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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

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Stefano Zazzera

On cosmological clustering of Gravitational Wave Events

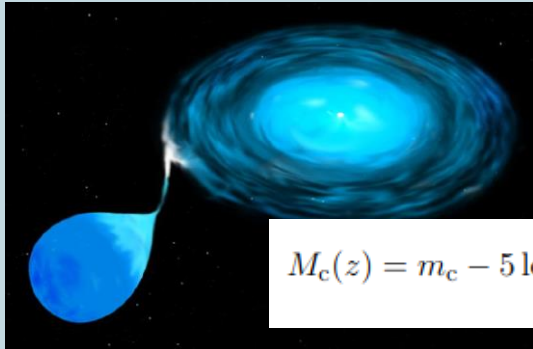
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Motivation

Can we use transient events as DM tracers?

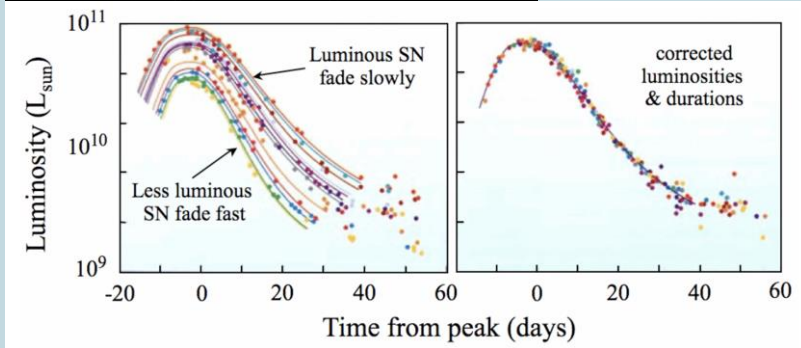
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Can we use transient events as DM tracers?



SN Ia

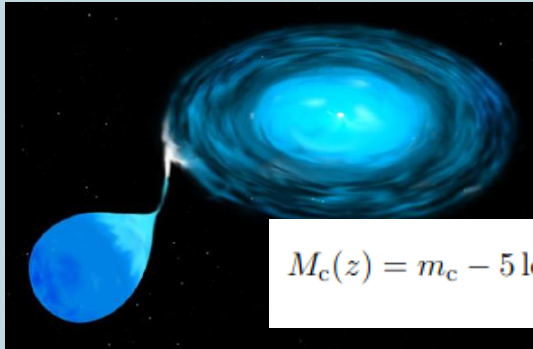
$$M_c(z) = m_c - 5 \log \left[\frac{d_L(z)}{10 \text{ pc}} \right] - K(z)$$



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

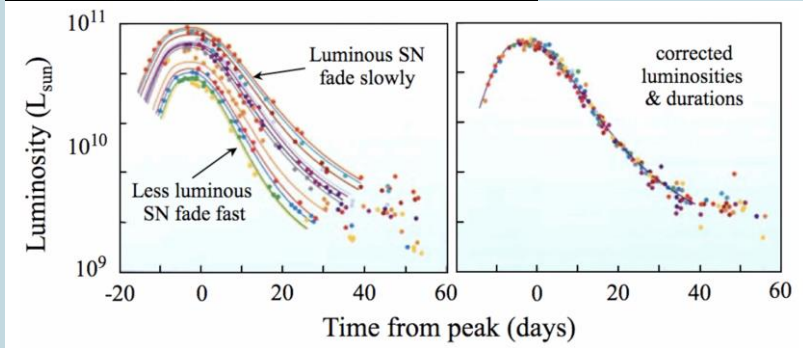
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SN Ia

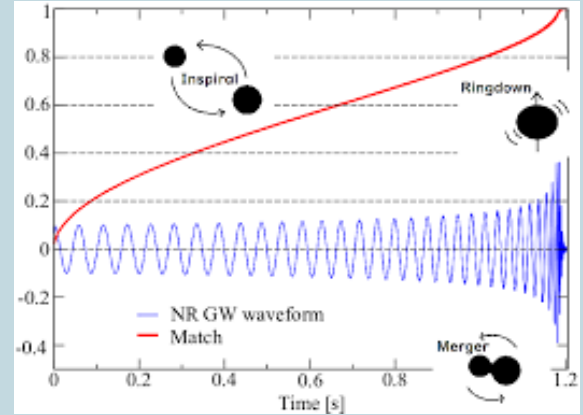
$$M_c(z) = m_c - 5 \log \left[\frac{d_L(z)}{10 \text{ pc}} \right] - K(z)$$



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

GW

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

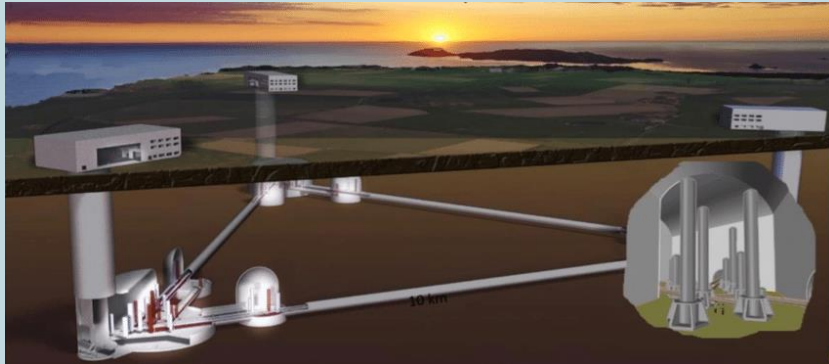


YES!

- 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?



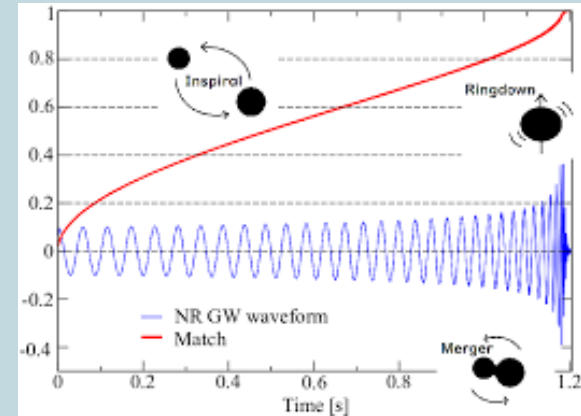
Credits: Einstein Telescope

Next Generation surveys:

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

GW

$$h \propto \frac{M_z^{5/3}}{d_L}$$



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;

Which density contrast do we observe?

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

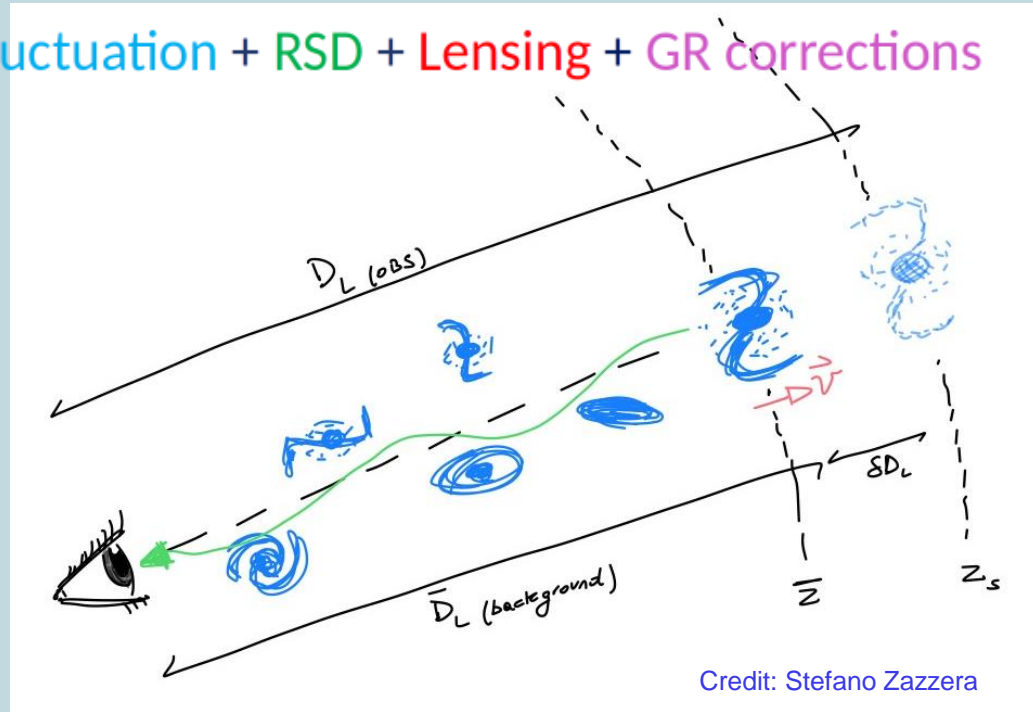
$$\Delta_N = \frac{N - \langle N \rangle}{\langle N \rangle}$$

Expand

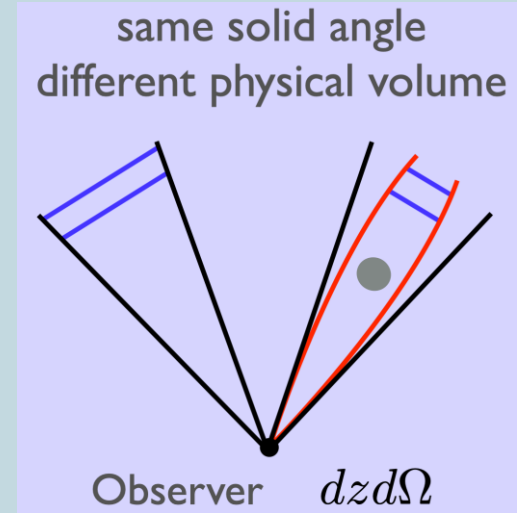
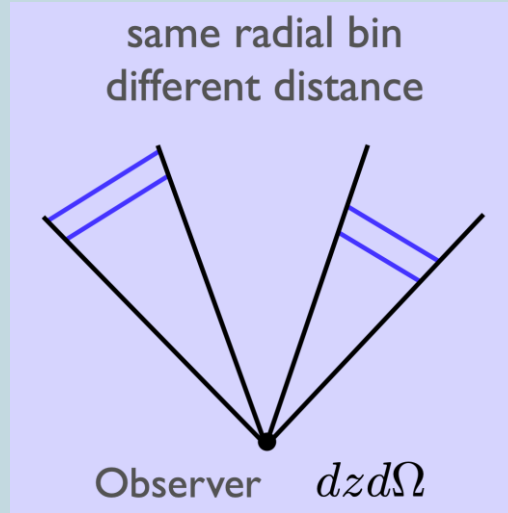
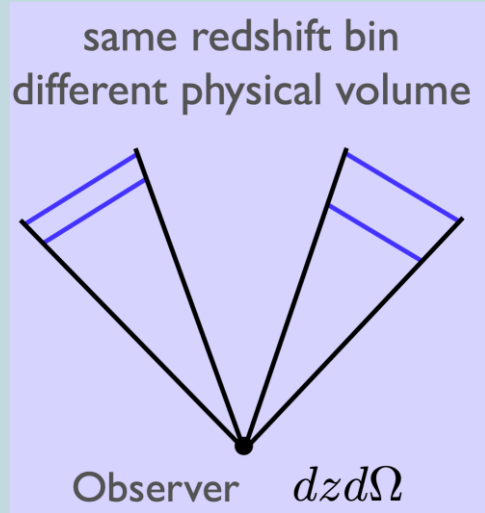
$$\Delta_O(D_L, \hat{n}) = \delta_n - \left[3 - b_e - \frac{5}{\gamma} s \right] \gamma \frac{\delta D_L}{\bar{D}_L} + \frac{\delta V(\mathbf{n}, D_L)}{\bar{V}(D_L)}$$

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

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



Which density contrast do we observe?



Credit: Camille Bonvin

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

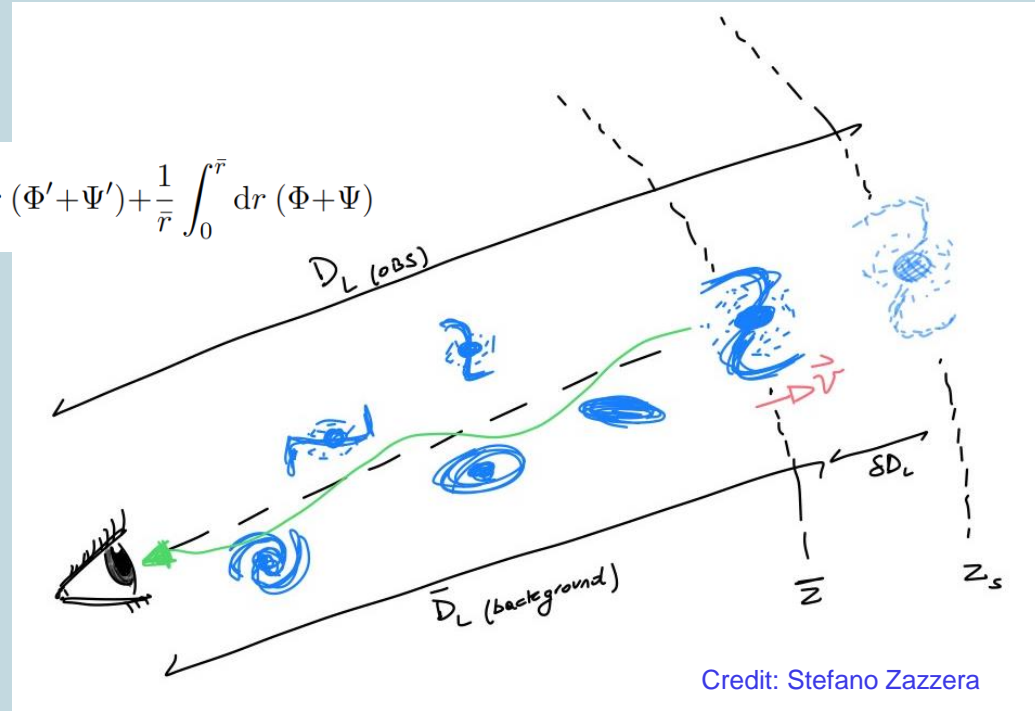
$$\Delta = \text{density} + \text{RSD} + \text{Doppler effect} + \text{Magnification Lensing} + \text{Potential terms}.$$

Which density contrast do we observe?

Luminosity Distance Perturbation

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

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



Which density contrast do we observe?

Density contrast

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

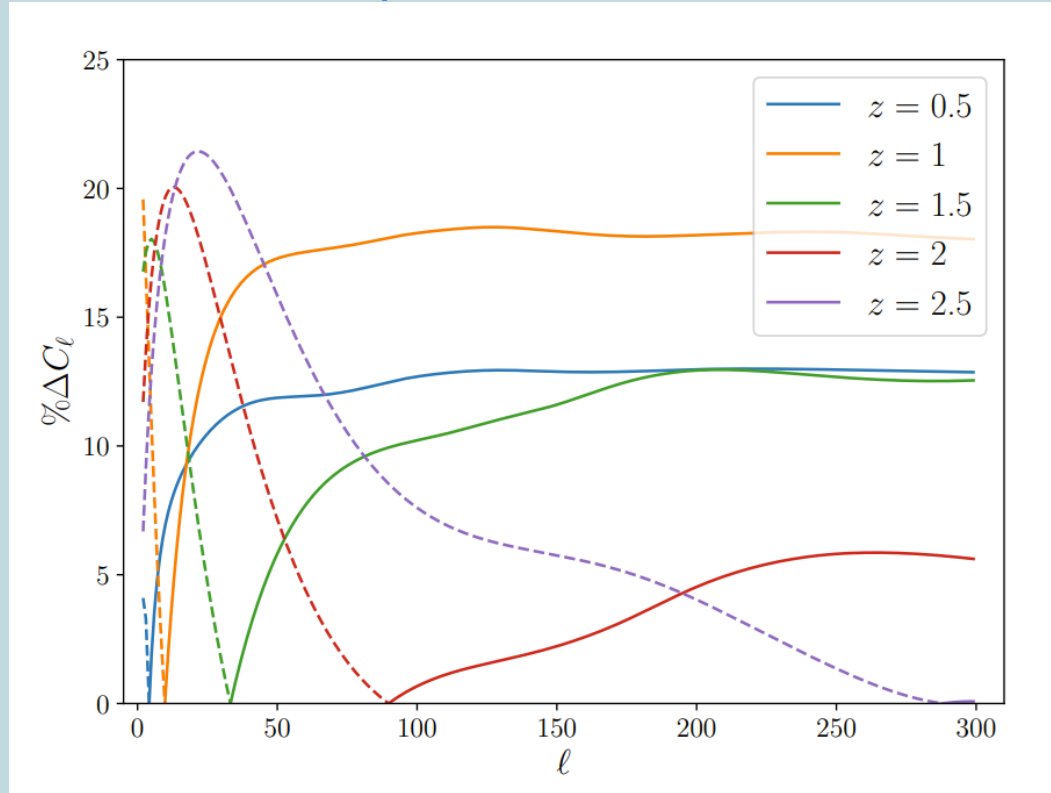
$$\beta \equiv \gamma \left[\frac{2}{\bar{r}\mathcal{H}} + \gamma \left(\frac{\mathcal{H}'}{\mathcal{H}^2} - \frac{1}{\bar{r}\mathcal{H}} \right) - 1 - b_e \right] - 5s + 1$$

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.

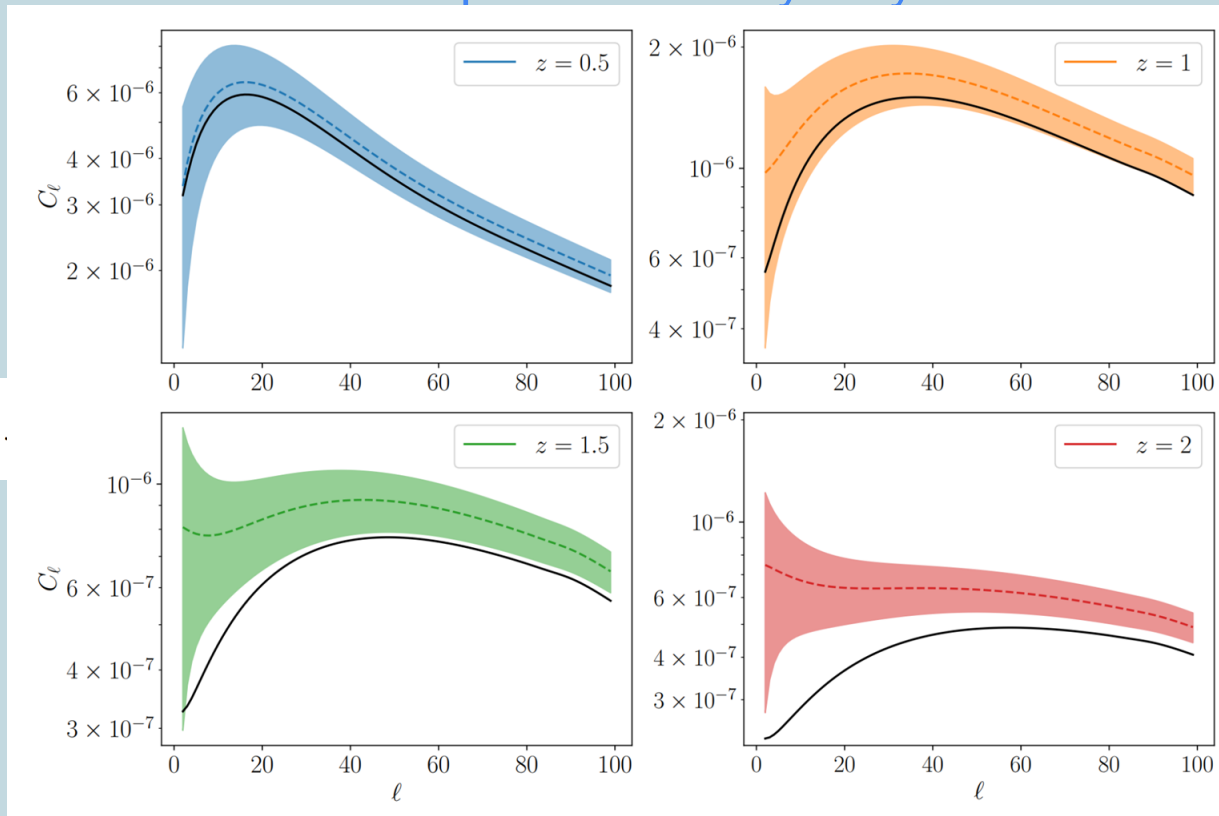
Differences between LD and z spaces



We cannot use the z expression for LD space

broad selection function

"Cosmic Variance limit" with respect to density only



$$\Delta C_\ell = \sqrt{\frac{2}{(2\ell + 1)f_{\text{sky}}}} (C_\ell + \dots)$$

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.

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

Evolution bias

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

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

GWs Biases*

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

Observed number density

Intrinsic merger rate

Chirp mass distribution

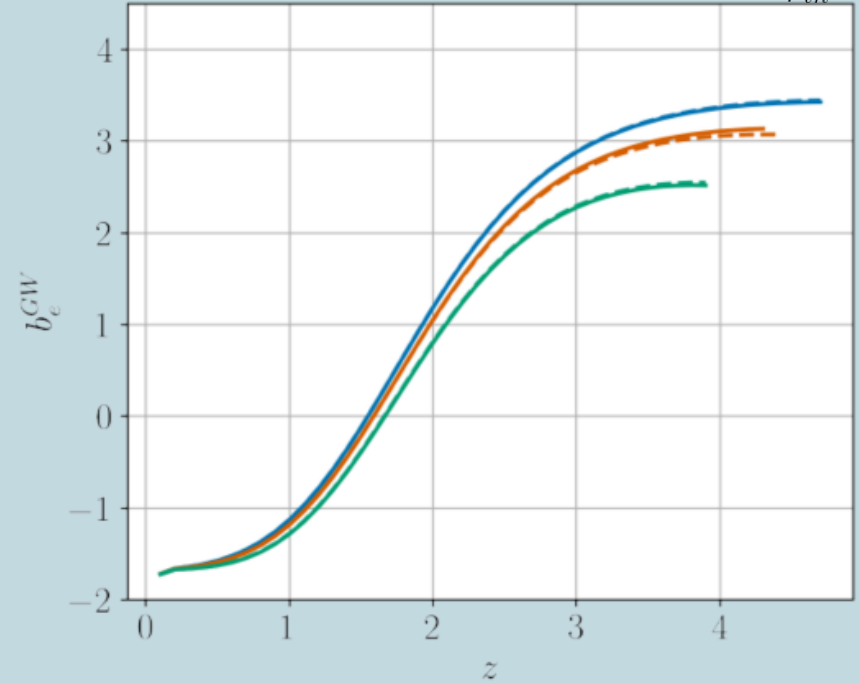
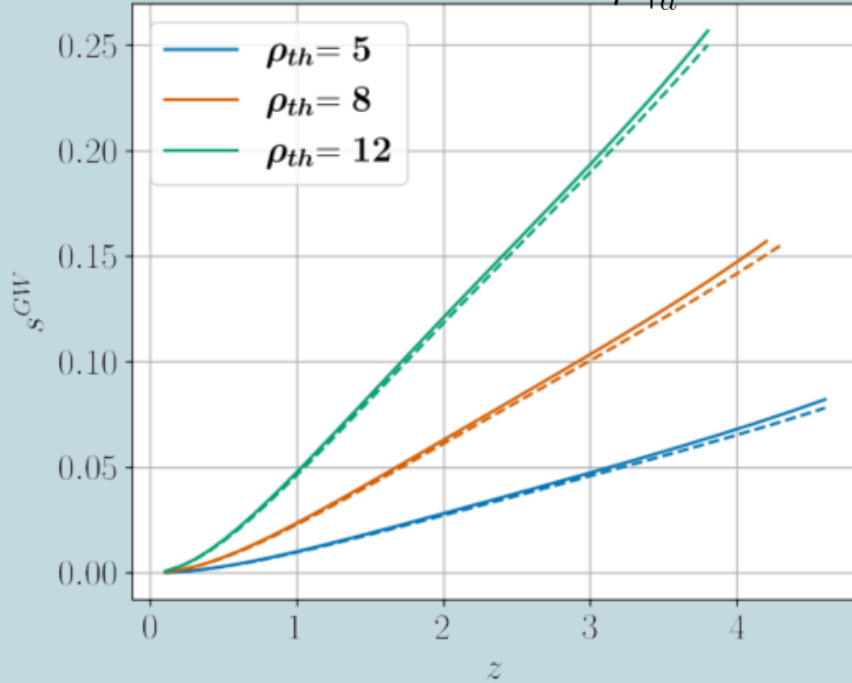
Survival function of event (Likelihood of detection)

* Inspirals of astrophysical Binary Black Holes

GWs Biases – Einstein Telescope

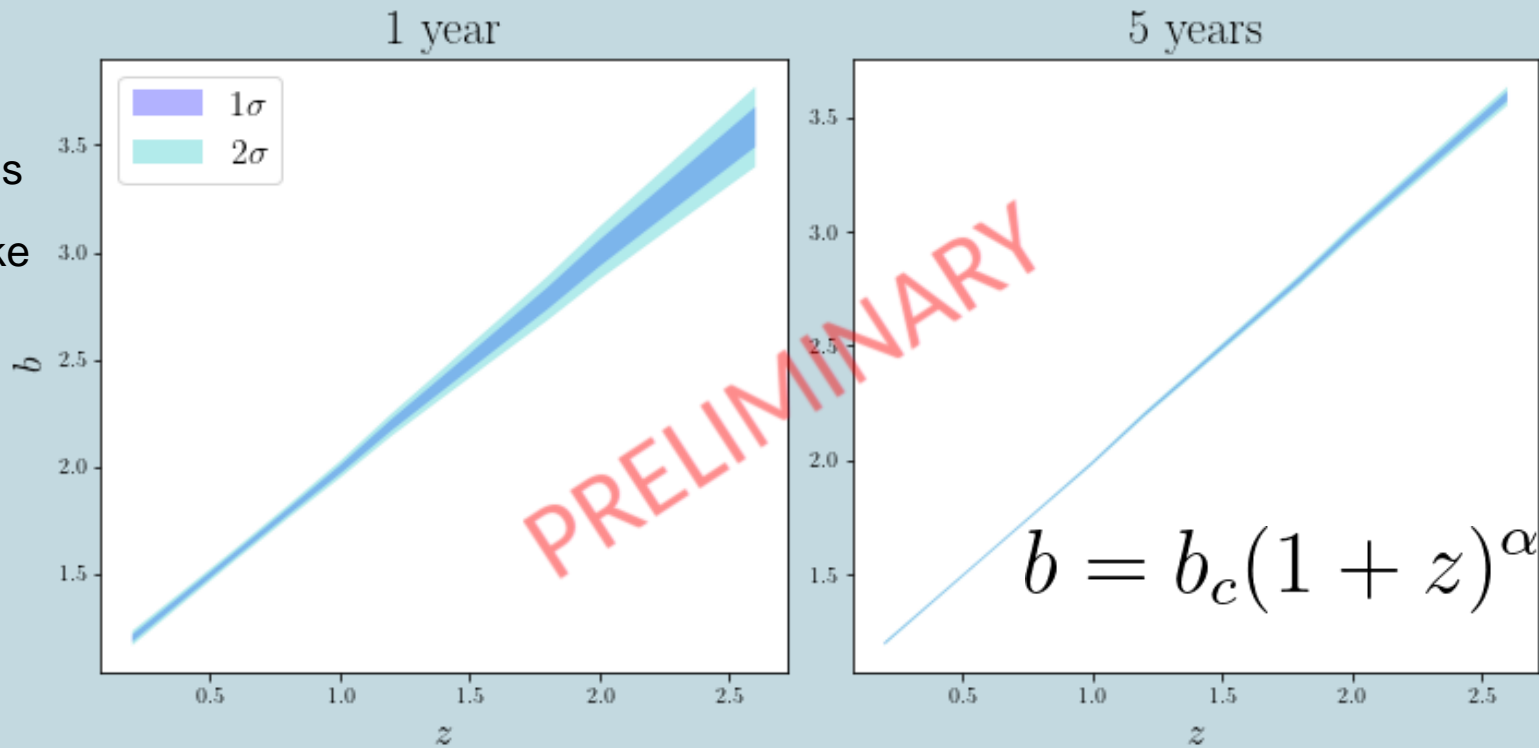
$$s^{GW} \equiv -\frac{1}{5} \frac{\partial \ln n}{\partial \ln \rho} \Big|_a$$

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



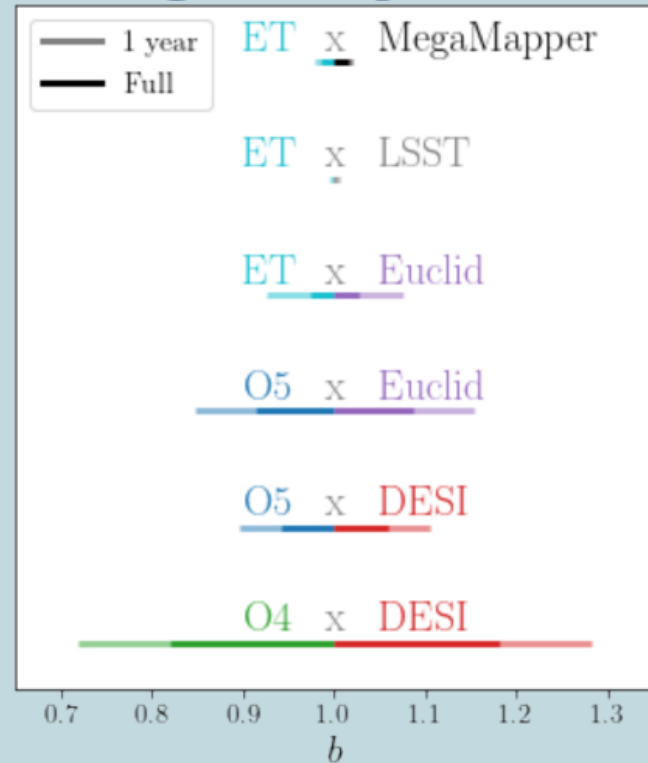
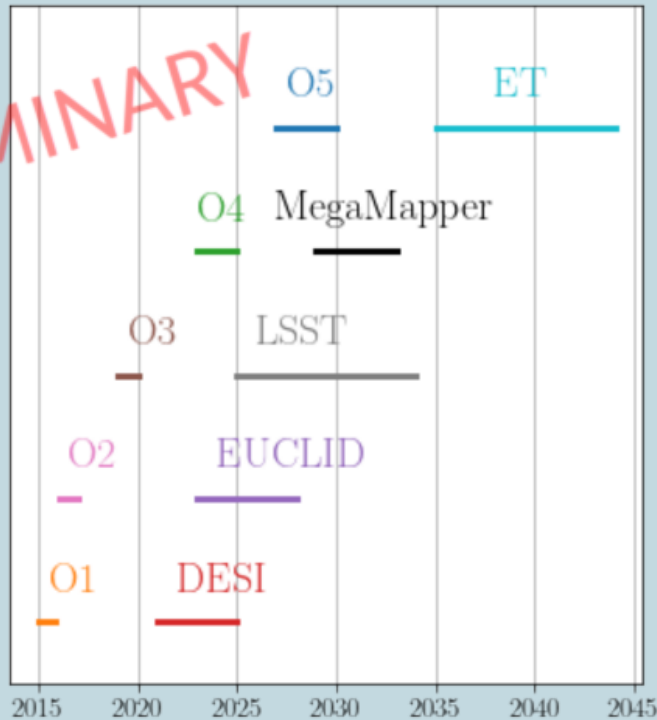
Clustering bias

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

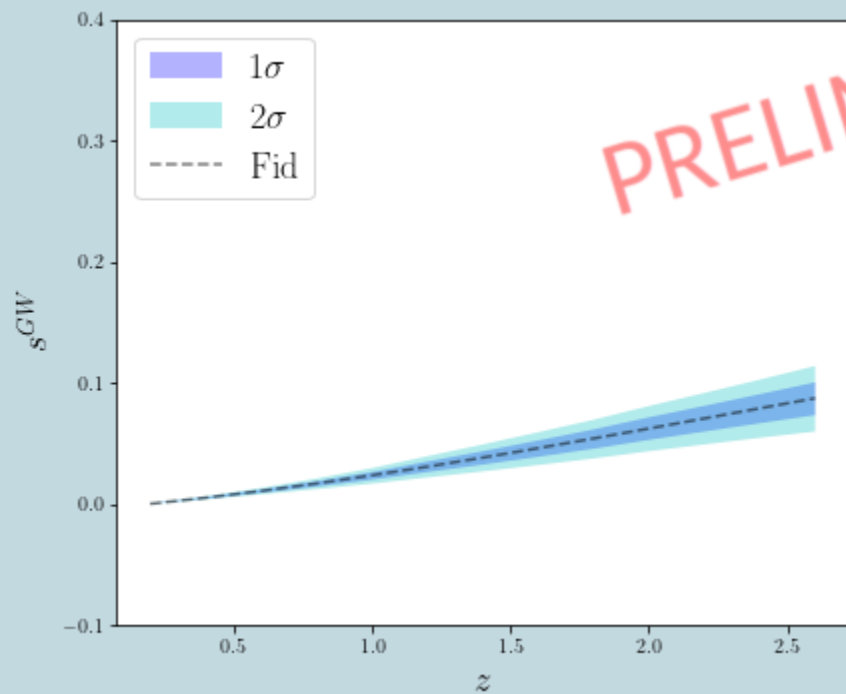


Cross-correlations with galaxy surveys

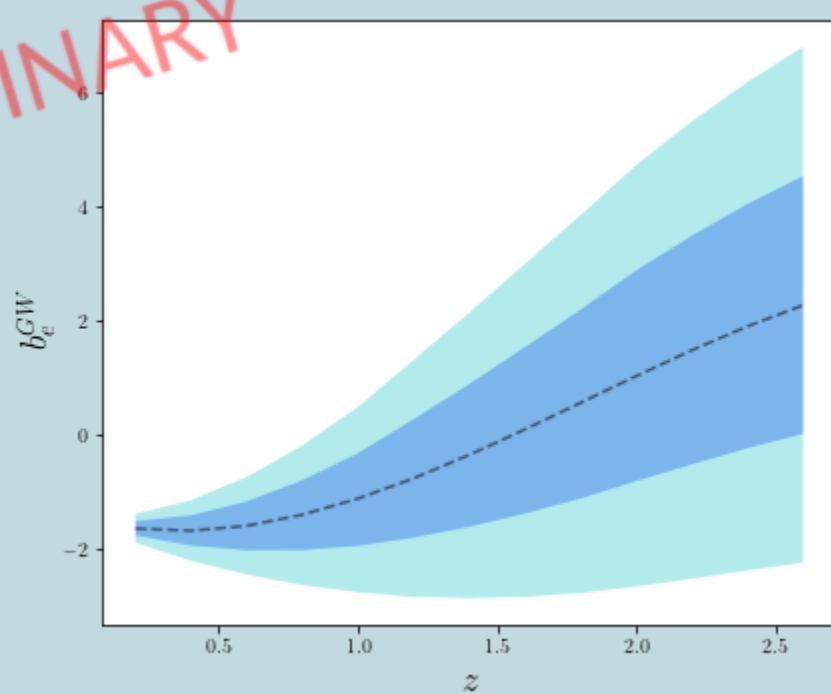
PRELIMINARY



Magnification bias



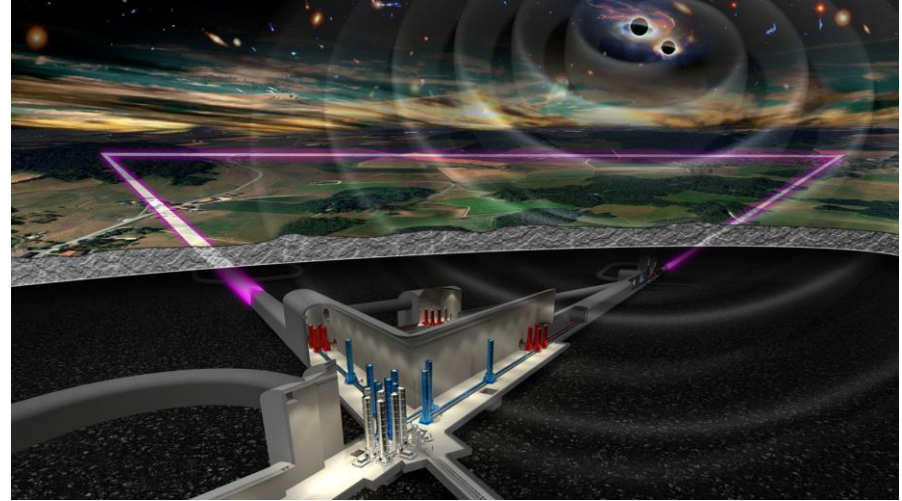
Evolution bias



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