CMB-S4: an Overview

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with inputs from previous presentations by
J. Carlstrom, E. Linder, J. Meyers, H. Nguyen, J. Ruhl, and others...

For the CMB-S4 collaboration

Outline

- Science Flow-Down
- Baseline Survey and Design
- The path to CMB-S4 and upcoming events
- Get involved !

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The Science Case

- The microwave sky is an extraordinarily rich source of information about our Universe
- The CMB carries the imprint of processes in the very early universe, and of interactions of CMB photons across the Hubble volume
- CMB-S4: Four broad science themes

Primordial Gravitational Waves and Inflation	The Dark Universe	Mapping Matter in the Cosmos	The Time-Variable Millimeter-Wave Sky

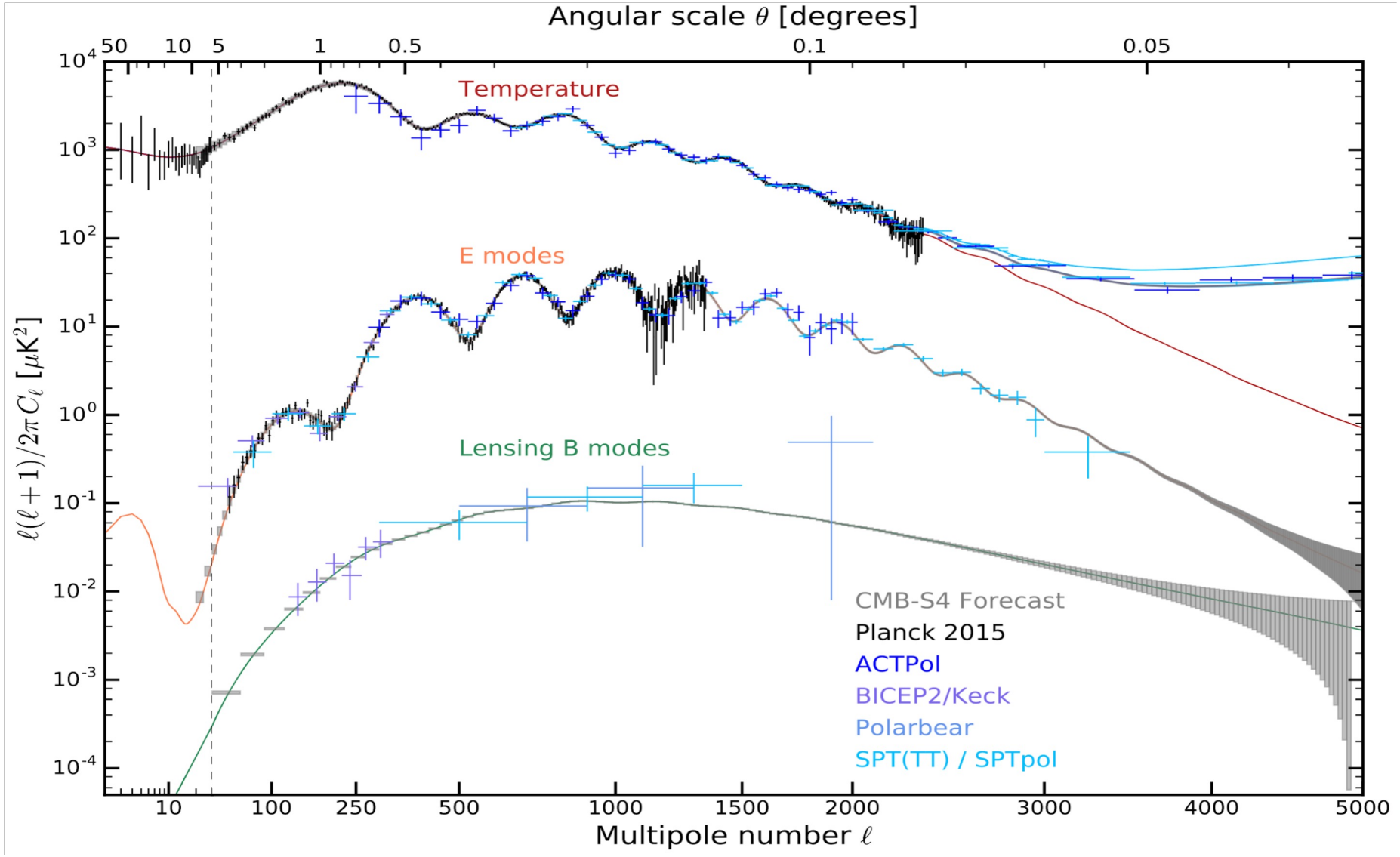
The Science Case

- Each theme has associated Science Goals and corresponding Science Requirements
- These drive the CMB-S4 Survey Measurement Requirements
- These requirements enable the full range of CMB-S4 Science

Science Case design drivers (being consolidated)

- **Science Theme 1: Primordial GW, Inflation**
  - *Design-driver:* **Confirm inflation!!** >5σ detection of r > 0.003 (95% CL upper limit r<0.001 if r=0)
- **Science Theme 2: The Dark Universe**
  - *Design-driver:* Determine N_{eff} with an uncertainty < 0.06 at 95% CL
- **Science Theme 3: Mapping Matter in the Cosmos**
  - *Design-driver 1:* On >50% sky, detect at 5σ clusters at z>1.5 with Y>2.4 10^{-5} arcmin^2
  - *Design-driver 2:* On >3% sky, detect at 5σ clusters at z>1.5 with Y>1.2 10^{-5} arcmin^2
- **Science Theme 4: Time-variable mm-wave Sky**
  - *Design-driver 1:* On >50% sky, detect GRB afterglows > 30 mJy @ 90 & 150 GHz
  - *Design-driver 2:* On >3% sky, detect GRB afterglows > 9 mJy @ 90 & 150 GHz
  - *Design-driver 3:* Timely alerts for follow-up

From Science Drivers to Observables…



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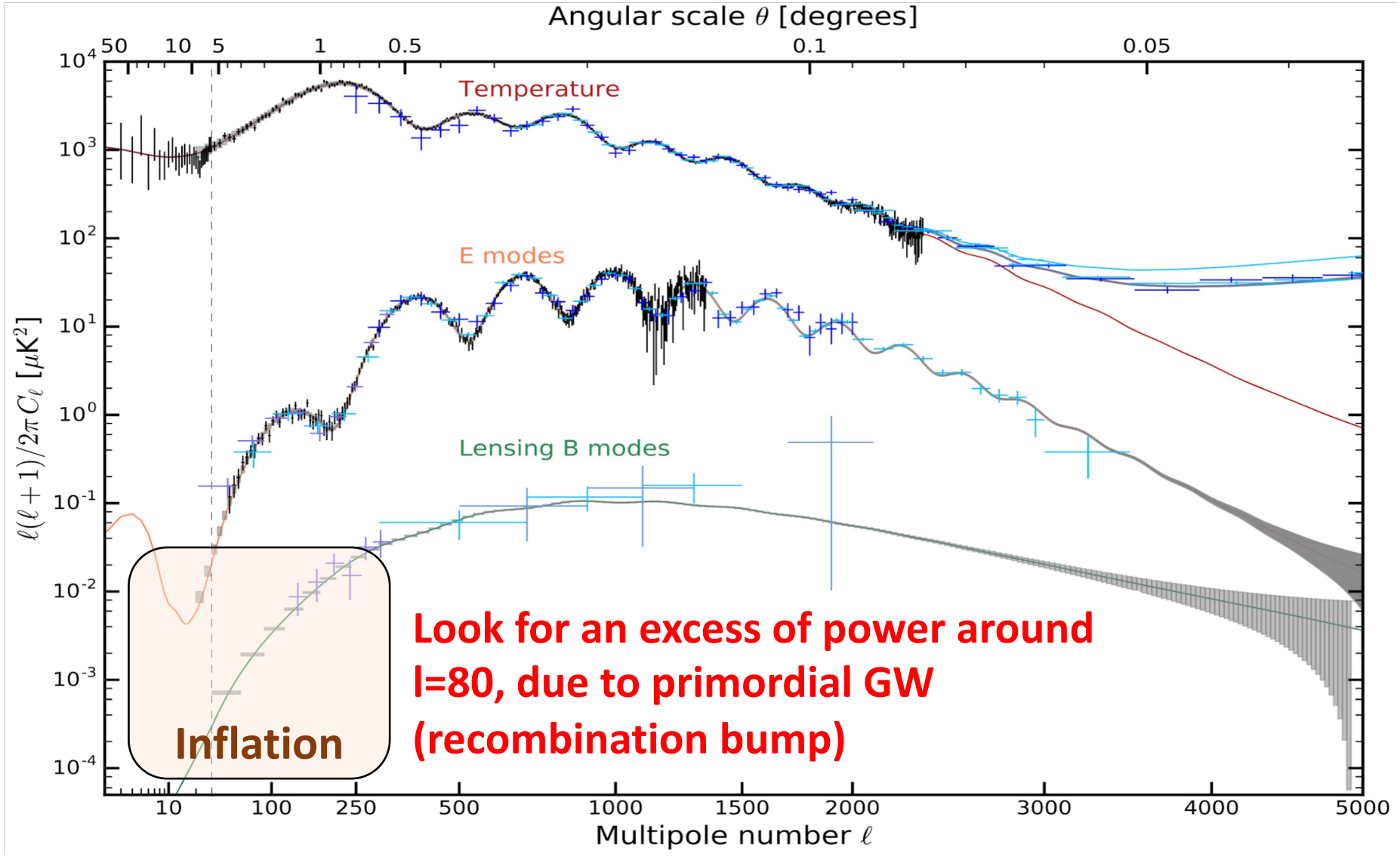

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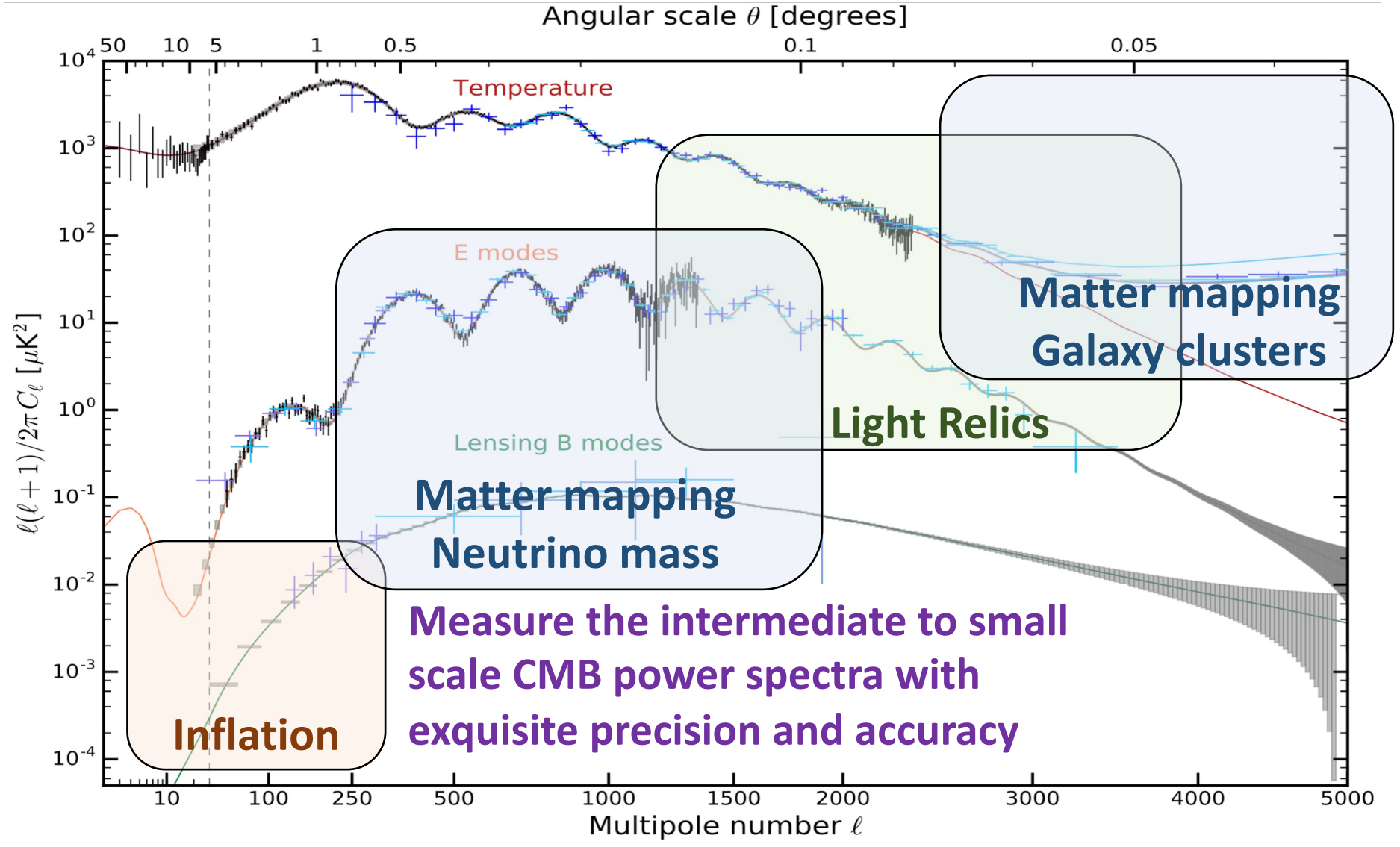

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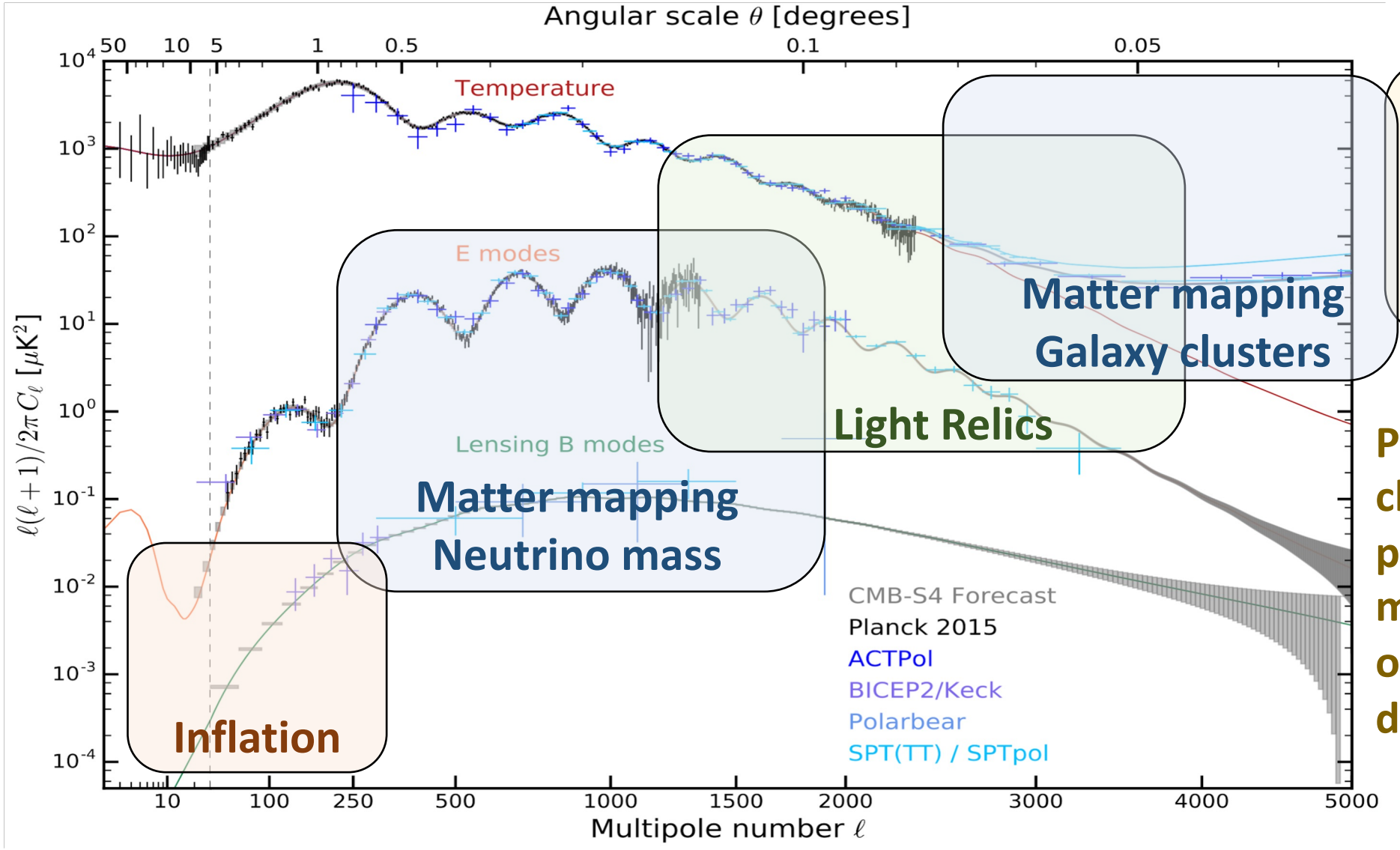


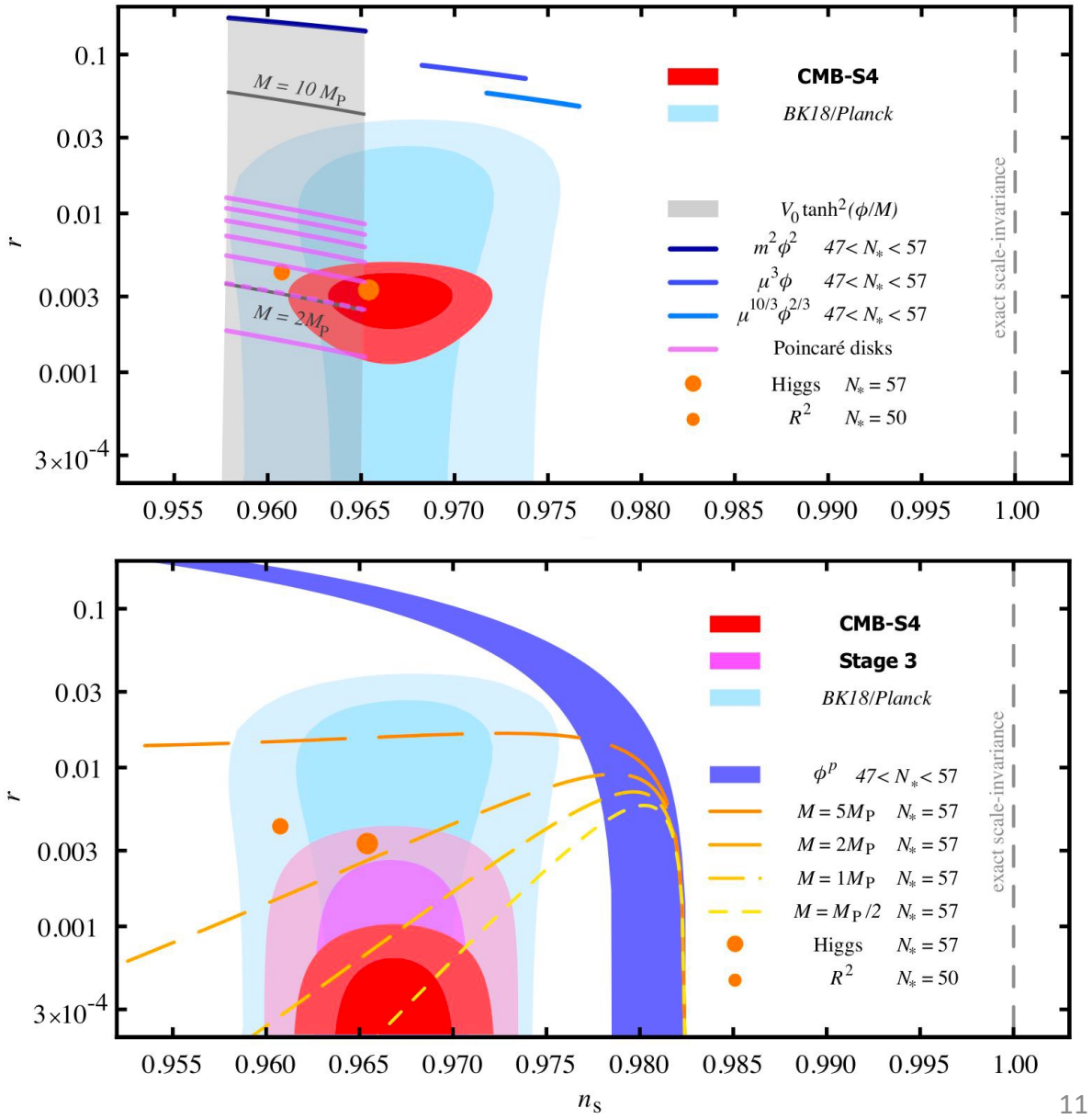
mm-wave Sky Maps
&
mm-wave Transients

Provide well-characterized, high precision and accuracy millimeter-wave maps of the sky, and daily detections of transients

Critical Thresholds on Inflation...

- Look for the unique signature of inflationary GW on CMB B-modes
- **Requirement: $\sigma_r < 0.0005$**

  (2 orders of magnitude below current constraints, ***to unambiguously detect r=0.003***)
- Energy scales of 10^{16} GeV
- Detect or rule-out *the most simple and compelling models* that naturally explain the measured value of n_s.

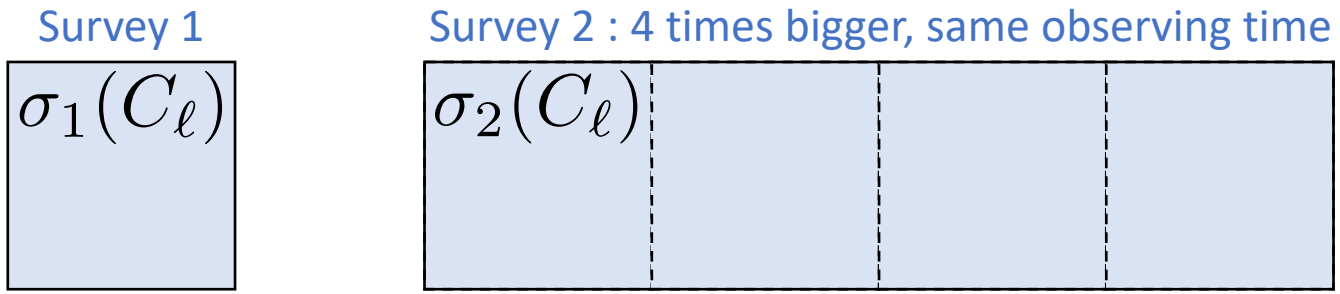


… and corresponding observations

- Look for recombination bump in BB spectrum
- To **First Order** the error is

$$\sigma(r) \;\propto\; \sigma(C_\ell) \propto \frac{C_\ell + N_\ell}{\sqrt{f_{\rm sky}}}$$

survey constraint $N_\ell / f_{\rm sky} = \text{Constant}$

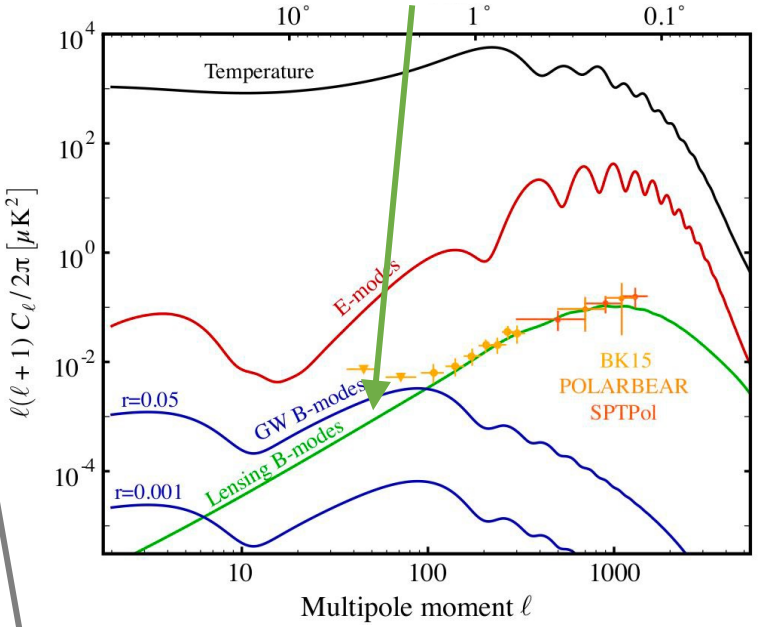


$C_\ell^{BB} \ll N_\ell^{BB} \longrightarrow \sigma_2(r) = 2 \times \sigma_1(r)$ Inflation

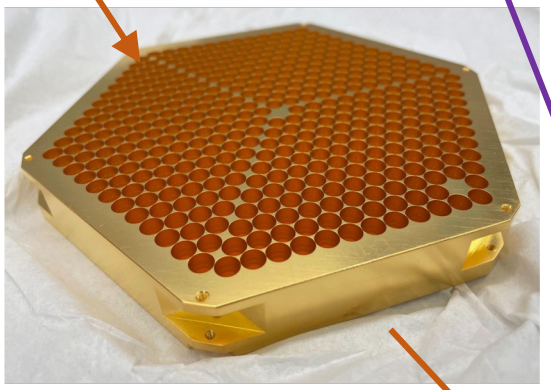
($C_\ell \gg N_\ell \longrightarrow \sigma_2(C_\ell) = \sigma_1(C_\ell)/2$ $N_{\rm eff}$)

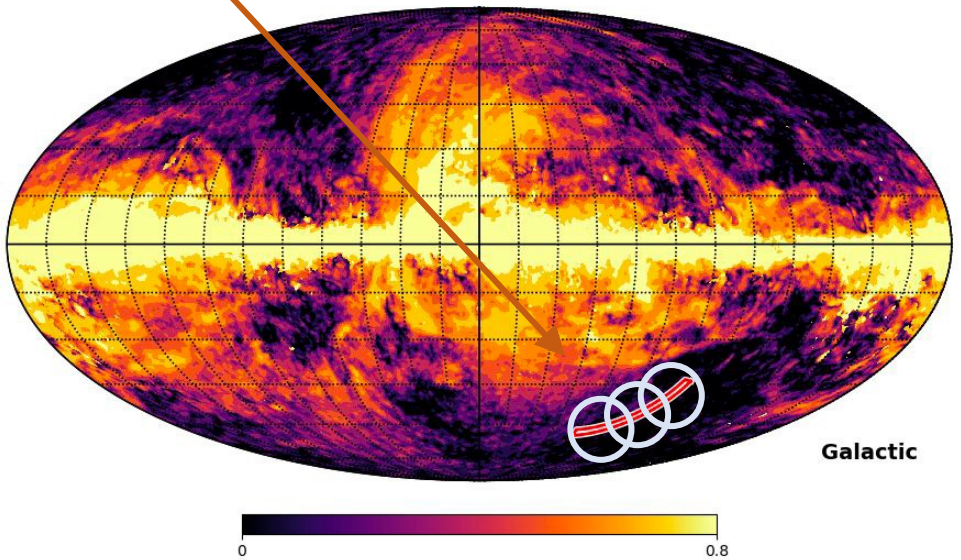
Next level considerations

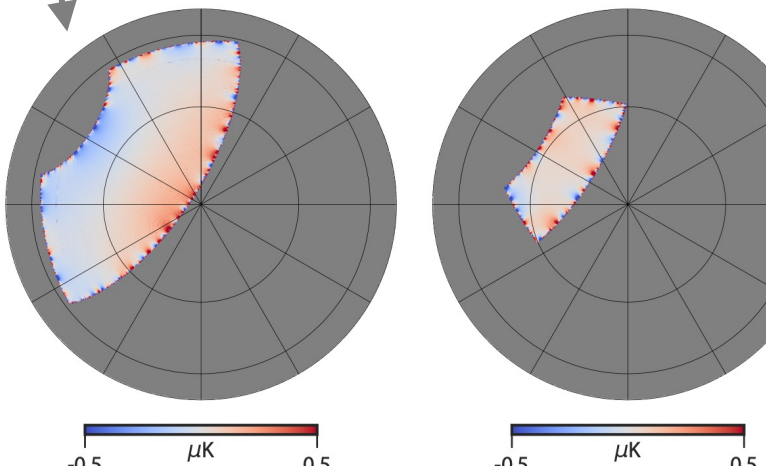
mode mixing *lensing BB* *(n_{det} x T_{obs})* *FOV* *foregrounds* *systematics...*



Many detectors







E to B leakage
Ghosh et al. 2021, JCAP 02, 036

Best f_{sky} = 3-5 %

Light relics

- New light species from extensions of the Standard Model of Particle physics. Examples include axions, sterile neutrinos, gravitinos, dark photons...

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

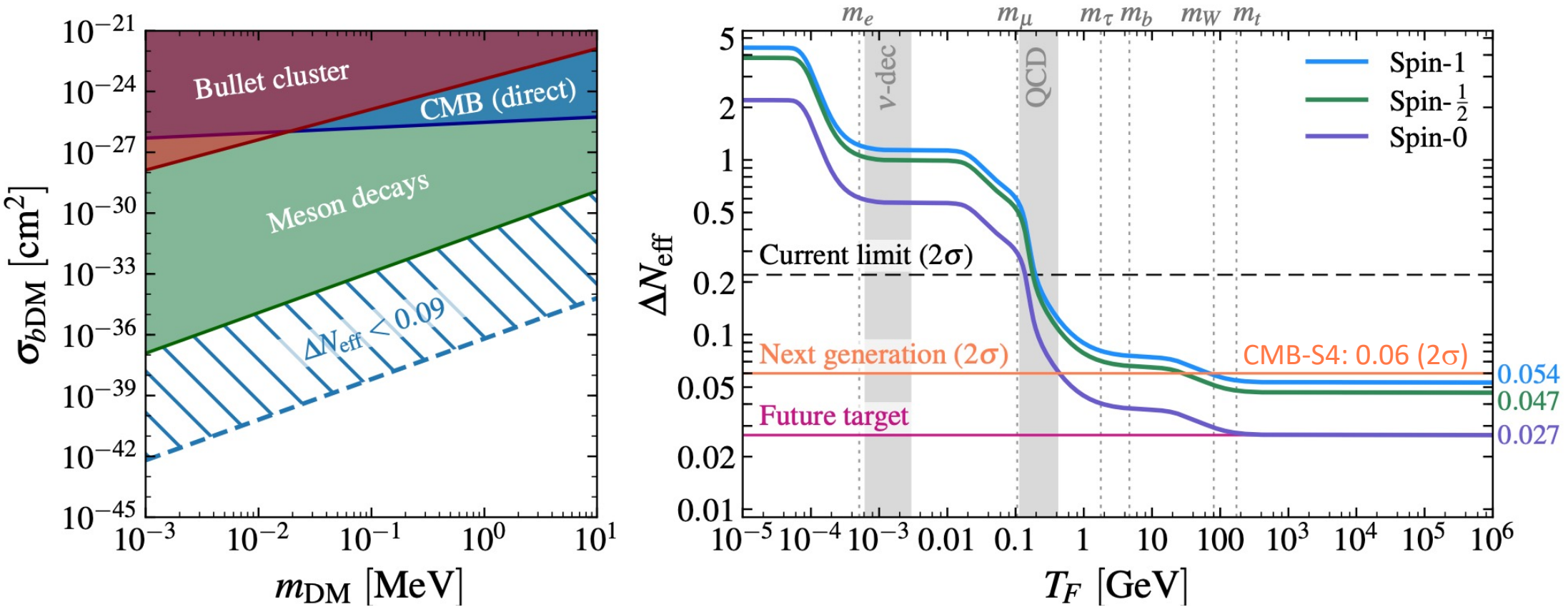
= N_ν if instantaneous ν decoupling before e^+-e^- annihilation.
With corrections: $N_{\rm eff} \approx 3.045$ for 3 neutrino species.
$\Delta N_{\rm eff} \geq 0.027$ for any additional degree of freedom.

- Modify the radiation density, and hence the CMB power spectra

- Planck (current): $\sigma(N_{\rm eff}) \sim 0.2$ CMB-S4: $\sigma(N_{\rm eff}) \sim 0.027$

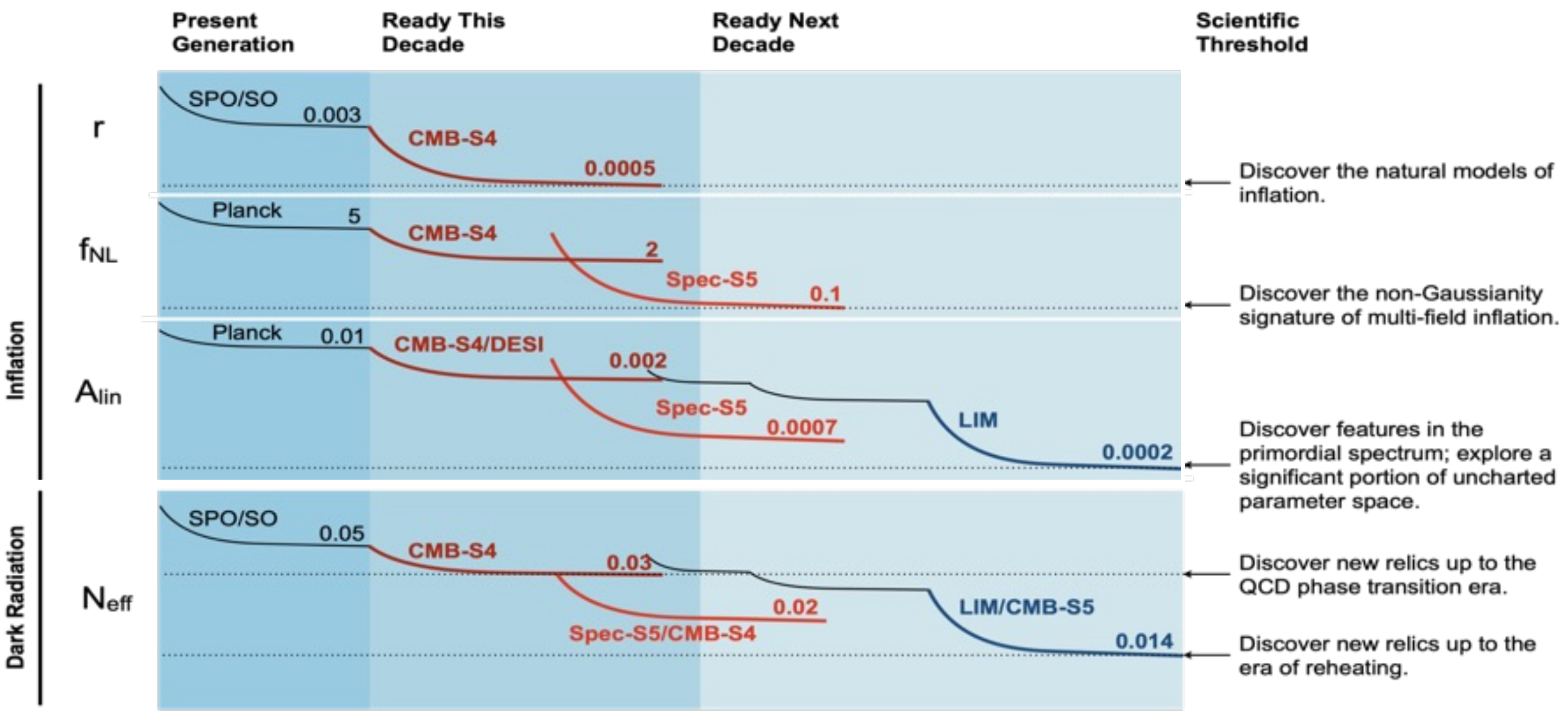
Light relics

Astro 2020 Science White Paper
Green et al. et al. arXiv:1903.04763



- Left: Limits on DM-baryon annihilation cross section for a Yukawa potential
- Right: ΔN_{eff} from a single light particle as a function of decoupling temperature

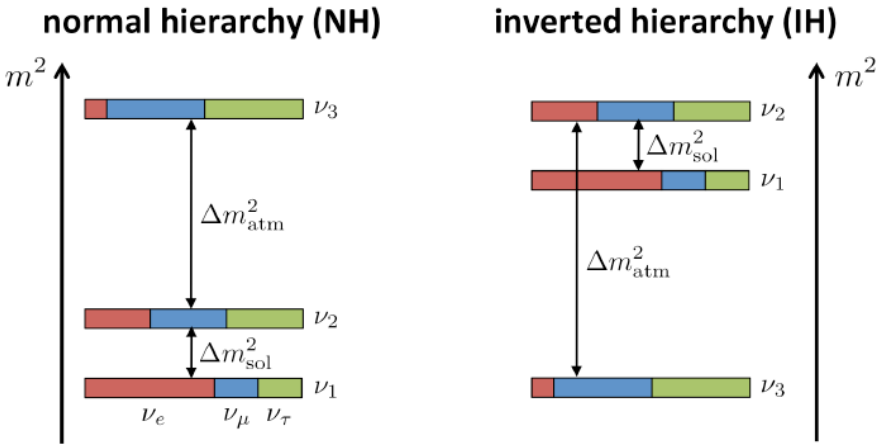
Inflation and Light relics in perspective



Matter mapping / Lensing / Galaxy clusters

- Matter in the Hubble volume will be mapped via
  - CMB lensing
  - Galaxy cluster detections (SZ effects), in particular at high redshift

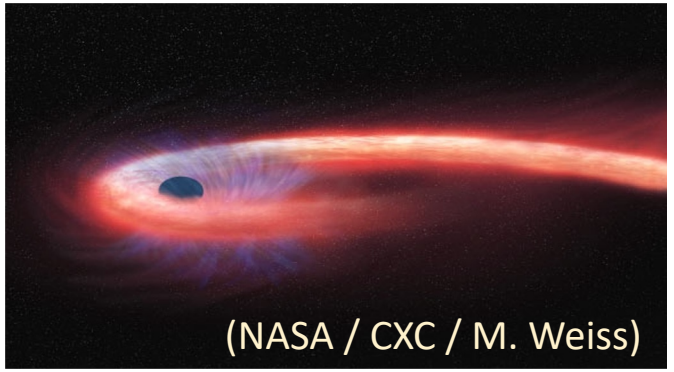
- Information about the growth of structure
  - Sum of the neutrino masses ⟶ ν hierarchy
  - Baryon pressure, velocities, baryonic feedback
  - Powerful in cross-correlation with LSS surveys



- Two surveys: wide (for statistics and x-correlation) and deep

Time-variable sky

- A very-sensitive, years-long survey such as CMB-S4 is uniquely suited to detect transient phenomena at millimeter wavelengths
  - Gamma-ray bursts
  - Variable stars (stellar flares)
  - Tidal disruption events
  - Solar system objects



- Make "timely" alerts
  - At least daily...
  - Cadence still being consolidated in the Sources / Transients Working Group

- Two surveys: wide (for statistics) and deep (for faint transients)

Time-variable sky: The GRB example

- GRBs
  - Extremely energetic events
  - Somewhat unclear origin
  - 400+ events per year at high Energy
- GRB afterglows
  - Already detected in the mm

GRB: Artist's conception (NASA /ESA / Kornmesser)

- Detection potential
  - Over 1000 events /year expected with CMB-S4 (untriggered afterglows)
  - Up to redshift $z > 20$!

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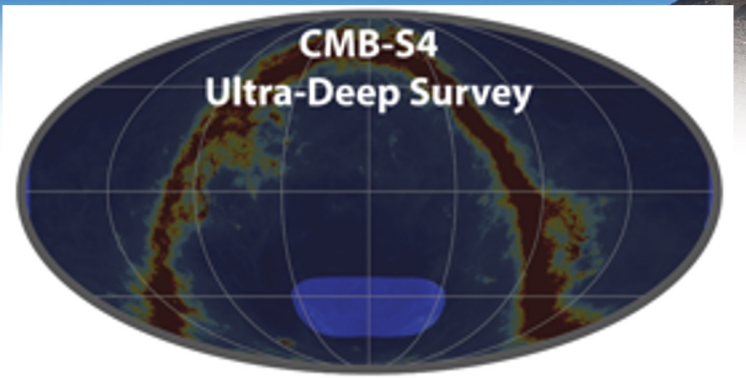
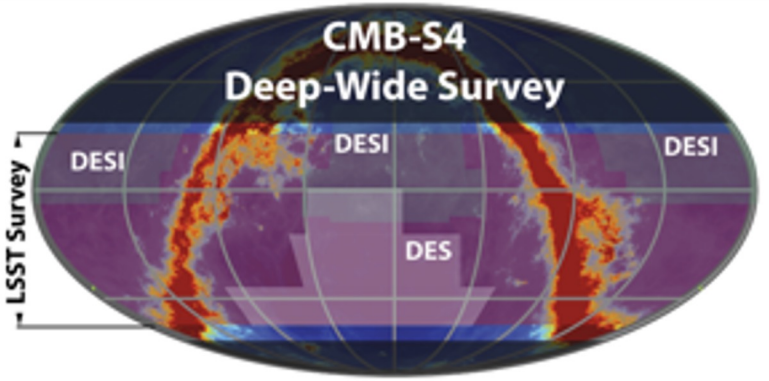
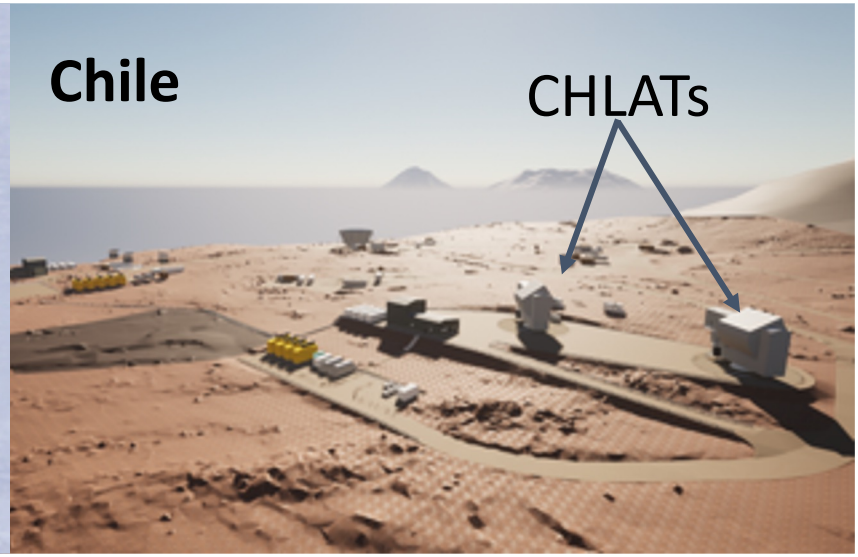
Current baseline

- Ultra-Deep Survey from the South Pole and Deep-Wide Survey from Chile with arcmin angular resolution
- 7-8 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 a factor 10 in detector count







Frequency bands and resolution

r

Frequency (GHz)	25	40	85	95	145	155	230	280
θ_{FWHM} (arcmin)	85.2	72.8	25.5	22.7	25.5	22.7	13.0	13.0

Small Aperture Telescopes

Frequency (GHz)	20	25	40	90	150	230	280
θ_{FWHM} (arcmin)	11.4	9.1	6.2	2.5	1.6	1.1	1.0

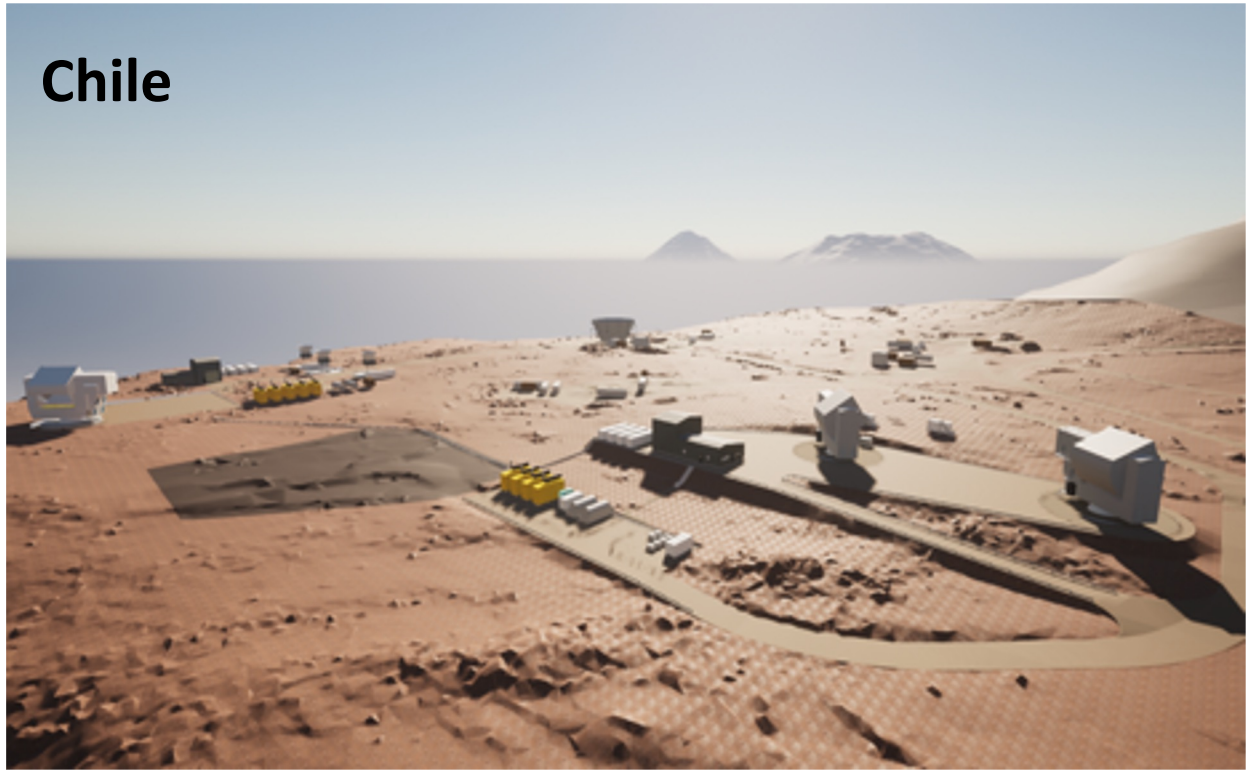
Large Aperture Telescope

N_{eff}

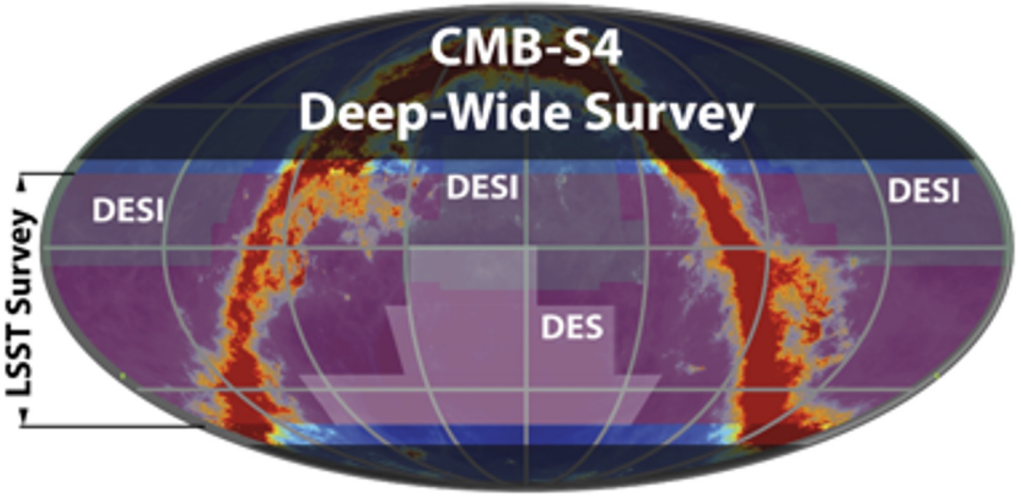
Frequency (GHz)	25	40	90	150	230	280
θ_{FWHM} (arcmin)	7.8	5.3	2.2	1.4	1.0	0.9

Large Aperture Telescopes

Two Large Aperture Telescopes in Chile



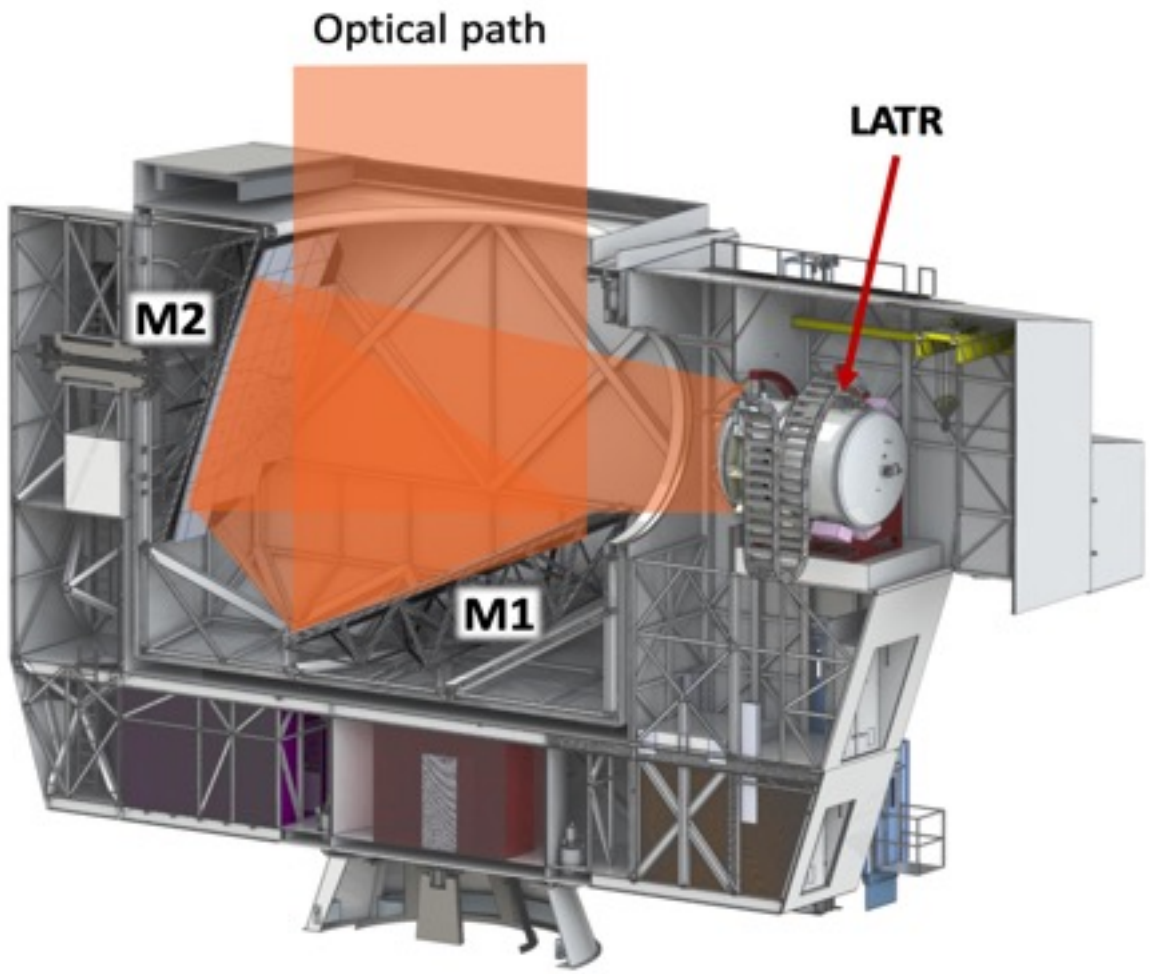
Two 6-m Large Area Telescopes



Deep and Wide field survey optimized for
matter mapping via CMB lensing, neutrino mass, light relics, and transient mm-wave phenomenon.

Overlaps with other optical surveys (DES, DESI, LSST) for cross-

Two Large Aperture Telescopes in Chile



Gallardo et. al.: arXiv: 2207.10012

6-meter primary diameter
Crossed-Dragone Design

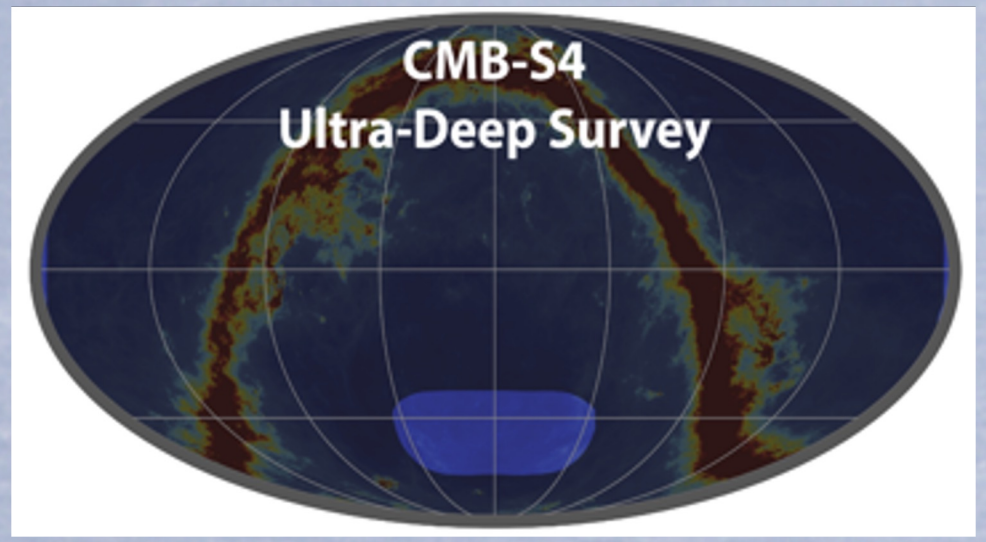
1.4’ angular resolution at 150 GHz

Design based on experience from CCAT-Prime and the upcoming Simon’s Observatory

Science Themes 2 and 3:
- The Dark Universe
- Matter Mapping

South Pole Large and small Aperture Telescopes

South Pole



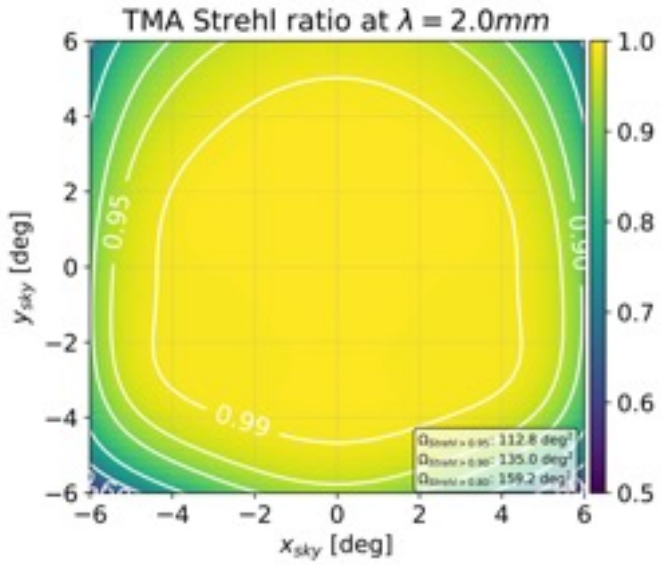
Large Area Telescope for B-mode Delensing

3 Small Area Telescopes for B-mode survey

SPT and Bicep/Keck Array

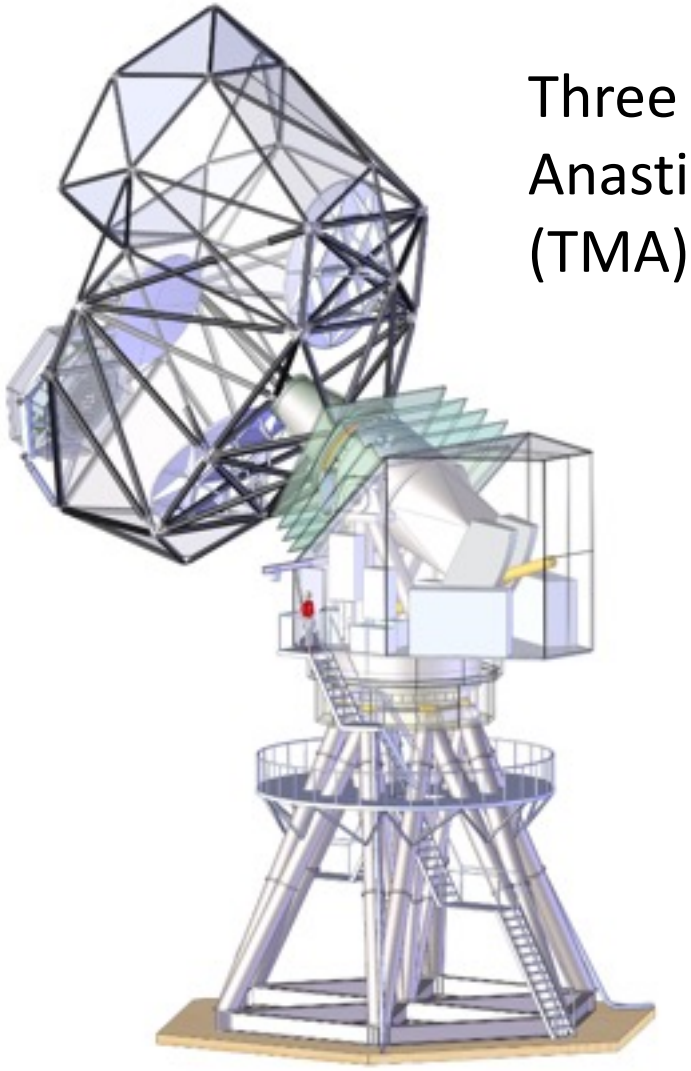
Science Theme 1:
- Inflation

South Pole Large Aperture Telescope



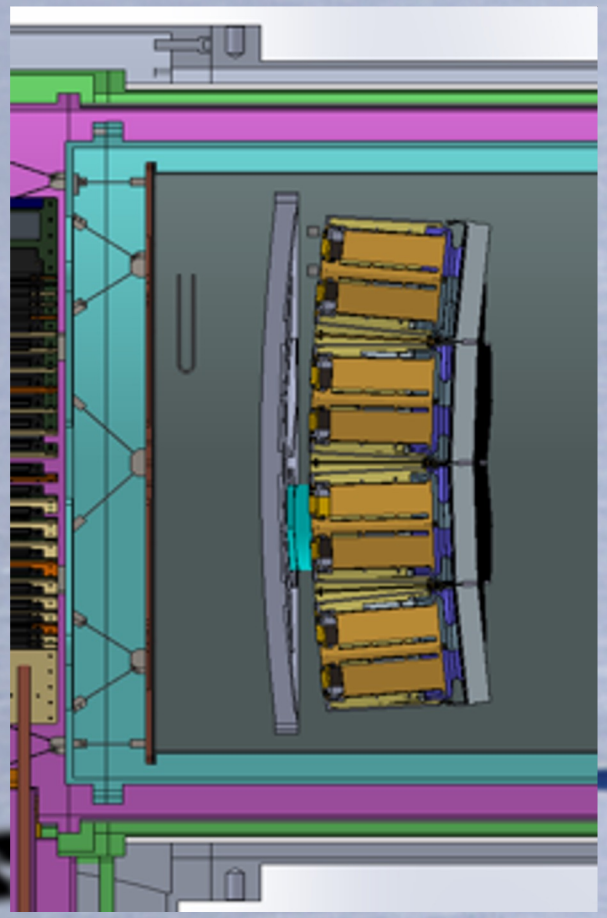
Optimized for the B-mode Delensing Survey

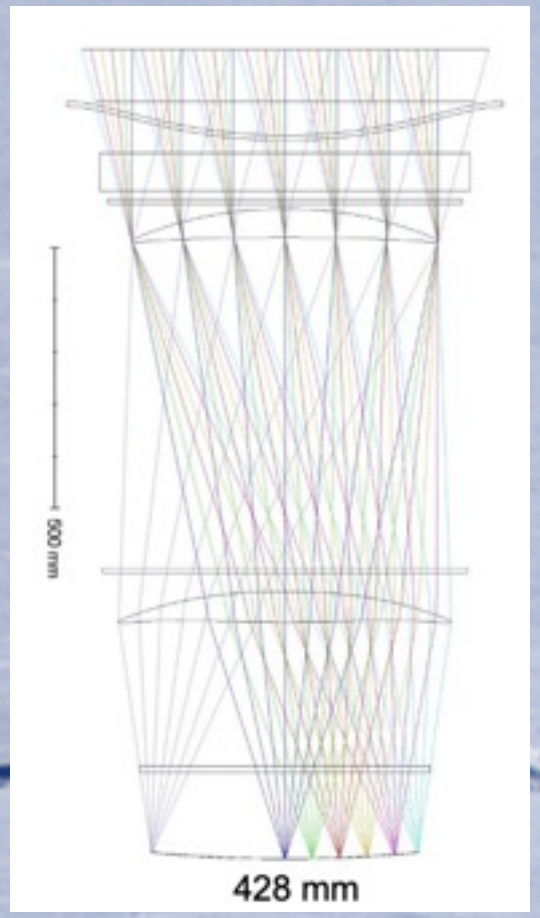
- Optimal beam over FOV
- Gapless mirrors to prevent B-mode contamination
- Boresight rotation to cancel polarization systematics

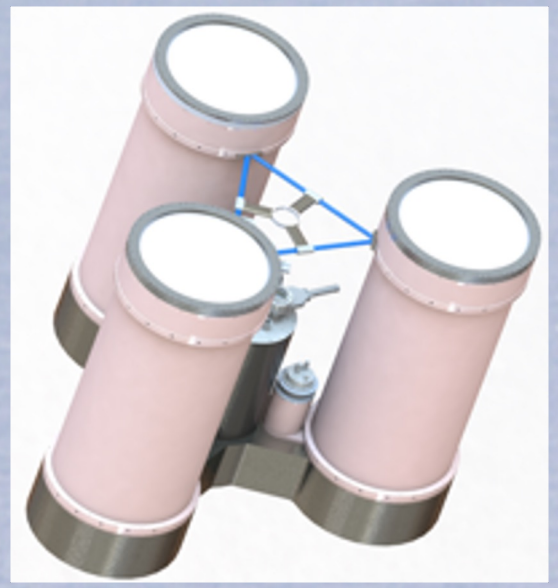


Three Mirror Anastigmat (TMA) Design

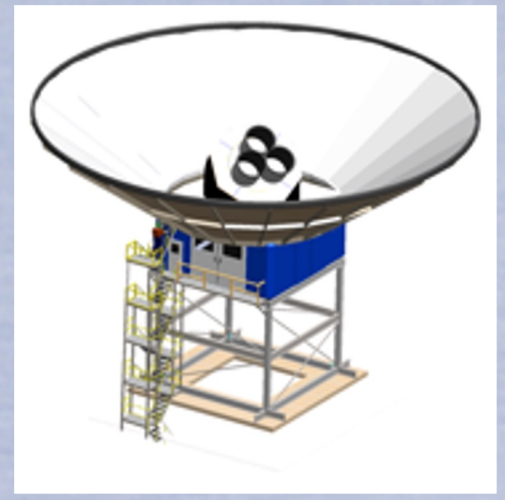
South Pole Small Aperture Telescopes

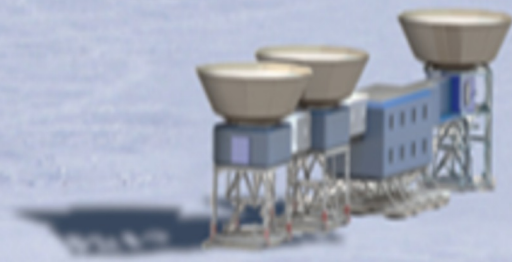






Cryostat





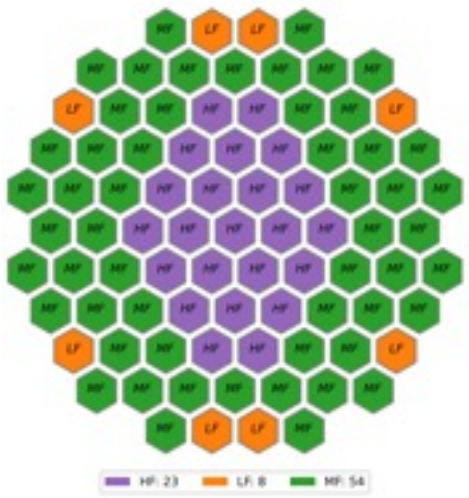
Support Tower and Ground shield

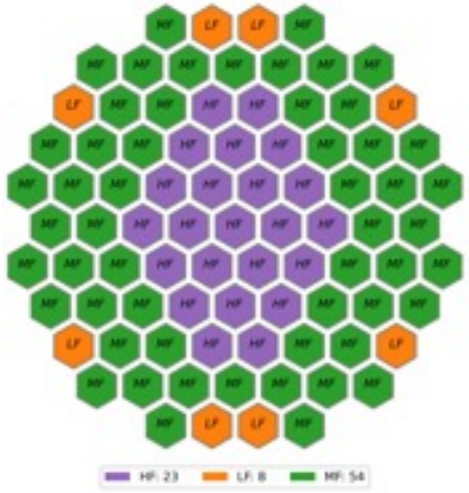
Focal Plane

Cold Refractor Optics

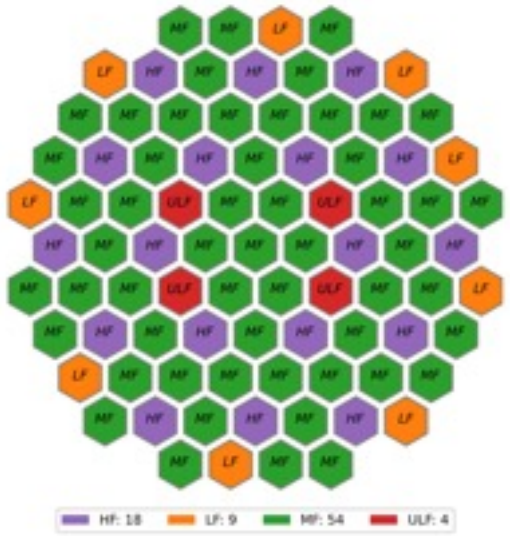
Builds upon proven BK Array Design

Telescope Focal Planes

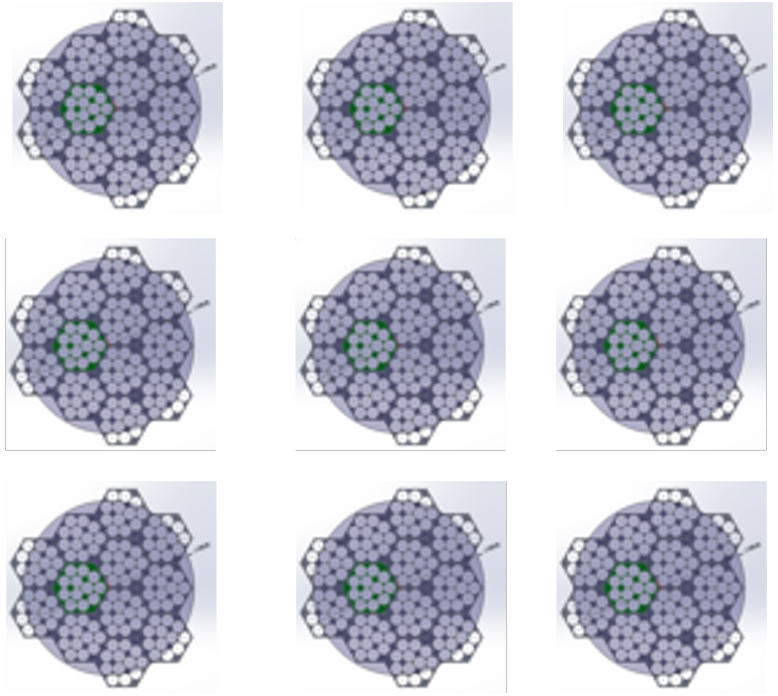




Chilean LAT Focal Plane
~ 270K detectors



South Pole LAT
Focal Plane
~ 130K detectors



South Pole SAT Focal Plane
~ 100K detectors (LF detectors
shown for illustration)

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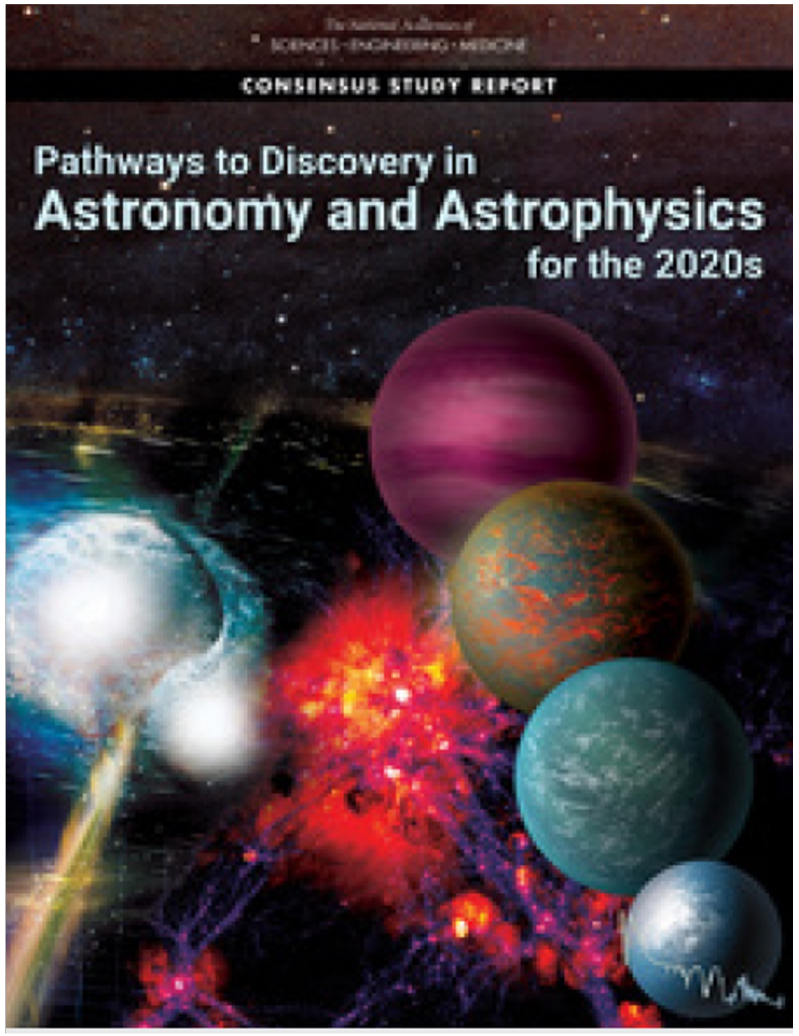
Community support for CMB-S4

- CMB community has united around **CMB-S4**
  - Designed to make transformational discoveries in fundamental physics, cosmology, astrophysics & astronomy
  - Recommended by 2014 P5 under all budget scenarios
  - Recommended by 2015 NAS report "A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research"
  - **Strongly recommended by Astro2020: "NSF & DOE should jointly pursue the design and implementation of CMB-S4"**
  - Prominently featured in recent Snowmass process / ongoing 2023 P5: Snowmass Cosmic Frontier report "Our top project priority is to complete construction of CMB-S4".



Upcoming events

- March-April 2024 (TBC): NSF Conceptual Design Review (NSF-CDR)
  - Function: Review a package containing the Conceptual Design
  - Expectations:
    - Conceptual Design, System Requirements, Supporting Budget Estimates, Risk Analysis, Forecasts of Interagency and International partnerships
    - Funding Request for the Preliminary Design Phase, with Contingencies
  - Outcome:

Formal exit from the Conceptual Design Phase entails the following NSF actions:

1. Successful completion of the CDR as described above,
2. Recommendation for advancement by the sponsoring Directorate,
3. Facilities Readiness Panel Review and Recommendation,
4. Approval for advancement to the Preliminary Design Phase by the Director, and
5. Award to support the Preliminary Design Phase.

Upcoming events

- Summer-Fall 2024 (dates TBC): DOE Critical Design 1 (CD-1)
  - Function: Determine that selected alternative is optimized for needs from CD-0
  - Expectations:
    - Analysis demonstrating that the proposed alternative is the correct one
    - Complete, independently reviewed conceptual design of chosen alternative and associated cost and schedule
    - Funding profile compatible with expected spending
    - Management plans, including Acquisition Strategy, Preliminary Project Execution Plan, Preliminary Hazard Analysis Report, Quality Assurance, Risk Assessment and Management Plan
    - Environmental assessment
  - Impacts: Release of Major Item of Equipment Funds, Start next phases of Design, Continuation of R&D and Prototyping

Director's review (Nov. 14-17) summary by Jim Strait

The Director's Review of the CMB-S4 Project went quite well. They agreed that **we are on track to be ready for an NSF Conceptual Design Review** should one be scheduled sometime in the first part of next year. They also gave us **many important recommendations and comments** that will help us move forward toward the NSF CDR and a later DOE CD-1 review. The final report will be shared when received.

The DOE/NSF P5 report will be presented at the December 7-8 meeting of the HEP Advisory Panel. A strong endorsement by P5, which we have reason to hope for, would give a strong push to the funding agencies to vigorously support CMB-S4. Meeting information: https://science.osti.gov/hep/hepap/Meetings.

The 11th of December, there will be a **"Town hall" meeting at Fermilab** at which the P5 report will also be presented. Meeting information here: https://indico.fnal.gov/event/61641/.

Later that week, date TBD, we will hold a **CMB-S4 "all-hands" meeting (on Zoom)** to bring you up to date on the outcome of the Director's Review, the P5 report and what it means for us, and the general status of the project. Likely dates are 13th or 15th of December, most likely at 8am Pacific.

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International involvement

CMB-S4 has members from 27 US states and 21 countries

enthusiasm from the international community!

International contributions to WG activities and to the project are actively encouraged !

How to get involved

- Apply for collaboration membership and get involved in Working Group activities (at individual level)
- Get organised and discuss with CMB-S4 project director for contributions to the project (see also next talk by Manuel Gonzalez)

- For "French" collaborators specifically
  - The Centre Pierre Binétruy is an International Research Lab located in Berkeley to actively promote collaboration between CNRS and Berkeley. Contact Radek for long term visits!

- The LBNL Physics Department Direction is also open to host long term international visitors for work on CMB-S4 (contact me if interested)

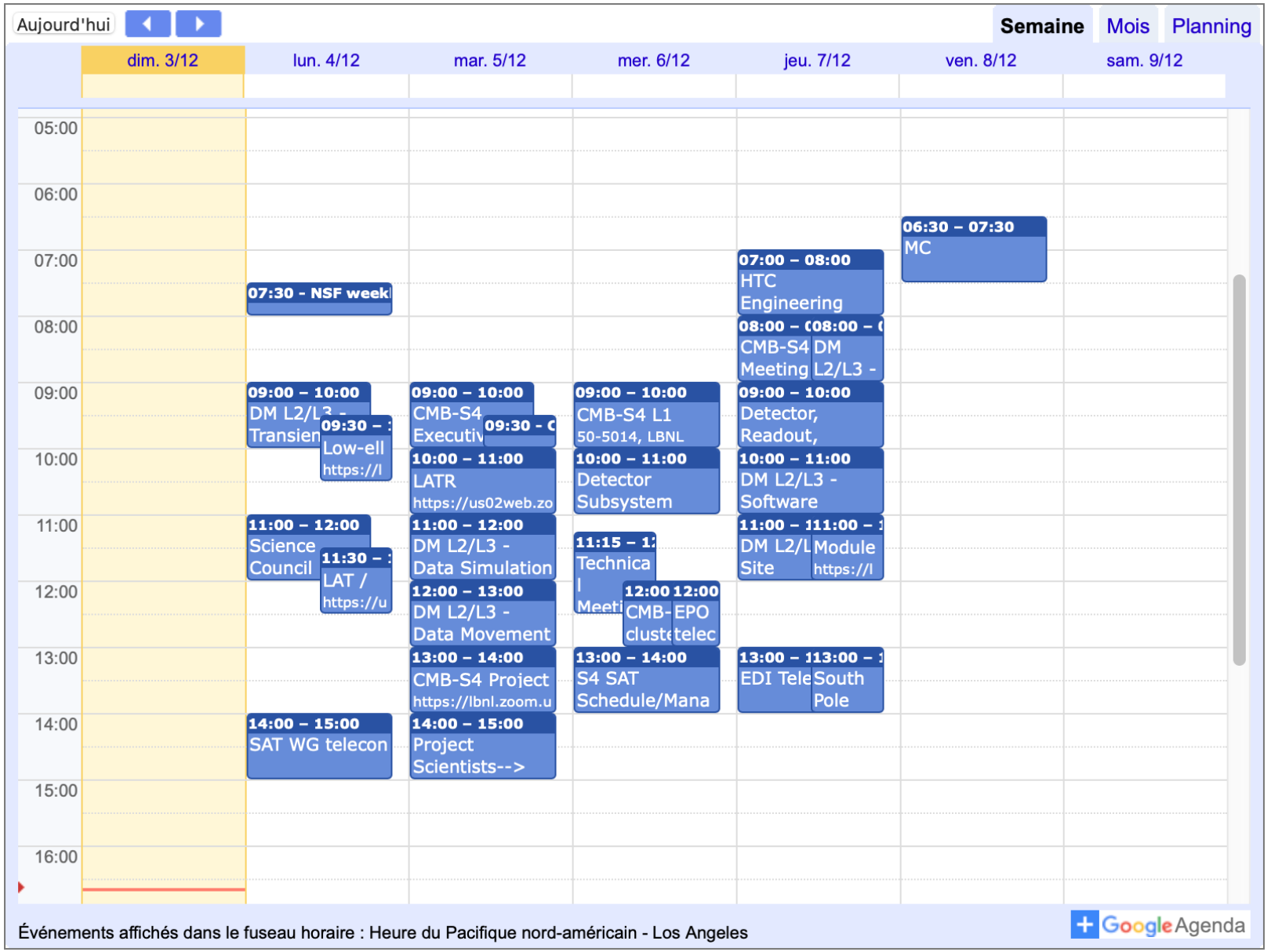
Working group activities (selection)

- Low-ell BB
  - Focused on the detection of primordial GW in low-ell BB C_l
  - Forecasting for r
  - Delensing
  - Foreground cleaning
  - Analysis of Alternatives (forecasts + map-based)
- Maps to C_l
  - Cosmological constraints using C_l power spectra
  - In particular N_{eff}
- …

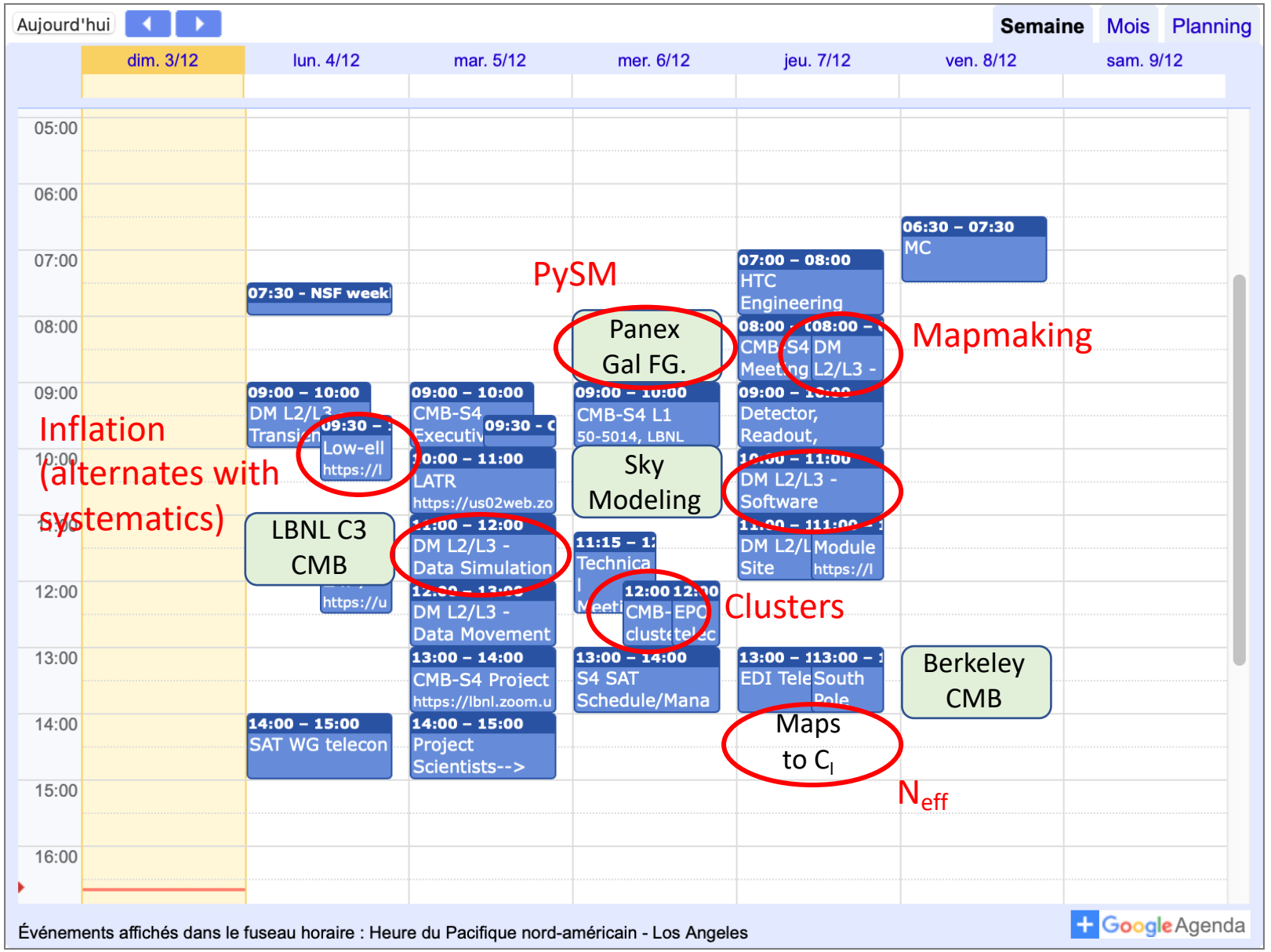
There is work to be done at interface Project / WGs

- Sky simulations and sky model validation
  - To provide reliable sky models for Data Challenges
  - To consolidate Analysis of Alternatives
- Consolidation of Scientific Requirements and Margins for the various science cases
- Preparation and Analysis of Data Challenge simulations
  - DC0 currently available for Collaboration Analysis (Essential for feedback in preparation of DC1)
  - DC1 will include systematics with inputs from Systematics Working Group

A typical week of CMB-S4



My typical week of CMB-S4



Summary

- The next generation of CMB observations are poised to make tremendous discoveries
  - r : Observe gravity operating on quantum scales
  - N_{eff} : Probe for light particles beyond the standard model
  - $\sum m_\nu$: Constrain the masses of neutrinos
  - New insights into dark energy, dark matter, structure formation
  - New discovery space for transients in the millimeter sky
- CMB-S4 offers a unique opportunity to study fundamental physics of the universe scaling up mature technology
- CMB-S4 will impact many fields: HEP, Cosmology, and Traditional Astronomy

CMB-S4 Collaboration meeting August 2023 in Stanford

Thank you!