José Fonseca

Instituto de Astrofísica e Ciências do Espaço, Universidade do Porto

jose.fonseca@astro.up.pt

# On cosmological clustering of Gravitational Wave Events

**CASTLE 2024 - Tagliolo Monferrato - 19/09/2024**

José Fonseca

Instituto de Astrofísica e Ciências do Espaço, Universidade do Porto

jose.fonseca@astro.up.pt

Stefano Zazzera

# On cosmological clustering of Gravitational Wave Events

**CASTLE 2024 - Tagliolo Monferrato - 19/09/2024**

# Motivation

### Can we use transient events as DM tracers?

# Motivation

## Can we use transient events as DM tracers?



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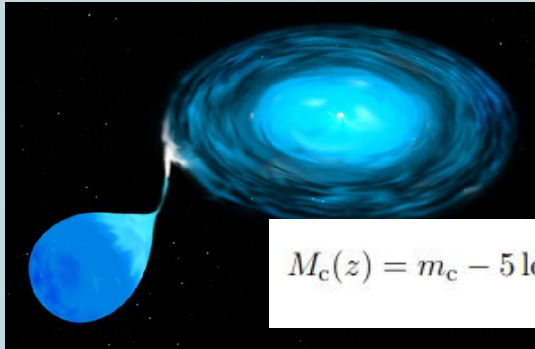
$$M_c(z) = m_c - 5 \log \left[ \frac{d_L(z)}{10\,\text{pc}} \right] - K(z)$$



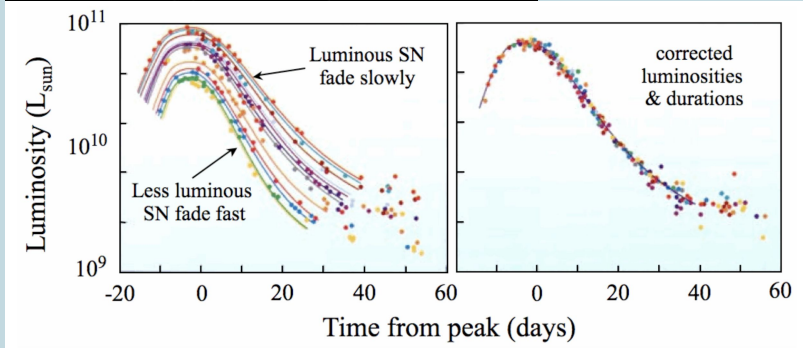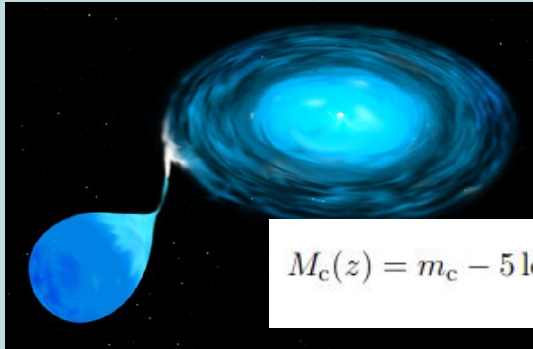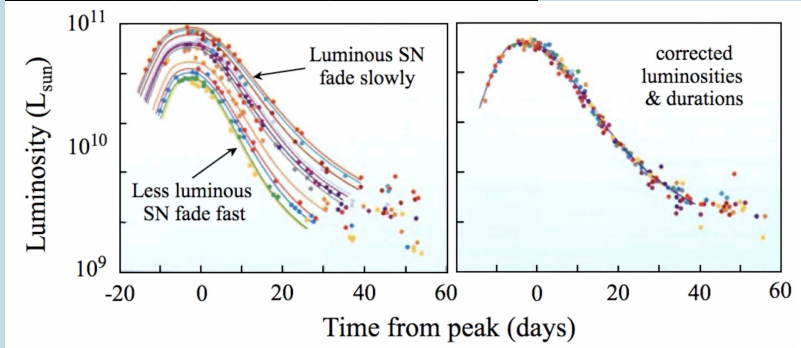LSST expects $10^7$ over 10yrs up to z=4

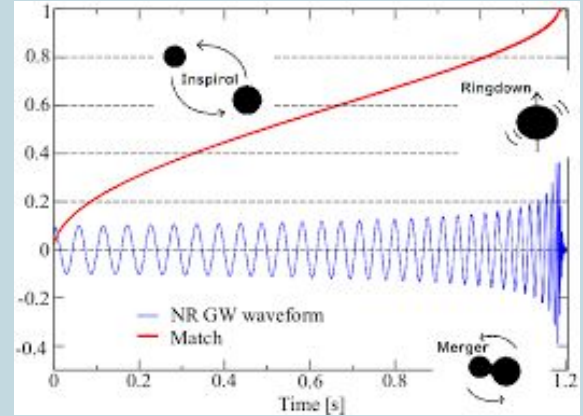# Motivation    Can we use transient events as DM tracers?



SNeIa

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



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;

- Miguel Quartin group with SNeIa.

# 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



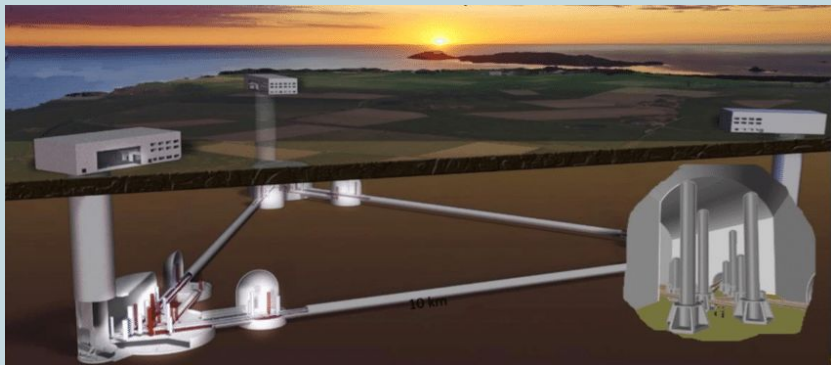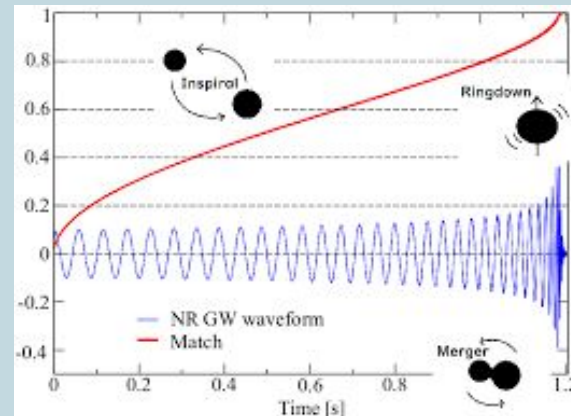$$h \propto \frac{\mathcal{M}_z^{5/3}}{d_L}$$

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;

- Namikawa et al (2021), in 3D space;

- Miguel Quartin group with SNeIa.

# Which density contrast do we observe?

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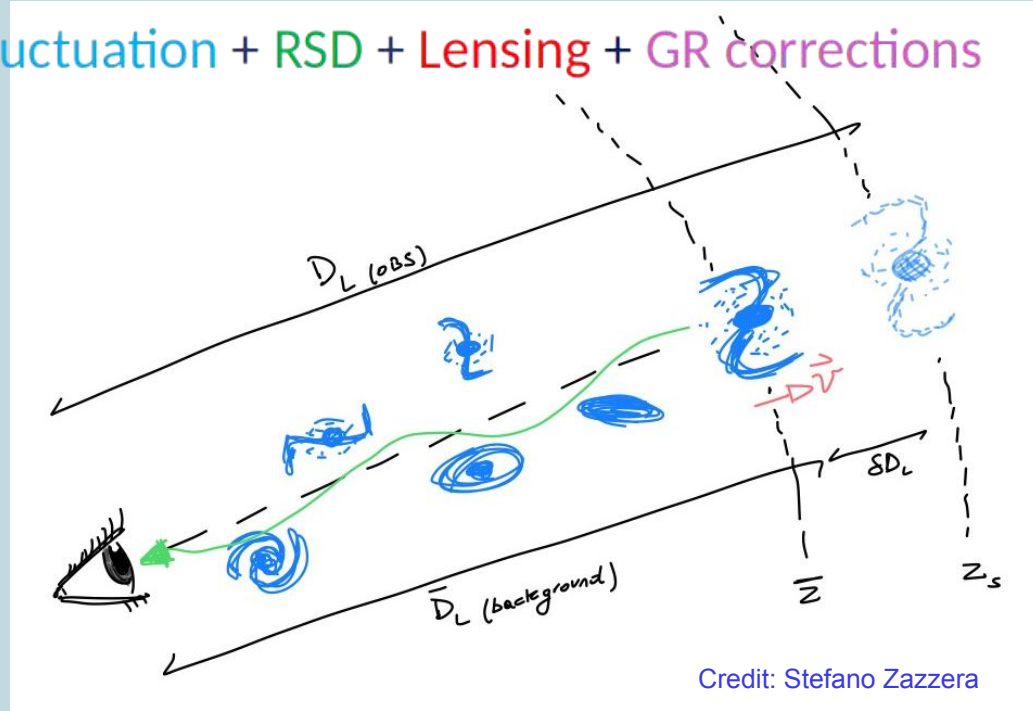
Density contrast

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

Expand

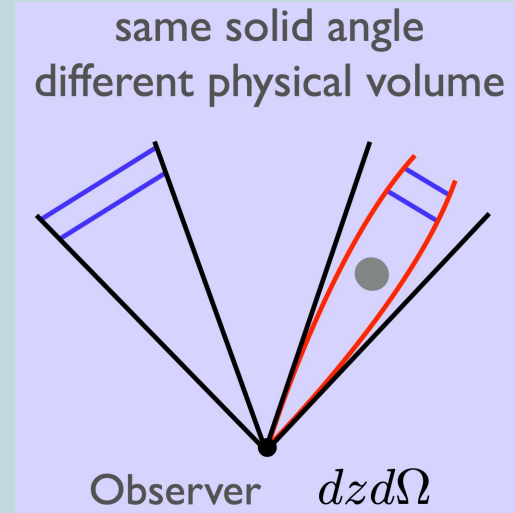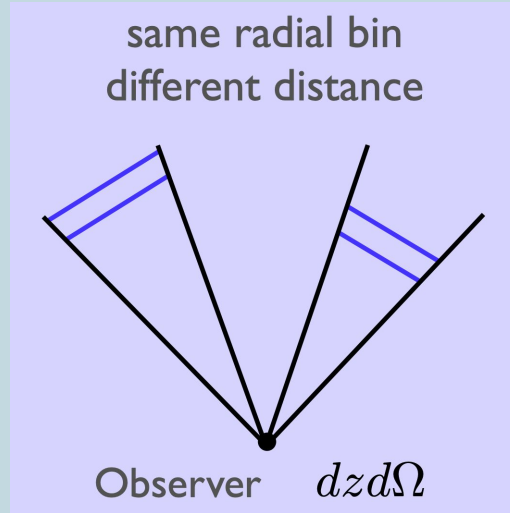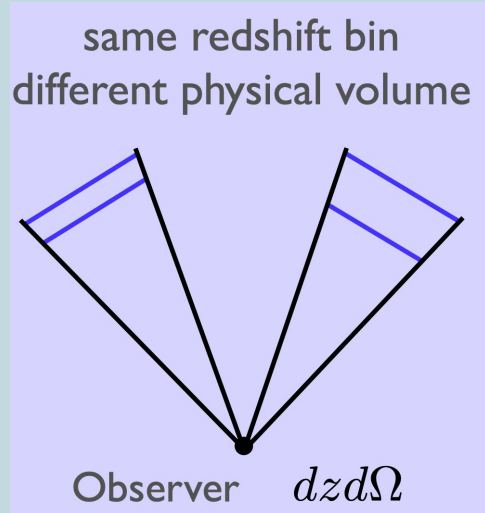$$\Delta_O(D_L, \hat{n}) = \delta_n - \left[ 3 - b_e - \frac{5}{\gamma} s \right] \gamma \frac{\delta D_L}{\bar{D}_L} + \frac{\delta V(\boldsymbol{n}, D_L)}{\bar{V}(D_L)}$$

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

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



Credit: Stefano Zazzera

JCAP08(2023)050 - arxiv:2304.14253

# Which density contrast do we observe?



same redshift bin
different physical volume

Observer    $dzd\Omega$

same radial bin
different distance

Observer    $dzd\Omega$

same solid angle
different physical volume

Observer    $dzd\Omega$

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

JCAP08(2023)050 - arxiv:2304.14253
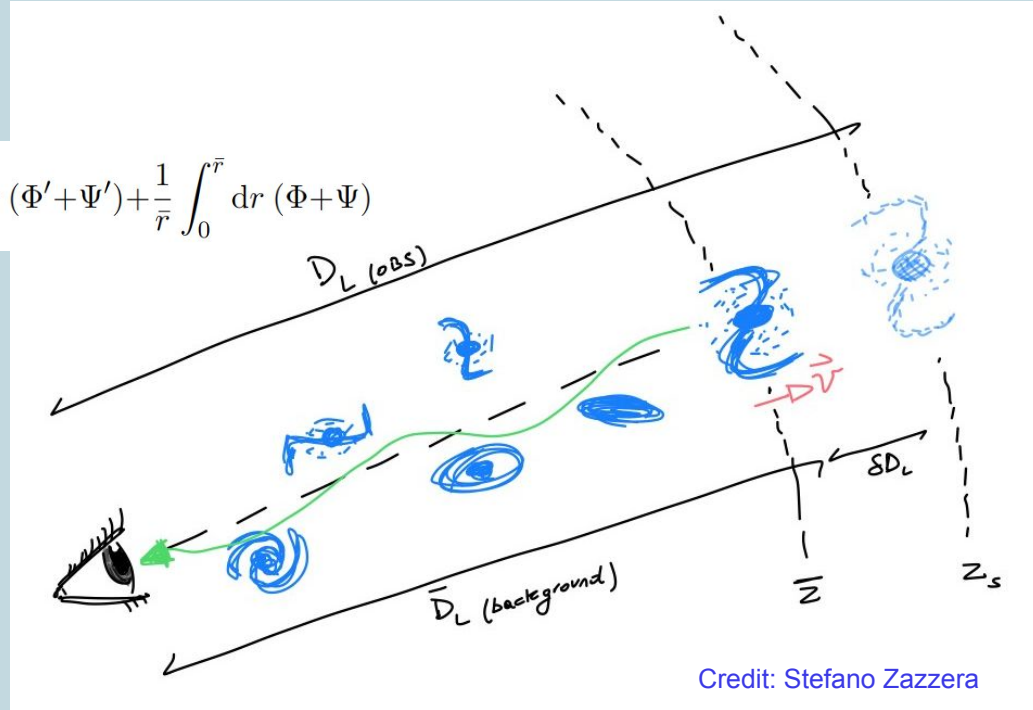
# Which density contrast do we observe?

## Density contrast

$$\Delta(\boldsymbol{n}, D_L) = \delta_n - 2\Phi + \Psi + \frac{\gamma}{\mathcal{H}}\frac{\mathrm{d}}{\mathrm{d}\lambda}\frac{\delta D_L}{\bar{D}_L} + v_r - 2\kappa_g + \frac{2}{\bar{r}}\int_0^{\bar{r}}\mathrm{d}r\,(\Phi + \Psi) - \beta\frac{\delta D_L}{\bar{D}_L}$$

$$= \delta_n + A_D(\boldsymbol{v}\cdot\boldsymbol{n}) + A_{LSD}\partial_r(\boldsymbol{v}\cdot\boldsymbol{n}) + A_\Psi\Psi + A_\Phi\Phi + A_{\Phi'}\Phi' + A_{\nabla\Phi}\partial_r\Phi$$

$$+ \frac{1}{\bar{r}}\int_0^{\bar{r}}\mathrm{d}r\,(A_{TD} + A_L\Delta_\Omega)(\Phi + \Psi) + A_{ISW}\int_0^{\bar{r}}\mathrm{d}r\,(\Phi' + \Psi'),$$

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

## B  Comparison of the amplitudes

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

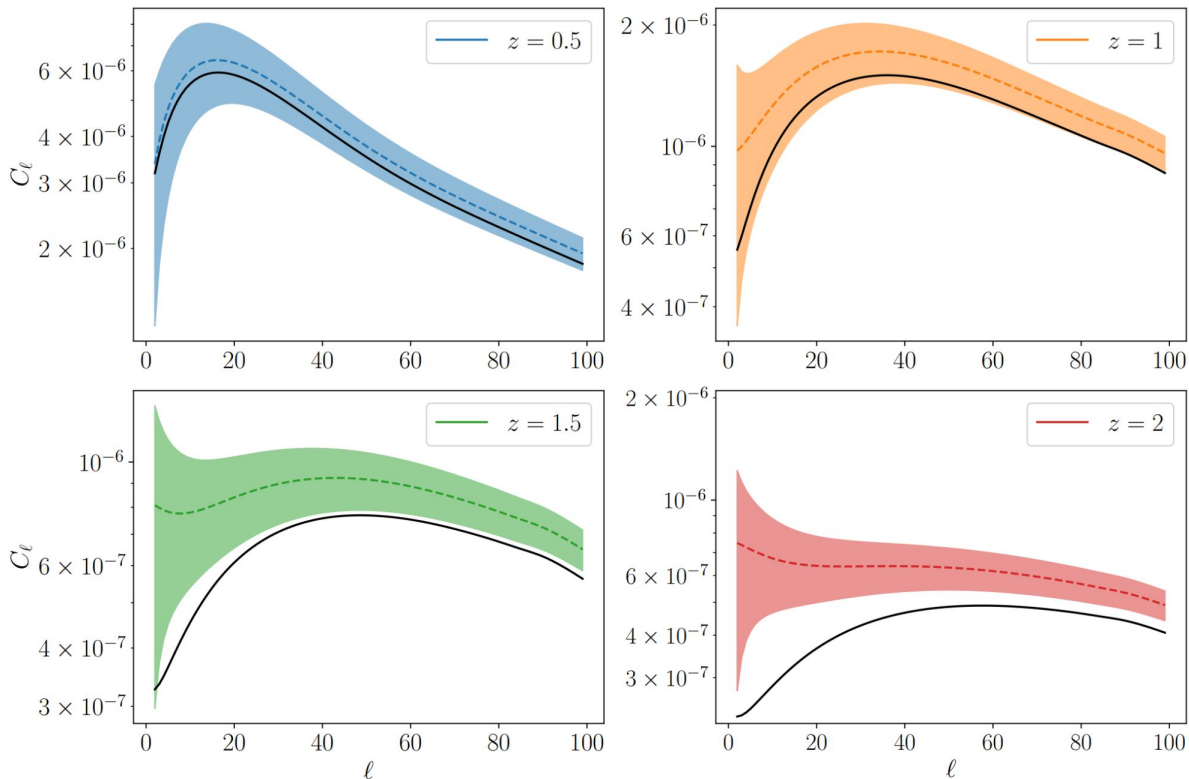## We changed CAMB to compute the angular power in LD space.

JCAP08(2023)050 - arxiv:2304.14253

# Differences between LD and z spaces



broad selection function
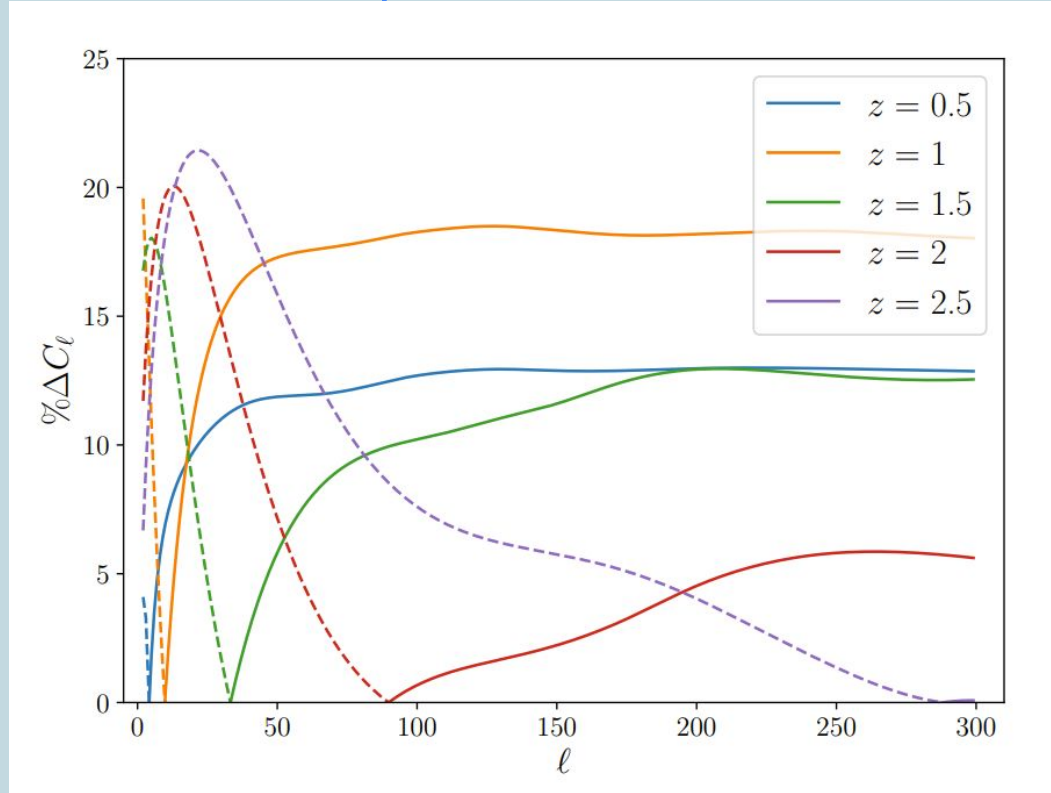
We cannot use the z expression for LD space
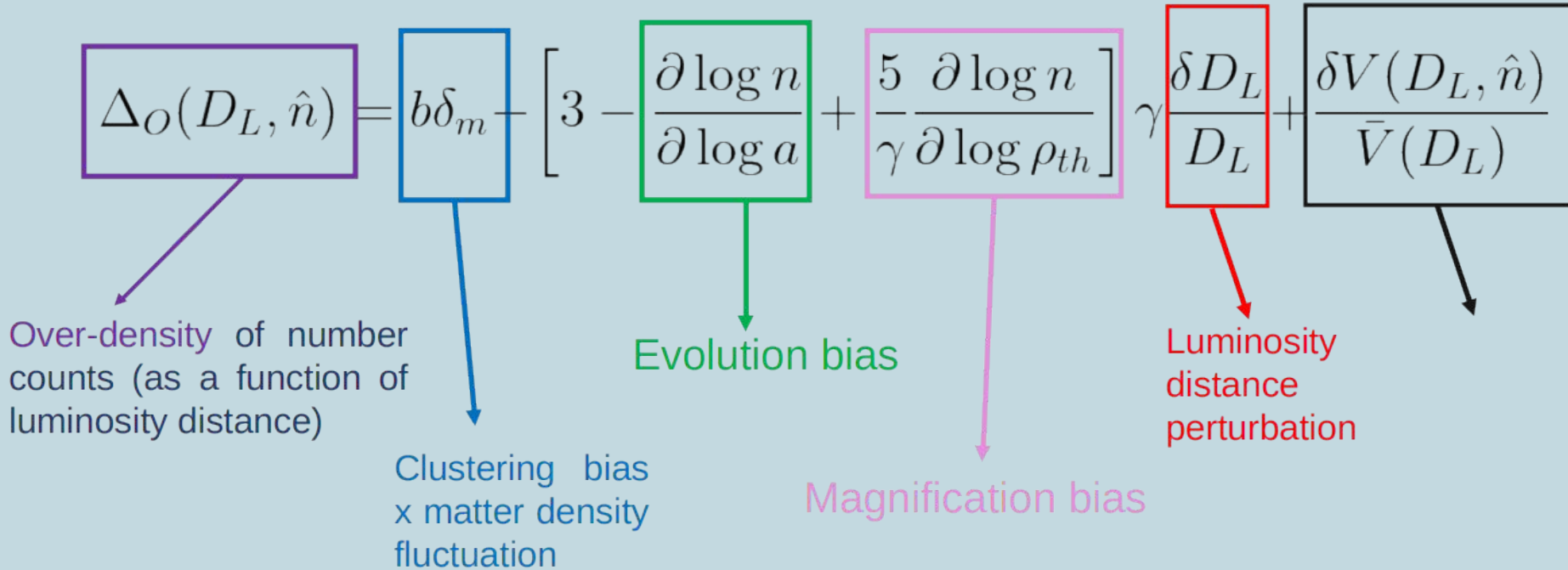
# "Cosmic Variance limit" with respect to density only

$$\Delta C_\ell = \sqrt{\frac{2}{(2\ell + 1)f_{\mathrm{sky}}}}\left(C_\ell + \right.$$

# 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.

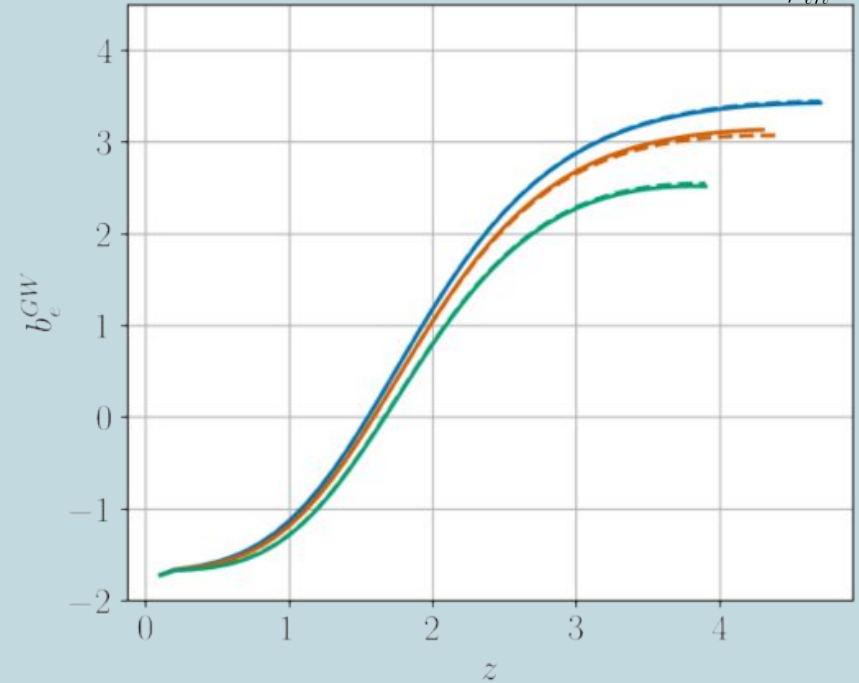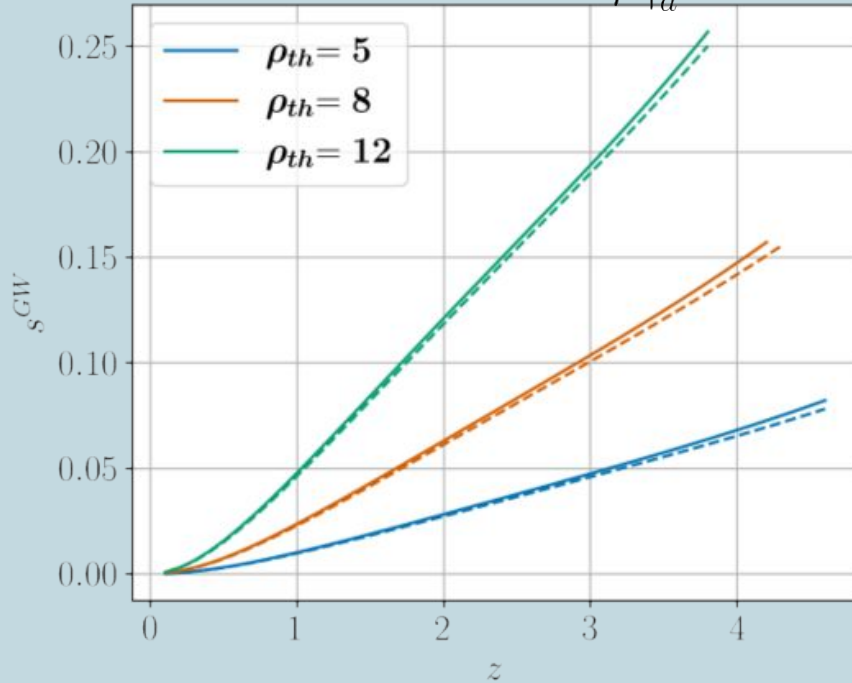$$b_e(a, L_c) \equiv \left.\frac{\partial \ln n(a, L_c)}{\partial \ln a}\right|_{L_c}$$

JCAP05(2024)095 - arXiv:2309.04391

# 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)
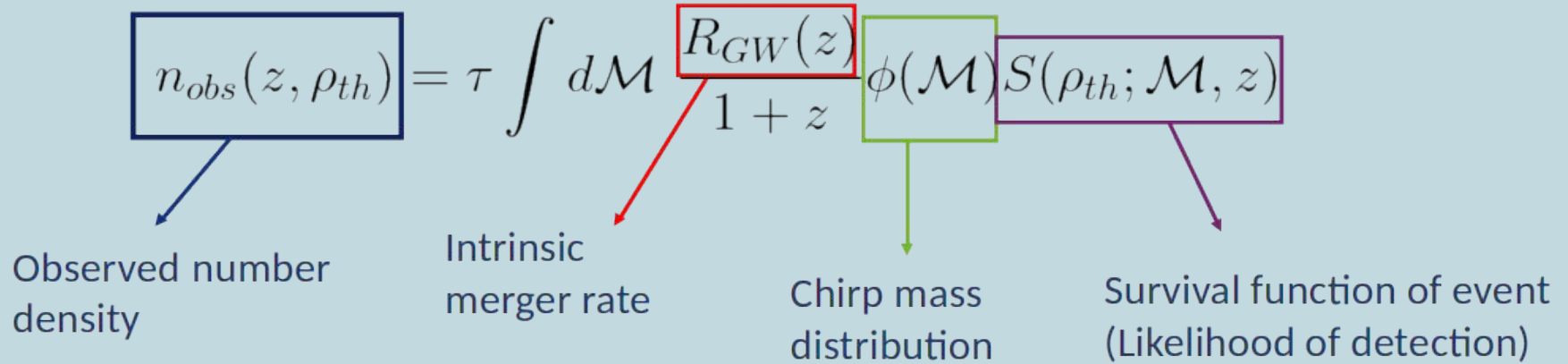
*Inspirals of astrophysical Binary Black Holes

JCAP05(2024)095 - arXiv:2309.04391

# GWs Biases — Einstein Telescope

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

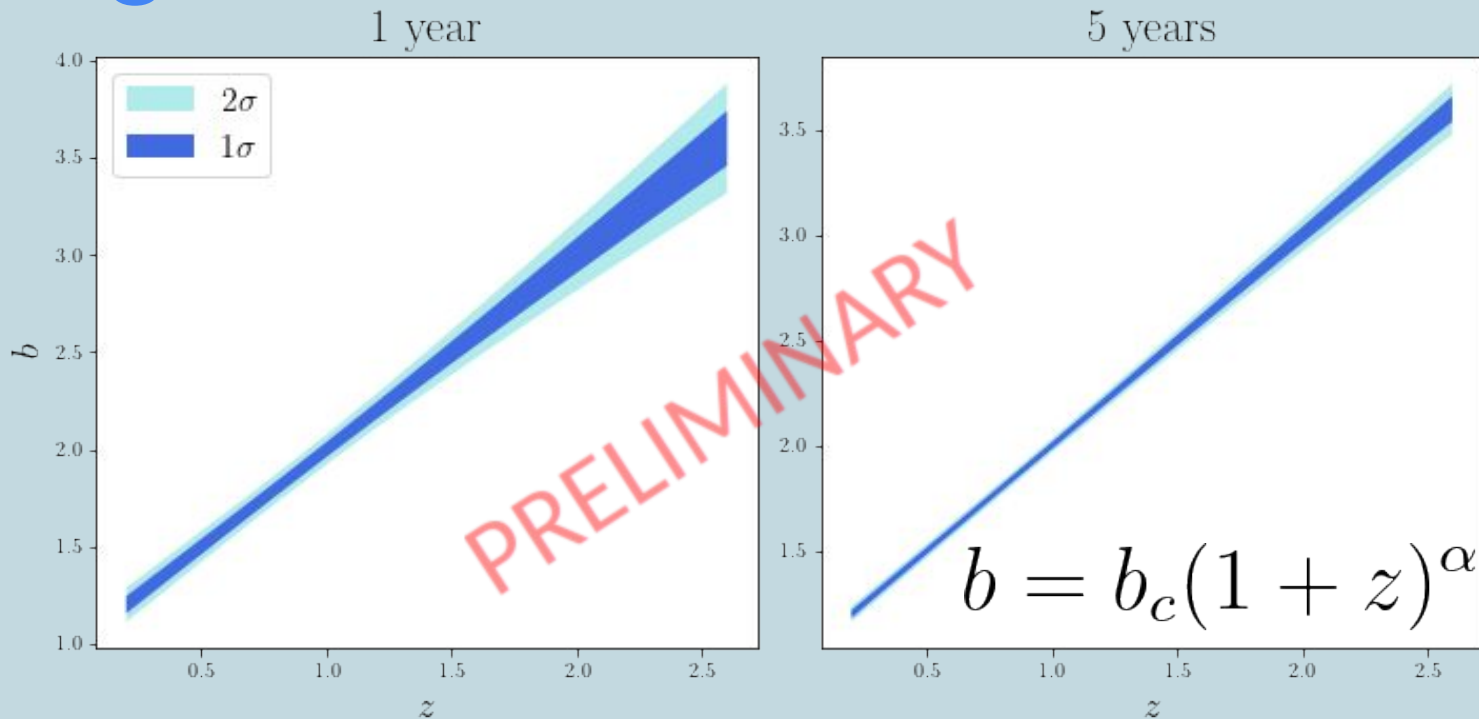$$b_e^{GW} \equiv \frac{\partial \ln n}{\partial \ln a}\bigg|_{\rho_{th}}$$

# Cross-correlations with galaxy surveys
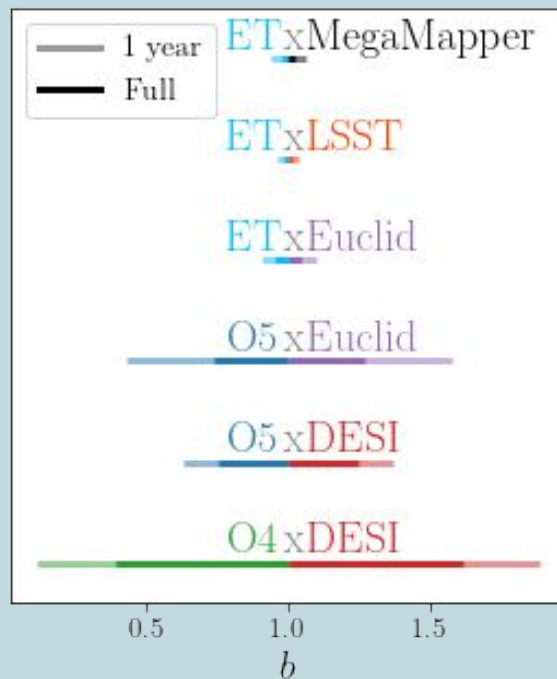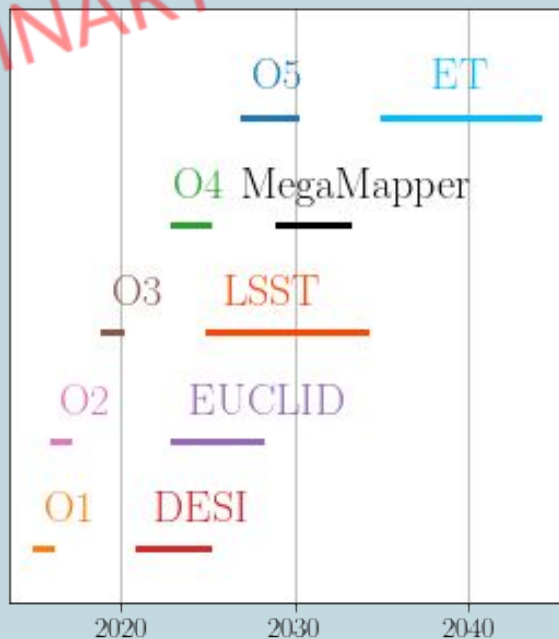
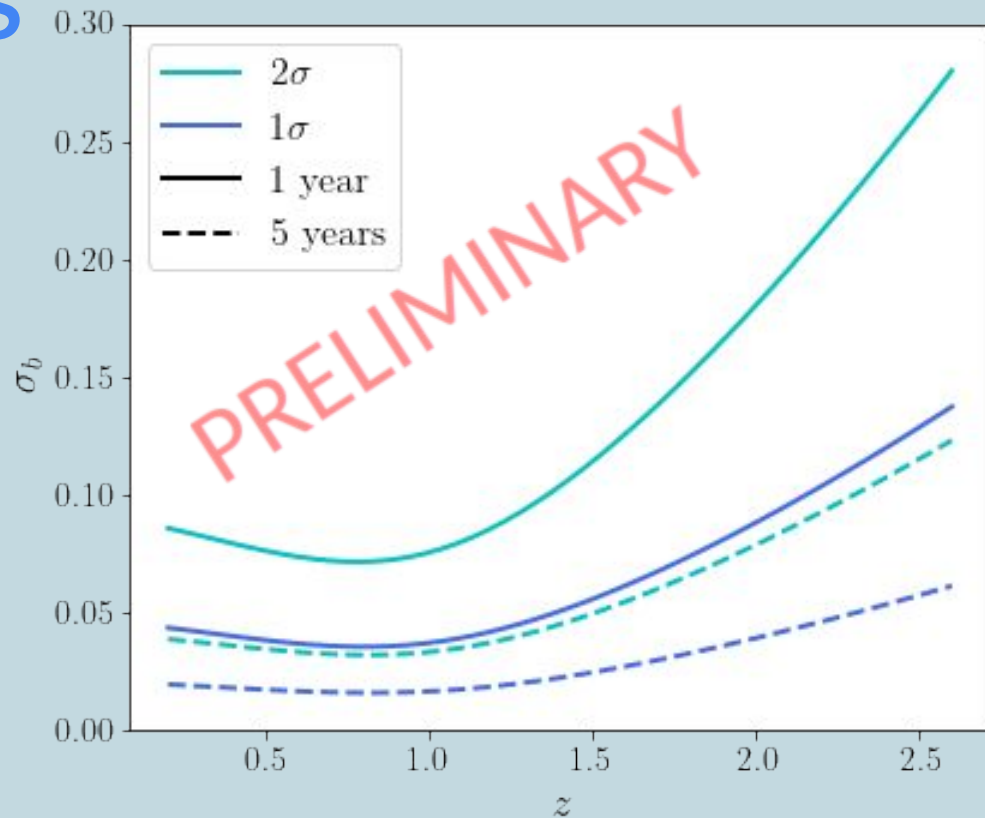# Clustering bias

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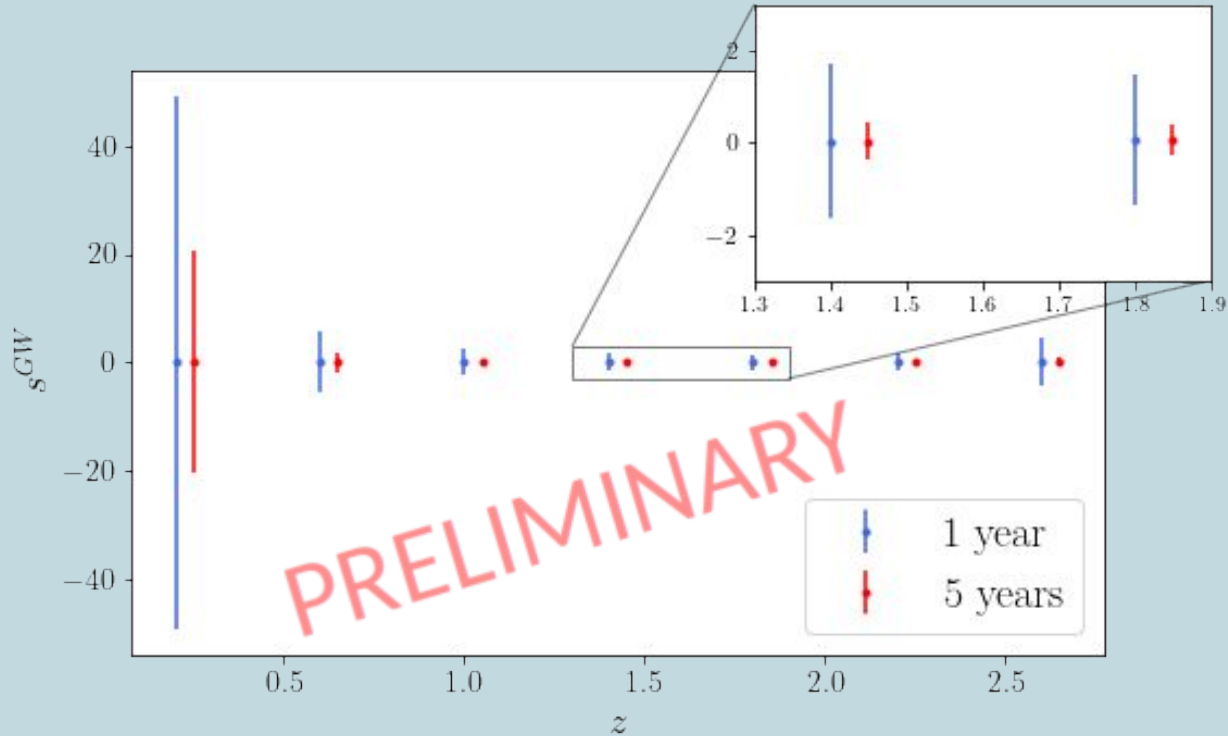cross-correlations
between an
ET-like and
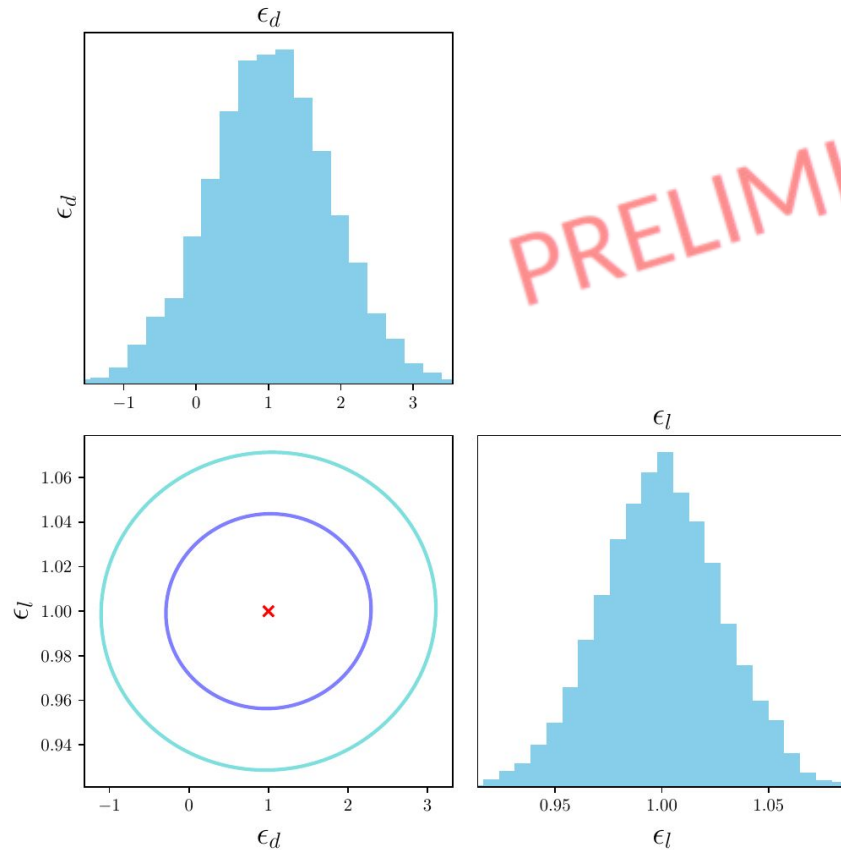LSST-like surveys



$$b = b_c(1 + z)^\alpha$$

# Clustering bias

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

# Magnification bias

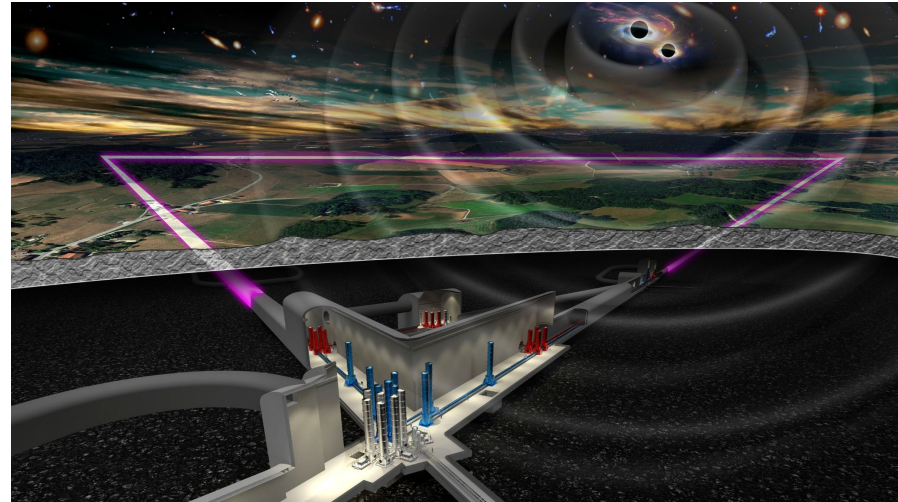# GR effects

# 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;

- Also a new way to test kappa.



Credits: NIKHEF