Review of Ground and Balloon-Borne CMB Experiments

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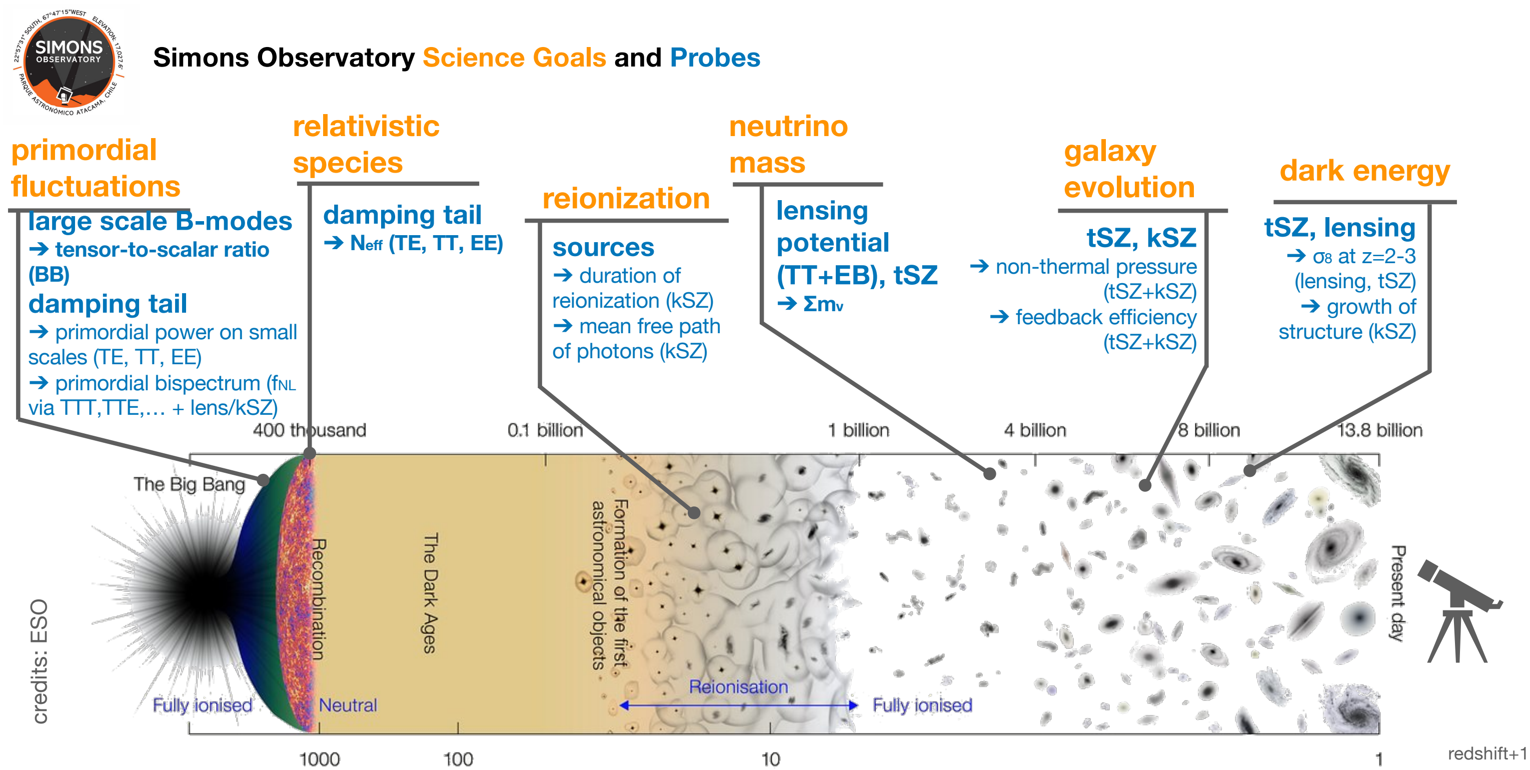
LBNL

Science Goals



Additional science includes (but is not limited to):

- helium fraction, cosmic birefringence, primordial magnetic fields
- high-redshift clusters
- dark matter annihilation and interactions
- isocurvature
- calibration of multiplicative shear bias (e.g., for LSST)
- new sample of dusty star-forming galaxies
- transient sources
- cosmic infrared background

THE SIMONS OBSERVATORY: SCIENCE GOALS AND FORECASTS

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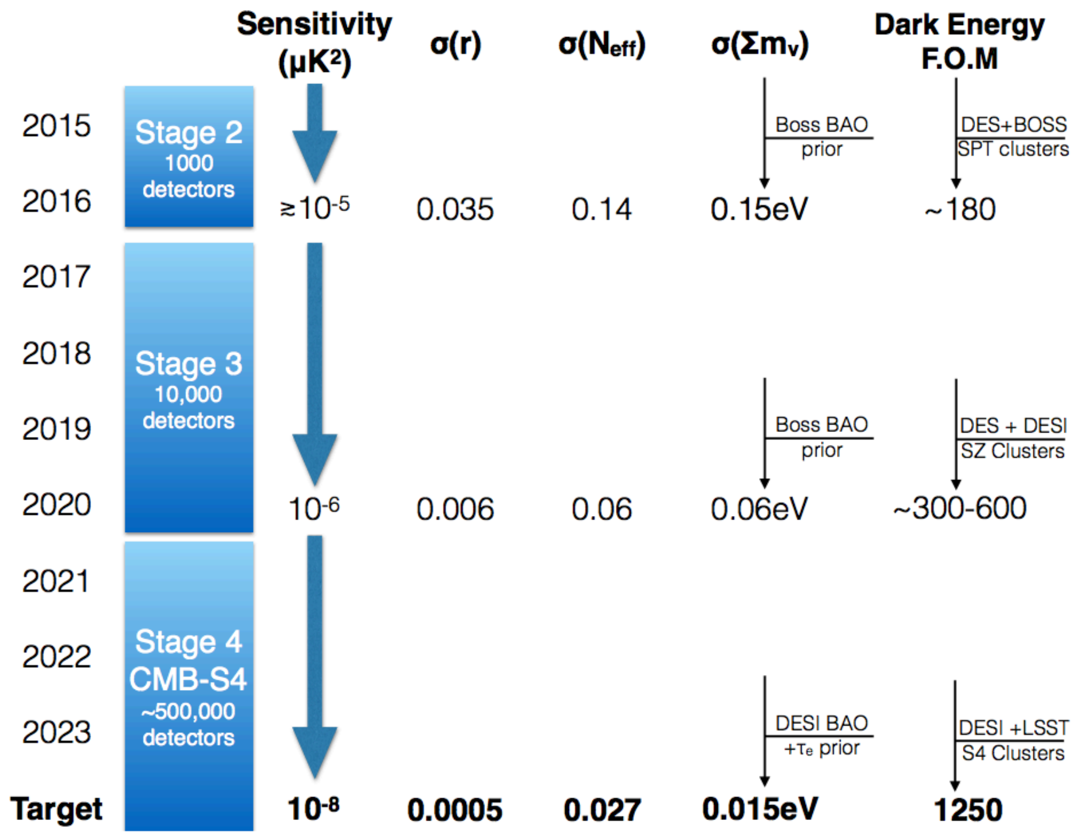
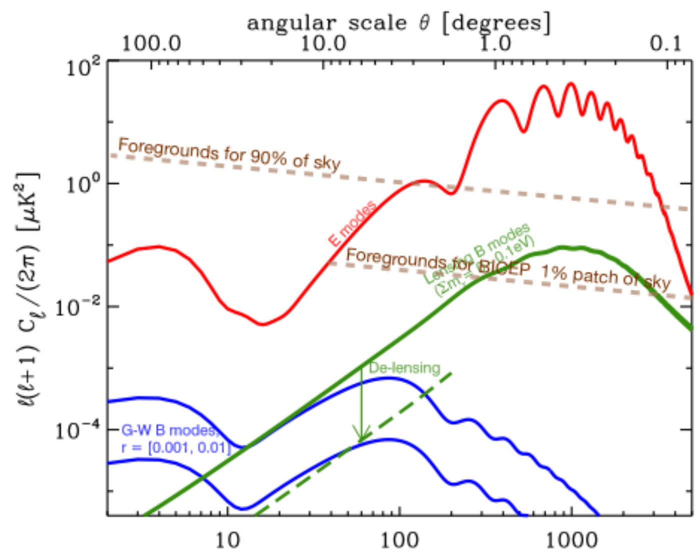


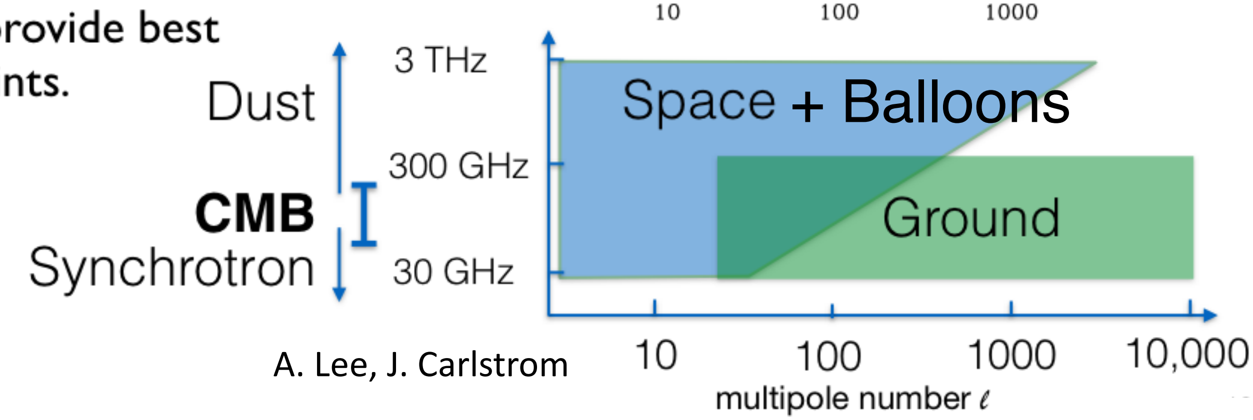
Sensitivity (μK²)
σ(r)
σ(N_eff)
σ(Σm_ν)
Dark Energy F.O.M
2015
2016
Stage 2
1000 detectors
≳10-5
0.035
0.14
Boss BAO prior
0.15eV
DES+BOSS SPT clusters
~180
2017
2018
2019
2020
Stage 3
10,000 detectors
10-6
0.006
0.06
Boss BAO prior
0.06eV
DES + DESI SZ Clusters
~300-600
2021
2022
2023
Target
Stage 4 CMB-S4
~500,000 detectors
10-8
0.0005
0.027
DESI BAO +τe prior
0.015eV
DESI +LSST S4 Clusters
1250

Complementarity of Space, Balloon, and Ground

Space and Ground Complementarity

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





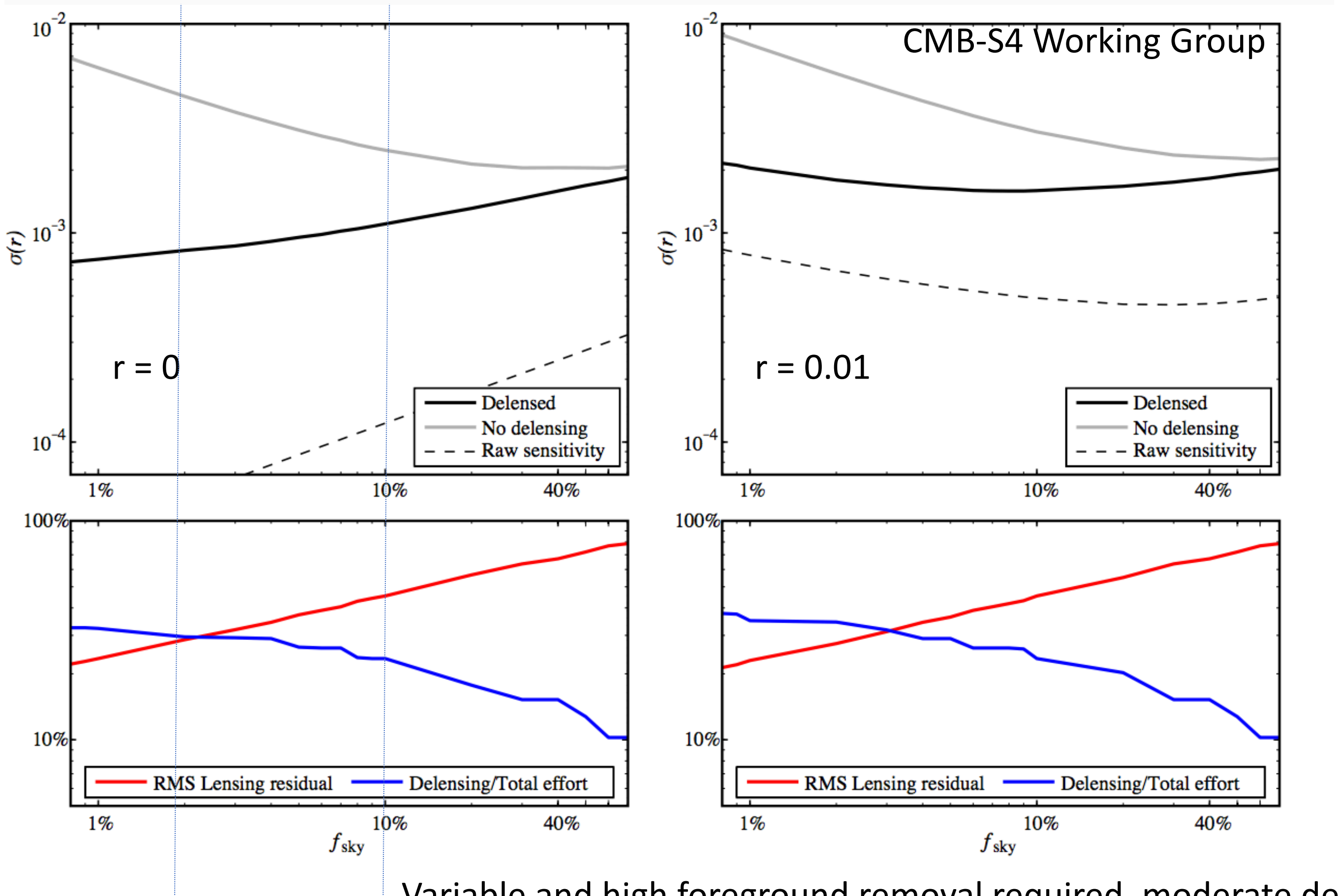
A. Lee, J. Carlstrom

Optimization of Experiments

Primordial Gravitational-Wave Search

- Sky Area
  - Few %, 10%, 80%
- Latitude (site)
  - Chile, South Pole, Tenerife, Ali, Greenland…..
- Modulator
  - None, HWP, VPN, Diode Switch, Waveguide Switch
- Angular Scales
  - Reionization, Recombination
- Frequency range
  - ELF (<20 GHz), LF (20-40 GHz), MF (90-150 GHz), HF (220-280 GHz), EHF (>280 GHz)
- Operating Temperature
  - 100 mK, 300 mK, 20K

Optimization of Sky Area for Ground Experiments



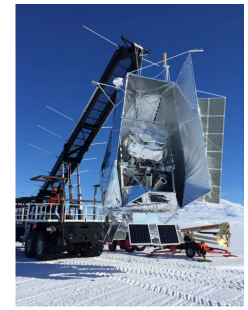
Foreground Removal Included

Variable and high foreground removal required, moderate delensing required

Deep delensing and foreground removal required

Optimization of Latitude/Site

South Pole: Continuous Observation of Sky Regions



Balloon:
Space-like Environment

Mid-Latitude:
Large Sky Accessible
Cross-linked observations

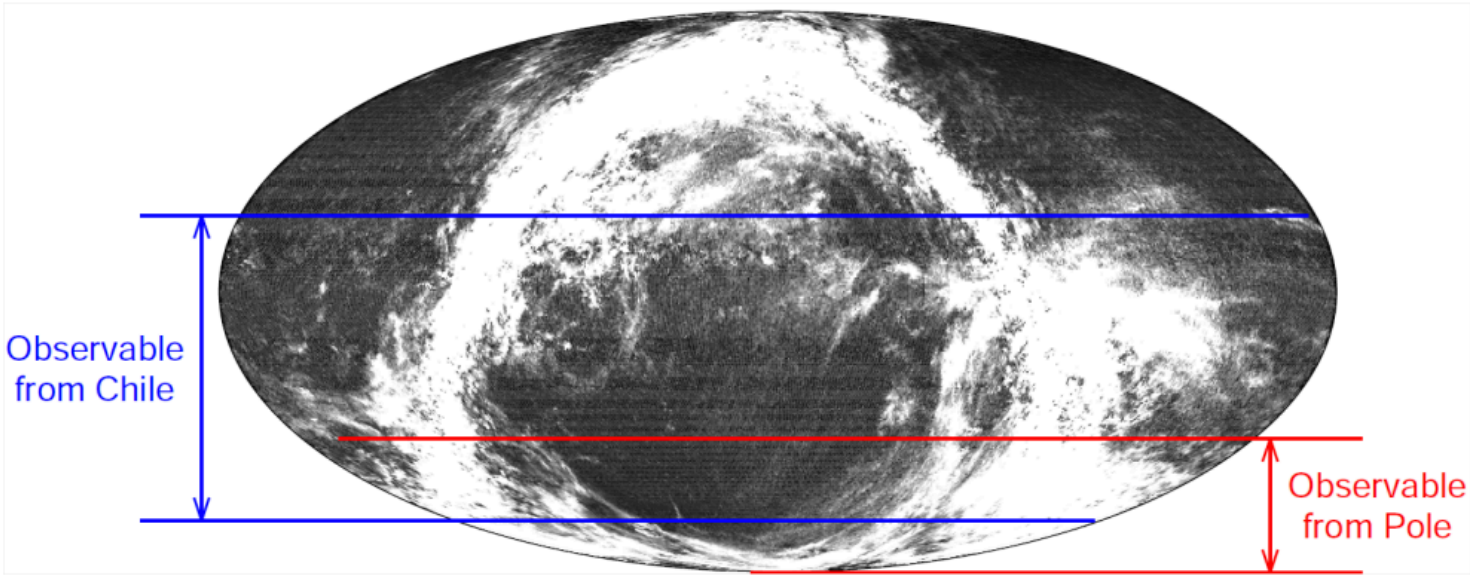
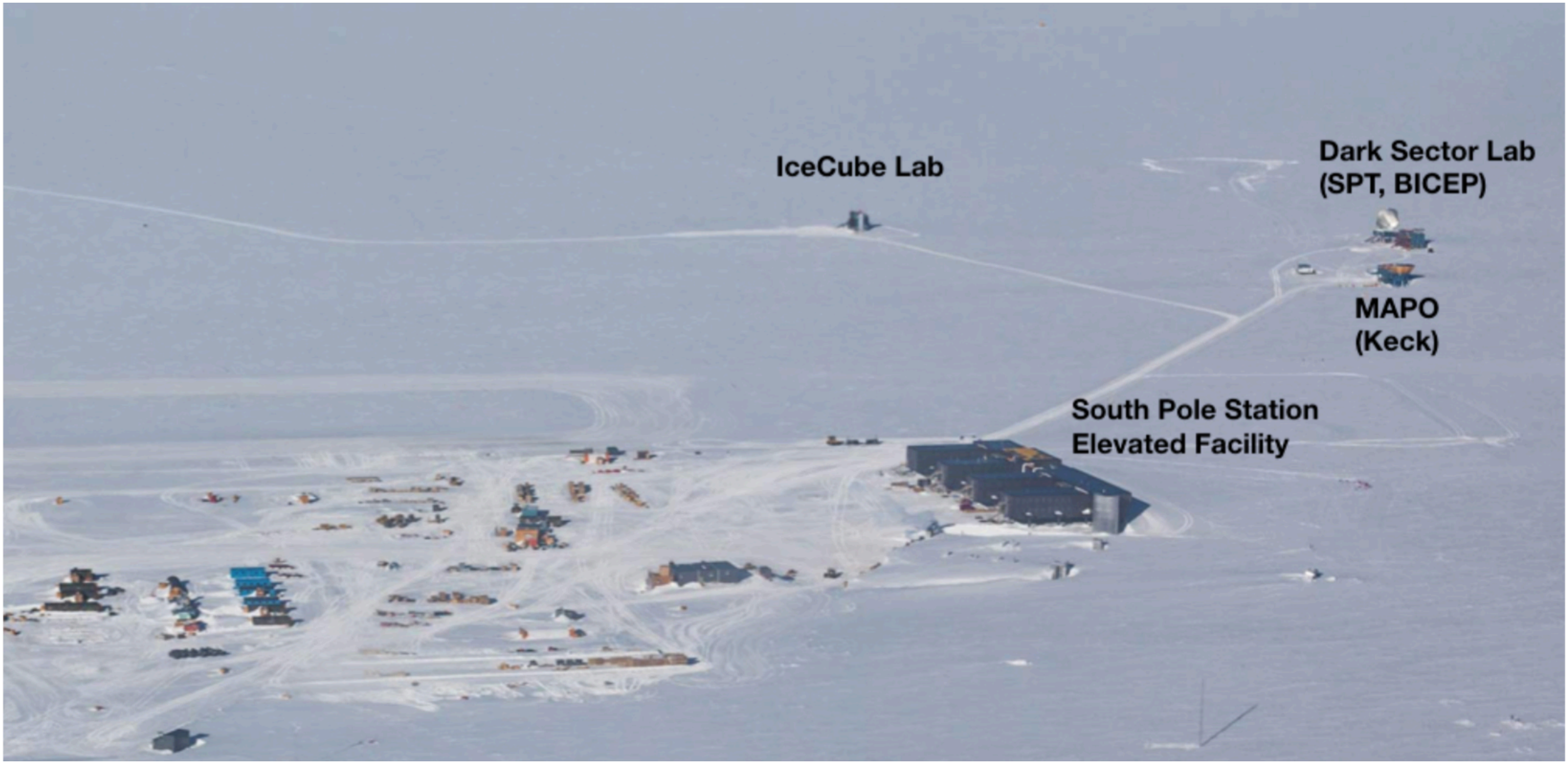
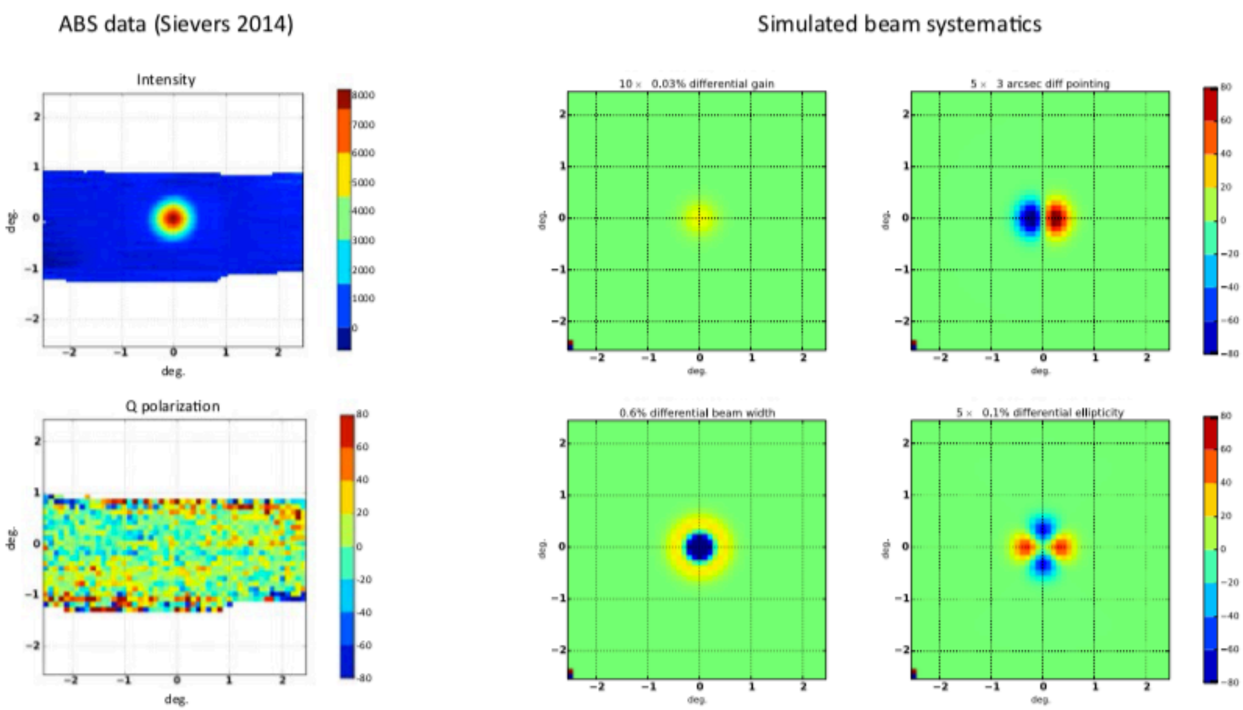


Figure 7: A Mollweide projection of the Planck 353 GHz polarized intensity map with the regions accessible by observing at elevation angles greater than 40° indicated. (The color scale is linear from 0 to 150 $\mu K_{\rm CMB}$, and heavily saturated on the Galactic plane.)


IceCube Lab
Dark Sector Lab
(SPT, BICEP)
MAPO
(Keck)
South Pole Station
Elevated Facility

Polarization Modulators

Polarization Modulators

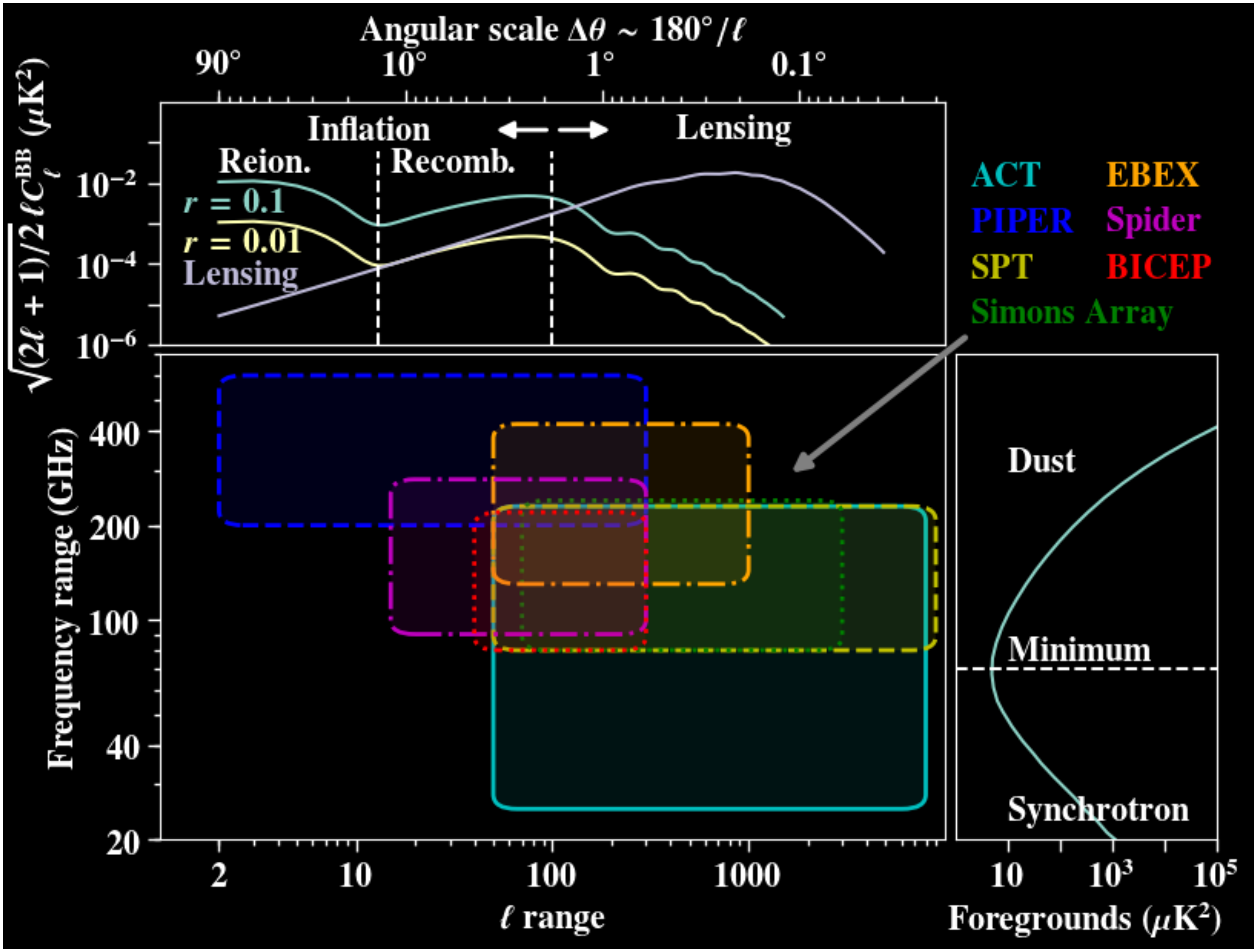


- Simulated monopole leakage ~ 0.03%, Measured <~ 0.1%
- Low Differential Bandpass
- Pol "attack angle" evenly distributed
- Each detector independent

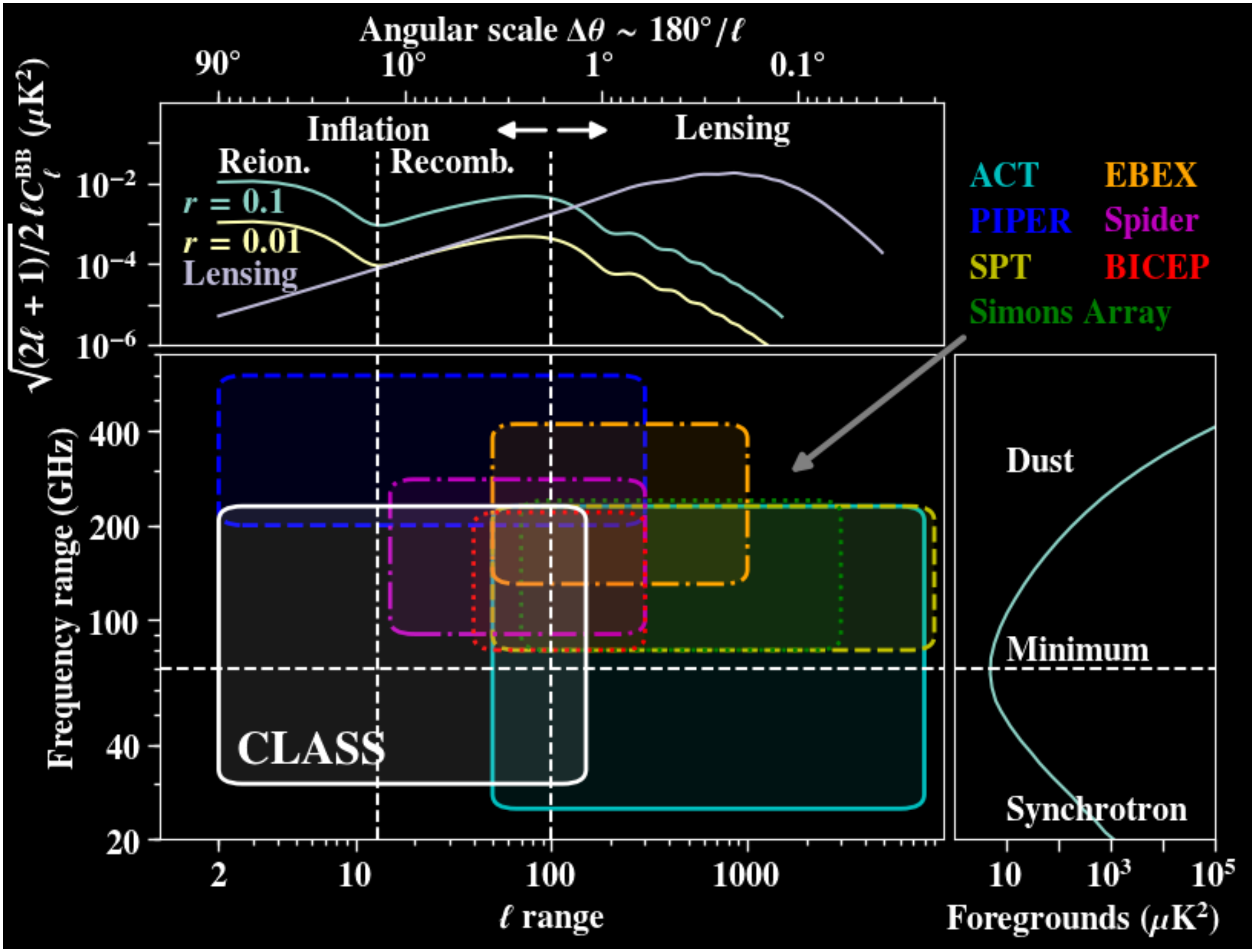
No Modulator

- Simple Instrument
- Broad frequency range
- Common-mode rejection of detector temperature

Angular Scale and Frequency Range



Angular scale $\Delta\theta \sim 180°/\ell$
90°
10°
1°
0.1°
$\sqrt{(2\ell+1)/2}\,\ell C_\ell^{BB}$ (μK^2)
Inflation
Lensing
Reion.
Recomb.
10^{-2}
10^{-4}
10^{-6}
r = 0.1
r = 0.01
Lensing
ACT
EBEX
PIPER
Spider
SPT
BICEP
Simons Array
Frequency range (GHz)
400
200
100
40
20
Dust
Minimum
Synchrotron
2
10
100
1000
ℓ range
10
10^3
10^5
Foregrounds (μK^2)



Angular scale $\Delta\theta \sim 180°/\ell$
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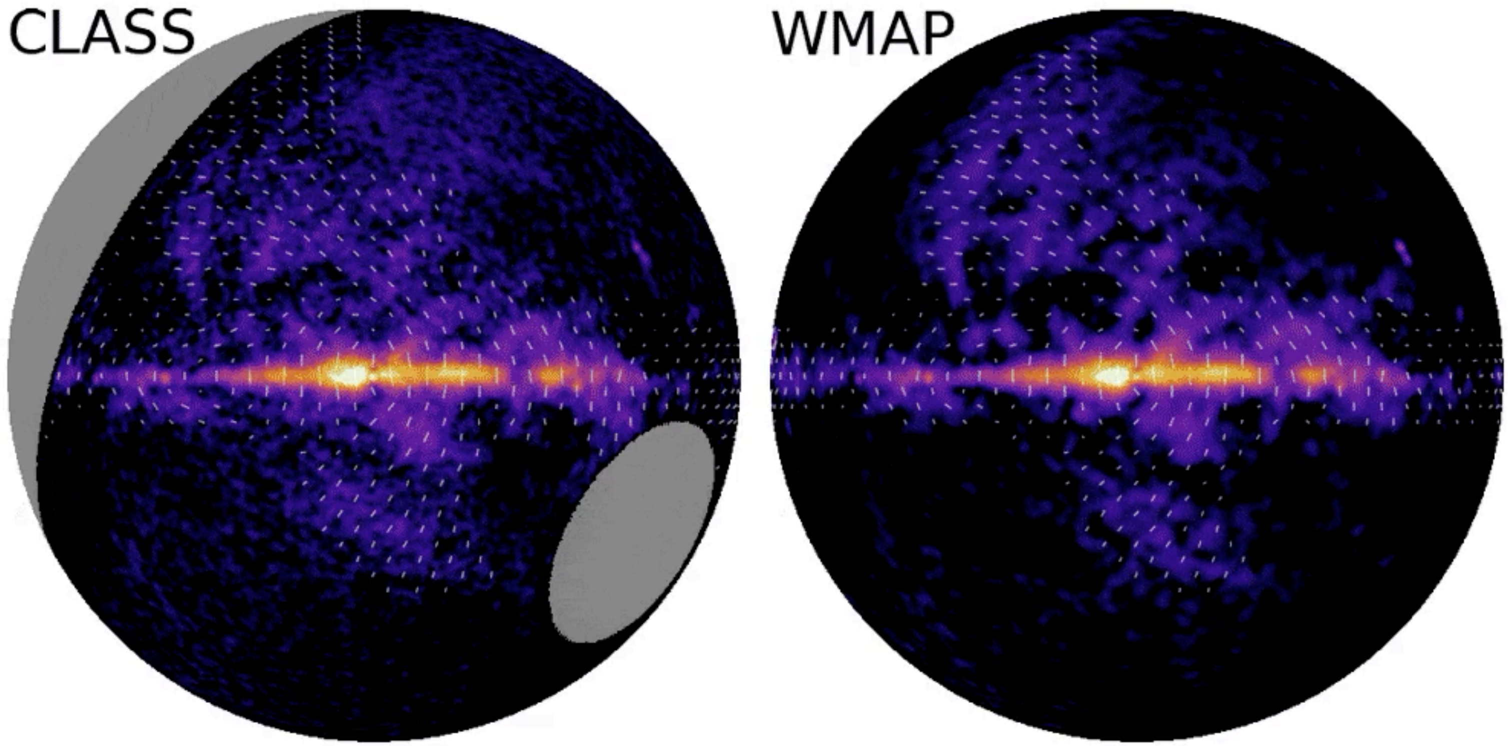
Frequency range (GHz)
400
200
100
40
20
CLASS
Dust
Minimum
Synchrotron
2
10
100
1000
ℓ range
10
10^3
10^5
Foregrounds (μK^2)

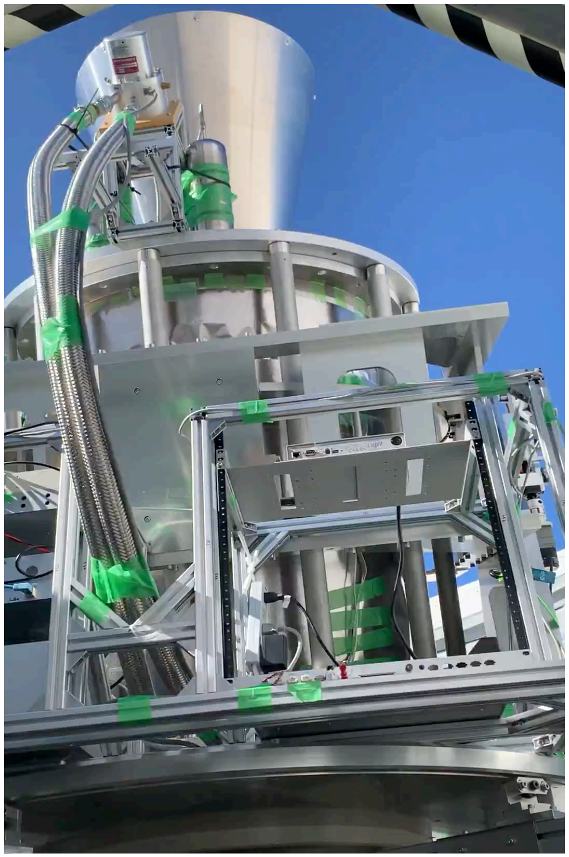
Preliminary 40 GHz Polarization Maps

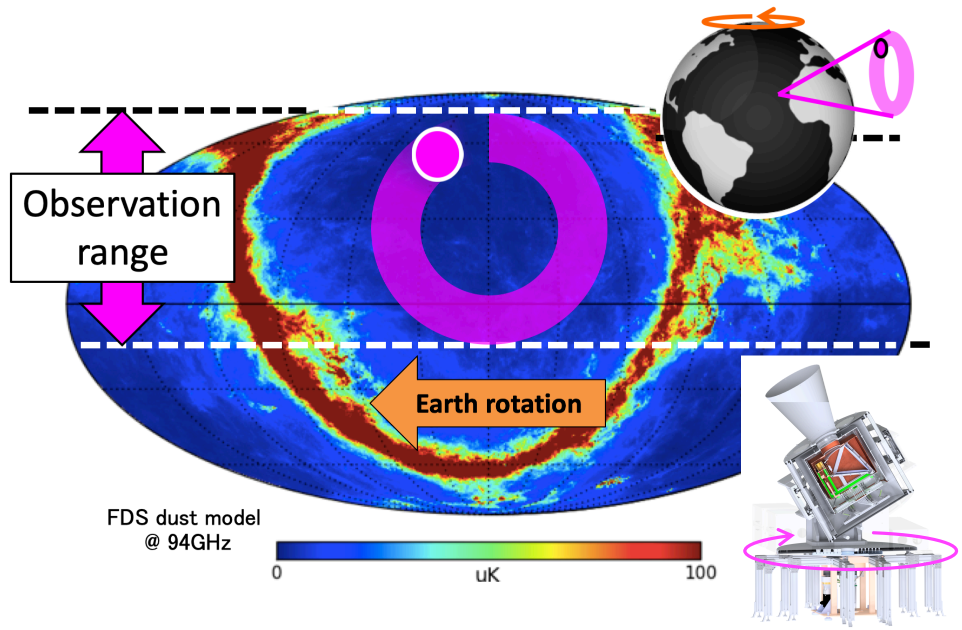


Space-like Measurement from the Ground

Please remember a presentation by R. Santos on Tuesday.

GroundBIRD – satellite's scan on the ground with high-speed scan & MKID, 120˚/s & $\ell \gtrsim 6$





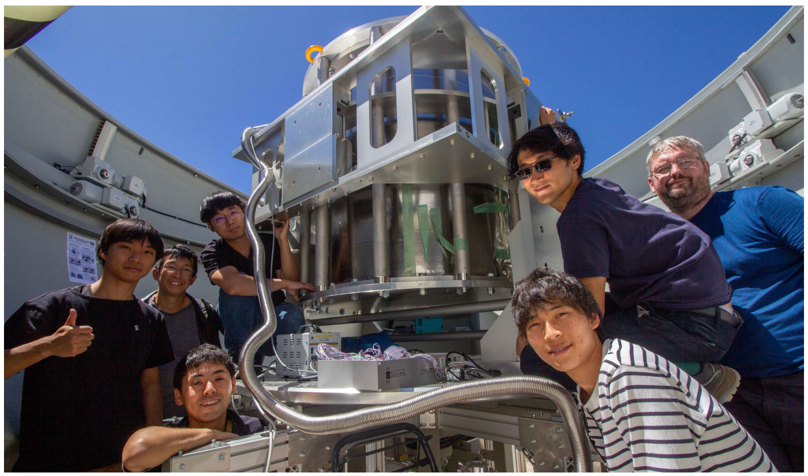
Hunting reionization bump from the ground

Target: $\delta r \sim 0.01$, $\delta \tau \sim 0.01$

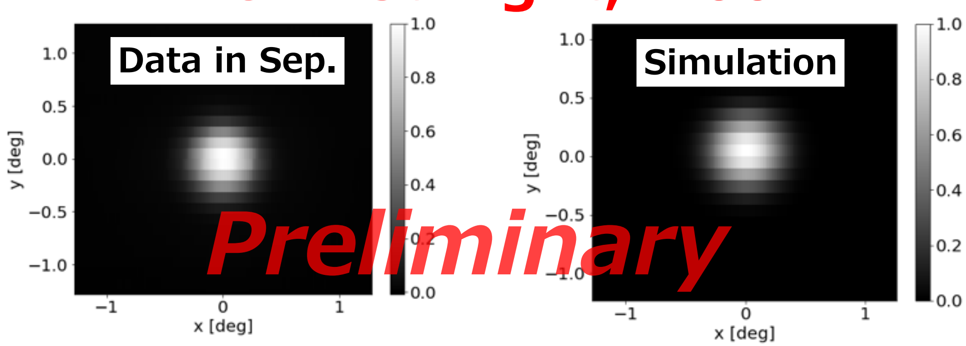
Please remember a presentation by R. Santos on Tuesday.

GroundBIRD was deployed!

at The Teide Observatory in Sep. 2019



The First Light, Moon



Acknowledgement: SRON. We are borrowing MKIDs.

~30m distance

GB + QUIJOTE makes world's largest #freq.

8 bands in 10-220 GHz

Robust strategy to FG

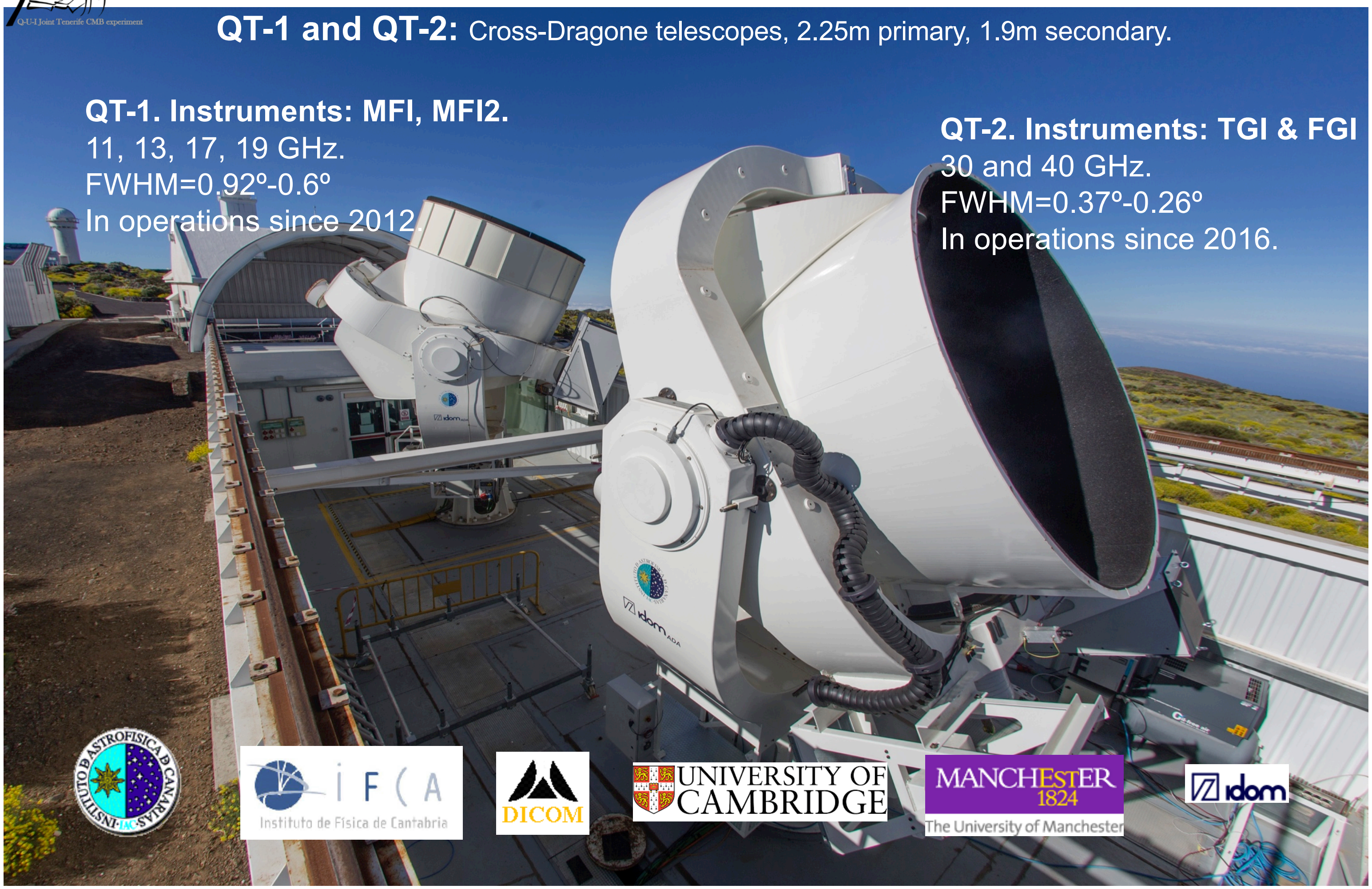
New Developments with ELF Experiments

The QUIJOTE experiment

QT-1 and QT-2: Cross-Dragone telescopes, 2.25m primary, 1.9m secondary.

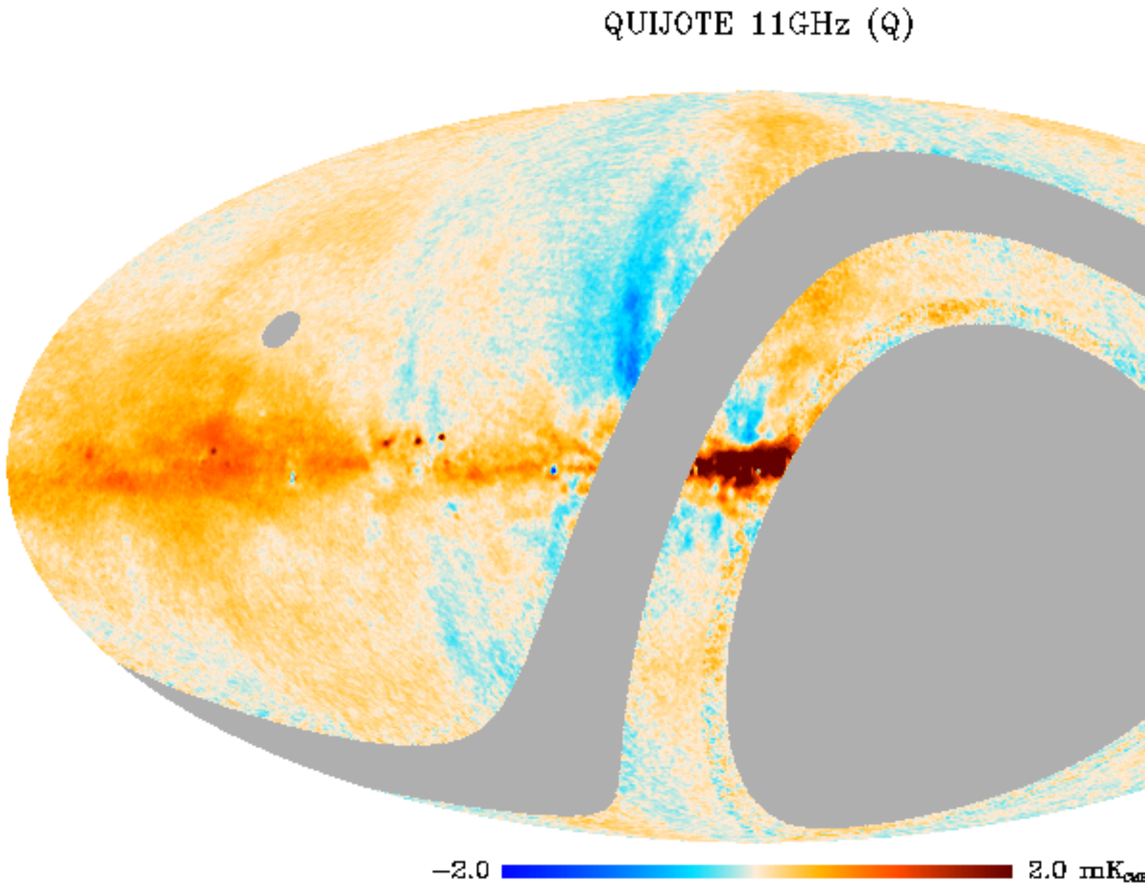
QT-1. Instruments: MFI, MFI2.
11, 13, 17, 19 GHz.
FWHM=0.92º-0.6º
In operations since 2012.

QT-2. Instruments: TGI & FGI
30 and 40 GHz.
FWHM=0.37º-0.26º
In operations since 2016.



Wide survey with the QUIJOTE MFI (10-20 GHz)

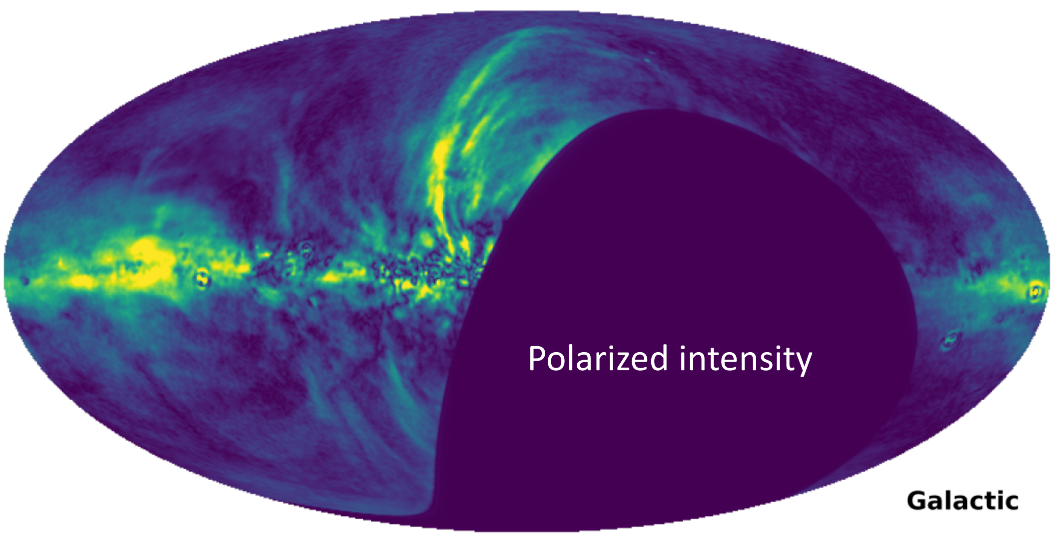
Preliminary maps
(Smoothed to 1º)

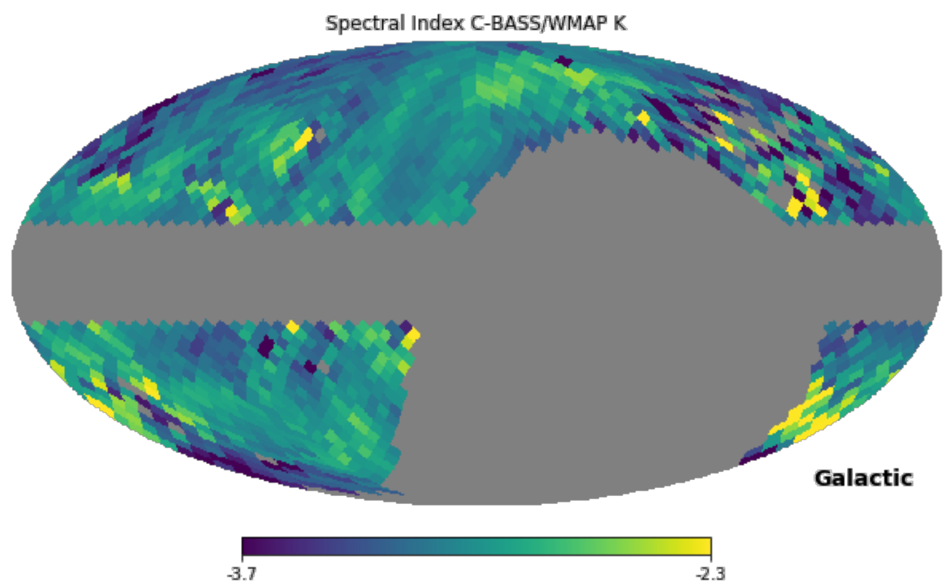



C-BASS North


C-BASS South

C-BASS: Northern data products to be released soon.
Papers on intensity and polarization results in preparation
C-BASS South observations continuing





ELFS and ELFS-S

European Low-Frequency Survey: Long-term plan for comprehensive low-frequency coverage to complement all-sky and southern ground-based surveys:

- 6-m-class telescopes in north and south
- ~100 GHz telescope in north

ELFS-South: Active proposal!

- 5-m telescope at SO site 10-30 GHz
- 5-10 GHz feed on C-BASS-S telescope
- Sensitivity to complement SO/LiteBIRD

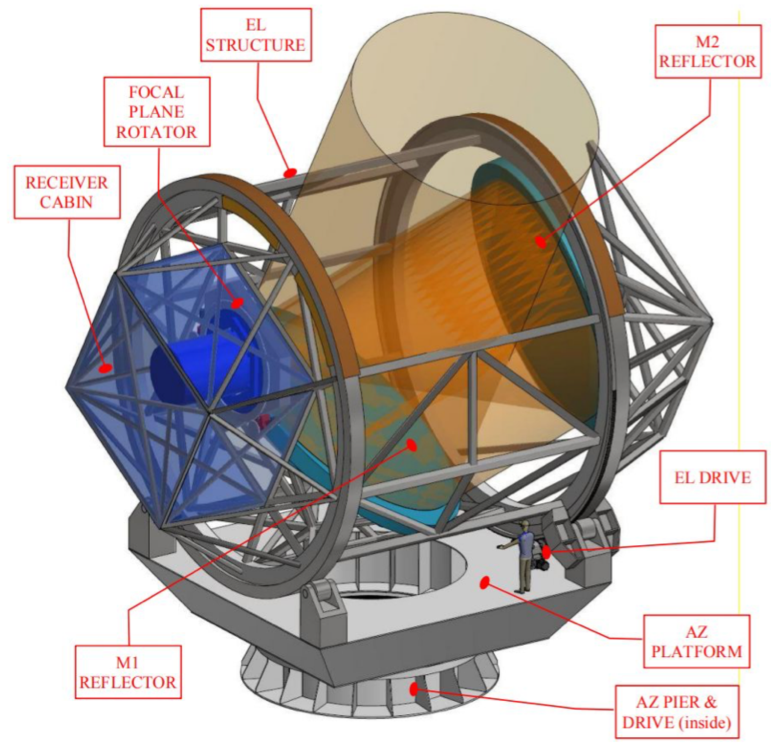
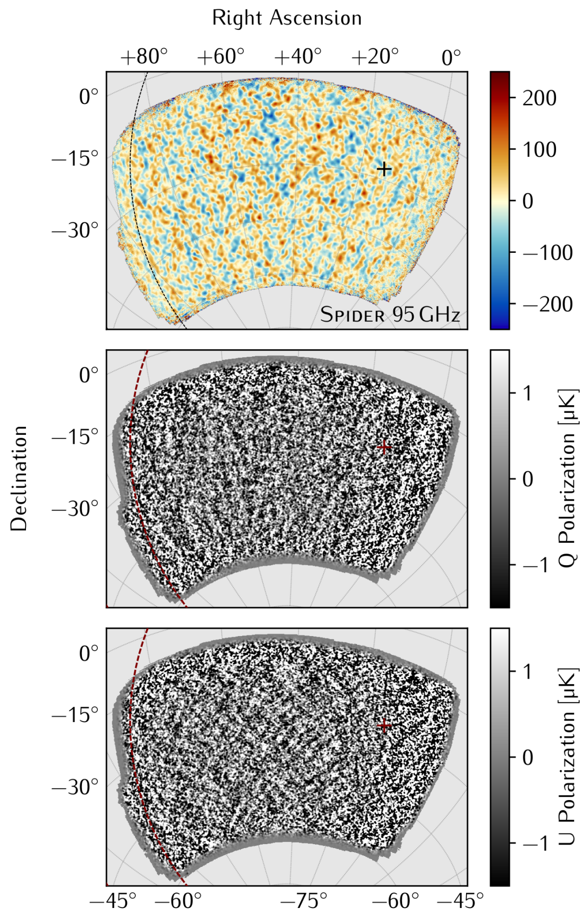
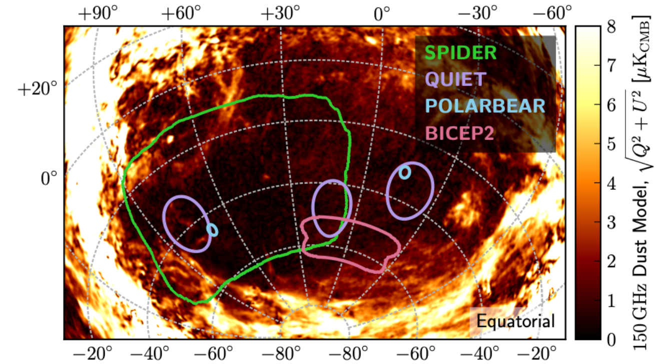


Fig 1: Possible implementation of the ELFS-S 10-30 GHz telescope

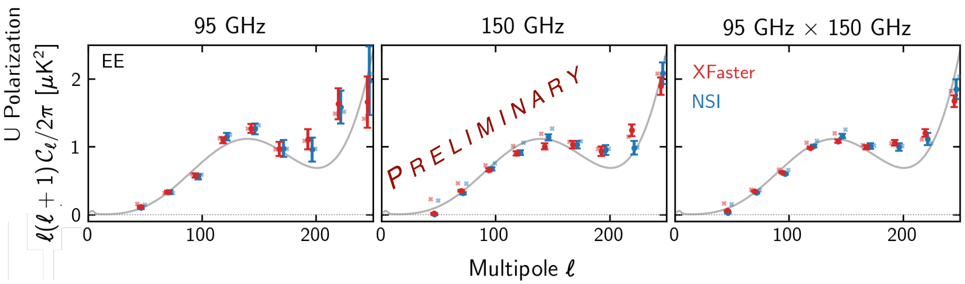
Balloon-Experiments

SPIDER Data





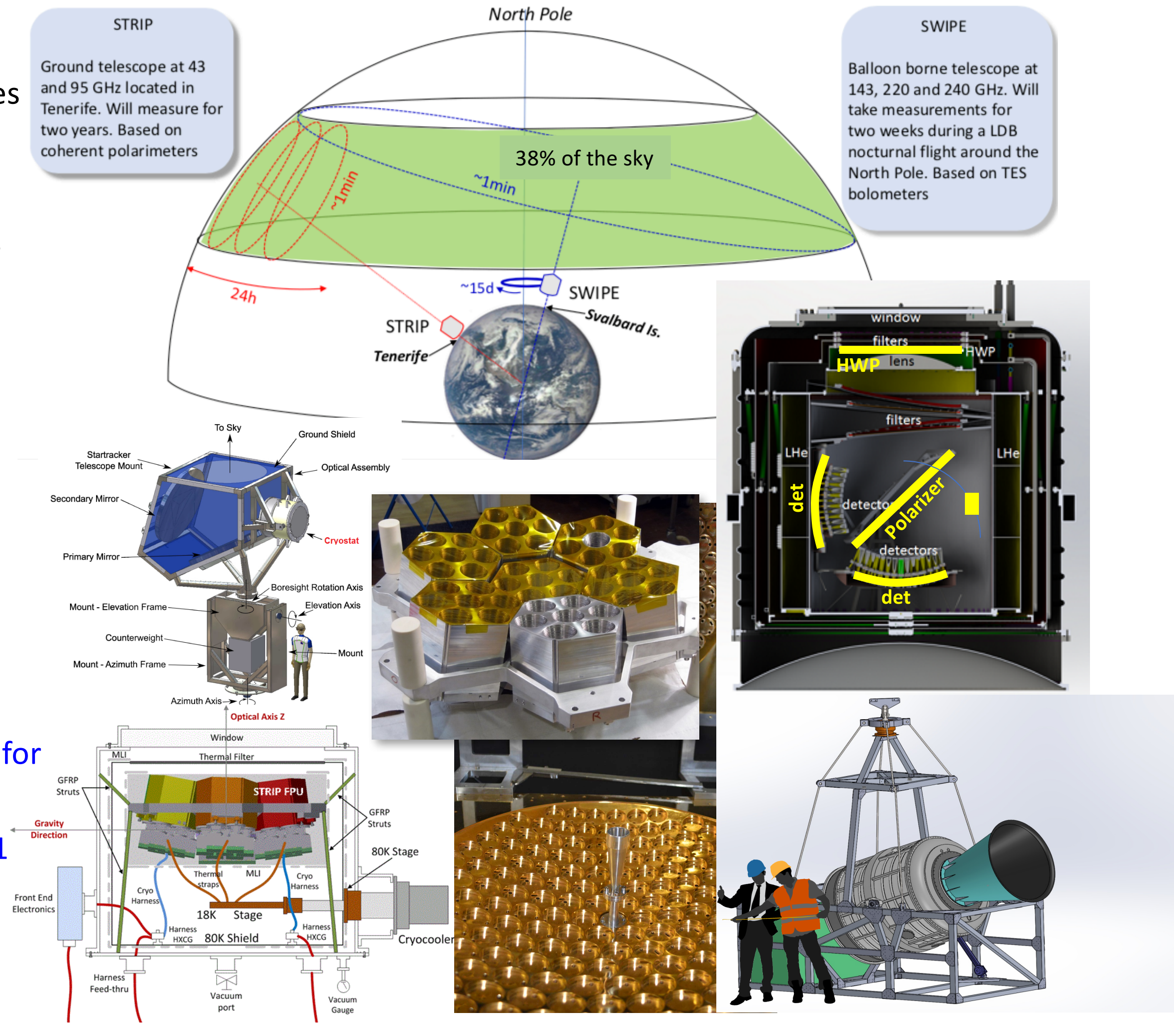
- Excellent receiver performance; limited impact from cosmic rays, beam non-idealities, gain drifts
- Some impact from RFI, scan-synchronous noise; necessitates harsher filtering (for now)
- Foreground analysis using multiple approaches, two power spectrum pipelines

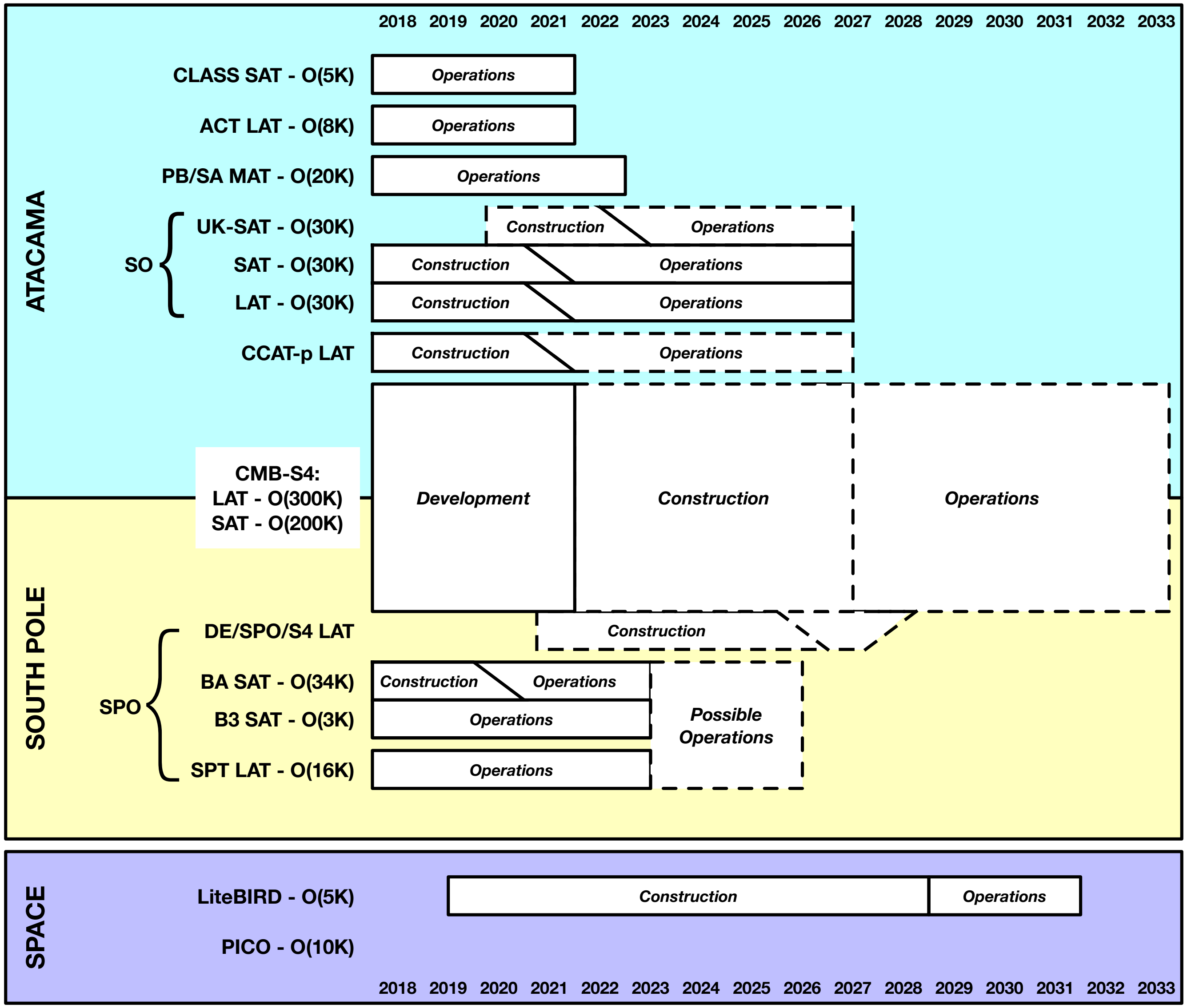


SPIDER EE - dust template (P353-P100)

LSPE: Large-Scale Polarization Explorer

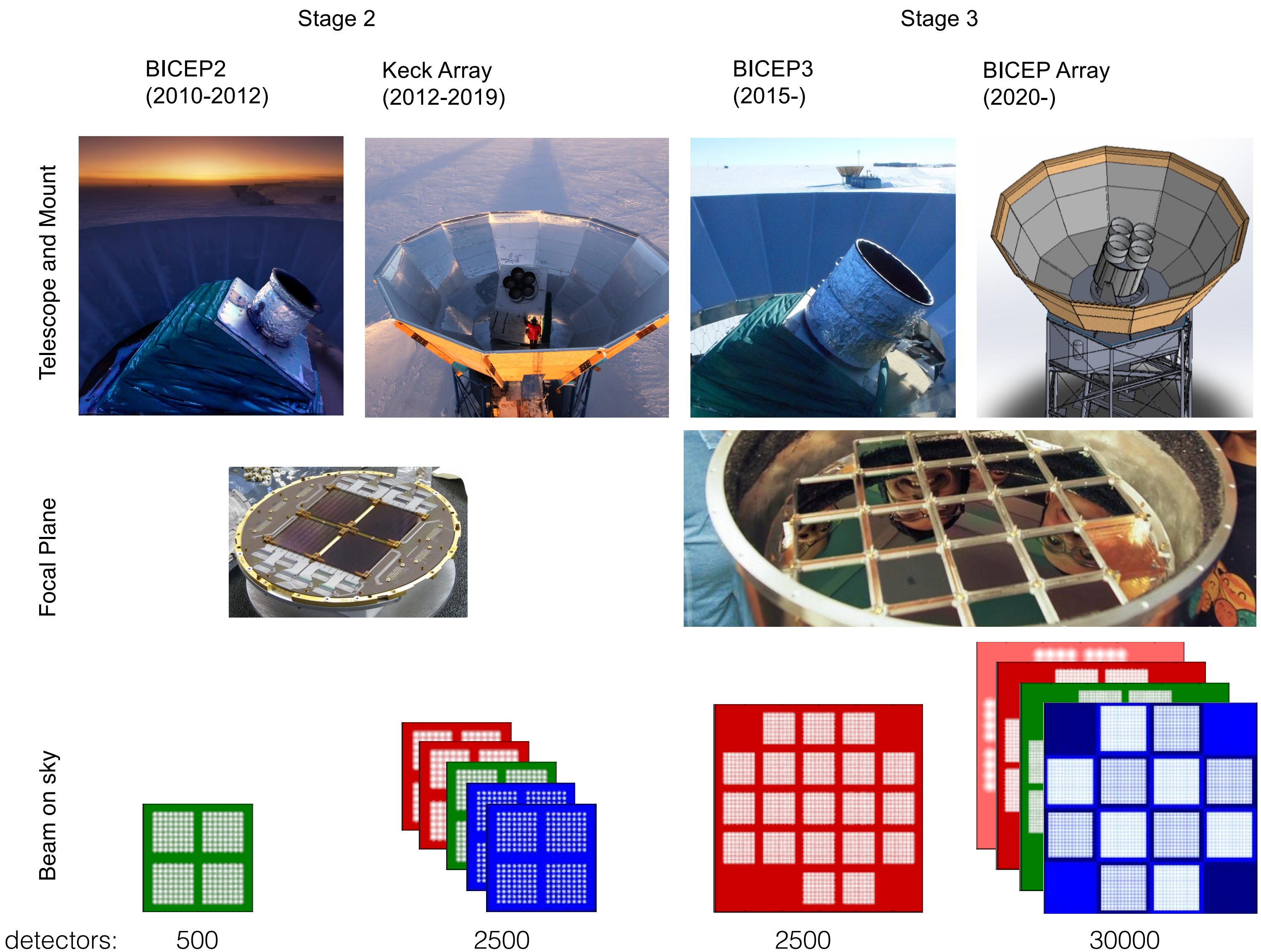
- Targets:
  Large-scale CMB Pol (τ,r)
  Accurate polarization angles
- Frequency coverage:
  40 – 250 GHz (5 bands)
- 2 instruments covering the same northern sky
- STRIP: coherent
  43 + 90 GHz,
  17% + 8% BW,
  20’ + 10’ FWHM,
  100 + 800 μK arcmin
- SWIPE: multimode TES
  145+210+240 GHz,
  30%+20%+10% BW,
  85’ + 85’ + 85’ FWHM,
  16 + 28 + 55 μK arcmin
- Commissioning in Tenerife for STRIP: end 2020
- Launch of SWIPE: end 2021
- Data in hands: 2022
- lspe.roma1.infn.it



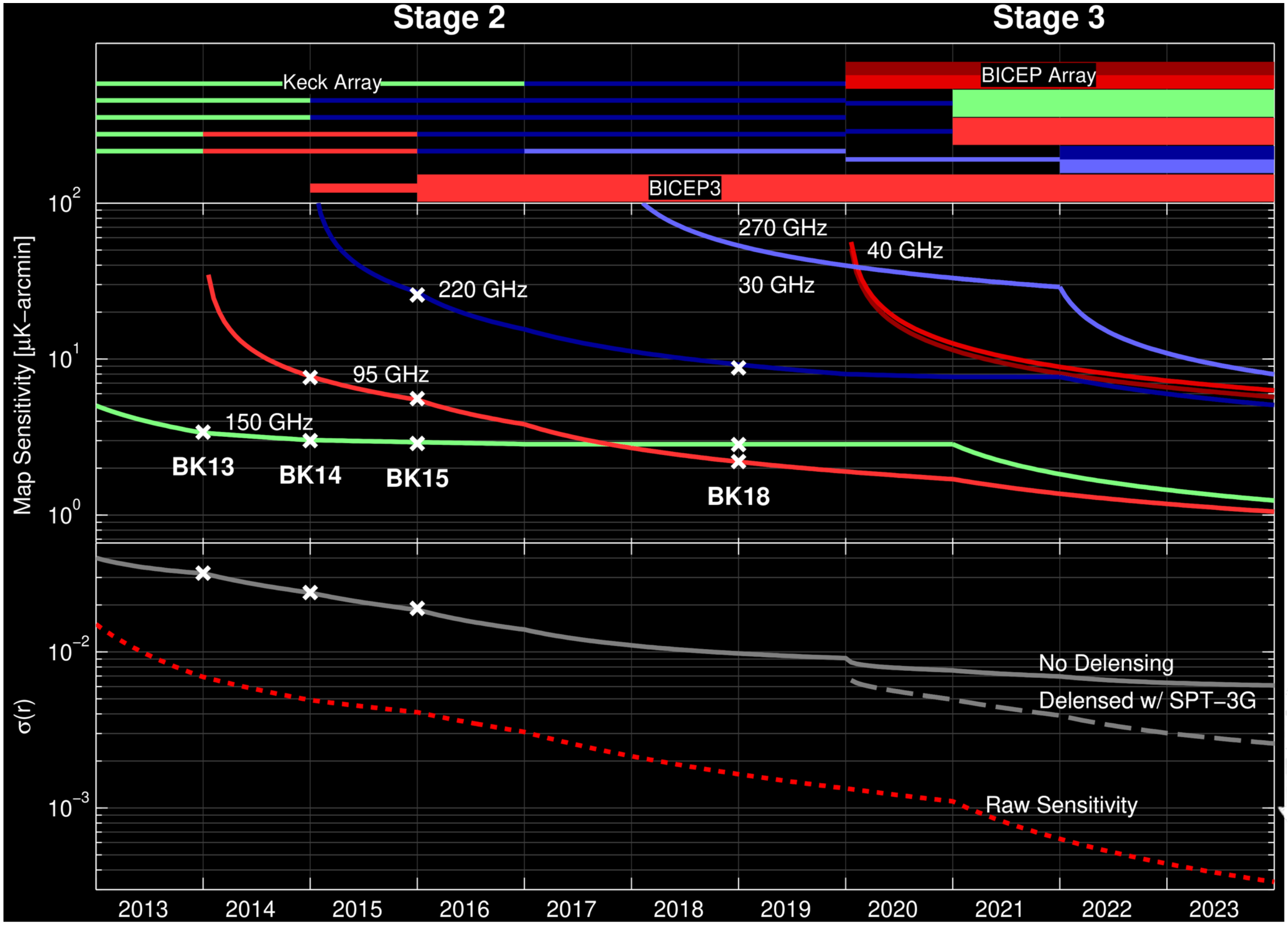


2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033
ATACAMA
CLASS SAT - O(5K)
Operations
ACT LAT - O(8K)
Operations
PB/SA MAT - O(20K)
Operations
SO
UK-SAT - O(30K)
Construction
Operations
SAT - O(30K)
Construction
Operations
LAT - O(30K)
Construction
Operations
CCAT-p LAT
Construction
Operations
CMB-S4:
LAT - O(300K)
SAT - O(200K)
Development
Construction
Operations
SOUTH POLE
DE/SPO/S4 LAT
Construction
SPO
BA SAT - O(34K)
Construction
Operations
B3 SAT - O(3K)
Operations
SPT LAT - O(16K)
Operations
Possible Operations
SPACE
LiteBIRD - O(5K)
Construction
Operations
PICO - O(10K)
2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033

South Pole Experiments

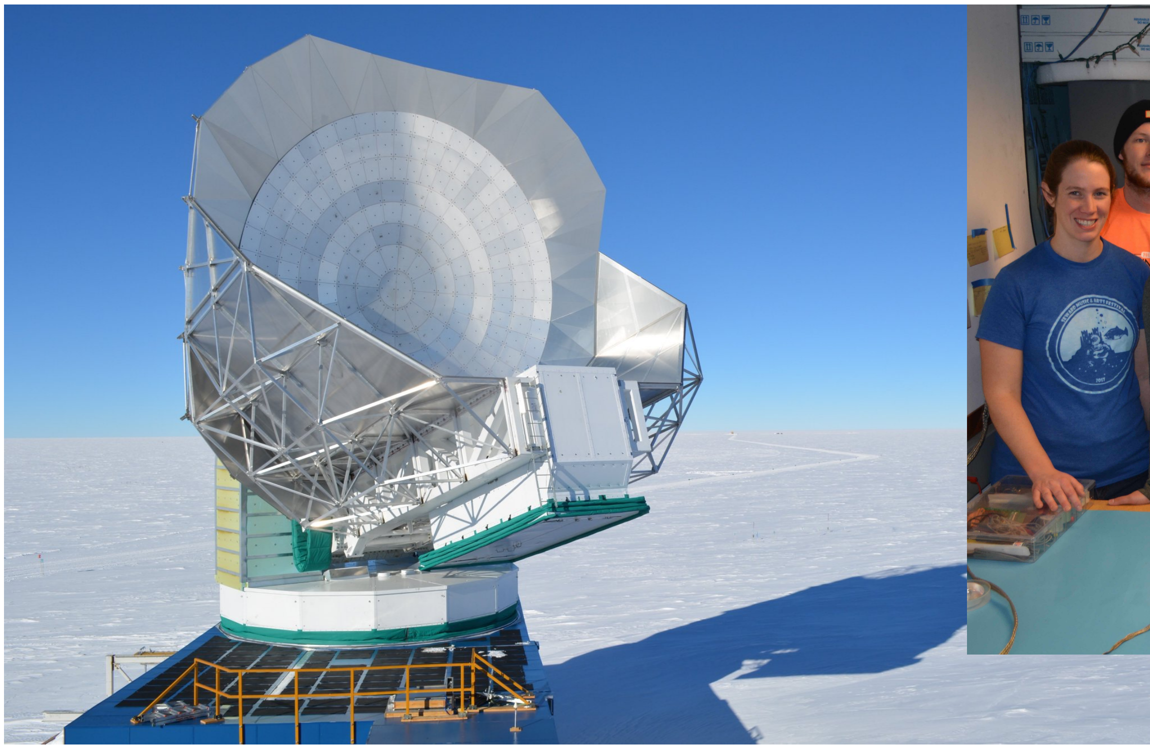


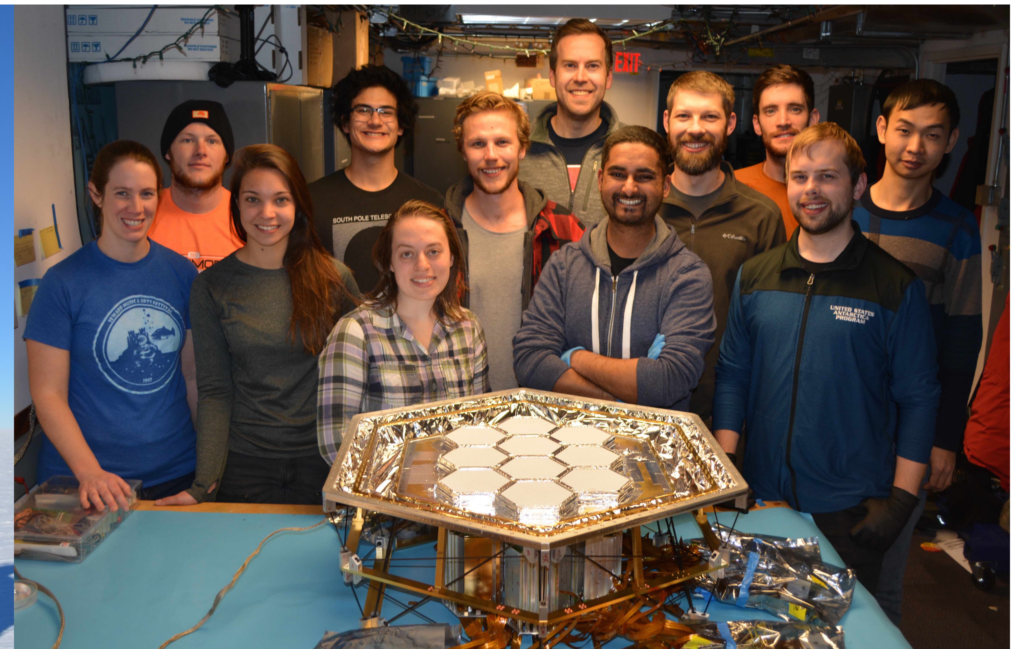
Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2015-)
BICEP Array
(2020-)
Telescope and Mount
Focal Plane
Beam on sky
detectors:
500
2500
2500
30000



delensing with SPT

South Pole Telescope and SPT-3G Instrument



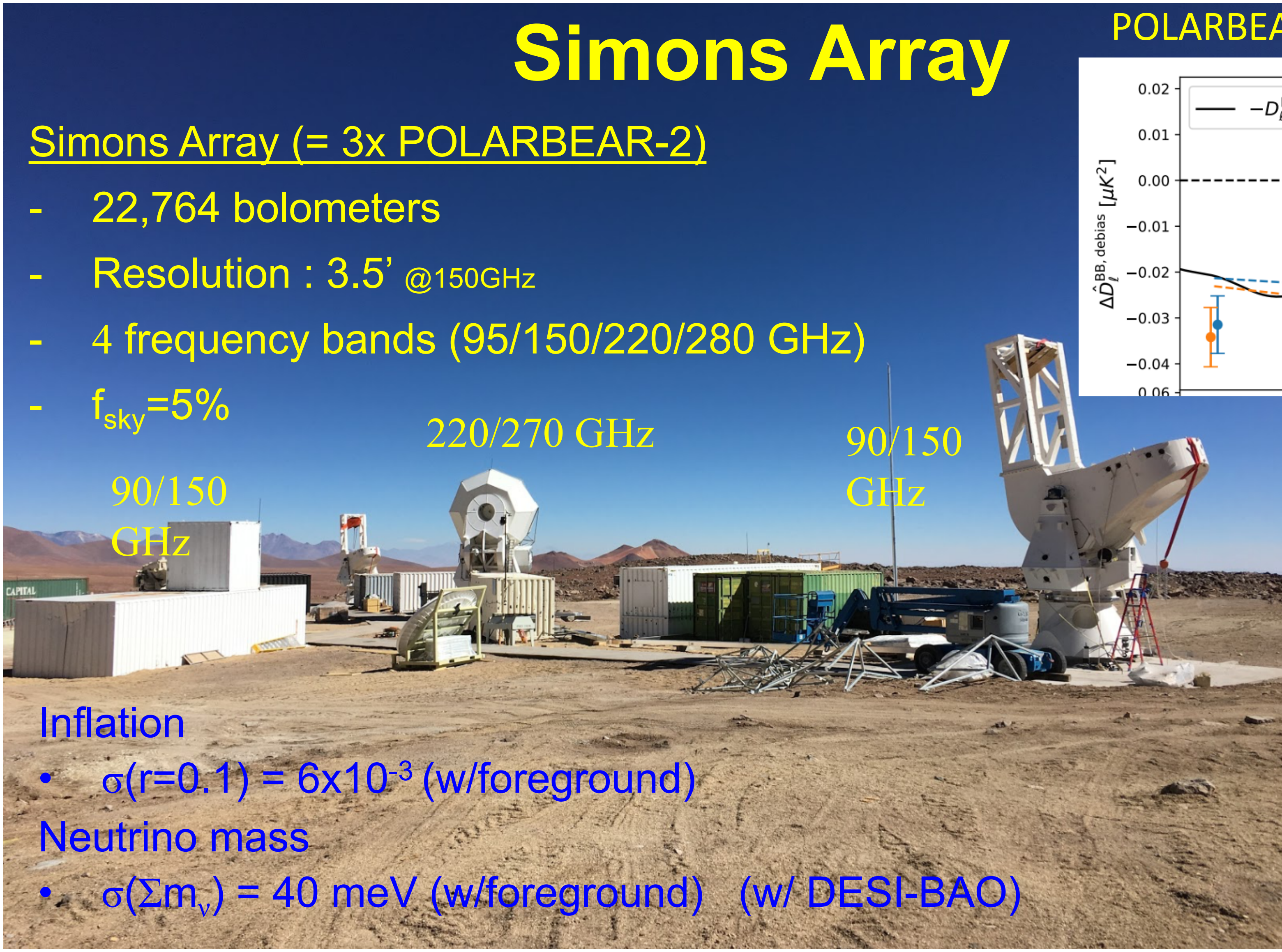


Chile Experiments

Simons Array

Simons Array (= 3x POLARBEAR-2)

- 22,764 bolometers
- Resolution : 3.5' @150GHz
- 4 frequency bands (95/150/220/280 GHz)
- f_{sky}=5%



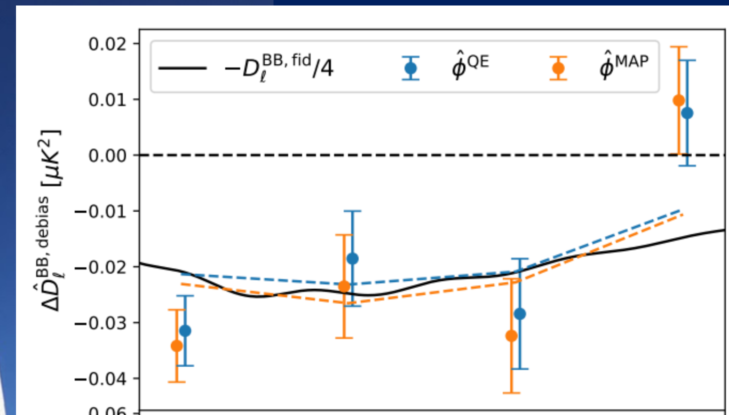
Inflation

- $\sigma(r=0.1) = 6\times10^{-3}$ (w/foreground)

Neutrino mass

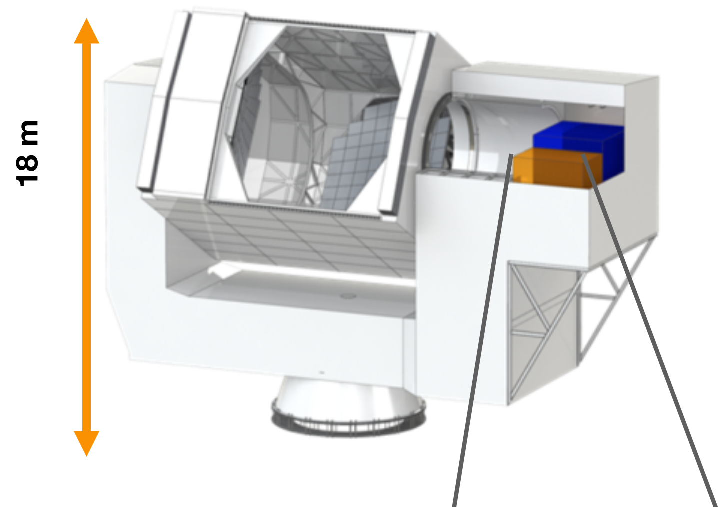
- $\sigma(\Sigma m_\nu)$ = 40 meV (w/foreground) (w/ DESI-BAO)

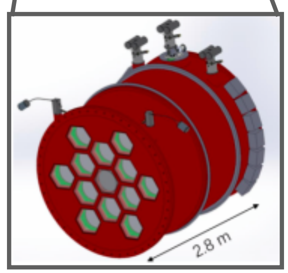
POLARBEAR Delensing Result



The Simons Observatory instruments and technology

Large Aperture Telescope



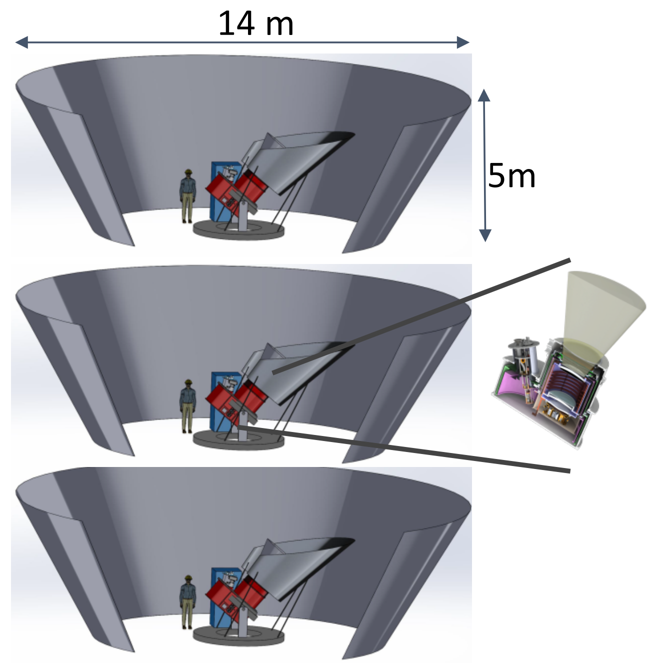


6 m crossed Dragone coupled to 13 optics tubes,

Baseline is 7 tubes for SO, with dichroic pixels:

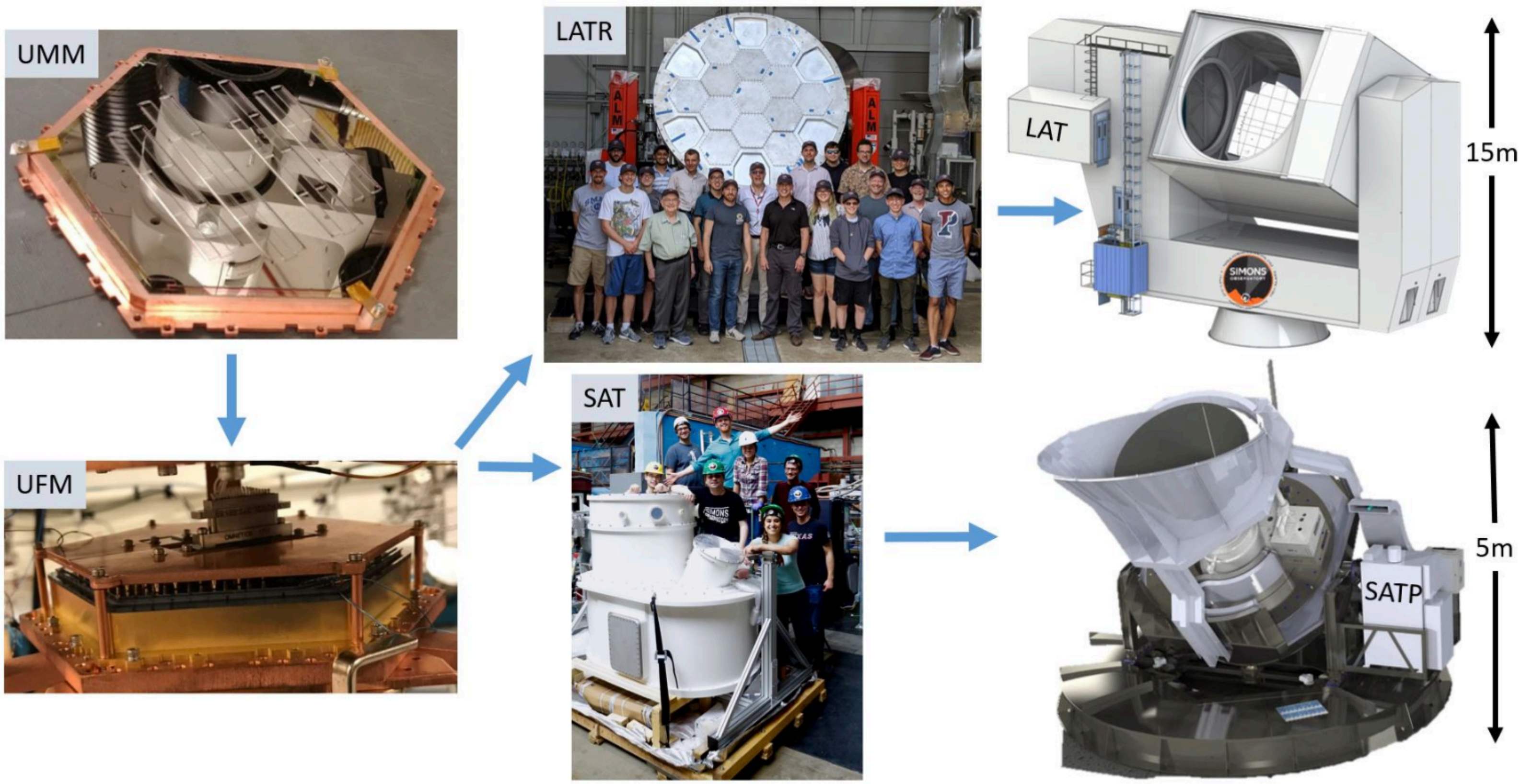
- One tube: 30/40 GHz
- Four tubes: 90/150 GHz
- Two tubes: 220/270 GHz

Small Aperture Telescopes



Three refractors 42 cm in diameter, rotating half-wave plate.
Dichroic pixels:
30/40 | 90/150 | 220/270 GHz

Instrument Development Progress



SIMONS OBSERVATORY

Anticipated Noise Performance

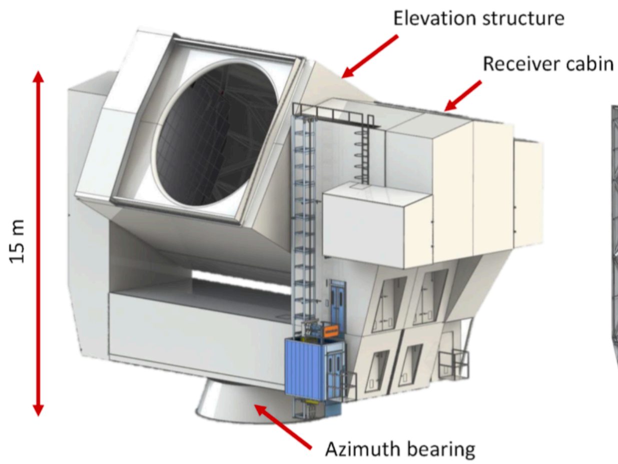
		SATs ($f_{\rm sky} = 0.1$)				LAT ($f_{\rm sky} = 0.4$)			
	Freq. [GHz]	FWHM (′)	Noise (baseline) [μK-arcmin]		Noise (goal) [μK-arcmin]	FWHM (′)	Noise (baseline) [μK-arcmin]		Noise (goal) [μK-arcmin]
LF	27	91	35		25	7.4	71		52
	39	63	21		17	5.1	36		27
MF	93	30	2.6	2 μK-amin	1.9	2.2	8.0	6 μK-amin	5.8
	145	17	3.3		2.1	1.4	10		6.3
HF	225	11	6.3		4.2	1.0	22		15
	280	9	16		10	0.9	54		37

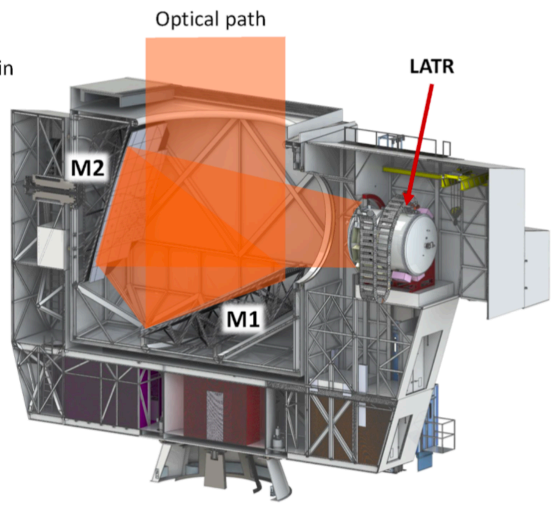
White noise levels for 5-yr survey; also include atmospheric noise model and combine with Planck

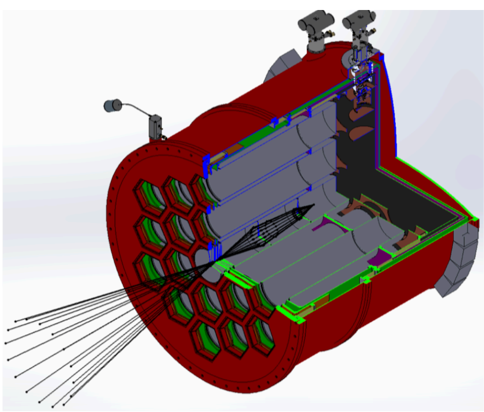
Table 1: Summary of SO key science goals[a]

	Current[b]	SO-Nominal (2022-27)		Method[d]	SWP
		Baseline	Goal		
Primordial perturbations (§2.1)					
r ($A_L = 0.5$)	0.03	0.003	0.002[e]	BB + external delensing	[28]
n_s	0.004	0.002	0.002	TT/TE/EE	[28]
$e^{-2\tau}\mathcal{P}(k = 0.2/\text{Mpc})$	3%	0.5%	0.4%	TT/TE/EE	[30]
$f_{\rm NL}^{\rm local}$	5	3	1	$\kappa\kappa$ × LSST-LSS	[23]
		2	1	kSZ + LSST-LSS	
Relativistic species (§2.2)					
$N_{\rm eff}$	0.2	0.07	0.05	TT/TE/EE + $\kappa\kappa$	[16]
Neutrino mass (§2.3)					
Σm_ν (eV, $\sigma(\tau) = 0.01$)	0.1	0.04	0.03	$\kappa\kappa$ + DESI-BAO	[11]
		0.04	0.03	tSZ-N × LSST-WL	
Σm_ν (eV, $\sigma(\tau) = 0.002$)		0.03[f]	0.02	$\kappa\kappa$ + DESI-BAO + LB	
		0.03	0.02	tSZ-N × LSST-WL + LB	
Beyond standard model (§2.4)					
$\sigma_8(z = 1-2)$	7%	2%	1%	$\kappa\kappa$ + LSST-LSS	[31]
		2%	1%	tSZ-N × LSST-WL	
H_0 (ΛCDM)	0.5	0.4	0.3	TT/TE/EE + $\kappa\kappa$	[3]
Galaxy evolution (§2.5)					
$\eta_{\rm feedback}$	50-100%	3%	2%	kSZ + tSZ + DESI	[2]
$p_{\rm nt}$	50-100%	8%	5%	kSZ + tSZ + DESI	[2]
Reionization (§2.6)					
Δz	1.4	0.4	0.3	TT (kSZ)	[1]

CMB-S4

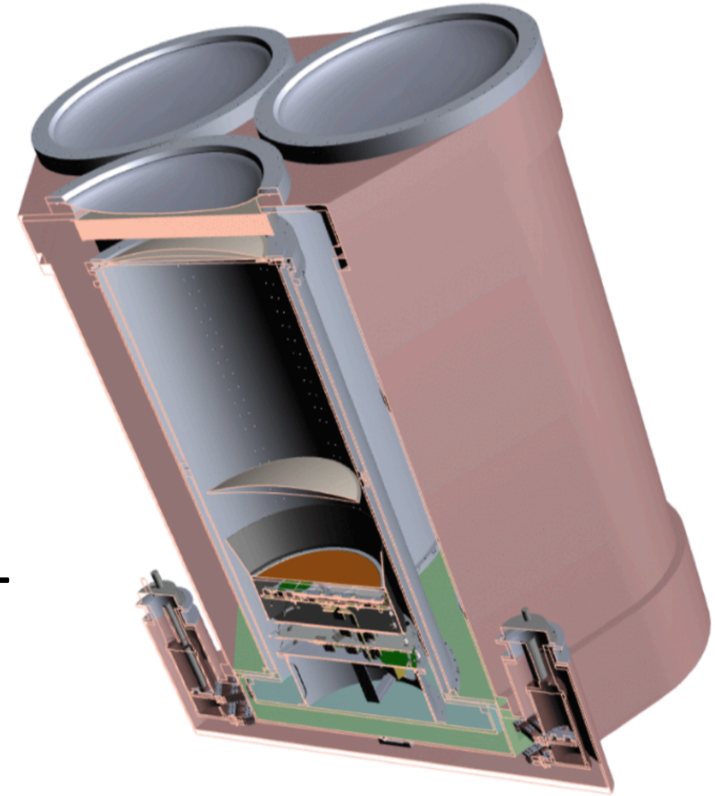




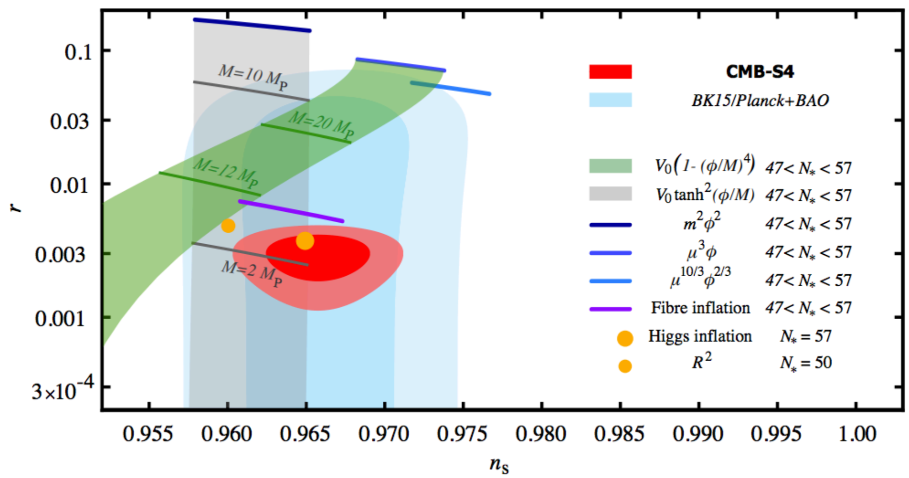


LAT

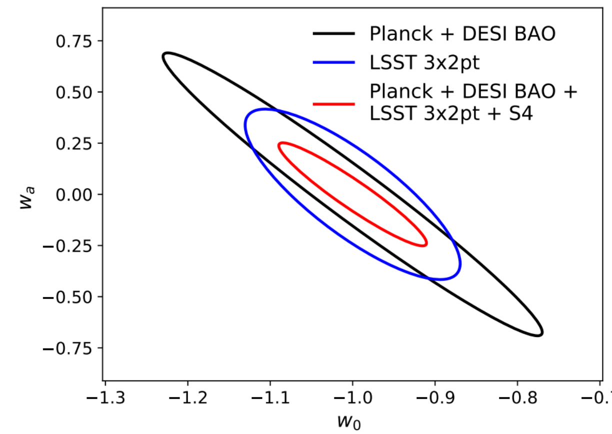
SAT



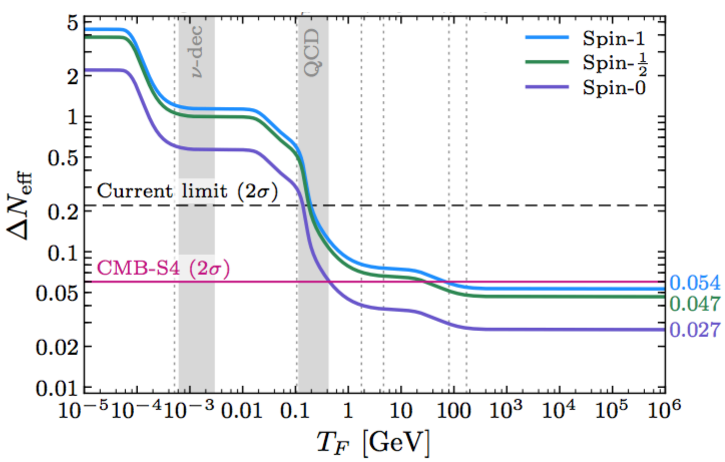
CMB-S4



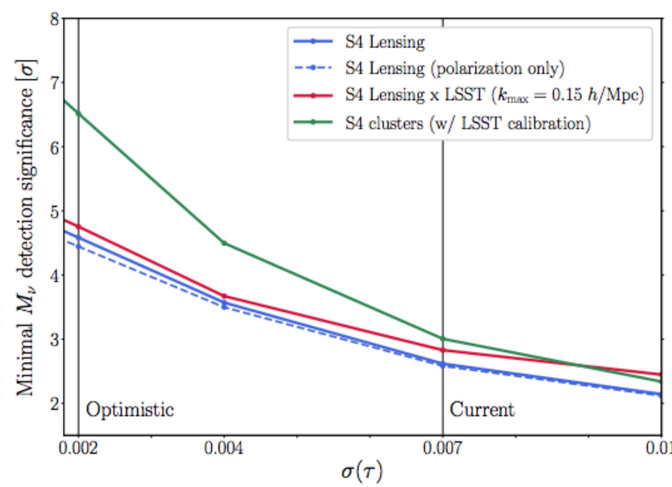
CMB-S4
BK15/Planck+BAO
$V_0(1-(\phi/M)^4)$ $47 < N_* < 57$
$V_0 \tanh^2(\phi/M)$ $47 < N_* < 57$
$m^2\phi^2$ $47 < N_* < 57$
$\mu^3\phi$ $47 < N_* < 57$
$\mu^{10/3}\phi^{2/3}$ $47 < N_* < 57$
Fibre inflation $47 < N_* < 57$
Higgs inflation $N_* = 57$
R^2 $N_* = 50$
$M=10\,M_P$
$M=20\,M_P$
$M=12\,M_P$
$M=2\,M_P$
r
n_s



Planck + DESI BAO
LSST 3x2pt
Planck + DESI BAO + LSST 3x2pt + S4
w_a
w_0



Spin-1
Spin-$\frac{1}{2}$
Spin-0
ν-dec
QCD
Current limit (2σ)
CMB-S4 (2σ)
0.054
0.047
0.027
$\Delta N_{\rm eff}$
T_F [GeV]



S4 Lensing
S4 Lensing (polarization only)
S4 Lensing x LSST ($k_{\rm max} = 0.15\ h$/Mpc)
S4 clusters (w/ LSST calibration)
Optimistic
Current
Minimal M_ν detection significance [σ]
$\sigma(\tau)$

Conclusions

- Very exciting time to be working in CMB cosmology!
- Broad science probing primary anisotropies and LSS
- Great potential to understand the first instant of the universe
- Many ways to build a B-mode machine, but must control:
  - Foregrounds
  - Gravitational Lensing
  - Systematic Errors
  - The interactions between these three!