Measurements from South Pole
&
CMB-S4

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for the South Pole Observatory and the
CMB-S4 Collaboration

Stage-3 ground based CMB experiments

Current (stage-3) CMB experiments are on sky with ~10,000 detectors per telescope

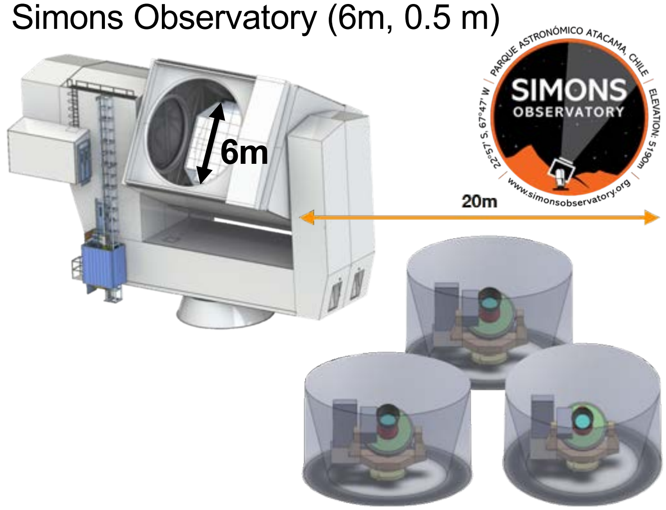
Chile, Atacama


Atacama Cosmology Telescope (6 m)


POLARBEAR/Simons Array (3 m)


CLASS (0.6 m)

Simons Observatory (6m, 0.5 m)



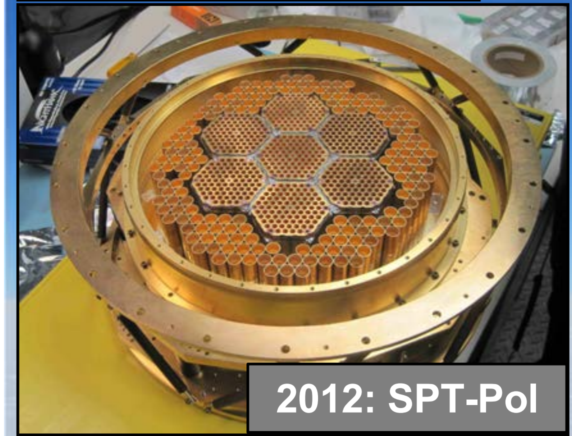
South Pole


BICEP-2/Keck Array/
BICEP-3/BICEP Array (< 0.7 m)


South Pole Telescope (10 m)

Measurements from South Pole

South Pole Telescope

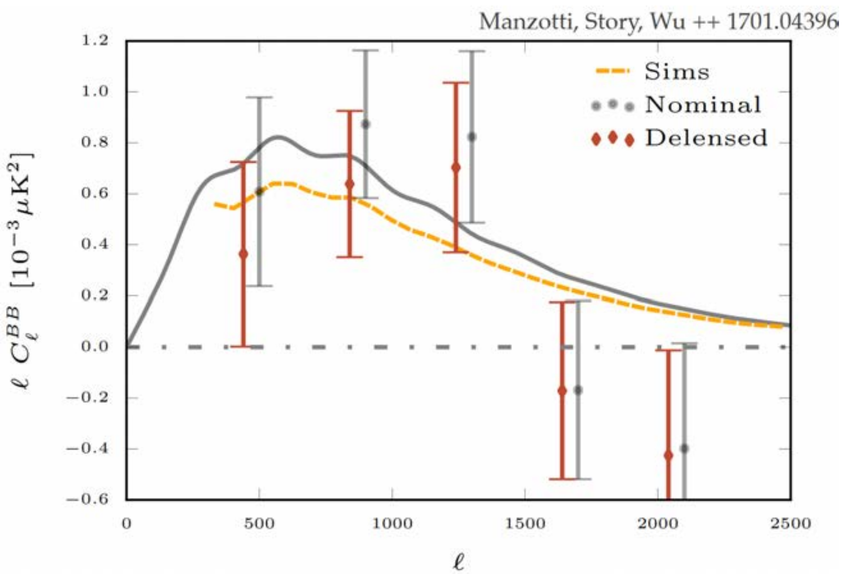


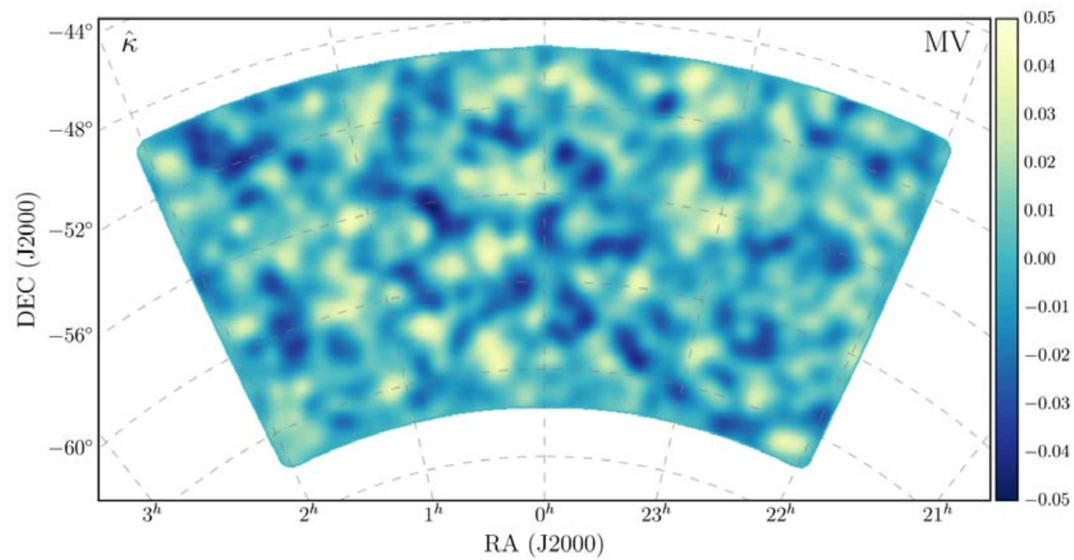
Telescope: 10 meter primary

Three generations (SPT-SZ, SPT-Pol, SPT-3G)

- SPT-SZ: 960 detectors @ 90/150/220 GHz
- SPT-Pol: 1,600 detectors @ 90/150 GHz + Pol
- SPT-3G: 16,000 detectors @ 90/150/220 GHz + Pol

Some Recent SPT-Pol results





Manzotti, Story, Wu, et al.

"CMB polarization B-mode delensing with SPT-Pol and Herschel"

arXiv:1701.04396 [astro-ph.CO] (2017)

De-lensed SPT-Pol BB with information from SPTpol E-mode maps and a lensing potential map estimated from the Herschel 500μm map of the CIB.
28% reduction in best fit A_L as expected

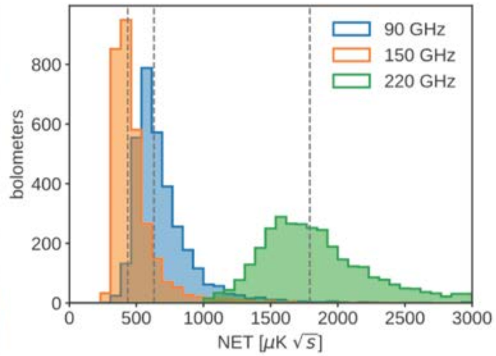
W. L. K. Wu, L. M. Mocanu, et al.

"A Measurement of the Cosmic Microwave Background Lensing Potential and Power Spectrum from 500 deg^2 of SPTpol Temperature and Polarization Data"

arXiv:1905.05777 [astro-ph.CO] (2019)

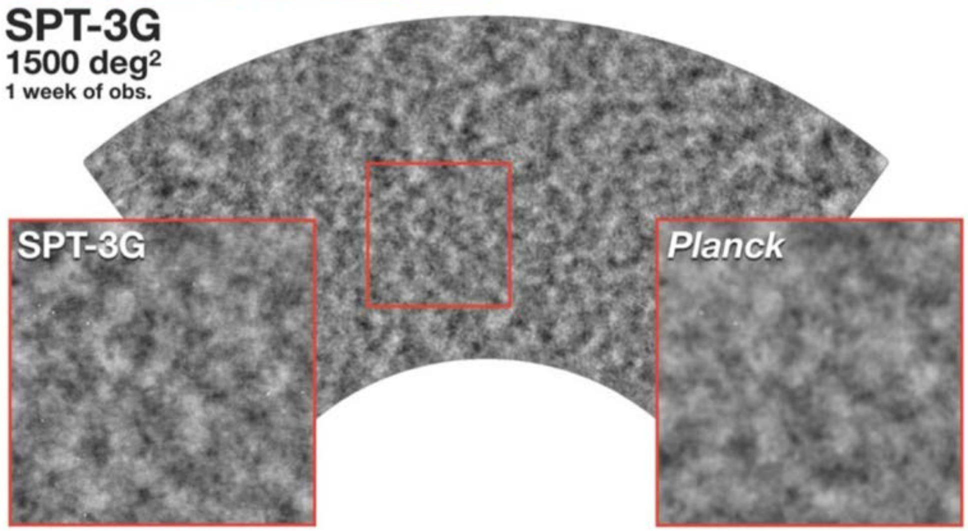
The most precise polarization-only lensing amplitude constraint to date (**10.1 σ**), and is more precise than our temperature-only constraint

SPT-3G Instrument & Expected Performance



Technology:
- Detector: Lenslet coupled sinuous antenna
- Readout: Frequency multiplexing readout (x68)

First light in January 30th 2017
~11,000 detectors routinely in operation



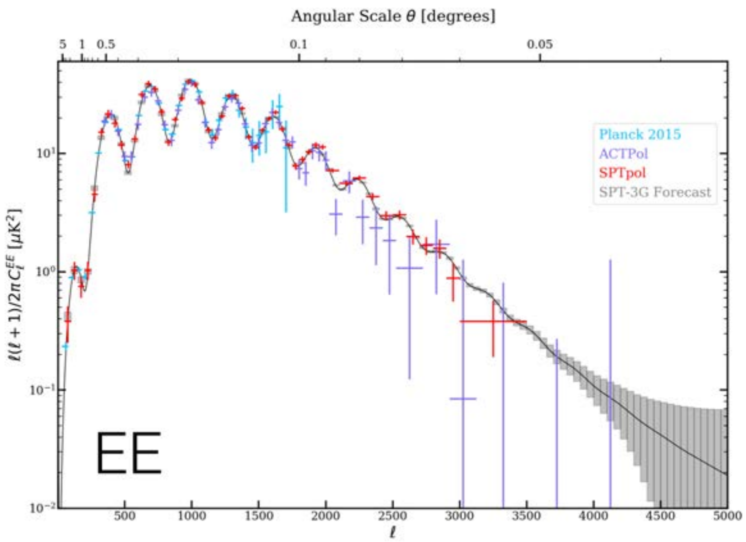
	95 GHz	150 GHz	220 GHz
Beam FWHM (arcmin)	1.6	1.2	1.1
Optically responsive $N_{\rm bolo}$	3800	3780	3820
$\rm NET_{bolo,\mathit{T}}$ [μK$\sqrt{s}$]	630	440	1800
$\rm NET_{array,\mathit{T}}$ [μK$\sqrt{s}$]	10	8	30
Projected Map Depth [μK-arcmin]	3	2	9

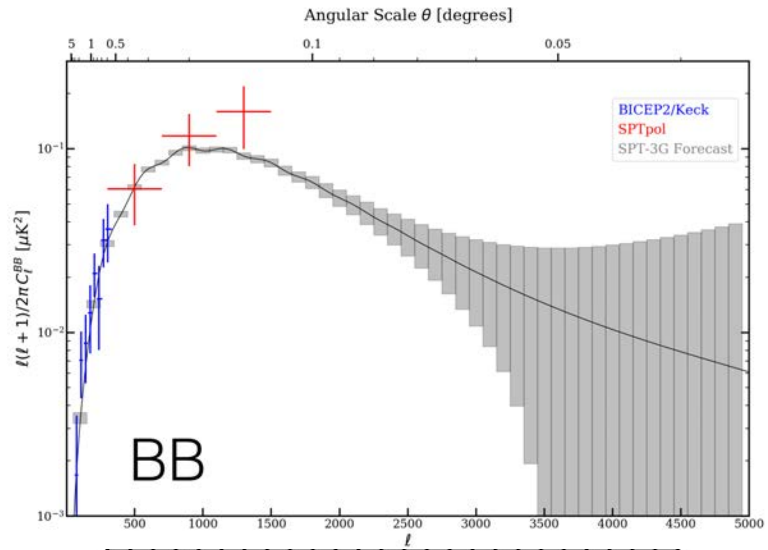
SPT-3G forecast

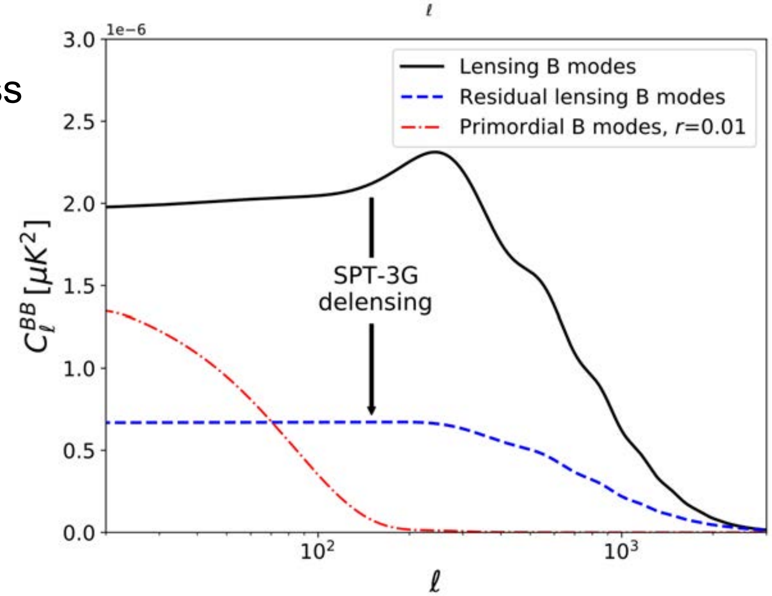
Bender, Moriond 2018

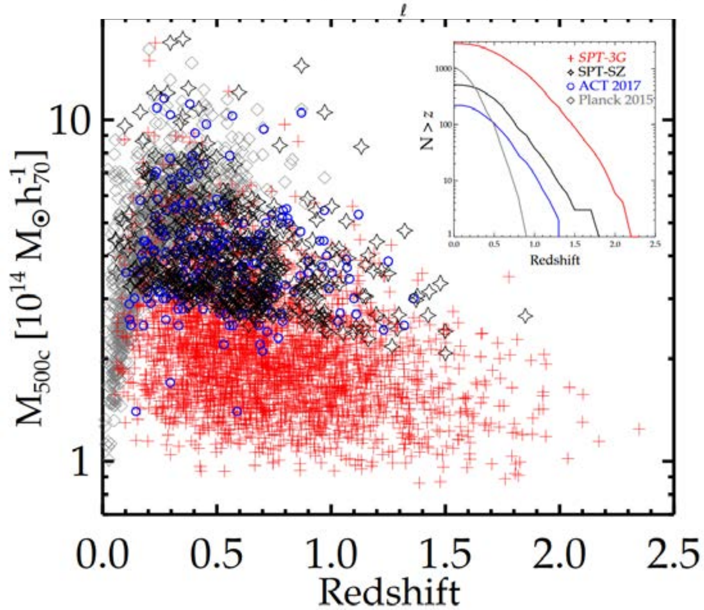
4-year 1,500 deg^2 survey

- $\sigma(\Sigma m_\nu)$ = 0.061 eV
- $\sigma(N_{eff})$ = 0.058
- Potential to subtract 2/3 of lensing power
- ~10,000 new clusters for growth probe
- Survey has large overlap with DES, cross correlation – lensing, tSZ, kSZ



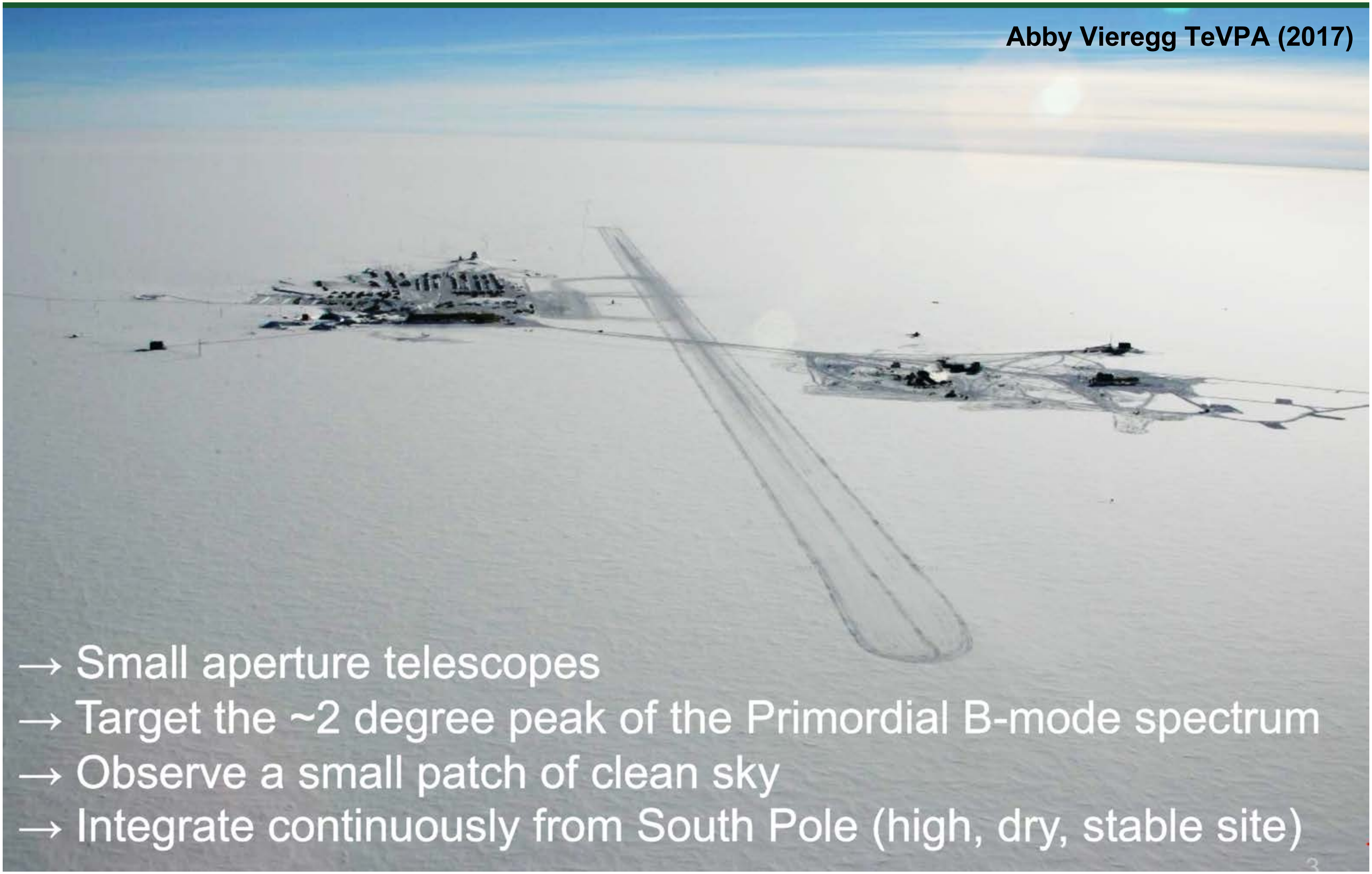







BICEP/Keck Program
photo: Keith Vanderlinde

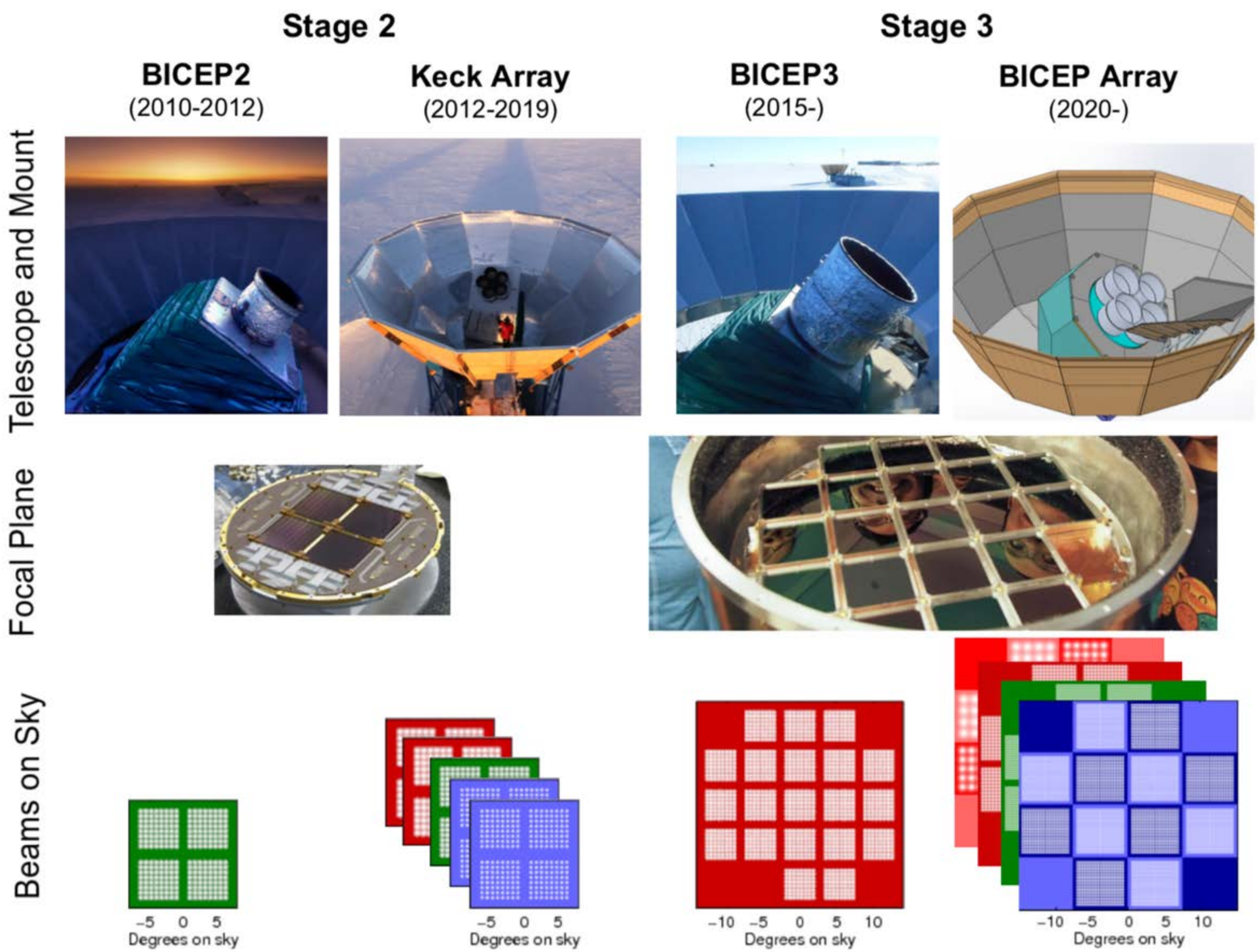
BICEP/Keck Experimental Strategy

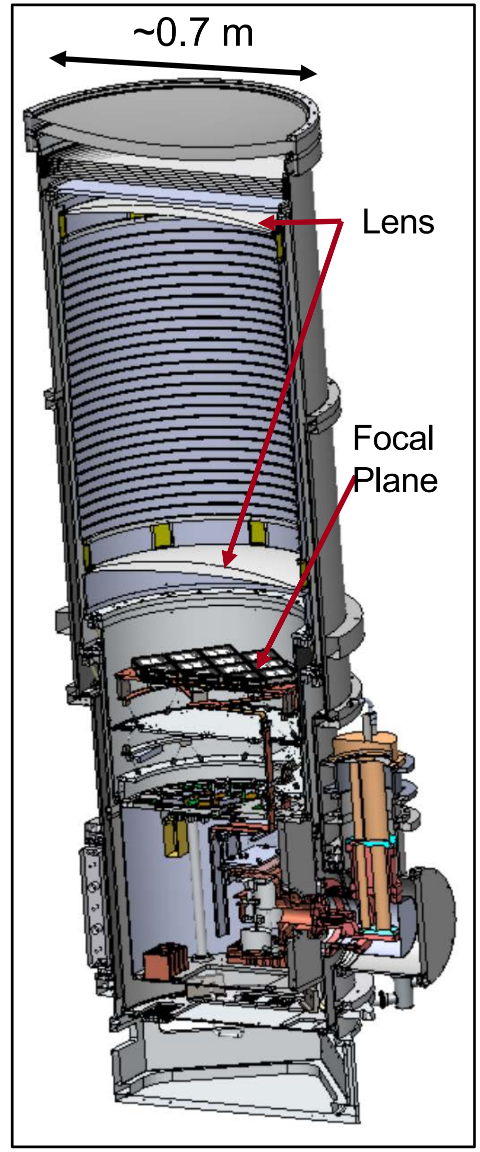


Abby Vieregg TeVPA (2017)

→ Small aperture telescopes
→ Target the ~2 degree peak of the Primordial B-mode spectrum
→ Observe a small patch of clean sky
→ Integrate continuously from South Pole (high, dry, stable site)

BICEP-Keck Instrument

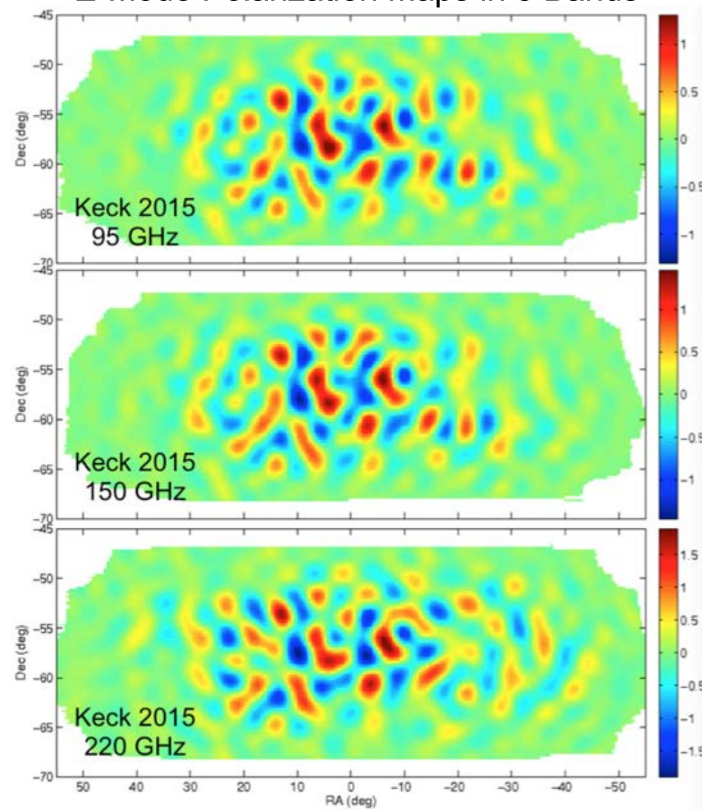




BICEP-Keck Results

Published B-Mode Sensitivity to r			
Experiment	**Year**	**Bands [GHz]**	**σ(r)**
DASI	2004	26…36	7.5
BICEP1 2yr	2009	100, 150	0.28
WMAP 7yr	2010	30…60	1.1
QUIET-Q	2010	43	0.97
QUIET-W	2012	95	0.85
BICEP1 3yr	2013	100, 150	0.25
BICEP2	2014	150	0.10
BK + Planck	2015	150 + Planck	0.034
BK14	2015	95, 150 + P	0.024
ABS	2018	150	0.7
BK15	2018	95,150,220 + P	0.019

E-Mode Polarization Maps in 3 Bands

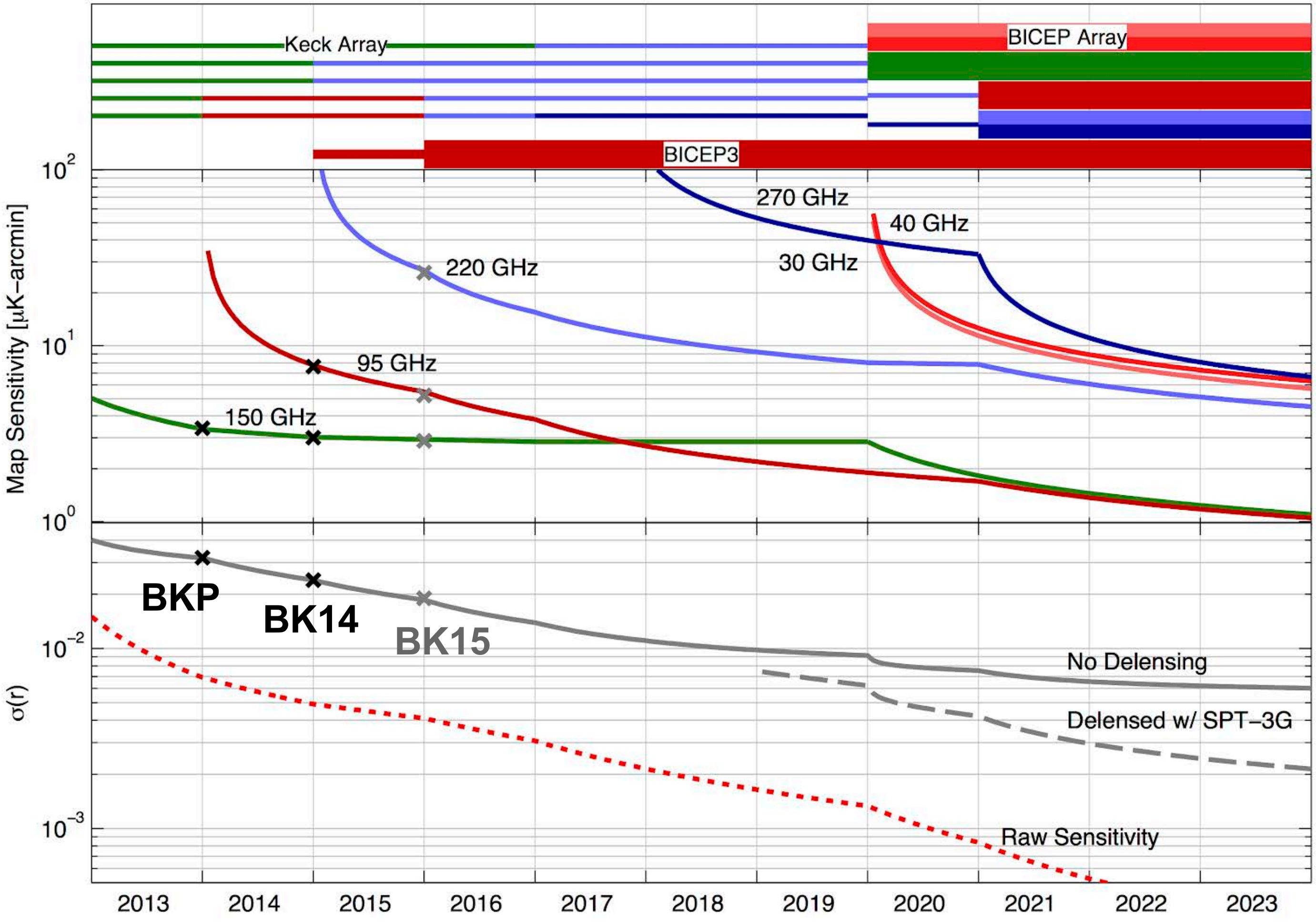


Keck Array, BICEP2 Collaborations (arXiv:1810.05216 [astro-ph.CO]) - 2018

"BICEP2 / Keck Array x: Constraints on Primordial Gravitational Waves using Planck, WMAP, and New BICEP2/Keck Observations through the 2015 Season"

$r < 0.06$ (95% c.l.), $\sigma(r) = 0.02$
Lensing B-mode detected at 8.8σ

BICEP-Keck Future Forecasts

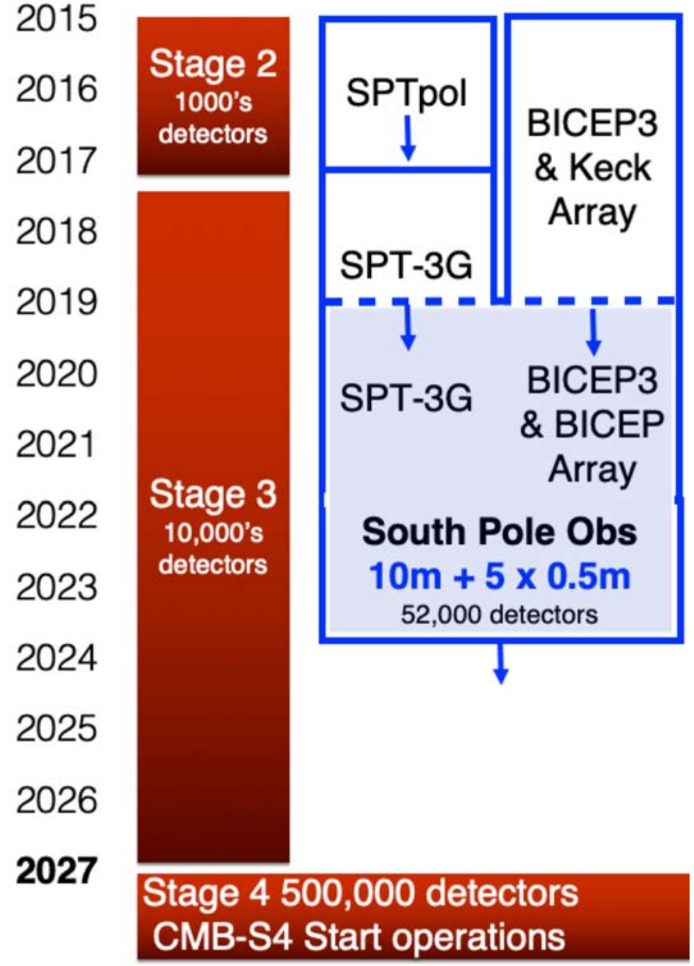


Receiver Observing Band (GHz)	Nominal Number of Detectors
Keck Array	
95	**288**
150	**512**
220	**512**
270	**512**
BICEP3	
95	**2560**
BICEP Array	
⟨ 30	192
40	300
95	4056
150	7776
⟨ 220	8112
270	13068

B3 + BA = 36,000 detectors

- Map sensitivity scaled from on-sky *demonstrated*: NETs, yields, data cuts, observing efficiency, filtering
- r forecasts use the multi-component foreground dust and synchrotron model from BKP, BK14, BK15
- **New collaboration formed with SPT for future delensing**

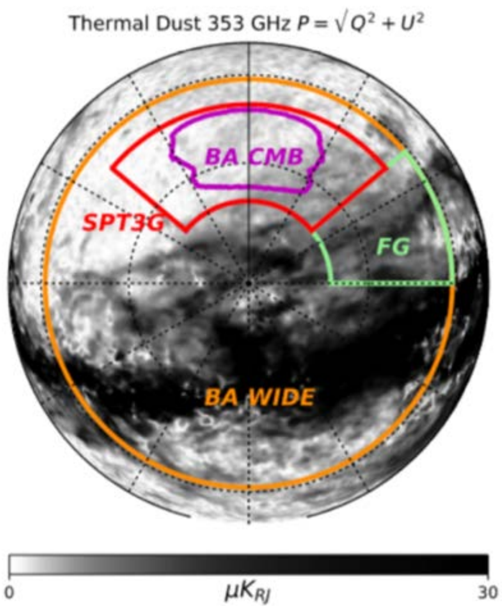
South Pole Observatory
(formed from SPT-3G, BICEP2 & BICEP Array)

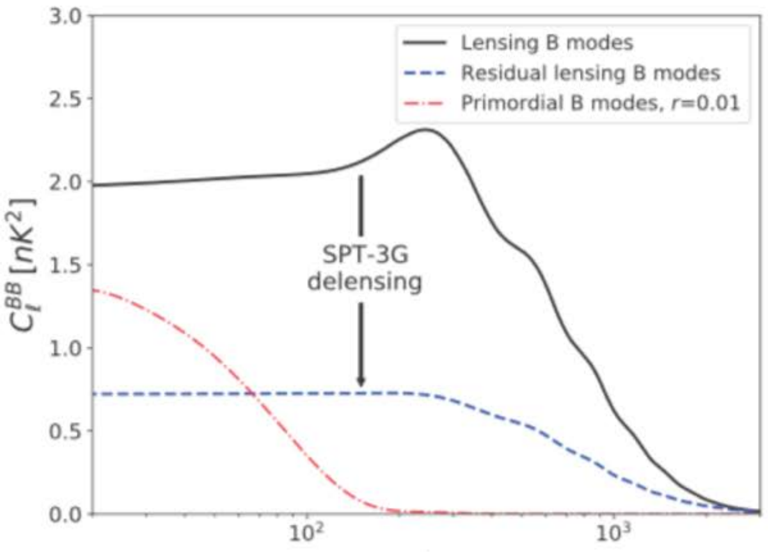


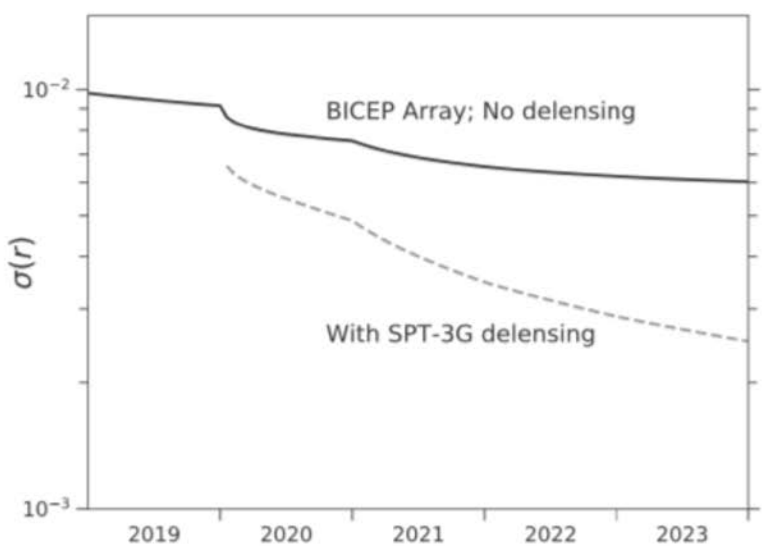
- 52,000 detectors spanning 30, 40, 95, 150, 220, 270 GHz
- Deep joint large aperture (~2uK arcm) and small aperture (~0.7 uK) survey f_{sky} = 0.03
- Targeting σ(r) ~ 0.0025 with de-lensing by 2023

South Pole Observatory
(formed from SPT-3G, BICEP2 & BICEP Array)

- The South Pole site enables deep surveys on a small patch of sky.
- Will use the SPT3G survey to delens the BICEP array data
- The SPT-3G survey depth (~2uK arcm @ 150 GHz) will remove over 2/3 of the lensing power, and will improve the BICEP array r-constraint by a factor of ~2.5.








CMB-S4
Next Generation CMB Experiment

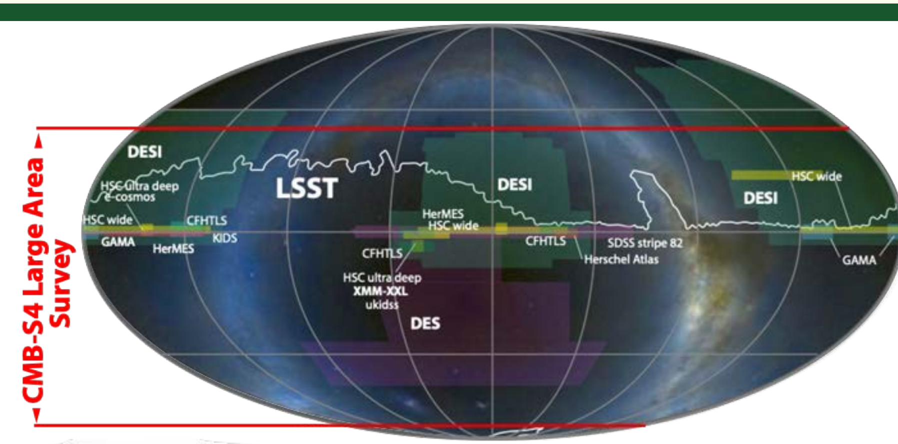
What is CMB-S4?

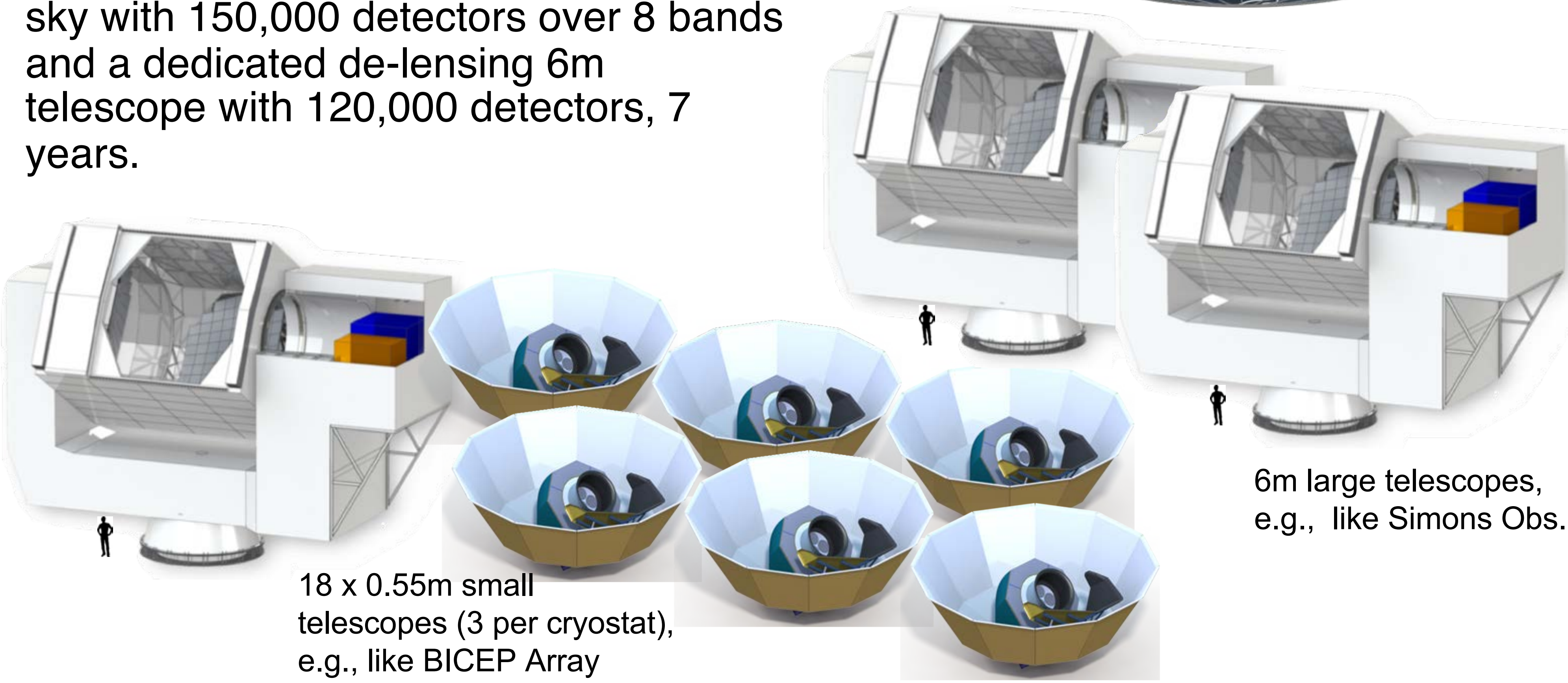
- CMB-S4 is a next generation ground-based experiment to pursue inflation, neutrino properties, dark energy, and new discoveries
- Core principle: One project, one collaboration, one dataset, two sites.
- ~500,000 detectors spanning 20-270 GHz using multiple telescopes at Chile and South Pole to map most of the sky, as well as deep targeted fields.
- Broad participation of the CMB community, including members from existing CMB experiments, National Labs, and the High Energy Physics community. International partnerships encouraged.
- Joint project between NSF (AST,PHY,OPP) and DOE (HEP), with an estimated cost of ~$600M, and a start of operations in FY2027.

CMB-S4 Reference Design for nested deep and wide surveys

Wide N_{eff} and Legacy Survey with 2 x 6m telescopes with 240,000 detectors over 6 bands, 7 years.

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, 7 years.

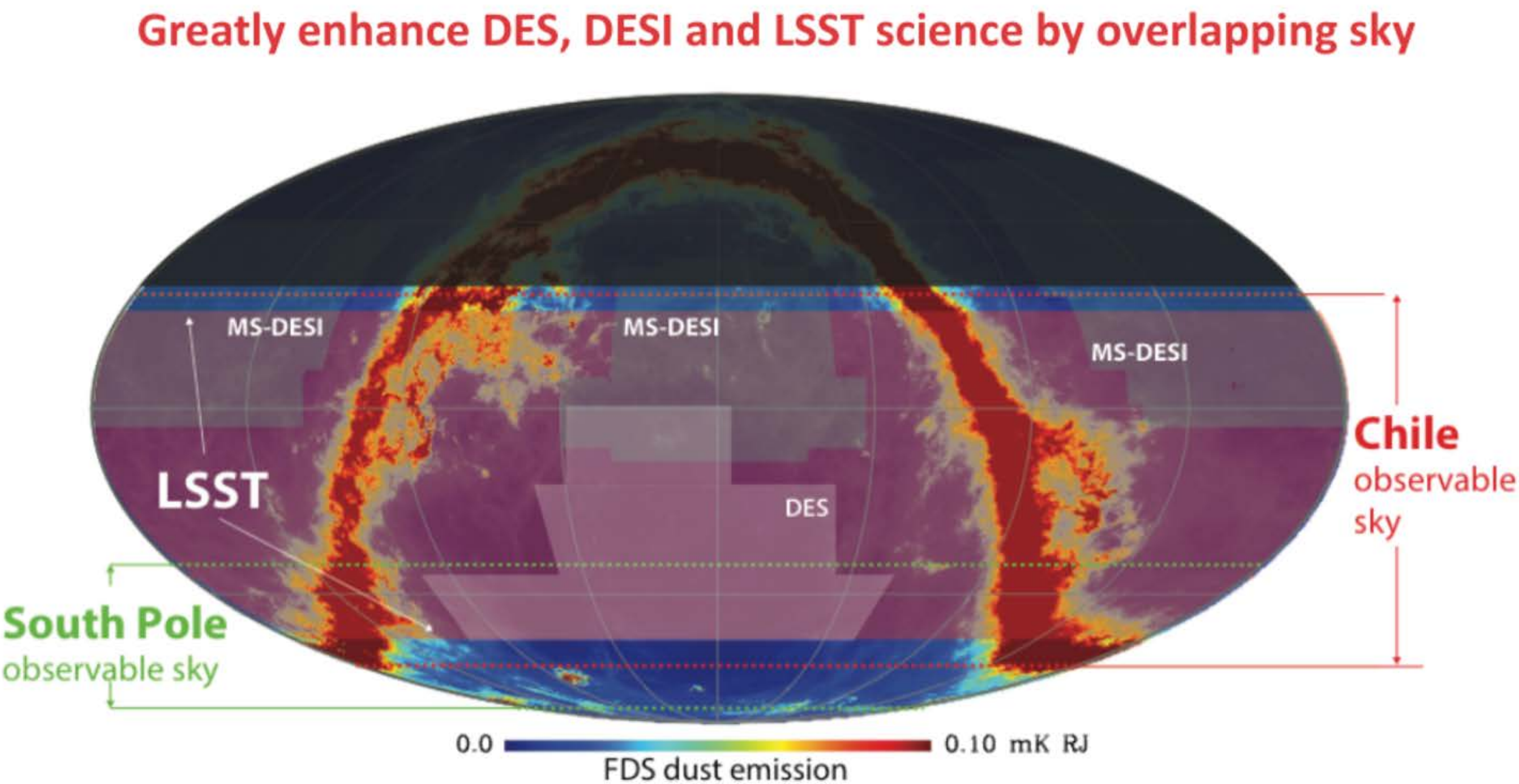




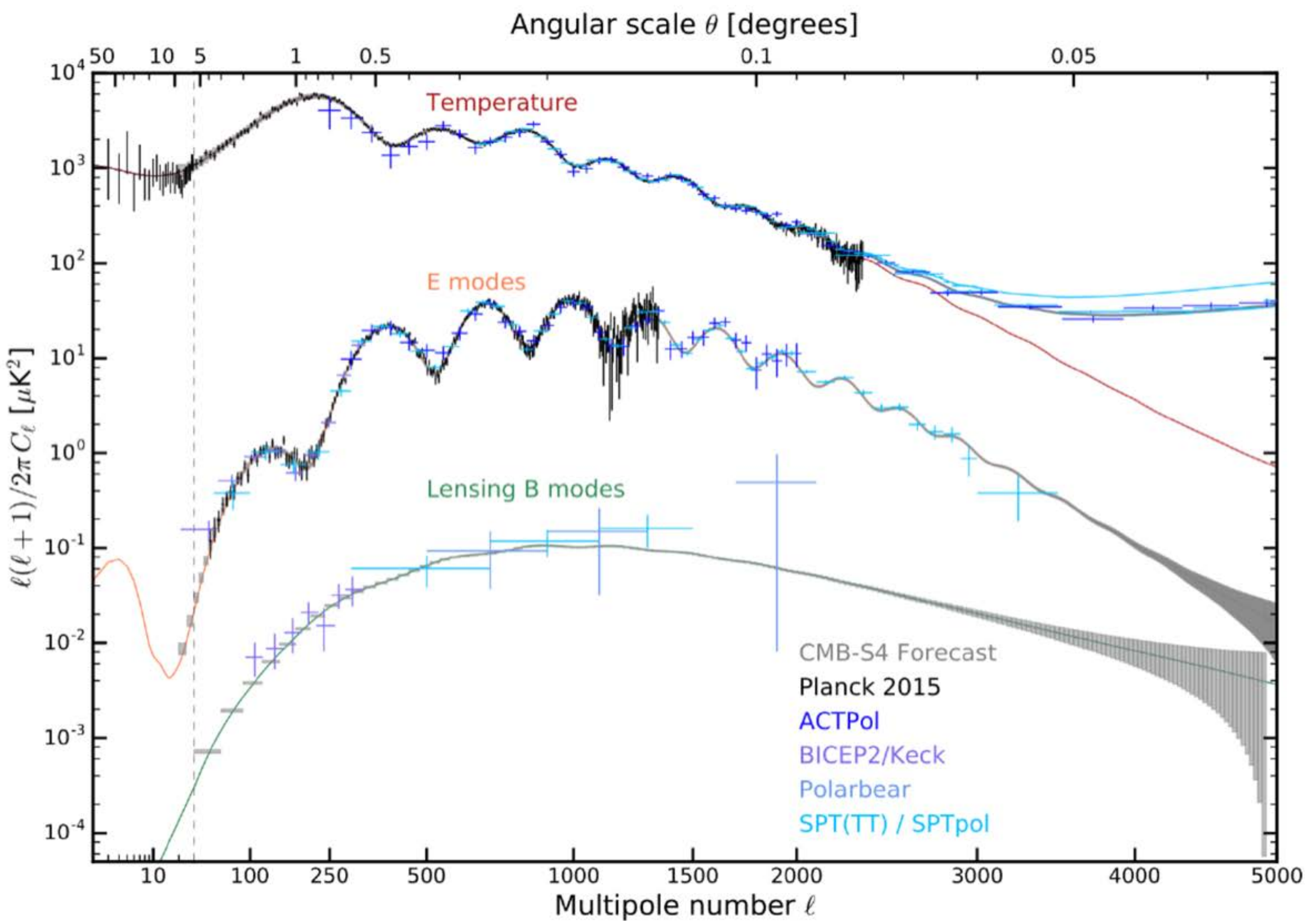
6m large telescopes,
e.g., like Simons Obs.

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

Complementary Sky Coverage from the South Pole and Chile

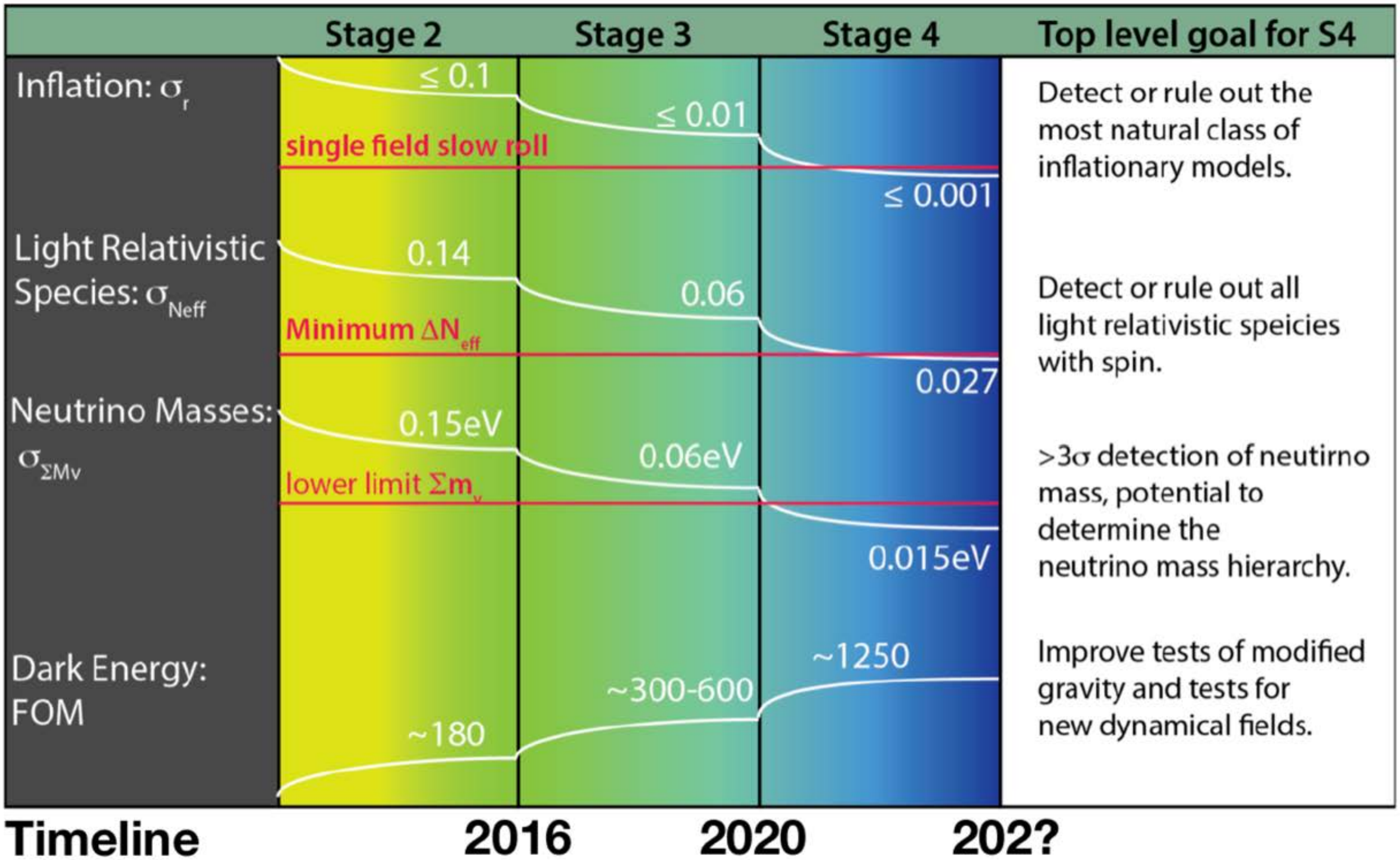


CMB-S4 Forecast, Angular Power Spectrum Sensitivity



CMB-S4 Science Book: https://arxiv.org/abs/1610.02743

CMB-S4 Science Goals



…also mm-wave transients, gamma-ray burst, so much more!

CMB-S4 Science Book: https://arxiv.org/abs/1610.02743

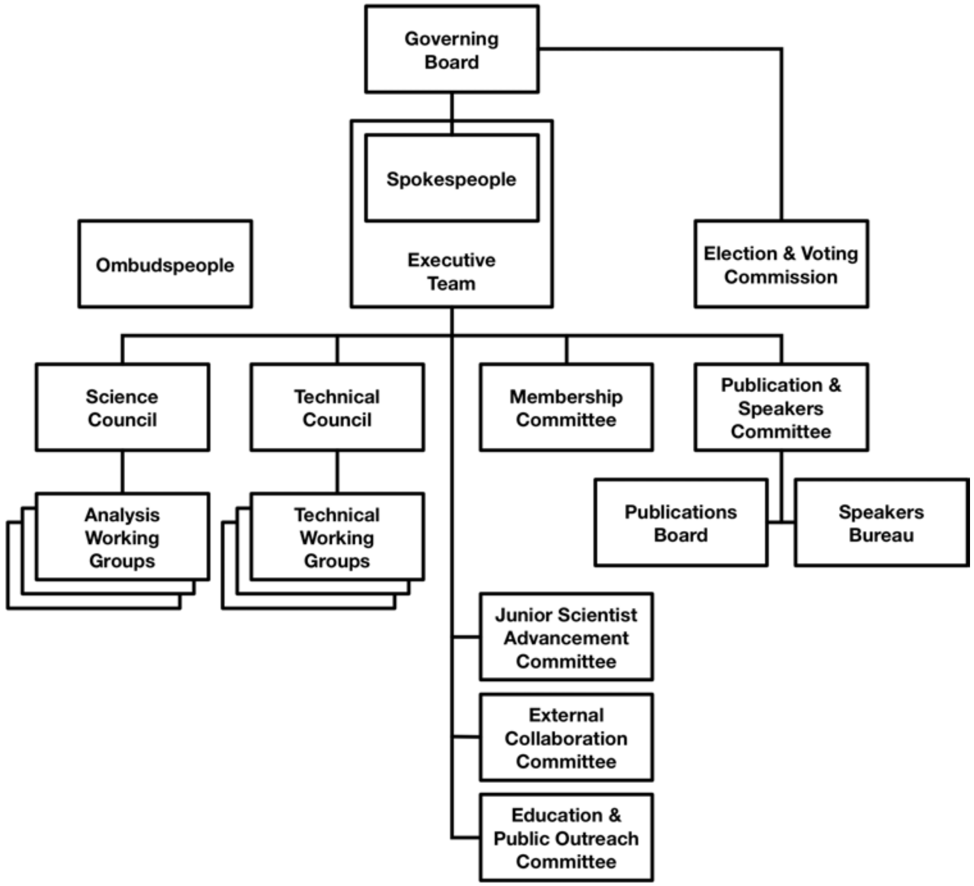
What is needed to realize CMB-S4

- **Theory/phenomenology**
  - Increased precision for analysis; new methods
- **Scaling up**
  - Detectors
  - Sky area and frequency coverage
  - Multiple telescopes, new designs
  - Computation, data analysis, simulations
  - Project management
- **Systematics**
  - Improved control, characterization, foreground mitigation

To date, ground-based experiments have been carried out by competing teams, mostly university-led groups. CMB-S4 requires the cooperation and collaboration of the entire CMB community, plus DOE lab production capabilities, and DOE/NSF cooperation and project management.

CMB-S4 Science Collaboration

- CMB-S4 Science Collaboration was established in 2018.
  - 200 members and growing
  - 65 members have leadership (org chart) roles
  - 76 institutions spanning 11 countries
- An Interim Project Office has also been established and is working.
- CMB-S4 publications:
  - Science Book
  - Technology Book
  - Concept Design Taskforce Report
  - Available at http://cmb-s4.org



Agency roles in CMB-S4

NSF

- Funds the world-leading ground-based CMB efforts (AST, PHY, OPP)
- Leads Stage 2 and 3 efforts, with small but key contributions from DOE
- Critical role in sustaining university efforts into CMB-S4
  - Possible capital investment from NSF for new CMB telescopes

DOE

- Key contributions to Stage 2 and 3 efforts
  - Detectors, readout, computing, large cryogenic components
- Critical role for DOE in scaling up for CMB-S4

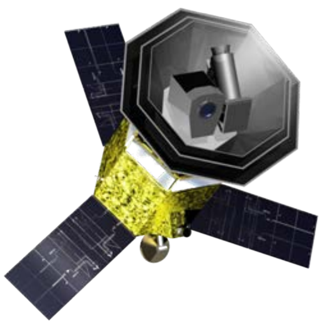
NSF and DOE activities will need to be closely coordinated for CMB-S4

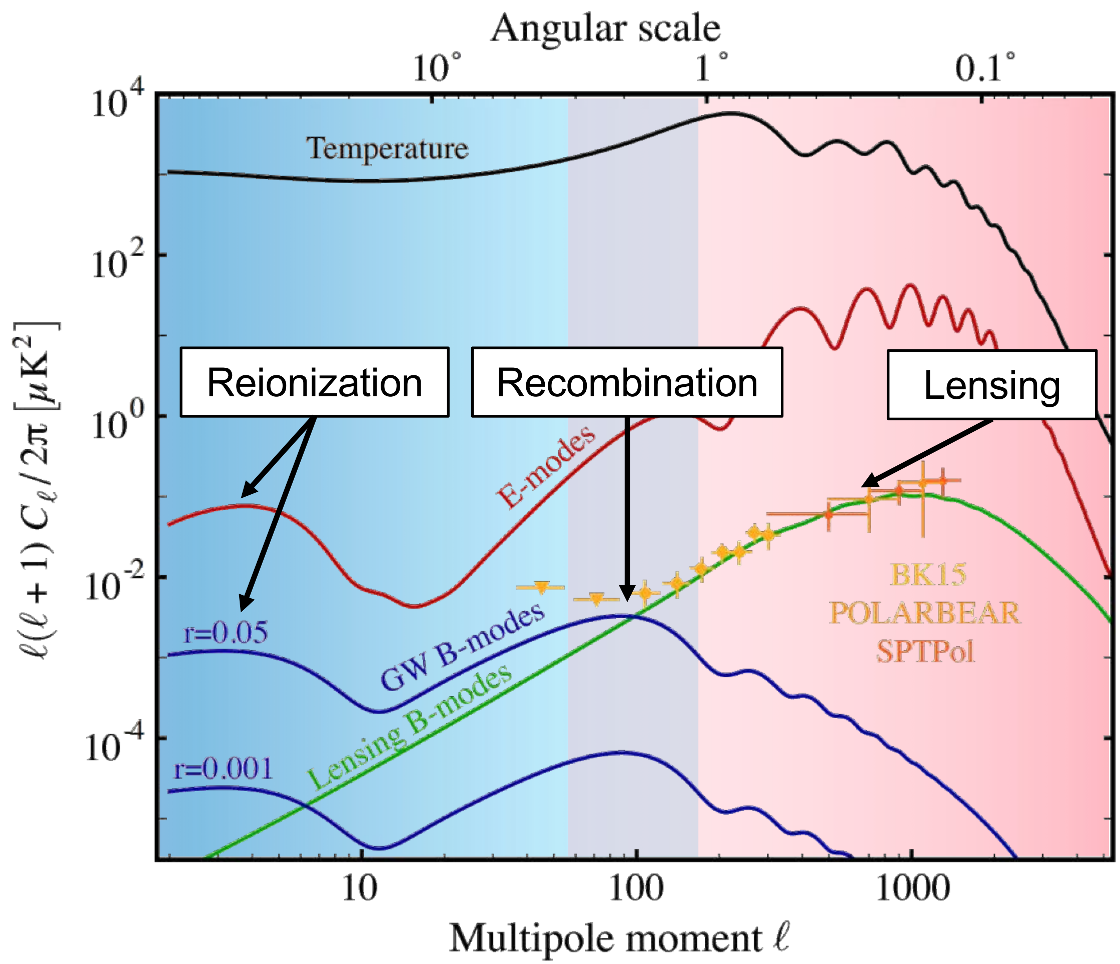
Notional DOE/NSF Project Development Timeline

Period	Step	Definition
Q3 FY2019	CD-0	Approve mission need
Q1 FY2021	Lead lab/institution selection	Lead lab/institution selection
Q2 FY2021	Decadal survey result	
Q2 FY2021	CD-1/3a and CDR review	Approve alternative selection and cost range
FY2022	CD-2 approval, PDR	Approve performance baseline
FY2023	CD-3b, FDR	Approve start of construction
FY2027	CD-4, MREFC project complete	Approve start of operation

Very similar time scale between LiteBIRD and CMB-S4 will benefit both experiments due to their complement data set

Complementarity of ground and space-based measurements – Angular scale, cross-check, de-lensing



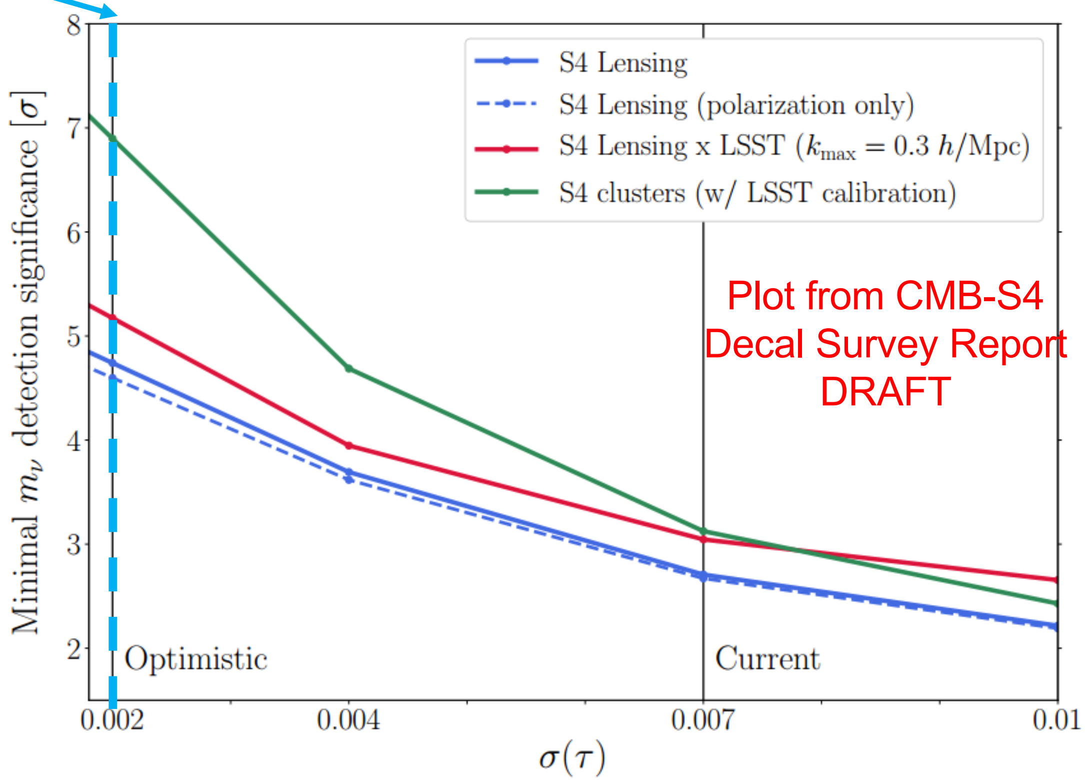


CMB-S4
Next Generation CMB Experiment

- Ground: resolution required for CMB lensing (and delensing), damping tail, clusters
- Space: all-sky, large angular scale for reionization peak
- Cross-check, improve recombination bump constraint with de-lensing, combined analysis to reach better r sensitivity

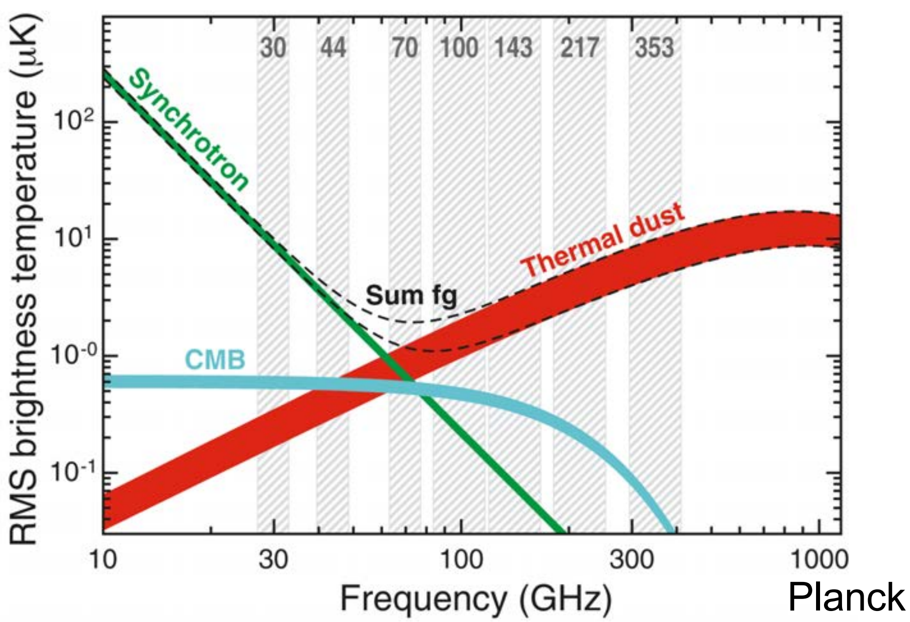
Complementarity of ground and space-based measurements – Neutrino mass constraint, optical depth

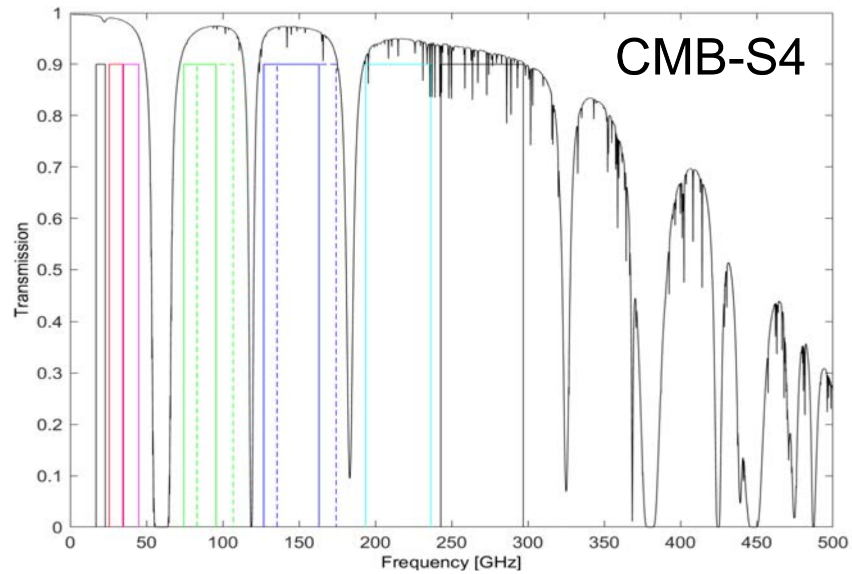
LiteBIRD's constraint from reionization bump

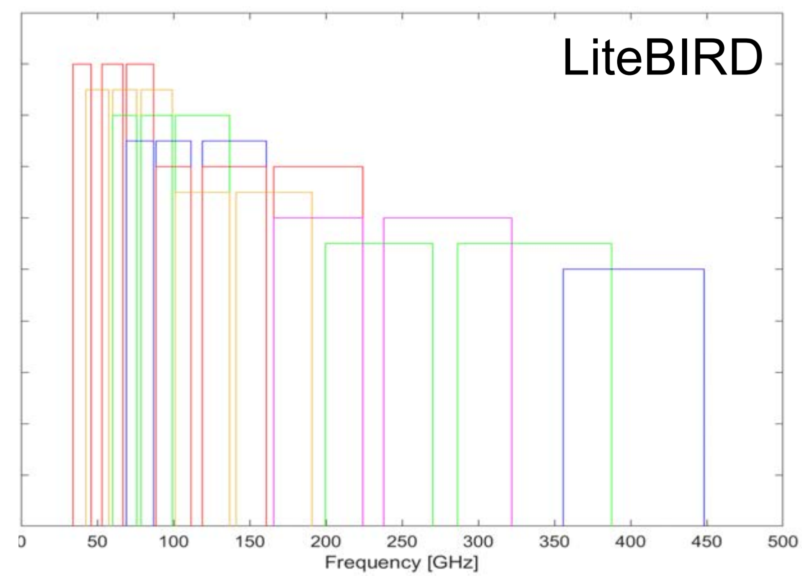


- CMB-S4's neutrino mass constraint is highly limited by degeneracy with the CMB optical depth
- LiteBIRD's access to reionization bump will put a stringent constraint on the optical depth, and enhance neutrino science from CMB-S4.

Complementarity of ground and space-based measurements – frequency coverage, foreground control







Multi-frequency observation is a key for foreground removal

CMB-S4 has 2 bands below LiteBIRD bands. CMB-S4 bands are restricted to atmospheric windows

LiteBIRD has 2 bands above CMB-S4 bands and unrestricted band placement

Conclusion

Princeton CMB-S4 Workshop participants September 2018

Very exciting that two large scale CMB polarization experiments are making progress towards similar deployment/launch schedule

LiteBIRD's and CMB-S4's complementary data set will allow us to do the best science possible

See http://cmb-s4.org for more information