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On cosmological clustering of Gravitational Wave Events

Based on
JCAP08(2023)050 - arxiv:2304.14253
JCAP05(2024)095 - arXiv:2309.04391

EREP 2024 - Coimbra - 23/07/2024

In collaboration with Stefano Zazzera, Tessa Baker and Chris Clarkson

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Motivation

Can we use transient events as DM tracers?

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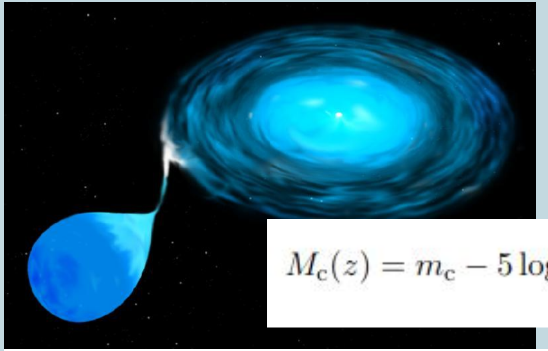
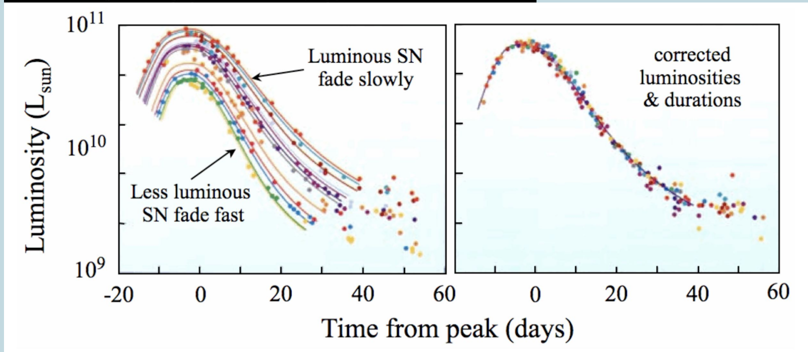
SNeIa



$$M_c(z) = m_c - 5\log\left[\frac{d_L(z)}{10\,\mathrm{pc}}\right] - K(z)$$



LSST expects 10^7 over 10yrs up to z=4

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Can we use transient events as DM tracers?

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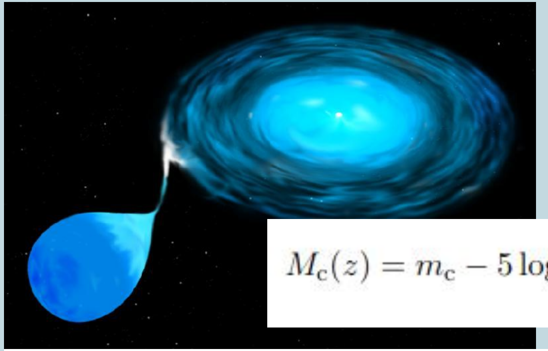
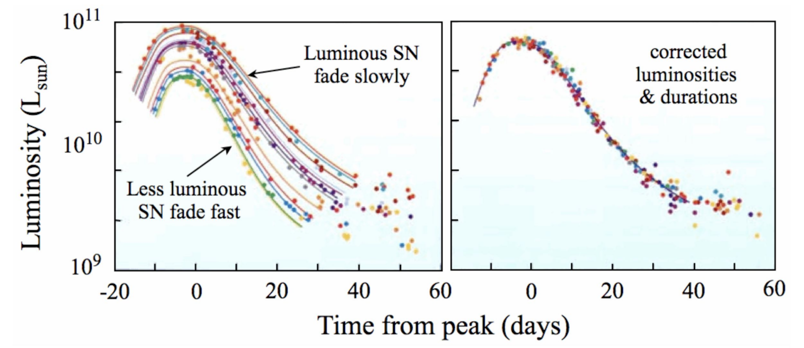


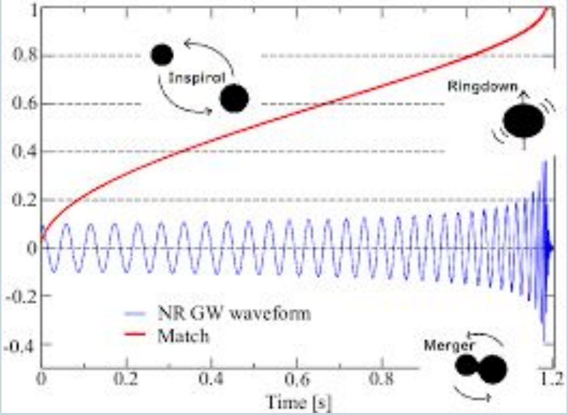
$$M_c(z) = m_c - 5\log\left[\frac{d_L(z)}{10\,\mathrm{pc}}\right] - K(z)$$



LSST expects 10^7 over 10yrs up to z=4

GW

$$h \propto \frac{\mathcal{M}_z^{5/3}}{d_L}$$

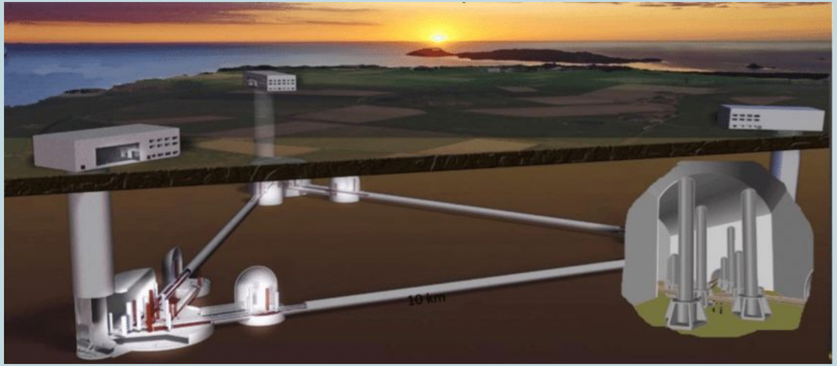


YES!

- Several works have done for when redshift is known (see eg Scelfo et al 2018, etc);
- Libanore et al (2021), angular power spectra with first corrections to the density contrast;
- Namikawa et al (2021), in 3D space;

Motivation

Can we use transient events as DM tracers?



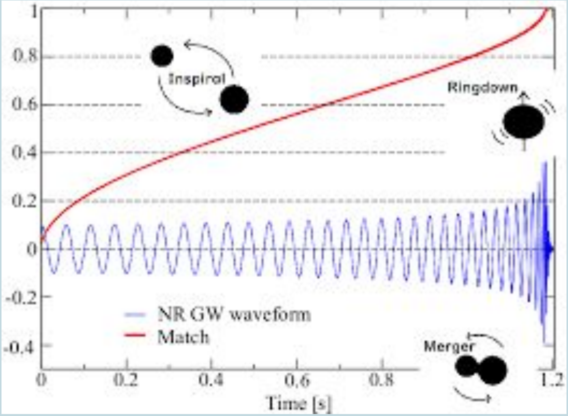
Credits: Einstein Telescope

Next Generation surveys:

$$N_{ET} \sim \mathcal{O}(10^5)$$
$$z_{ET} \sim 10$$

GW

$$h \propto \frac{\mathcal{M}_z^{5/3}}{d_L}$$



YES!

- Several works have done for when redshift is known (see eg Scelfo et al 2018, etc);
- Libanore et al (2021), angular power spectra with first corrections to the density contrast;
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Which density contrast do we observe?

Density contrast = matter density fluctuation + RSD + Lensing + GR corrections

Density contrast

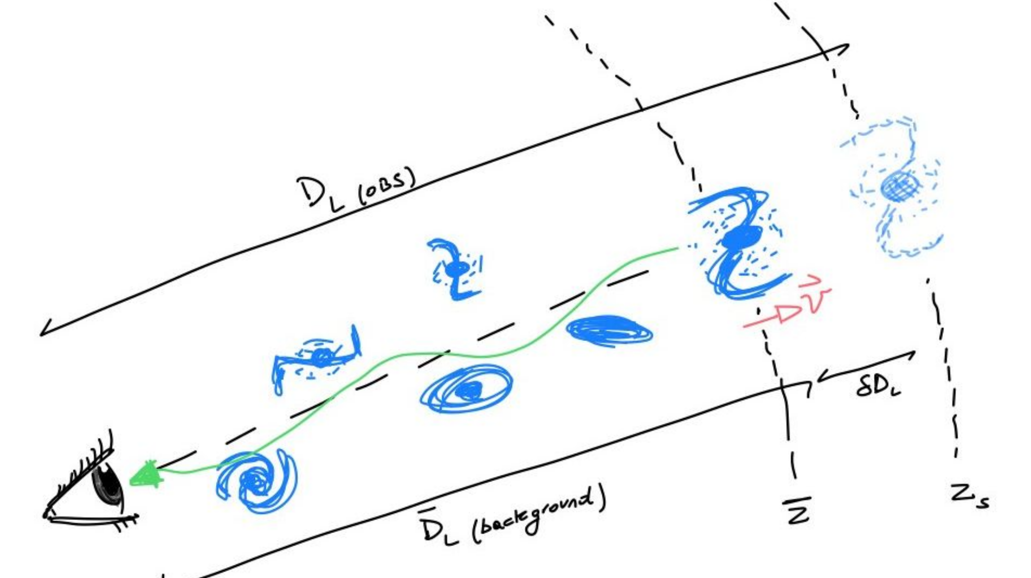
$$\Delta_N = \frac{N - \langle N \rangle}{\langle N \rangle}$$

Expand

$$\Delta_O(D_L, \hat{n}) = \delta_n - \left[3 - b_e - \frac{5}{\gamma} s\right] \gamma \frac{\delta D_L}{\bar{D}_L} + \frac{\delta V(\boldsymbol{n}, D_L)}{\bar{V}(D_L)}$$

$$\gamma \equiv \frac{\bar{r}\mathcal{H}}{1 + \bar{r}\mathcal{H}}$$

For the volume perturbation we followed Bonvin&Durrer (2011)



Credit: Stefano Zazzera

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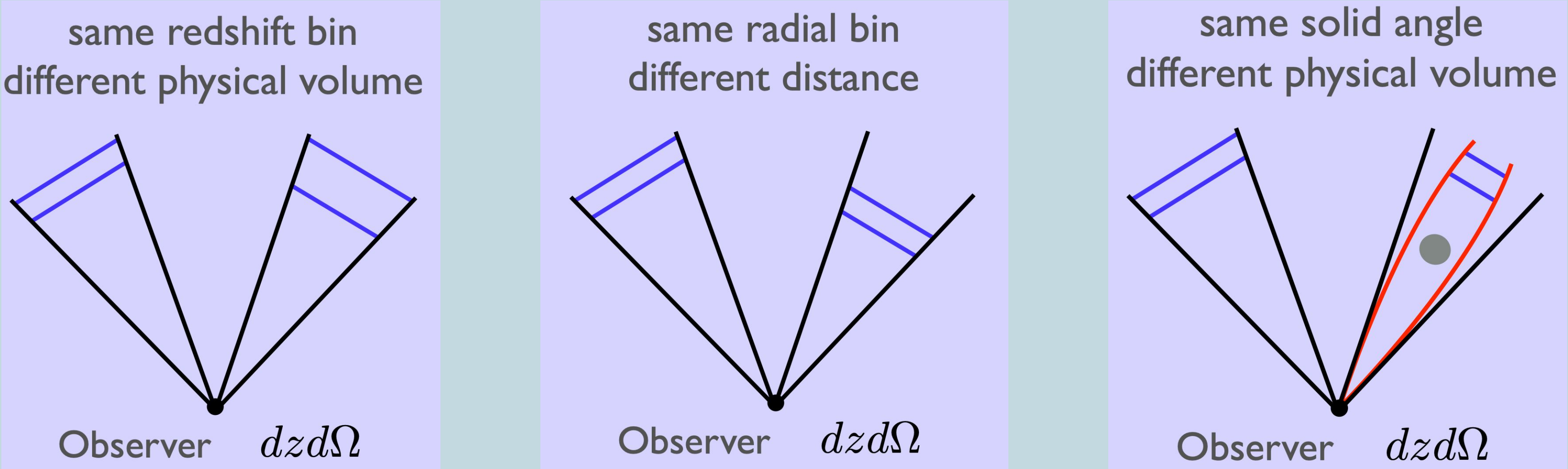
Which density contrast do we observe?



Credit: Camille Bonvin

See Challinor & Lewis 2011, Bonvin & Durrer 2011 for full derivation

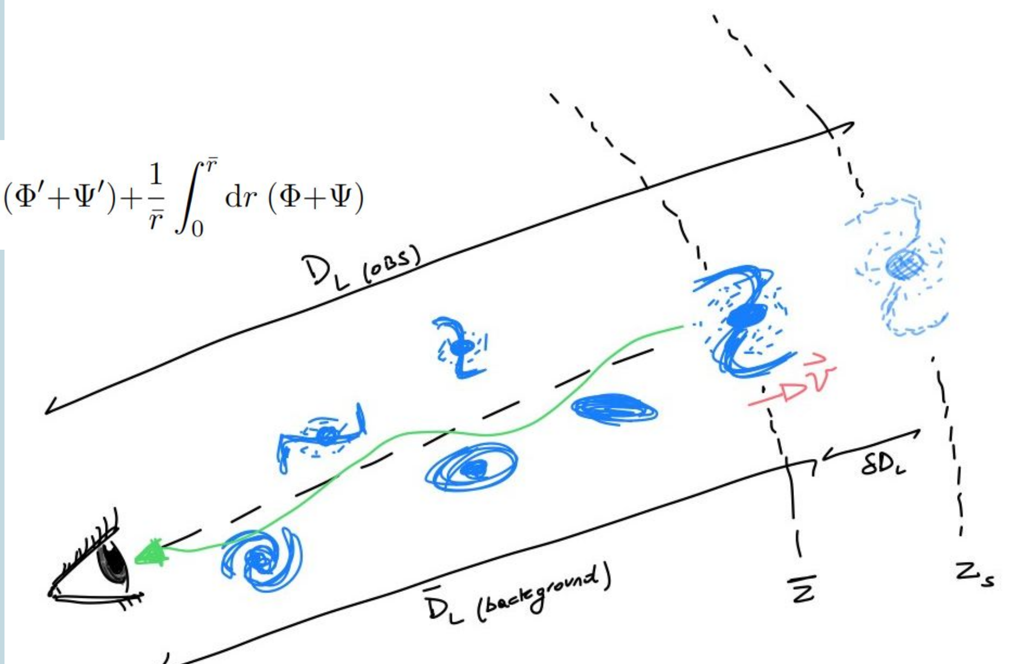
$$\Delta = \text{density} + \text{RSD} + \text{Doppler effect} + \text{Magnification Lensing} + \text{Potential terms}\,.$$

Which density contrast do we observe?

Luminosity Distance Perturbation

$$\frac{\delta D_L}{\bar{D}_L} = 2\boldsymbol{v}\cdot\boldsymbol{n} - \frac{1}{2}\int_0^{\bar{r}} \mathrm{d}r\, \frac{\bar{r}-r}{\bar{r}r}\Delta_\Omega(\Phi+\Psi) - \Phi - 2\Psi - 2\int_0^{\bar{r}} \mathrm{d}r\, (\Phi'+\Psi') + \frac{1}{\bar{r}}\int_0^{\bar{r}} \mathrm{d}r\, (\Phi+\Psi)$$

- Note that we do not measure redshift - therefore different from Bertacca et al (2018);
- The perturbation is with respect to a background afine parameter which we can take as the background redshift;
- Agrees with Sasaki (1987), Pyne & Birkinshaw (2004), Hui & Greene (2006).



Credit: Stefano Zazzera

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Which density contrast do we observe?

Density contrast

$$\Delta(\boldsymbol{n}, D_L) = \delta_n - 2\Phi + \Psi + \frac{\gamma}{\mathcal{H}}\frac{\mathrm{d}}{\mathrm{d}\lambda}\frac{\delta D_L}{\bar{D}_L} + v_r - 2\kappa_g + \frac{2}{\bar{r}}\int_0^{\bar{r}}\mathrm{d}r\,(\Phi+\Psi) - \beta\frac{\delta D_L}{\bar{D}_L}$$
$$= \delta_n + A_D(\boldsymbol{v}\cdot\boldsymbol{n}) + A_{LSD}\partial_r(\boldsymbol{v}\cdot\boldsymbol{n}) + A_\Psi\Psi + A_\Phi\Phi + A_{\Phi'}\Phi' + A_{\nabla\Phi}\partial_r\Phi$$
$$+\frac{1}{\bar{r}}\int_0^{\bar{r}}\mathrm{d}r\,(A_{TD} + A_L\Delta_\Omega)(\Phi+\Psi) + A_{ISW}\int_0^{\bar{r}}\mathrm{d}r\,(\Phi'+\Psi')\,,$$

$$\beta \equiv \gamma\left[\frac{2}{\bar{r}\mathcal{H}} + \gamma\left(\frac{\mathcal{H}'}{\mathcal{H}^2} - \frac{1}{\bar{r}\mathcal{H}}\right) - 1 - b_e\right] - 5s + 1$$

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B Comparison of the amplitudes

Term	LDS	RS
$A_{LSD,RSD}$	$-\frac{2\bar{r}}{1+\bar{r}\mathcal{H}}$	$-\frac{1}{\mathcal{H}}$
A_D	$3-10s+\frac{\bar{r}\mathcal{H}}{1+\bar{r}\mathcal{H}}\left(\frac{4}{\bar{r}\mathcal{H}}+2b_e\right)-2\left(\frac{\bar{r}\mathcal{H}}{1+\bar{r}\mathcal{H}}\right)^2\left(\frac{\mathcal{H}'}{\mathcal{H}^2}-\frac{1}{\bar{r}\mathcal{H}}\right)$	$\frac{5s-2}{\bar{r}\mathcal{H}}-5s+b_e-\frac{\mathcal{H}'}{\mathcal{H}^2}$
A_Ψ	$-1+10s+\frac{\bar{r}\mathcal{H}}{1+\bar{r}\mathcal{H}}\left(\frac{3}{\bar{r}\mathcal{H}}-2-2b_e\right)+2\left(\frac{\bar{r}\mathcal{H}}{1+\bar{r}\mathcal{H}}\right)^2\left(\frac{\mathcal{H}'}{\mathcal{H}^2}-\frac{1}{\bar{r}\mathcal{H}}\right)$	$1+\frac{5s-2}{\bar{r}\mathcal{H}}-5s+b_e-\frac{\mathcal{H}'}{\mathcal{H}^2}$
A_Φ	$-3+5s+\frac{\bar{r}\mathcal{H}}{1+\bar{r}\mathcal{H}}\left(\frac{1}{\bar{r}\mathcal{H}}-1-b_e\right)+\left(\frac{\bar{r}\mathcal{H}}{1+\bar{r}\mathcal{H}}\right)^2\left(\frac{\mathcal{H}'}{\mathcal{H}^2}-\frac{1}{\bar{r}\mathcal{H}}\right)$	$5s-2$
$A_{\Phi'}$	$\frac{\bar{r}}{1+\bar{r}\mathcal{H}}$	$\frac{1}{\mathcal{H}}$
$A_{\nabla\Phi}$	$\frac{\bar{r}}{1+\bar{r}\mathcal{H}}$	0
A_{TD}	$3-5s+\frac{\bar{r}\mathcal{H}}{1+\bar{r}\mathcal{H}}\left(-\frac{1}{\bar{r}\mathcal{H}}+1+b_e\right)-\left(\frac{\bar{r}\mathcal{H}}{1+\bar{r}\mathcal{H}}\right)^2\left(\frac{\mathcal{H}'}{\mathcal{H}^2}-\frac{1}{\bar{r}\mathcal{H}}\right)$	$5s-2$
A_L	$\frac{1}{2}\left[\left(\frac{\bar{r}-r}{r}\right)\left(5s-3+\frac{\bar{r}\mathcal{H}}{1+\bar{r}\mathcal{H}}\left(\frac{2}{\bar{r}\mathcal{H}}-1-b_e\right)+\left(\frac{\bar{r}\mathcal{H}}{1+\bar{r}\mathcal{H}}\right)^2\left(\frac{\mathcal{H}'}{\mathcal{H}^2}-\frac{1}{\bar{r}\mathcal{H}}\right)\right)+\frac{1}{1+\bar{r}\mathcal{H}}\right]$	$\frac{1}{2}(5s-2)\frac{\bar{r}-r}{r}$
A_{ISW}	$-1+10s+\frac{\bar{r}\mathcal{H}}{1+\bar{r}\mathcal{H}}\left(\frac{4}{\bar{r}\mathcal{H}-2-2b_e}\right)$	$\frac{2-5s}{\bar{r}\mathcal{H}}+5s-b_e+\frac{\mathcal{H}'}{\mathcal{H}^2}$

We changed CAMB to compute the angular power in LD space.

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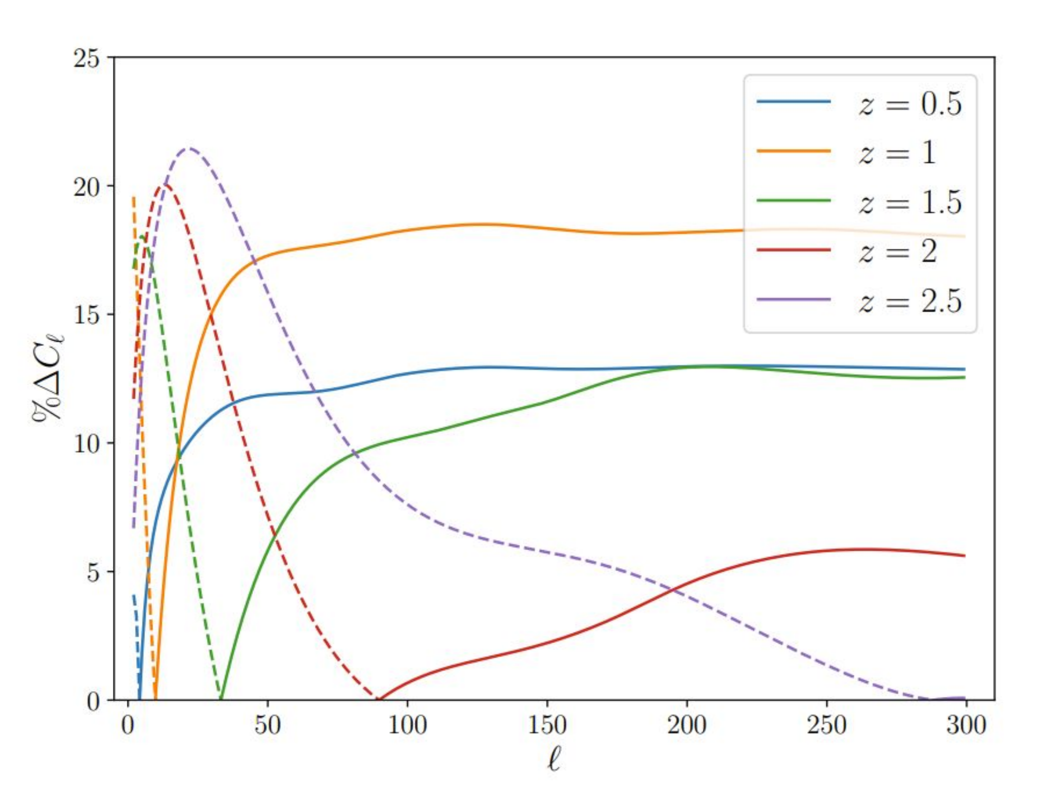
Differences between LD and z spaces



broad selection function

We cannot use the z expression for LD space

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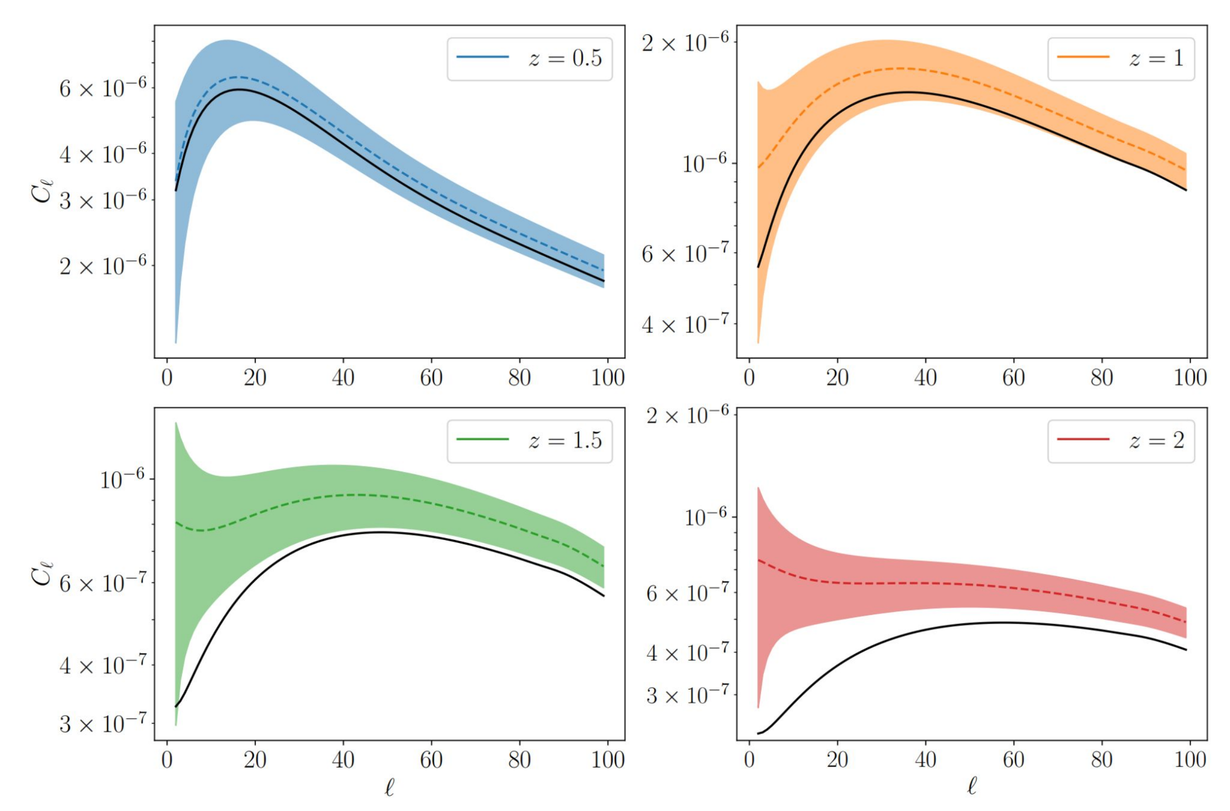
"Cosmic Variance limit" with respect to density only

$$\Delta C_\ell = \sqrt{\frac{2}{(2\ell+1) f_{\rm sky}}}\,(C_\ell + .$$



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The biases

$$\Delta_O(D_L,\hat{n}) = b\delta_m + \left[3 - \frac{\partial \log n}{\partial \log a} + \frac{5}{\gamma}\frac{\partial \log n}{\partial \log \rho_{th}}\right]\gamma\frac{\delta D_L}{D_L} + \frac{\delta V(D_L,\hat{n})}{\bar{V}(D_L)}$$

Over-density of number counts (as a function of luminosity distance)

Clustering bias x matter density fluctuation

Evolution bias

Magnification bias

Luminosity distance perturbation

The biases

Magnification bias

- The change in the number density with respect to the luminosity cut at fixed redshift.

$$s(a, L_c) \equiv -\frac{\partial \ln n(a, L_c)}{\partial \ln L_c}\bigg|_a$$

Evolution bias

- The change in comoving number density with respect to redshift at fixed luminosity cut.

$$b_e(a, L_c) \equiv \frac{\partial \ln n(a, L_c)}{\partial \ln a}\bigg|_{L_c}$$

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GWs Biases*

$$n_{obs}(z,\rho_{th}) = \tau \int d\mathcal{M} \, \frac{R_{GW}(z)}{1+z} \phi(\mathcal{M}) S(\rho_{th};\mathcal{M},z)$$

- $n_{obs}(z,\rho_{th})$: Observed number density
- $R_{GW}(z)$: Intrinsic merger rate
- $\phi(\mathcal{M})$: Chirp mass distribution
- $S(\rho_{th};\mathcal{M},z)$: Survival function of event (Likelihood of detection)

*Inspirals of astrophysical Binary Black Holes

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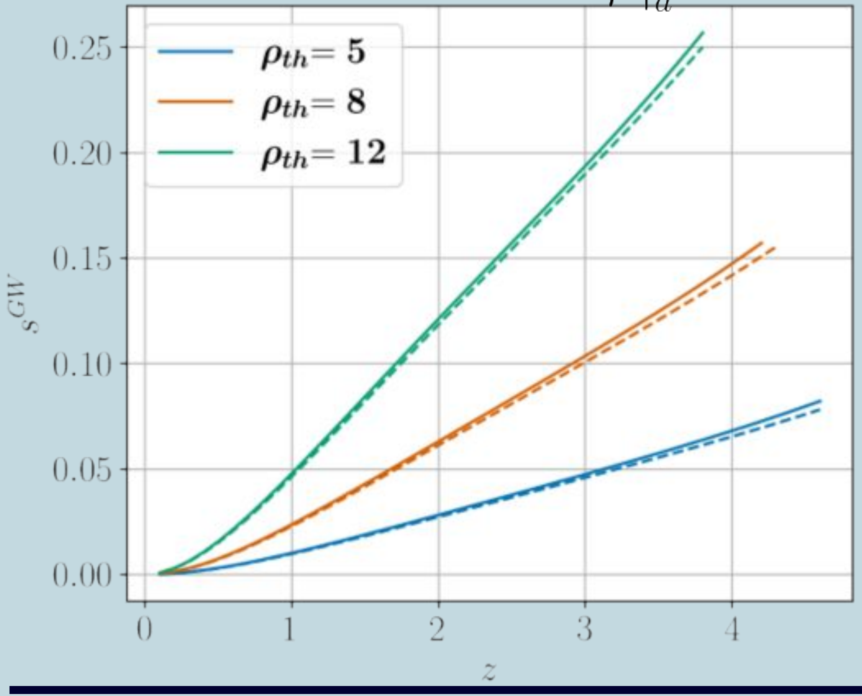
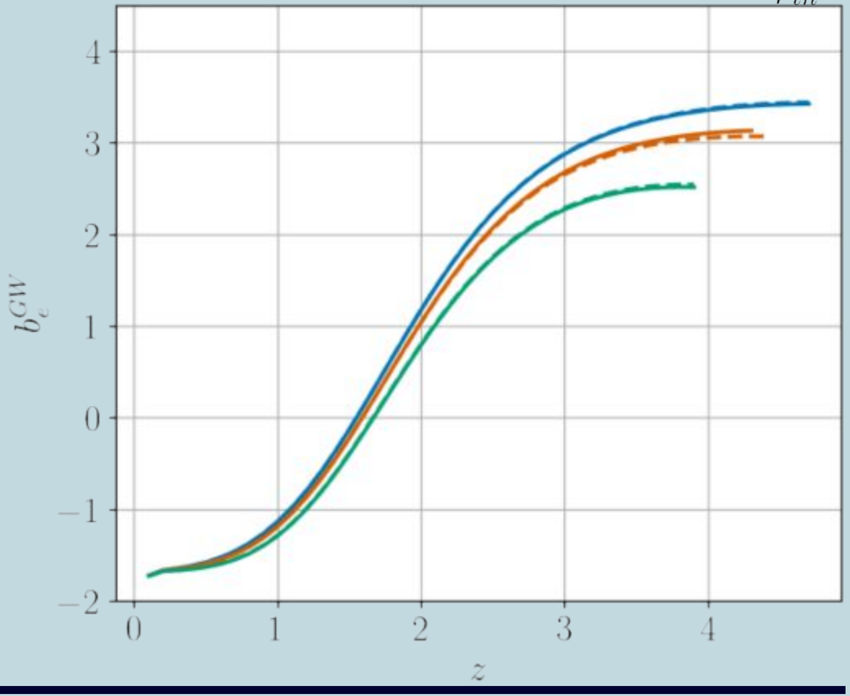
GWs Biases – Einstein Telescope

$$s^{GW} \equiv -\frac{1}{5}\frac{\partial \ln n}{\partial \ln \rho}\bigg|_a$$

$$b_e^{GW} \equiv \frac{\partial \ln n}{\partial \ln a}\bigg|_{\rho_{th}}$$





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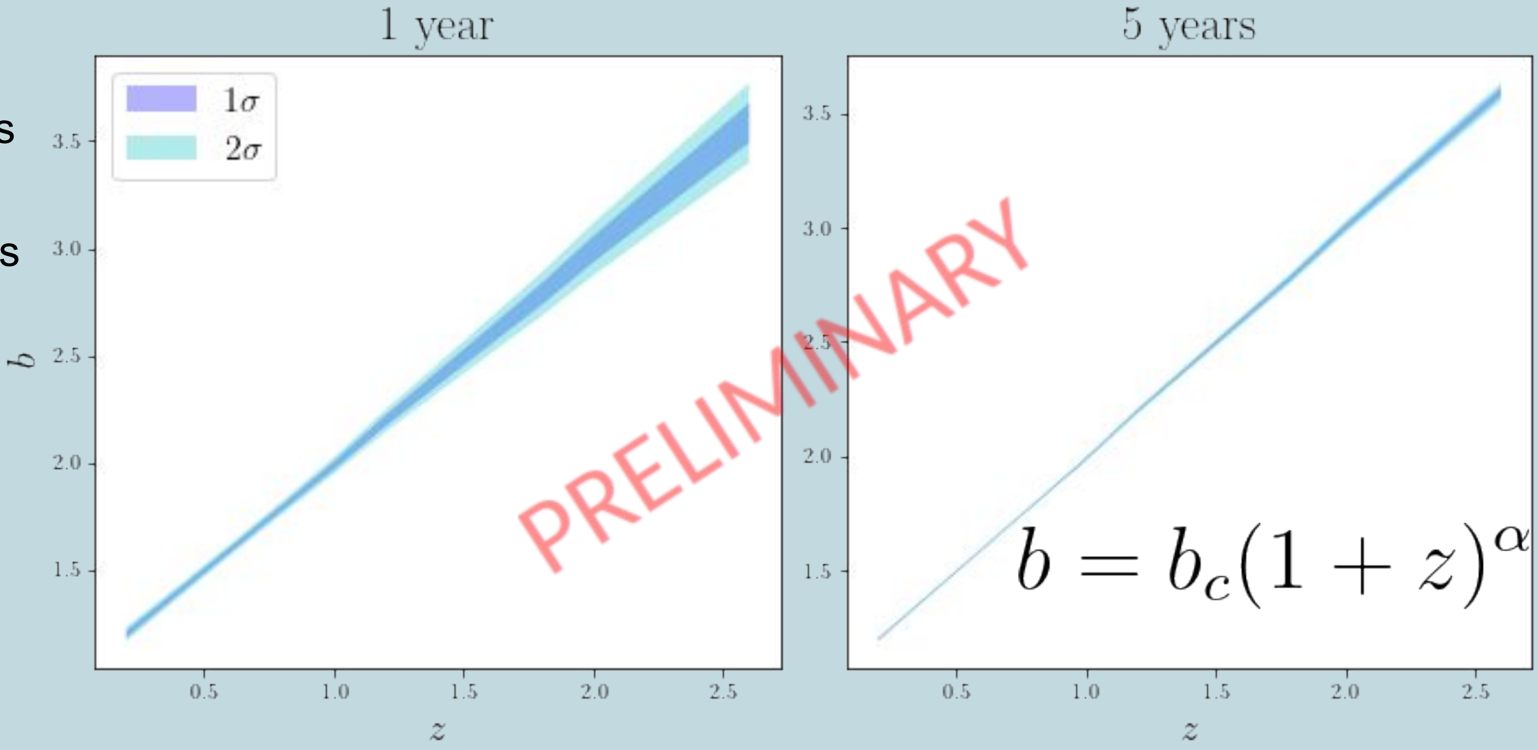
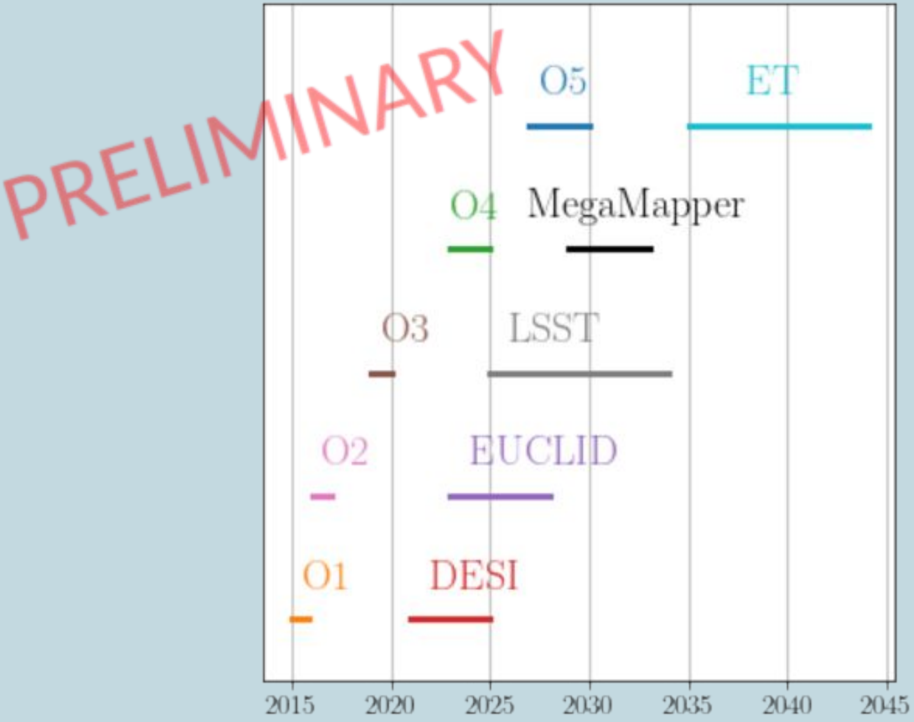
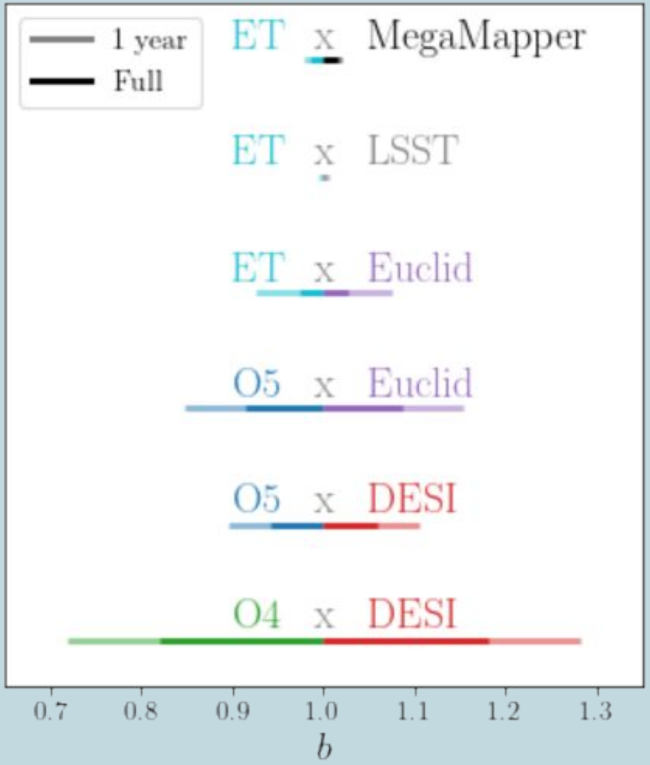
Clustering bias

Constraints from cross-correlations between an ET-like and LSST-like surveys



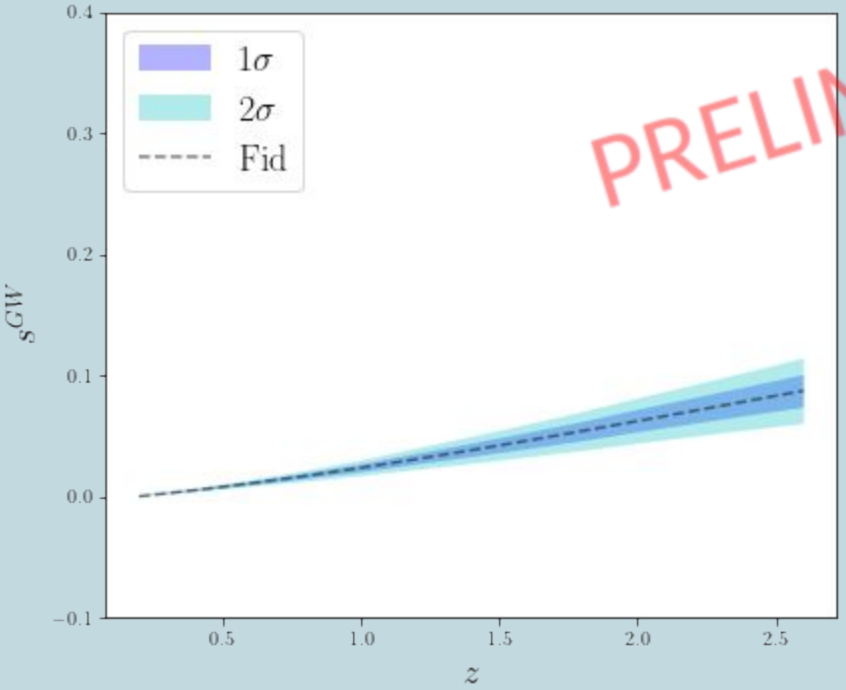
Cross-correlations with galaxy surveys



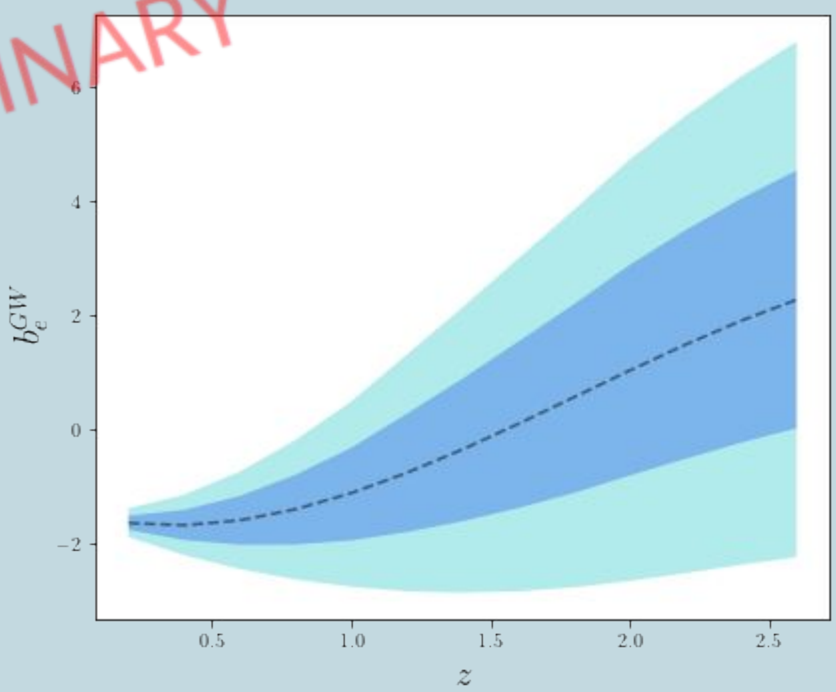


Magnification bias

Evolution bias

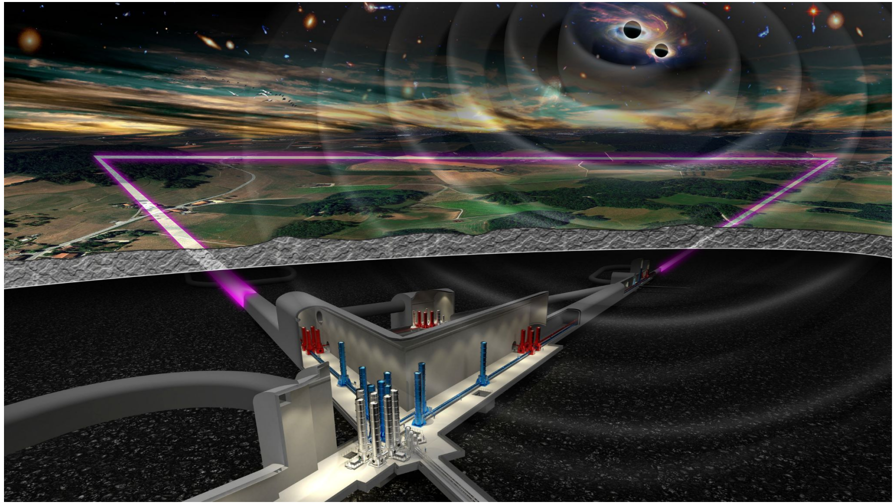


PRELIMINARY



Summary

- In the coming years one may start using transient events as tracers of Dark Matter. We considered transients for which we can only determine their luminosity distance;
- We have computed the density contrast in Luminosity Distance Space and rederived the luminosity distance perturbation in an FLRW universe and implemented it in CAMB;
- Modelling the biases for GWs will help us use them as LSS tracers;
- Cross-correlations with galaxies will be able to constrain BBHs population bias parameters and help us understand their evolution.



Credits: NIKHEF