CMB-S4 Update

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for the CMB-S4 Collaboration

CMB-S4
Next Generation CMB Experiment

the development trail

- Snowmass Physics Planning exercise (2013)
  - Influential CMB community papers for Snowmass:
    - Inflation Physics from the Cosmic Microwave Background and Large Scale Structure, Astroparticle Physics 63, 66 (2015), arXiv:1309.5381
    - Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure, Astroparticle Physics 63, 55 (2015), arXiv:1309.5383
  - CMB "stages" and development of the CMB-S4 concept: What we need to build to obtain our science goals.

- Input to Particle Physics Project Priority Panel, P5 (2013-2014)

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CMB Stages

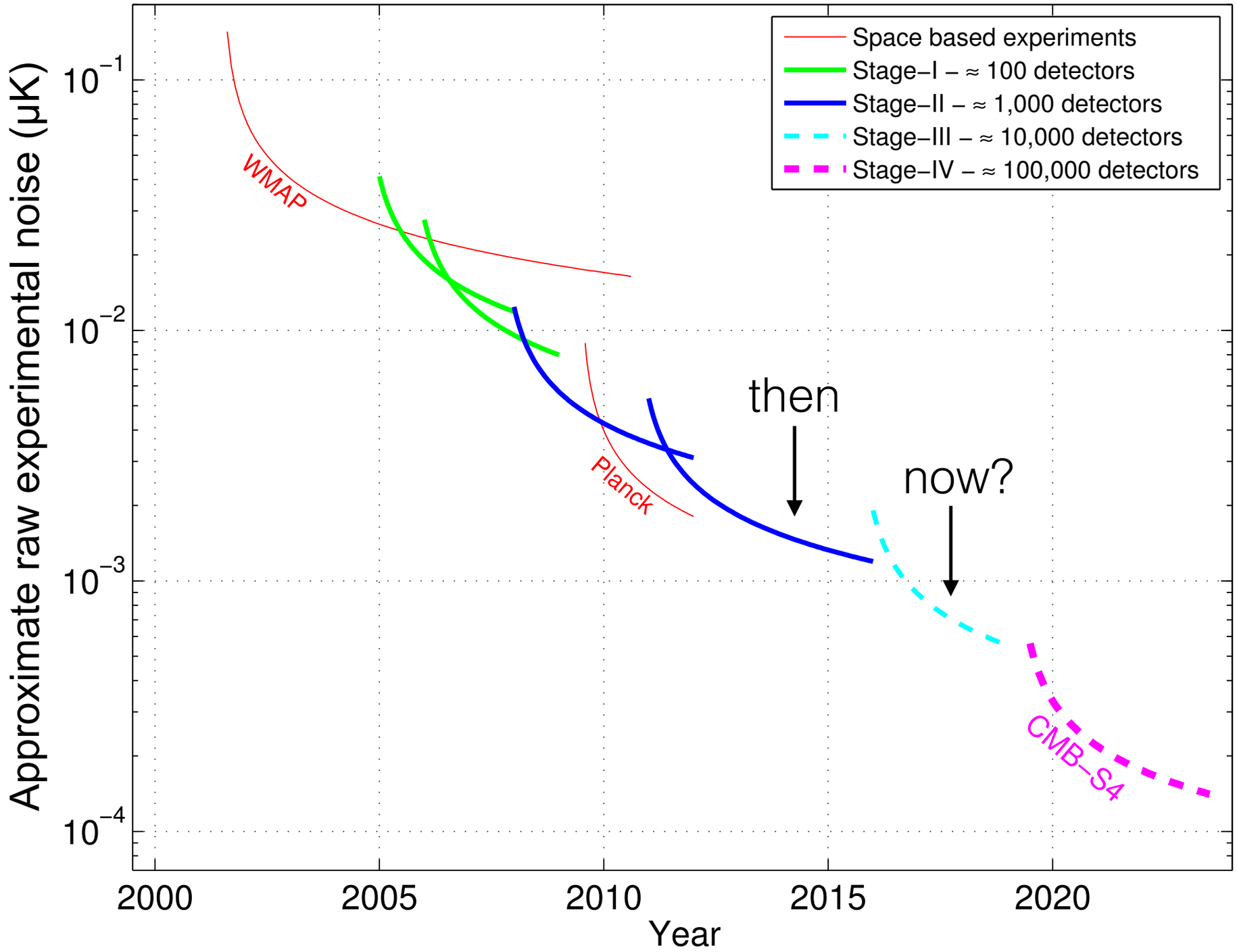

Figure by Clem Pryke for 2013 Snowmass documents

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Stage 4 CMB experiment: CMB-S4

- **A next generation ground-based program to pursue inflation, neutrino properties, thermal relics, dark energy and new discoveries.**
- **Greater than tenfold increase in sensitivity of the combined Stage 3 experiments (>100x current Stage 2) to cross critical science thresholds.**
- **O(500,000) detectors spanning 30 - 300 GHz using multiple telescopes, large and small, at South Pole and Chile to map most of the sky, as well as deep targeted fields.**
- **Broad participation of the CMB community, including the existing CMB experiments (e.g., ACT, BICEP/Keck, CLASS, POLARBEAR/Simons Array, Simons Obs & SPT), National Labs and the High Energy Physics community.**
- **International partnerships expected and desired.**

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

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

Science Book Figure 3

		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\approx 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	0.006	0.06	0.06eV	~300-600
2021 +n?	Stage 4 CMB-S4 ~500,000 detectors					
2022 +n?						
2023 +n?					DESI BAO +τ_e prior	DESI +LSST S4 Clusters
Target		**10^{-8}**	**0.0005**	**0.027**	**0.015eV**	**1250**

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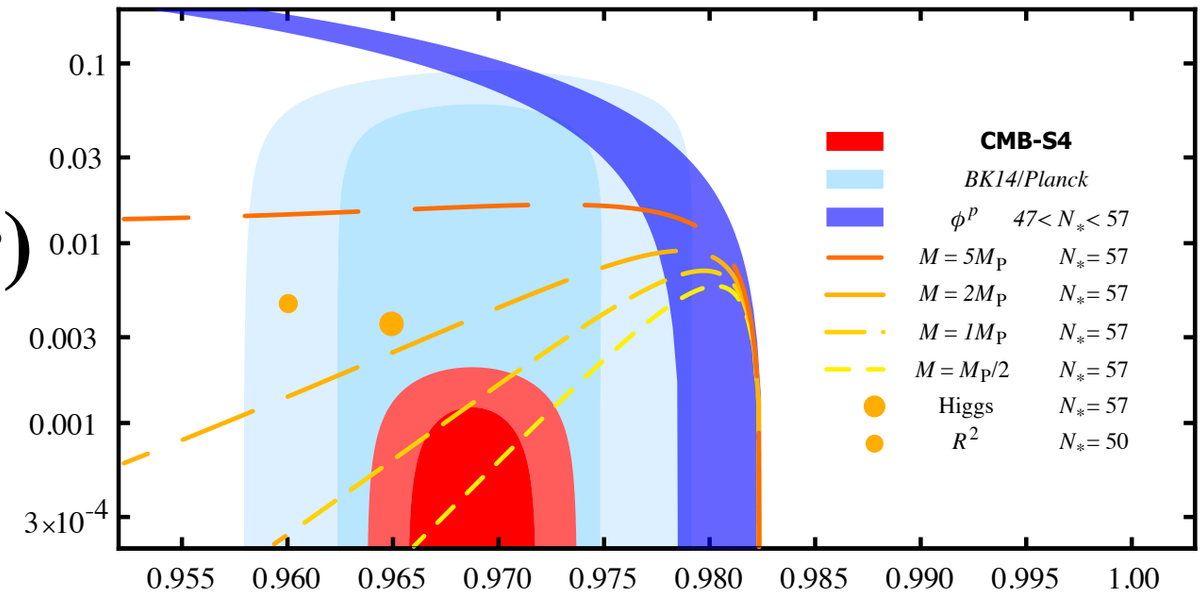
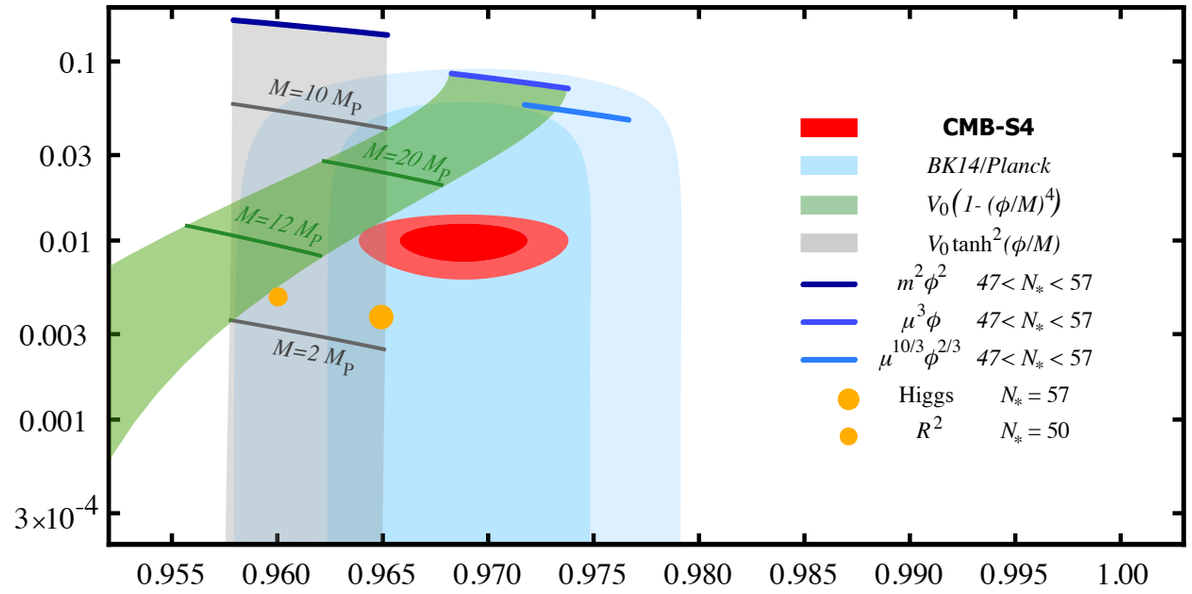
SB projected inflation reach of CMB-S4

for nominal 3% f_{sky} and 10^6 realistic detector years

r = 0



r = 0.01



A detection of primordial B modes with CMB-S4 would provide evidence that the theory of quantum gravity must accommodate a Planckian field range for the inflaton.

Conversely a non-detection of B modes with CMB-S4 will mean that a large field range is not required.

Targeting r upper limit of 0.001 at 95% C.L.

This is the driving specification for the CMB-S4 deep survey

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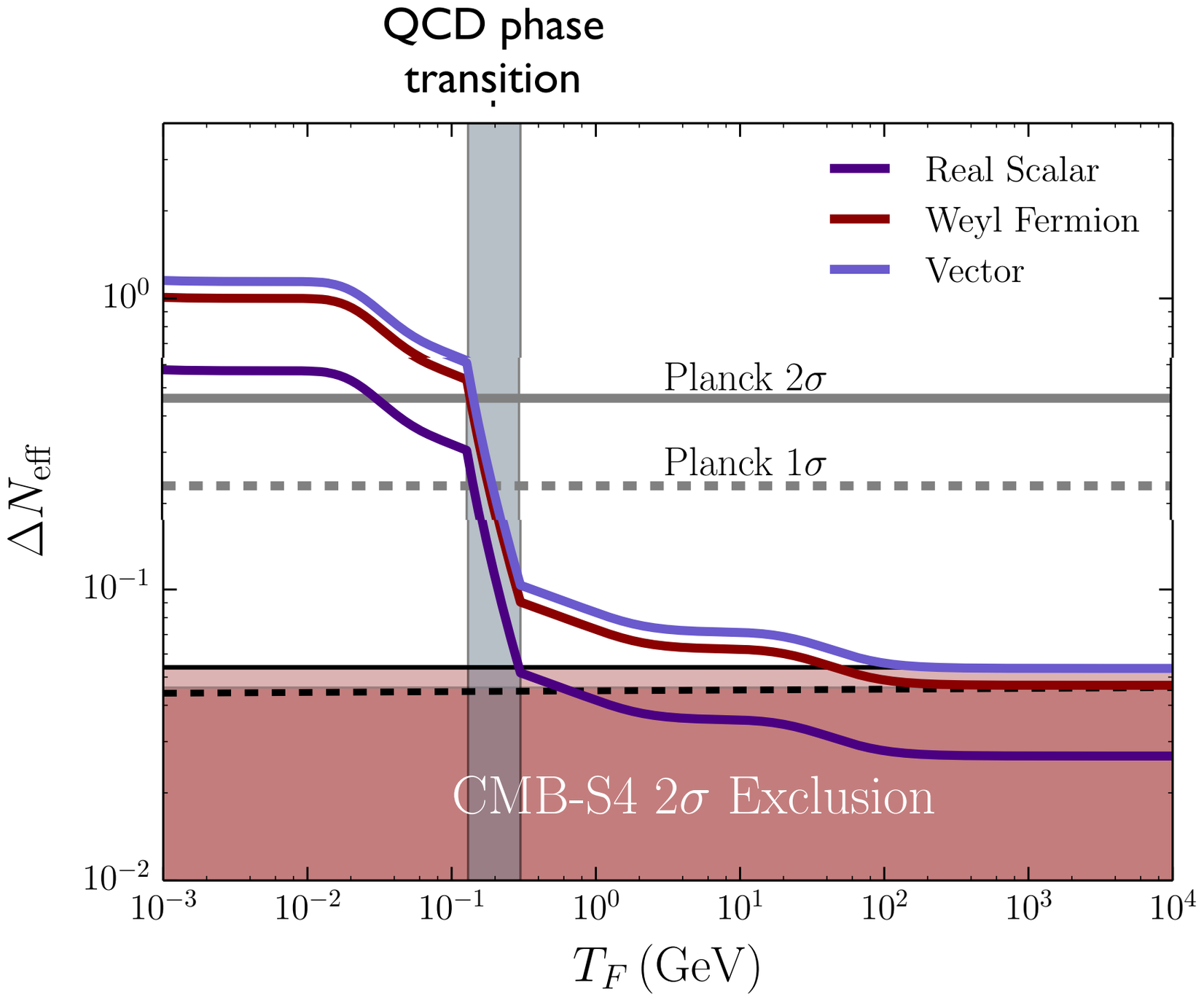
N_{eff} - thermal relics



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

- Natural target:
  $\Delta N_{eff} < 0.027$ limits axion SM couplings for $T_{freeze\text{-}out} < T_{reheat}$

This is the driving specification for the CMB-S4 wide survey

Green, Meyers in CMB-S4 Science Book
Also Baumann, Green & Wallisch, "A New Target for Cosmic Axion Searches" arXiv:1604.08614

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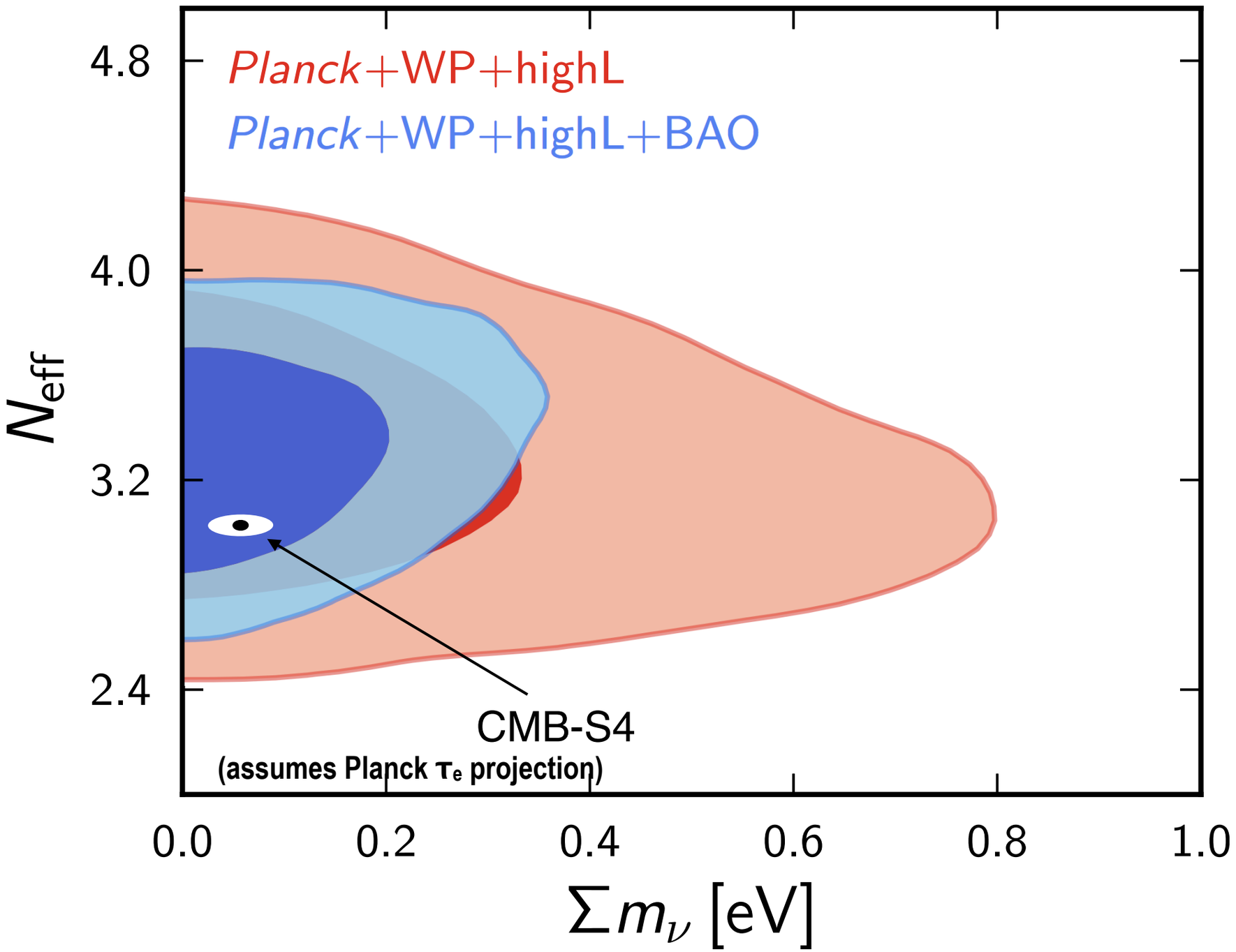
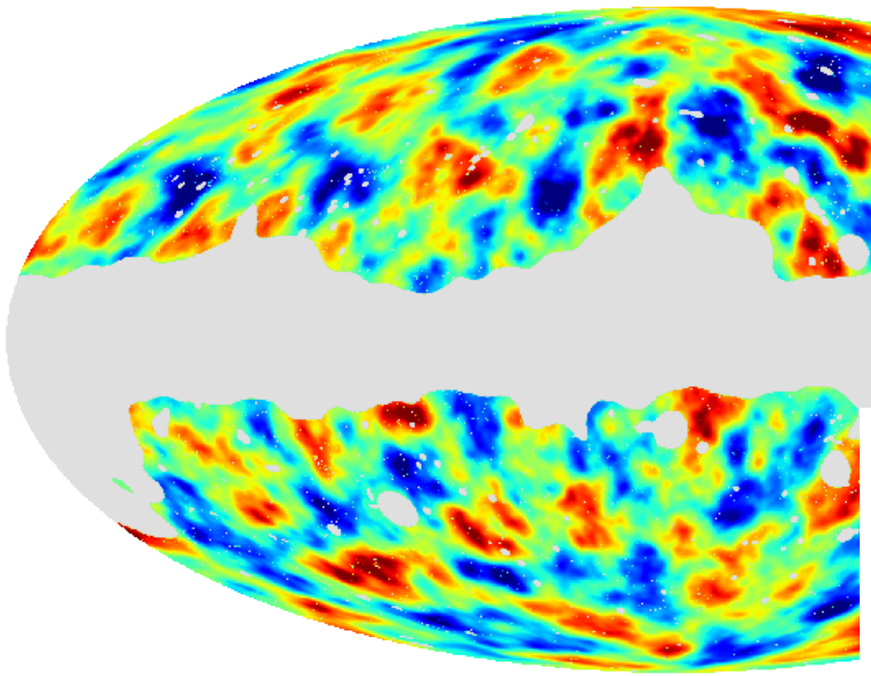
Snowmass CMB-S4 N_{eff} - Σm_ν projections



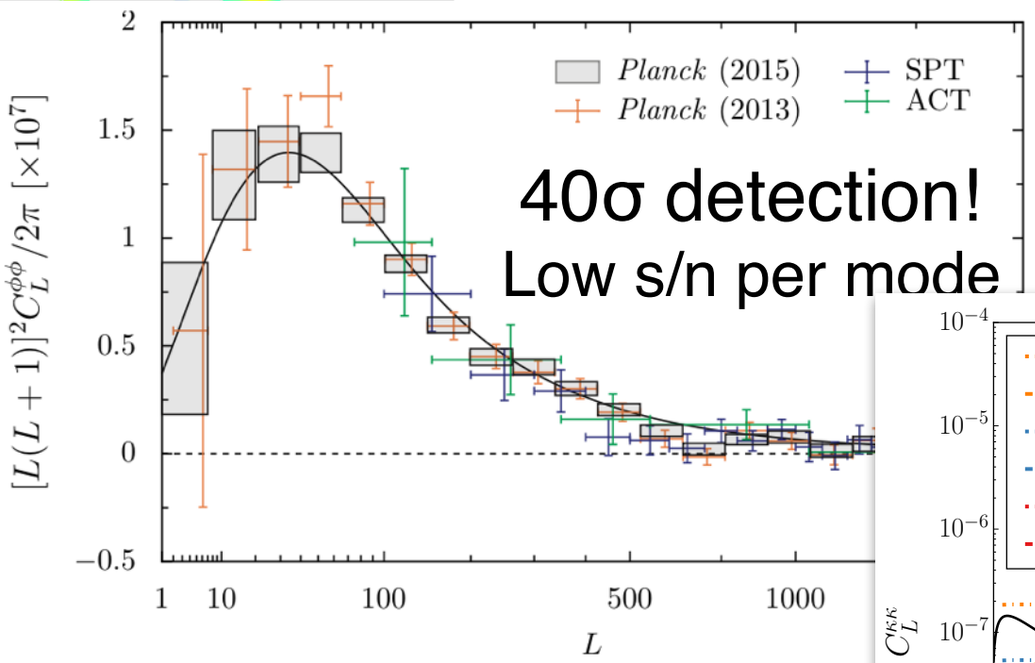
CMB-S4 forecast: arXiv:1309.5383; see also Wu et al, ApJ 788,138 (2014)

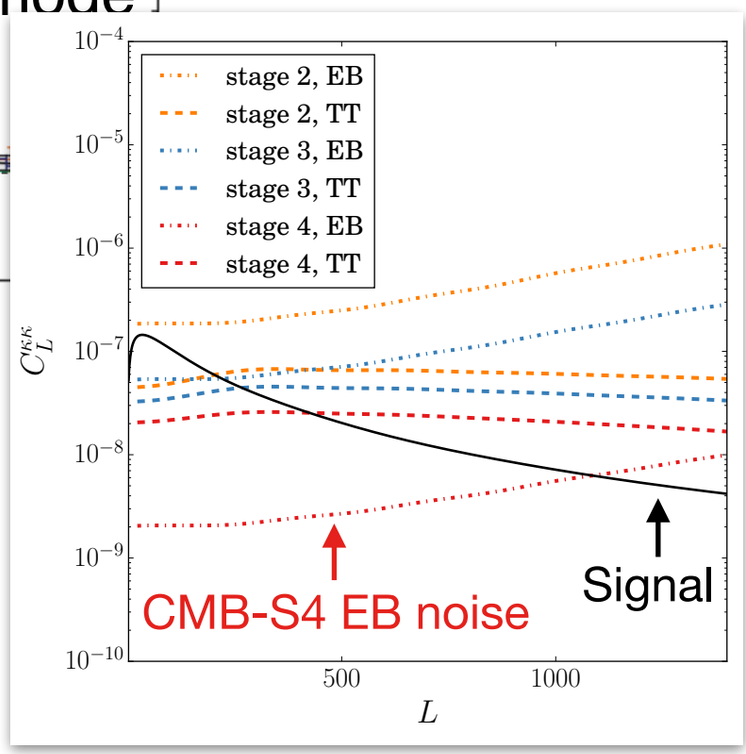
CMB lensing

Planck lensing potential reconstruction
(projected mass map).



Planck XV arXiv:1502.01591





CMB-S4 will measure modes with s/n > 1 up to L ~ 1100 over most of the sky.

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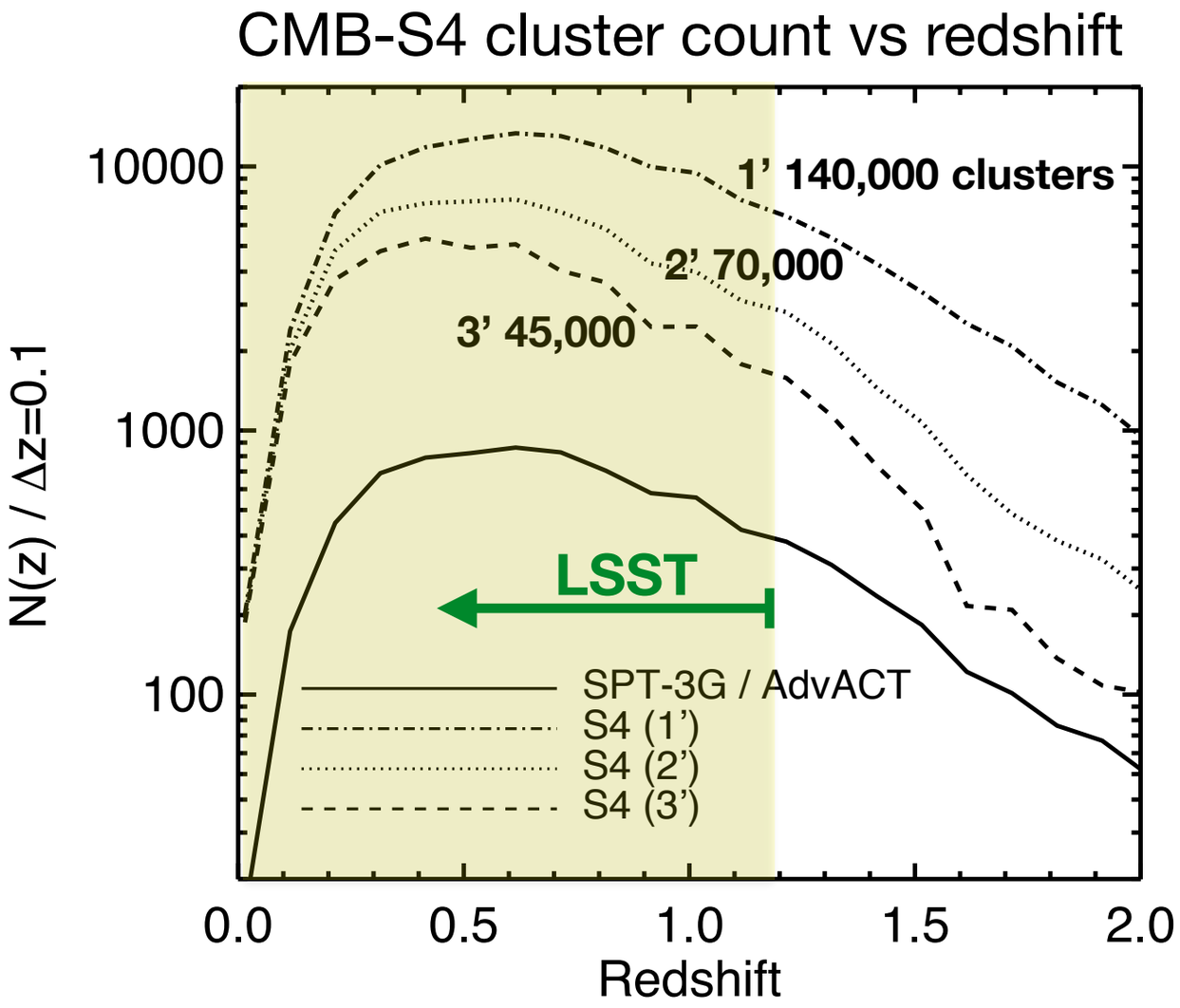
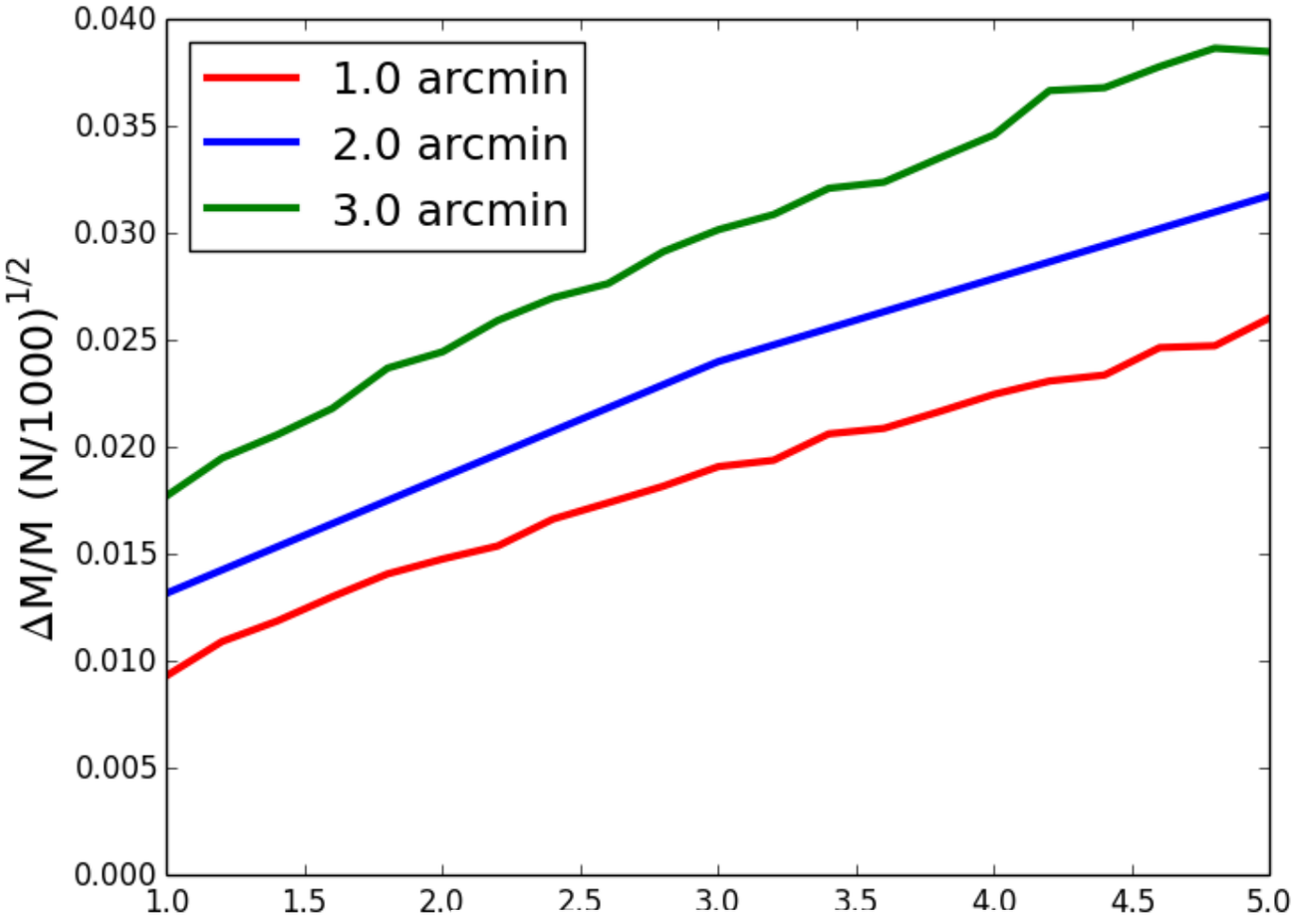
CMB-S4 SZ cluster projections and lensing mass calibration for dark energy via growth of structure





CMB-S4 will provide the definitive survey of massive, high-z clusters (z>1) with **"built in" mass calibration**

Strong driver for high angular resolution

	2.0'	**1.5'**	**1.0'**
Total	43800	76800	122800
z >1.5	1420	3640	7850
z > 2.0	180	560	1390

From CMB-S4 Science Book

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Cosmic Structure Science

(significant effort over last year on CMB-S4 "high-ℓ" science)

see Jim Bartlett's Talk

- **SZ Cluster Cosmology: Dark Energy / Modified Gravity / Neutrino masses**
  - SZ galaxy cluster counts (dN/dz) to z~3
  - mass scaling calibration with CMB-lensing at % level
  - evolution of amplitude $\sigma_8(z)$ at % level
- **The evolution of massive clusters, cluster astrophysics**
  - Unique SZ catalog of clusters at z > 1.5
- **Tracing baryons with stacked kSZ and tSZ maps**
  - Thermodynamics of the circumgalactic medium out to the peak of cosmic star formation
  - Impact of baryon feedback on the matter power spectrum, P(k)
- **Cross-correlation of CMB lensing maps with galaxy density and shear surveys**
- **Constrain reionization of the universe with kSZ**

today's 4 to 6 σ results will be > 500 σ from CMB-S4

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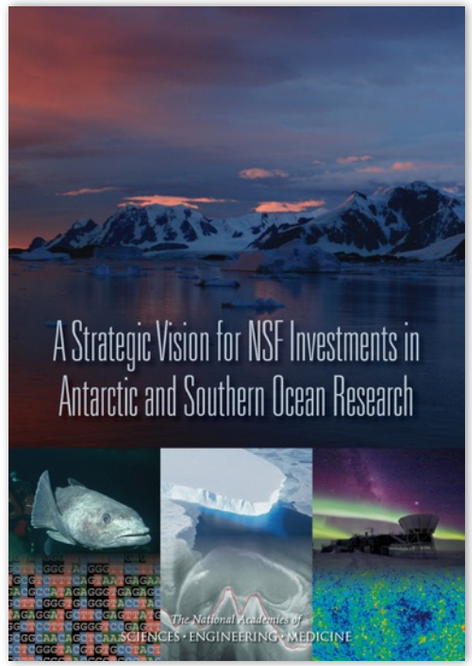
growing support

- P5 report (2014): *Building for Discovery*
  - "Support CMB experiments as part of the core particle physics program. The multidisciplinary nature of the science warrants continued multi-agency support"
  - CMB-S4 project recommended under all budget scenarios
  - Ramp up CMB-S4 project as LSST ramps down (~ FY19)

- NAS/NRC report (2015): *A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research*
  - Recommended continuation of studies of the Cosmic Microwave Background as one of three strategic priorities, specifically calling out role of South Pole in CMB-S4



- AAAC* (2015, 2016, 2017):
  - 2016 report: "We encourage DOE, NSF, and the university community to continue working toward a plan for a future (Stage 4) ground based CMB experiment"

* Astronomy and Astrophysics Advisory Committee

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gaining traction

- CMB-S4 community organization — workshops, working groups, white papers, science and technology books

- DOE HEP Cosmic Frontier CMB Cosmic Vision Group

- Growing involvement of DOE HEP labs. Argonne, Fermilab, LBNL & SLAC working on coordinated R&D plan.

- **Joint DOE and NSF Concept Definition Task Force**

Continuing series of open workshops to advance CMB-S4

U. Minnesota
Jan 16, 2015

U. Michigan
Sep 21-22, 2015

LBNL, Berkeley
March 7-9, 2016

U. Chicago
Sep 19-20, 2016

SLAC, Stanford
Feb 27-28, 2017

Continuing series of open workshops to advance CMB-S4

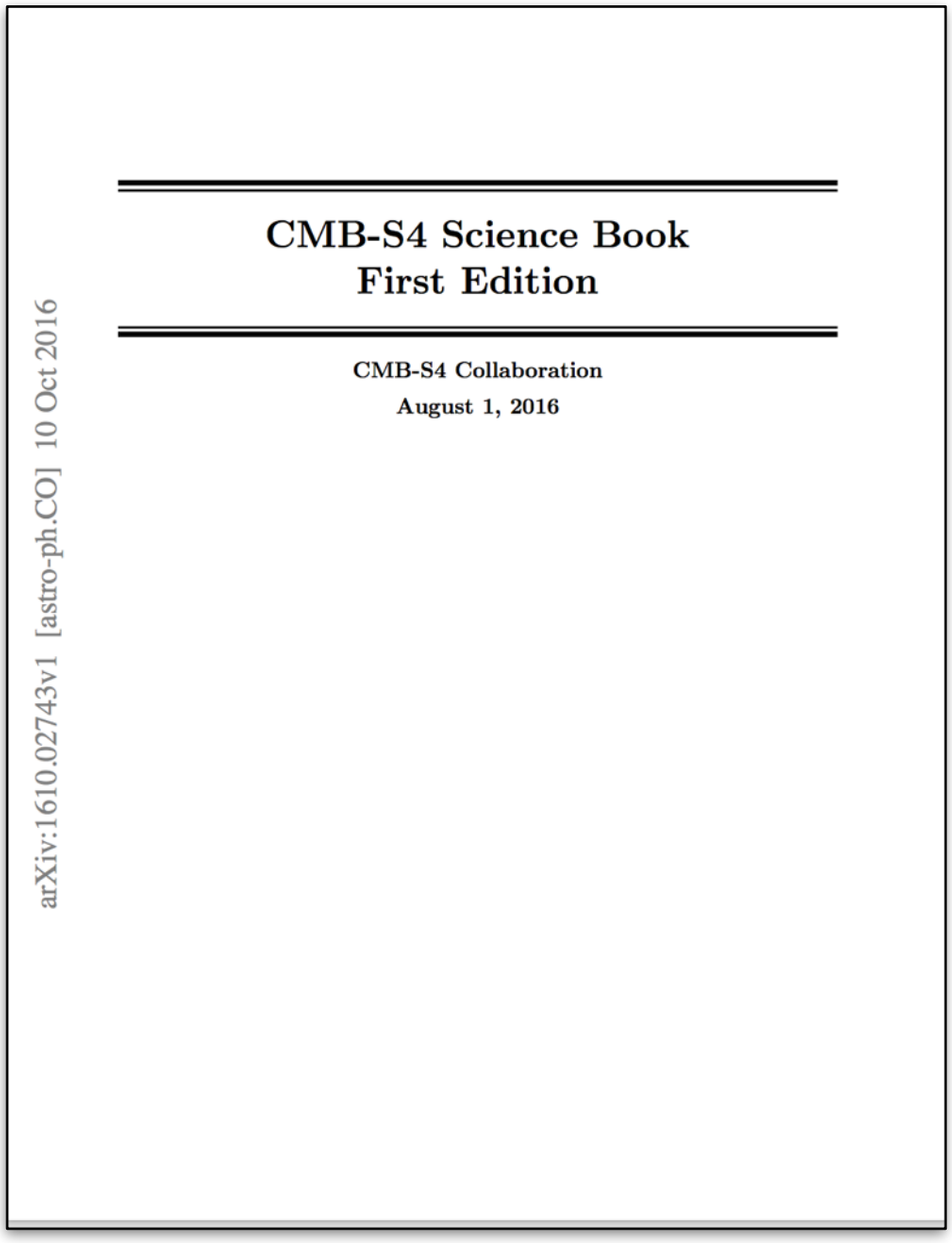
Harvard August 24-25, 2017

Next Workshops:

- March 2018 at Argonne Nat Lab
  (March 5-8 ok? if not might move to April)
- September 2018 at Princeton University

CMB-S4 Science Book

First Edition of
CMB-S4 Science Book
available http://cmb-s4.org



Science Book: 8 chapters (220 pages):

1) Exhortations
2) Inflation
3) Neutrinos
4) Light Relics
5) Dark Matter
6) Dark Energy
7) CMB lensing
8) Data Analysis, Simulations & Forecasting

Covers the HEP Cosmic Frontier Science Case, strawman concept based on initial projections

Next step: CMB-S4 Concept Definition & Expanded Science Case

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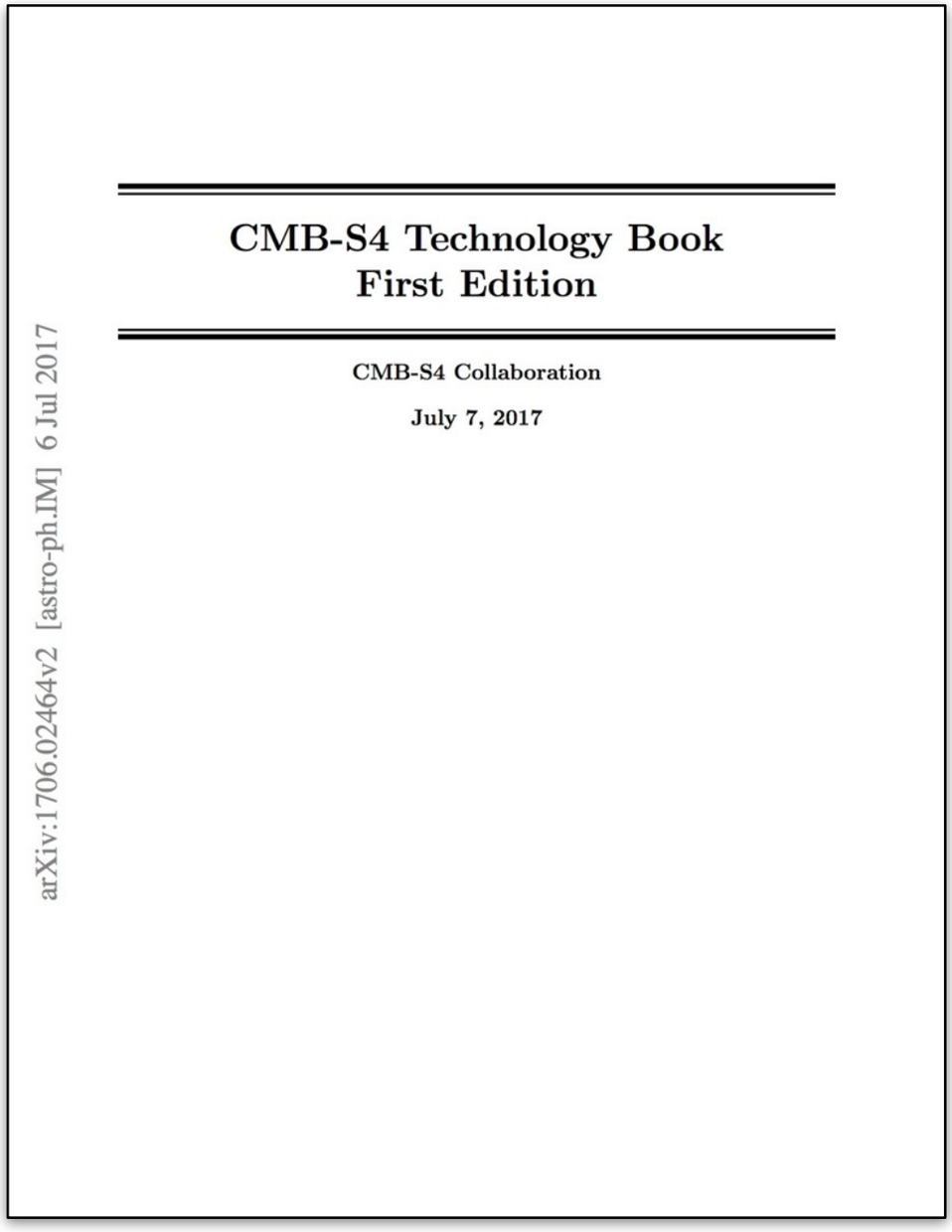
CMB-S4 Technology Book

First Edition of
CMB-S4 Technology Book
available http://cmb-s4.org



Technology Book: 6 chapters (184 pages):

1) Introduction and Overview
2) Telescope Design
3) Receiver Optics
4) Focal Plane Optical Coupling
5) Focal Plane Sensors and Readout
6) Conclusion and Future Work

A compilation of technologies with readiness levels and R&D required for scaling to CMB-S4

Next step: Prioritizing and coordinating R&D

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Concept Definition Task force (CDT)

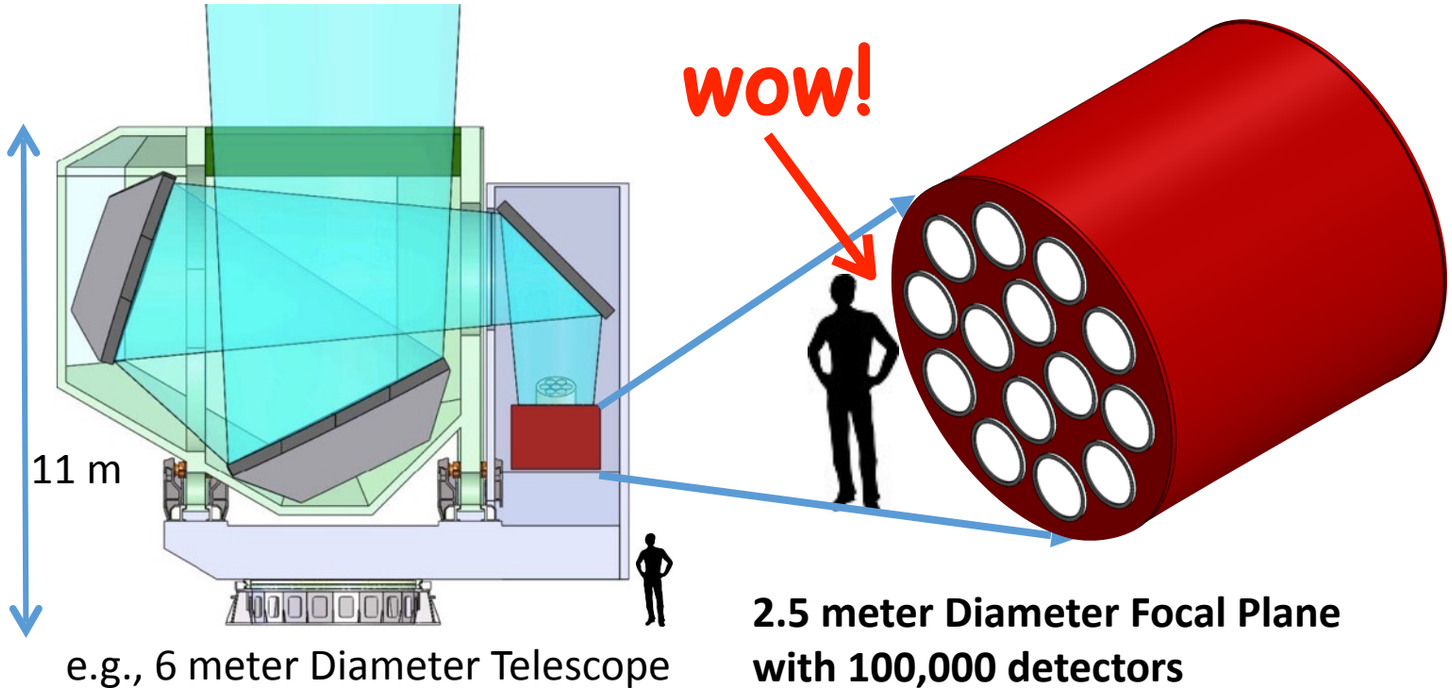
- Joint NSF & DOE task force to report to AAAC set up in Fall 2016, with **report due October 2017**

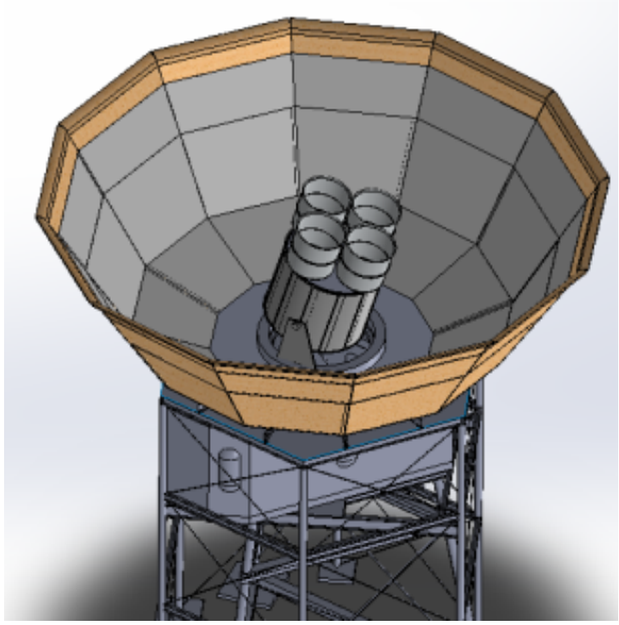
DOE Office of High Energy Physics (HEP) and NSF Divisions of Astronomical Sciences (AST), Physics (PHY), and Office of Polar Programs (OPP) request that the Astronomy and Astrophysics Advisory Committee (AAAC) establish a Cosmic Microwave Background Stage 4 ***Concept Definition Task force*** *(CMB-S4 CDT) as a subcommittee in order to develop a concept for a CMB-S4 experiment.*

The CDT is very significant in that its report will enable the agencies to move forward

CMB-S4 concept

- One collaboration, one project, with two sites: South Pole and Atacama, Chile
- Small and large telescopes for B-mode, de-lensing, high-ℓ cosmic structure science
- 500,000 detectors (300k on 3 large telescopes; 200k on 14 small telescopes)
- Order 8 frequency bands for CMB and foreground mitigation on small telescopes
- Two surveys: 4 yr deep B-mode w/ de-lensing (f_{sky} ~ few %)
  7 yr broad for N_{eff} and cosmic structure science (f_{sky} = 40%)





High resolution Science + de-lensing:
300,000 detectors on 3 large telescopes

Figure from Simons Obs, Mark Devlin / Mike Niemack

Low resolution B-mode Science:
200,000 det. on 14 small telescopes

Figure from BICEP Array

Atacama CMB (Stage 3)

and the Simons Observatory is being planned.

CLASS 1.5m x 4
72 detectors at 38 GHz
512 at 95 GHz
2000 at 147 and 217 GHz

Upgrading to Simons Array (Polarbear 2.5m x 3)
22,764 detectors
90, 150, 220, 280 GHz

ACT 6m
AdvACTpol:
88 detectors at 28 & 41 GHz
1712 at 95 GHz
2718 at 150 GHz
1006 at 230 GHz

Photo: Rahul Datta & Alessandro Schillaci

South Pole CMB (Stage 3)

10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz

BICEP3
2560 detectors
95 GHz

Keck Array
2500 detectors
150 & 220 GHz

Upgrading to BICEP Array:
30,000 detectors
35, 95, 150, 220, 270 GHz

Photo credit Cynthia Chiang

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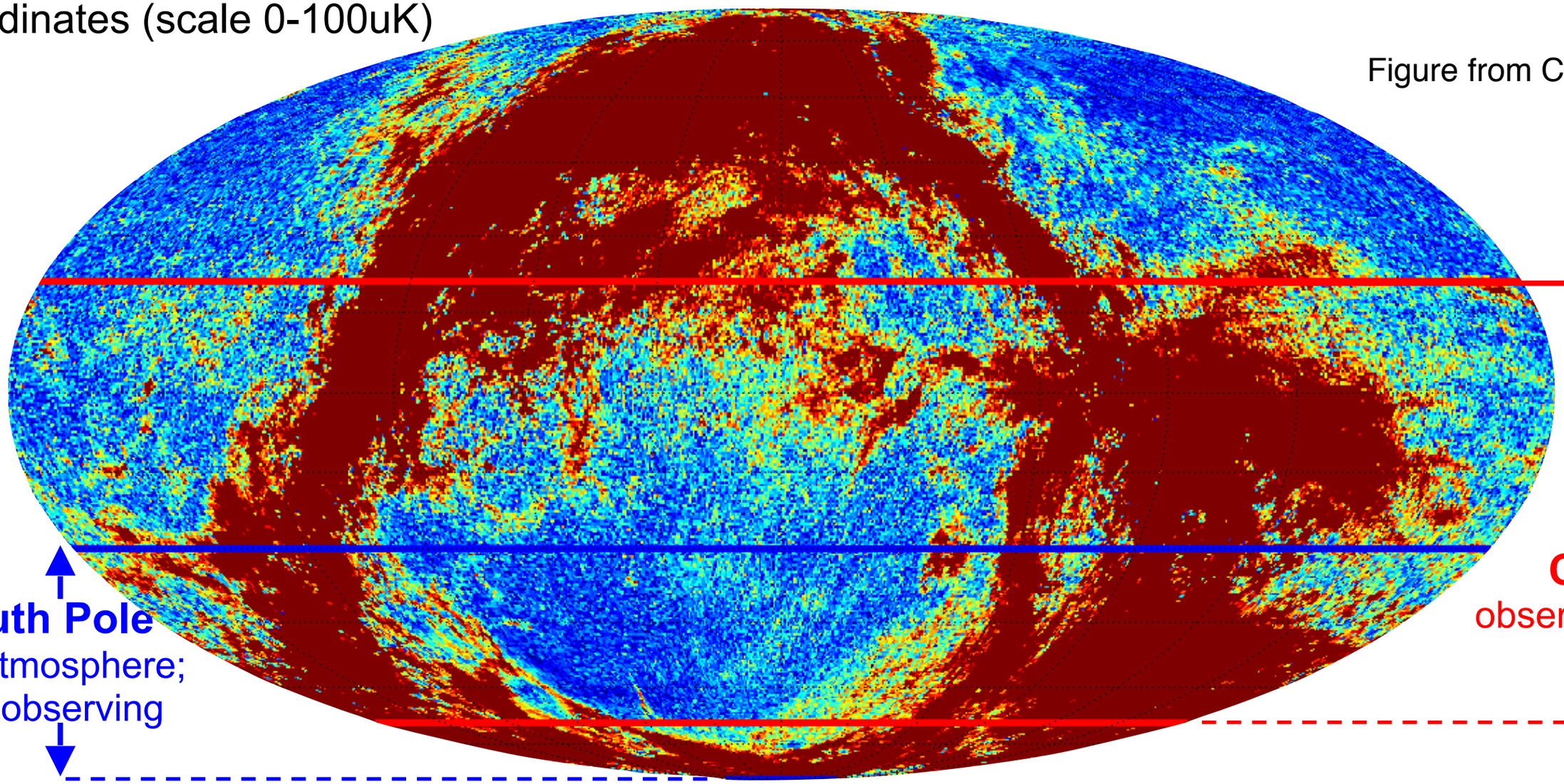
Telescopes at Chile and South Pole (established, proven CMB sites)

Planck 353 GHz polarized intensity map in celestial coordinates (scale 0-100uK)

Figure from Clem Pryke



South Pole excellent for ultra deep fields

Chile excellent for wide sky coverage

(a northern site would decrease sample variance)

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Next Steps

- Establishing the CMB-S4 Science Collaboration
  - Clearly we've been functioning as an effective collaboration, delivering Snowmass docs, P5 input, Science Book, Technology Book, holding workshops, etc., and generally advancing CMB-S4
  - The next step is to make it an official collaboration, with clear organization structure and governance.
  - The plan to form collaboration agreed on at last workshop — election of Interim Collaboration Coordination Committee members is in progress.
  - Hope to have **collaboration established by next workshop in March 2018**

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Post CDT

After the CDT is submitted in October 2017:

- Finish establishing the CMB-S4 science collaboration
- Prepare for Astronomy and Astrophysics Decadal Survey and for the NSF MREFC* funding line
  - Develop the full CMB-S4 science case, not just HEP's, and communicate it to larger astro community; recruit astro experts
  - Develop the CMB-S4 project for input to Decadal Survey
  - Coordinate with NASA CMB probe mission study.
- Develop phasing plan so DOE would have option to proceed before Decadal & MREFC.

* Major Research Equipment & Facility Construction

wrap up comments

CMB-S4 continues to gain momentum. Expect increased involvement from agencies after CDT report is submitted.

Formal CMB-S4 collaboration is being established.

Next CMB-S4 workshop March 2018 at Argonne Nat Lab

International partners for CMB-S4 are expected and desired. The modularity of the concept allows many options.

Go to cmb-s4.org for more information on CMB-S4,
e.g., wiki's for workshops and working groups, join email lists, etc.

Backup Slides

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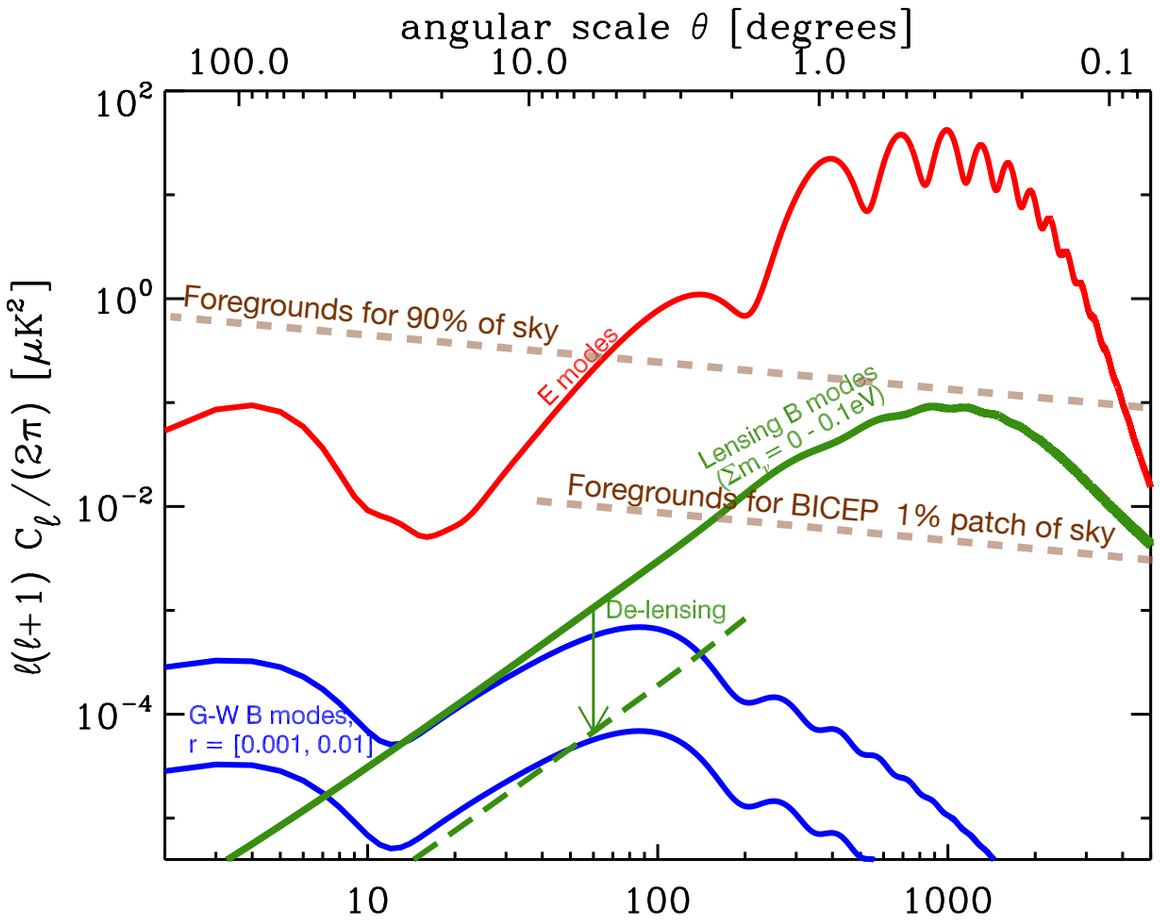
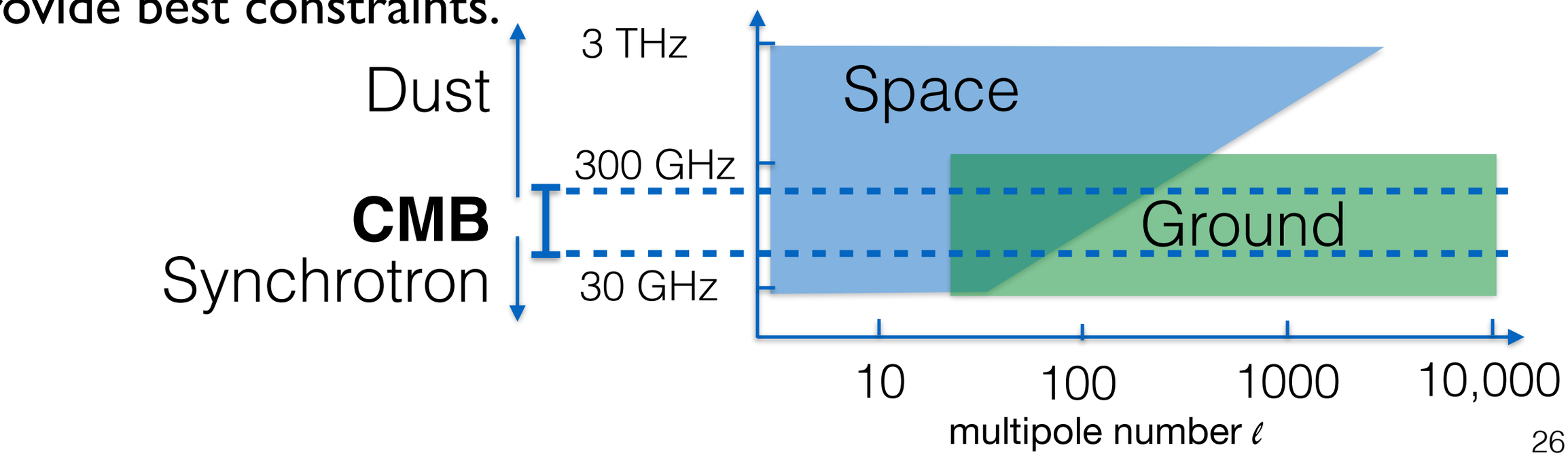
Complementary strengths of ground and space

- **Ground:** Resolution required for CMB lensing (+de-lensing!), damping tail, clusters….
- **Space:** All sky for reionization peak; high frequencies for dust.
- Combined data will provide best constraints.





NASA funding CMB satellite study for input to A&A 2020 Decadal Survey

- **'Inflation Probe' mission study funded and ongoing (one of eight probe studies)**
  - **Probe of Inflation and Cosmic Origins: PICO**
  - **$400M-$1000M cost range**
  - **studying feasibility of a combination of imager and spectrometer**
  - **50 page report & cost estimates due 12/2018**
- **Study open for participation by all interested parties.**
  For more information:
  - **contact Shaul Hanany**
  - **wiki: https://z.umn.edu/cmbprobe**
  - **mailing list: cmbprobe@lists.physics.umn.edu**
- **Likely outcome**
  - **decadal survey recommends a funding wedge for NASA Probe Line.**
  - **Specific Probes are competed later (~2022/3)**