Simons Observatory and Future ground-based CMB measurements

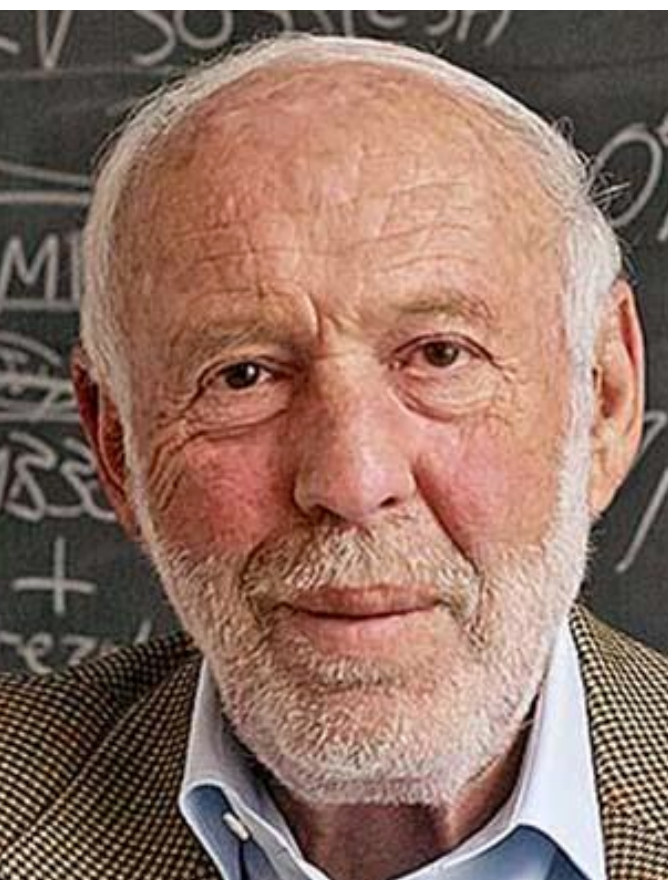
Thuong D. Hoang
Cornell University
on behalf of the Simons Observatory Collaboration

15th Rencontres du Vietnam
Quy Nhon, Vietnam August 2019

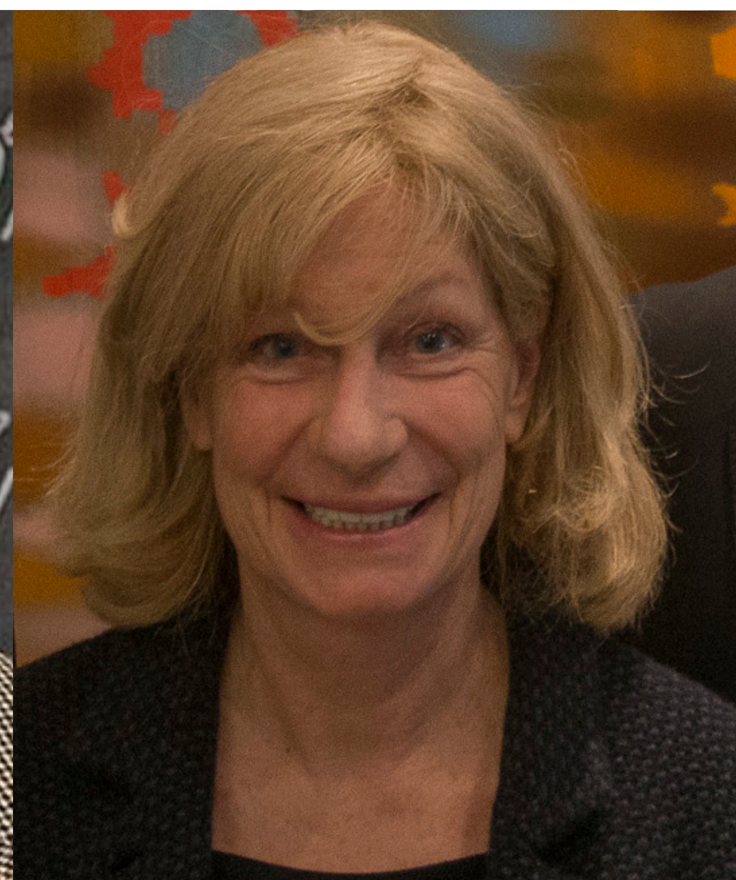
SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION

The Simons Observatory is funded by a generous grant from the **Simons Foundation** and the **Heising-Simons Foundation**



James Harris Simons



Marilyn Simons

Liz Simons

Mark Heising

The Simons Observatory collaboration

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

- **10 Countries**
- **40+ Institutions**
- **160+ Researchers**

→ ~ 287

- **90 postdocs**
- **85 students**

Canada
- CITA/Toronto
- Dunlap Institute/Toronto
- McGill University
- Simon Fraser University
- 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 (SO)
• One 6m Large Aperture Telescope (LAT)
• Three 0.42m Small Aperture Telescope (SAT)
Simons Array
CLASS
ACT
5200m, Cerro Toco, Atacama Desert, Chile

The Simons Observatory science goals and probes

1. Primordial fluctuations

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

2. Relativistic species

damping tail
➔ N_{eff} (TE, TT, EE)

3. Reionization

sources
➔ duration of reionization (kSZ)
➔ mean free path of photons (kSZ)

4. Neutrino mass

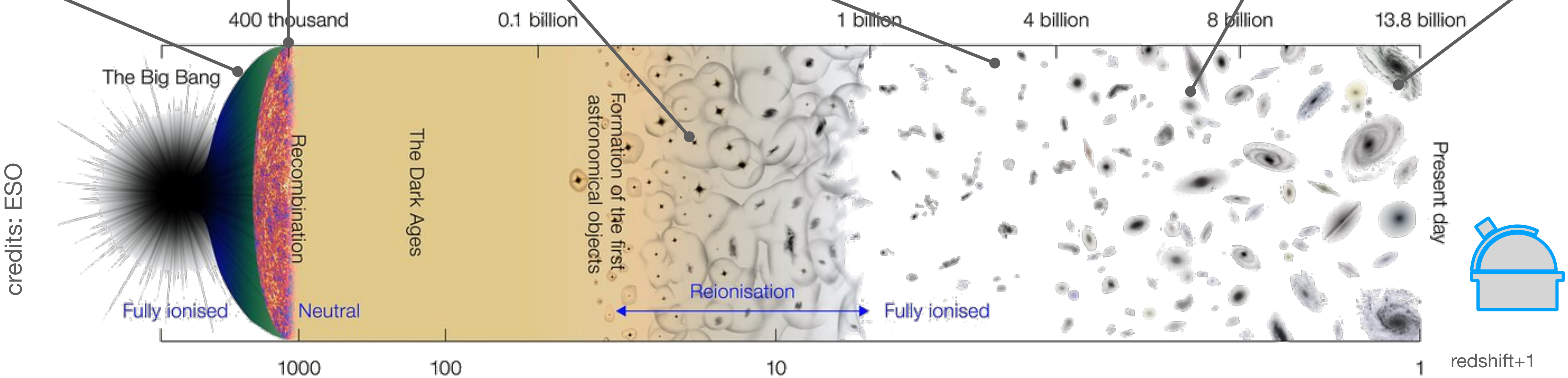
lensing + BAO (TT+EB), SZ cluster+weak lesing, tSZ distortion+BAO,
➔ Σm_ν

5. Galaxy evolution

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

6. Dark energy

SZ cluster, lensing
➔ σ_8 at z=1-2 (lensing, tSZ)
➔ growth of structure (kSZ)



Science: Targets
r, N_{eff}, m_ν, σ_8, reionization
Large Aperture Telescope (6m)
➡ N_{eff}, m_ν, σ_8, cluster science
Small Aperture Telescope (0.42m)
➡ Primordial B − modes

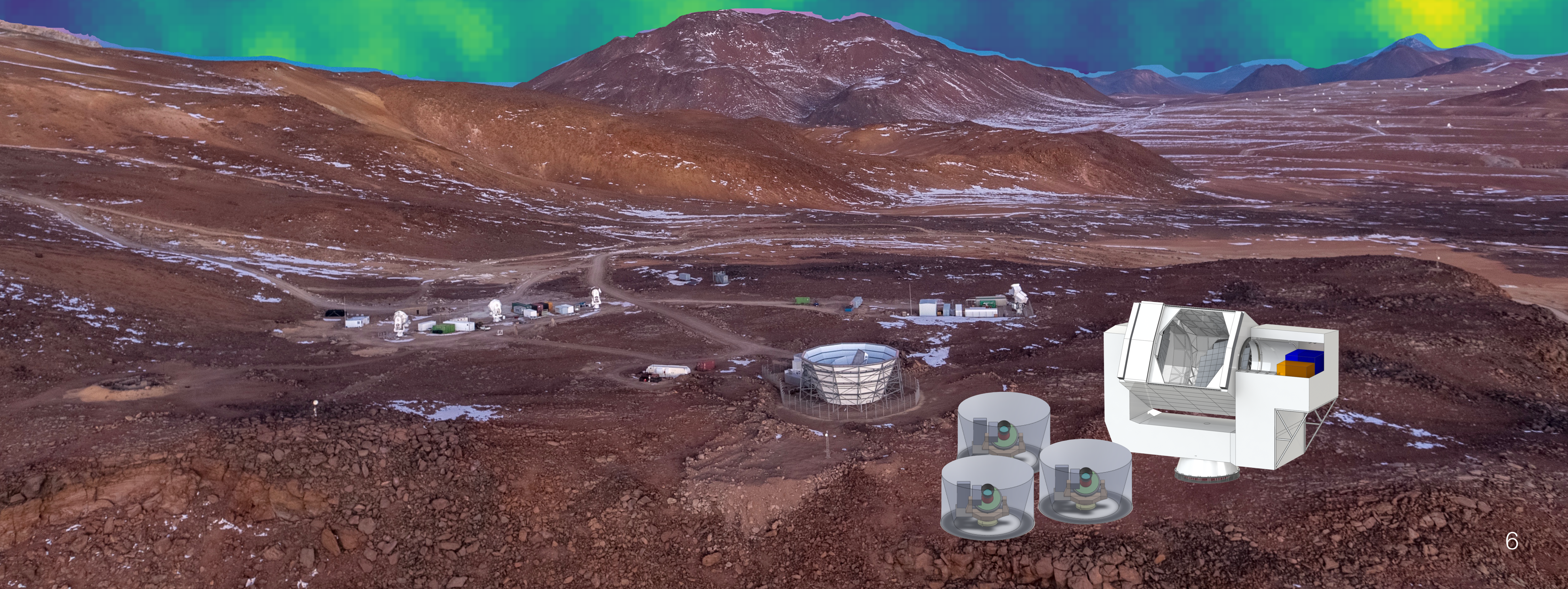
The Simons Observation: Science goals and forecasts

arXiv:1808.07445

arXiv:1907.08284

The Simons Observatory science goals

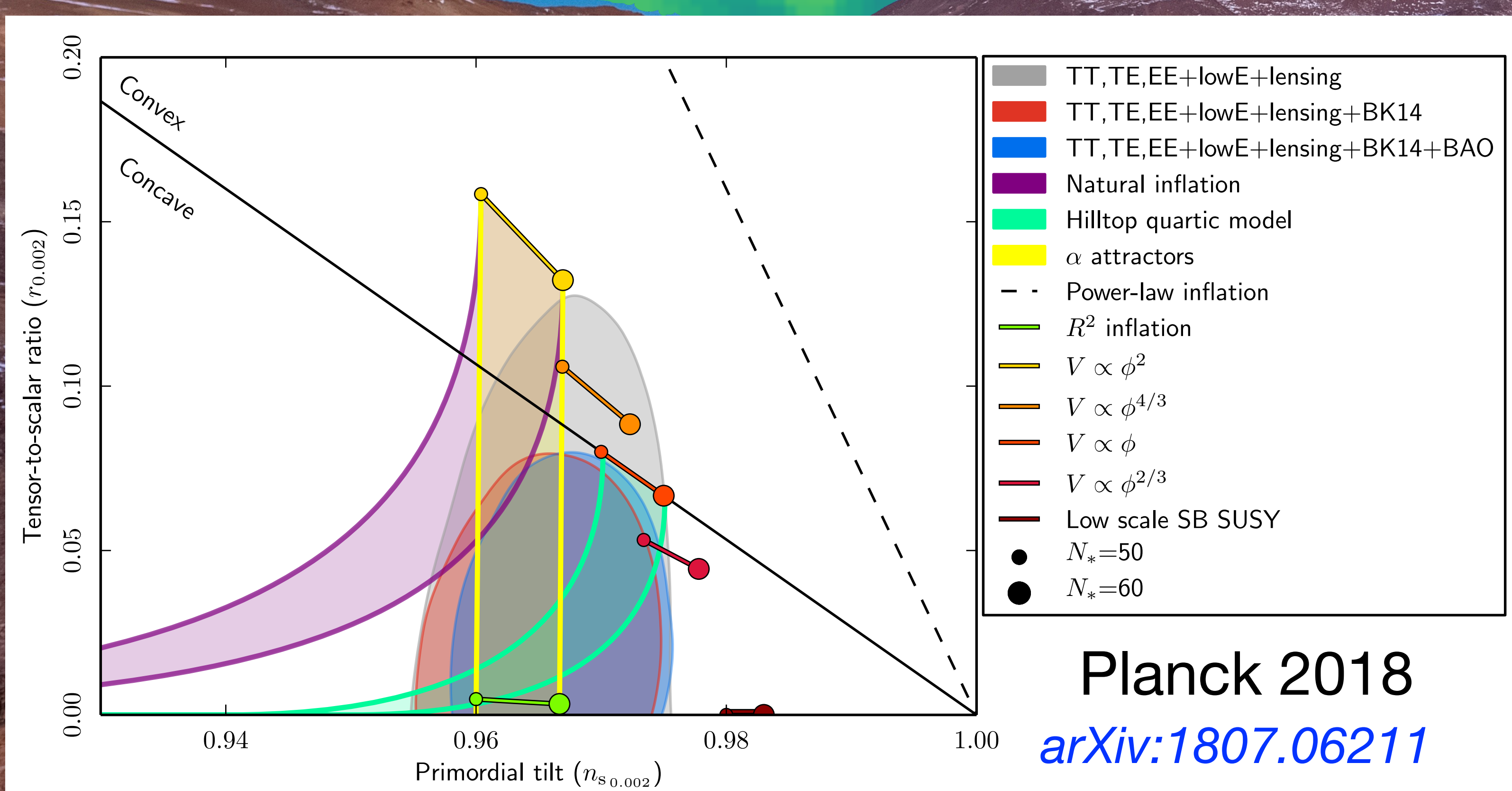
- **CMB primordial B-modes: Tensor-to-scalar r**



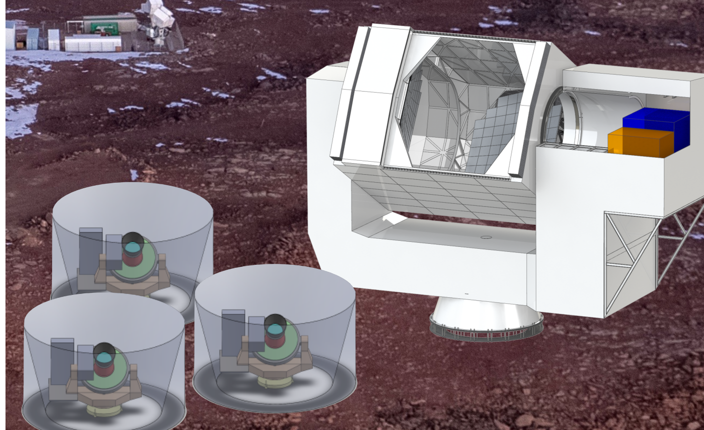
The Simons Observatory science goals

- **CMB primordial B-modes: Tensor-to-scalar r + lensing of CMB fields: (E-modes->B-modes), Large Scale Structure->B-modes**

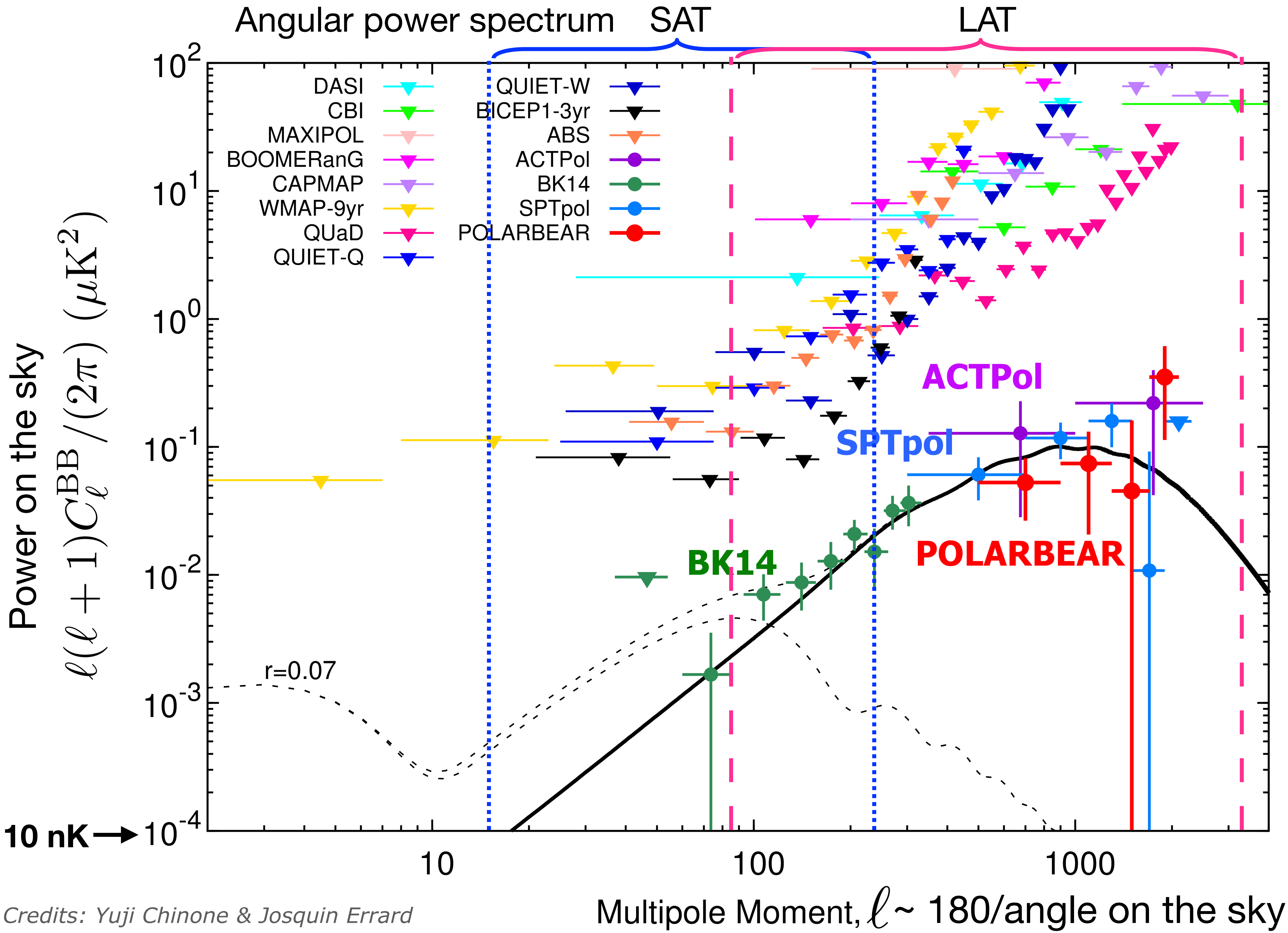
- **Constraining inflationary models**



Planck 2018
arXiv:1807.06211

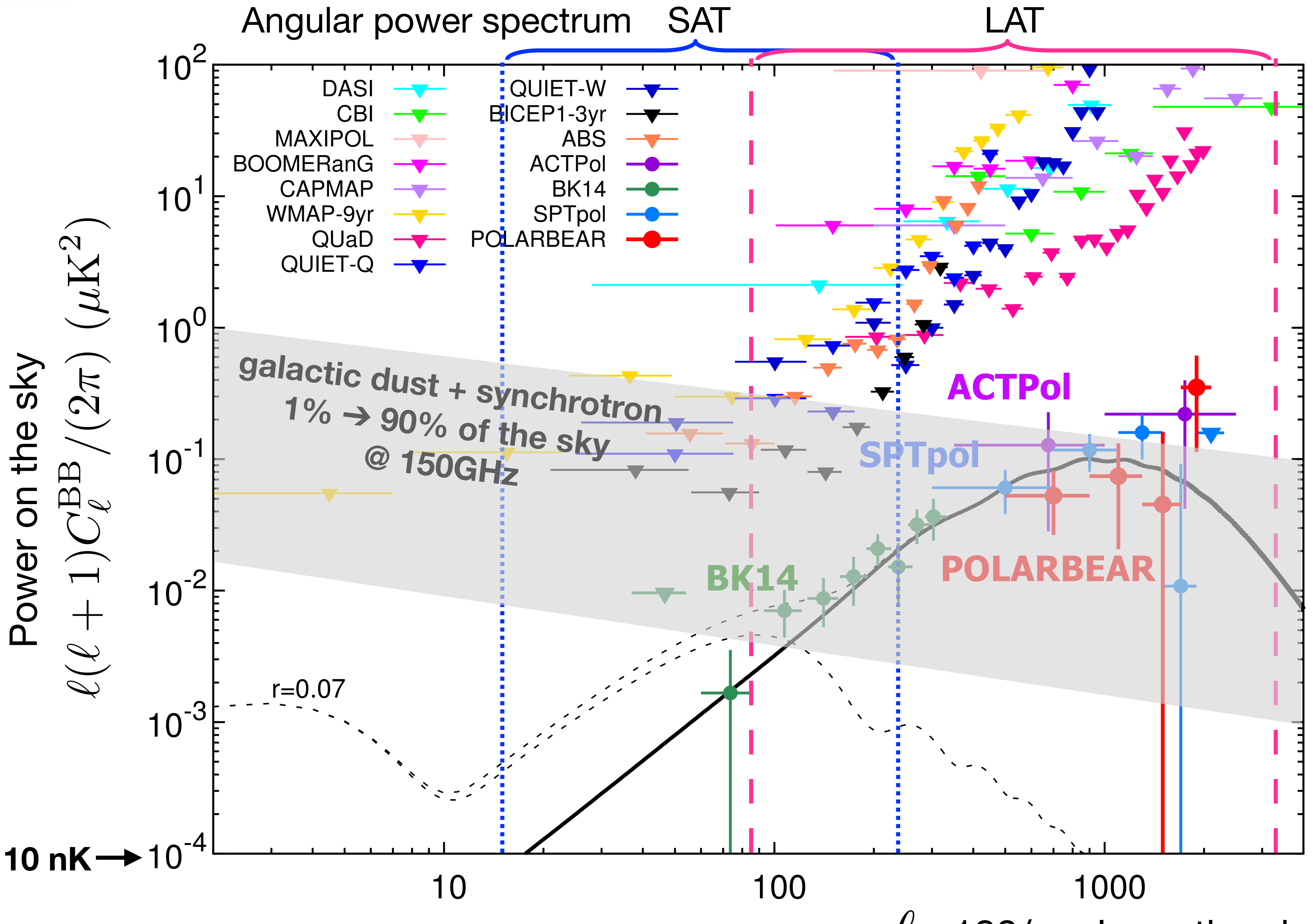


The Simons Observatory science goals



Credits: Yuji Chinone & Josquin Errard

The Simons Observatory science goals



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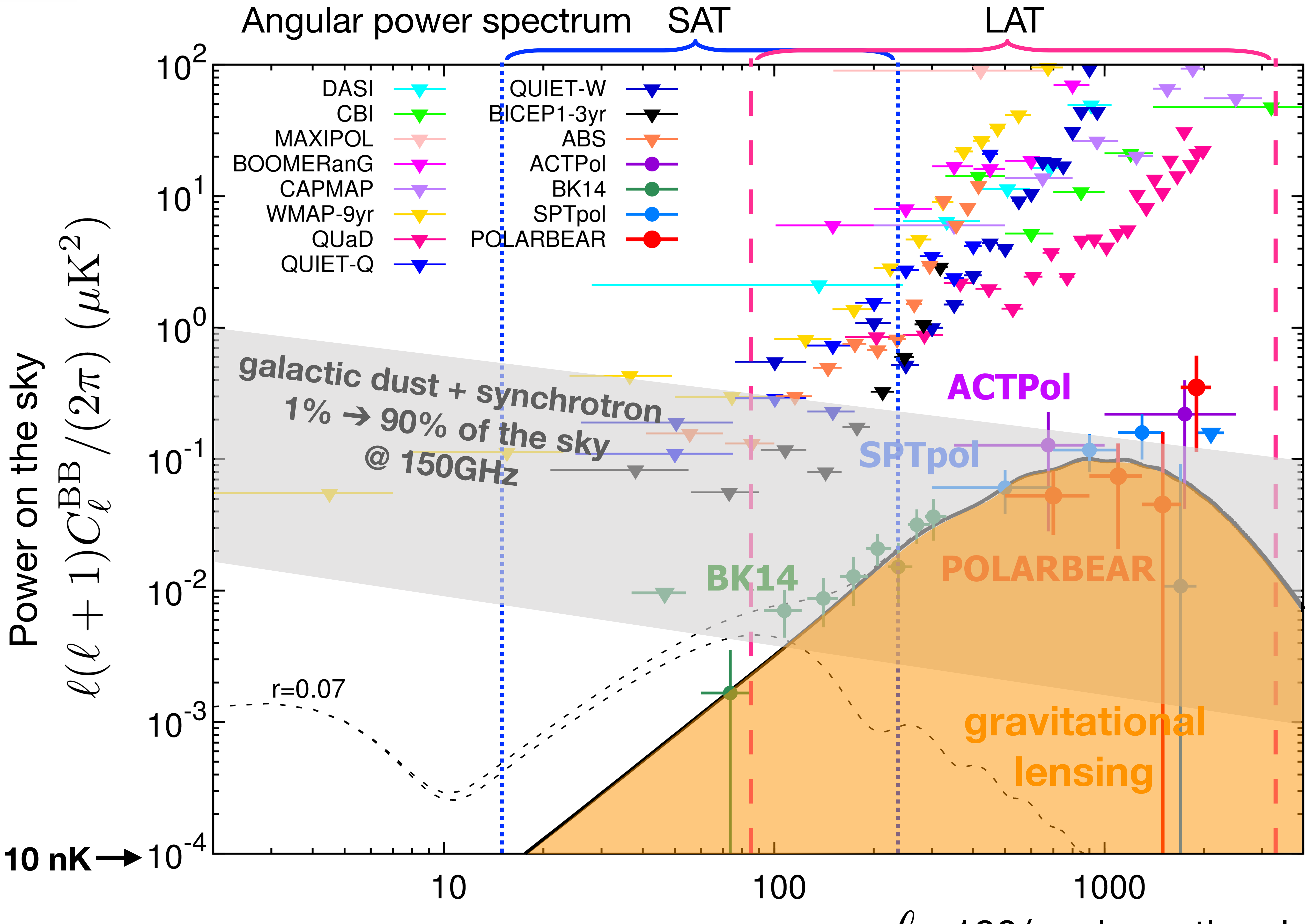
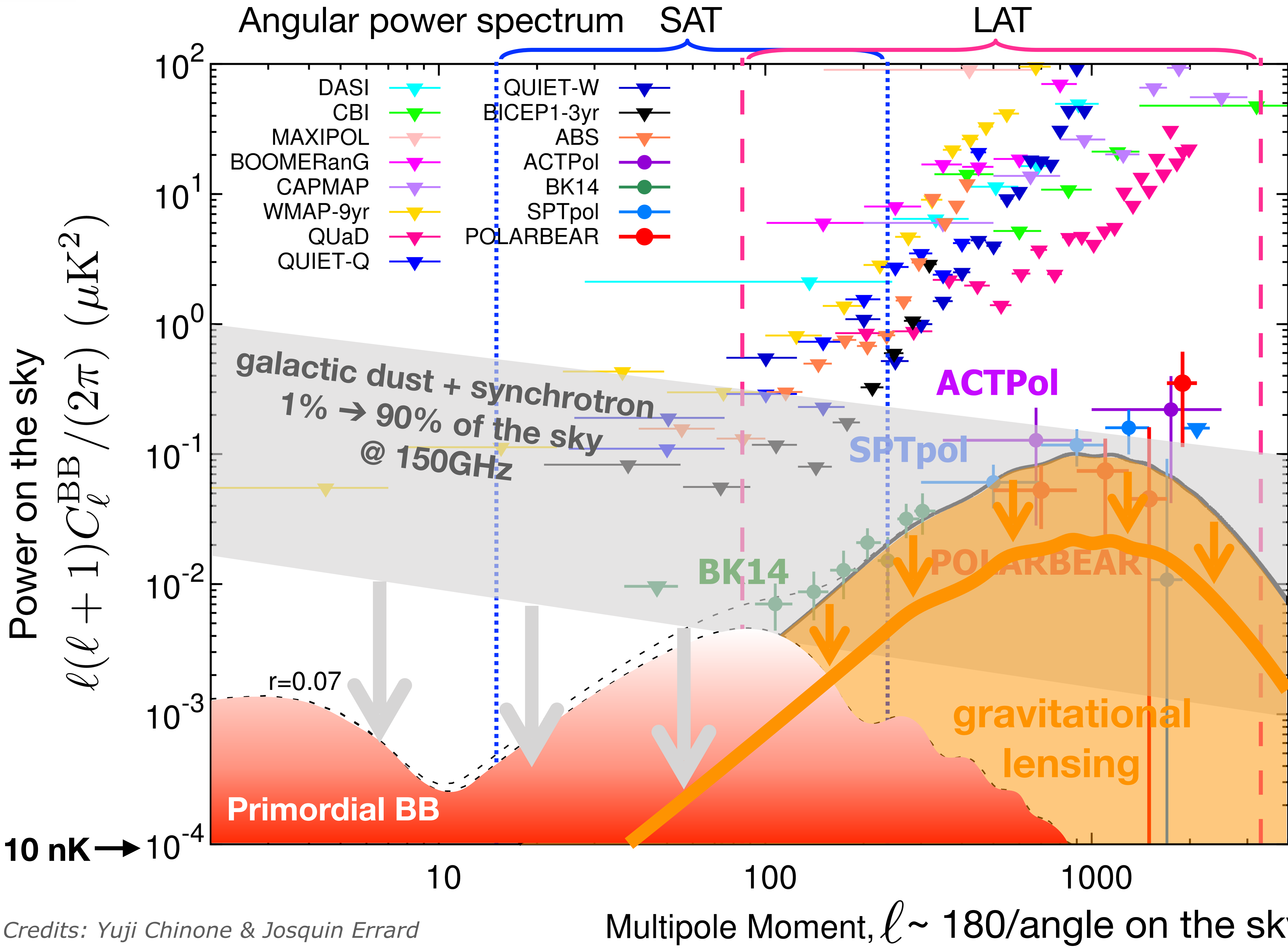
The Simons Observatory science goals



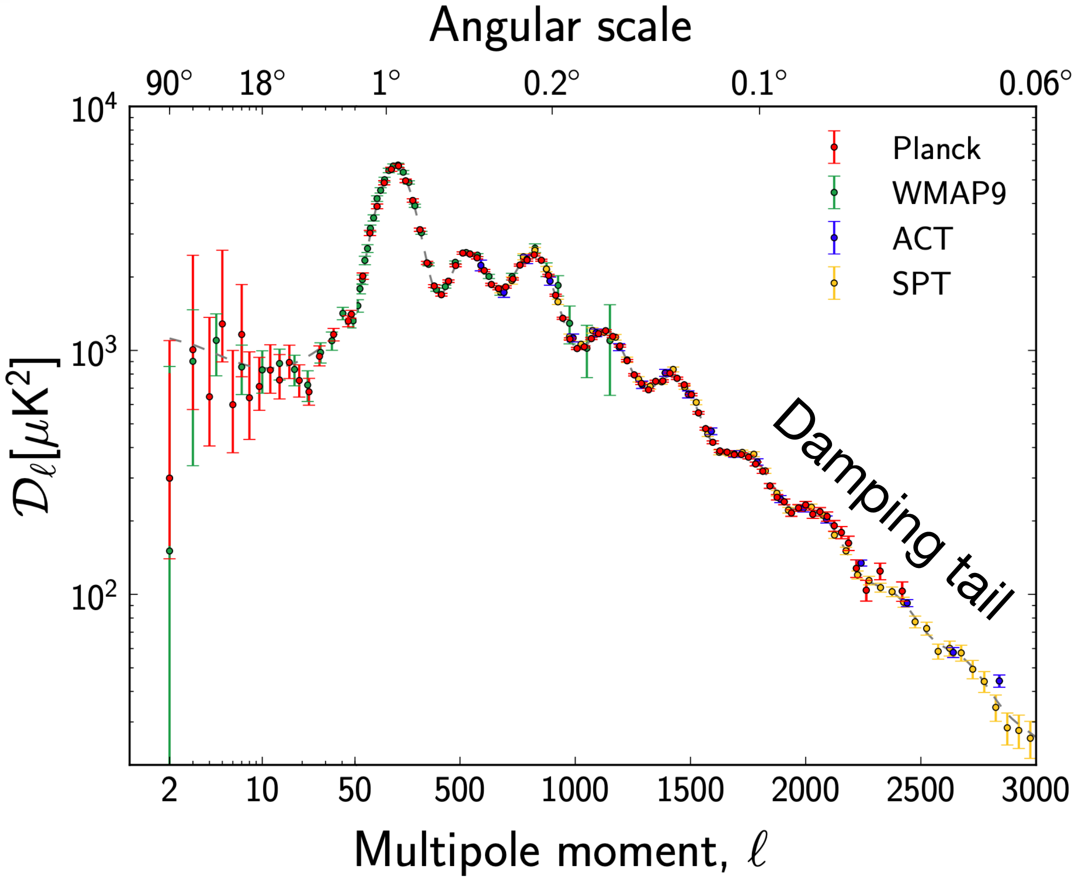
Credits: Yuji Chinone & Josquin Errard

The Simons Observatory science goals



Credits: Yuji Chinone & Josquin Errard

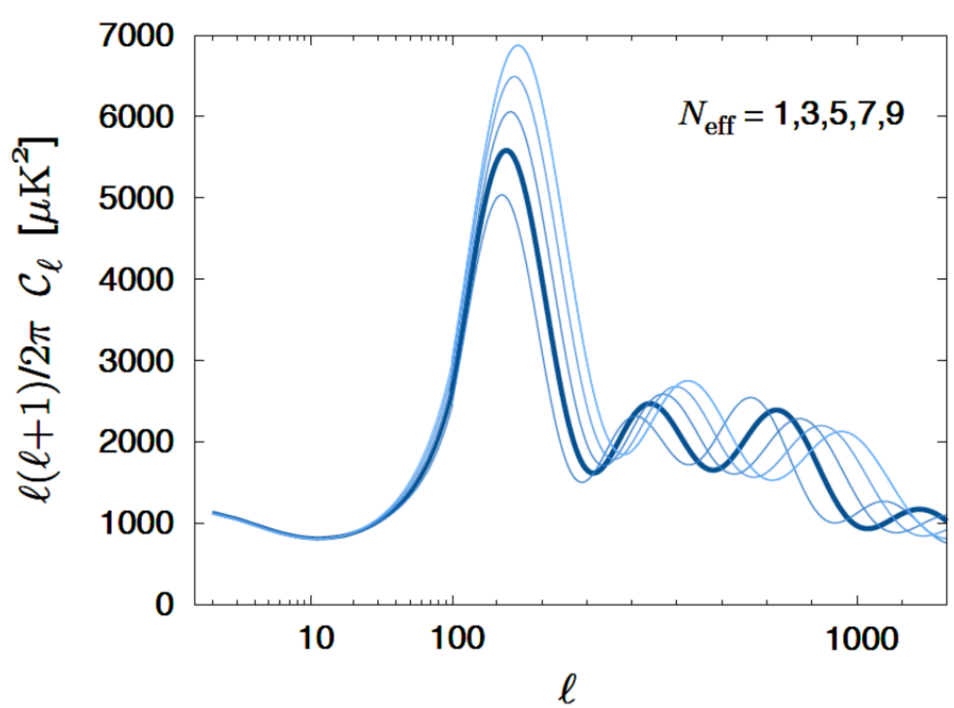
The Simons Observatory science goals: Neutrino

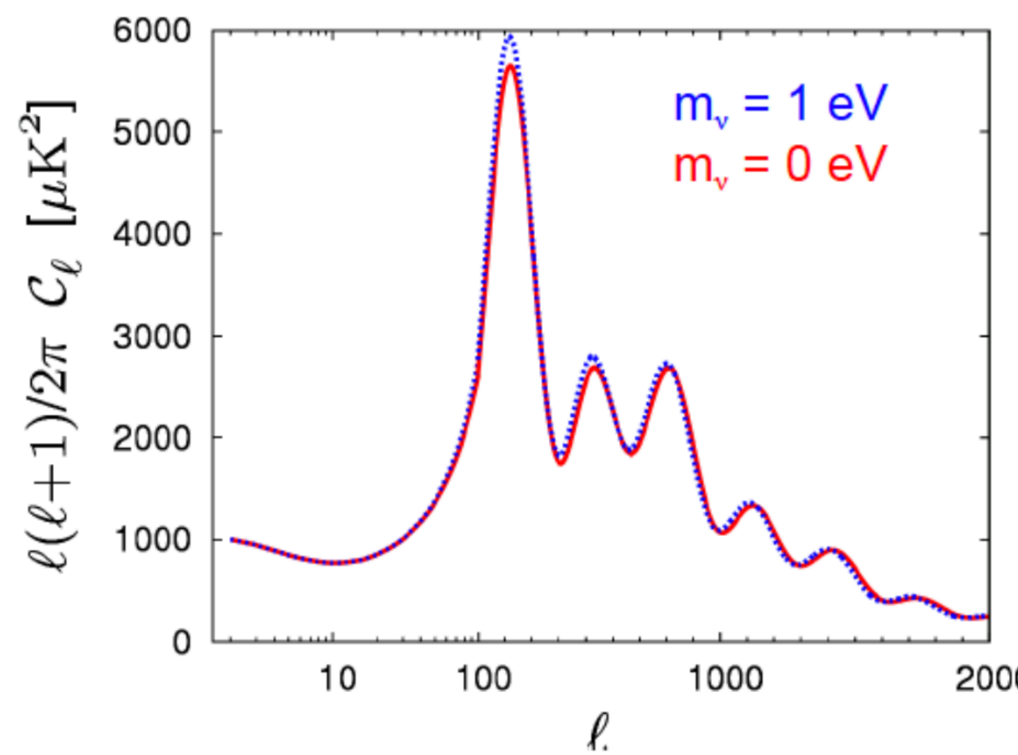


Planck 2018 result

Parameter	Value	Description
$\Omega_b h^2$	0.02237 ± 0.00015	Physical baryon density parameter
$\Omega_c h^2$	0.1200 ± 0.0012	Physical dark matter density parameter
Ω_Λ	0.6847 ± 0.0073	Dark energy density parameter
τ	0.0544 ± 0.0073	Reionization optical depth
n_s	0.9649 ± 0.0042	Scalar spectral index
$10^9 A_s$	2.092 ± 0.034	Amplitude scalar of power spectrum
H_0	67.36 ± 0.54	Hubble constant
Ω_b	0.0486 ± 0.0010	Baryon density parameter
Ω_m	0.3153 ± 0.0073	Matter density parameter
Ω_c	0.2589 ± 0.0057	Dark matter density parameter
$\rho_c\,(\mathrm{kg/m^3})$	$(8.62 \pm 0.12) \times 10^{-27}$	Critical density
Age/Gyr	13.797 ± 0.023	Age of the Universe
σ_8	0.8111 ± 0.0060	Fluctuation amplitude at $8h^{-1}$ Mpc
N_{eff}	$3.00^{+0.57}_{-0.53}$	Effective number of relativistic degrees of freedom
$\sum m_\nu$	$0.12\,\mathrm{eV/c^2}$	Sum of three neutrino masses (Planck + BAO)
...	...	...

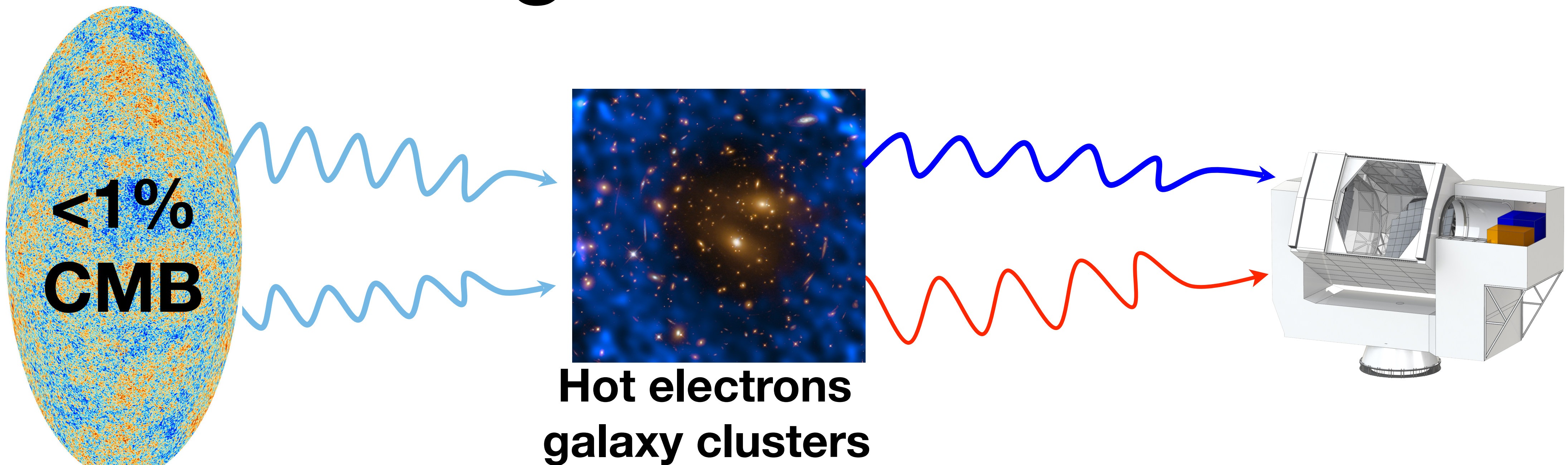
- Cosmological parameters



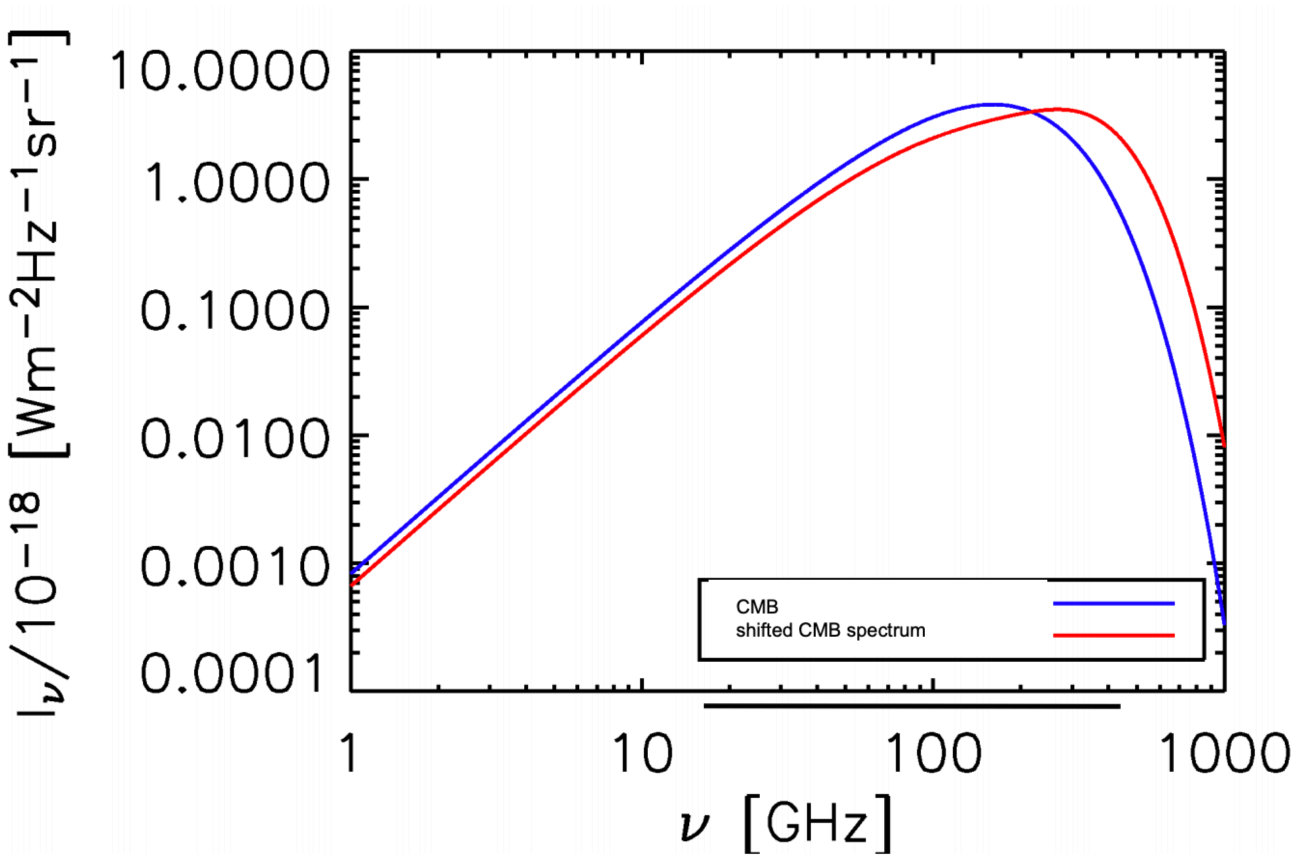


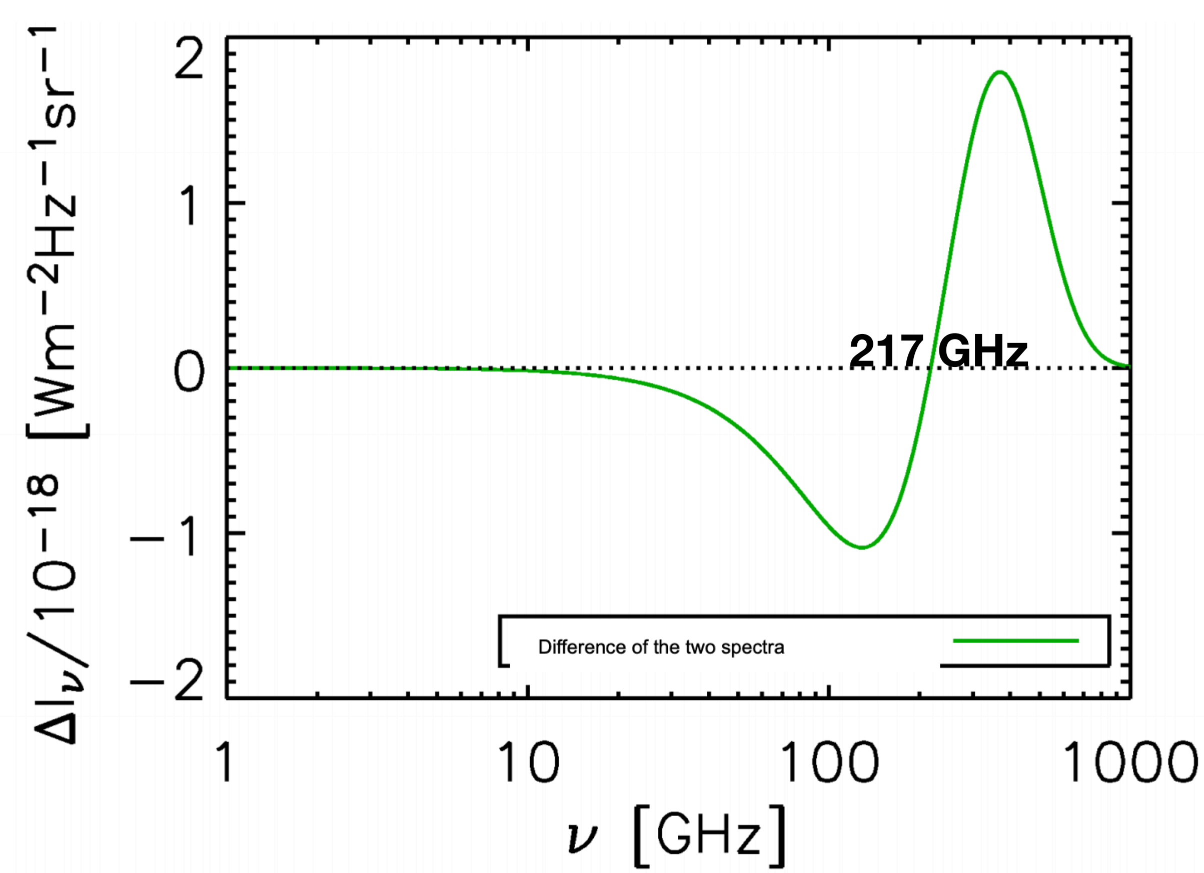
- N_{eff}: Effective number of relativistic species. The small angular scales is very sensitive to the radiation content of the early Universe.
- $\sum m_\nu$: Sum of the neutrino masses impacts growth of large scale structure, massive neutrinos slow down the cosmic structure formation.

SO science goals: Cosmic Structure



Sunyaev and Zeldovich 1970,1972

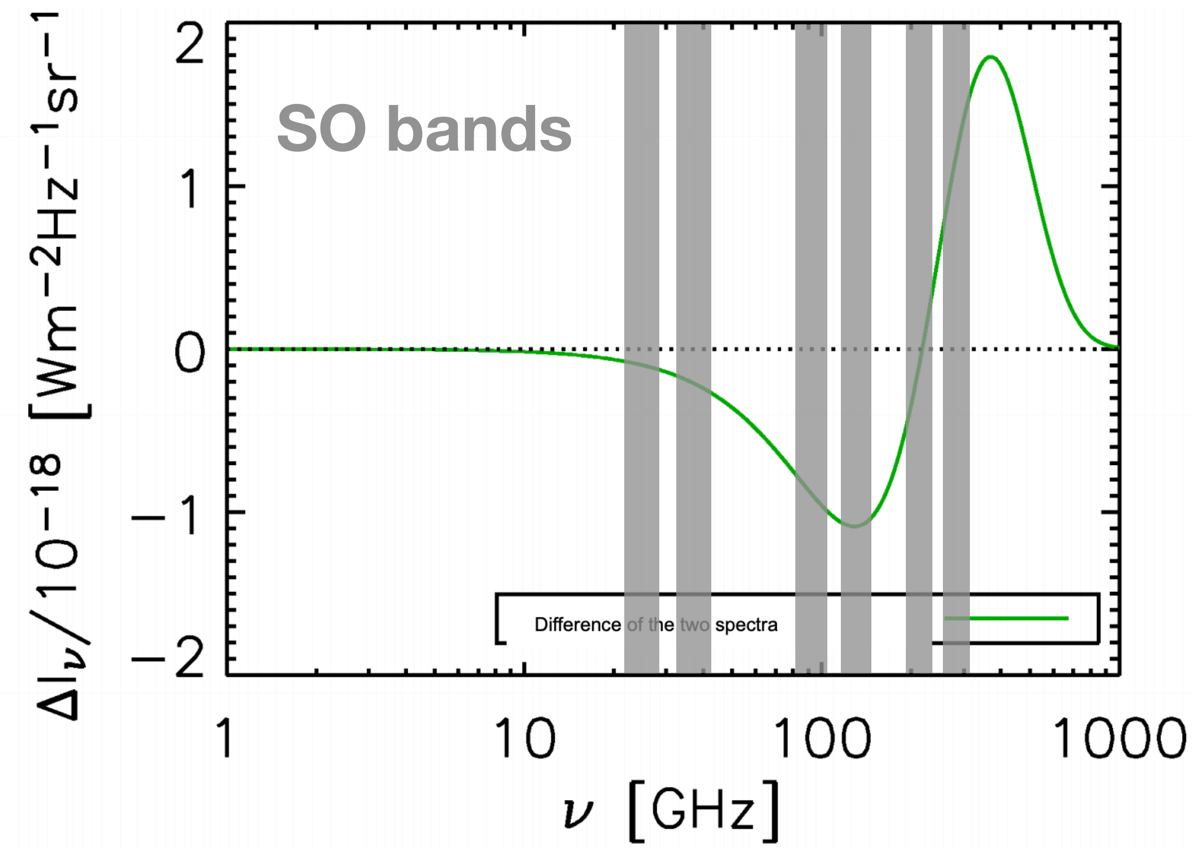


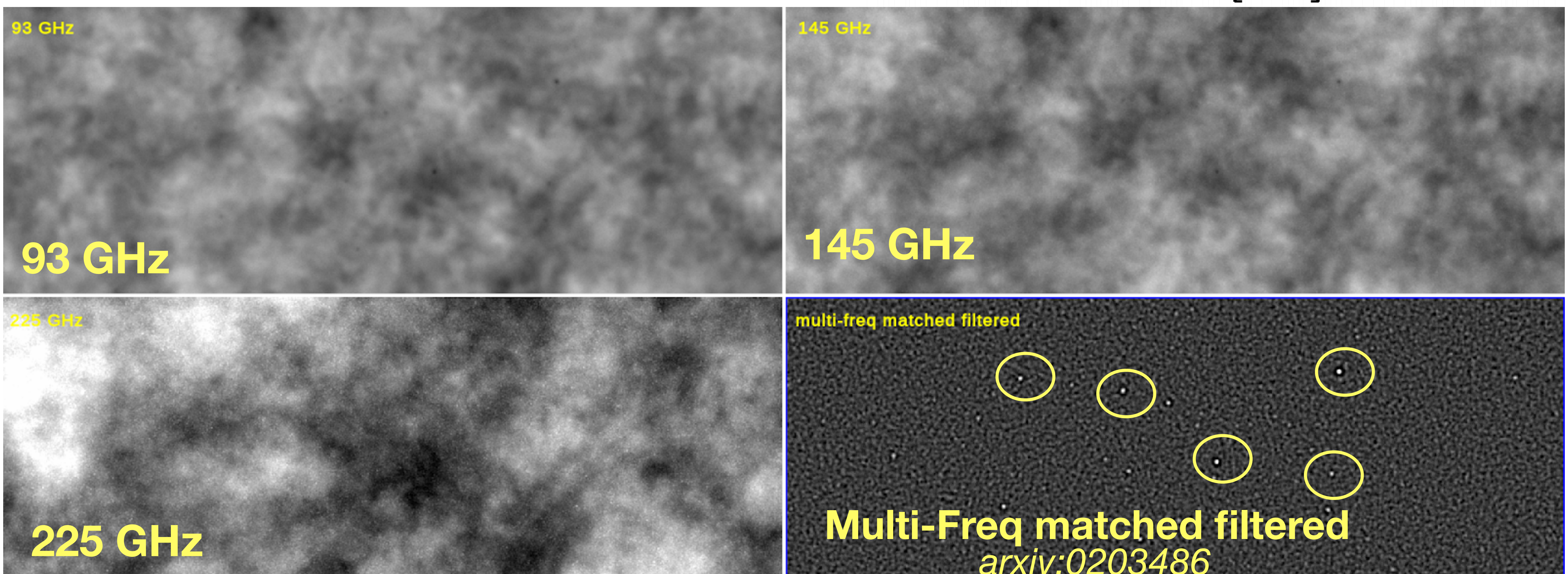


- **The Sunyaev-Zel'dovich (SZ) power spectrum, kinetic SZ, CMB data as a probe of the Large Scale Structure**

SO science goals: Cosmic Structure

- **Galaxy clusters strong depend on cosmological parameters**
- **SZ clusters constrain cosmology via cluster counts**





The Simons Observatory science goals

SO Science Goals

ID	Title	Parameter	Baseline	Goal	Current[a]	SO Method
SR-1a	Primordial fluctuations	r	**0.003**	**0.002**	0.03	BB
SR-1b		P(k=0.2 /Mpc)	**0.5%**	**0.4%**	6%	T/E/k
SR-1c		f_{NL}	**2**	**1**	5	kSZ+LSST
			3	**1**		kk+LSST
SR-2	Relativistic Species	N_{eff}	**0.07**	**0.05**	0.2	T/E
SR-3	Neutrino mass	Σm_ν (eV)	**0.04**	**0.03**	0.1	kk+DESI
			0.04	**0.03**		tSZ-N+LSST
			0.05	**0.04**		tSZ-Y+DESI
SR-4a	Dark Energy	σ_8(z=1-2)	**2%**	**1%**	7%	kk+LSST
			2%	**1%**		tSZ+LSST/k
SR-4b		H_0 (LCDM)	**0.4**	**0.3**	0.7	T/E
SR-5a	Galaxy Evolution	feedback efficiency in massive halos	**3%**	**2%**	50-100%	tSZ+kSZ
SR-5b		non-thermal pressure in massive halos	**8%**	**5%**	50-100%	tSZ+kSZ
SR-6	Reionization	duration Δz	**0.6**	**0.3**	1.4	T/E (kSZ)

All are 1-sigma

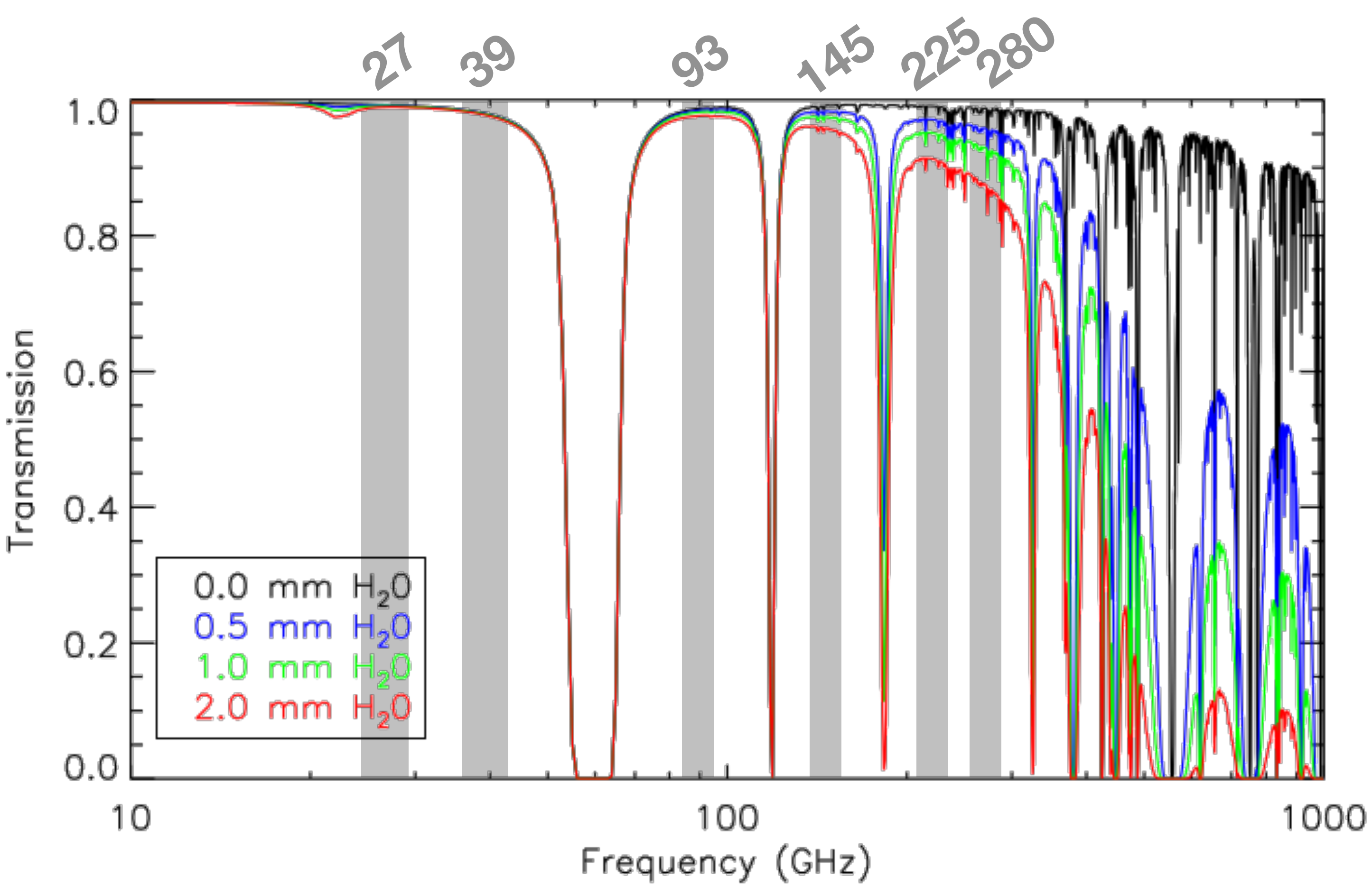
'The Simons Observatory: Science Goals and Forecasts', SO Collaboration in prep

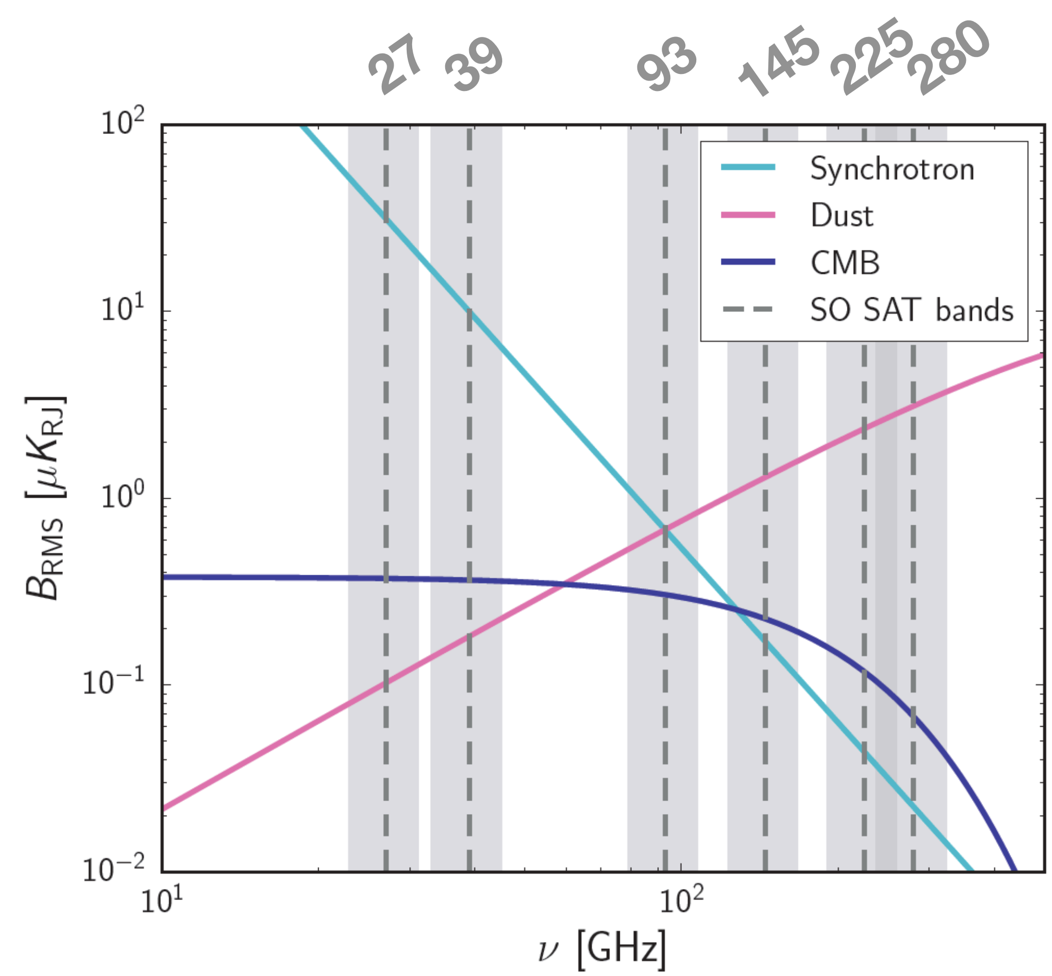
[a]Current constraints are from Planck T/E and kk, combined with BAO data. Bicep2/Keck BB provides the current constraint on r (r<0.07 at 95%). SPT T provides the current constrain on Δz.

- Baseline: Noise level of $2\mu\mathrm{K}-\mathrm{arcmin}$ for SAT, $6.5\mu\mathrm{K}-\mathrm{arcmin}$ for LAT
- Goal: Noise level of $1.4\mu\mathrm{K}-\mathrm{arcmin}$ for SAT, $4\mu\mathrm{K}-\mathrm{arcmin}$ for LAT
- All forecasts assume SO + Planck.
- Baseline is conservative instrument performance include systematic error budget.

SO Frequency Bands

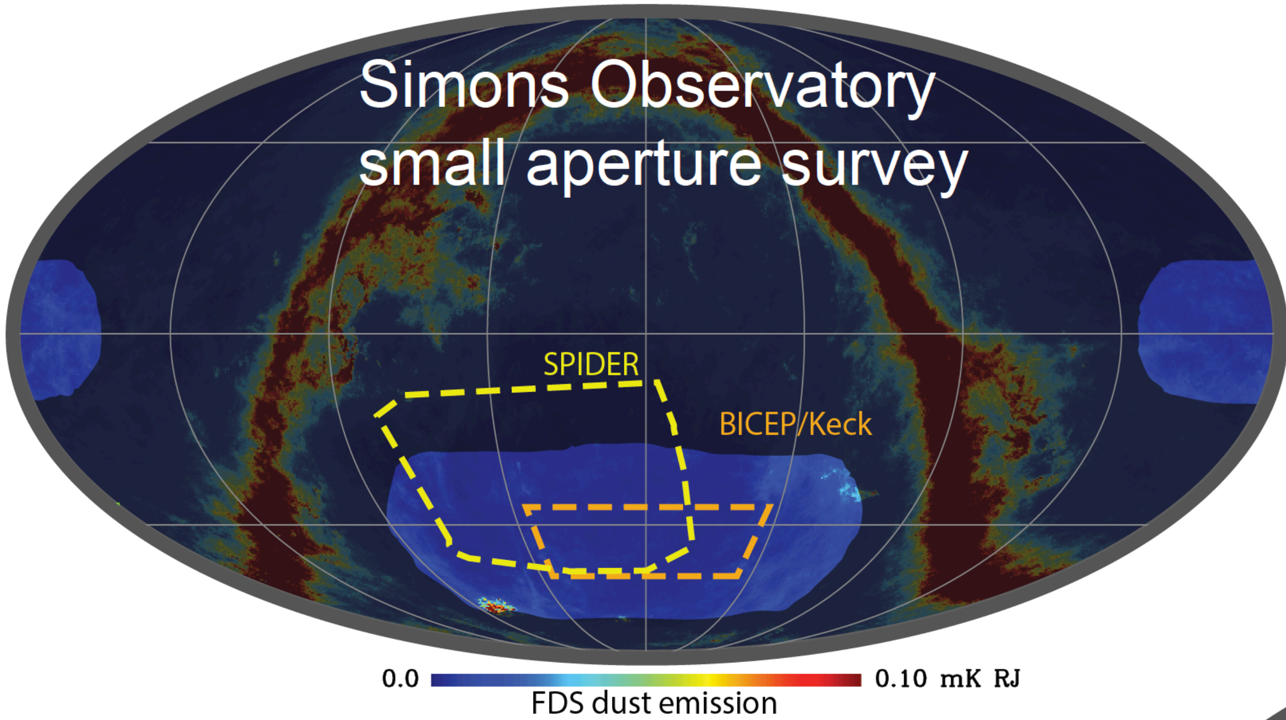
	Freq. [GHz]	SATs ($f_{sky} = 0.1$) FWHM ($'$)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]	LAT ($f_{sky} = 0.4$) FWHM ($'$)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
LF	27	91	35	25	7.4	71	52
	39	63	21	17	5.1	36	27
MF	93	30	2.6 (2 μK-amin)	1.9	2.2	8.0 (6 μK-amin)	5.8
	145	17	3.3	2.1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





- We exploit almost **all available atmospheric windows** on both LAT and SAT

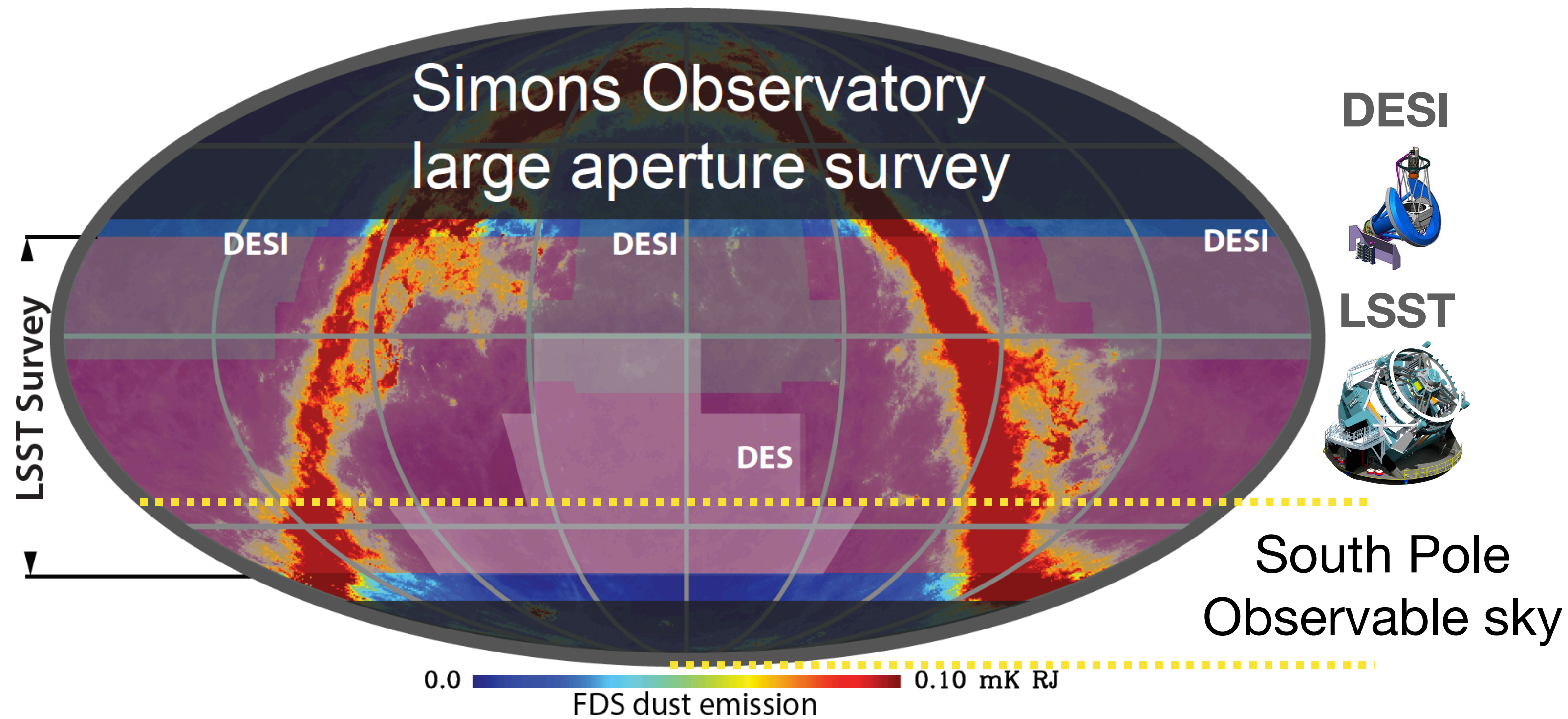
SO Sky Coverage



$$f_{sky} \approx 10\,\%$$

- **Low foreground regions for Inflation and Lensing**

$$f_{sky} \approx 40\,\%$$

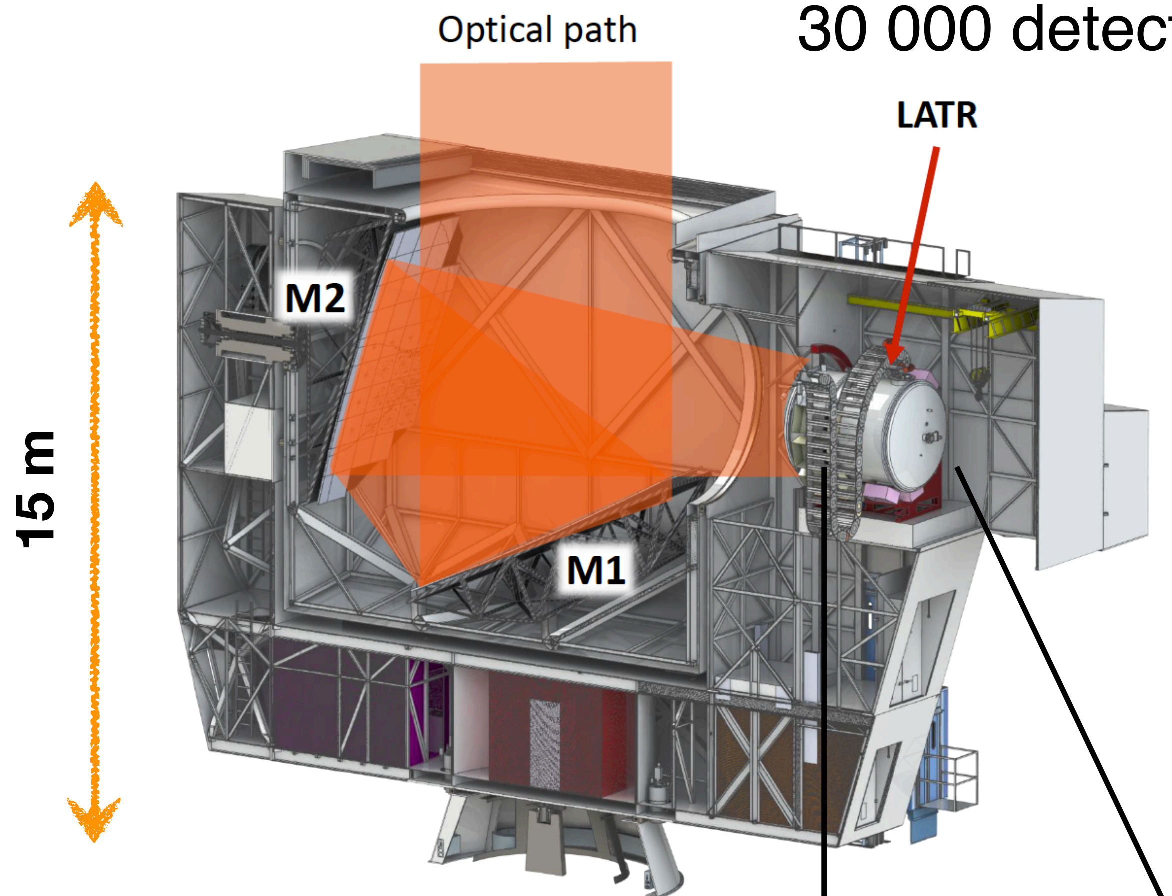


- **Overlap with optical surveys Large Synoptic Survey Telescope (LSST), Dark Energy Spectroscopic Instrument (DESI) measurements for neutrinos, dark energy, dark matter, and astrophysics.**

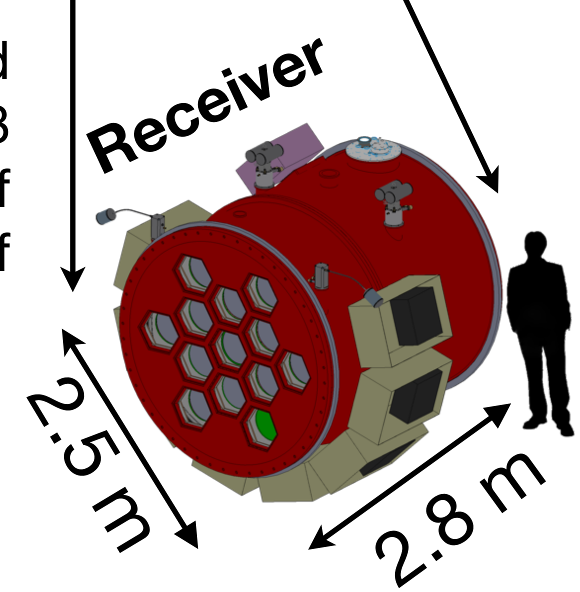
Stevens et al arXiv:1808.05131

The Simons Observatory instruments

Large aperture telescope (LAT)



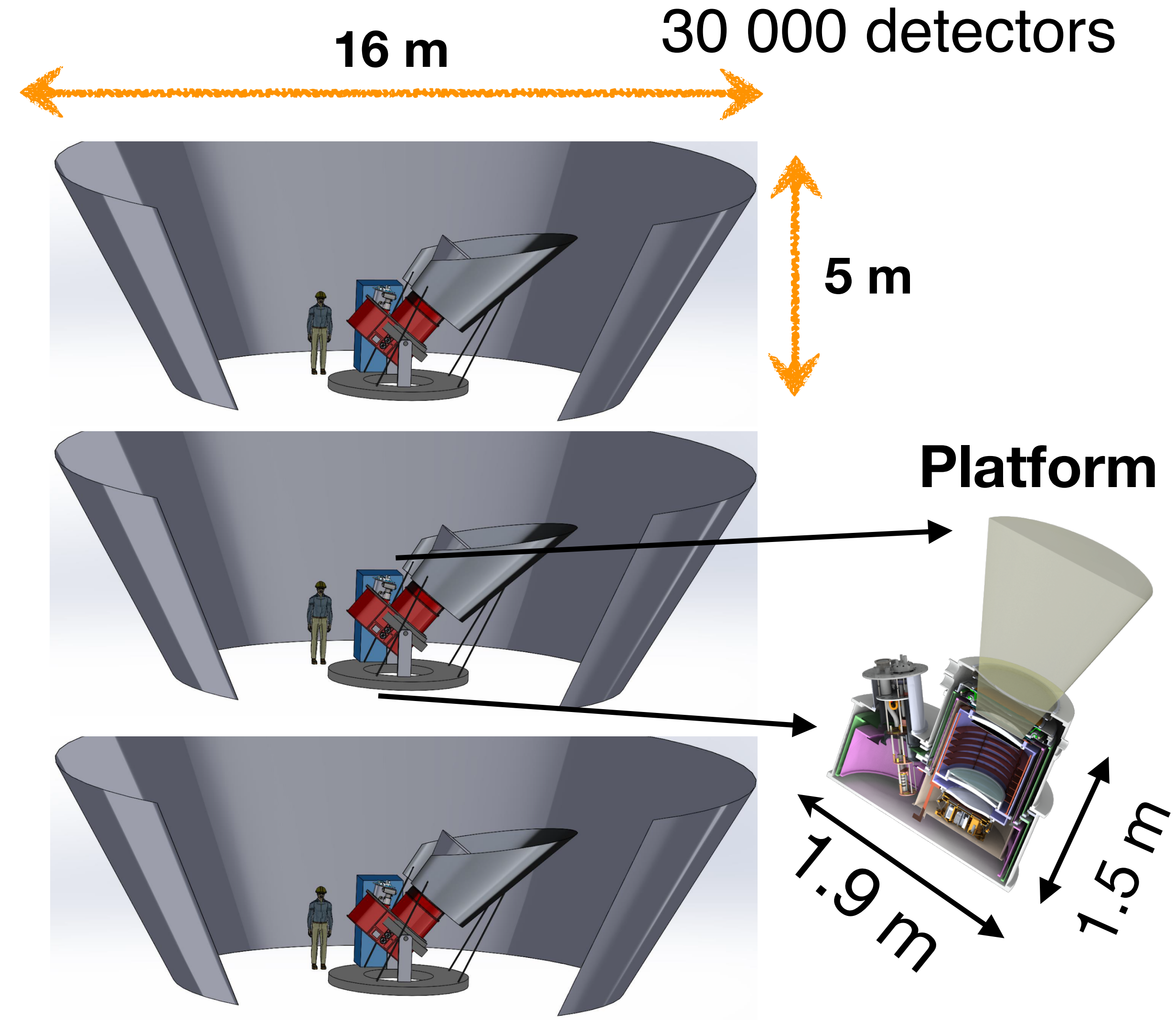
6m Crossed Dragone coupled to 13 tubes, each tube is 38 cm in diameter. Capable of 100 000 detectors. Field of view (FOV) 8° (1 tube~1.3°).



Baseline=7 tubes for SO:

- One tube: 27/39 GHz
- Four tubes: 93/145 GHz
- Two tubes: 225/280 GHz

Small aperture telescopes (SAT)



Three 42 cm diameter refractors, rotating half-wave plate. FOV 35°
Frequency bands:
27/39 | 93/145 (2-SAT)| 225/280 GHz (1-SAT)

FIRST LIGHT IN 2020

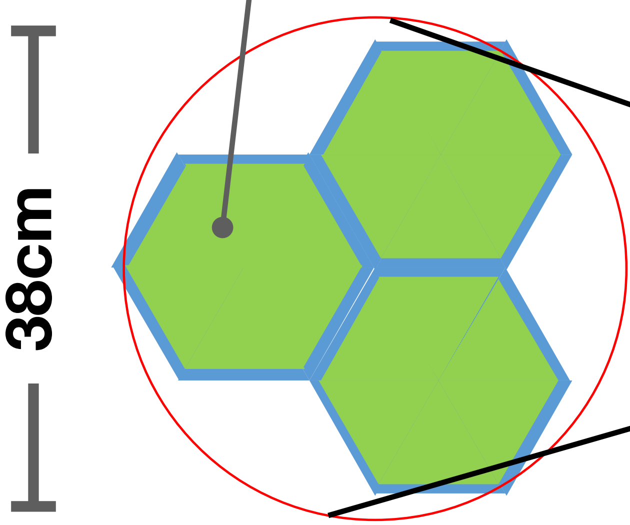
arXiv:1808.10037 arXiv:1808.04493

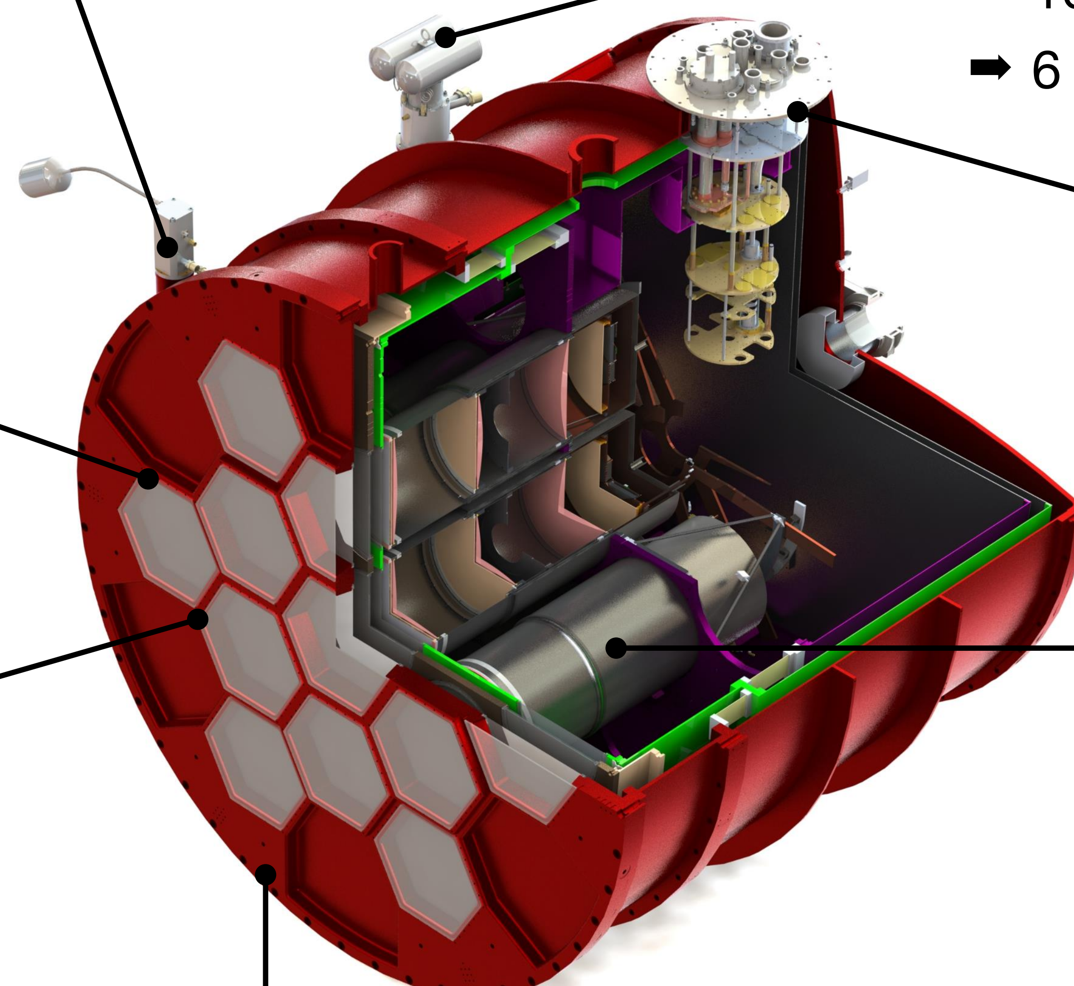
Large Aperture Telescope Receiver (LATR)

- **Total weight ~ 5000kg! (~elephant)**
  when populated with 13 tubes

- **2 Cryomech pulse tube PT90s**
  ➡ 180 W of cooling at 80 K

- Fabricated from 150mm diameter silicon wafers





- **2 Cryomech pulse tube PT420 coolers**
  ➡ 165 watts of cooling at 40 K
  ➡ 6 watts of cooling at 4 K

- **Dilution Refrigerator**
  ➡ 17 mW at 1K
  ➡ 500 uW at 100 mK

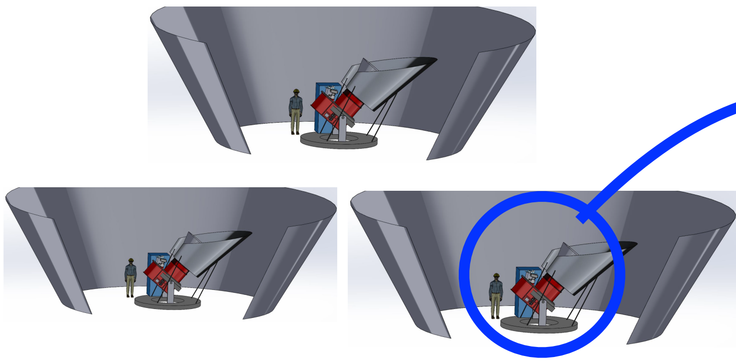
- **Optics tubes**
  ➡ Three anti-reflection coated silicon lenses.
  ➡ Cold (1K) Lyot Stop.

- 1200 kg cooled to 4K
- 200 kg cooled to 100 mK
- **Up to 13 optics tubes**

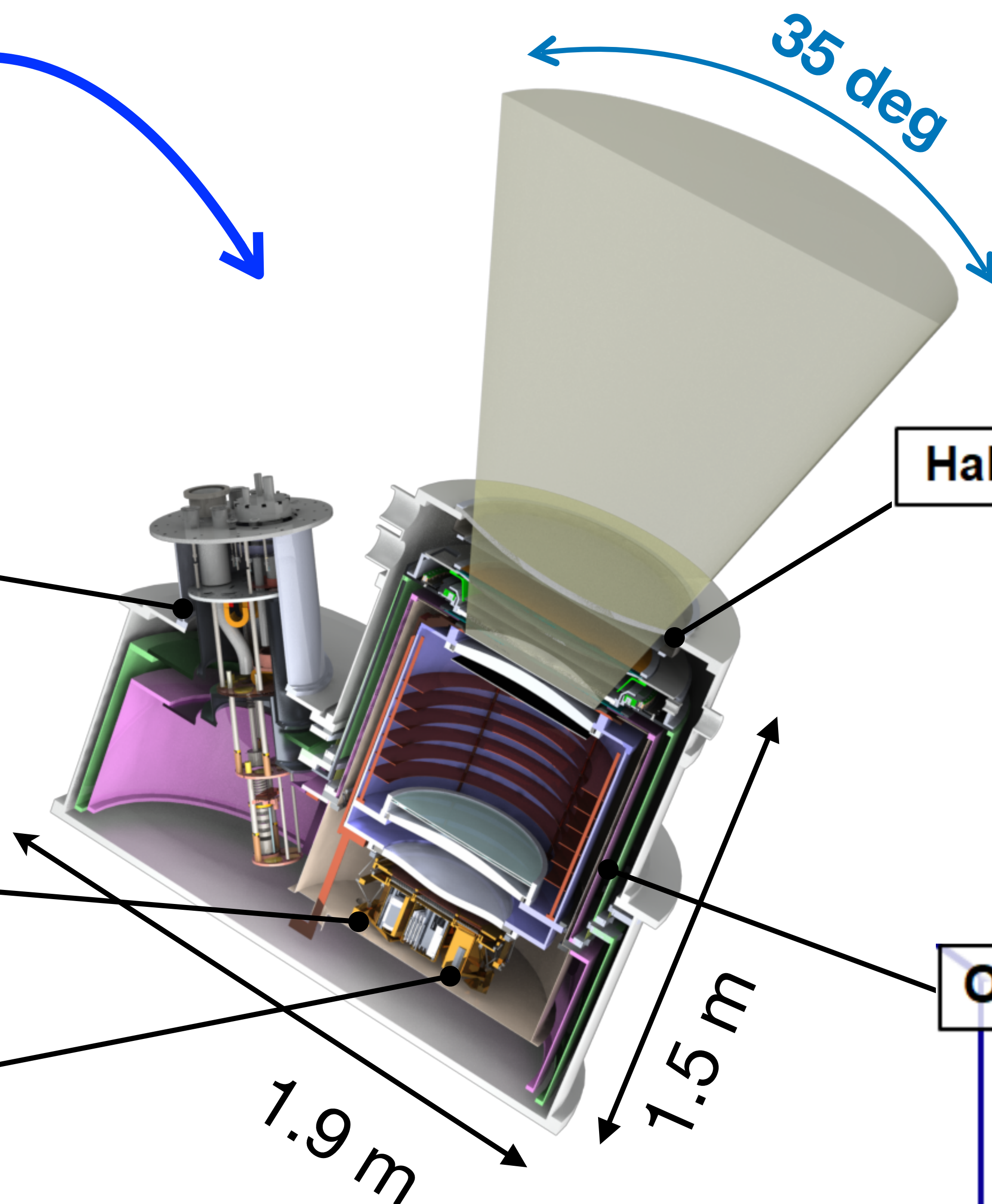
➡ 7 currently planned for SO

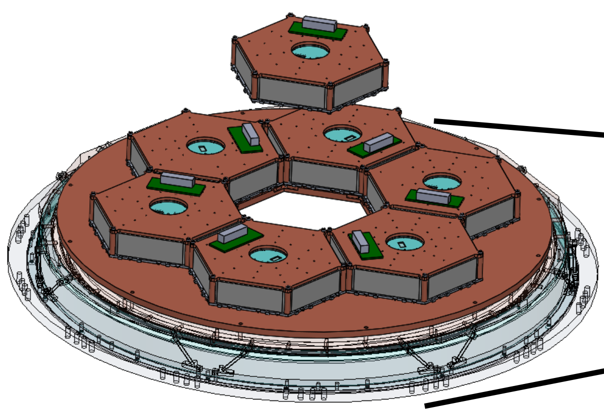
- **100 000 detectors capacity in this cryostat**
  ➡ 30 000 planned for SO
- The optics tubes can be replaced while cryostat is installed.
- Collaboration with CCAT and built by Vertex

Small Aperture Telescope Platform (SATP)

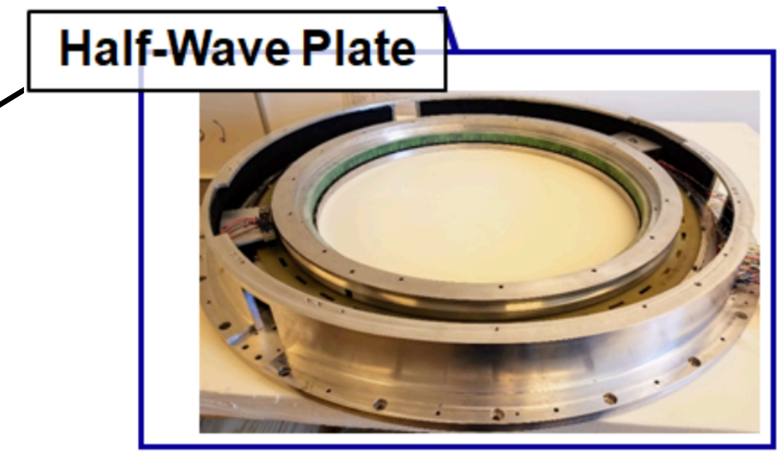


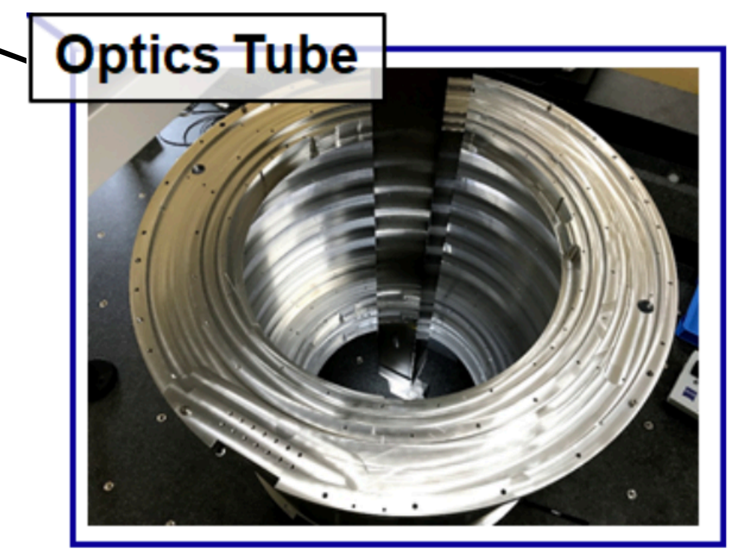
- **Dilution Refrigerator**
  ➡ 100 mK





- Focal plane: 7 wafers

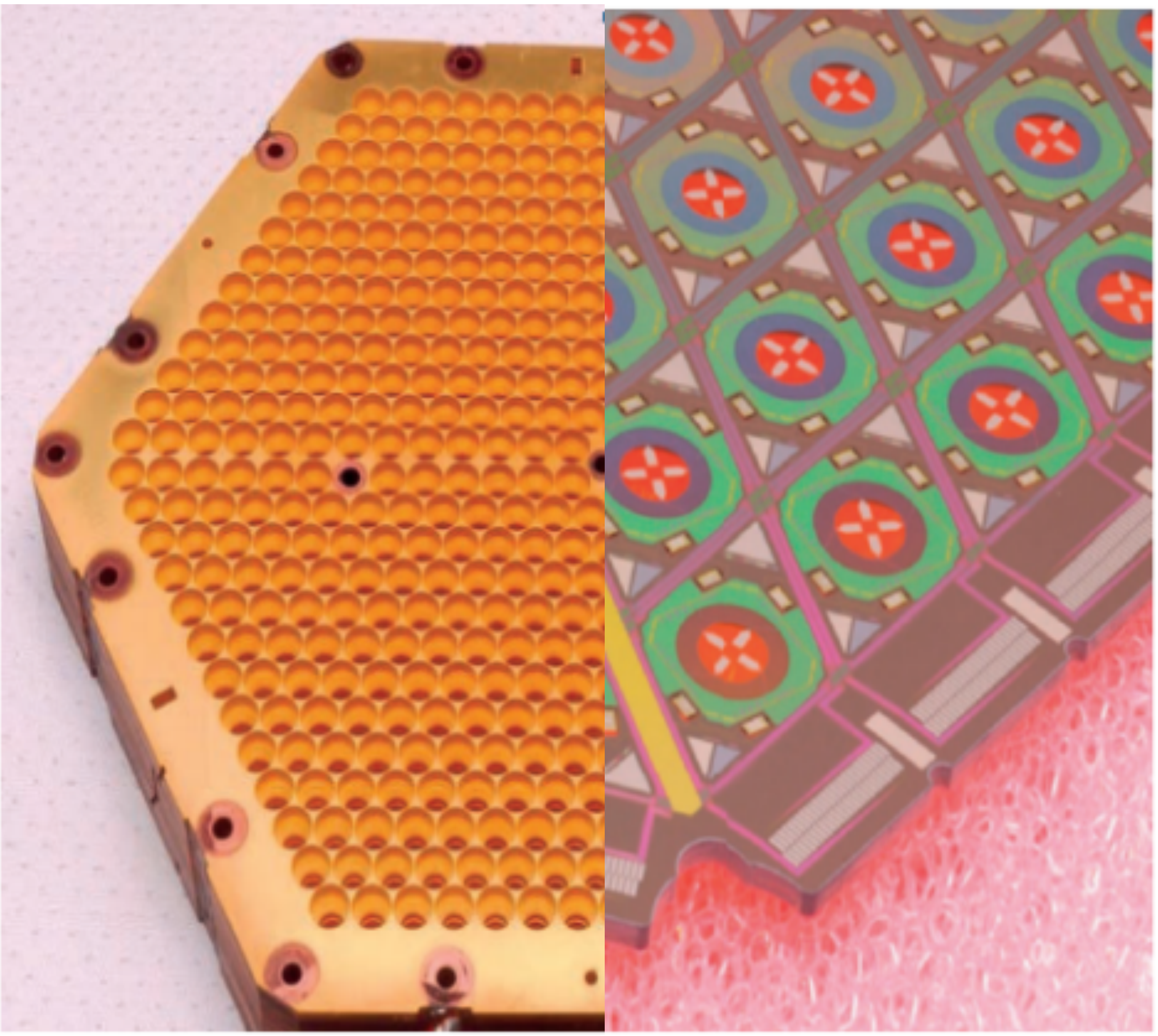


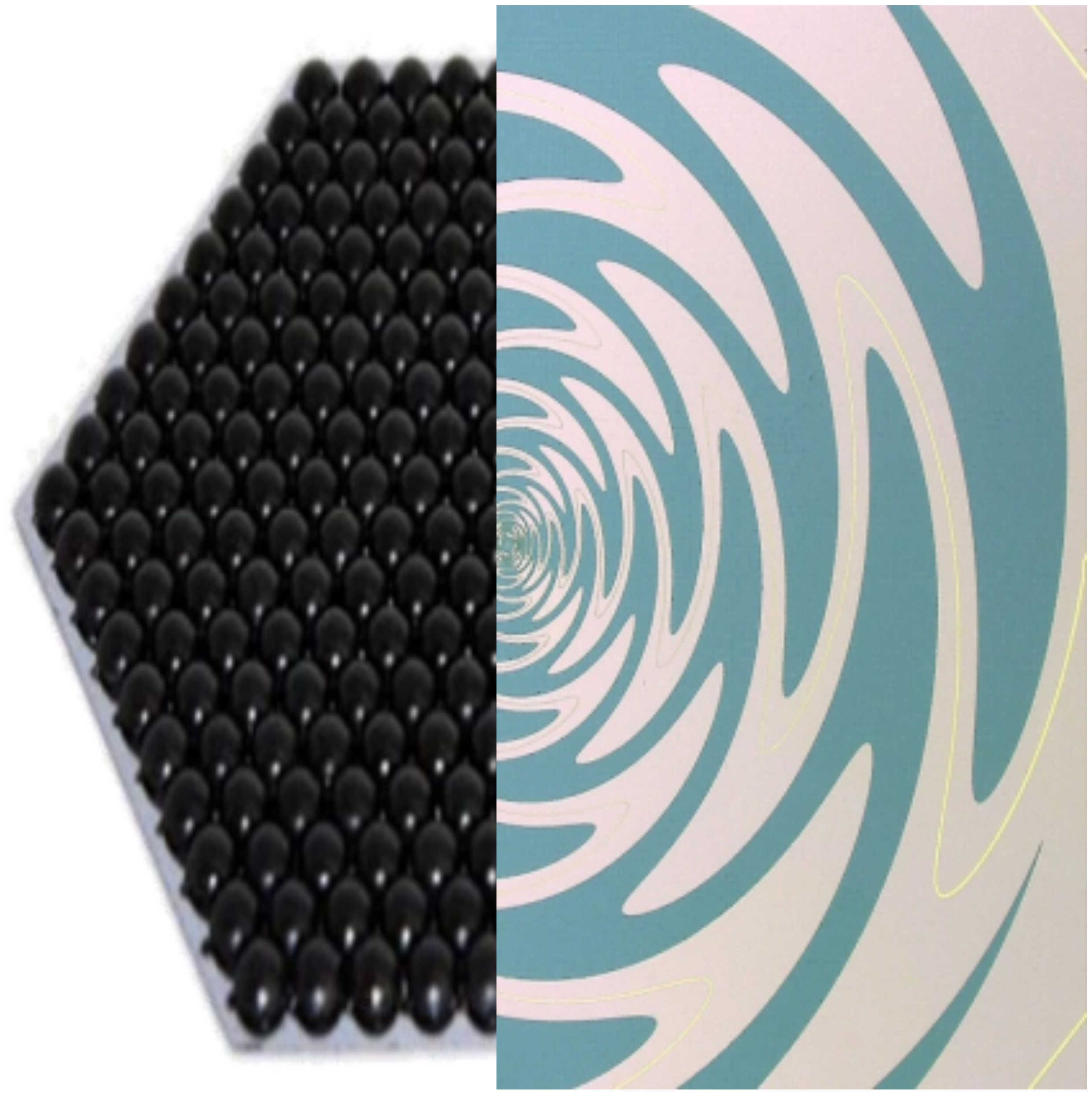


➡ for Simons Observatory: 21 wafers of ~30 000 detectors

The Simons Observatory Detectors

- **Two detector architectures**

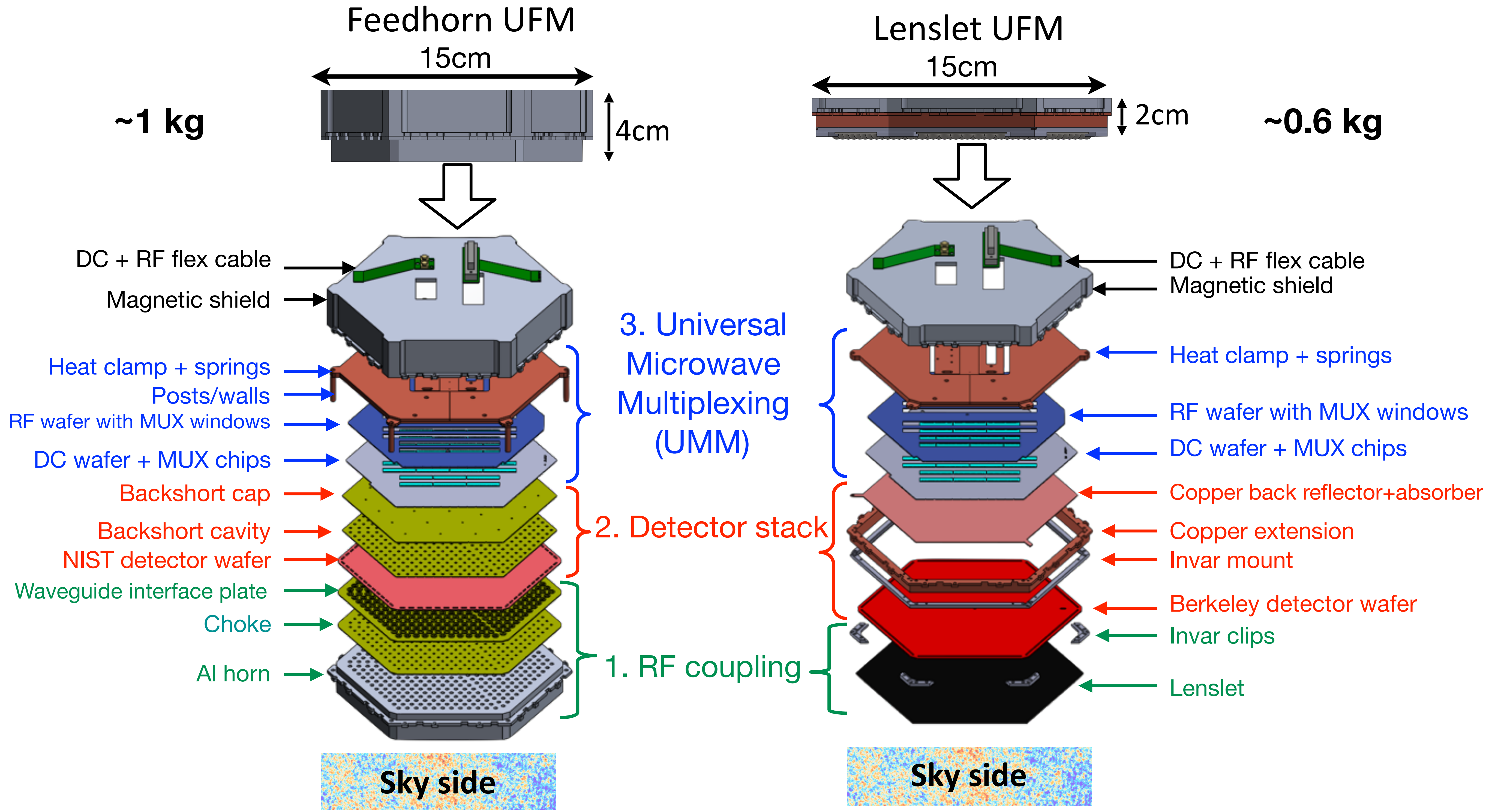




Orthomode transducers (OMT) feedhorn Array
Mid-Frequency (MF), High-Frequency (HF)
(NIST: ACT, SPT, SPIDER)

Sinuous antenna + lenslet array
Low-Frequency (LF), MF
(Berkeley: Polarbear, Simons Array, SPT)

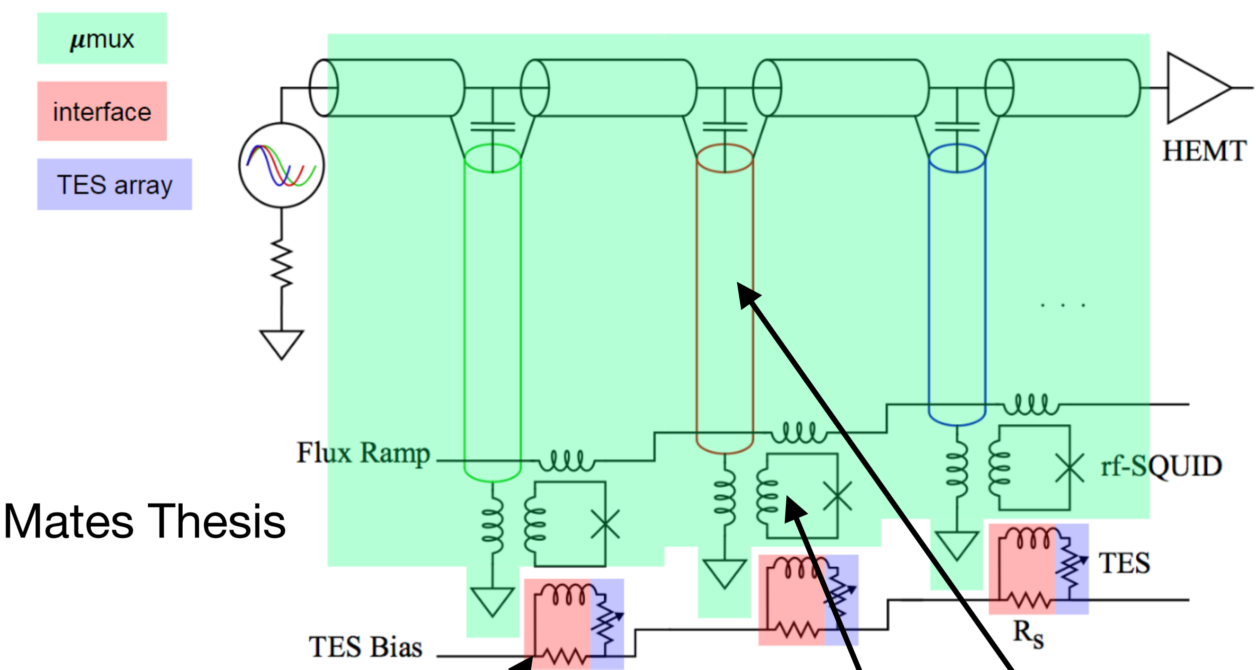
The Universal Focal plane Module (UFM)



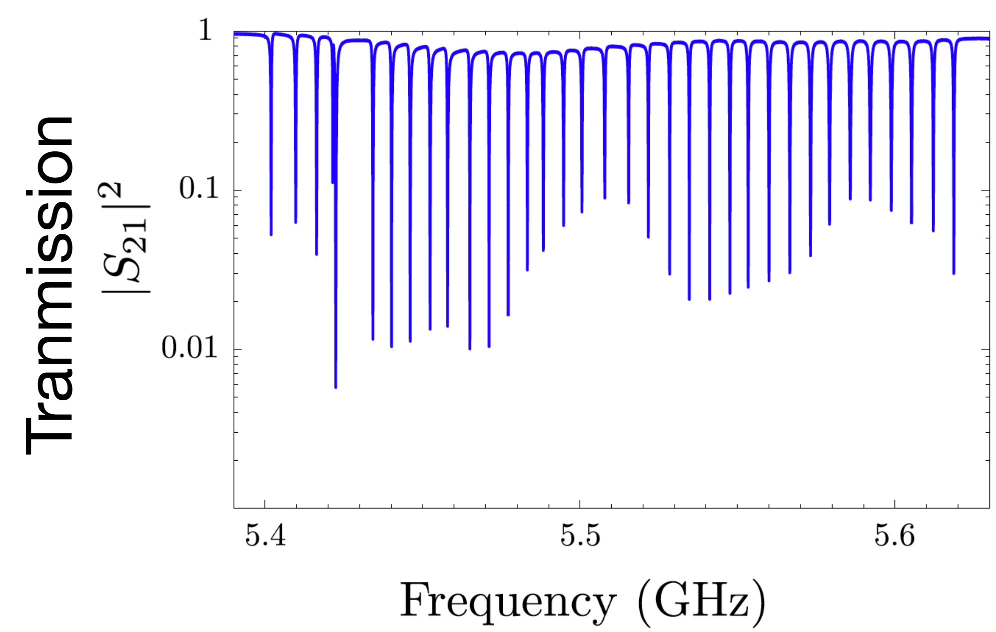
- Many stacked wafers to improve bolometer efficiency
- The Transition Edge Sensor (TES) will be AlMn alloys with critical temperature 160 mK
- The normal resistance target is 8 $m\Omega$
- ~ 2000 TES per detector wafer

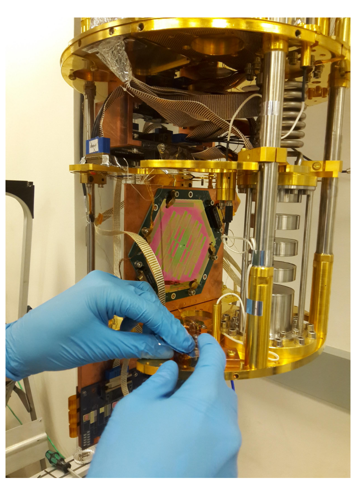
The Simons Observatory Detector Readout

- Frequency domain multiplexing: Microwave SQUID Multiplexer (μmux) concept.
- Each detector is coupled to a resonant circuit such that its output signal is converted to a change in the resonance of the circuit.
- Readout ~ 2000 detectors per wafer.

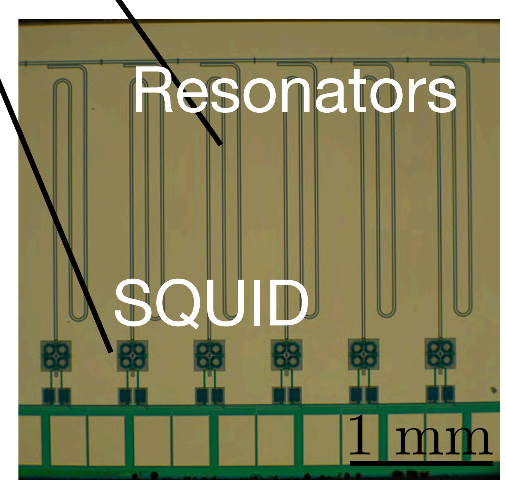


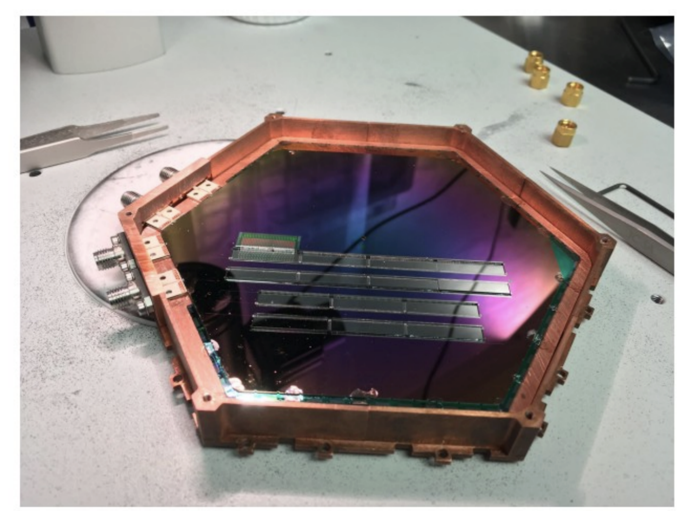
J.A.B. Mates Thesis





DC wafer





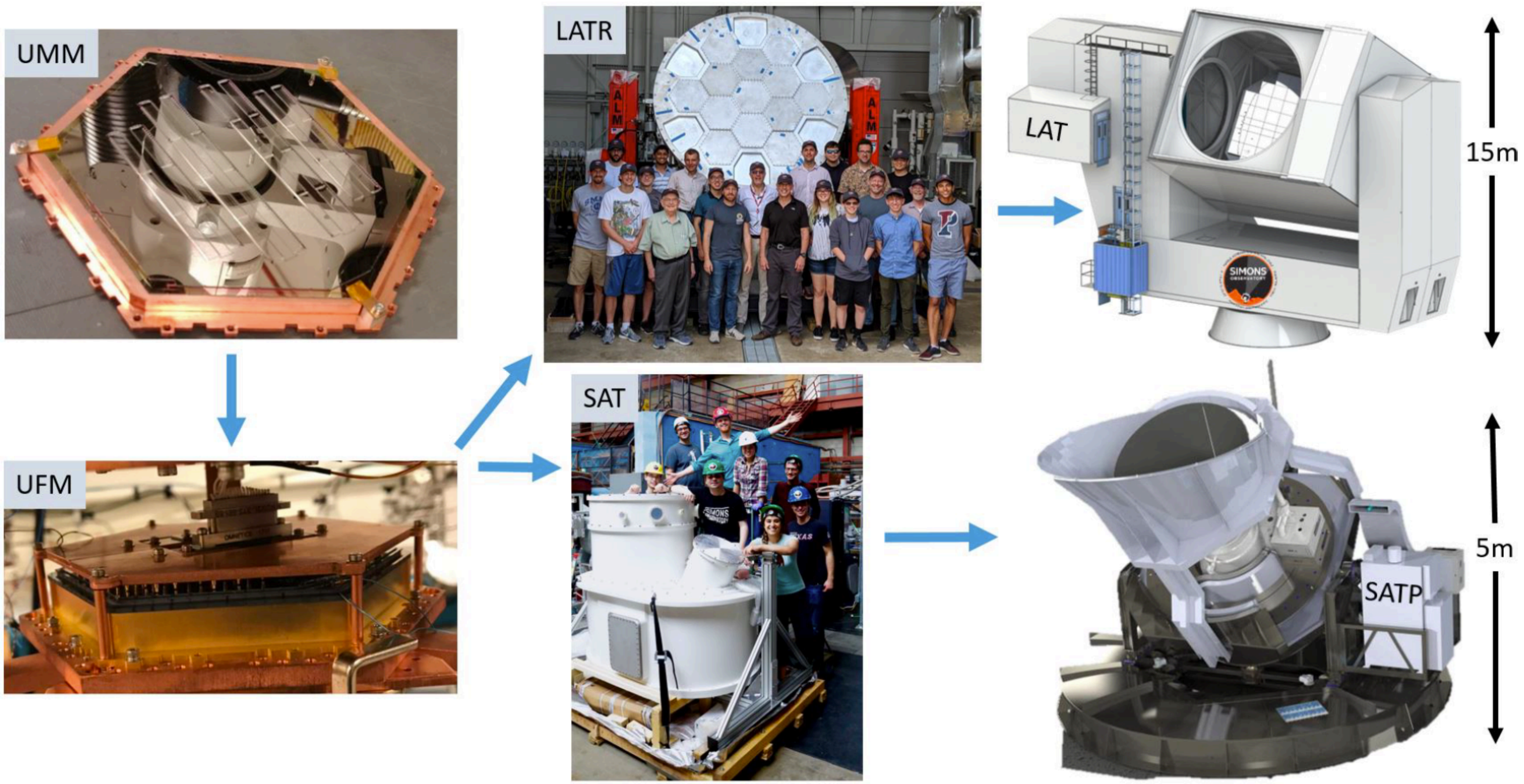
- **Cornell, Princeton universities are testing the Universal Microwave-Multiplexing module (UMM) and the Universal Focal plane Module (UFM).**

The Simons Observatory Progress 2019

- Princeton, Cornell

- University of Pennsylvania

- Vertex - Germany



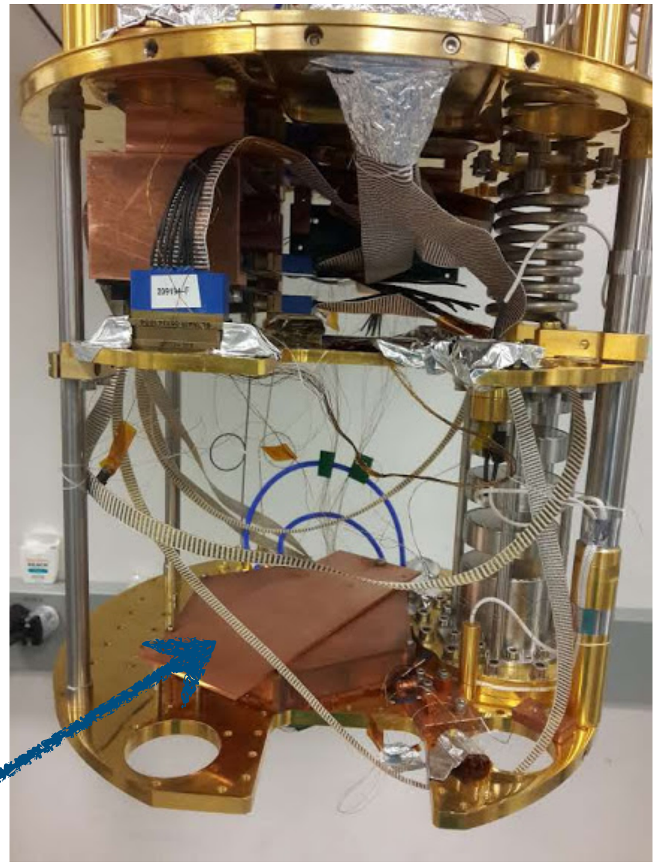
- University California San Diego

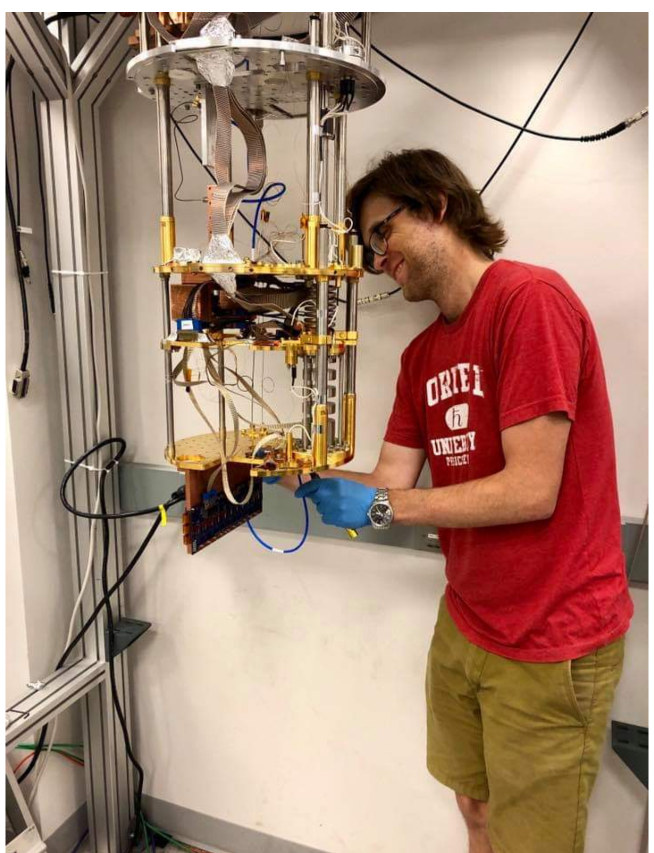
- Vertex - Germany

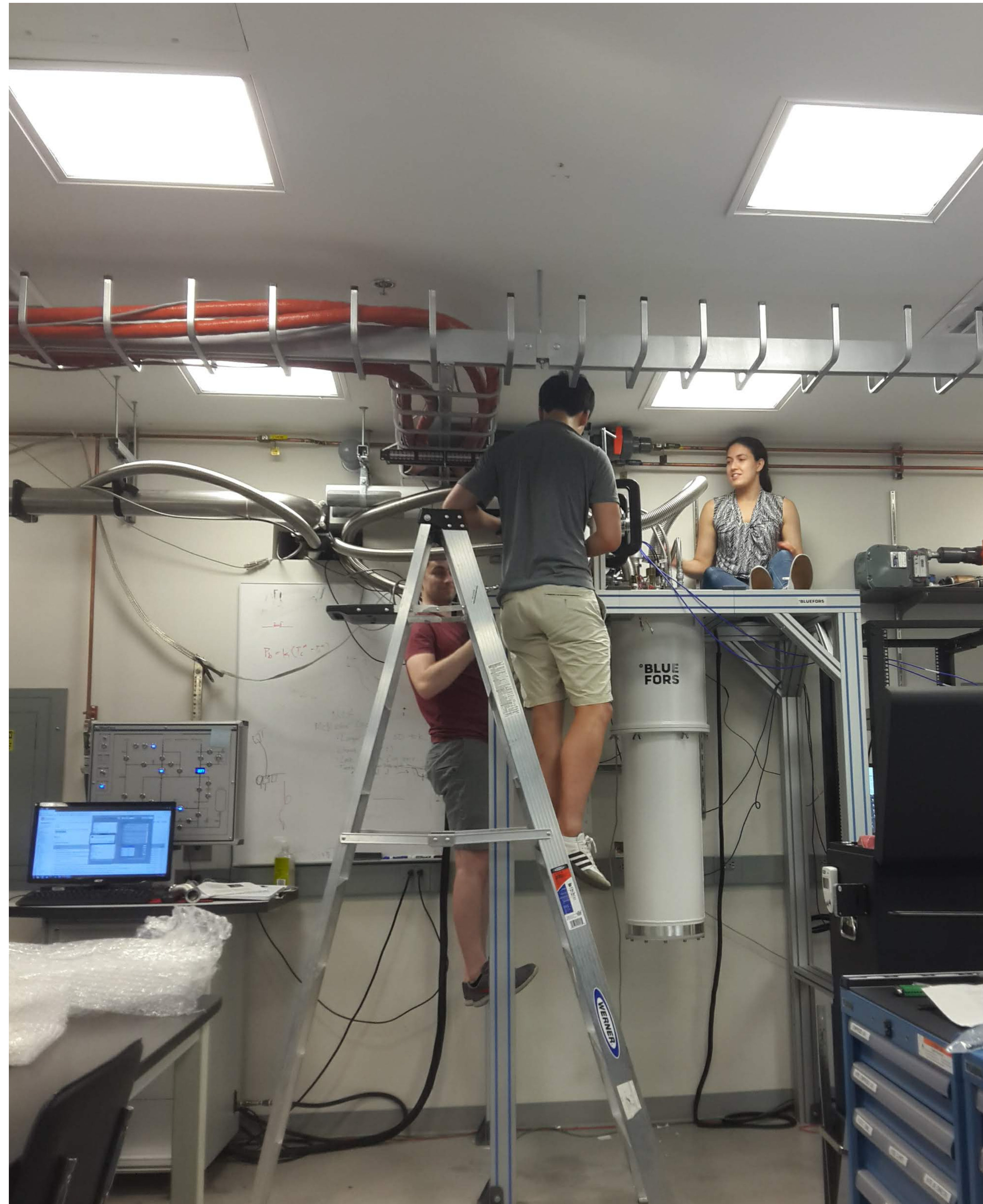
- **The Universal Microwave-Multiplexing module (UMM) is combined with the detector wafer to form the Universal Focal plane Module (UFM)**

The Simons Observatory Progress 2019

Cornell UFM testbed

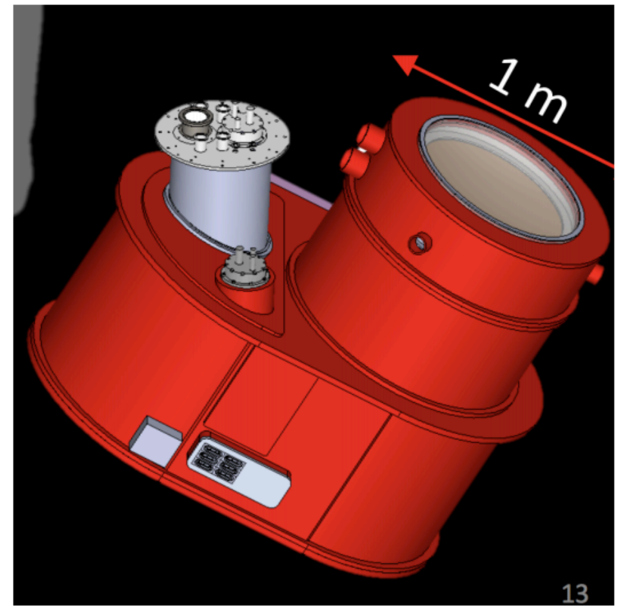


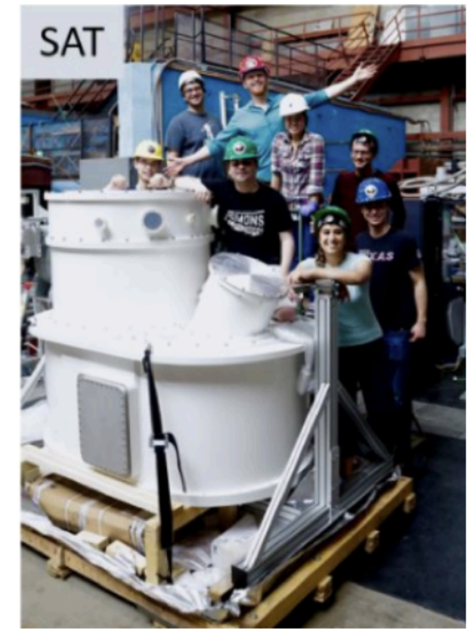




The Simons Observatory Progress 2019

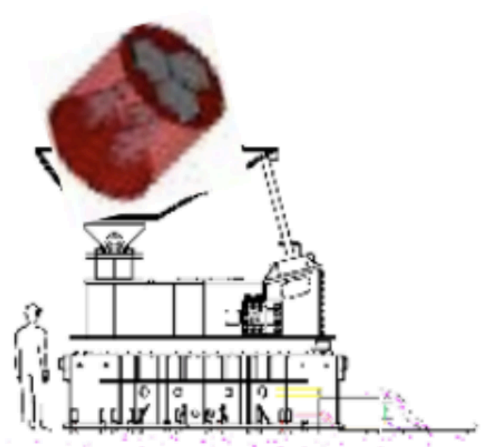
Small Aperture Telescope (SAT)

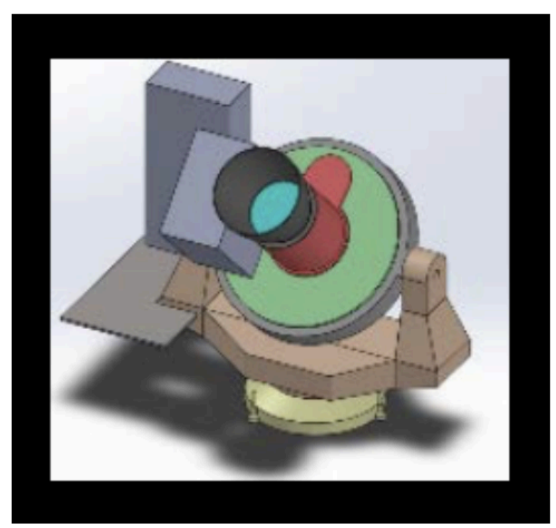




2017 2018 2019

Small Aperture Telescope Platform (SATP)

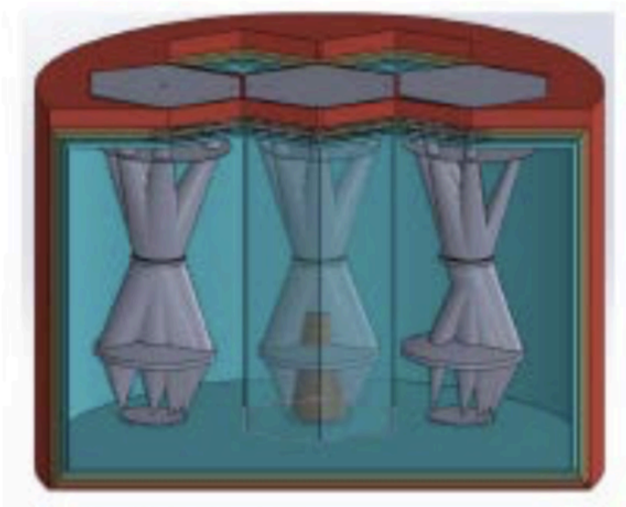


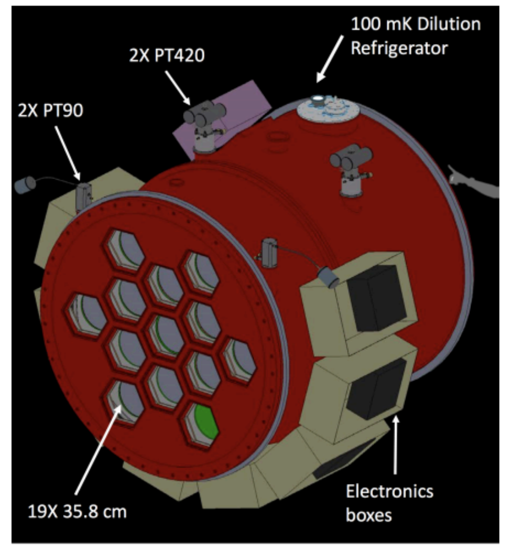


2017 2018 2019

The Simons Observatory Progress 2019

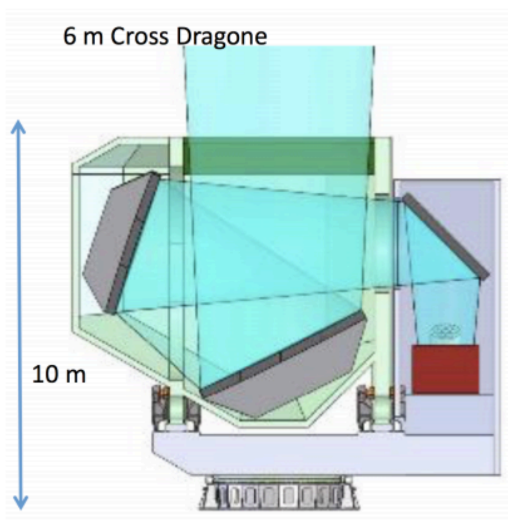
Large aperture telescope Receiver (LATR)

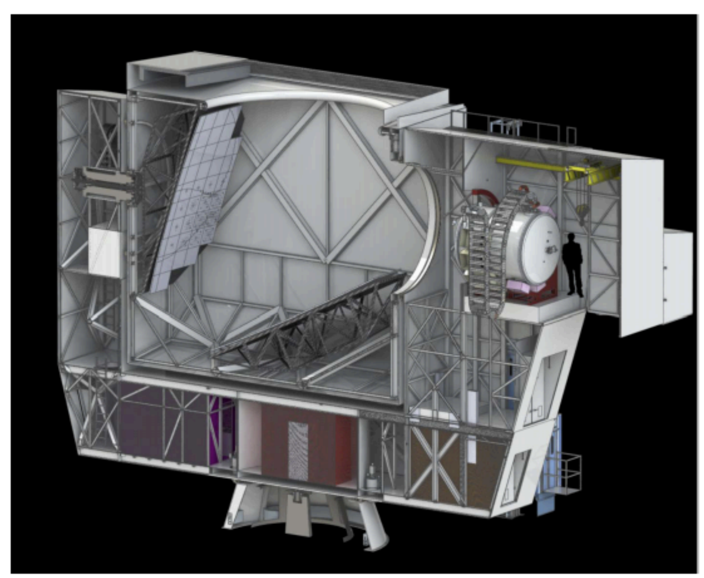




2017 2018 2019

Large aperture telescope (LAT)





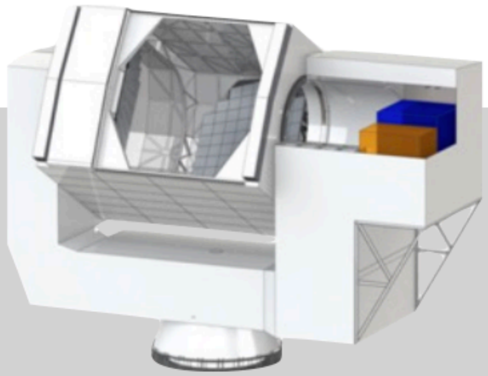
Sub-Contracts in place

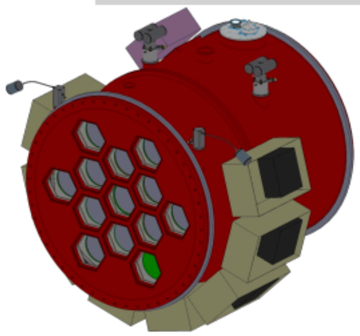
Construction underway

2017 2018 2019

Simons Observatory Schedule

Large Aperture telescope construction by VERTEX



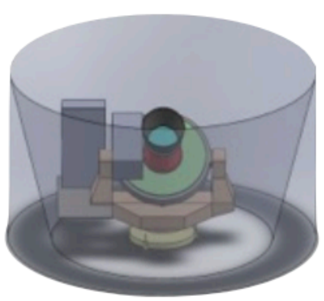


Large Aperture Receiver Design | Manufacture | Cryo-genic test | integration and test | ship and testing

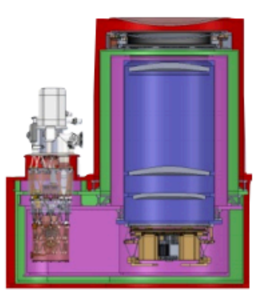
scientific observations

2018 — 2019 — 2020 — 2021 …… 2026

First SAT on sky 2020



Small Aperture Platform Design | Platform Fabrication | accep-tance test | ship | install and test



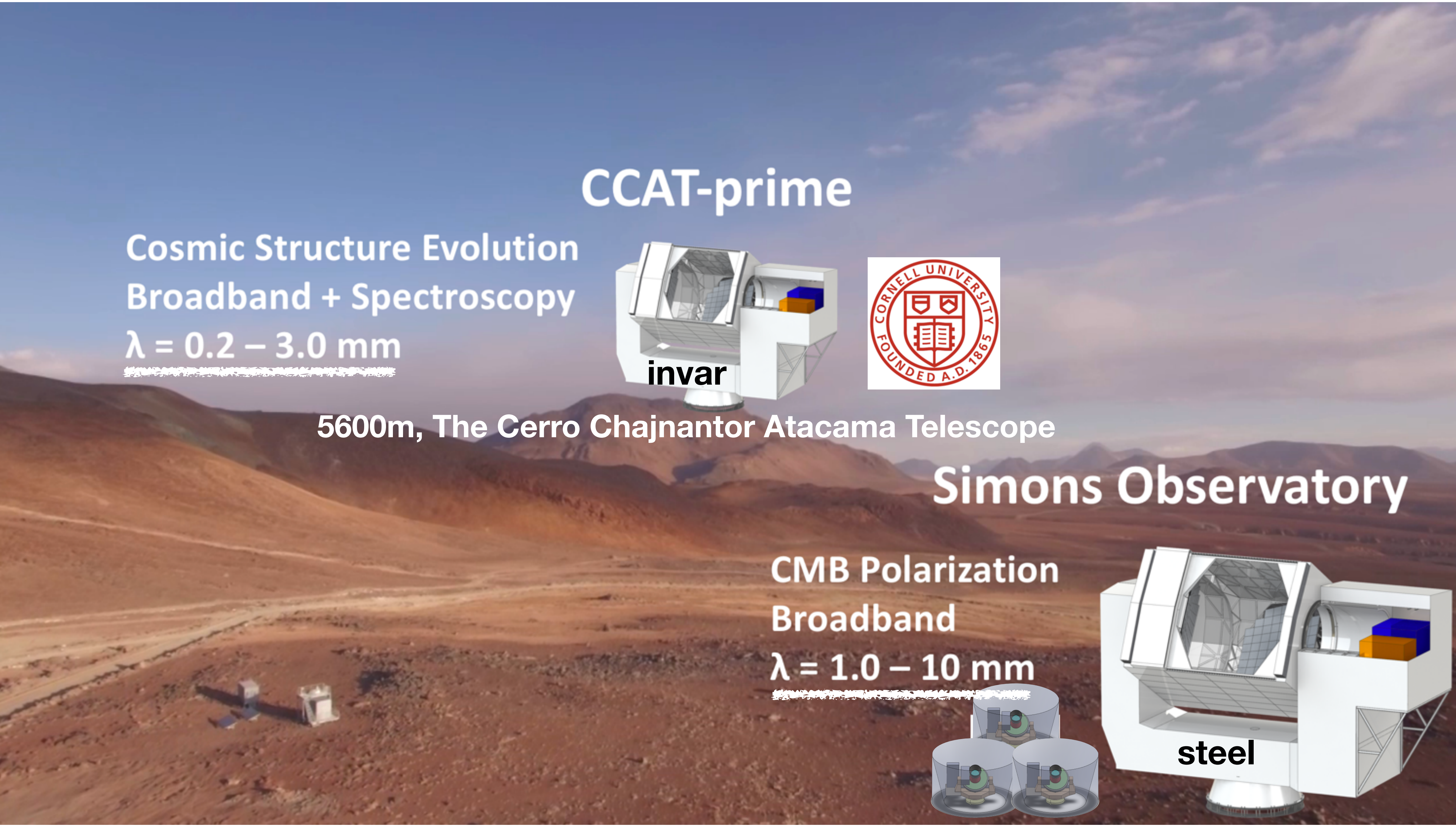
Small Aperture Camera Design | Manufacture | Cryo-genic test | integration and test | ship and testing

scientific observations

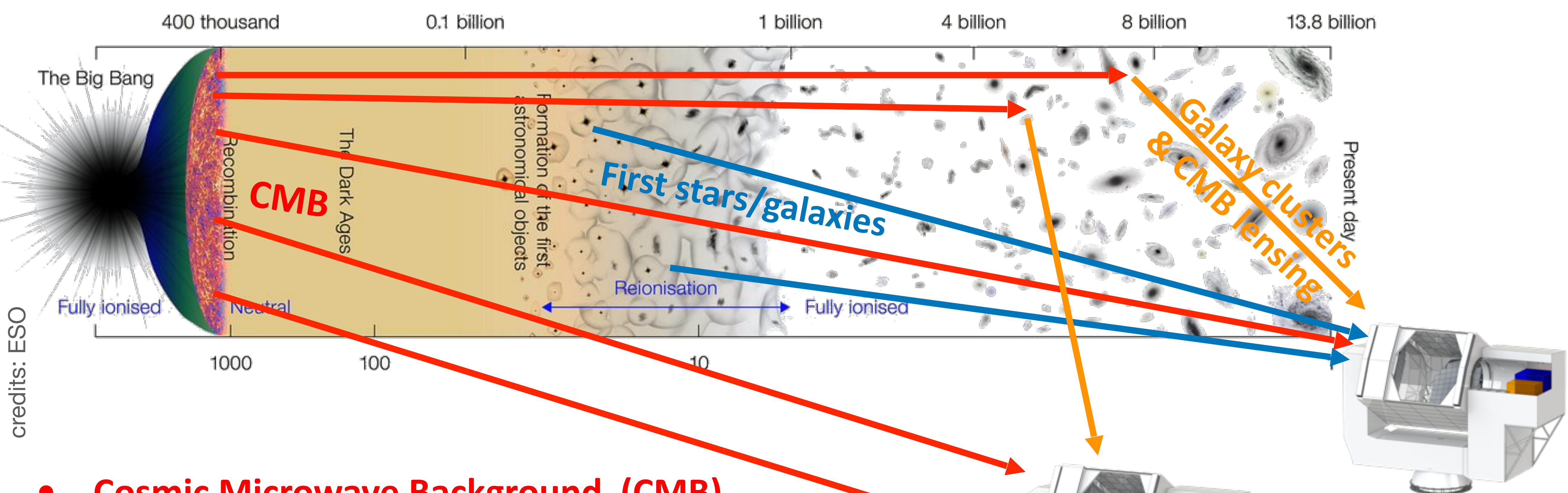
- site design and construction
- analysis pipeline development
- calibration strategy
- etc.

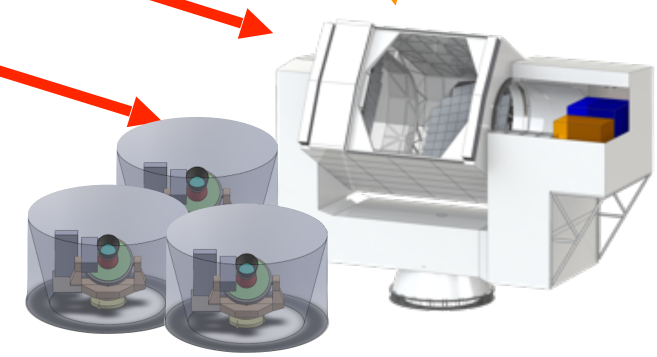
125 M$

Upcoming Atacama Telescopes



CMB and Cosmic Structure Science





- **Cosmic Microwave Background (CMB)**
  - **Probing inflation immediately after the big bang, dark matter, cosmology**

    Primary SO goal, Secondary CCAT goal
- **Galaxy clusters & CMB lensing**
  - **Measuring structures via effects on the CMB & characterizing dark energy**

    Primary CCAT and SO goals
- **First stars/galaxies**
  - **Spectroscopic measurements of ionized carbon from the first galaxies.**

    Primary CCAT goal

CCAT-prime

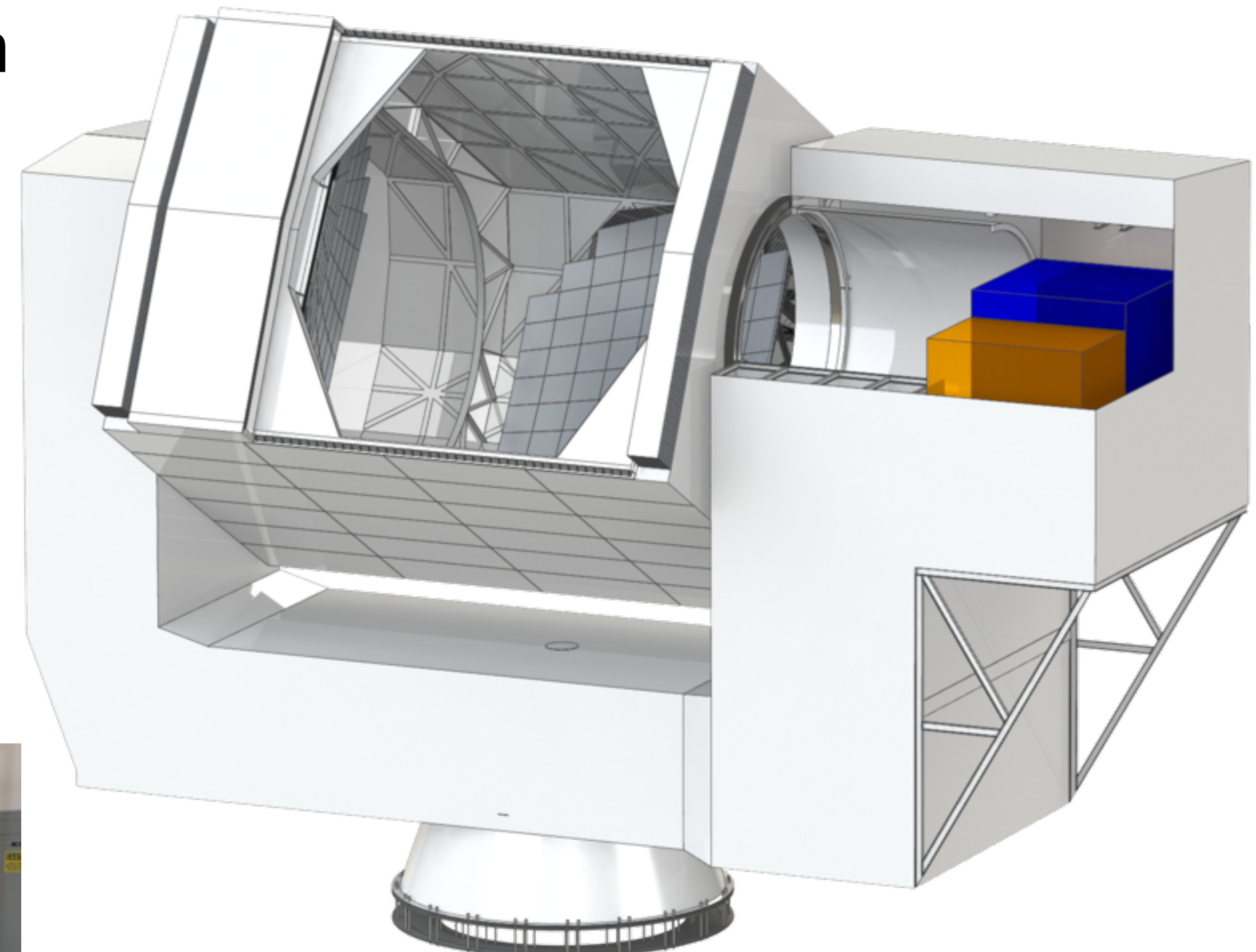
A Large Aperture Telescope that can map the CMB 10x faster

Director: Terry Herter, Cornell   *http://www.ccatobservatory.org/*

- 6m telescope similar to SO LAT but with lower coefficiency of thermal expansion (CET) material for short wavelengths.

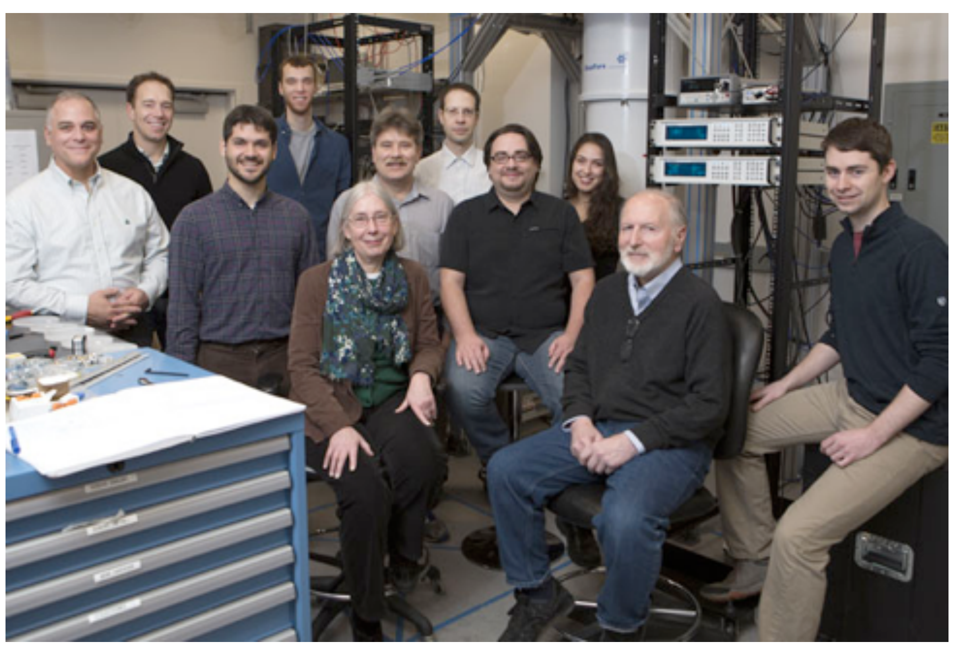
Mike Niemack arXiv:1511.04506
Stacey et al arXiv:1807.04354
Vavagiakis et al arXiv:1807.00058

- Higher elevation for sub-millimeter observations.
- First light in 2021



Telescope vendor: Vertex GmBH

some of my colleagues



- **CCAT-prime consortium: Cornell, U. Cologne, U. Bonn, Max Planck, Canadian University consortium, Chilean Universities, ++**

Slide from CCAT collaboration, Michael Niemack

CMB-S4

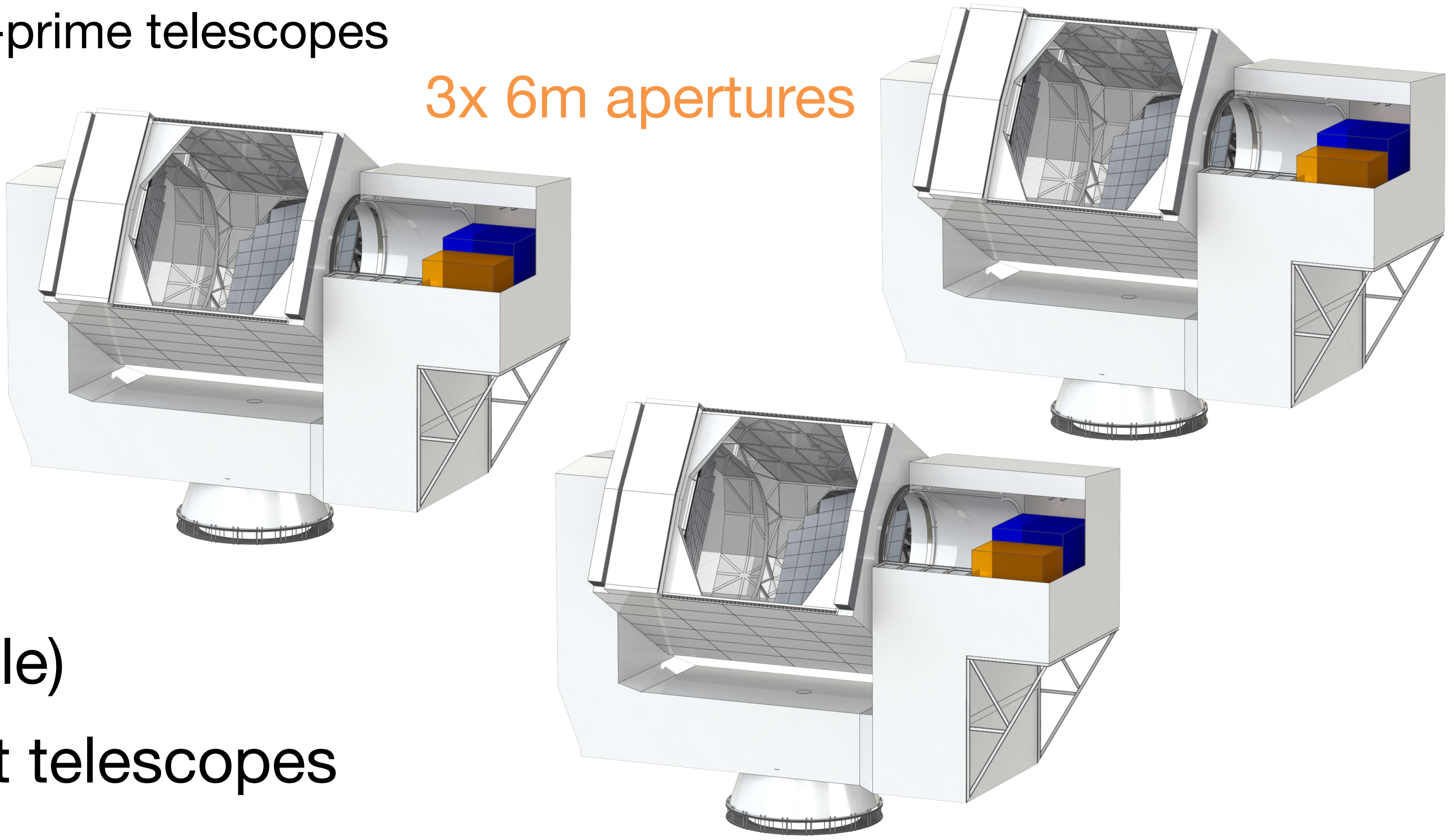
Collaboration formed 2018

https://cmb-s4.org/

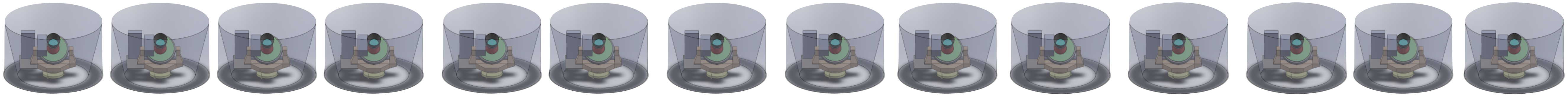
Primarily: SO (ACT + Polarbear) and South Pole Observatory (BICEP/Keck + SPT) plus CCAT-prime

- Science: Inflationary Gravity Waves, Light Relics, Large Scale Structure
- CMB-S4 Reference Design
  - Could use Simons Observatory & CCAT-prime telescopes
- Survey outline:
  - ~40% sky survey for N_{eff}
  - ~10% sky survey for r
  - Roughly 400 000 detectors!
  - Multiple sites (Chile & South Pole)
  - Multiple high optical throughput telescopes

3x 6m apertures



14x 0.5m apertures



Science Targets $r, N_{eff}, m_{\nu}, \sigma_8$, reionization

SIMONS OBSERVATORY
PARQUE ASTRONÓMICO ATACAMA, CHILE
22°57' S, 67°47' W
ELEVATION: 5190m
www.simonsobservatory.org

★ SO SAT first light 2020

★ SO LAT first light 2021

CCAT-prime

★ CCAT-prime first light 2021

Thanks!

CMB-S4
Next Generation CMB Experiment

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QUY NHON VIETNAM