Mass Mapping

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March 13, 2019
The CMB is a unique source for lensing.

- Gaussian, well-understood power spectrum.
- From a redshift which is: (a) unique, (b) known, (c) highest
- Broad Lensing Kernel — possible to correlate with both low-z and high-z tracers of structure
The precision of next generation CMB lensing maps will be comparable to galaxy surveys for the high redshift universe.
CMB Lensing Cosmology: $\Sigma m_\nu$

- Goal: Significant measurement of at least the minimal sum of the neutrino mass ($\Sigma m_\nu = 58$ meV)
- Difficulty — Constraint from CMB is driven by the amplitude of the lensing power spectrum; parameter degeneracies ($\Omega_m$, $\tau$)
- Combined with DESI BAO and making use of high-$\ell$ data (or results from dedicated low-$\ell$ CMB experiments) can achieve this goal
- In Context:
  - DESI (see e.g., 1611.00036)
  - KATRIN (terrestrial) electron anti-$\nu$ mass <0.2eV

<table>
<thead>
<tr>
<th>Data</th>
<th>$\sigma\Sigma m_\nu$ [eV]</th>
<th>$\sigma_{N_{\nu,eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck</td>
<td>0.56</td>
<td>0.19</td>
</tr>
<tr>
<td>Planck + BAO</td>
<td>0.087</td>
<td>0.18</td>
</tr>
<tr>
<td>Gal ($k_{\text{max}} = 0.1h\text{Mpc}^{-1}$)</td>
<td>0.030</td>
<td>0.13</td>
</tr>
<tr>
<td>Gal ($k_{\text{max}} = 0.2h\text{Mpc}^{-1}$)</td>
<td>0.021</td>
<td>0.083</td>
</tr>
<tr>
<td>Ly-(\alpha) forest</td>
<td>0.041</td>
<td>0.11</td>
</tr>
<tr>
<td>Ly-(\alpha) forest + Gal ($k_{\text{max}} = 0.2$)</td>
<td>0.020</td>
<td>0.062</td>
</tr>
</tbody>
</table>

![Graph showing constraints on $\Sigma m_\nu$ and $\sigma(\tau)$](image)
Synergy with Other Surveys: DESI

- $E_G$
  - Test of GR, modified gravity models; ~percent level constraints from Stage IV (factor of 5x improvement)

\[ E_G(\ell) = \Gamma \frac{C_{\kappa g}^{\ell}}{\beta C_{\ell}^{gg}} \]

- redshift space distortion parameter
- galaxy-galaxy autopower spectrum

CMB lensing convergence-galaxy angular cross-power spectrum

Pullen+15; MNRAS 449, 4326
See also
Zhang+07, PRL.99:141302
Pullen+16 MNRAS.460.4098P, Singh+18
Bianchini & Reichardt, 18
Synergy with Other Surveys: DESI

- Ly-α Forest x CMB lensing
  - First detection (5σ) July 2016!
  - Potentially powerful test of cosmology (sum neutrino mass, alternative models of DM)
  - Interpretation limited by knowledge of baryonic physics

- Improved Cosmological parameter constraints (Doux+18)


See also:
Vallinotto+ 2009, PRL 103, 091304
Synergy with Other Surveys: LSST

- Improved Cosmological Constraints via cross-correlations with other LSS tracers
  - e.g., $\sigma_8$, halo bias, FNL (Schmittfull & Seljak, PRD 97, 123540 (2018))

- Calibration of Systematic Errors:
  - Shear Calibration; CMB-lensing can be complimentary to other shear calibration techniques (image simulations, “Metacalibration”)

- High-redshift mass calibration via CMB halo lensing (clusters, AGN, other sources; e.g., Raghunathan+17, Melin+15, and others)

Schaan et al. 2017; PhysRevD, 95,12, 123512
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S. Raghunathan

Madhavacheril, Battaglia, Miyatake 2017
One of the *legacies* of CMB-S4 will be a high signal-to-noise mass map of $\geq 50\%$ of the sky.

- This will be the “ultimate” de-lensing map for future space-based missions.

- In combination with next generation imaging and spectroscopic surveys this lensing map will place tight constraints on key cosmological parameters ($\Sigma m_v, \sigma_8$), and can be used to test models of gravity.

- Cross correlations with the map will provide valuable systematic cross checks for key observables (e.g., cosmic shear) in Stage IV imaging surveys.

- It will be a unique probe of the mass distribution in the high-redshift universe, contributing to astrophysical and cosmological studies in a regime that is being explored by numerous surveys and facilities in the next decade.