Looking through the same lens:
Shear calibration with CMB lensing

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arXiv:1607.01761

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Weak gravitational lensing

**Galaxy lensing**

- perfect disk
- shear $\sim 1\%$
- shape $\sim 20\%$

$\rightarrow$ SNR $\sim 5\%$ for one galaxy,
SNR $\sim 10^3$ with $10^9$ galaxies

**CMB lensing**

- Arcmin deflections, coherent on degree scale
- Smoothed peaks, extra power, $E \rightarrow B$, correlates modes
Shear calibration: the case for redundancy

\[ \langle e \rangle = (1 + m) \gamma_{\text{true}} + \alpha e_{\text{PSF}} + c \]

Scary: \(m(z)\) degenerate with growth, hence dark energy EOS

"Required" for LSST: \(< 0.5\%\) (Huterer+06, Massey+12, ES+16)

Image simulations: \(3-5\%\) DES (Jarvis+15), \(1\%\) KiDS (Fenech-Conti+16)

Difficult:
- Noise/Model biases
- Selection bias: simulate below the detection limit (Hoekstra+15)
- Mode coupling: simulate below the image resolution
- PSF size error

→ Redundancy is valuable
Shear calibration with CMB lensing

**Principle:**
Vallinotto12,13, Das+13
\( \kappa_{\text{gal}} \sim (1+m) \sigma_8 \)
\( \kappa_{\text{CMB}} \sim \sigma_8 \)

**Value:**
Purely empirical, self-calibration
No assumption on galaxy population/morphologies

**Just the beginning!**
Liu+16, Baxter+16, Miyatake Madhavacheril+16, Singh+16
\( \sim 10-20\% \) calibration, (mostly) fixed cosmology & nuisances

**Questions:**
Competitive with image simulations / requirements?
Varying cosmology & nuisance?
Robustness to photo-z, IA?
What combination is best?
Forecast: LSST & CMB S4 lensing

- **Observables:**
  - clustering
  - gal - shear
  - shear - shear
  - gal - CMB lensing
  - shear - CMB lensing
  - CMB lensing auto

- **Constrain:** cosmology, $b_i$, $m_i$, $\Delta z_i$, $\sigma_z$
  - No prior on $b_i$, $m_i$. Priors on $\Delta z_i$, $\sigma_z$.

- **Realistic, conservative:**
  - Full non-Gaussian covariances
  - Explore likelihood with MCMC

- **Built on CosmoLike** (Eifler Krause+14)
  - Extended to include CMB lensing
  - Soon to be public!
CMB S4 lensing can calibrate the shear \sim LSST requirements

Varying cosmo & nuisance params
Better at high z where most challenging
Purely empirical, self-calibration
CMB S4 lensing replaces a prior on $m$
Summary: Shear calibration with CMB lensing

arXiv:1607.01761

- CMB S4 lensing can constrain the shear bias to 0.5% ~ LSST requirements
- Purely empirical, self-calibration, no assumption on galaxy population/morphologies
- Works best at high z where most difficult
  - Robust to IA, photo-z degradation, non-linearities & baryons, CMB S4 specs
  - In the works: “delensing” with CIB, iterative reconstruction, photo-z outliers, correlated mi
More shear self-calibration with CMB lensing!
8.4m telescope in Chile
Survey starts 2022-23
~ half the sky
Sources: 26 arcmin$^{-2}$
Lenses: redmagic-like

18,000 deg$^2$, 26 sources/arcmin$^2$, 0.25 lenses/arcmin$^2$, shape noise = 0.26
$\sigma_z/(1+z) = 5\%$ for sources, known to 0.2\% for sources
$\sigma_z/(1+z) = 1\%$ for lenses, known to 0.06\% for lenses
Forecast: LSST

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<th>LSST specifications</th>
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<tbody>
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<td>$\Omega_s$</td>
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Stage 4: ~500,000 detectors
Beam: 1′
Sensitivity: 1μK′

\[ l_{\min} = 30, \quad l_{\max, T} = 3000, \quad l_{\max, E, B} = 5000 \]

Foreground cleaned input map
Assumed no systematics
Forecast: CMB S4

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Assumed no systematics!
But, the SNR...

- SNR in $\kappa_{\text{CMB}}$ is 75% of $\kappa_{\text{gal}}$; and marginalizing over systematics degrades constraints by factor of a few for LSST

- SNR is not all; info not only one amplitude; hard to have intuition with high-dimensional parameter space

- Calibrating the shear useful for cosmo params, but also for maps (cf Planck)

- Shear does things CMB lensing can’t: small scales, lower $z$
CMB lensing & reconstruction

$T(\hat{n}) = T_0(\hat{n}) + \vec{d} \cdot \vec{\nabla} T_0(\hat{n})$

Arcmin deflections, coherent on degree scale
Breaks statistical isotropy $\rightarrow$ reconstruction
Different systematics (SZ, point sources)

Probes broad z-range

Smothes BAO peaks

Smidt+10

Challinor

Adds small-scale fluctuations
Why no “$m_{\text{CMB}}$” in CMB lensing?

CMB lensing systematics:

- biases in $<\kappa_{\text{CMB}} \kappa_{\text{CMB}}>$: $<S^2 \kappa_{\text{CMB}}>$ $<S^4>$
- biases in $<\kappa_{\text{CMB}}$ anything$>$: $<S^2$ anything$>$
- Remove with: multiple wavelength project out bispectrum (Osborne+14)
- ( Likely) less important in polarization

![Graph](graph.png)

- Aggressive masking, $l_{\text{max}} = 2500$
- van Engelen+14
Galaxy lensing: systematics/uncertain physics

- Non-linear gravity/Baryonic effects
  Rudd+08, Zentner+08, van Daalen+11,14, Velliscig+14, Osato+15, Hellwing+16

- Consistent joint analysis of probes

- Intrinsic alignments
  up to 1%-10% of cosmic shear
  II: remove auto-correlation, z-cut;
  GI: remove red galaxies?
  Kiessling et al 2015, Kirk et al 2015

- Shape measurement
  shear bias <~0.4% , Huterer+06, Massey+12

- Photo-z uncertainties
  bias and scatter known to 0.3%, Huterer+06;
  1.65-1.66 spectra for calibration, Ma Bernstein 08
Statistics < Systematics

Shear calibration
Photo-z uncertainties
Intrinsic alignments
Non-linear/baryonic effects
Consistent joint analyses

→ Signal-to-noise/FoM is not all
→ Systematics are limiting
Shear alone/LSST alone:
Self-calibration to ~2%
Relies on mildly non-linear scales
**Lensing-lensing correlations:**
- requires auto spectra
- IA always present
- fixed angular scale ← arbitrary small physical scales
Tracer-lensing correlations:
+ no lensing auto
+ fairly insensitive to cosmology (distance ratios)
+ no IA if perfect photo-z
+ fixed angular scale ← not arbitrary small physical scales
CMB S4 lensing can calibrate the shear ~ requirements while varying cosmo & nuisance params better at high z where most challenging purely empirical, self-calibration.
CMB lensing replaces a prior on $m$

68% constraints, relative to LSST fiducial

- Green line: LSST, no m-prior
- Black line: LSST, m-prior
- Red line: LSST & S4, no m-prior
- Orange line: LSST & S4, m-prior
Shear calibration
The calibration from simulation can be a large factor → needs to be precisely measured
discussed above, in 'calibration selection bias' from the 'galaxy selection bias' between size and ellipticity or shear. We distinguish this...

Our objective is to establish a shear calibration relation in

4.3 Calibration selection bias
Figure 6. The multiplicative bias as a function of seeing for galaxies with $r < 25$ mag. The red line shows the reference case with $\epsilon = 0$, which impacts the bias as well (see Appendix C). The PSF, the lower the SNR as the flux is spread over more pixels. The seeing also determines how well galaxies are rected bright galaxies (i.e. when considering the full range in magnitude, but overcorrection the catalog by duplicating the fainter galaxies such that the input counts follow the power-law relation seen at log is incomplete for faint galaxies to account for incompleteness (for STEP1 is the main reason that a small bias was observed and Kitching et al. (2012). The lack of faint galaxies in the magnitude range simulated by STEP1 we reproduce the simulations contains a su a yt a hh a tt h a tc a no n l i f f f =0 ( r e dl i n e ) , T h e h i s t o g r a m s h o w st h e e x t e c t d by the PSF size: the larger $\mu > 0)$. It appears that the choice of brighter galaxies. These results demonstrate that it is important to ensure that the input catalog used for image simulation contains a sufficient number of galaxies fainter of the sample of sources used to measure the weak lensing source of correlated noise, a a yt a tt h a tc a no n l i f f f $=0$ $\epsilon$ $25$ (black points) and an extreme case with $\epsilon = 0$ (red line). Figure 7 shows that this effects the local background determina-
tion the catalog by duplicating the fainter galaxies such that the input counts follow the power-law relation seen at log is incomplete for faint galaxies to account for incompleteness (for 

Go 1.5mag deeper than limit
Subtlety of selection biases

- (Does NOT imply a multiplicative bias in either algorithm)
- Implies that selection effects can bias the shear by ~5%
- These effects are subtle and can be easily missed
Robustness

- **IA contamination:**
  Unaccounted IA in the data produce $<1\sigma$ bias in $m_i$, without mitigation

- **Non-linearities/baryons:**
  Varying $l_{\text{max}}$ beyond 1000 does not affect $m_i$ much

- **Wider photo-z errors:**
  Weakening prior on photo-z only weakens $m_i$ constraints in the lower z-bins

- **CMB S4 specs:**
  $m_i$ constraints are sensitive to noise, but not much to $l_{\text{max}}$ or resolution
Robustness to IA

Mean redshift

IA contamination

Combi2: $g_{\Delta 03}, g_{\Delta 02}, g_{\Delta 01}, g_{\Delta 00}$
Combi1: $K_{\Delta 03}K_{\Delta 02}K_{\Delta 01}K_{\Delta 00}$

LSST full & CMB S4 lensing

LSST requirement
In conclusion, we find that shear calibration from CMB lensing will be possible at a level competitive with or even better in the highest redshift bins, where shear calibration is otherwise most challenging. We show a shear calibration of intrinsic alignments and Gaussian photo-z uncertainties, the shear calibration from CMB S4 lensing is only biased at a fraction of the statistical uncertainty. This shear calibration is sensitive to the noise level in CMB S4 maps, but insensitive to the beam and maximum multipole at which component separation is performed, within sensible values.

Thus stage 3 CMB surveys such as AdvACT and SPT-3G, as well as the Simons Observatory, will already provide redundancy and serve as a cross check, in order to reliably measure the properties of dark energy, the neutrino masses and possible modifications to general relativity.

We show that CMB lensing from S4 can calibrate the shear multiplicative biases for LSST down to 0.0005% in most of the redshift range. This method performs robustly to photo-z outliers.

In the systematics-limited era of stage 4 weak lensing surveys, this method will provide redundancy and serve as a cross check, in order to reliably measure the properties of dark energy, the neutrino masses and possible modifications to general relativity.

Fixing the source photo-z scatter \( \sigma_z/(1+z) = 0.05 \), Varying the prior on it.
Non-linearities / Baryons

FIG. 9. In this figure, we vary the maximum multipole included in the lensing-lensing correlations and compare the resulting shear calibrations from combination 1 (i.e. $\pi_{\text{gal}}$, $\pi_{\text{gal}}$, $\pi_{\text{gal}}$, $\pi_{\text{CMB}}$, $\pi_{\text{CMB}}$, $\pi_{\text{CMB}}$). Between $\ell_{\text{max}} = 5,000$ and $\ell_{\text{max}} = 9,300$, the shear calibration is only degraded by 10-40%. Besides, the calibration from combination 2 (i.e. $g\pi_{\text{gal}}$, $g\pi_{\text{CMB}}$; not shown in this figure) only uses lower multipoles ($\ell_{\text{max}} = 4,20, 714, 939, 1212$ for the four lens bins). As a result, the calibration from the full LSST & CMB S4 lensing is rather insensitive to the maximum multipole included, beyond $\ell_{\text{max}} = 1,000$. Therefore, it should be robust to uncertainties in non-linearities and baryonic effects in the matter power spectrum.
In this study, we answer the following questions: can CMB lensing calibrate the shear bias down to a useful value for the CMB lensing power spectrum (black line) is compared to the reconstruction noise per unit signal-to-noise ratio. When varying the sensitivity (left), we quote the white noise level in temperature, and use a different sensitivity, but is relatively insensitive to the beam and maximum multipole available. This framework to include CMB lensing. We jointly analyze all the two-point correlation functions of galaxy positions, shear and CMB lensing convergence. We include the non-Gaussian covariances and explore photo-z uncertainties, non-linear and baryonic effects. How robust is this calibration to intrinsic alignments, distributions and survey parameters may evolve in the future, in particular for WFIRST. Nevertheless, these results shear calibration for Euclid and WFIRST may differ from each other and from LSST. Furthermore, the exact redshift and assumptions on the CMB S4 experiment? To do so, we

![CMB S4 specs?](image)

- **Noise**
  - $\ell (\ell + 1)C^{\ell}_{\ell}/(2\pi)$ vs. $\ell$
  - Mean redshift vs. $\ell$
  - Shear bias 68% constraints vs. $\ell$

- **Beam**
  - $\ell (\ell + 1)C^{\ell}_{\ell}/(2\pi)$ vs. $\ell$
  - Mean redshift vs. $\ell$
  - Shear bias 68% constraints vs. $\ell$

- **$l_{\text{max}}$**
  - $\ell (\ell + 1)C^{\ell}_{\ell}/(2\pi)$ vs. $\ell$
  - Mean redshift vs. $\ell$
  - Shear bias 68% constraints vs. $\ell$
Parameter dependence

The width of the lines or bands corresponds to the range of variation across tomographic bins. On these plots, a high absolute value corresponds to a strong parameter dependence. A positive value corresponds to an observable growing with the parameter. A horizontal curve corresponds to a multiplicative factor, and a slanted curve corresponds to a tilt in the observable, when the parameter is varied. Two curves identical modulo multiplicative factor correspond to a perfect degeneracy between parameters.

For example, all observables scale roughly as $\Omega_0^2$ in the linear regime and $\Omega_0^3$ in the non-linear regime. The parameter $\Omega_0^m$ typically produces a tilt, and is strongly degenerate with $h_0$ for clustering (top left panel).

The figure also allows to visualize parameter degeneracies and covariances. If two curves $d \ln O / d \ln p_1(\ell)$ and $d \ln O / d \ln p_2(\ell)$ are identical modulo a multiplicative factor, then the parameters $p_1$ and $p_2$ are perfectly degenerate. If these two curves are only similar modulo multiplicative factor (where "similarity" depends on the covariance matrix), then the parameters $p_1$ and $p_2$ are partially degenerate, and have a non-zero covariance.

Fig. 13 shows the confidence regions for the 7 cosmological parameters varied in our analysis. The negative correlations for $\Omega_0^m$, $\Omega_b^0$, $\Omega_w^0$, $\Omega_w^a$, and $\Omega_w^a$ and the positive correlations for $\Omega_0^m$, $h_0$, and $\Omega_b^0$, can be understood in light of Fig. 12.
Euclid & CMB S4

Mean redshift

Shear bias 68% constraints

full
sources
lenses×10
CMB lensing efficiency

Schaan+16
Shear bias 68% constraints

Mean redshift

WFIRST & CMB S4

Schaan+16