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

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1 November 2023

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This work is presented on behalf of the Simons Observatory collaboration. Simons Observatory is supported by the Simons Foundation, the Heising-Simons Foundation, and other research institutions within the collaboration.

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Overview

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

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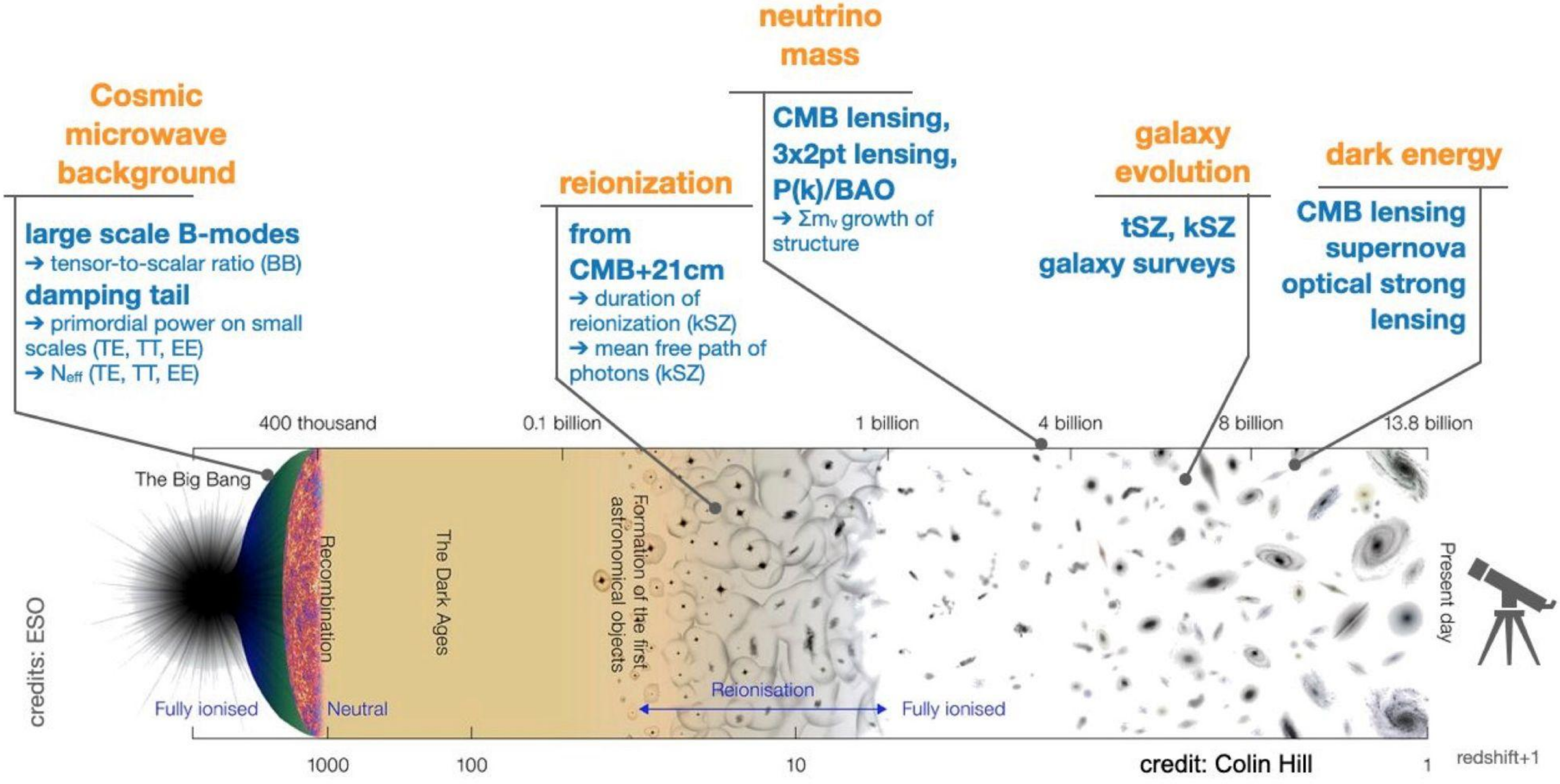
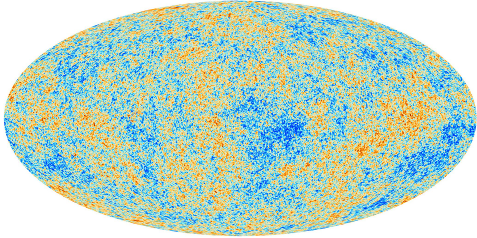
SIMONS OBSERVATORY UNITED KINGDOM

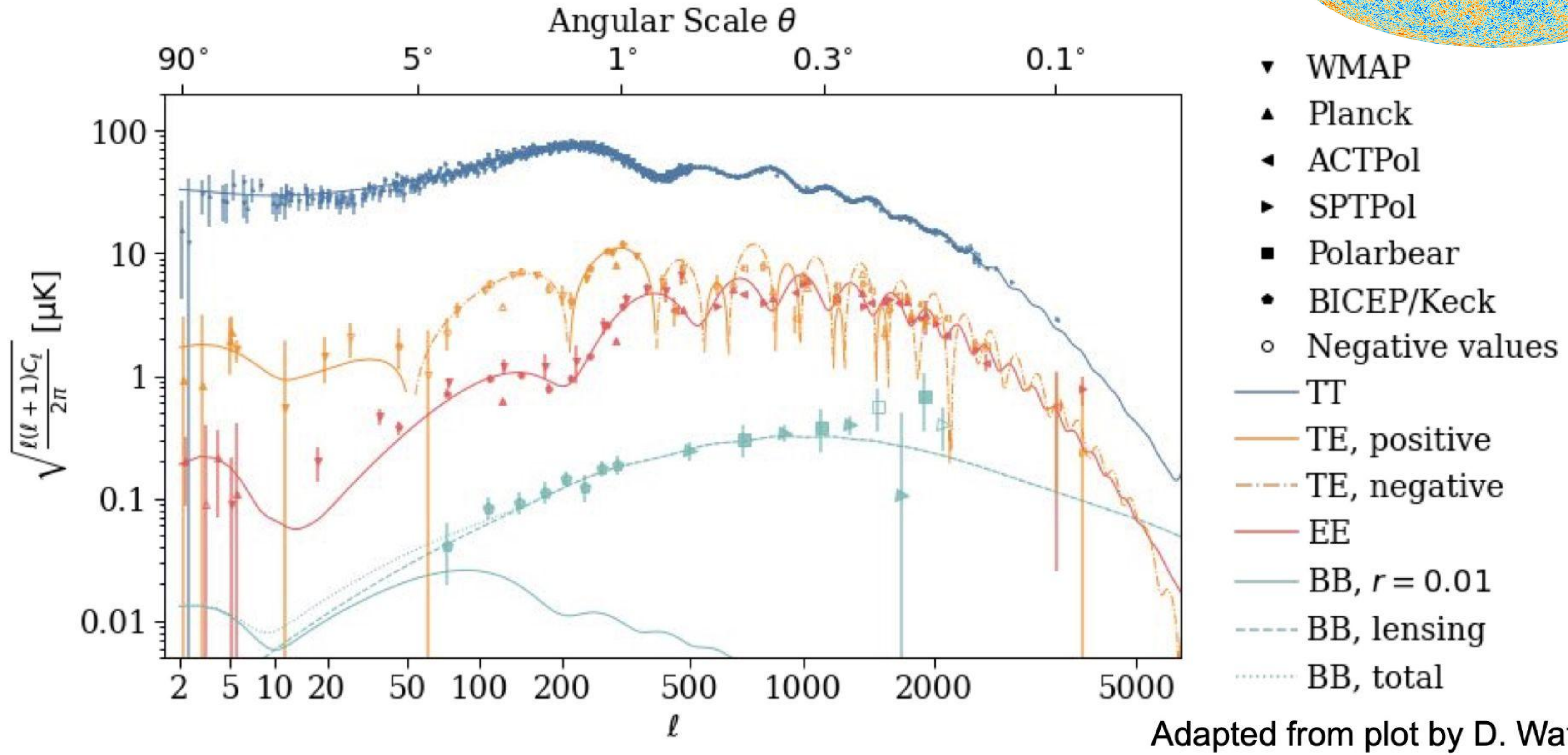
Overview is Simons Observatory

Cosmology with the CMB



CMB Power Spectrum





Adapted from plot by D. Watts

(from Lee/Staggs Astro2020 talk)

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

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

SO Site in Chile: Next to Existing Telescopes

5,200 meters

high and dry

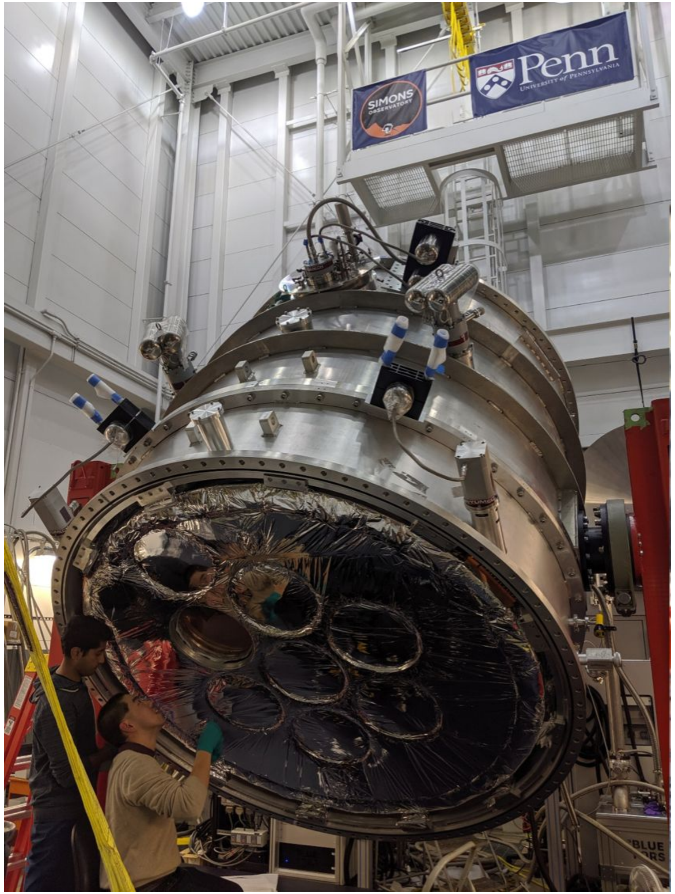
23 degree South Latitude

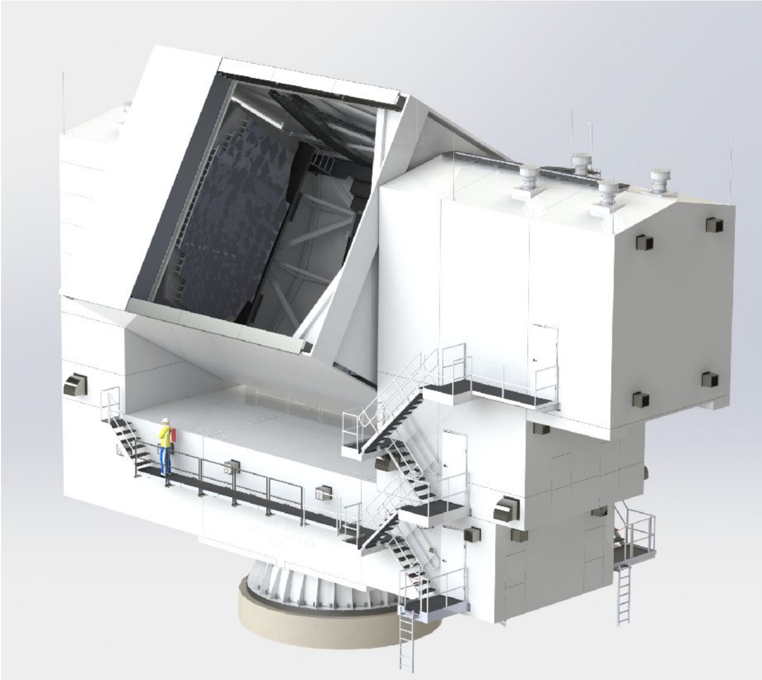
Established site

Room for expansion

The Simons Observatory

SO Construction is Underway





New 6-meter-primary telescope

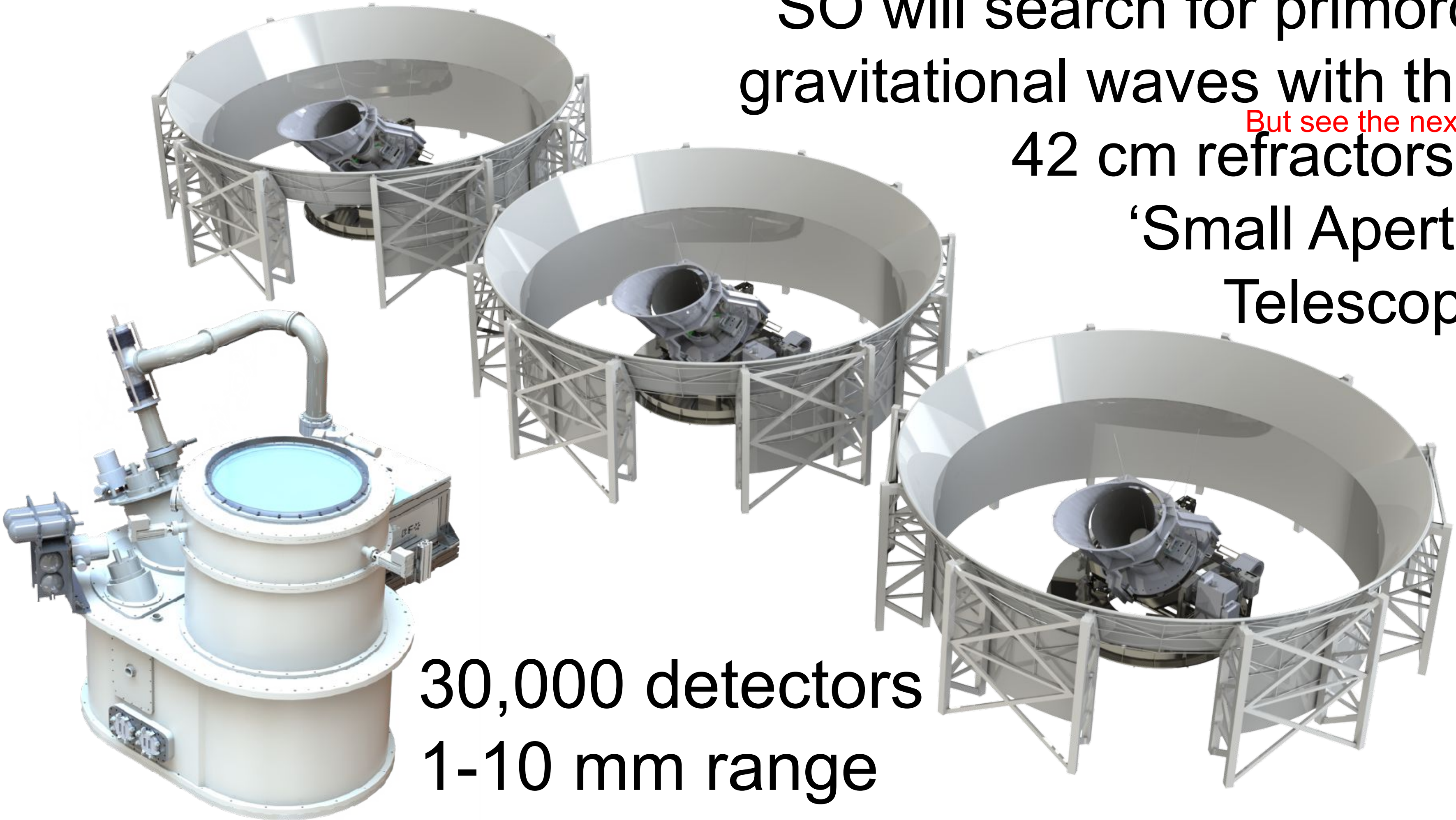
Detectors measure 6 wavelength bands:

1-10 mm (30-280 GHz)

>30,000 Transition Edge Sensor detectors

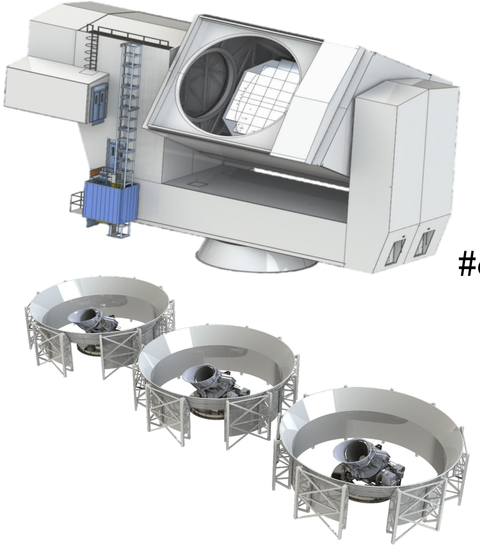
SO will search for primordial gravitational waves with three 42 cm refractors, or 'Small Aperture Telescopes'

But see the next slide…



30,000 detectors
1-10 mm range

+3 SATs with UK and Japan funds



#optics tube
7/13

#optics tube
(7+1)/13

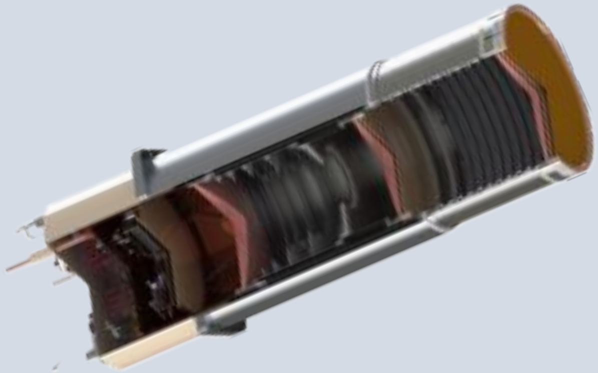
Twice better sensitivity to primordial gravitational waves

2023～

2026～

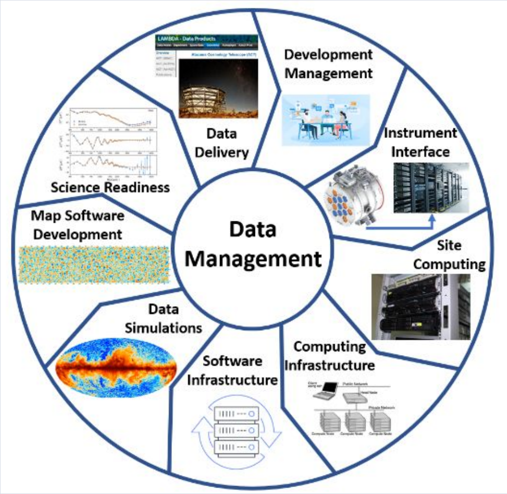
Advanced SO – Project Definition

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)

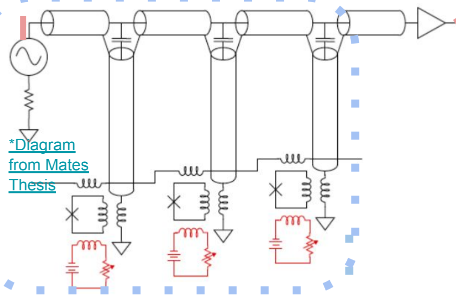
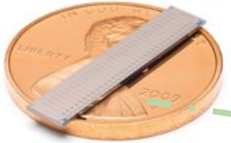


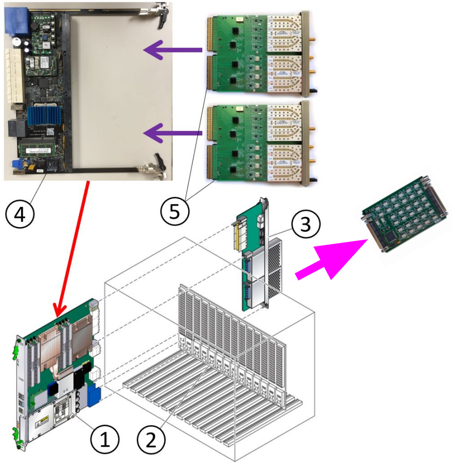
*Diagram from Mates Thesis

Superconducting Multiplexer Chip (fabricated at NIST)

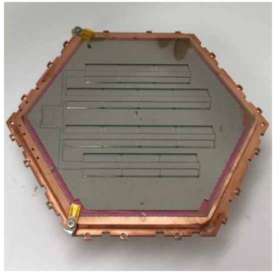


Microwave SQUID Multiplexing

- 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

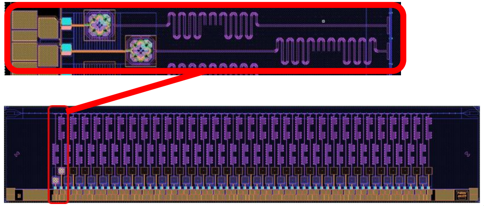


Room temperature SMuRF Electronics. Generate + digitize probe tones and apply amplifier, squid, and detector biases (designed + fabricated at SLAC)



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

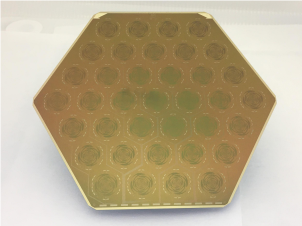
Mux Chip $\lambda/4$ Resonators + SQUIDs

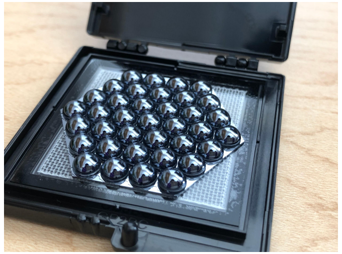


Simons Observatory Detectors (2/2)

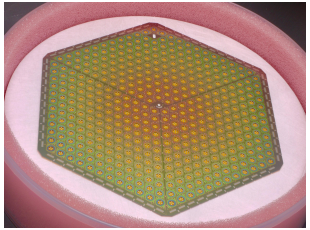
Note: UK SATs + LAT tube will use KIDs not TES's, these are being developed at Cardiff

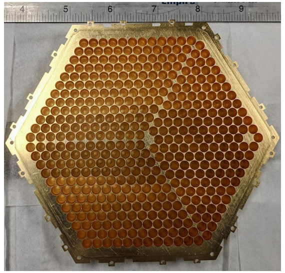
Low frequency (LF) detector arrays & lenslets





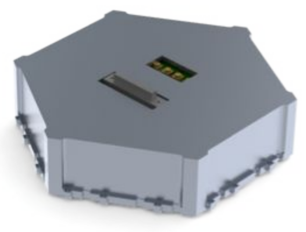
Mid frequency (MF) and ultra-high frequency (UHF) detector & horn arrays

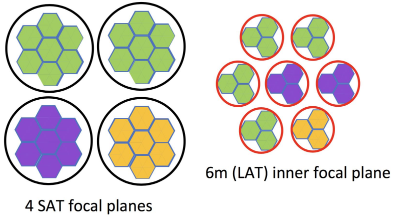




SO will use **dual-polarization, dichroic TES bolometer detectors**, cooled to 100 mK**.** The LF detector arrays build on the proven performance of POLARBEAR and the MF and UHF on ACT.

Detector modules



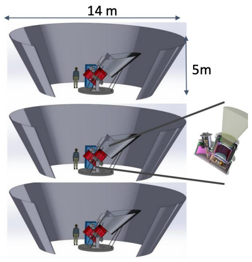


Top: The **universal focal-plane modules** (UFMs) contain the cold readout, detectors, and optical coupling. Bottom:UFM frequency distribution *(green:MF, purple:UHF, yellow:LF)*.

SO detectors

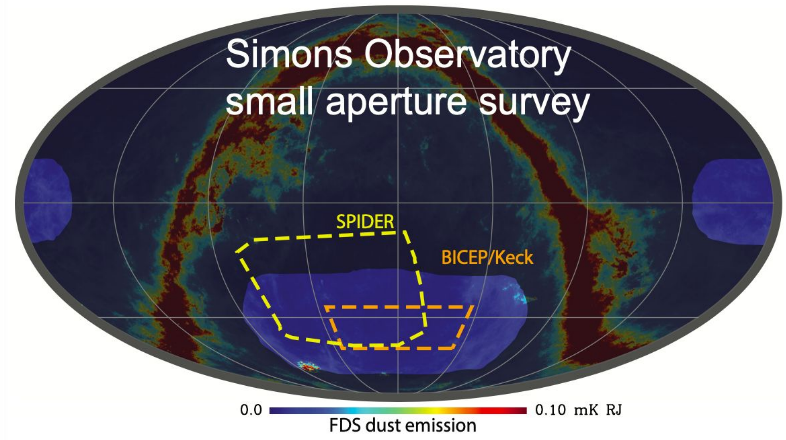
- >60,000 TES bolometer detectors across the LATR and four SATs
- Spanning six spectral bands centered between 27-270 GHz.
- Focal planes are populated with close-packed UFMs.
- The UFMs are common to the SATs and LATR and maintain a common footprint across frequency bands.

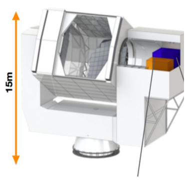
SO Surveys



Freq. [GHz]	SATs ($f_{\mathrm{sky}} = 0.1$) FWHM (′)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-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

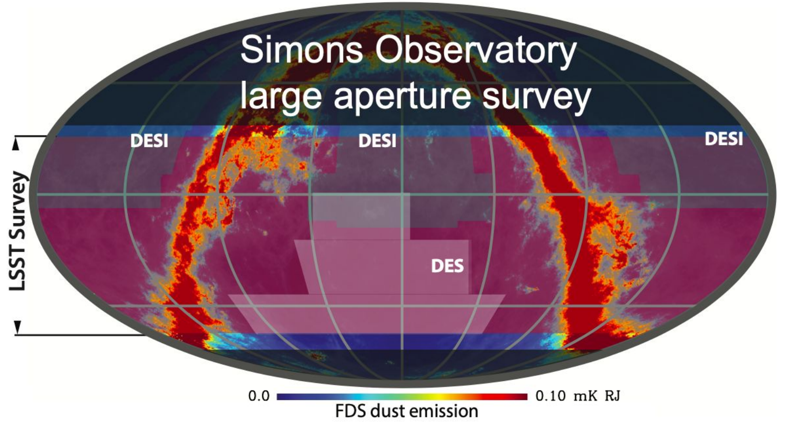
} 2 μk-arcmin (93 and 145 GHz, baseline)





Freq. [GHz]	LAT ($f_{\mathrm{sky}} = 0.4$) FWHM (′)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-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

} 6 μk-arcmin (93 and 145 GHz, baseline)



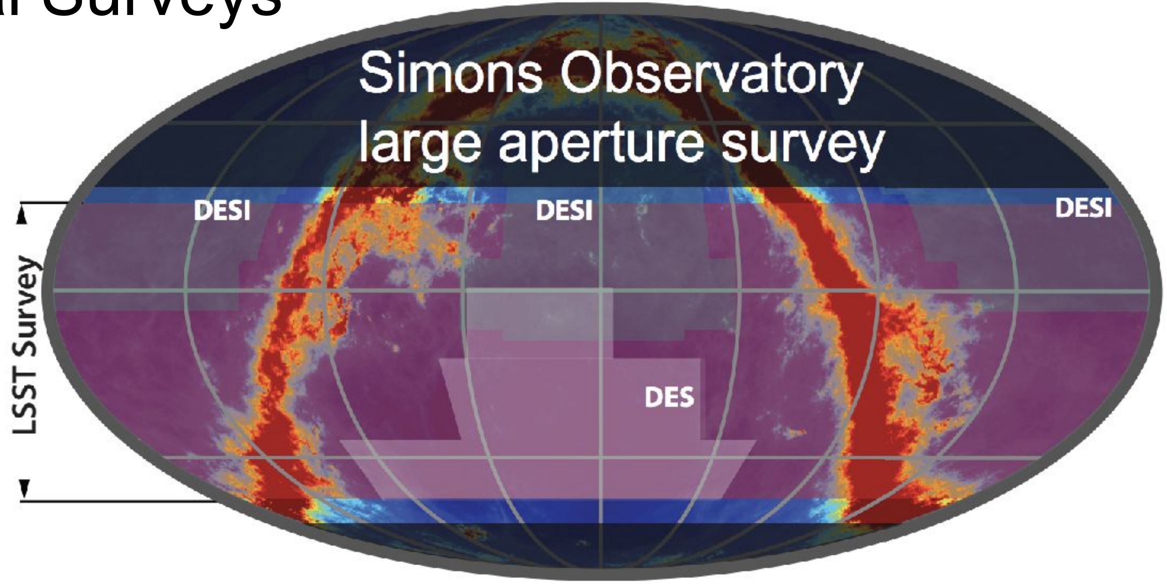
From June, 2020 SO+LSS Zoomference

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

(from Lee/Staggs Astro2020 talk)

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	r	0.0024	**0.003**	0.002	0.03	BB + ext delens	3.4
perturbations	$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	0.4%	**0.5%**	0.4%	3%	$TT/TE/EE$	4.2
	$f_{\mathrm{NL}}^{\mathrm{local}}$	1.8	**3**	1	5	$\kappa\kappa\times$ LSST-LSS + 3-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	$\kappa\kappa$ + 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%	$\kappa\kappa$ + LSST-LSS	5.3
		1.2%	**2%**	1%		tSZ-N $\times$ LSST-WL	7.1
	H_0 (ΛCDM)	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	$f_{\rm NL}$ (equilateral)	30	T/E
	$f_{\rm NL}$ (orthogonal)	10	
	n_s	0.002	$TT/TE/EE + \kappa\kappa$
Big bang nucleosynthesis	Y_P (varying $N_{\rm eff}$)	0.007	$TT/TE/EE + \kappa\kappa$
	$\Omega_b h^2$ (ΛCDM)	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	$\log_{10}(\lambda_{\rm mfp})$	0.3	$TT/TE/EE$ (kSZ)
	Ionization efficiency (ζ)	40	$TT/TE/EE$ (kSZ)

Identifying transient events with SO

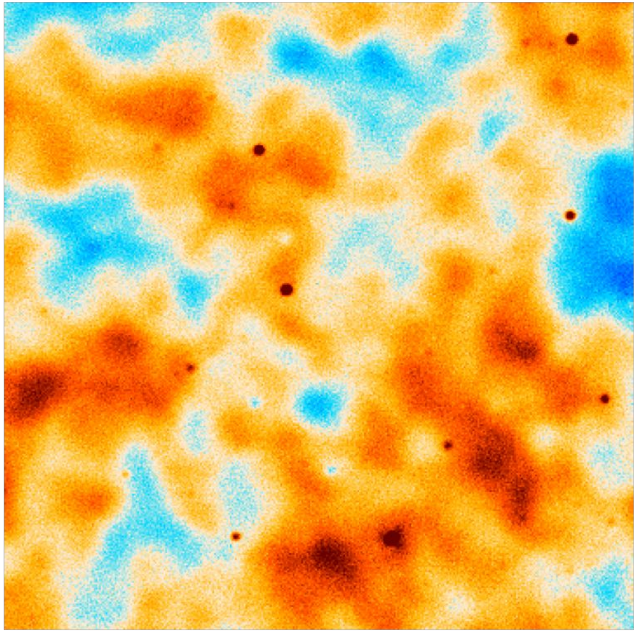
SO: New Opportunities in mm-Transient Science

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



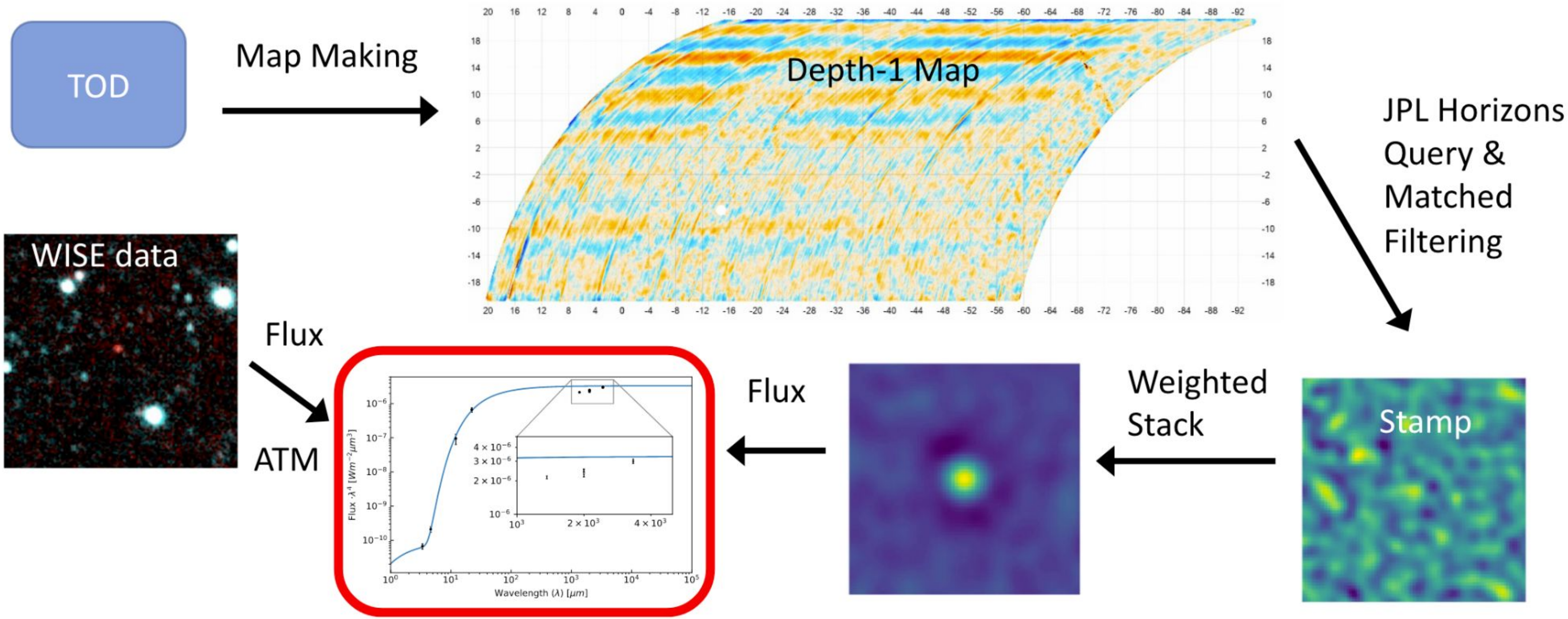
[Previous | Next | ADS]

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)

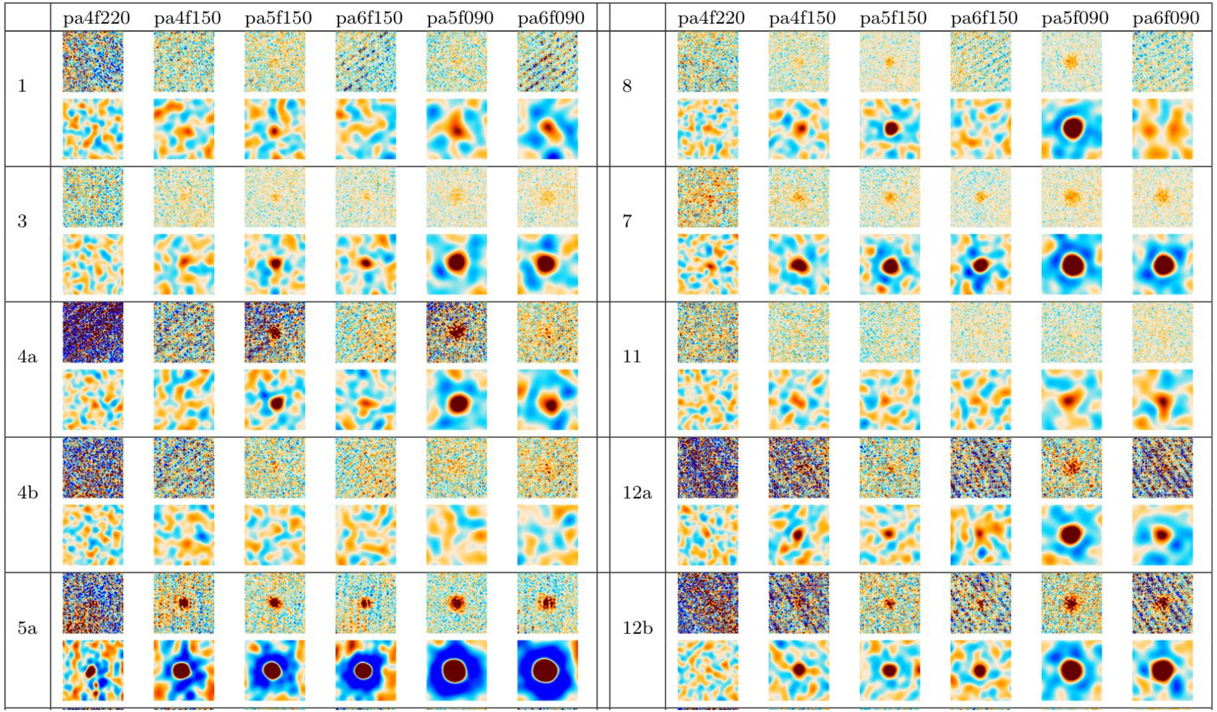
Subjects: Millimeter, Gamma Ray, AGN, Blazar, Transient, Variables

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



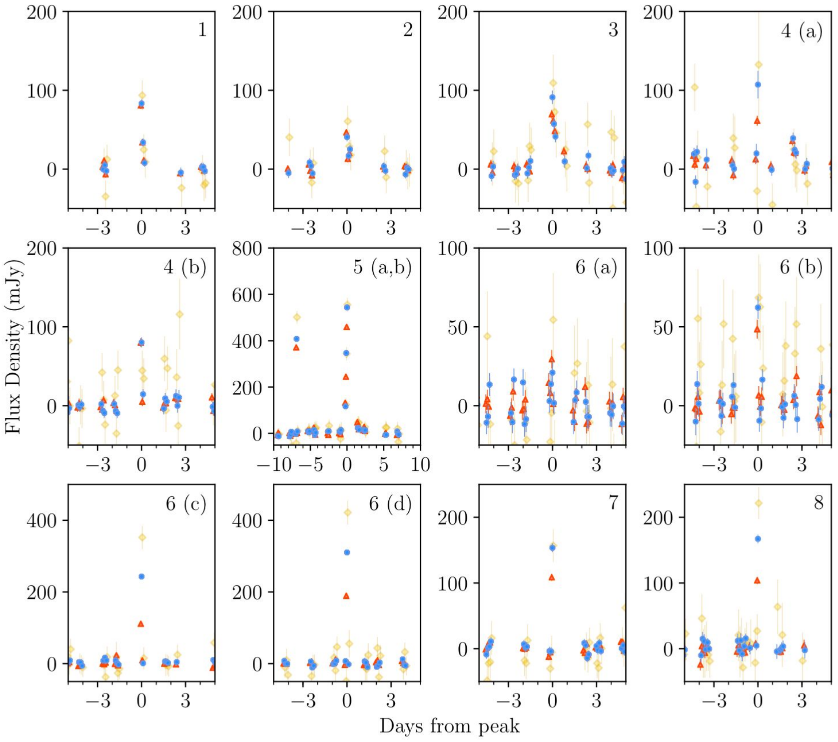
Other approaches under discussion, but could also do:

- 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

Li et al. (2023), The Atacama Cosmology Telescope: Systematic Transient Search of 3-Day Maps, arXiv:2303.04767

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

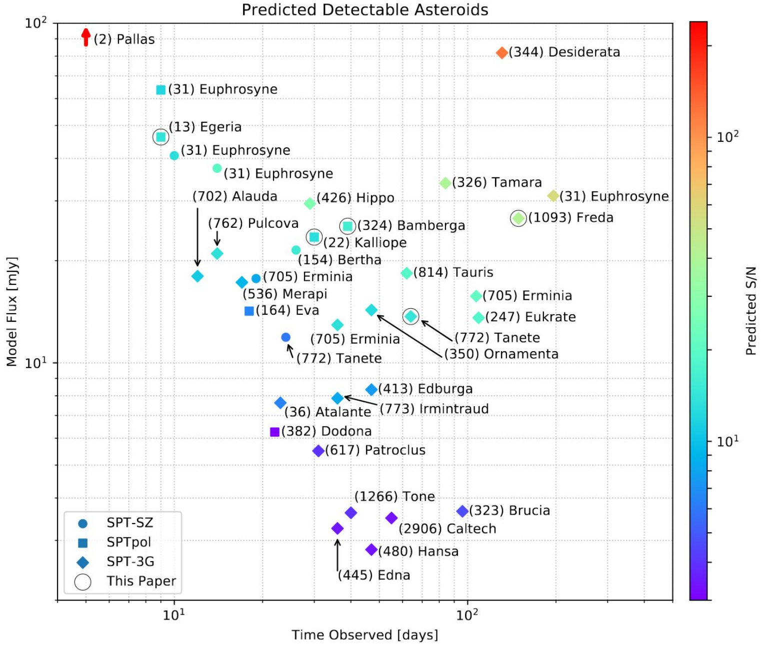


Figure 7. Objects with predicted S/N > 3 at 2.0 mm in all historic and planned future SPT data. We expect to observe (2) Pallas, plotted off scale, with a mean flux density near 725 mJy.

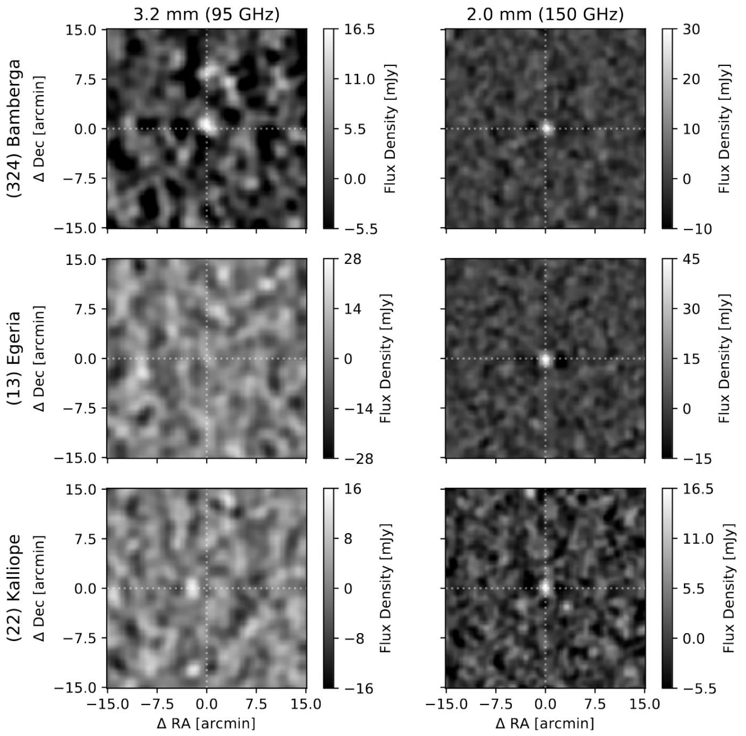
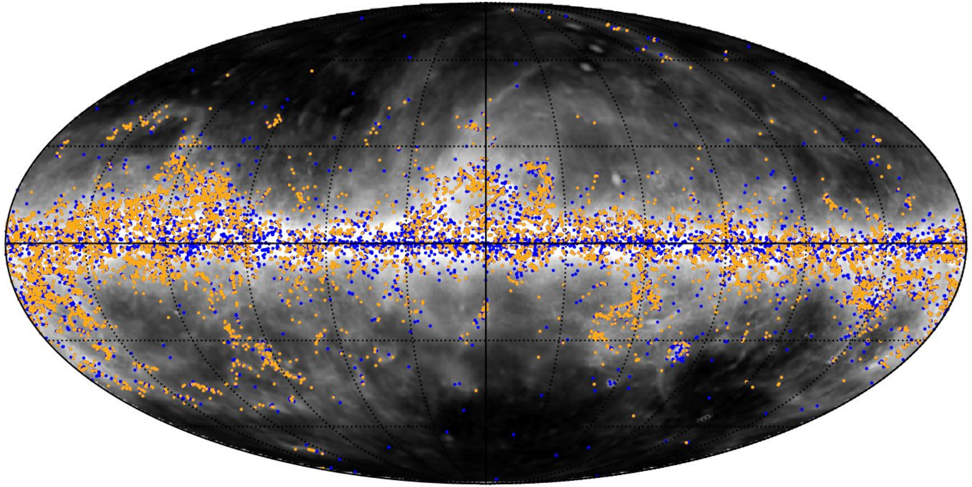


Figure 4. Mean flux measurements of (324) Bamberga (top horizontal panels), (13) Egeria (middle horizontal panels), and (22) Kalliope (bottom horizontal panels) at 3.2 mm (left vertical panels) and 2.0 mm (right vertical panels). Color scales for (13) Egeria and (22) Kalliope at 3.2 mm are set at 4-sigma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

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

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 ~2% polarisation on average
- Expect to see ~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)

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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 by Connie Walker & Federico Di Vruno. Four hubs:

- **SatHub** (leads: Meredith Rawls, Mike Peel, Siegfried Eggl)
  - 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

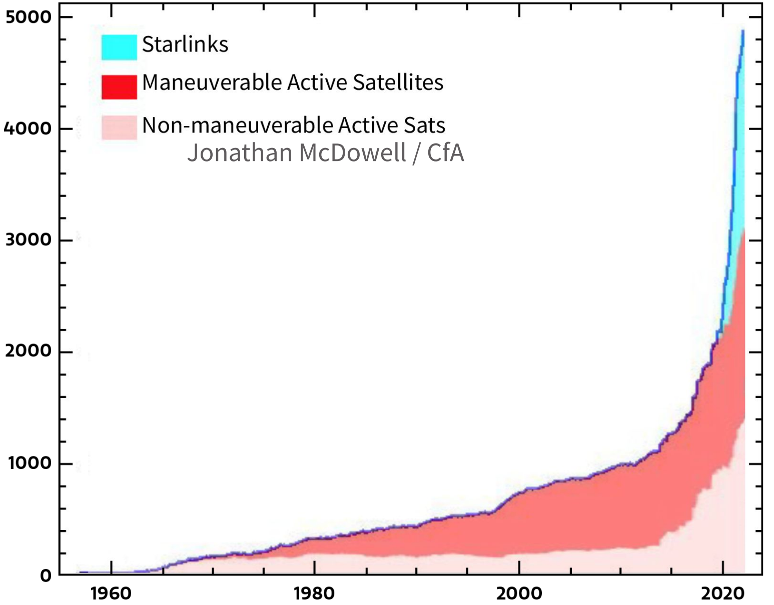
The WMAP CMB satellite is one of many that are frequently seen by optical telescopes.

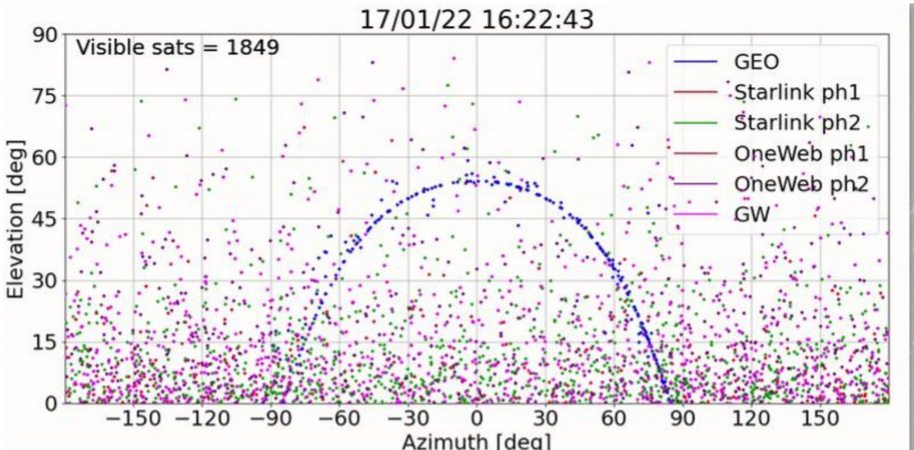
... and that was before Starlink started launching in 2019. We now have **twice the number of satellites in the last 5 years**. Mostly in Low Earth Orbit (LEO)

Mega constellations came as a surprise to astronomy!

Proposals are for **over 400,000 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

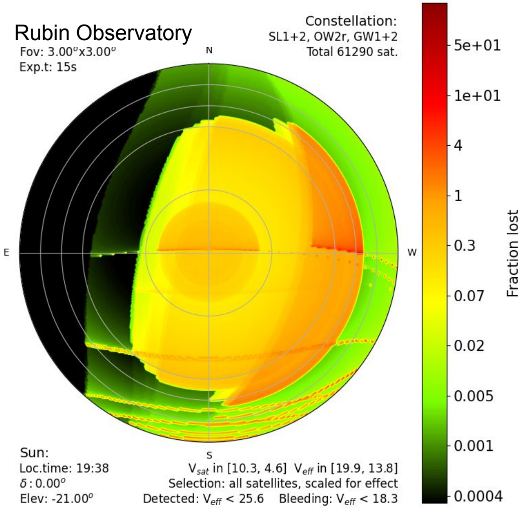
Constellations have a **significant effect in optical and infrared**.

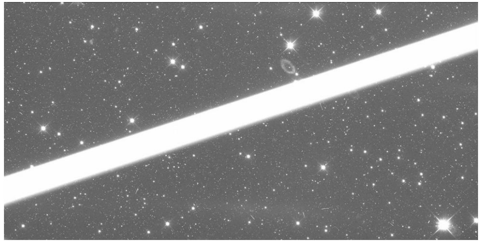
Particularly **reflections from the sun** in late evenings / early mornings

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

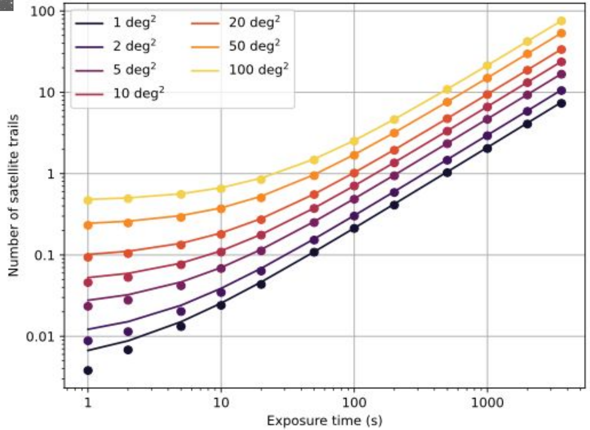




SATCON2 algorithms report

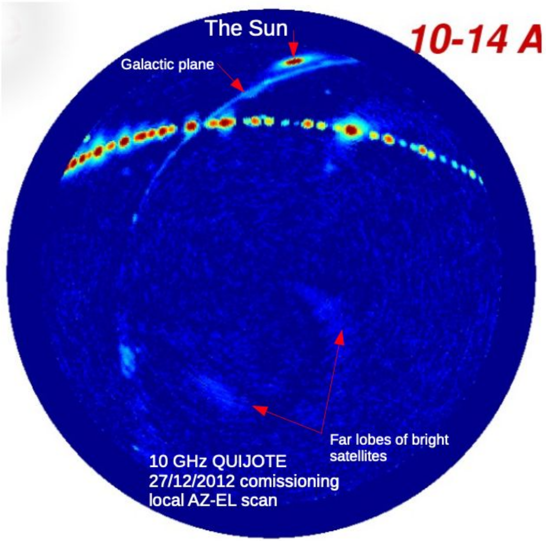
Satellite	Operational altitude [km]	Mag at op. alt.	Mag dispersion	Mag at 1000km
Starlink original	550km	4.6	0.7	5.9
		4.0	0.7	5.3
		4.2	(model)	5.5
Starlink DarkSat	550km	5.1	(single)	6.4
Starlink VisorSat	550km	6.2	0.8	7.5
		5.8	0.6	7.1
OneWeb	1200	7.6	0.7	7.2

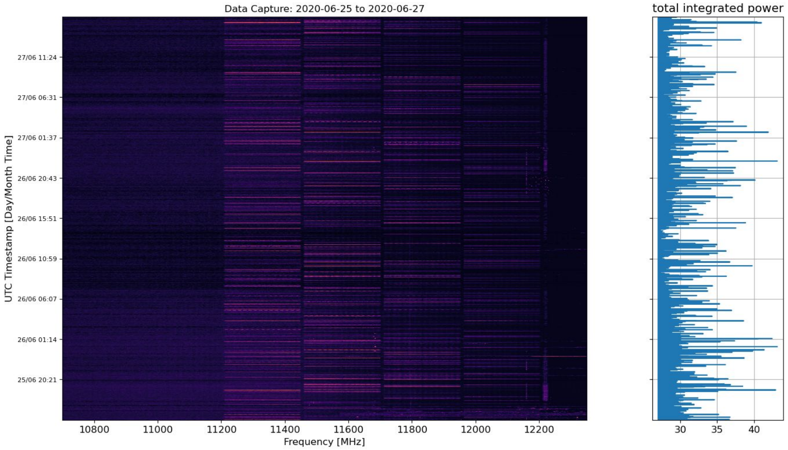
Bassa et al.
arXiv:2108.12335



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!)
- 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?

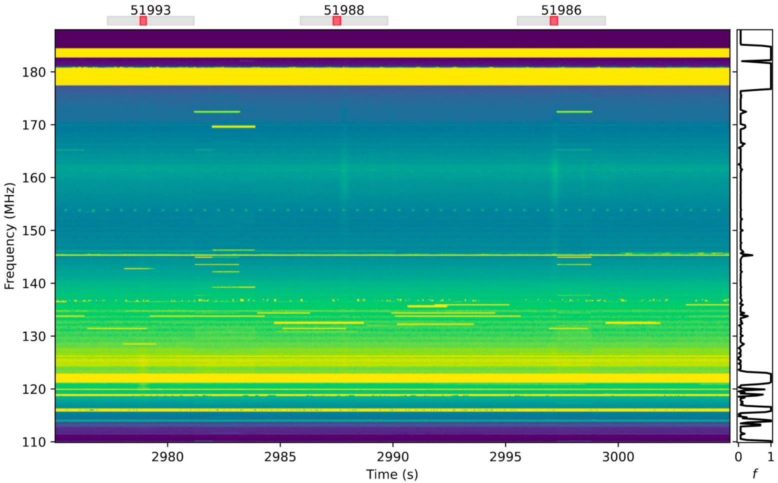


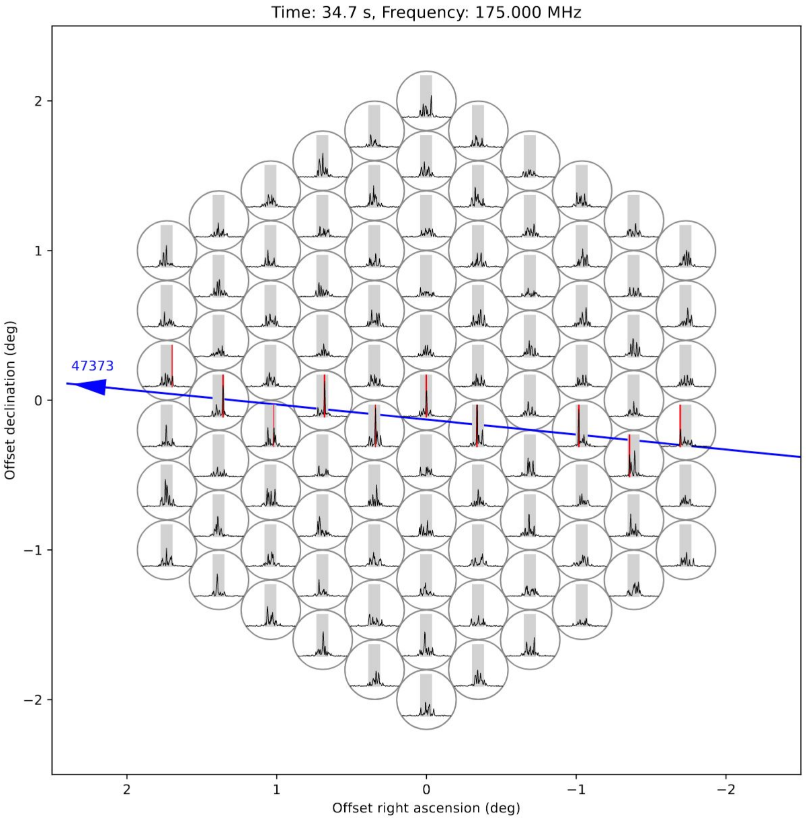


Above: QUIJOTE 10-14GHz observations from Tenerife in 2012 - pre-starlink.
Left: satellite dish observations, F. Di Vruno

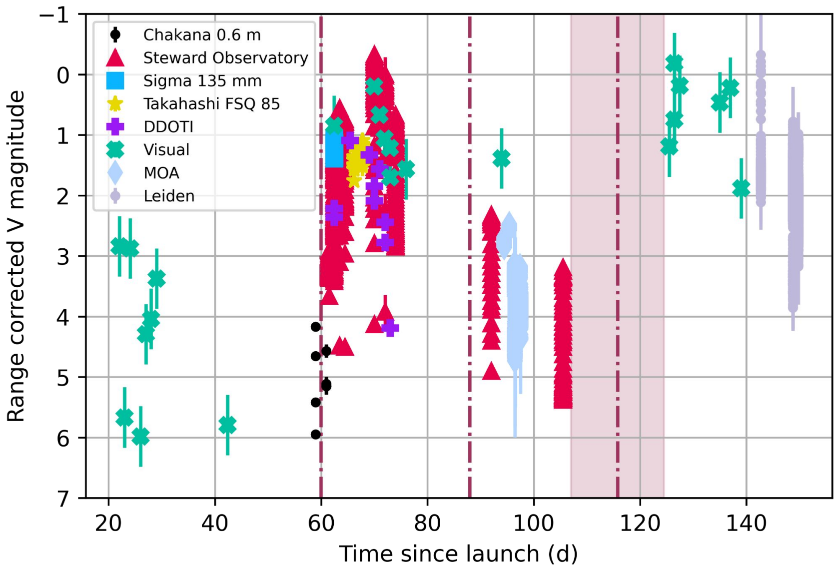
Unintended emission at low frequencies

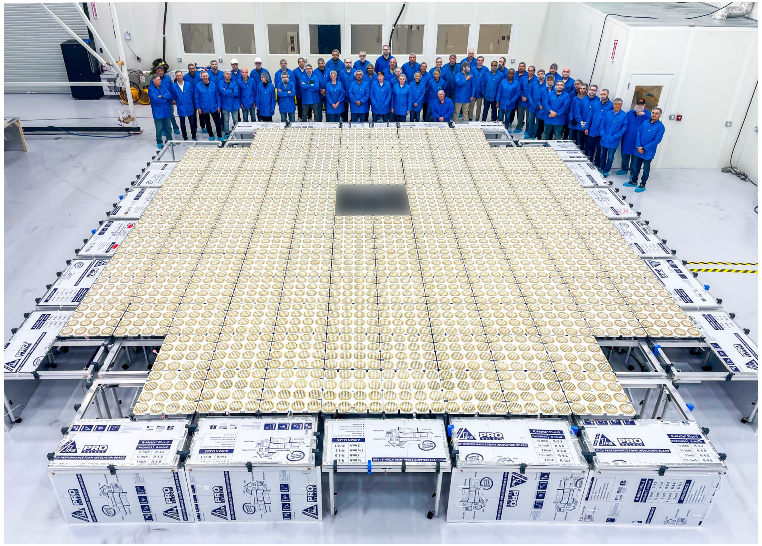
- LOFAR sees Starlink passing overhead!
- Unintended emission from back-end electronics seen at ~150-180MHz
- Not permitted bands for transmitting...
- Di Vruno et al. (2023), A&A (published), arXiv:2307.02316





BlueWalker3: optical bright, maybe also thermally bright?





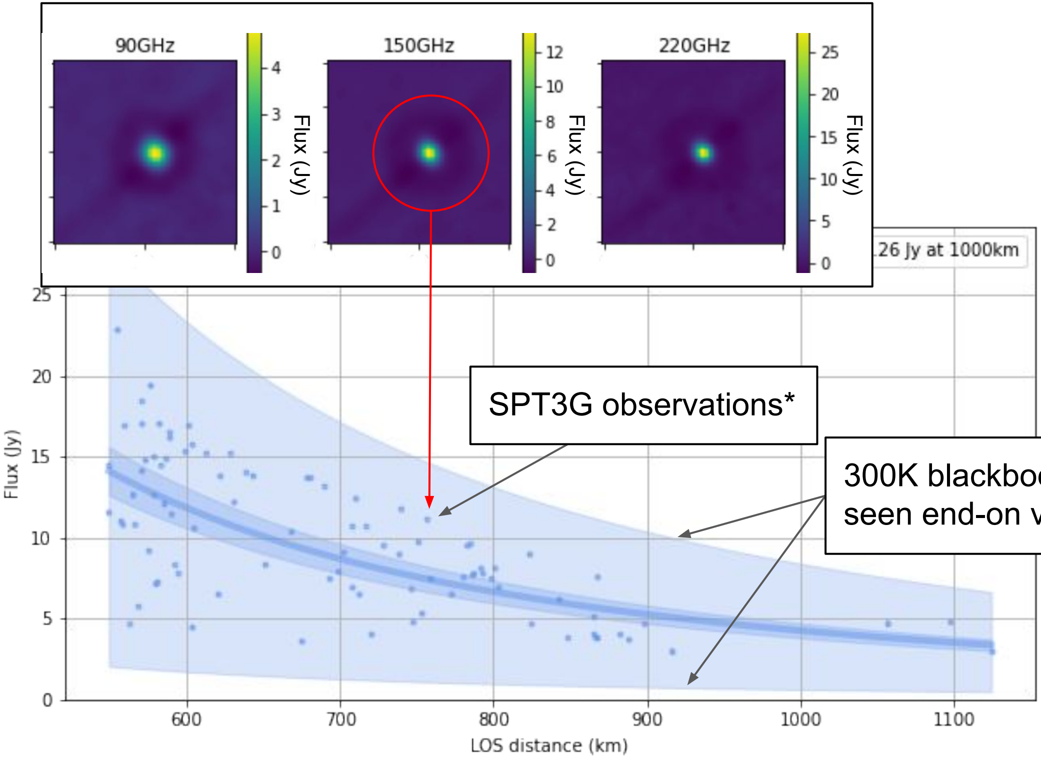
- 64m^2 phased array, prototype for mobile phone connections using standard phones + satellite
- Optical measurements show it to be brighter than all except top 10 stars (Nandakumar et al., Nature accepted - to be announced next week!)
- (+ launch vehicle adapter bright & untracked for first few days, + 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

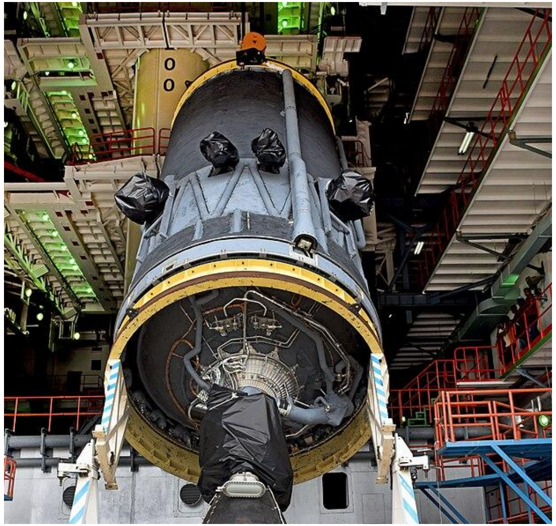
Even if not actively emitting RF signal, satellites can be millimeter bright!



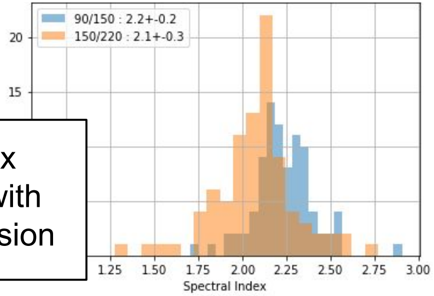
SPT3G observations*

300K blackbody LVM3 seen end-on vs side-on

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



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



Spectral index ~consistent with thermal emission

Imperial College London

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?