Precision Cosmology with the Cosmic Microwave Background

Sara M. Simon

Fermilab

February 9, 2023

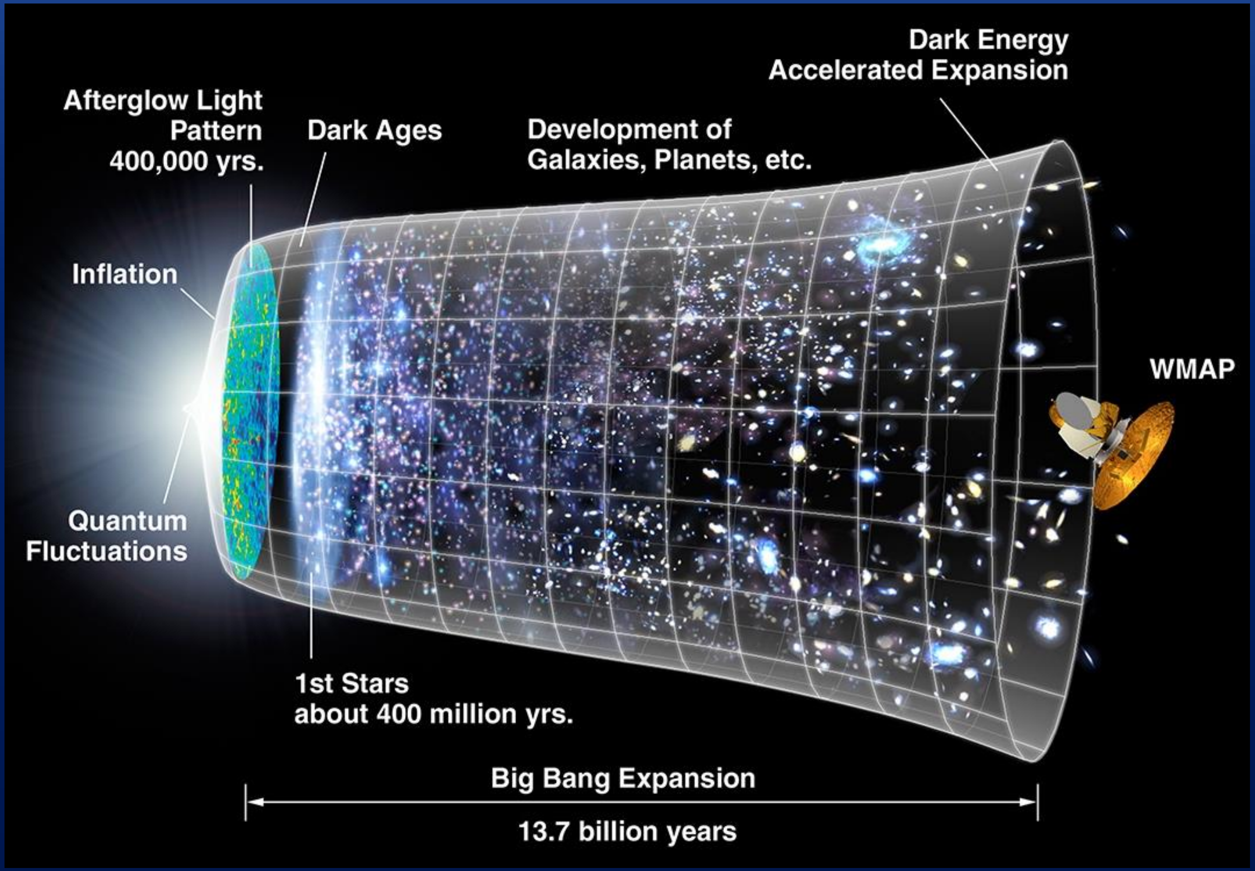
Photo courtesy of Jon Ward

Overview

- Measurements of the cosmic microwave background (CMB) continue to reveal a wealth of information about our universe
- Improved measurements will expand our understanding of neutrinos, dark matter, dark energy, and cosmological models
- Future CMB projects will revolutionize the field, but require bold steps in instrumental development
  - Novel technology development: production and systematic control
  - An Example: Feedhorns
- Technologies developed for CMB experiments open new opportunities for scientific exploration

ΛCDM Cosmology

- Expanding, flat universe that began in a hot, dense state
- Dominated by dark energy and dark matter



NASA WMAP Science Team

- ΛCDM model describes our universe incredibly well… BUT it leaves many fundamental questions unanswered

The CMB answers fundamental questions

- CMB can measure the energy scale of inflation (*r*)
  - One of the few ways to probe early universe ~10^{-36} s after its beginning

The CMB answers fundamental questions

- CMB can measure the energy scale of inflation (*r*)
  - One of the few ways to probe early universe ~10^{-36} s after its beginning
- CMB measures the sum of the neutrino masses ($\sum m_v$)
  - Compliment to neutrino oscillation experiments that measure Δm_{ij}^2

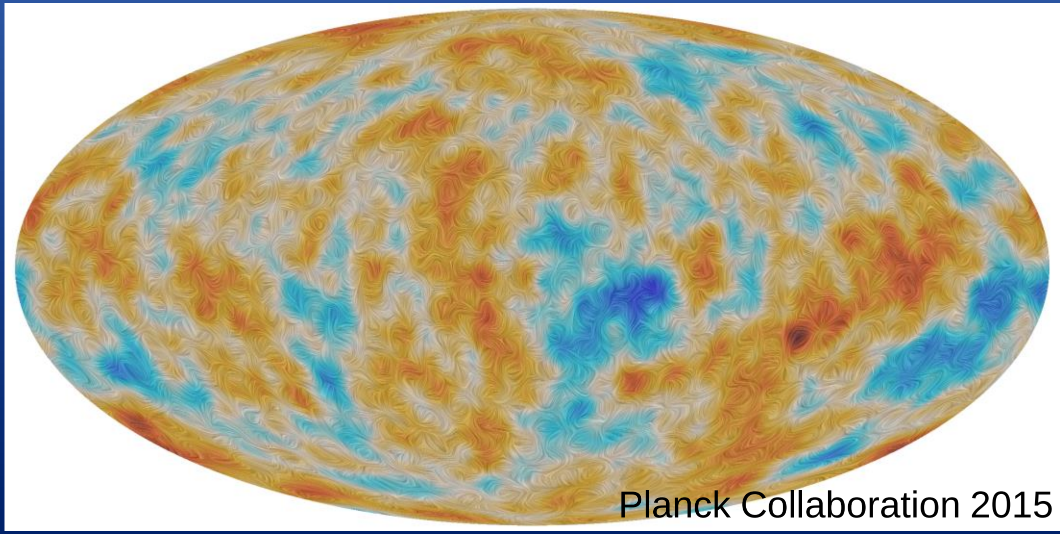
The CMB answers fundamental questions

- CMB can measure the energy scale of inflation (*r*)
  - One of the few ways to probe early universe ~10^{-36} s after its beginning
- CMB measures the sum of the neutrino masses ($\sum m_\nu$)
  - Compliment to neutrino oscillation experiments that measure Δm_{ij}^2
- CMB measures the number of relativistic species (N_{eff})
  - Constrain/probe theories that predict new light particles

The CMB answers fundamental questions

- CMB can measure the energy scale of inflation (*r*)
  - One of the few ways to probe early universe ~10^{-36} s after its beginning
- CMB measures the sum of the neutrino masses ($\sum m_\nu$)
  - Compliment to neutrino oscillation experiments that measure Δm_{ij}^2
- CMB measures the number of relativistic species (N_{eff})
  - Constrain/probe theories that predict new light particles
- CMB constrains dark matter and dark energy through the growth of structure (σ_8), the expansion rate (H_0), and the amounts of dark matter and dark energy
  - Extremely accurate probe of these mysterious dark components
  - Highly complementary to supernovae and large-scale structure studies

CMB Temperature and Polarization Maps



Temperature and Polarization Power Spectra
Maps of Lensing and Sources

Science

- Theories of the early universe (*r*)
- $\sum m_\nu$ and N_{eff}
- Contents and nature of dark matter and dark energy
- Formation and evolution of structure
- Information about astrophysical processes

Current State of the Field: CMB Instruments

Temperature Only
BOOMERanG -1998
DASI - 2000
WMAP - 2001
Atacama Cosmology Telescope (ACT) - 2007
SPT - 2007

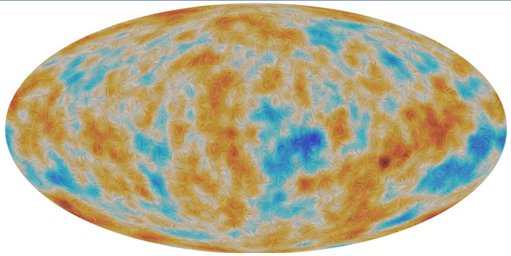
Next Few Years:
60k+ detectors
Simons Observatory (SO) - 2023

Added Polarization
QUaD - 2005
BICEP - 2006
QUIET - 2008
Planck - 2009
BICEP2 - 2010
Keck Array - 2010
ABS - 2012
ACTPol - 2013
POLARBEAR - 2012
SPT-Pol - 2012
BICEP 3 - 2015
SPIDER - 2015

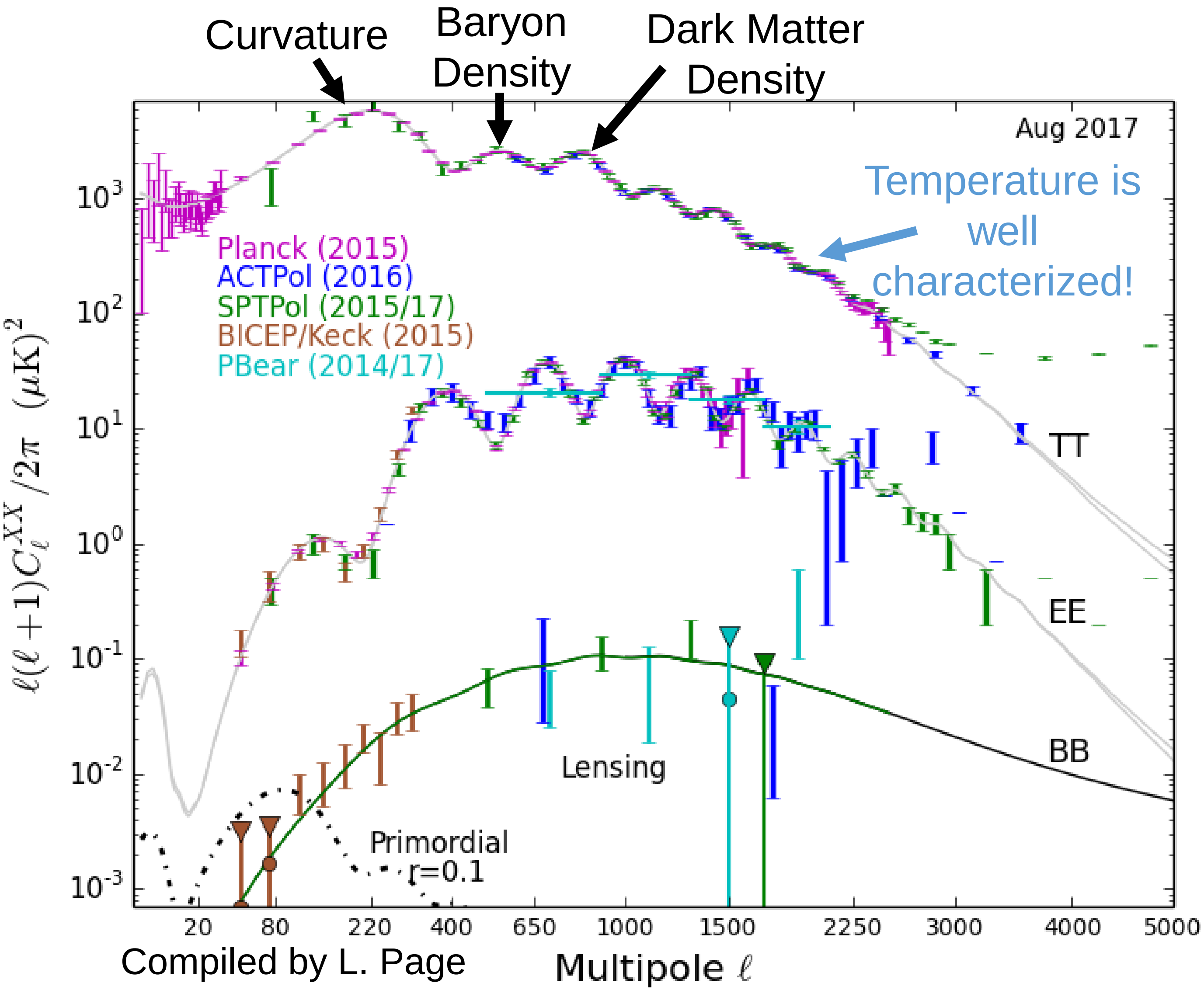
Current Generation:
<10k detectors
CLASS - 2016
Advanced ACTPol (AdvACT) - 2017
SPT-3G - 2017
POLARBEAR 2 - 2019
Simons Array - 2019
BICEP Array - 2019/2020
SPIDER 2 – 2022

Next 10 Years
CMB-S4 (~500k detectors) - ~2030
LiteBIRD - late 2020s

Current State of the Field-Temperature



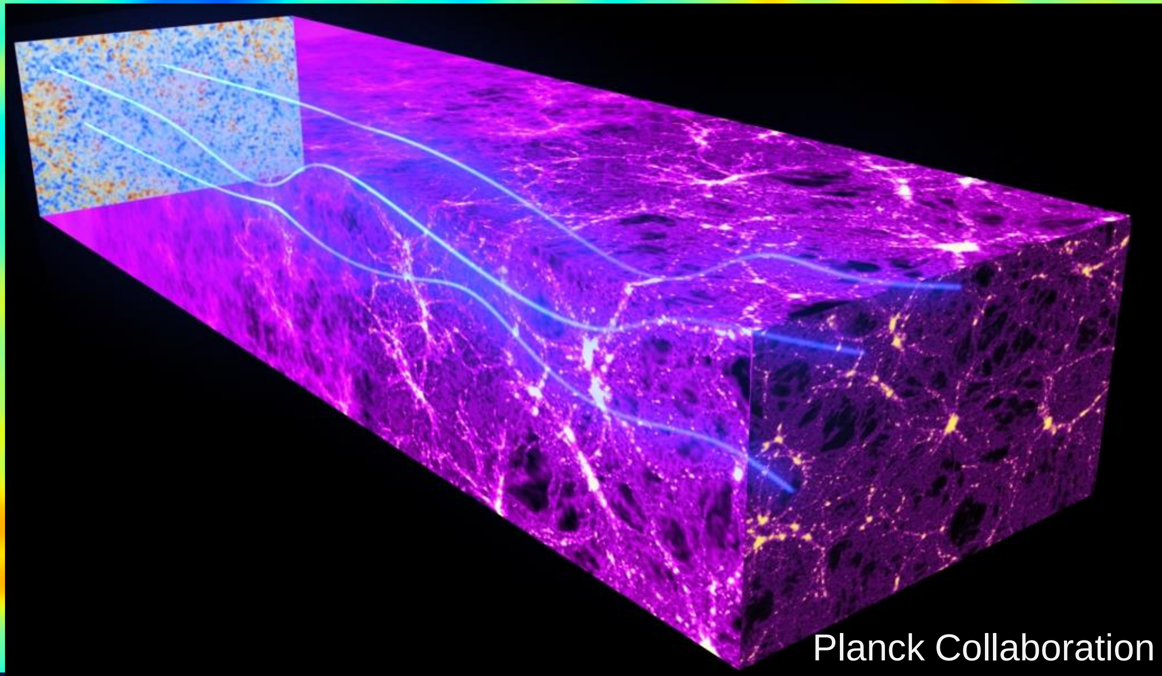
Planck Collaboration 2015



Compiled by L. Page

CMB Lensing

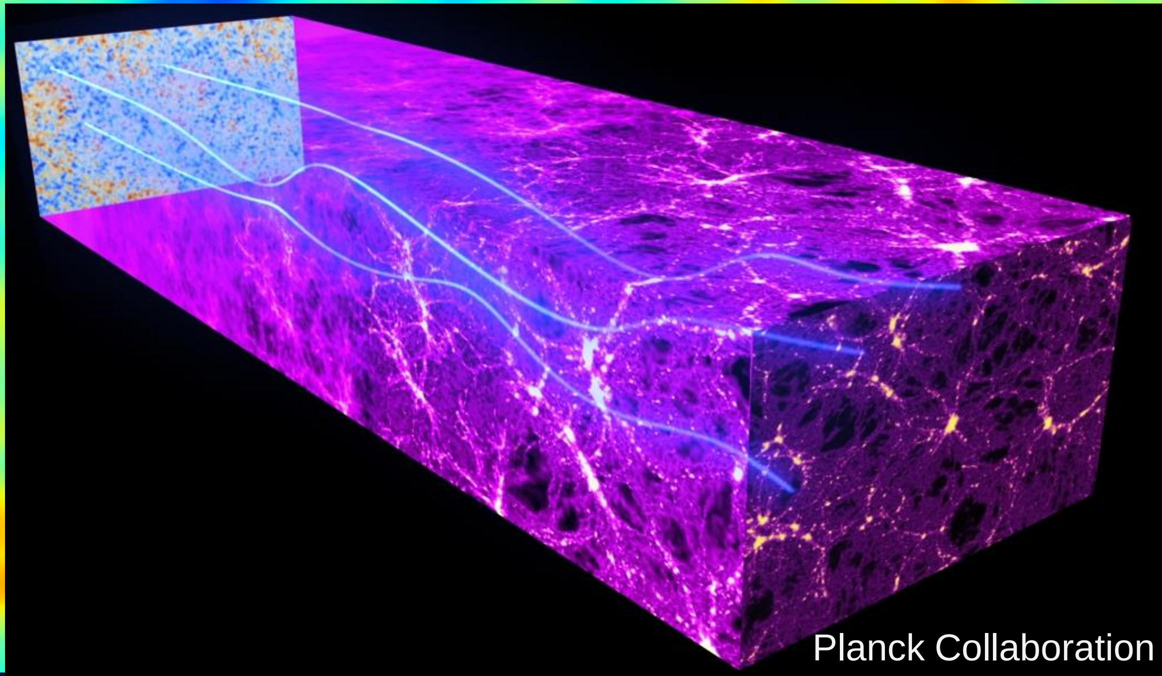
- Photons from the CMB are gravitationally deflected by structure
- Can reconstruct maps of the dark matter distribution
- Lensing probes the growth of structure → dark energy, $\sum m_\nu$
- Need improved temperature + polarization measurements on small angular scales across large areas of the sky



Planck Collaboration

CMB Lensing

- Photons from the CMB are gravitationally deflected by structure
- Can reconstruct maps of the dark matter distribution
- Lensing probes the growth of structure → dark energy, $\sum m_\nu$
- Need improved temperature + polarization measurements on small angular scales across large areas of the sky

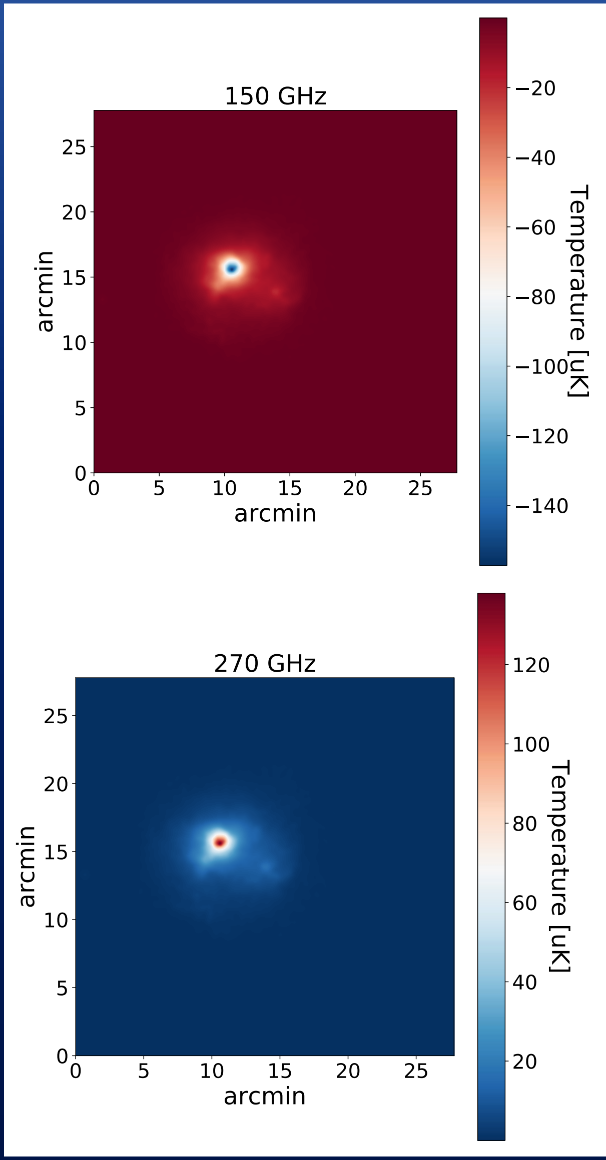


Galaxy Clusters via the Sunyaev-Zel'dovich (SZ) Effect

- Photon energy boosted from scattering off high energy electrons in galaxy clusters via inverse Compton scattering

- Galaxy clusters are largest bound structures in the universe → mass profiles highly sensitive to effects of dark matter and dark energy on structure formation
  - Signal does not dim with distance → picture of evolution
  - Increased sensitivity to cluster outskirts → cluster astrophysics

- Cluster mass estimates are currently limited at the 5-10% level



Particles Beyond the Standard Model

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

Standard Model: $N_{eff} = 3.046$

Beyond the Standard Model: ΔN_{eff}

$\Delta N_{eff} \geq 0.047$ Spin $\frac{1}{2}$, 1, $\frac{3}{2}$

$\Delta N_{eff} \geq 0.027$ Spin 0

Planck (current): $\sigma(N_{eff}) \sim 0.2$

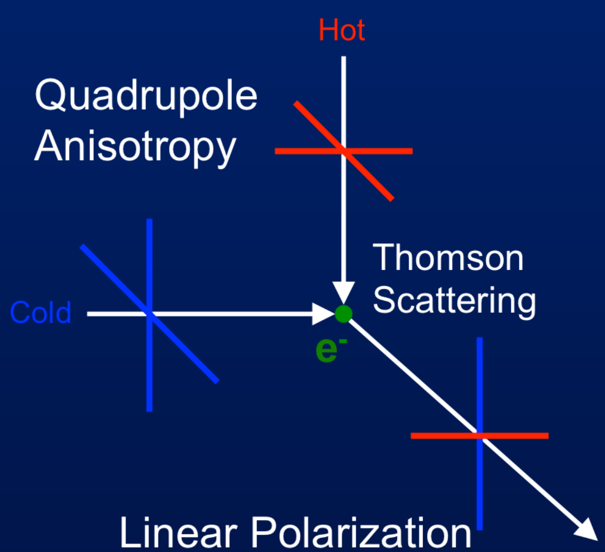
Simons Observatory: $\sigma(N_{eff}) \sim 0.07$

CMB-S4: $\sigma(N_{eff}) \sim 0.027$

Polarization in the CMB

CMB linearly polarized at decoupling by Thomson Scattering → Need quadrupolar anisotropy to cause linear polarization →

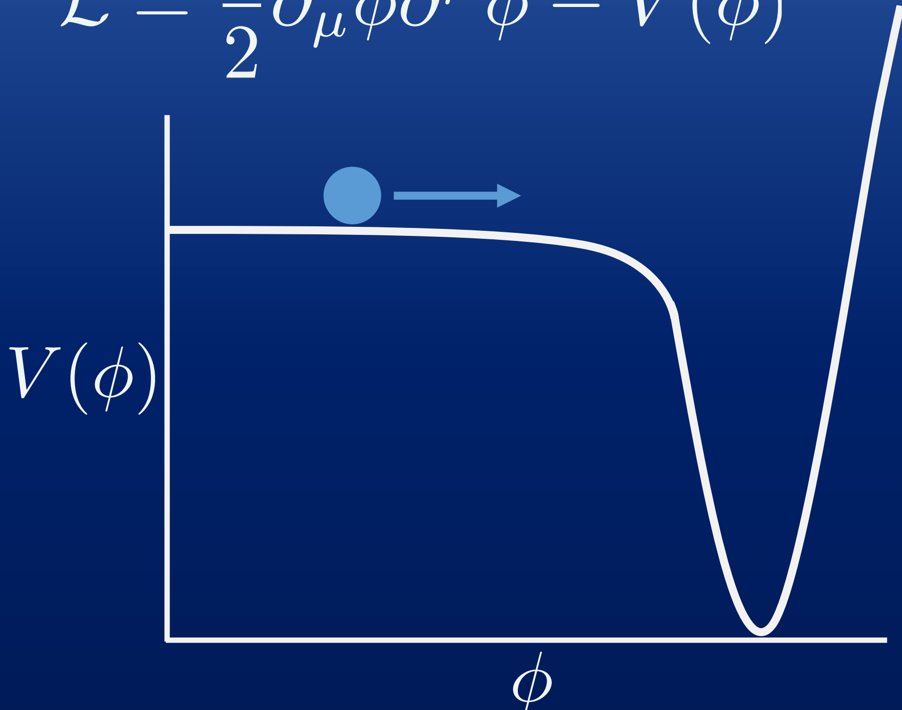
- Scalar (Density) Perturbations → E-mode Polarization (Even Parity)
- Tensor (G-wave) Perturbations → E-mode Polarization (Even Parity); B-mode Polarization (Odd Parity)
- Vector (Vorticity) Perturbations → B-mode Polarization (Odd Parity)



U. Seljak and M. Zaldarriaga, 1997
M. Kamionkowski, A. Kosowsky, and A. Stebbins, 1997

Did a period of inflation occur in the early universe?

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - V(\phi)$$



$$V(\phi) >> \frac{1}{2}\left(\frac{d\phi}{dt}\right)^2$$ Inflation

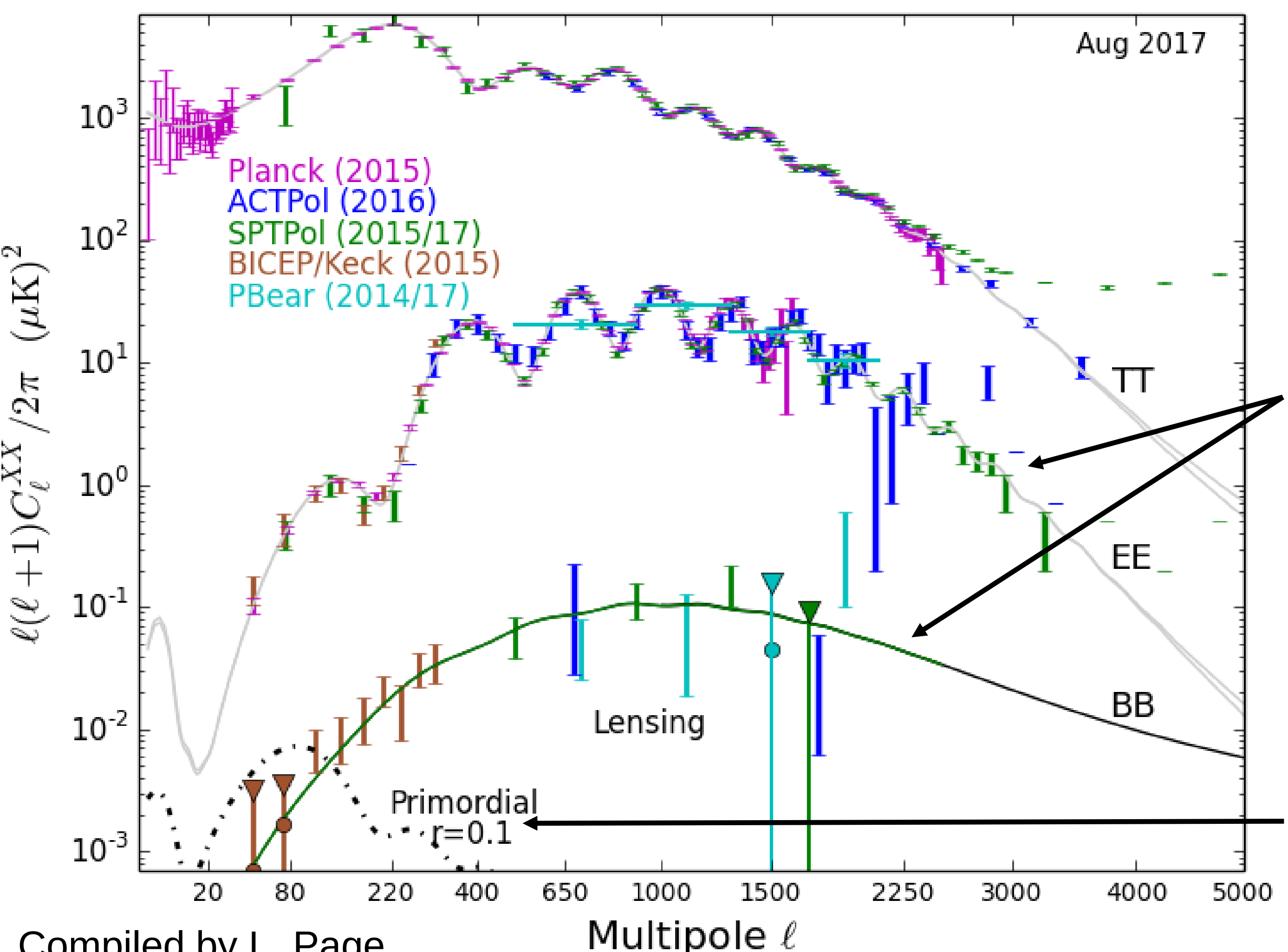
$$V(\phi) < \frac{1}{2}\left(\frac{d\phi}{dt}\right)^2$$ Inflation ends

- Inflation offers several explanations
  - Expansion yields nearly flat, homogeneous, isotropic universe
  - Seeds density fluctuations
  - Creates tensor perturbations (gravitational waves)
- B-modes are the cleanest channel to detect inflation → quantify with tensor-to-scalar ratio *r*
- *r* directly measures energy scale of inflation
- Probe quantum gravity and fundamental physics ~10^{-36} s after the universe began at grand unification theory energy scales (10^{16} GeV)

A.D. Linde, 1982

A. Albrecht and P.J. Steinhardt, 1982

Current State of the Field-Polarization



Compiled by L. Page

Small Angular Scales: Information about the formation of structure → neutrinos, dark energy, dark matter

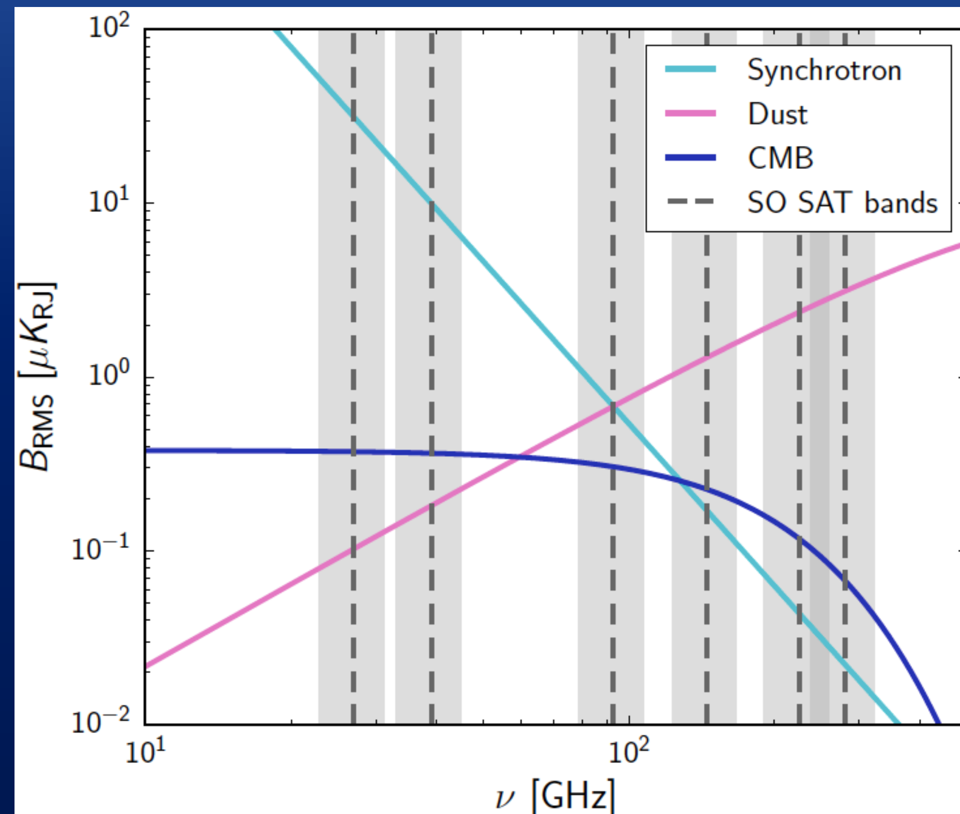
Large Angular Scales: Constrain *r*, early universe theories

Measurement Challenges

- The amplitude of the B-mode signal is small (BICEP2/Keck Array *r*<0.06) → Need high sensitivity

- Polarized foreground contamination from synchrotron and dust emission → Need wide frequency coverage

- Fluctuations in the unpolarized atmosphere, especially on large angular scales (ground-based) → Need to lower atmospheric noise

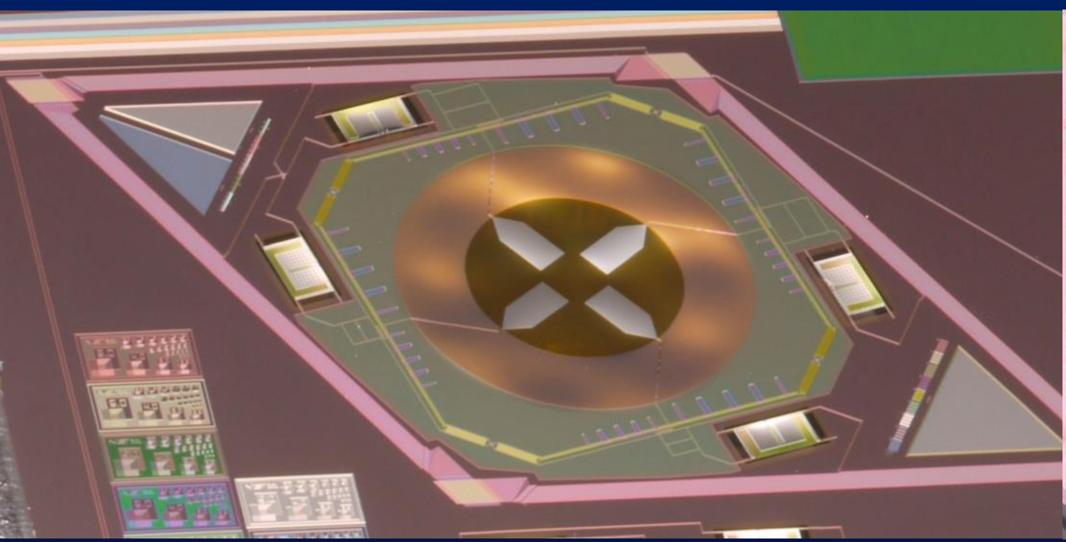
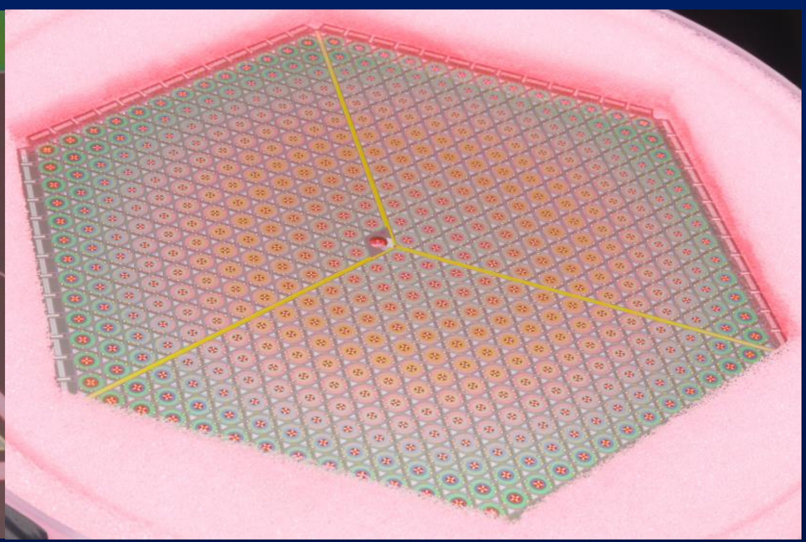


The Simons Observatory Collaboration, 2018

Future Progress in CMB Science

- **Progress is now driven by instrumental advancements**

- Multichroic pixels → increased sensitivity and frequency coverage
- Increased pixel count → increased sensitivity
  - Increased number of pixels/array
  - Increased number of arrays
- Improved broadband optics → increased sensitivity and frequency coverage
- Polarization modulators → lower atmospheric noise

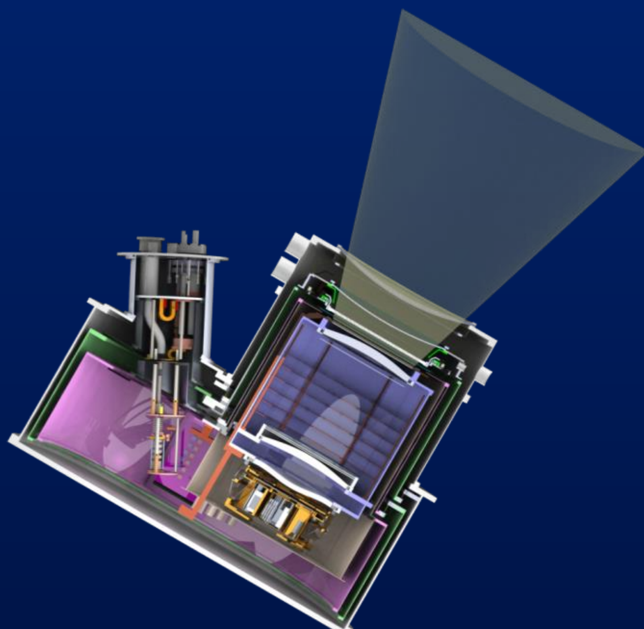
Sensitivity Alone is Not Sufficient

- **The science achievable with future experiments like SO and CMB-S4 will depend on how well we model and mitigate systematic effects and how well we calibrate our telescopes**
  - Future experiments like SO and CMB-S4 will have unmatched sensitivity
  - As sensitivity increases, so does susceptibility to systematic effects
  - Need improved simulations of systematics → inform instrument design and removal in analysis
  - Need improved calibration → characterize instrument and remove these systematic effects

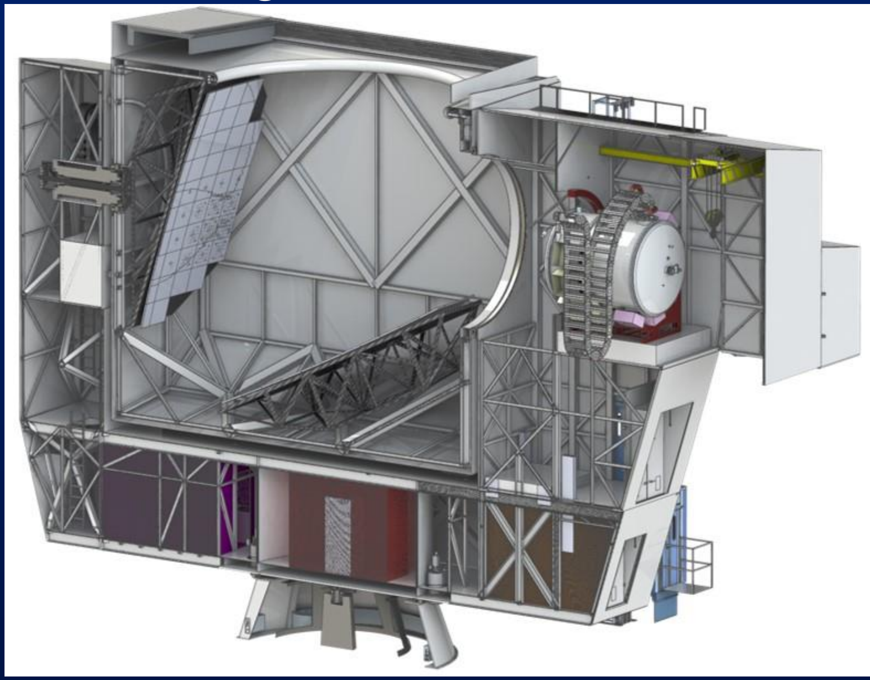
Simons Observatory

- Located at an elevation of ~5200 m in the Atacama Desert in Chile
- Multichroic cameras 27/39 GHz, 90/150 GHz, 220/280 GHz
- 60,000+ detectors total

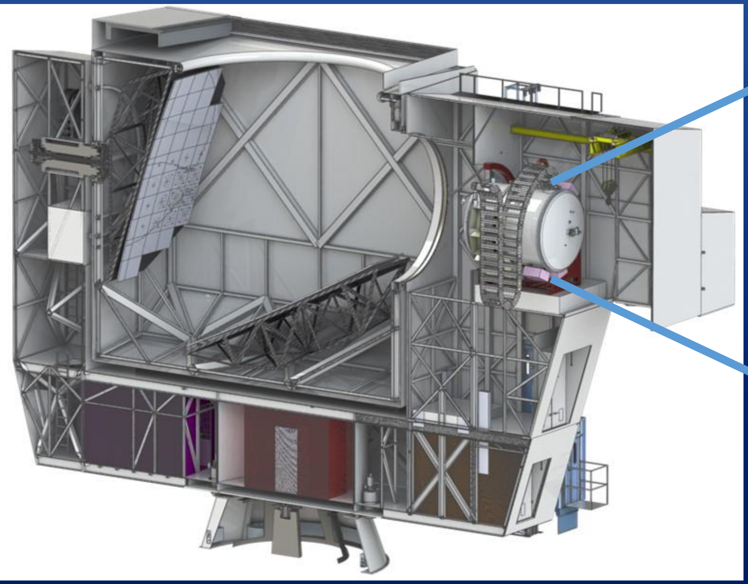
Small Aperture Telescopes (SATs):
- Three ~0.5 m refractive telescopes
- Measure/constrain primordial B-mode

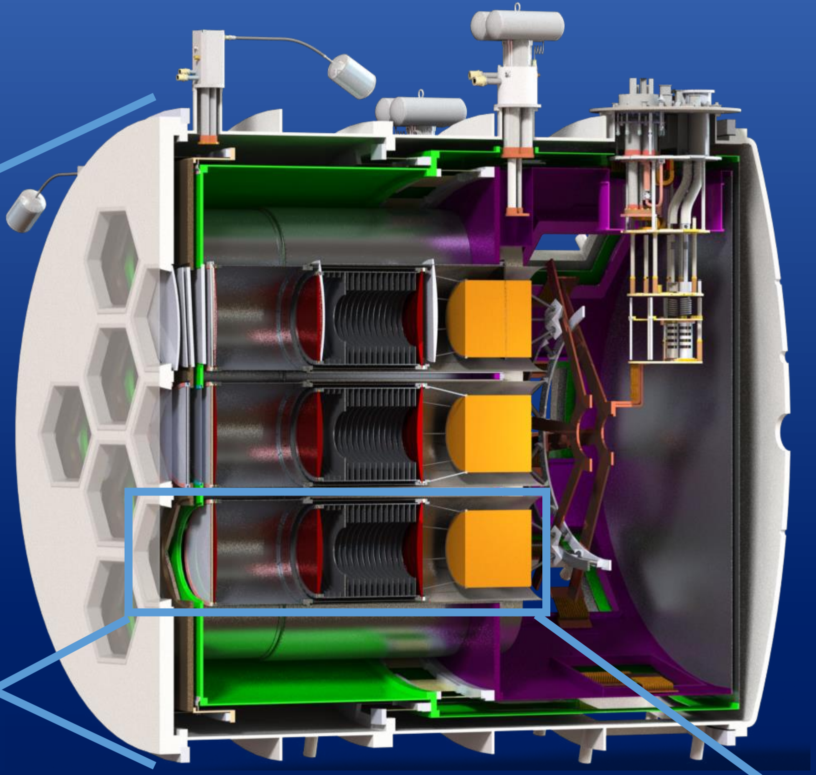


Large Aperture Telescope (LAT):
- One ~6 m crossed-Dragone telescope with 7 optics tubes
- Small angular scale science

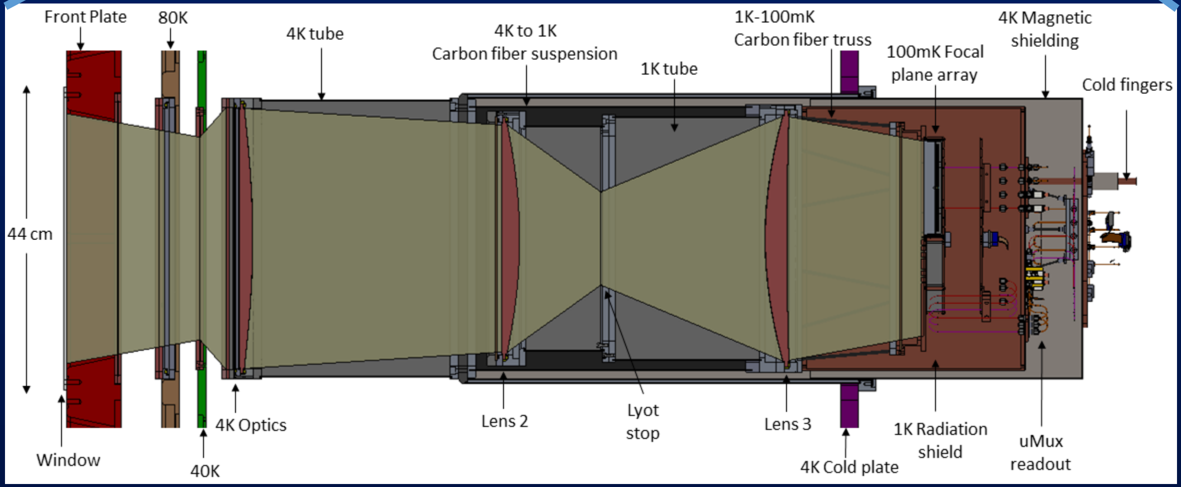


LAT Optics



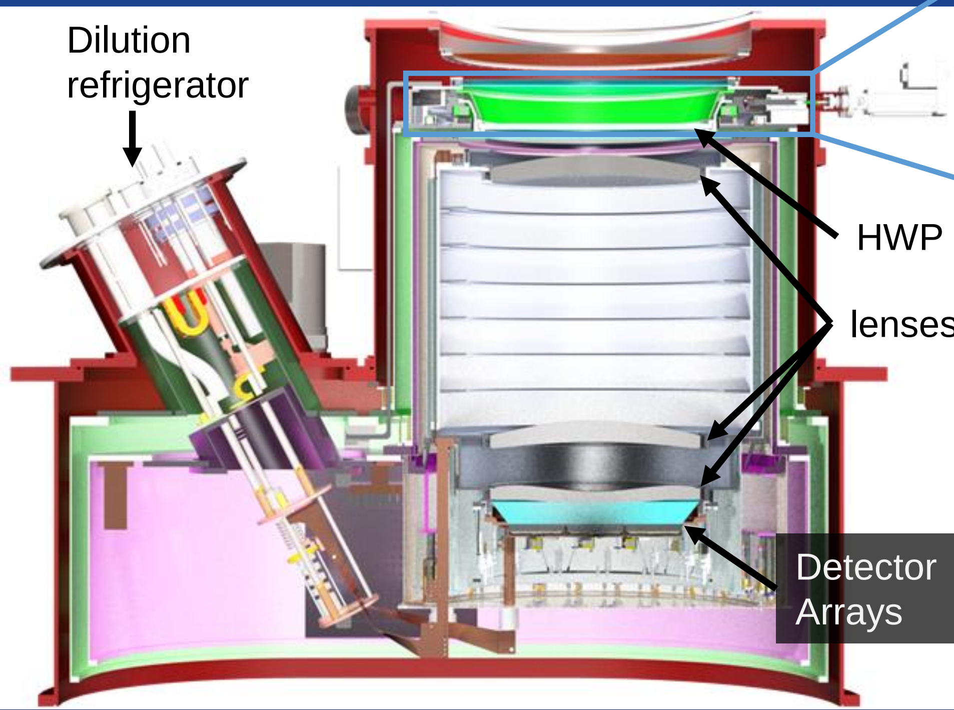


- 6 m Crossed-Dragone
- Beam full width at half maximum (FWHM) at 150 GHz is 1.4 arcmin
- 1.3˚ field of view (FOV) per optics tube
- 7.8˚ FOV total



SAT Optics

Polarization Modulation: Continuously-rotating Half-wave Plate (HWP)



- Refractive design, 3 lenses
- 17 arcmin FWHM at 150 GHz
- FOV=35˚

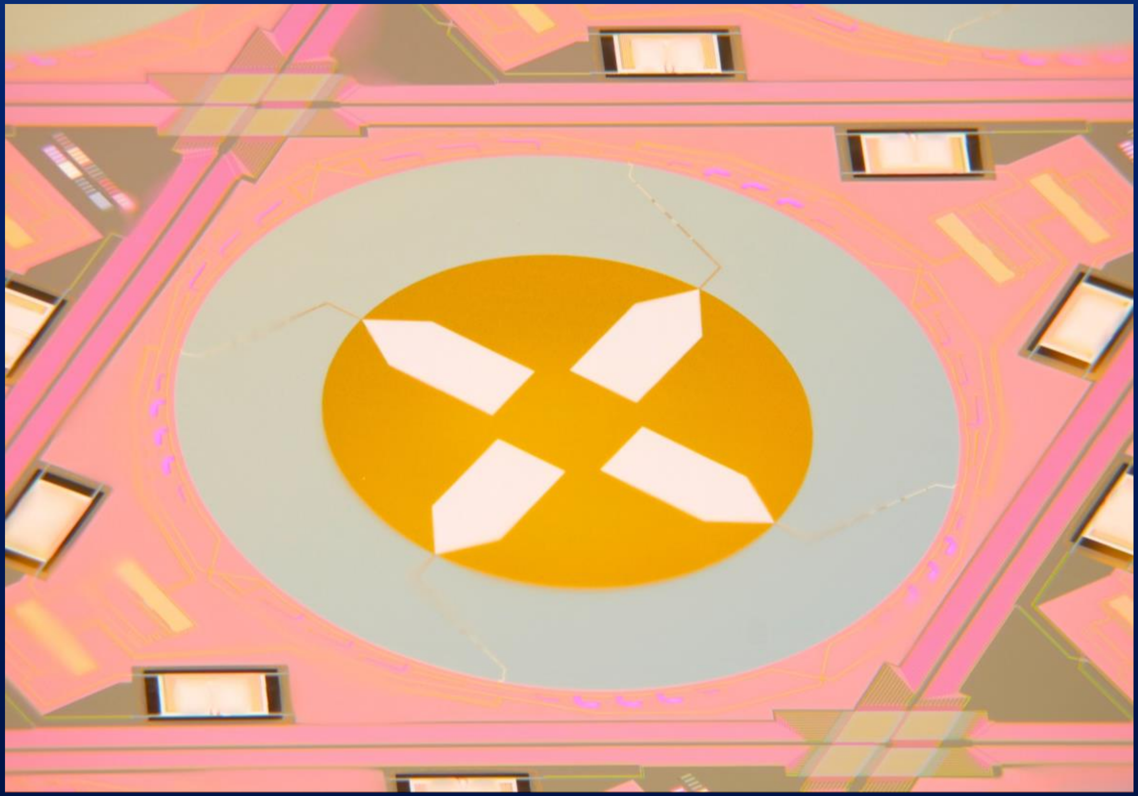
- Atacama B-mode Search (ABS) pioneered HWPs for ground-based CMB experiments

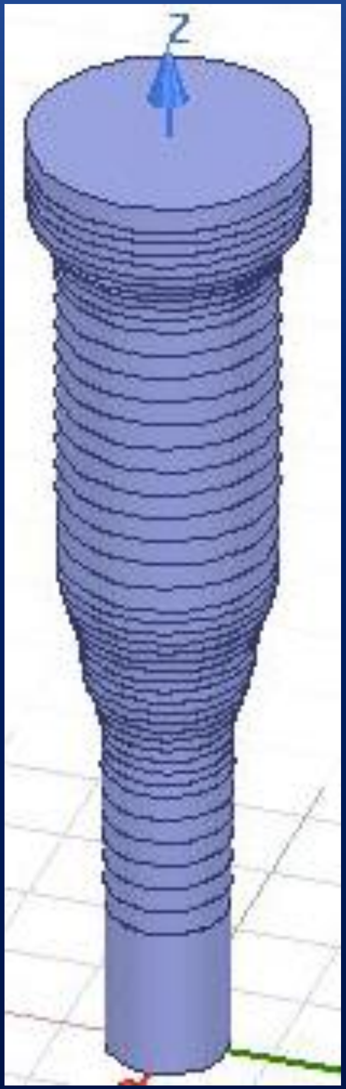
- Polarization modulation mitigates atmospheric noise, systematic effects, and instrumental polarization leakage

- Can be used to calibrate and characterize instrument

Feedhorn-Coupled Arrays

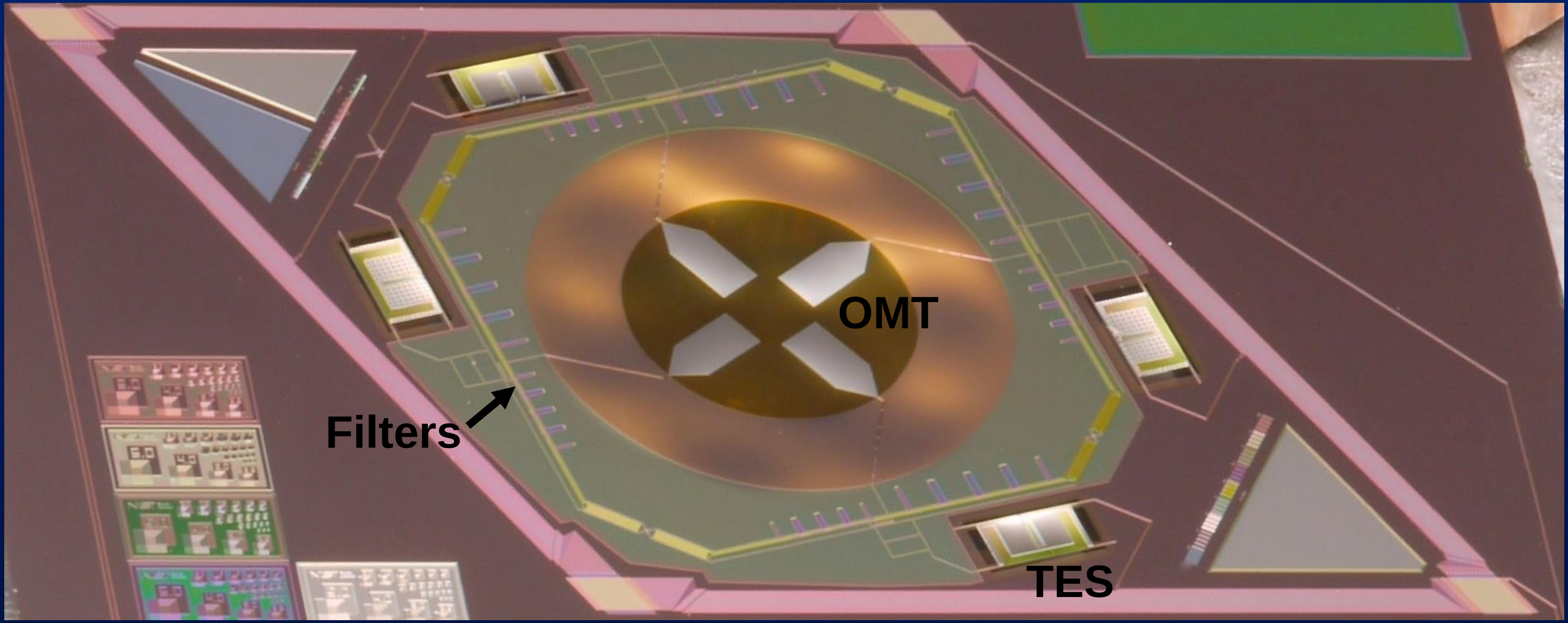
- Feedhorn defines the detector beam
- Couples light onto the ortho-mode transducer (OMT)
- OMT splits light into two orthogonal polarizations





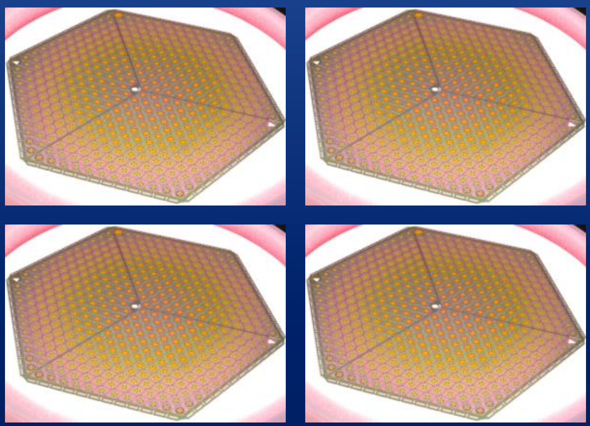
Detectors and Readout

- 4 detectors/pixel: 2 orthogonal polarizations for each of 2 bands
- Transition-edge sensors (TESs): use the steep superconducting-to-normal transition of a superconductor to make an extremely sensitive detector (~160 mK)
- Read out with µMUX→~1000 detectors/line (vs ~64)



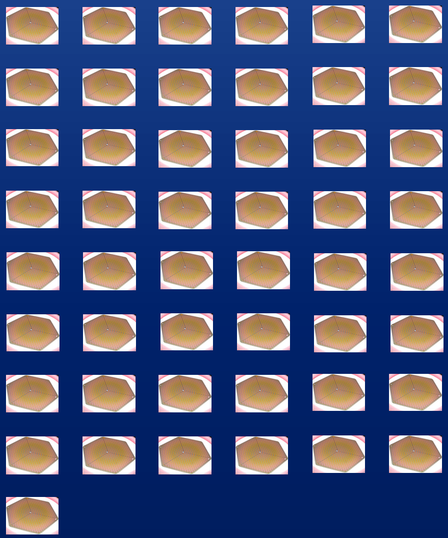
Production for Next-Generation Experiments

AdvACT



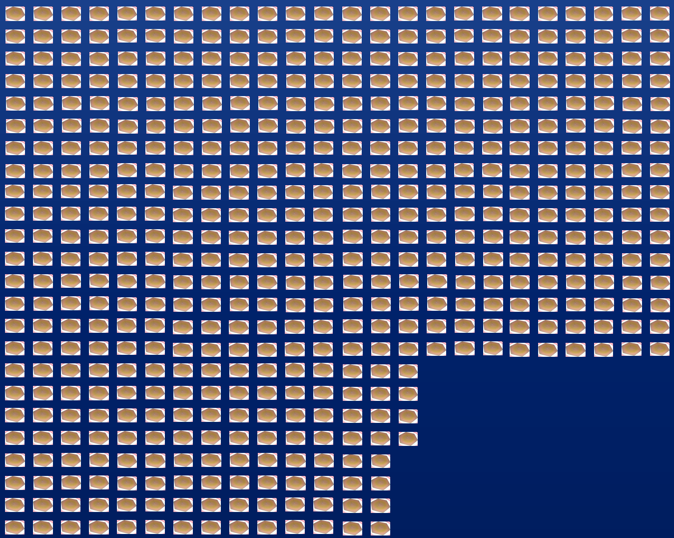
4
150 mm detector arrays

SO



49
150 mm detector arrays

CMB-S4

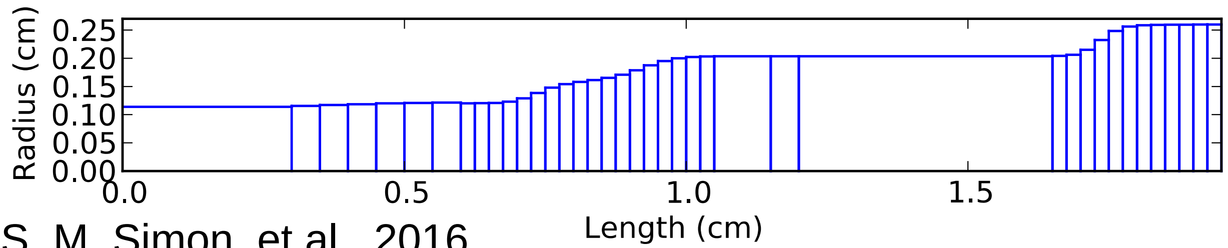


~500
150 mm detector arrays

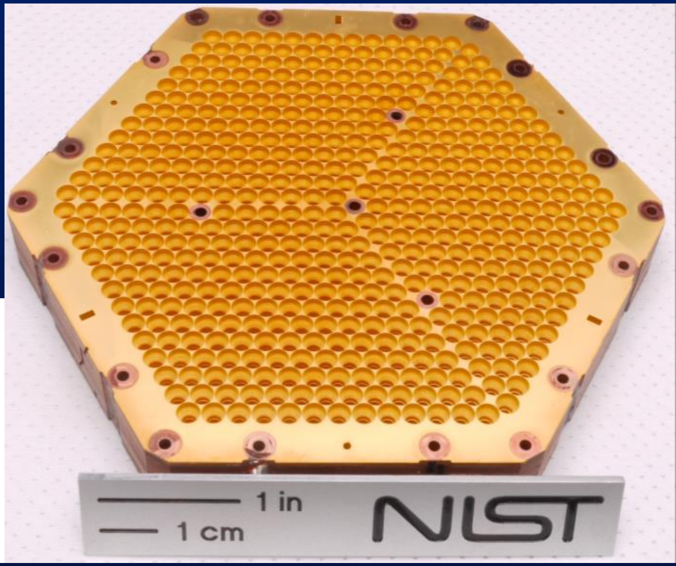
Scalability in production rate and cost are necessary to build next-generation experiments

Feedhorn Array Production

- Individually pattern silicon wafers with photolithography that you stack up to build the feedhorn profile
- Can create many feedhorn geometries
- Several weeks to produce a single array → Time and cost prohibitive for next-generation experiments

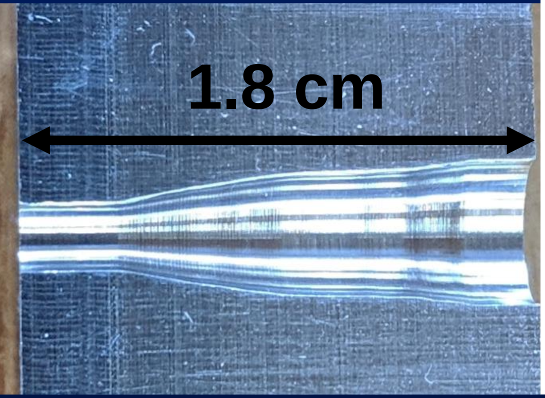


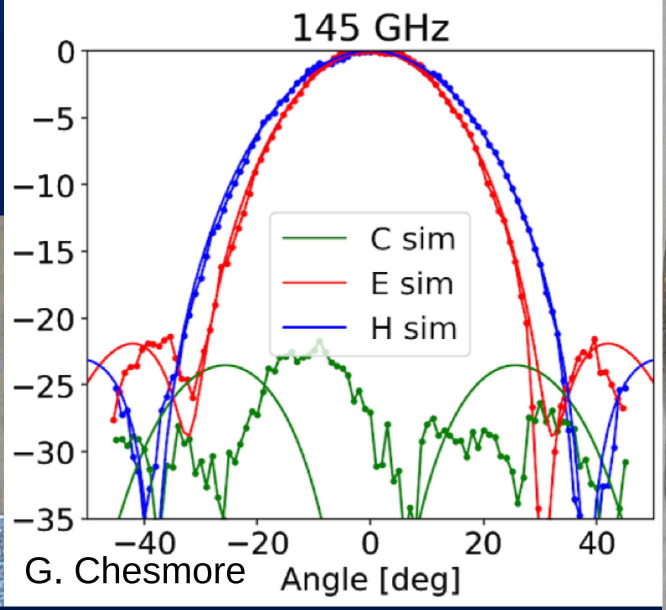
S. M. Simon, et al., 2016

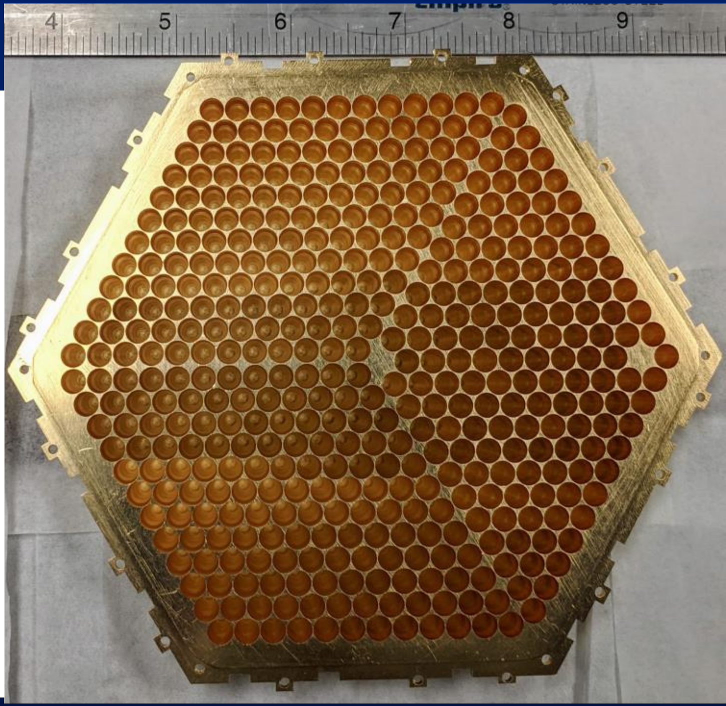


Direct-Machined Feedhorns

- Machine feedhorn profiles into metal with custom drill and reamer set
- ~5 arrays/week → ~1/20 cost
  - Can be done commercially + in parallel
  - Aluminum is cost-effective and easy to machine
- Validate with beam maps and laser metrology

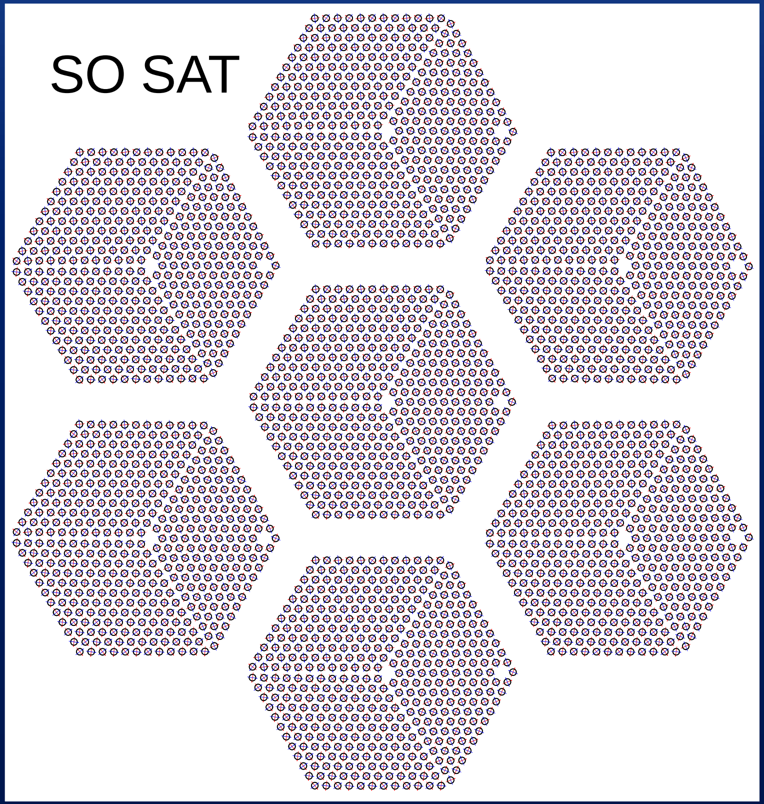






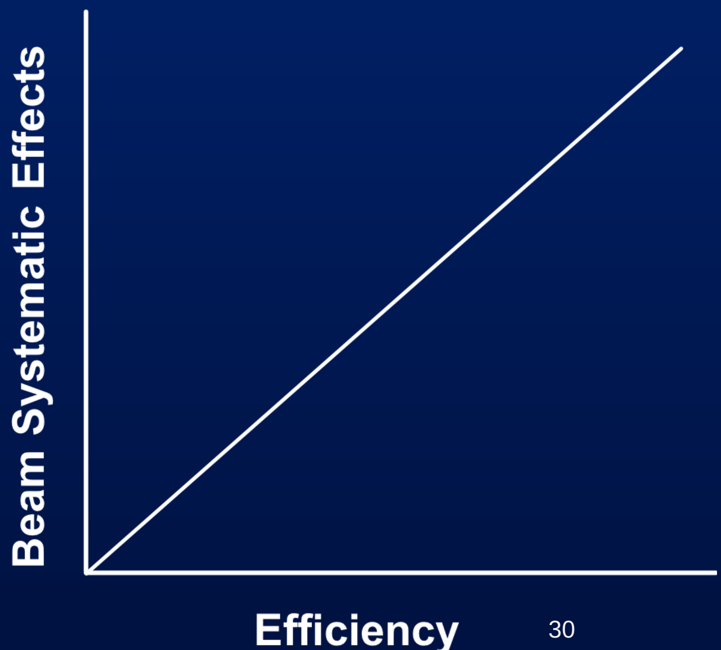
We need advances in modeling as much as we need advances in technology!

- Developed an instrument sensitivity calculator to estimate noise
- Developing an end-to-end instrument model
  - Science forecasts
  - Instrument design feedback
  - Set requirements on systematic effects and calibration
  - Build up analysis pipeline
- Interplay between sensitivity, systematics, and calibration is critically important



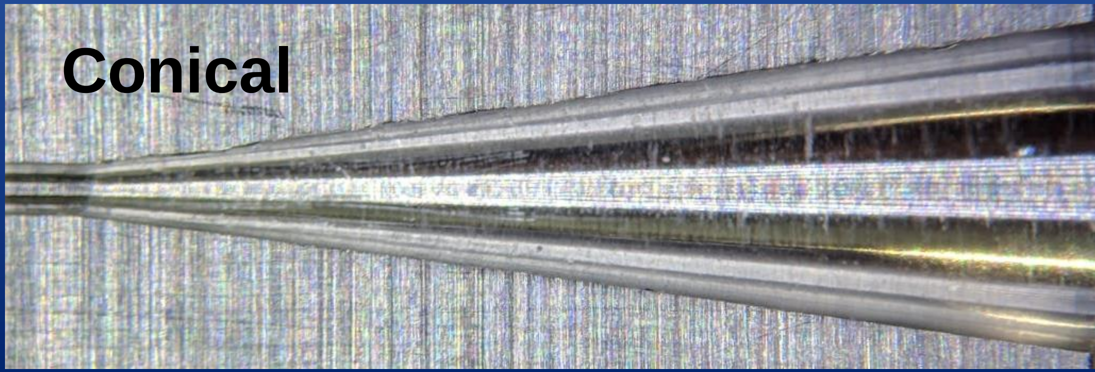
Ideal Feedhorn Properties: Sensitivity vs. Systematics

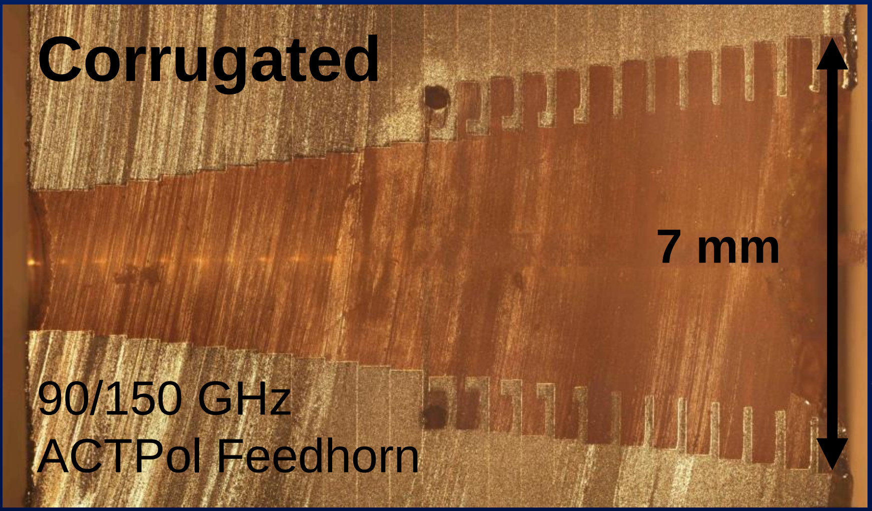
- **Sensitivity:** High beam coupling efficiency
- **Systematic Effects:** Maximal beam symmetry → Asymmetry leads to temperature to polarization and E-mode to B-mode leakage
- **Calibration:** Beam calibration with planet observations and external calibrators reduces beam effects by at least ~10x



Previous State of the Art

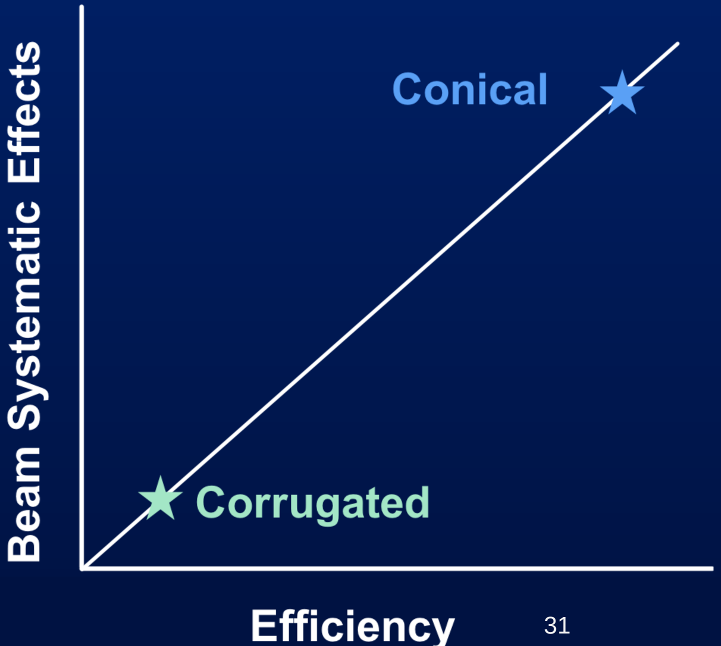
- Conical Feedhorns
  - High coupling efficiency
  - Poor beam symmetry
- Corrugated Feedhorns
  - Difficult to fabricate
  - Near ideal beam symmetry
  - Low coupling efficiency





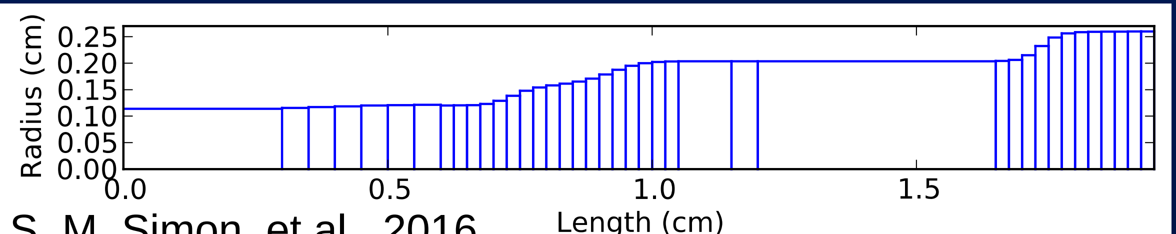
5.15 mm

Aperture size requirement for SO

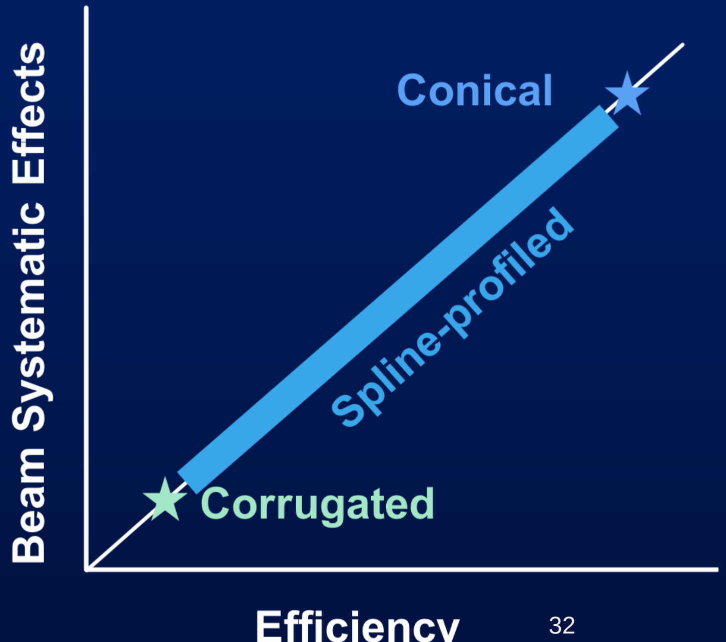


New State of the Art: Spline-Profiled Feedhorns

- Tunability between beam symmetry and efficiency
- Used on AdvACT: 27/39 GHz, 90/150 GHz, 150/230 GHz
- Increased AdvACT mapping speed by factor of ~1.8 at 90/150 GHz compared to corrugated design
- Monotonically increasing profile → enables direct machining and high performance

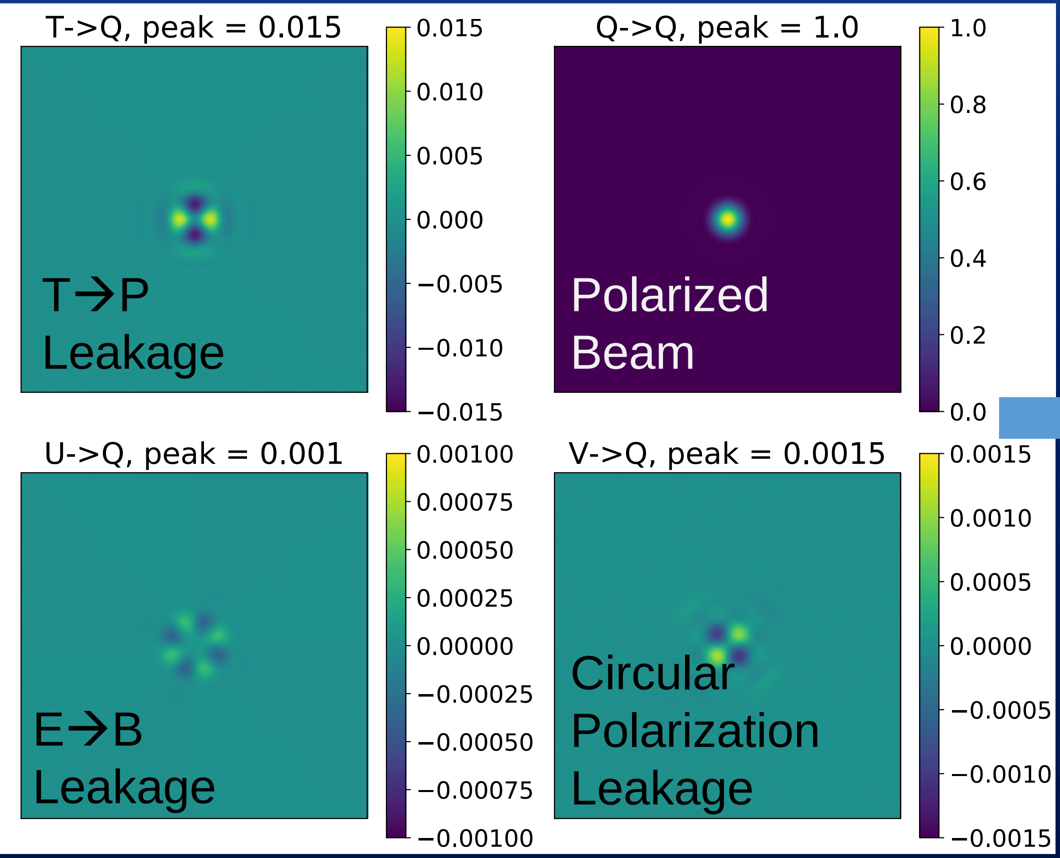


S. M. Simon, et al., 2016

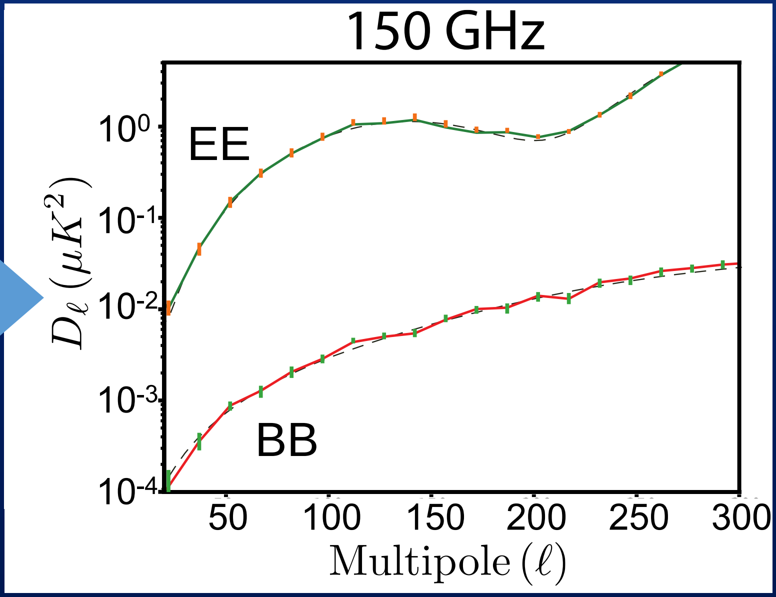


Optimized Performance

Average Leakage Beams: 150 GHz Band



Estimated Power Spectra



Systematics acceptable with calibration→ Gain 10% more sensitivity!

Need this level of rigor for every aspect of the project

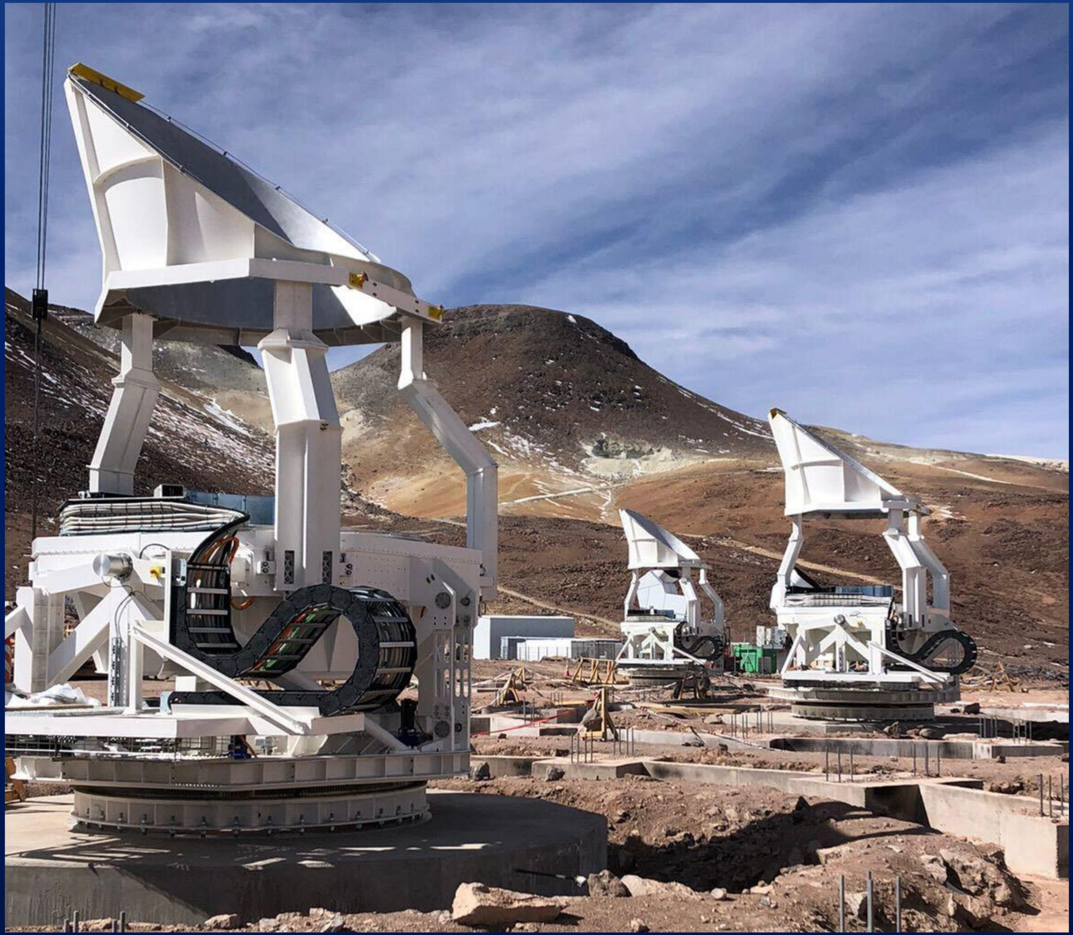
- Instrument design decisions
  - Do our instrument designs meet our requirements?
  - What design changes are the most impactful?

- Calibration plan
  - What are the calibration requirements?
  - What calibration hardware can meet these requirements?
  - How well do we have to understand our calibrators?
  - How often do we have to calibrate throughout our science observations?

Simons Observatory: Fielding in 2023

Groundbreaking science

Laying groundwork for CMB-S4 and future CMB projects



Developing technologies with improved performance that can be fabricated at scale

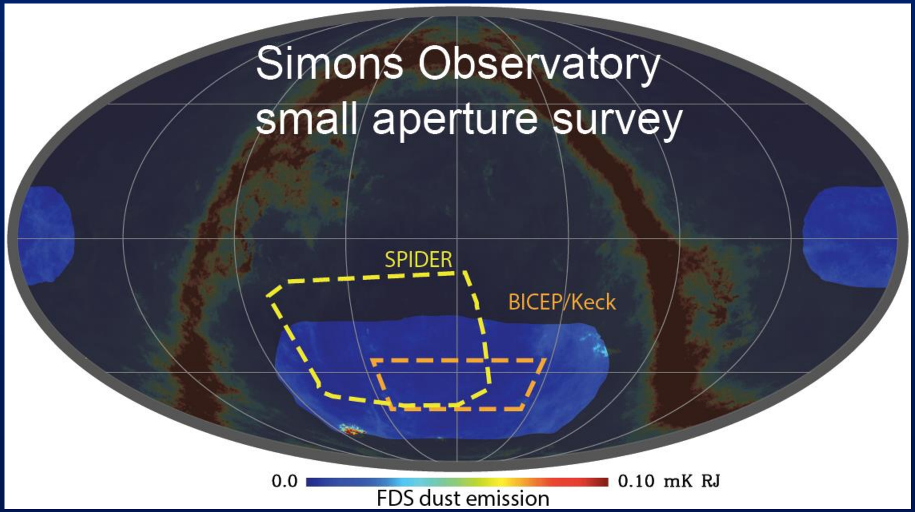
Developing tools for instrument modeling and analysis pipelines

Balance between sensitivity, systematic effects, and calibration

Survey Strategy

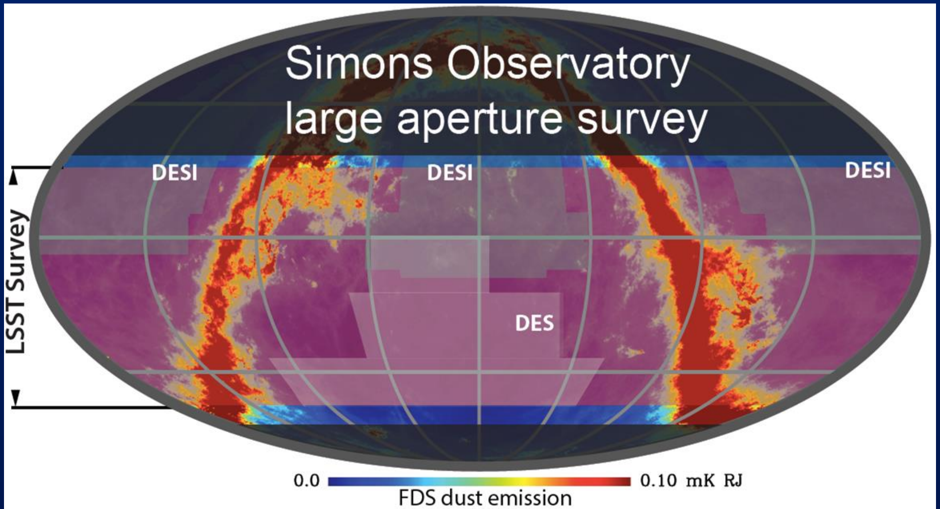
SO: 5 years of observation beginning in 2023
CMB-S4: Observation beginning ~2030

SATs



10% sky

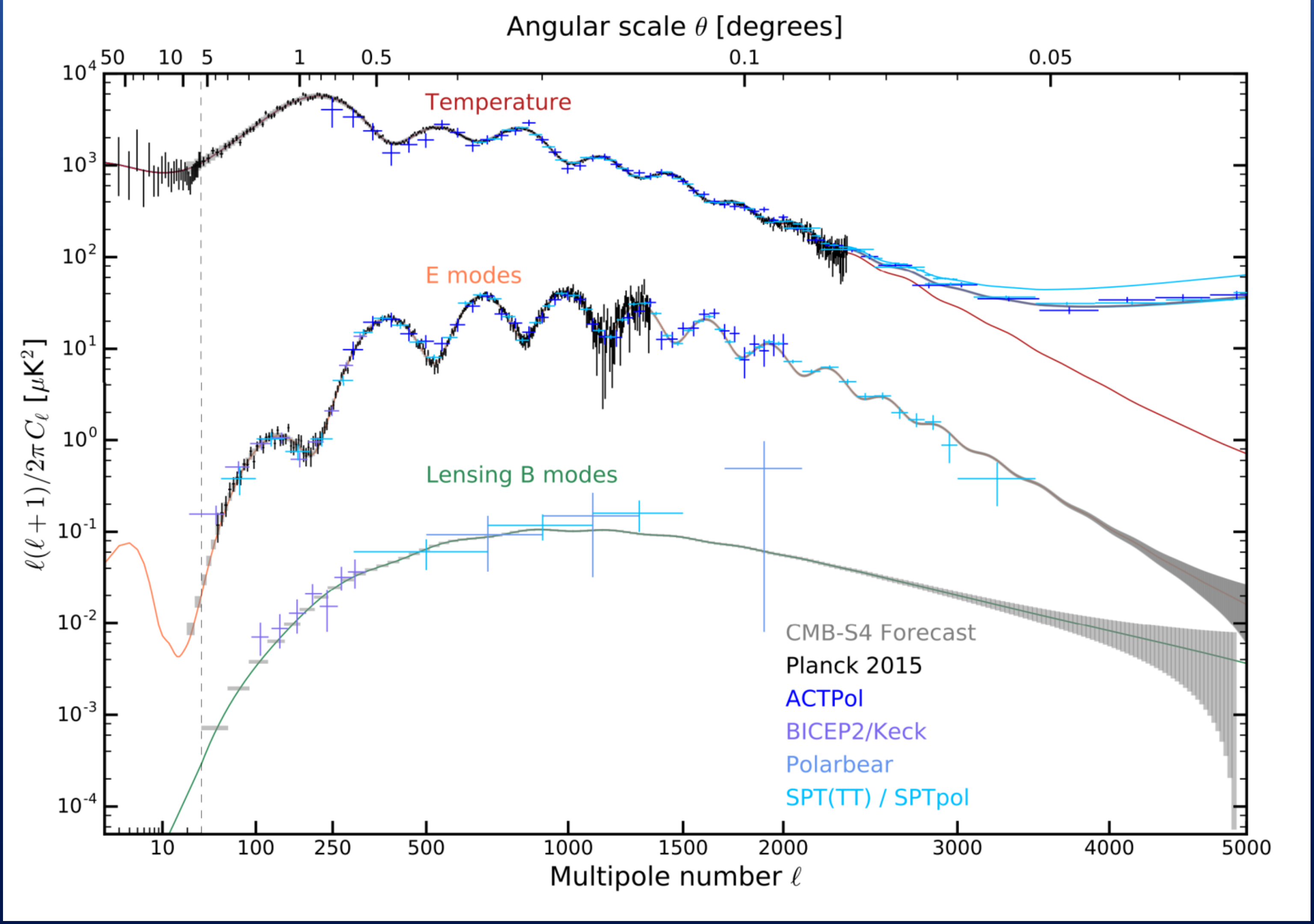
LAT



40% sky

The Simons Observatory Collaboration, 2018

CMB-S4 Spectra



The CMB-S4 Collaboration, 2016

Science Forecasts

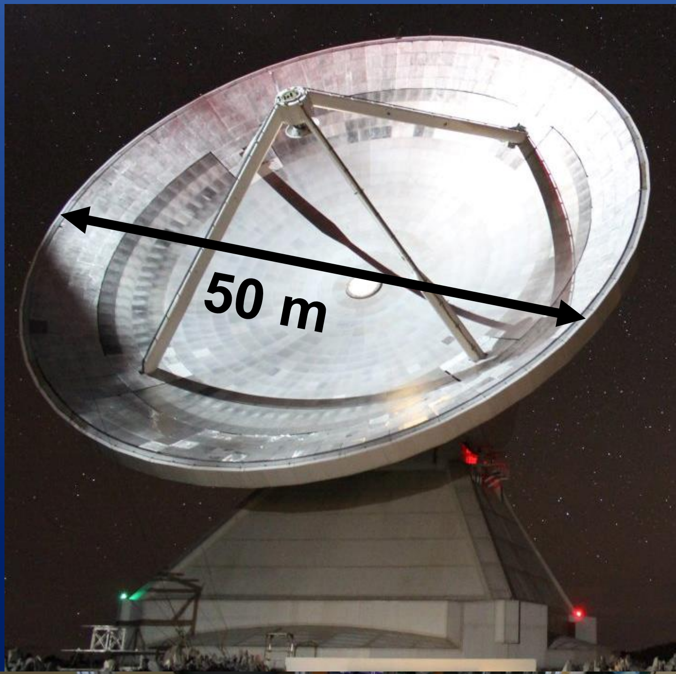
Parameter	Current Best	SO Baseline	CMB-S4 Baseline	Method
$\sigma(r)$	0.03	0.003	0.0005	BB + ext delens
$\sigma(N_{eff})$	0.2	0.07	0.027	TT/TE/EE + $\kappa\kappa$
$\sigma(\sum m_\nu)$	0.1 eV	0.04 eV	0.015 eV	$\kappa\kappa$ + DESI-BAO
$\sigma(H_0)$	0.5	0.4	0.24	TT/TE/EE + $\kappa\kappa$
$\sigma(\sigma_8)$ (%)	7%	2%	0.1%	$\kappa\kappa$ + LSST-LSS + DESI-BAO

The Simons Observatory Collaboration, 2018
The CMB-S4 Collaboration, 2016

Plus:
SO: 20,000+ galaxy clusters
CMB-S4: 100,000+ galaxy clusters

New Avenues: TolTEC

- High-resolution SZ camera for the Large Millimeter Telescope (LMT) in Mexico
- TolTEC has 5-10 arcsecond resolution and several advantages over X-ray
- Use CMB technologies (e.g. feedhorns)
- Handfuls to hundreds of high-resolution individual SZ cluster observations
  - Resolve substructure → reduce uncertainties from astrophysical processes that limit cluster cosmology
- First light was in 2022
- TolTEC is a unique opportunity to open a new discovery space for cluster astrophysics and improve our understanding of dark energy and dark matter



Images courtesy of Grant Wilson

Summary

- The next generation of CMB observations are poised to make tremendous discoveries
  - r : Observe gravity operating on quantum scales
  - N_{eff} : Probe for particles beyond the standard model
  - $\sum m_{\nu}$: Constrain the masses of neutrinos
  - New insights into dark energy, dark matter, structure formation

- Simons Observatory, TolTEC, and CMB-S4 will be on the forefront of these next-generation observations
  - Require advances in technology, production, and understanding our instruments