Title: Precision cosmology with the next generation of CMB and optical surveys

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Abstract: Ground-based cosmic microwave background (CMB) experiments are now pushing into discovery space where new insights on inflation, dark matter, dark energy and neutrino physics will be obtained by unraveling signatures buried beneath the primordial fluctuations. I will present new results from the Atacama Cosmology Telescope (ACT) that exemplify the power of high-resolution measurements of the microwave sky, including high-fidelity maps of dark matter through gravitational lensing. These maps set the stage for a robust measurement of the neutrino mass scale and hierarchy with upcoming ACT and Simons Observatory data. I will also discuss a new proposal for dramatically improving the sensitivity to primordial non-Gaussianity using measurements of the cosmic velocity field, and sketch a path towards using this technique to detect or rule out multi-field inflation using a combination of upcoming CMB data from the Simons Observatory and optical galaxy data from the Vera Rubin Observatory.
Precision cosmology with next generation CMB and optical surveys

Mathew Madhavacheril
Peebles Fellow, Perimeter Institute

ACT
Perimeter Seminar, 27 April 2021
Precision cosmology with next generation
CMB and optical surveys

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The CMB as a backlight

Neutrino mass
Cosmic inflation
Mass mapping
Velocity mapping
CMB (older, farther, microwave)
galaxies (newer, nearer, optical)

Image: PICO team
CMB
e.g. ACT, Simons Observatory

galaxies
e.g. Rubin/LSST
WHAT WE KNOW

- Age and expansion rate
- Dark matter dominated
- Accelerating expansion
- Gaussian, nearly-scale invariant initial conditions

\[ \langle T \rangle = 2.7 \text{ K} \]
\[ \Delta T = \pm 4 \times 10^{-5} \text{ K} \]

Snapshot of fluctuations at \( t=380k \text{ years} \)

*Planck Satellite (2009-2013)*
WHAT WE KNOW

• Age and expansion rate*
• Dark matter dominated
• Accelerating expansion
• Gaussian, nearly-scale invariant initial conditions

• Why is expansion accelerating?
  o Dark energy?
  o Modified gravity?

• Particle nature of dark matter?
• Additional light particles?
• Neutrino mass generation mechanism?

• An inflationary phase?
  o Multi-field?
  o Gravitational waves?

• Missing baryons?
• Galaxy formation / evolution
• Reionization epoch
• Cosmic web structure
Science goals

**Dynamics**
- Why is expansion accelerating?
  - Dark energy?
  - Modified gravity?

**Fundamental particles**
- Neutrino mass generation mechanism?

**Initial conditions**
- An inflationary phase?
  - Multi-field? Primordial non-Gaussianity?

Constraining the Lagrangian for beyond-Standard Model physics
Constraining (possibly) string phenomenology

Mathew Madhavacheril, Perimeter Institute
The CMB as a backlight

Interactions with matter as it evolves and structure forms
Neutrino physics open questions

- Flavor oscillations seen -> have mass (quantum oscillation of superpositions of mass eigenstates)
- What is the absolute mass scale?

This is tied to physics beyond the Standard Model; sensible ways to add mass require extensions
Neutrino physics open questions

- Flavor oscillations seen -> have mass
- What is the absolute mass scale?
- What is the hierarchy or ordering of mass states?

Oscillation experiments only tell us about the difference of mass squared

\[ \text{sum} > 60 \text{ meV} \quad \text{sum} > 100 \text{ meV} \]

6-10 orders of magnitude lighter than all the other Standard Model particles. Why?
Neutrino physics open questions

- Flavor oscillations seen -> have mass
- What is the absolute mass scale?
- What is the hierarchy or ordering of mass states?
- Need to extend Standard Model Lagrangian by adding **new particles** to generate mass for ordinary neutrinos

![Diagram showing normal and inverted hierarchy](image)

- normal hierarchy (NH)
- inverted hierarchy (IH)

\[
\begin{align*}
\text{normal hierarchy (NH)} & : \Delta m^2_{\text{sol}} < \Delta m^2_{\text{atm}} \\
\text{inverted hierarchy (IH)} & : \Delta m^2_{\text{atm}} < \Delta m^2_{\text{sol}}
\end{align*}
\]

- \( m^2 \) increases from left to right
- \( m^2 \) increases from top to bottom
- \( \nu_e, \nu_\mu, \nu_\tau \)
- \( \nu_1, \nu_2, \nu_3 \)
- \( \Delta m^2_{\text{sol}} \), \( \Delta m^2_{\text{atm}} \)

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Mathew Madhavacheril, Perimeter Institute
Neutrino physics open questions

- Flavor oscillations seen -> have mass
- What is the absolute mass scale?
- What is the hierarchy or ordering of mass states?
- Are there additional sterile neutrino species?
- Laboratory measurements (e.g. KATRIN) in the next decade < 200 meV

Cosmological measurements tell us the absolute mass scale and hierarchy.
Projected 1σ uncertainty: 10-30 meV
Cosmic density
smoothed by massive neutrinos

We need to measure the total matter distribution, but most of it is dark matter!

Simulations from Ben Moore (Zurich)
Massive neutrinos smooth the matter distribution
(few percent level)

80% of the matter is invisible (dark matter)
Massive neutrinos smooth the matter distribution (few percent level)

80% of the matter is invisible (dark matter)

How do we measure the matter distribution?
With gravitational lensing of the microwave sky.
Gravitational lensing: the CMB acts as a backlight for matter.

Measures **total** matter dominated by **dark matter**

Robust probe: Can be modeled very well with **linear** theory
Unlensed CMB

Mathew Madhavacheril, Perimeter Institute
Lensed CMB
small-scale deflections

coherent over large (degree) scales

$$\langle T(\ell_1)T(\ell_2) \rangle_{\text{CMB}} = f(\ell_1, \ell_2)\phi(\ell_1 + \ell_2)$$

Lensed CMB

Mathew Madhavacheril, Perimeter Institute
Lensed CMB

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small-scale deflections

coherent over large (degree) scales

\[ \langle T(\ell_1)T(\ell_2) \rangle_{\text{CMB}} = f(\ell_1, \ell_2) \phi(\ell_1 + \ell_2) \]

Lensed CMB

Mathew Madhavacheril, Perimeter Institute
OBSERVED CMB (MICROWAVE LIGHT)

$$\langle T(\ell_1)T(\ell_2)\rangle_{\text{CMB}} = f(\ell_1, \ell_2)\phi(\ell_1 + \ell_2)$$

RECONSTRUCTED LENSING (DARK) MATTER DISTRIBUTION

Key point: Large-scale lenses change small-scale CMB features
Need high-resolution to measure this!
Massive neutrinos smooth the matter distribution

We need high-resolution measurements of the microwave sky to map the matter distribution

How do we measure the high-resolution microwave sky?
ACT

Wide area 30% sky for science
Noise 3-6x lower than Planck

We can build big / high-resolution experiments on the ground
Wide area 30% sky for science
Noise 3-6x lower than Planck

We can build big / high-resolution experiments on the ground
High-resolution ACT CMB data
(great for lensing!)

->

New dark matter maps from ACT
OBSERVED CMB (MICROWAVE LIGHT)

RECONSTRUCTED LENSSING MATTER DISTRIBUTION

Key point: Large-scale lenses change small-scale CMB statistics

Need **high-resolution** to measure this!
Mass mapping: Gravitational potential measured with ACT microwave data through *lensing*


Omar Darwish, grad student at Cambridge
Overlaid with distribution of 10 billion year old galaxies (measured by Planck)

- **White** - dark matter peaks
- **Black** - dark matter voids
- **Red** - galaxy peaks
- **Blue** - galaxy voids

Cross-correlation with Sloan galaxies fits Standard Model

Darwish, MM et al. ACT collab., MNRAS 2020

Implements novel foreground cleaning technique from MM+ PRD 2018

Important step towards improved neutrino mass measurements
  e.g. Sherwin, van Engelen, Sehgal, MM et al ACT 2016
Cosmic density
smoothed by massive neutrinos
Measure statistics of lensing map to constrain neutrino mass

\[ \text{CMB Lensing Potential Power (2D)} \]

- Y-axis: How much lensing
- X-axis: For a lens of this (1/angle) scale

Blurring due to neutrino mass

\[ \Sigma m = \begin{align*} 
&= 0.0 \text{ eV} \quad \text{---} \quad \Sigma m = 1.0 \text{ eV} \\
&= 0.1 \text{ eV} \\
&= 0.2 \text{ eV} \\
&= 0.3 \text{ eV} \\
&= 0.4 \text{ eV} \\
&= 0.5 \text{ eV} \\
&= 0.6 \text{ eV} \\
&= 0.7 \text{ eV} \\
&= 0.8 \text{ eV} \\
&= 0.9 \text{ eV} \\
&= 1.0 \text{ eV} 
\end{align*} \]

Abazajian et al. (incl. MM) 2016, CMB-S4 science book
We need more data...
So we went wide.
Upcoming ACT release: High-fidelity dark matter mapping over wide sky.

**ACT 30% sky - 6x more than previously shown**

You are seeing the dark matter distribution by eye!

**PRELIMINARY**

**MM et al, in prep** (data up to 2019)

**Forecast:** constrain **neutrino mass to ~60 meV**, close to ruling out inverted hierarchy (>100 meV)

~1% constraint on amplitude of fluctuations (~4x improvement over Planck)

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**Worked hard for sub-percent precision lensing!**

- **MM+ 2020** (noise-simulation robustness)
- **MM+ 2018** (foreground robustness)
Ground-based: large telescopes, high resolution
FUNDED and UNDER CONSTRUCTION
Observing from 2023 onwards

Simons Observatory

40% sky for science
Noise 2-3 times < ACT
1-2 arcmin resolution
30, 40, 98, 150, 220, 270 GHz

~ 300 members
(including Perimeter)
~$80 million in funding in place
Simons Observatory

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My roles:
- **Lead**: Gravitational lensing reconstruction
- **Lead**: Systematics and science interfaces
- **Member**: Theory and Analysis Committee
Rubin / LSST *

2021

Mid-2020s

Late-2020s

ACT *

Polarbear/Simons Array

Simons Observatory *

SPT

BICEP

CMB-S4 *

LiteBIRD

PICO *

* MM membership
~0.7% for measurement of lensing with Simons Observatory

Simons Observatory collaboration
(incl. MM)
arXiv:1808.07445

My role:
Leading the group that reconstructs this signal
- Exclude inverted hierarchy with Simons Obs.
- Possible measurement of minimal mass with Simons Obs. (<2029)
- Proposed CMB-S4 experiment (starting 2027+) will measure the minimal mass
- Set target for direct detection

Mathew Madhavacheril, Perimeter Institute
Neutrinos smooth the matter distribution

We measure the matter distribution from the microwave sky using gravitational lensing

Can also learn about the very early universe using relics buried in the CMB and galaxy distribution
- Exclude inverted hierarchy with Simons Obs.
- Possible measurement of minimal mass with Simons Obs. (<2029)
- Proposed CMB-S4 experiment (starting 2027+) will measure the minimal mass
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Mathew Madhavacheril, Perimeter Institute
Y-axis: How much lensing

X-axis: For a lens of this (1/angle) scale

10^7[L(L+1)/2\pi]^2 C_L

Project: Understand and mitigate impact of telescope pointing and beam errors
Project: End-to-end tests of foreground and dust contamination

~0.7% for measurement of lensing with Simons Observatory

Simons Observatory collaboration (incl. MM)
arXiv:1808.07445

My role: Leading the group that reconstructs this signal
Neutrinos smooth the matter distribution.

We measure the matter distribution from the microwave sky using gravitational lensing.

Can also learn about the very early universe using relics buried in the CMB and galaxy distribution.
Science example:
Multi-field inflation
- **Exponential expansion** driven by energy density of one or many scalar fields
- Solves horizon, flatness and relic problems

**Inflation**
- **Exponential expansion** driven by energy density of one or many **scalar fields**
- Solves horizon, flatness and relic problems
- Generates primordial fluctuations quantum mechanically

**Inflation**
- **Exponential expansion** driven by energy density of one or many *scalar fields*
- Solves horizon, flatness and relic problems
- Generates primordial fluctuations quantum mechanically
- **Next stage with Simons Observatory:**
  1. measure gravitational waves (not this talk!)
  2. measure non-Gaussianity (this talk)
- Inflation driven by energy density of one or many scalar fields
- Current measurements (Planck CMB) consistent with single field
- Multiple fields naturally motivated by e.g. string theory
  - Predicts possibly detectable amounts of departure from Gaussianity
  - This shows up as excess clustering of galaxies on the largest scales  \[ \Phi_{NG} = \Phi_L + f_{NL} \Phi_L^2 \]  

*Dalal et al 2007*
Galaxy surveys like Rubin/LSST measure clustering

Y-axis:
How much clustering

X-axis:
(1/length) scale

Vera Rubin Observatory
LSST survey
Beginning in a couple of years
Several billion galaxies
Galaxies cluster with dark matter

Mathew Madhavacheril, Perimeter Institute
Galaxy surveys like Rubin/LSST measure clustering

Y-axis: How much clustering

X-axis: (1/length) scale

$P \ [\text{Mpc}^3]$

$k \ [\text{Mpc}^{-1}]$

$f_{\text{NL}}=0$

Mathew Madhaveril, Perimeter Institute
Multi-field inflation predicts excess clustering

Y-axis: How much clustering

Primordial non-Gaussianity

X-axis: (1/length) scale

fNL=0

fNL=5

galaxies (fNL=50)

Mathew Madhaverchil, Perimeter Institute
Multi-field inflation predicts excess clustering

\[ \Phi_{NG} = \Phi_L + f_{NL} \Phi_L^2 \]

- Current constraint from Planck CMB
  \( \sigma(f_{NL}) \sim 5 \)
- Rubin/LSST
  \( \sigma(f_{NL}) \sim 2 \)
- MFI generically predicts \( f_{NL} \sim 1 \)

Y-axis: How much clustering

X-axis: \((1/\text{length})\) scale

Mathew Madhavacheril, Perimeter Institute
Can we improve large-scale clustering measurements beyond what galaxy surveys can measure?
Can we improve large-scale clustering measurements beyond what galaxy surveys can measure?

Yes, by a lot!

New idea: reconstruct large scale velocity field using CMB imprint of moving clouds of electrons
Munchmeyer, MM et al, PRD 2018
**kSZ (kinetic Sunyaev Zeldovich) effect:** Doppler shifts of CMB photons scattering off electrons with bulk velocity

$$\frac{\Delta T_{kSZ}(\vec{n})}{T_{CMB}} \sim \int d\chi e^{-\tau(z)}v_r \delta_e(\vec{n}, \chi)$$

Currently detected only at the 4-8\(\sigma\) level
But expected to improve quickly with (deeper) CMB and larger galaxy volume.
SNR O(100-1000) expected!
How might we measure kSZ?

- Cosmic velocity mode
- CMB temperature
- Galaxy positions

Smith, MM+ 2018
MM+ 2019

(unified framework) (combination with...)

Legacy Survey of Space and Time
Multi-field inflation from the cosmic velocity field: 1.5-3x improvement

New application of the kinetic Sunyaev Zeldovich (kSZ) effect that probes cosmic velocities using CMB x galaxy cross-correlation

Y-axis: How much clustering

X-axis: (1/length) scale

Rule out or detect MFI that predicts fNL \sim 1

Mathew Madhavacheril, Perimeter Institute
Multi-field inflation from the cosmic velocity field: 1.5-3x improvement

New application of the kinetic Sunyaev Zeldovich (kSZ) effect that probes cosmic velocities using CMB x galaxy cross-correlation

Next: Apply similar technique as lensing for velocity reconstruction

ACT and DES data, first demo, sigma(fNL) ~ 10

SO and LSST 2-year data, sigma(fNL) ~ 5

Eventually:
SO and LSST 5-year data, sigma(fNL) ~ 2
SO and LSST 10-year data, sigma(fNL) ~ 1
S4 and LSST 10-year data, sigma(fNL) ~ 0.5

Rule out or detect MFI that predicts fNL ~ 1

Mathew Madhavacheril, Perimeter Institute
Well-motivated prediction of non-Gaussianity from cosmic inflation due to multiple scalar fields

Galaxy surveys (like Rubin/LSST) alone don’t probe this

The combination of CMB data from Simons Observatory and galaxy data from Rubin/LSST does!

Rule out or detect MFI that predicts $f_{NL} \sim 1$
Multi-field inflation from the cosmic velocity field: 1.5-3x improvement

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SO and LSST 2-year data, sigma(fNL) \( \sim 5 \)

**Eventually:**

SO and LSST 5-year data, sigma(fNL) \( \sim 2 \)

SO and LSST 10-year data, sigma(fNL) \( \sim 1 \)

S4 and LSST 10-year data, sigma(fNL) \( \sim 0.5 \)

**Rule out or detect MFI that predicts fNL \( \sim 1 \)**

Mathew Madhavacheril, Perimeter Institute
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Rule out or detect MFI that predicts fNL ~ 1

Mathew Madhavacheril, Perimeter Institute
Conclusion

- The next decade of cosmology exploits the CMB as a backlight
- We reach sub-percent precision on gravitational lensing (challenge and opportunity)
  - Allowing us to understand massive neutrinos
- A new application of the CMB+galaxy inferred cosmic velocity field
  - Detect or rule out a smoking gun signal from inflation