Evaluation of P5 Report Execution Status
CMB-S4

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Project Director: Jim Yeck

on behalf of the CMB-S4 Collaboration

U.S. DEPARTMENT OF ENERGY

Outline

- CMB-S4 Science Goals, *Why CMB-S4?*
- Vision, Genesis, and Trajectory, *How did we get here?*
- Instrument Design, *What is CMB-S4?*
- Science Collaboration and Integrated Project Office, *Who are we?*
- Status and Project Plan

Why CMB-S4? To make transformational advances

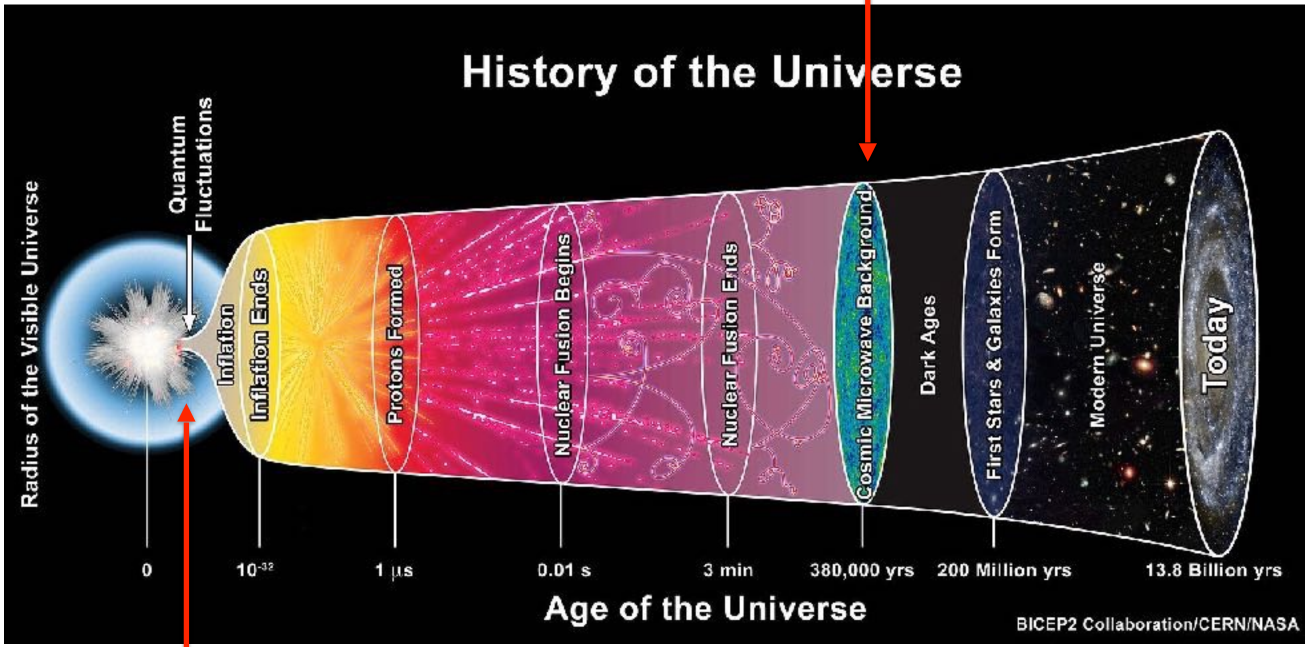
- CMB-S4 is designed to cross critical thresholds in key cosmological parameters in the search for **primordial gravitational waves** and **relic particles**. These goals drive the experimental design and cannot be met with any precursor experiments.

- CMB-S4 instrument and survey strategy are designed to be an extremely powerful complement to other cosmological surveys—breaking degeneracies and increasing sensitivity —to investigate **neutrino properties**, **dark energy**, and **dark matter** through measuring the growth of structure in the universe.

- CMB-S4 will provide unique astrophysical information in areas ranging from the **reionization** of the Universe, to the role of **baryonic feedback** in structure and galaxy formation, and by opening up the mm-wave transient universe for **Multi-Messenger Astrophysics**.

Why CMB-S4? To make transformational advances

CMB released at 380,000 years



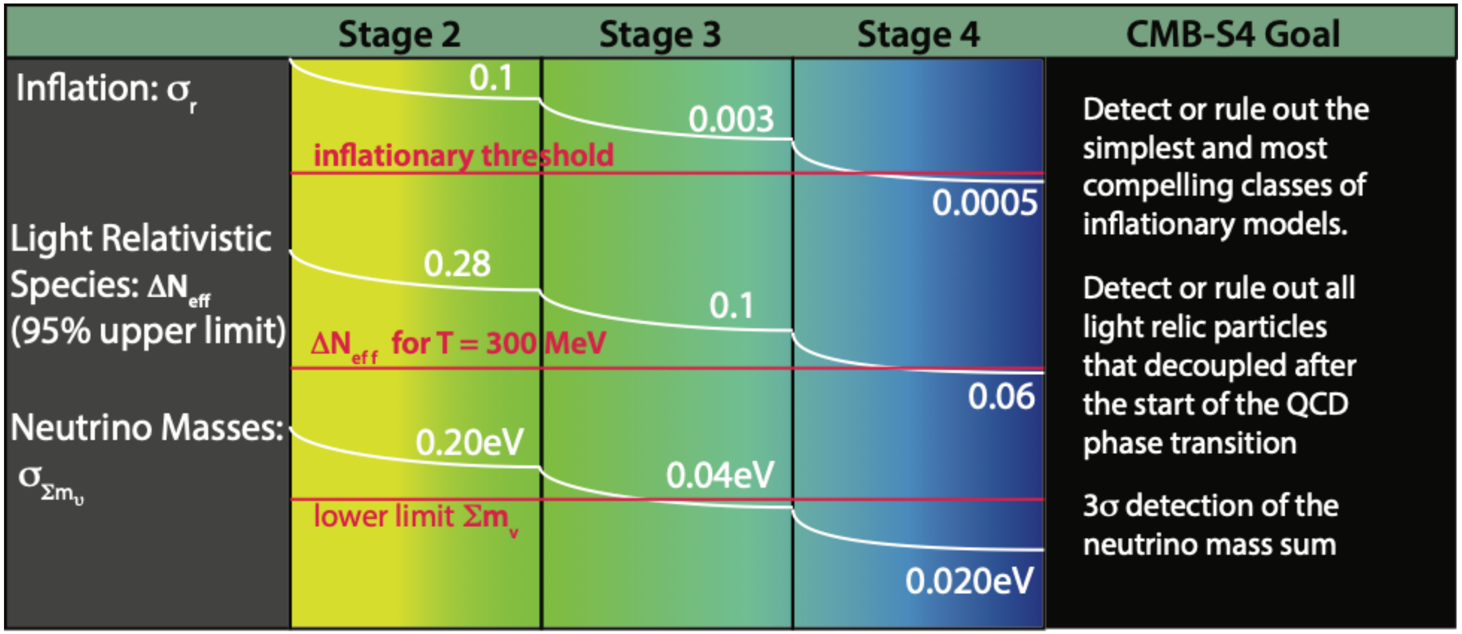
CMB provides backlight to probe all matter in the universe and the growth of structure.

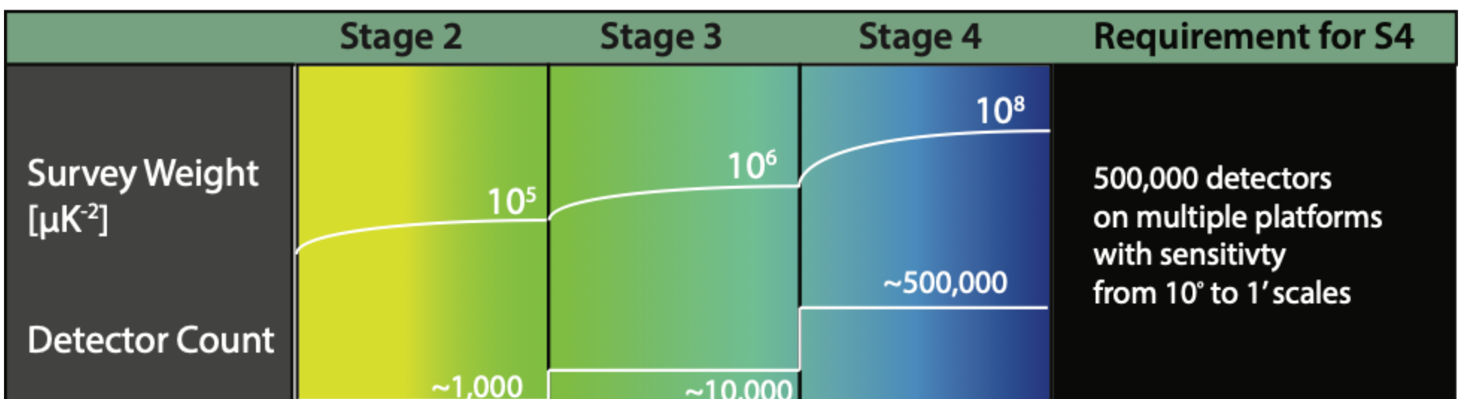
Gravitational waves generated by Inflation will induce unique B mode CMB polarization

Energy scale of inflation; quantum gravity

CMB provides measure of all contributions to the energy density of the Universe, independent of particle interaction cross sections

Why CMB-S4? To make transformational advances





CMB-S4: Vision and Genesis

Genesis with the 2013 Snowmass Physics planning exercise

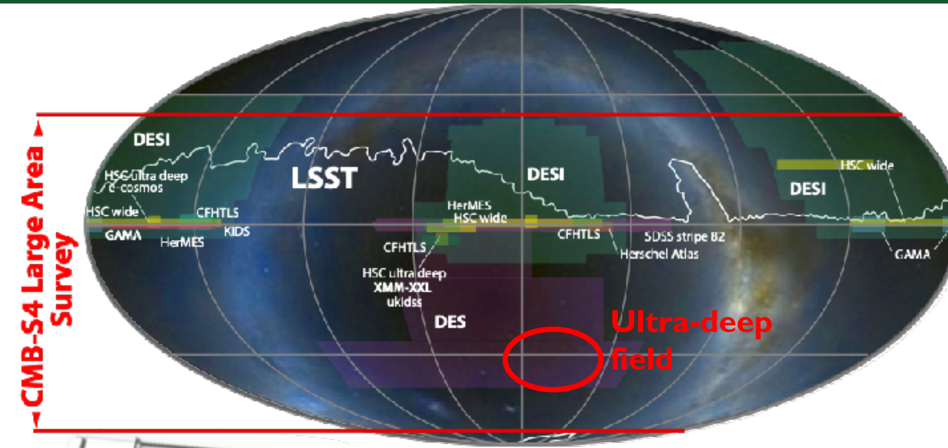
The CMB community advocated CMB-S4 -- a single, multiagency, ground-based experiment to obtain sufficient sensitivity to achieve unique and fundamental science goals.

The technology had matured sufficiently to design the definitive, ground based CMB experiment. The challenge is in scaling up to unprecedented levels.

CMB-S4 Design in a nutshell
Nested deep-wide and ultra-deep-narrow surveys

- **Deep wide N_{eff} and Legacy Survey** with 2 x 6m telescopes targeting ~60% of sky with 240,000 detectors over 6 bands.
  Conducted from Chile over 7 yrs.

- **Ultra-deep "r" survey** with 18 x 0.55m small refractor telescopes targeting ≥ 3% of sky with 150,000 detectors over 8 bands and a dedicated de-lensing 6m telescope with 120,000 detectors.
  Nominally from South Pole over 7 yrs

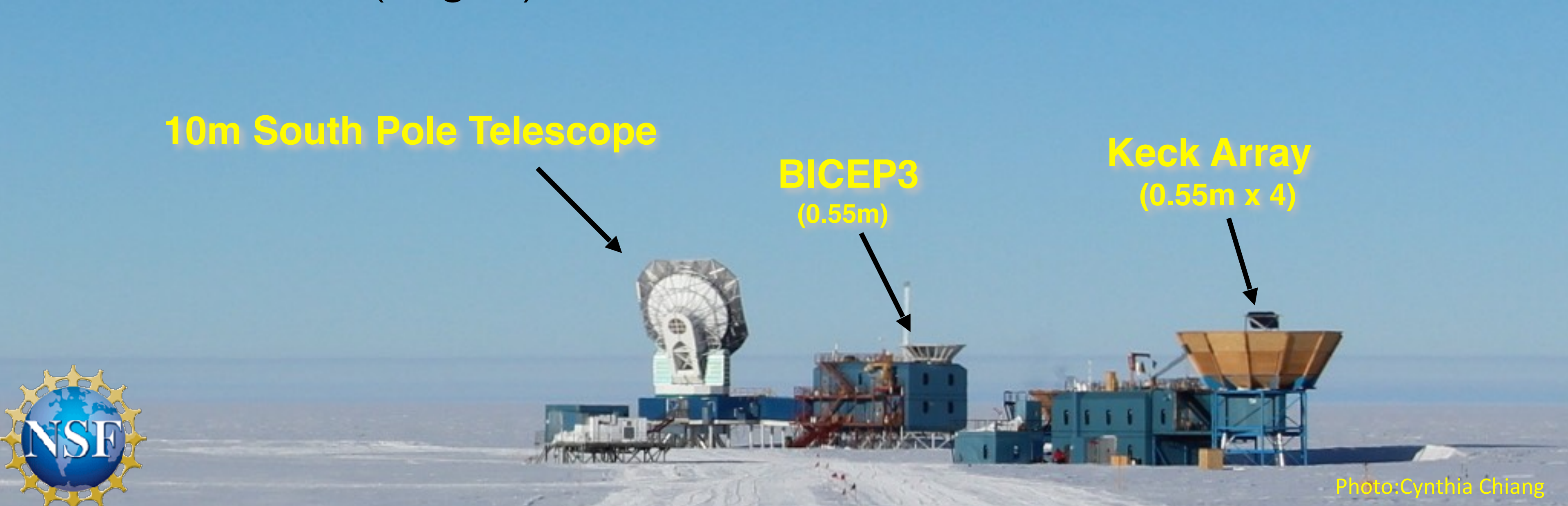


6m large telescopes,
e.g., like Simons Obs.

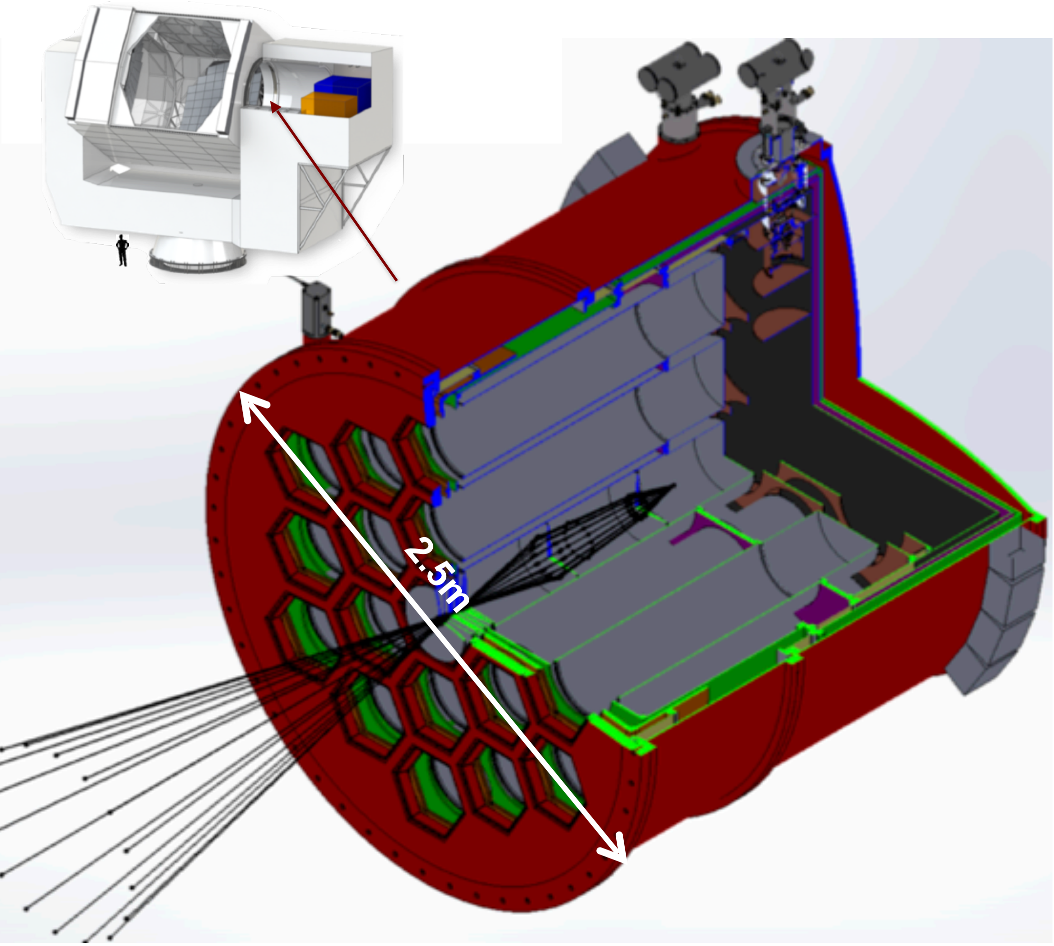
18 x 0.55m small
telescopes (3 per cryostat),
e.g., like BICEP Array

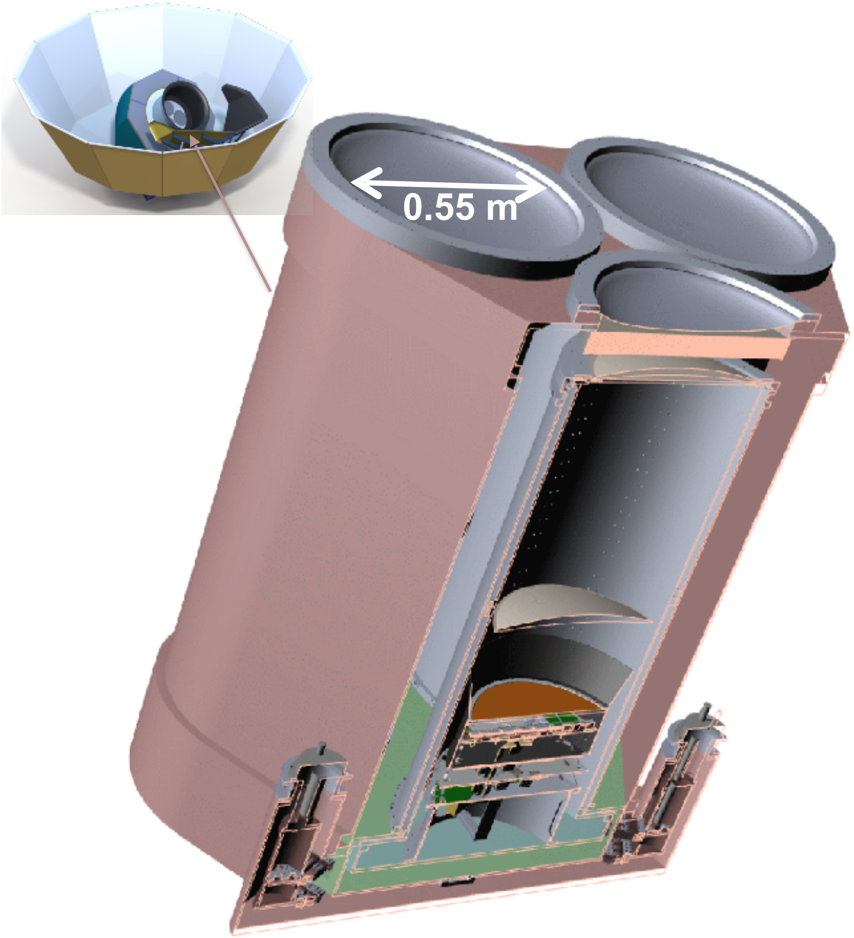
Atacama CMB (Stage 3)

South Pole CMB (Stage 3)



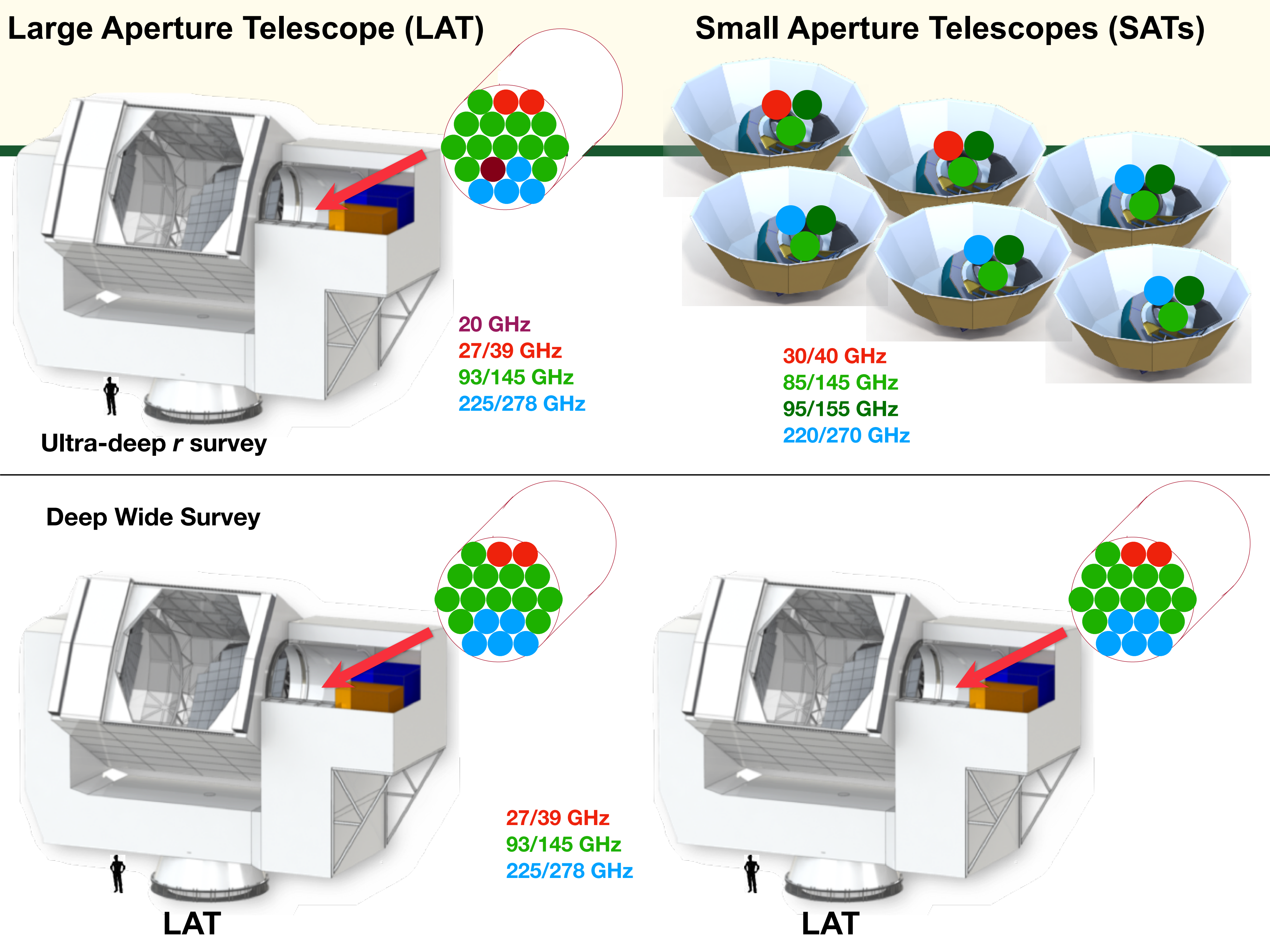
A lot of detectors, a lot of data, large cryogenics, unprecedented precision required…



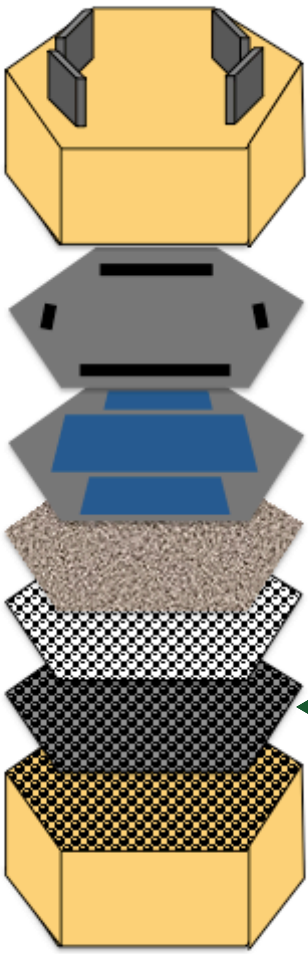


LAT cryostat
19 optics tubes
(each tube is dichroic, except 20GHz)

SAT cryostat
3 optics tubes
(each tube is dichroic)


Large Aperture Telescope (LAT)
Small Aperture Telescopes (SATs)
20 GHz
27/39 GHz
93/145 GHz
225/278 GHz
30/40 GHz
85/145 GHz
95/155 GHz
220/270 GHz
Ultra-deep r survey
Deep Wide Survey
27/39 GHz
93/145 GHz
225/278 GHz
LAT
LAT

Detector wafers and modules



Back plate. Houses connectors. Feeds flex cables to IO wafer. Mechanical assembly and EMI shielding.

Input/Output (IO) wafer. Routes Input/Output lines.

Detector Interface (DI) wafer(Nyquist inductors, shunt resistors) w. mux chip

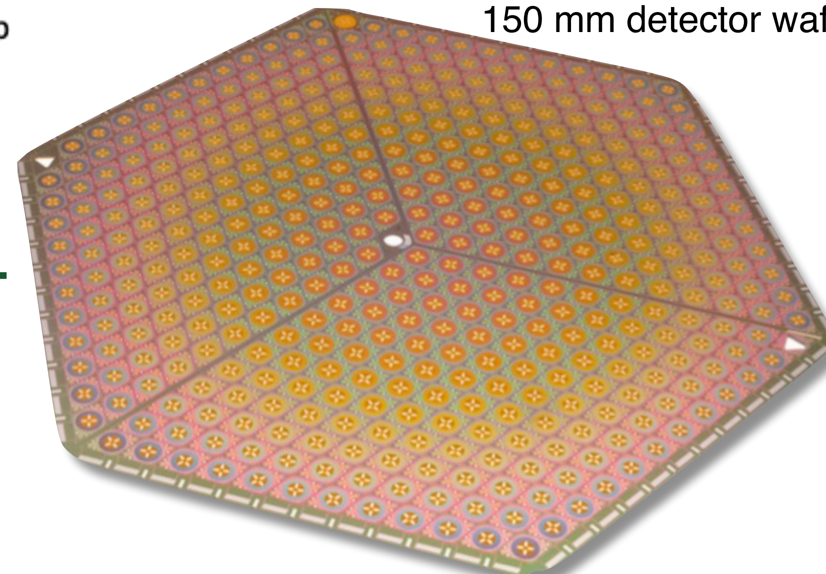
Backshort wave plate w/ A4K shield.

Backshort wave guide.

Detector wafer.

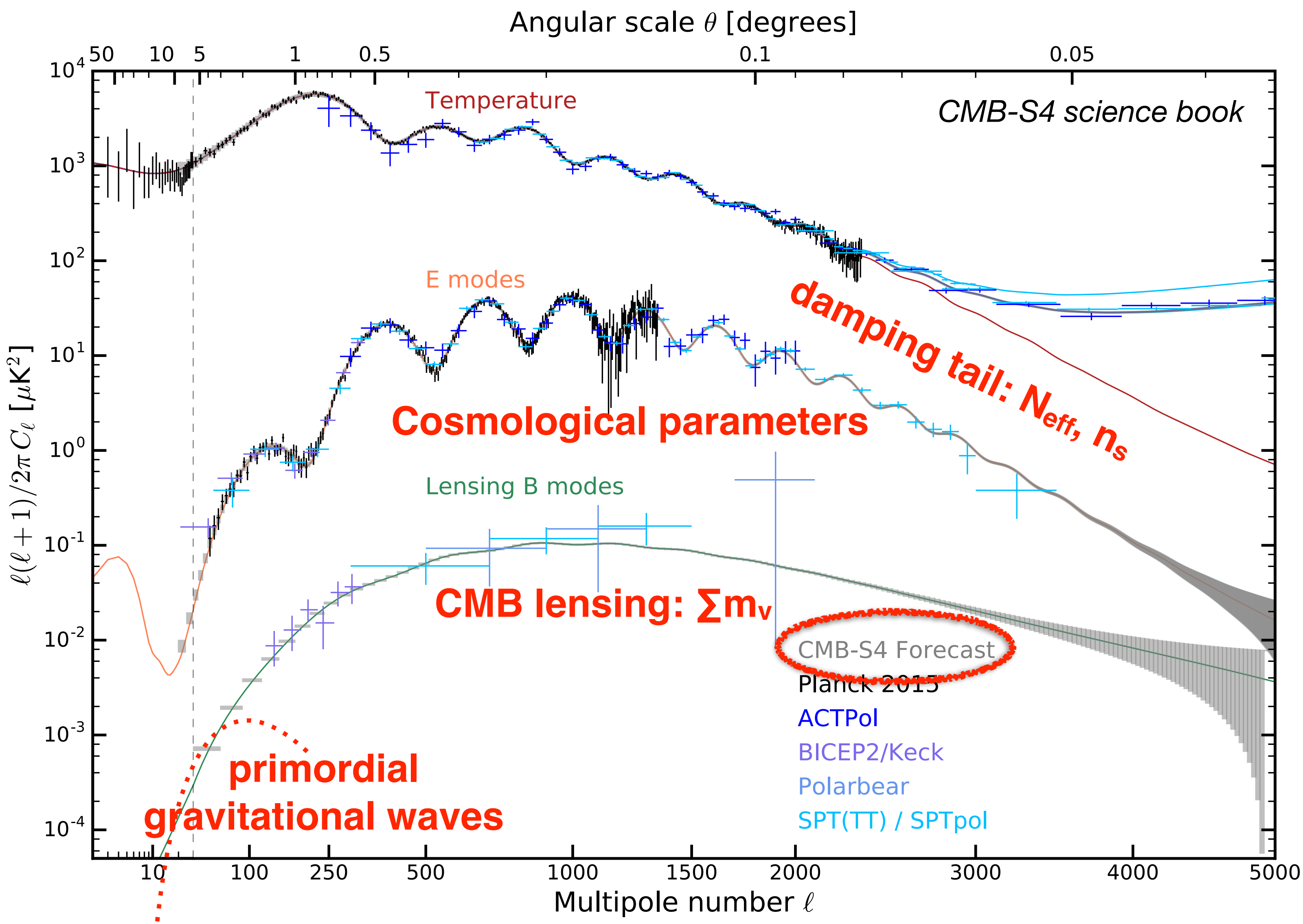
Feedhorn array. Includes mechanical mounting flange/feet.

150 mm detector wafer



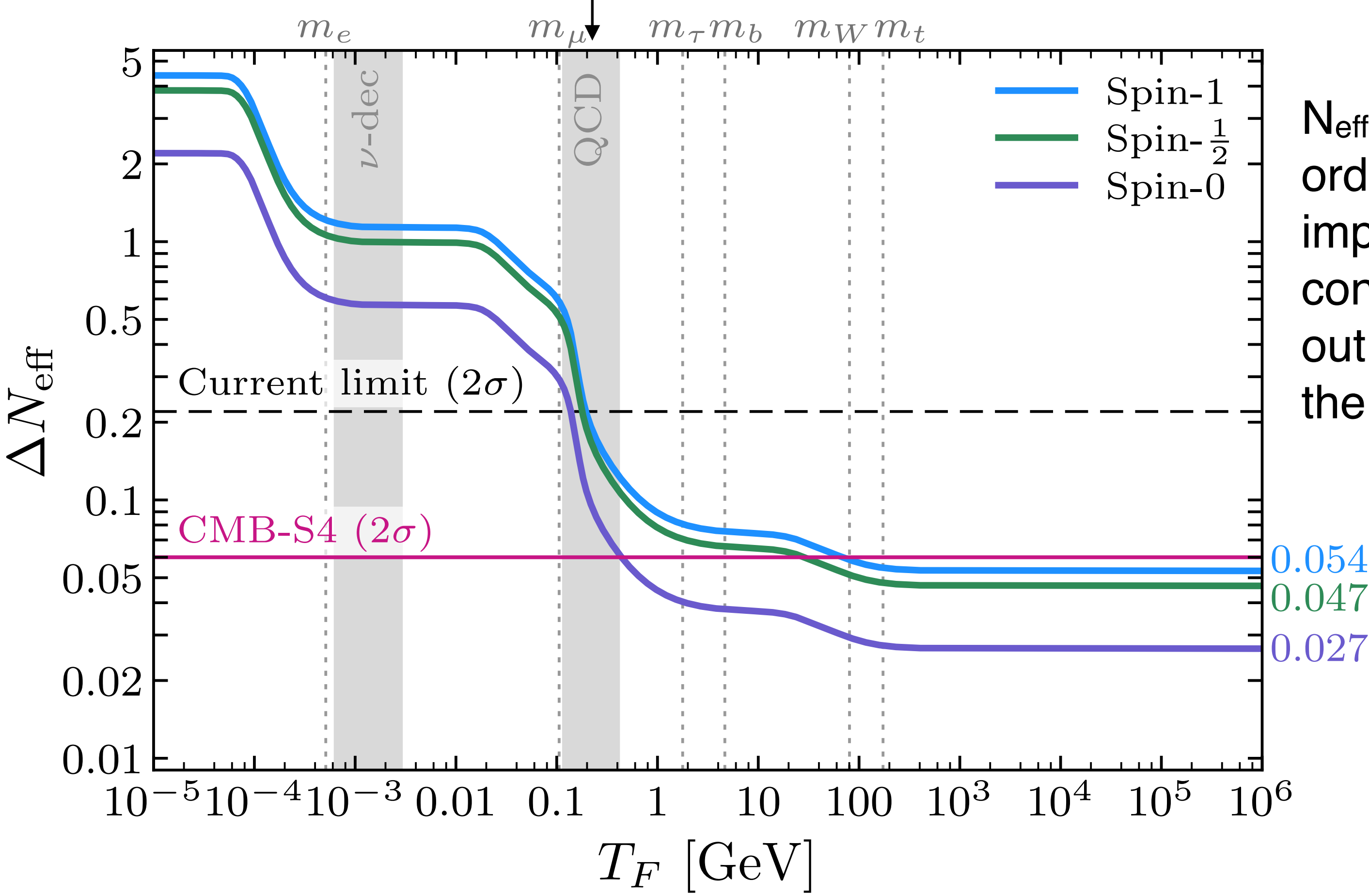
CMB-S4 requires 500 science grade detector wafers

CMB-S4 power spectra



CMB-S4: Light Relics, N_{eff}

QCD phase transition

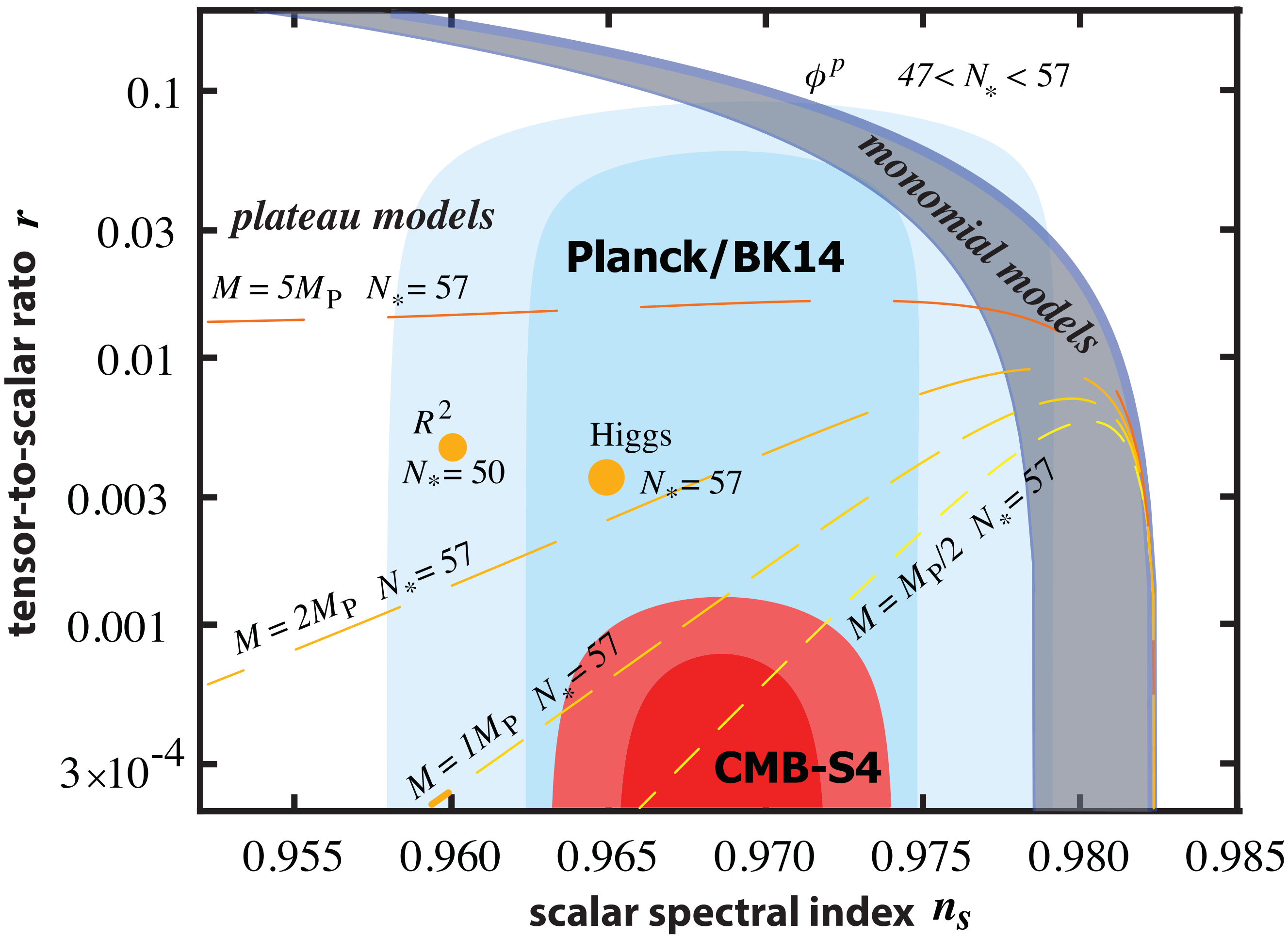


freeze-out temperature

← *late times* *early times* →

N_{eff} constraint leads to orders of magnitude improvement of constraint on the freeze-out temperature of any thermal relic

CMB-S4: Inflationary constraints



CMB-S4 will detect or exclude models that naturally explain the observed value of n_s

Detection of r would give the energy scale of inflation, provide evidence for the quantization of gravity, and fundamental insights into physics and cosmology

CMB-S4: Trajectory

- 2014: Recommended by Particle Physics Project Prioritization Panel (P5); CMB-S4 project phasing in as LSST phases out.
- 2015: NAS/NRC report calls out CMB-S4 as a strategic priority for Antarctic Science
- 2017 DOE & NSF sponsored CMB-S4 Concept Definition Task Force (CDT report) enthusiastically accepted by AAAC
- 2018 *Official* Collaboration established and elections held
- 2018 Integrated Project Office (IPO) started

* AAAC: Astronomy and Astrophysics Advisory Committee, FACA cmt advises NSF, DOE and NASA

Recent progress and next goal

- *CMB-S4 Science Case, Reference Design, and Project Plan* (aka Decadal Survey Report, 282 pages) posted July 9, 2019
- CMB-S4 Decadal Input White Paper submitted July 10, 2019 and detailed RFI response submitted Nov 8th, 2019
- CMB-S4 project established:
  - **Achieved DOE Critical Decision CD-0 for a Major Item of Equipment (MIE) project on July 26, 2019**
  - **Awarded NSF MSRI-RI Design and Development grant to help get on the Major Research Equipment & Facilities Construction (MREFC) track, started Oct 1, 2019**
- Next goal:
  - **Advance from Reference Design to Baseline Design for DOE CD-1 and NSF PD, targeting April 2021**
  - **Transition to Permanent Integrated Project Organization**
    - U. Chicago is Host for NSF MREFC preparation
    - DOE “Host/Lead Lab” is required, planned for March 2020

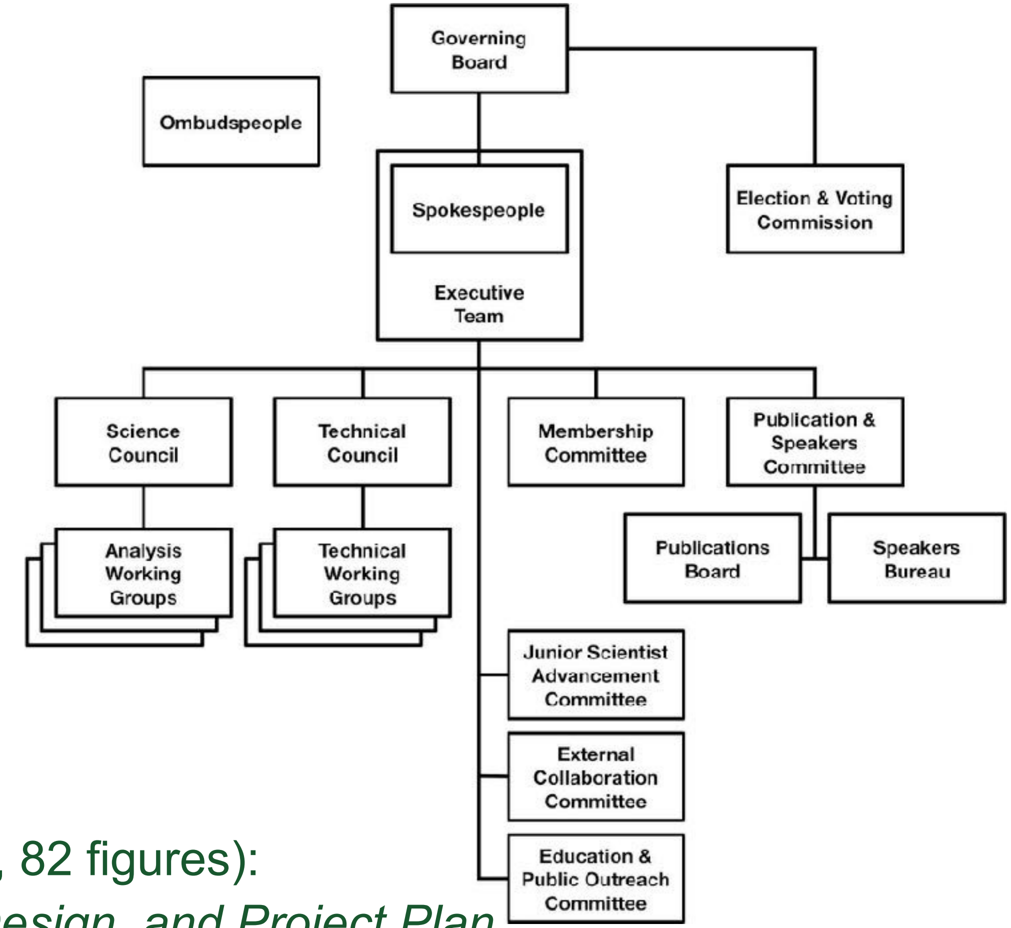
CMB–S4 Collaboration

10th CMB-S4 Workshop, UCSD October 2019

- CMB-S4 twice a year major workshops since 2015
- CMB-S4 working groups have advanced the Science case and Technology areas; see wiki on cmb-s4.org
- Technical groups integrated with the Integrated Project Office (IPO)
- Dedicated community; a lot of contributed effort.

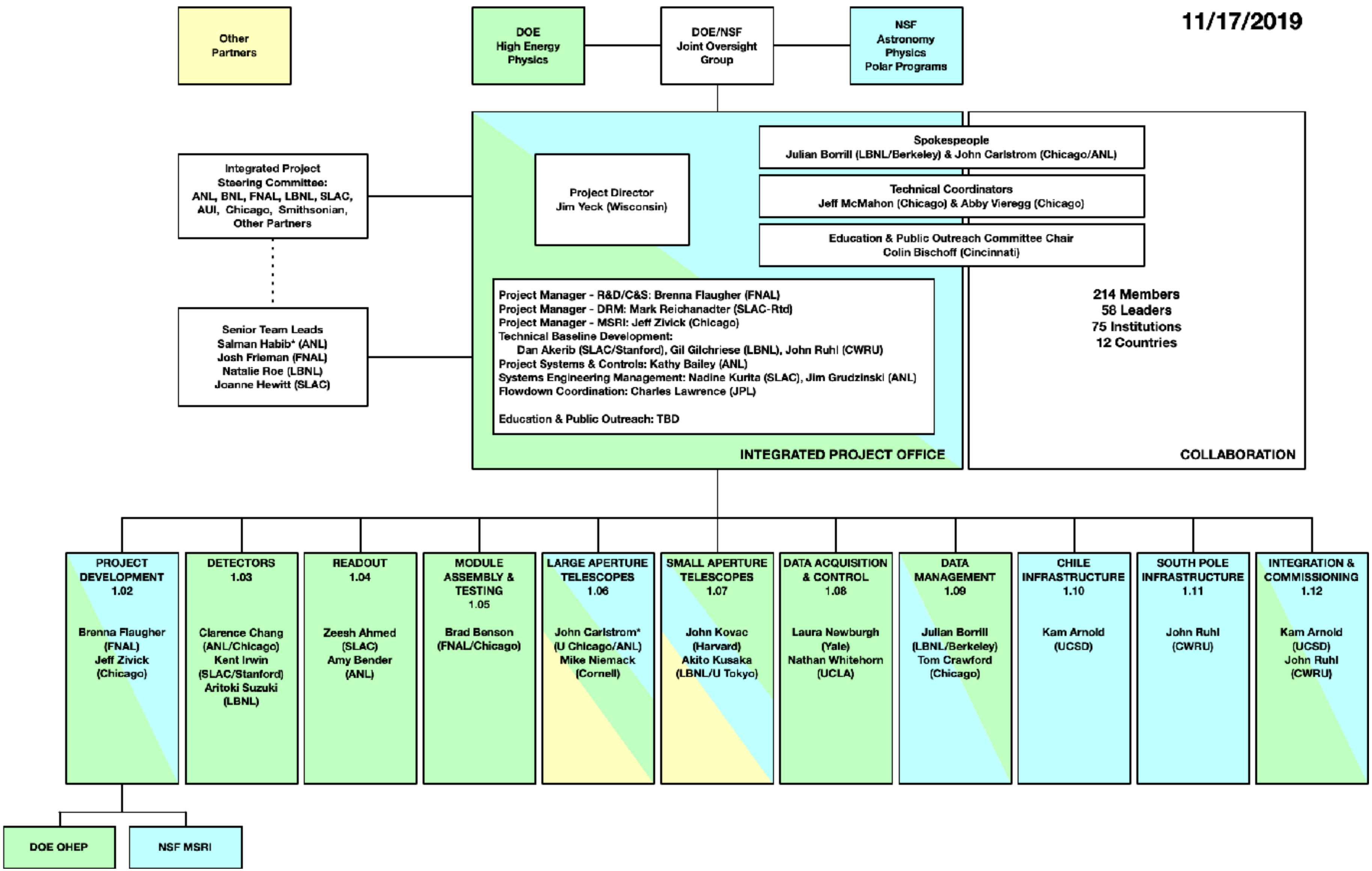
CMB-S4 Collaboration

- Twice yearly CMB-S4 workshops
- Communications through many telecons, CMB-S4 wiki, etc.
- Formally established in Spring 2018
  - 217 Members
  - 76 Institutions & 12 Countries
  - 65 members have leadership roles
- Integrated with the IPO
- Produced the
  - *CMB-S4 Science Book*
  - *CMB-S4 Technology Book*
  - Decadal Survey Report (287 pages, 82 figures): *CMB-S4 Science Case, Reference Design, and Project Plan*
  - Decadal Survey Project White Paper (10 pages)
  - Submitted RFI-I response to Decadal Survey

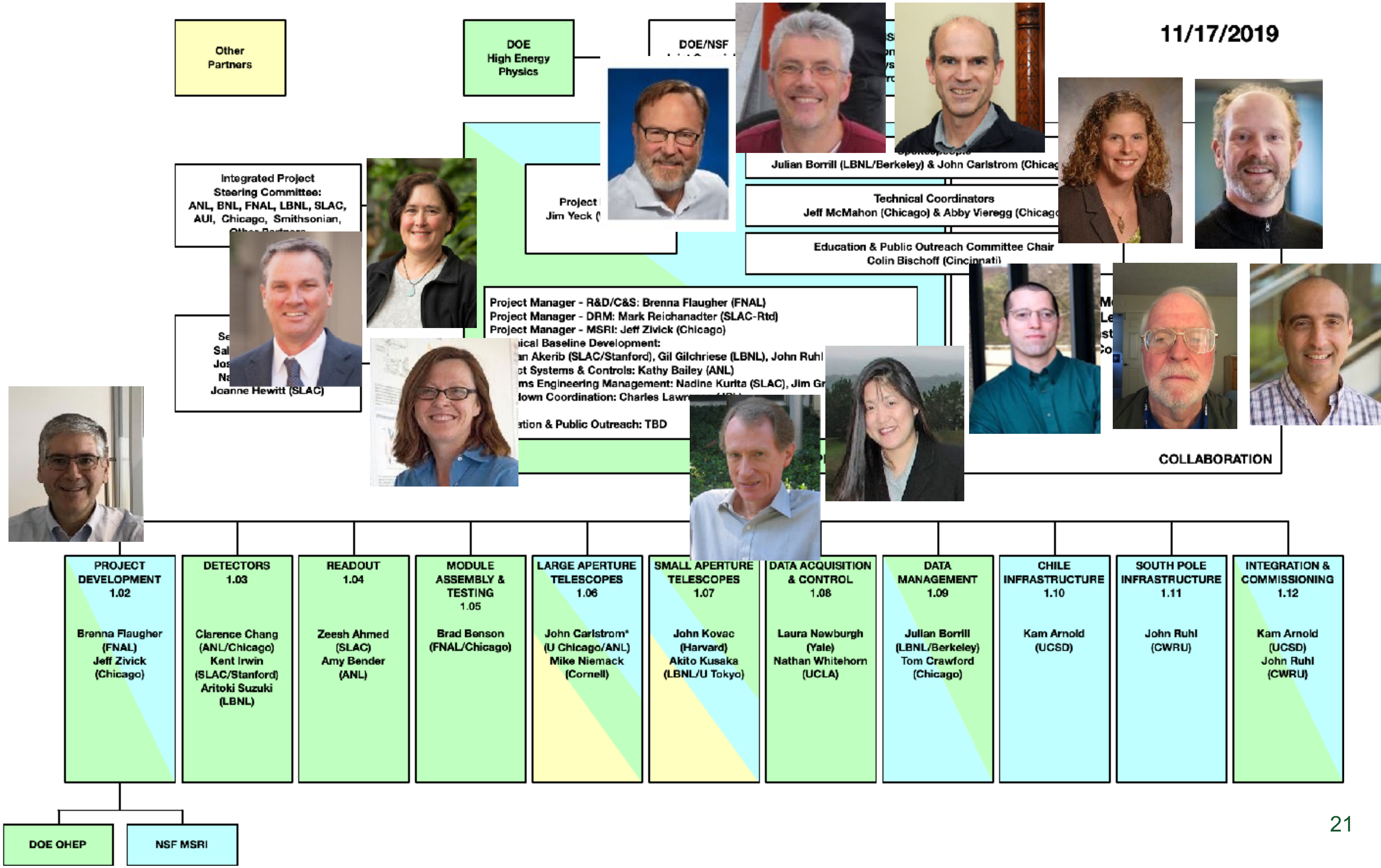


CMB-S4.org

Integrated Project Office (IPO)



IPO – Primarily Contributed Support



L2 Leads – Currently 100% Contributed Support*

Detectors


Clarence Chang


Toki Suzuki


Kent Irwin

Readout


Amy Bender


Zeesh Ahmed

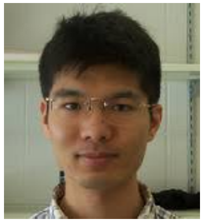
LATs


Mike Niemack


John Carlstrom

SATs


John Kovac


Akito Kusaka

Data Acquisition


Laura Newburgh


Nathan Whitehorn

Data Management


Tom Crawford


Julian Borrill

S. Pole Site + I&C


John Ruhl

Chile Site + I&C


Kam Arnold

Modules & Testing


Brad Benson

*NSF MSRI will cover summer salary for some L2 managers.

WBS and Dictionary follows Project Organization

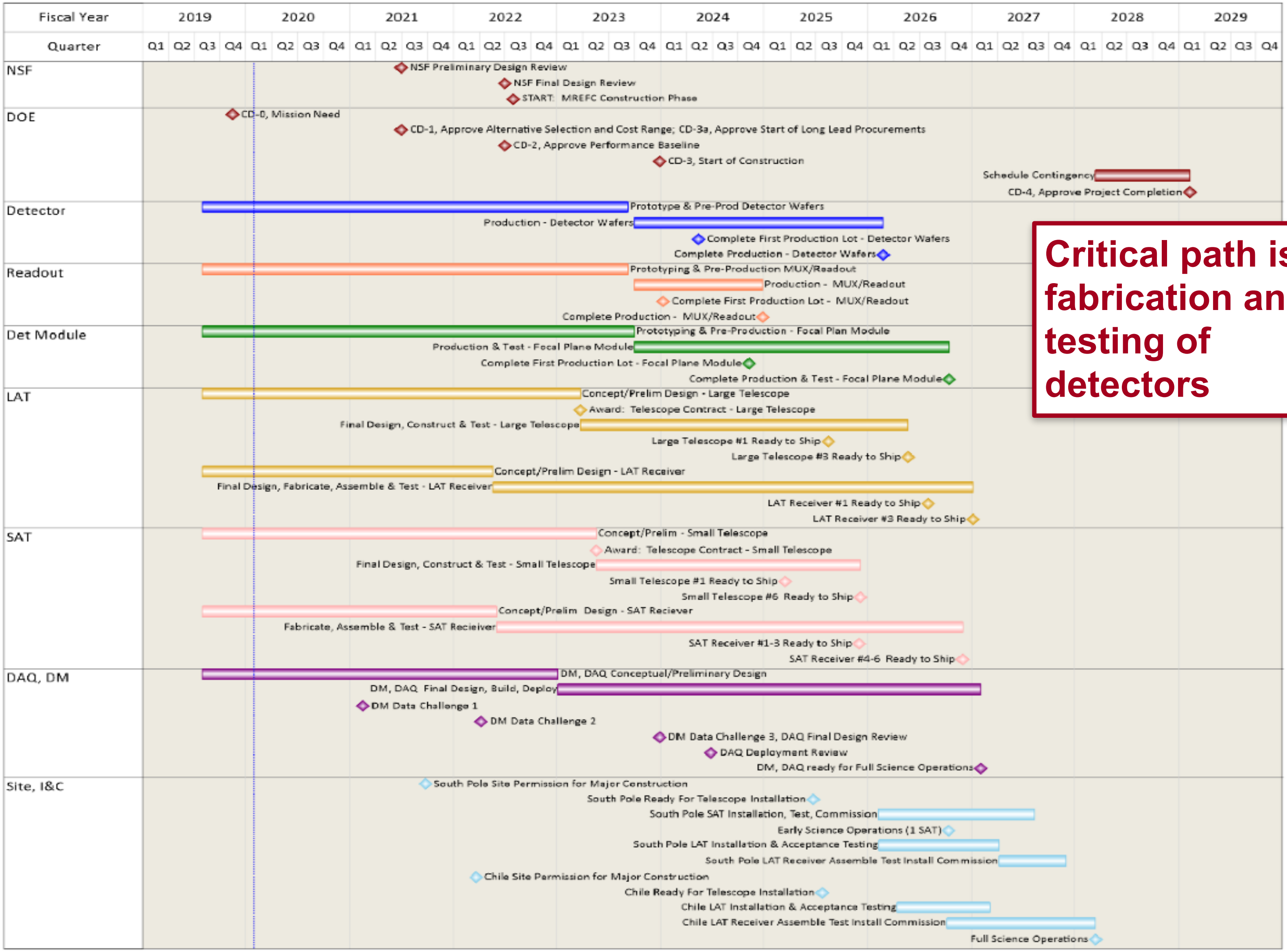
Control Account
1.01 - Project Management
1.02 - Pre-CD1/PDR
1.03 - Detectors
1.04 - Readout Electronics
1.05 - Module Assembly and Test
1.06 - Large Telescope
1.07 - Small Telescope
1.08 - Observation Control and Data Acquisition Systems
1.09 - Data Management
1.10 - Chile Infrastructure
1.11 - South Pole Infrastructure
1.12 - Integration and Commissioning

P6 Schedule development started in Aug. 2018. Included in Dec 2018 and Nov 2019 annual reviews.

Includes:

- 1100 activities, 1928 relationships
- 6 Level 1, 20 Level 2, and 299 Level 3 Milestones

CMB-S4 Project Schedule Overview
FY2029 end date includes 1 year of schedule contingency



Critical path is fabrication and testing of detectors

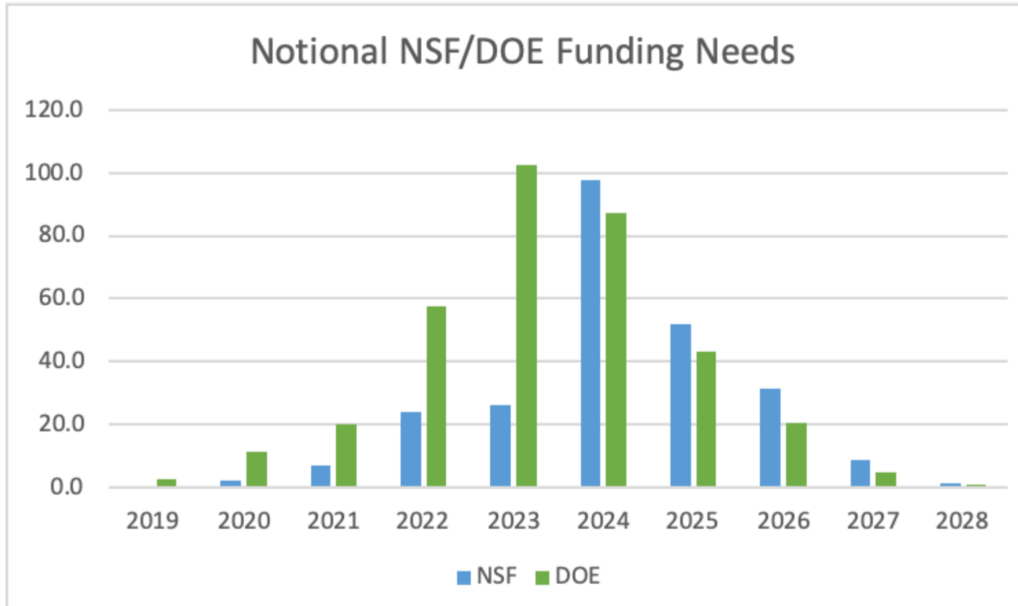
NSF DOE Notional Scope/Funding Split

The TPC escalated to year of expenditure and including 35% contingency is $600M.

In-kind contributions with a value of 10-15% of the project scope are under discussion, and expected. They would lower cost to agencies.

Project is funding limited up to CD-1/PD (June 2021)

Technically limited from 2022, except high level milestones limit start of activities (i.e. Start of Construction 2023)



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	Total
NSF	0.0	2.0	6.8	24.1	26.2	97.9	51.7	31.2	8.7	1.0	249.6
DOE	2.3	11.1	20.2	57.7	102.6	87.2	42.9	20.5	4.8	0.9	350.3

NSF/DOE Project Development/Decision Timeline

	NSF	DOE	Comments
FY2018-19	Interim Project Office Established		Coordinated pre-project development
Q3 FY2019	Initial Input to Decadal Survey White Paper Decadal Survey Report		Reference Design (NSF Conceptual Design) and Initial Project Plans
Q4 FY2019	NSF MSRI award to start Preliminary Design.	Critical Decision 0 July 2019	Based on Decadal Survey Report/IPO Plans
FY2020	NSF Lead Institution Q1 - October 1, 2019	DOE Lead Laboratory Q2 – March 1, 2020	Permanent Integrated Project Organization
Q2 CY2021	Decadal Survey Report Forecast – February 2021		NSF scientific merit review
Q3 FY2021	PD Stage Concluded Provisional Report – 4/1	CD1/3a Approval Review – 4/1	Coordinated agency review plans
FY2022	Final Design Proposal Q1 FY2022	CD2/3b Approved Q2 FY2022	Potential MREFC budget request approval 08/21
Q4 FY2023	FD Complete	CD3 Approved	NSB Approval
Q1 FY2029	MREFC Project Complete	CD4 Approved	Schedule includes 1 year of float (Q1 FY28 Early Finish)

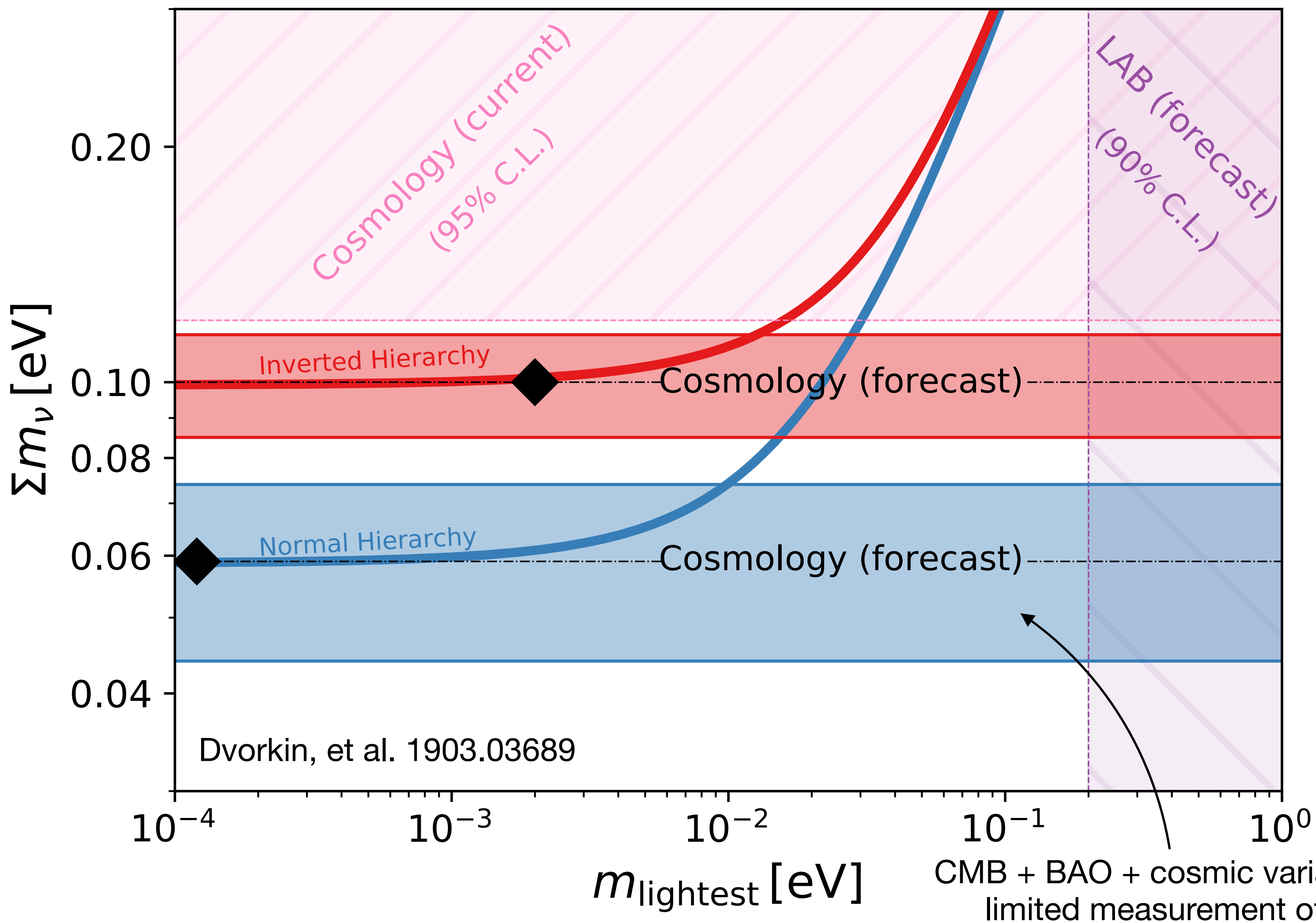
Last words

CMB-S4 is launched and continues to gain momentum

- It will deliver the transformational science goals first envisioned in Snowmass / P5.
- We are on the path to baseline design for CD-1/PD in April 2021.
- Project plan is in place and the team is in executing.
- Need funding to ramp up. Collaborators are ready to bet their careers, we need to enable their success with development support.

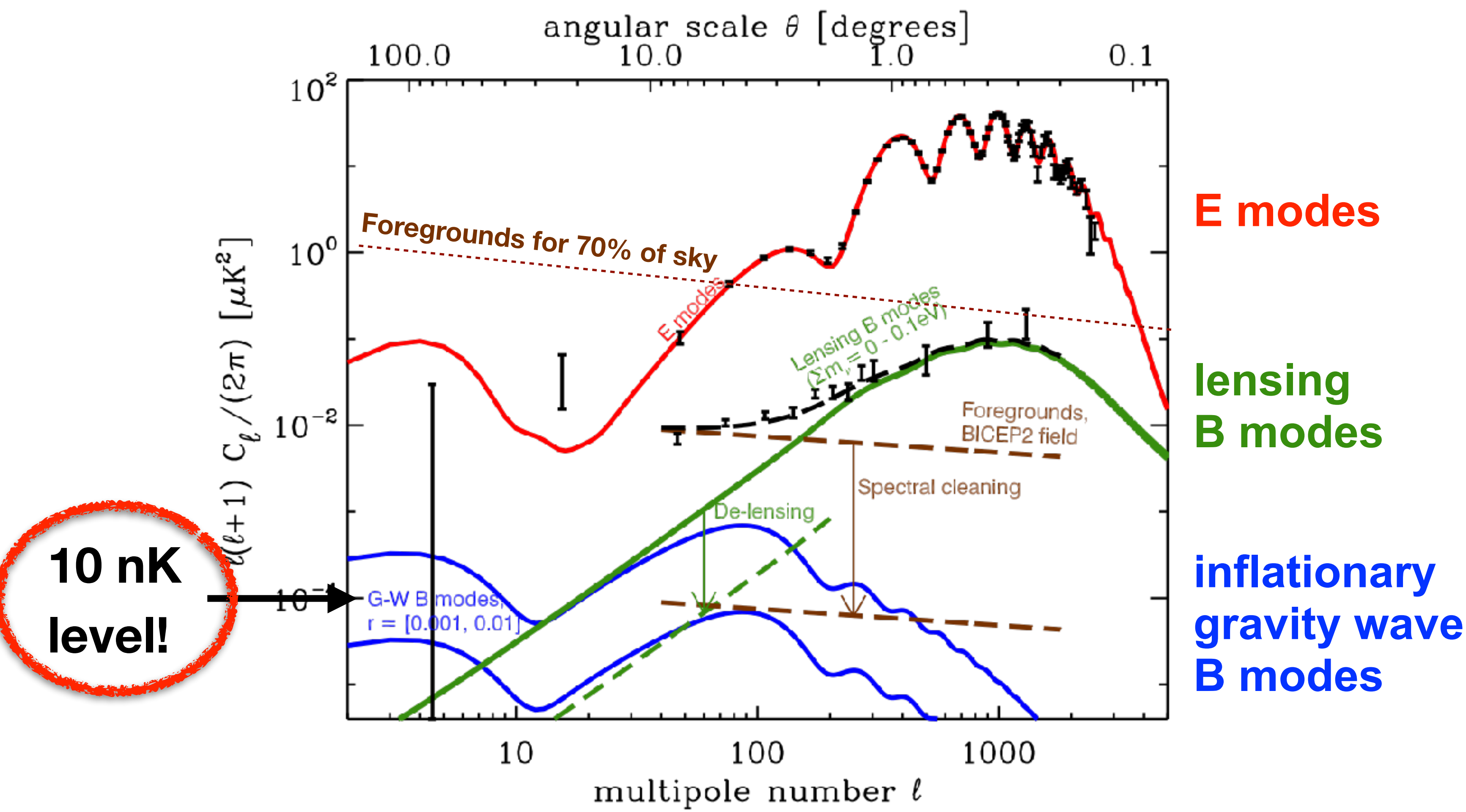
Extra slides

CMB-S4: Neutrino mass scale



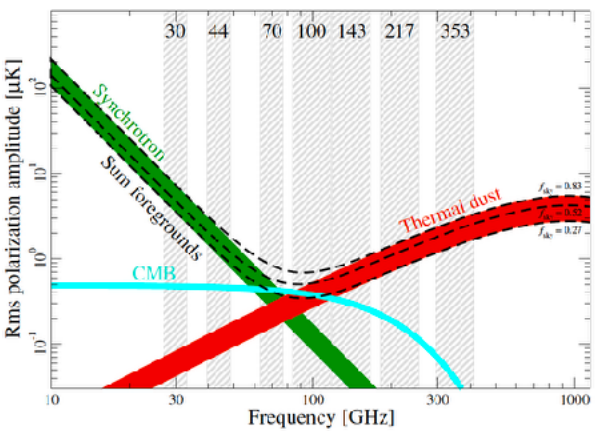
CMB + BAO + cosmic variance-limited measurement of τ

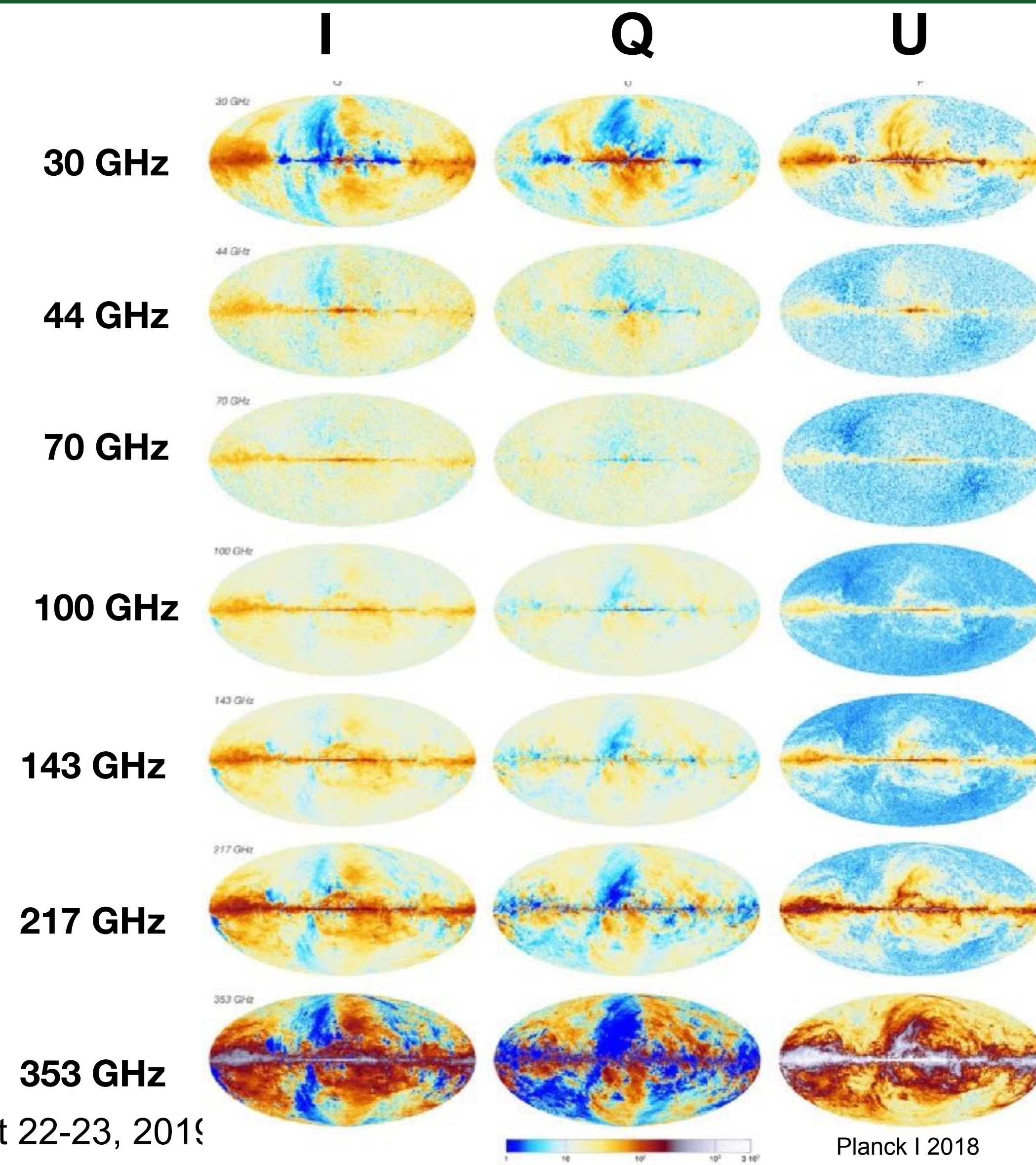
The path forward is through extremely challenging multi-frequency polarization measurements



Multiple frequency channels to remove foregrounds

Planck polarized all sky maps at seven frequencies





Planck I 2018

CMB detector requirements and specifications:

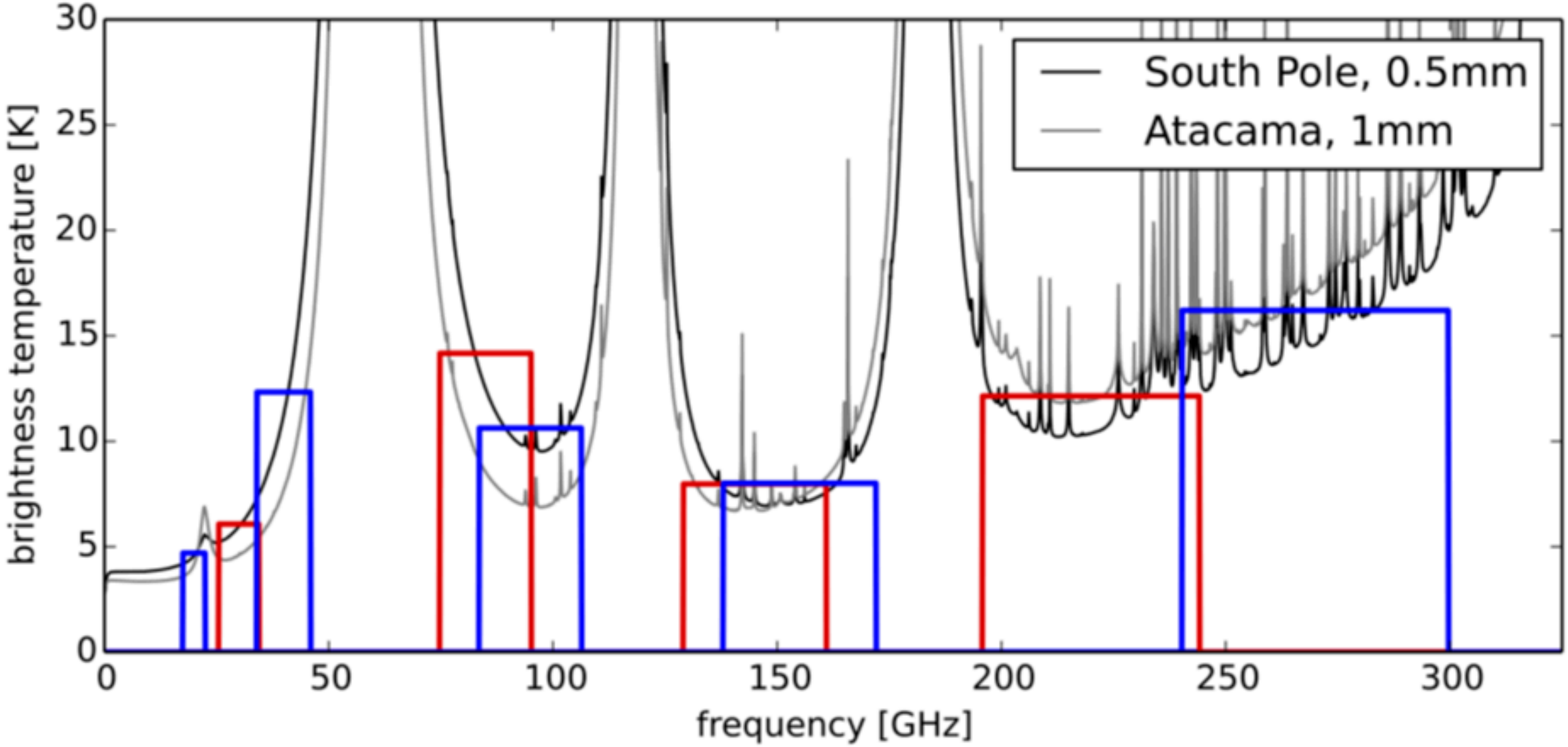


Figure 67. *Calculated atmospheric brightness spectra (at zenith) for the South Pole at 0.5 mm PWV and Atacama at 1.0 mm PWV (both are near median values). Atmospheric spectra are generated using Ref. [563]. The tophat bands are plotted on top of these spectra, with the height of each rectangle equal to the band-averaged brightness temperature using the South Pole spectrum.*