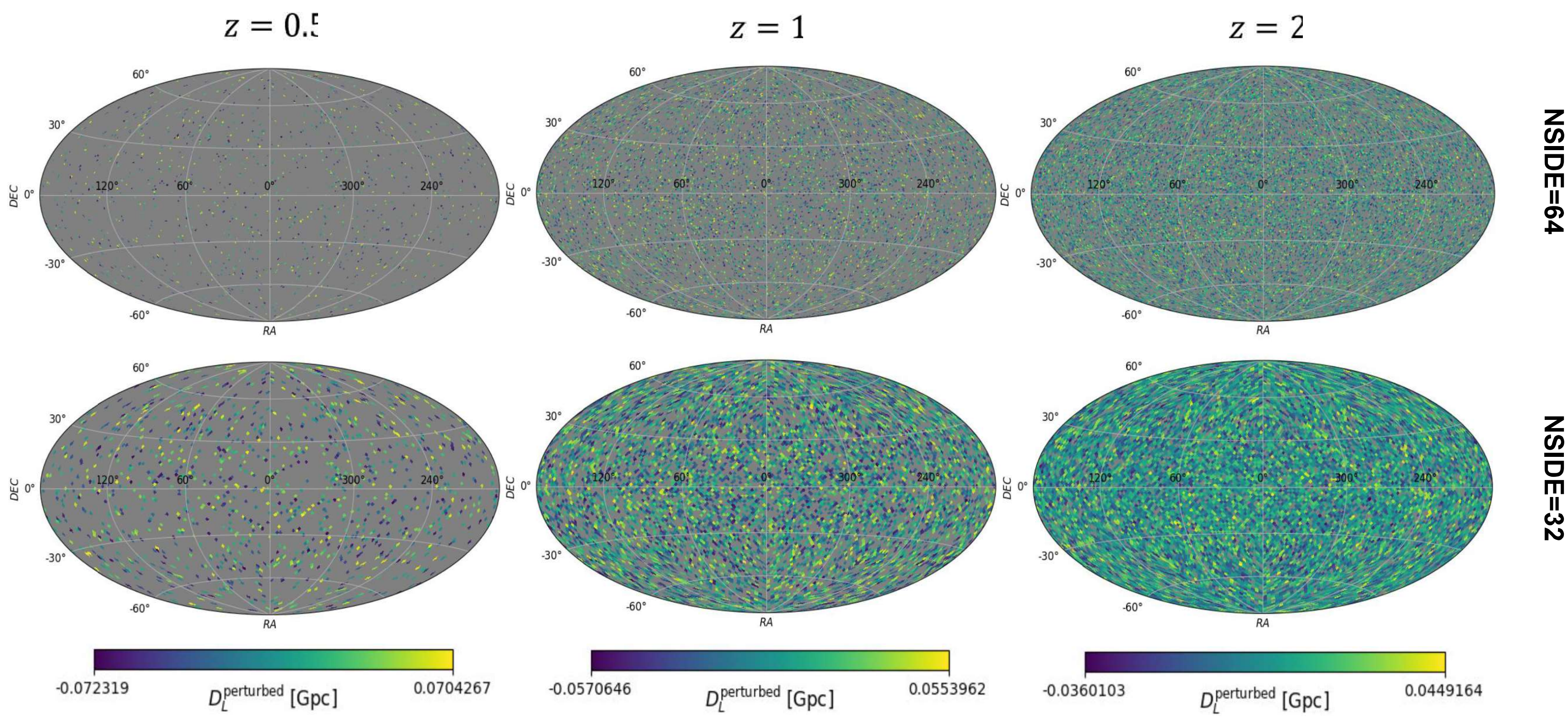
**6.** Assigning new GW events to the nearest halos in the DEMNUni 3D catalogs.

**7.** Computation of the perturbed $D_L$ for the GW events in the ET-like catalog.

**Picciolini+ in prep.**

# Results: perturbed $D_L$ projected maps

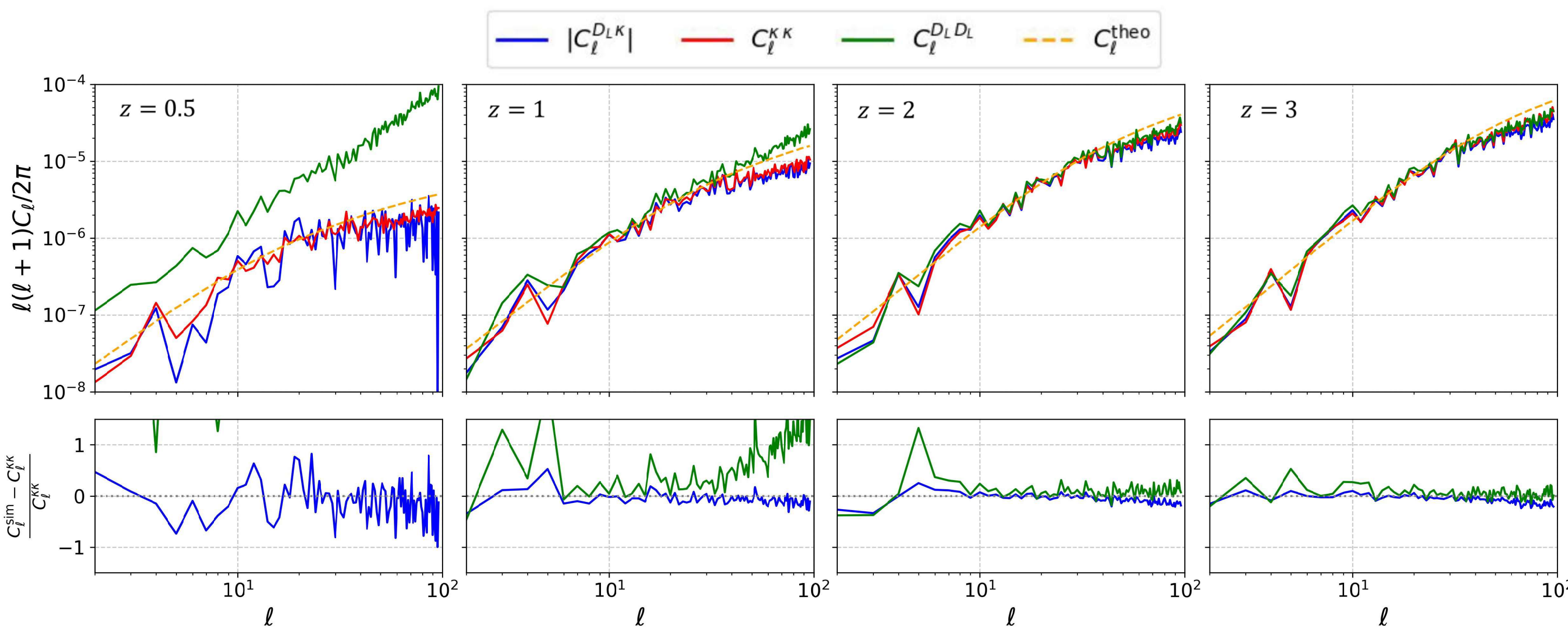



Picciolini+ in prep.

# Results: $D_L$ angular auto- and cross-spectra with $\kappa$

We construct an **estimator of $D_L$ perturbations**. For each pixel $j$, the estimator is defined as the average, over all GW events falling in that pixel, of the relative difference between the *perturbed* and *unperturbed* $D_L$.

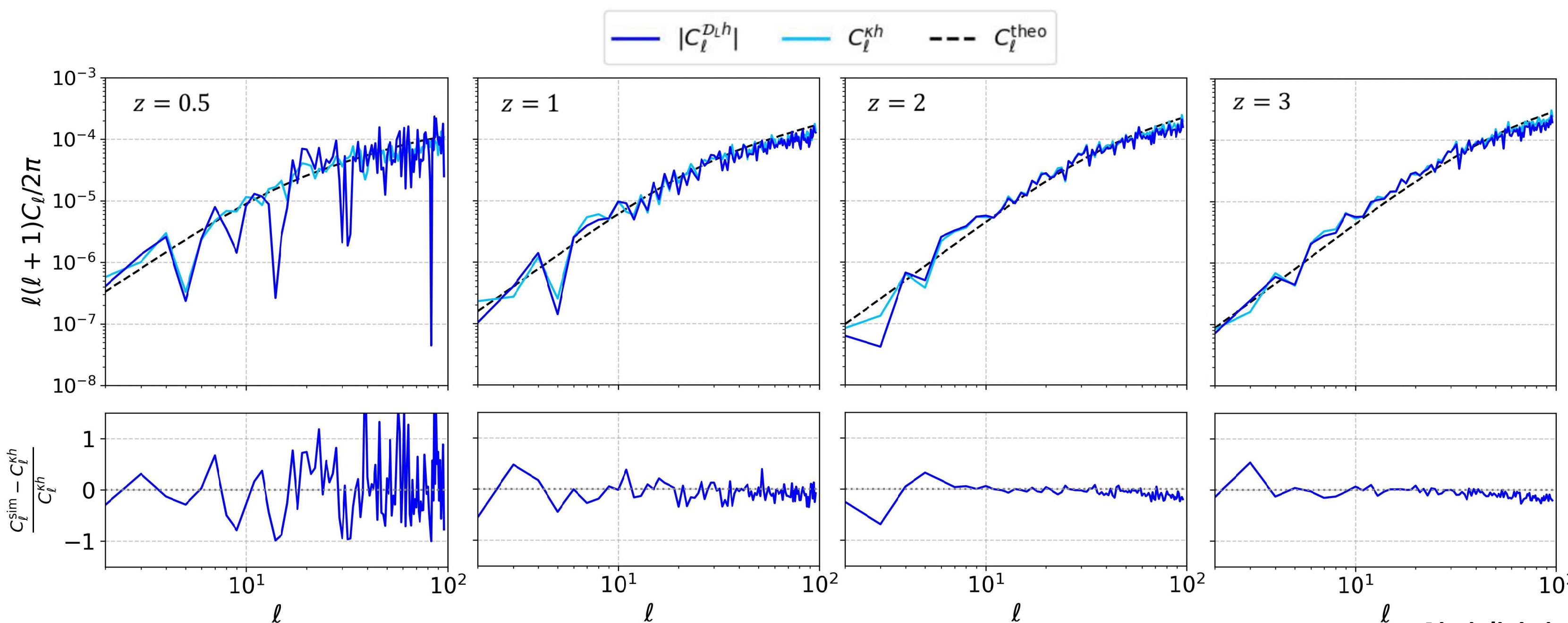
$$\mathrm{EST}_j = \frac{1}{N_j^{\mathrm{GW}}} \sum_{i=1}^{N_j^{\mathrm{GW}}} \left( \frac{\mathcal{D}_L^i - \bar{\mathcal{D}}_L^i}{\bar{\mathcal{D}}_L^i} \right)$$




Picciolini+ in prep.

# Results: cross-correlation with the halo distribution

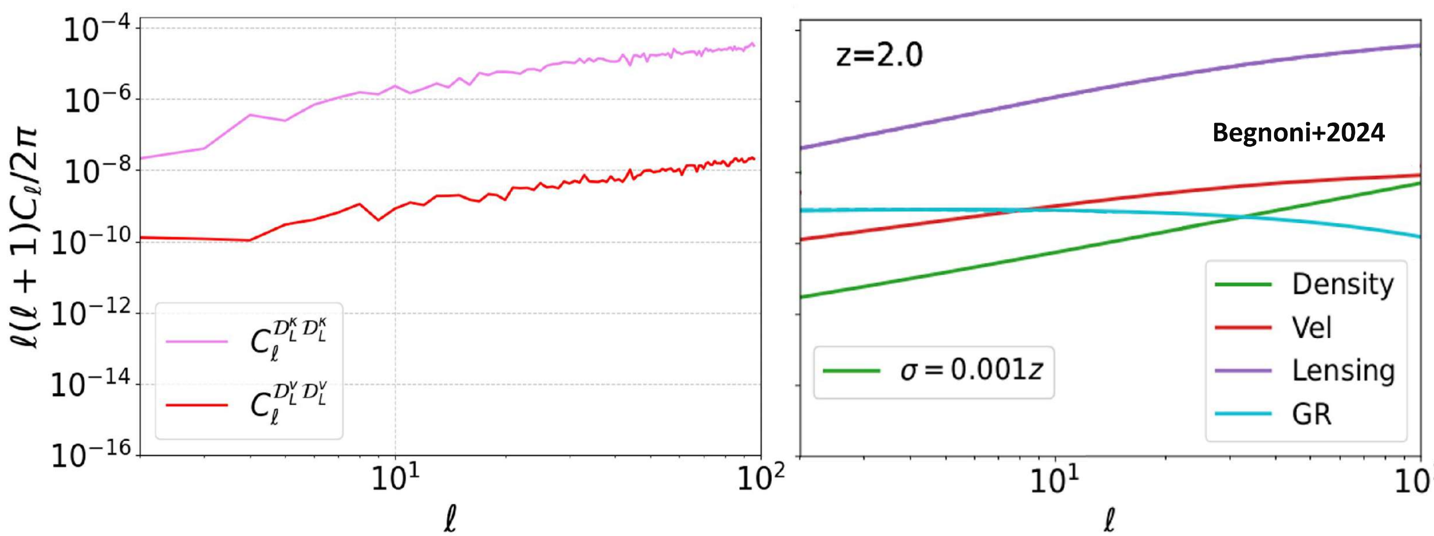
We cross-correlate the $D_L$ estimator with the **halo density distribution** from DEMNUni. This cross-correlation is particularly interesting, as the theoretical prediction depends explicitly on the **halo bias**.




Picciolini+ in prep.

# Results: LSS-contributions to the perturbed $D_L$

We compare the individual contributions form convergence and peculiar velocity respectively to the $D_L$ perturbation obtained from the DEMNUni with the corresponding **theoretical predictions** of *weighted* $D_L$ from Begnoni+2024




Picciolini+ in prep.

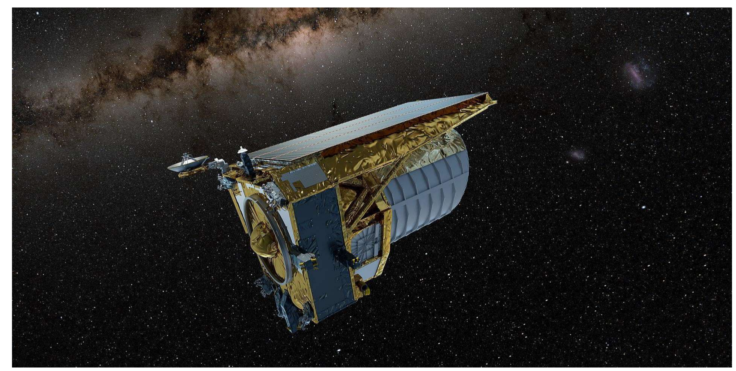
# Future developments

We developed a pipeline to generate **ET-like catalogues of GW** events produced by the coalescence of BBH systems. We measured the anisotropic distribution of the perturbed $D_L$ inferred from the waveform of the gravitational signal induced by LSS in the DEMNUni.

This allowed us to produce **mock maps of perturbed** $D_L$ derived from GW events, and to construct an **estimator** of the angular power spectrum of the $D_L$ perturbations.

**Next steps**

- Extend the pipeline to built synthetic GW mocks from **Euclid galaxy catalogues**
- Produce **multiple mock realizations** (for covariance estimation)
- Measure cross-correlations with Euclid GC, WL, and CMB lensing maps
- Extend the pipeline to modified gravity simulations



Altogether, these developments could contribute to establishing the perturbed $D_L$ from GWs, and its cross-correlations with galaxy surveys, as a **novel and independent cosmological probe**.

Picciolini+ in prep.

# Cosmological forecasts from GW-magnification and Euclid-like 3x2pt

We investigated the synergy between Euclid-like photometric surveys and future GW observatories for cosmological parameter inference

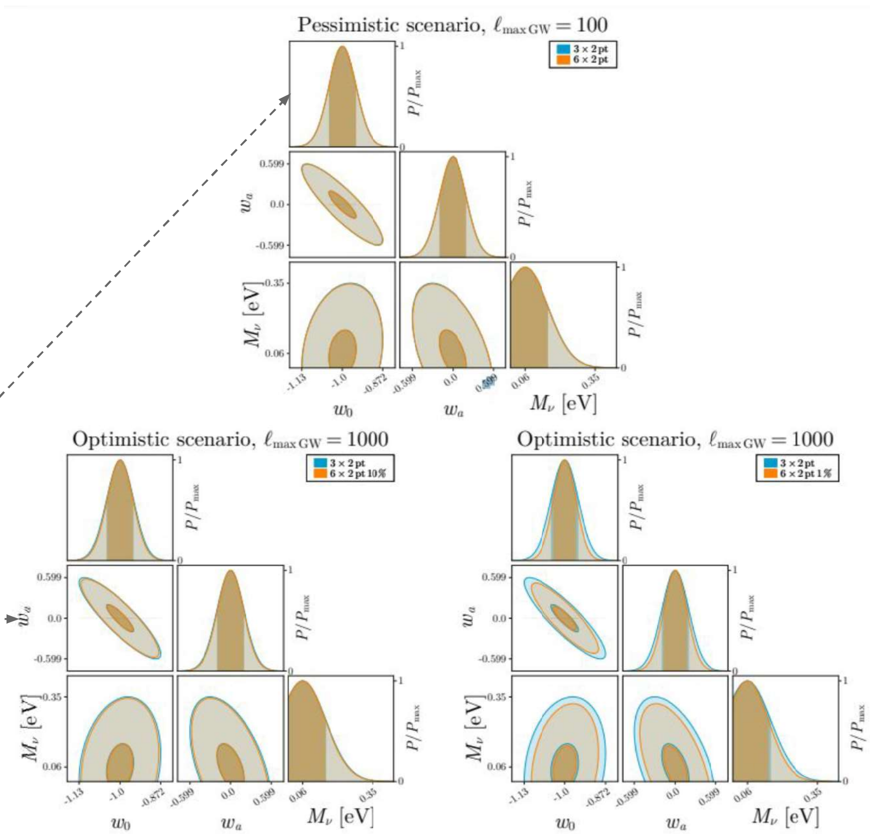
We implemented a Fisher matrix approach for the 6×2pt statistics composed by WL, photo-GC, GW-magnification together with their cross-correlations.

We focussed on dynamical dark energy and massive neutrino scenarios.

We found that the improvement to galaxy survey performance is below 1%, in the case of $\ell_{max}$= 100 for GW-Cls and a luminosity distance error of σ($D_L$)=10%.

When extending the analysis to $\ell_{max}$= 1000, the GW-magnification reduces the errors by 3%-5%, if σ($D_L$)=10%, and by 10%-18% if σ($D_L$)=1%, especially for $M_\nu$, $w_0$ and $w_a$.

Our analysis is optimistic: a much more detailed and realistic approach will be needed, especially by including systematic effects.




Beltrame+2024

**Thank you!**