Future CMB delensing with galaxies surveys.

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- Worry : they might ask for iterative delensing
- Worry : they might ask for internal bias item Possible TODO : temperature N_{eff}

The measurement of the CMB polarization is a promising experimental dataset to test the inflationary paradigm and to probe the physics of the early universe. A particular component, the so called B-modes is indeed a direct signature of the presence of gravitational waves in the early universe. However improving the level of noise is not enough. This is even more true if the aim is to not only detect the amplitude of gravitational waves but also the shape of their spectrum to test for example inflation consistency relations. Removing the lensing component from the measurement of CMB B-modes will be important to constraint the amplitude of the primordial gravitational wave contribution to the signal. Here we discuss the role of current and future large scale structure surveys in improving the reconstruction of the lensing potential that lenses the CMB photons. We find that..

I. INTRODUCTION

Inflation Physics with CMB
Current constraints
Now limiting by delensing
Done what are the prospects/
This paper is organized as follow:

II. THEORY

As for the temperature, the intensity map of photons on the sky, also the Q and U mode decomposition of their polarization is modified by lensing as:

$$Q(\hat{\mathbf{n}}) = Q_{\text{unlensed}}(\hat{\mathbf{n}} + \mathbf{d}); \quad U(\hat{\mathbf{n}}) = U_{\text{unlensed}}(\hat{\mathbf{n}} + \mathbf{d}) \quad (1)$$

where $\mathbf{d}$ is the deflection angle directly related to the lensing potential ϕ.

As a first approximation, the B mode resulting from the lensing of primordial E mode by a convergence field κ is:

$$B^{\text{lens}}(\mathbf{l}) = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W(\mathbf{l},\mathbf{l}') E(\mathbf{l}') \kappa(\mathbf{l}-\mathbf{l}') \quad (2)$$

where

$$W(\mathbf{l},\mathbf{l}') = \frac{2\mathbf{l}' \cdot (\mathbf{l}-\mathbf{l}')}{|\mathbf{l}-\mathbf{l}'|^2} \sin(2\varphi_{\mathbf{l},\mathbf{l}'}), \quad (3)$$

As usual we define the power spectrum as:

$$\langle B^{\text{lens}}(\mathbf{l})\ B^{\text{lens}^*}(\tilde{\mathbf{l}}) \rangle \equiv (2\pi)^2 \delta^D(\mathbf{l}-\tilde{\mathbf{l}}) C_l^{BB,\text{lens}} \quad (4)$$

From this we get that the power spectrum of the lensing component of the B-modes:

$$C_l^{BB,\text{lens}} = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W^2(\mathbf{l},\mathbf{l}') C_{l'}^{EE} C^{\kappa\kappa}_{|\mathbf{l}-\mathbf{l}'|}. \quad (5)$$

Now the full B-mode power spectrum measured on the sky is

$$C_l^{BB,\text{full}} = C_l^{BB,r} + C_l^{BB,\text{lens}} + N_l^{BB}. \quad (6)$$

If we have an LSS measurements I($\hat{n}$) that traces the lensing potential responsible for the lensing of the CMB we can build a template of the lensing B mode on the sky with a weighted convolution:

$$\hat{B}^{\text{lens}}(\mathbf{l}) = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W(\mathbf{l},\mathbf{l}') f(\mathbf{l},\mathbf{l}') E^N(\mathbf{l}') I(\mathbf{l}-\mathbf{l}') \quad (7)$$

where $f(\mathbf{l},\mathbf{l}')$ is a weight that must be determined.

The residual lensing B mode will be

$$B^{\text{res}}(\mathbf{l}) = B^{\text{lens}}(\mathbf{l}) - \hat{B}^{\text{lens}}(\mathbf{l}) = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W(\mathbf{l},\mathbf{l}') \times \Big(E(\mathbf{l}')\kappa(\mathbf{l}-\mathbf{l}') - f(\mathbf{l},\mathbf{l}') E^N(\mathbf{l}') I(\mathbf{l}-\mathbf{l}')\Big) \quad (8)$$

and its power spectrum

$$\begin{aligned} C_l^{BB,\text{res}} = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W^2(\mathbf{l},\mathbf{l}') [& C_{l'}^{EE} C^{\kappa\kappa}_{|\mathbf{l}-\mathbf{l}'|} \\ & -(f(\mathbf{l},\mathbf{l}') + f^*(\mathbf{l},\mathbf{l}')) C_{l'}^{EE} C^{\kappa I}_{|\mathbf{l}-\mathbf{l}'|} \\ & + f^*(\mathbf{l},\mathbf{l}') f(\mathbf{l},\mathbf{l}') (C_{l'}^{EE} + N_{l'}^{EE}) C^{II}_{|\mathbf{l}-\mathbf{l}'|}] \end{aligned} \quad (9)$$

We can now easily choose $f(\mathbf{l},\mathbf{l}')$ so that the residual lensing B mode power is minimized. We find:

$$f(\mathbf{l},\mathbf{l}') = \left(\frac{C_{l'}^{EE}}{C_{l'}^{EE} + N_{l'}^{EE}} \right) \frac{C^{\kappa I}_{|\mathbf{l}-\mathbf{l}'|}}{C^{II}_{|\mathbf{l}-\mathbf{l}'|}} \quad (10)$$

Notice that the first term consists in the usual inverse variance filter applied to the measured E-mode and the second minimize the difference between the reconstructed ϕ and the CMB lensing potential.

We finally have that the residual power is:

$$C_l^{BB,\text{res}} = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W^2(\mathbf{l},\mathbf{l}') C_{l'}^{EE} C^{\kappa\kappa}_{|\mathbf{l}-\mathbf{l}'|} \times \left[1 - \left(\frac{C_{l'}^{EE}}{C_{l'}^{EE} + N_{l'}^{EE}} \right) \rho^2_{|\mathbf{l}-\mathbf{l}'|} \right] \quad (11)$$

with

$$\rho_l = \frac{C_l^{\kappa I}}{\sqrt{C_l^{\kappa\kappa} C_l^{II}}}. \tag{12}$$

The bigger ρ_l is for a LSS field the more it is correlated with the lensing potential acting on the CMB photons. An higher correlation allows for a better reconstruction of the ϕ^{CMB} and, as a consequence, of B^{lens}.

A. Multiple tracers of the lensing potential

Let's now assume that we have n different tracers of the gravitational potentials I_i with $i \in \{1, .., n\}$. It can be shown that the optimal way to combine them to estimate ϕ or, in other word, maximizing the correlation factor ρ is:

$$I = \sum_i c^i I^i$$
$$c_i = (C^{-1})_{ij} C^{\kappa I^j} \tag{13}$$

where C is the covariance matrix of the LSS tracers. The "effective" correlation of these combined tracers with gravitational lensing is:

$$\rho^2 = \sum_{i,j} \frac{C^{\kappa i}\ (C^{-1})_{ij}\ C^{\kappa j}}{C^{\kappa\kappa}}. \tag{14}$$

The gain we have in adding a new tracer is not only proportional to its correlation with the CMB lensing but it also depends on how much it is correlated with the already used set of tracers. For example there s a very small gain in adding different CIB frequencies because they are highly correlated with each other. On the contrary a CMB reconstructed lensing potential or some low redshift survey like D.E.S can help.

III. TRACERS MODEL

In this equation, $\chi(z)$ is the comoving distance to redshift z, χ_* is the comoving distance to the last-scattering surface at $z_* \simeq 1090$, $H(z)$ is the Hubble factor at redshift z, c is the speed of light, and $\Psi(\chi(z)\hat{\mathbf{n}}, z)$ is the three-dimensional gravitational potential at a point on the photon path given by $\chi(z)\hat{\mathbf{n}}$. Note that the deflection angle is given by $\mathbf{d}(\hat{\mathbf{n}}) = \nabla\phi(\hat{\mathbf{n}})$, where ∇ is the the two-dimensional gradient on the sphere. Because the lensing potential is an integrated measure of the projected gravitational potential, taking the two-dimensional Laplacian of the lensing potential we can define the lensing convergence $\kappa(\hat{\mathbf{n}}) = -\frac{1}{2}\nabla^2\phi(\hat{\mathbf{n}})$, which depends on the projected matter overdensity δ [**?**]:

$$\kappa(\hat{\mathbf{n}}) = \int_0^{z_*} dz\, W^\kappa(z)\delta(\chi(z)\hat{\mathbf{n}}, z). \tag{15}$$

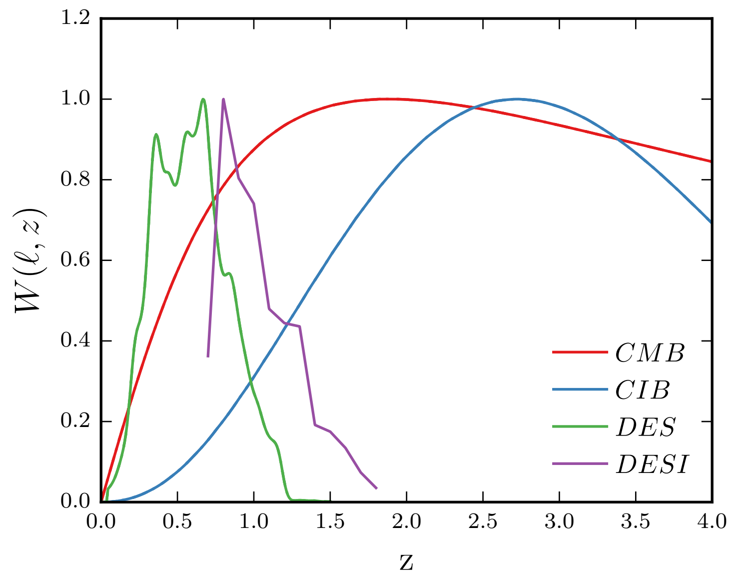

FIG. 1. Comparison of the different kernels used in this analysis. This allow to understand how well and where in redshift space different LSS surveys trace the CMB lensing potential. Redshift distribution of D.E.S galaxies (I suspect this is the benchmark, anyway taken from Giannantionio et al.). DESI taken from their white paper.

The lensing kernel W^κ is

$$W^\kappa(z) = \frac{3\Omega_\mathrm{m}}{2c}\frac{H_0^2}{H(z)}(1+z)\chi(z)\frac{\chi_* - \chi(z)}{\chi_*}, \tag{16}$$

where Ω_m and H_0 are the present day values of the Hubble and matter density parameters, respectively.

where $P_{init}(k)$ is the scalar power spectrum at an early time with k being the Fourier wave number. The functions $\Delta_\ell^X(k)$ and $\Delta_\ell^Y(k)$ are one of the following (see e.g., [**? ?**]):

A. Galaxies

The galaxy overdensity $g(\hat{\mathbf{n}})$ in a given direction on the sky is also expressed as a LOS integral of the matter overdensity:

$$g(\hat{\mathbf{n}}) = \int_0^{z_*} dz\, W^g(z)\delta(\chi(z)\hat{\mathbf{n}}, z), \tag{17}$$

where the kernel is

$$W^g(z) = \frac{b(z)\frac{dN}{dz}}{\left(\int dz' \frac{dN}{dz'}\right)} \tag{18}$$

B. Cosmic infrared Background

In this work, the CMB lensing potential is estimated from maps of the cosmic infrared background (CIB).

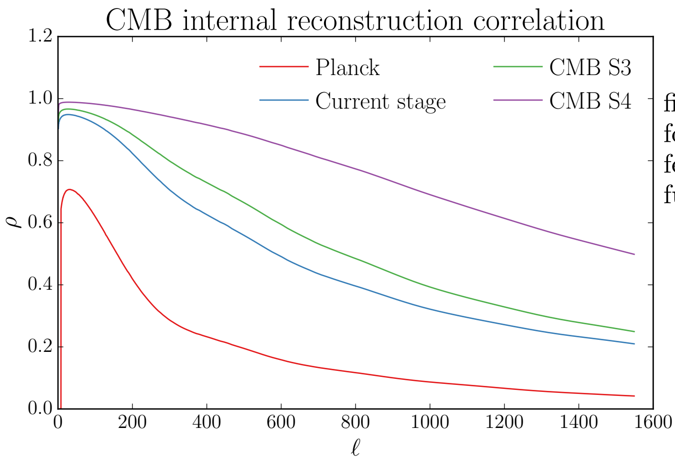

FIG. 2. Correlation factor between CMB reconstructed potential and the real lensing potential for different CMB experiments

Following [?], we model the CIB power as $C_\ell^{\text{CIB-CIB}} = 3500(l/3000)^{-1.25}\text{Jy}^2/\text{sr}$. We test that this model provides an accurate fit for the power of the *Herschel* 500 μ map used in this work. For the cross-spectrum $C_\ell^{\text{CIB-}\phi}$, we use the single-SED model of [4]. This places the peak of the CIB emissivity at redshift $z_c = 2$ with a broad redshift kernel of width $\sigma_z = 2$. This model is rescaled to agree with the results of ?] and ?] by choosing the corresponding linear bias parameter. Other multi-frequency CIB models are available [e.g., ?]; however, given the level of noise, we are relatively insensitive to this choice. With these assumptions, depending on angular scale, $45-65\%$ of the CIB is correlated with the CMB lensing potential, as shown in Fig. ??.

C. Weak Lensing

[1–3, 5–7, 9–14]

D. Internal CMB lensing

The ability of CMB experiments themselves to reconstruct the lensing potential with rapidly improve with the increasing sensitivity.

Internal delensing is already competitive with galaxies delensing at very large scale. Potentially

To derive the delensing performance let us assume that our lensing reconstruction, given certain instrumental noise level and beam, results in a lensing map with reconstruction noise $N_l^{\kappa\kappa}$, so that its power spectrum is

$$C_l^{\kappa_{\rm rec}\kappa_{\rm rec}} = C_l^{\kappa\kappa} + N_l^{\kappa\kappa} \tag{19}$$

IV. FORECAST

In this section we forecast the expected delensing efficiency and the relative importance of galaxies tracers for current and future experiments. We focus on 3 different scenarios: the current stage, the 3G one and the futuristic CMB Stage 4.

A. Fisher method

We defined the B-modes noise spectrum:

$$N_l^{BB} = (\Delta_P/T_{\rm CMB})^2\, e^{l^2\theta^2_{\rm FWHM}/(8\ln 2)} \tag{20}$$

where $\theta_{\rm FWHM}$ is the full half width of the telescope beam and Δ_P is the instrumental noise of the experiment. The gaussian covariance is then:

$$\sigma(C_l^{BB,\rm full}) = \sqrt{\frac{2}{(2l+1)f_{\rm sky}}}\left(C_l^{BB,\rm lens} + N_l^{BB}\right). \tag{21}$$

With this we can simply quantify the constraints on the tensor to scalar ration r:

$$\sigma(r) = \left[\sum_l \frac{\left(\frac{\partial C_l^{BB,r}}{\partial r}\right)^2}{\sigma^2(C_l^{BB,\rm full})}\right]^{-\frac{1}{2}} \tag{22}$$

$$\approx \left[\frac{\sum_l (2l+1) f_{\rm sky}\left(\frac{\partial C_l^{BB,r}}{\partial r}\right)^2}{2}\right]^{-\frac{1}{2}} \langle C_l^{BB,\rm lens} + N_l^{BB}\rangle_{l<100}$$

where to go from the first to the second line we use the fact that most of the constraint comes from large scale modes at $\ell < 100$, thus larger mode can be ignore here. We quantify the improvement due to delensing as the factor α defined as the ration of the error before and after delensing:

$$\alpha = \frac{\langle C_l^{BB,\rm lens} + N_l^{BB}[\Delta_P]\rangle_{l<100}}{\langle C_l^{BB,\rm res}[\Delta_P] + N_l^{BB}[\Delta_P]\rangle_{l<100}} \tag{23}$$

B. Current generation

Very recently delensing has been proven possible on real data using both the internal CMB lensing potential reconstruction as well as external tracers. Here we discuss the improvement due to combining this two probes. This is already possible both on full sky using Planck data or in smaller sky patches combining Herschel or Planck CIB data with SPT and BK data. Furthermore we test how much current relative low redshift galaxies surveys like D.E.S can improve delensing efficiency on smaller patch of the sky like the Bicep-Keck SPT-Pol footprint.

We model the current generation pf CMB experiments after 3 experiments: a full sky Planck experiment together with a deep low noise experiemtn and a high resolution one on a smaller patch of the sky.

The correlation attainable using current experiments is shown in Fig. 3.

At large angular scale the CMB internal reconstruction is clearly the best tracers for delensing. Because of the large level of noise in current experiment, its efficiency became comparable to the CIB one at few degrees ($\ell \simeq 400$).

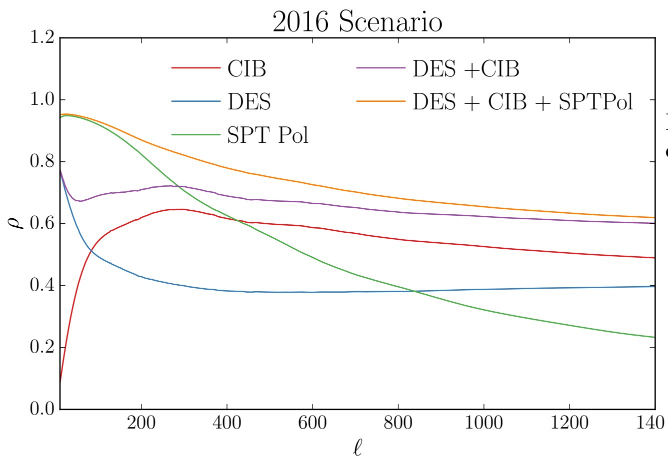

FIG. 3. Correlation factor between current galaxies survey and internally reconstructed ϕ CMB lensing potential as a function of the multipole ℓ.

C. CMB-S3 Era

The accuracy of CMB is rapidly improving. For example the next generation of the SPT telescope, SPT3G has been deployed and is currently taking data. Furthermore other experiments have considerably increased the number of detectors (AdvACT etc.). We will assume a level of noise of 3 μK-arcmin the level predicted for SPT3G. The correlation attainable using current experiments is shown in Fig. 4,

D. CMB-S4 Era

An ambitious program for a generation 4 ground CMB experiment is currently under planning. Moreover satellite experiments have been proposed.

The correlation attainable using current experiments is shown in Fig. 5,

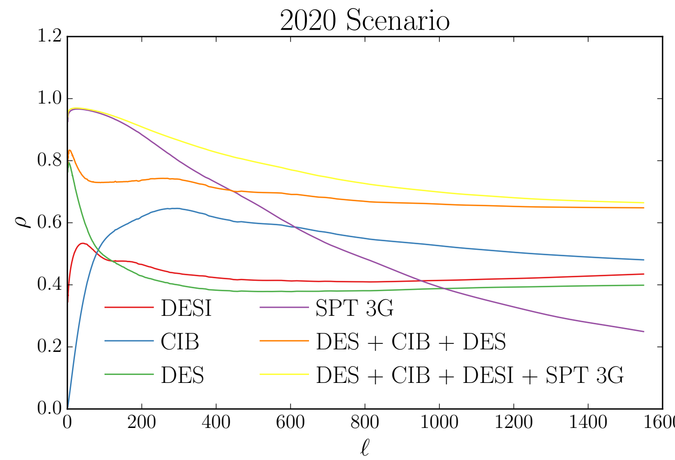

FIG. 4. Correlation factor. Same as Fig. 3 but for stage 3 experiments.

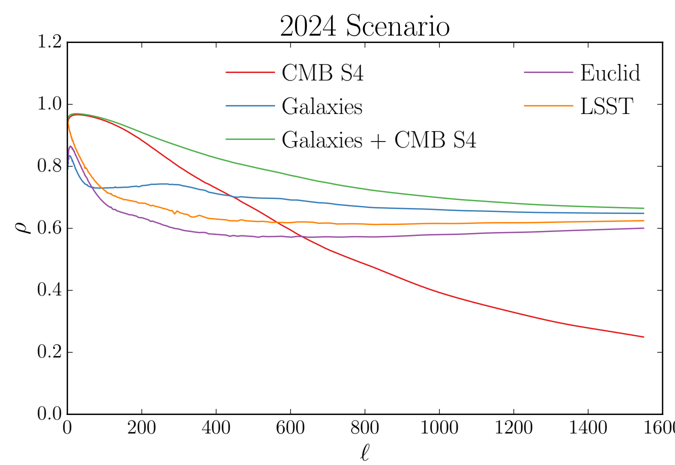

FIG. 5. Correlation factor. Same as Fig. 3 but for stage 4 experiments.

E. Bias uncertainties degradation

The uncertainties in the theoretical assumptions used to model the galaxies can cause a degradation of the improvement of inflationary constraint of delensed spectra. In this section we quantify this effect. We will now marginalize over unknown galaxies parameters but we will use a full dataset of CMB and galaxies data. The idea is that as shown in the low level of noise in galaxies surveys might allow us to internally calibrate them. We

TABLE I. α: improvement on r constraint

Surveys	α
des	1.34
cib	1.71
cmb current	1.79
gals current	2.03
cmb S3	2.15
gals S3	2.16
gals S4	2.16
comb current	2.66
comb S3	3.14
cmb S4	4.36
comb S4	5.27

will use a Fisher approach the Fisher matrix is:

$$F_{pq} = \sum_{l_a=l_{\min}^{BB}}^{l_{\max}^{BB}} \sum_{l_b=l_{\min}^{BB}}^{l_{\max}^{BB}} \frac{\partial C_{l_a}^{BB,\mathrm{del}}}{\partial \theta_p} \left[\mathrm{Cov}^{BB,BB}\right]^{-1}_{l_a,l_b} \frac{\partial C_{l_b}^{BB,\mathrm{del}}}{\partial \theta_q} + \sum_j \frac{\frac{\partial C_j^{\kappa I}}{\partial \theta_p} \frac{\partial C_j^{\kappa I}}{\partial \theta_q}}{(\Delta C_j^{\kappa I})^2} + \sum_j \frac{\frac{\partial C_j^{II}}{\partial \theta_p} \frac{\partial C_j^{II}}{\partial \theta_q}}{(\Delta C_j^{II})^2} \tag{24}$$

$$\alpha_{\mathrm{marginalized}} = \sigma_0(r)/\sigma_{\mathrm{marginalized/delensed}}(r) \tag{25}$$

where the parameter array contains both the tensor to scalar rate $\theta = r$, and the galaxies surveys parameters like the bias b_i or p_i [8].

We compute the derivatives of the power spectra as described

V. CONCLUSIONS

Delensing or more in general the ability to separate the lensing component of the B-mode from a possible primordial inflationary signal is crucial to fully exploit the capabilities of future experiments. In this paper we studied the possible impact of large scale structure surveys in this important endeavor. For current experiment CIB data had already proven to be very efficient in delensing. If no High res experiment is avaiable to reconstruct the lensing potential phi even a low-z experiment like D.E.S will improve th delensign efficiency by 10% if combined with Planck lensing and a CIB tracers. As expected the lower the noise in the CMB experiment the more the delensign efficiency will be predominately come from the internal CMB reconstruction of the lensing potential. Indeed using the CMB itself we reconstruct only the lenses that actually lens the CMB obtained an almost perfect cleaning in the absence of noise. This approach will need a careful study of possible biases coming from using the same source (the CMB) we are delensing to reconstruct the lensing effect itself. This has already been applied to data and studied. However the fairly good efficiency of galaxies tracers might come in end to cross-check these internal biases. This will probably be needed to confirm a possible detection of gravitation waves if this rely heavily on delensing.

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