



CMB observations from the ground: Simons Observatory and CMB-S4

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CMB observables

- Total intensity anisotropies
- Polarization anisotropies:
 - E-modes and B-modes
- Gravitational lensing
- Sunyaev-Zel'dovich effect:
 - kinematic and thermal
- And others ... (spectral distortions).

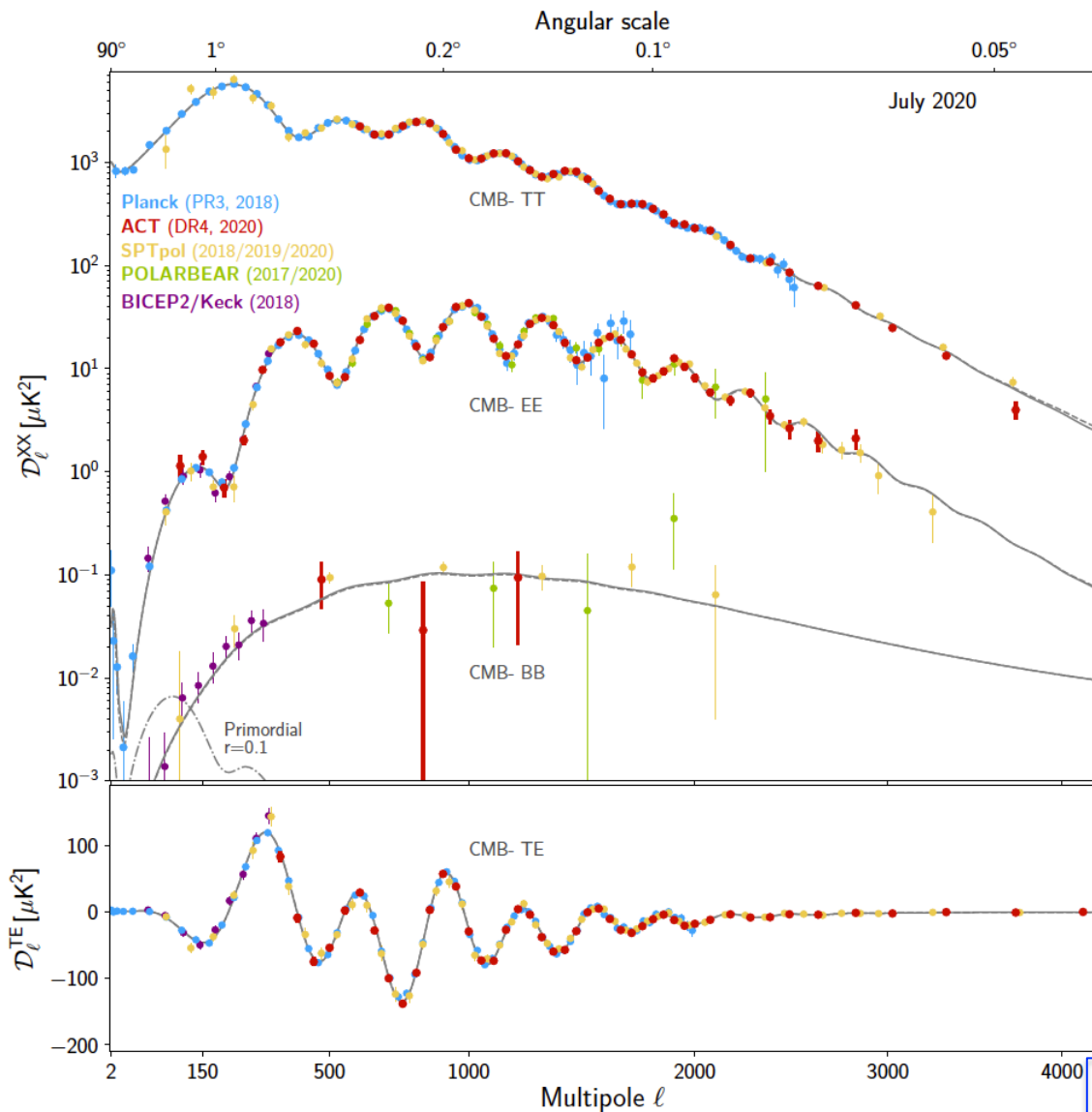
Primordial GW

Basic cosmological parameters
+
Light relic particles
Dark matter/dark matter interactions
Light elements abundances
Primordial power spectra
Expansion rate
+
Astrophysics (Galactic)

Dark energy
Dark matter (interactions)
Neutrino masses

Cosmological parameters
Dark energy
Astrophysics (Clusters)

Current status

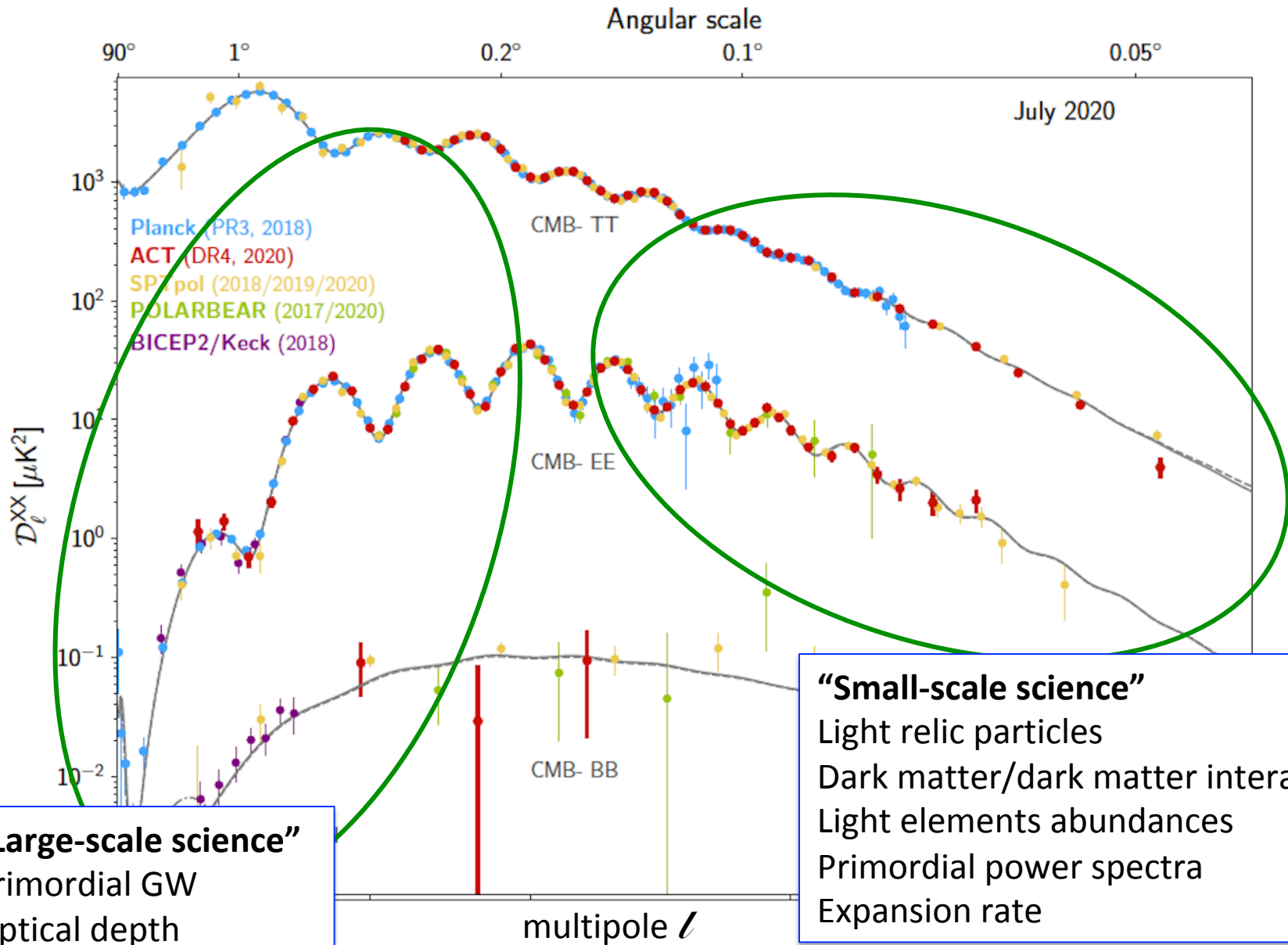


Well-established standard cosmological model (6 parameters determined with high precision).

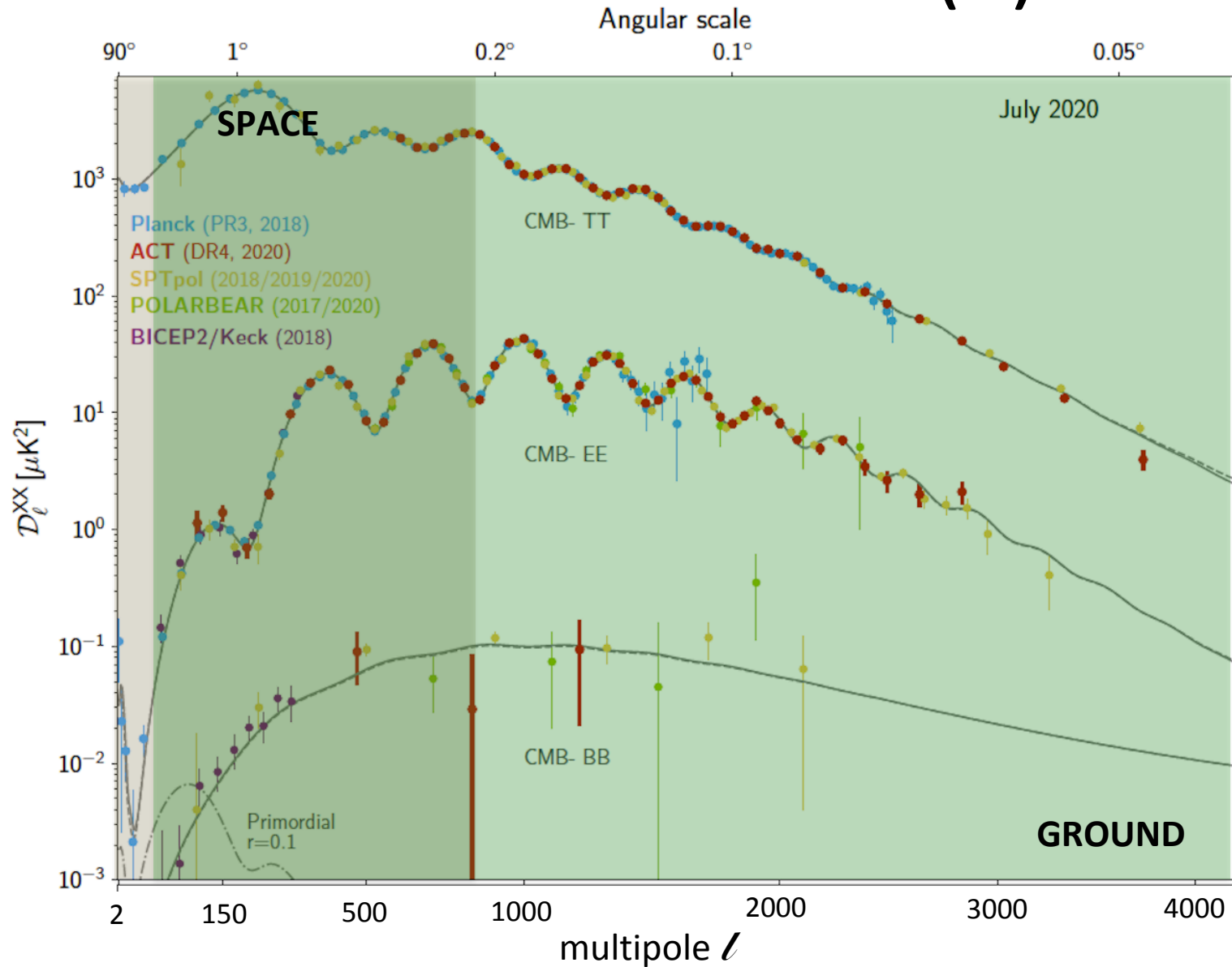
Exploration of the fundamental information contained in CMB has been barely started.

N.B. A lot of the science will require complementary data sets (BAO, WL, etc).

CMB information



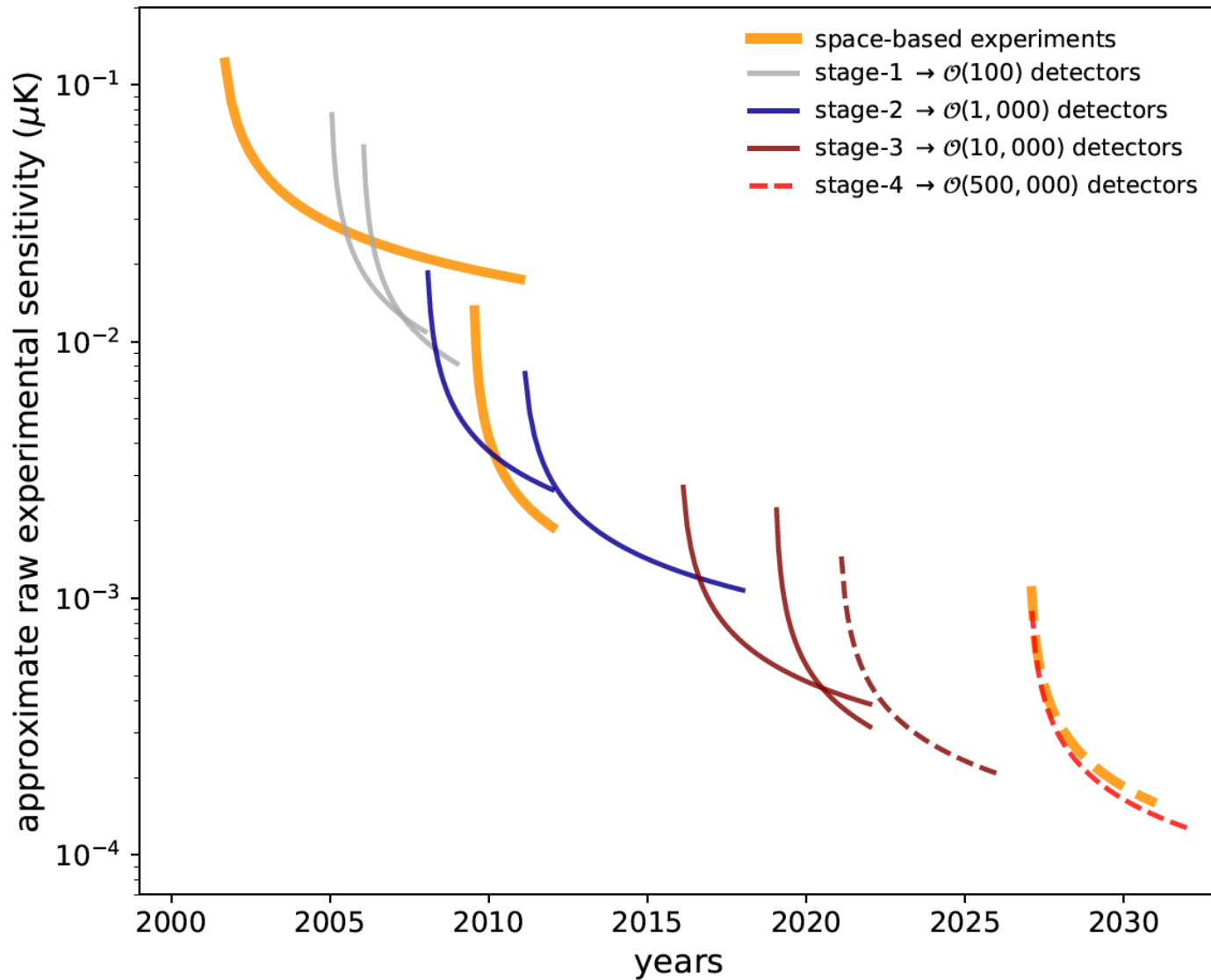
CMB information (2)



Challenges

- Sensitivity → number of detectors
- Galactic (and extra-galactic) non-cosmological contributions – foregrounds → multifrequency observations
- Environmental effects → hardware + analysis mitigations
- Instrumental effects → advance modeling/ calibration + analysis mitigation

CMB from the ground (sensitivity)



CMB from the ground (the last decade)

Science-driven expansion of capabilities + cost-driven consolidation of teams

- Late 2010s:

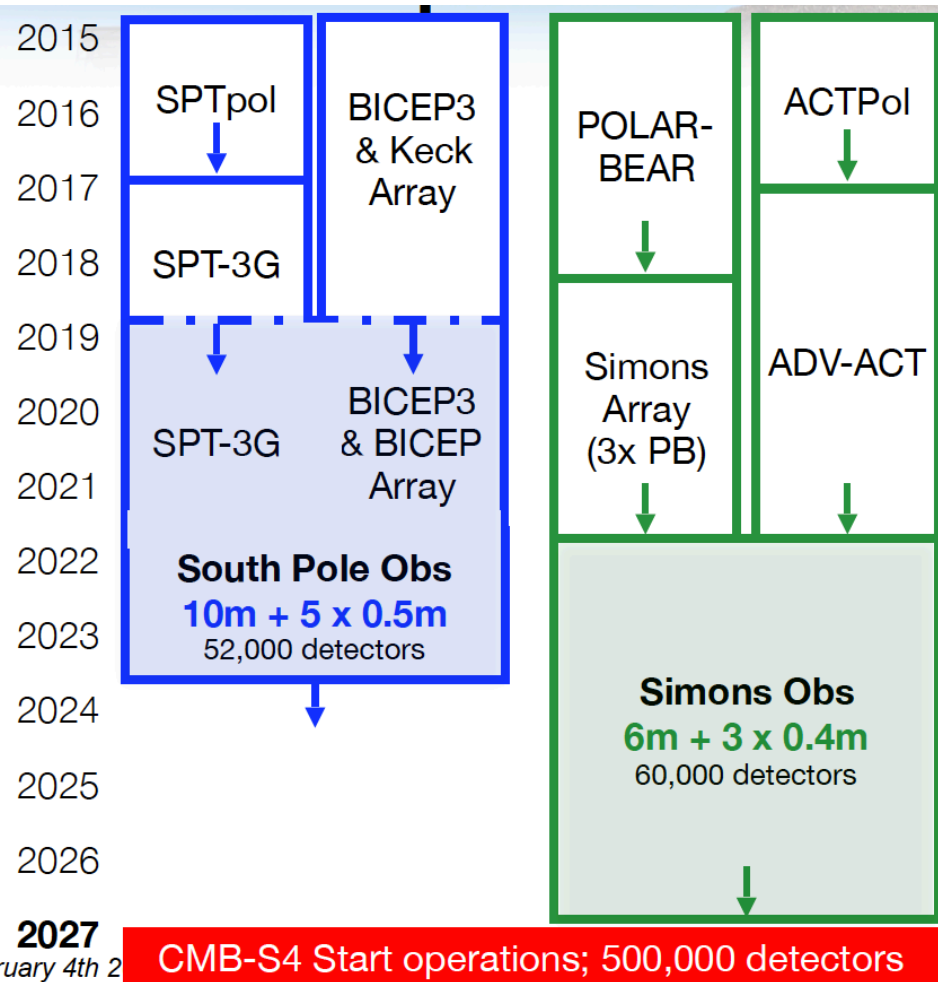
- single-site, single resolution
- O(10K) detectors
- ACT, BICEP/Keck, POLARBEAR, SPT, etc

- Early 2020s:

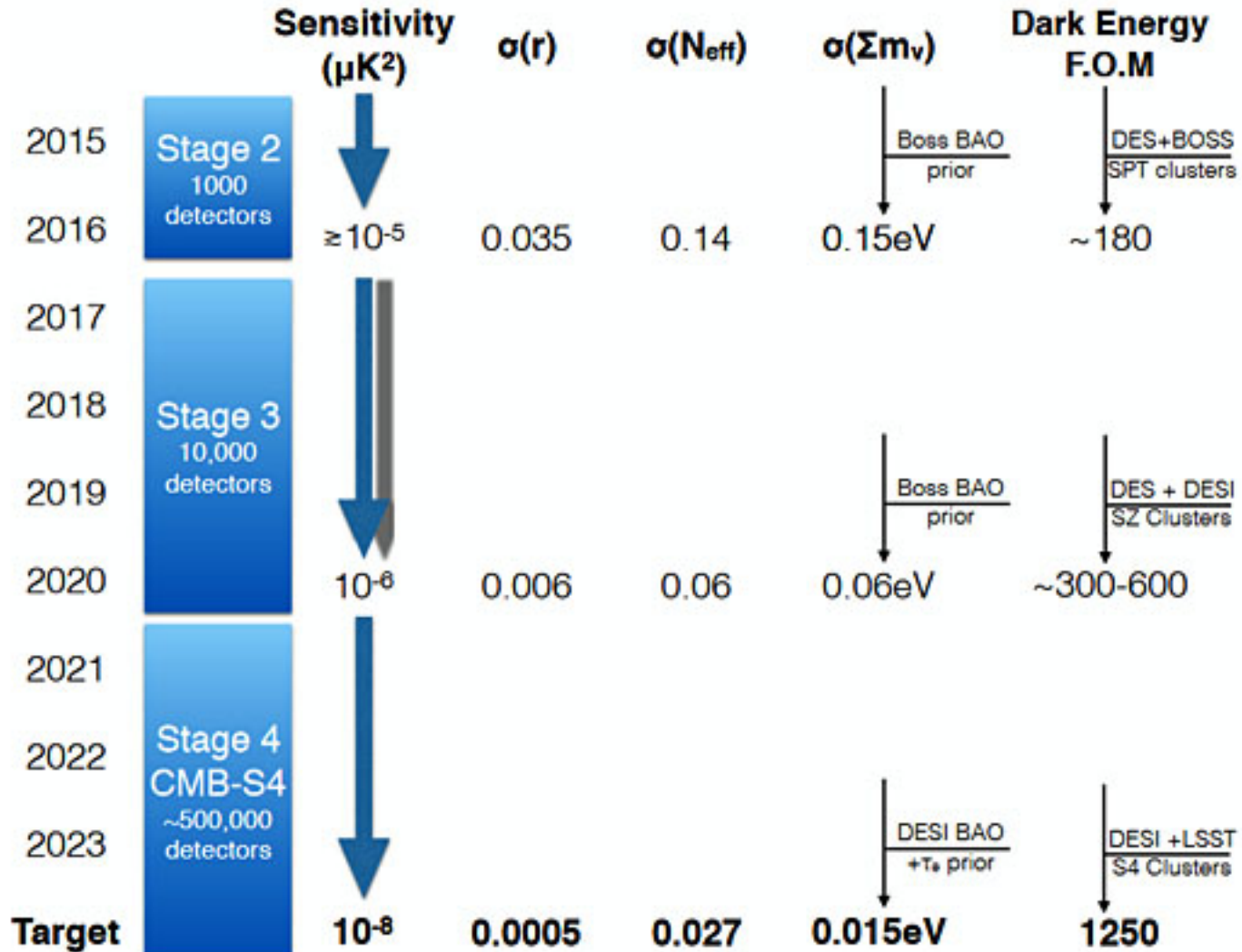
- single-site, dual-resolution
- O(50K) detectors
- Simons Observatory (SO), South Pole Observatory (SPO)

- Late 2020s:

- dual-site, dual-resolution
- O(500K) detectors
- **CMB-S4**



Ground-based generations



This talk is about ...

- Simons Observatory (nominal and – briefly – enhanced)
 - ➔ will make a significant progress over current state on the intermediate timescale (~ 5 years)
- CMB-S4:
 - ➔ an ‘ultimate’ effort aimed at crossing the key, science driven thresholds in the science goals.

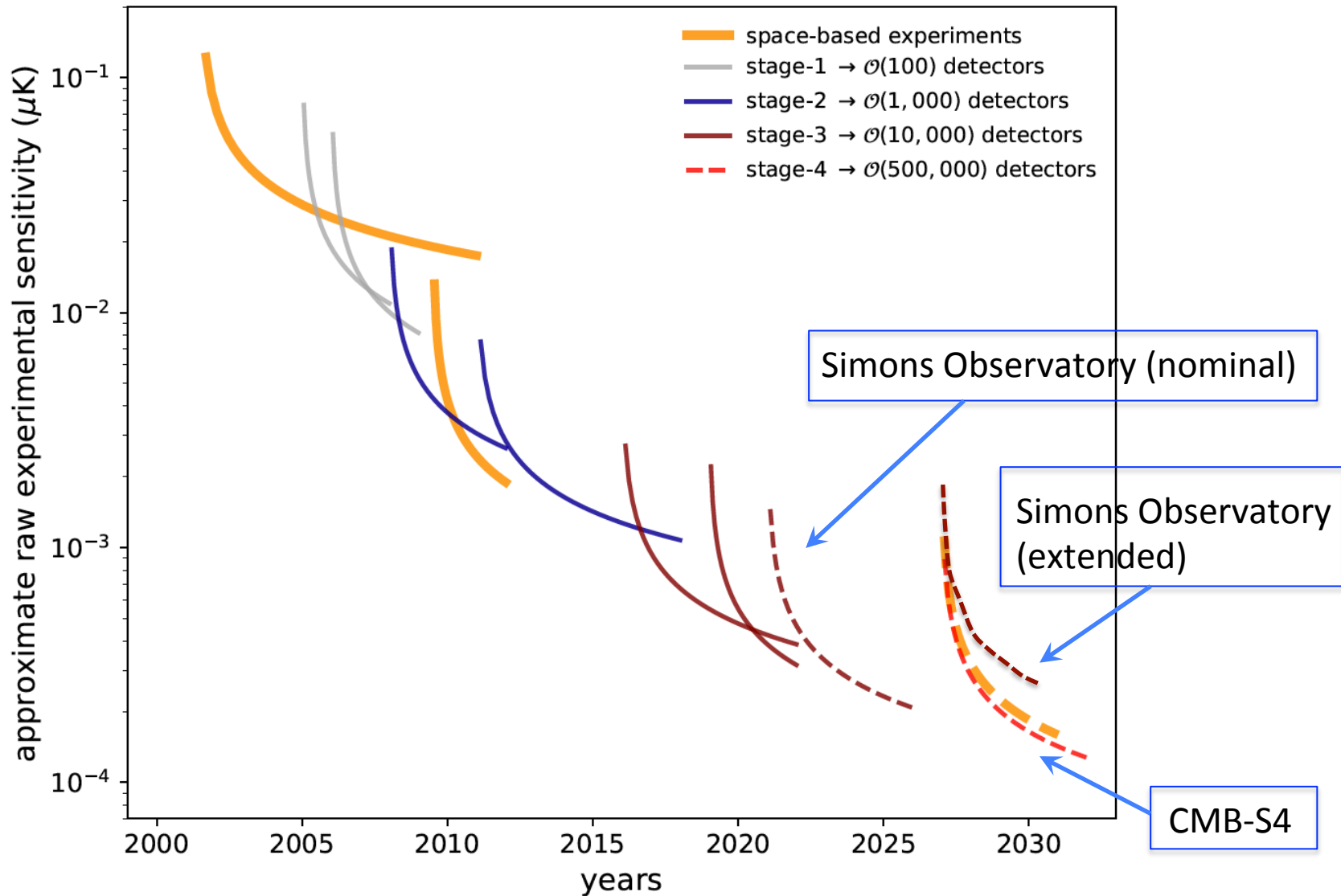
THE SETUP

THE FINAL ASSAULT

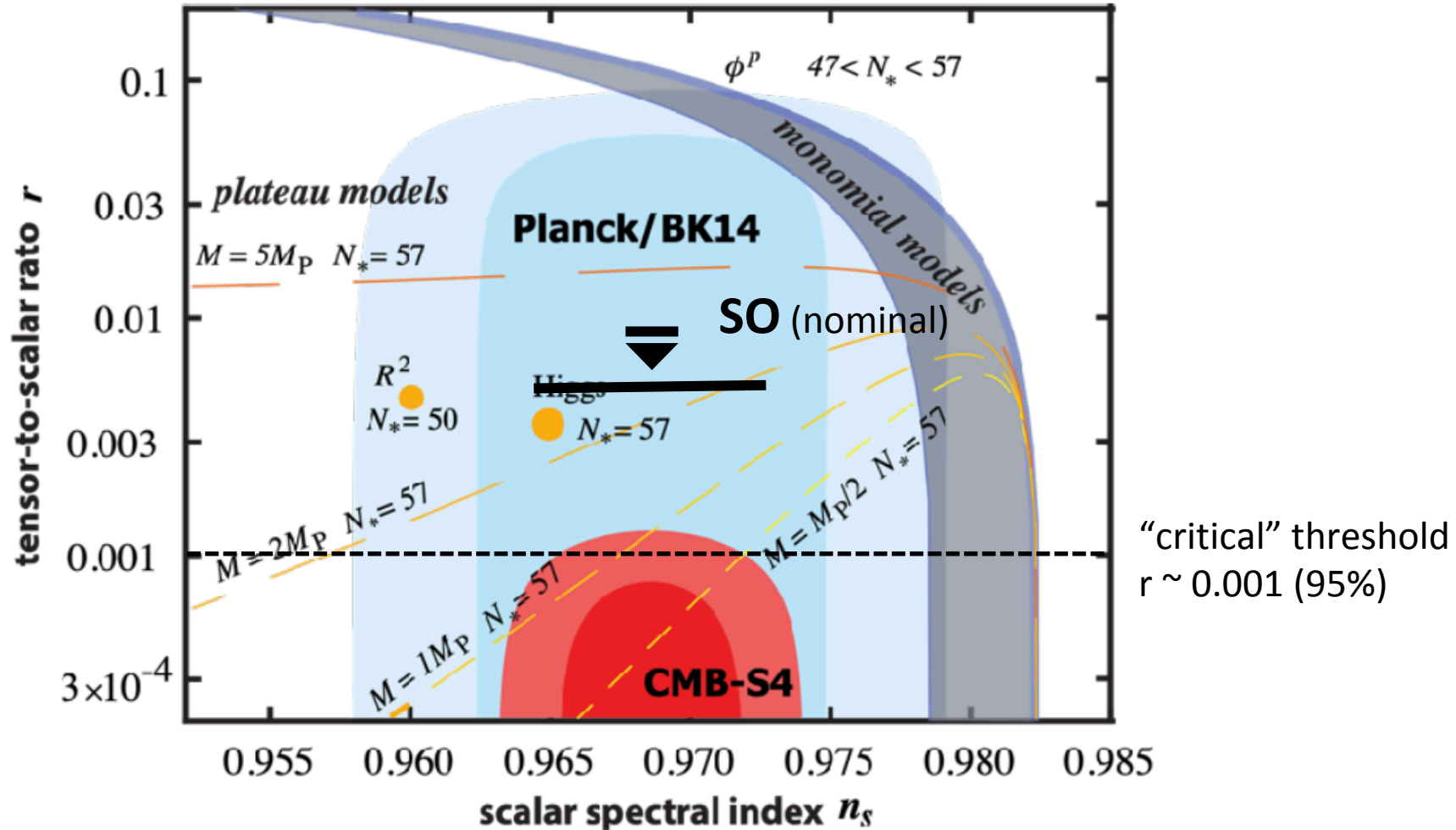
A history bit ...

- SO is a result of a merger of two major experiments:
 - Atacama Cosmology Telescope (ACT) and POLARBEAR/Simons Array
- CMB-S4 is a project which brings together essentially all major US-led CMB experiments:
 - Including ACT, SPT, BICEP/Keck, POLARBEAR, ...
 - And two sites: South Pole and Atacama ...
- Both mergers are driven by the science goals and the funding considerations.

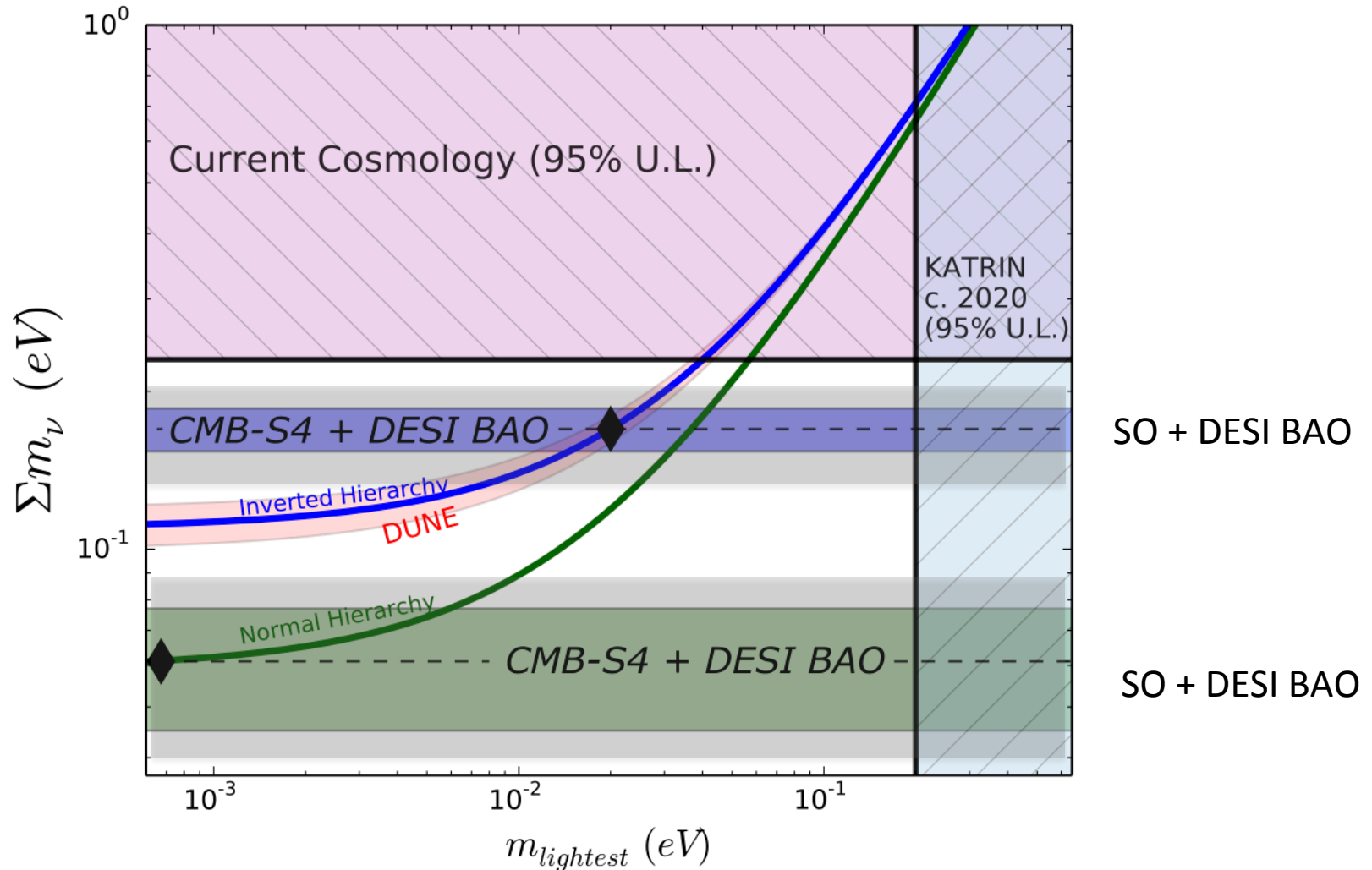
CMB from the ground (sensitivity)



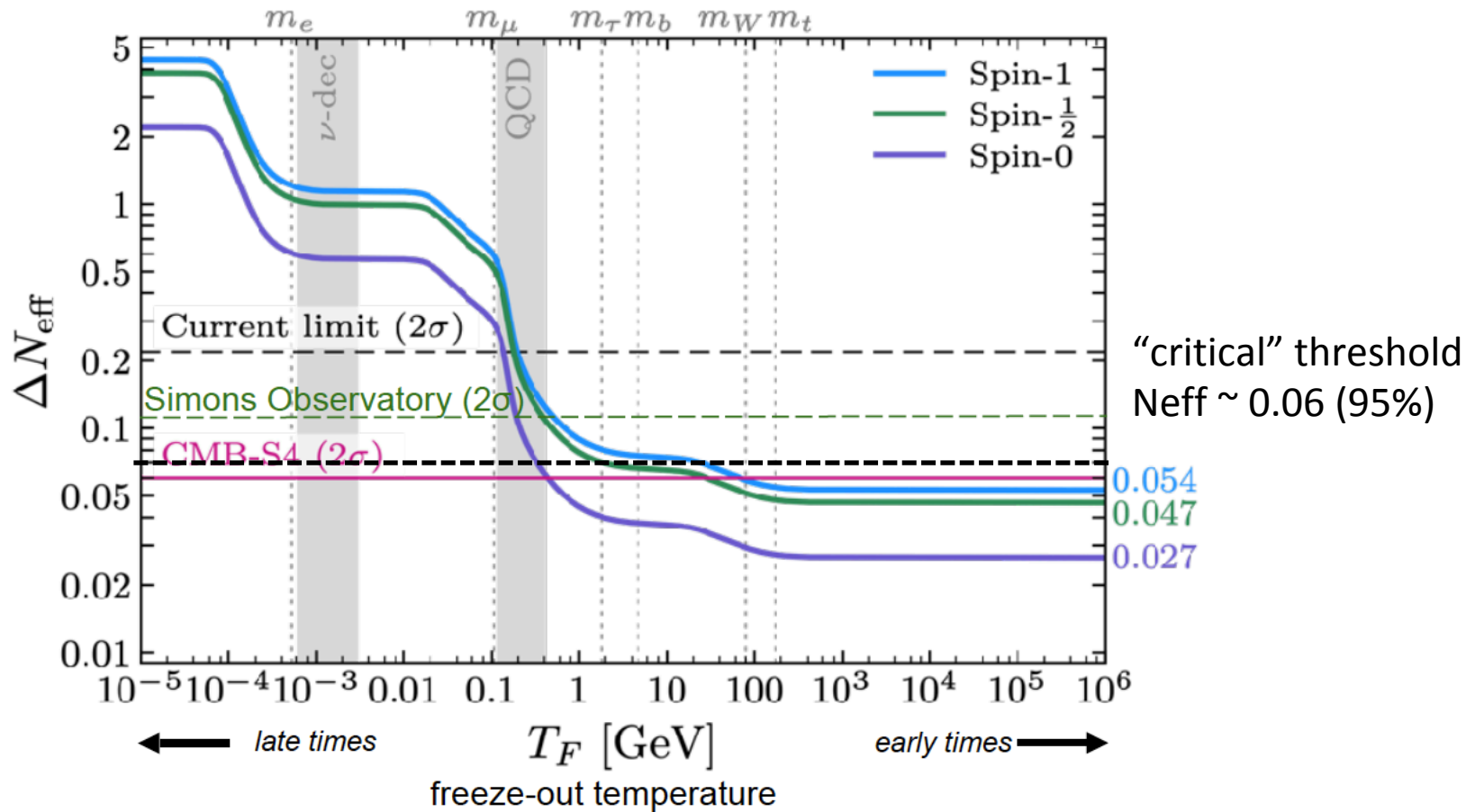
Science goals (B-modes)



Science goals (neutrino mass)



Science goals (light relics)

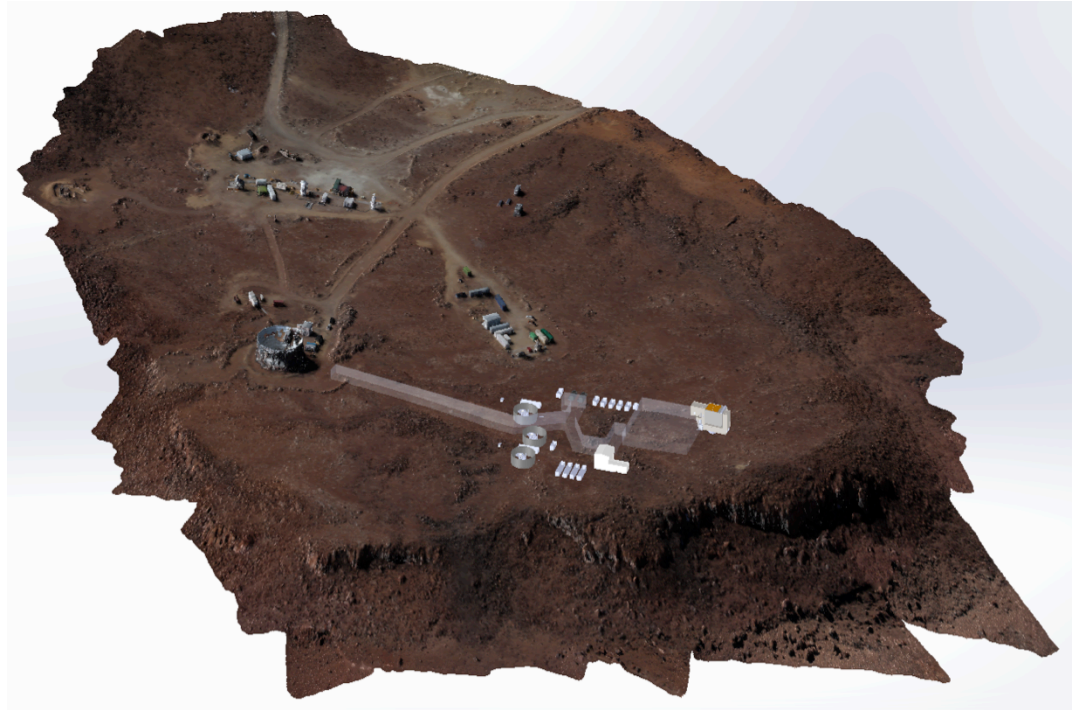


Legacy science

- Transients,
- Galactic science ...
- Planet X (9);
- ...

Simons Observatory - intro

- A major Stage-III CMB experiment operating from the Atacama site in Chile.
- A result of a merger of POLARBEAR/Simons Array and ACT teams.
- Multiple telescopes with a range of apertures permitting to target small and large angular scale science.
- Pathfinder for Stage-IV efforts.



The Simons Observatory

United States

- Arizona State University
- Carnegie Mellon University
- Center for Computational Astrophysics
- Cornell University
- Florida State
- Haverford College
- Lawrence Berkeley National Laboratory
- NASA/GSFC
- NIST
- Princeton University
- Rutgers University
- Stanford University/SLAC
- Stony Brook
- University of California - Berkeley
- University of California – San Diego
- University of Michigan
- University of Pennsylvania
- University of Pittsburgh
- University of Southern California
- West Chester University
- Yale University

Japan

- KEK
- IPMU
- Tohoku
- Tokyo
- Kyoto

- **10 Countries**
- **40+ Institutions**
- **306 Researchers**

Canada

- CITA/Toronto
- Dunlap Institute/Toronto
- McGill University
- Perimeter Institute
- University of British Columbia

Chile

- Pontificia Universidad Catolica
- University of Chile

Europe

- APC – France
- Cambridge University
- Cardiff University
- IJCLab - France
- Imperial College
- Manchester University
- Oxford University
- SISSA – Italy
- University of Sussex

South Africa

- Kwazulu-Natal, SA

Australia

- Melbourne

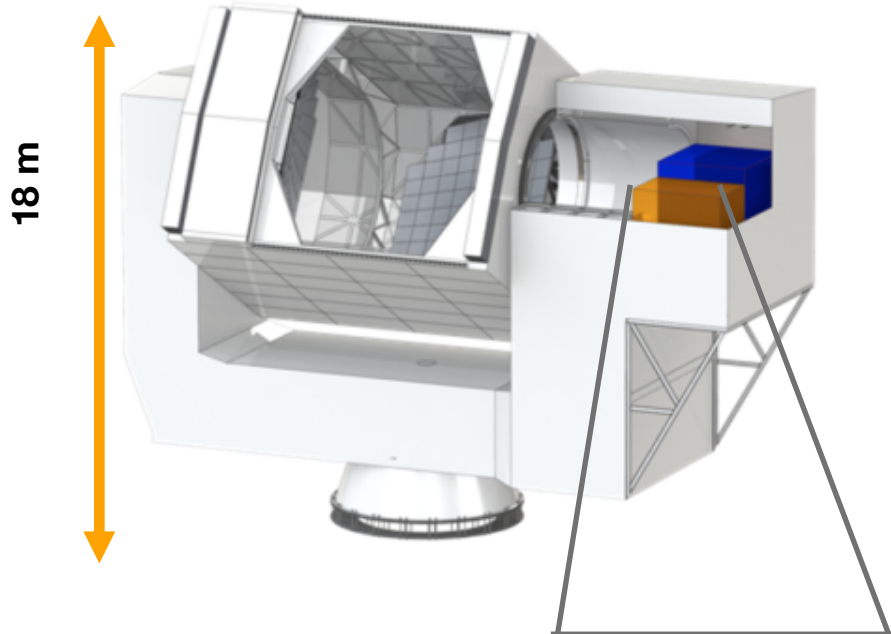
Middle East

- Tel Aviv



Simons Observatory - telescopes

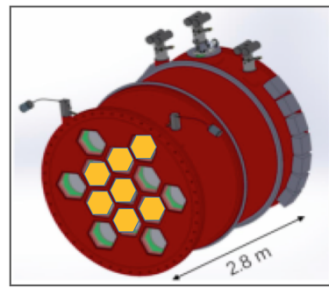
Large Aperture Telescope



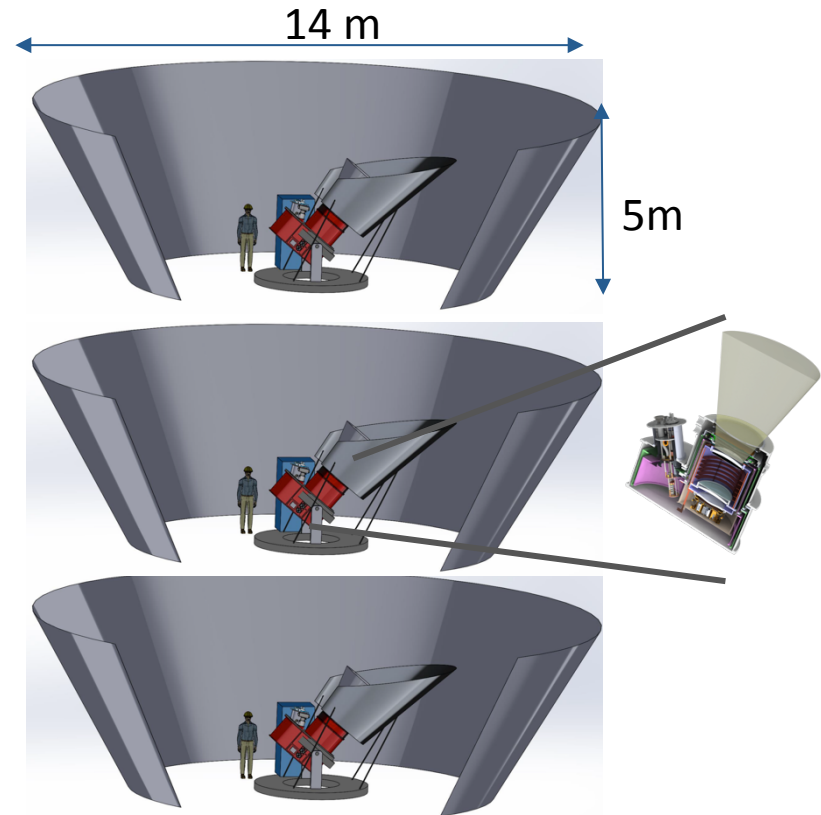
6 m crossed Dragone coupled to 13 optics tubes,

SO-Nominal uses 7 tubes, with dichroic pixels:

- One tube: 30/40 GHz
- Four tubes: 90/150 GHz
- Two tubes: 220/270 GHz



Small Aperture Telescopes



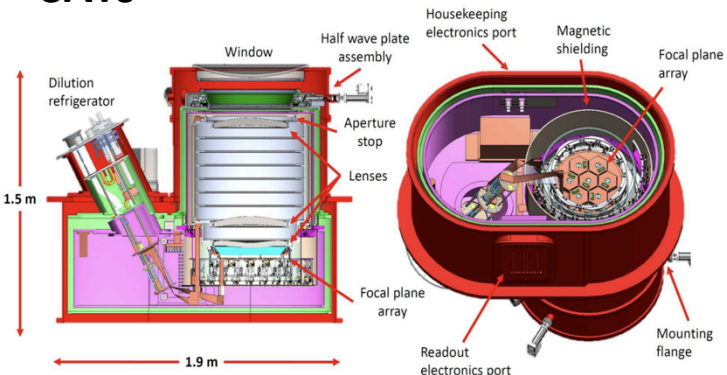
SO-Nominal deploys three refractors 42 cm in diameter, rotating half-wave plate.

Dichroic pixels:

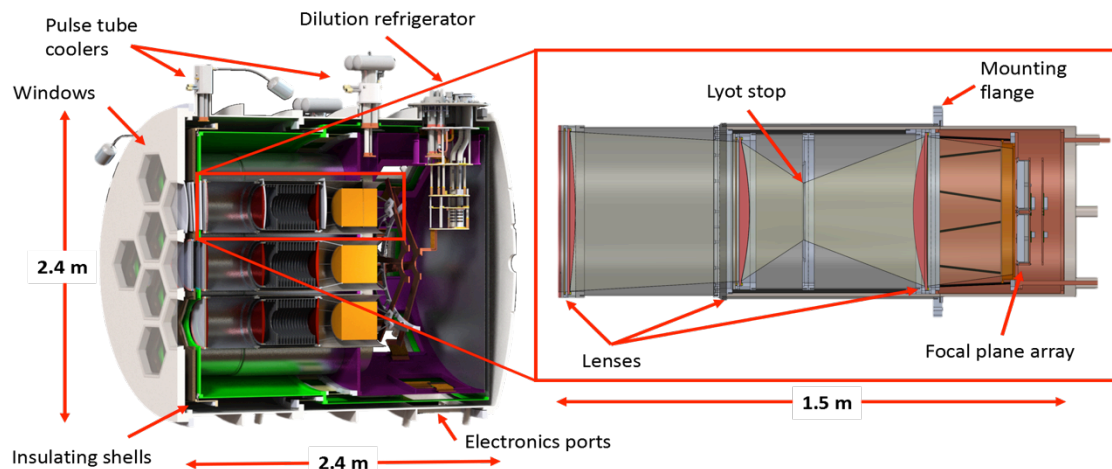
30/40 | 90/150 | 220/270 GHz

SO – technology

SATs

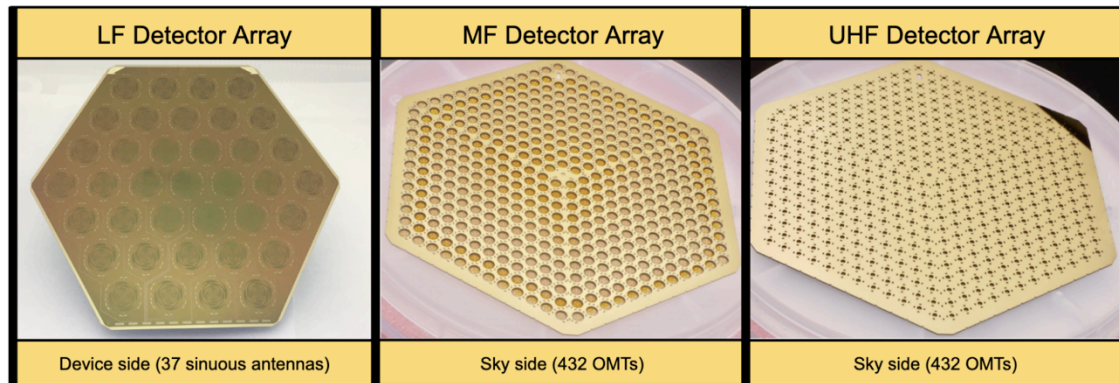


LAT



+ 910x μ mux to read closely packed Arrays of detectors

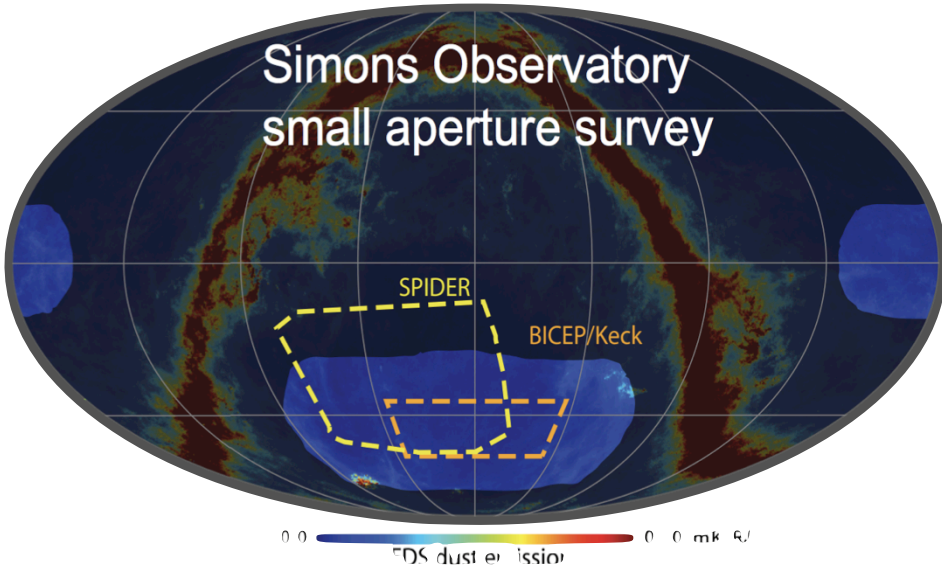
6 enabling technologies identified:
LAT, LATR, μ mux, large AR coating,
Large filters, HWP



100 mK TESes in dichroic arrays

Simons Observatory - surveys

Simons Observatory
small aperture survey



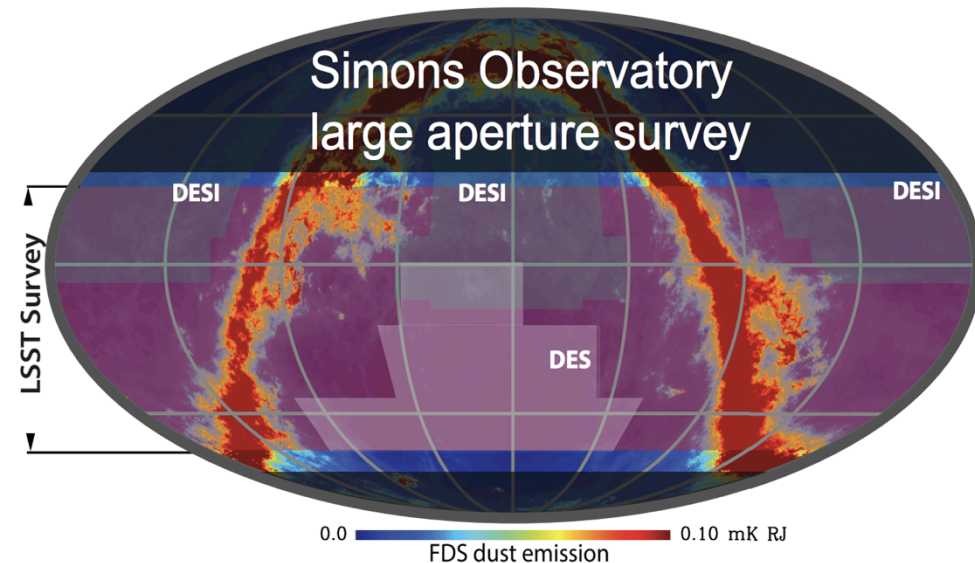
Effective $f_{\text{sky}} \sim 10\%$

Optimized for Primordial B-modes

Small-scales science goals
require wide a survey ...

- Baseline $f_{\text{sky}} \sim 0.4$, Potentially as large as 0.7
- Overlap with Rubin-LSST, DESI, Euclid
- Observing cadence being refined for both cosmology and transient/Planet 9 searches

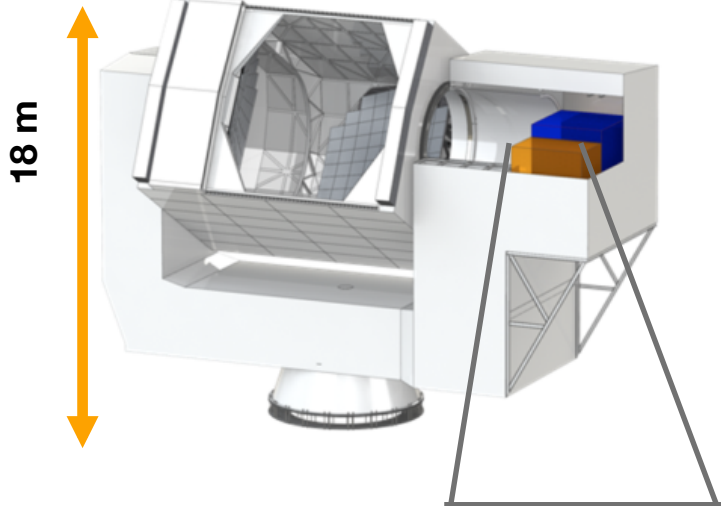
Simons Observatory
large aperture survey



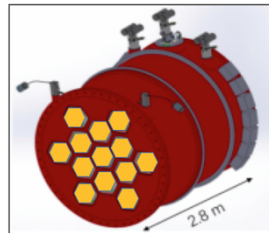
Simons Observatory enhanced

(to double mapping speed)

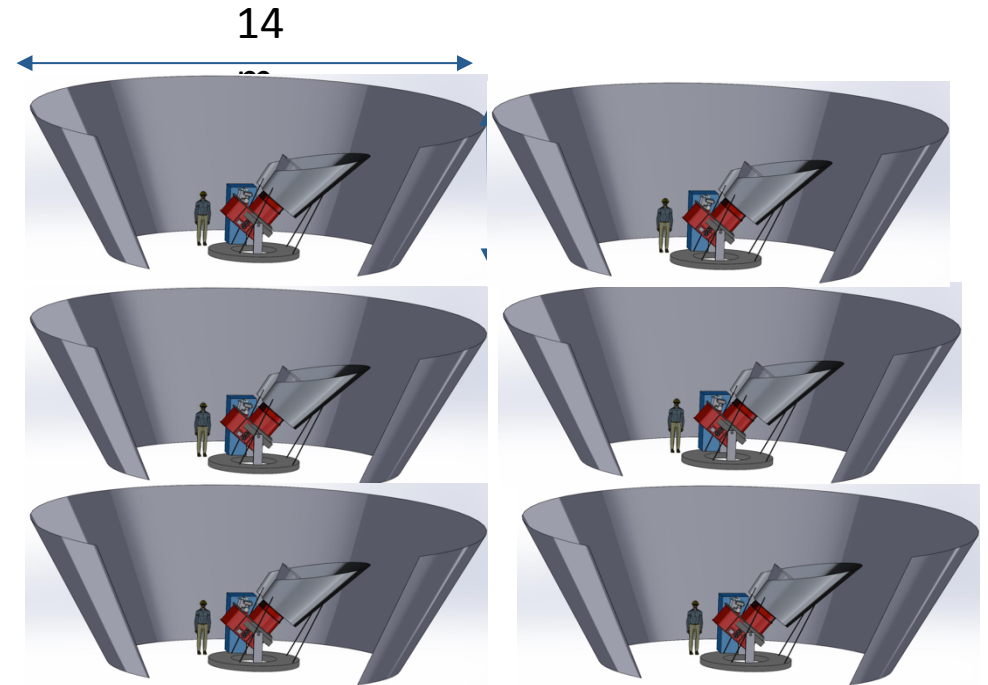
Large Aperture Telescope



SO-Enhanced fills
all **13 tubes** on
the LAT.

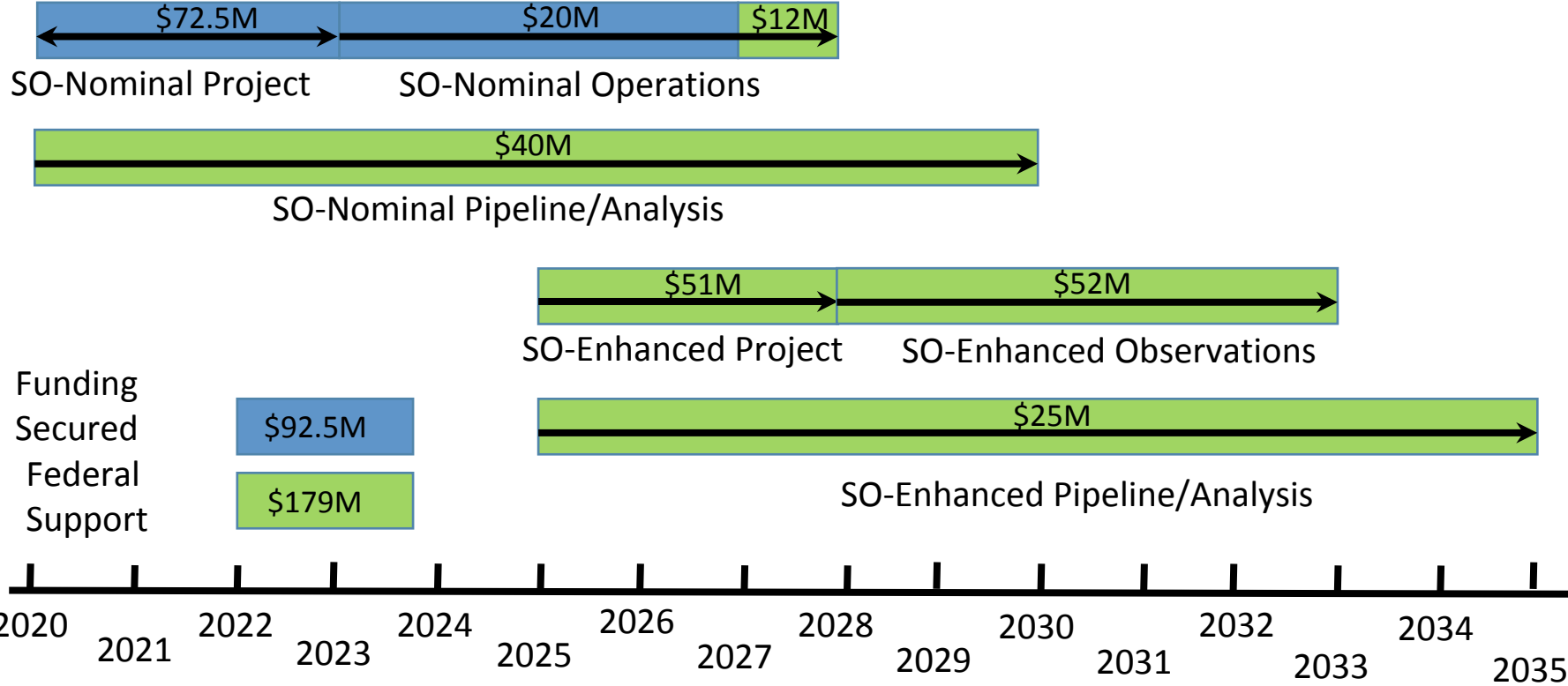


Small Aperture Telescopes



SO-Enhanced adds 3 SATs to SO-Nominal

Simons Observatory - timeline



SO@IN2P3

- Strong involvement in data analysis – building on over a decade of involvement in POLARBEAR/Simons Array projects (Stompor, Errard) and more recently in ACT (Louis).
- Now two IN2P3 labs, APC, IJCLab, and the total of 7 researchers (Bartlett, Errard, Ganga, Garrido, Louis, Melin (CEA), Stompor) + 3 PhD students.
- Leadership in B-mode science working group (Errard, Stompor) and small-scale science working group (Louis), strong contribution to pipeline development.
- Representation in the governance: SO Theory and Analysis Committee (Errard), SO Membership and Data Management Committees (Stompor).

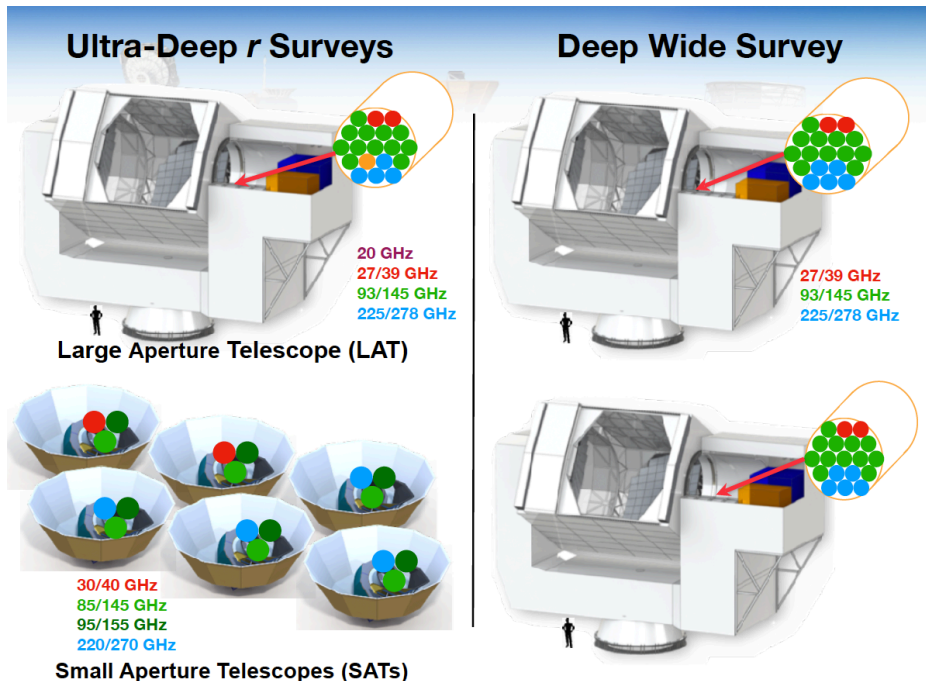
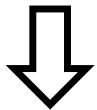
CMB-S4 – intro

- An ‘ultimate’ ground based CMB experiment design to exploit the scientific potential of CMB anisotropies reaching some critical thresholds.
- Brings together almost all CMB community in the US and big part of the international community
- Multiple telescopes operating from multiple sites.
- Will deploy $\sim 500,000$ detectors with the total price tag of ~ 0.5 B\$.

CMB-S4 – instruments

- South Pole:

18 x 0.55m small refractor telescopes ~150,000 detectors with 8 bands, a dedicated de-lensing 6m telescope with 120,000 detectors, 7 bands



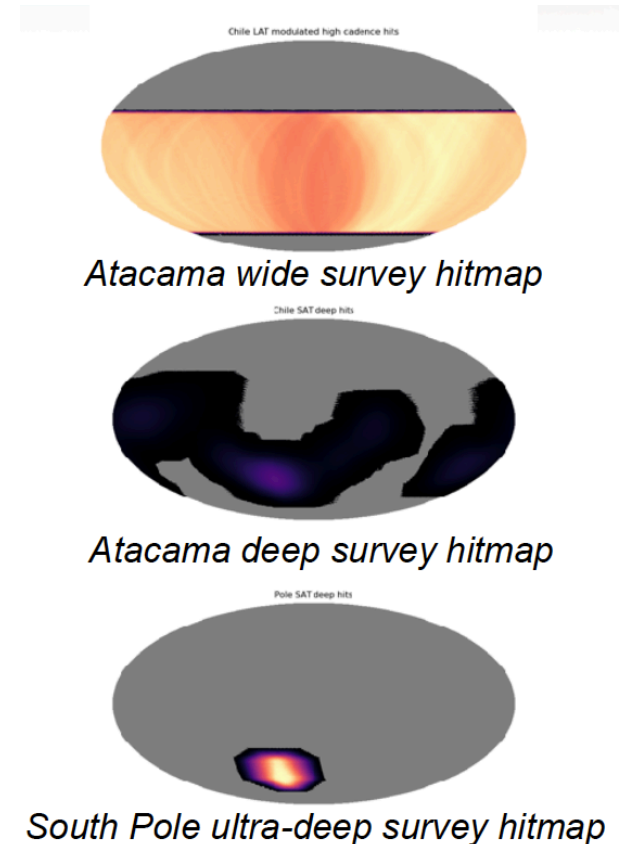
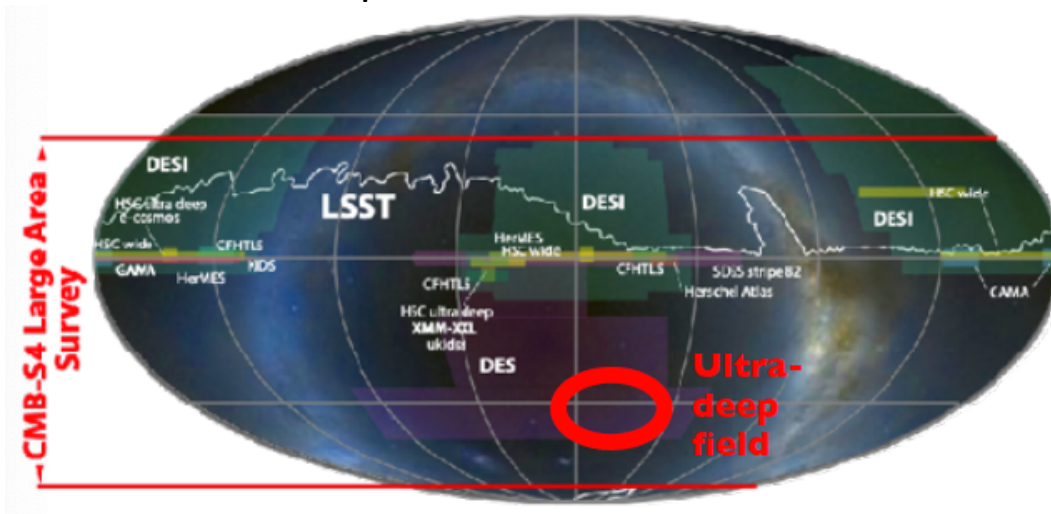
- Chile

← 2x 6m telescope with 120,000 detectors each and 7 bands.

- The instrument will feature kilo-pixel arrays, dichroic, horn-coupled, superconducting TES detectors and time-domain multiplexing.

CMB-S4 - observations

- Two surveys:
 - Deep wide Neff and Legacy Survey with 2 x 6m telescopes targeting ~60% of sky with 240,000 detectors over 6 bands. From Chile over 7 yrs.
 - Ultra-deep “r” survey with 18 x 0.55m small refractor telescopes targeting $\geq 3\%$ 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, with option to move up to 9 SATs to Chile.



CMB-S4 collaboration

- 217 Members: ~60% SO, ~40% SPO
- 75 Institutions
- 12 Countries including France;
- 7 members 6 (Bartlett, Delabrouille, Errard, Ganga, Stompor, Tristram) at IN2P3 (APC, IJCLab), 1 at INSU (IAP) – personal, “best-of-effort” involvement.

CMB-S4 - schedule

- August 2020 - DOE lead lab selection (LBNL);
- 2020 - NSF CDR for MREFC
- 2021 - Decadal Survey recommendation; DOE CD-1/3a, NSF PDR
- 2022 - DOE CD-2, NSF FDR
- 2023 - DOE CD-3
- 2024 - NSF MREFC
- 2028 - DOE CD-4 ← Observations start !!!

CMB-S4 at IN2P3

- Strong interest in finding a place within the CMB-S4 collaboration beyond data analysis.
- Relevant expertise from past/current projects:
 - QUBIC, NIKA, etc. but also Planck.
- On-going discussions of how to leverage those and our current involvement in intermediate term projects, e.g., SO:
 - need in-depth study of potential options:
 - expect converging within ~6 months from now.