The Simons Observatory

mm-Universe Conference
KICP Chicago, IL

Max Silva-Feaver
Mossman Fellow
Yale University

2025-06-23

Simons Observatory

A laboratory for Fundamental Physics, Cosmology, and Astrophysics

primordial fluctuations

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

relativistic species

damping tail
➔ N_{eff} (TE, TT, EE)

reionization

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

neutrino mass

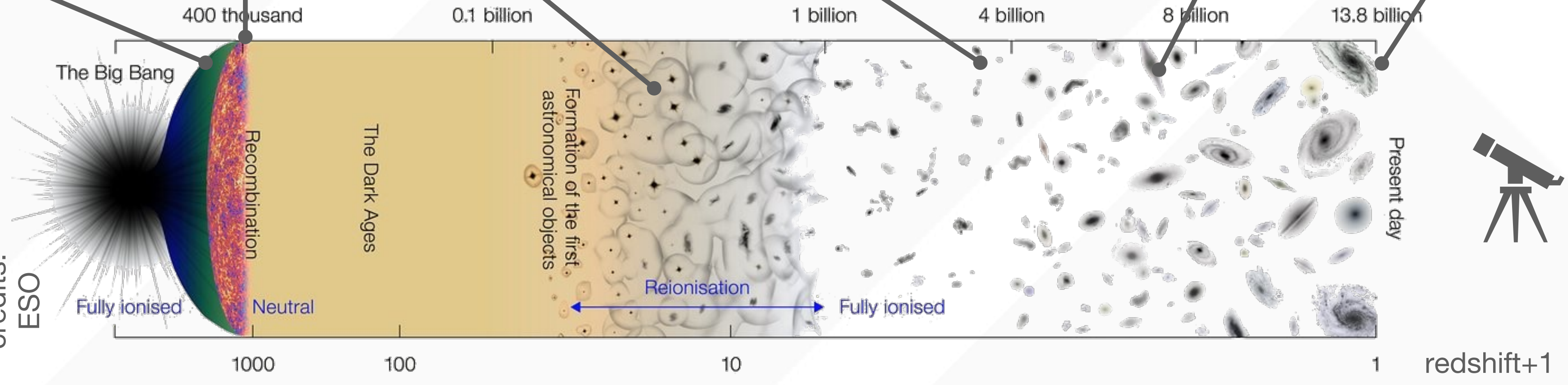
Lensing potential (TT+EB), tSZ
➔ Σm_ν

galaxy evolution

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

dark energy

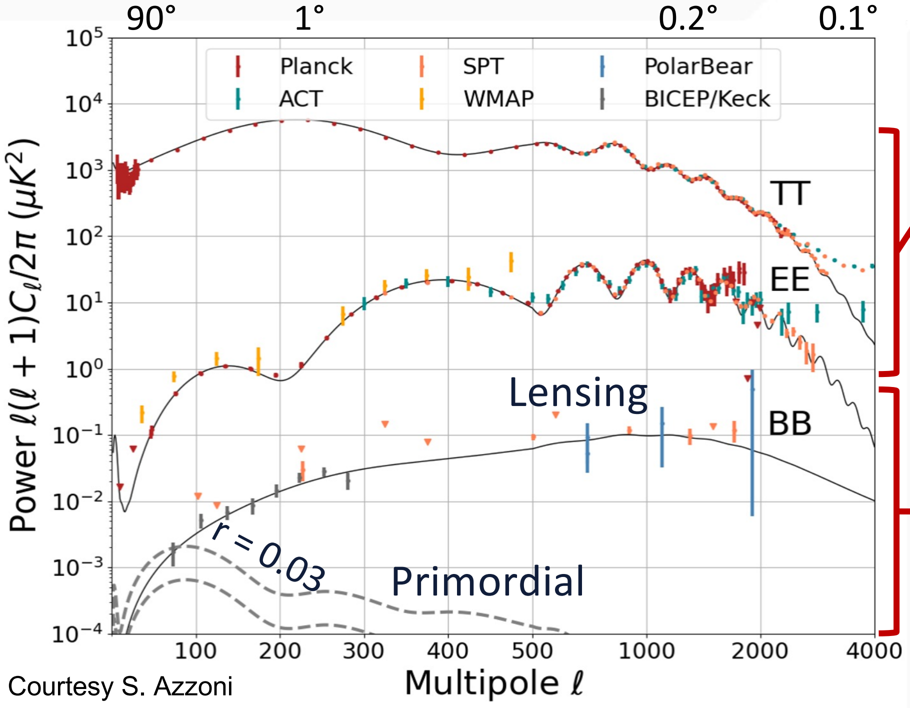
tSZ, lensing
➔ σ_8 at z=2-3 (lensing, tSZ)
➔ growth of structure (kSZ)



credits: ESO

The Cosmic Microwave Background

Current Tests of Inflation



Scalar fluctuations: generate **T / E** modes

Tests for initial conditions:

- **Anisotropies at small scales**
- **Spectral distortions**
- **Non-Gaussianity**

Measurements compatible with single-field inflation

ie Planck Collab. 2018, X and IX, ACT DR6++

Tensor fluctuations: generate **E / B** modes:

Probes: CMB polarization

- E-modes: photon-baryon plasma velocity
- B-modes rule out many inflationary and non-inflationary models

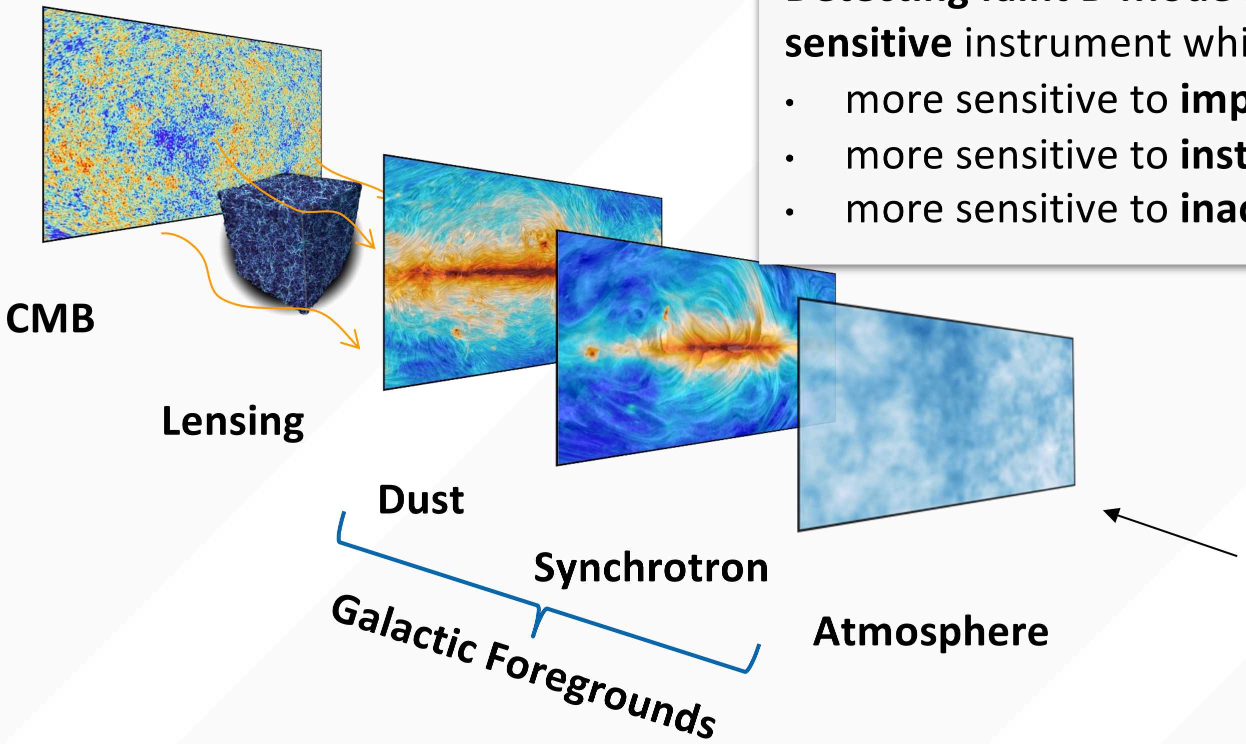
Still no detection of Primordial Gravitational Waves

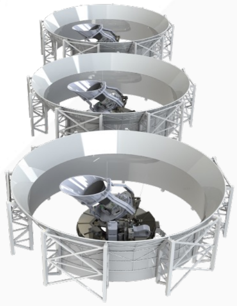
current constraints: tensor-to-scalar ratio **r < 0.032** (95% C.L.) from **BICEP/Keck 2022**

The Cosmic Microwave Background
Observational Challenges

Detecting faint B-Mode signal requires a more sensitive instrument which is:

- more sensitive to **imperfect foreground modelling**
- more sensitive to **instrument systematics**
- more sensitive to **inaccurate delensing**





Courtesy S. Azzoni

Physics Beyond Cosmology
What else can we see with Simons Observatory?

Time Domain Astrophysics

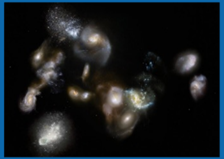

Tidal Disruption Events


Stellar Flares


Variable AGN

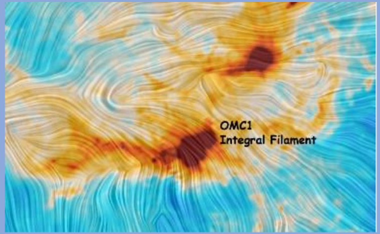
Extragalactic Astronomy


Sources


Galaxy Clusters

Galactic Astronomy

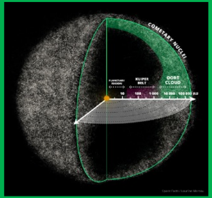

Interstellar Dust



Star Formation, Magnetic Fields and Turbulence

SO enables detailed studies of astrophysics including:
- ISM/IGM Physics
- Time domain studies of high energy astrophysical events.
- Cross wavelength follow up and identification of new sources.
- Detailed studies of solar system anomalies.

Planetary Science


Exo-Oort Clouds


Planet 9

The Simons Observatory

15+ Countries, 60+ Institutions, 375+ Researchers

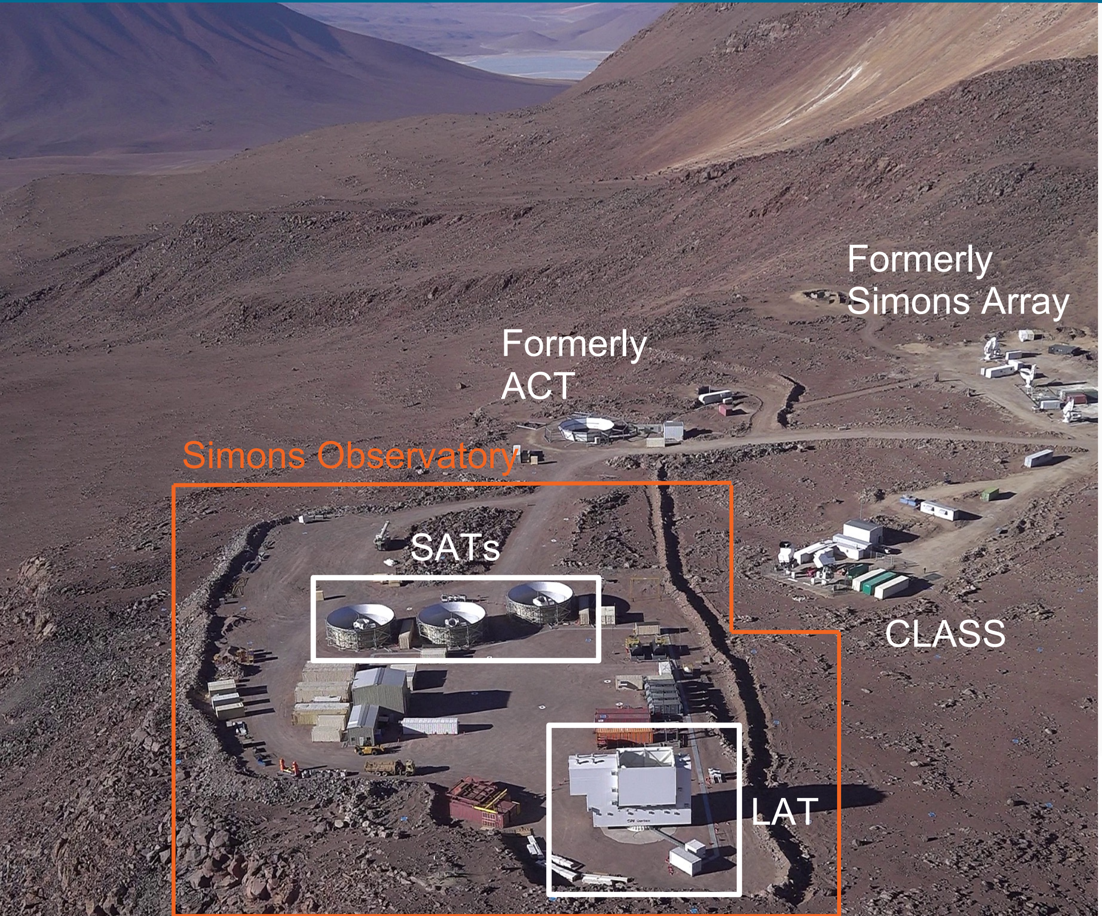
July 2024
@ UChicago

SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION

The Simons Observatory

Where are we and why?

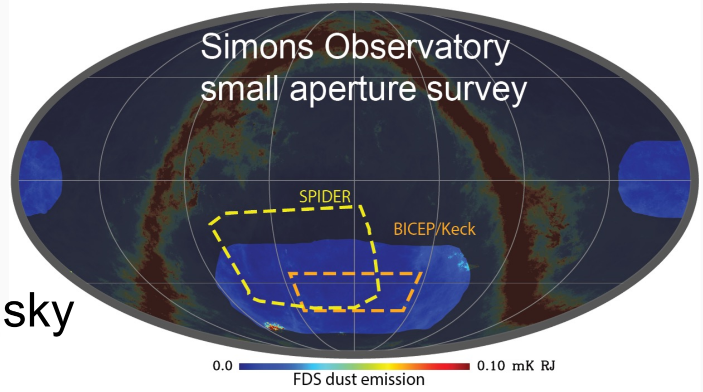


High Altitude (5200m) Plateau in the Atacama Desert in northern Chile. **Above most of the atmosphere and dry**--ideal for radio astronomy.

The Simons Observatory
Covering Large and Small Scales

Small aperture telescopes (SATs)
Small "deep" sky patch
Primordial B-modes

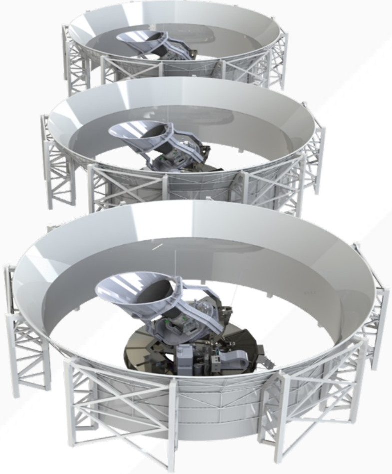
10% of sky

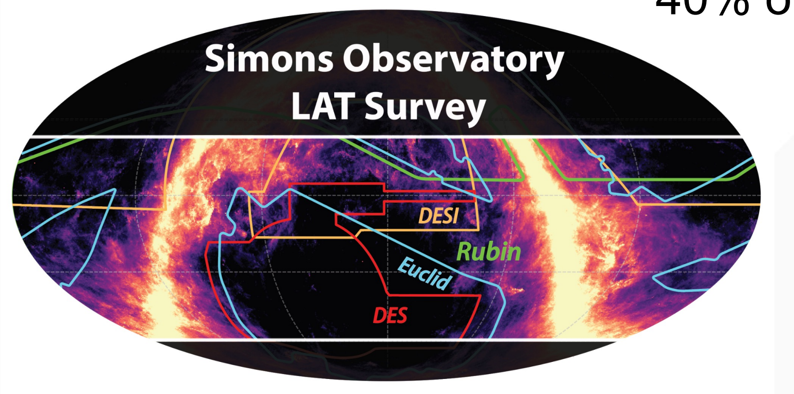


SO Forecast Paper JCAP 02 2019 808.07445

Large aperture telescope (LAT)
Large sky patch – overlap with optical/infrared surveys
Lensing - N_{eff} , Σm_ν , ***w(z), cluster science***

40% of sky

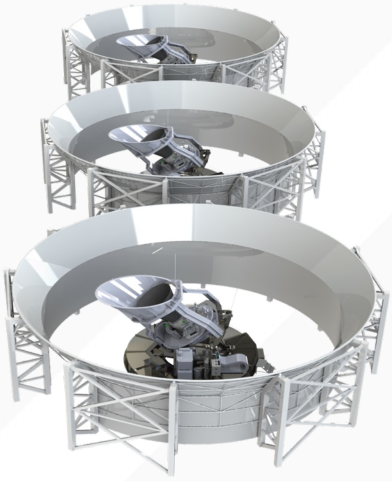


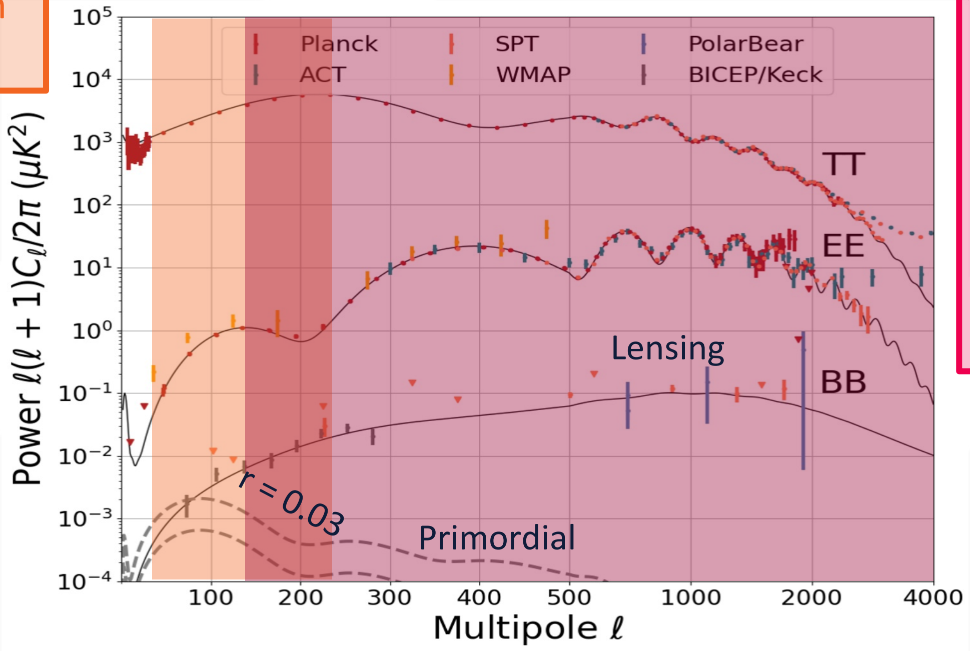


SO LAT Extended Forecast 2025 Arxiv 2503.00636

The Simons Observatory
Covering Large and Small Scales

Small aperture telescopes (SATs)
Small “deep” sky patch
Primordial B-modes



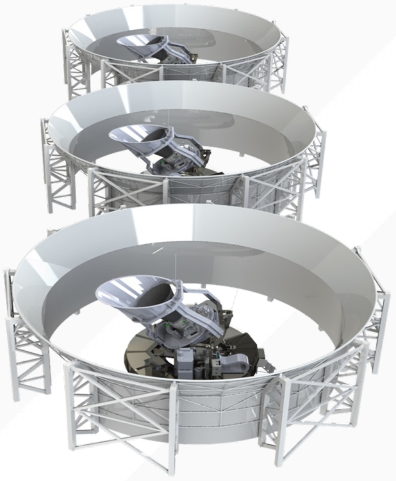


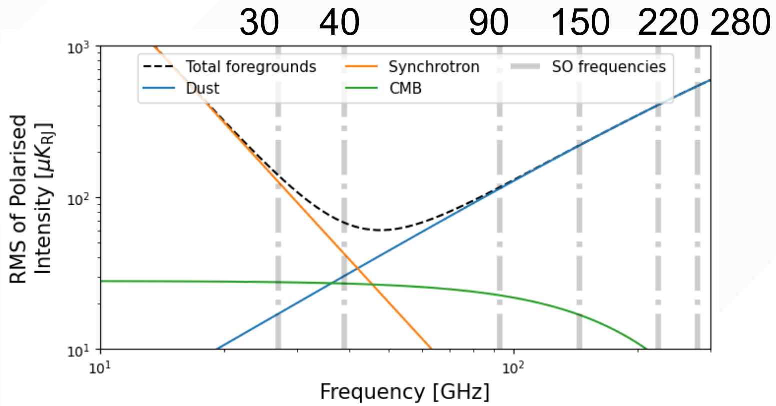
Large aperture telescope (LAT)
Large sky patch – overlap with optical/infrared surveys
Lensing - N_{eff} , Σm_ν , ***w(z), cluster science, time domain, astrophysics***

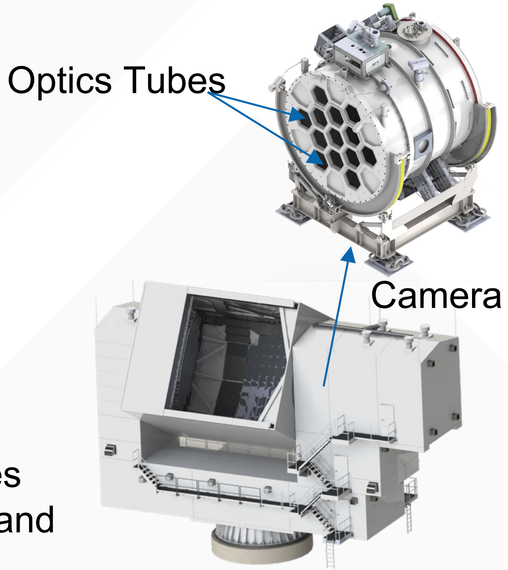
The Simons Observatory
Frequency Coverage for Foreground Cleaning

SATs
1 X 30/40 GHz SATs
3 X 90/150 GHz SATs
2 X 220/280 GHz SATs

LAT
1 X 30/40 GHz Optics Tubes
8 X 90/150 GHz Optics Tubes
4 X 220/280 GHz Optics Tubes





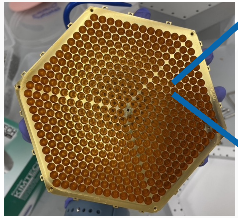


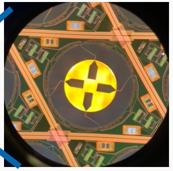
SO uses 6 observing bands to remove foreground contamination exploiting the different spectral indices between galactic foregrounds (synchrotron and dust) and the CMB.

The Simons Observatory
Large Detector Count for High Sensitivity

SATs – 60k detectors
30/40 GHz – 1.6k detectors
3 X 90/150 GHz – 36k detectors
2 X 220/280 GHz – 24k detectors

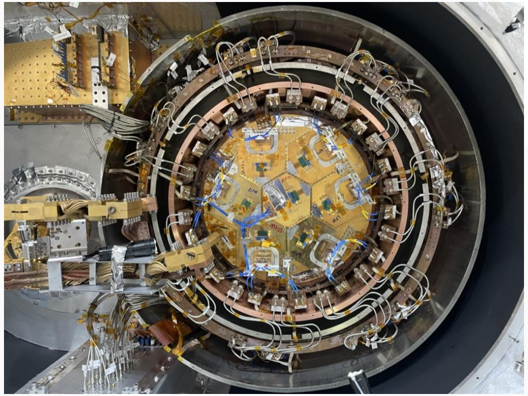
Detector Array



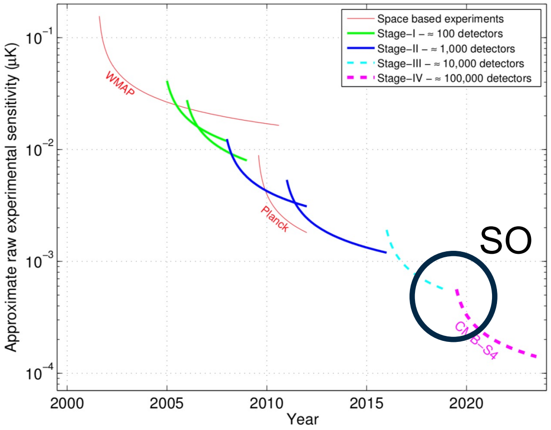


Dual Polarization & Frequency Pixels

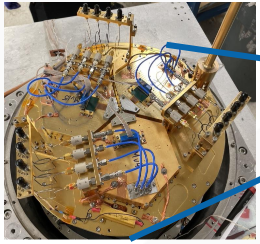
LAT – 62k detectors
30/40 GHz – 708 detectors
90/150 GHz – 41k detectors
220/280 GHz – 21k detectors

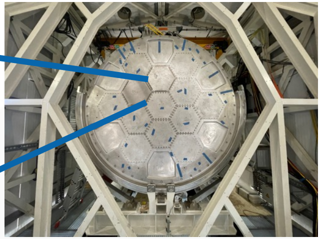


7 X Detector arrays densely packed per SAT



Increased detector count enables higher survey sensitivity





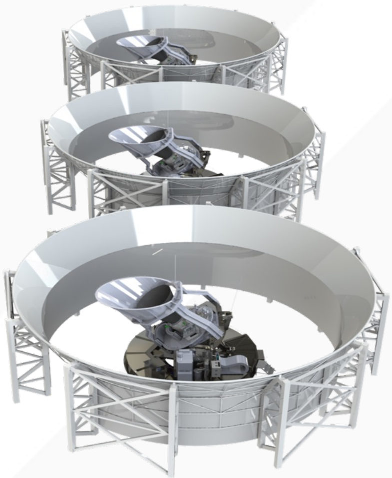
3 X Detector arrays packed per LAT Optics Tube

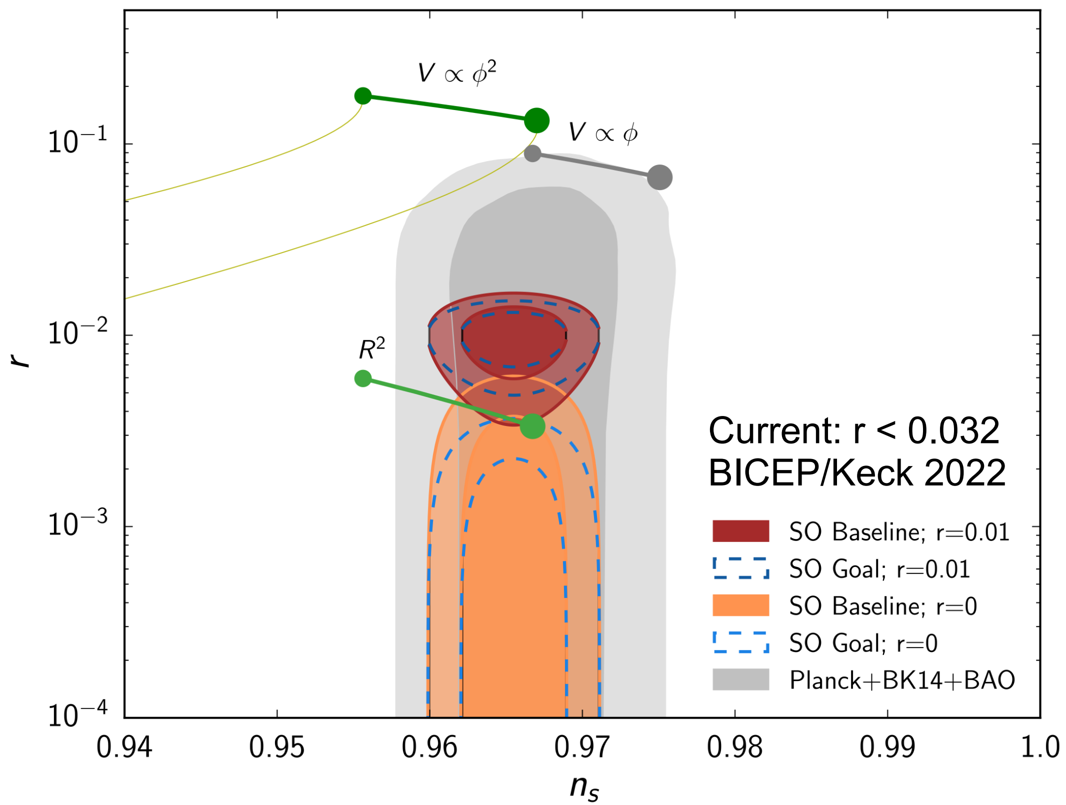
The Simons Observatory

Detecting Primordial Gravitational Waves from Inflation

Initial 3 SATs target **σ(r) = 0.002-0.003**

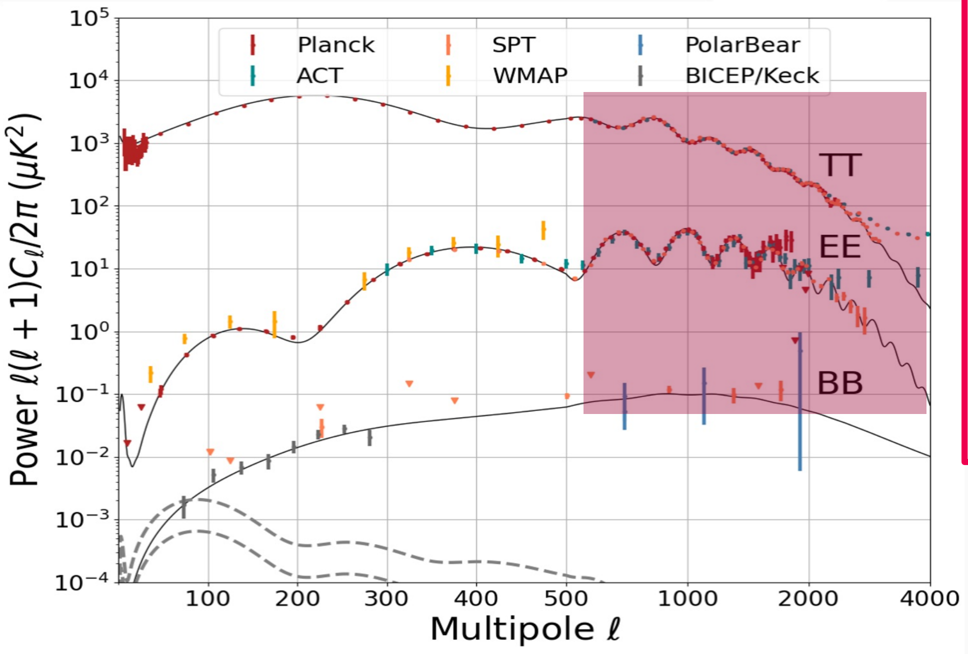
Will provide evidence for quantized gravity or rule out R^2 inflation.





SO Forecast Paper JCAP 02 2019 808.07445

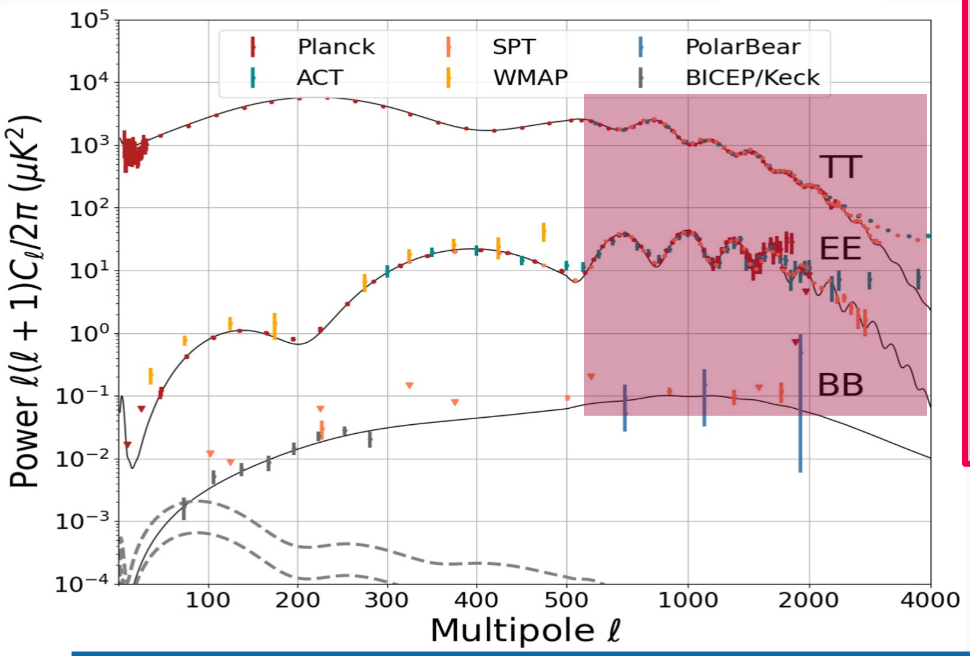
The Simons Observatory
Constraining additional light relativistic species



LAT constraints from the **small-scale damping tail, Lensing, and Cross Correlations**

- Through Neff can exclude all additional particles with spin that decouple up to the QCD phase transition.
- Will be able to constrain Normal vs Inverted neutrino mass ordering

The Simons Observatory
Constraining additional light relativistic species



LAT constraints from the **small-scale damping tail, Lensing, and Cross Correlations**

- Through Neff can exclude all additional particles with spin that decouple up to the QCD phase transition.
- Will be able to constrain Normal vs Inverted neutrino mass ordering

Talk by Frank Qu “Mass mapping and precision cosmology with CMB lensing” at 9:15am on Friday

The Simons Observatory
Commissioning In Chile

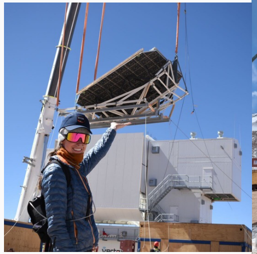
Feb 2024
LAT receiver
fully integrated

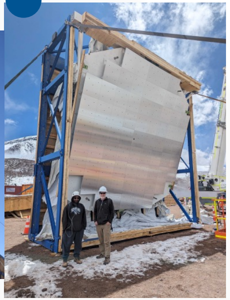
Feb 2025
First light
for LAT

Aug 2023
First light
for 1st SAT

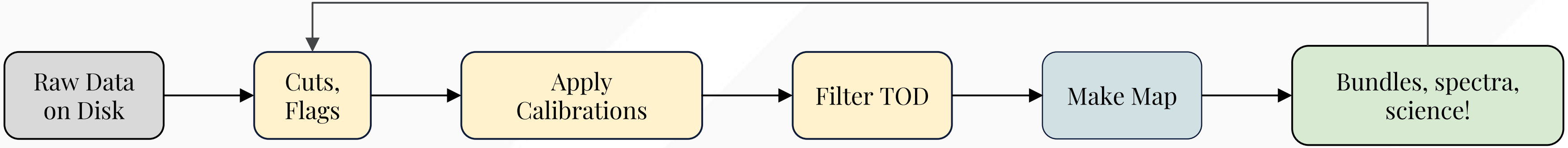
Dec 2023
First light
for 2nd SAT

Sept 2024
First light
for 3rd SAT

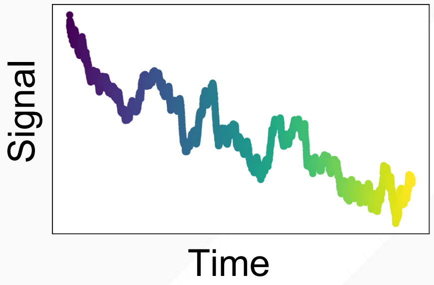




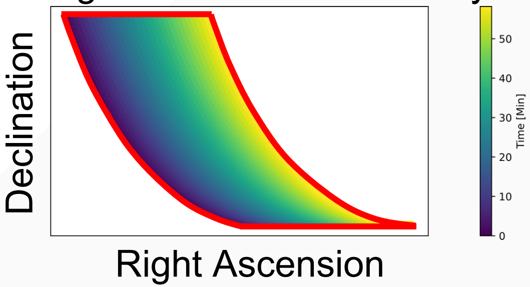
The Simons Observatory
Data reduction and mapmaking



Raw Single Detector Signal

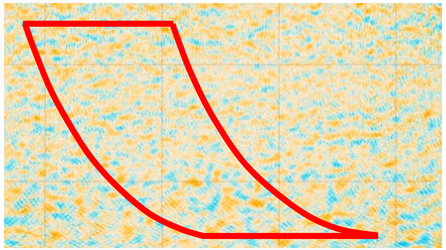


Single Detector Path on Sky



+

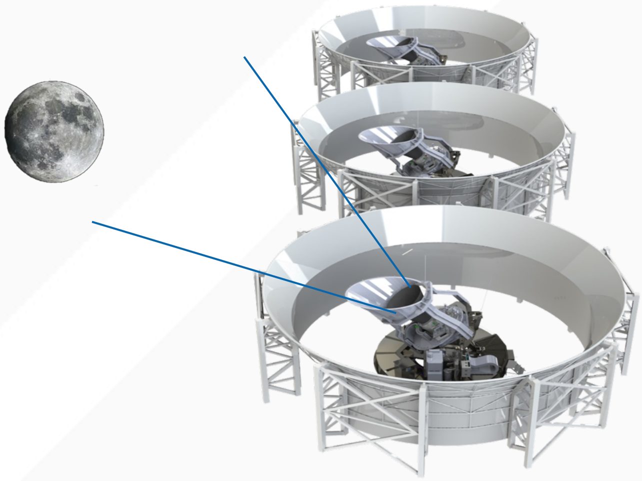
Filter, Calibrate,
+ optimally
average all 10k
detector signals
into a map



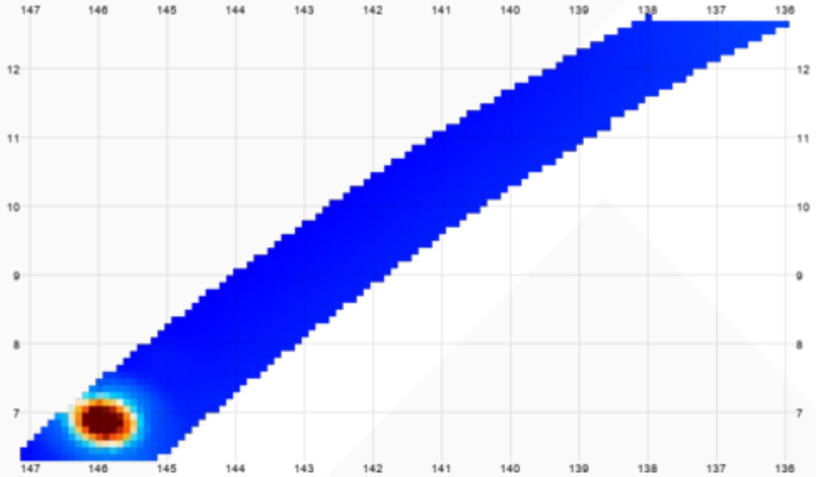
Open source data reduction pipeline allows rapid feedback on instrument performance when commissioning the telescopes.

Simons Observatory
SAT/Observatory First Measurements

First observation of the moon (bright and regularly available) to reconstruct telescope pointing.



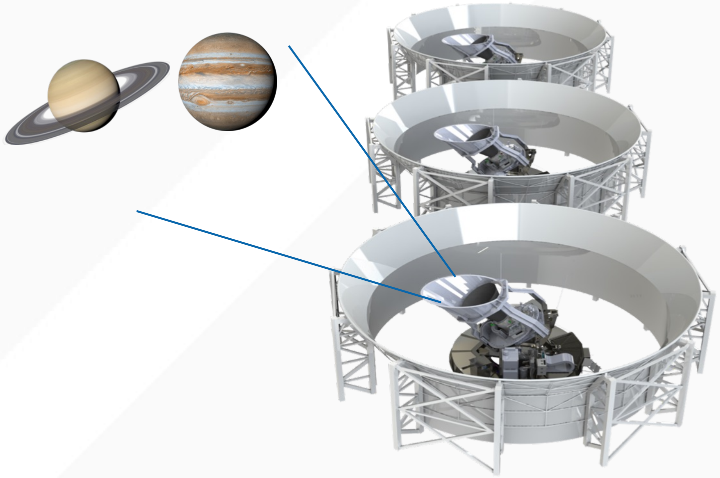
First map made within ~1 day of data taken

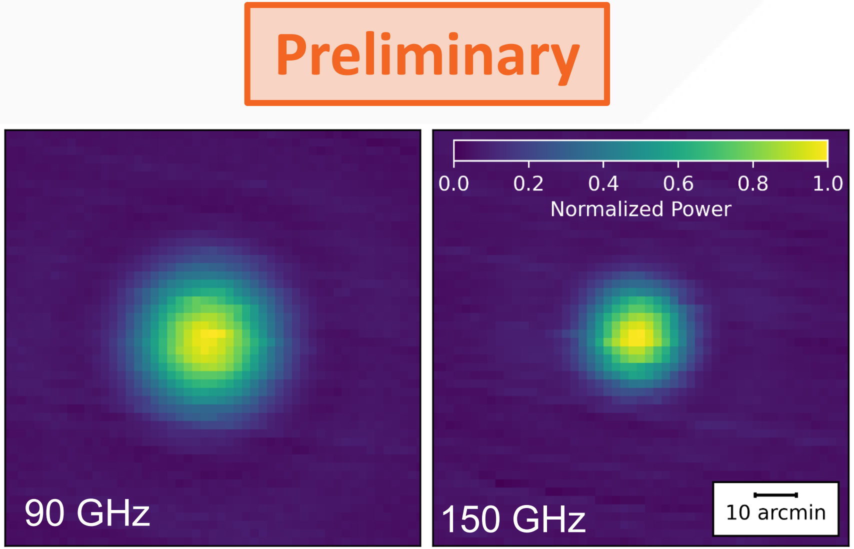


First light for the 1st telescope (SAT) in the observatory Aug 2023

Simons Observatory
SAT/First Calibration Measurements

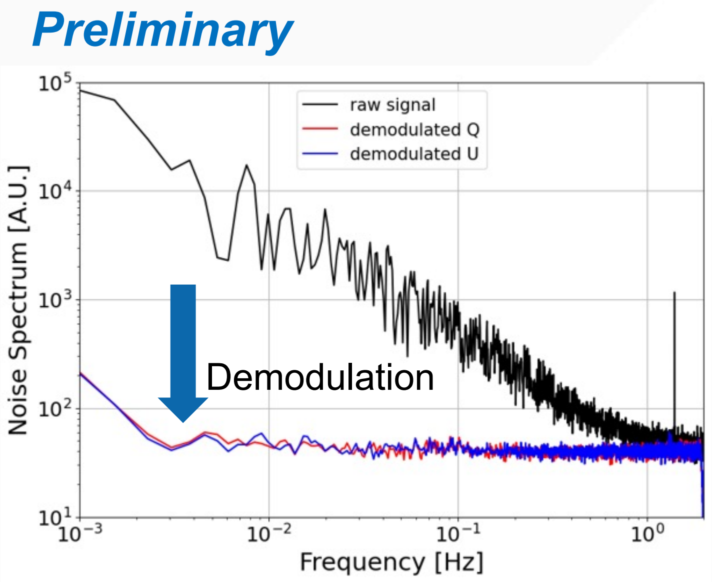
Observe solar system objects to calibrate gain and angular (beam) response of the telescopes.





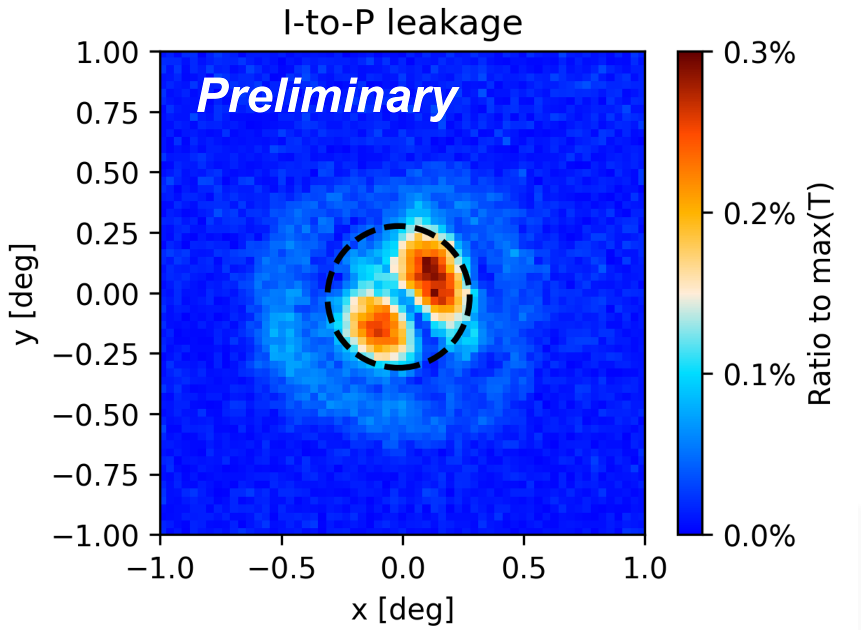
First maps made within ~1 month of data taken

The Simons Observatory
SAT Commissioning



Polarization noise spectrum is white down to very low frequencies. Atmospheric noise suppressed from SAT instrument design -> Half Wave Plate.

Fraction of I to total polarization amplitude P =√(Q^2 + U^2)

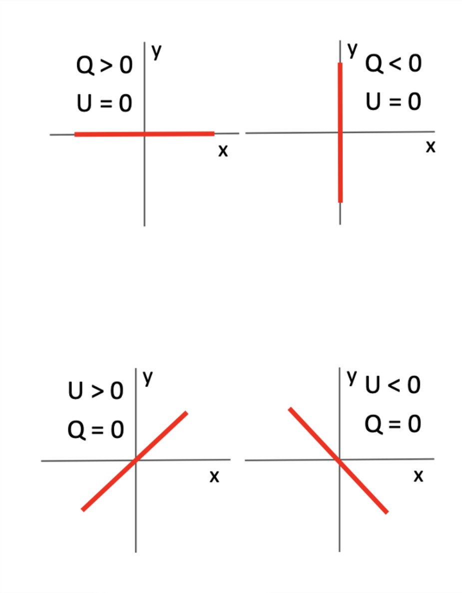


Total temperature to polarization beam constrained to <0.3%.

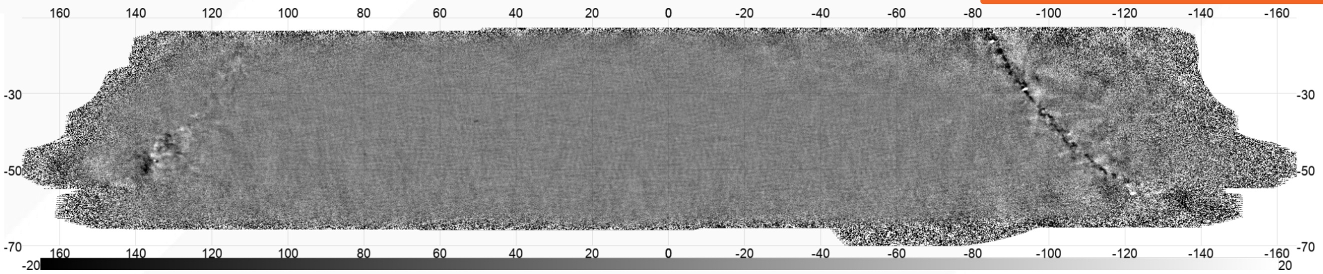
Simons Observatory
SAT/Observatory First CMB Maps

Preliminary

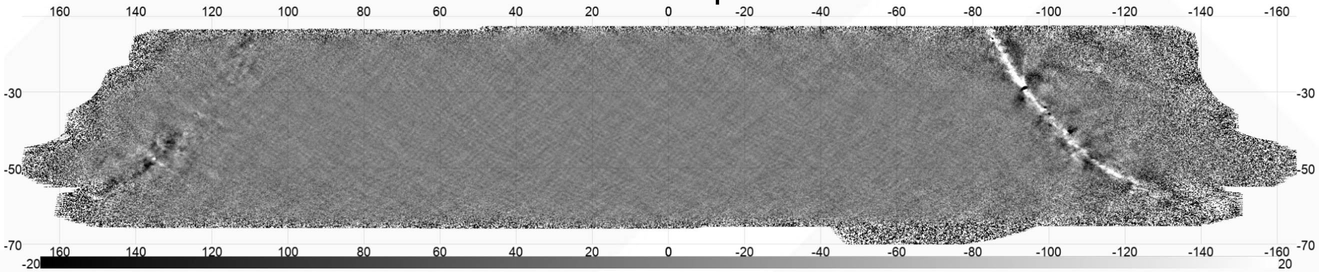
First maps made within ~1 month of data taken



90 GHz Q-Map



90 GHz U-Map

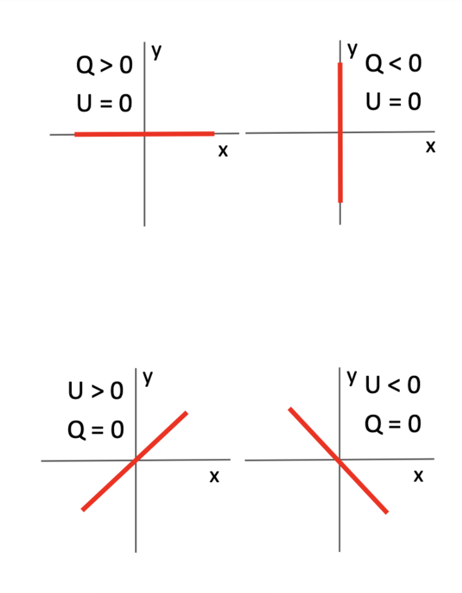


CMB maps from early commissioning/science survey demonstration measurements show **clear E-mode signal** away from galactic center, and polarized sources in the galactic plane

Simons Observatory
SAT/Observatory First CMB Maps

Preliminary

First maps made within ~1 month of data taken



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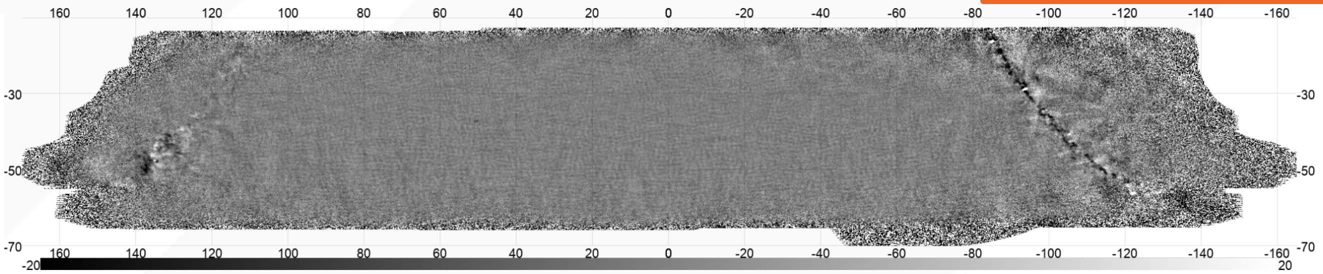
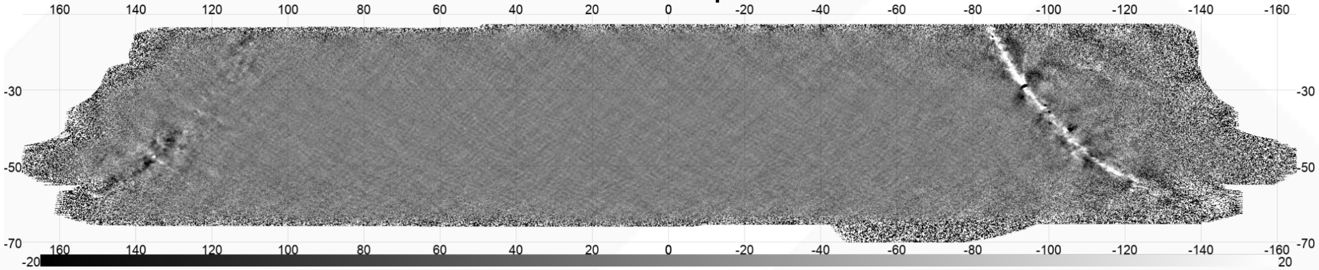


90 GHz U-Map

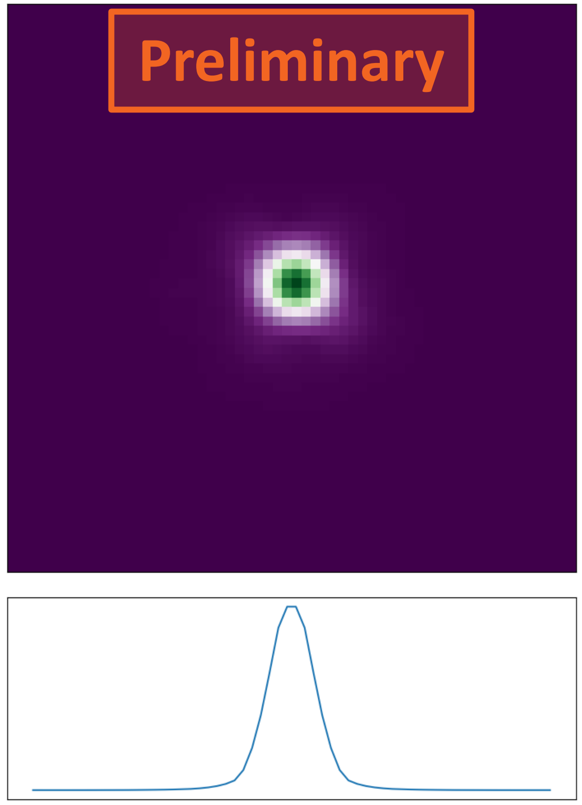


C
cl

Talk by Susanna Azonni “Simons Observatory SAT Characterization From Early Survey Data” at 3:10pm on Wednesday

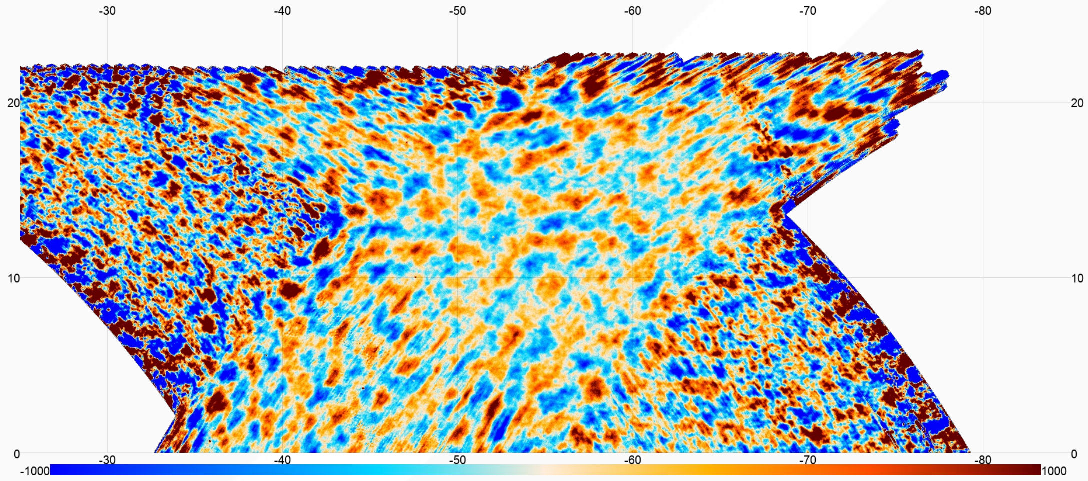
Simons Observatory
LAT/First Light Measurements

Initial measurements to align mirrors and calibrate pointing, beam, and gain response of LAT

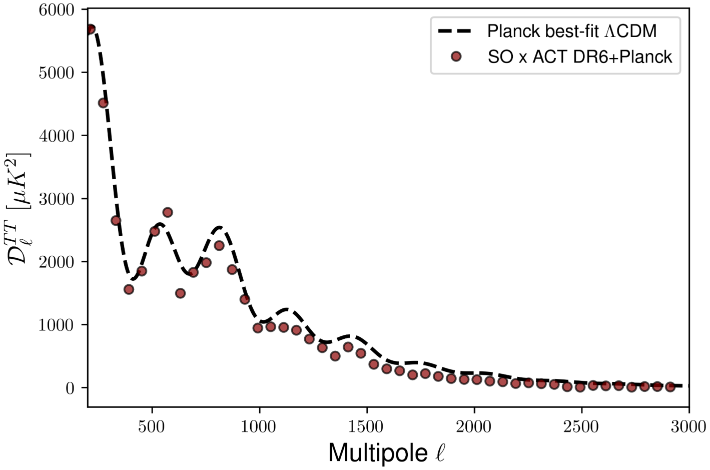


First map made within ~1 day of data taken

Preliminary

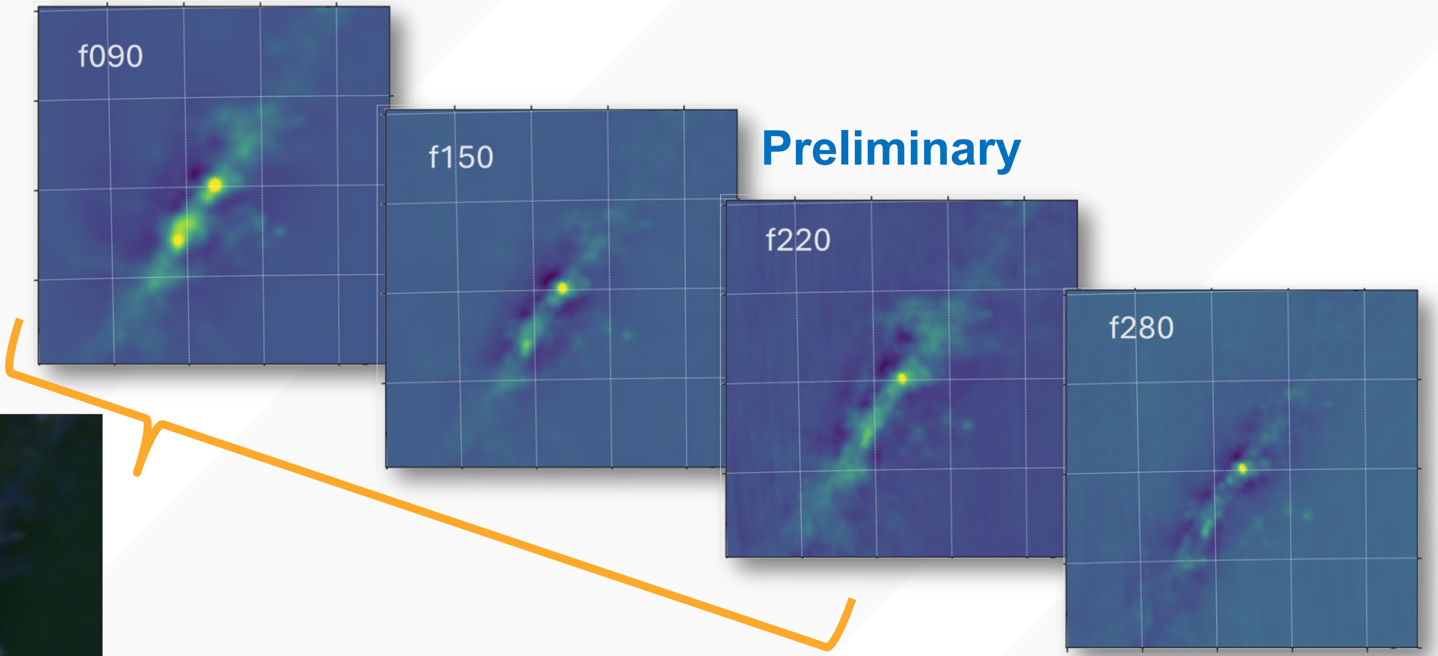


Preliminary

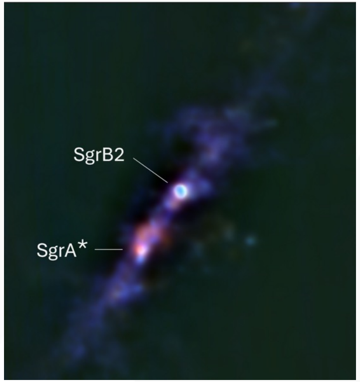


Very preliminary single frequency CMB maps from **<10 Hours** of observations **calibrated using Mars**. TT cross spectra with ACT+Planck map shows good agreement with expected amplitude without any gain rescaling.

Simons Observatory
Early LAT Commissioning



Preliminary

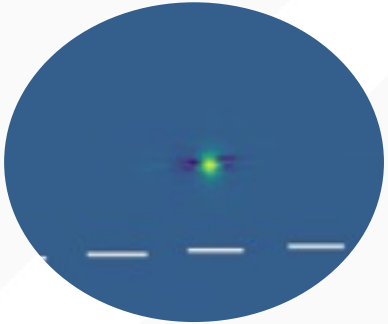


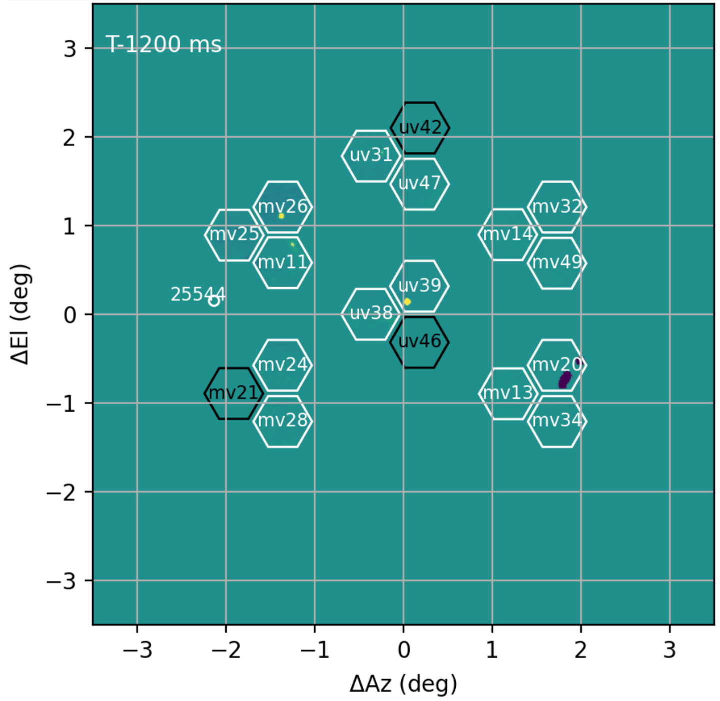
RGB false color map

Early multifrequency maps of the galactic center from 20 min of LAT observations.

Simons Observatory
Early Tests of LAT Transient Pipeline

Preliminary





Detection of thermal emission from the International Space Station!

Estimated to be O(100 Jy) at 100 GHz.

SO: Time Domain

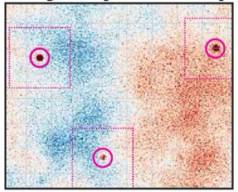
Daily monitoring of ~half the sky

Publish light curves of all sources detected >3σ at day/week/month depth
~7.5k (12k) AGN at **day** (week) cadence

Transient alerts issued to the public **within 30 hours of data collection**, along with associated light curves!

Much more:
https://doi.org/10.48550/arXiv.2503.00636

Daily Depth-1 Maps



SO Time Domain Pipeline

Source extraction, forced photometry, etc.

open-source python pipeline

photutils
An Astropy Package for Photometry

PREFECT

Storage and API access

Database, API service, downloads, etc.

postgresql as backing database

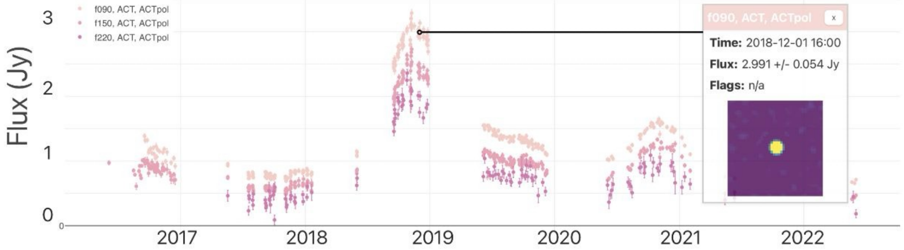
FastAPI

SQLModel

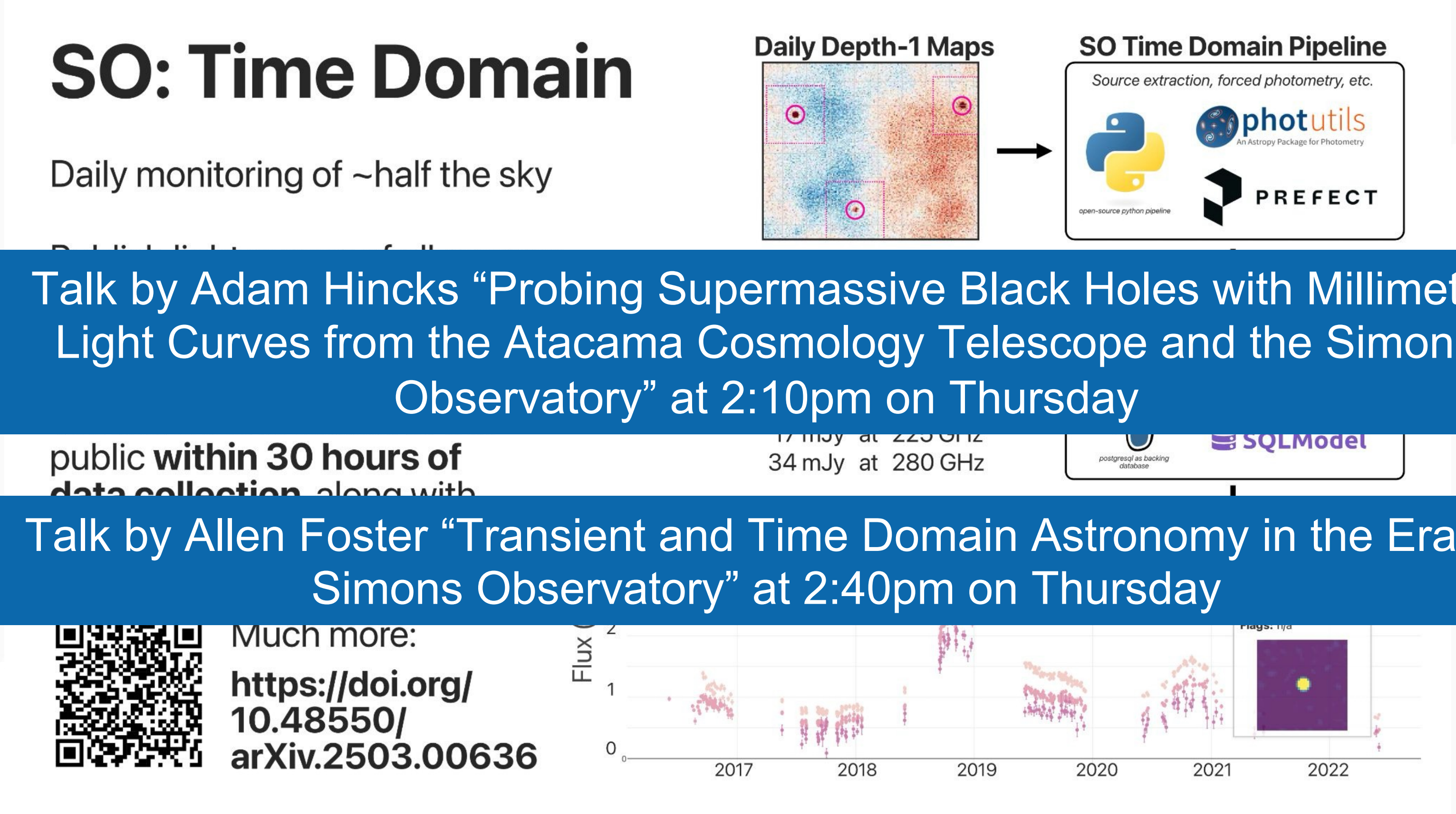
Goal Daily Sensitivity

27 mJy	at	27 GHz
19 mJy	at	39 GHz
7 mJy	at	**93 GHz**
9 mJy	at	**145 GHz**
17 mJy	at	225 GHz
34 mJy	at	280 GHz

Interactive Visualization



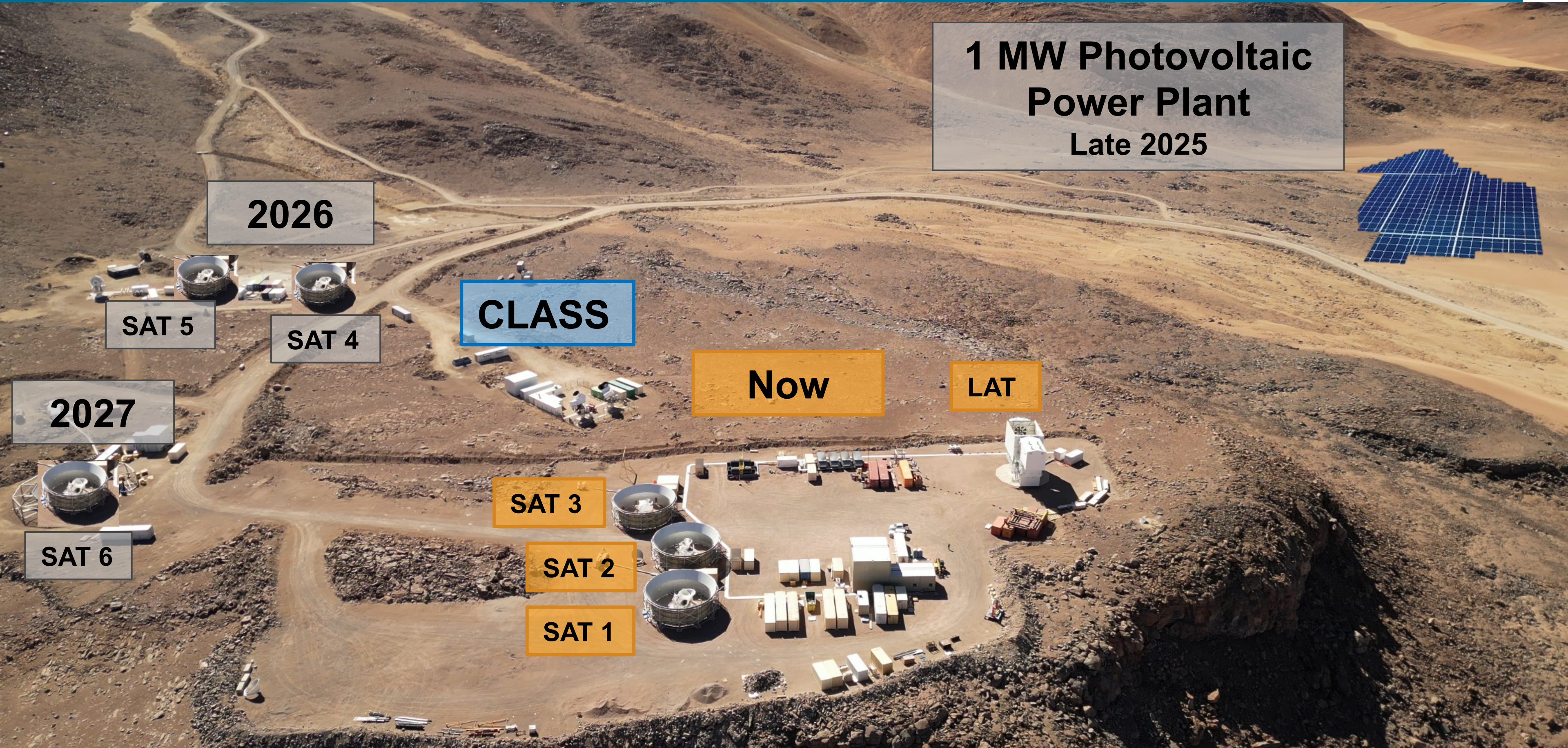
Simons Observatory
Early LAT Time Domain Pipeline



Talk by Adam Hincks "Probing Supermassive Black Holes with Millimetre Light Curves from the Atacama Cosmology Telescope and the Simons Observatory" at 2:10pm on Thursday

Talk by Allen Foster "Transient and Time Domain Astronomy in the Era of Simons Observatory" at 2:40pm on Thursday

Timeline for SO expansions



Conclusion

The **Simons Observatory** will be the most sensitive probe of fundamental physics from the CMB for the coming decade allowing us to:

- Detect the evidence for quantum gravity or rule out R^2 type inflation models.
- Detect the presence of additional relic light relativistic species.
- Provide a rapid public transient database for multiwavelength astrophysics studies.

Observatory commissioned over the last ~2 years and now moving into the nominal science survey.

Detailed commissioning results and early data releases coming soon!

Backups

Table 9
Summary of SO key science goals[a]

	Parameter	SO-Baseline[b] (no systematics)	**SO-Baseline**[c]	SO-Goal[d]	Current[e]	Method
Primordial perturbations	r	0.0024	**0.003**	0.002	0.03	BB + ext delens
	$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	0.4%	**0.5%**	0.4%	3%	$TT/TE/EE$
	$f_{\mathrm{NL}}^{\mathrm{local}}$	1.8	**3**	1	5	$\kappa\kappa \times$ LSST-LSS + 3-pt
		1	**2**	1		kSZ + LSST-LSS
Relativistic species	N_{eff}	0.055	**0.07**	0.05	0.2	$TT/TE/EE + \kappa\kappa$
Neutrino mass	Σm_ν	0.033	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO
		0.035	**0.04**	0.03		tSZ-N $\times$ LSST-WL
		0.036	**0.05**	0.04		tSZ-Y + DESI-BAO
Deviations from Λ	$\sigma_8(z=1-2)$	1.2%	**2%**	1%	7%	$\kappa\kappa$ + LSST-LSS + DESI-BAO
		1.2%	**2%**	1%		tSZ-N $\times$ LSST-WL
	H_0 (ΛCDM)	0.3	**0.4**	0.3	0.5	$TT/TE/EE + \kappa\kappa$
Galaxy evolution	η_{feedback}	2%	**3%**	2%	50-100%	kSZ + tSZ + DESI
	p_{nt}	6%	**8%**	5%	50-100%	kSZ + tSZ + DESI
Reionization	Δz	0.4	**0.6**	0.3	1.4	TT (kSZ)

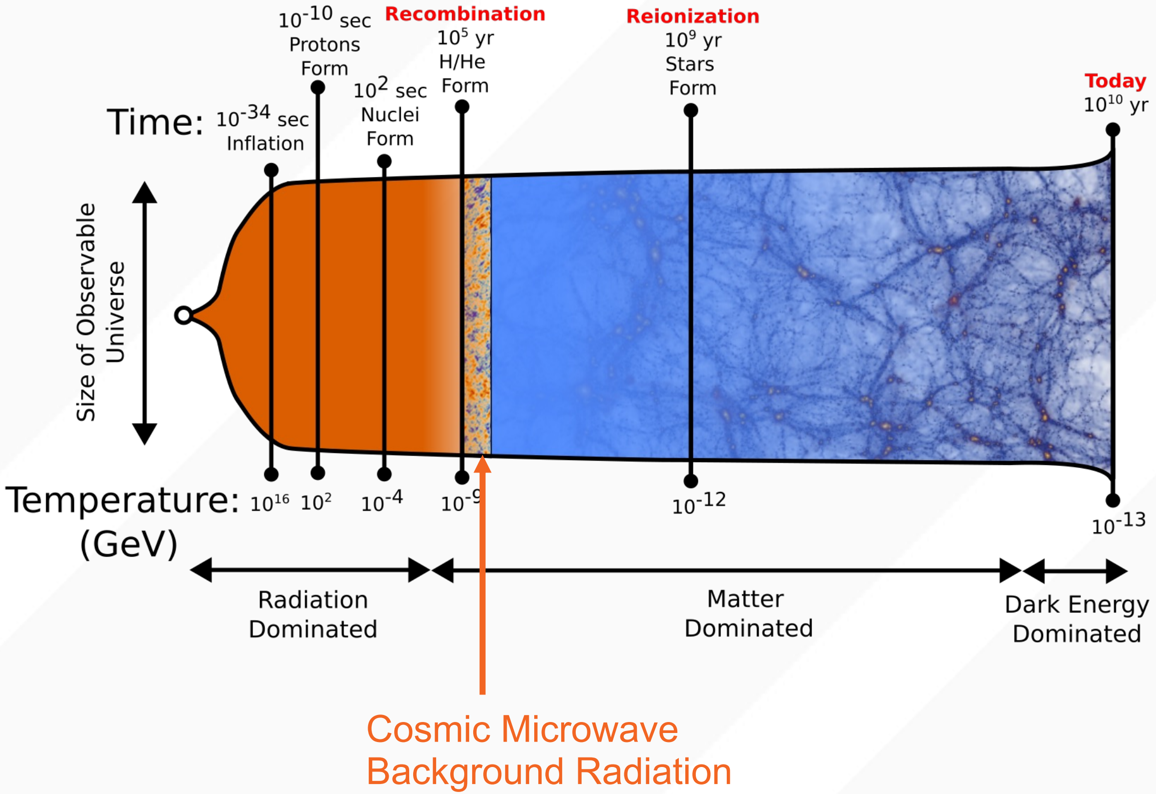
LAT SO Nominal

Frequency (GHz)	FWHM (arcmin)	Baseline (μK-arcmin)	Goal (μK-arcmin)	Frequency Bands	Detector Number	Optics Tubes
27	7.4	71	52	LF	222	1
39	5.1	36	27		222	
93	2.2	8.0	5.8	MF	10,320	4
145	1.4	10	6.3		10,320	
225	1.0	22	15	UHF	5,160	2
280	0.9	54	37		5,160	

LAT ASO Full

Frequency (GHz)	FWHM (arcmin)	Baseline (μK-arcmin)	Goal (μK-arcmin)	Frequency Bands	Detector Number	Optics Tubes
27	7.4	58	39	LF	222	1
39	5.1	30	20		222	
93	2.2	5.25	3.5	MF	20,640	8
145	1.4	5.7	3.8		20,640	
225	1.0	14	9	UHF	10,320	4
280	0.9	33	22		10.320	

The Cosmic Microwave Background
A Laboratory to Study Fundamental Physics



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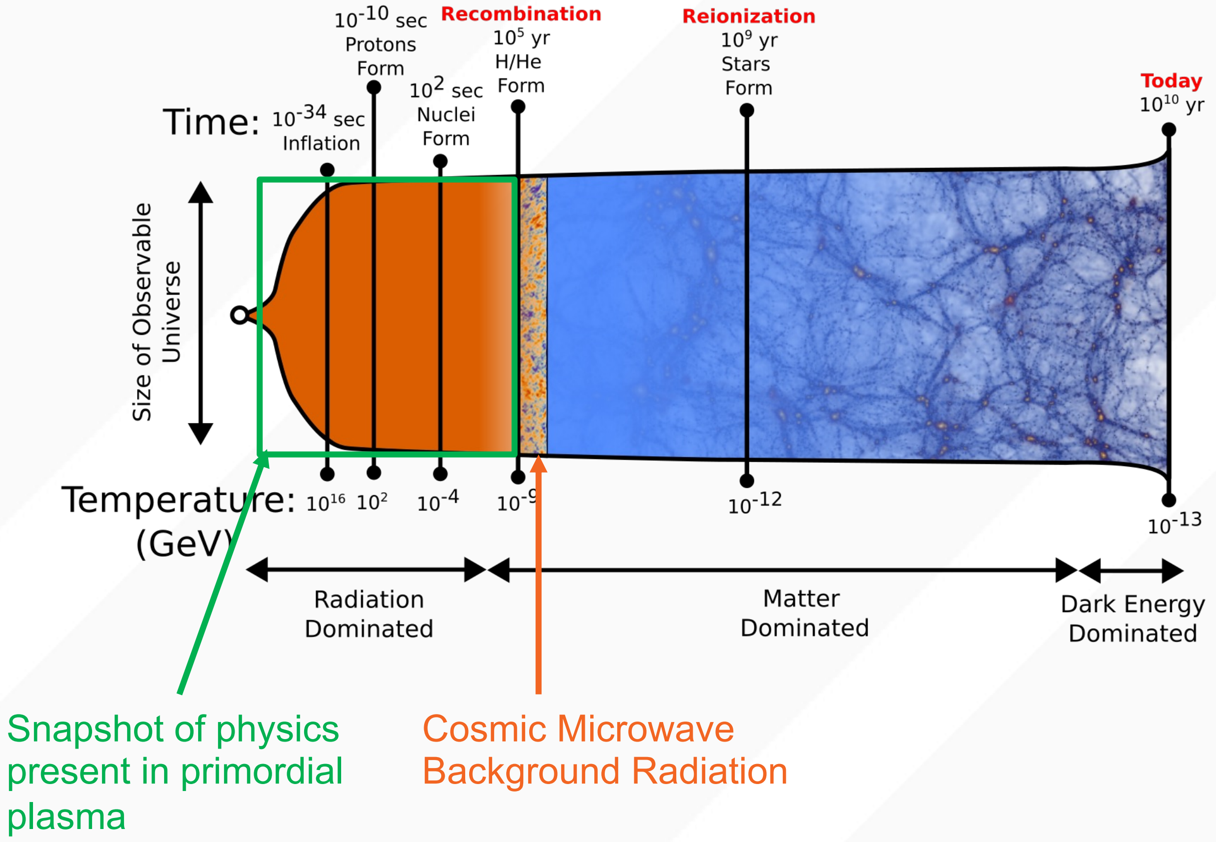

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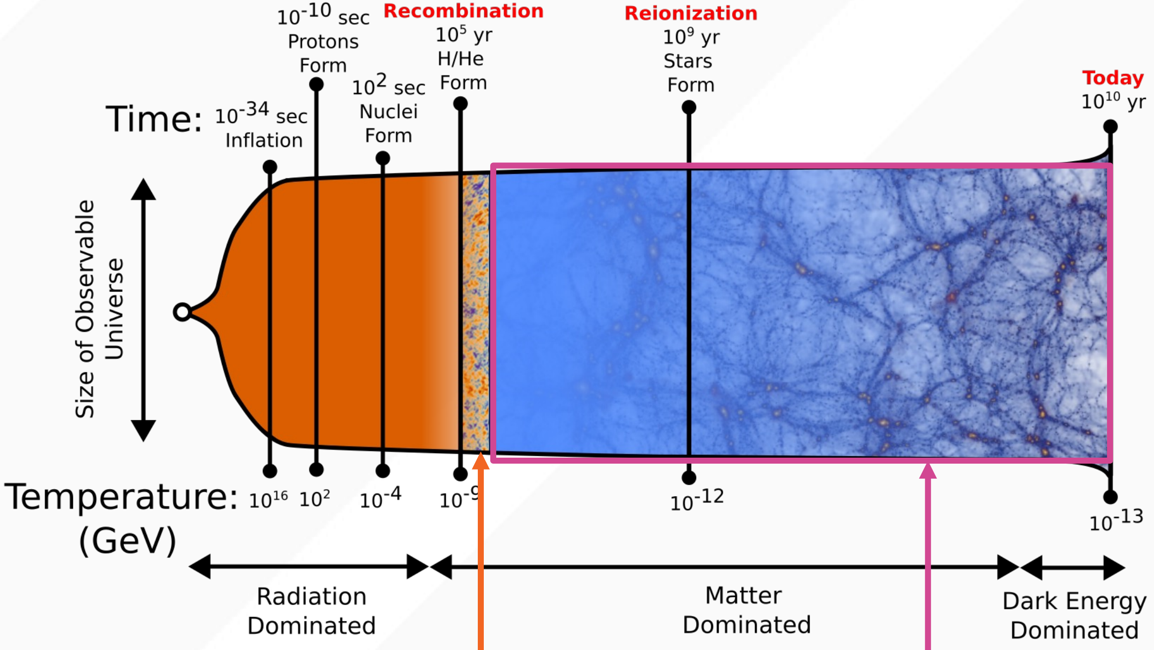
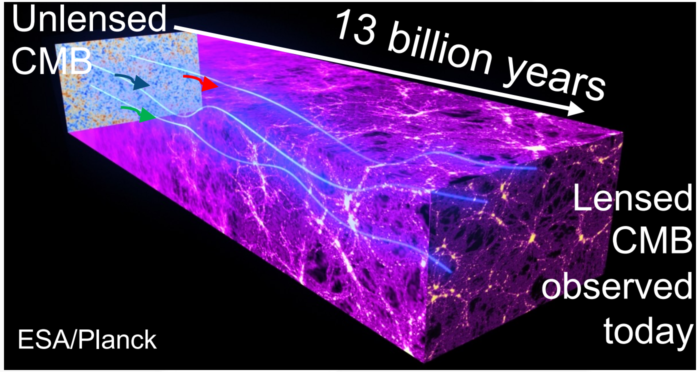


Cosmic Microwave Background Radiation

Backlight to large scale structure (dark matter, galaxy formation)



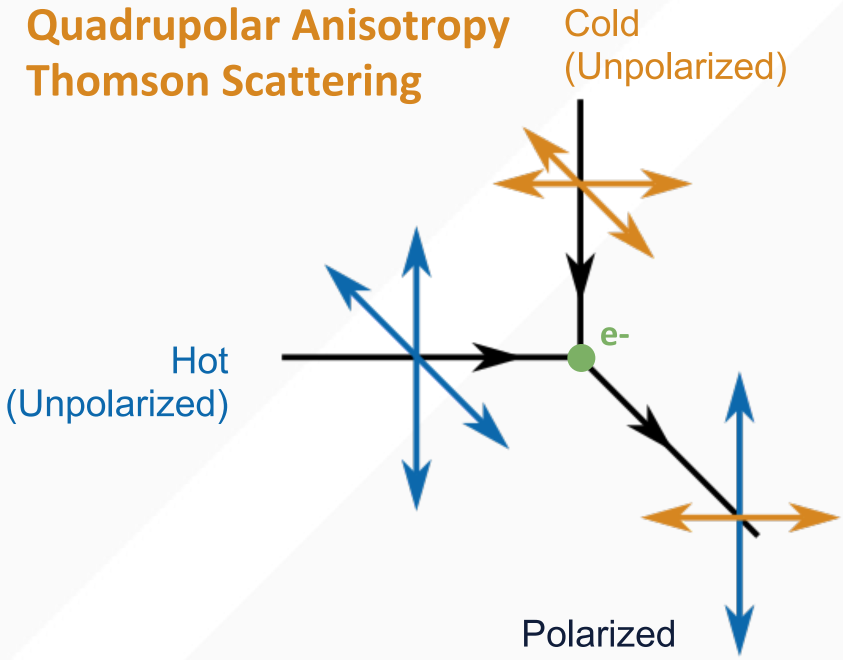
Structure between recombination and us deflects the CMB on arcminute scales and induces degrees scale correlations.

Sensitive to the **sum of the neutrino masses, dark matter, growth of structure.**

The Cosmic Microwave Background

Polarized CMB

Quadrupolar Anisotropy
Thomson Scattering

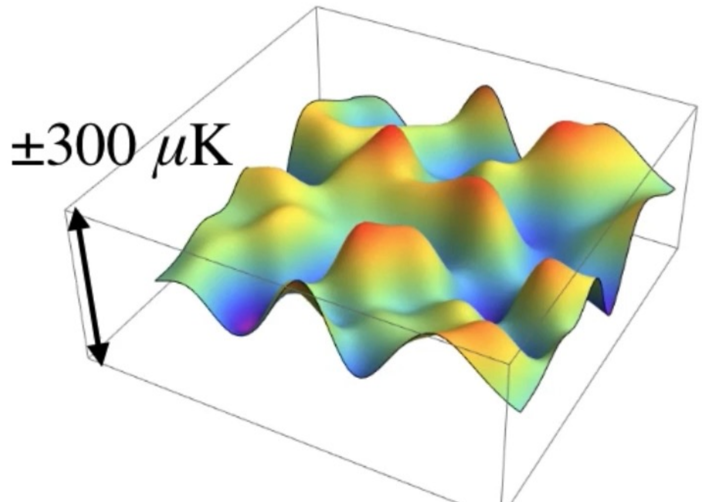


Electrons in a radiation background with a **quadrupolar anisotropy** generate polarized emission via **Thomson scattering.**

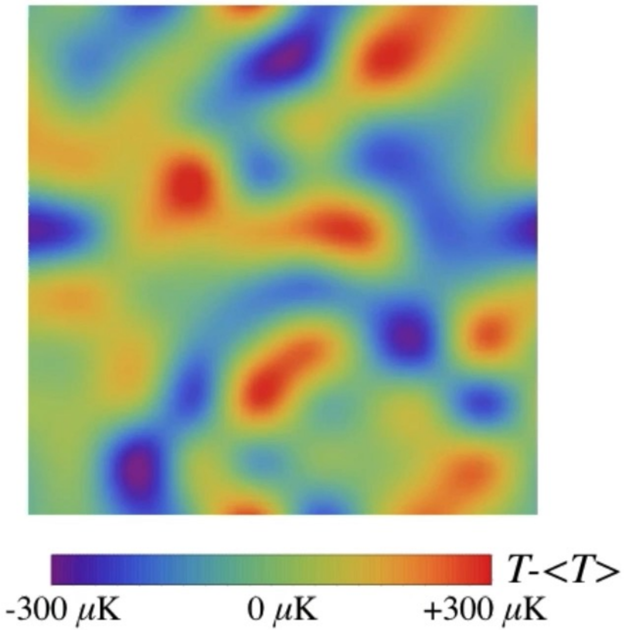
Polarization field of CMB provides 2-additional degrees of freedom to further constrain fundamental physics

The Cosmic Microwave Background

Encoding the Primordial Plasma



Courtesy of Yacine Ali-Haïmoud



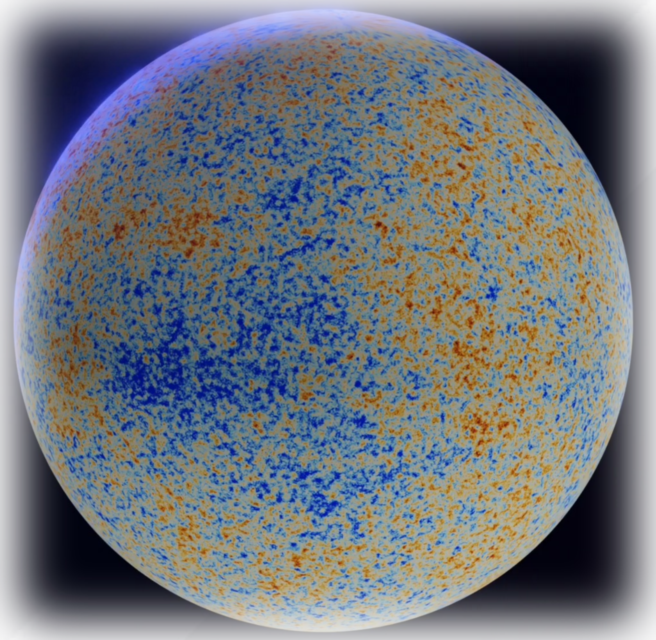
Prior to Recombination, **Matter and Radiation** are tightly coupled forming an ideal fluid.

Quantum fields source density and velocity fluctuations in the fluid.

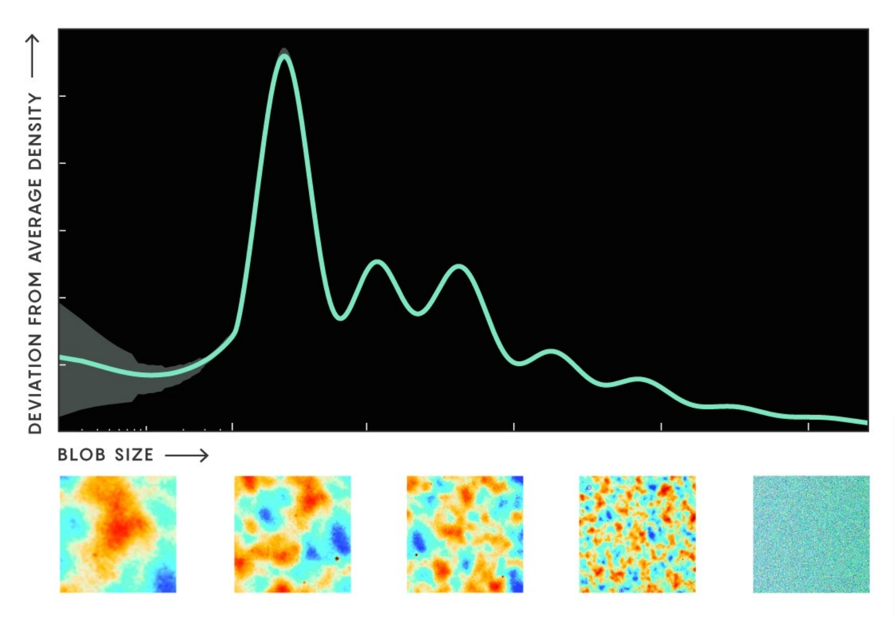
The maps we see are an imprint of the state of the Universe when **Matter and Radiation Decoupled.**

The Cosmic Microwave Background

What do we observe?



Dillon Berger @InertialObservr

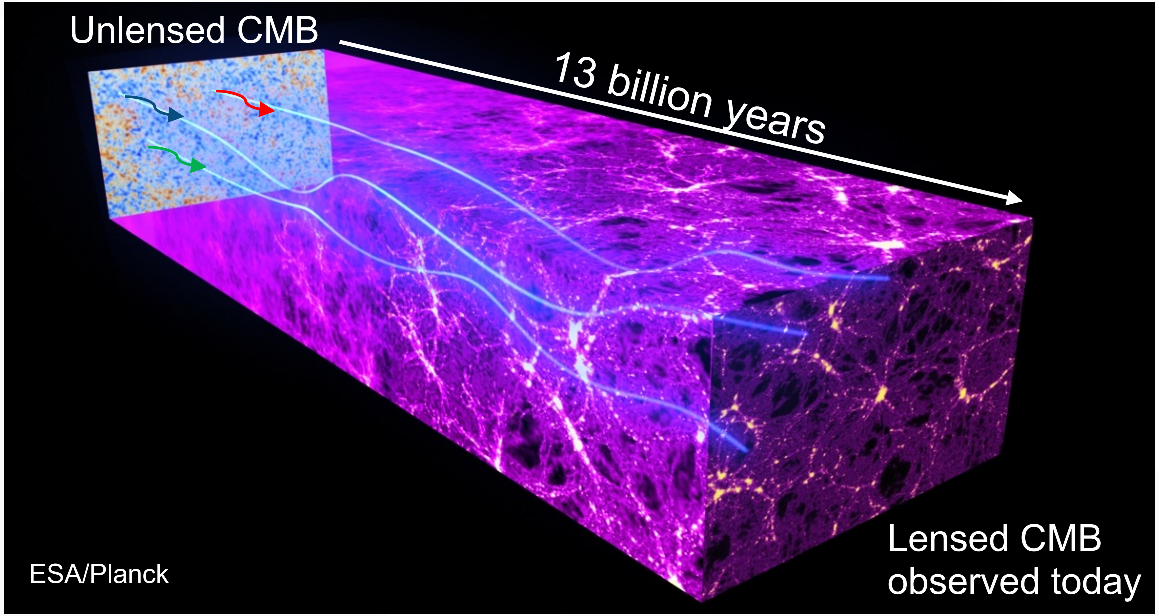


Lucy Reading-Ikkanda/Quanta Magazine; Planck 2013 XVI

The Cosmic Microwave Background
A Backlight to the Large Scale Structure

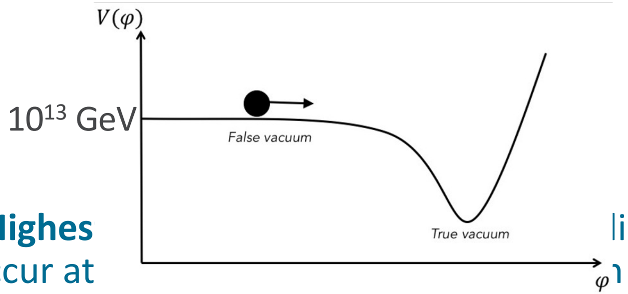
Structure between recombination and us deflects the CMB on arcminute scales and induces degrees scale correlations.

Sensitive to the **sum of the neutrino masses, dark matter, growth of structure.**

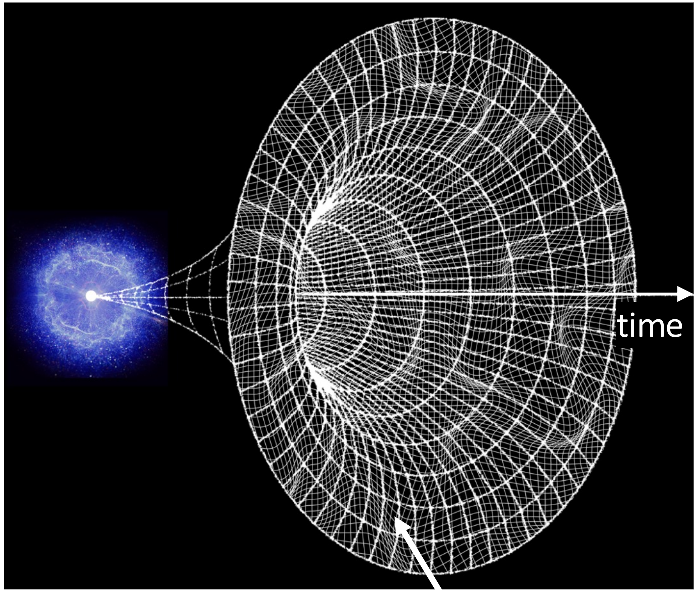


Primordial gravitational waves from inflation

Theoretical motivation for inflation: Horizon problem, flatness problem, lack of magnetic monopoles



“Highes licted to occur at gravity becomes relevant, well beyond those accessible with the LHC

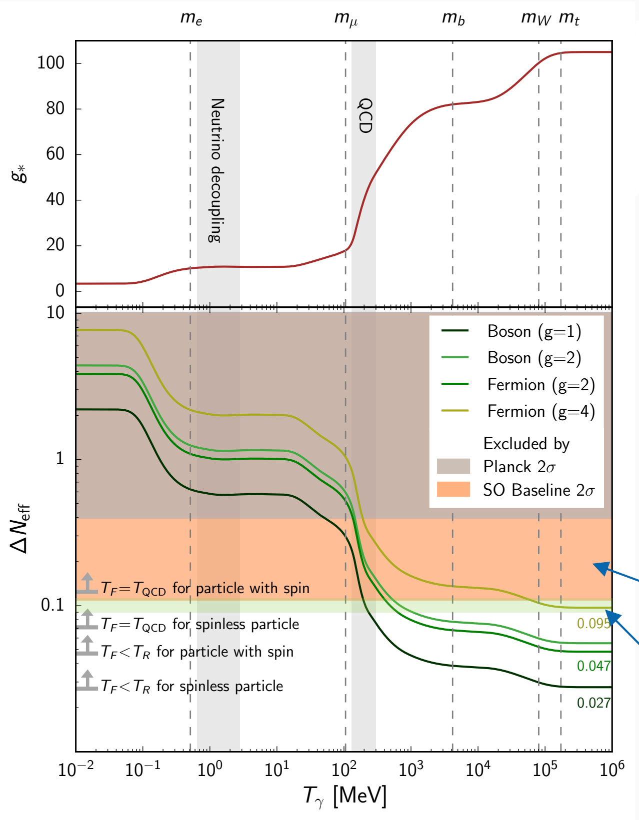


Tensor perturbations leave polarization signatures in the CMB

SO aims to constrain tensor to scalar ratio *r* to σ(*r*)<0.002

The Simons Observatory

Constraining additional light relativistic species



Initial 7 OT Forecast

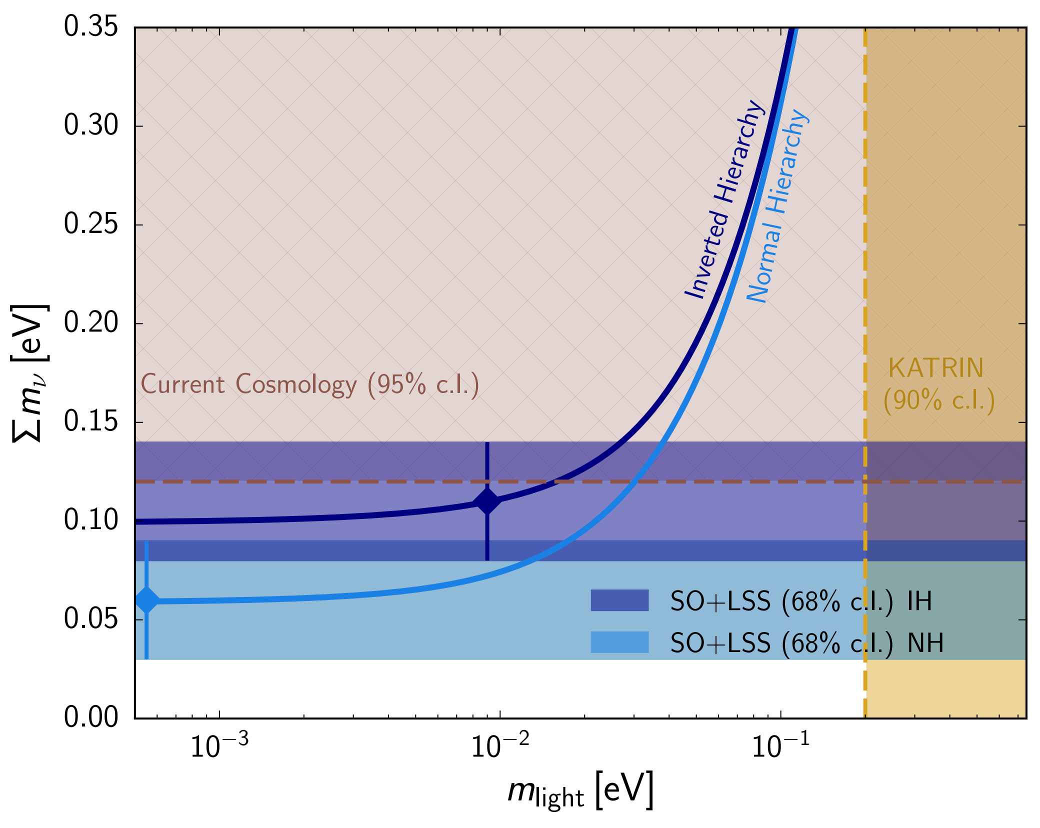
Extended 13 OT Forecast

LAT constraints from the **small scale damping tail.**

Neff encodes effects on primordial radiation density from light species. If only 3 standard neutrino interactions **Neff = 3.046 deviations mean new phyiscs - 4th Neutrino, Axion++**

The Simons Observatory

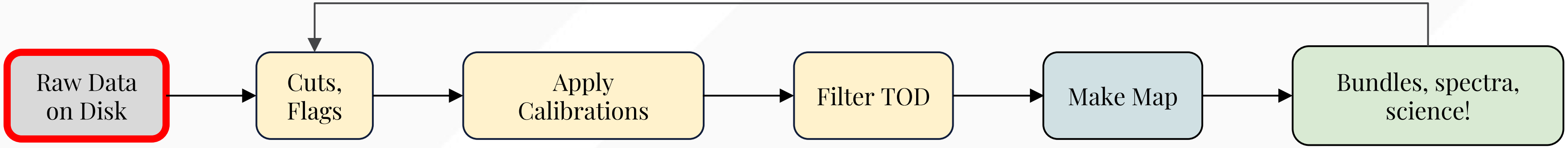
Constraining the sum of the neutrino masses Σm_ν

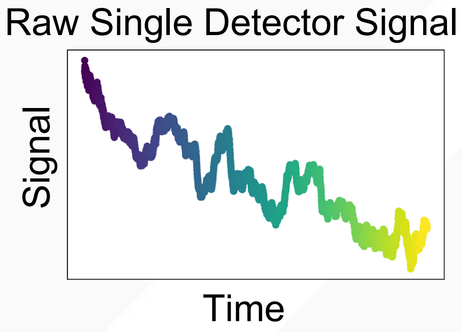


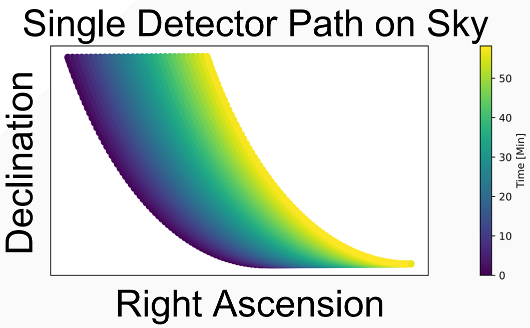
LAT constraints on Σm_ν

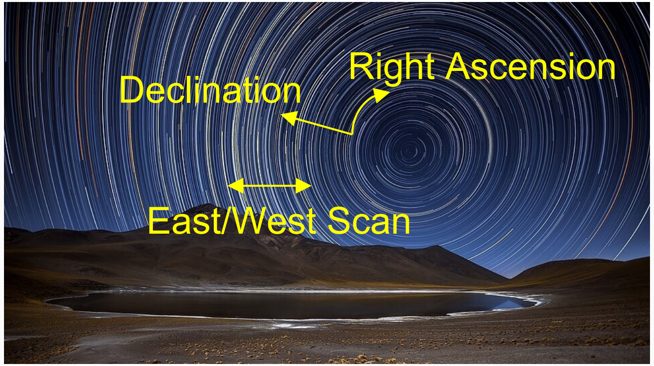
Massive neutrinos suppress structure growth at late times. Combining primary CMB with CMB lensing, and external galaxy surveys (BAO) **we can set a limit on the minimum total neutrino mass to distinguish normal vs inverted mass ordering.**

CMB Telescopes don't take images like an optical camera









Open source data reduction pipeline allowed rapid feedback on instrument performance when commissioning the telescopes.

The Simons Observatory
Data reduction and mapmaking

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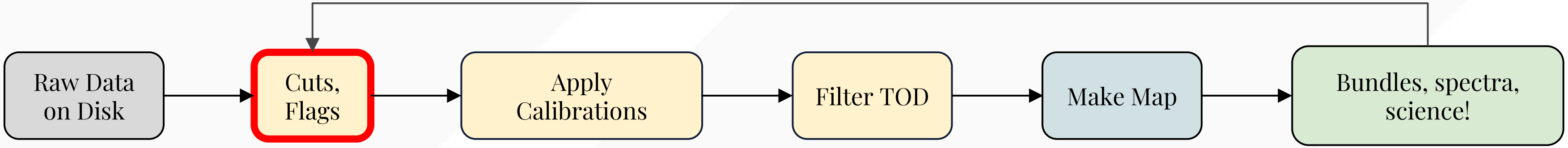

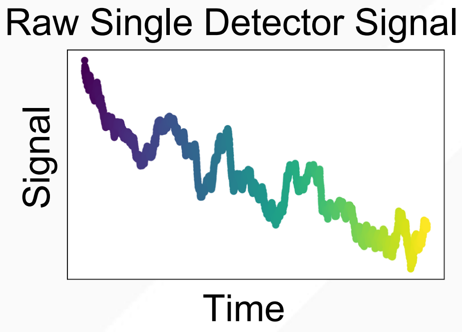

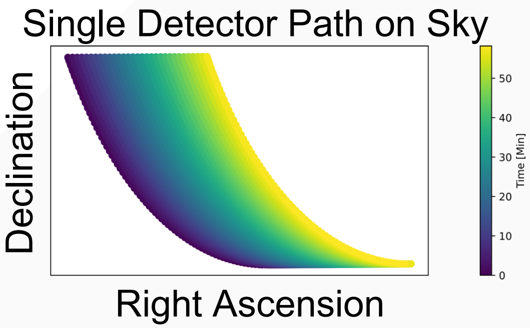

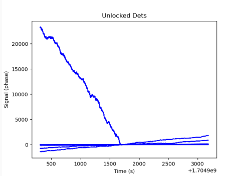

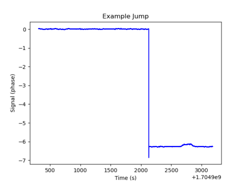

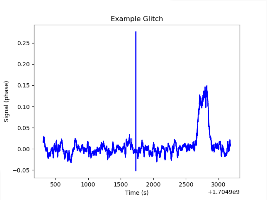

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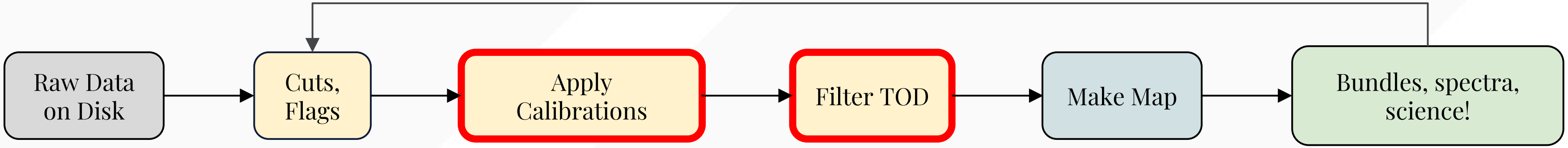
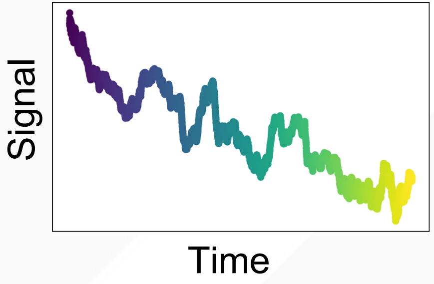
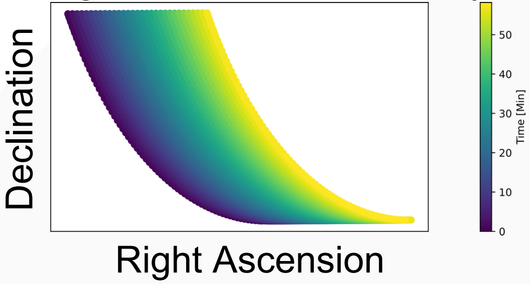


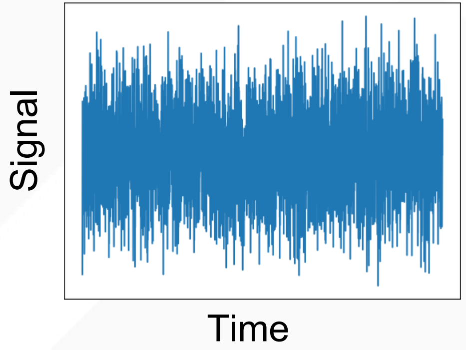
Raw Single Detector Signal



Single Detector Path on Sky



Filtered Single Detector Signal



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