Using CMB measurements in combination with low redshift probes

\[ \Sigma m_v \]

Mild discrepancies between low and high redshift measurements

Sensitivities of large ground based CMB experiments approaching minimal neutrino mass -- >3-5 sigma with CMBS4

Multiple distinct probes with different systematics (This talk: large scale lensing power and lensing-calibrated clusters)
The CMB: A high-z anchor

Recombination era photons that map matter fluctuations at $z\sim1100$
**CMB: Well-understood power spectrum**

Recombination era photons that map matter fluctuations at $z \sim 1100$

Snapshot when matter dominated (dark energy negligible)

Neutrinos still very relativistic

$D_\ell \propto A_s \exp(-\tau)$

Amplitude of primordial fluctuations

Optical depth

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Some time later...
Structure forms

Neutrinos start to become non-relativistic $z<300$

Dark energy component starts to dominate around $z\sim 1-2$

Both of these affect the growth of structure
The CMB acts as a backlight for lenses at low-z

Sensitive to projected mass density

Lensing “Convergence” field very close to gaussian

Sensitive to **linear** matter power spectrum over large range of scales
Lensing moves power around (2-pt peak smearing)

Smoothing of 2 pt oscillations

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Reconstructing the lensing field -> 4-pt lensing

Given an underlying gravitational potential

- Real space: lensing remaps points conserving surface brightness
- Fourier space: mode-coupling

\[
\langle X(l_1)X'(l_2) \rangle_{\text{CMB}} = f_{XX'}^{\mathcal{D}}(l_1, l_2) \phi(l_1 + l_2)
\]

This triangle configuration allows one to use a quadratic estimator for the underlying potential

\[
\hat{\phi}(L) \sim \sum_l X(l)X'(L - l)
\]

Credit: Alex van Engelen
Mathew Madhavacheril, Princeton University
CMB lensing by large-scale structure

Power spectrum of reconstructed potential measured to 2.5% by Planck

Some sensitivity to dark energy equation of state

One of the best probes of sum of neutrino masses
Massive neutrinos suppress power on small scales due to free-streaming of neutrinos out of gravitational wells

$$\delta_m = \delta_{cb} (\Omega_c + \Omega_b)/\Omega_m$$

K > k_free_streaming

suppressed amplitude of perturbations and growth rate (neutrinos contribute to expansion but not source potentials)

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CMB 2-pt power spectrum peak smearing adds a lot of information!

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Tension between CMB 4-pt lensing and primary CMB

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Atacama Cosmology Telescope

1.4 arcminute resolution CMB experiment

- Analyzing data from ACTPol
- Ongoing observations for Advanced ACT
ACTPol two-season measurement of lensing power spectrum (based on 12% of data in the can)

Not an easy measurement! Requires exquisite characterization of noise and calculation of noise-dependent biases and higher order corrections.

More scales available for cosmology analysis

Sherwin, van Engelen, Sehgal, MM + ACTPol 2016

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Current status of measurements

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Current status of measurements

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Future Surveys: How well can we constrain neutrino mass?
CMB Stage IV experiment

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Orders of magnitude improvement in lensing reconstruction; polarization dominated era

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Tau degeneracy

\[ \propto A_s / m_{\nu} \]

Optical depth

Planck Lensing 2015

Amplitude of primordial fluctuations

Optical depth

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Our knowledge of the optical depth becomes a limiting factor (requires $L<30$ polarization)

A space-based experiment will help! (Measure low-ell polarization)

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Degeneracies with dark energy equation of state

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Small-scale CMB lensing: looking inside halos
CMB lensing by small-scale structure

CMB has low power on small scales

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CMB lensing by small-scale structure

Super-Massive cluster at z=1.0

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CMB lensing by small-scale structure

Difference is dipole aligned with background gradient
Reconstructing halo lensing

Large-scale gradient \( \hat{\kappa} \propto \hat{\nabla} \cdot \begin{bmatrix} [\hat{\nabla}^2 T]_{\text{low}} & T(\hat{\theta}) \end{bmatrix}_{\text{high}} \)

Hu, DeDeo, Vale 2007

Quadratic estimator picture in real space
Halo Lensing of the CMB now detected

- MM, Sehgal + ACTPol (PRL 2015) 3.2 sigma
- Baxter et. al (SPT) 3 sigma
- Planck 2015 5 sigma

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Probe 2: Count clusters and calibrate masses with lensing
Counting Clusters

Measure the statistics of the density field, in particular its variance

\[
\sigma^2 = \langle \delta^2 \rangle = \frac{1}{V} \int \delta^2(x) d^3x = \int \frac{k^3}{2\pi^2} P(k) d\ln k
\]

In practice, you calculate and measure variance smoothed over some length scale, typically \( R = 8h^{-1}\text{Mpc} \), \( \sigma_8 \)

\[
\sigma_8 \sim \text{rms of matter fluctuations}
\]
Halo model

In this model, when the density fluctuation goes above a critical value, a dark matter halo forms.
Halo model

\[
\frac{dN}{dM dV} = \frac{1}{\sqrt{2\pi}\sigma^2} \exp \left( -\frac{1}{2} \frac{\delta_c^2}{\sigma^2} \right) \frac{\rho_M \, d\ln\sigma^{-1}}{M \, dM}
\]

Press, Schechter, 1974
Measure halo abundance by measuring masses of clusters as a function of redshift

$$\frac{dN}{dM dV} = \frac{1}{\sqrt{2\pi} \sigma^2} \exp \left(-\frac{1}{2} \frac{\delta_c^2}{\sigma^2} \right) \frac{\rho_M}{M} \frac{d \ln \sigma^{-1}}{dM}$$

Sensitive to $\sigma_8(z)$, use to constrain $w(z)$ and $\Sigma_{mv}$
Mass calibration of clusters with the CMB

- Very early stages, few sigma detection
- Alternative to optical lensing (background galaxies)
  - Redshift uncertainties
  - Shape measurement biases
  - Not enough galaxies at high redshift
With CMB-S4: O(100,000) clusters

Find clusters internally with SZ effect (CMB scattering off hot gas)

Mathew Madhavacheril, Princeton University

Also see:
Louis, Alonso 2016
Raghunathan et. al. 2017
With CMB-S4: $\mathcal{O}(100,000)$ clusters

Competitive and complementary to optical lensing

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With CMB-S4: $O(100,000)$ clusters

Redshift resolution breaks degeneracy with dark energy equation of state

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CMB lensing offers a clean probe of the growth of structure

Multiple avenues towards independent measurements with different systematics
- Large scale lensing
  - Two-point power spectrum
  - Four-point reconstruction
  - Degenerate with tau and $w$
- Small scale lensing
  - Degenerate with tau

3-5 sigma measurement of neutrino mass possible

Thank you.