CMB-S4 Update

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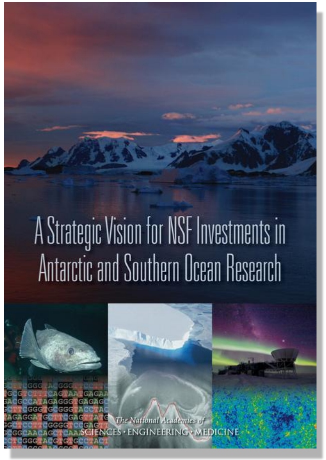
Outline

- Why CMB-S4?
- Science Overview
- Design & Project Overview
- Analysis of Alternatives
- Current Status and Summary

To learn more about development of CMB-S4 see the excellent talk "An Introduction to CMB-S4" that Julian Borrill gave at your June workshop

The start of CMB-S4

- 2013: during the Snowmass Physics Planning exercise, building on the success of the field, the CMB community conceived CMB-S4 as the definitive ground-based experiment with sufficient sensitivity to achieve transformative science goals using field-proven technology.
- 2014: recommended by Particle Physics Project Prioritization Panel (P5) under all budget scenarios.
- 2015: recommended as a strategic priorities for Antarctic Science in the NASEM report “A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research”
- 2015: start of twice yearly major CMB-S4 workshops.



CMB-S4

Why CMB-S4?
To make transformational advances

- CMB-S4 will cross critical thresholds in key cosmological parameters in the search for primordial gravitational waves and relic particles.
- CMB-S4 will provide unique astrophysical information, from the reionization of the Universe to the role of baryonic feedback in structure and galaxy formation. It will provide a powerful and unprecedented catalog of high-redshift clusters and galaxies, and open up the mm-wave transient universe for Multi-Messenger Astrophysics.
- CMB-S4 instrument and survey strategy are designed to be an extremely powerful complement to other astronomical surveys— breaking degeneracies and increasing sensitivity —to investigate neutrino properties, dark energy, and dark matter.

What will it take?

- Tenfold increase in sensitivity over Stage 3 experiments.
- O(500,000) detectors spanning 20 - 300 GHz using multiple telescopes, large and small, at South Pole and Chile, to map deep targeted fields, as well as a large fraction of the sky.
- Broad participation of the CMB, Astronomical and Particle Physics community, including the existing CMB experiments, the National Labs and International Partners

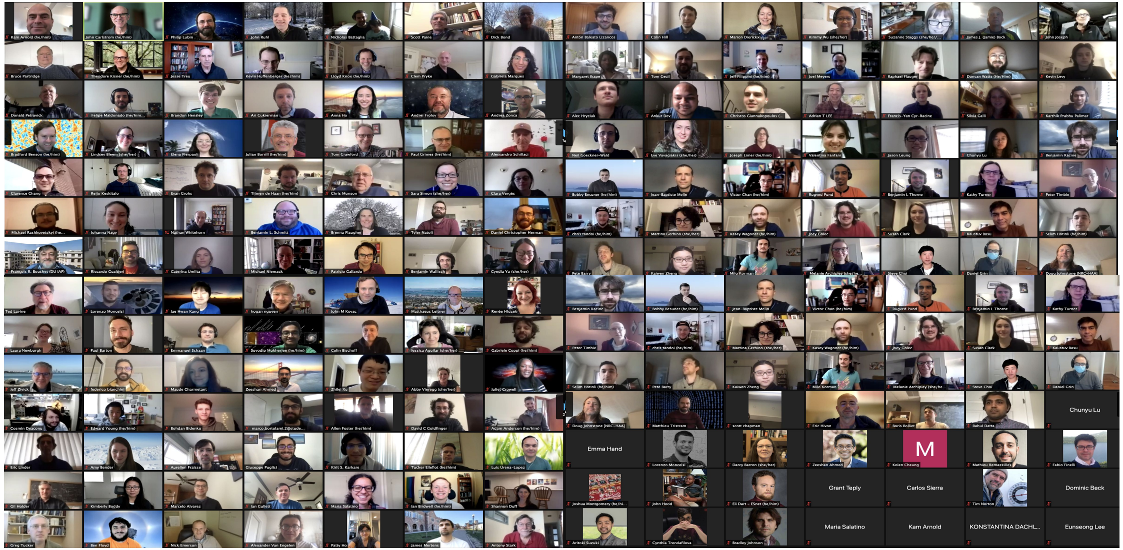
Scale of CMB-S4 exceeds capabilities of the University-led CMB groups.

→ Partnership of CMB community and National labs will do it.

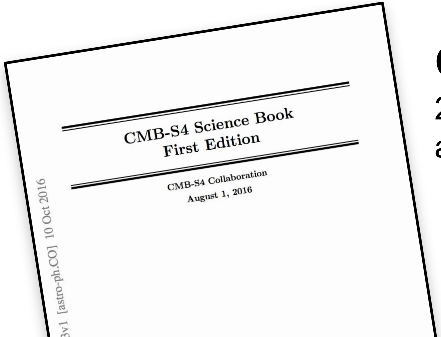
Community Organization

building the partnership

- The CMB-S4 Science Collaboration is highly active and engaged
  - 342 members
  - 112 institutions
  - 18 countries
  - 26 U.S. States
  - 2 major collaboration meetings/year
- Produced *CMB-S4 Science Book* (2016, arXiv:1610.02743) and *CMB-S4 Technology Book* (2017, arXiv:1706.02464)
- Produced *CMB-S4 Science Case, Reference Design, and Project Plan,* for input to Astro2020 (arXiv:1907.04473)
- Completed *CMB-S4 Preliminary Baseline Design Report* (will revise and post after the AoA)



13th Collaboration meeting, August 2021

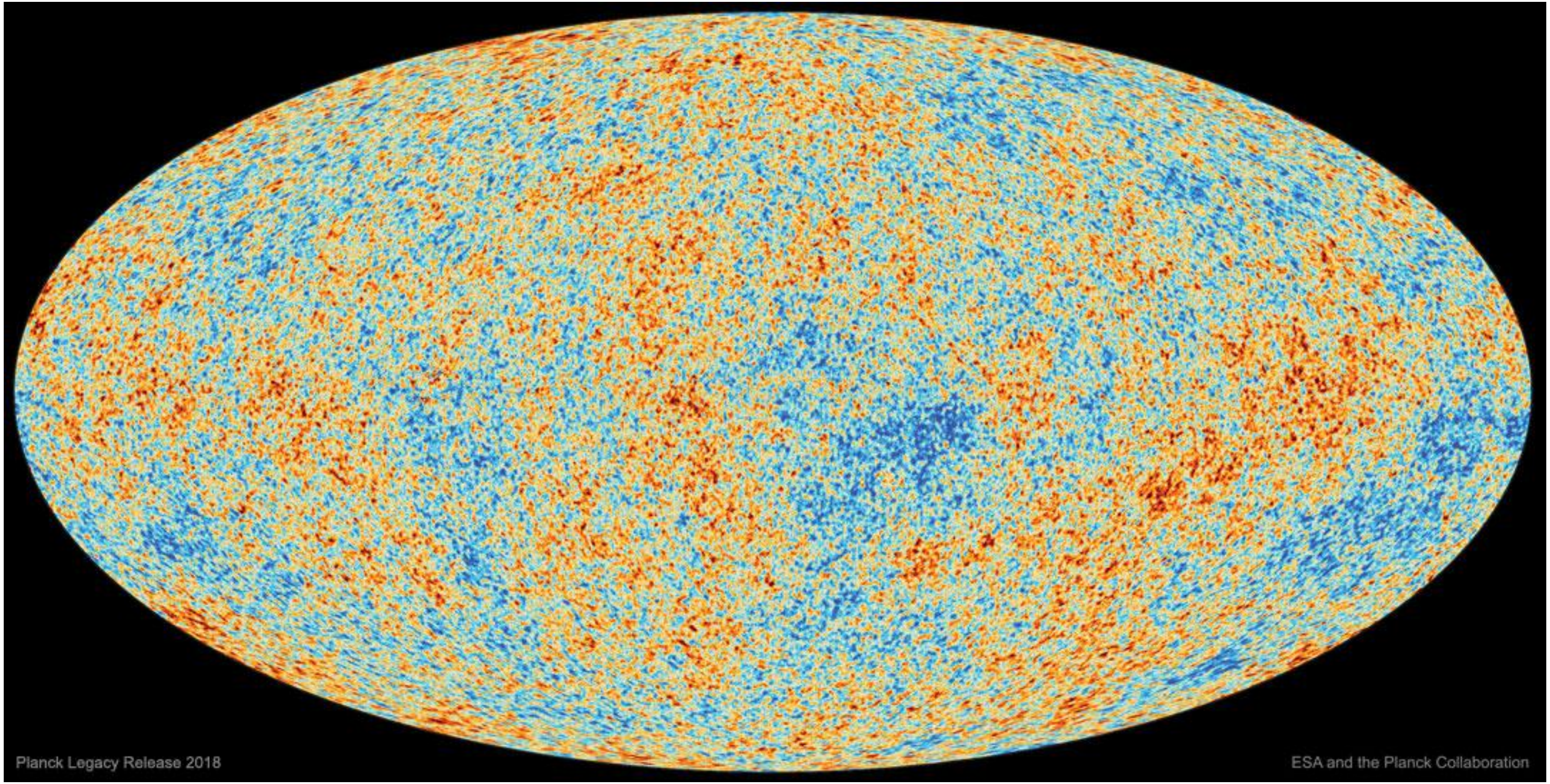


CMB-S4 Science Book

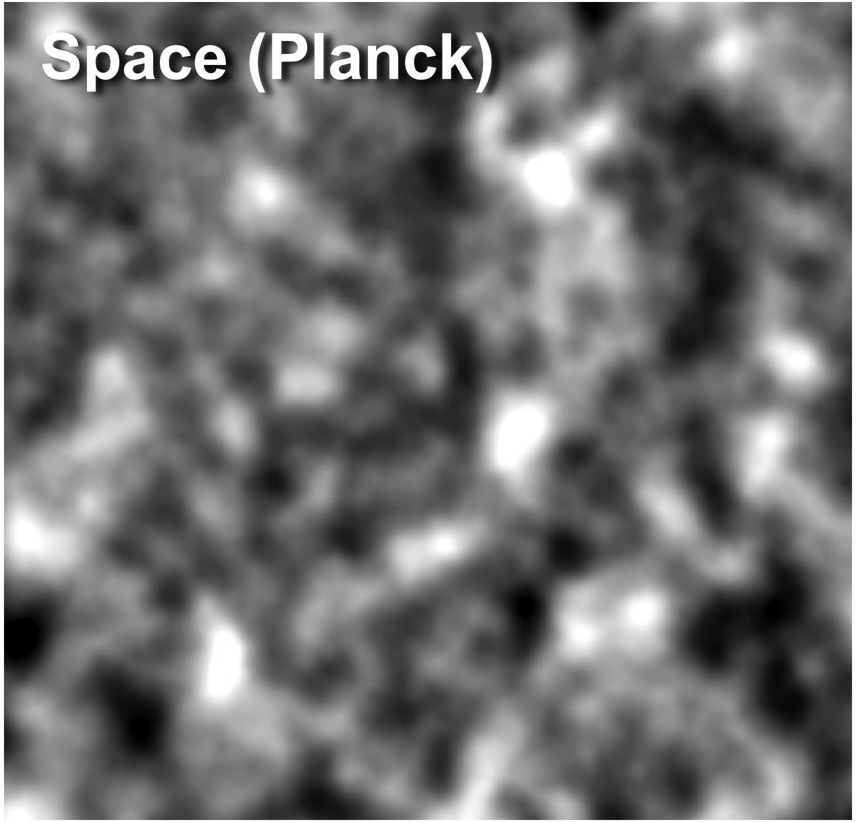
200 pages, >1200 citations

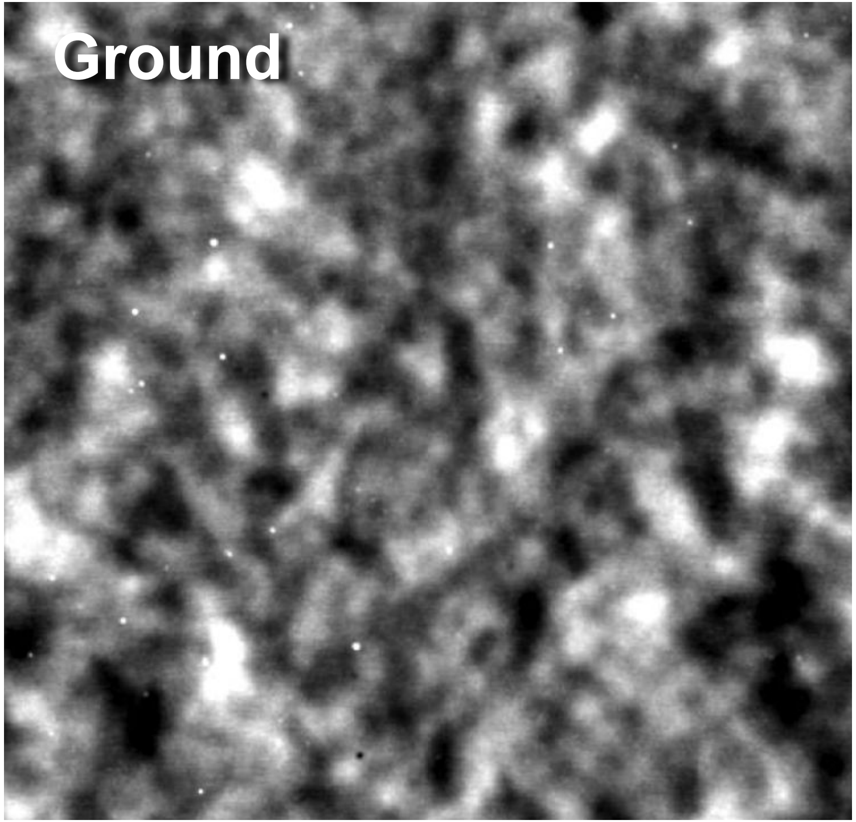
available at http://cmb-s4.org

Planck is amazing



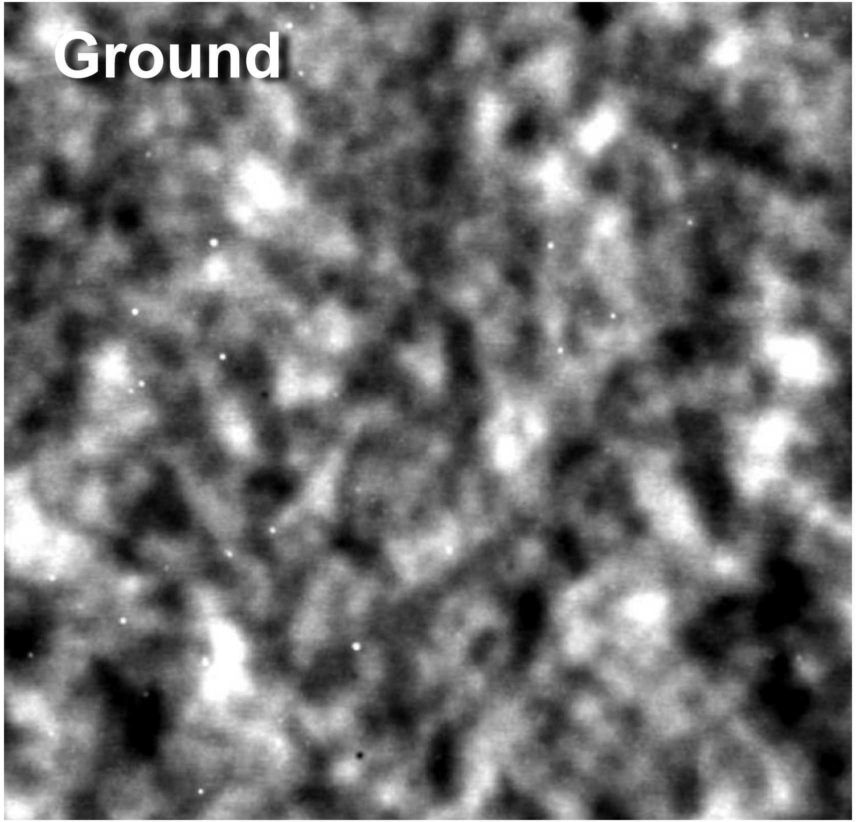
Transformational Discoveries Will Come From Ground-Based Telescopes





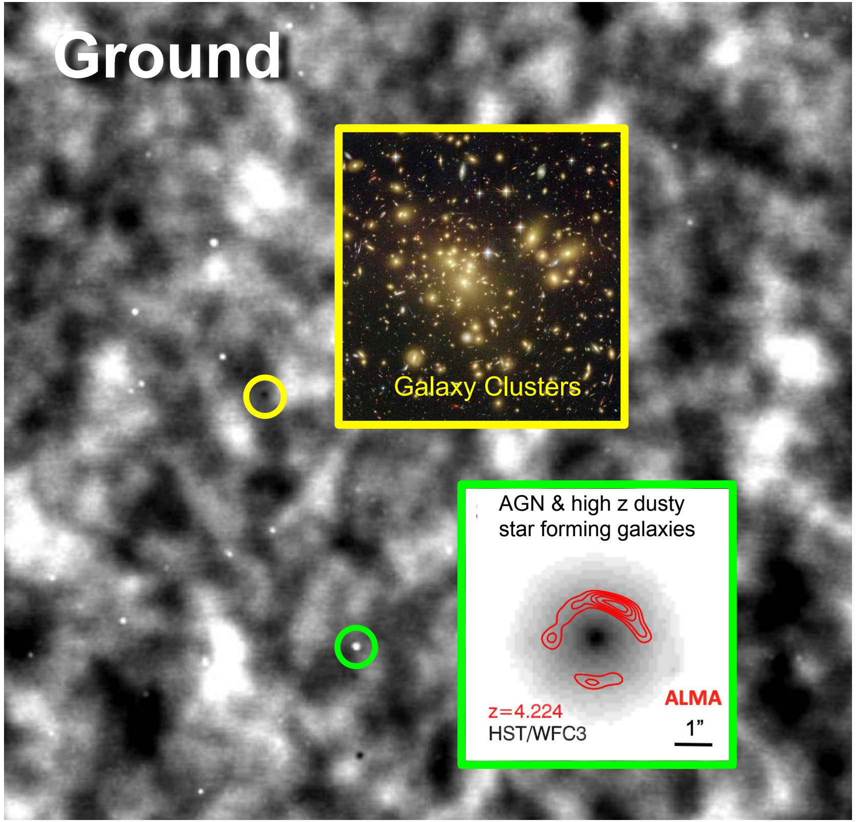
Ground-Based For Targeted Sensitivity And Angular Resolution

- Increased depth and angular resolution are needed to extract cosmological physics and to greatly expand the astrophysics impact of CMB measurements
- CMB-S4 will conduct **ultra-deep measurements focused on small sky area**, and will use **large apertures for high angular resolution over ultra-deep and deep-wide fields**
- These measurements are most practically and cost effectively done from the ground



Mapping the millimeter sky - it's not just CMB

- Our CMB science goals require maps of the mm-wave sky at high sensitivity and resolution.
- These necessarily include a wide range of additional science, from CMB lensing mass maps and sources appearing either backlit by the CMB or as mm-wave foregrounds.
    - Extragalactic: large scale structure, galaxies, galaxy clusters, GRBs, ...
    - Galactic: star forming clouds, dust & synchrotron emission, …
    - Solar system: planet 9, …
    - mm sky surveys provides objects for ALMA, VLA, Gemini, VLT, and others to follow up at all λ's



CMB-S4 Science Themes, Goals and Requirements

Organized into four Broad Science Themes

1. Primordial Gravitational Waves and Inflation
2. The Dark Universe
3. Mapping Matter in the Cosmos
4. The Time-Variable Millimeter-Wave Sky

Each theme has associated Science Goals and Level 1 Science Requirements, which drive the CMB-S4 Survey Measurement Requirements and enable the full range of CMB-S4 Science.

CMB-S4 Science Goals

The science goals are aligned with DOE CD-0 Mission Need and Astro2020; the science requirements are designed to enable the full range of CMB-S4 Science.

Goal 1: Test models of inflation by measuring or putting upper limits on r, the ratio of tensor fluctuations to scalar fluctuations.

Goal 2: Determine the role of light relic particles in fundamental physics, and in the structure and evolution of the Universe.

Goal 3: Measure the emergence of galaxy clusters as we know them today. Quantify the formation and evolution of the clusters and the intracluster medium during this crucial period in galaxy formation.

Goal 4: Explore the millimeter-wave transient sky. Measure the rate of mm-transients for the first time. Use the rate of mm-wave GRBs to constrain GRB mechanisms. Provide mm-wave variability and polarization measurements for stars and active galactic nuclei.

Science Requirements

Science Requirement 1.0: CMB-S4 shall test models of inflation by putting an upper limit on r of $r \leq 0.001$ at 95% confidence if $r = 0$, or by measuring r at a 5σ level if $r > 0.003$.

Science Requirement 2.0: CMB-S4 shall determine $N_{\rm eff}$ with an uncertainty ≤ 0.06 at the 95% confidence level.

Science Requirement 3.1: CMB-S4 shall detect at $\geq 5\sigma$ all galaxy clusters at $z \geq 1.5$ with an integrated Compton $Y_{\rm SZ,500} \geq 2.4 \times 10^{-5}\,\rm arcmin^2$ over at least 50% of the sky.

Science Requirement 3.2: CMB-S4 shall detect at $\geq 5\sigma$ all galaxy clusters at $z \geq 1.5$ with an integrated Compton $Y_{\rm SZ,500} \geq 1.2 \times 10^{-5}\,\rm arcmin^2$ over at least 3% of the sky.

Science Requirement 4.1: CMB-S4 shall detect GRB afterglows brighter than 30 mJy at 93 and 145 GHz over at least 50% of the sky and enable followup by issuing timely alerts to the community.

Science Requirement 4.2: CMB-S4 shall detect GRB afterglows brighter than 9 mJy at 93 and 145 GHz over at least 3% of the sky and enable followup by issuing timely alerts to the community.

1. Primordial Gravitational Waves and Inflation

Inflationary B-modes are a Big Deal!

- A key test of inflation and our origins

$$\text{time} = 10^{-36}\left(\frac{r}{0.01}\right)^{-\frac{1}{2}} \text{seconds}$$

- A relic from 10^{36} times earlier than the light elements created at t = 1 second.

$$\text{energy} = 10^{16}\left(\frac{r}{0.01}\right)^{\frac{1}{4}} \text{GeV}$$

- Probing physics at the scale of superstring theory.

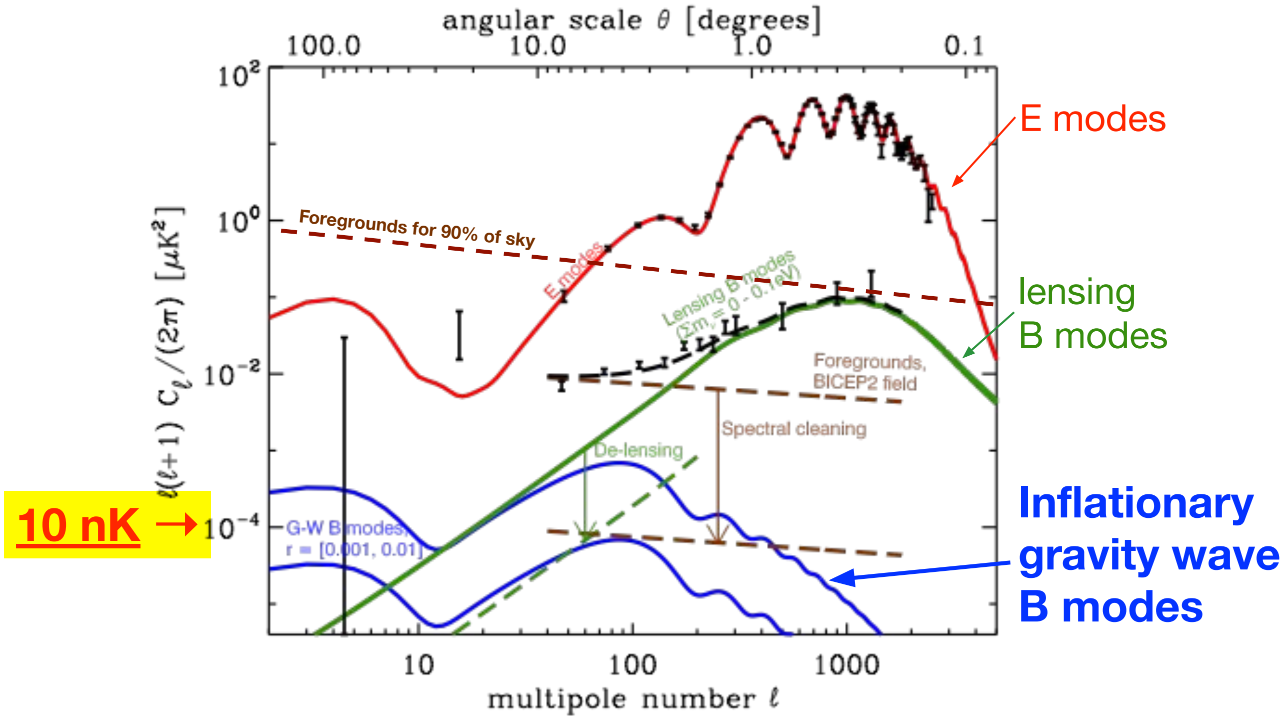
- Insights into quantum gravity

From 2010 A&A Decadal Survey:
"The most exciting quest of all is to hunt for evidence of gravitational waves that are the product of inflation itself*. … the next great quest of CMB research is to detect this polarization, thereby probing the behavior of the particles or fields driving inflation."*

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"

Inflationary B-modes

No More Easy Digging, We've Hit Rock!



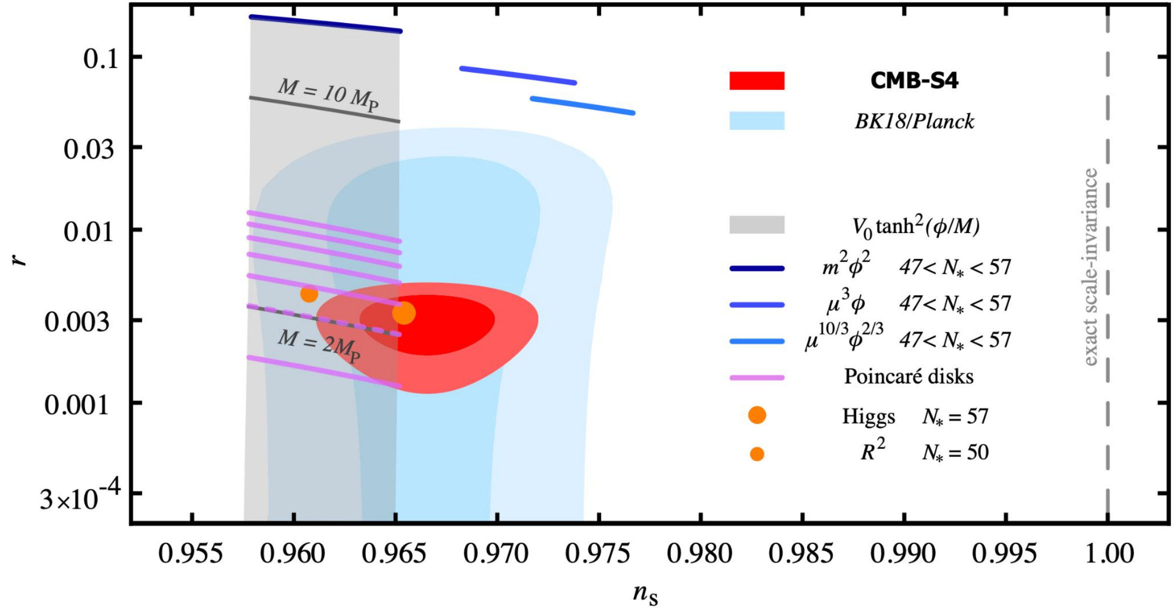
CMB-S4 will search for 10nK signal in a 10K background!

Foregrounds mitigation and de-lensing requires multiple frequency bands and broad angular range with exceptional sensitivity and control of systematics.

CMB-S4 must dig two orders of magnitude deeper than current experiments, and through the foreground dominated regime

Inflationary B-modes

Historic opportunity to open up a window to the primordial Universe



Inflation models that naturally explain the observed nearly scale invariant spectrum of density fluctuations predict $r > 10^{-3}$.

CMB-S4 is designed to detected a well-motivated class of models at 5σ, e.g., Starobinsky R^2 models.

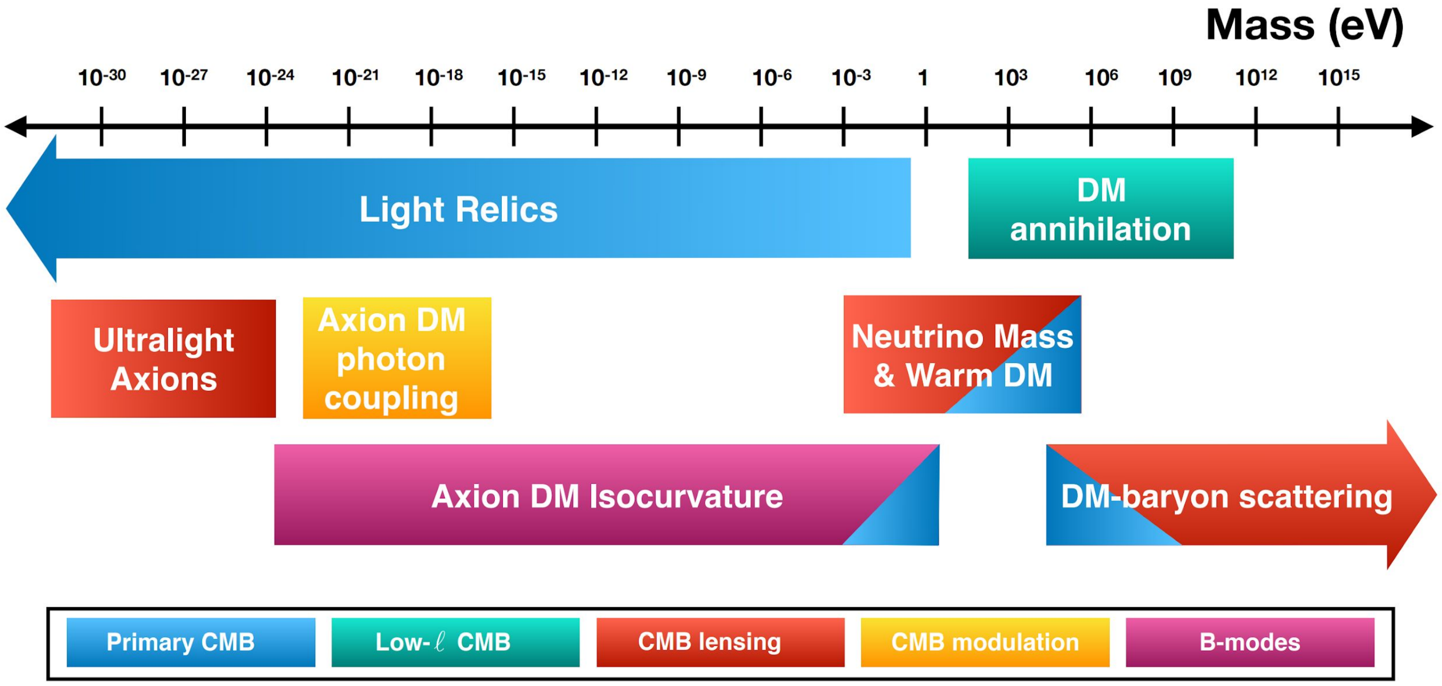
CMB-S4 sensitivity ensures that a non-detection of r would rule out the leading inflationary models, and motivate alternate models for the origin of the universe.

CMB-S4 Reqt:

If r > 0.003: measure at 5*σ*
If r = 0: set r ≤ 0.001 at 95% C.L.

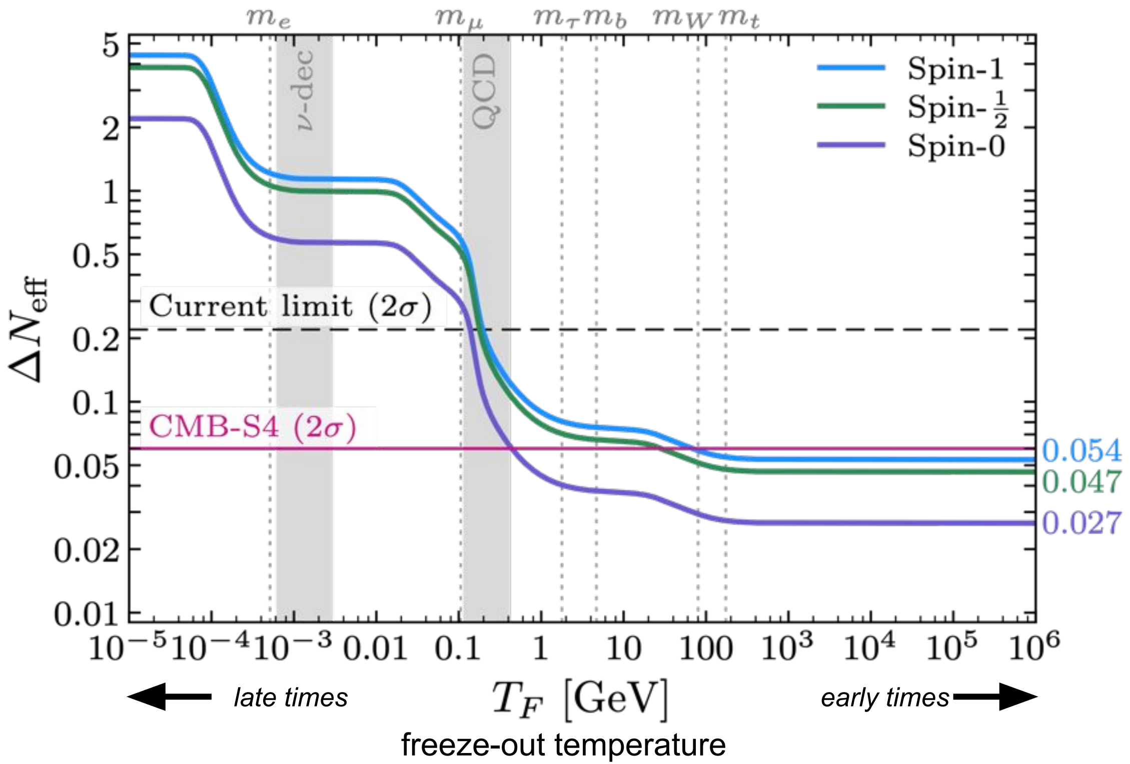
2. The Dark Universe

CMB Insights Into The Dark Universe Across The Mass Spectrum



CMB-S4 will probe dark sector physics across an enormous range in mass

Thermal history of the Universe and Light Relic Particles

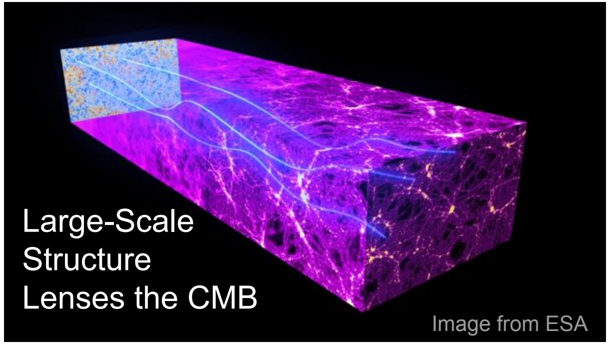


CMB-S4 will provide a precise measurement of the thermal history of the universe, a key test of cosmology.

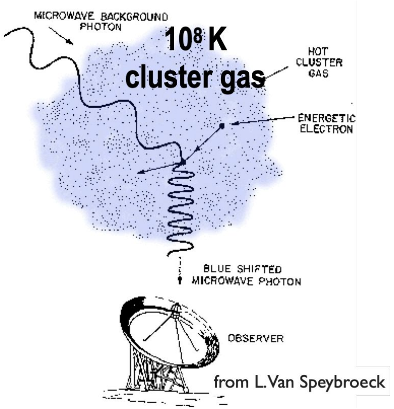
E.g., additional light particles that appear frequently in extensions to the standard model of particle physics will be constrained by CMB-S4.

CMB-S4 requirement to detect all light relics that decoupled after the start of the QCD Quark to Hadron transition, providing orders of magnitude improvement on the freeze-out temperature of any thermal relic.

3. Mapping Matter in the Cosmos



CMB lensing



Sunyaev Zel'dovich Effect

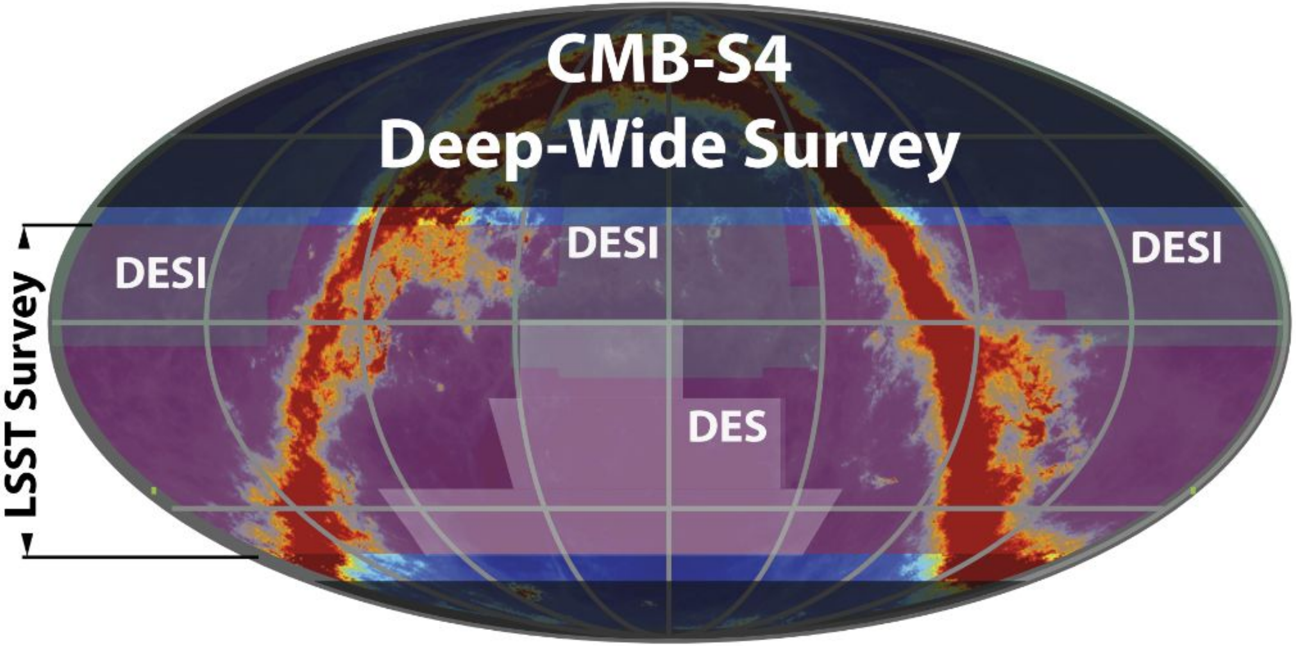
CMB-S4 will exploit these two effects—both caused by interactions between CMB photons and intervening structure—to:

1. Make high-fidelity maps of ***all*** the mass in the Universe (including dark matter), with unprecedented resolution and precision.
2. Find all massive Galaxy Clusters in the universe, regardless of distance from us
3. Characterize the hot gas in galaxies and galaxy clusters, including in the outskirts and at very high redshift (where X-ray measurements become increasingly expensive).

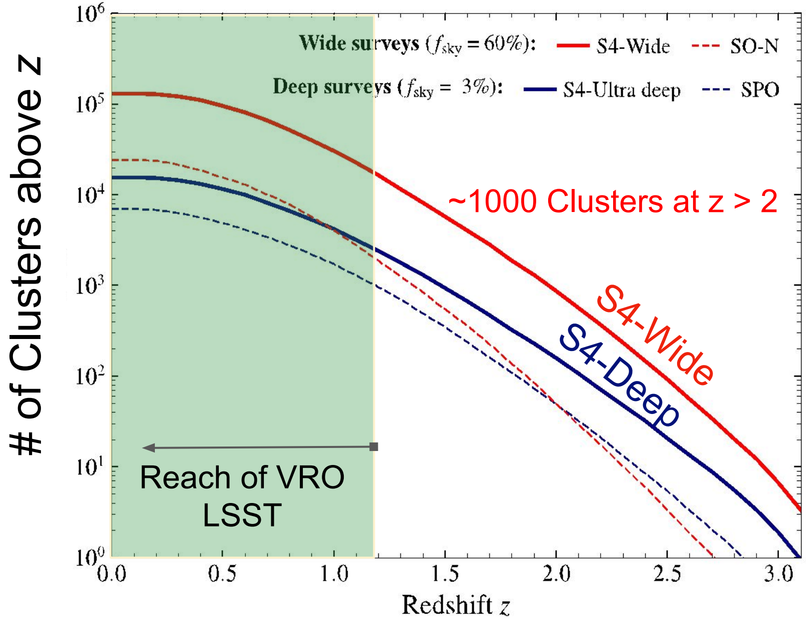
3. Mapping Matter in the Cosmos

Strong synergy with existing and upcoming surveys and missions such as DES, DESI, VRO-LSST, Roman, Euclid.

- Cross-correlation of CMB lensing and SZ measurements with other tracers of structure will increase reach, break degeneracies, and allow invaluable cross checks
- CMB-S4 will provide the deepest mm survey of our Galaxy (from 13 to 1 mm) with full polarization sensitivity



Galaxy Clusters and Dusty Galaxies in the early Universe



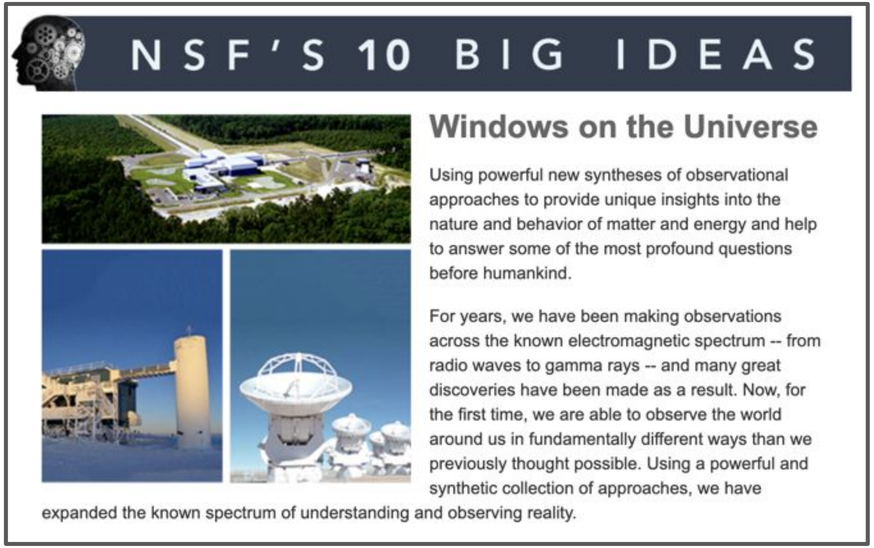
CMB-S4 will produce catalogs of

- ~1000 clusters at z ≳ 2, at the peak of cosmic star formation when galaxy clusters first emerged over 10B yr ago, which will not be found through other surveys, such VRO LSST.
- Dusty star forming galaxies to the highest redshifts at which they exist, including a large sample of protoclusters at z > 4.

These catalogs will be the gold standard for follow-up studies of clusters, protoclusters, and dusty galaxies for years to come—an immense community resource.

4. The Time-Variable Millimeter-Wave Sky

CMB-S4 will be mm-wave Vera Rubin Obs LSST



Astro2020: “*An important requirement for our strong endorsement is that the project broadly engage astronomers beyond the traditional CMB community… It is essential that CMB-S4 produce transient alerts…*”.

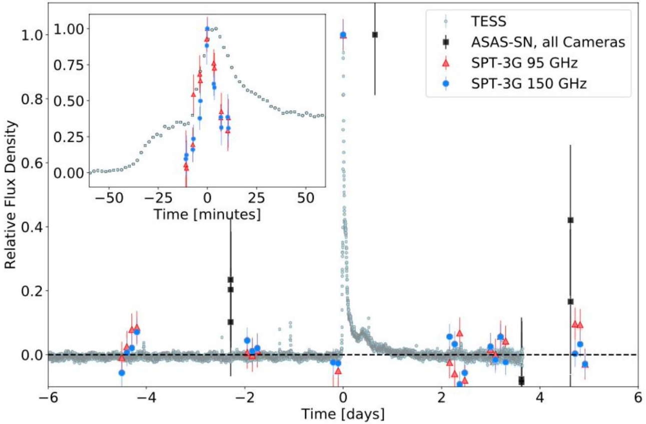
CMB-S4 is designed to participate and fill a major gap in Multi-Messenger Astronomy.

- Groundbreaking depth and sky coverage: mJy sensitivity with polarization info on 50% of the sky in one observing day, and deeper for 3% of the sky

Insights and potential discoveries in

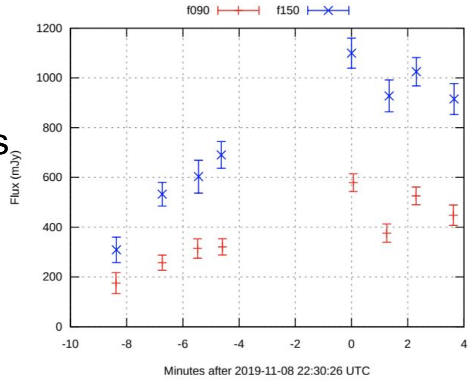
- Sources of LIGO Gravitational Wave and IceCube Neutrino events
- Orphan GRB afterglows
- Tidal disruption events
- AGN flares and monitoring
- Solar system: eg., planet 9, comets, asteroids…
- …

E.g., Transients in recent CMB data

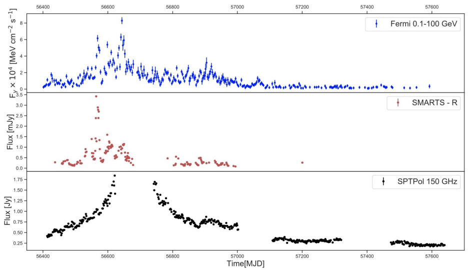


Guns et al. (2021, SPT-3G): 15 >10-sigma events from 10 independents sources, all associated either with a star or an AGN

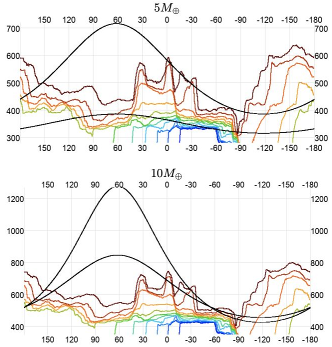
Naess et al. (2021, ACT): 3 >20-sigma events from 3 independent sources, all associated with a star



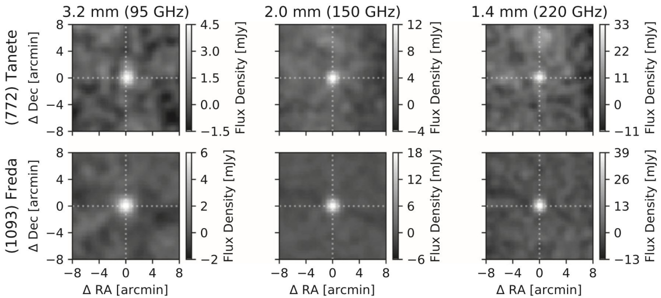
Other transient / variable / moving object science with CMB data:



Multi-wavelength monitoring of bright AGN (Hood+23)



”Planet 9” searches (Naess+21)



Asteroids (Chichura+22)

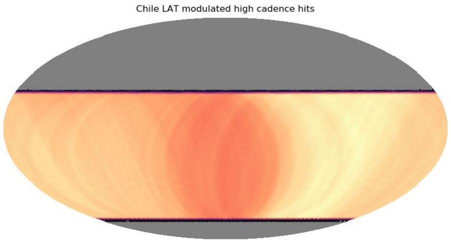
CMB-S4 To Use Proven Developed Sites

Photo: Debra Kellner

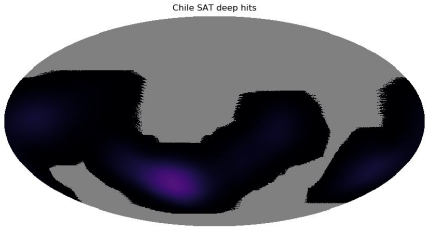
Photo: USAP

CMB-S4 Exploits The Unique Attributes Of Both Sites

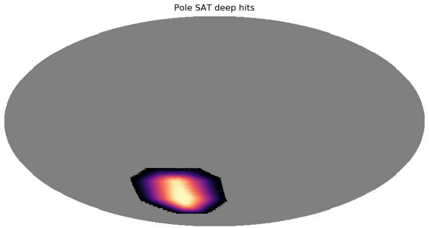
- Atmosphere above both sites has exceptional low water vapor, which is critical for CMB measurements
- The biggest difference between the sites is in the types of sky surveys their latitudes can support.
  - Wide-area surveys can only be performed from the Atacama.
  - Compact ultra-deep surveys can only be performed from the South Pole.
- The exceptional atmospheric stability of South Pole sites leads much lower “sky noise” at the degree angular scales, for the r measurement.



Chile deep-wide survey hitmap

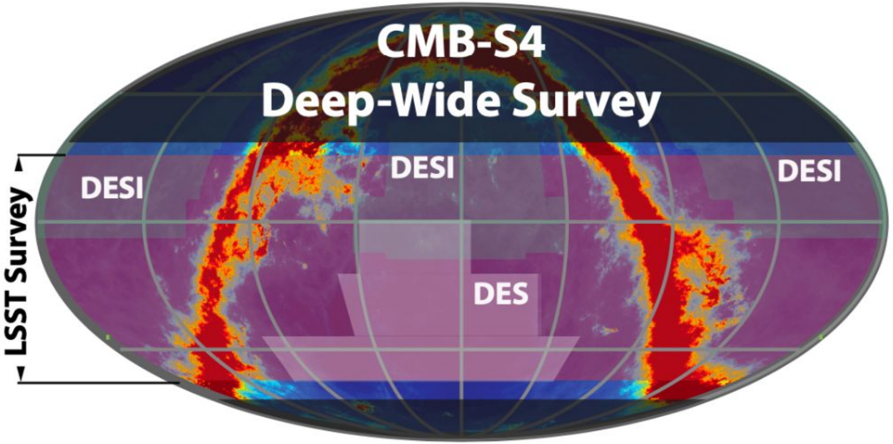


Example of Chile deep survey hitmap

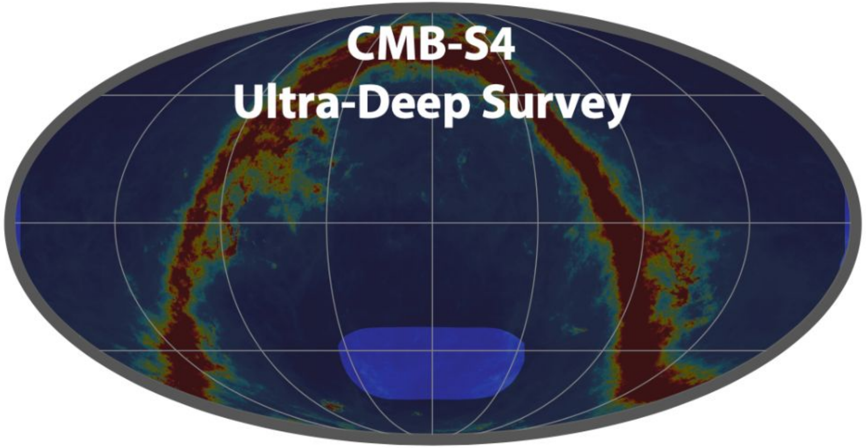


South Pole ultra-deep survey hitmap

Surveys



The Deep Wide Survey from Chile



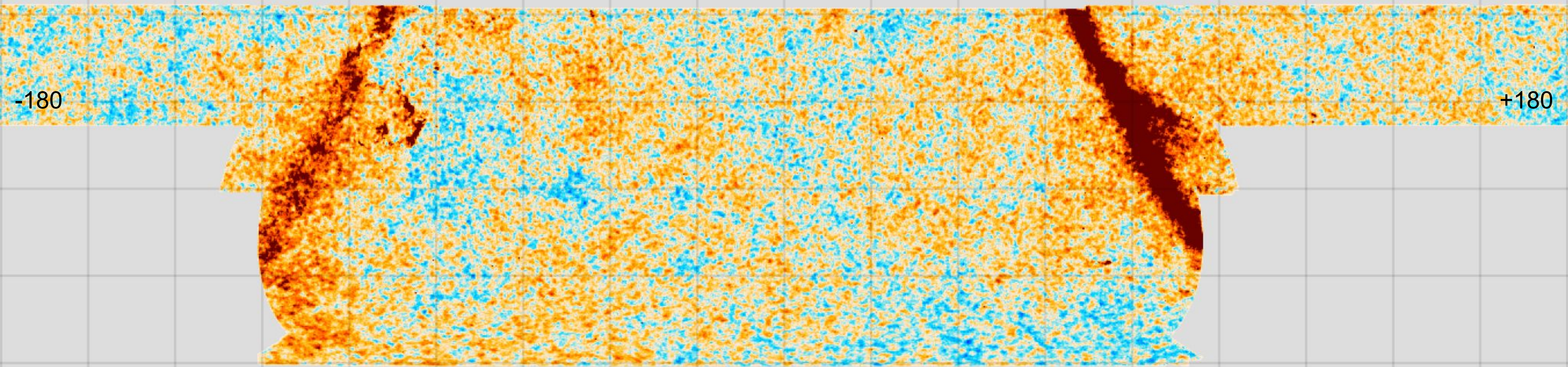
The Ultra-Deep Survey from South Pole

The use of the Chile and South Pole Sites for wide and deep surveys, respectively, follows the trend of the Stage 3 experiments.

Chile update: Going wide with AdvACT, CLASS, SO

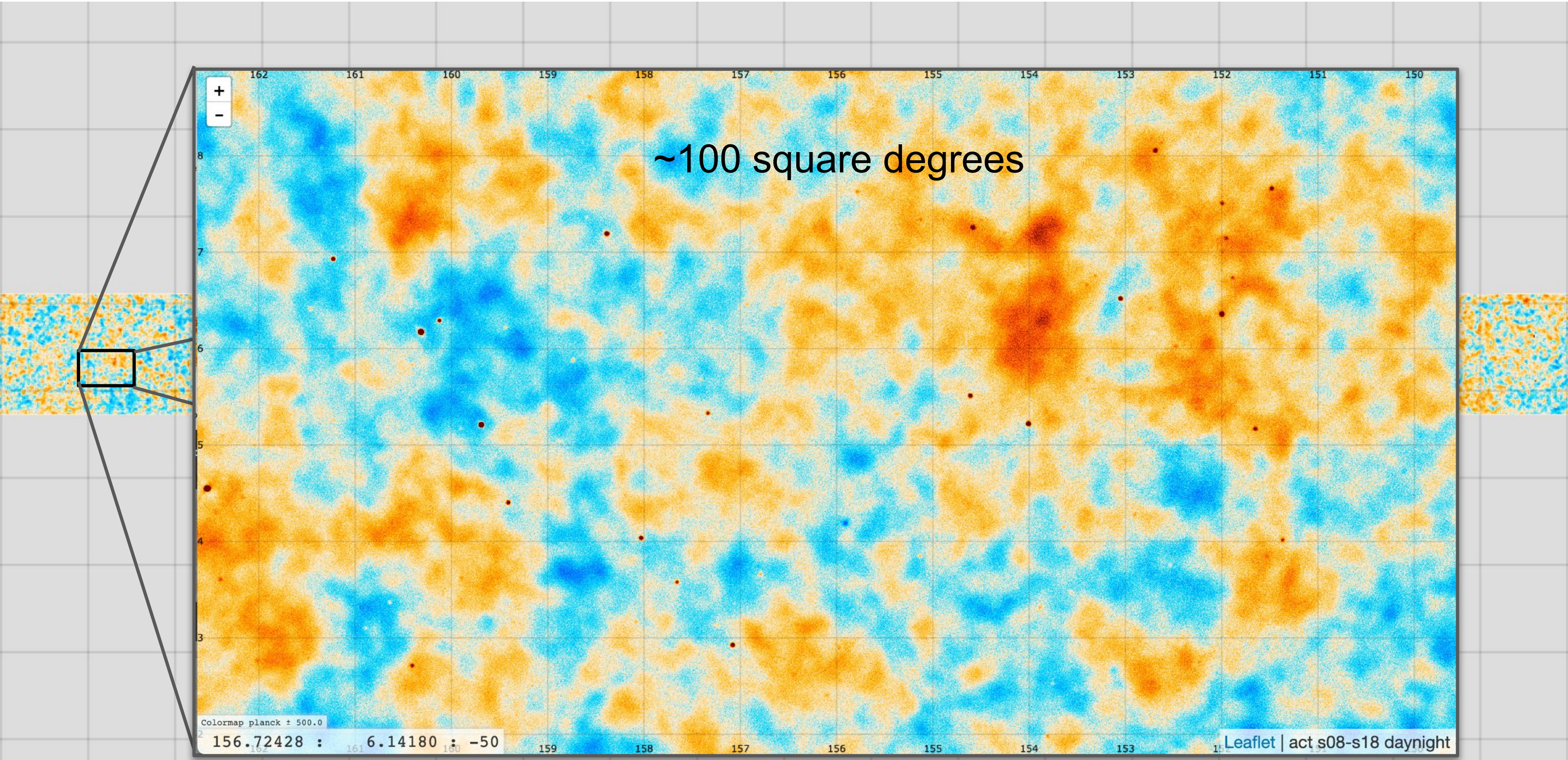
AdvACT DR5 90 + 150 GHz data with Planck

See https://phy-act1.princeton.edu/public/snaess/actpol/dr5/atlas/



- AdvACT data acquired to date ~2x Planck Sensitivity over 50% of Sky;
- SO should be >5x deeper than Planck;
- The **CMB-S4 wide survey will be ~5x deeper than SO survey, covering 60% of the sky.**

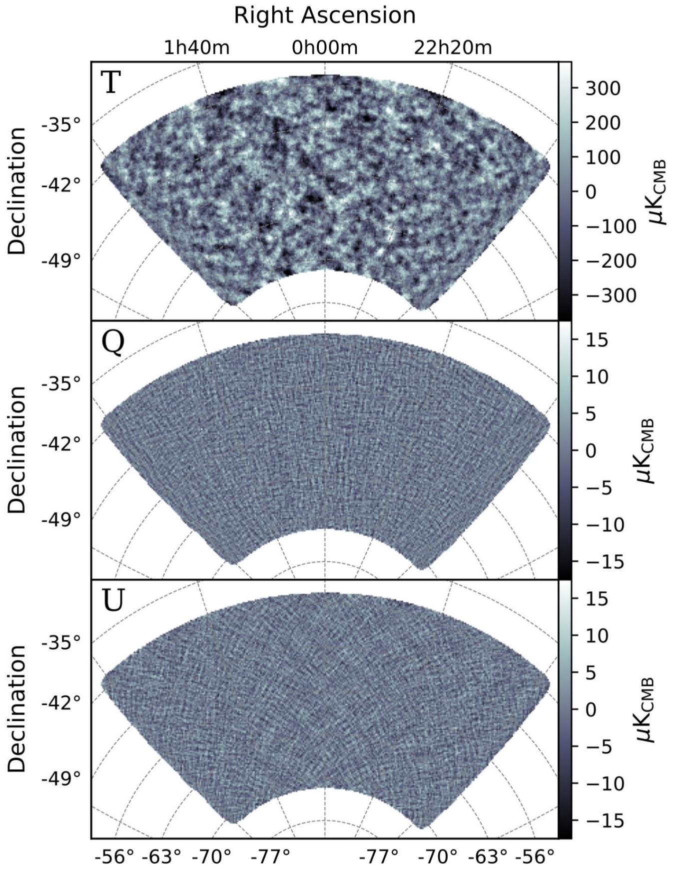
Chile update: ACT DR5 (ACT + Planck)



South Pole update: Going deep with SPT and BK

SPT-3G 1500 deg^2 survey, aligned with BICEP Array field

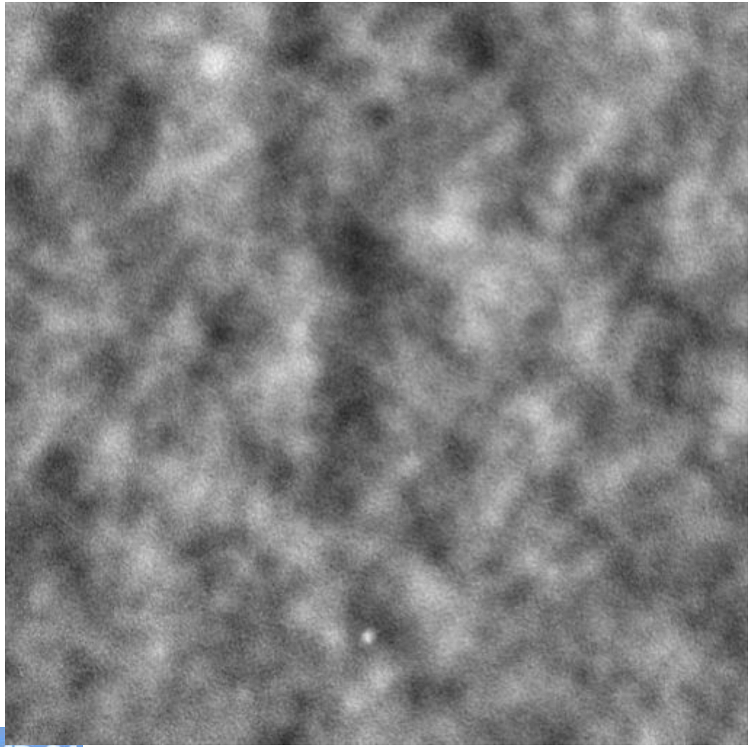
- SPT-3G currently is >10x deeper than Planck.
- When complete in 2024, SPT-3G survey will be another √2 deeper and **comparable to the CMB-S4 wide-field depth, which will cover 60% of the sky.**
- The CMB-S4 ultra-deep field will be ~5x deeper than completed SPT-3G deep survey.



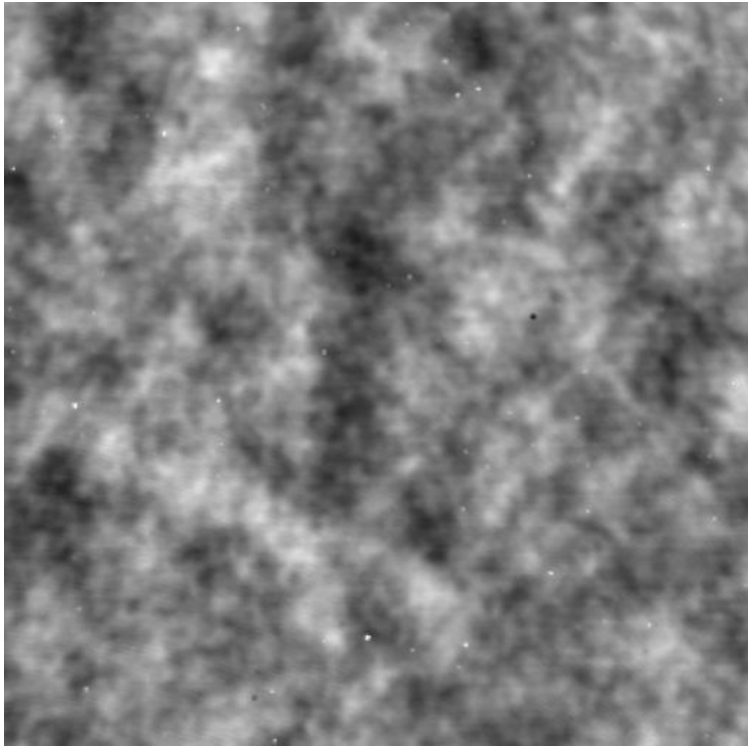
SPT-3G comparison to Planck over 100 deg^2

each high pass filtered at ell = 40

Planck 100 GHz



SPT-3G 95 GHz

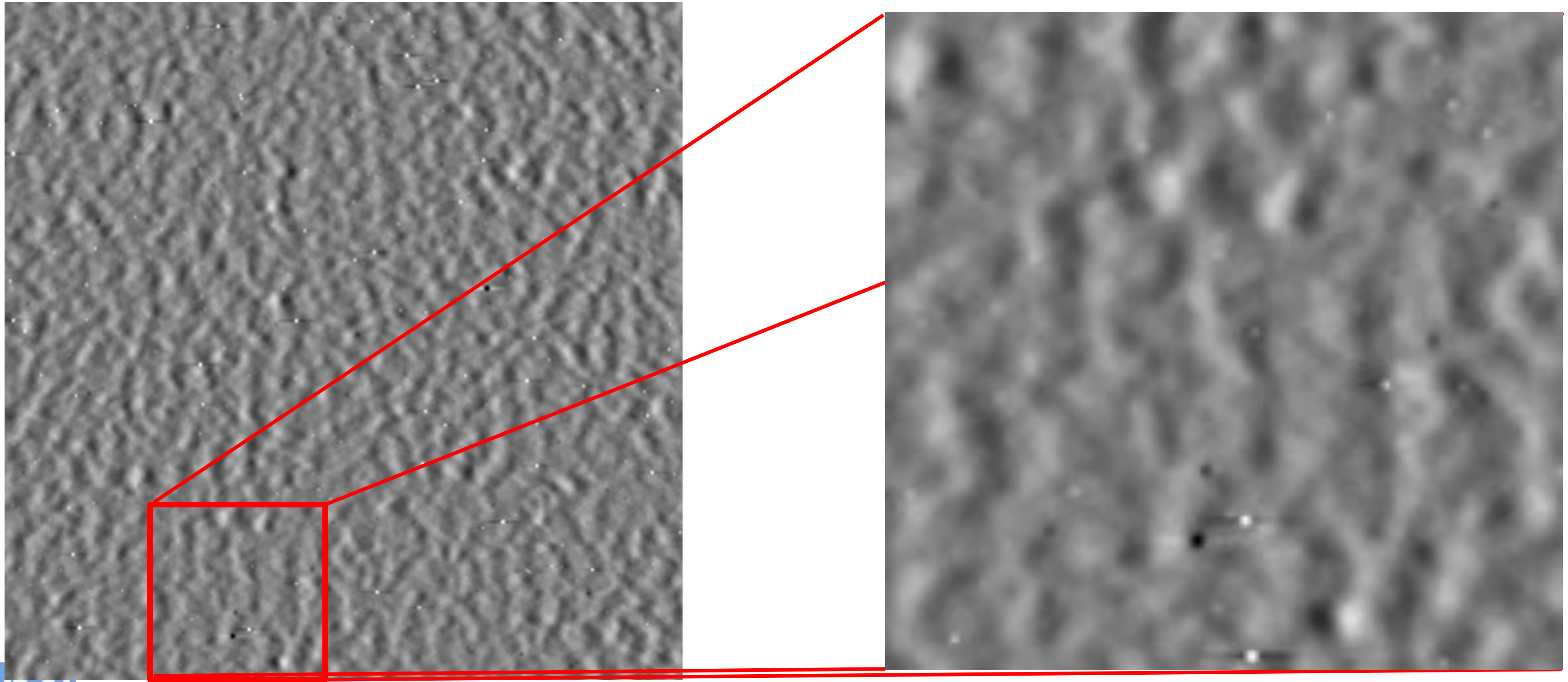


CMB-S4

Filter and zoom in

SPT-3G 95 GHz, filtered

SPT-3G 95 GHz, filtered, 10 deg^2



CMB-S4 In A Nutshell

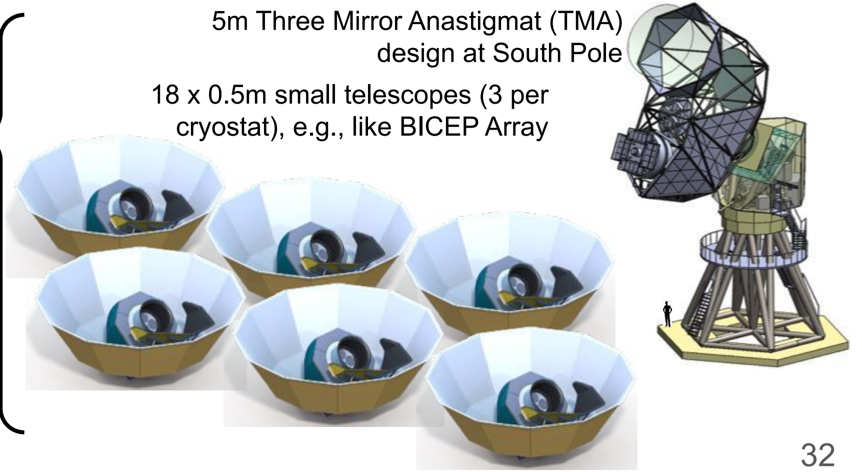
- **2 x 6m telescopes** targeting 60% of sky with **269,184 detectors** from **Chile** over 7 yrs.

6m C-D design in Chile, e.g., like Simons Observatory and CCAT-prime telescopes

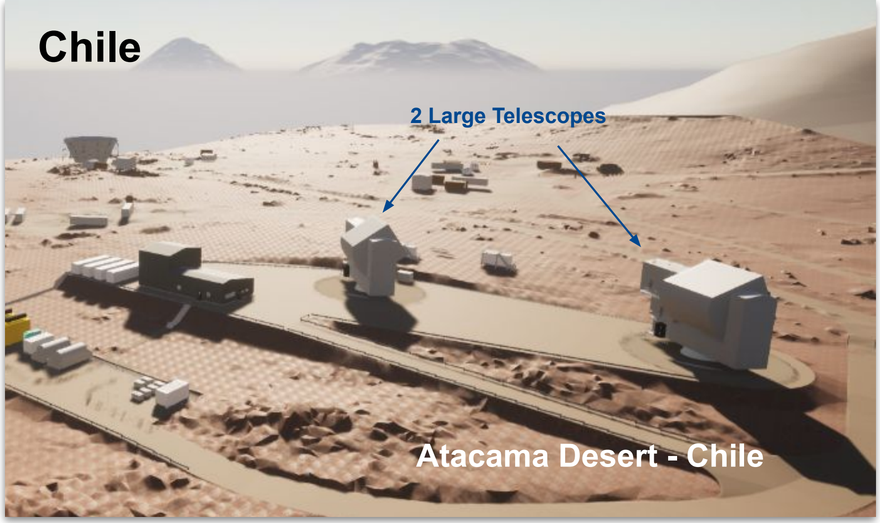
- **18 x 0.5m small refractor telescopes** targeting ~3% of sky with **154,560 detectors** and a dedicated "de-lensing" **5m telescope** with **126,360 detectors** from **South Pole** over 7 yrs.

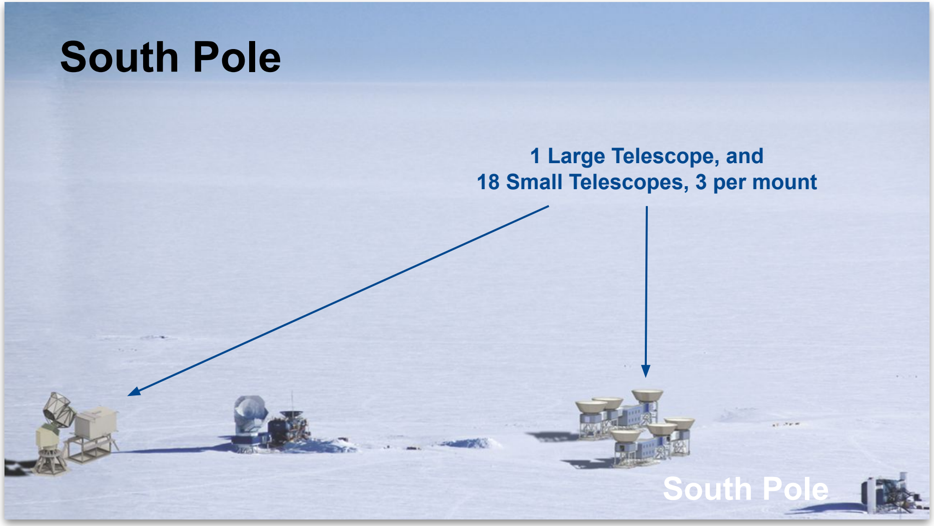
5m Three Mirror Anastigmat (TMA) design at South Pole

18 x 0.5m small telescopes (3 per cryostat), e.g., like BICEP Array



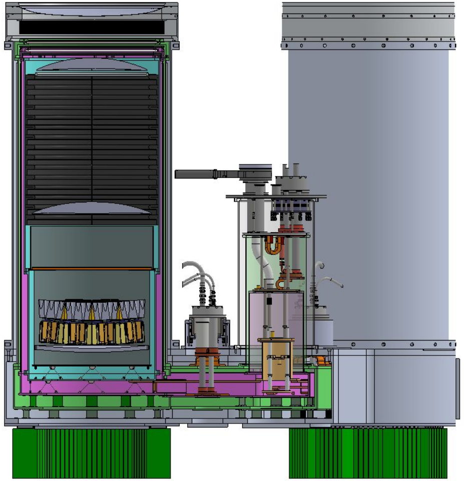
CMB-S4 In A Nutshell



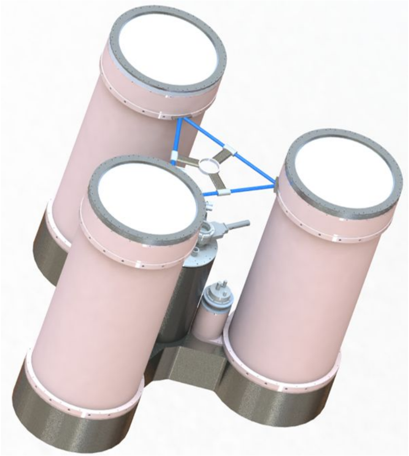


Small Aperture Telescopes (SATs)

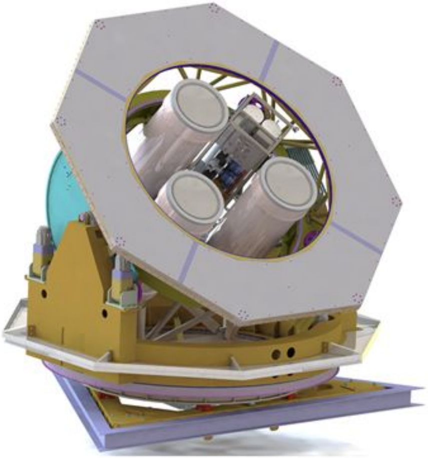
Building on the BICEP design



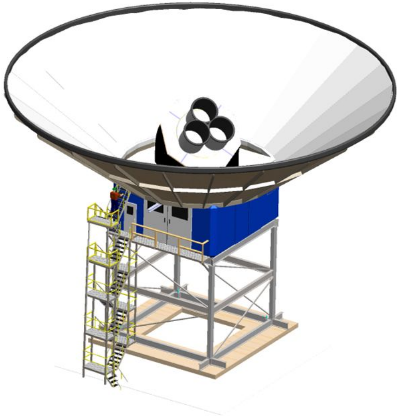
compact, refracting telescopes in a cryogenic receiver



3-receiver cryostat sharing one cryogenic system

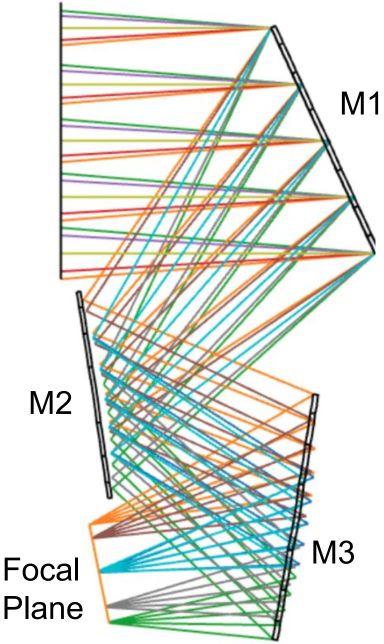


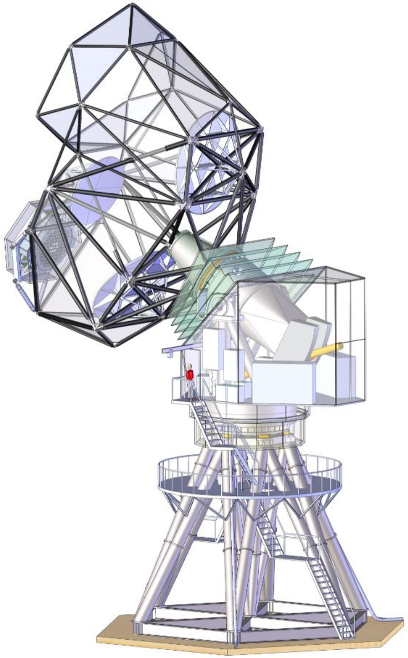
3-axis mount, with full 360 degree boresight rotation



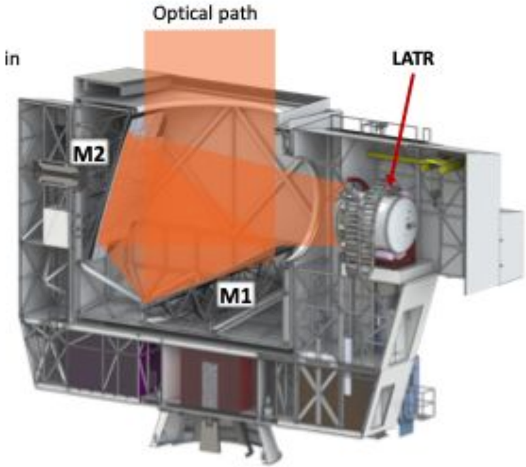
Ground shield and warm baffle system

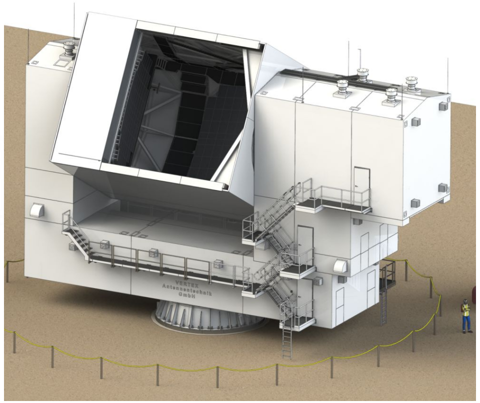
High Throughput Large Aperture Telescopes (LATs)





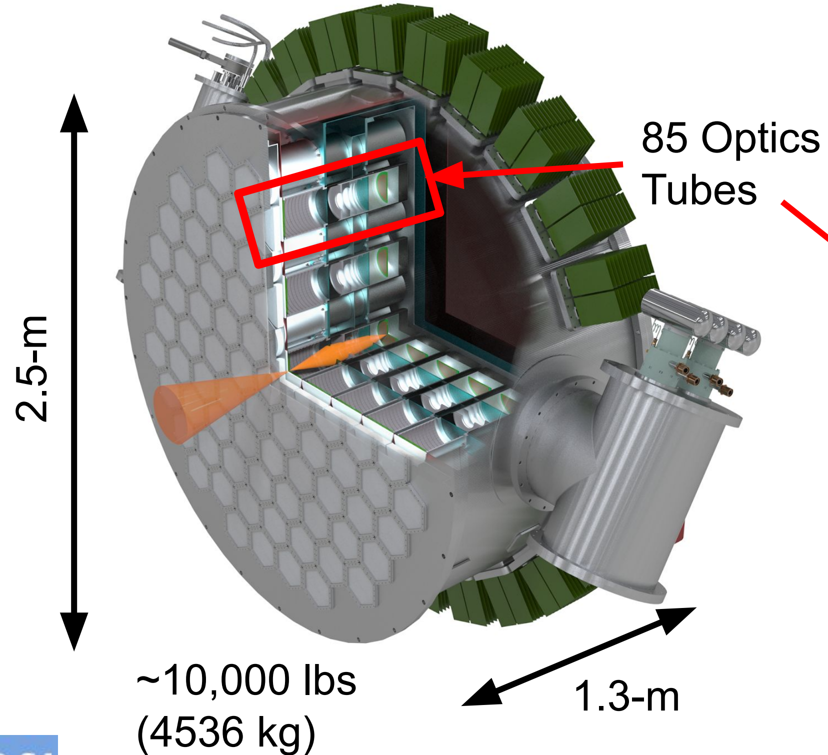
South Pole Design:
5m Three Mirror Anastigmat (TMA)
Padin Applied Optics 2018, 57(9)



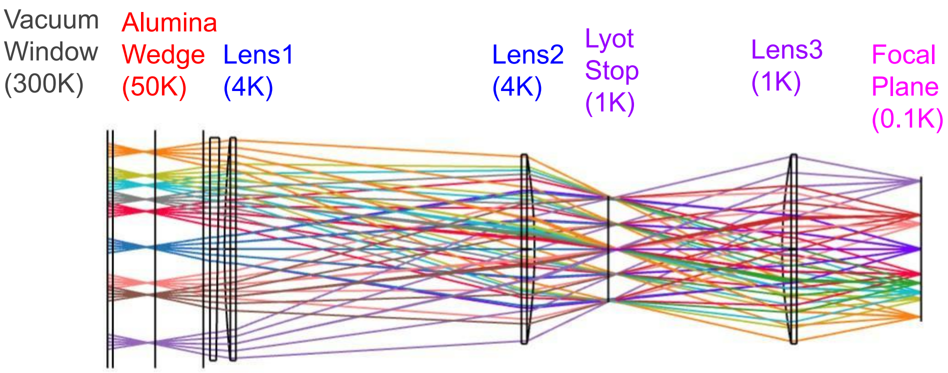


Chile Design: Two 6-m Crossed Dragone (CD) telescopes
Parshley et al. arXiv:1807.06678

Large Aperture Telescope Receivers

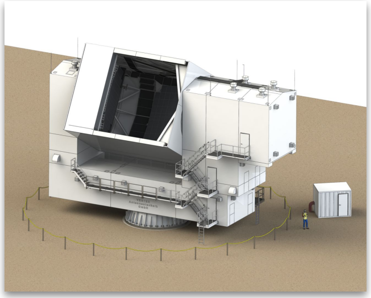


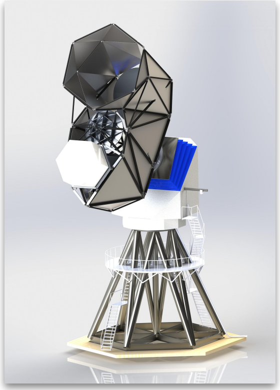
- Each LAT receiver will have a 2.0-m diameter focal plane with ~130,000 TES detectors operating at 100 mK
- 85x detector wafers per receiver, each in an optics tube with 3x cryogenic lenses per tube



Why 2 LAT Designs?

- Chile - Legacy Survey (60% sky)
  - Two 6m Crossed Dragone telescopes in Chile provide 1.4' resolution at 150 GHz, focused on "high ell" anisotropy.
  - Benefits from mature CCAT and Simons Observatory LAT design, currently being built in Chile
- South Pole - Delensing B-mode Survey (~3% sky)
  - 5 meter aperture with TMA design provides sufficient 1.6' resolution and allows monolithic (gapless) mirrors
  - TMA design also provides survey uniformity and low-ell B-mode sensitivity
    - TMA design provides better image quality across the focal plane, allowing uniform frequency coverage of small area B-mode survey
    - Monolithic mirrors eliminate large angle sidelobes from diffraction from panel gaps to prevent B-mode contamination
    - Boresight rotation to mitigate B-mode systematics by converting polarization sensitivity (Q ↔ U)



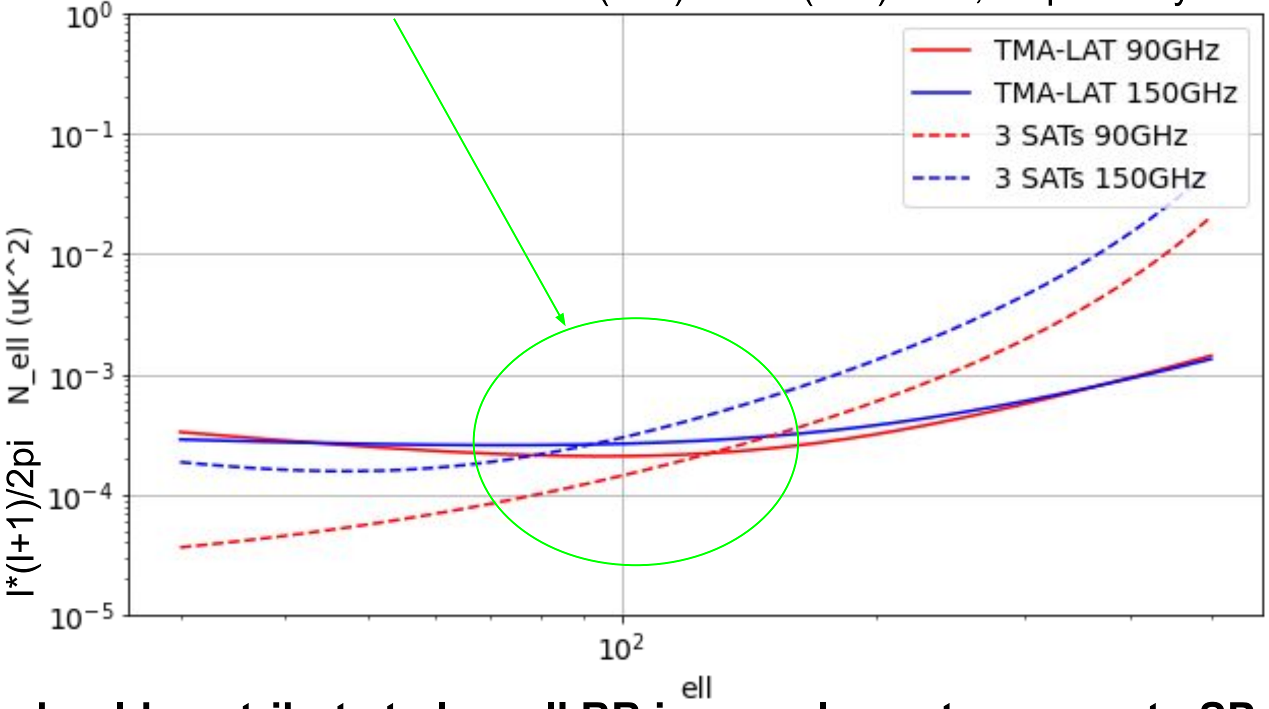


LAT design overview in:
Gallardo et al. 2022 arxiv:2207.10012

Why 2 LAT Designs?

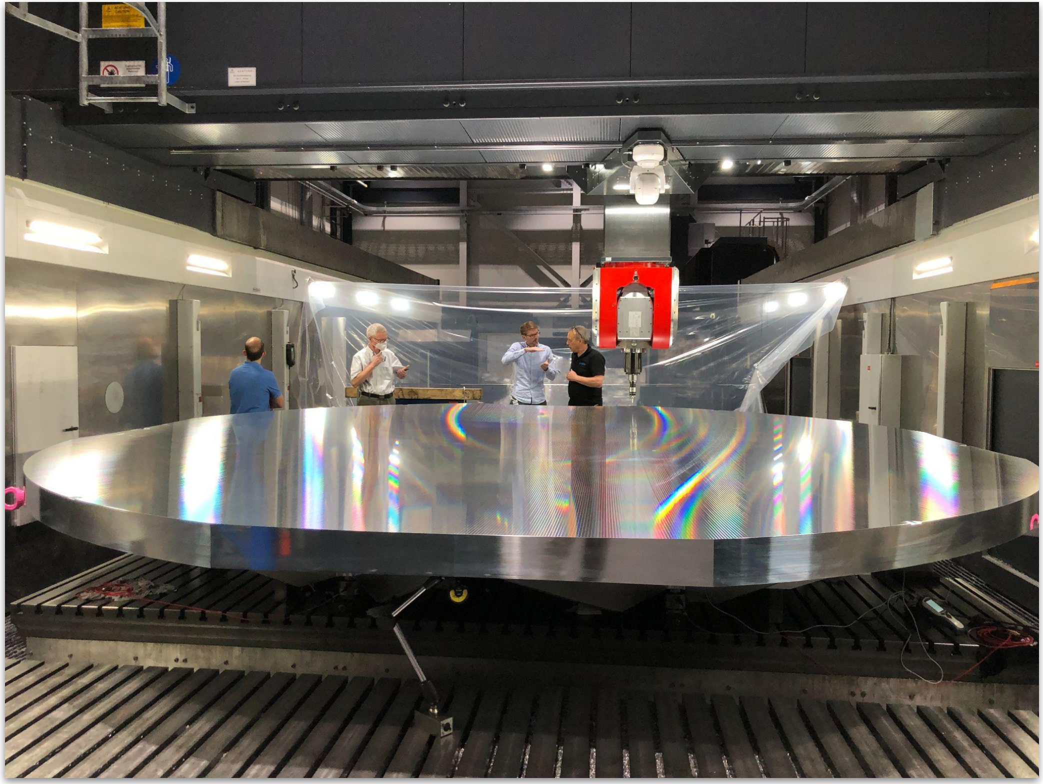
SPLAT TMA sensitivity for low-ell B-mode is significant

Comparing noise(ell) for SPLAT with 3-SATs (9 optics tubes);
the curves cross at ell ~120 (~90) for 90 (150) GHz, respectively.



SPLAT should contribute to low-ell BB in complementary ways to SP SATs, e.g., allowing cross-checks with different beam systematics.

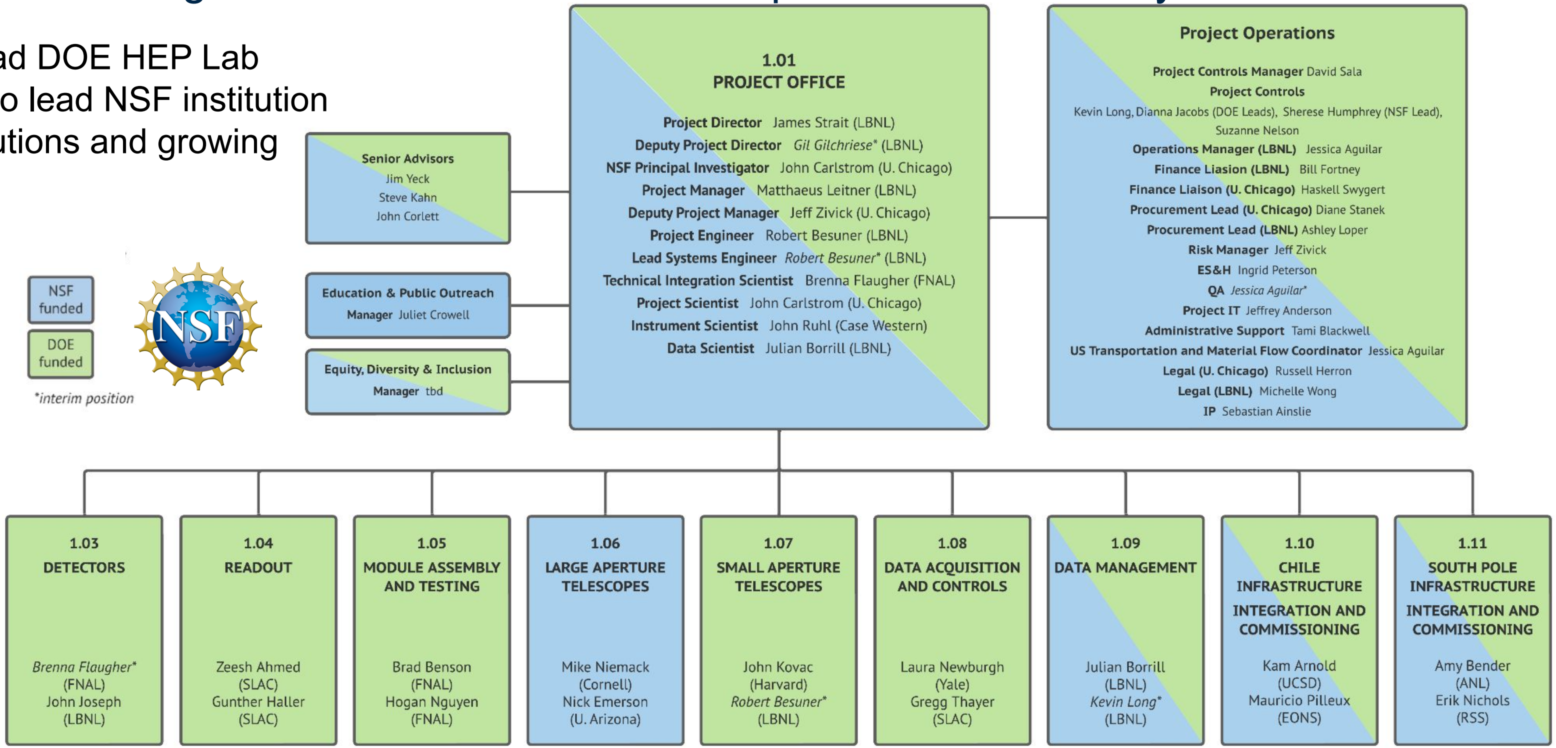
TMA primary mirror completed and delivered to Chicago



Well Established Integrated DOE/NSF Supported CMB-S4 Project

Accomplished Management and CMB and Telescope Scientists Fill Key Positions

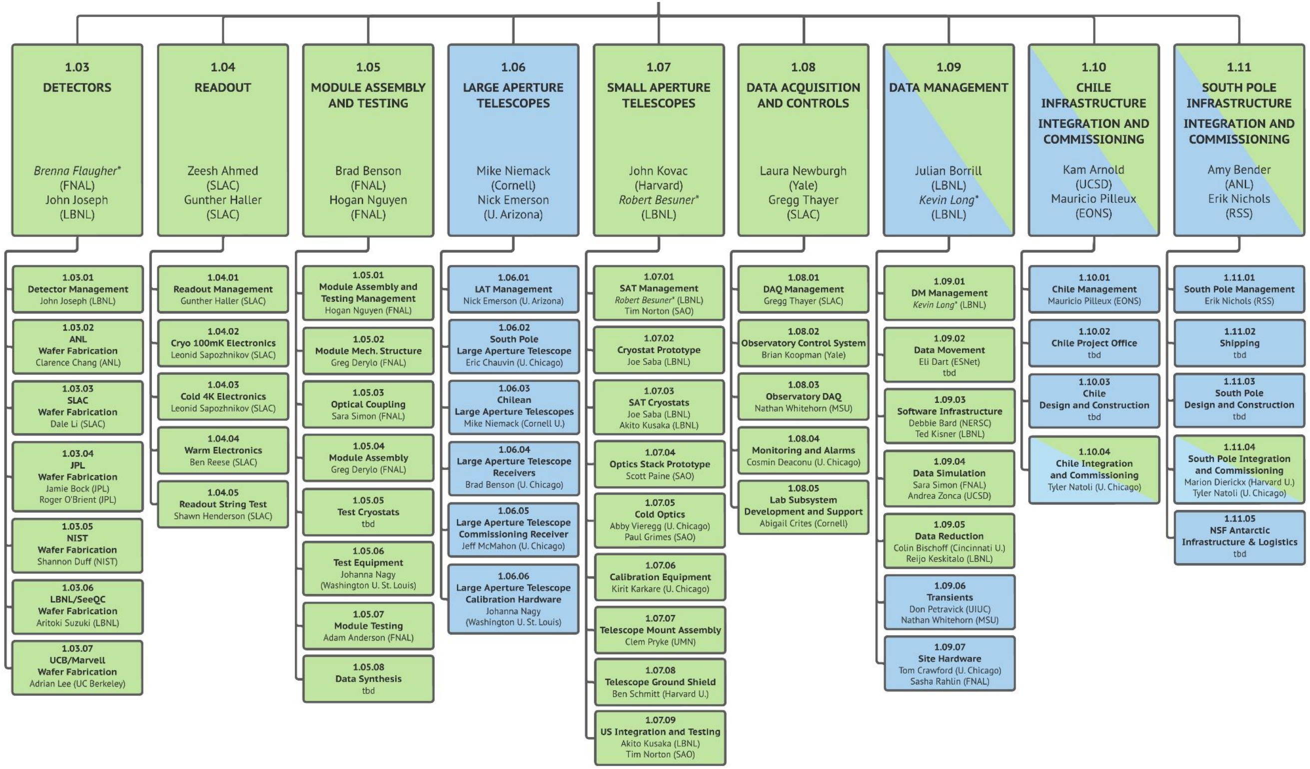
- LBNL lead DOE HEP Lab
- UChicago lead NSF institution
- 19 Institutions and growing



- Experienced Project Office & Project Operations staff are in place
- Expertise in science and technology from across the CMB community
- Proposed DOE and NSF scope is identified
- Management tools are in place

Organization is Developed To The Lowest Technical Levels

Project Organization Is Distributed Across National Laboratories and Universities

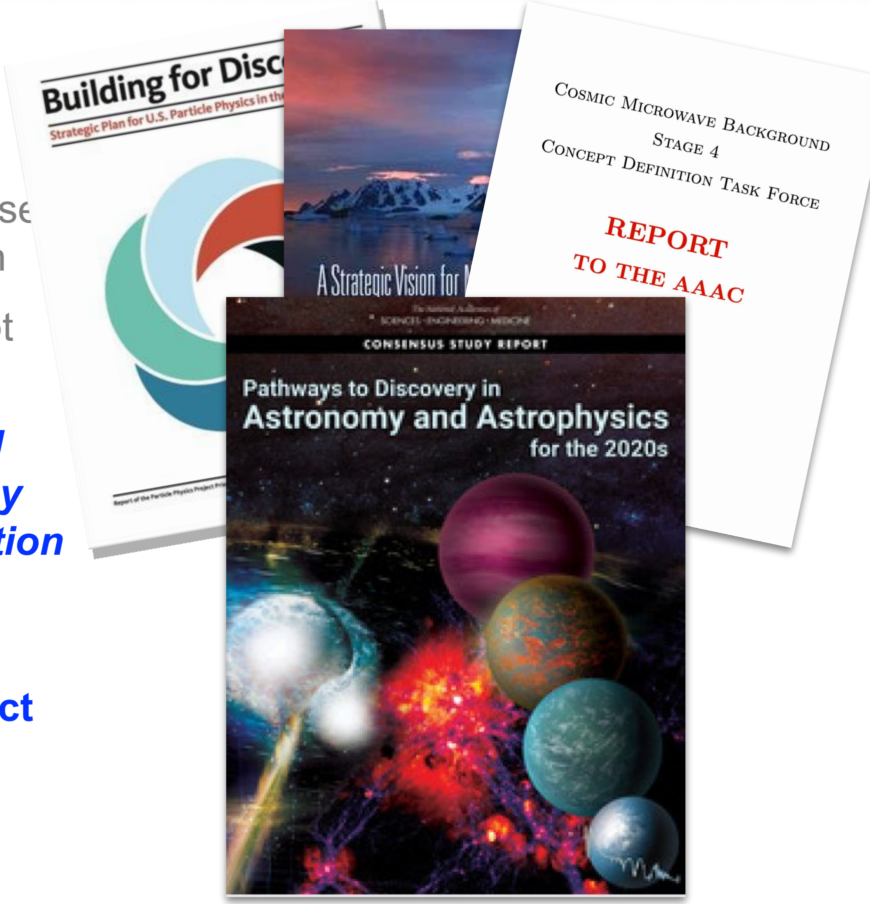


Date:

Approved:

Received critical Astro2020 endorsement

- 2014: P5 recommended CMB-S4 under all budget scenarios
- 2015: NAS report recommended CMB-S4 science case as 1 of 3 strategic Investments for Antarctic Research
- 2017: AAAC unanimously approved CMB-S4 Concept Definition Task Force report
- **2021: Astro2020:** “***Recommendation: The National Science Foundation and the Department of Energy should jointly pursue the design and implementation of the next generation ground-based cosmic microwave background experiment (CMB-S4).***”
- **2022: Snowmass/Cosmic Frontier: “Our top project priority is to complete construction of CMB-S4”**

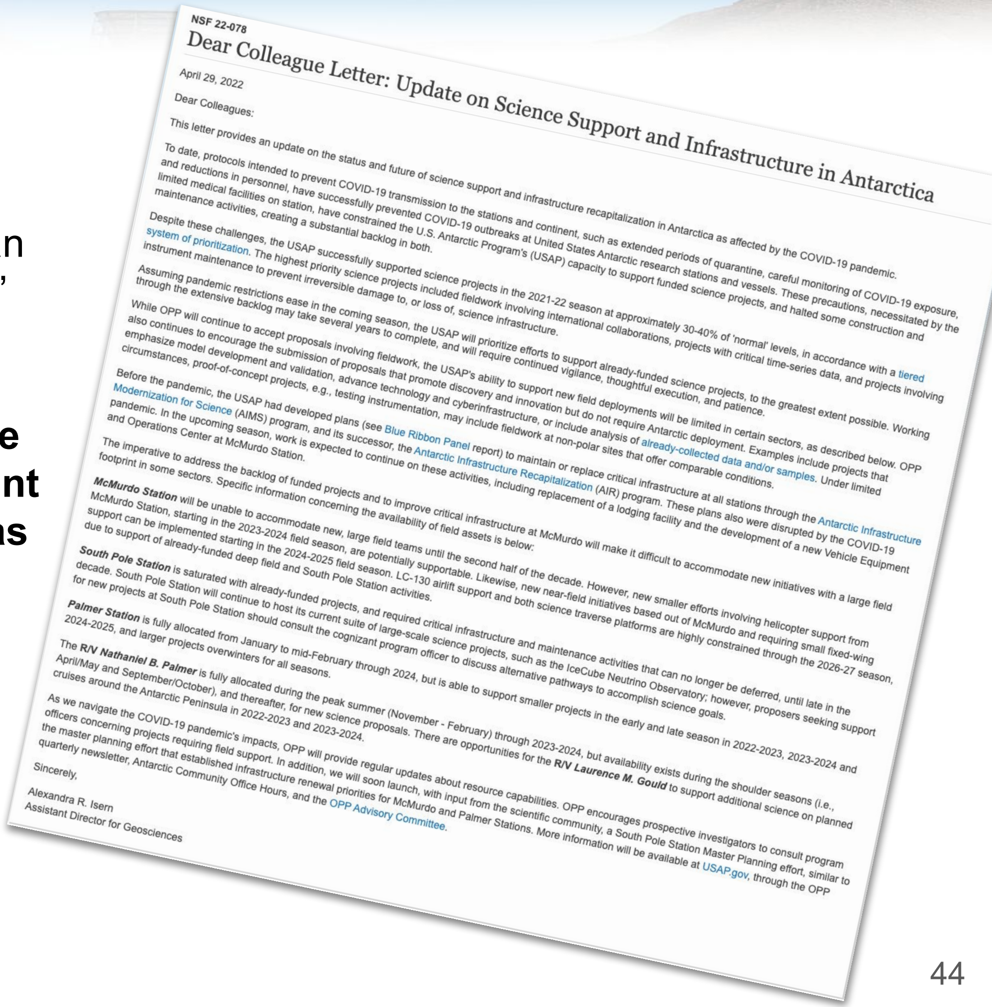


So, all appeared to be go, go, go!

Then…

"South Pole Station is saturated with already-funded projects, and required critical infrastructure and maintenance activities that can no longer be deferred, until late in the decade..."

CMB-S4 was requested to develop alternative configurations that would fit within the current logistical constraints of the South Pole. It was made clear that the future of the project depended on this "Analysis of Alternatives"



NSF 22-078

Dear Colleague Letter: Update on Science Support and Infrastructure in Antarctica

April 29, 2022

Dear Colleagues:

This letter provides an update on the status and future of science support and infrastructure recapitalization in Antarctica as affected by the COVID-19 pandemic.

To date, protocols intended to prevent COVID-19 transmission to the stations and continent, such as extended periods of quarantine, careful monitoring of COVID-19 exposure, and reductions in personnel, have successfully prevented COVID-19 outbreaks at United States Antarctic research stations and vessels. These precautions, necessitated by the limited medical facilities on station, have constrained the U.S. Antarctic Program's (USAP) capacity to support funded science projects, and halted some construction and maintenance activities, creating a substantial backlog in both.

Despite these challenges, the USAP successfully supported science projects in the 2021-22 season at approximately 30-40% of 'normal' levels, in accordance with a tiered system of prioritization. The highest priority science projects included fieldwork involving international collaborations, projects with critical time-series data, and projects involving instrument maintenance to prevent irreversible damage to, or loss of, science infrastructure.

Assuming pandemic restrictions ease in the coming season, the USAP will prioritize efforts to support already-funded science projects, to the greatest extent possible. Working through the extensive backlog may take several years to complete, and will require continued vigilance, thoughtful execution, and patience.

While OPP will continue to accept proposals involving fieldwork, the USAP's ability to support new field deployments will be limited in certain sectors, as described below. OPP also continues to encourage the submission of proposals that promote discovery and innovation but do not require Antarctic deployment. Examples include projects that emphasize model development and validation, advance technology and cyberinfrastructure, or include analysis of already-collected data and/or samples. Under limited circumstances, proof-of-concept projects, e.g., testing instrumentation, may include fieldwork at non-polar sites that offer comparable conditions.

Before the pandemic, the USAP had developed plans (see Blue Ribbon Panel report) to maintain or replace critical infrastructure at all stations through the Antarctic Infrastructure Modernization for Science (AIMS) program, and its successor, the Antarctic Infrastructure Recapitalization (AIR) program. These plans also were disrupted by the COVID-19 pandemic. In the upcoming season, work is expected to continue on these activities, including replacement of a lodging facility and the development of a new Vehicle Equipment and Operations Center at McMurdo Station.

The imperative to address the backlog of funded projects and to improve critical infrastructure at McMurdo will make it difficult to accommodate new initiatives with a large field footprint in some sectors. Specific information concerning the availability of field assets is below:

McMurdo Station will be unable to accommodate new, large field teams until the second half of the decade. However, new smaller efforts involving helicopter support from McMurdo Station, starting in the 2023-2024 field season, are potentially supportable. Likewise, new near-field initiatives based out of McMurdo and requiring small fixed-wing support can be implemented starting in the 2024-2025 field season. LC-130 airlift support and both science traverse platforms are highly constrained through the 2026-27 season, due to support of already-funded deep field and South Pole Station activities.

South Pole Station is saturated with already-funded projects, and required critical infrastructure and maintenance activities that can no longer be deferred, until late in the decade. South Pole Station will continue to host its current suite of large-scale science projects, such as the IceCube Neutrino Observatory; however, proposers seeking support for new projects at South Pole Station should consult the cognizant program officer to discuss alternative pathways to accomplish science goals.

Palmer Station is fully allocated from January to mid-February through 2024, but is able to support smaller projects in the early and late season in 2022-2023, 2023-2024 and 2024-2025, and larger projects overwinters for all seasons.

The ***R/V Nathaniel B. Palmer*** is fully allocated during the peak summer (November - February) through 2023-2024, but availability exists during the shoulder seasons (i.e., April/May and September/October), and thereafter, for new science proposals. There are opportunities for the ***R/V Laurence M. Gould*** to support additional science on planned cruises around the Antarctic Peninsula in 2022-2023 and 2023-2024.

As we navigate the COVID-19 pandemic's impacts, OPP will provide regular updates about resource capabilities. OPP encourages prospective investigators to consult program officers concerning projects requiring field support. In addition, we will soon launch, with input from the scientific community, a South Pole Station Master Planning effort, similar to the master planning effort that established infrastructure renewal priorities for McMurdo and Palmer Stations. More information will be available at USAP.gov, through the OPP quarterly newsletter, Antarctic Community Office Hours, and the OPP Advisory Committee.

Sincerely,

Alexandra R. Isern
Assistant Director for Geosciences

Analysis of Alternatives (AoA)

- NSF requested that we develop and analyze alternative options that fit within the current South Pole logistical infrastructure, for which a primary, but not sole constraint, is station power generation.
- Our future depends on developing a supportable path forward using the South Pole
- The South Pole scope is primarily directed to achieve the Inflationary goals, so therefore our AoA efforts are focused primarily on achieving the r requirement.
- **We believe that it is crucial that we not relax our level-1 science goals, especially for *r*.**
- As a result, the CMB-S4 Project and Science Collaboration have been focused on the AoA since March, 2022, including science forecasting, project scope and schedule, risks, survey duration(s), and costing, as well as opportunities to use SPO and SO data.

From Preliminary Baseline Design to SP Alternatives

Preliminary Baseline Design: (6 SPSATs + SPLAT at SP; 2 CHLATs in Chile)

- SAT design based on evolution of the BK SAT designs to provide low-ell sensitivity
- CHLAT based on CCAT/SO design to conduct deep-wide survey
- SPLAT TMA design to provide:
  - Sufficient de-lensing power to meet r goals
  - Additional low-ell sensitivity[1] to meet r goal for all foregrounds models considered and to provide r science margin
  - Cross-checks for low-ell systematics

[1]using conservative low-ell noise model based on SPT-3G achieved performance

From Preliminary Baseline Design to SP Alternatives

⇒ **Alternative 1** (3 SPSATs + SPLAT at SP; 2 CHLATs in Chile)

- Reduce number of SP SATs to reduce station power requirements to fit within current SP capabilities while maintaining low-ell sensitivity and cross checks with SPLAT & SPSATs

⇒ **Alternative 2** (4 SPSATs at SP, 3 or 5 CHLATs in Chile)

- Reduce SP SATs and omit SP LAT (de-lens with additional CHLATs) to reduce station power to fit within current SP capabilities; giving up cross checks with SPLAT & SPSATs

⇒ **Alternative 3** (No telescopes at SP; 9+ CHSATs and 3+ CHLATS)

- Chilean SATs (CHSATs) equipped with HWP to mitigate “sky noise”
- Giving up low-ell LAT data & cross checks with SPLAT & SPSATs

Comparison of SP and Chile Efficiency for Ultra-Deep r-Survey

From our ApJ paper; the ability to focus on a deep field 24/7 at **South Pole offers 2.5x advantage** in SAT Detector-Years required to reach CMB-S4 *r* sensitivity, assuming all else being equal.

This factor is due to **only geometry**, and does not include other site specific issues:

- Atmospheric properties: weather, opacity and “sky noise”
- Different foregrounds of the fields
- Impact of horizon features and 24 hour solar diurnal heating/cooling

Table 7
Same as Table 6, but Assuming Additional Foreground Decorrelation Parameters

Number of **SAT tubes**

Chile\Pole	0	6	9	12	18	30
0		8.4	6.7	6.0	**5.2**	4.4
6	16	7.3	6.2	**5.6**	5.0	4.3
9	12	6.8	**5.9**	5.4	4.9	4.3
12	9.7	**6.4**	5.7	5.3	4.8	4.2
18	**7.8**	5.8	5.3	5.0	4.6	4.1
30	6.0	5.1	4.8	4.6	4.3	4.0

Values are $\sigma(r) \times 10^{-4}$

Keeping only the 28% Cleanest Part of the Sky, Assuming an Observing Efficiency in Chile the Same as at the South Pole, i.e, strictly geographical considerations. (Note ~2.5x more SATs are required in Chile under these assumptions.)

Also see Decadal Survey Report Appendix 1.3 “*Flowdown to distribution of SATs and delensing LAT across sites”*

Improved r Forecasting for SP v Chile comparisons

- We are investigating:
  - Realistic survey scan strategies for Chile and South Pole
  - Improved foreground models from the **Pan-Experiment Galactic Science Group**, allowing us account for different regions of the sky, especially for Chile
  - Impact of observing efficiency differences between sites, including weather statistics
  - Scaling from achieved performances of BK SATs, SPT and ACT LATs
  - Required de-lensing effort, and LATs needed to achieve it for each Alternative
  - Sensitivity impact of using SAT half-wave plates in Chile, to mitigate “sky noise”
- Also need to weigh the
  - Systematic and sidelobe risks of different SAT configurations
  - Site requirements for solar and ground screening
  - Impact of 24 hour solar diurnal heating/cooling in Chile
  - Technical risks and required R&D

AoA Effort

To carry out the AoA we assembled a “tiger team” of experts representing the key components and constituencies.

- Instrument modeling - Jeff McMahon & John Ruhl
- Observation modeling - Reijo Keskitalo & Sara Simon
- Galactic foreground modeling - Susan Clark & Brandon Hensley
- Delensing - Raphael Flauger & Marius Millea
- Forecasting - David Alonso, Colin Bischoff, Josquin Errard & Raphael Flauger
- Coordination - Julian Borrill & John Carlstrom
- Data presentation - Cooper Jacobus

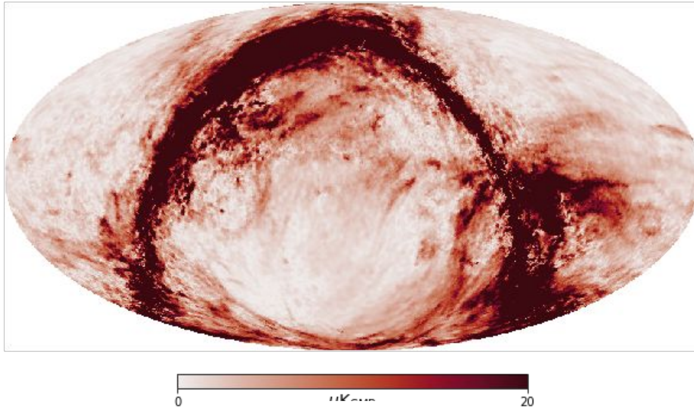
These were supported by the entire Project & Collaboration, and particularly the CMB-S4 Low-ell BB Analysis Working Group and the Pan-Experiment Galactic Science Group.

A “Shout Out” to the Pan-Experiment Galactic Science Group

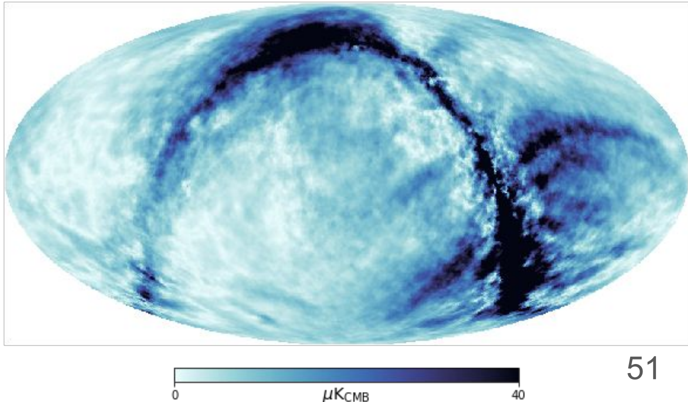
- AoA foregrounds modeling was coordinated through the **Pan-Experiment Galactic Science Group**: experts in Galactic astrophysics and CMB foregrounds across most of the current and upcoming CMB experiments as well as members of the interstellar medium community

- Three sky models, all consistent with current data:
  - **Low Complexity:** Small-scale fluctuations in amplitudes only, no decorrelation
  - **Best Estimate:** Parameter maps based on component separation with extrapolation to small scales in both amplitudes and spectral parameters
  - **High Complexity:** Near maximum-allowed decorrelation for dust emission, line-of-sight dust SED variations, AME polarization, synchrotron curvature

353 GHz P



30 GHz P



Available on Github: https://github.com/galsci/pysm

Summary

- We have a spectacular, transformational science case, including a historic opportunity to investigate the origin of the universe by making a definitive measurement of primordial gravitational waves, as predicted by Inflation
- We have successfully developed alternative configurations that can achieve the science, with reduced infrastructure at the South Pole.
- The alternatives vary in required scope, observing time, risk, and cost.
- The AoA has been “vetted” by the Collaboration and reviewed by an external expert panel.
- The next step is a briefing with DOE and NSF, scheduled for early December.
- We then expect to work with the agencies to pursue the alternative pathway with the highest chance of success (least science risk) and with well understood risk mitigation strategies, and construct CMB-S4 for operation in the 2030’s.