CMB Lensing

A map of all the matter in the Universe, in projection

- Planck fidelity
- Simulated sky
- CMB-S4 fidelity

On its own, we can use this map to precisely measure the amplitude of large-scale structure at intermediate redshifts, with important applications to dark energy, modified gravity, and studies of neutrino masses. In concert with catalogs of objects, we can use this map to weigh samples (of e.g., galaxies and galaxy clusters) to as high a redshift as such sources can be found. The technique of CMB lensing tomography, enabled by CMB-S4 and galaxy catalogs from—for example—the Large Synoptic Survey Telescope (LSST), will allow for the creation of mass maps in broad redshift slices out to redshifts as high as 5, making possible new precision tests of cosmology. Such results explore the connection between visible baryons and the underlying dark-matter structure. In conjunction with cosmic-shear surveys (e.g., LSST) that measure the low-redshift mass distribution, a map of the high-redshift mass distribution can be constructed, gaining new insight into the first galaxies. By calibrating cluster masses at high redshift, the abundance of galaxy clusters can be used as an additional probe of dark energy and neutrino masses.
CMB Lensing

500σ
~0.2% precision

σ(Σmν) ~ 15-30 meV
(minimal is 60 meV)

See talk by Boryana Hadzhiyska
CMB Lensing Challenges

- **ESTIMATORS**
  The most broadly-used estimator *(Hu and Okamoto 2002)* is not optimal for CMB-S4’s low noise!
  - Several next-gen approaches available *(Carron & Lewis 2018, Millea, Anderes, Wandelt 2019, Millea+ 2021, Hadzhiyska+ 2019)*

- **BARYONIC FEEDBACK (AGN, SNe)**
  is a concern *(Chung, Foreman, AvE 2020)* but can likely be mitigated *(McCarthy, Foreman, AvE 2020)*

- **FOREGROUNDS**
  Several mitigation methods available *(Osborne+2013, Madhavacheril & Hill 2018, Schaan & Ferraro 2018, Sailer+2020)*
Patchy $\tau$
Patchy $\tau$

@ Milky Way

Galaxy Cluster

Screening
Patchy τ Screening

- Reconstruced τ maps from patchy screening (Dvorkin & Smith 2009)

- ~10σ correlation with Rubin galaxy sample at z<1 (Feng & Holder 2018)

- ~4-17σ correlation with 21cm from reionization (HERA,SKA) depending on foreground treatment / contamination (Roy+2020)

- Also correlated with Compton-y (Namikawa+2021)
Patchy $\tau$

Scattering a.k.a. Polarized SZ

$P_{\text{today}}$

$P_{\text{cluster}}$

Milky Way

Galaxy Cluster

$pSZ$

$p_{\text{cluster}}$

$p_{\text{today}}$
Patchy $\tau$ Scattering

- We will detect the polarized quadrupole scattering (pSZ) from the S4-selected clusters (Louis+2017)

Louis+2017
See also Hall & Challinor 2014
Non-Gaussianity

- Primordial scalar NG:
  still some improvement over Planck possible

- Primordial tensor NG:
  Low B-mode noise with S4 will allow for new constraints on e.g. \(<\text{BTT}>\) bispectra

See talk by Will Coulton

<table>
<thead>
<tr>
<th>Type</th>
<th>Planck actual (forecast)</th>
<th>CMB-S4</th>
<th>CMB-S4 + low-(\ell) Planck</th>
<th>Rel. improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>(\sigma(f_{\text{NL}}) = 5\ (4.5))</td>
<td>(\sigma(f_{\text{NL}}) = 2.6)</td>
<td>(\sigma(f_{\text{NL}}) = 1.8)</td>
<td>2.5</td>
</tr>
<tr>
<td>Equilateral</td>
<td>(\sigma(f_{\text{NL}}) = 43\ (45.2))</td>
<td>(\sigma(f_{\text{NL}}) = 21.2)</td>
<td>(\sigma(f_{\text{NL}}) = 21.2)</td>
<td>2.1</td>
</tr>
<tr>
<td>Orthogonal</td>
<td>(\sigma(f_{\text{NL}}) = 21\ (21.9))</td>
<td>(\sigma(f_{\text{NL}}) = 9.2)</td>
<td>(\sigma(f_{\text{NL}}) = 9.1)</td>
<td>2.4</td>
</tr>
</tbody>
</table>

CMB-S4 Science Book (2016)
Non-Gaussianity

- $f_{NL}$ from scale-dependent halo bias (Dalal+ 2007)
- CMB-S4 lensing maps can be used with e.g. the Rubin Survey to achieve $\sigma(f_{NL}) \sim 1$

Schmittfull & Seljak 2018

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{plot.png}
\caption{\textbf{Determination of $f_{NL}$ constraints.} The baseline forecast is driven by several factors including CMB lensing precision as a function of minimum $\ell$ (solid), redshift kernels (dashed), and shot noise (dotted).}
\end{figure}
Galactic Science

- High-resolution maps from the ground reveal detail not seen by Planck!
- Studying magnetic fields in star-forming regions
- Turbulence, coupling between gas and dust

See talk by Susan Clark
Dust in galaxies
Hot electrons in galaxy clusters
Neutral hydrogen in galaxies
CMB lensing mass
Starlight from galaxies
Free electrons in galaxies

CIB
tSZ
HI
Lensing
Optical
kSZ

The CMB as a Backlight
Websky Sims from Stein, Alvarez, Bond, AvE, Battaglia 2020