Synergy between next generation CMB and LSS probes of cosmology

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Current CMB

Planck also measured polarization across the sky

SZ effect: ~1000 galaxy clusters

gravitational lensing

Much ground-based data too
Some current Large-Scale Structure

Photometric surveys:
HSC (1400 deg$^2$), KiDS (1400 deg$^2$), DES (5000 deg$^2$)
Map the density and lensing of galaxies

Spectroscopic: BOSS
Galaxy clustering, redshift-space distortions

FIG. 1. Galaxy distribution of the redMaGiC Y1 sample used in this analysis. The fluctuations represent the raw counts, without any of the corrections derived in this analysis. We have restricted the analysis to the contiguous region shown in the figure. The area is 1321 square degrees.

FIG. 2. Redshift distribution of the combined redMaGiC sample in 5 redshift bins. They are calculated by stacking Gaussian PDFs with mean equal to the redMaGiC redshift prediction and standard deviation equal to the redMaGiC redshift error. Each curve is normalized so that the area of each curve matches the number of galaxies in its redshift bin.

The redMaGiC algorithm produces a redshift prediction $z_{RM}$ and an uncertainty $z_{error}$ which is assumed to be Gaussian. This sample was chosen instead of other DES photometric samples because of its small redshift uncertainty, which is obtained at the expense of number density.

The redMaGiC algorithm makes use of an empirical red-sequence template generated by the training of the redMaPPer cluster finder [34, 35]. As described in [35], training of the red-sequence template requires overlapping spectroscopic redshifts, which in this work were obtained from SDSS in the Stripe 82 region [36] and the OzDES spectroscopic survey in the DES deep supernova fields [37].

For the redMaGiC samples in this work, we make use of two separate versions of the red-sequence training. The first is based on SExtractor MAG AUTO quantities from the Y1 coadd catalogs, as applied to redMaPPer [38]. The second is based on a simultaneous multi-epoch, multi-band, and multi-object fit (MOF) (see Section 6.3 of Y1GOLD), as applied to redMaPPer [39]. In general, due to the careful handling of the point-spread function (PSF) and matched multi-band photometry, the MOF photometry yields lower color scatter and, hence, smaller scatter in red-sequence photo$z$s. For each version of the catalog, photometric redshifts and uncertainties are primarily derived from the fit to the red-sequence template. In addition, an afterburner step is applied (as described in Section 3.4 of [13]) to ensure that redMaGiC photo$z$s and errors are consistent with those derived from the associated redMaPPer cluster catalog [13].

As described in [13], the redMaGiC algorithm computes color-cuts necessary to produce a luminosity-thresholded sample of constant co-moving density. Both the luminosity threshold and desired density are independently configurable, but in practice higher luminosity thresholds require a lower density for good performance. We note that in [13] the co-moving density was computed with the central redshift of each galaxy ($z_{RM}$).
What’s coming in next decade?

**CMB:**
Ground-based from Chile and South Pole
Higher resolution and sensitivity than Planck

- **ACT:** data thru 2021, ~16000 deg²
- **SPT:** ~ 2500 deg²
- Simons Observatory: starts in 2022
- S4: late 2020s

**LSS:**
Deeper photo and spectro surveys

- **DESI:** ~2019-24
- **LSST:** ~2022-32
- **Euclid:** ~ 2022 launch
- **SPHEREx:** ~2023 launch, **WFIRST** launch ~2025, plus more
More area - in practice (CMB)

Coverage (colour = depth) of the Atacama Cosmology Telescope from 2013-16. Since 2016 have gone deeper on the largest swathe.

Fig: Simone Aiola, Sigurd Naess for ACT
Map of CMB from ACT+Planck (preliminary)

Maps from Sigurd Naess

80 deg

T \sim 20,000 \text{ deg}^2

Aiola et al in prep
Naess et al in prep

100 \text{ deg}^2 \text{ Intensity zoom}

100 \text{ deg}^2 \text{ polarization (U) zoom}
Map of CMB from ACT+Planck (preliminary)

Map of CMB from ACT+Planck (preliminary)

ACT I>500 only

T \sim 20,000 \text{ deg}^2

Aiola et al in prep
Naess et al in prep

100 \text{ deg}^2 \text{ Intensity zoom}

100 \text{ deg}^2 \text{ polarization (U) zoom}
Polarization of the CMB from ACT (preliminary)

ACT Q

ACT U

PRELIMINARY ~25 x 85 deg

RA=180 90+150 GHz

Aiola et al in prep
The field is moving: SZ clusters

- Find clusters through thermal Sunyaev Zel’dovich effect: hot electrons
- Atacama Cosmology Telescope data taken through 2018 (at 90, 150 GHz)
- 2634 confirmed clusters with redshifts to date. Also see SPT talk.

**Black** = cluster search area; **Pink** = HSC (s18a); **Blue** = DES; **Green** = SDSS; **Yellow** = ESO/VST

Preliminary, from Matt Hilton for ACT
A larger SZ cluster sample than ever before

S18: 2634 clusters to date

Preliminary, from Matt Hilton for Atacama Cosmology Telescope
(1) Weighing SZ clusters using weak lensing

~20k SZ clusters coming from SO!

Higher neutrino mass $\rightarrow$ fewer massive clusters
CMB needs optical data: calibrate masses

- Planck/ACT w HSC - Miyatake et al 2018
- ACT w KiDS - Robertson et al in prep, 20$\sigma$
- SPT w Magellan/HST - Boquet et al 2019

SO+LSST: measure neutrino mass sum

$\sigma(\Sigma M_\nu) = 0.03$ eV, and $\sigma_8$ to 2% at $z=1-2$

(SO Collaboration 2019)

Dark energy above $z=1$
Neutrino mass
(also galaxy evolution)
(2) Tracing matter with CMB lensing and galaxy densities

Non-Gaussian fluctuations predict a scale-dependent bias at large scales. Measure $f_{\text{NL}}$ to $\sigma \sim 1$ from SO x LSST (Schmittfull & Seljak 2018).

galaxy bias $f_{\text{NL}}$
dark energy above $z=1$
neutrino mass
(3) ... and including galaxy lensing too

Galaxy lensing and density maps in redshift bins, correlated with CMB lensing e.g. Abbott et al 2018 for DES/SPT.

With multiple redshifts and probes can disentangle neutrino mass, \( w \) and curvature.

and constrain biases, intrinsic alignment, photo-z uncertainty

Increased confidence in \( w \)

Disentangling neutrino mass, dark energy, curvature
(4) Measuring the motion of electrons (kinetic SZ) located using a galaxy survey.

Motion of electrons $\rightarrow$ Doppler shift of CMB.

SO x DESI forecast to constrain growth rate to 10% (Victoria Calafut for SO Collab 2019).

WebSky simulations (George Stein, Marcelo Alvarez, Dick Bond)

Kinematic SZ S/N (Projected-field Estimator)

<table>
<thead>
<tr>
<th>Mission</th>
<th>Year</th>
<th>SN Ratio</th>
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<tbody>
<tr>
<td>Planck x WISE (Hill et al. 2016)</td>
<td>2016</td>
<td>3</td>
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<tr>
<td>Stage-3 x WISE (~2019)</td>
<td>2019</td>
<td>116</td>
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<tr>
<td>Post-Stage-3 x WISE (~2023)</td>
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<td>CMB-S4 x SPHEREx (~2028)</td>
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<tr>
<td>Post-Stage-3 x LSST (~2025)</td>
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<tr>
<td>CMB-S4 x LSST (~2028)</td>
<td>2028</td>
<td>615</td>
</tr>
</tbody>
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Astro2020 White Paper
A key goal: measure ‘r’.

CMB lensing contaminates: SO needs to remove ~50% of lensing power.

‘External’ delensing combines CIB, WISE, LSST clustering to make a template lensing map.

Could remove up to 70% of lensing power (see work by Baleato, Namikawa ++) - important for $\sigma(r) \sim 0.001$ regime.
CMB and LSS: we are better together!
But these are all joint analyses, so need commonality in:

- Simulations
- Data formats
- Theory codes
- Likelihoods

For this science, new **CMB maps** in coming decade will cover half the sky, and come from ground-based data combined with Planck.

**LSS surveys** in coming decade: LSST, DESI, Euclid, SPHEREx, WFIRST, eROSITA plus radio and more.

Using data together will improve constraints on **dark energy**, **neutrino mass**, **spatial curvature**, \( f_{\text{NL}} \), **tensor-to-scalar ratio**

and probably more importantly, will give confidence that systematic errors are not driving our cosmology.