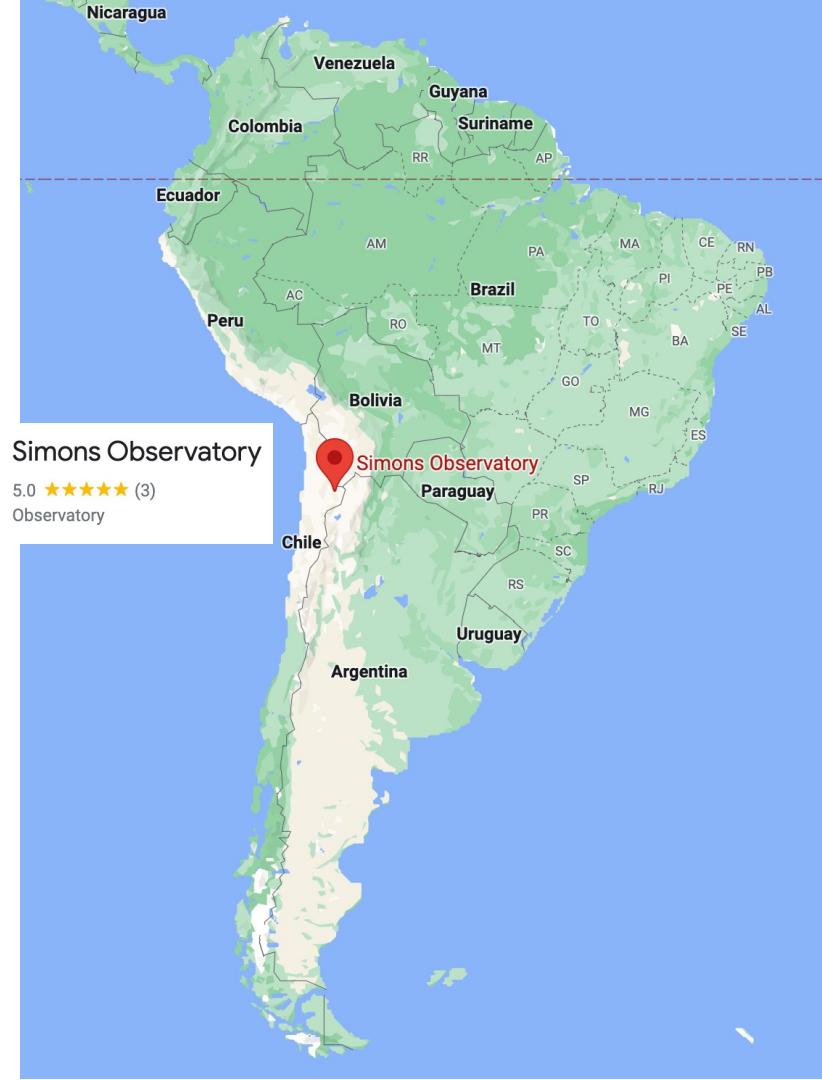


The Simons Observatory Small Aperture Telescopes

Aashrita Mangu
On behalf of the Simons Observatory
amangu@berkeley.edu

TAUP 2023



Simons Observatory Collaboration



July 2022



> 300 Collaborators
across 40+ institutions in
10 countries!



CMB Telescopes

low-frequency noise and
instrumental systematic effects

white
instrumental
noise

atmosphere

galactic and extra-galactic
foregrounds

gravitational
lensing

ΔT ΔE

ΔB

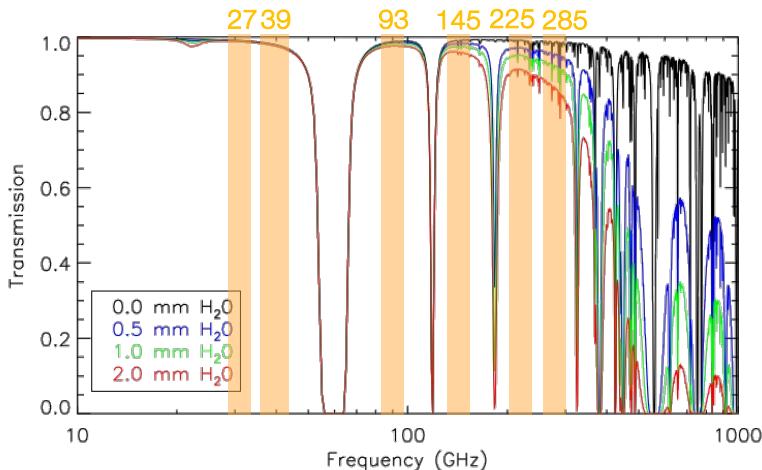
clusters



Image Credit: J. Errard

The Simons Observatory

- Atacama Desert, Chile @ 5200m
- Precipitable water vapor (PWV) \sim 1mm
- 6 frequency bands: 27 to 285 GHz
- one 6m Large Aperture Telescope (LAT) with \sim 30,000 detectors
- Three 0.42m Small Aperture Telescopes (SATs) with \sim 30,000 detectors total



SO Science

Mostly SAT Data

Mostly LAT Data

primordial fluctuations

large scale B-modes
→ tensor-to-scalar ratio (BB)
→ primordial power at small scales (TE, TT, EE)

relativistic species, He

damping tail
→ N_{eff} , Y_p (TE, TT, EE)

neutrino mass

lensing potential (TT+EB), tSZ
→ Σ_{ν}

galaxy evolution

tSZ, kSZ
→ non-thermal pressure (tSZ+kSZ)
→ feedback efficiency (tSZ+kSZ)

dark energy

tSZ, lensing
→ σ_8 at $z=2-3$ (lensing, tSZ)
→ growth of structure (kSZ)

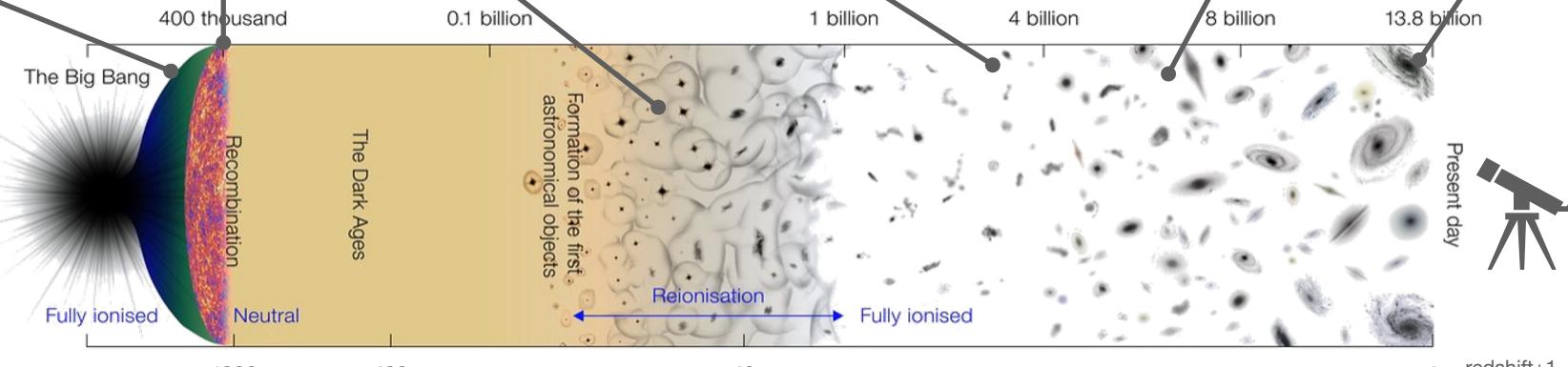
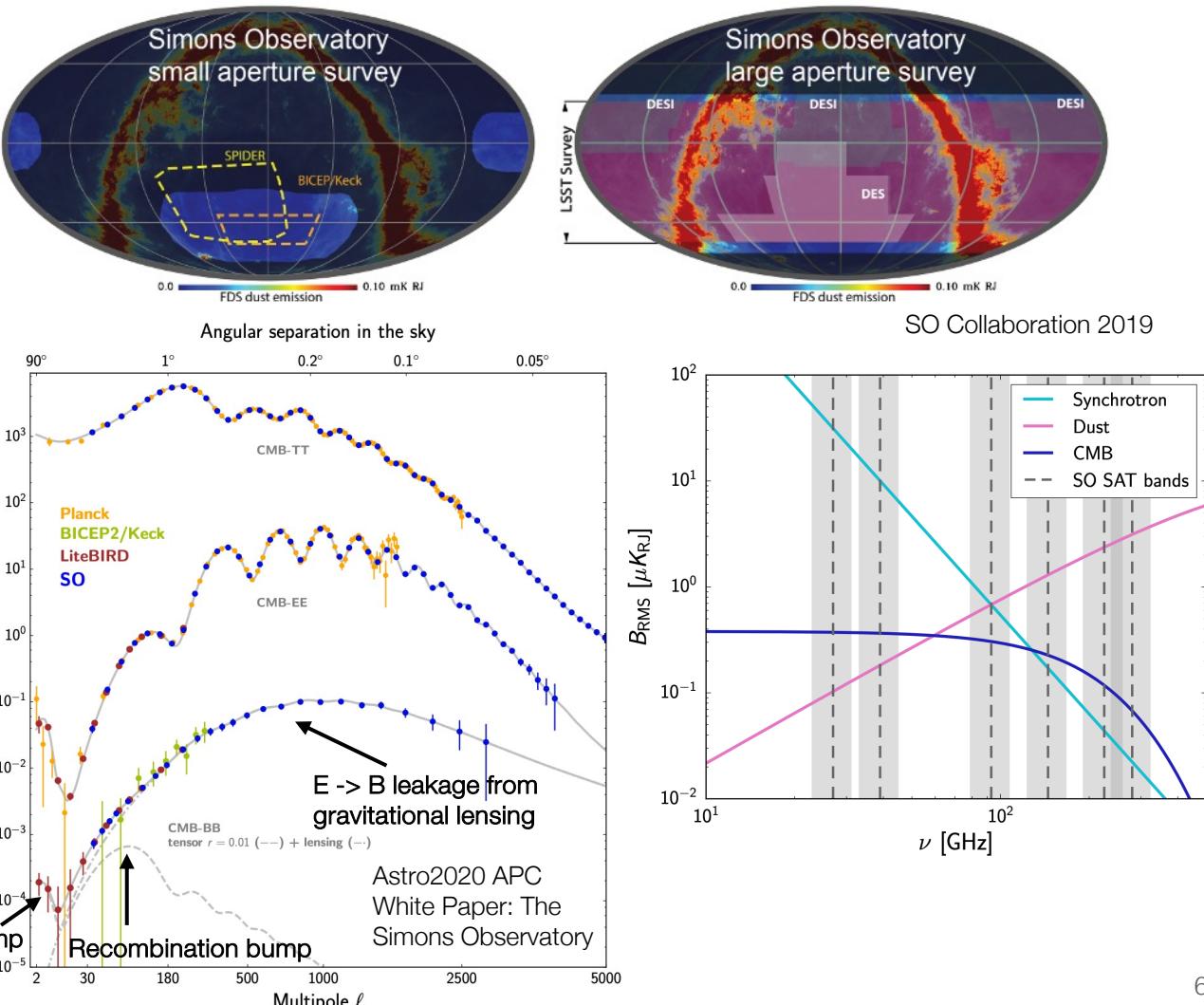


Image Credit: J. Errard

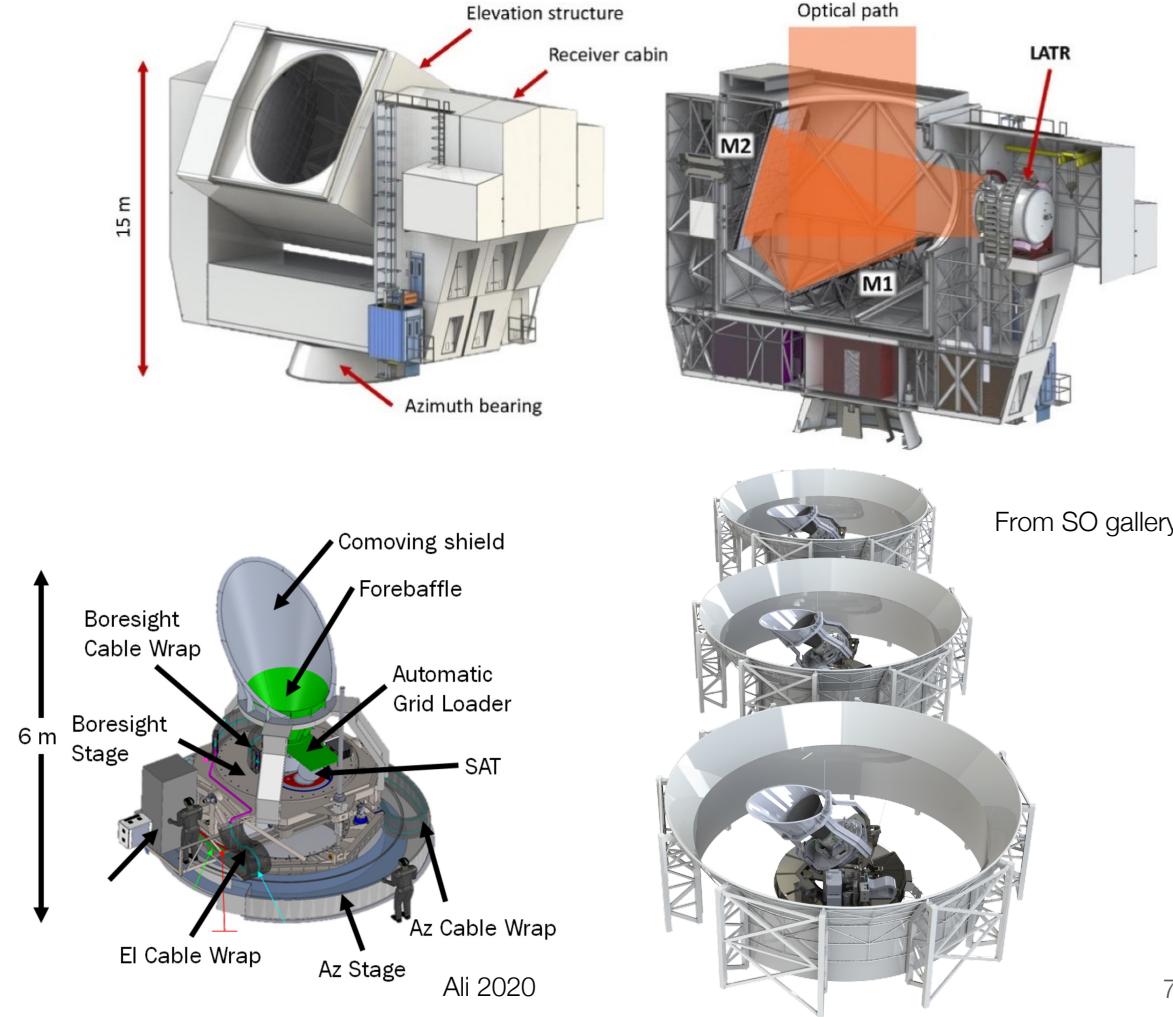
SO Science

- SAT target degree angular scales; dichroic instruments at:
 - MF: 93/145 GHz
 - UHF: 225/285 GHz
 - LF: 27/39 GHz
- SATs map ~10% of sky
- LAT maps ~40% of sky
- Nominal 5 year survey
- Primary SO SAT science goal characterizing primordial r : $\sigma(r) = 0.003$ for an $r = 0$ model



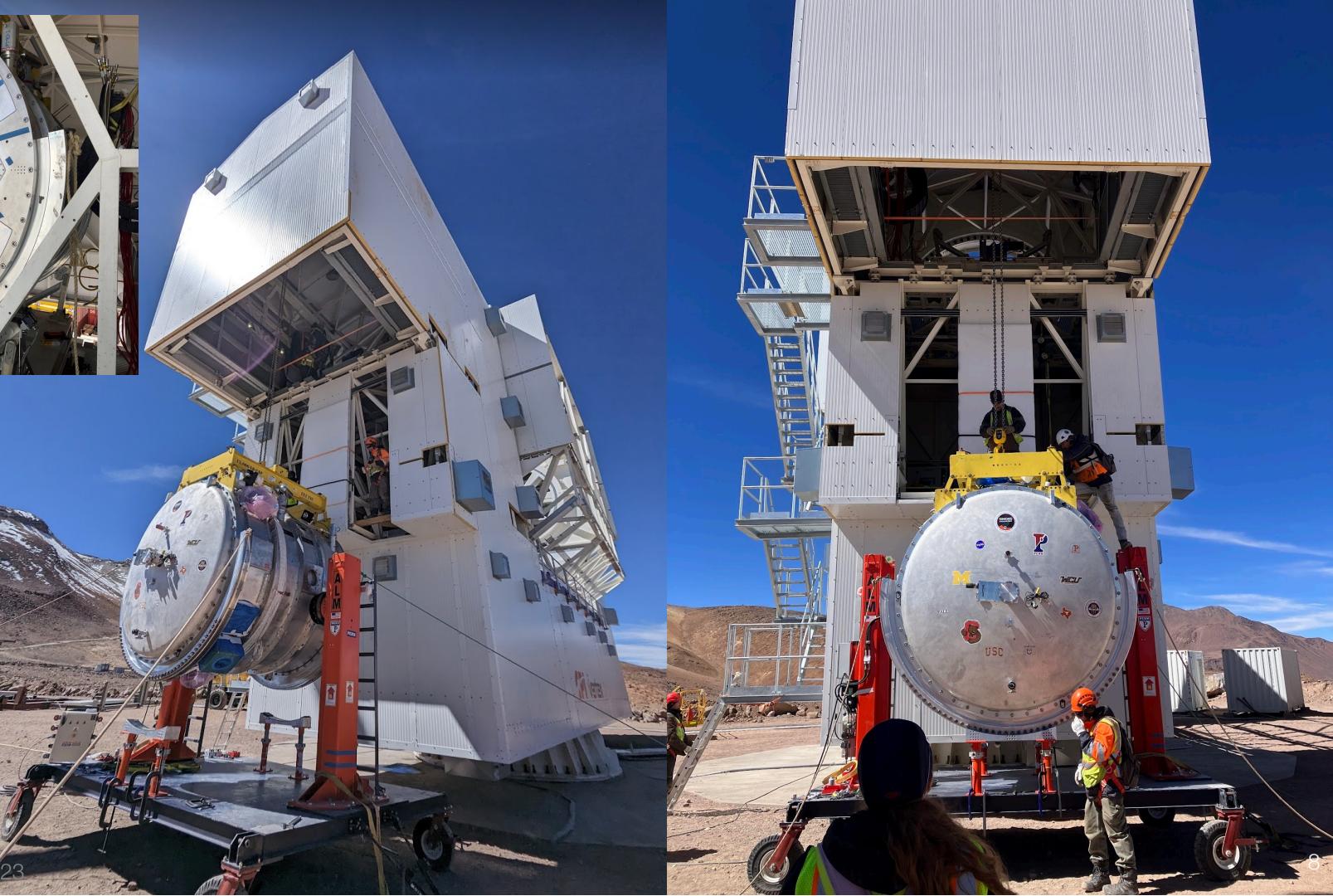
SO Telescopes

- LAT covers small angular scales
- SAT covers large angular scales: primordial B-modes!
- SAT + LAT data -> foreground characterization and separation over many angular scales to increase foreground cleaning strategy
- LAT + LSS surveys -> reconstruction of lensing potential for lensing B-mode removal from SAT patch
- Note: r forecast does not assume any LAT lensing data!

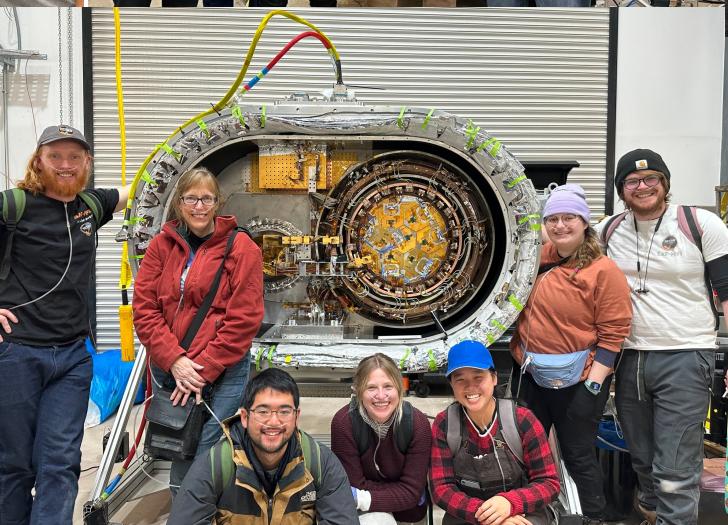
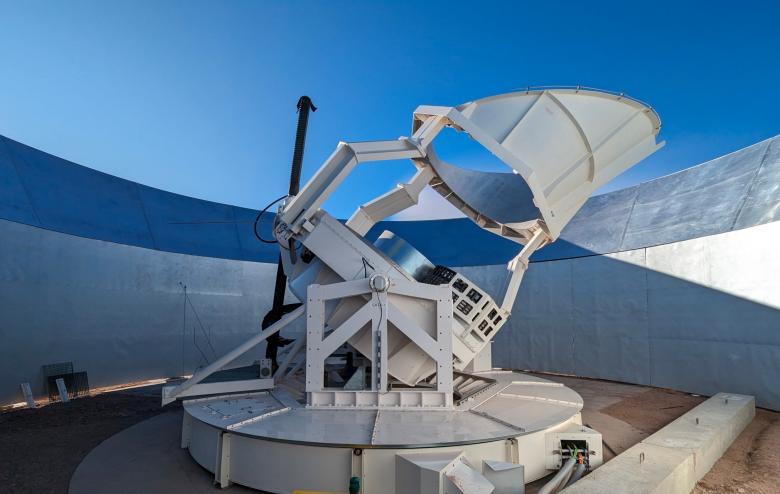
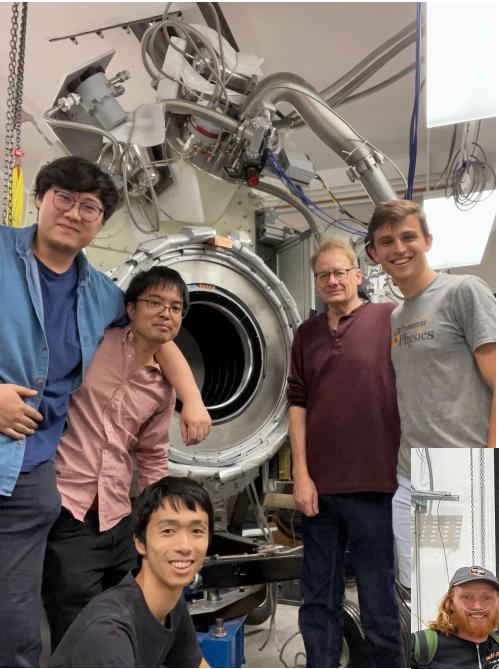




LAT Interlude

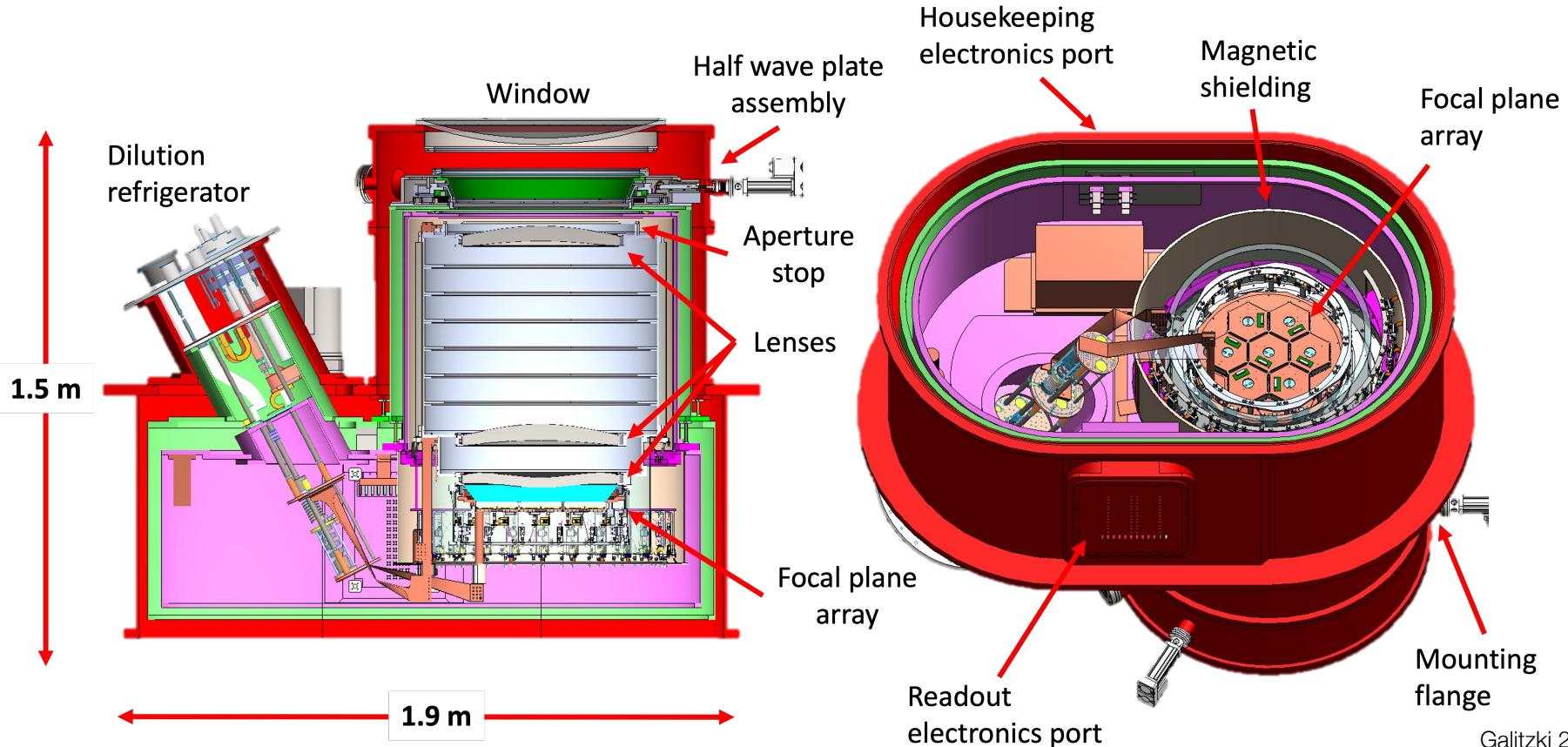


SATs!



Aashrita Mangu TAUP 2023

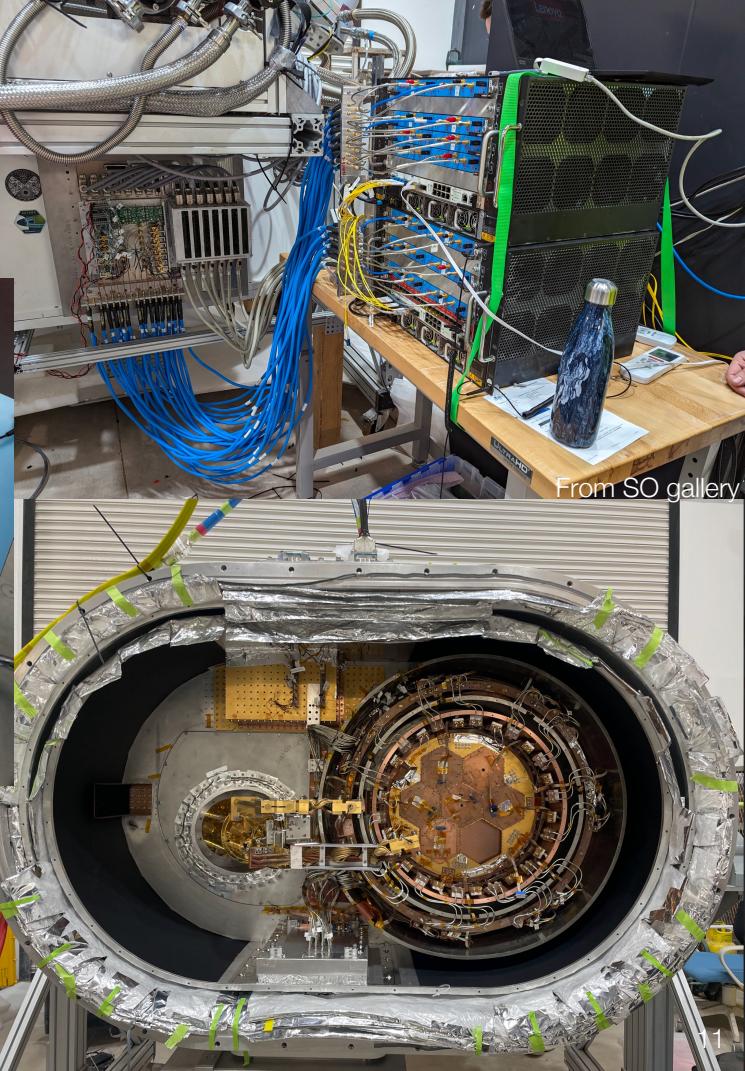
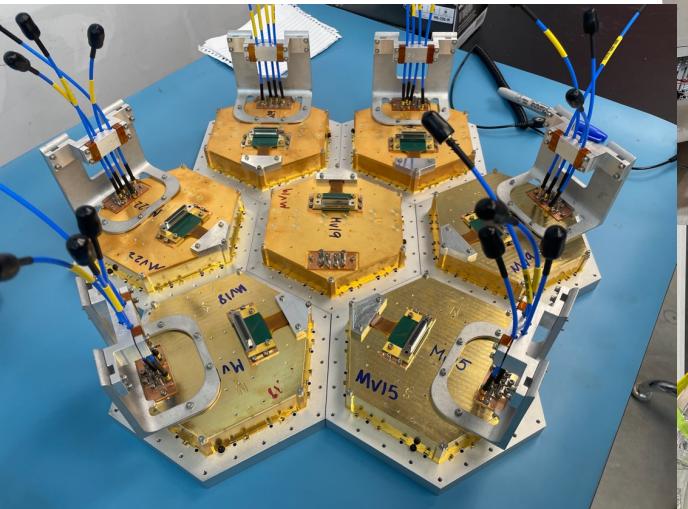
Structure of a SAT



Galitzki 2018

SAT-MF1 Deployment

- Finished assembly of the SAT-MF1 receiver in Chile at the site
- Platform constructed
- SAT-MF1 is in the SAT Platform ready to start cooling!
- First light and data is around the corner!



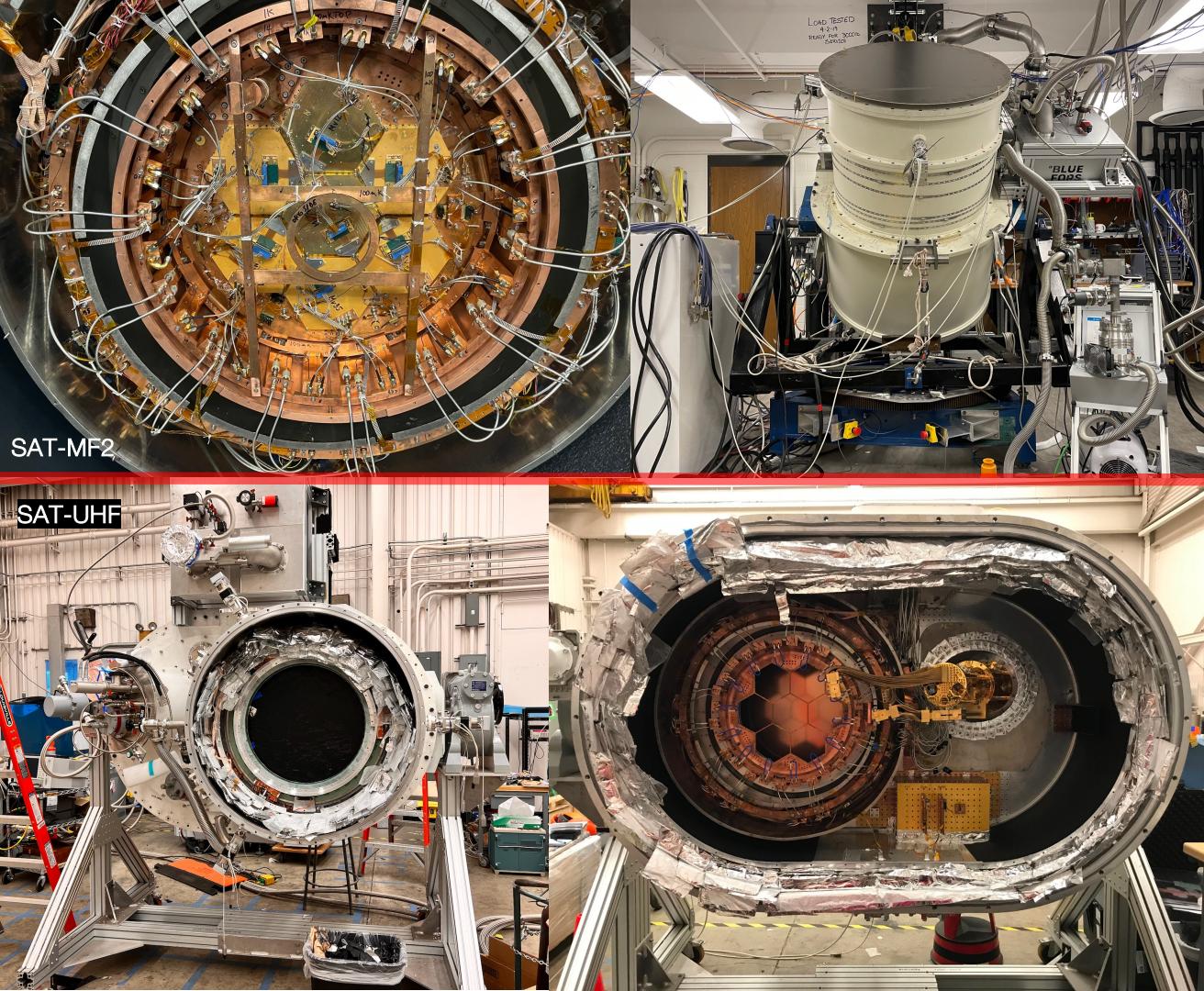
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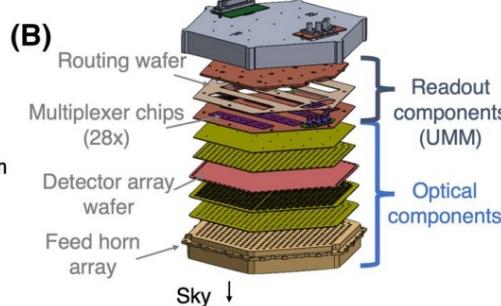
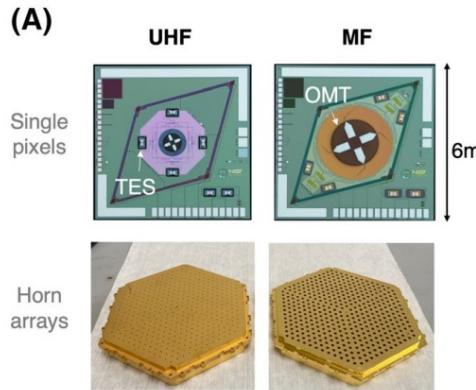


SAT-MF2/SAT-UHF

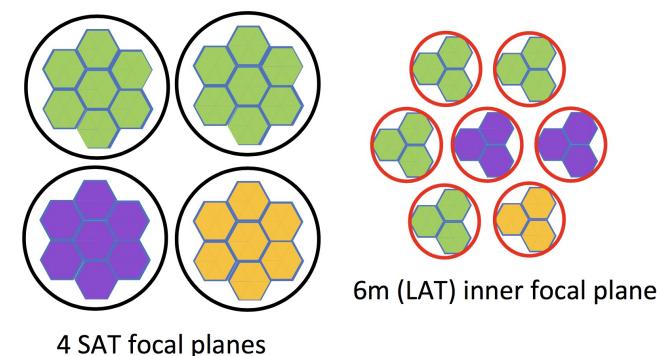
- SAT-MF2 (top) packed and shipping to Chile
- SAT-UHF preparing for final cryogenic validation with focal plane modules installed. Packing and shipping after this run.
- Platforms are ready to go!



SO Detectors



- Dual-polarized dichroic transition edge sensors (TESSs)
- Universal Focal Plane Modules (UFMs) are closely packed
- > 60,000 TES detectors across LAT and SATs



SO Nominal Forecasting

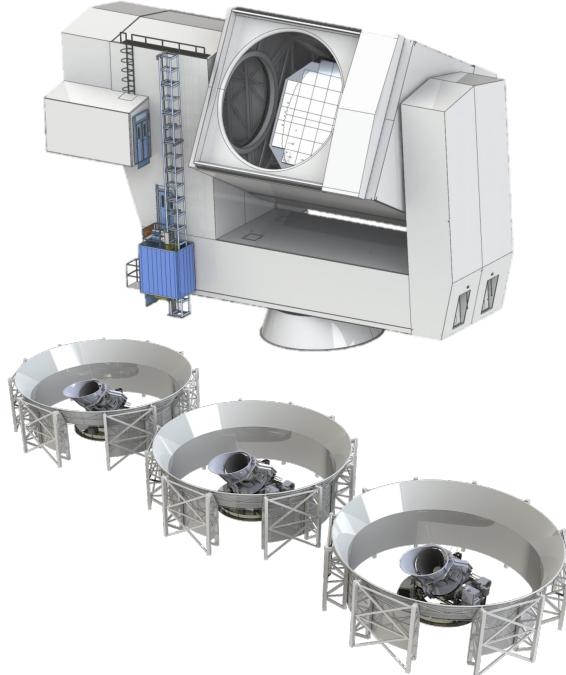
Title	Parameter	Baseline	Goal	Current	Method
Primordial Perturbations	r	0.003	0.002	0.03	BB
Relativistic Species	N_{eff}	0.07	0.05	0.2	TT/TE/EE + $\kappa\kappa$
Neutrino Mass	Σm_ν	0.04	0.03	0.1	$\kappa\kappa$ +DESI
Deviations from Λ	$H_0(\Lambda\text{CDM})$	0.4	0.3	0.5	TT/TE/EE + $\kappa\kappa$
Galaxy Evolution	Feedback efficiency in massive halos	3%	2%	50-100%	kSZ+tSZ+DESI
Reionization	Δz	0.6	0.3	1.4	TT (kSZ)

SAT focus

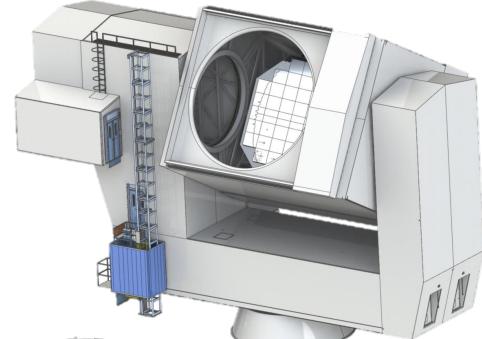
SO Collaboration 2019,
adapted from a table by N. Galitzki

Note: SO = SO Nominal (current) + SO:UK + SO:Japan + Advanced SO

SO:Japan + SO:UK



With SO:J and SO:UK

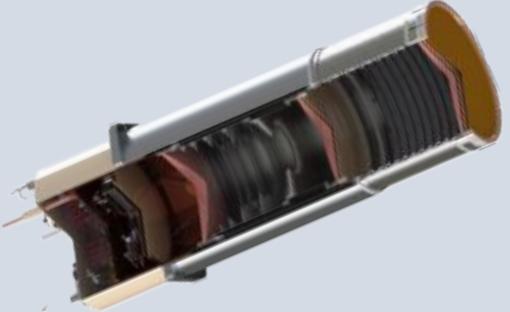


- Funded in Japan (1x, LF) and UK (2x, using MKIDS and not TESs)
- Double number of SATs!

Advanced Simons Observatory



Optics Tubes



- Six New Optics Tubes
- Double Mapping Speed for Delesning and other science
- Enable Transient Detection
- No Development Required

Data Management



- Full Maps Processed in 6 Months
- Daily Transient Alerts
- Verification and Systematics Mitigation
- Community Maps and Tools

Photovoltaic Array



- 9% increase in Observing Efficiency
- Reduced Carbon Footprint
- Reduced Maintenance Costs

- LAT : 7 -> all optics tubes populated out of 13
- Data management advances
- Replace 70% of power at site with solar energy using photo voltaic arrays

[NSF Announcement](#)

Looking ahead

- Nominal SO full observations starting 2024
- SO:Japan and SO:UK scheduled for full observations in ~2026 => look forward to updated forecasting papers with updated sensitivity estimates!
- ASO scheduled for full observations in ~2028
- Look out for instrument papers coming up!



Thank You!

www.simonsobservatory.org

@SimonsObs





Back Up Slides



Time Domain Astrophysics

Tidal Disruption Events



Stellar Flares



Variable AGN



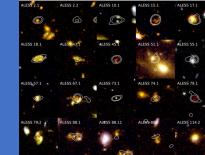
Training the Next Generation



Extragalactic Astronomy



Missing Baryons



Sources

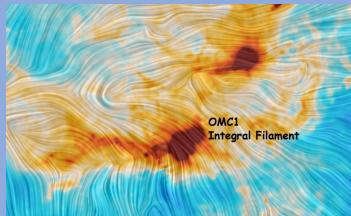


Galaxy Clusters



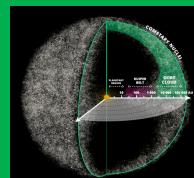
Galactic Astronomy

Interstellar Dust



Star Formation, Magnetic Fields
and Dust Turbulence

Planetary Science

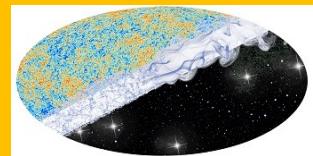


Exo-Oort Clouds

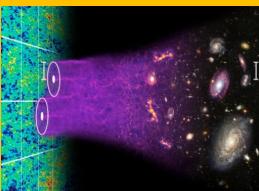


Planet 9

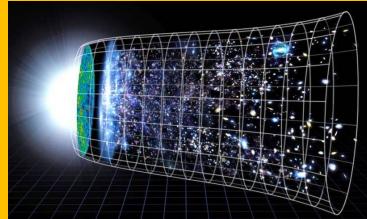
Cosmology and Particle Physics



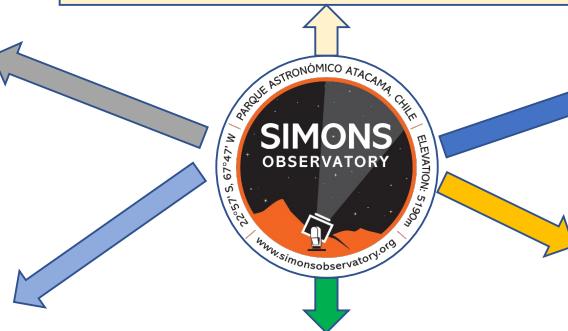
H_0 Tension and New Physics



Light Relics and
Neutrinos



The Evolution of the Universe
Over Cosmic Time



	Parameter	SO-Baseline ^a (no syst)	SO-Baseline ^b	SO-Goal ^c	Current ^d	Method	Sec.
Primordial perturbations	r	0.0024	0.003	0.002	0.03	<i>BB</i> + ext delens	3.4
	$e^{-2\tau}\mathcal{P}(k=0.2/\text{Mpc})$	0.4%	0.5%	0.4%	3%	<i>TT/TE/EE</i>	4.2
	$f_{\text{NL}}^{\text{local}}$	1.8 1	3 2	1	5	$\kappa\kappa \times \text{LSST-LSS} + 3\text{-pt}$ $\text{kSZ} + \text{LSST-LSS}$	5.3 7.5
Relativistic species	N_{eff}	0.055	0.07	0.05	0.2	<i>TT/TE/EE + $\kappa\kappa$</i>	4.1
Neutrino mass	Σm_ν	0.033	0.04	0.03	0.1	$\kappa\kappa + \text{DESI-BAO}$	5.2
		0.035	0.04	0.03		$\text{tSZ-N} \times \text{LSST-WL}$	7.1
		0.036	0.05	0.04		$\text{tSZ-Y} + \text{DESI-BAO}$	7.2
Deviations from Λ	$\sigma_8(z = 1 - 2)$	1.2% 1.2%	2% 2%	1% 1%	7%	$\kappa\kappa + \text{LSST-LSS}$	5.3
	$H_0 (\Lambda\text{CDM})$	0.3	0.4	0.3	0.5	<i>TT/TE/EE + $\kappa\kappa$</i>	4.3
	η_{feedback}	2%	3%	2%	50-100%	$\text{kSZ} + \text{tSZ} + \text{DESI}$	7.3
Galaxy evolution	p_{nt}	6%	8%	5%	50-100%	$\text{kSZ} + \text{tSZ} + \text{DESI}$	7.3
	Δz	0.4	0.6	0.3	1.4	<i>TT</i> (kSZ)	7.6

^a This column reports forecasts from earlier sections (in some cases using 2 s.f.) and applies no additional systematic error.

^b This is the nominal forecast, increases the column (a) uncertainties by 25% as a proxy for instrument systematics, and rounds up to 1 s.f.

^c This is the goal forecast, has negligible additional systematic uncertainties, and rounds to 1 s.f.

^d Primarily from [44] and [287].

Table 9. Summary of SO key science goals. All of our SO forecasts assume that SO is combined with *Planck* data.

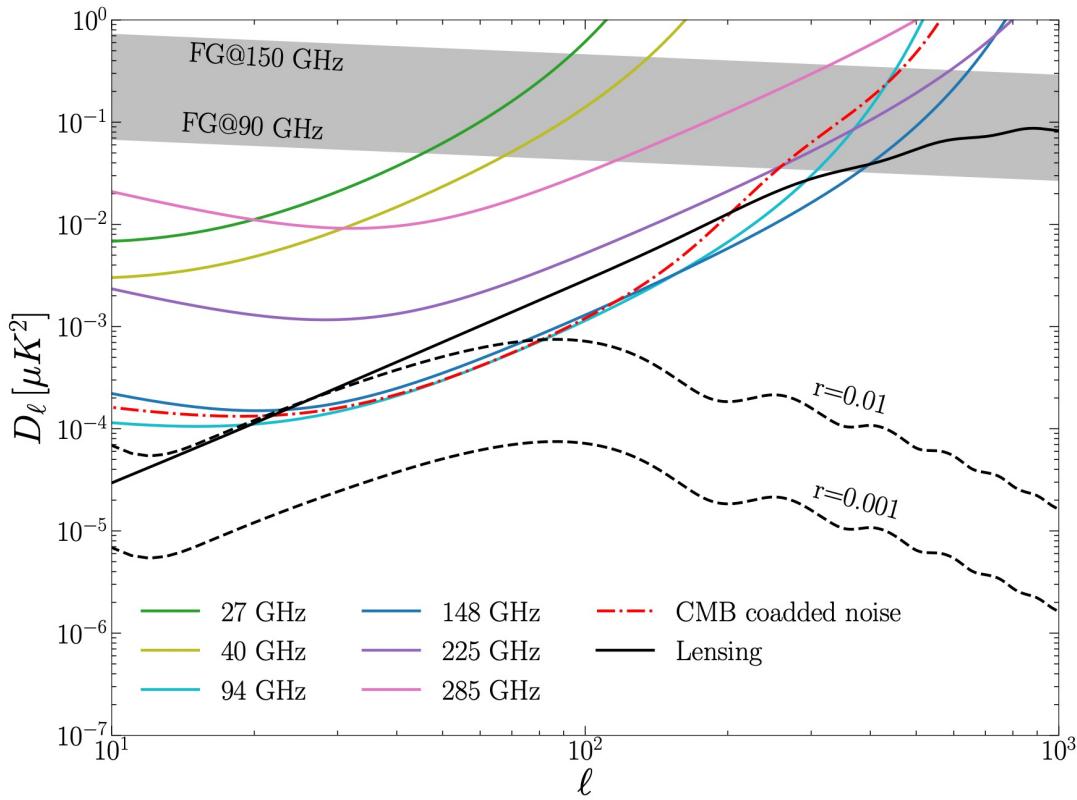


Figure 1: Relevant sky signal and noise power spectra. CMB lensing B -mode power spectrum (solid black) and contribution from primordial tensor fluctuations for $r = 0.01$ and $r = 0.001$ (dashed black). The different colored lines show the SO SAT noise power spectra for the six different frequency bands. The gray band shows the estimated combined B -mode foreground power spectra between 90 GHz and 150 GHz for a 10% sky area. The red dash-dotted line shows the CMB coadded noise after component separation.

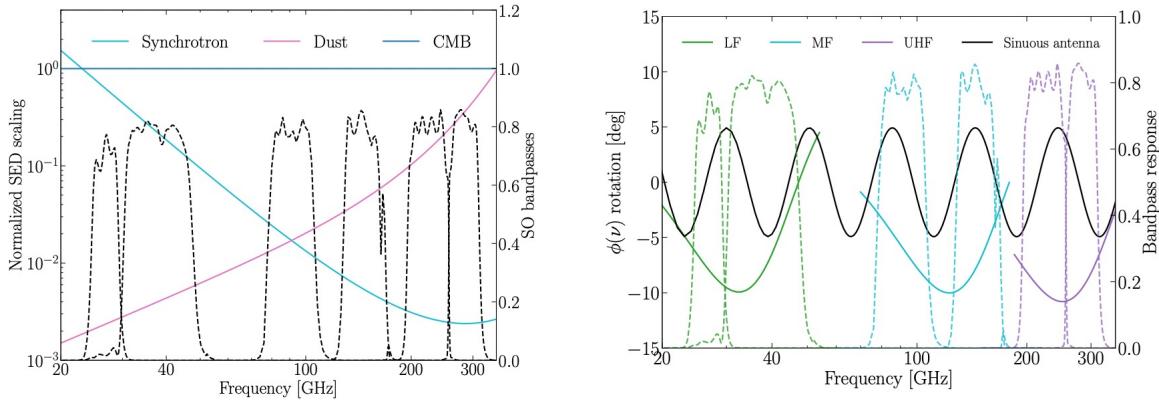


Figure 2: (Left) SED scaling laws and simulated SO bandpasses. The signals are normalized to thermodynamic CMB units. The synchrotron scaling has a reference frequency (and value of unity) at $\nu_0 = 23$ GHz. The dust reference frequency is $\nu_0 = 353$ GHz. Note the SED and frequency axes are log scaled (while the bandpass axis is linear). (Right) Frequency dependent polarization angle rotations compared to SO bandpasses. The black curve represents the polarization rotation from a broadband sinuous antenna design (which is only planned for the LF bands in SO). The solid green, blue, and purple curves represent the frequency dependent rotation from a 3-layer HWP, for the LF, MF, and UHF bands. The simulated SO bandpasses are in dashed lines with the same corresponding colors.

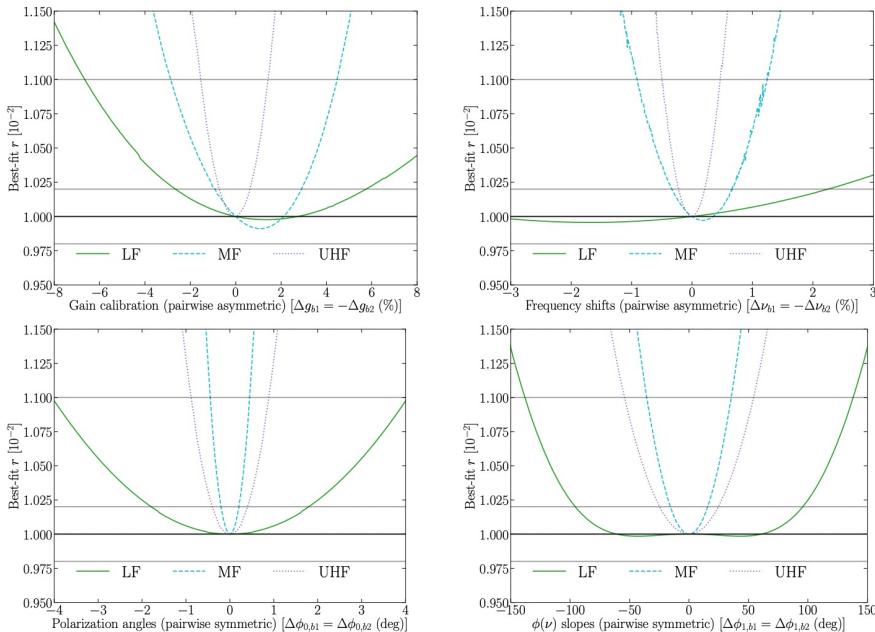
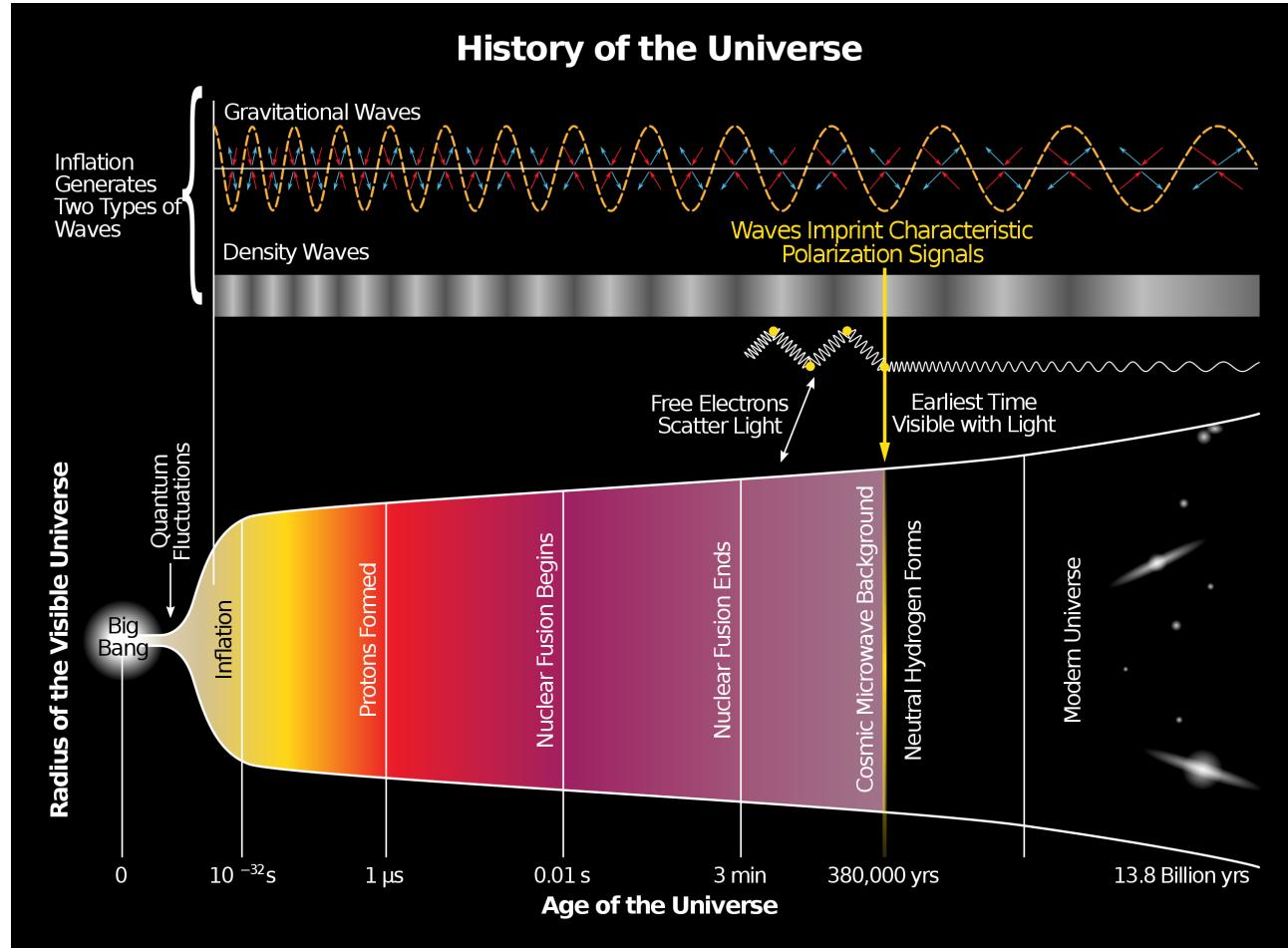
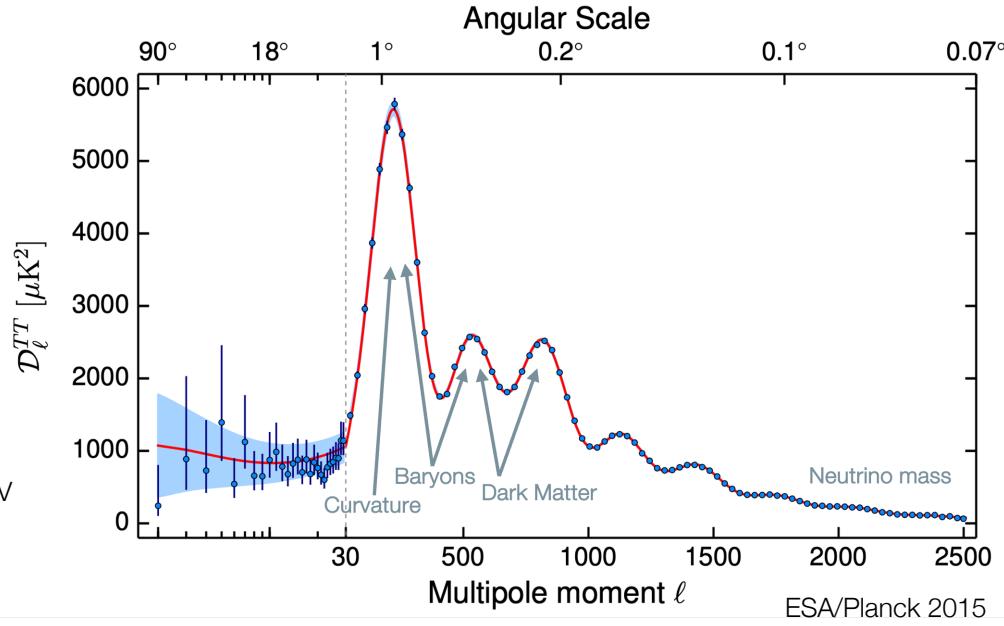
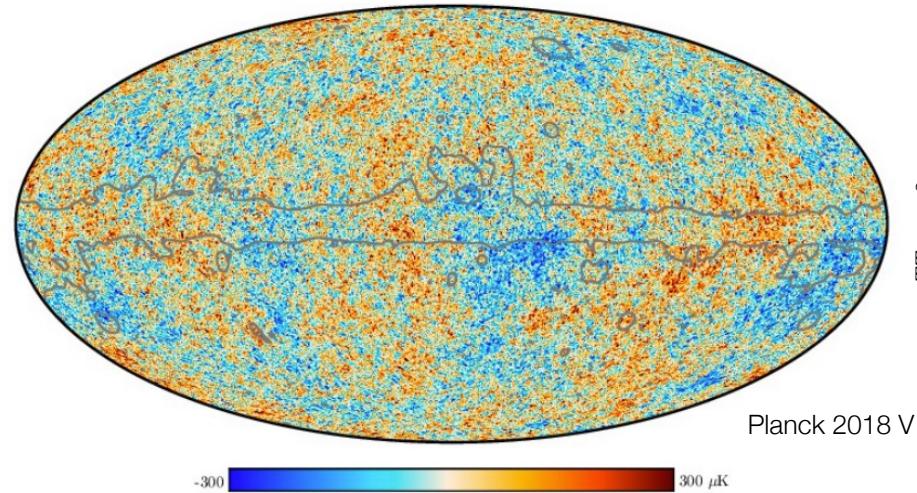


Figure 3: **Top:** Bias on r as a function of the difference in gain calibration (left) and frequency shifts (right). Both top panels show antisymmetric variations (i.e., the parameter values change by the same amount but in opposite directions for the two frequency bands in a pair) for the LF (solid, green), MF (dashed, blue) and UHF (dotted, purple) frequency pairs. In both cases, the tightest requirement, corresponding to \sim percent-level calibration of both systematics, is found for the UHF band. The requirements on the LF band, on the other hand, are a factor ~ 3 laxer, owing to the reduced sensitivity and angular resolution of that band. **Bottom:** Bias on r as a function of the polarization angle systematic parameters $\Delta\phi_0$ (left) and $\Delta\phi_1$ (right), corresponding to the offset and frequency slope of a linear frequency-dependent polarization angle (see Eq. 2.16). Both bottom panels show symmetric variations of the parameters (i.e., the parameter values change by the same amount in both frequency bands in a pair) for the LF, MF and UHF band pairs. In both cases, the tightest requirement is found for the MF band. This is due to the large amplitude of CMB E -modes leaked into B -modes, which is more relevant for the MF band, while the LF/UHF bands have a lower weight in the final cosmological constraints.

History of the Universe



CMB Temperature



- Temperature anisotropies in CMB
- Acoustic peaks seen from (mostly) density waves
- Very well studied

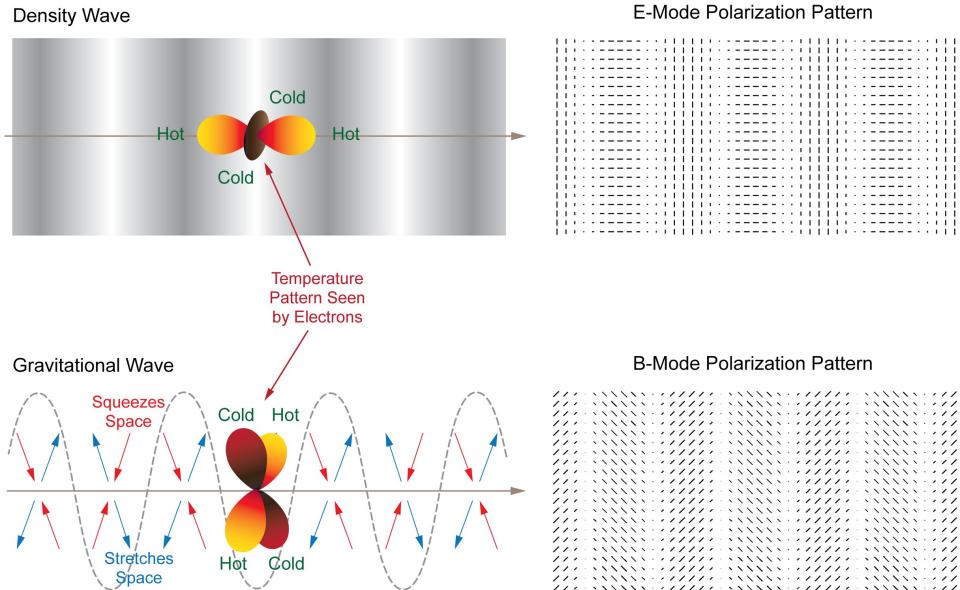
Temperature data provides interesting cosmological data like curvature of the universe, dark matter density, etc!

CMB Polarization

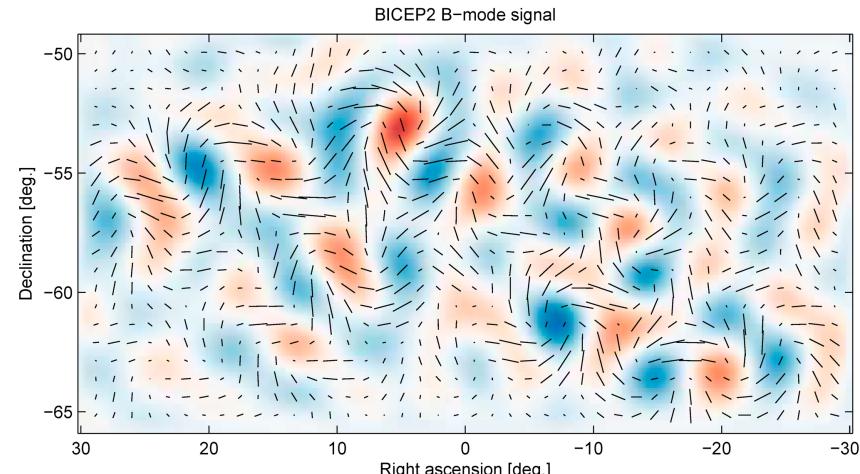
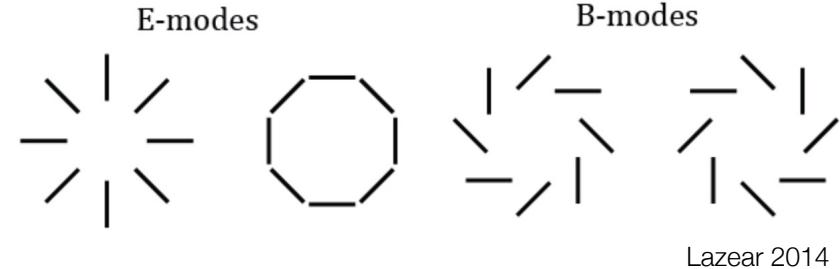
Polarization anisotropies!

Sources of B modes:

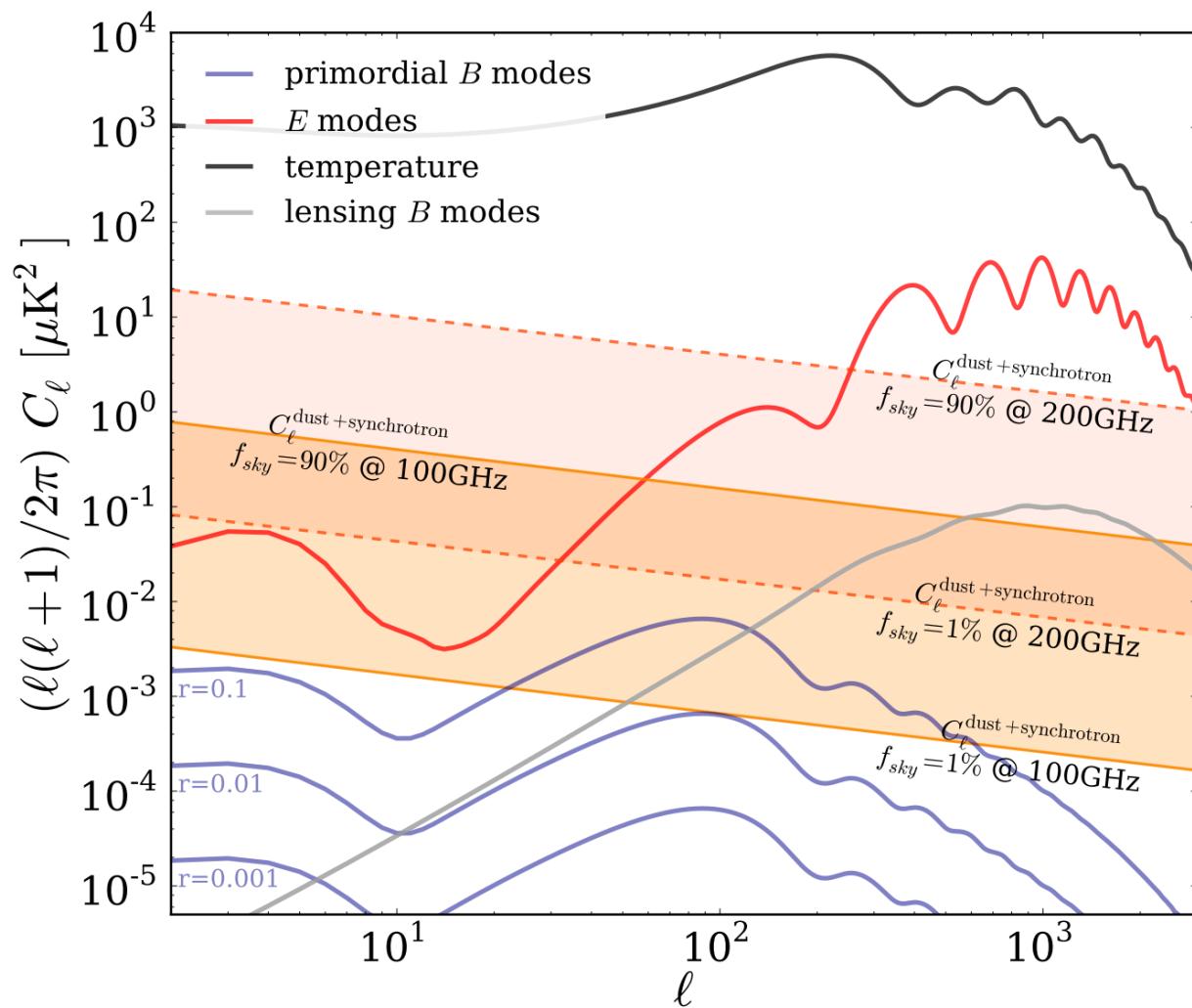
- Inflationary gravitational waves
- Gravitational lensing of E modes
- Galactic foregrounds

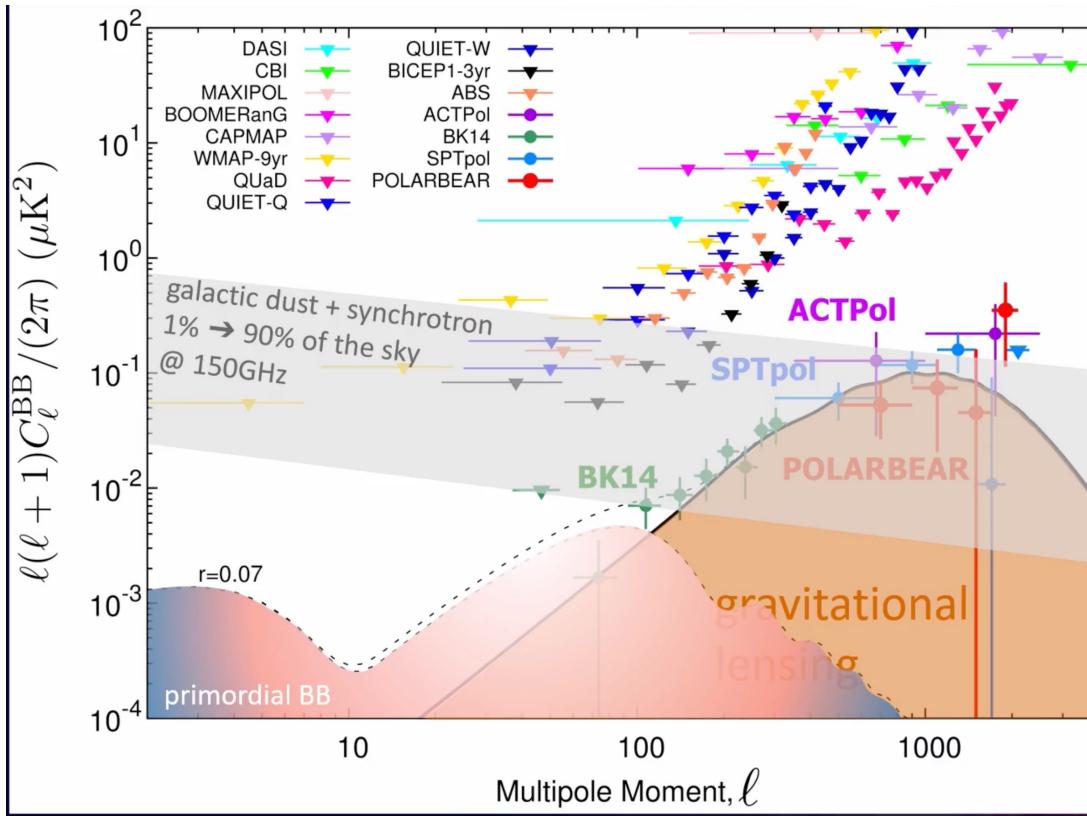


Aashrita Mangu TAUP 2023



BICEP collaboration





Galitzki SO
talk, SPIE

The Simons Observatory

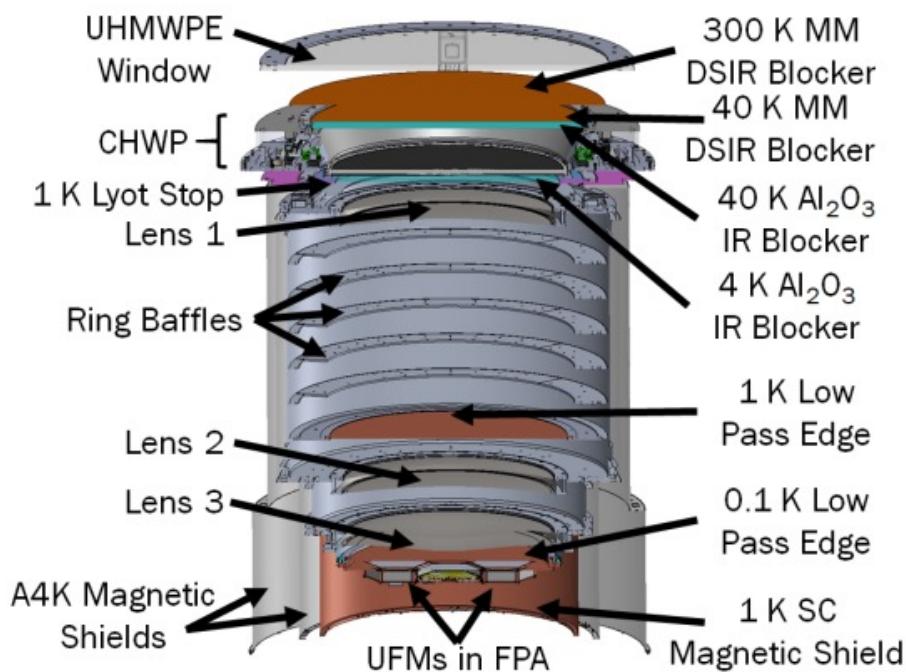
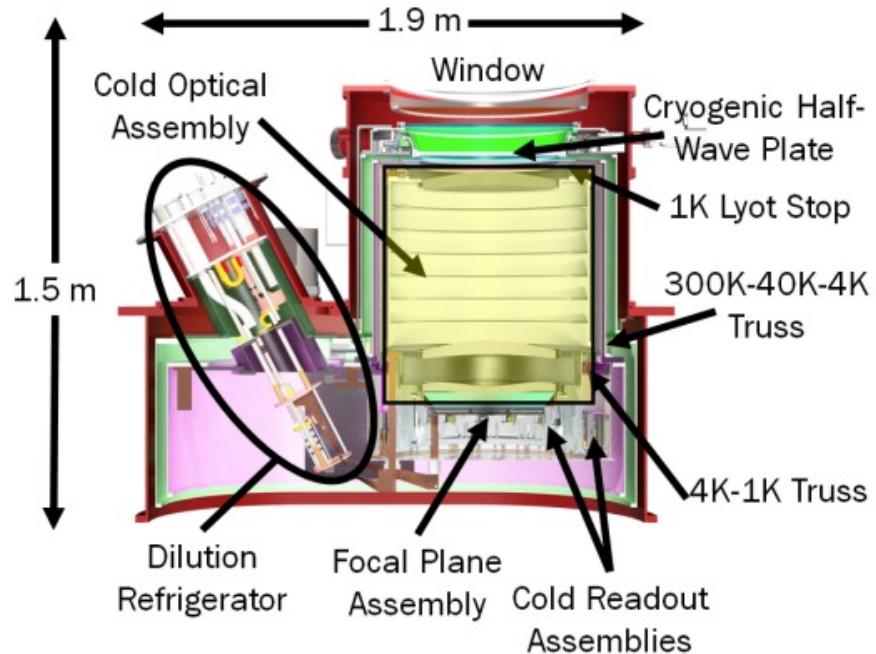
- 3 SATs map ~10% of sky at noise level of $\sim 2\mu\text{K}$ -arcmin combining MF bands
- Assumed 20% observation efficiency

Focal Plane	Freq. (GHz)	n_{TES}	Ω_{Beam} (arcmin)	Obs. Length (Years)	Map Depth ($\mu\text{K}\cdot\text{arcmin}$)	All SATs
LF	27	1050	91	1	35	FOV 35°
LF	39	1050	63	1	21	Aperture 42 cm
MF 1 & 2	93	23000	30	5	2.6	f-# ~ 1.6
MF 1 & 2	145	23000	17	5	3.3	T_{CHWP} 50 K
HF	225	12000	11	5	6.3	T_{Optics} 1 K
HF	280	12000	11/9	5	16	T_{FP} 100 K

Ali 2020

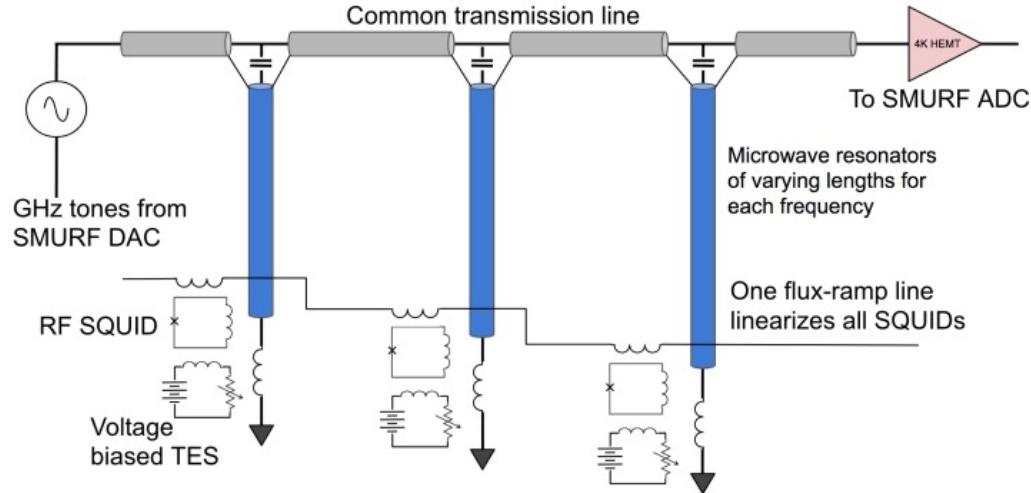
SAT Structure

Basic structure of a small aperture telescope



Ali 2020

Microwave Multiplexing TES Readout



M.S. Rao 2020

CHWP

