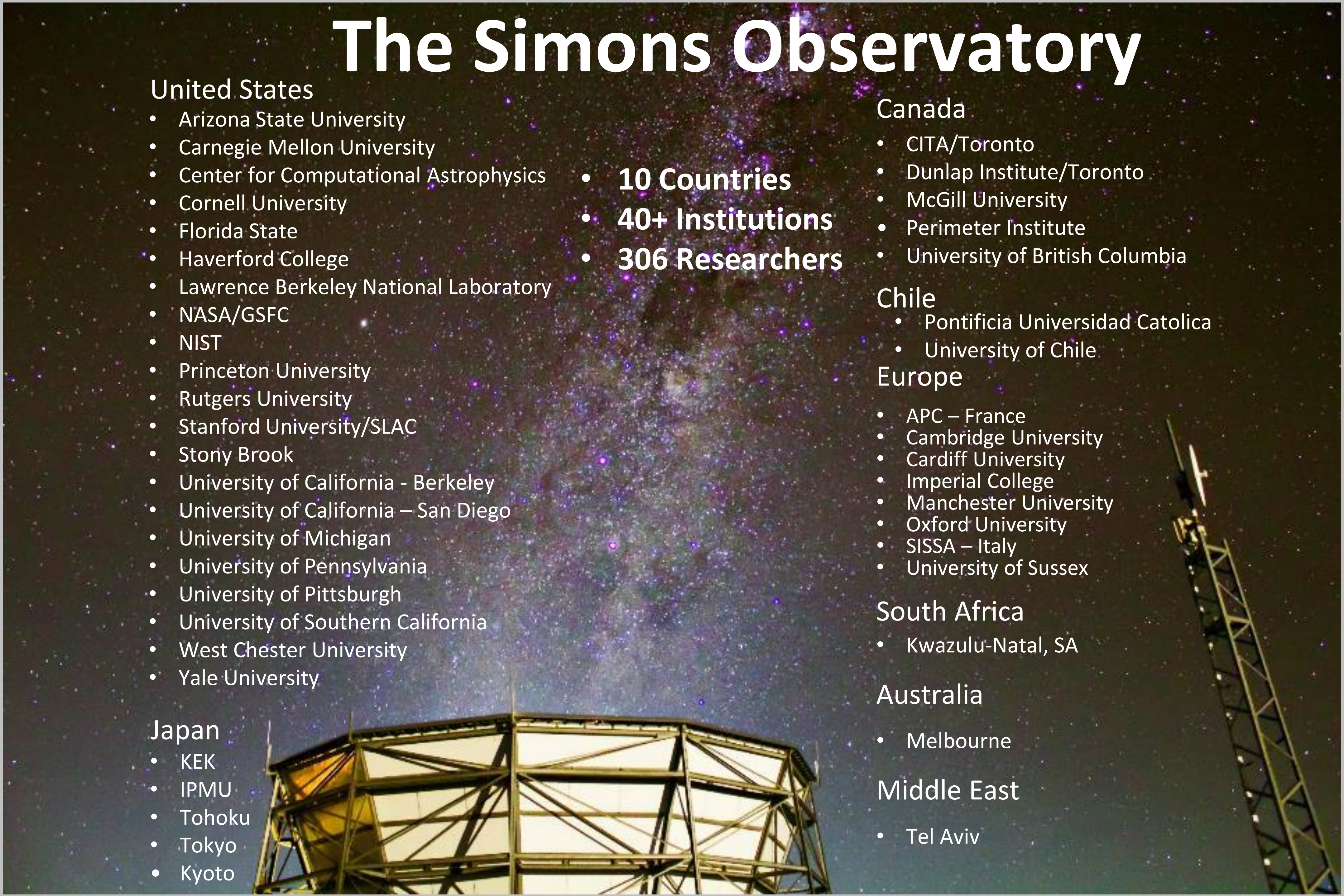
The Simons Observatory Astro2020 Panel

Adrian Lee and Suzanne Staggs
for the SO Collaboration



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
- Imperial College
- Manchester University
- Oxford University
- SISSA – Italy
- University of Sussex

South Africa
- Kwazulu-Natal, SA

Australia
- Melbourne

Middle East
- Tel Aviv

Simons Observatory Mission

Measure CMB anisotropies in temperature and polarization across a wide range of frequencies and angular scales in pursuit of new information about the universe and its evolution, in two operational phases: SO-Nominal and SO-Enhanced.

SO-Nominal construction is fully funded privately and has already begun.

Simons Observatory Collaboration Summer 2018

SO Addresses Key Astrophysics Questions

- **Origin of the universe**
  - Gravitational waves, shape of primordial spectrum, non-Gaussianity
  - Cosmological model
- **Dark matter**
  - CMB lensing probes large-scale distribution of mass in the universe
  - CMB fluctuations sensitive to many possible dark matter properties
- **Feedback and IGM**
  - KSZ and TSZ measures distribution of electron momentum and pressure. In combination with LSS surveys can be a novel probe of the inter cluster medium and feedback
- **Variable radio sky**
- **Search for Planet 9**
- **Galactic Science**
  - Legacy arcmin-resolution millimeter-wave sky maps
  - Map of large-scale distribution of magnetic fields in the Galaxy through measurements of synchrotron and polarized dust

SO Members are Committed to Outreach and Engagement

- **Education**
  - Undergraduate Summer Research (~30 students/summer)
  - Mentorship Program (~50 mentees, half from URM)
  - Work with schools
    - Cosmology webinar for teachers (~100 teachers so far)
    - Skype a Scientist (>50 classrooms)
- **Outreach**
  - Average 75 events per year reaching 10s of thousands
  - Organized three Science/Astro on Tap Series
  - Recent event connecting 8th graders to Jessica Meir aboard Shuttle
- **Engagement**
  - Multiple "hack-a-thons" to transfer skills

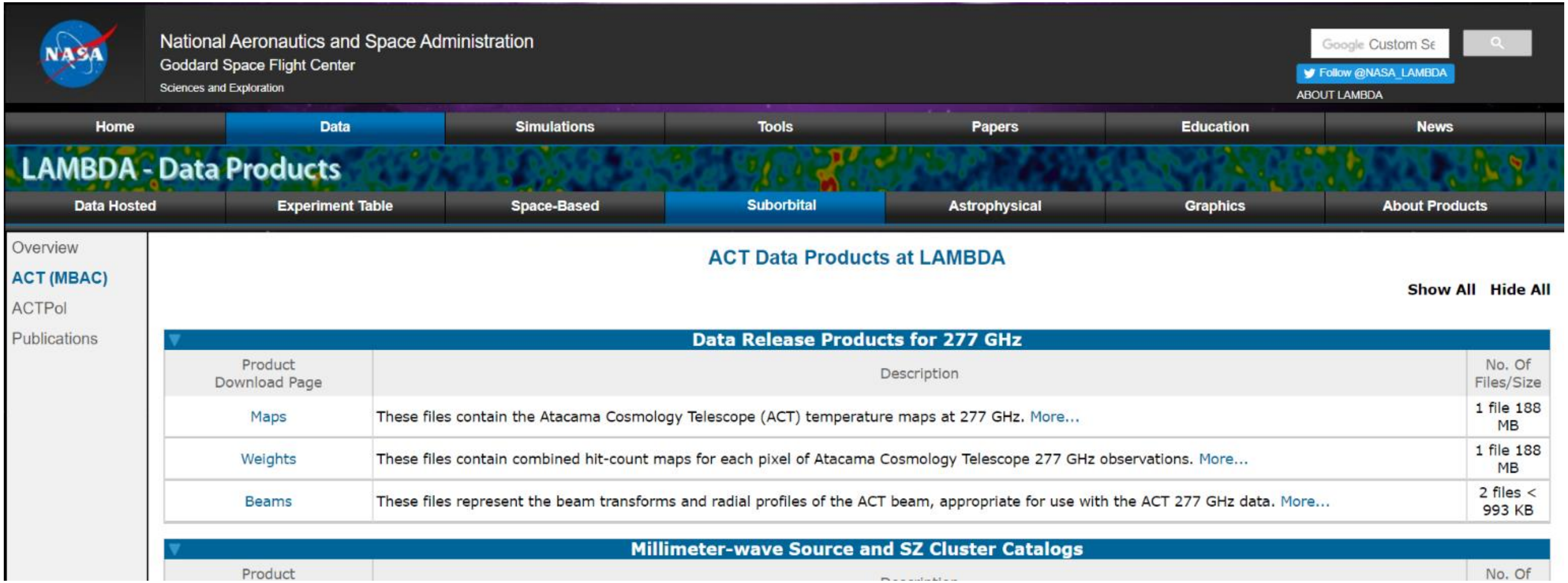
Art and Science Book

STEM Camp in Trenton, NJ

Community Engagement Builds on a Proven Track Record

- Timely release of the data products
  - Calibrated maps
  - Cluster and source lists
- Source code for data pipeline
- Community schools for data usage; online software tutorials

Like ACT, SO data products will be publicly available



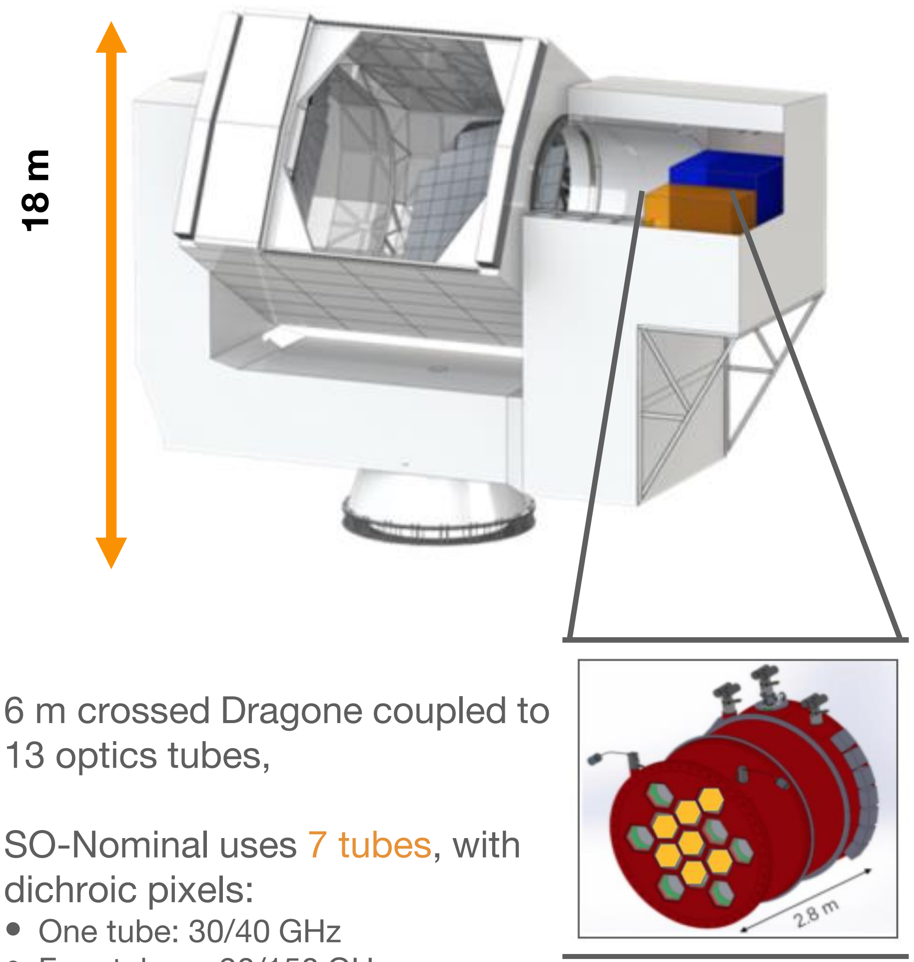
Product Download Page	Description	No. Of Files/Size
Maps	These files contain the Atacama Cosmology Telescope (ACT) temperature maps at 277 GHz. More...	1 file 188 MB
Weights	These files contain combined hit-count maps for each pixel of Atacama Cosmology Telescope 277 GHz observations. More...	1 file 188 MB
Beams	These files represent the beam transforms and radial profiles of the ACT beam, appropriate for use with the ACT 277 GHz data. More...	2 files < 993 KB

https://lambda.gsfc.nasa.gov/product/act/act_prod_table.cfm

SO-Nominal and SO-Enhanced Configurations

SO-Nominal Instrumentation Suite

Large Aperture Telescope

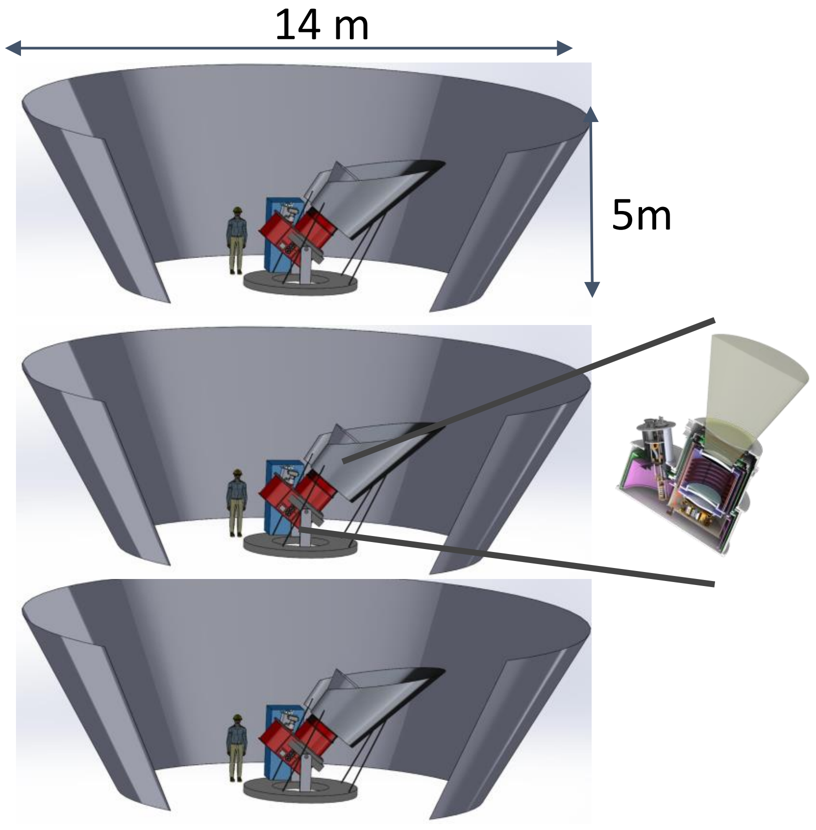


6 m crossed Dragone coupled to 13 optics tubes,

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

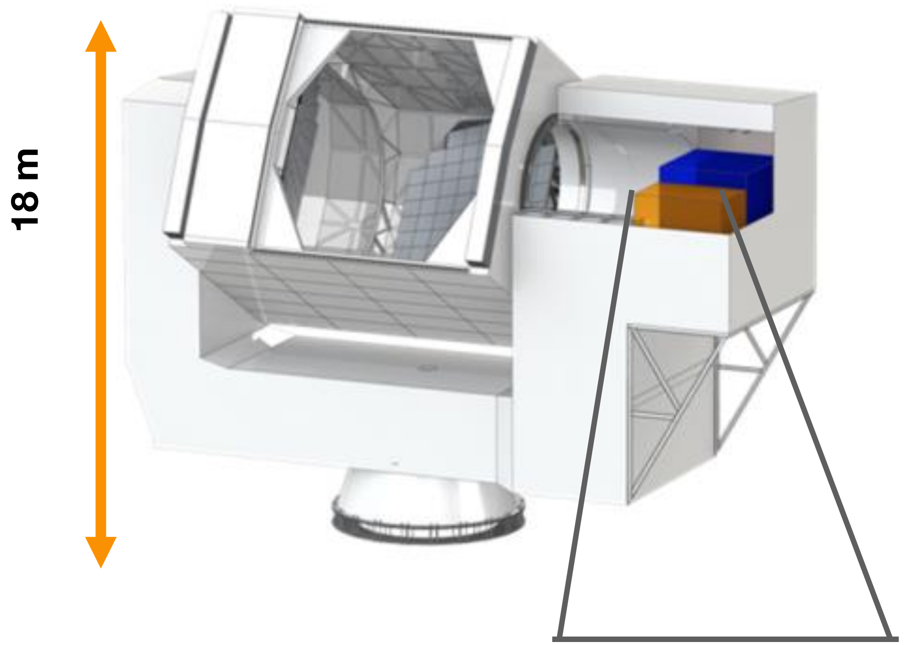


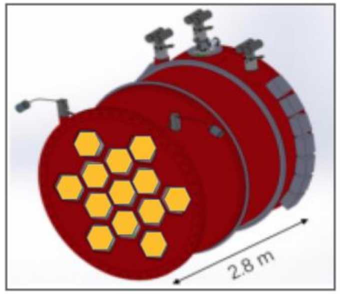
SO-Nominal deploys three refractors 42 cm in diameter, rotating half-wave plate.
Dichroic pixels:
30/40 | 90/150 | 220/270 GHz

SO uses two types of optical systems to provide a large dynamic range of angular scales.

SO-Enhanced Doubles the Mapping Speed

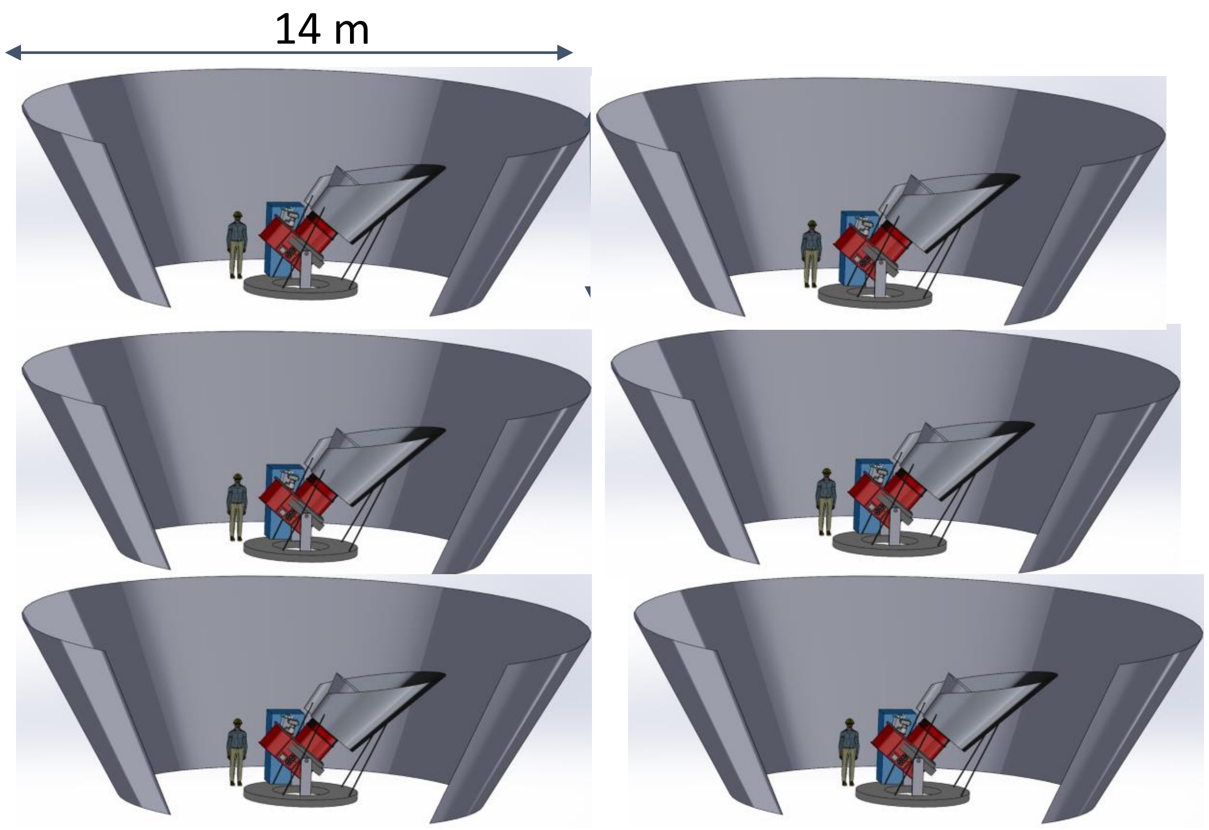
Large Aperture Telescope





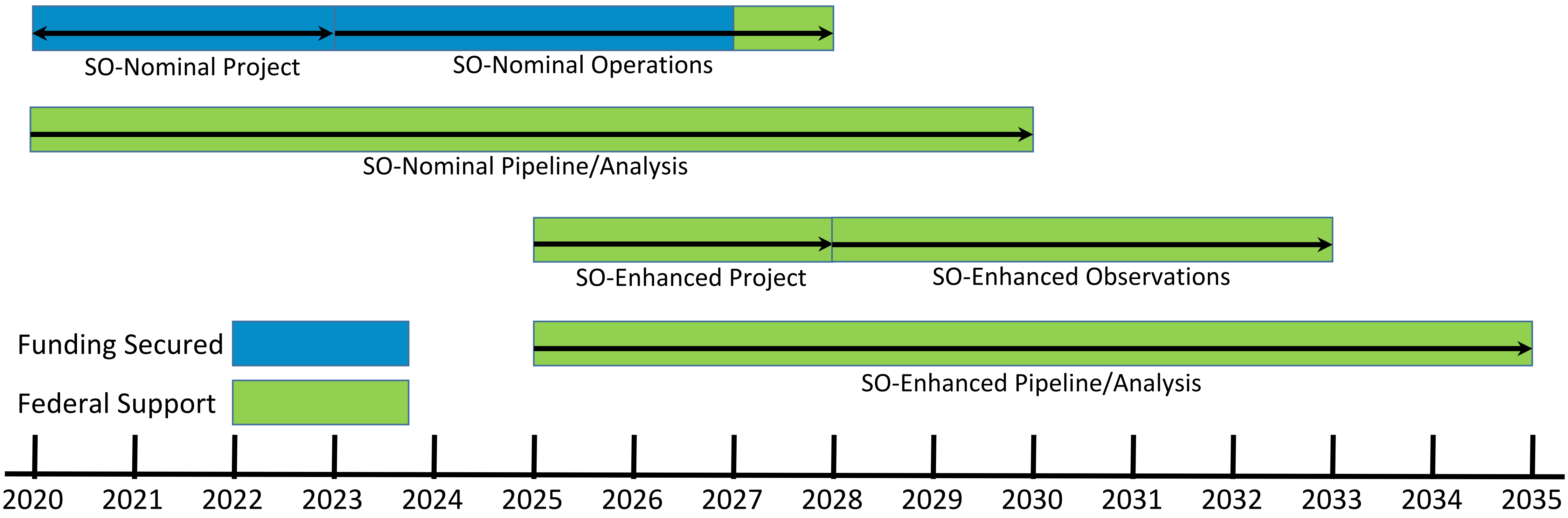
SO-Enhanced fills all 13 tubes on the LAT.

Small Aperture Telescopes

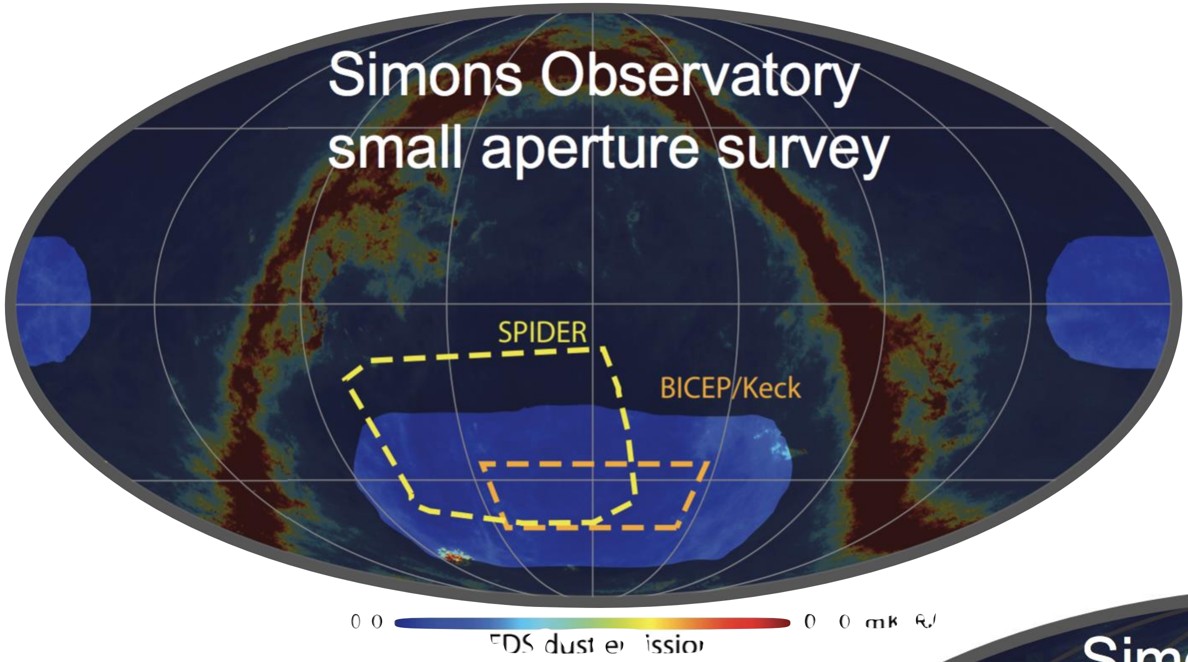


SO-Enhanced adds 3 SATs to SO-Nominal

SO-Nominal and SO-Enhanced Schedule



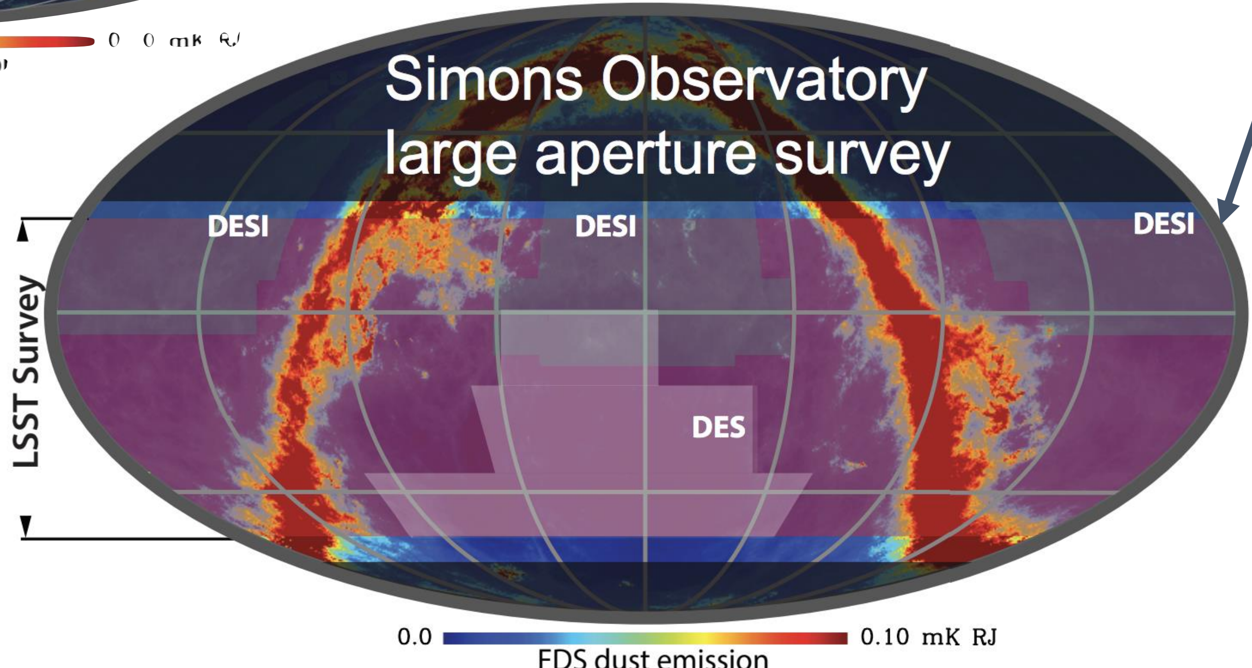
Two Surveys to Maximize the Science Return



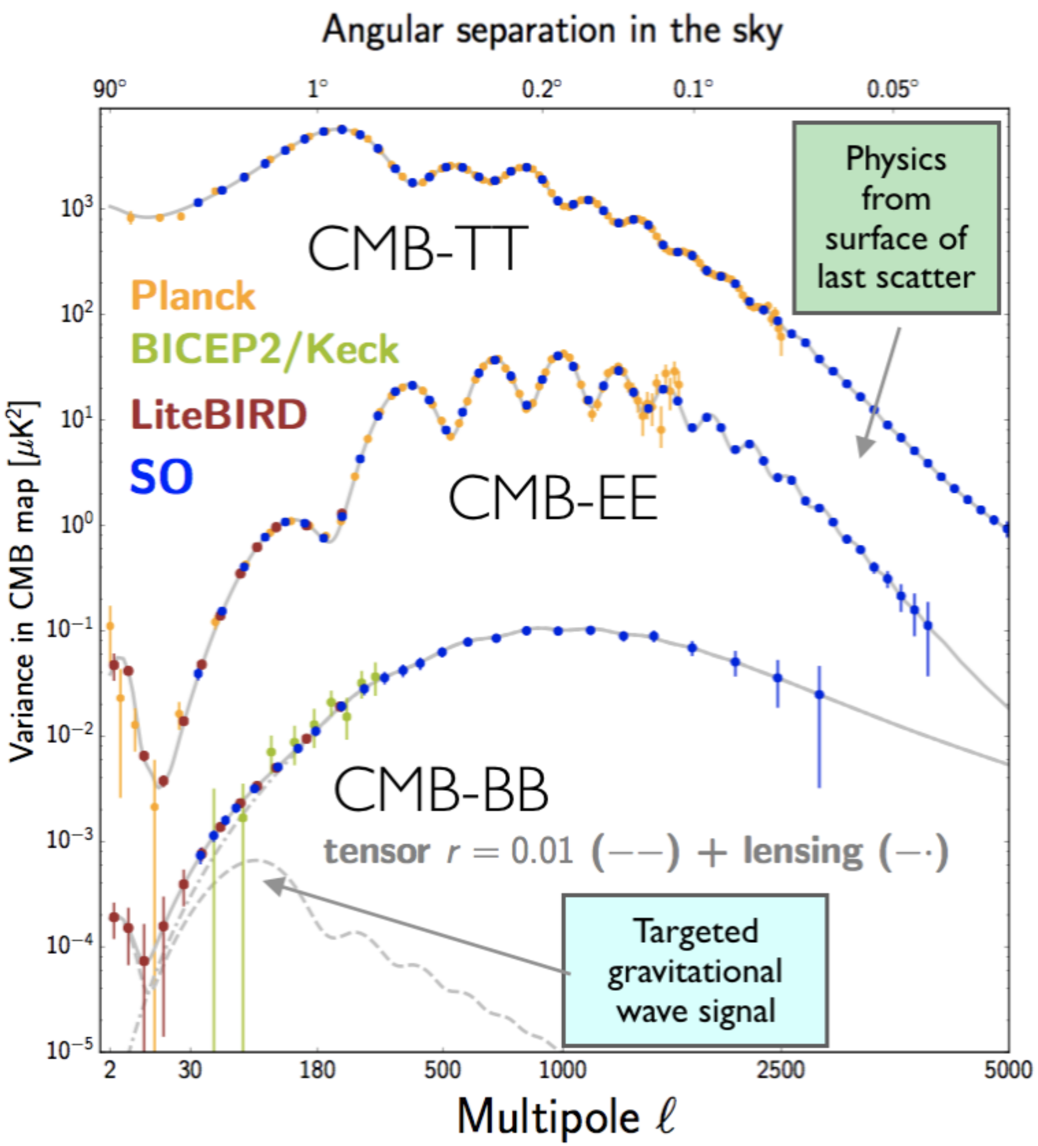
Effective f_{sky} ~ 10%
Optimised for Primordial B-modes

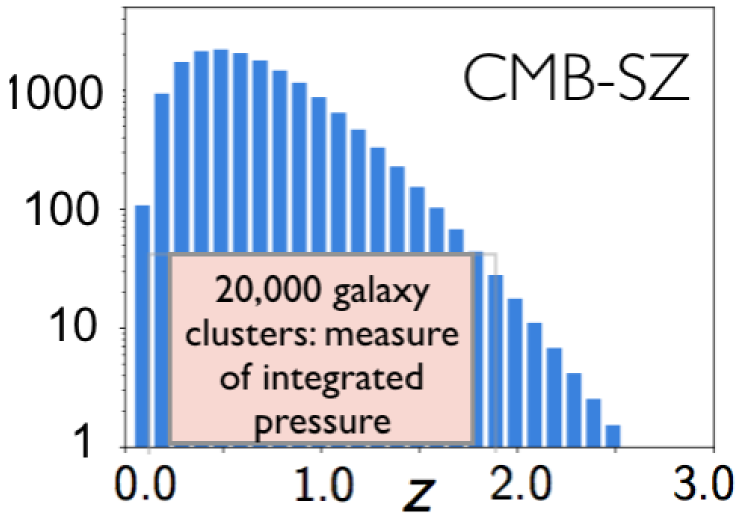
All SO science goals, except tensors, drive us to wide area, with maximum optical overlap

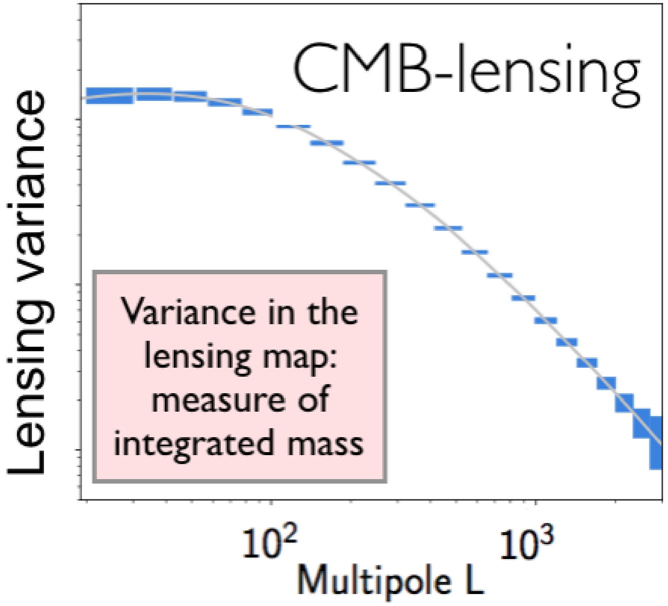
- Baseline f_{sky} ~0.4, Potentially as large as 0.7
- Overlap with Rubin-LSST, DESI, Euclid
- Observing cadence being refined for both cosmology and transient/Planet 9 searches



SO Observables Enable a Wide Range of Science







ALSO:

- kSZ
- Y-maps
- Millimeter sources and transients
- Planet 9
- Legacy arcmin-resolution mm-wave sky maps

Sensitive Maps in Six Frequency Bands

SO-Nominal		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

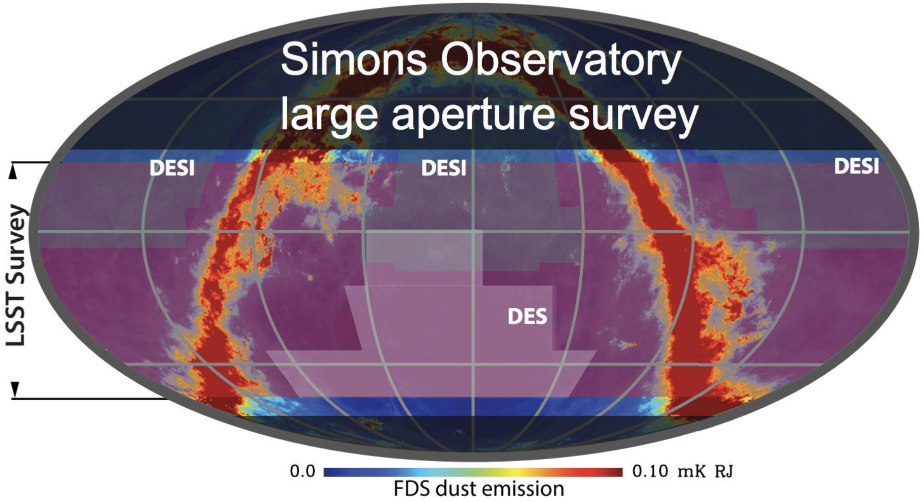
More details in the SO Forecast Paper:
Journal of Cosmology and Astroparticle Physics, Issue 02 (2019) (cited 160+ times)

SO Science Targets

SO-Nominal Key Science Goals

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

The mid-latitude location enables overlap with optical surveys greatly expanding the scientific return.



Plus:

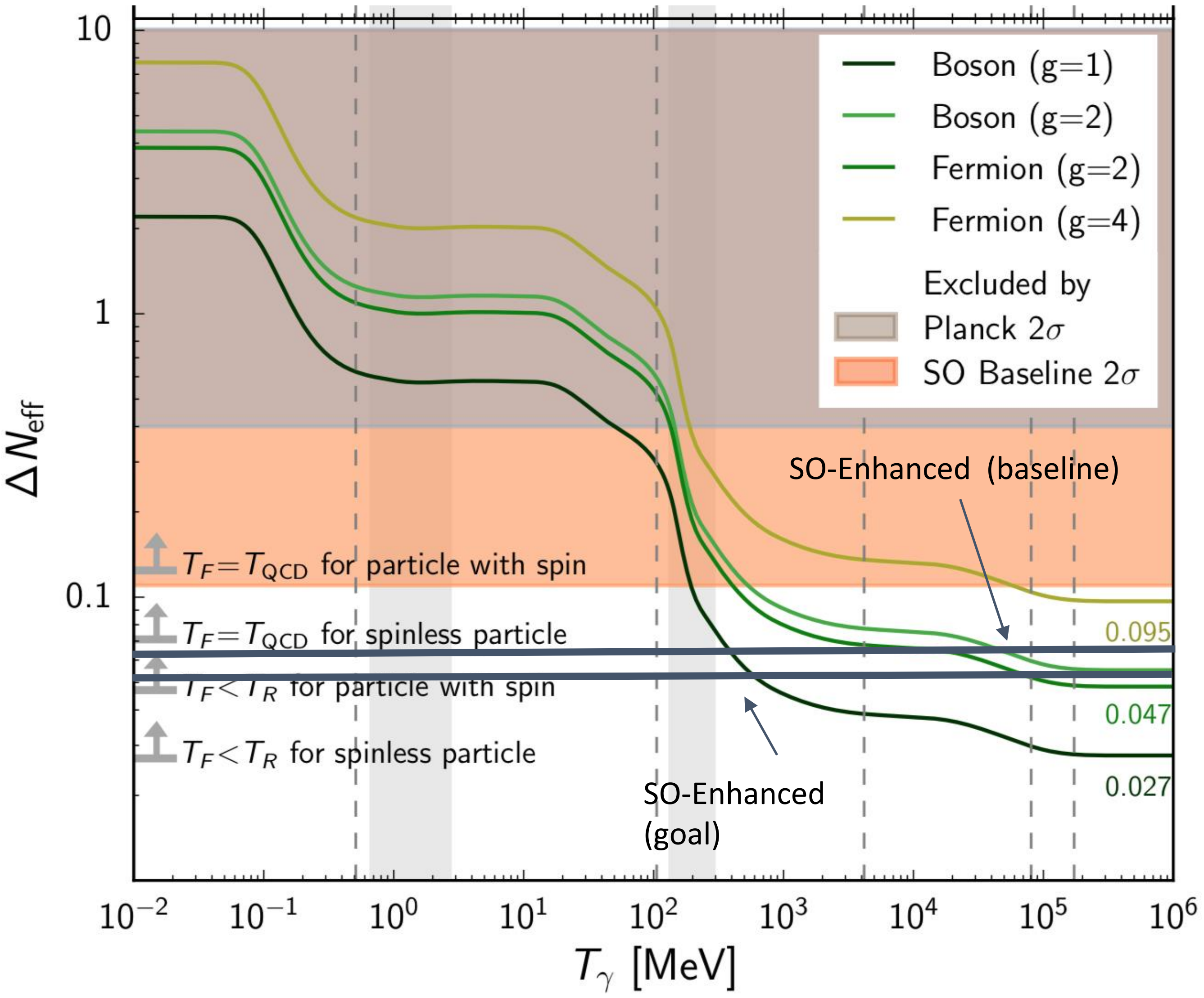
- **Transients**
- **AGN, mm sources**
- **Planet 9**
- **Galactic Science**

SO-Enhanced Science Highlights

	SO-Nominal (Goal)	SO-Enhanced (Goal)
Lensing and SZ (LAT)		
Minimal neutrino mass detection (Σm_ν=0.06 eV)[a]	3σ	4σ
Lensing detection (polarization-only)	160σ (110σ)	220σ (180σ)
Number of SZ clusters	20000	33000
Kinematic SZ detection (DESI cross-correlation)	190σ	240σ
Measurement of Optical Depth from kSZ, $\sigma(\tau)$ [b]	0.007	0.003
Primordial polarization (SATs)		
Tensor-to-scalar ratio	$\sigma(r) = 0.002$	$\sigma(r) = 0.001$[c]

SO-Enhanced doubles the number of detectors and adds another five years of observations

SO LAT Science: Light Relics and Early Universe Science



SO measures the relativistic density; it will see 2σ signal of any new particle with spin that decoupled after the start of the QCD phase transition

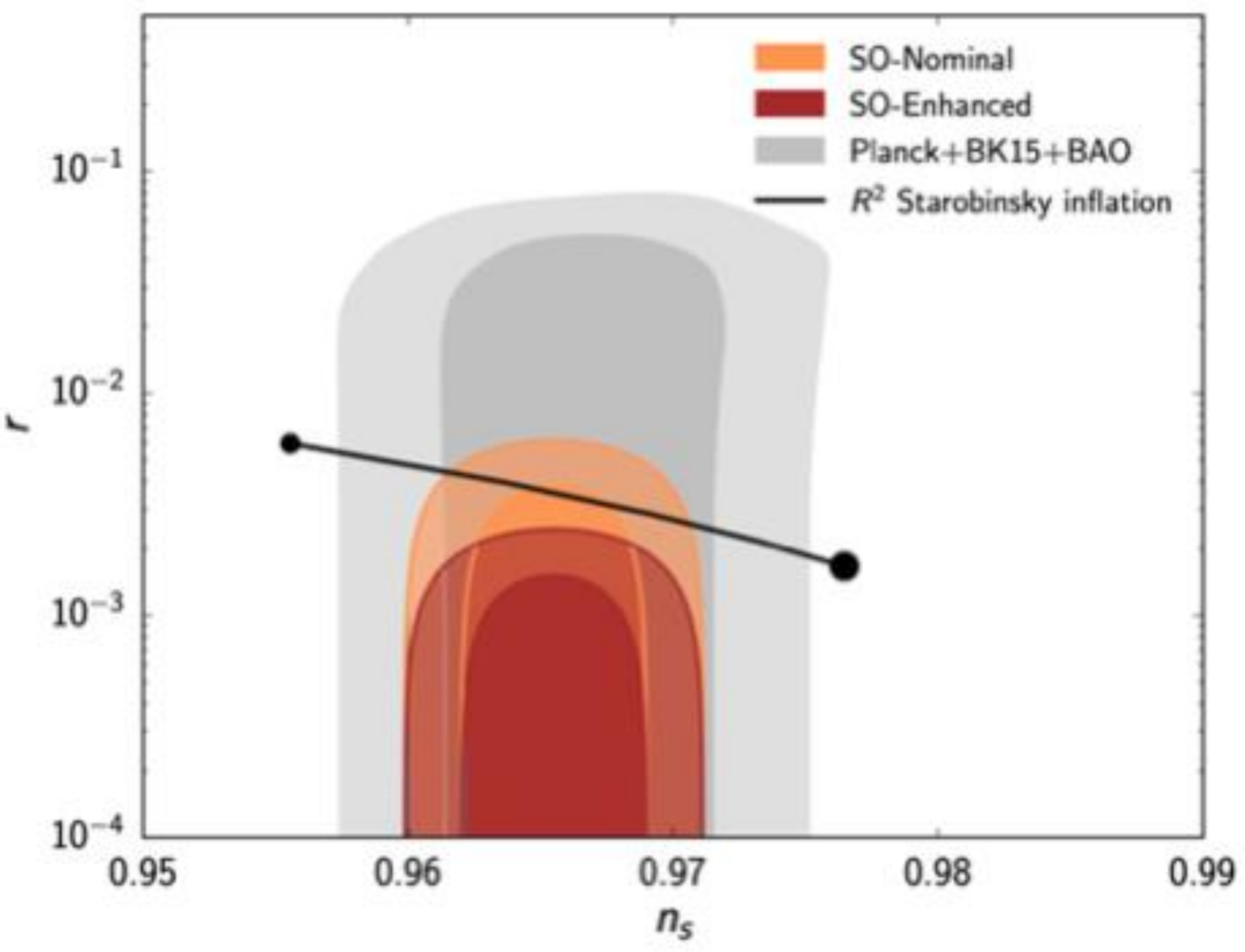
$\sigma(N_{\rm eff}) = 0.05$ (SO-Nominal)

Forecasts are strongly robust to foregrounds (driven by TE + EE)

Other damping tail science:
- BBN (Y_p)
- H_0 improvement (~2x)
- Dark matter interactions
- Ultra-light axions
- and more

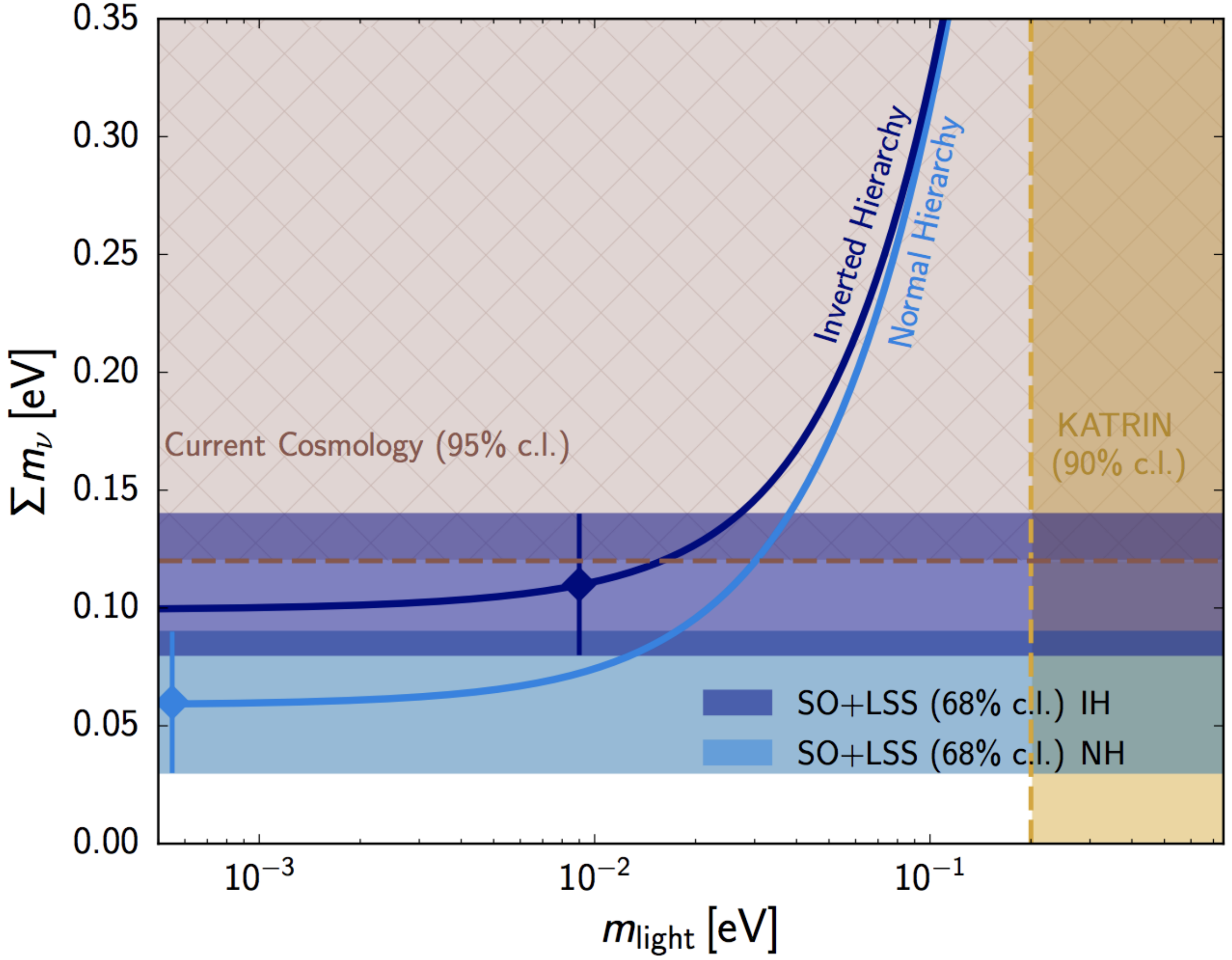
Degree-Scale Primordial B-modes from Chile

- The site in Chile provides larger sky coverage.
  - Can be delensed with 50% of the power removed by existing, external sources (e.g. CIB).
  - Internal delensing is not required, but the wide-field LAT data provide a useful crosscheck.
  - Lower sample variance error if a signal is detected.
  - If a signal is detected, there are multiple low-foreground patches for comparison and confirmation.



σ(r)=0.002 (SO-Nominal, goal)
σ(r)=0.001 (SO-Enhanced, goal)

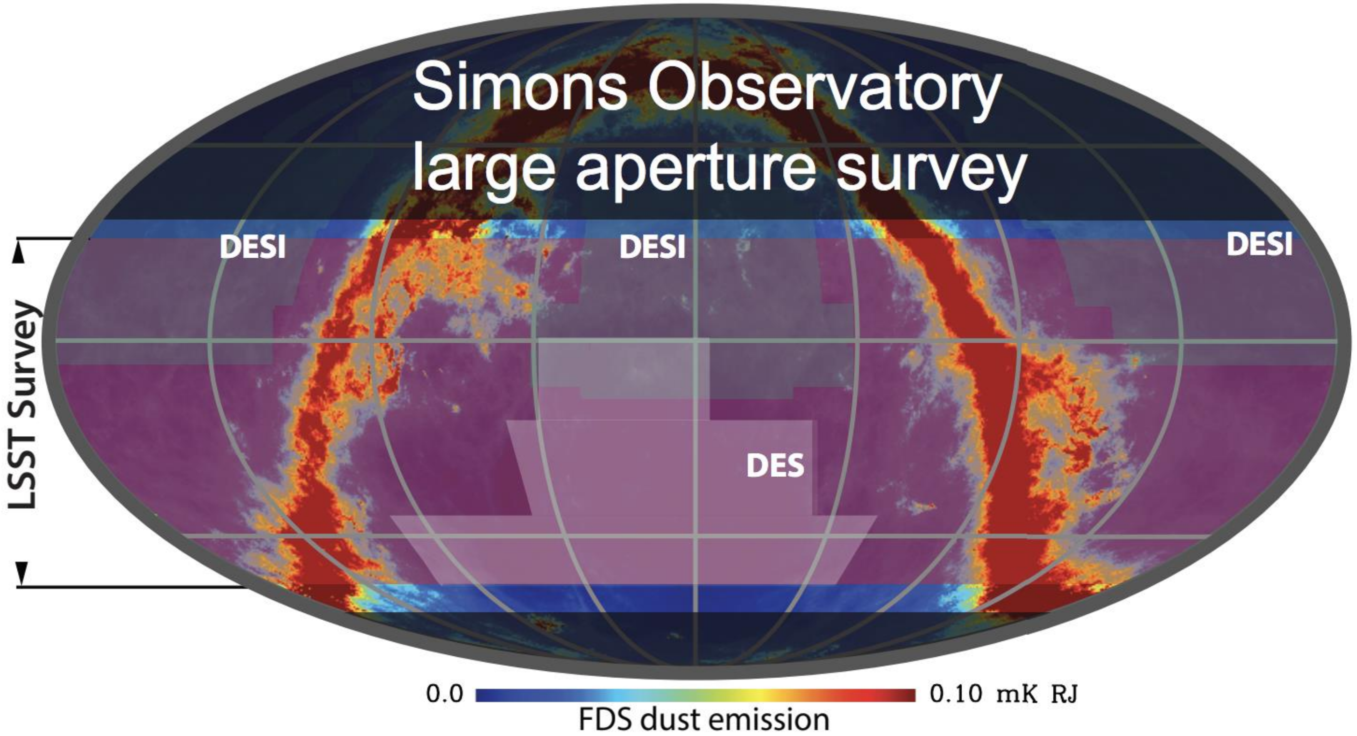
SO LAT Science: Neutrino Masses



Constraints derived from CMB lensing power spectrum (+DESI BAO), tSZ cluster counts (+Rubin-LSST WL), and tSZ power spectrum (+DESI BAO)

$\boxed{\sigma(\Sigma m_\nu) = 0.03\text{-}0.04 \text{ eV}}$ → 0.016 eV SO-Enhanced w/ Cosmic-Variance-limited τ

Synergy with Rubin Observatory, DESI, Euclid



Joint science projects from

CMB: SO lensing, tSZ, kSZ

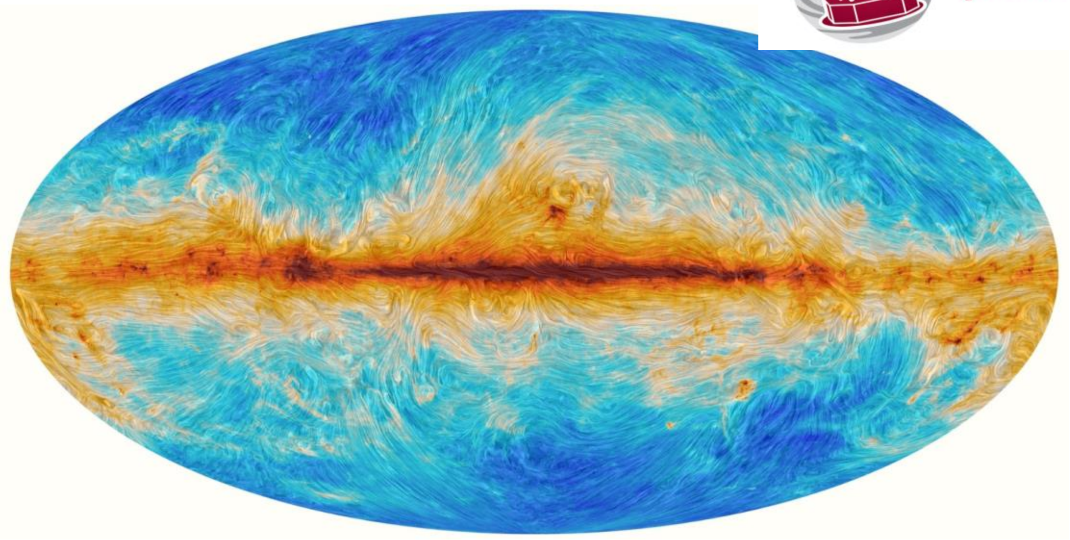
Optical: galaxy shear, clustering and clusters

- **Neutrino mass**
- **Structure growth: sigma8 at z>1**
- **Non-Gaussianity: fnl**
- **Cluster mass calibration**
- **Shear bias calibration**
- **Constraints on baryonic feedback**

Galactic science

- Arcminute-resolution half-sky maps from 30-280 GHz
- SO working group led by Brandon Hensley & Susan Clark
- Topics include:
  - Mapping magnetic fields
  - Polarized dust SED
  - Polarized synchrotron SED
  - ISM turbulence
  - Dust/synchrotron connection
  - AME spectrum and polarization
  - Molecular line emission
  - Star formation and magnetic fields

planck



SO: higher resolution, lower noise, half-sky

Panel Question #1: Transient Science

To enable the transient science that SO envisions, what data products (alerts, difference maps, etc.) will be provided to the community, with what astrometric accuracy, and on what timescales relative to observations?

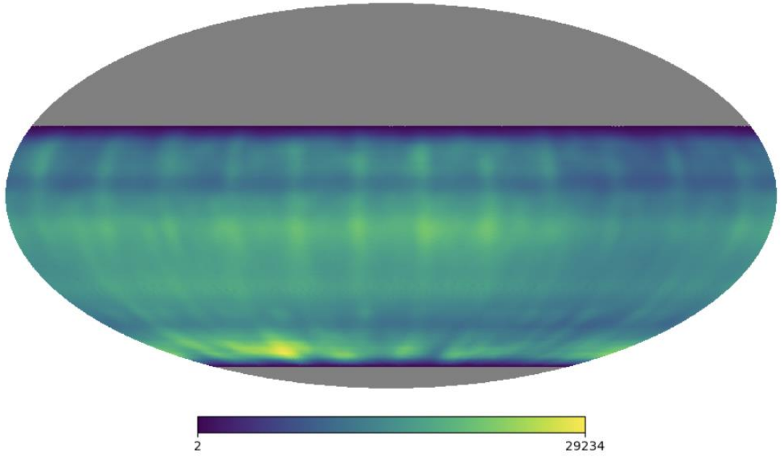
(1) **'Discovery' transients: orphan afterglows of GRBs, and/or jetted TDEs**. Of interest on timescales of days - alerts would enable optical follow up.

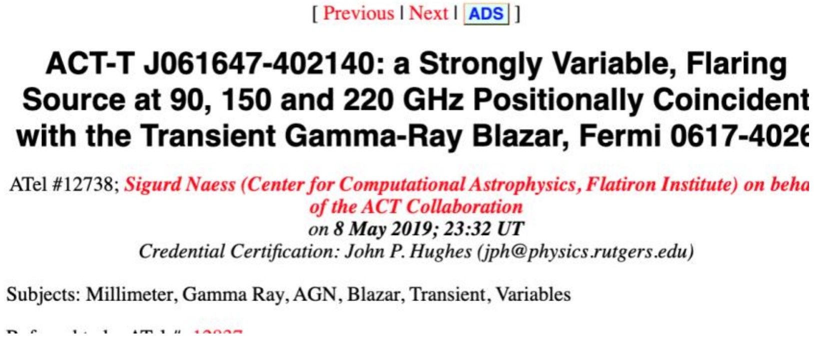
Will make daily maps using matched filter method, and difference to identify candidates.

Anticipate releasing alerts (on daily basis) with position and flux at our 6 frequencies. Astrometric accuracy is expected to be ~1 arcsec. Difference maps could also be made available.

(1) **Variable AGN**: expect to track thousands daily/weekly/monthly.

Matched-filtered maps will be made at these cadences, and per-frequency light-curves released. A model being considered is to release light-curves as they are made, with dedicated alerts for highly flaring objects.




[Previous | Next | ADS]

ACT-T J061647-402140: a Strongly Variable, Flaring Source at 90, 150 and 220 GHz Positionally Coincident with the Transient Gamma-Ray Blazar, Fermi 0617-4026

ATel #12738; *Sigurd Naess (Center for Computational Astrophysics, Flatiron Institute) on beha of the ACT Collaboration*
on 8 May 2019; 23:32 UT
Credential Certification: John P. Hughes (jph@physics.rutgers.edu)

Subjects: Millimeter, Gamma Ray, AGN, Blazar, Transient, Variables

Panel Question #8: Transient Science

Are the hardware and software capabilities necessary for generating transient science data products included at full scope within the project budget?

Yes. Our budget covers:

- the making of maps and associated computing costs
- personnel to handle web delivery of science products

We also anticipate covering minor costs associated with:

- travel associated with engaging with the broader transient community
- development of Zoom-based online tutorials on using the relevant SO data

SO-Nominal Construction

Simons Observatory Project Work Breakdown Structure

Simons Observatory
WBS 1
Bazarko – Project Manager

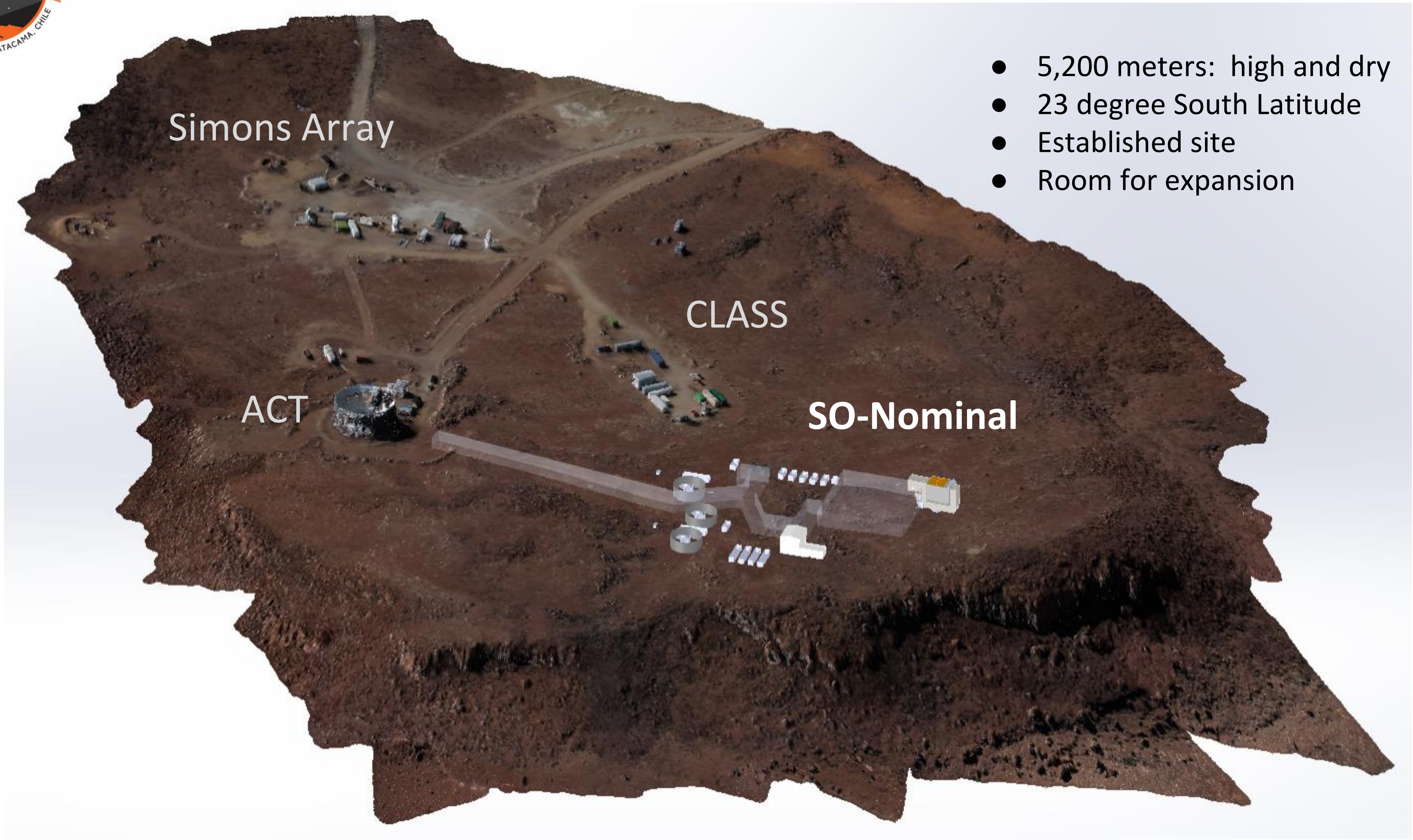
Large Aperture Telescope

Small Aperture Telescopes

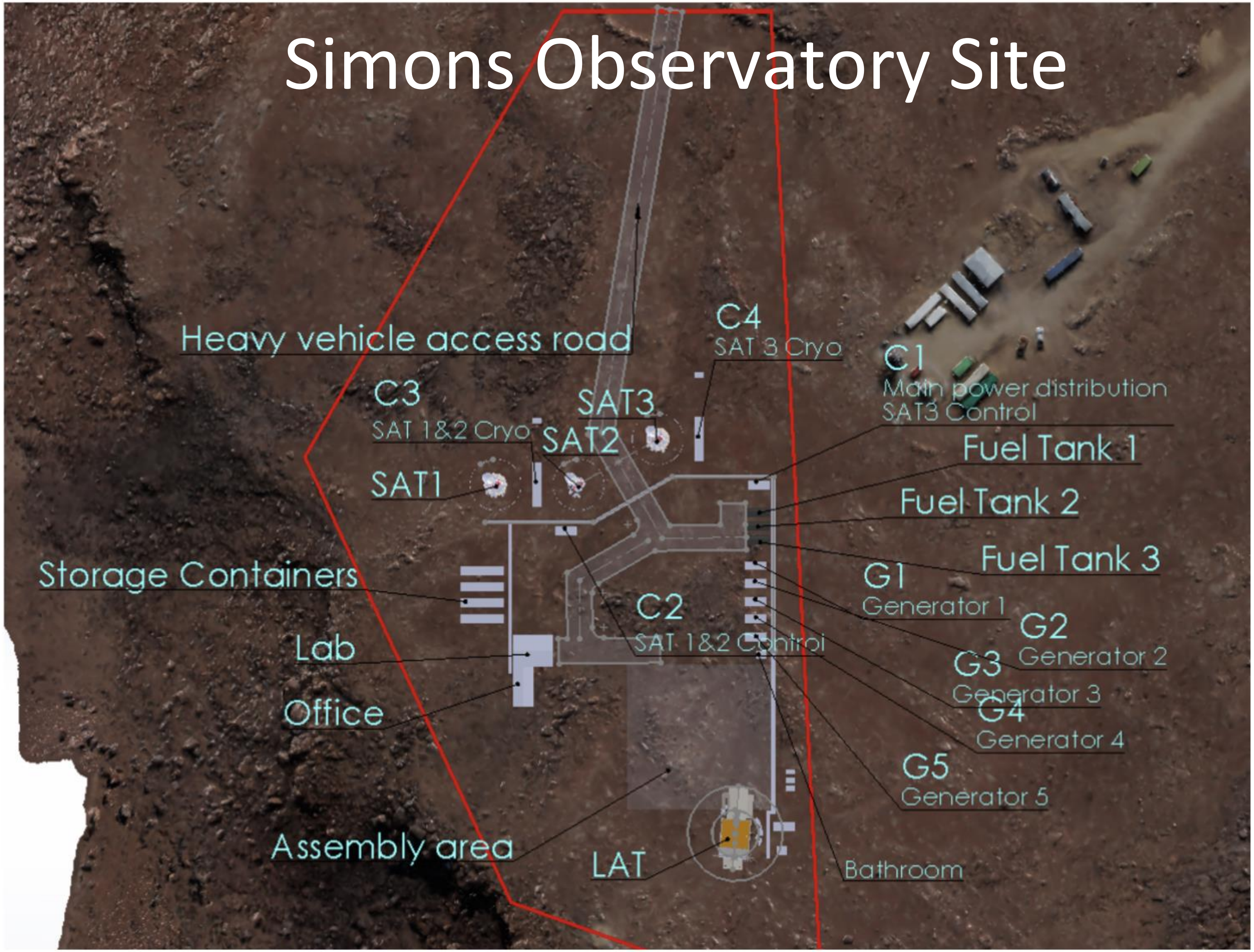
- LAT
  WBS 1.1
  Limon
  - 1.1.1 Co-rotator
  - 1.1.2 Hardware interfaces
  - 1.1.3 Software interfaces
  - 1.1.4 Testing
  - 1.1.5 Optical design optimization
  - 1.1.6 Management
- LAT Receiver
  WBS 1.2
  Devlin
  - 1.2.1 LATR Cryostat
  - 1.2.2 LATR Optics Tubes
  - 1.2.3 LATR integration & Test
  - 1.2.4 LATR Housekeeping electronics
- SAT Platform
  WBS 1.3
  Keating
  - 1.3.1 SATP Design & Procure
  - 1.3.2 SATP Test
  - 1.3.3 SATP interfaces & Integration
- SAT
  WBS 1.4
  Lee
  - 1.4.1 SAT Cryostat
  - 1.4.2 SAT Optics Tubes
  - 1.4.3 SAT integration & Test
  - 1.4.4 SAT Housekeeping electronics
- Detectors/Readout
  WBS 1.5
  Staggs
  - 1.5.1 Detectors
  - 1.5.2 Readout
  - 1.5.3 Universal Focal Plane Module
  - 1.5.4 Det/Readout Testing
- Data Management
  WBS 1.6
  Aiola
  - 1.6.1 Subsystem Management
  - 1.6.2 Data Acquisition
  - 1.6.3 Site Computing
  - 1.6.4 Data Movement
  - 1.6.5 Software Infrastructure
  - 1.6.6 Data Synthesis Simulations
  - 1.6.7 Data Reduction TOD2Maps
- Site
  WBS 1.7
  Arnold
  - 1.7.1 External Drivers
  - 1.7.2 Low-Elevation Facility
  - 1.7.3 Power Generation/Trans
  - 1.7.4 Communication to/from Site
  - 1.7.5 Telescope Foundations
  - 1.7.6 Non-Foundation HEF infrastructure
  - 1.7.7 Access Site w People & Equip
  - 1.7.8 Telescope Install & Verf.
  - 1.7.9 Ops & Maintenance
  - 1.7.10 Legal Issues
  - 1.7.11 Management
  - 1.7.12 Safety
  - 1.7.13 Chilean Outreach
  - 1.7.14 Personnel deployment
- Integration & Test
  WBS 1.8
  McMahon
  - 1.8.1 Requirements Tracking
  - 1.8.2 Test Cryostat
  - 1.8.3 Calibration

The SO Site

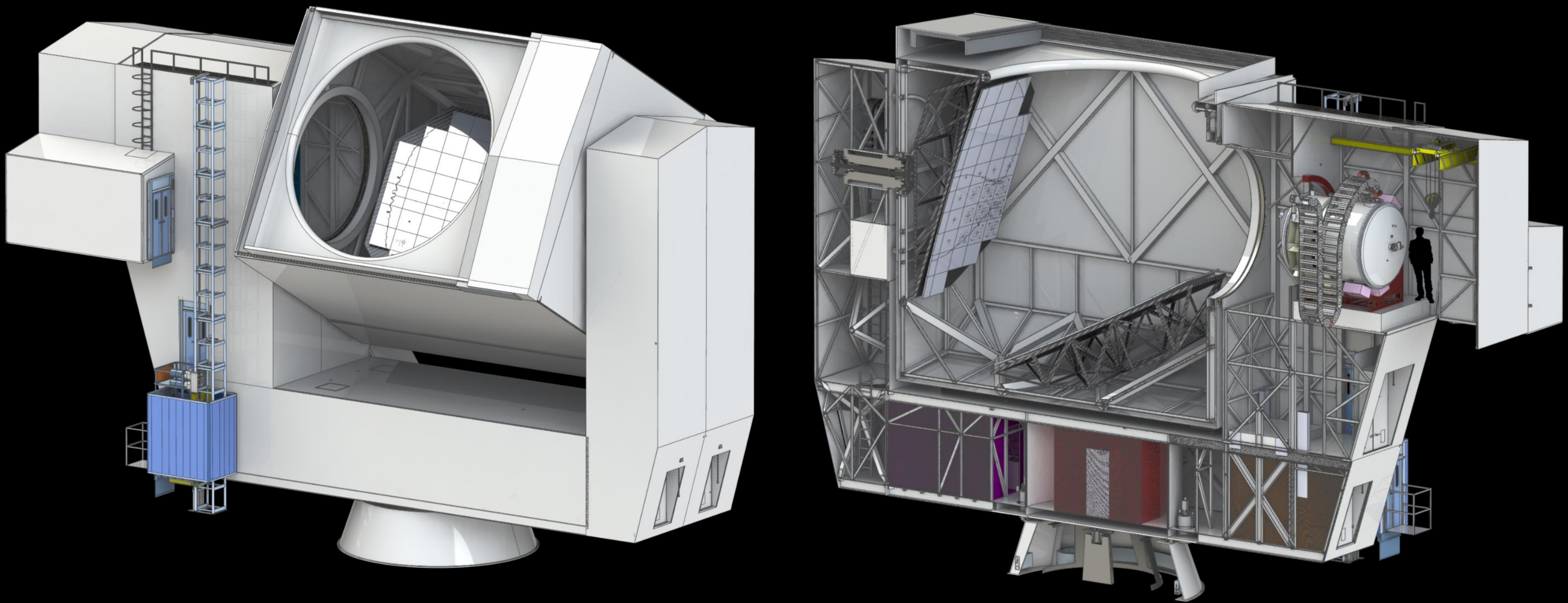
- 5,200 meters: high and dry
- 23 degree South Latitude
- Established site
- Room for expansion



Simons Observatory Site

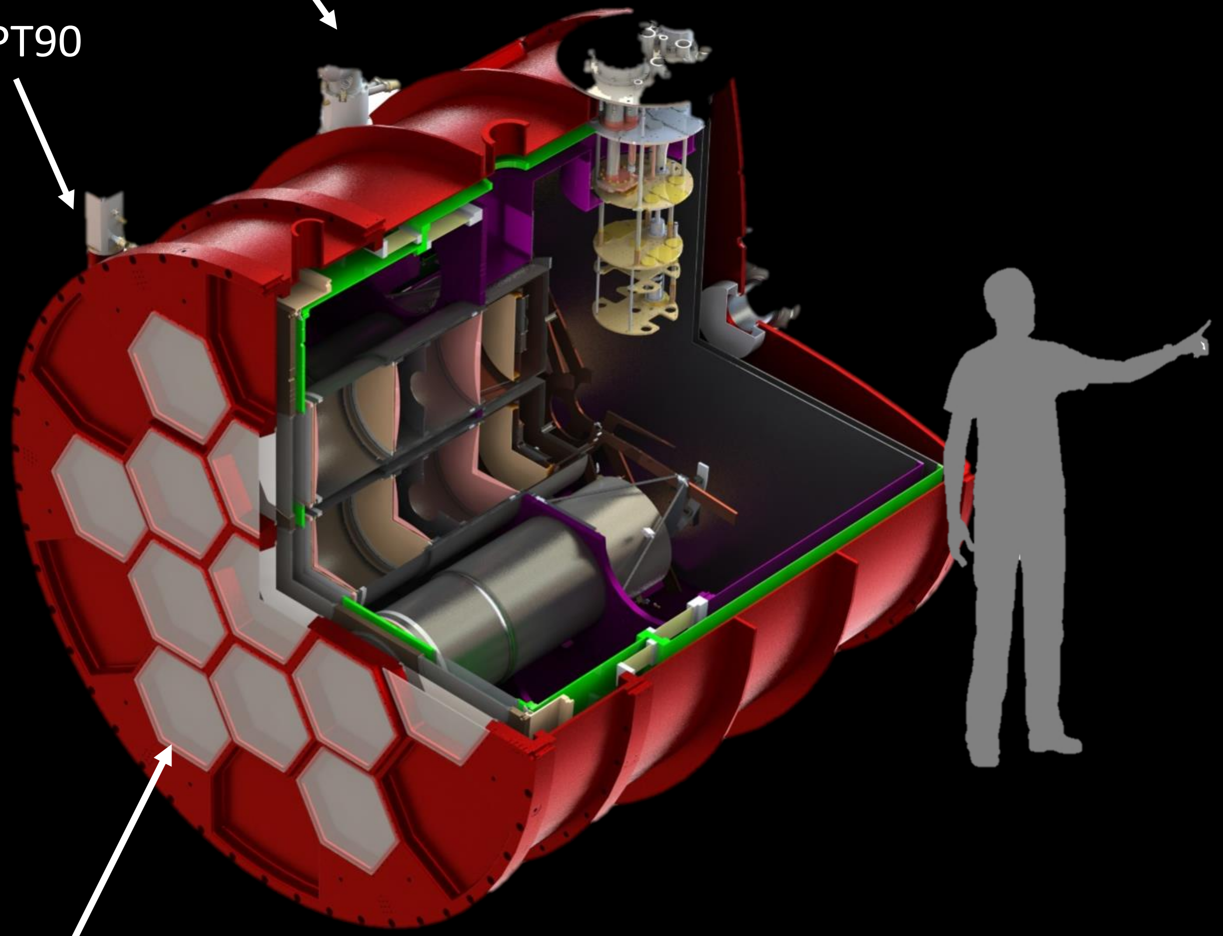


Simons Observatory Large Aperture Telescope

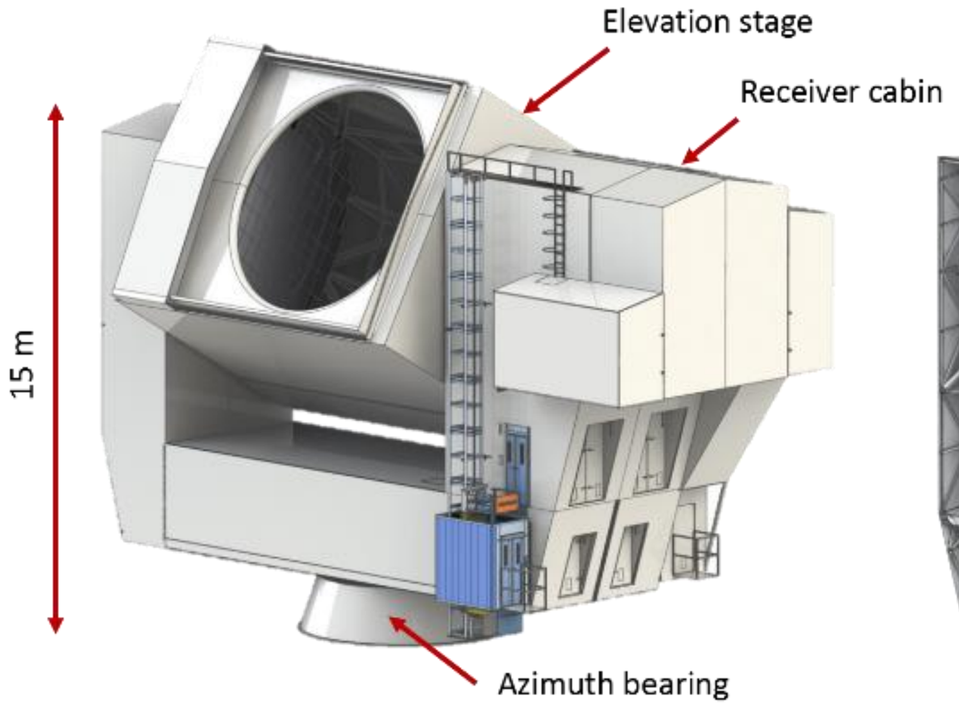


- 6 meter off-axis Cross Dragone design
- 9 degree field of view – 9 times the throughput of ACT
- 1.7 arcmin resolution at 150 GHz

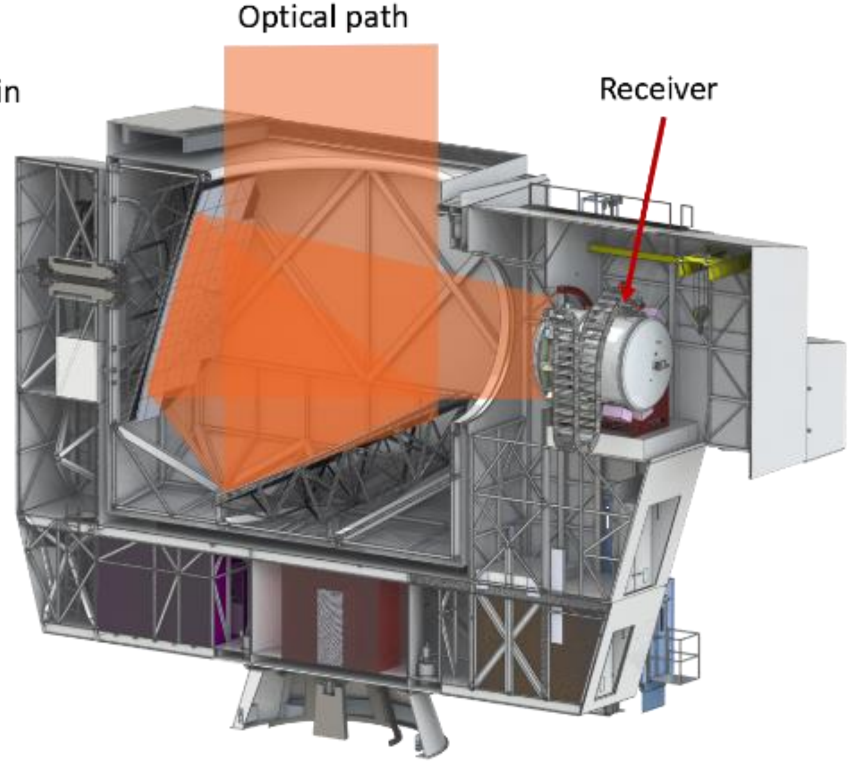
Simons Observatory Large Aperture Telescope Receiver



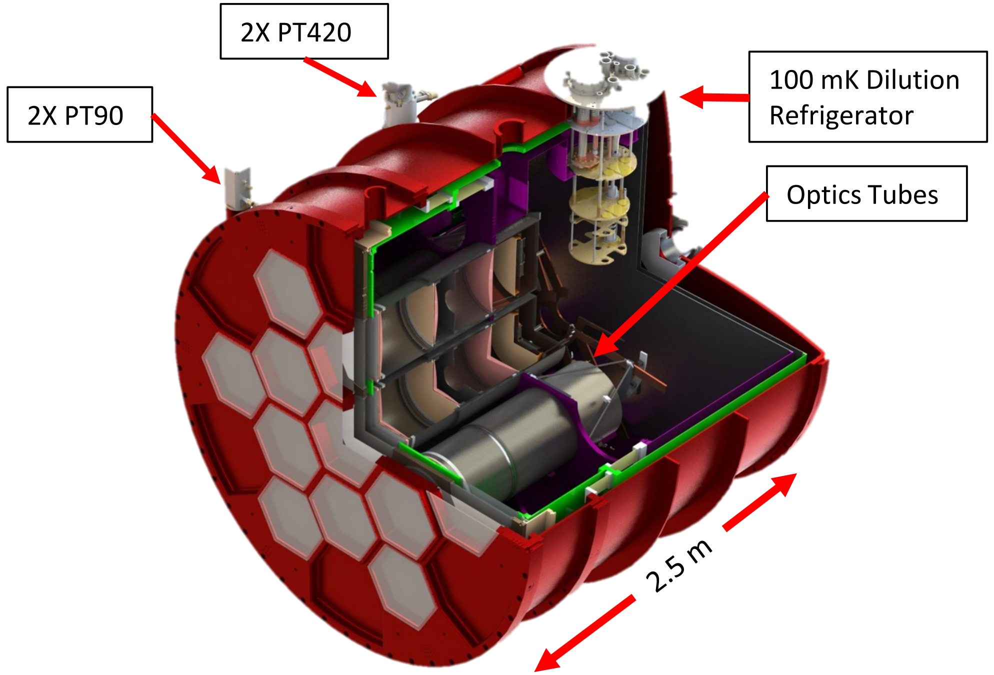
- **2 PT90s** – 180 Watts @80 K
- **3 PT420 coolers**
  - 165 Watts @40 K
  - 6 Watts @4 K
- **Dilution Refrigerator**
  - 17 mW @1K
  - 500 uW @100 mK
- 1200 kg cooled to 4K
- 200 kg cooled to 100 mK
- **Up to 13 optics tubes**
  - ~6-9 planned for SO
- **80,000+ detector capacity**
  - 40,000 planed for SO
- Optics tubes can be replaced while installed.



Elevation stage
Receiver cabin
15 m
Azimuth bearing

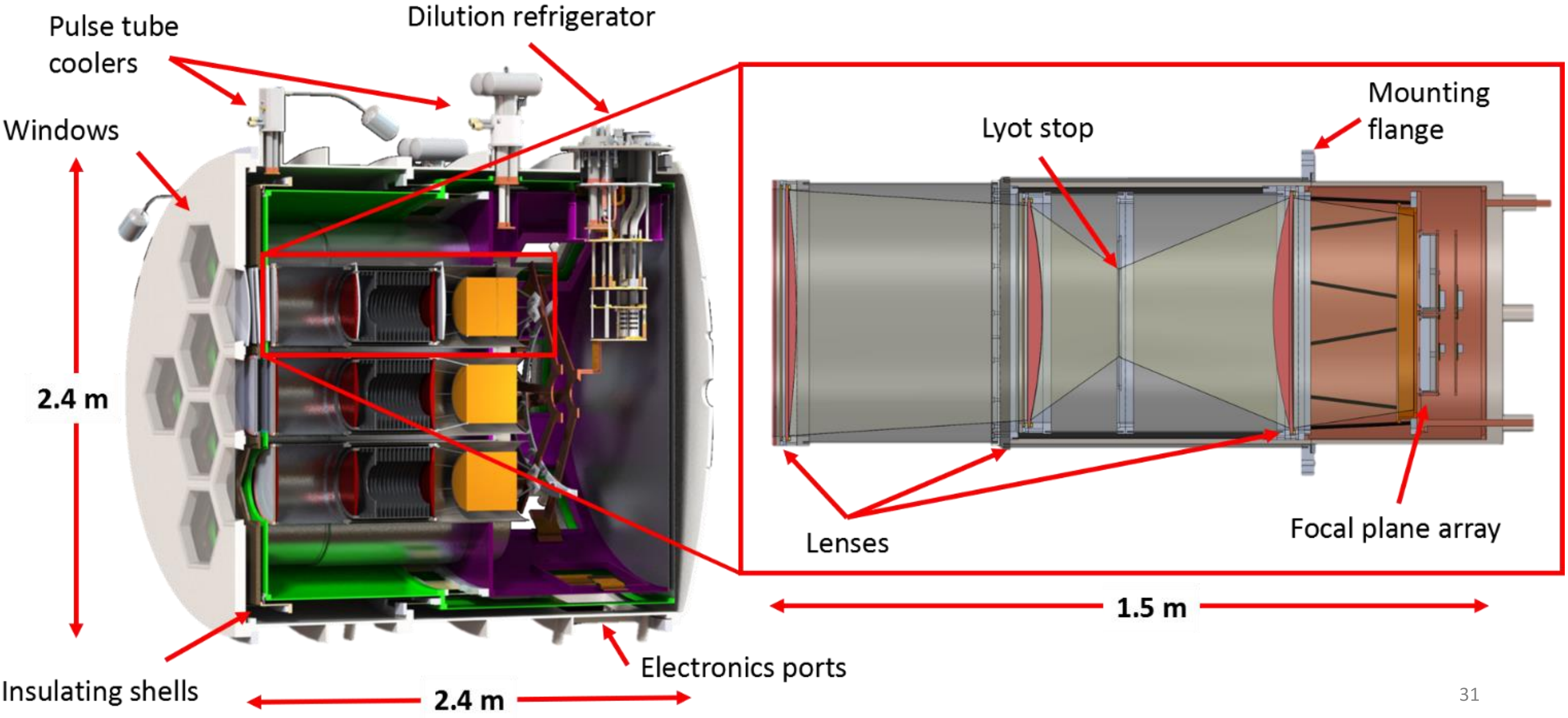


Optical path
Receiver



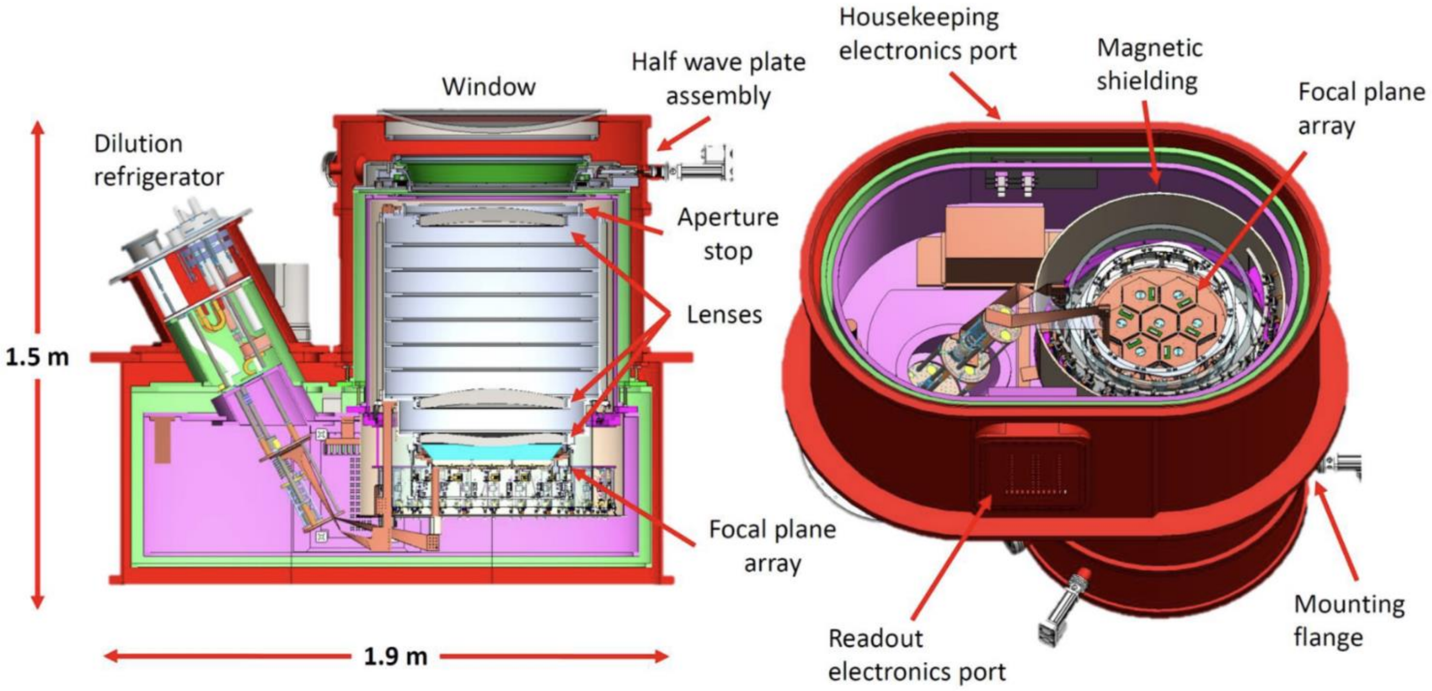
2X PT420
2X PT90
100 mK Dilution Refrigerator
Optics Tubes
2.5 m

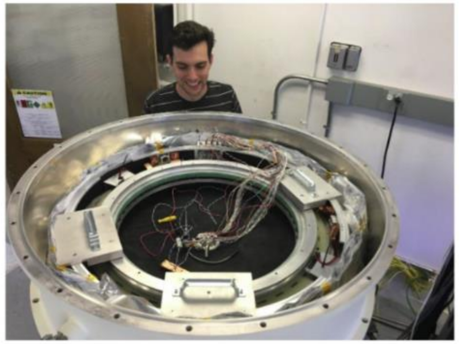
Large Aperture Telescope Receiver



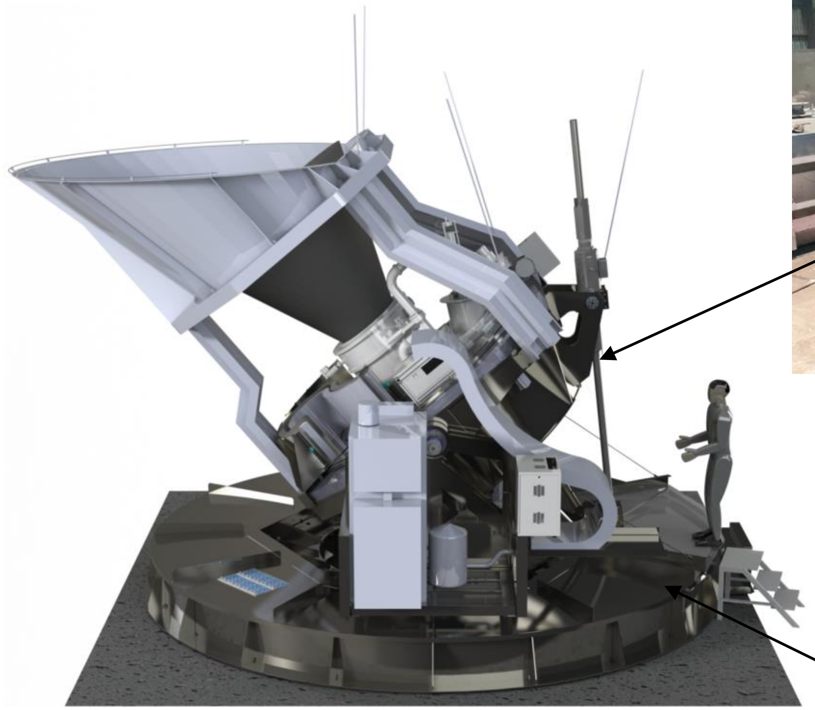
Small Aperture Telescopes

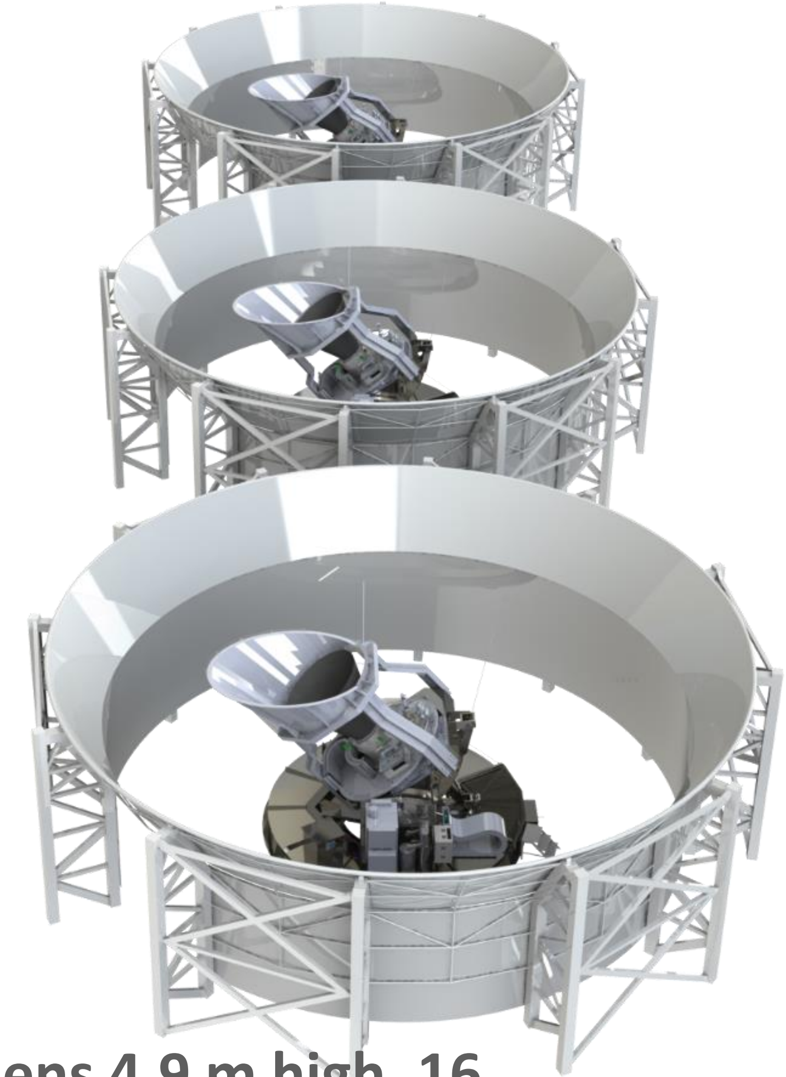
- 42 cm aperture size, 35 degree FoV
- 3 SATs, each with 7 150-mm detector arrays
- Continuously rotating HWP





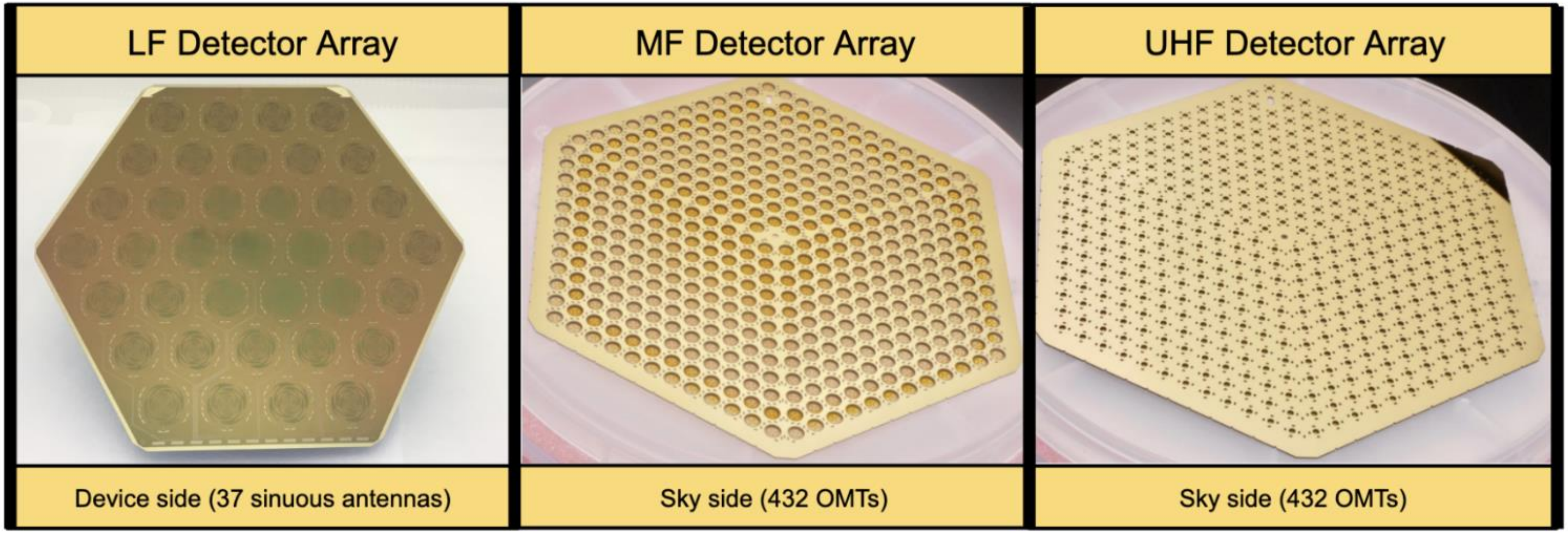
SAT Platforms and Ground Screens





Ground screens 4.9 m high, 16 meters in diameter

SO Detectors

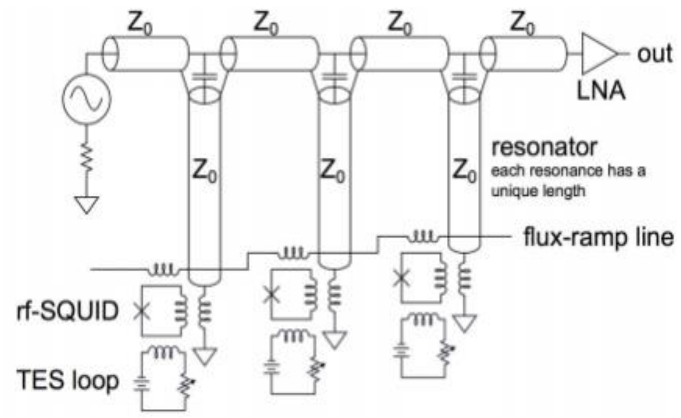


SO detector arrays use 100 mK TESes in dichroic arrays with two optical coupling methods. Prototype arrays of all three bands are shown here.

SO Readout

One of six enabling technologies* for SO is the 910x μmux readout for close-packed 100 mK TES arrays.

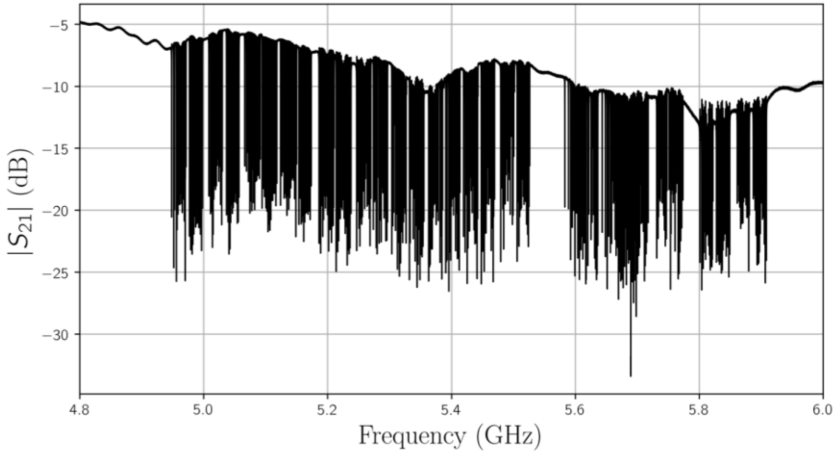
Targeting mux factor ~ 10x larger than other TES readout methods.



μMux:

- Send in a comb of narrow frequency bands (MHz tones)
- Dissipationless rf SQUID couples δI from a TES detector into δf of a resonant circuit.

Mates et al, 2008



Henderson et al, 2019: 528x demonstration with NIST mux chips and SLAC readout electronics

SO needs compared to this 528x demo:

- New packaging format
- Larger mux factor (910x)

*Also: LAT, LATR, large filters, large AR coatings, HWPs

SO Readout Challenges

While there have been challenges with the readout development, it is on track to be successfully deployed in 2021 well before SO-Enhanced. Performance depends on:

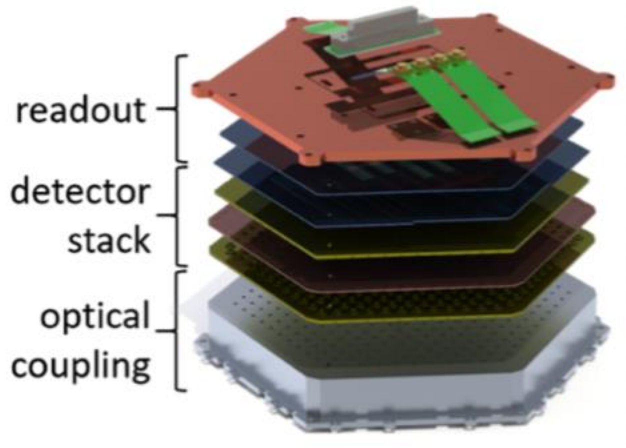
1) Fabrication of resonator multiplexing chips
2) Incorporation of resonator chips into packaging that couples behind the detector wafer
3) Room temperature electronics

- Early SO readout packaging lowered the intrinsic Q's of the resonators, impacting the readout noise performance.
- We baselined 910x (using 4-6 GHz) and improved the packaging design.
- The Qs achieved in current SO packaging no longer limit the readout noise performance.

We are currently optimizing the performance of all three factors in concert to maximize yield and minimize noise.

Development, deployment, and first observations with SO detectors and readout are fully funded and not part of any federal funding request.

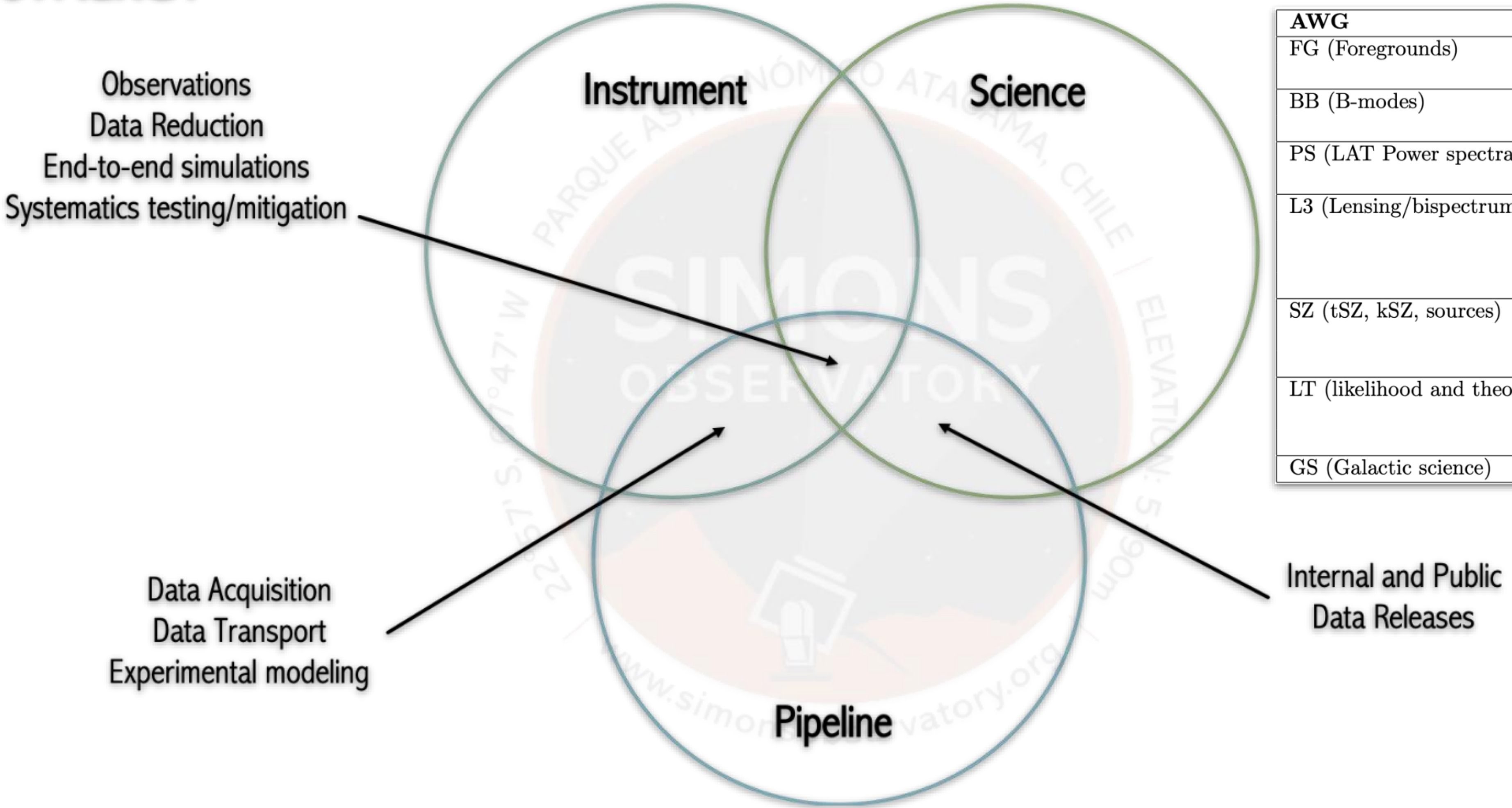
For SO, all the readout components fit behind a ~150 mm detector wafer, and all 1728 detectors are read out on 2 coaxial pairs, with 910x multiplexing.



SO Detector Module
Exploded View

SO Pipeline and Data Management

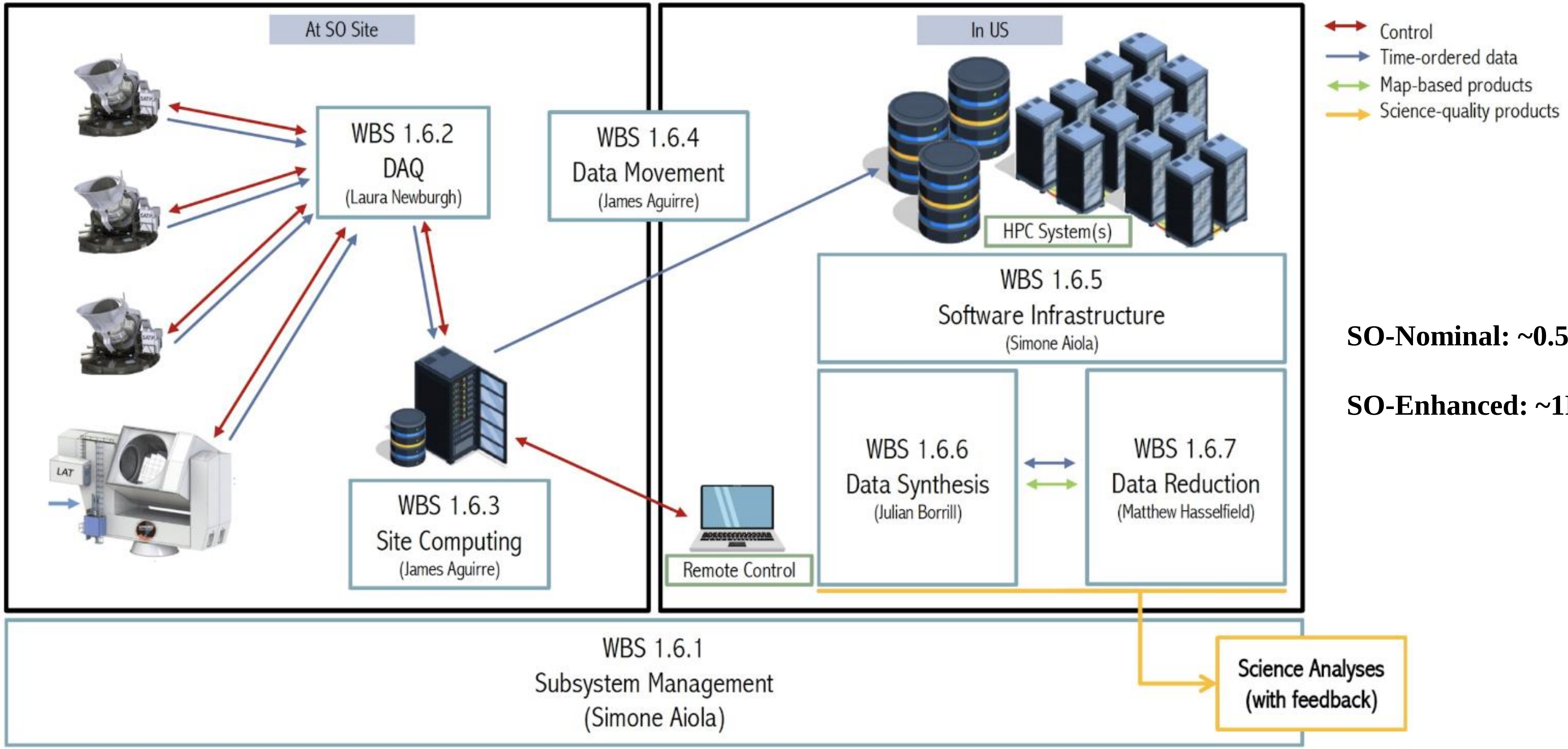
SYNERGY



AWG	sub-WG	Name
FG (Foregrounds)	FG.1	Foreground modeling
	FG.2	Component separation
BB (B-modes)	BB.1	BB cleaning and spectra
	BB.2	BB likelihood
PS (LAT Power spectra)	PS.1	Power spectra
	PS.2	PS Likelihood
L3 (Lensing/bispectrum)	L3.1	Reconstruction
	L3.2	Cross-correlation
	L3.3	Delensing
	L3.4	Bispectrum
SZ (tSZ, kSZ, sources)	SZ.1	Thermal SZ
	SZ.2	kinetic SZ
	SZ.3	Extragalactic sources
LT (likelihood and theory)	LT.1	Likelihood
	LT.2	Theory code
	LT.3	Sampling framework
GS (Galactic science)	GS.1	Galactic Science

Pipeline effort historically understaffed and not formally coordinated → analysis bottleneck

SO established Data Management team to coordinate resources, workflow, and fundings → aim to fast turnaround and timely data releases



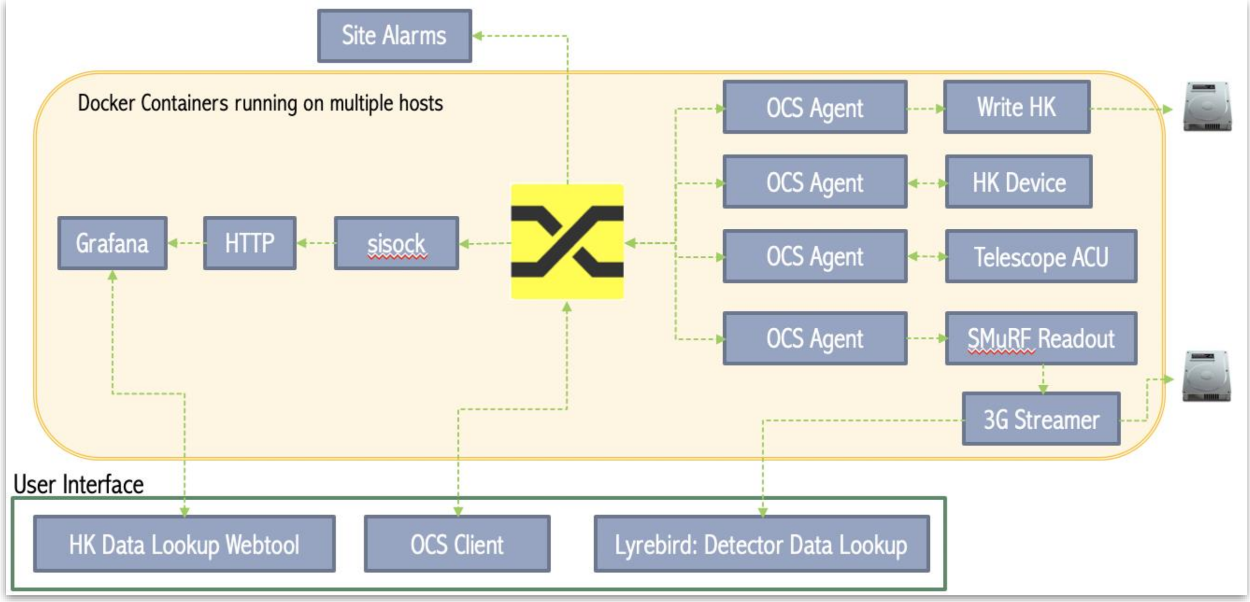
SO-Nominal: ~0.5PB/yr

SO-Enhanced: ~1PB/yr

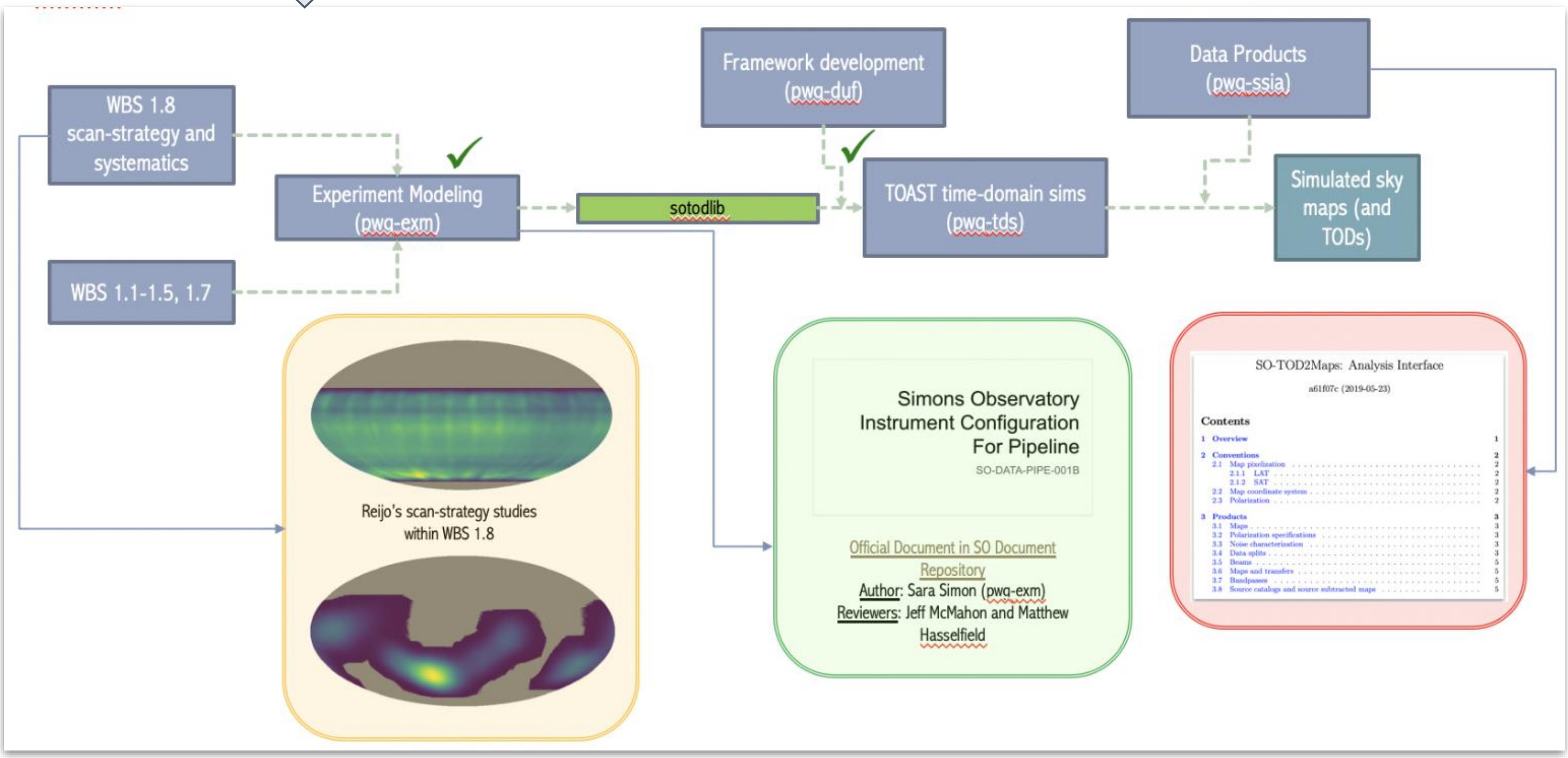
<u>Core team:</u> coordination and main development effort, funded at all times for project and operations

<u>Builder team:</u> collaborators (funded outside DM) involved in specific time-limited tasks

Observatory Control System: developed and deployed to testing labs. Public and easily scalable for future experiments. GitHub: https://github.com/simonsobs/ocs



Data reduction and sims: coordinated effort to simulate and reduce data. Plan to test pipelines on existing data before first light. Generic CMB-analysis pipeline already public



PWG	Name	L3
ssia	Science and Systematics Interfaces Awareness	1.6.1
duf	Databases, Utilities, Framework	1.6.5
exm	Experiment Modeling	1.6.6, 1.6.7
mbs	Map-Based Simulations	1.6.6
tds	Time-Domain Simulations	1.6.6
fct	Flagging, Conditioning, other TOD operations	1.6.7
qds	Quality Assurance, Quality Cuts, Data Selection	1.6.7
pmn	Projection, Mapping, (map-space) Noise	1.6.7
bcp	Beams, Cal, Polcal, Pointing Model	1.6.7
hwp	HWP (Half Wave Plate)	1.6.7

SO is Community Oriented

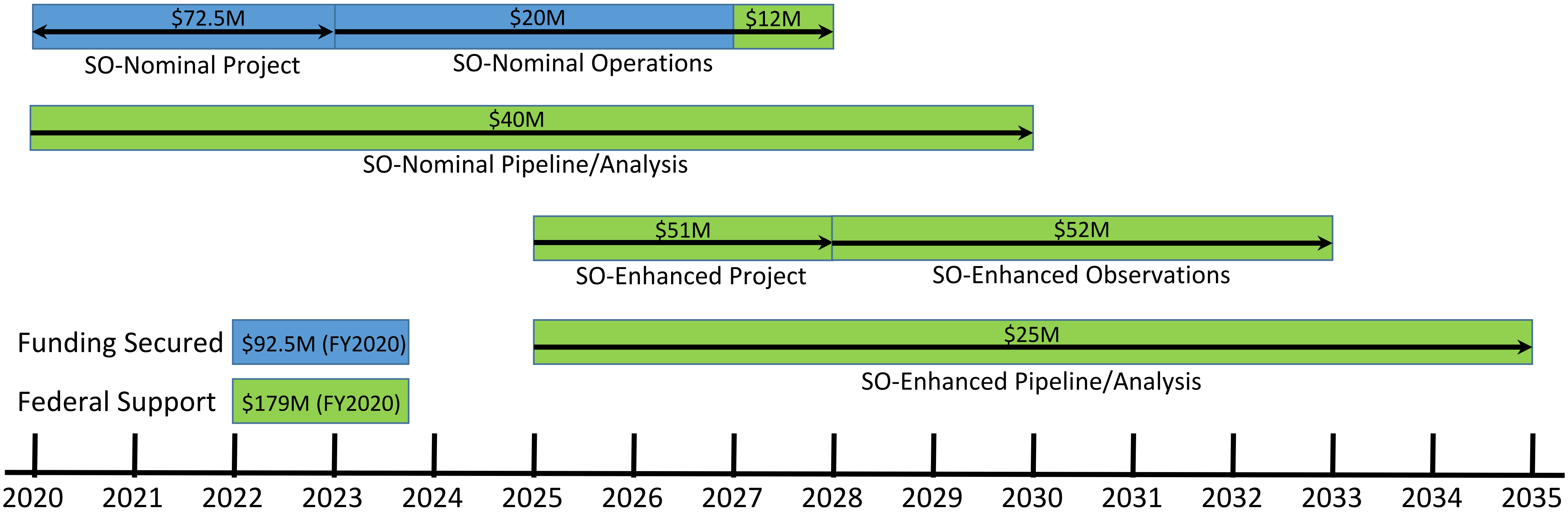
- Data Releases
  - ACT data in SO format (before SO data release)
  - Realistic SO-LAT and SO-SAT map-based simulations (to be released in 2020)
  - Regular releases of products on NASA LAMBDA and other platforms
    - Data Products
      - Multi-frequency maps
      - Lensing potential maps
      - tSZ (gas pressure) maps
      - CMB+kSZ+ISW (blackbody) maps
      - Catalog of tSZ clusters
      - Point source catalogs
      - Likelihoods and spectra (and software) for cross-correlations
      - Primary CMB likelihoods for data combinations
      - Transient alerts

SO is Community Oriented

- Software Releases (currently public on SO GitHub)
    - DAQ software: https://github.com/simonsobs/ocs
    - Data representation and core library: https://github.com/simonsobs/so3g
    - Time-ordered data analysis software: https://github.com/simonsobs/sotodlib
    - Map-domain analysis software (pixell): https://github.com/simonsobs/pixell
        - Tutorials: https://github.com/simonsobs/pixell_tutorials
    - Map-based sims software: https://github.com/simonsobs/mapsims
    - SO Noise levels: https://github.com/simonsobs/so_noise_models
    - Power spectrum pipeline: https://github.com/simonsobs/PSpipe
    - B-mode analysis pipeline: https://github.com/simonsobs/BBPipe

Timeline & Conclusions

SO-Nominal and SO-Enhanced Timelines



Conclusions

- SO is committed to timely delivery of public data products for a broad community base
- SO-Enhanced is a shovel-ready experiment that can take an important step in CMB research
  - We are well into the construction phase for SO-Nominal, and only need to copy parts to build SO-Enhanced.
- SO-Enhanced is a cost effective, highly leveraged concept
  - Private-public partnership is an effective way to use federal funding

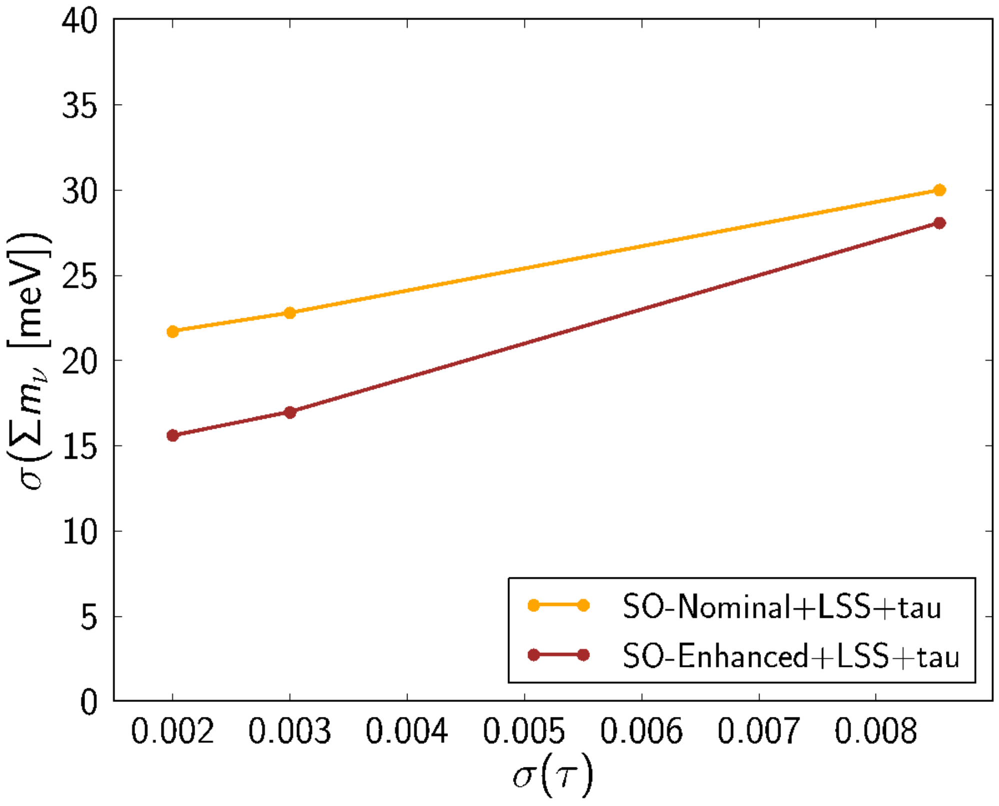
Responses to Remaining Questions

Panel Question #2

How strongly will SO parameter limits depend on the success and timeline of the LiteBIRD mission?

The only parameter that depends on the results of the LiteBIRD mission is the sum of neutrino masses which depends on τ, the optical depth to reionization. CLASS may also be able to make a good measurement of τ, and SO-Enhanced will probe a new measure through the 4-pt kSZ.

If both LiteBIRD and SO detect r at different angular scales, this will set limits on the slope of tensor fluctuations and, thus, early universe models. This goes beyond our core science goals.



Panel Question #5

How does SO view itself in relation to CMB-S4, LiteBIRD, PICO, and any other concepts for CMB projects on the ground and missions in space? Does the SO team see these projects/missions as essential for SO, helpful for SO, and/or competitive with SO in their scientific and/or technical aspects?

The SO program is a logical step toward next generation CMB science goals

- Long term, it is scientifically imperative to measure the CMB as well as we can.
- SO represents a logical step toward those goals
  - An iterative approach has been very successful over the past 30 years of CMB research
- SO has developed technology and pipelines which are directly applicable to future CMB experiments including CMB-S4, LiteBIRD, and PICO
- SO does not require any of these experiments to achieve our main science goals
  - SO would benefit, however, from the results of these experiments.

Panel Question #7

How would the governance structure of SO be modified to reflect any new (e.g., federal) funding sources?

- The SO-Nominal governance will remain in place through the completion of the construction and first light (2023).
- The Simons Foundation has a strong track record of working with the NSF on large programs.
- The SO is committed to remaining flexible on the future of its governance depending on the form of the federal support.
  - Multiple MSIP's and other PI grants would need to be given standing within the existing governance structure.
  - A single large program (MREFC) would require a significant restructuring of the governance.
  - Joint Private/Federal support would require a hybrid model which will likely include a joint oversight group with the Simons Foundation and the Agencies.

Backup: Basis of Estimate

Table 15: SO-Nominal Operations and Pipeline and Analysis budgets.

WBS 1 SO-Nominal Operations	RY2020	RY2021	RY2022	RY2023	RY2024	RY2025	RY2026	RY2027	RY2028	RY2029	Total (Real Yr.)	Total (FY2020)
Cost												
(1.1-1.5, 1.8) University ops				2,482,583	2,557,061	2,633,772	2,712,786	3,652,939			14,039,141	12,057,835
1.7 Site operations				2,503,169	2,578,264	2,655,612	2,735,280	3,733,381			14,205,705	12,198,596
Reserves				1,495,726	1,540,597	1,586,815	1,634,420	2,215,896			8,473,454	7,276,929
Total Cost				6,481,477	6,675,922	6,876,199	7,082,485	9,602,217				
									Total Activity Cost		$36,718,301	$31,533,361

WBS 1 SO-Nominal Pipeline and Analysis	RY2020	RY2021	RY2022	RY2023	RY2024	RY2025	RY2026	RY2027	RY2028	RY2029	Total (Real Yr.)	Total (FY2020)
Cost												
1.6 Data Management	154,500	1,785,141	909,877	2,247,926	3,474,638	2,384,825	2,456,370	3,606,815	1,892,791	1,949,575	20,862,458	17,402,933
1-AWG Analysis Work Groups	360,000	1,440,352	1,483,563	1,528,069	1,573,912	1,621,129	1,669,763	1,719,856	1,771,451	1,824,595	14,992,689	12,945,600
Reserves	154,350	967,648	718,032	1,132,799	1,514,565	1,201,786	1,237,840	1,598,001	1,099,273	1,132,251	10,756,544	9,104,560
Total Cost	668,850	4,193,141	3,111,472	4,908,794	6,563,114	5,207,740	5,363,972	6,924,672	4,763,515	4,906,420		
									Total Activity Cost		$46,611,691	$39,453,093

Table 16: SO-Enhanced Hardware construction, Operations, and Pipeline and Analysis budgets.

WBS 2 SO-Enhanced Telescope and Site upgrade	RY2025	RY2026	RY2027	RY2028	RY2029	RY2030	RY2031	RY2032	RY2033	RY2034	Total (Real Yr.)	Total (FY2020)
Cost												
2.2 LATR expansion	2,117,235	2,548,513	1,488,585								6,154,334	5,171,041
2.3 SATP	1,797,056	2,238,157	710,085								4,745,298	4,001,942
2.4 SAT	3,687,706	3,798,337	2,969,427								10,455,470	8,776,511
2.5 Detectors & Readout	5,951,241	5,079,865	5,232,261								16,263,367	13,642,206
2.7 Site	1,293,881	673,949	241,827								2,209,658	1,877,163
2.9 Program Mgmt & Syst Eng	2,102,556	2,165,632	2,230,601								6,498,790	5,441,049
Reserves	5,084,903	4,951,336	3,861,836								13,898,075	11,672,974
Total Cost	22,034,578											
									Total Activity Cost		$60,224,990	$50,582,886

WBS 2 SO-Enhanced Operations	RY2025	RY2026	RY2027	RY2028	RY2029	RY2030	RY2031	RY2032	RY2033	RY2034	Total (Real Yr.)	Total (FY2020)
Cost												
(2.1-2.5, 2.8) University ops				4,849,544	4,995,030	5,144,881	5,299,228	5,458,204			25,746,887	19,141,373
2.7 Site operations				5,308,408	5,326,054	5,485,836	5,650,411	5,819,923			27,590,631	20,952,532
Reserves				3,047,386	3,096,325	3,189,215	3,284,891	3,383,438			16,001,255	12,028,172
Total Cost				13,205,338	13,417,409	13,819,932	14,234,530	14,661,565				
									Total Activity Cost		$69,338,774	$52,122,077

WBS 2 SO-Enhanced Pipeline and Analysis	RY2025	RY2026	RY2027	RY2028	RY2029	RY2030	RY2031	RY2032	RY2033	RY2034	Total (Real Yr.)	Total (FY2020)
Cost												
2.6 Data Management	178,312	183,661	885,895	908,888	936,154	4,356,535	3,061,470	2,712,754	2,194,263	2,260,091	17,678,023	12,434,267
2-AWG Analysis Work Groups						1,879,333	1,935,713	1,993,784	2,053,598	2,115,205	9,977,632	6,992,000
Reserves	53,494	55,098	265,768	272,666	280,846	1,870,760	1,499,155	1,411,961	1,274,358	1,312,589	8,296,696	5,827,880
Total Cost	231,805	238,760	1,151,663	1,181,554	1,217,001	8,106,628	6,496,337	6,118,499	5,522,219	5,687,886		
									Total Activity Cost		$35,952,351	$25,254,147

Table 13: WBS 1: SO-Nominal Operations and Pipeline and Analysis

WBS	Title	Description
1	SO-Nominal Operations	Data-taking operations of SO-Nominal
1.1-1.5, 1.8	University operations	Support for researchers operating and maintaining the observatory, operation of 1.1 LAT, 1.2 LATR, 1.3 SATP, 1.4 SAT, 1.5 Detectors \& Readout, 1.8 Calibration
1.7	Site Operations	Power for site operations, support for site engineers, maintenance of high elevation and low elevation facilities

WBS	Title	Description
1	SO-Nominal Pipeline and Analysis	Data handling, map making, and data analysis for SO-Nominal
1.6	Data Management	Data storage and analysis computing, maintenance of site computing, networking and data storage, staff for data acquisition and pipeline development and map making
1-AWG	Analysis Working Groups	Support for data reduction and analysis of sky maps and production of final science deliverables

Table 14: WBS 2: SO-Enhanced Hardware upgrade, Operations, and Pipeline and Analysis

WBS	Title	Description
2	SO-Enhanced Telescope and Site upgrade	Enhancement of SO-Nominal to about double the observatory capabilities by adding three SAT/SATPs and six LATR optics tubes
2.2	Large Aperture Telescope Receiver expansion	Fabrication, integration, installation, and commissioning of six optics tubes in the LATR. This includes manufacture of silicon lenses, metal mesh and alumina filters, and cryo-mechanical components, and integration with detectors and readout and housekeeping electronics.
2.3	Small Aperture Telescope Platforms	Procurement, installation, and commissioning of three platforms for the Small Aperture Telescopes, including the ground screens and related baffles.
2.4	Small Aperture Telescopes	Procurement, integration, installation, and commissioning of three Small Aperture Telescopes. This includes procurement of the cryostats and cryogenic refrigerators, manufacture of the silicon lenses, metal mesh and alumina filters, and cryo-mechanical components, and integration with detectors and readout and housekeeping electronics
2.5	Detectors and Readout	Fabrication, assembly, and test, of the detectors and cold and warm readout electronics for SO-Enhanced. This includes deployment of 39 Universal Focal Plane modules, where each UFM is includes a 150 mm detector wafer stack coupled to microwave multiplexed readout.
2.7	Site	Expansion of the SO Site for three SATP platforms, including concrete foundations and expanded electrical and cooling systems.
2.9	Program Mgmt and Systems Engineering	Management and systems engineering during the construction phase of SO-Enhanced.

WBS	Title	Description
2	SO-Enhanced Operations	Data-taking operations of SO-Enhanced
2.1-2.5, 2.8	University operations	Support for researchers operating and maintaining the observatory, operation of 2.1 LAT, 2.2 LATR, 2.3 SATP, 2.4 SAT, 2.5 Detectors \& Readout, 2.8 Calibration
2.7	Site Operations	Power for site operations, support for site engineers, maintenance of high elevation and low elevation facilities

WBS	Title	Description
2	SO-Enhanced Pipeline and Analysis	Data handling, map making, and data analysis for SO-Enhanced
2.6	Data Management	Data storage and analysis computing, maintenance of site computing, networking and data storage, staff for data acquisition and pipeline development and map making
2-AWG	Analysis Working Groups	Support for data reduction and analysis of sky maps and production of final science deliverables

Table 17: Basis of estimate for SO-Nominal Operations and Pipeline and Analysis

SO-Nominal Operations		
component	cost Y2020$	Description
WBS 1.1-1.5, 1.8 University Ops	2,411,567	Average annual support for 9 postdocs, 8 graduate students, 10 months faculty summer salary, 7 summer undergraduates, 1 administrator, travel. Four years with 20% overhead (Simons Foundation), one year with 60% overhead.
WBS 1.7 Site Ops	2,439,719	Average annual cost of site operations, including power generation and fuel deliveries, three site engineers. Four years with 20% overhead (Simons Foundation), one year with 60% overhead.
Total SO-Nominal operations (5 yr)	24,256,432	

SO-Nominal Pipeline and Analysis		
component	cost Y2020$	Description
WBS 1.6 Data Management		
Computing	3,900,000	Analysis computing and data storage
DAQ and Pipeline staff	13,502,933	Support for 5 student-years, 30 postdoc-years, and 39 staff-years of effort on data acquistion and pipeline development
1-AWG Analysis Working Groups	12,945,600	Support for 4 postdocs, 4 graduate students, 4 summer students, 4 faculty summer salary, travel over 9.25 yr
Total SO-Nominal Pipeline & Analysis	30,348,533	

Table 18: Basis of estimate for SO-Enhanced Operations and Pipeline and Analysis

SO-Enhanced Operations		
component	cost Y2020$	Description
WBS 2.1-2.5, 2.8 University Ops	3,828,275	Annual support for 12 postdocs, 15 graduate students, 10 months faculty summer salary, 7 summer undergraduates, 1 administrator, travel
WBS 2.7 Site Ops	4,190,506	Annual cost of site operations, including power generation and fuel deliveries, four site engineers.
Total SO-Nominal operations (5 yr)	40,093,905	

SO-Enhanced Pipeline and Analysis		
component	cost Y2020$	Description
WBS 2.6 Data Management		
Computing	2,750,000	Analysis computing and data storage
DAQ and Pipeline staff	9,684,267	Support for 5 student-years, 23 postdoc-years, and 26 staff-years of effort on data acquistion and pipeline development
2-AWG Analysis Working Groups	6,992,000	Support for 4 postdocs, 4 graduate students, 4 summer students, 4 faculty summer salary, travel over 5 yr
Total SO-Nominal Pipeline & Analysis	19,426,267	

Table 19: Basis of estimate for SO-Enhanced Telescope and Site upgrade

SO-Enhanced basis of estimate		Methodology: Analogy wth SO-Nominal, except as noted
component	cost Y2020$	Description
WBS 2.2 LATR		
Si lenses	403,466	silicon material, commercial grinding into lenses, technician to cut metamaterial AR coating
metal mesh filters	494,400	production of filters at Cardiff University
Alumina filters	97,629	alumina material, technician to apply AR coating
mechanical components	176,020	procurement costs for six LATR optics tube assembles
magnetic shielding	92,700	procurement costs for six LATR optics tube assembles
LATR UFM, test mechanical	150,872	procurement costs for six LATR optics tube assembles
Housekeeping electronics	124,886	diode and ROX thermometers and readout electronics
University personnel	3,631,069	Support for 4.4 graduate students, 2.4 postdocs, 3 months of faculty summer salary each year, and 1.75 staff engineers
WBS 2.3 SATP		
3 platforms	2,408,342	Contract with Vertex, excluding NRE
forebaffles	61,800	engineering estimate
Ground screens	772,500	estimate based on contracted SO-Nominal cost
University personnel	759,299	Support for 0.6 graduate students, 0.6 postdocs, 0.3 months of faculty summer salary each year, and 0.3 staff engineers
WBS 2.4 SAT		
Mechanical Cryostat	664,350	cost of three SAT cryostats based on contracted SO-Nominal cost
Electrical Cryostat	150,071	diode and ROX thermometers and readout electronics
Cryogenic refrigerators	1,436,850	dilution refrigerators and pulse tube coolers
Support: pumps, vacuum equip	47,380	pumps, hoses
Si lenses	378,525	silicon material, grinding into lenses, technician to cut metamaterial AR coating
metal mesh filters	278,100	production of filters at Cardiff University
Alumina filters	152,891	alumina material, technician to apply AR coating
mechanical components	183,083	procurement costs for three SAT optics tube assemblies
magnetic shielding	69,525	procurement costs for three SAT optics tube assemblies
Focal plane array mechanical	60,255	procurement costs for three SAT optics tube assemblies
SAT UFM, test mechanical	134,028	procurement costs for three SAT optics tube assemblies
Half Wave Plate	278,100	procurement costs for three SAT optics tube assemblies
University personnel	4,943,354	Support for 4.2 graduate students, 3.3 postdocs, 2.6 months of faculty summer salary each year, and 2.5 staff engineers
WBS 2.5 Detectors & Readout		
detectors	2,410,200	21 NIST detectors for SATs, 18 NIST dets for LATR
feedhorns	200,850	5463 per feedhorn
cold multiplexing fab, wafers (NIST)	2,123,989	choke wafers 4,075, mux fab & screen $18/channel, DC/RF wafer $16,400
Warm readout	2,524,530	SMuRF = 60,000; ATCA crates 2 per SAT, 2 for LATR plus supporting items
Cold wiring & amplification	1,533,294	SAT 14 chains 269,583; LATR 36 chains 679,886
University personnel	4,849,344	Support for 4.2 graduate students, 4.1 postdocs, 4.1 months of faculty summer salary each year, and 1.2 staff engineers
WBS 2.7 Site		
Low-Elevation Facility (LEF)	339,831	$8,592 cost/person-quarter. 3 persons for 8 quarters
Telescope Foundations	1,000,000	estimate based on contracted SO-Nominal cost
Non-Foundation HEF Infrastructure	150,000	Costs to expand Sie electrical distribution and cooling systems
Accessing site w/ people & equipment	72,000	Truck leasing, maint, fuel, road maintenance, shipments to Site
Telescope Installation & Verification	32,000	rentals for installation
Site personnel	245,140	One site engineer for two years
University personnel	38,192	Support for 1 month of faculty summer salary each year
WBS 2.9 Program Mgmt and Syst Eng		
Program Mgmt and Syst Eng personnel	5,441,049	Support for eight staff members
Total SO-Enhanced	38,909,913	

Computing and Data Processing

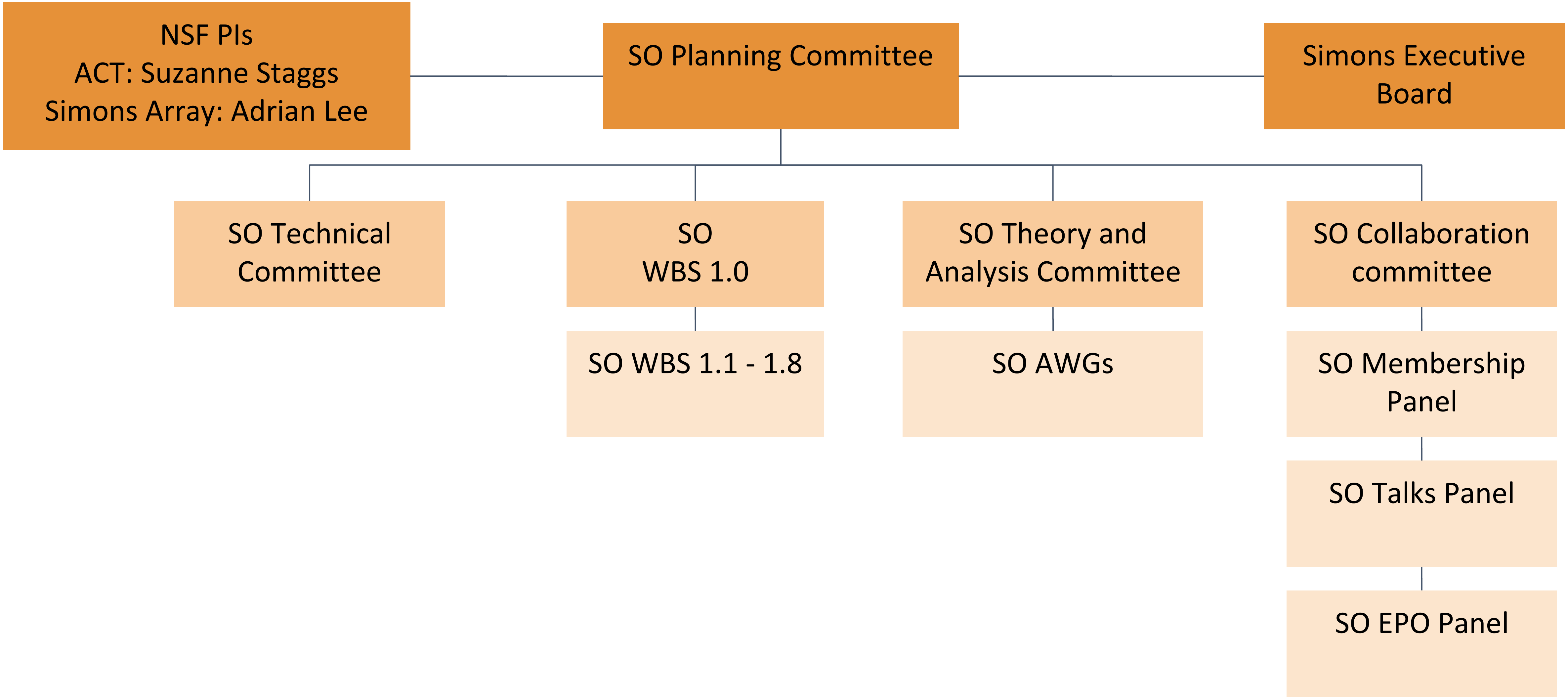
- We budgeted roughly 7M$ for SO-Nominal and SO-Enhanced

- <u>Baseline:</u> data will be transferred from Chilean site to North America (UCSD) via fiber connection
  - MoU with ALMA is ongoing
  - Data will be distributed and backed up within 24hrs
  - Limited amount of computation at the site for quality check and small-scale map-making

- <u>Three centers for analysis and storage:</u>
  - *Simons Foundation @ UCSD:* full copy of the data and limited HPC computation
  - *Princeton:* full copy of the data and HPC computation
    - To manage risks connected to long queue times on gov-supported HPC systems
  - *NSF computing centers (XSEDE program and successor program):* similar to Princeton but larger HPC systems for full-scale runs and sims
    - This mitigates risks related to the assumption that we will have enough support at NERSC
    - Conversation with U Texas/TACC have started and plan to use ACT as pathfinder
    - We will engage in a multi-year project agreement to sustain SO data needs

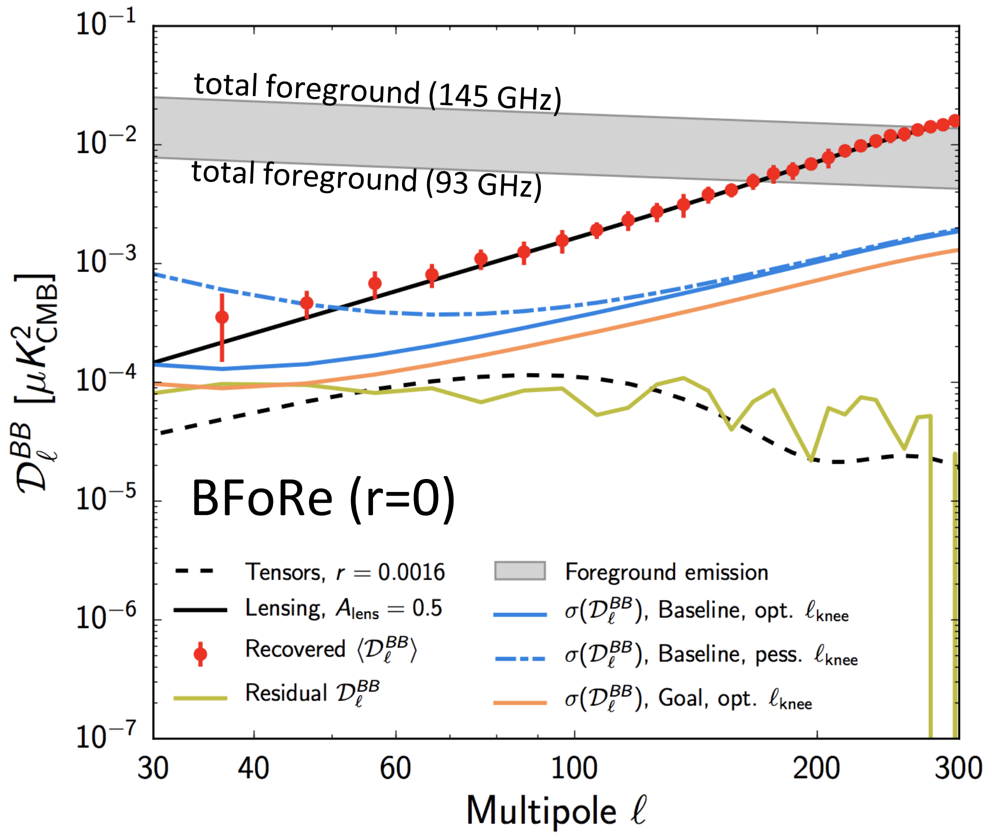
Backup

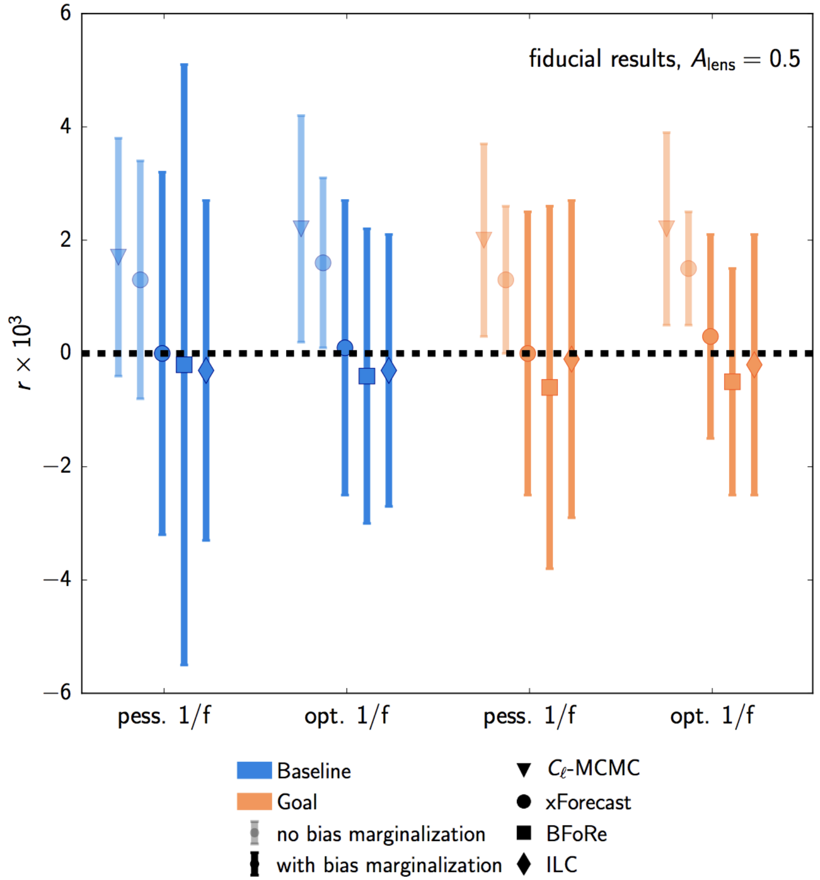
SO Governance Structure



SAT BB forecasting based on full-sky simulated maps (PySM) w/ multiple sets of realistic foregrounds

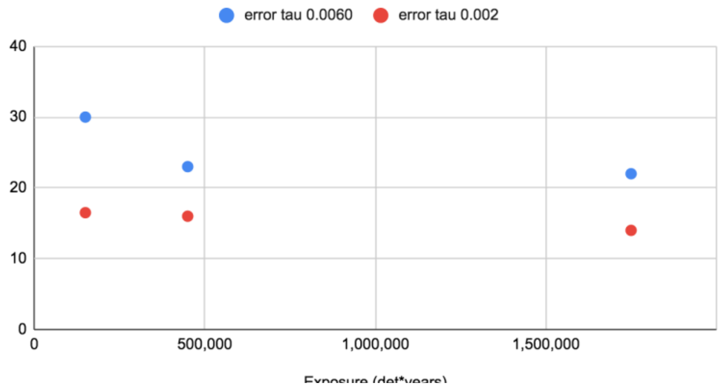
Sky models are combined with SO SAT noise model, then coupled to several foreground mitigation schemes (cross-spectrum analysis, xForecast, BFoRe, harmonic-space ILC) to infer *r*



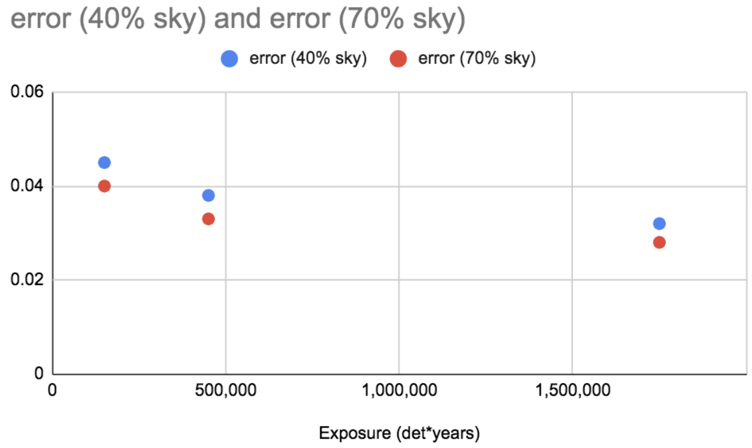


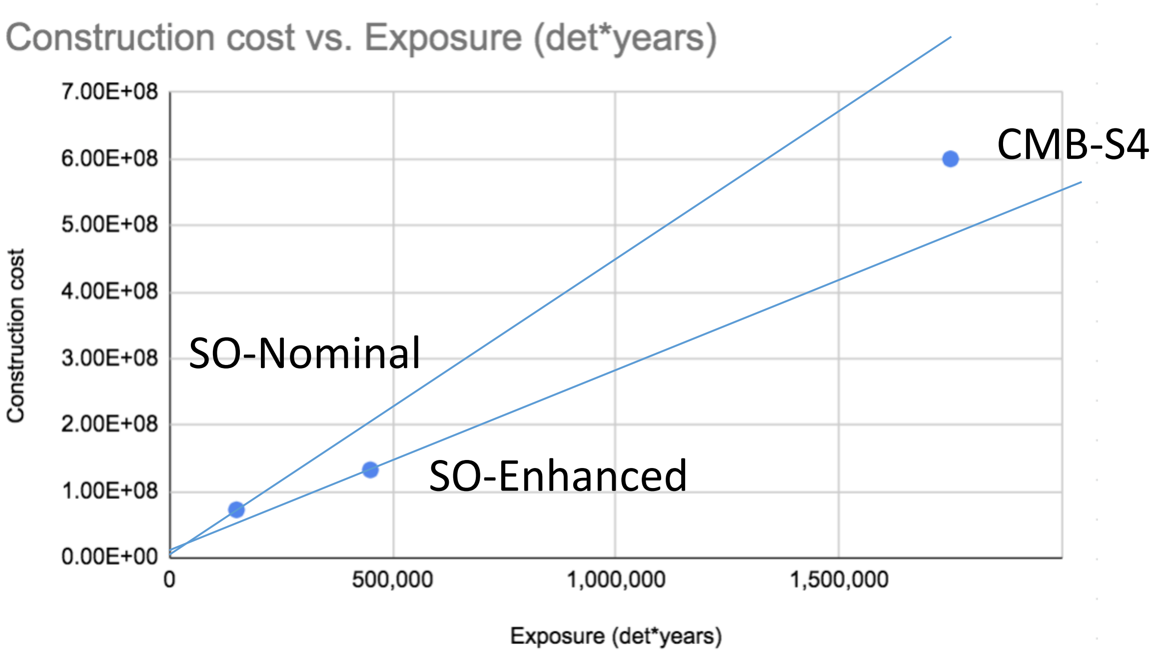
Scalings for Costs & Constraints

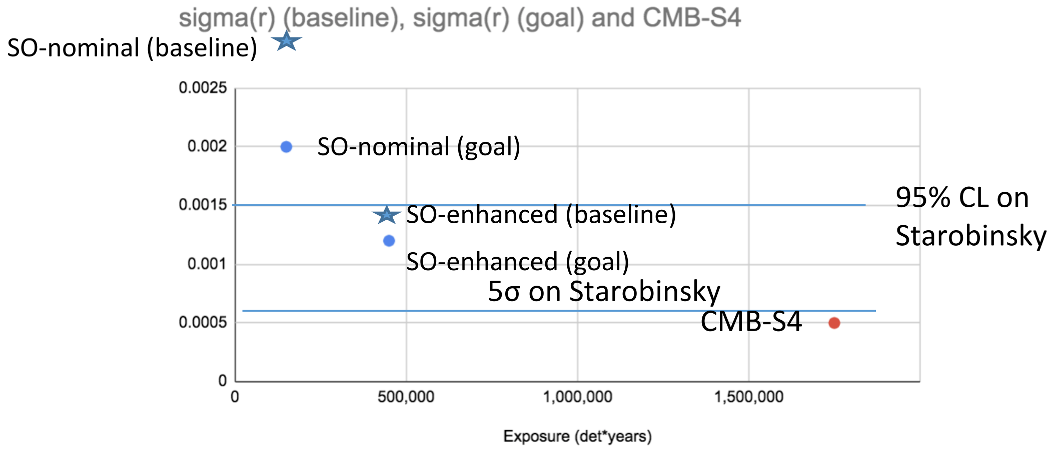
Σm_ν (meV)



$\sigma(N_{eff})$







Science and Planning - 2018

V0 – Initial Instrument Concepts – Oct. 2016
V1 – Detailed Instrument Concept – Jan. 2017
V2 – Frequency Balance – June 2017
V3 – Sensitivity Budget and Tracking - 2018

Science Traceability Matrix

ID	Title	Parameter	Baseline	Goal	Current	Method
SR-1a	**Primordial fluctuations**	**r**	**0.003**	**0.002**	**0.04**	**BB**
SR-1b		P(k=0.2 h/Mpc)	0.5%	0.4%	6%	T/E
SR-1c		fnl	3	1	5	kk+LSST+3-pt
SR-2	Relativistic Species	N_{eff}	0.07	0.05	0.11	T/E
SR-3	Neutrino mass	m_{ν} (eV)	0.04	0.03	0.1	kk+DESI
			0.04	0.03		tSZ-N+LSST
			0.05	0.04		tSZ-Cl+DESI
SR-4	Dark Energy	sigma_8(z=2-4)	3%	2%	7%	kk+LSST
			3%	2%		tSZ+LSST/k
SR-5a	Galaxy Evolution	feedback efficiency in massive halos	6%	3%	50-100%	tSZ+kSZ
SR-5b		non-thermal pressure in massive halos	15%	12%	50-100%	tSZ+kSZ
SR-6	Reionization	duration delta(z)	0.6	0.3	1.4	T/E (kSZ)

Measurement Requirements - SAT

ID	Title	Description	Trace
MR-1S	#Bands	30, 40, 90, 150,220, 280 GHz	SR-1a
MR-2S	angular resolution	90, 60, 30, 30, 30, 30'	SR-1a
MR-3S	sensitivity white noise	(Baseline) 35, 22, 2.6, 3.3, 6.3, 16 uK/amin	SR-1a
		(Goal) 25, 17, 1.9, 2.1, 4.2, 10 uK/amin	
MR-4S	1/f noise	knee l<25	SR-1a
MR-5S	pol systematics	systematics below 40% of statistical errors	SR-1a
MR-6S	sky area	10% effective sky area with low FG	SR-1a

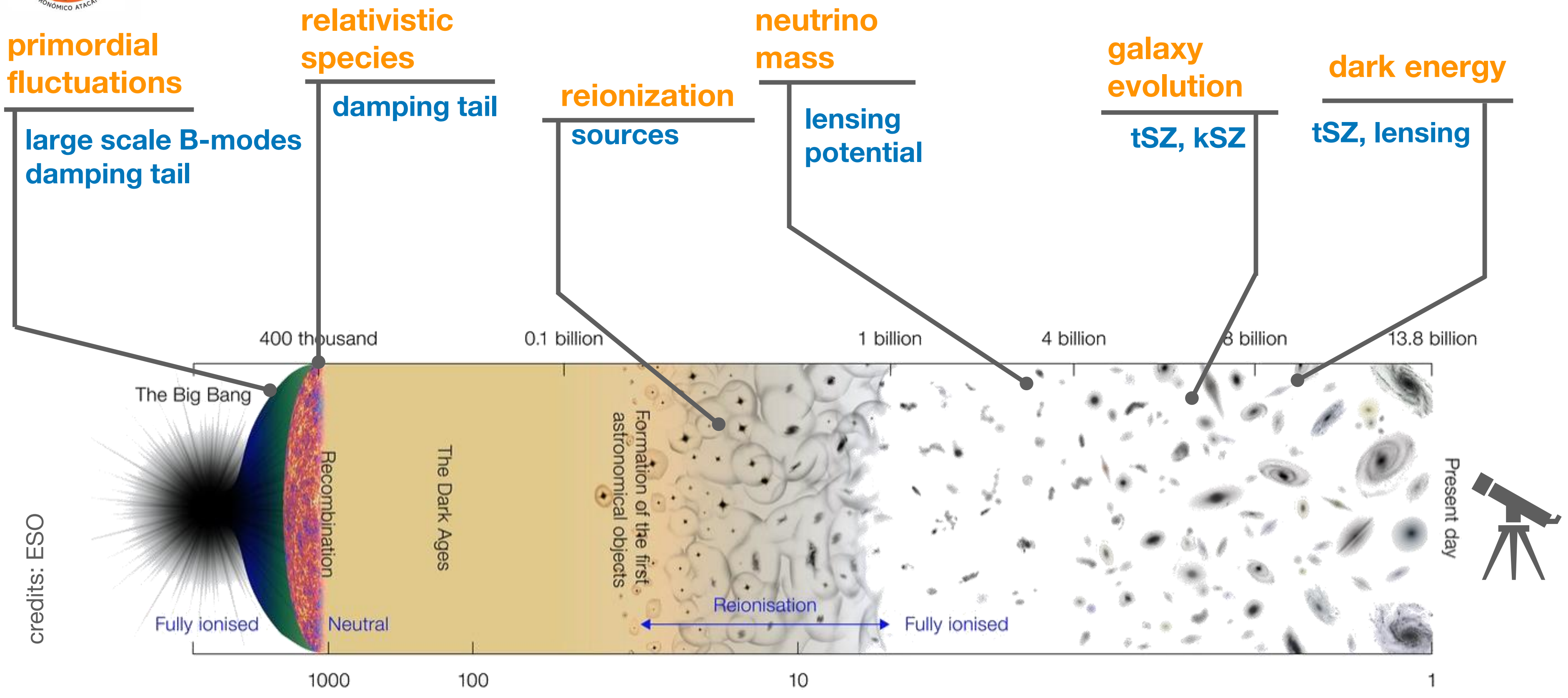
Measurement Requirements - LAT

ID	Title	Description	Trace
MR-1L	#Bands	30, 40, 90, 150,220, 280 GHz	SR-3-6
MR-2L	angular resolution	7.5, 5.5, 2.2, 1.4, 1.0,1.0'	SR-3-6
MR-3L	sensitivity white noise	(Baseline) 71, 36, 8.0, 10.0, 22, 54 uK/amin	SR-1b-6
		(Goal) 52, 27, 5.8, 6.3, 15, 38 uK/amin	
MR-4L	1/f noise	knee l<1000	SR-3-6
MR-5L	pol systematics	systematics below 40% of statistical errors	SR-1b-6
MR-6L	sky area	40+% sky, overlapping with LSST (f=0.35-4), DESI (f=0.1)	SR-1b-6

Table 12: Key Event Dates for SO-Enhanced

Project Phase	**Milestone Date**
Start of Development	January 1, 2025
Start of Conceptual Design	January 1, 2025
Preliminary Design Review (PDR)	February 1, 2025
Critical Design Review (CDR)	April 1, 2025
Delivery of SATs	August 15, 2027
Delivery of LATR Optics Tubes	February 1, 2027
Date of End of Construction	August 15, 2027
Date of First Light/Signal Reception	January 1, 2027
Date of Start of Commissioning	December 1, 2026
Operations Readiness Date	January 1, 2028
End of Operations	December 31, 2032

Simons Observatory Science Goals and Probes



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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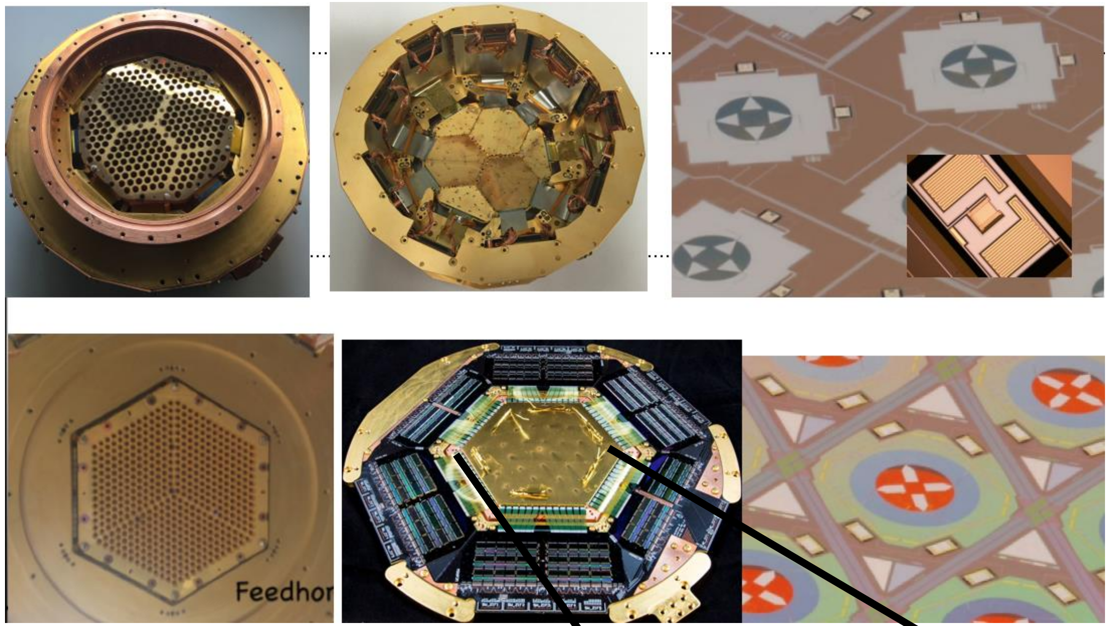
SO Readout Packaging Format in Context

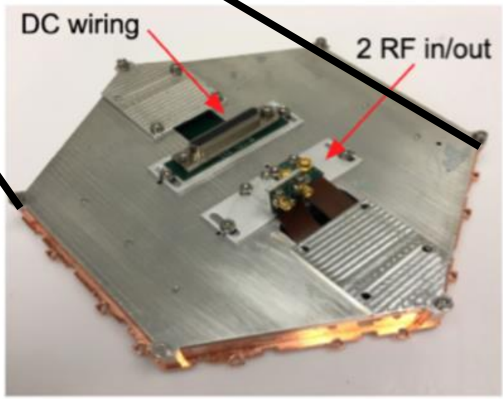
Fielded 100 mK dichroic TES arrays for CMB:

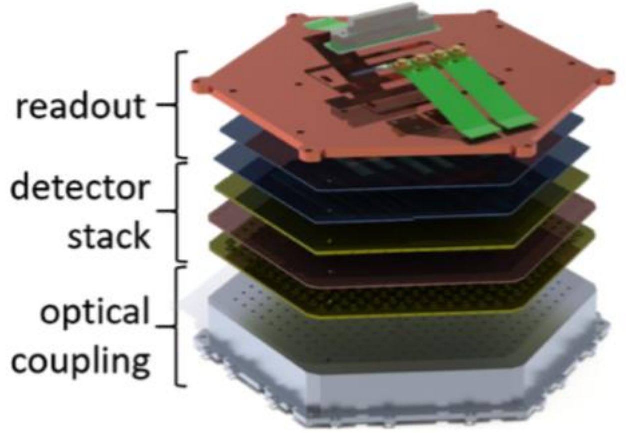


The last two generations of ACT kilopixel detector arrays were not designed for close-packed focal planes.

The ACT arrays were comparable in TES density to SO arrays, but only used 33x to 66x time-division multiplexing

For SO, all the readout components fit behind a ~150 mm detector wafer, and all 1728 detectors are read out on 2 coaxial pairs, with 910x multiplexing.





SO Detector Module
Exploded View

Current SO Detectors & Readout Schedule compared to SO-Enhanced Need Dates