(Some) Current Challenges For CMB Cosmology

John Kovac, Harvard University

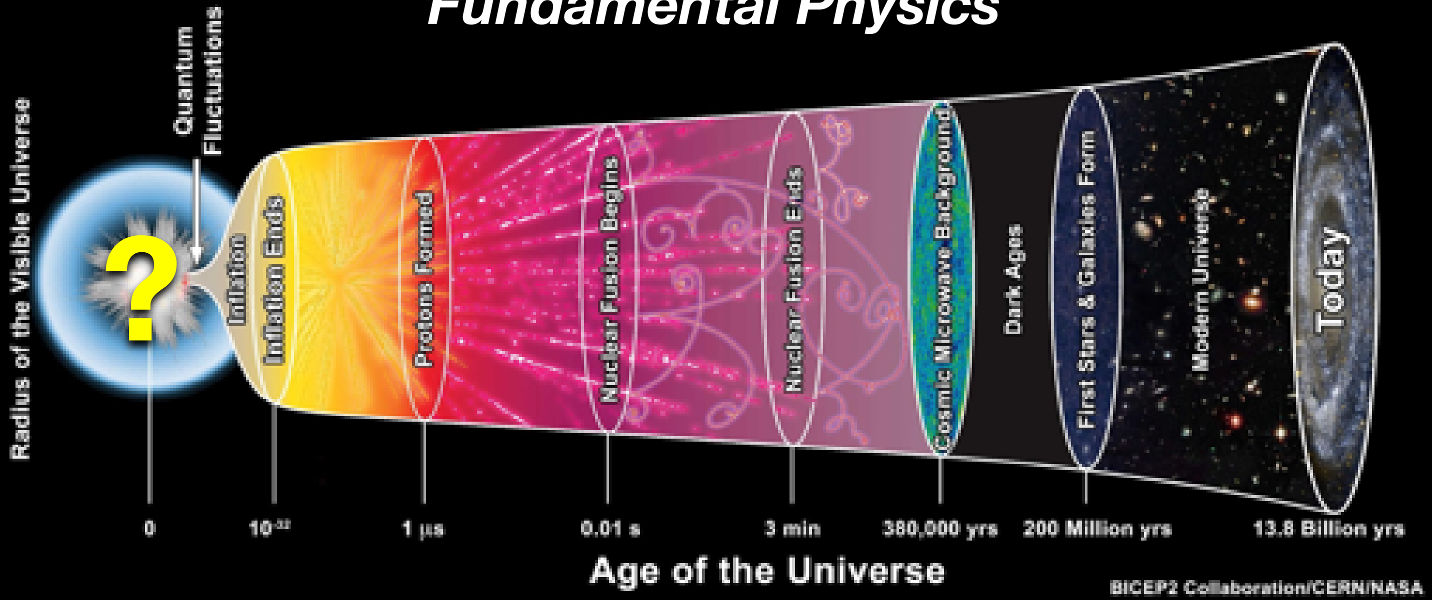
BICEP/Keck/South Pole Observatory
& CMB-S4 collaborations

30th Anniversary of Rencontres du Vietnam

Windows on the Universe

8 Aug 2023

The CMB Probes Cosmology and Fundamental Physics



Inflation

- Test simplest models of Inflation
- Measure the ***Energy-scale of Inflation (~10^{16} GeV)***

Neutrinos & relics

- Detect or rule out the production of any new ***light relic particle species***
- Measure structure growth to detect the ***sum of the neutrino masses***

Dark Energy

- Use CMB as back-light to measure evolution of structure via lensing and Sunyaev-Zel'dovich effect
- ***Tests of gravity and the nature of dark energy***

slide from Aug 2006 Rencontres du Vietnam:

"CMB from the South Pole: Past, Present, and Future"

- Amundsen-Scott South Pole Station
  - elevation: 2335m
  - current temp: -78C
  - humidity: > 75%

- Hanoi, Vietnam
  - elevation: 6m
  - current temp: +32C
  - humidity: > 75%

CMB ***can*** be detected from low, warm, humid places

http://bicep.rc.fas.harvard.edu/student_cmb_lab/

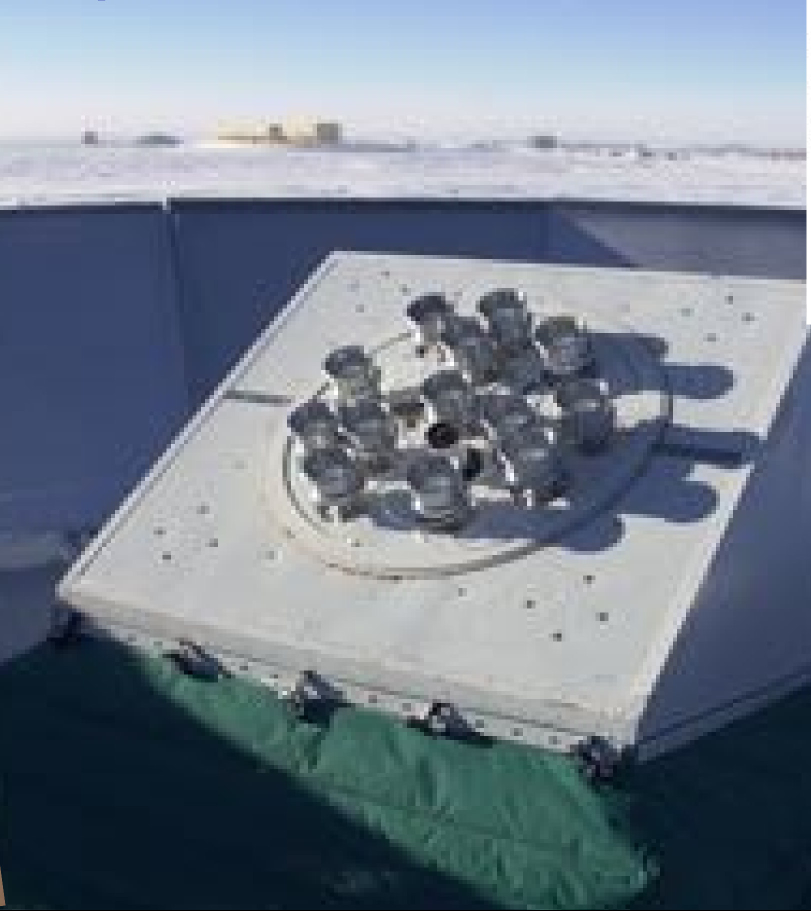
for example: New Jersey

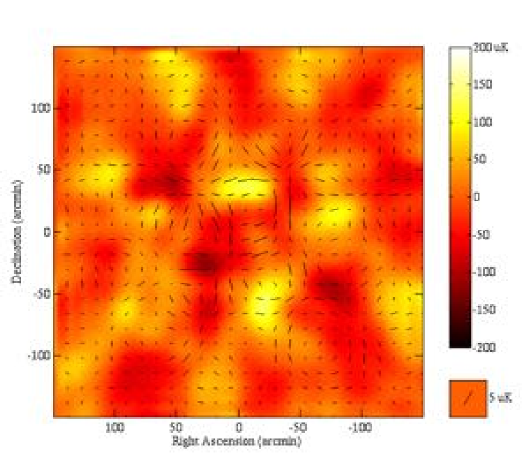
…or a Boston rooftop!   great student / outreach project

1993: start of Rencontres du Vietnam AND permanent CMB at South Pole

…a hard learning curve

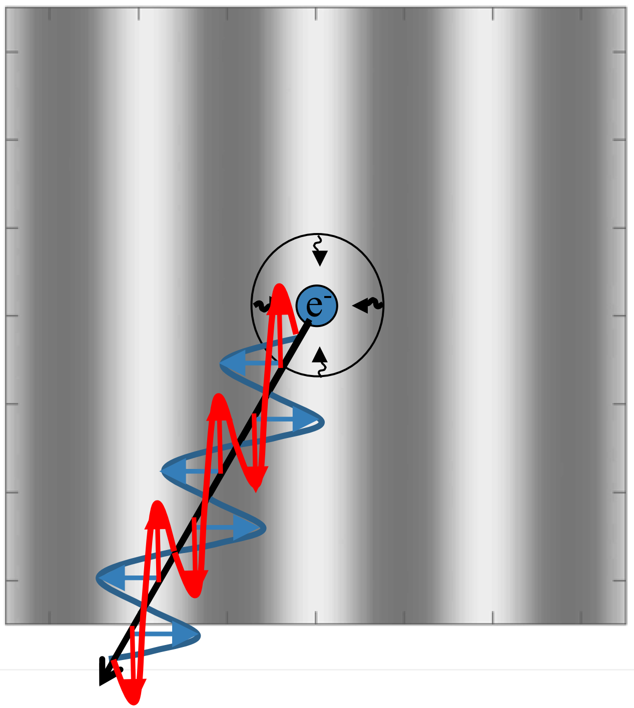
2002 – DASI at South Pole
first detects polarization of CMB





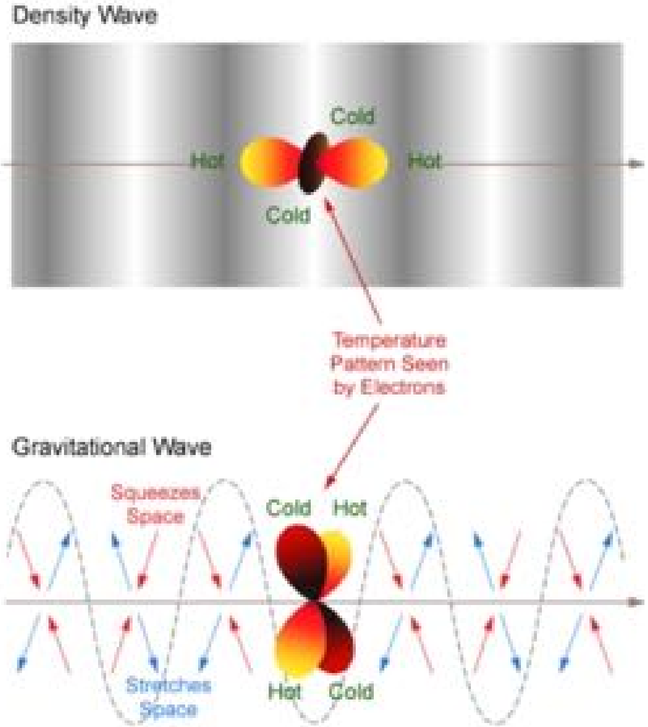
Making E/B CMB Polarization

Thomson scattering from density waves



Vertical is stronger than Horizontal by only 1 part in ~1,000,000

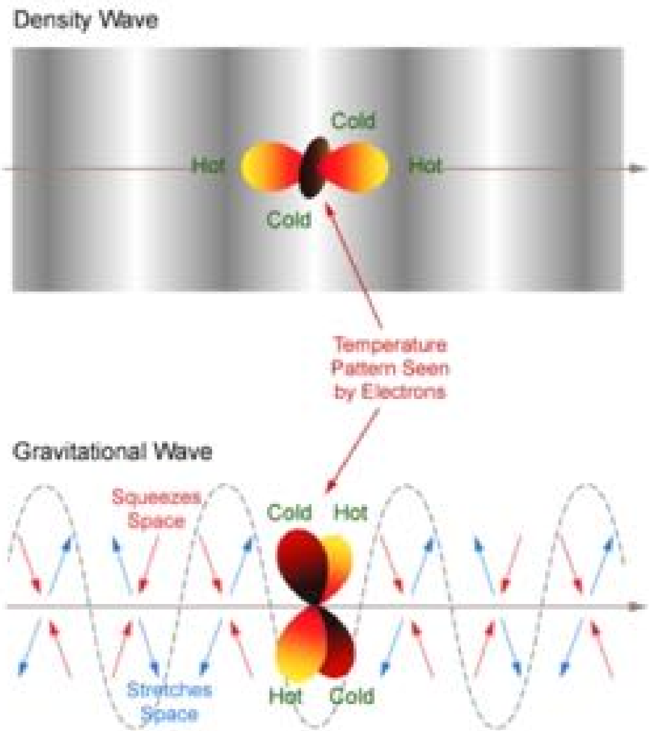
Making CMB Polarization

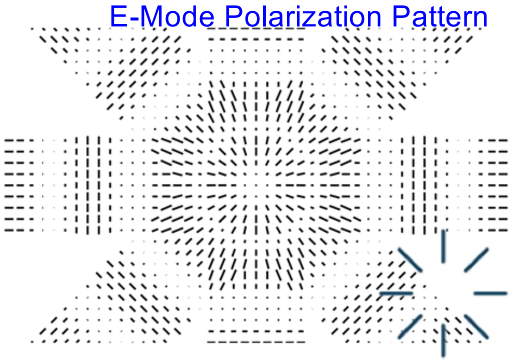


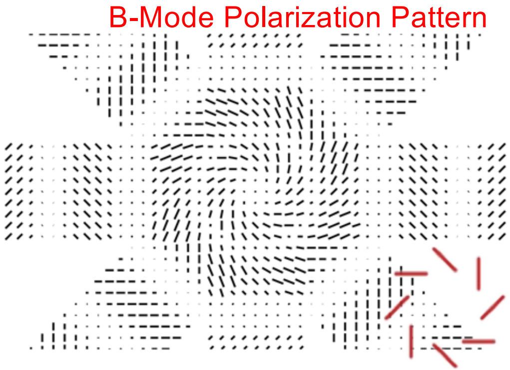
E-Mode Polarization Pattern

B-Mode Polarization Pattern

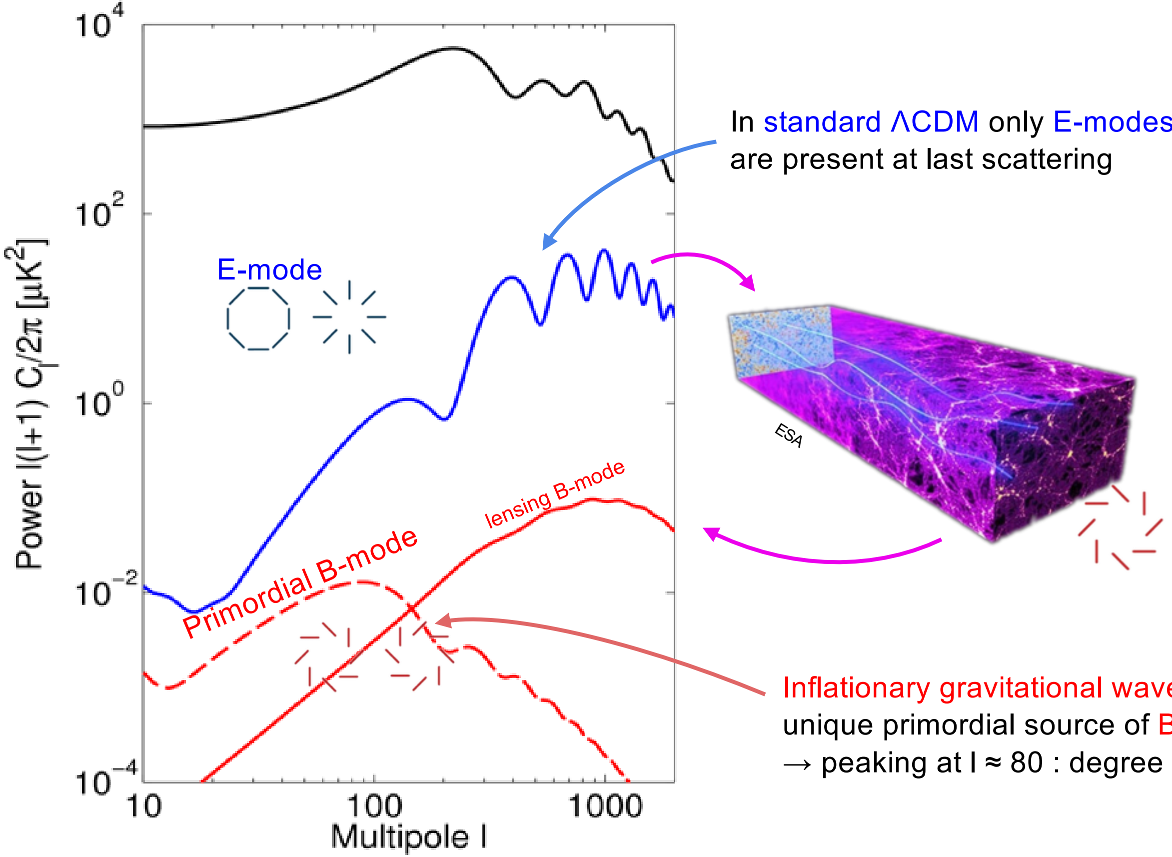
Making CMB Polarization







CMB Polarization Observables



In standard ΛCDM only E-modes are present at last scattering

During propagation some of the E-modes are confused into B-modes by lensing

Inflationary gravitational waves are unique primordial source of B-modes
→ peaking at $l \approx 80$: degree scales

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.

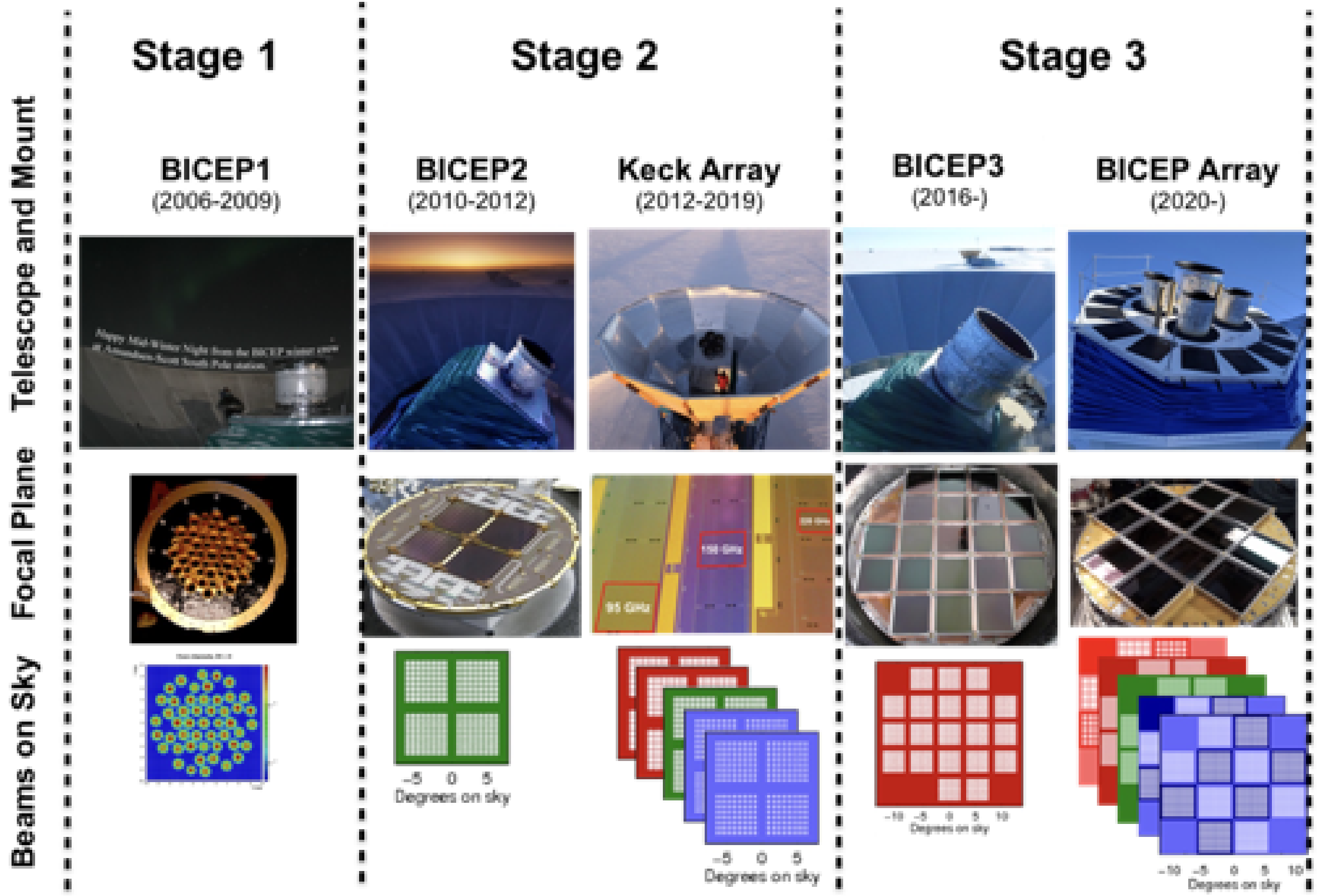
$$\text{energy} = 10^{16} \left(\frac{r}{0.01}\right)^{\frac{1}{4}} \text{GeV}$$

- 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"

Specialized B-mode machines: Small Aperture Telescopes

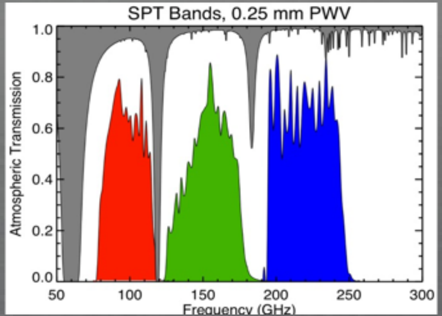


BICEP/Keck Collaboration
~60 scientists (at least half postdocs and students)

Funded By:

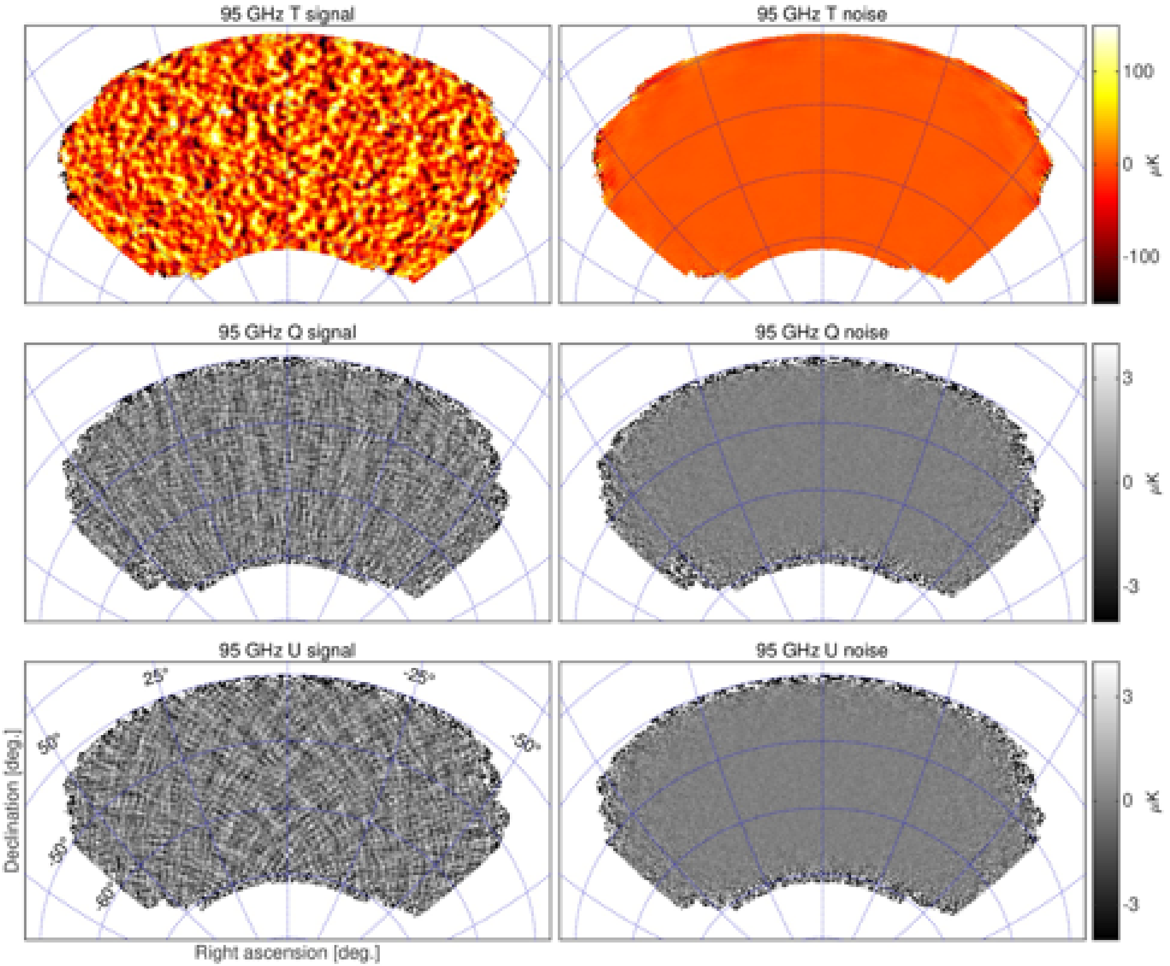
South Pole Environment

- **High Altitude (~10,000 ft)**
- **Extremely Dry**
  - water vapor in winter is ~4x less than Chile, ~6x less than Hawaii
- **Stable Atmosphere**
  - During 6-month night, the sky is ~30-100x more stable than in Chile



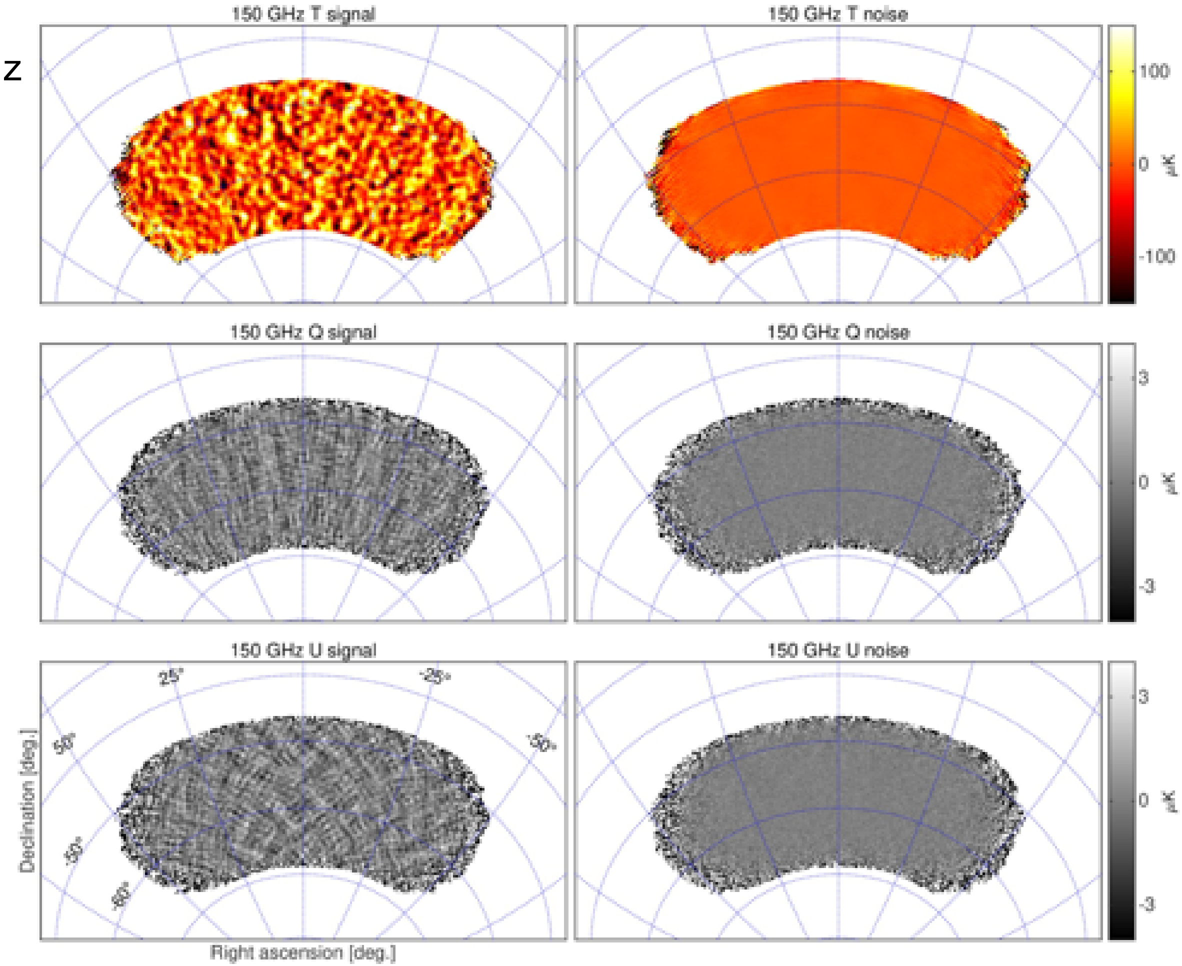
“Relentless Observing”

95GHz Maps



BK18: arxiv/2110.00483

150GHz Maps



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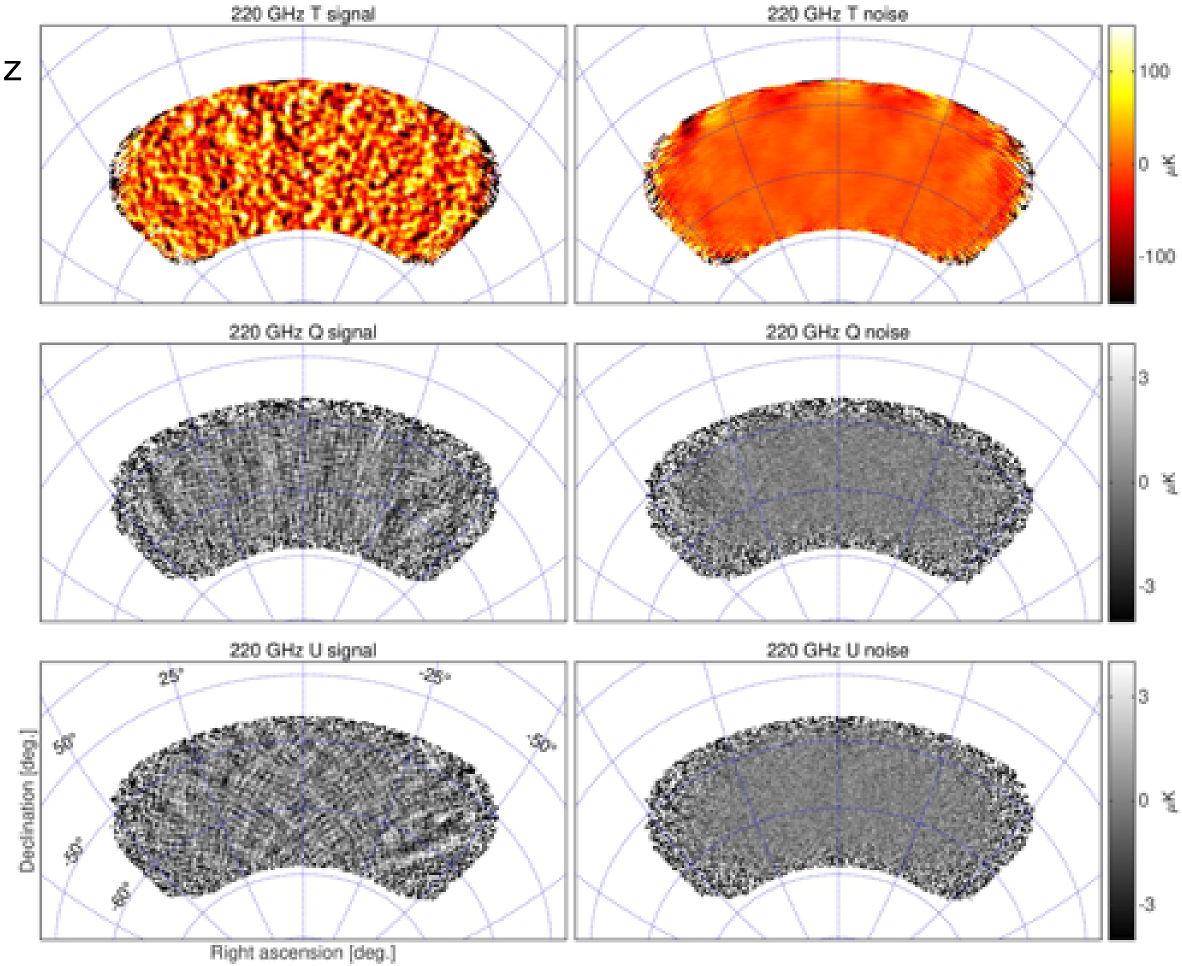
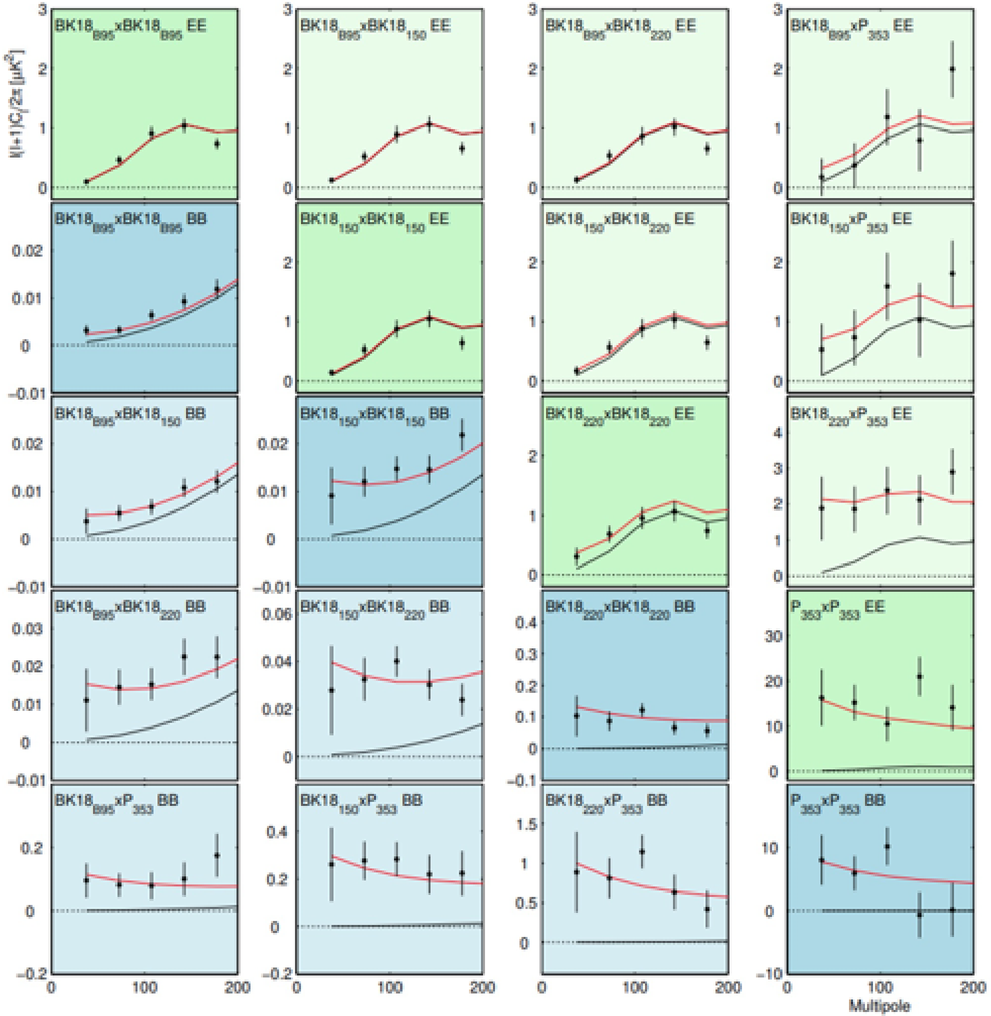
220GHz
Maps



BK18: arxiv/2110.00483

BK18 auto/cross spectra between: BICEP3 95GHz, BICEP2/Keck 150GHz, Keck 220GHz, and Planck 353GHz



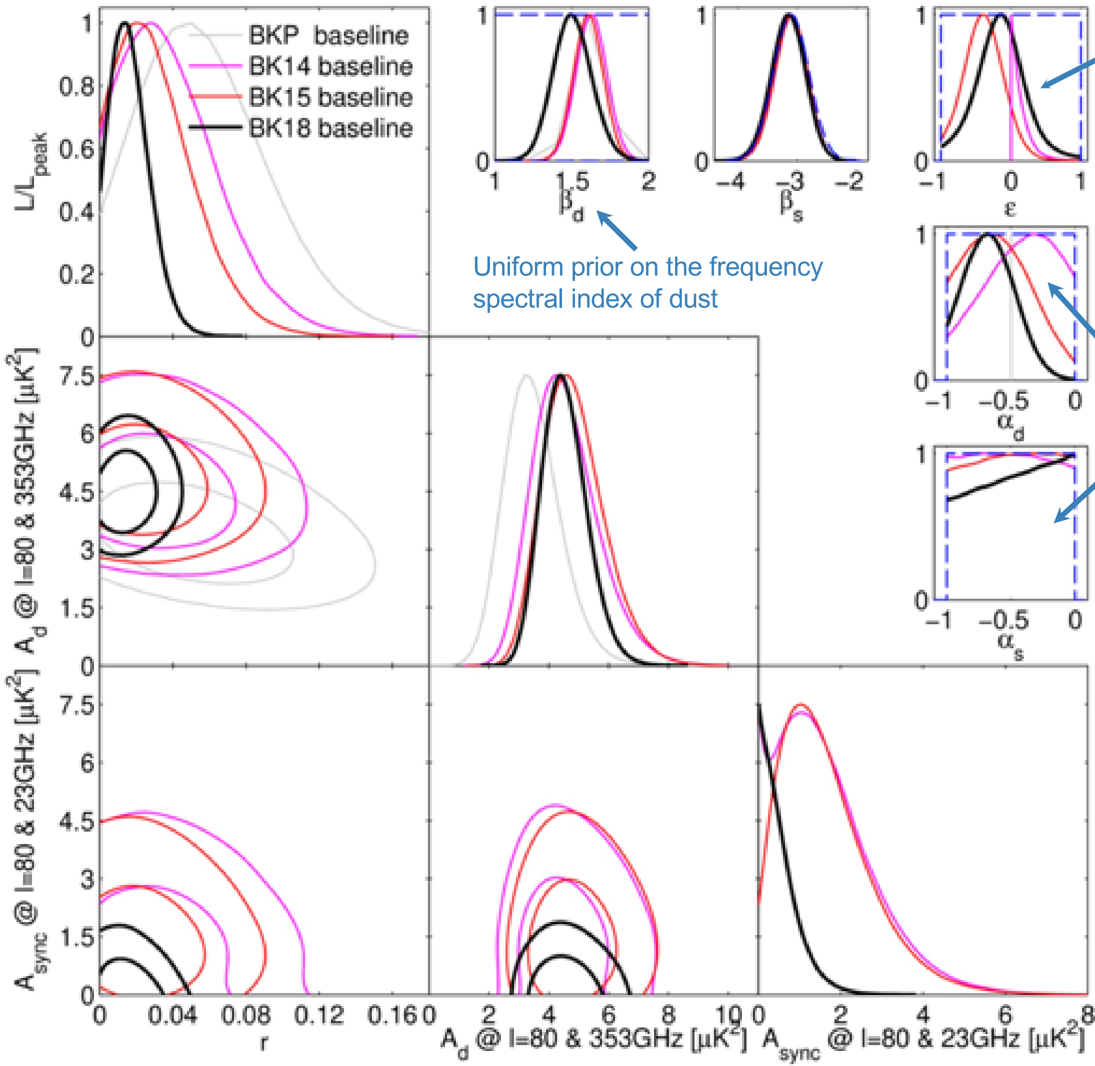
Green panels are EE spectra

Black lines are LCDM

Red lines are LCDM+foreground

Blue panels are BB spectra

BK18: arxiv/2110.00483



Allow dust/sync correlation in [-1,1]

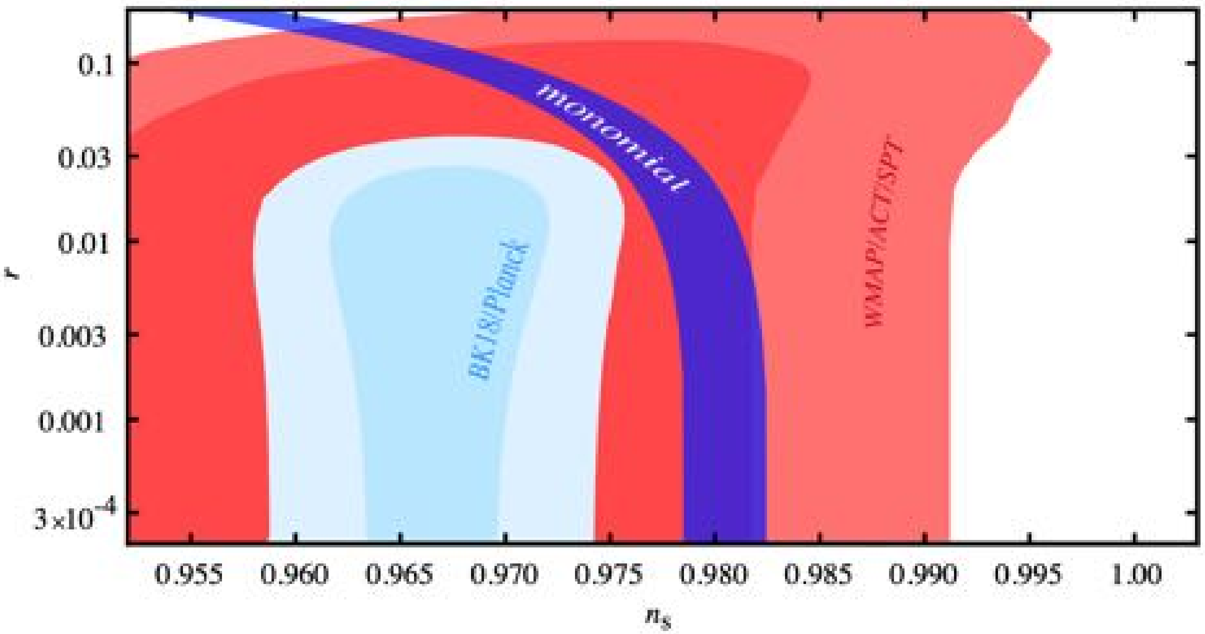
Uniform prior on the frequency spectral index of dust

Marginalize over generous ranges in spatial spectral indices

BK18: arxiv/2110.00483

Constraints on Inflation

Monomial models

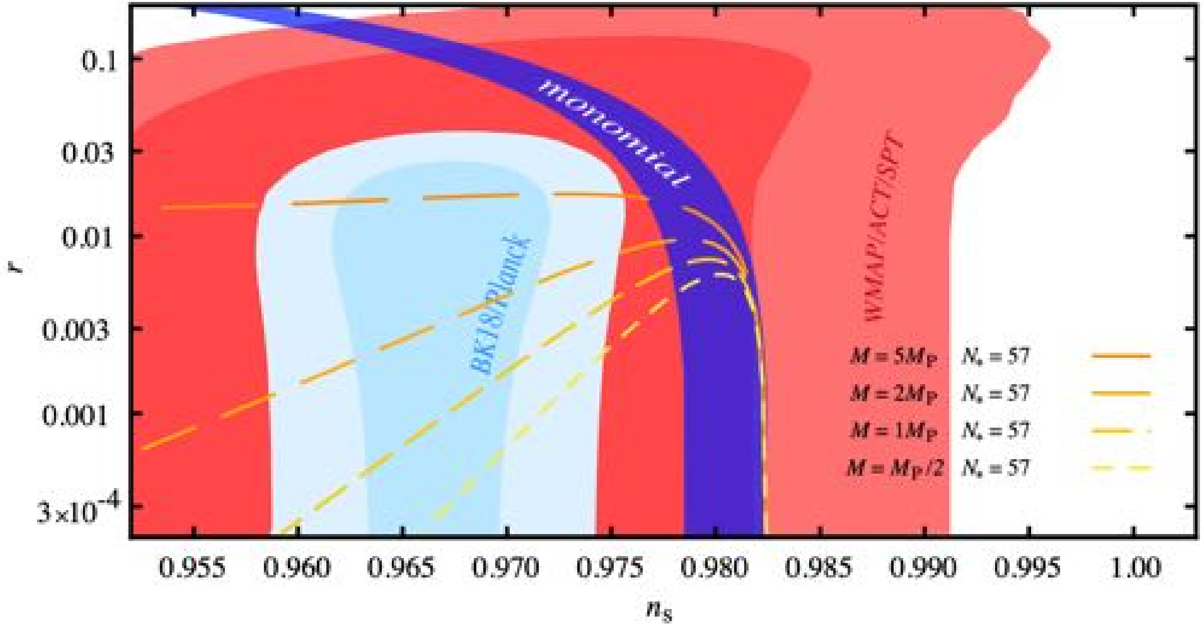


in their simplest form are essentially excluded by current data

Slide from Raphael Flauger (see also CMB-S4 Decadal Survey Report)

Constraints on Inflation

Plateau models for $M \approx M_P$



SFSR

Convex, Concave

Simple:

$$1 - n_s \simeq 2/N_*$$

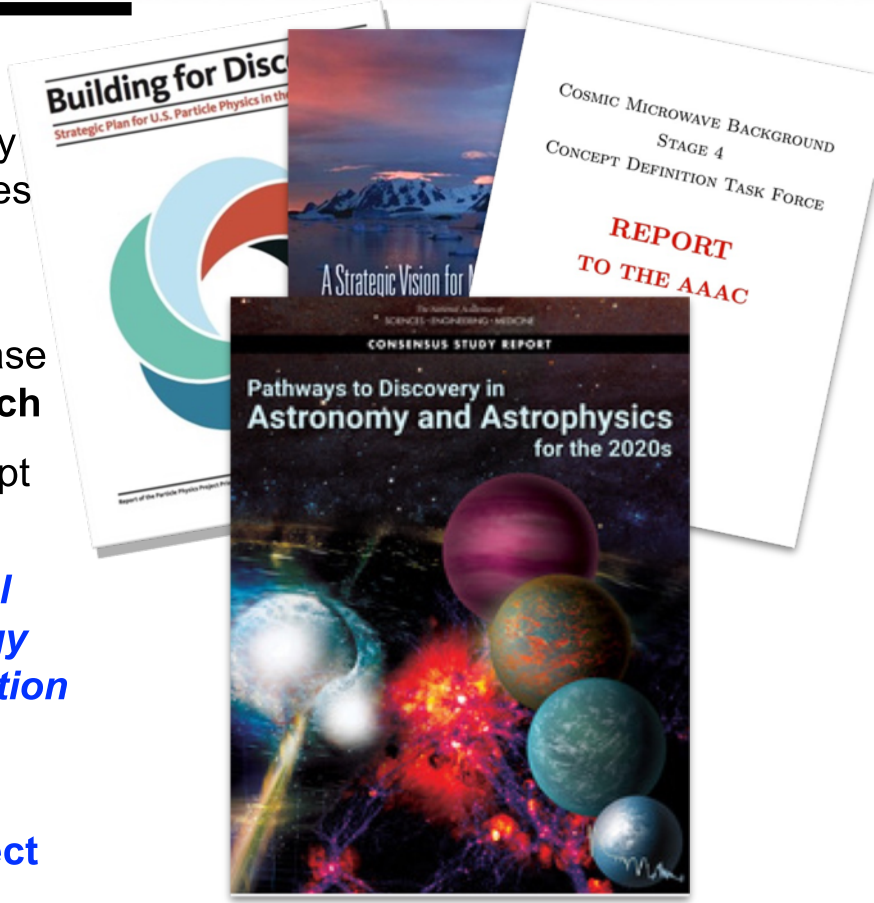
Super-Planckian

Interesting class of targets for CMB-S4

Slide from Raphael Flauger (see also CMB-S4 Decadal Survey Report)

which brings us to… CMB-S4

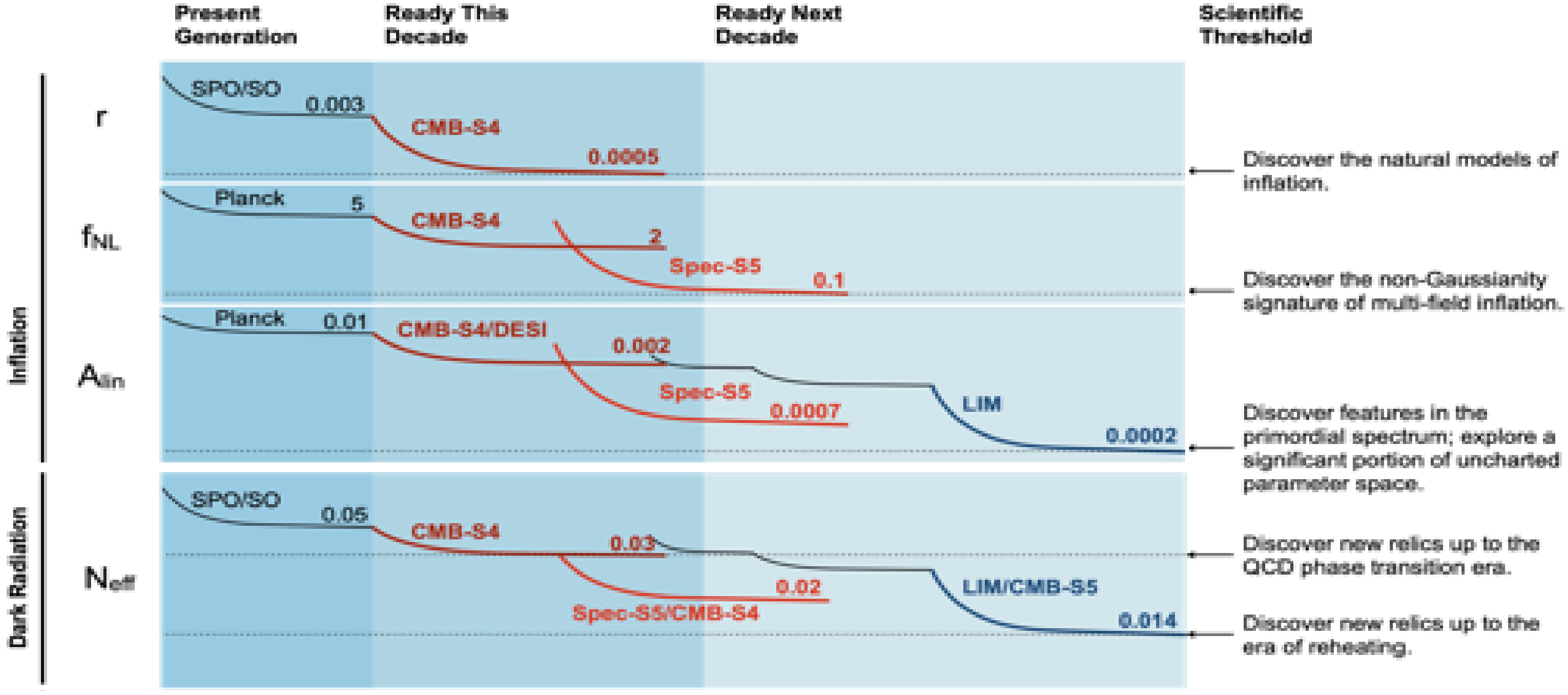
- 2013: In US **Snowmass** process, CMB community conceives CMB-S4 as definitive ground-based survey deliver transformative science with proven approaches
- 2014: **P5** recommended CMB-S4 under all budget scenarios
- 2015: NAS report recommended CMB-S4 science case as 1 of 3 strategic Investments for **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”**



CMB-S4 aims for transformative advances:

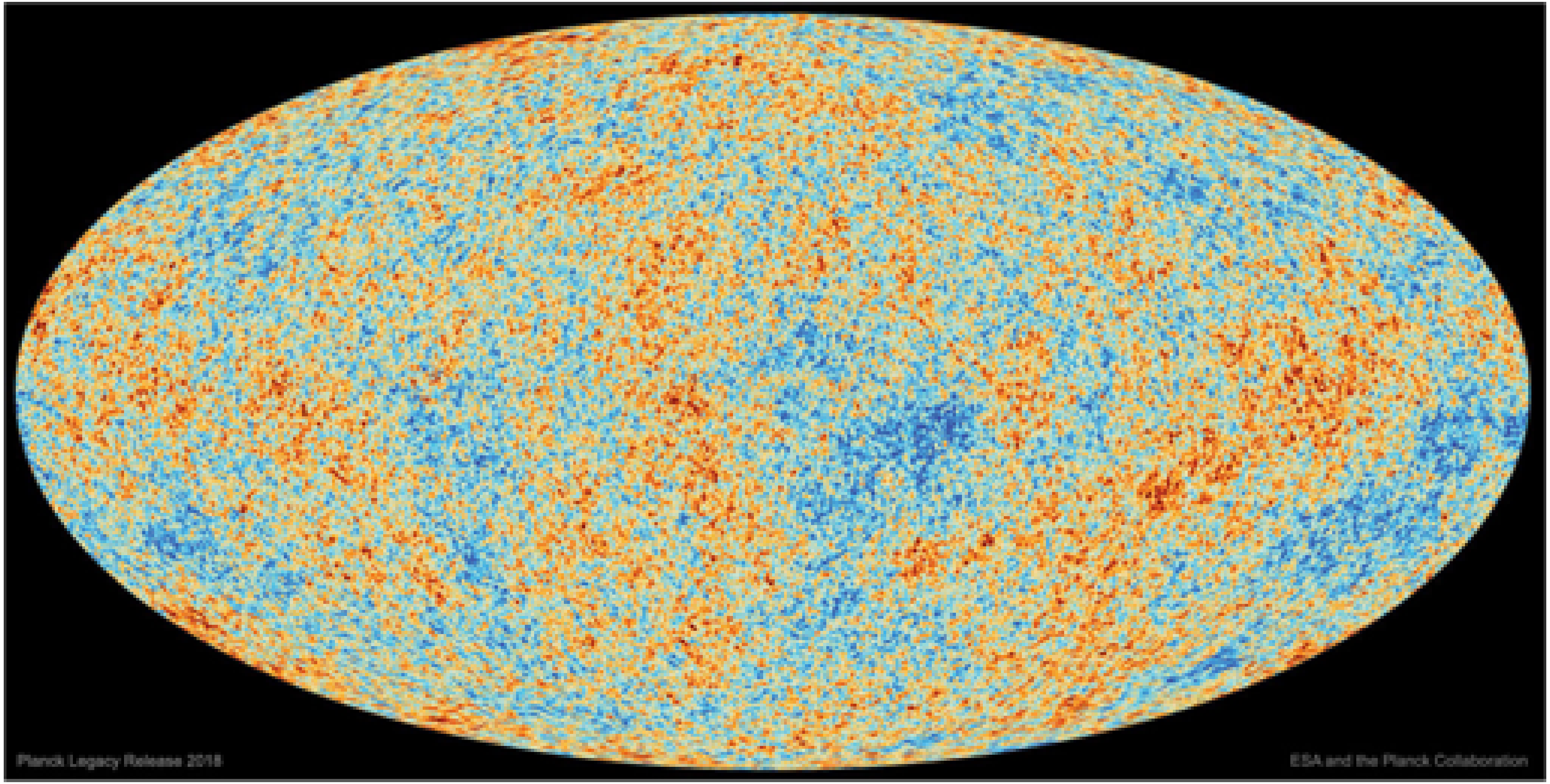
- CMB-S4 will cross critical thresholds in key cosmological parameters in the search for primordial gravitational waves and relic particles.
- CMB-S4 will provide unique astrophysical information, from the reionization of the Universe to the role of baryonic feedback in structure and galaxy formation. 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.

CMB-S4 Science Goals in 7-9 years

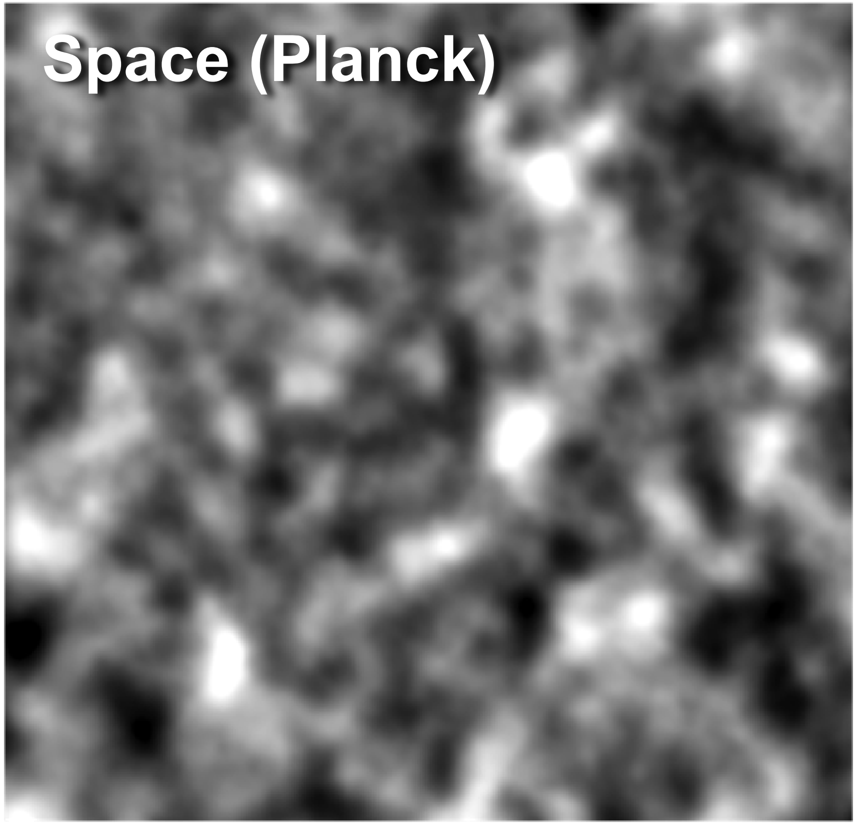


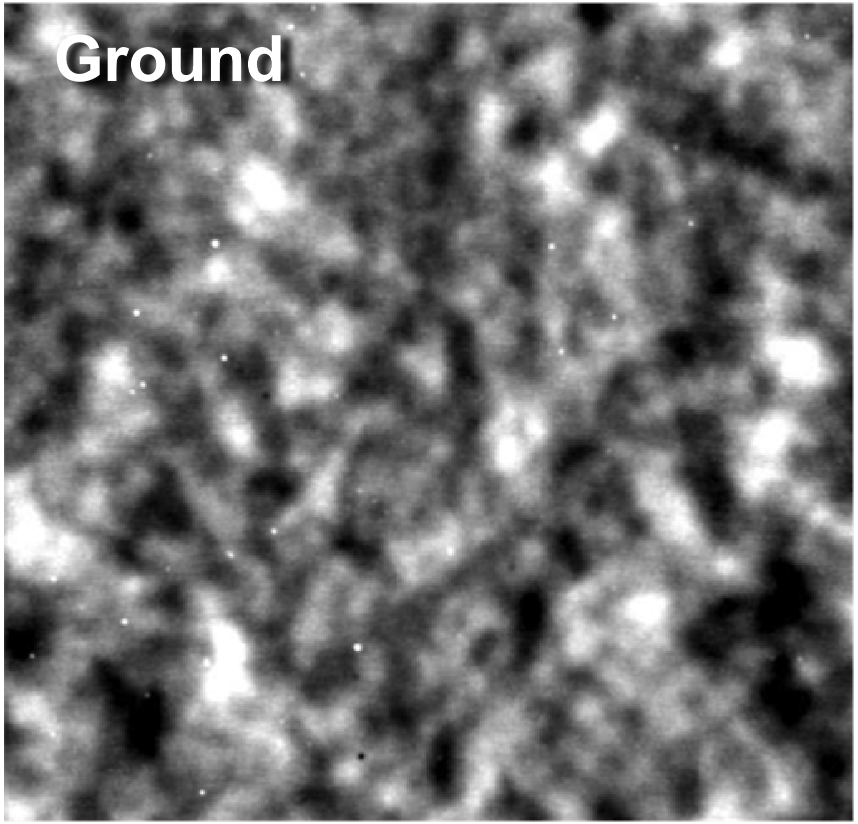
CMB-S4

Planck is amazing



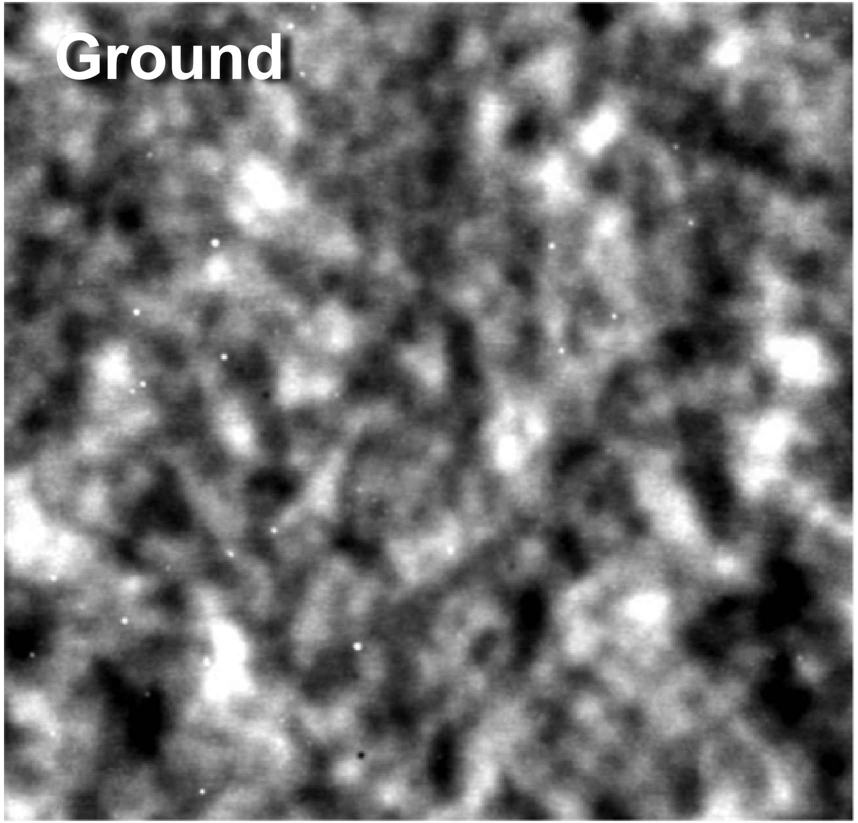
Transformative Discoveries Will Come From Ground-Based CMB Telescopes





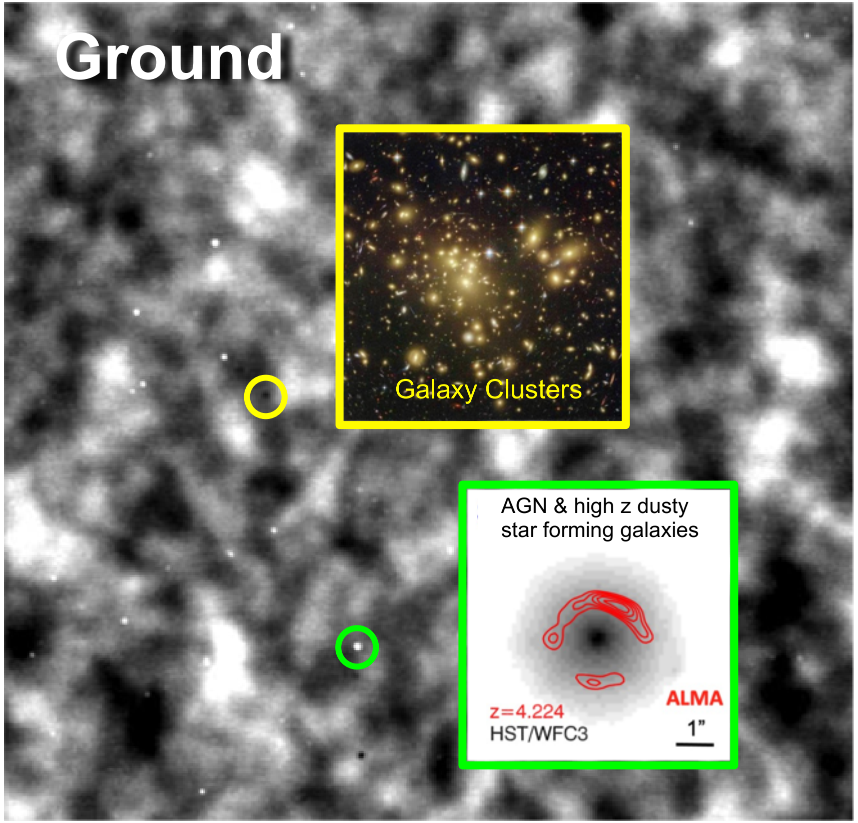
Ground-Based For Targeted Sensitivity And Angular Resolution

- 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



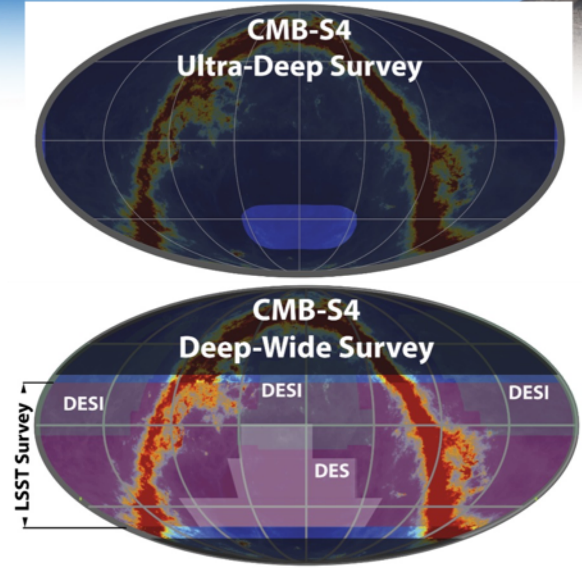
What does it take?

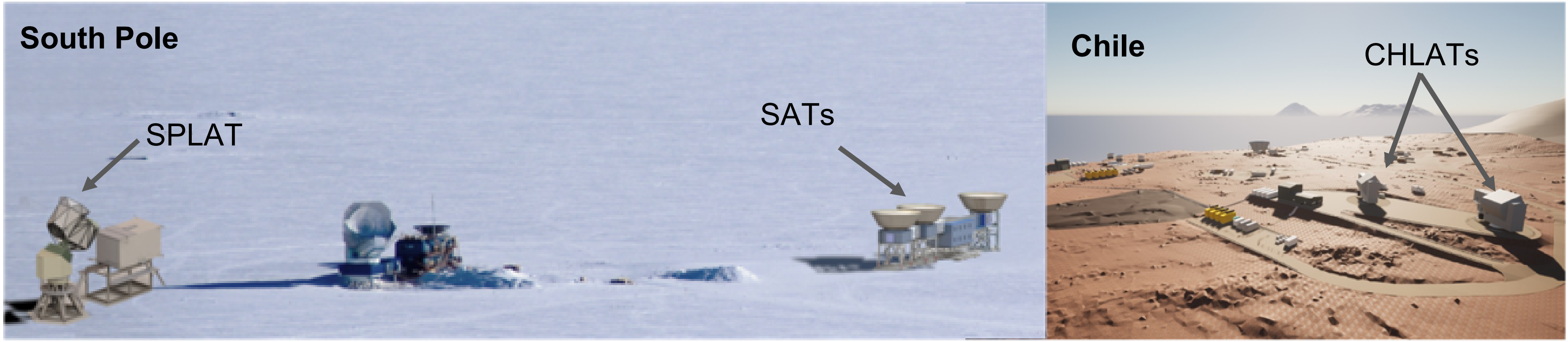
Ultra-Deep Survey from the South Pole and Deep-Wide Survey from Chile with arcmin angular resolution

7 frequency bands (20-300 GHz) for foreground subtraction

Uses mature technology successfully demonstrated in current experiments (ACT, Polar Bear, SPT, BK Array, etc ..)

Exceeds current generation by ~10x in channel count





CMB-S4 Science Themes, Goals and Requirements

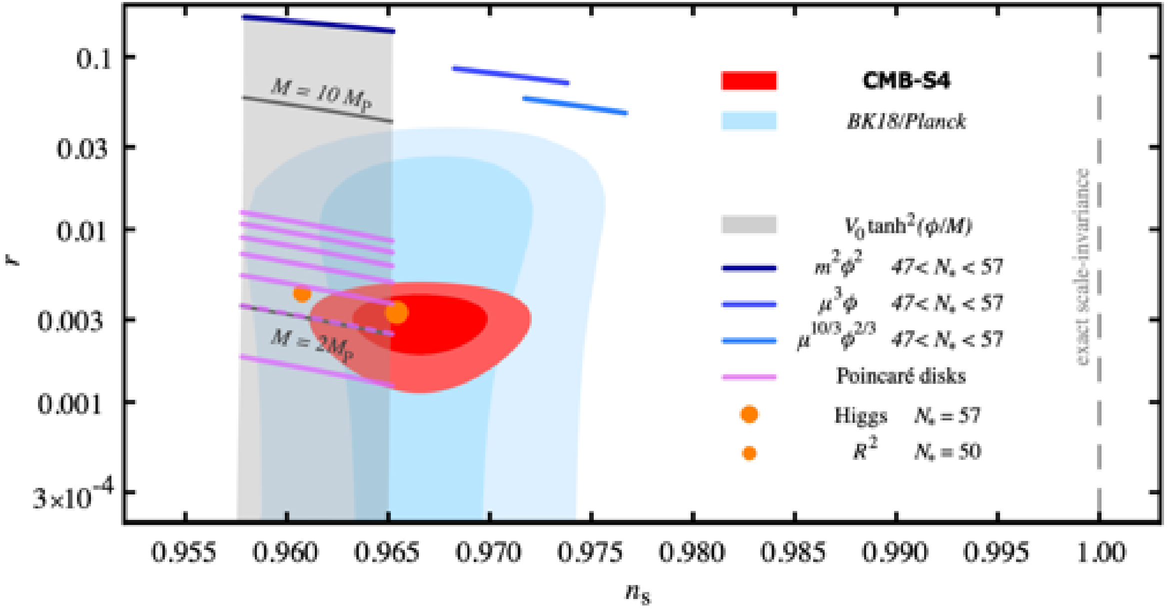
Organized into four Broad Science Themes

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.

See: CMB-S4 Science Case, Reference Design, and Project Plan, for input to Astro2020 (arXiv:1907.04473)

1. Inflationary B-modes



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.

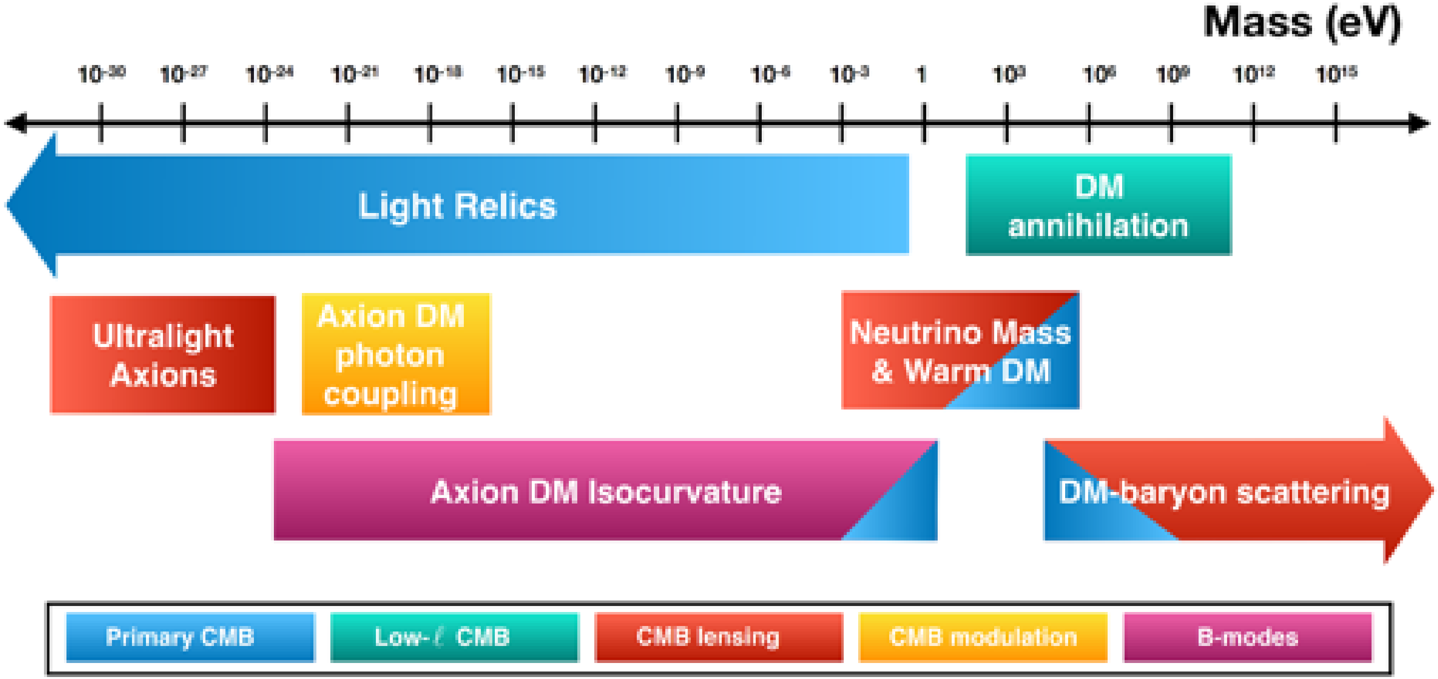
CMB-S4 sensitivity ensures that a non-detection of r would rule out the leading inflationary models, and motivate alternate models for the origin of the universe.

CMB-S4 Reqt:

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

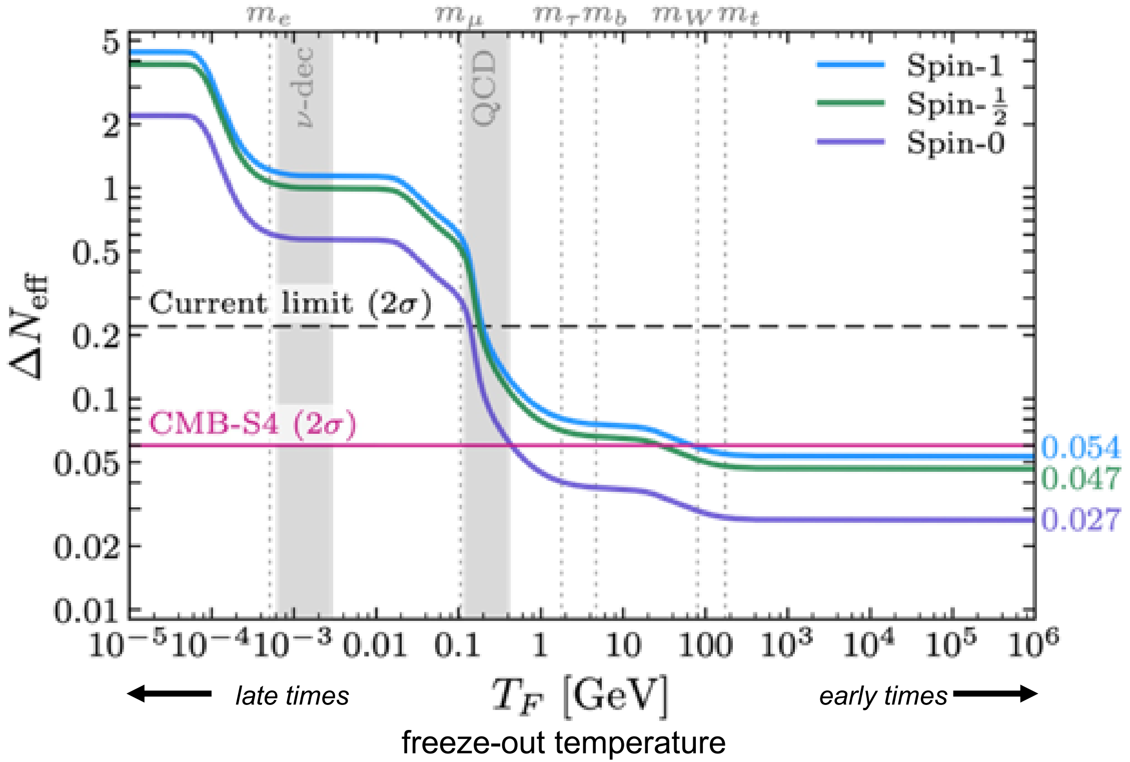
2. The Dark Universe

CMB Insights Into The Dark Universe Across The Mass Spectrum



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

2. Thermal history of the Universe and Light Relic Particles

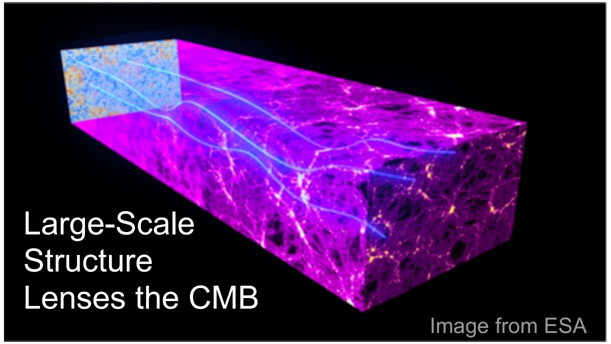


CMB-S4 will provide a precise measurement of the thermal history of the universe, a key test of cosmology.

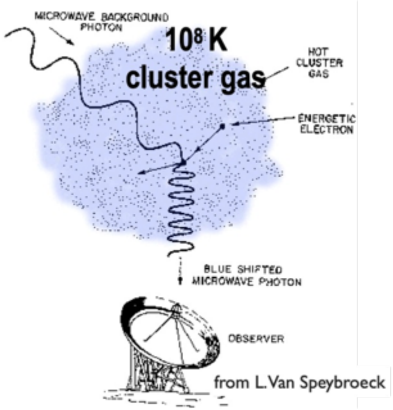
E.g., additional light particles that appear frequently in extensions to the standard model of particle physics will be constrained by CMB-S4.

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

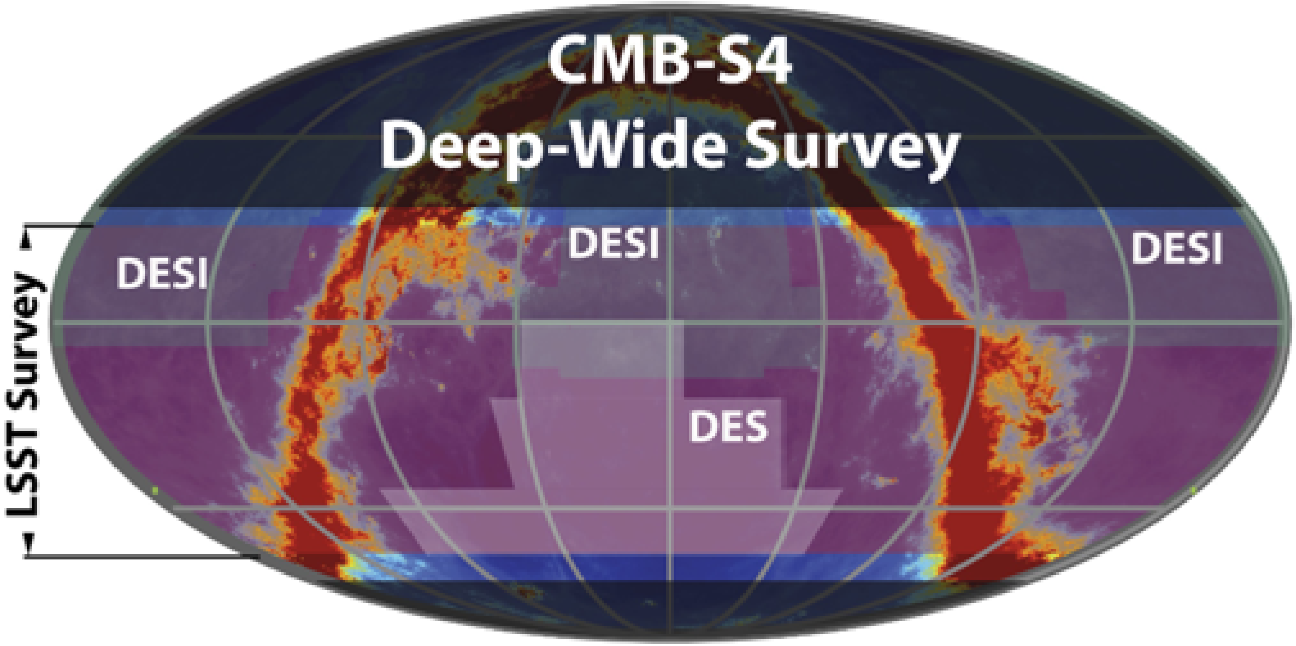
CMB-S4 will exploit these two effects—both caused by interactions between CMB photons and intervening structure—to:

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).

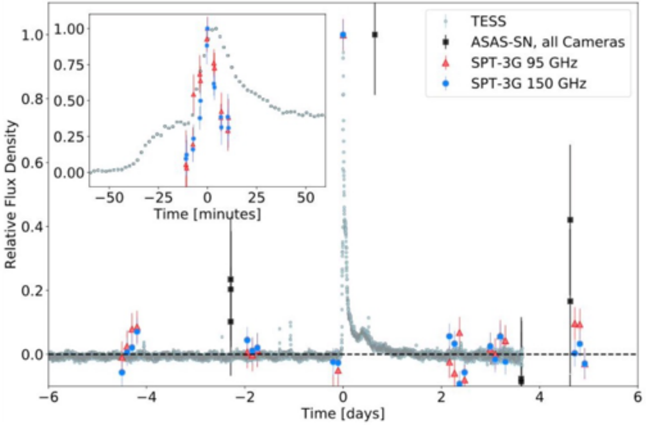
3. Mapping Matter in the Cosmos

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

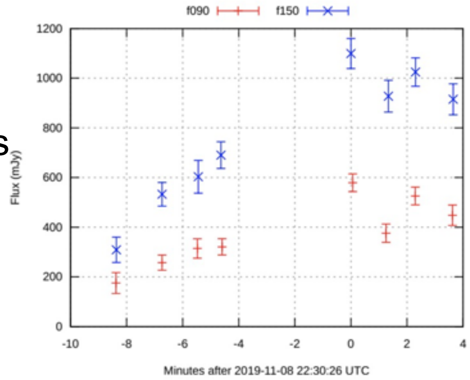


4. Transients in recent CMB data

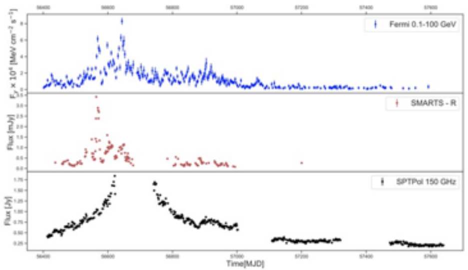


Guns et al. (2021, SPT-3G): 15 >10-sigma events from 10 independents sources, all associated either with a star or an AGN

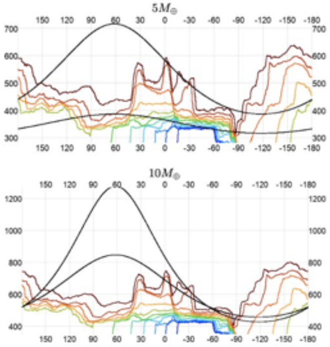
Naess et al. (2021, ACT): 3 >20-sigma events from 3 independent sources, all associated with a star



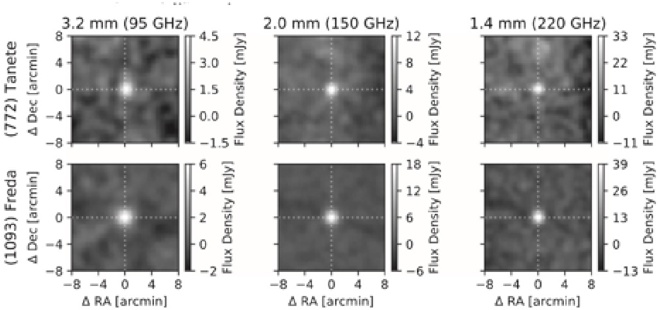
Other transient / variable / moving object science with CMB data:



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



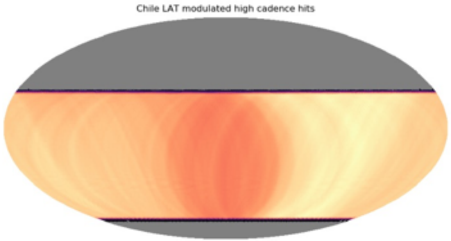
"Planet 9" searches (Naess+21)



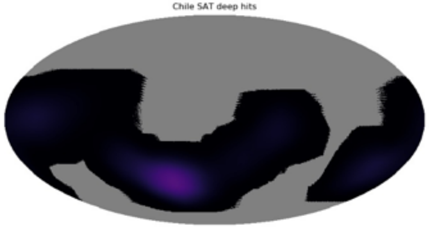
Asteroids (Chichura+22)

CMB-S4 Exploits The Unique Attributes Of Both Sites

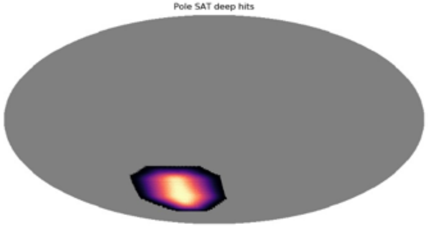
- Atmosphere above both sites has exceptional low water vapor, which is critical for CMB measurements
- The biggest difference between the sites is in the types of sky surveys their latitudes can support.
  - Wide-area surveys can only be performed from the Atacama.
  - Compact ultra-deep surveys can 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

A "Shout Out" to the Pan-Experiment Galactic Science Group

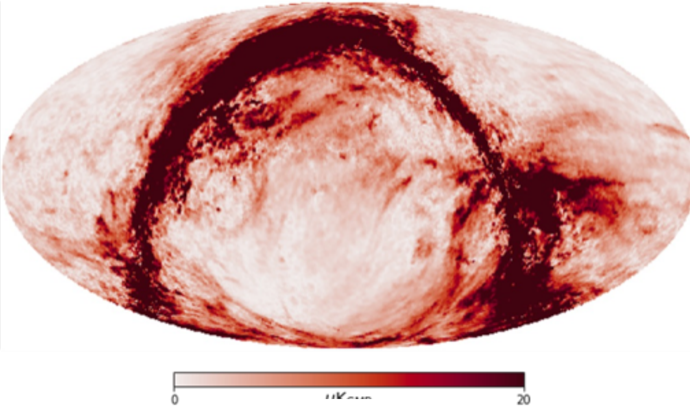
(a great way to get involved!)

- 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

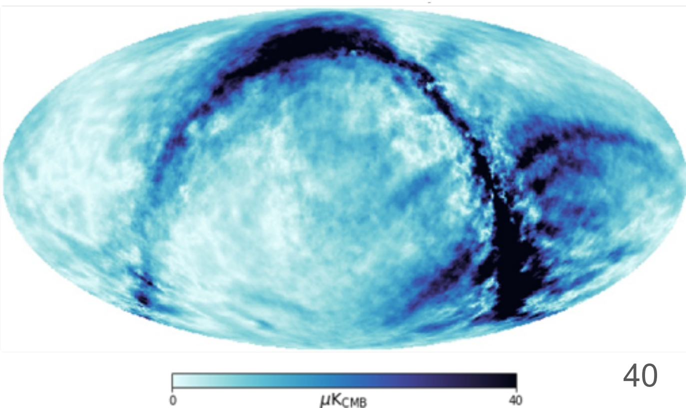
- Three sky models, all consistent with current data:
  - **Low Complexity:** Small-scale fluctuations in amplitudes only, no decorrelation
  - **Best Estimate:** Parameter maps based on component separation with extrapolation to small scales in both amplitudes and spectral parameters
  - **High Complexity:**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

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

353 GHz P



30 GHz P



Summary

- CMB experiments offer spectacular, transformative science, including the opportunity to investigate the origin of the universe by making a definitive measurement of primordial gravitational waves predicted by Inflation.
- Stage 3 efforts—including South Pole Observatory (BICEP/Keck+SPT) and in Chile (ACT, Simons Observatory and CLASS) are paving the way
- LiteBIRD (due to launch end of this decade) and balloons offer complimentary measurements
- CMB-S4 will be the **definitive ground-based survey CMB-S4**

- **Opportunities for collaboration abound!**