

Observing the CMB with Simons Observatory and satellites across the EM spectrum

Mike Peel

14 November 2023

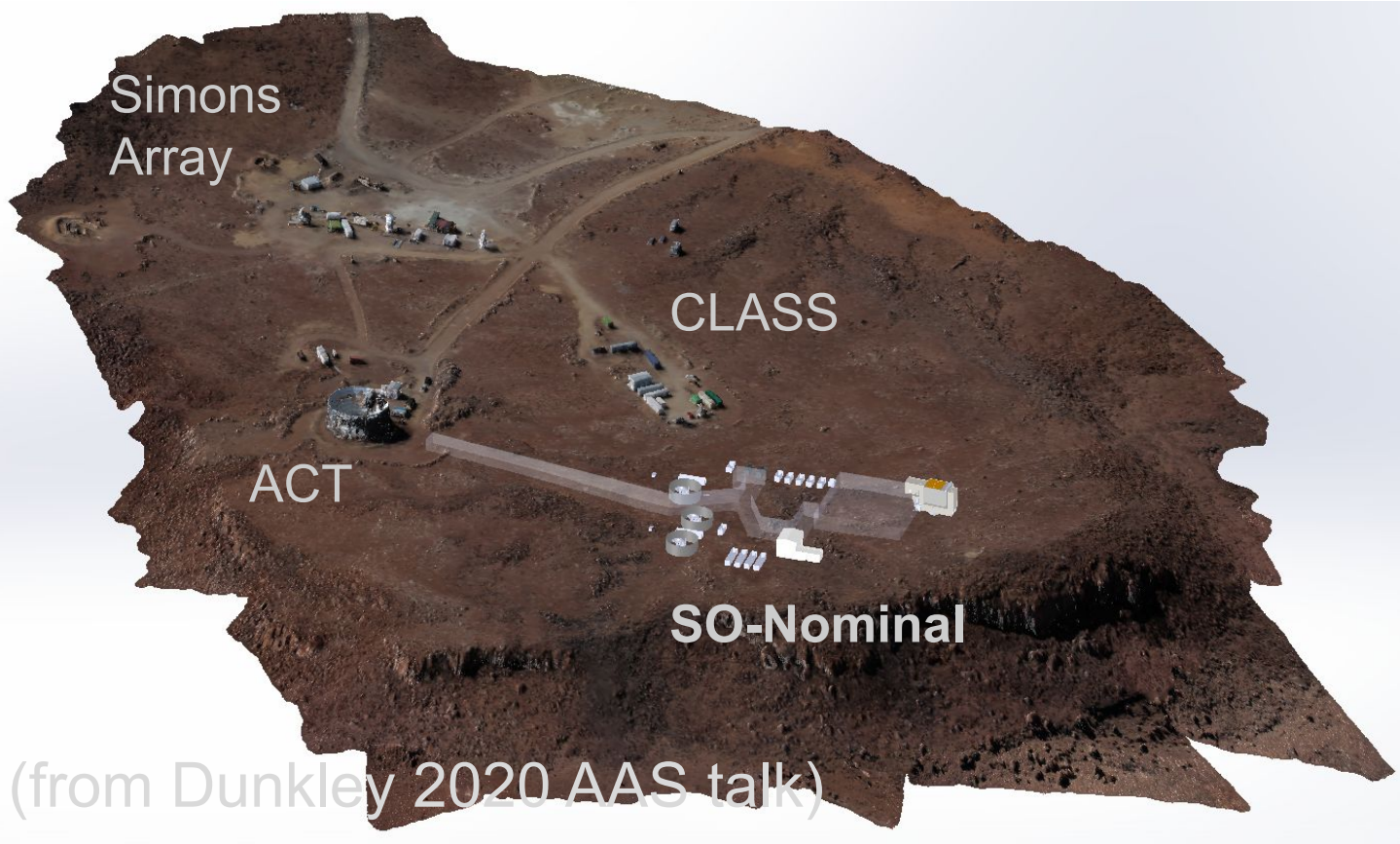
INPE, São Jose dos Campos, Brasil

Overview

1. Overview of Simons Observatory
2. Identifying transient events with SO
3. Satellites across the electromagnetic spectrum
4. Questions?

Overview of Simons Observatory

SO Site in Chile: Next to Existing Telescopes



5,200 meters

high and dry

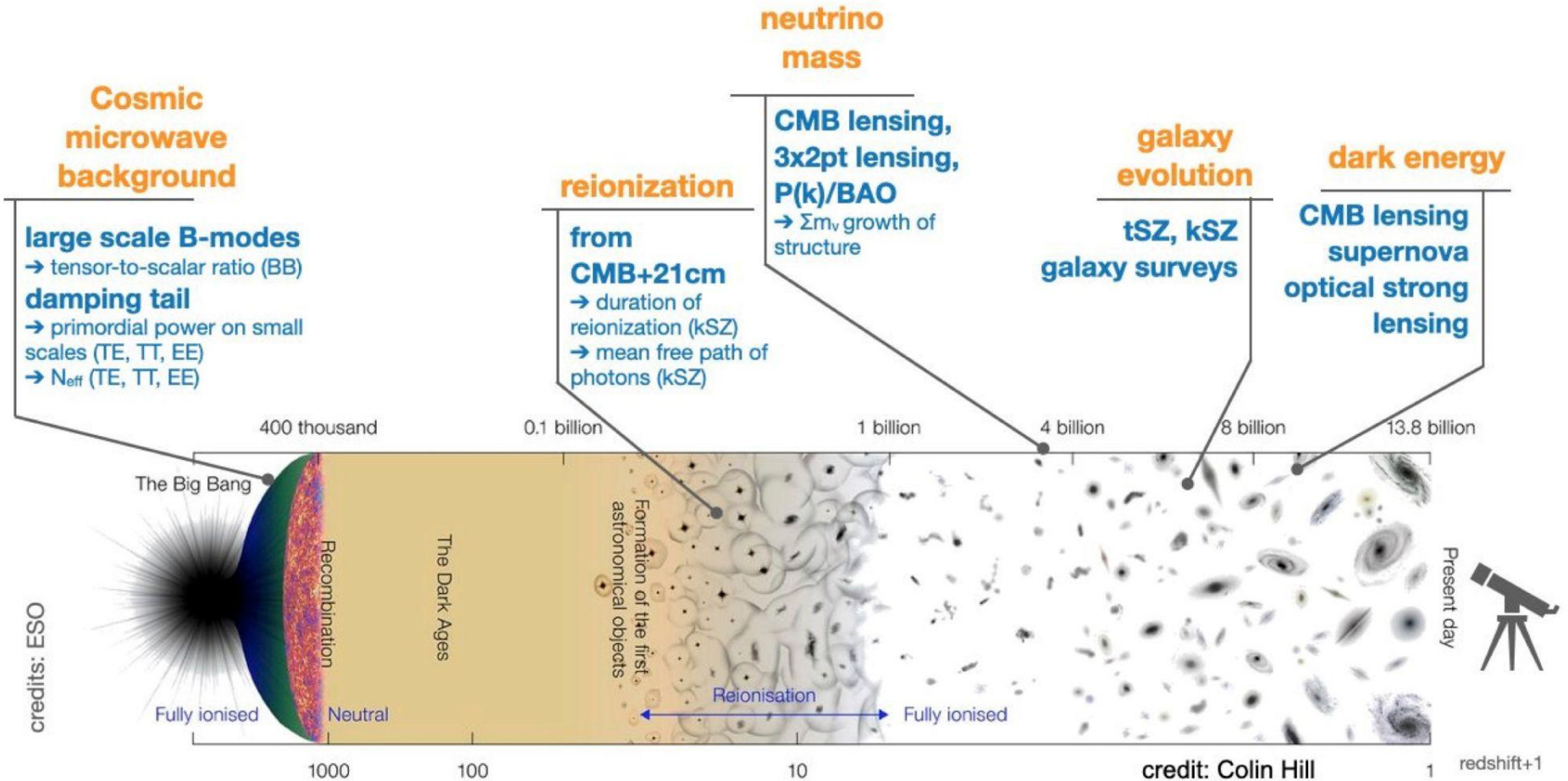
23 degree
South Latitude

Established
site

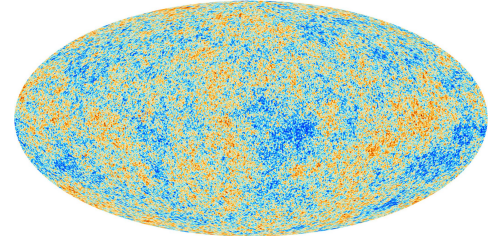
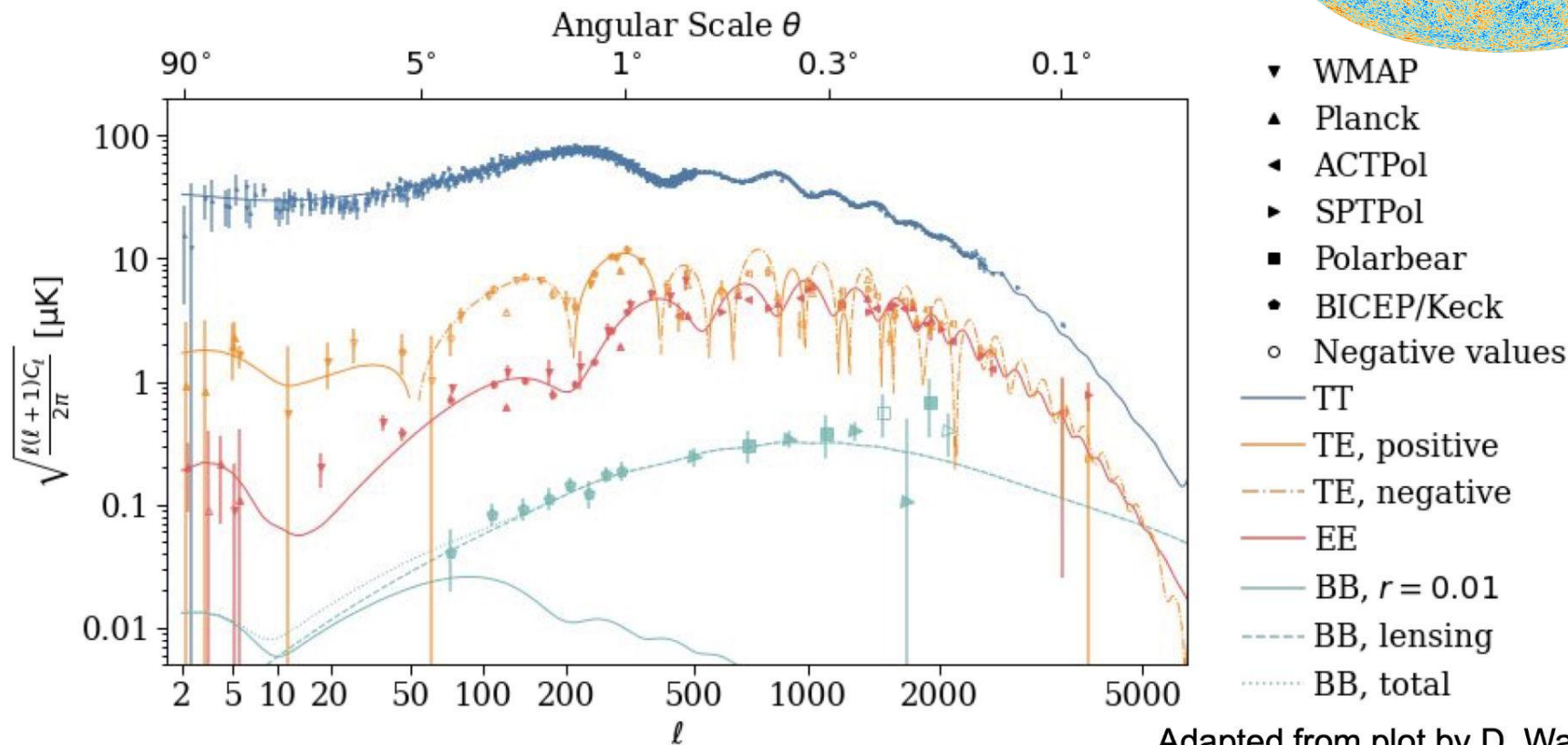
Room for
expansion

(from Dunkley 2020 AAS talk)

Cosmology with the CMB



CMB Power Spectrum



Adapted from plot by D. Watts

Member Institutions

10 Countries
40+ Institutions
300+ Researchers

Europe

- APC – France
- Cambridge University
- Cardiff University
- Imperial College
- Manchester University
- Oxford University
- SISSA – Italy
- University of Sussex
- Stockholm University

Middle East

- Tel Aviv

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

Australia

- Melbourne

(from Lee/Staggs Astro2020 talk)

Canada

- CITA/Toronto
- Dunlap Institute/Toronto
- McGill University
- Perimeter Institute
- University of British Columbia

Japan

- KEK
- IPMU
- Tohoku
- Tokyo
- Kyoto

Chile

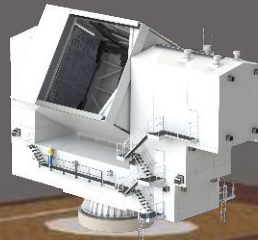
- Pontificia Universidad Catolica
- University of Chile

South Africa

- Kwazulu-Natal, SA

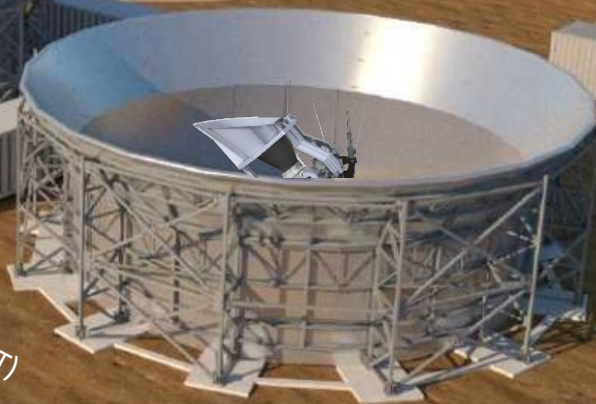
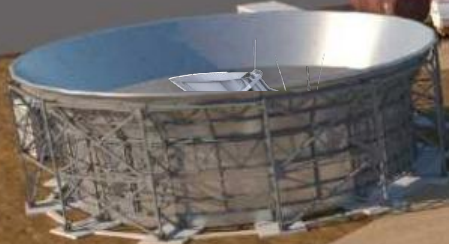
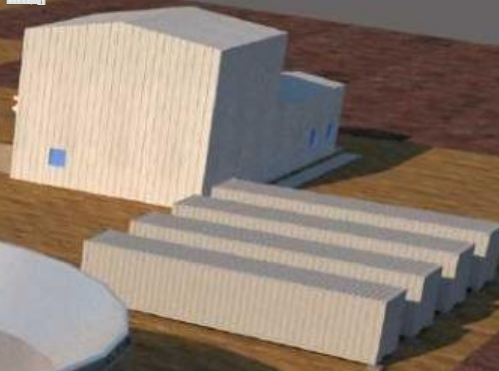
The Simons Observatory

Power Generation



Large Aperture Telescope (LAT)

High bay and Control Room



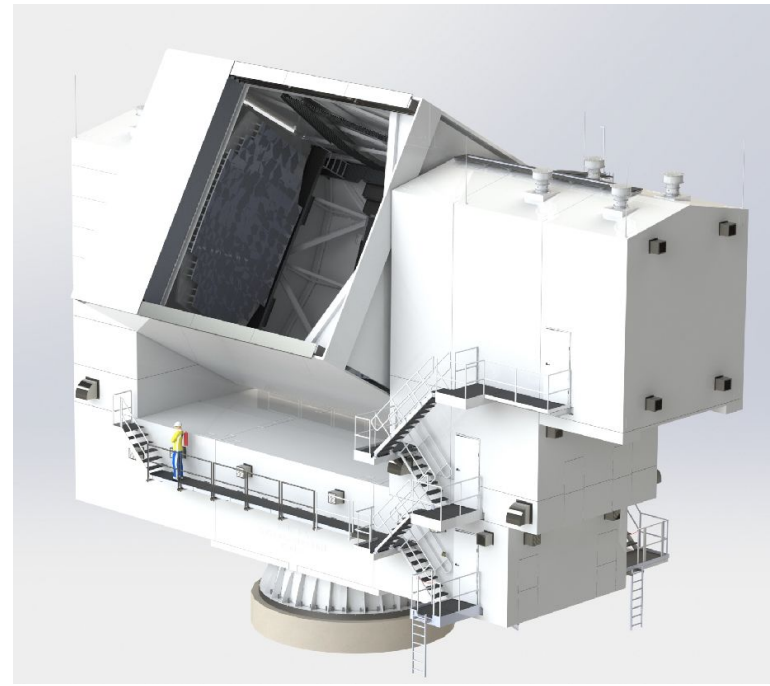
Small Aperture Telescopes (SAT)



Located at 5200 meters in Northern Chile

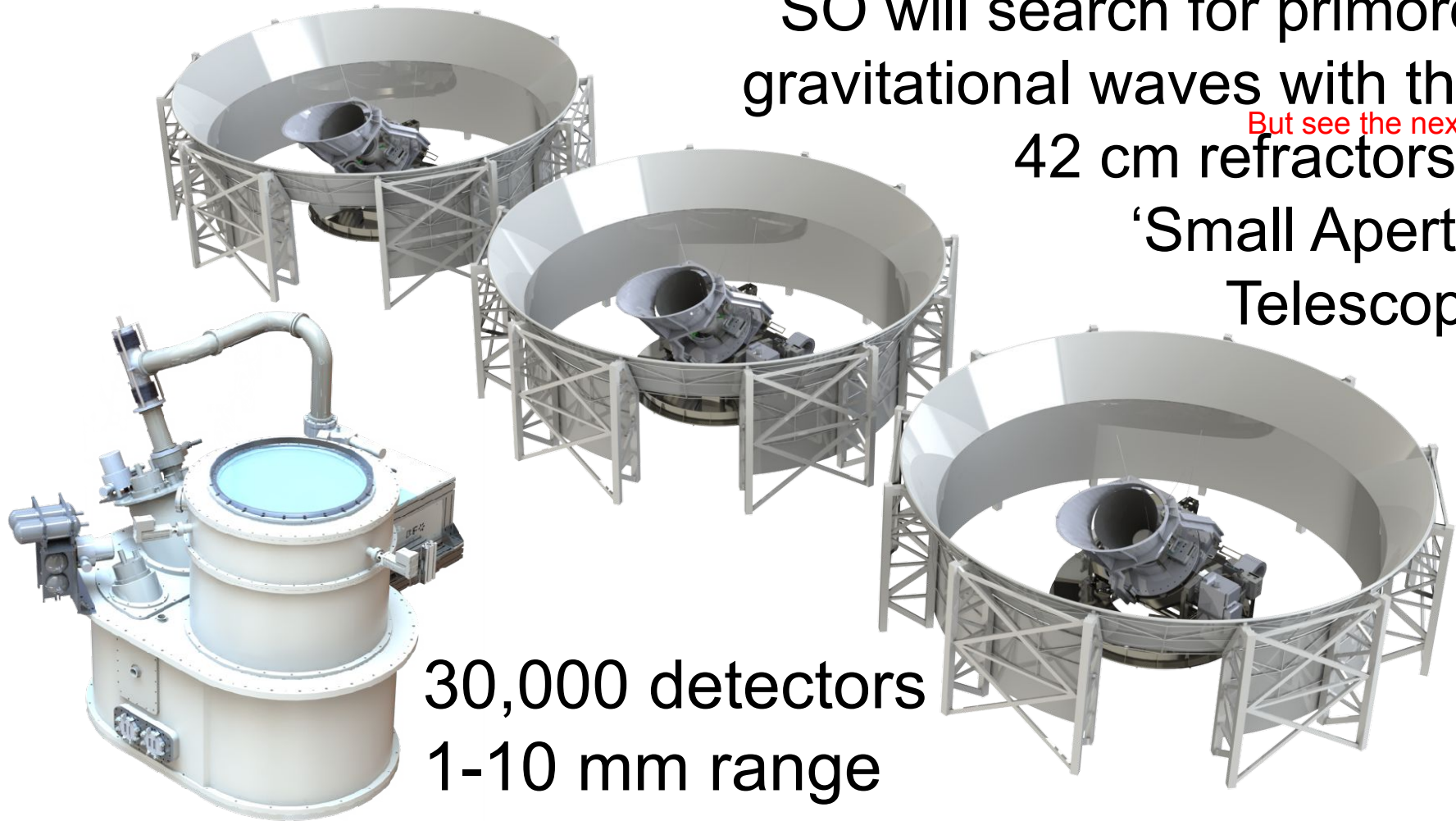


SO Construction is Underway



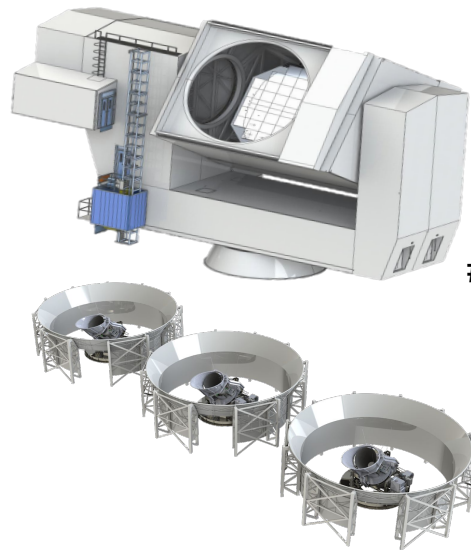
New 6-meter-primary telescope
Detectors measure 6 wavelength bands:
1-10 mm (30-280 GHz)
>30,000 Transition Edge Sensor detectors₉

SO will search for primordial
gravitational waves with three
42 cm refractors, or
But see the next slide...
'Small Aperture
Telescopes'

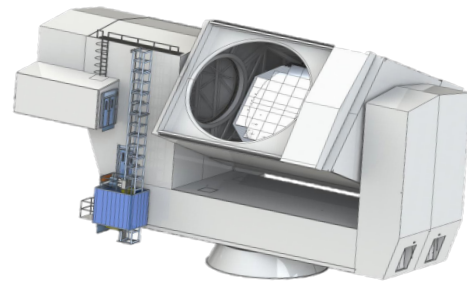
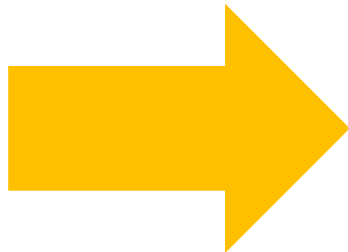


30,000 detectors
1-10 mm range

+3 SATs with UK and Japan funds



#optics tube
7/13



#optics tube
(7+1)/13

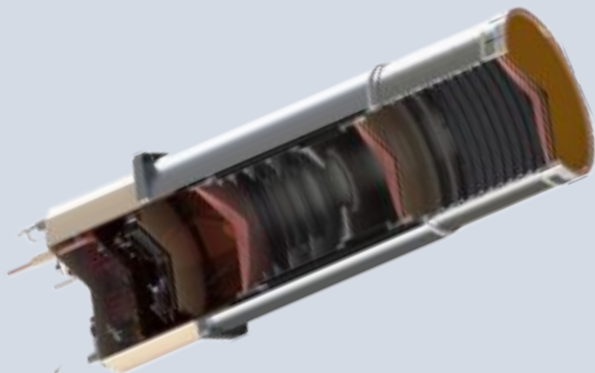
Twice better sensitivity to primordial
gravitational waves

2023~

2026~

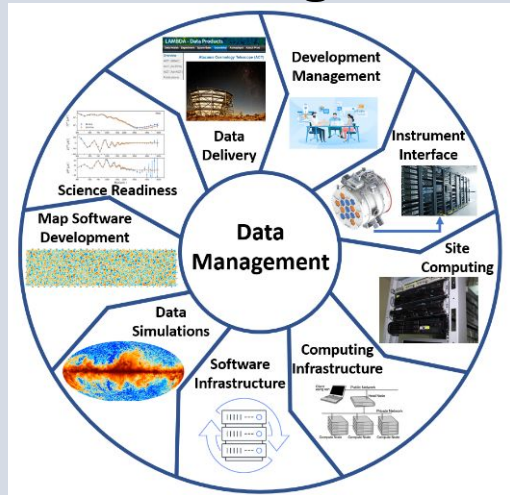
Advanced SO – Project Definition

Optics Tubes



- Six New Optics Tubes
- Double Mapping Speed
- Enable Transient Detection
- No Development Required

Data Management



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

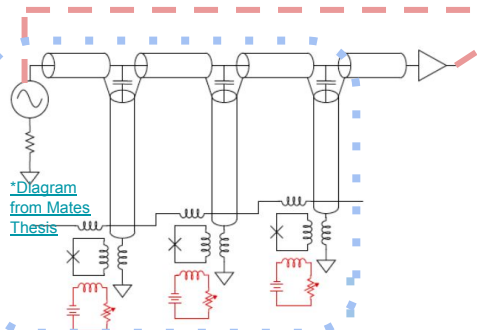
Photo Voltaic Array



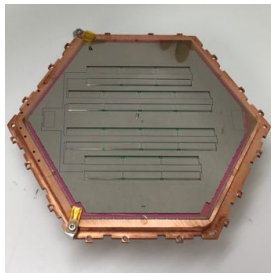
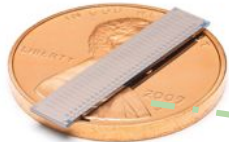
- 9% increase in Observing Efficiency
- Reduced Carbon Footprint
- Reduced Maintenance Costs



Simons Observatory Readout (1/2)



Superconducting Multiplexer Chip (fabricated at NIST)

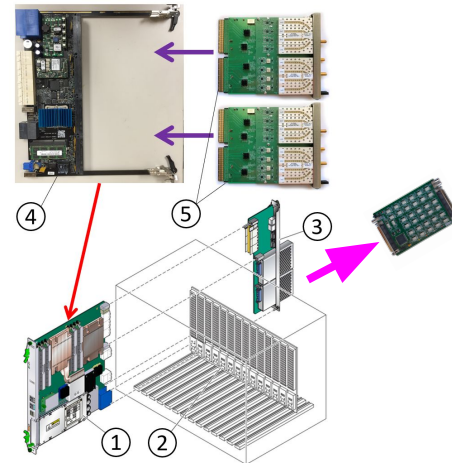
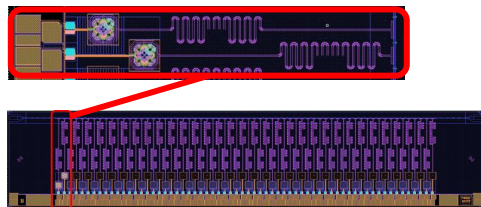


uMux modules: 100 mK focal plane readout assembly with 1848 channels, 1000x mux.

Microwave SQUID Multiplexing

- 1000x multiplexing factor
- 2 in/out coax lines per MF/UHF detector array
- <10% increase in array NET from readout noise.
- Flux ramp modulation minimizes coupling to readout 1/f noise sources
- Tone tracking readout maximizes system linearity

Mux Chip $\lambda/4$ Resonators + SQUIDs

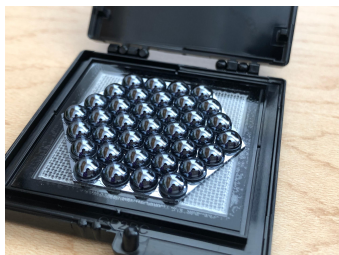
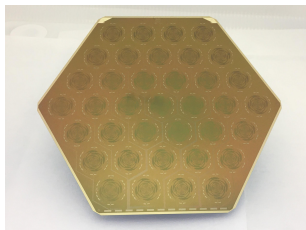


Room temperature SMuRF Electronics. Generate + digitize probe tones and apply amplifier, squid, and detector biases (designed + fabricated at SLAC)

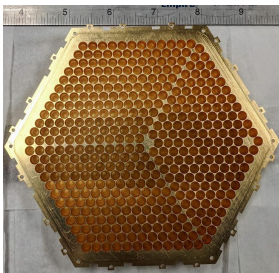
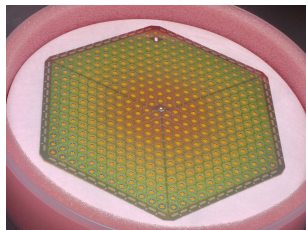


Simons Observatory Detectors (2/2)

Low frequency (LF) detector arrays & lenslets



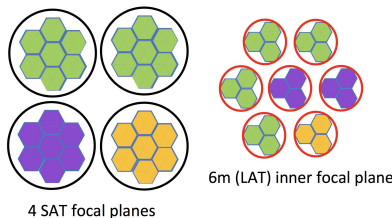
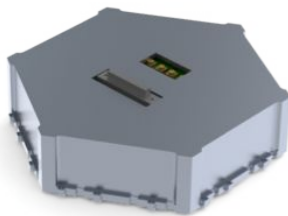
Mid frequency (MF) and ultra-high frequency (UHF) detector & horn arrays



SO will use **dual-polarization, dichroic TES bolometer detectors**, cooled to 100 mK. The LF detector arrays build on the proven performance of POLARBEAR and the MF and UHF on ACT.

Note: UK SATs + LAT tube will use KIDs not TES's, these are being developed at Cardiff

Detector modules

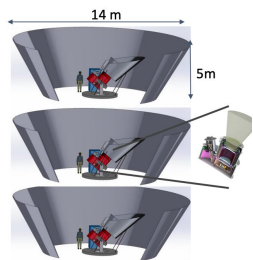


Top: The **universal focal-plane modules** (UFMs) contain the cold readout, detectors, and optical coupling. Bottom: UFM frequency distribution (*green:MF, purple:UHF, yellow:LF*).

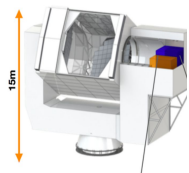
SO detectors

- >60,000 TES bolometer detectors across the LATR and four SATs
- Spanning six spectral bands centered between 27-270 GHz.
- Focal planes are populated with close-packed UFMs.
- The UFMs are common to the SATs and LATR and maintain a common footprint across frequency bands.

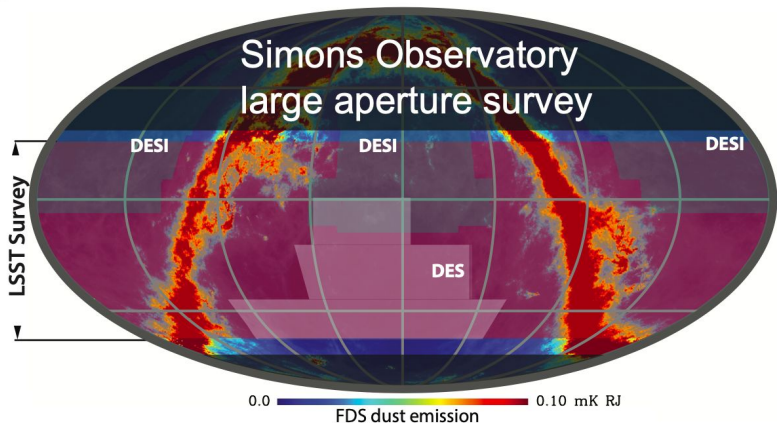
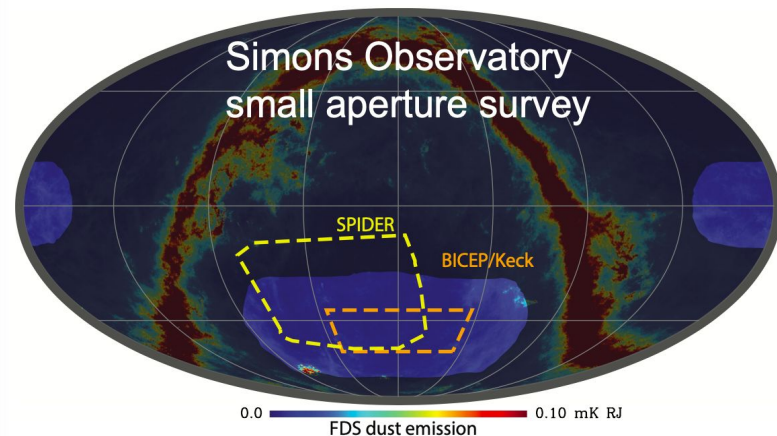
SO Surveys



Freq. [GHz]	FWHM (')	SATs ($f_{\text{sky}} = 0.1$)	
		Noise (baseline) [$\mu\text{K-arcmin}$]	Noise (goal) [$\mu\text{K-arcmin}$]
27	91	35	25
39	63	21	17
93	30	2.6	1.9
145	17	3.3	2.1
225	11	6.3	4.2
280	9	16	10



Freq. [GHz]	FWHM (')	LAT ($f_{\text{sky}} = 0.4$)	
		Noise (baseline) [$\mu\text{K-arcmin}$]	Noise (goal) [$\mu\text{K-arcmin}$]
27	7.4	71	52
39	5.1	36	27
93	2.2	8.0	5.8
145	1.4	10	6.3
225	1.0	22	15
280	0.9	54	37

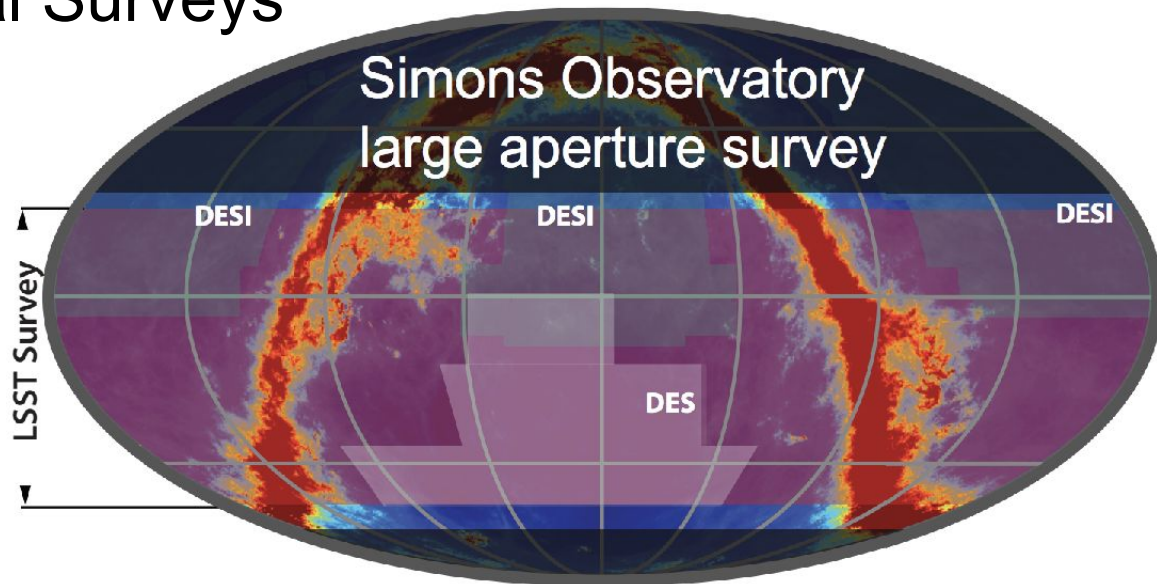


SO Synergy with Optical Surveys

SO's 2023-28 observing timeline overlaps with Rubin Observatory, DESI, Euclid

CMB and optical surveys both measure large-scale matter and baryon distribution.

Better together!
Growth of cosmic structure, constraints on baryonic feedback, calibrating systematic effects...



ACT and SO are community oriented.
Regular planned releases of maps, catalogs, likelihoods on NASA LAMBDA and/or other platforms

Code, notebooks and tutorials: to read and manipulate maps, and to train students

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 Science Goals

From: The Simons Observatory:
science goals and forecasts

Peter Ade, et al.,
JCAP02 (2019)
056

<https://ui.adsabs.harvard.edu/abs/2019JCAP...02..056A/abstract>

Parameter		SO-Baseline ^a (no syst)	SO-Baseline ^b	SO-Goal ^c	Current ^d (2018-19)	Method	Sec.
Primordial perturbations	r	0.0024	0.003	0.002	0.03	$BB + \text{ext delens}$	3.4
	$e^{-2\tau}\mathcal{P}(k=0.2/\text{Mpc})$	0.4%	0.5%	0.4%	3%	$TT/TE/EE$	4.2
	$f_{\text{NL}}^{\text{local}}$	1.8	3	1	5	$\kappa\kappa \times \text{LSST-LSS} + 3\text{-pt}$	5.3
		1	2	1		kSZ + LSST-LSS	7.5
Relativistic species	N_{eff}	0.055	0.07	0.05	0.2	$TT/TE/EE + \kappa\kappa$	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		tSZ-N \times LSST-WL	7.1
		0.036	0.05	0.04		tSZ-Y + DESI-BAO	7.2
Deviations from Λ	$\sigma_8(z=1-2)$	1.2%	2%	1%	7%	$\kappa\kappa + \text{LSST-LSS}$	5.3
		1.2%	2%	1%		tSZ-N \times LSST-WL	7.1
	$H_0 (\Lambda\text{CDM})$	0.3	0.4	0.3	0.5	$TT/TE/EE + \kappa\kappa$	4.3
Galaxy evolution	η_{feedback}	2%	3%	2%	50-100%	kSZ + tSZ + DESI	7.3
	p_{nt}	6%	8%	5%	50-100%	kSZ + tSZ + DESI	7.3
Reionization	Δz	0.4	0.6	0.3	1.4	TT (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]. [44] BICEP2 and Planck collaborations, Joint Analysis of BICEP2/Keck Array and Planck Data, Phys. Rev. Lett. 114 (2015) 101301 [287] Planck collaboration, Planck 2018 results. VI. Cosmological parameters

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

Additional Goals and Data Combinations

[SO Collaboration \(2019\)](#)

Table 11
Catalogs and additional science from SO

	Parameter	SO-Baseline	Method
Legacy catalogs	SZ clusters	20,000	tSZ
	AGN	10,000	Sources
	Polarized AGN	300	Sources
	Dusty star-forming galaxies	10,000	Sources
Primordial perturbations	f_{NL} (equilateral)	30	T/E
	f_{NL} (orthogonal)	10	
	n_s	0.002	$TT/TE/EE + \kappa\kappa$
Big bang nucleosynthesis	Y_P (varying N_{eff})	0.007	$TT/TE/EE + \kappa\kappa$
	$\Omega_b h^2$ (Λ CDM)	0.00005	$TT/TE/EE + \kappa\kappa$
Dark matter	DM–baryon interaction (σ_p , MeV)	5×10^{-27}	$TT/TE/EE + \kappa\kappa$
	UL axion fraction (Ω_a/Ω_d , $m_a = 10^{-26}$ eV)	0.005	$TT/TE/EE + \kappa\kappa$
Dark energy or modified gravity	w_0	0.06	tSZ + LSST
	w_a	0.2	tSZ + LSST
	Growth rate ($\Delta(\sigma_8 f_g)/\sigma_8 f_g$)	0.1	kSZ + DESI
Shear bias calibration	$m_{z=1}$	0.007	$\kappa\kappa$ +LSST
Reionization	$\log_{10}(\lambda_{\text{mfp}})$	0.3	$TT/TE/EE$ (kSZ)
	Ionization efficiency (ζ)	40	$TT/TE/EE$ (kSZ)

Identifying transient events with SO

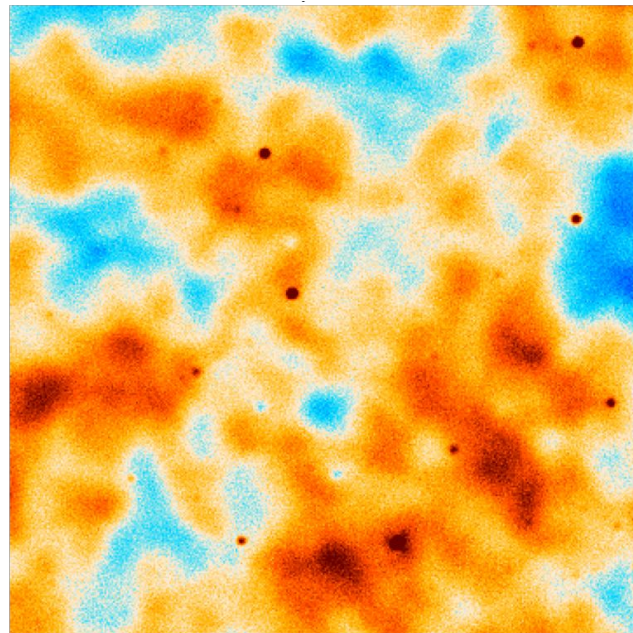
SO: New Opportunities in mm-Transient Science

Variable Active Galactic Nuclei:
track thousands daily/weekly/monthly at
1-10 mm.

Potential of mm transients:
e.g. orphan afterglows of Gamma Ray
Bursts

Potential follow-up of Rubin Observatory
optical transients

In addition to wealth of CMB science (early
and late-time signals), 30k high-z dusty
galaxies, 20k clusters and Galactic science



[[Previous](#) | [Next](#) | [ADS](#)]

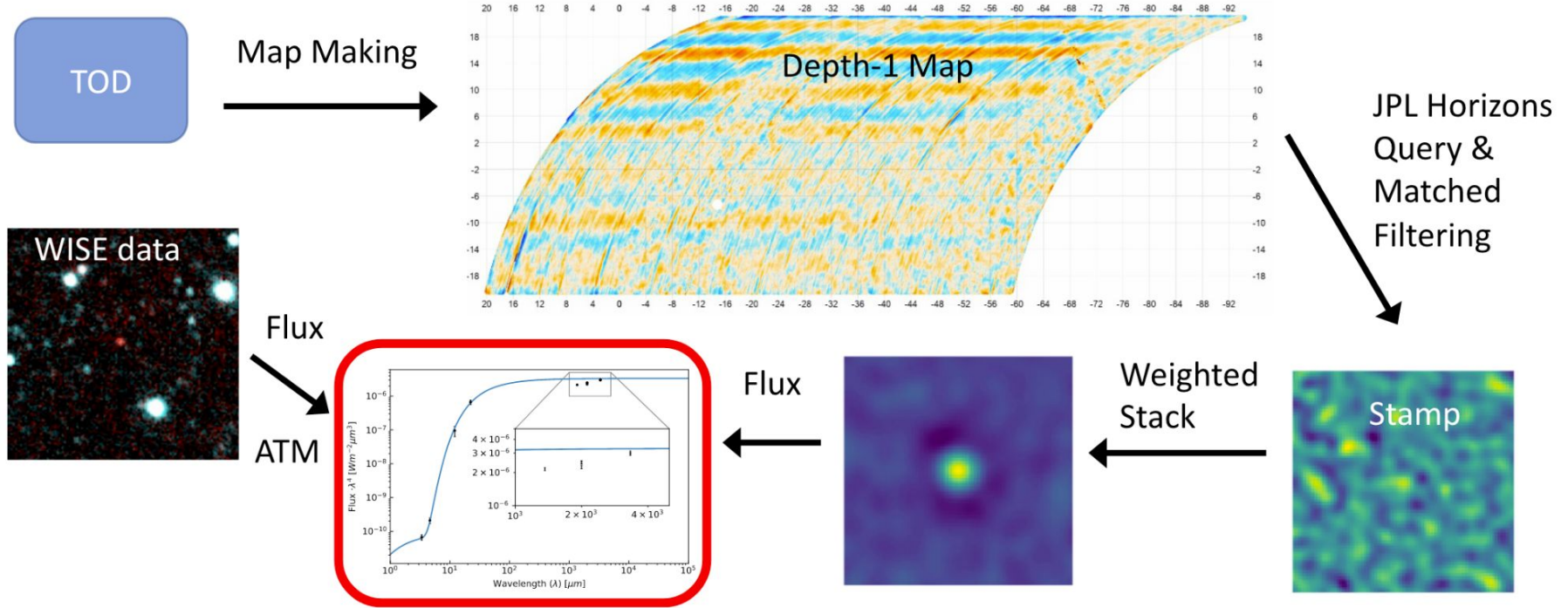
**ACT-T J061647-402140: a Strongly Variable, Flaring
Source at 90, 150 and 220 GHz Positionally Coincident
with the Transient Gamma-Ray Blazar, Fermi 0617-4026**

ATel #12738; *Sigurd Naess (Center for Computational Astrophysics, Flatiron Institute) on behalf
of the ACT Collaboration
on 8 May 2019; 23:32 UT*

Credential Certification: John P. Hughes (jph@physics.rutgers.edu)

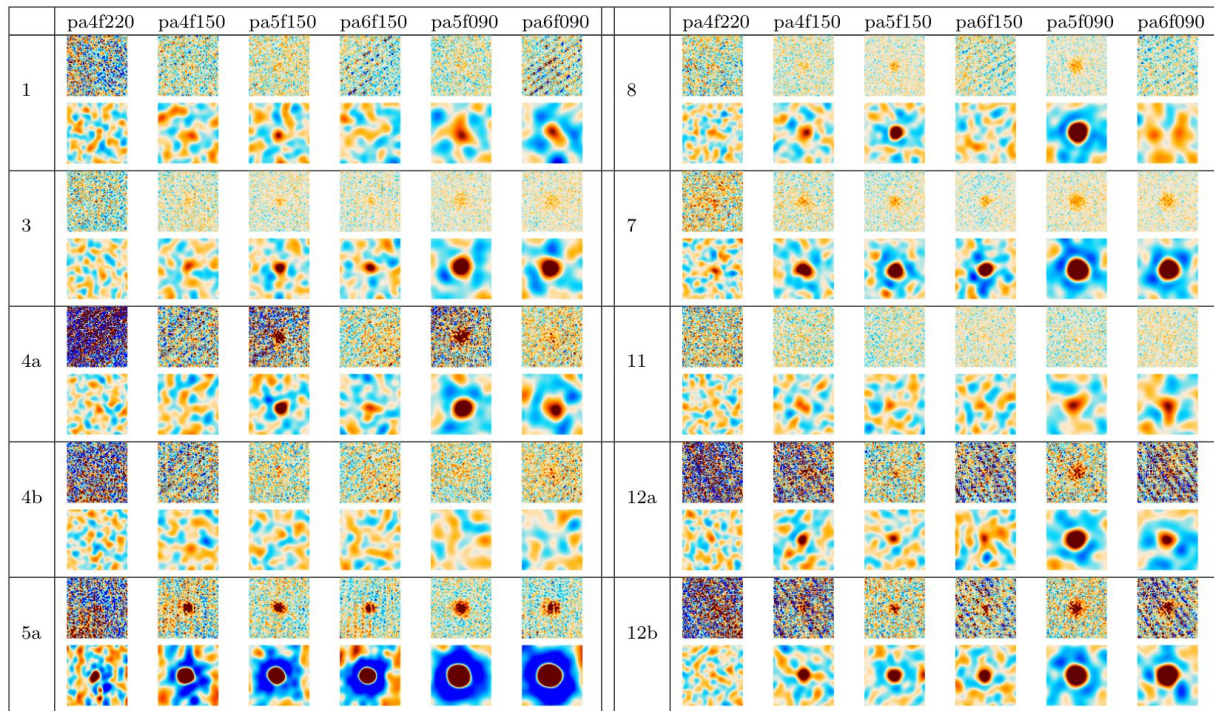
Subjects: Millimeter, Gamma Ray, AGN, Blazar, Transient, Variables

Depth-1 maps: example from Atacama Cosmology Telescope



Orlowski-Scherer et al. (2023), The Atacama Cosmology Telescope: Millimeter Observations of a Population of Asteroids or: ACTeroids, arXiv:2306.05468

3 day maps: example from Atacama Cosmology Telescope

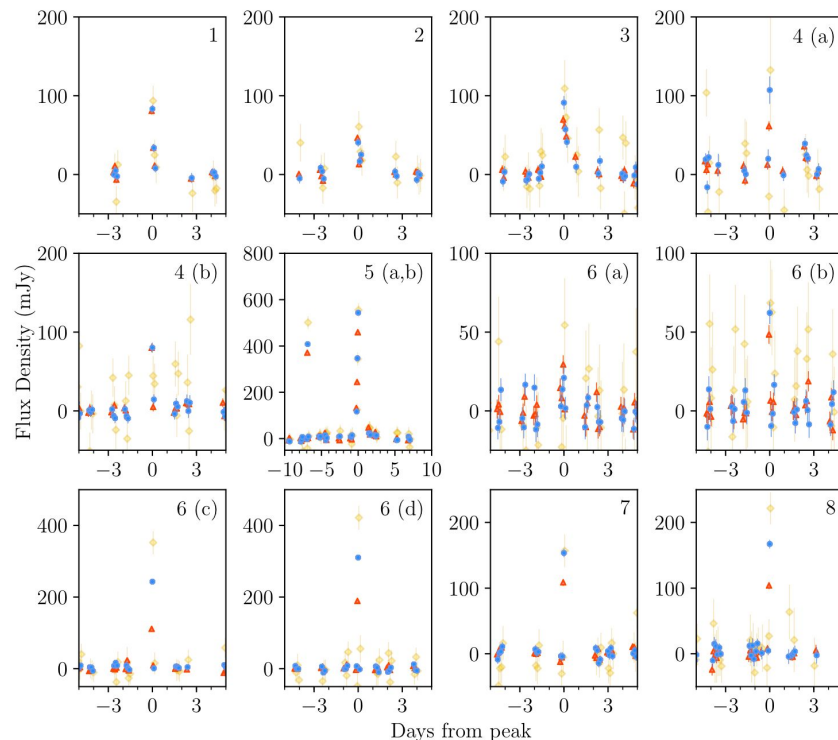


Other approaches under discussion, but could also do:

- Looking for variable sources directly in the time-ordered data
- Stacking on moving sources where positions are well known
- Follow-up of optical/radio transients identified with other surveys

Stellar flares

- Example from South Pole Telescope:
Guns et al. (2021), Detection of Galactic and Extragalactic Millimeter-Wavelength Transient Sources with SPT-3G, arXiv:2103.06166
- From variable stars, mostly known X-ray transmitters, but mix of types:
 - M dwarfs
 - RS CVn
 - BY Dra variable
 - Rotational variable
- SO will see many of these, at fainter flux density levels, and across more of the sky



Asteroids - examples from South Pole Telescope

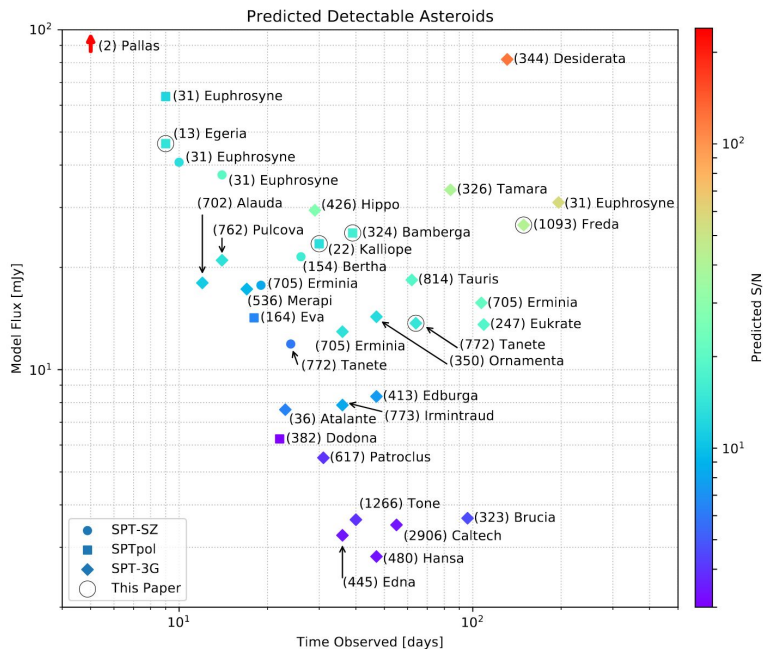


Figure 7. Objects with predicted $S/N > 3$ at 2.0 mm in all historic and planned future SPT data. We expect to observe (2) Pallas, plotted off scale, with a mean flux density near 725 mJy.

Chichura et al. (2022), Asteroid Measurements at Millimeter Wavelengths with the South Pole Telescope, arXiv:2202.01406

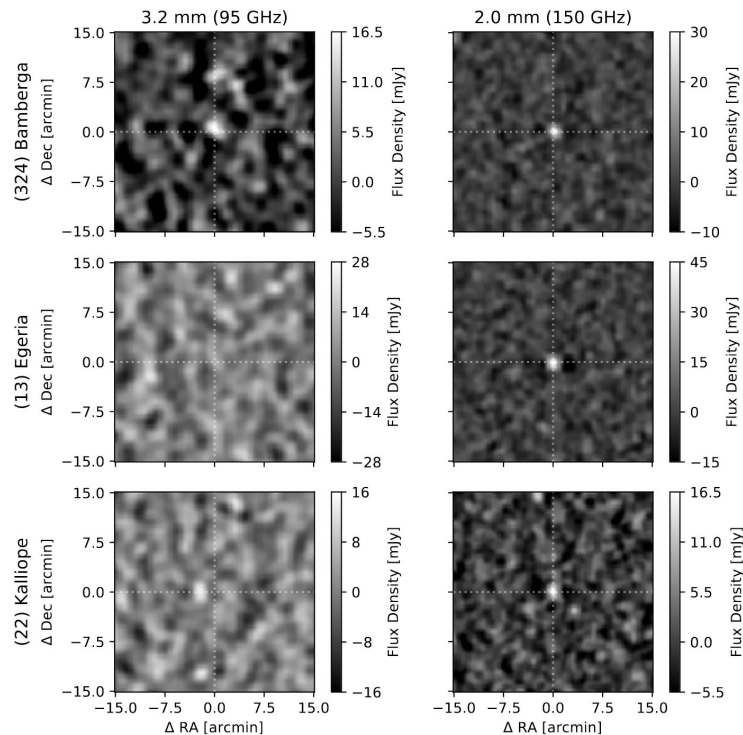
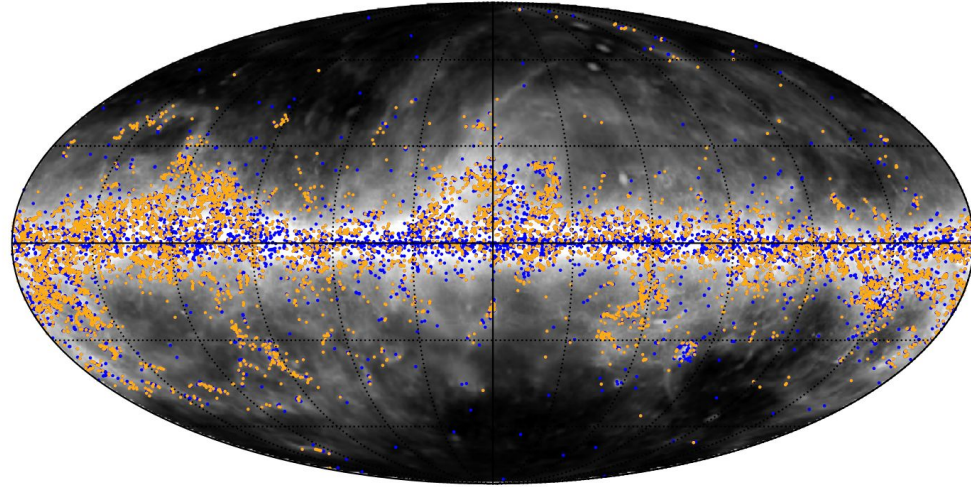


Figure 4. Mean flux measurements of (324) Bamberga (top horizontal panels), (13) Egeria (middle horizontal panels), and (22) Kalliope (bottom horizontal panels) at 3.2 mm (left vertical panels) and 2.0 mm (right vertical panels). Color scales for (13) Egeria and (22) Kalliope at 3.2 mm are set at 4-sigma levels; the rest peak near the mean flux values detected for each asteroid.

Also lots of Galactic & extragalactic sources to analyse

- E.g., Clancy et al. (2023), "Polarization fraction of Planck Galactic cold clumps and forecasts for the Simons Observatory", MNRAS (accepted), arXiv:2303.02788
- Based on Planck data, stacking analysis shows $\sim 2\%$ polarisation on average
- Expect to see $\sim 12,000$ cold clumps in intensity + ~ 430 in polarisation in SO
- Also many extragalactic sources (radio sources like quasars, thermal sources like nearby galaxies, etc.)
- (some varying, others not, but all interesting, e.g., spectral energy distributions/component separation/etc.)



Cold cores in Planck data: blue, complete set, orange, high S/N & well-separated subset used in Clancy et al. (2023)

Satellites across the electromagnetic spectrum

New IAU Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference.

Led by **NOIRLab** (USA) and **SKAO** (UK)

Open for membership (see website for link to join!)

Director: ~~Piero Benvenuti~~ Richard Green. Co-directors: Connie Walker & Federico Di Vruno. Four hubs:

- **SatHub** (leads: Meredith Rawls, Mike Peel, Siegfried Eggli)
 - Collection & analysis of satellite observations
 - Software tools
 - Training + outreach
- **Policy** (leads: Andrew Williams, Richard Green)
 - Coordinate policy action & diplomacy (COPUOS, etc.)
- **Community Engagement** (leads: John Barentine, Jessica Heim): beyond professional astronomers
- **Industry and Technology** (leads: Chris Hofer, Tim Stevenson, advisor Patricia Cooper): engaging industry



<https://cps.iau.org/>

Satellite constellations

Satellites have always been an issue for astronomy.

West Ford (1961-63) launched 480,000,000 2cm-long dipoles to reflect 8GHz (3.5cm) signals, some still in orbit - only stopped because of a global outcry.

The Iridium satellite constellation interferes with radio astronomy observations at 1.6GHz in the protected band

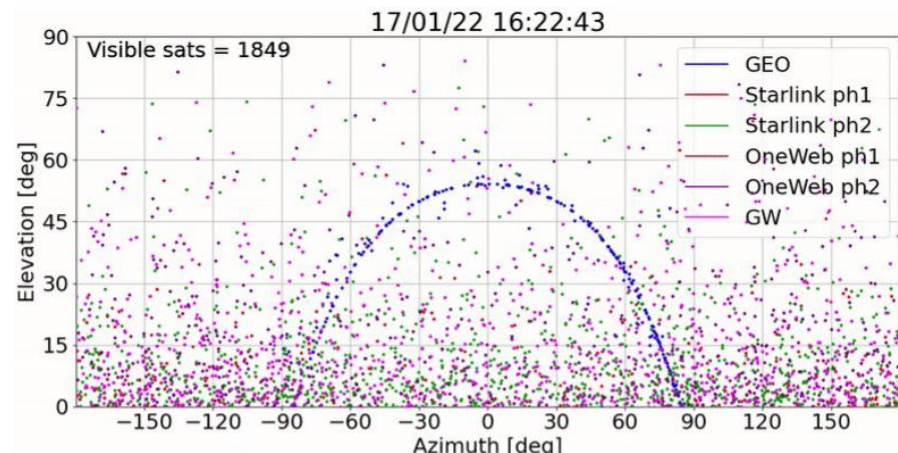
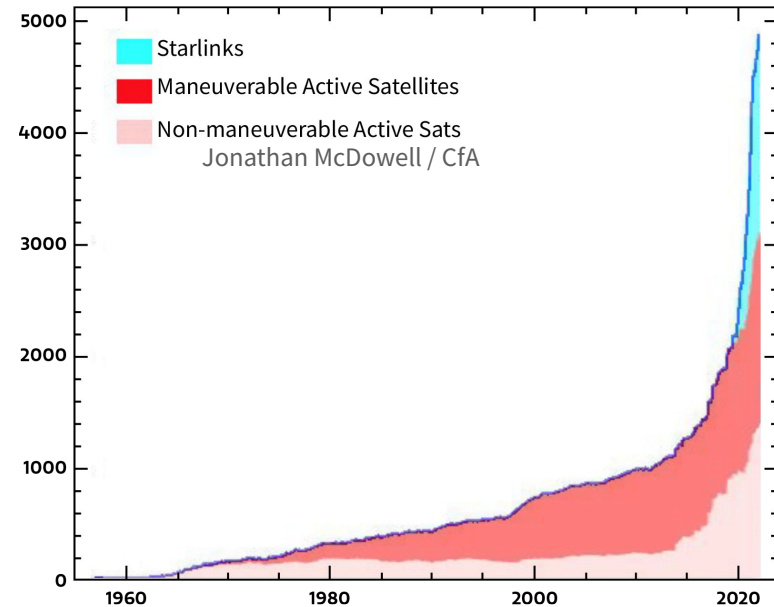
The WMAP CMB satellite is one of many that are frequently seen by optical telescopes.

... and that was before Starlink started launching in 2019. We now have **twice the number of satellites in the last 5 years**. Mostly in Low Earth Orbit (LEO)

Mega constellations came as a surprise to astronomy!

Proposals are for **over 1,000,000 new satellites in the next decade**, via Starlink/OneWeb/Kuiper/... Increasing number of companies thinking about LEO!

Also: military links (e.g., US military interest in Starlink, live demo of Starlink wartime usage in Ukraine...)



Accidental optical light

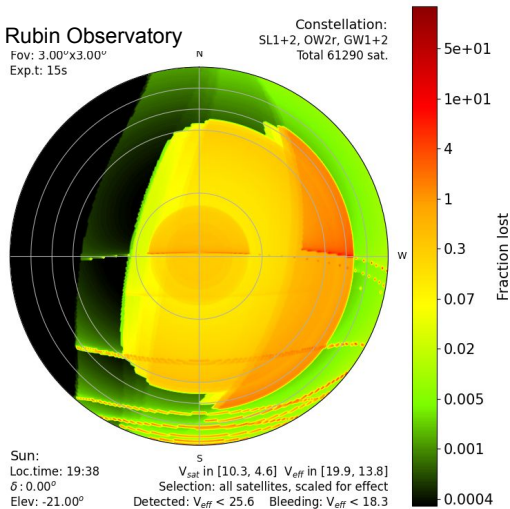
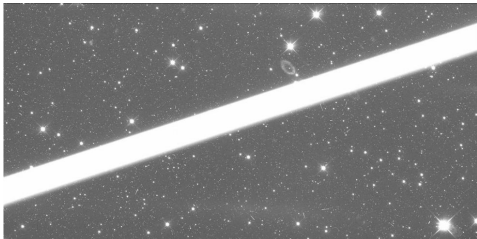
Constellations have a **significant effect in optical and infrared.**

Particularly **reflections from the sun** in late evenings / early mornings

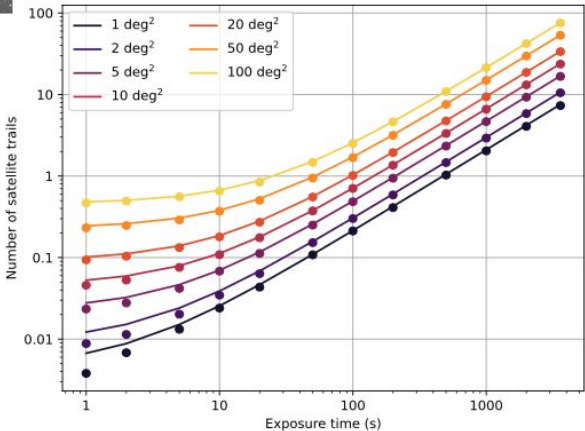
Up to $V=+3$ in parking orbits. **Need 7th magnitude** or better.

Significant effect on future optical telescope surveys like LSST with Vera C. Rubin Observatory. Even seen with Hubble...

Starlink currently launching Gen 2 mini's, heading towards Gen 2 - much larger but possibly fainter due to mitigations



SATCON2 algorithms report

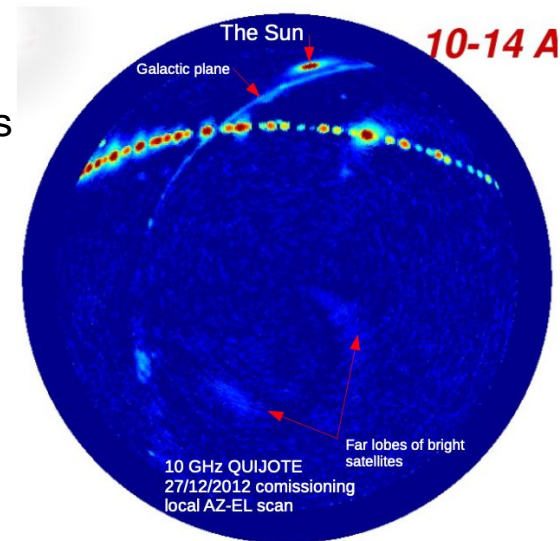
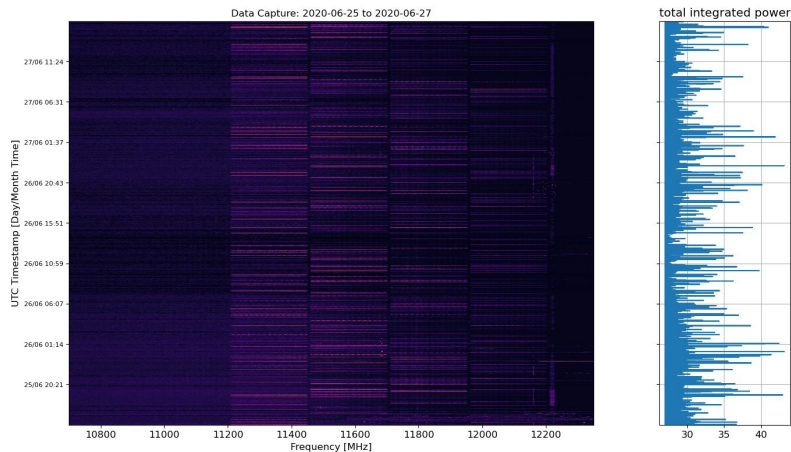


Bassa et al.
arXiv:2108.12335

Satellite	Operational altitude [km]	Mag at op. alt.	Mag dispersion	Mag at 1000km
Starlink original	550km	4.6	0.7	5.9
		4.0	0.7	5.3
		4.2	(model)	5.5
Starlink DarkSat	550km	5.1	(single)	6.4
Starlink VisorSat	550km	6.2	0.8	7.5
		5.8	0.6	7.1
OneWeb	1200	7.6	0.7	7.2

Potential impact at radio frequencies

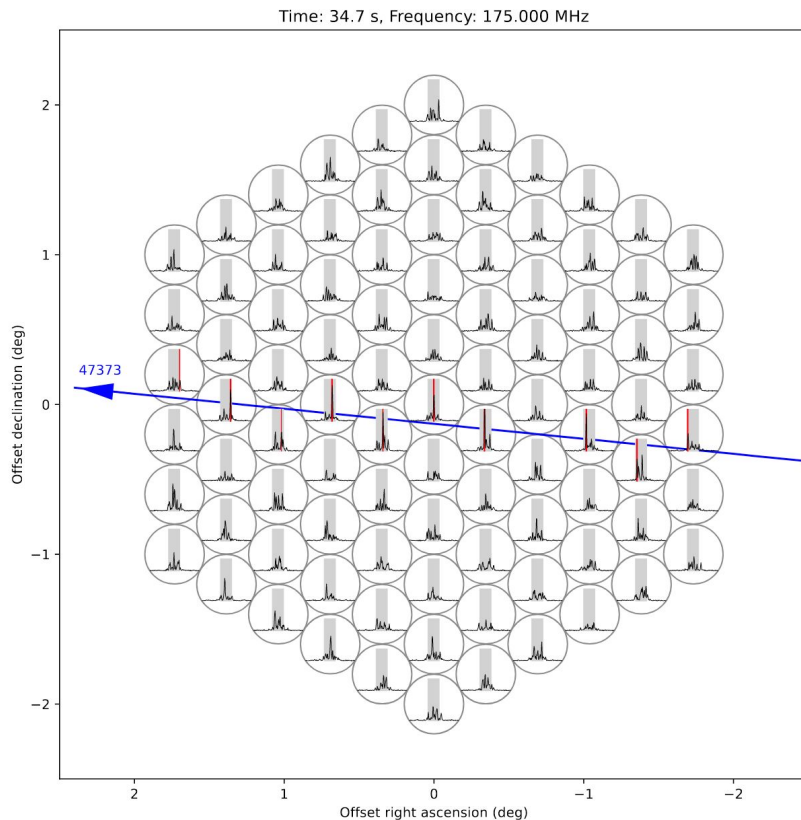
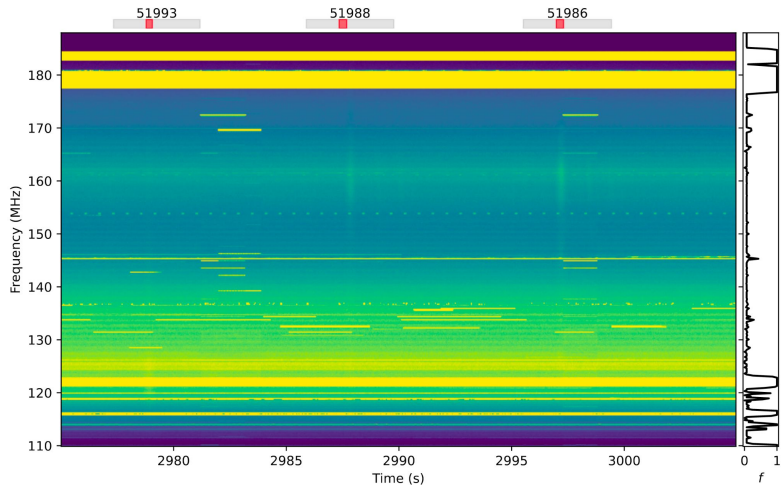
- We don't know much yet - need observations to assess actual impact
- Active 10-20GHz transmissions - plus 40GHz soon? (and octaves!)
- (Latest Starlink filing of ~30k satellites from Tonga is 120-180GHz!)
- Sidelobe coupling also a concern, particularly for CMB experiments
- Difficult to filter out with broadband detectors, unless using FPGAs
- Highly variable - need to accurately know satellite positions, or see as transients?



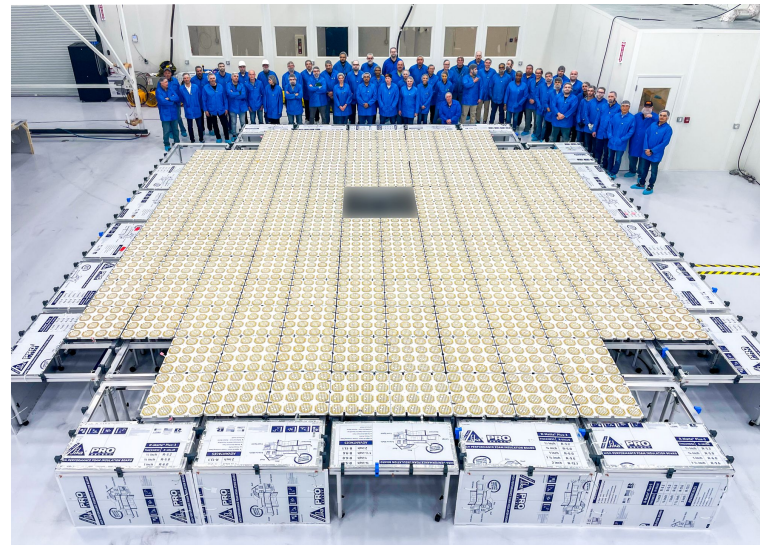
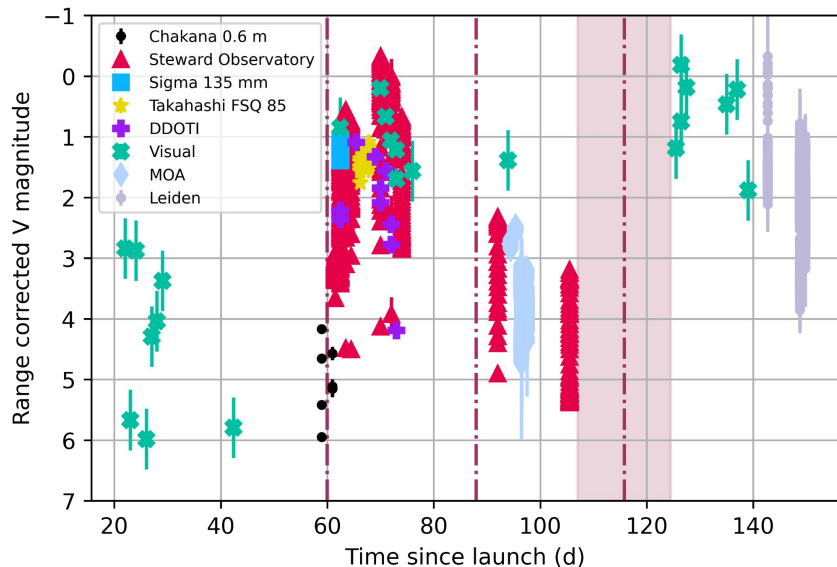
Above: QUIJOTE 10-14GHz observations from Tenerife in 2012 - pre-starlink.
Left: satellite dish observations, F. Di Vruno

Unintended emission at low frequencies

- LOFAR sees Starlink passing overhead!
- Unintended emission from back-end electronics seen at $\sim 150\text{--}180\text{ MHz}$
- Not permitted bands for transmitting...
- Di Vruno et al. (2023), A&A (published), arXiv:2307.02316
- (Also Grigg et al., 2023, 2309.15672)



BlueWalker3: optical bright, maybe also thermally bright?



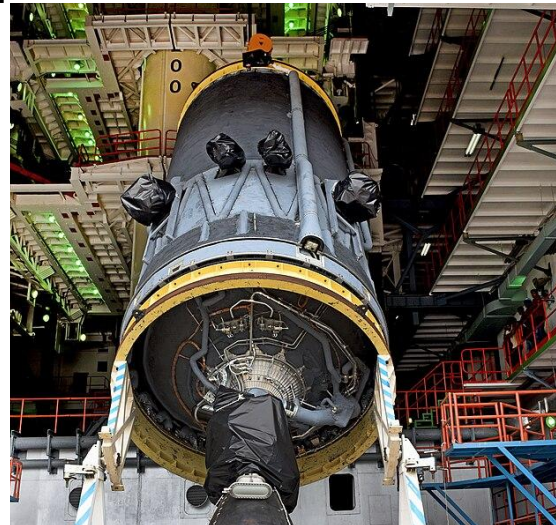
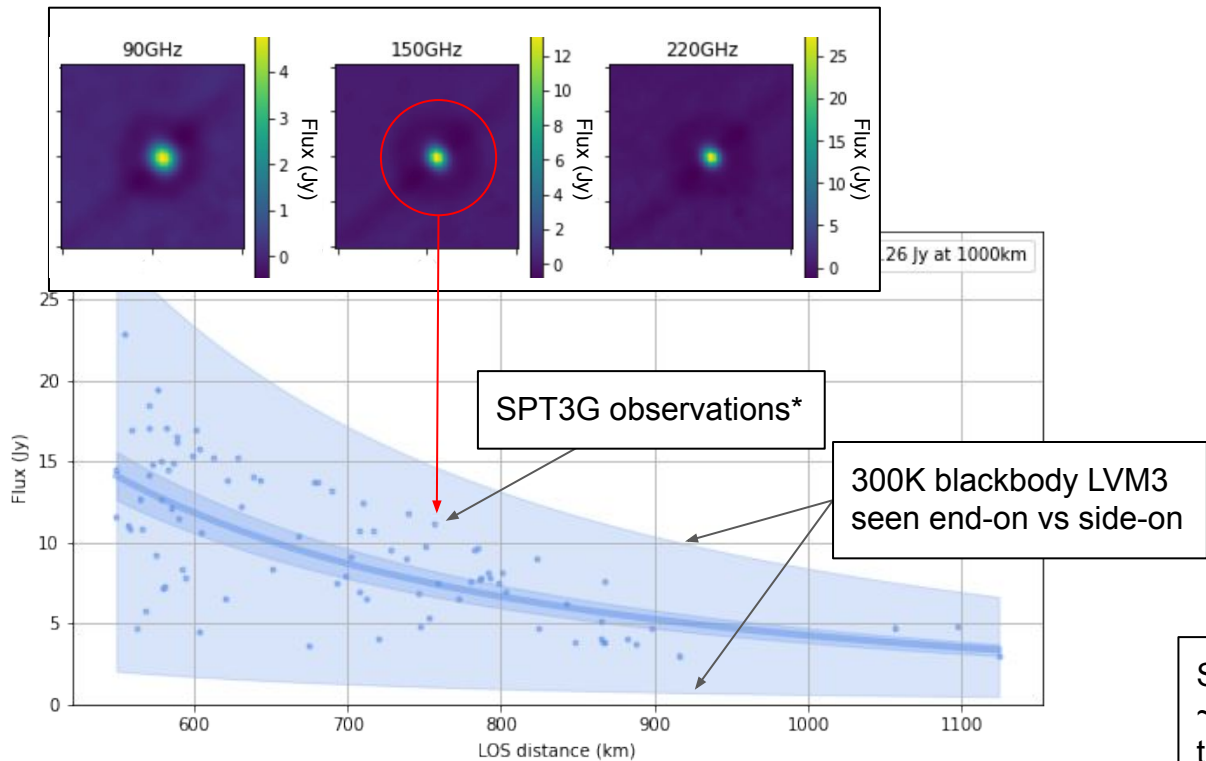
- 64m^2 phased array, prototype for mobile phone connections using standard phones + satellite
- Optical measurements show it to be brighter than all except top 10 stars (Nandakumar et al., Nature, 2023)
- (+ launch vehicle adapter bright & untracked for first few days, + position predictions degrade over time)
- Thermal brightness unknown: have SCUBA2/JCMT time to observe ISS + BW3, observations later this year

PRELIMINARY

(with thanks to Allen Foster)

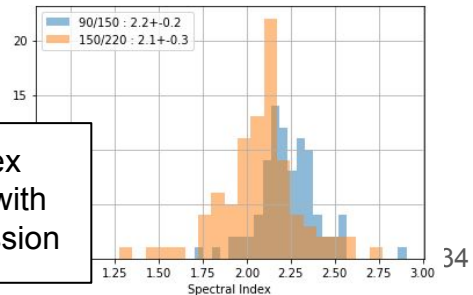
Example from SPT3G - Thermal Emission

Even if not actively emitting RF signal, satellites can be millimeter bright!



LVM3 Upper stage : 4m diam. x 13.5m long

Spectral index
~consistent with
thermal emission



* observed both in direct sunlight and in Earth's shadow

Conclusions

- Simons Observatory is under construction, will start observations soon
- SATs will give powerful constraints for B-modes on large angular scales
- LAT will give high resolution science, including transients
- Expect to see transients from a variety of different sources (stars, AGN, other Galactic and solar system objects)
- May also see satellites through their thermal emission (and/or octaves of active transmissions)
- Lots to learn in the years to come!
- Questions?