Science Goals of the Simons Observatory

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for the SO Collaboration
CMB at Atacama

Cerro Toco
5190 metres in the Atacama Desert
Why CMB Observations From Chile?

Large Surveys:
(1) Access to Large Low Foreground Regions
(2) Overlap with optical surveys
(3) Overlap with ALMA

Foreground + optical survey coverage map
Moore’s law for CMB surveys

Approximate raw experimental sensitivity ($\mu K$)

Year

Space based experiments
Stage–I – $\approx 100$ detectors
Stage–II – $\approx 1,000$ detectors
Stage–III – $\approx 10,000$ detectors
Stage–IV – $\approx 100,000$ detectors

AdvACT
SPT3g
Simons Array

Abazajian+ 2014
(CMBS4 Snowmass white paper)
Simons Observatory

- Merger of ACT and Polarbear/Simons Array teams
Simons Observatory

United States
- Carnegie Mellon University
- Columbia University
- Cornell University
- Florida State
- Haverford College
- Johns Hopkins University
- Lawrence Berkeley National Laboratory
- NASA/GSFC
- NIST
- Princeton University
- Rutgers University
- Stanford University/SLAC
- Stony Brook
- University of California - Berkeley
- University of California – San Diego
- University of Colorado
- University of Illinois at Urbana-Champaign
- University of Michigan
- University of Pennsylvania
- University of Pittsburgh
- West Chester University

Canada
- CITA/Toronto
- Dalhousie University
- Dunlap Institute/Toronto
- McGill University
- University of British Columbia

Chile
- Pontificia Universidad Catolica
- University of Chile

Europe
- APC - France
- Cardiff University
- Imperial College
- Manchester University
- Oxford University
- SISSA – Italy

Japan
- KEK
- IPMU

South Africa
- Kwazulu-Natal, SA
San Diego three weeks ago
San Diego three weeks ago

SO Members here this week: 14+

Not pictured: Aiola, Duivenvoorden, Freese, Gerbino, Gudmundsson, Ho
(apologies to anyone I missed)
Simons Observatory Timeline

• 2016-17: Planning and technology development

• 2016-18: Logistical upgrades to the site infrastructure

• By end of 2020: Construction and installation of telescopes

• By end of 2020: Production of new CMB-S4-type receivers with partially filled focal planes

• 2021 and beyond: Observing!
The Simons Observatory is a Stepping Stone to CMB-S4 in Chile

- Technology, Theory and Analysis Development
- Detectors, Optics, Telescopes, Receivers, Simulations, Software.
- Development complements CMB-S4 funding from DOE and NSF
- S4-capable telescopes and receiver prototypes for Chile
- Accelerate the S4 process and benefit the entire S4 community.
Small-aperture telescopes

Two possible configurations

- Multiple telescopes, each with a single set of multichroic bands
- Include HWP (see Lyman’s talk)
- Up to 8 bands between 30 - 300 GHz — details TBD

2-refractor setup    crossed Dragone setup
Large-aperture telescope

- 1’.5 - 1’.8 res at 150 GHz
  => 5+ metre aperture

- Up to 8 bands between 30 - 280 GHz — details TBD

**Design Considerations:**
- FWHM 1.8’ (subject to change)
- Focal plane
- Image Quality
- Focal Plane Area
- Net telescope sensitivity
- Cost/buildability
- Camera placement/access
- Co-moving ground shield/baffles

Large Telescope
One possible configuration!
Choices are currently under consideration.
Science goals
- Be able to test isotropy, frequency spectrum, scale dependence of any signal
  - Several patches of sky at $f_{\text{sky}} = \text{few} \%$ (deep)
$N_{\text{eff}}$

- $N_{\text{eff}}$ defined via 
  \[ \rho_r = \rho_\gamma \left( 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right) \]

- $\nu + \text{other } \rho_r$: 
  CMB damping

- $\nu + \text{free-streaming } \rho_r$: 
  CMB phase shift 
  (detected with Planck, Follin+ 2015)

\[ N_{\text{eff}}^{\text{CMB}} = 3.04 \pm 0.18 \]

- $\Delta N_{\text{eff}} \geq 0.027$ 
  for particles in TE with SM
\[ \Delta N_{\text{eff}} \]

- Best results for wide survey — \( f_{\text{sky}} \sim 10-40\% \)
- Target noise: few uK-arcmin
- Done in conjunction with small-patches surveys for \( r \)
- Driven by TE power
  Some dependence on atm. power and point sources in TT
- Possible challenge: beam systematics

- Delensing of TT and EE can help! see Anthony Challinor’s talk
  [Green, Meyers, AvE 2016]
Figure 2–3: Visualizing the impact on cosmological power spectra of varying the total neutrino mass. Each curve represents a change in the total neutrino mass of 0.1 eV. At top left, the impact on the matter power spectrum is shown, with the top-right panel showing the relative change, in comparison to the no-mass case. The massive neutrinos wash out structure on scales $k > 0.01 \ h / \text{Mpc}$. Similar behavior is seen in the two-dimensional CMB lensing power spectra (middle row). The bottom row shows the impact on the CMB temperature power spectrum.

Figure 14. The effect of massive neutrinos on the matter power spectrum and CMB lensing power spectrum. Top Left: The effect of neutrino mass on the matter power spectrum. Top Right: The change to the matter power spectrum relative to the case with massless neutrinos. Bottom Left: The projected matter power spectrum observed through CMB lensing shows the same suppression with neutrino mass. Bottom Right: The relative change to the lensing potential power spectrum.

The lower limit on $\Sigma m_\nu$ is a reflection of the lower limit on the sum of the masses, $P m_\nu \leq 58 \text{meV}$, that is determined from neutrino oscillation experiments \cite{278}. This sets a clear observational target for future observations. Any probe of $P_{mm}$ at late times is, in principle, sensitive to the sum of the neutrino masses. The question we will be most interested in is whether a given probe is sensitive to the lower limit, $P m_\nu = 58 \text{meV}$ (or $\Sigma m_\nu = 0.0006$) under realistic circumstances. In this subsection, we will discuss the two methods through which CMB-S4 can directly constrain the neutrino mass, CMB lensing and SZ cluster abundances. We will also compare these observables to other cosmological probes of the neutrino mass from upcoming large scale structure surveys such as DESI and LSST.
Lensing autospectrum - $\Sigma m_\nu$

Current Data

- Planck
- SPT (2012)
- SPTpol
- ACTPol
- BICEP/Keck
- POLARBEAR

New SPT-2500 points not shown
See Kyle Story’s talk
Lensing autospectrum - $\Sigma m_\nu$

SO forecast

<1% precision

Possibility with CMB-S4

~0.2% precision

Errors blown up by x10!
Lensing autospectrum - $\Sigma m_\nu$

Challenges

Roughly same weight for T and P.
Statistically independent.
Separate systematics:

- **Temp:** Extragalactic NG [AvE+2013, Osborne+2015, Ferraro & Hill 2017]
- **Pol:** Galactic NG [Challinor+(CORE)2017, AvE+ in prep]
Fig. 3. A small region of the reconstructed Planck all-sky Compton parameter maps for NILC (left) and MILCA (right) at intermediate Galactic latitudes in the southern sky centred at (0°, -45°) in Galactic coordinates. The colour scale is in units of $y \times 10^6$.

Fig. 4. In-scan and cross-scan contributions in the NILC (top line) and MILCA (bottom line) $y$-maps in Compton parameter units times $10^6$. From left to right we present the original $y$-maps, and their in and cross scan contributions for a small region at intermediate Galactic latitudes in the southern sky centred at (0°, -45°) in Galactic coordinates.
tSZ - finding & counting clusters

• Potential for discovery of $\sim 10^4$ of clusters, at high $z$
  (Planck: $10^3$; S4: $\sim 10^5$)

• Internal mass calibration via CMB halo lensing, or optical weak lensing
  [Louis & Alonso 2016, Madhavacheril+ in prep]

• Can be competitive with lensing for $\Sigma m_\nu$
Fig. 3. A small region of the reconstructed Planck all-sky Compton parameter maps for NILC (left) and MILCA (right) at intermediate Galactic latitudes in the southern sky centred at (0, -45) in Galactic coordinates. The colour scale is in units of $y \times 10^6$.

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Planck Compton-$y$ map
tSZ - power spectrum

Abundance ($\sigma_8$) and gas physics
Low-M, high-z halos

Planck 2015
tSZ - higher order

Abundance ($\sigma_8$) and gas physics intermediate-M, intermediate-z halos

ACT realspace PDF
SZ skewness, kurtosis (150 GHz) [Hill+2011]

Planck SZ Bispectrum [XXII 2015]

SPT SZ Bispectrum (150 GHz) [Crawford+2012]

See Will Coulton’s Poster
kSZ

• Power spectrum
  10% constraint on $\Delta z$ (fixed late-time)

• Power spectrum of the power spectrum
  see Simone Ferraro’s talk for details

• also, cross-corr with tracers Emmanuel Schaan
Summary

• Simons Observatory will happen, & soon!  
  Construction in 2020, observing in 2021+

• Planning and optimization currently ongoing

• Many science targets:
  • r, mnu, N_{eff}, w, (g)astrophysics

• Through a number of separate channels:
  CMB power spec at high ell
  lensing auto
  lensing crosses
  tSZ in several ways
  kSZ in several ways
Extra slides
\( N_{\text{eff}} + Y_p \)

- Delensing TT, EE (see Anthony Challinor’s talk) breaks degeneracy

- Phase shift info affected by lensing

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**Figure 29.** The phase shift in the locations of the acoustic peaks. Also plotted is the range of values of \( \ell \) including an additional relativistic fluid, \( N_{\text{fluid}} = 1 \), and, \( N_{\text{fluid}} = 0 \). Whenever the primordial helium abundance \( \Delta Y_p\) can arise from a wide variety of changes to the particle content and thermal in determining the expansion rate. All chains were run until the variation in their means were chosen to be adiabatic. With this choice, our analytic results imply that this fluid does from lensing can be seen in both the TT and EE spectra. The solid and dashed (blue) and (red) curves were rescaled by the same constant factor chosen such that the height of the seventh peak of the TT spectrum matches for the red and blue curves.

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**Figure 6.** The analysis makes use of the generalized CLASS, implemented in forecasts in the limit of perfect delensing (we will just output spectra without computing the lensing), but is an involved procedure to implement on real data. The utility of this implemented in forecasts in the limit of perfect delensing (we will just output spectra without computing the lensing), but is an involved procedure to implement on real data. The utility of this.
The current best constraint on \( \tau \) comes from Planck [320], roughly corresponding to an external prior of \( \tau = 0.06 \pm 0.01 \). We see in Figure 15 that this prior is sufficient to reach \( \sigma(\Sigma m_\nu) < 30 \text{ meV} \) for a wide range of experimental configurations. On the other hand, we also note that there is little improvement with decreased noise or beamsize as we saturate at \( \sigma(\Sigma m_\nu) \approx 26 \text{ meV} \), even if we increase \( f_{\text{sky}} > 0.4 \). Of course, the reason is that we are limited by the \( \tau \)-degeneracy.

**Figure 16.** Forecasts for \( \sigma(\Sigma m_\nu) \) assuming \( \text{CDM} + P_m \) using CMB-S4 and DESI BAO. We vary sensitivity in \( \mu K \cdot \text{arcmin} \) and \( \tau \)-priors, \( \tau = 0.06 \). We fixed the resolution using 1' beams and set \( f_{\text{sky}} = 0.4 \). The white and blue dashed lines correspond to the low-'cosmic variance limit and Planck Blue Book values respectively.

In order to reach the target, \( \sigma(\Sigma m_\nu) < 20 \text{ meV} \), one needs a better measurement of \( \tau \). As shown in the bottom panel of Figure 15, we can reach \( \sigma(\Sigma m_\nu) \approx 20 \text{ meV} \) for a variety of plausible configurations of CMB-S4 with Planck's designed reach in sensitivity, a measurement at the level of \( \sigma(\Sigma m_\nu) \approx 0.006 \). However, as before, we see that there are only moderate improvements coming from lower noise or smaller beams. A similar limitation applies to other cosmological probes, as seen in Table 3-1, which also saturate at a similar sensitivity.

More generally, improved measurements of \( \tau \) and \( H_0 \) may become available before, during or after CMB-S4. We therefore also examine impacts of measurements even further in the future in evaluating the value of the legacy data from CMB-S4. There are ground-based CMB instruments [24, 321] designed to observe very large angular scales, with possible reach to constrain \( \tau \); the CLASS experiment is forecasted to reach \( \sigma(\tau) = 0.004 \) [322], for example. Space missions [323, 324] are proposed to constrain the primordial gravitational waves through the so-called reionization bump during the 2020s; they are designed to reach sensitivity well beyond that required to achieve a cosmic-variance limited \( \tau \) measurement, \( \sigma(\tau) \approx 0.002 \). Measurement of...
**kSZ$^2$ power spectrum**

See Simone Ferraro’s talk

![Graph showing $\bar{K}_{tot}^{-2} L^2 C_{KK}^L / (2\pi)$ vs. $L$ for different cases.](image)

- **reion. kSZ**
- **late-time kSZ**
- **$N_{KL}^{KK}$**

![Graph showing $f_{sky}^{-1/2} (S/N)$ vs. Noise (µK-arcmin) for different bin counts.](image)

- **1-bin**
- **2-bin**
- **3-bin**

$\theta_{FWHM} = 1'$

$\theta_{FWHM} = 3'$

Note that the reionization kSZ makes a larger contribution than the late-time kSZ, even though the $z$-dependence of small-scale physics means that it is robust to a wide range of possible contaminants. For further details, refer to the paper by Smith & Ferraro.