An Update on the Search for Inflation with Ground-Based Cosmic Microwave Background Experiments

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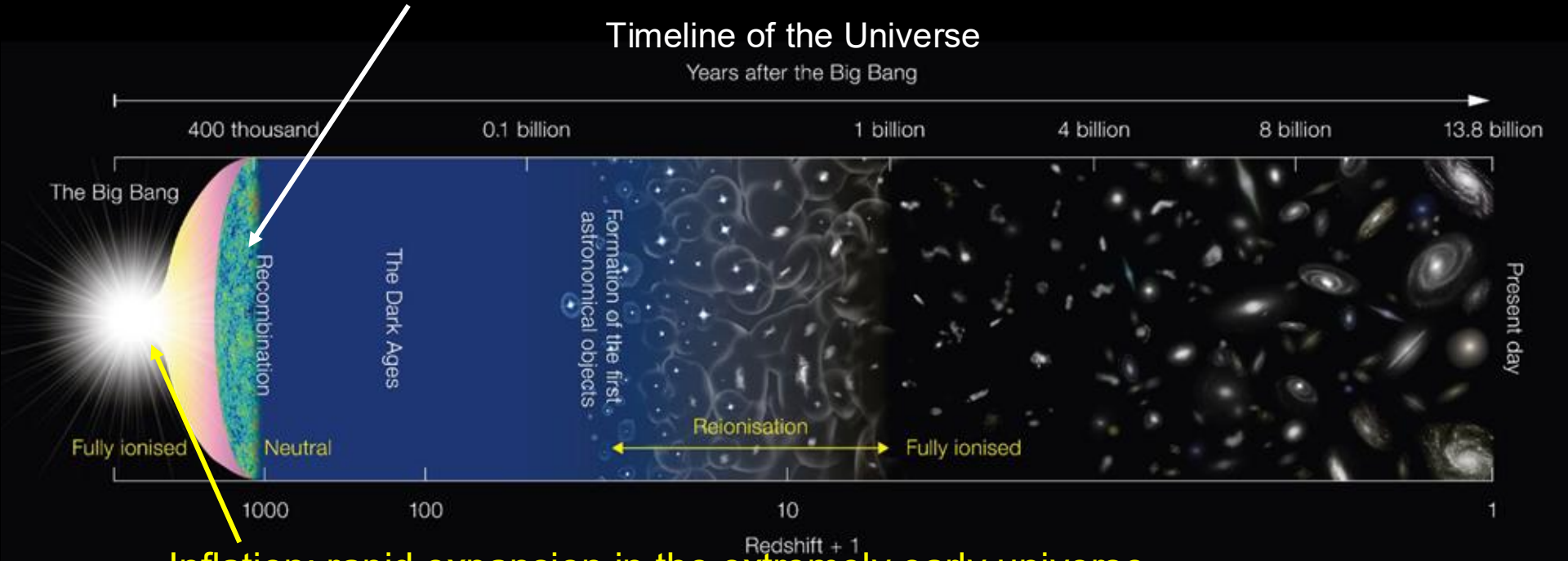
Encoded in the Cosmic Microwave Background (CMB) is the origin, composition, and evolution of the Universe, including information about Dark Energy, Dark Matter, Neutrino Mass, Light Relics, and more



Inflation: rapid expansion in the extremely early universe.

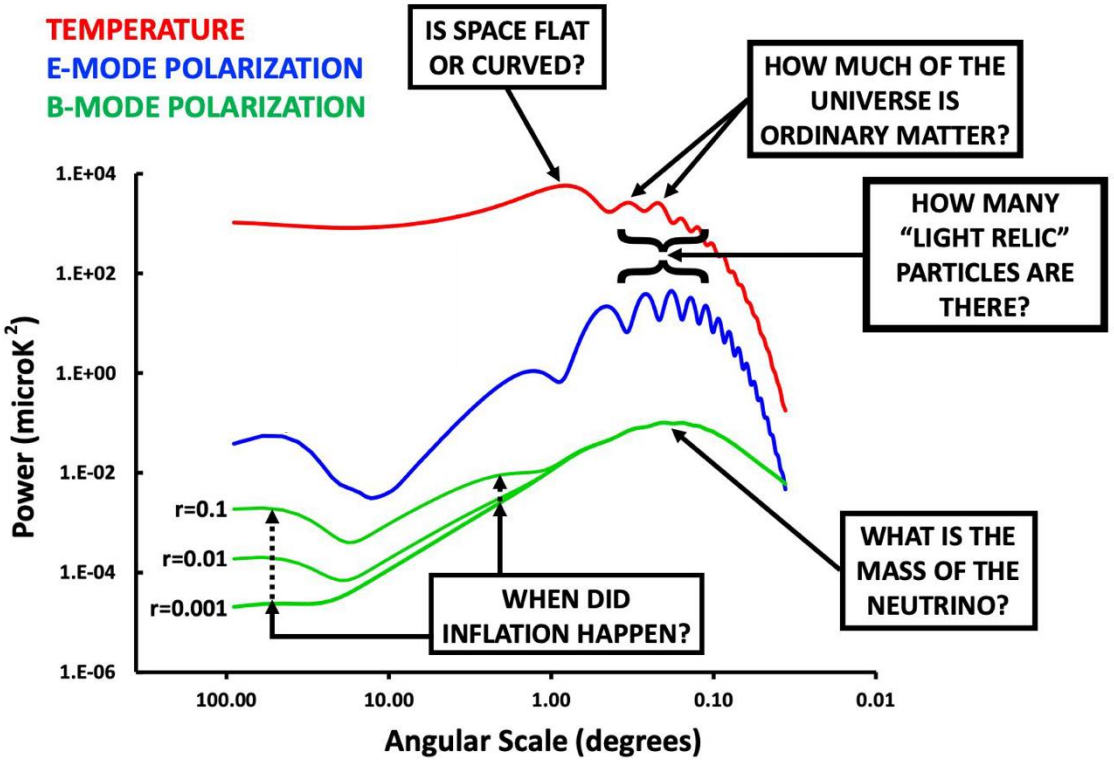
Did inflation happen?

What drove it? When did it happen?

The CMB can tell you if and when (at what energy scale) inflation happened

A Wealth of Information is Encoded in the CMB Power Spectrum

- We need to measure the anisotropy from angular scales of degrees to arcminutes with exquisite sensitivity and fidelity, in polarization.
- The current measurements are incredible. Measuring nanokelvin fluctuations on the 3K microwave background, in polarization.
- Even more exciting fundamental science lies ahead, as sensitivity increases in the next decade.

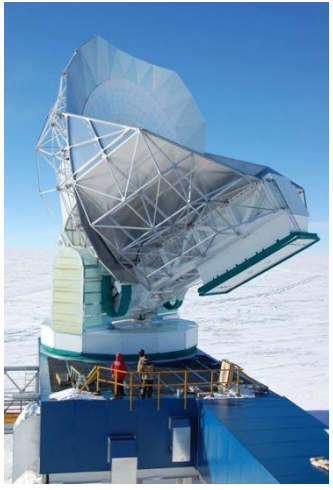


Small and Large Aperture Telescopes

To measure the large range of angular scales needed to extract the information, you need two types of telescopes.

Small: ~0.5 m aperture
really good at one thing: searching for signals from inflation in the early universe

Large: ~6-10 m aperture
Broad science case across particle physics and astrophysics including neutrino masses, number of light relics, inflation, galaxy clusters, transients, etc.

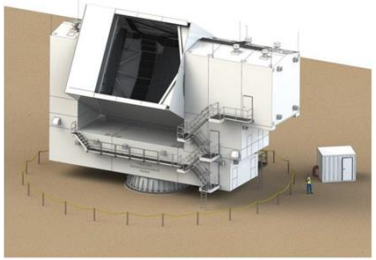


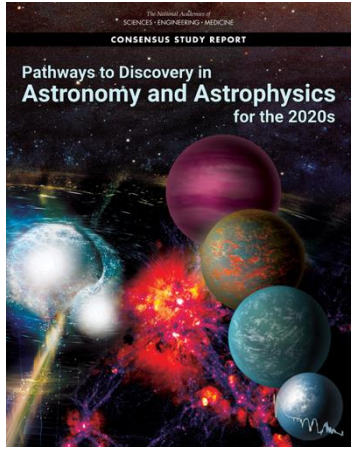
Two Key Sites For Precision CMB Measurements

The strengths of these sites are complementary: More sky coverage in Chile, Continuous observing access to low-foreground regions at South Pole

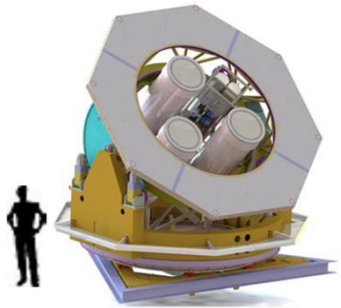
The Rise and Fall of CMB-S4

- Both P5 and the Astro2020 decadal survey ranked investigating inflation as an extremely high priority.
  - The 2023 P5 report ranked CMB-S4 as the top new large construction priority, due to the importance of inflation science.
  - From 2020 A&A Decadal Survey: “One of the most exciting opportunities in the coming decade is that CMB measurements may reveal remnant gravitational waves from this early epoch”



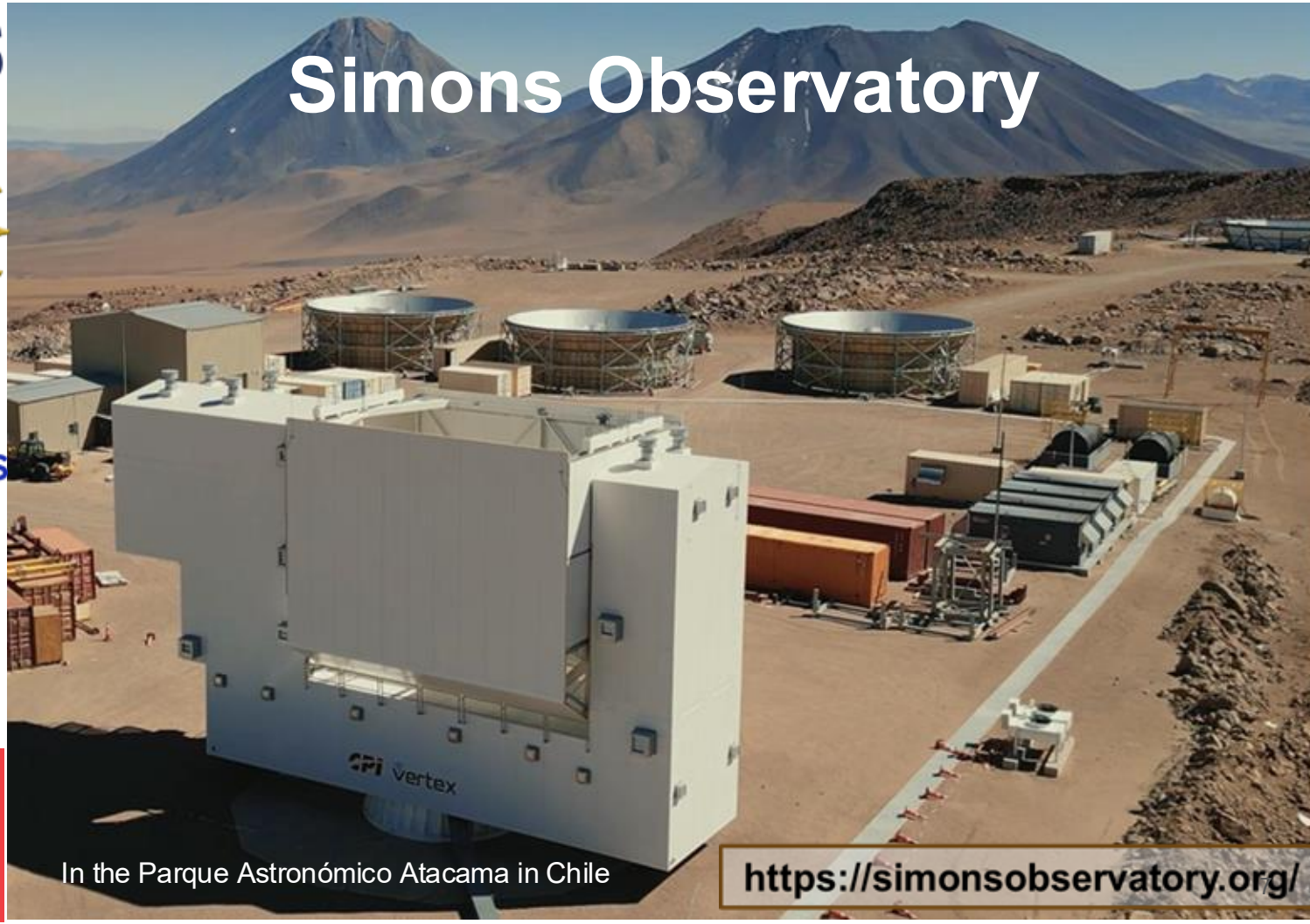


- **July 2025:** ”DOE and NSF have jointly decided that they can no longer support the CMB-S4 Project. DOE and NSF will continue to partner with the CMB science community to explore the potential science that can be achieved with limited upgrades to existing experiments to further this important U.S.-led research.”



- So where do we go from here, and how far can we get without building CMB-S4?

Simons Observatory



In the Parque Astronómico Atacama in Chile

https://simonsobservatory.org/

SIMONS FOUNDATION

SIMONS OBSERVATORY

NSF

UKRI UK Research and Innovation

HEISING-SIMONS FOUNDATION

科研費 KAKENHI

Japan Society for the Promotion of Science 日本学術振興会

Agencia Nacional de Investigación y Desarrollo
Ministerio de Ciencia, Tecnología, Conocimiento e Innovación
Gobierno de Chile

Ministerio de Bienes Nacionales
Gobierno de Chile

Simons Observatory - Instruments (100,000 bolometers deployed)

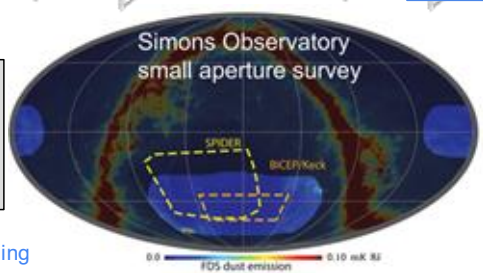
Two types of telescopes that target P5 and Astro 2020 Science Goals.

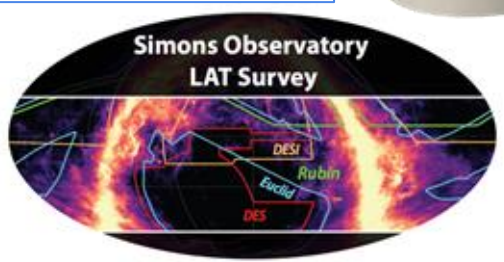
Small Aperture Telescopes (SATs)
- 0.42-meter aperture x 6 SATs.
- 6 funded, 3 deployed, remaining 3 deploying in 2026/27

Large Aperture Telescope (LAT)
- 6-meter aperture (huge focal plane)
- >10x the mapping speed of ACT, complete

Instrument commissioned, 4 years of operations are funded, 10 years of operations are planned

Large Sky Coverage allowing flexible survey strategy



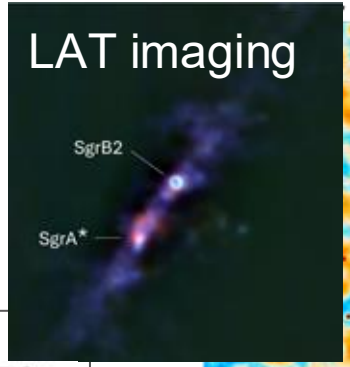


Access to 70% of the Sky
Overlap with DESI and Euclid

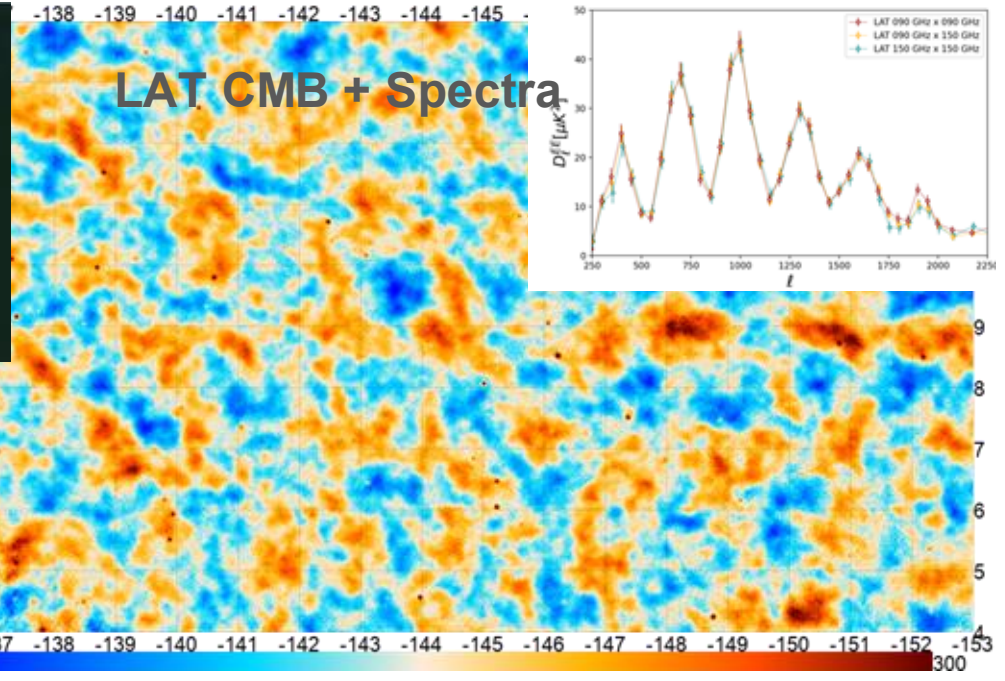
SO's Scientific Surveys are Underway

(preliminary results)

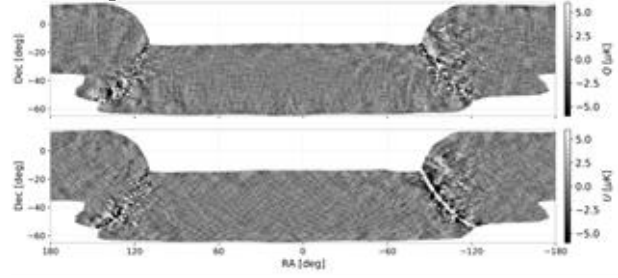
LAT imaging

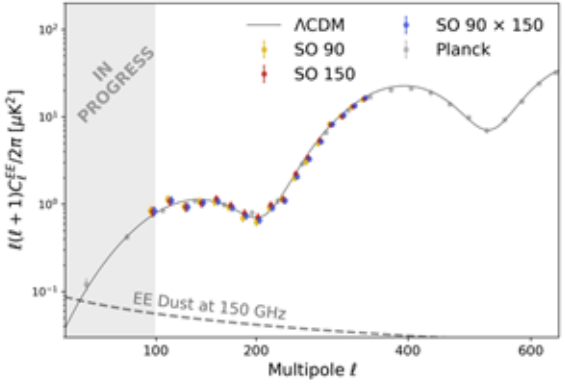


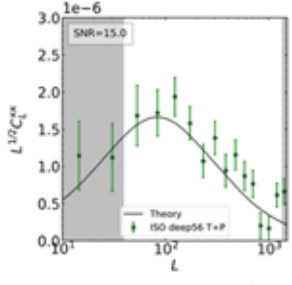
LAT CMB + Spectra



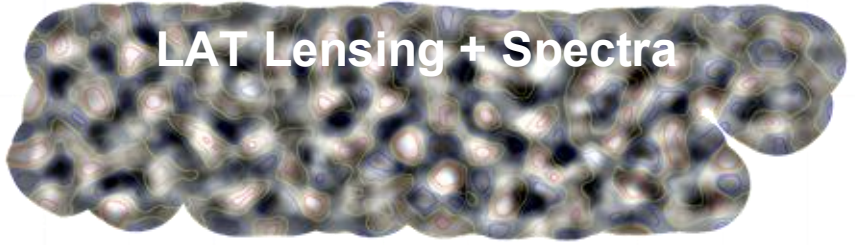
SAT polarization







LAT Lensing + Spectra



Simons Observatory Science Targets

Search for B-modes from the early universe & inflation signatures

Study the dark universe

Matter mapping

Time-variable mm sky

Numbers show 1-σ unless catalog no. or distances	Current	SO 2025-2034
Primordial perturbations		
r ($A_L = 0.3$)	0.01	0.0012
n_s	0.003	0.002
$e^{-2\tau}\mathcal{P}(k = 0.2/\mathrm{Mpc})$	1%	0.4%
$f_{\mathrm{NL}}^{\mathrm{local}}$	5	1
Relativistic species		
$N_{\mathrm{eff.}}$	0.13	0.045
Neutrino mass		
m_ν (eV, $\sigma(\tau) = 0.01$)	0.06	0.03
m_ν (eV, $\sigma(\tau) = 0.002$)		0.015
Accelerated expansion		
$\sigma_8(z = 1 - 2)$	7%	1%
Galaxy evolution		
η_{feedback}	50-100%	2%
p_{nt}	50-100%	4%
Reionization		
Δz	∼1.4	0.3
τ	0.007	0.0035
Cluster catalog	10000	33,000
AGN catalog	20000	96,000
Galactic science		
Molecular cloud B-fields	10s	> 860
$\sigma(\beta_{dust})$	0.02	0.005
Solar System Science		
Distance limit for 5 $M_\oplus$ Planet 9	500 AU	900 AU
Asteroid detections		∼ 10,000
Transient detection distance		
Long GRBs, on-axis		1300 Mpc
Low-luminosity GRBs		70–210 Mpc
TDEs, on-axis		670 Mpc

https://arxiv.org/abs/1808.07445
https://arxiv.org/abs/2503.00636
& SAT white paper, in prep

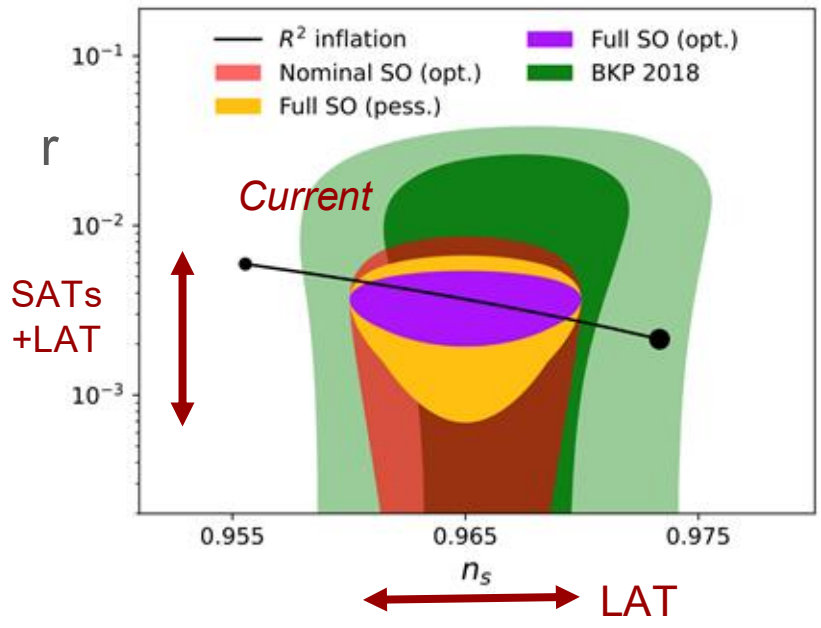
SO Science: Inflation

How did the initial expansion of space take place?

Constrain *r* (tensor-to-scalar ratio, a measure of the energy scale of inflation) to σ=0.001

Constrain scalar slope (measure of scale-dependence of primordial density fluctuations), n_s, to 0.002

Non-Gaussianity (f_{NL}) of density fluctuations (a marker of the specific physics of inflation), through CMB bispectrum & Correlations of lensing and kSZ with DESI & Rubin



n_s is crucial for distinguishing between models. The SO LAT measures this.

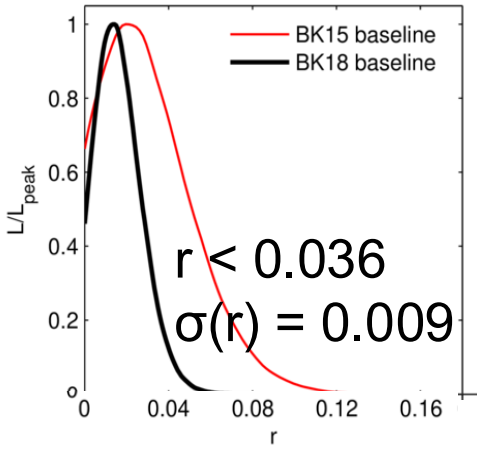
Telescopes at the South Pole

South Pole Observatory (SPO) = SPT + BICEP

A joint BICEP and SPT science program to pursue Inflation

The South Pole site is well-suited for an inflation survey: continuous, extremely deep observation of a small patch of sky from a site with a uniquely dry and stable atmosphere.

Currently Operating: BICEP3 & BICEP Array
Cooled Refractor Telescopes Targeting Degree Scale CMB Polarization

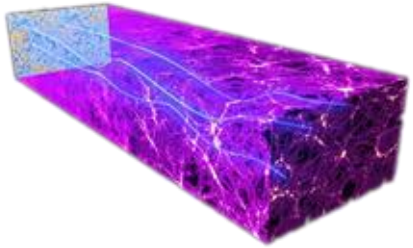


BICEP/Keck collaboration
arXiv:2110.00483

- Current world-best constraint on *r*
- BICEP Program has been leading for over a decade
- New Results with significantly more data (through 2024, 15 years of observations) expected ~this year

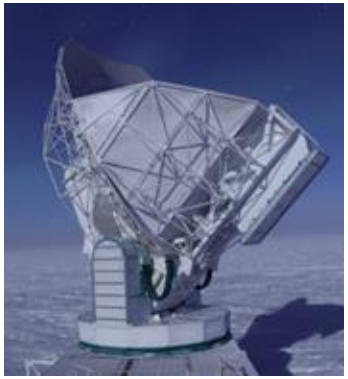
- BICEP3 and BICEP Array currently observing with four BICEP3-class receivers (55 cm) and a smaller Keck receiver.
- The fifth BICEP3-class receiver (BA4, 90/150 GHz dichroic pixels) to deploy for 2027 season with full operation in 2029, and benefits from CMB-S4 R&D.

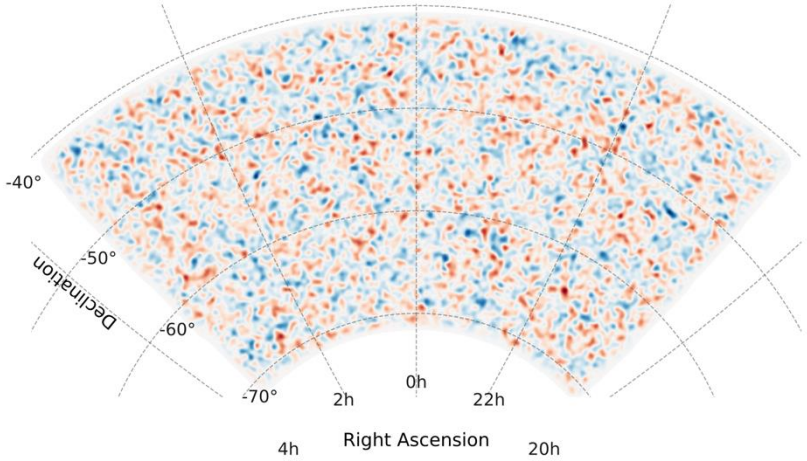
To Dig Farther You Must Remove The Signal from Gravitational Lensing

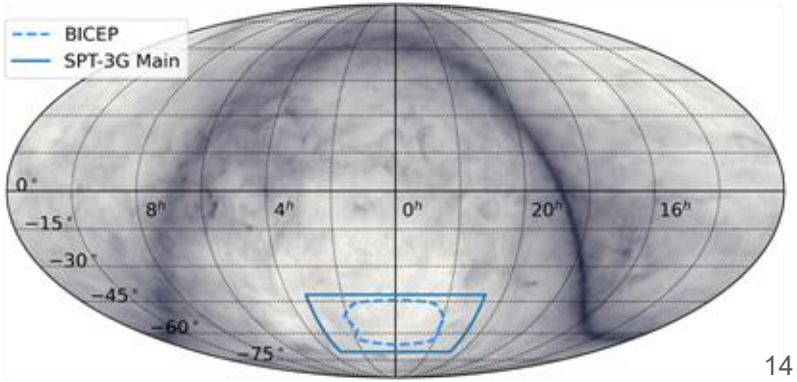


High resolution maps can be used to reconstruct the lensing deflection map, which can then be used to calculate and remove the lensing signal, enabling a deeper search for inflationary gravitational waves

This is where SPT comes into the story on constraining *r*.





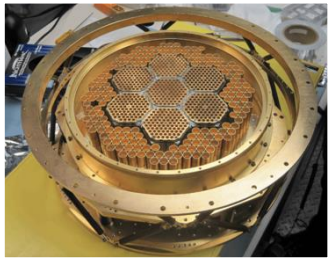


The South Pole Telescope:

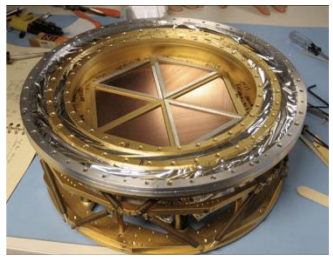
A powerhouse for cosmology, astrophysics, and particle physics.

(CMB Power Spectrum Measurements, Cosmological Constraints, Event Horizon Telescope, Galaxy Clusters, New Types of Sources, Transients, etc.…)

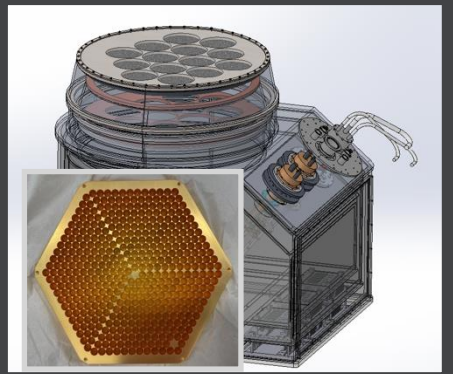
2018: **SPT-3G**
~16000 detectors
95, 150, 220 GHz
+polarization



2012: **SPTpol**
~1500 detectors
95, 150, 220 GHz
+polarization



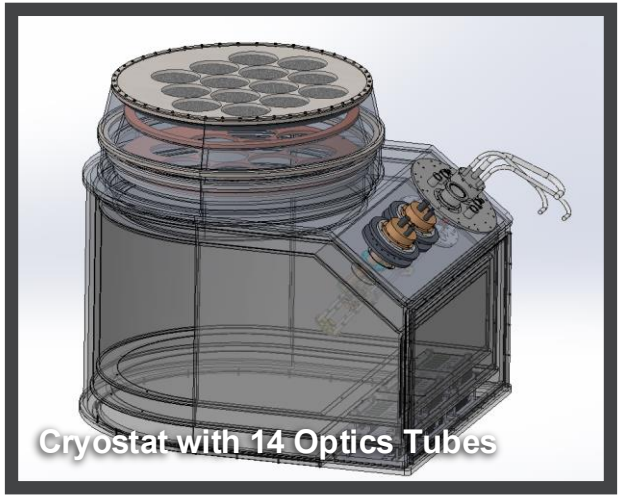
2007: **SPT-SZ**
~960 detectors

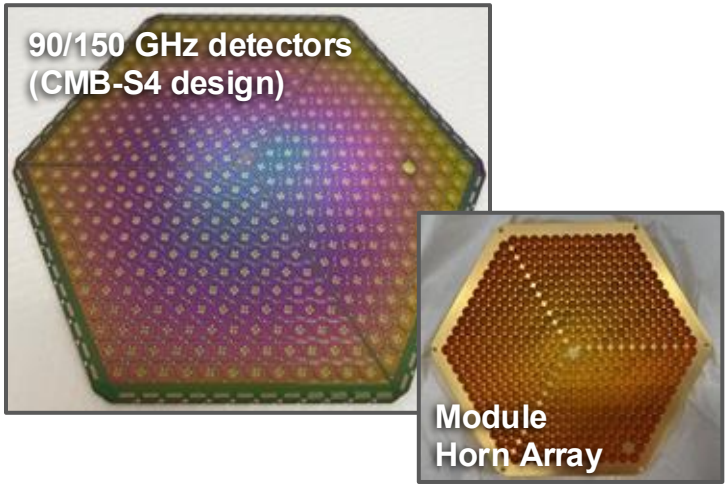


NOW BUILDING
2029: **SPT-3G+**
~24000 detectors
95, 150 GHz

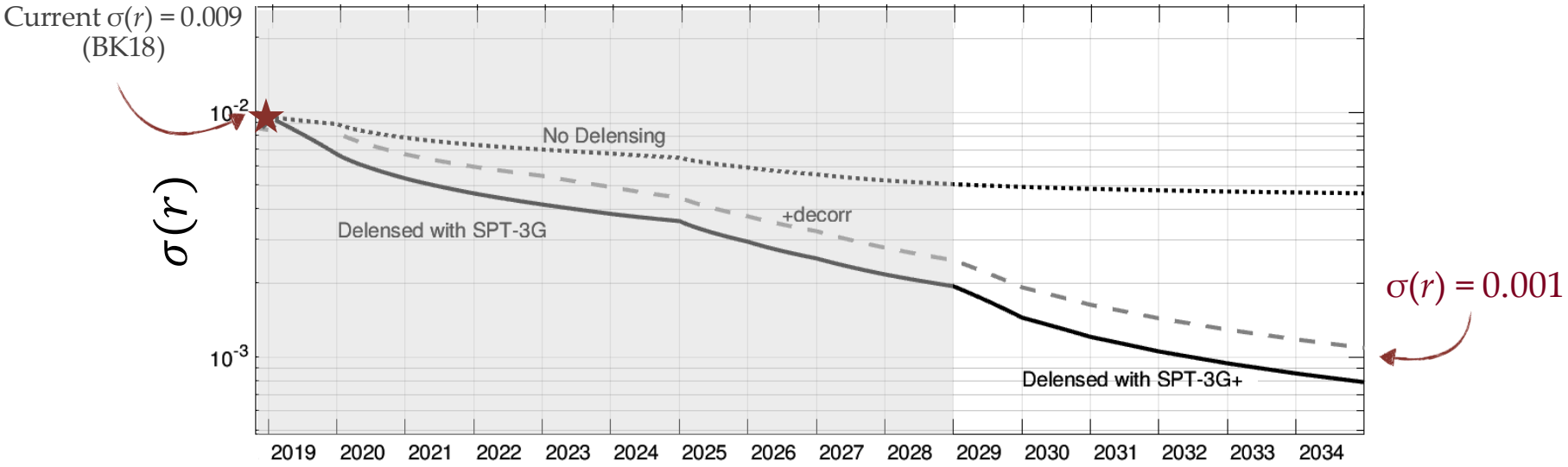
SPT-3G+: A New Camera For SPT

- Optimized to measure CMB lensing for constraining r.
- >7x larger mapping speed than SPT-3G.
  - High-throughput, 14 optics tube cryostat
  - ~24,000 polarization-sensitive transition-edge sensor detectors (14 wafers)
  - 95 / 150 GHz dichroic pixels
- Projected map depth for 6-year survey: ~0.7 μK-arcmin at each of 95 & 150 GHz
- Planned to install for 2029 observations.





Inflationary Constraints with SPT-3G+ and BICEP Array



Simons Observatory is targeting a similar level of constraint on $\sigma(r)$ with different instrumentation and observing strategy. The two efforts will provide invaluable crosschecks and increased sensitivity when combined.

Conclusions

- The science case for inflation remains extremely compelling.
- We can reach $\sigma(r) = 0.001$ in the coming decade with instruments that are currently being built and are planned to install (SPT-3G+, BICEP Array Upgrade, and completed installation of Simons Observatory). This is within a factor of 2 of the CMB-S4 science goal at a fraction of the cost.
- These experiments also offer a broad science case across particle physics and astrophysics, which is extremely exciting.