The Simons Observatory

Josquin Errard (APC/CNRS)
Observing the Universe at Millimeter Wavelengths
June 26, 2023
josquin@apc.in2p3.fr

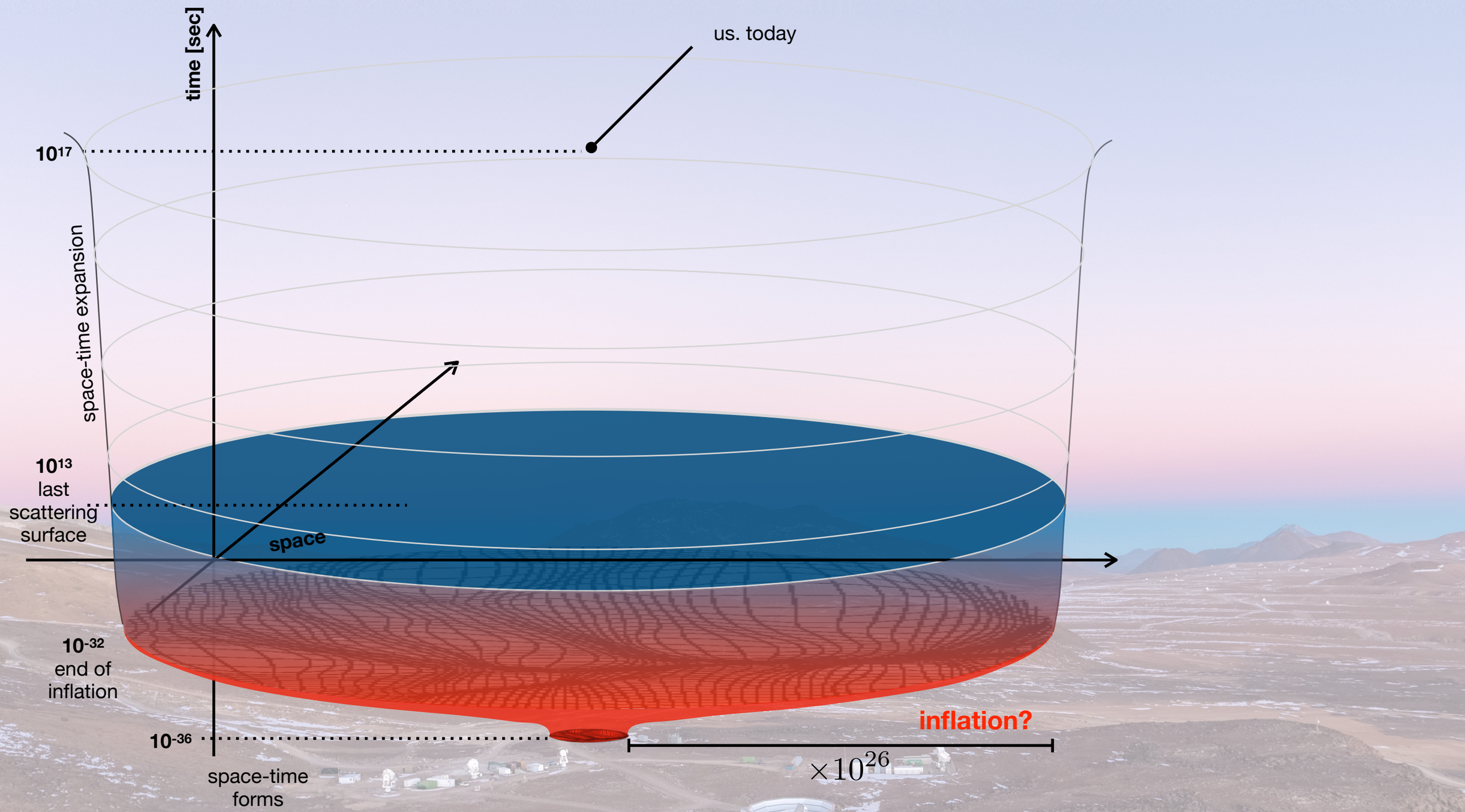
Science from the large scale cosmic microwave background polarization structure

European Research Council

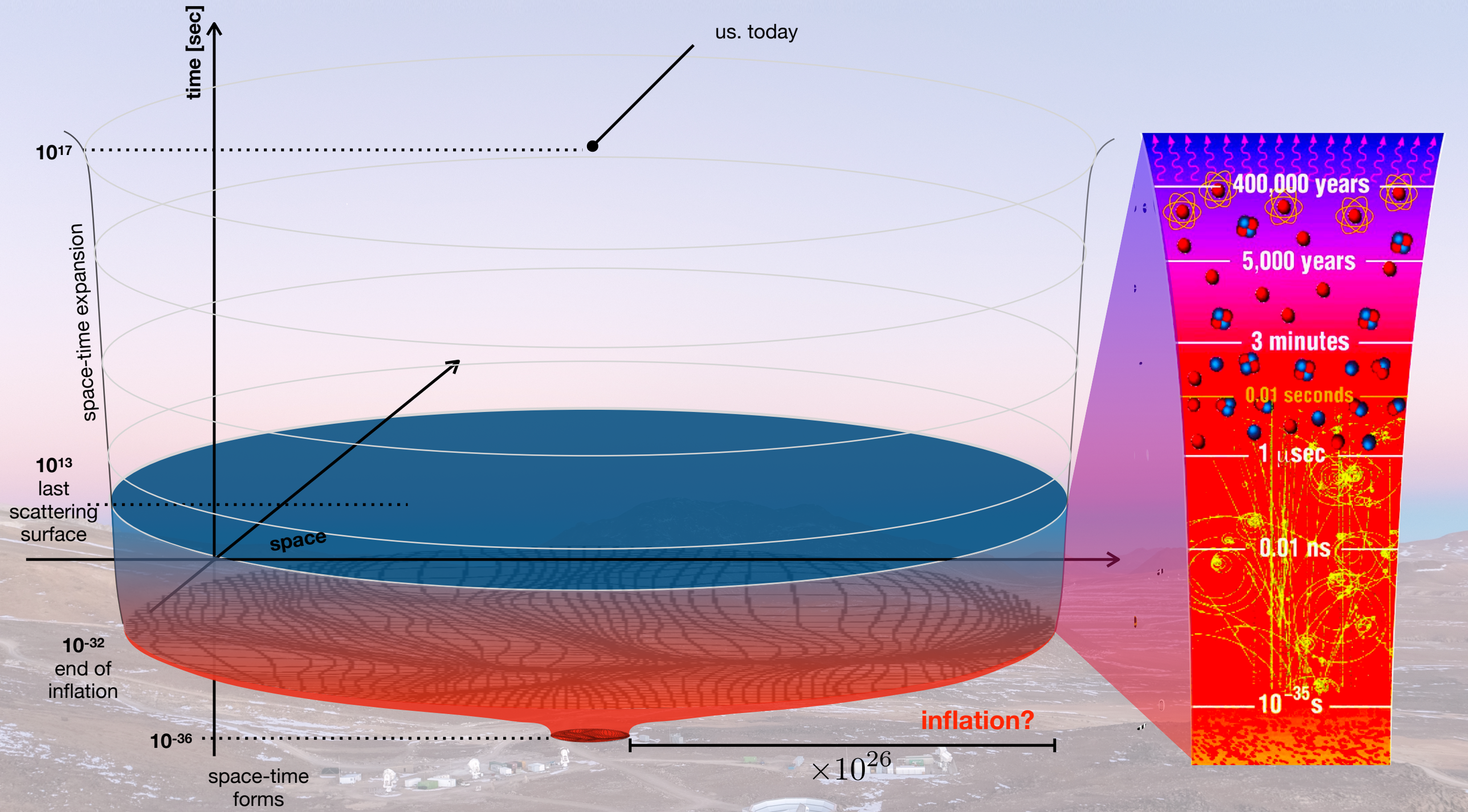
mm Universe 2023

The Simons Observatory

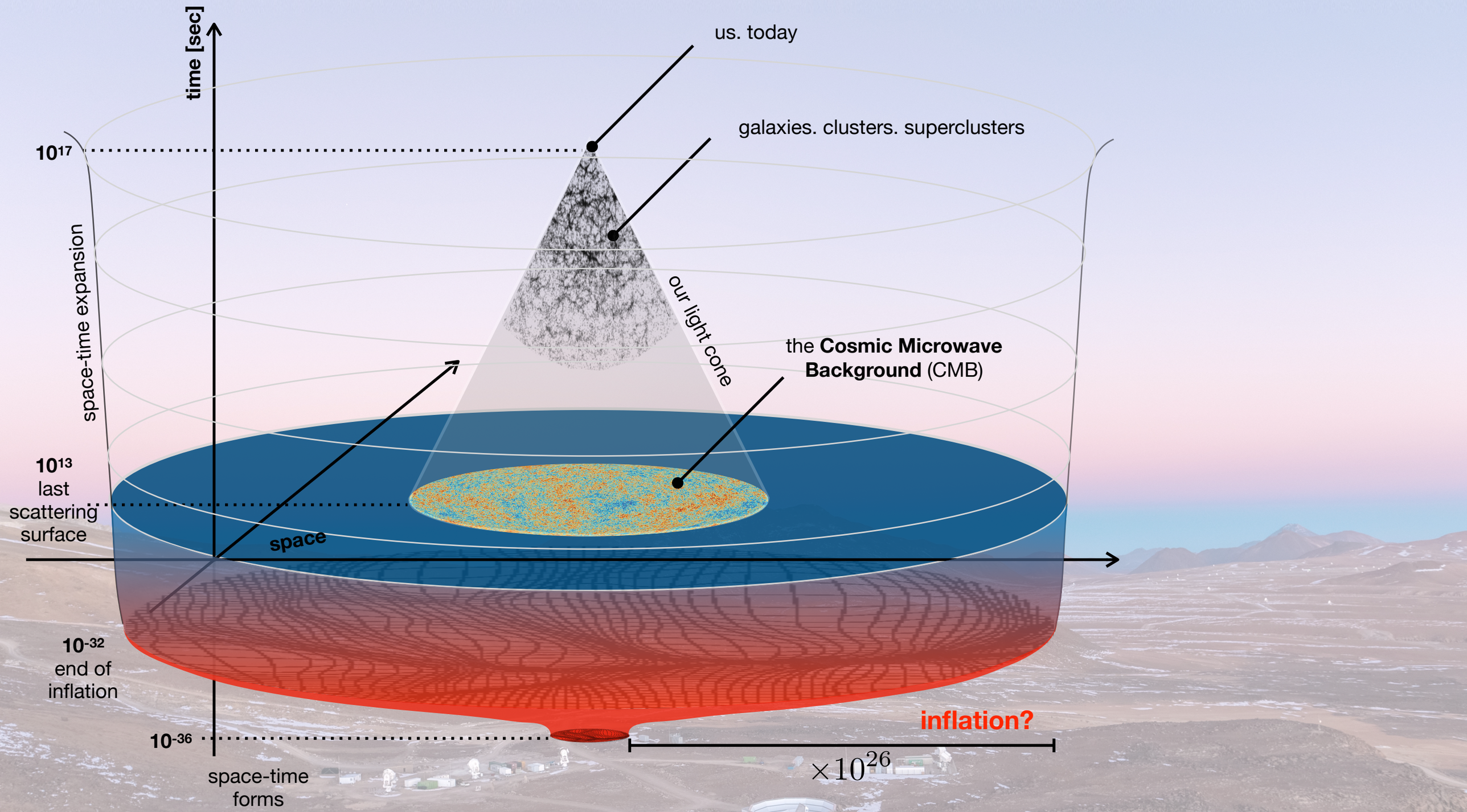
Chajnantor plateau
CCATp
ALMA
POLARBEAR/Simons Array
CLASS
ACT
Simons Observatory
17,000ft / 5,200m above see level



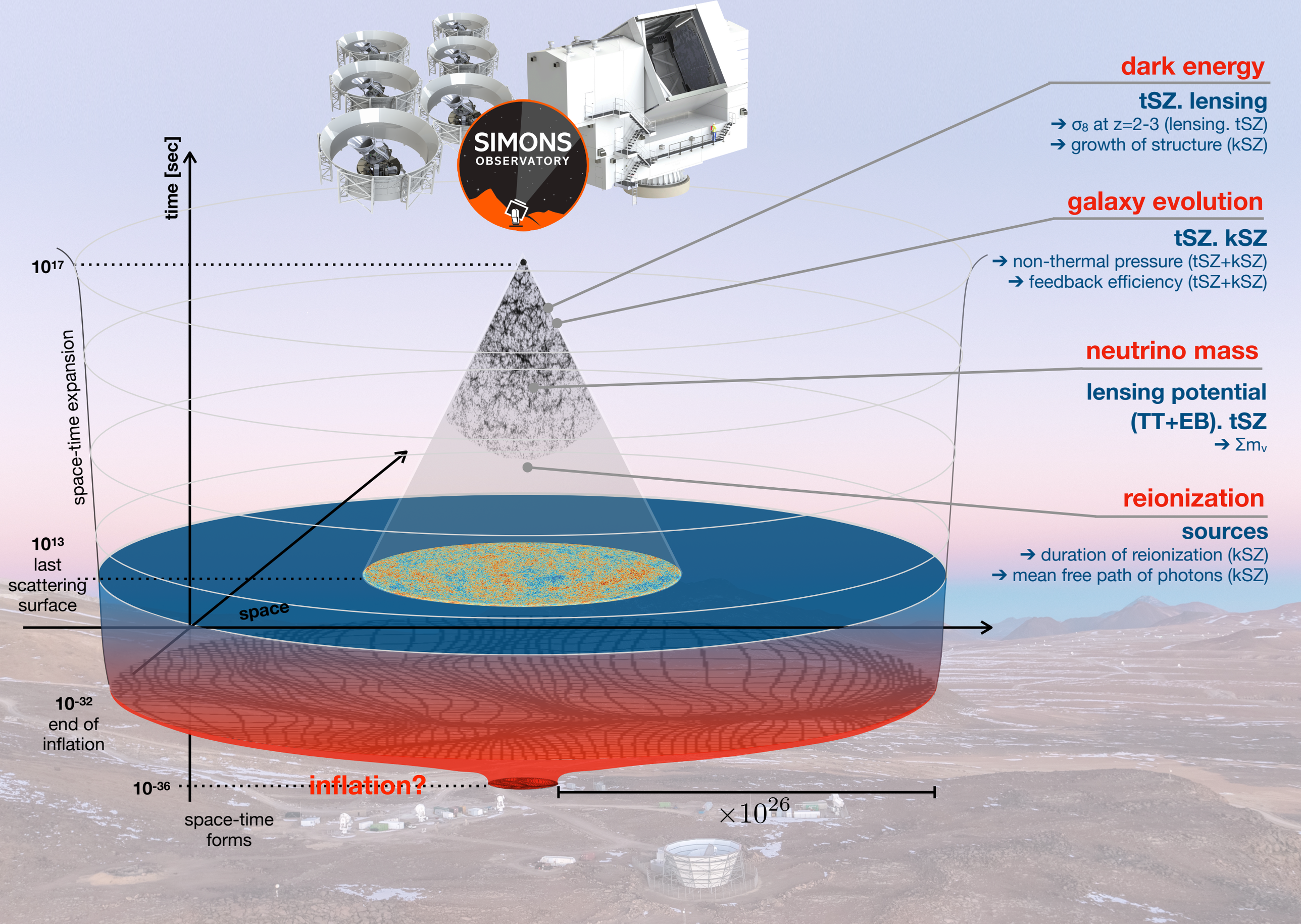
Josquin Errard, Simons Observatory, mmUniverse 2023



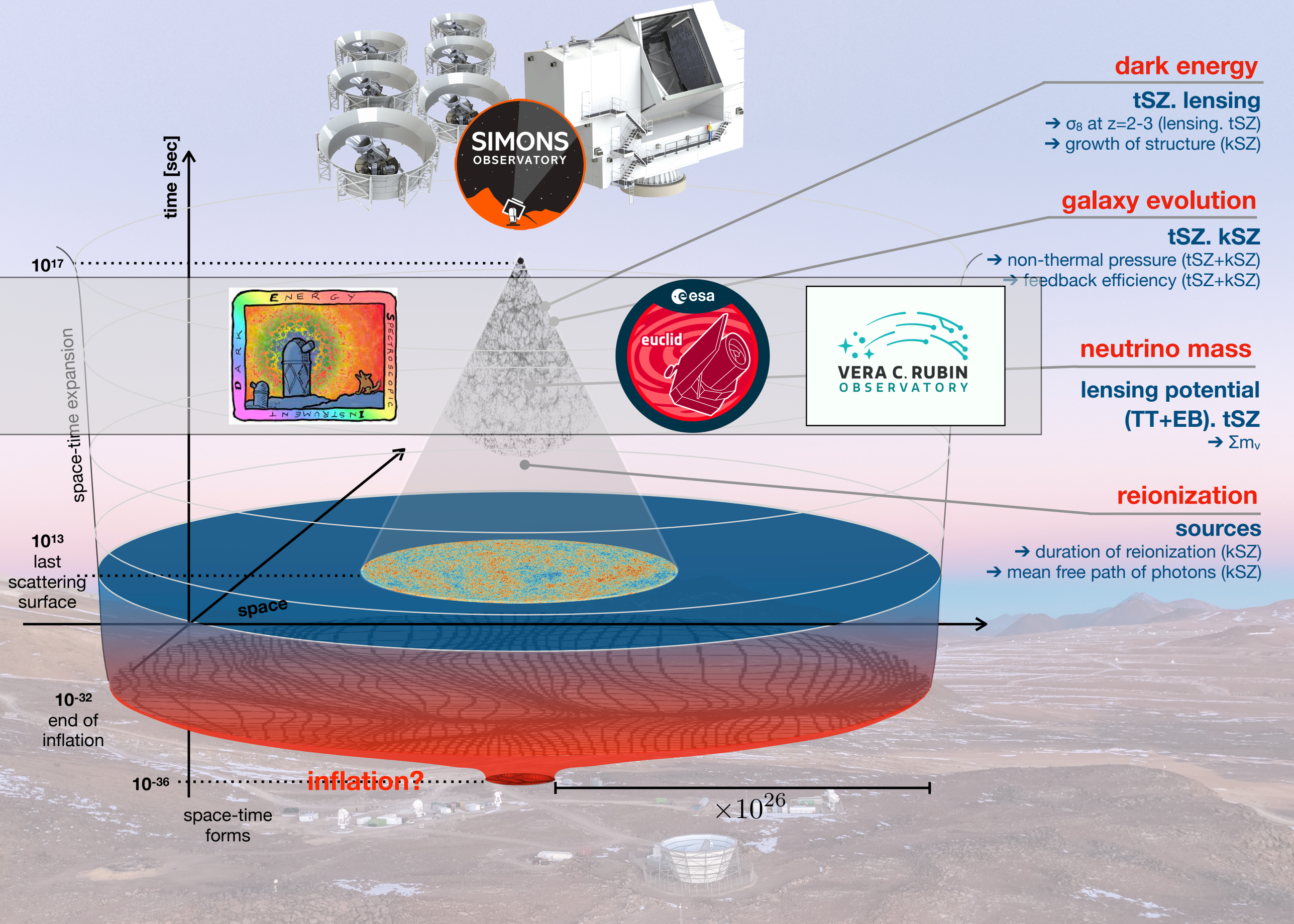
Josquin Errard, Simons Observatory, mmUniverse 2023



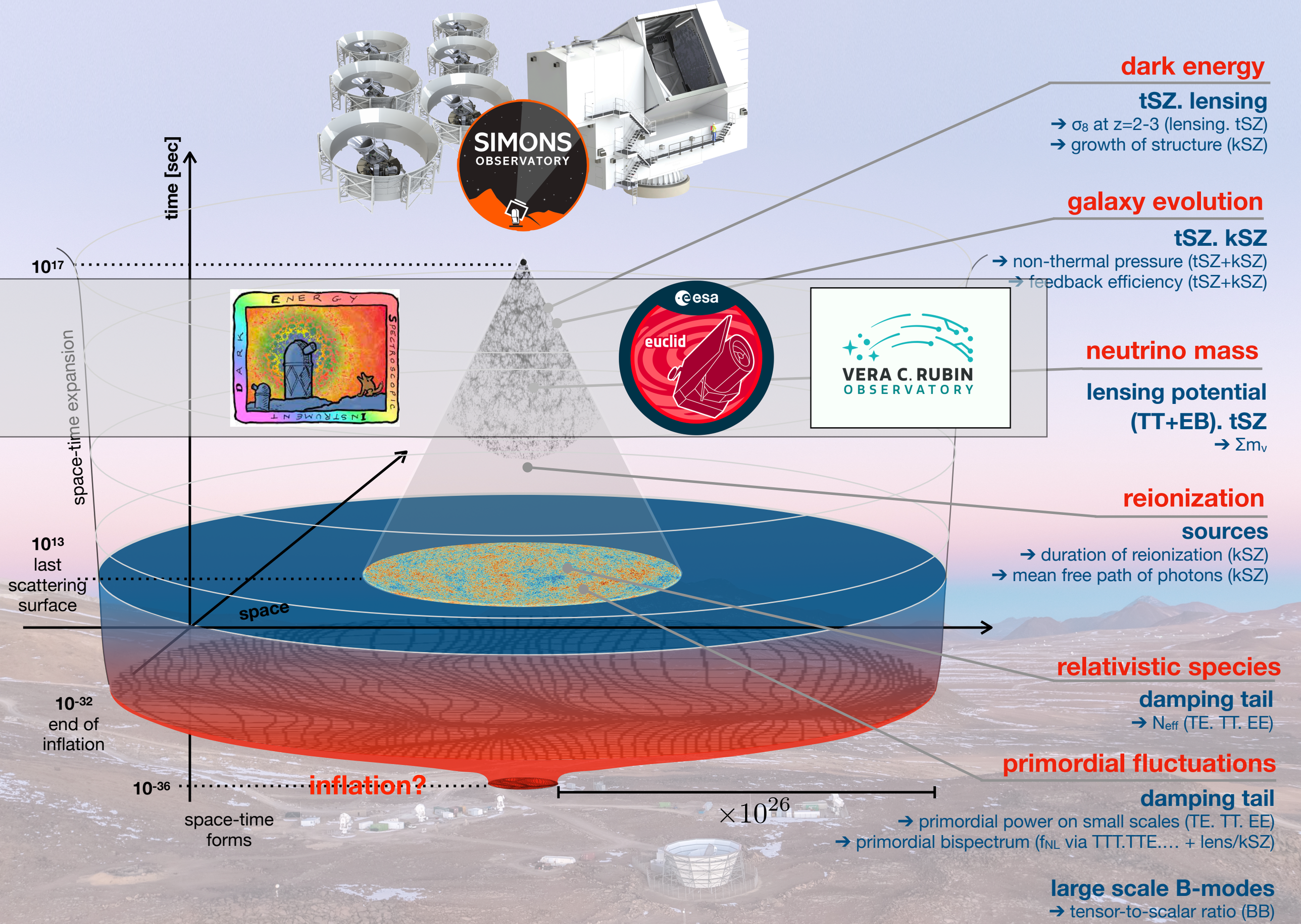
Josquin Errard, Simons Observatory, mmUniverse 2023



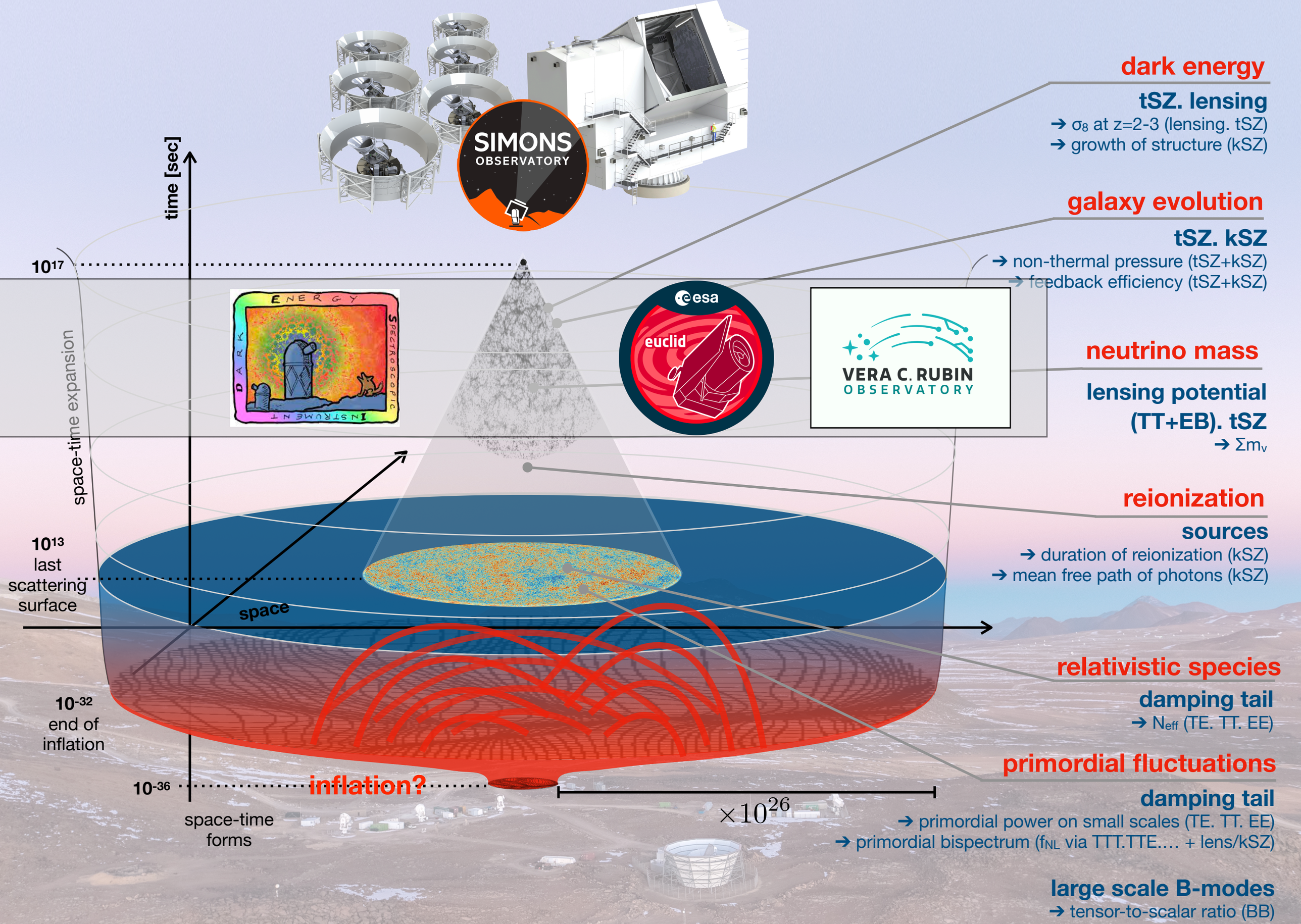
Josquin Errard, Simons Observatory, mmUniverse 2023



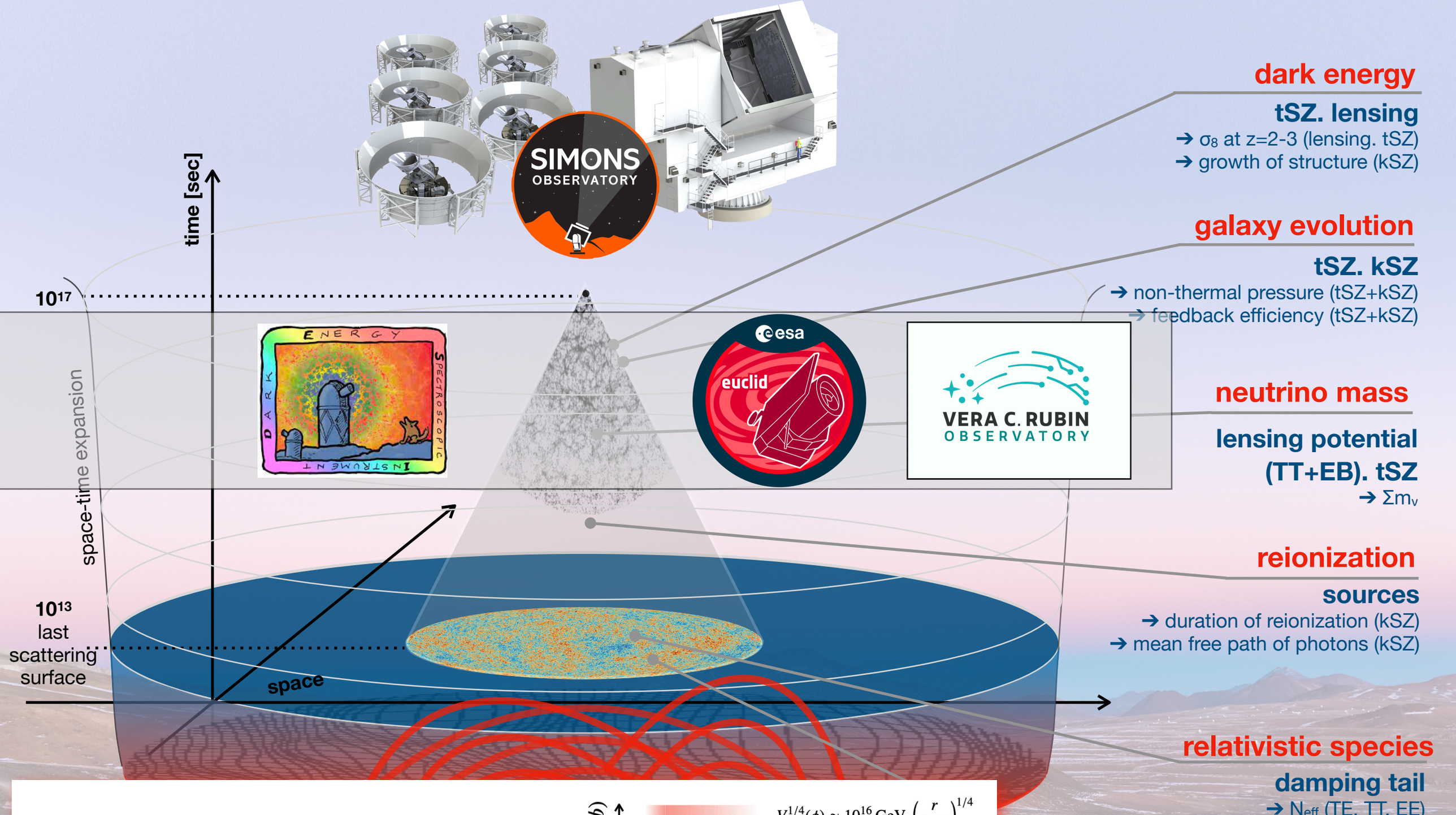
Josquin Errard, Simons Observatory, mmUniverse 2023



Josquin Errard, Simons Observatory, mmUniverse 2023



Josquin Errard, Simons Observatory, mmUniverse 2023



dark energy

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

galaxy evolution

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

neutrino mass

lensing potential (TT+EB). tSZ
- ➔ Σm_ν

reionization

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

relativistic species

damping tail
- ➔ N_{eff} (TE. TT. EE)

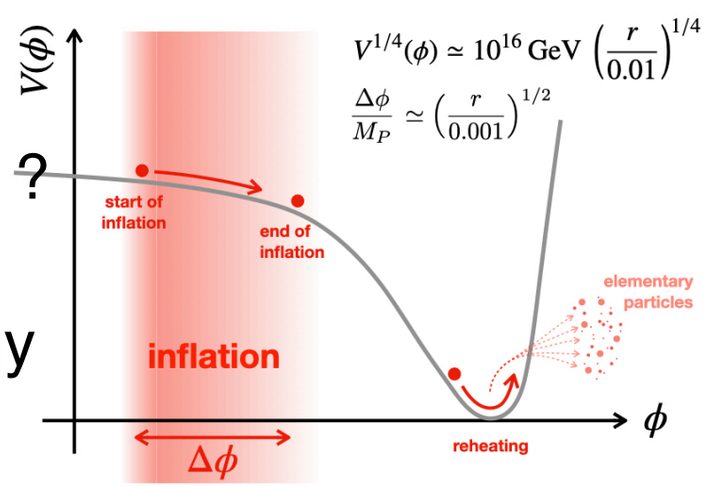
primordial fluctuations

damping tail
- ➔ primordial power on small scales (TE. TT. EE)

ordial bispectrum (f_{NL} via TTT.TTE.... + lens/kSZ)

large scale B-modes
- ➔ tensor-to-scalar ratio (BB)

- where did **V(Φ) come from** ?
- why did the field start in **slow-roll** ?
- why is the potential so **flat** ?
- how do we convert the field energy into **particules** ?

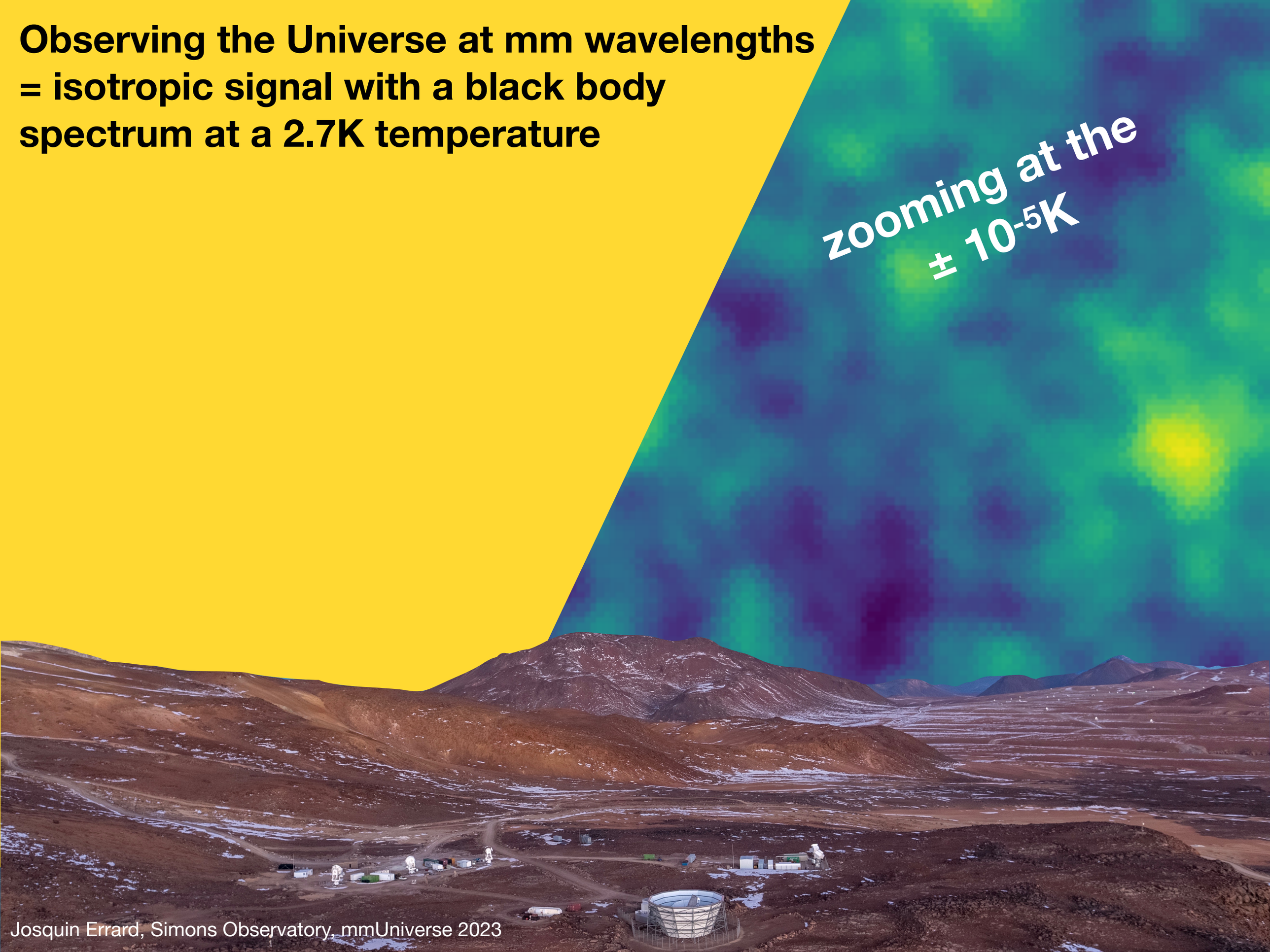


Josquin Errard, Simons Observatory, mmUniverse 2023

Observing the Universe at mm wavelengths = isotropic signal with a black body spectrum at a 2.7K temperature

Josquin Errard, Simons Observatory, mmUniverse 2023

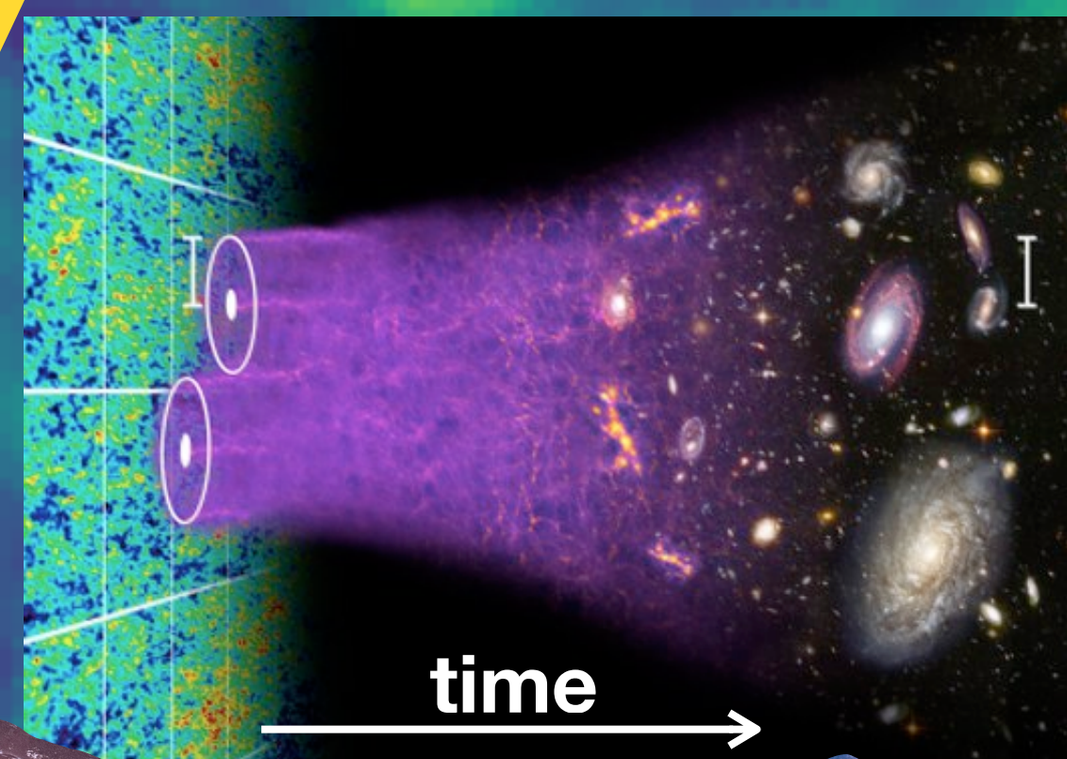
Observing the Universe at mm wavelengths = isotropic signal with a black body spectrum at a 2.7K temperature

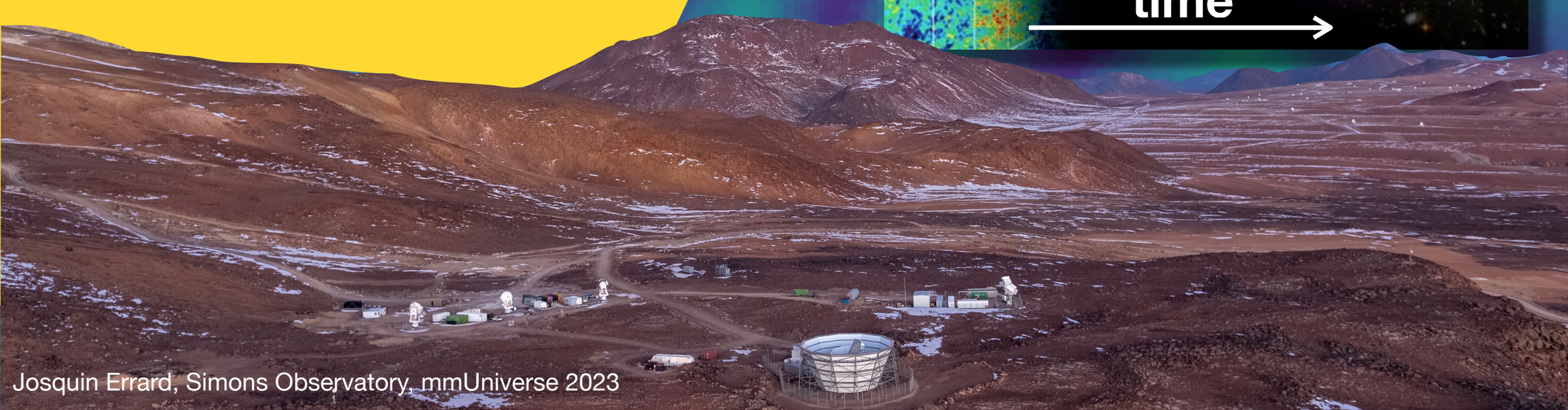


Josquin Errard, Simons Observatory, mmUniverse 2023

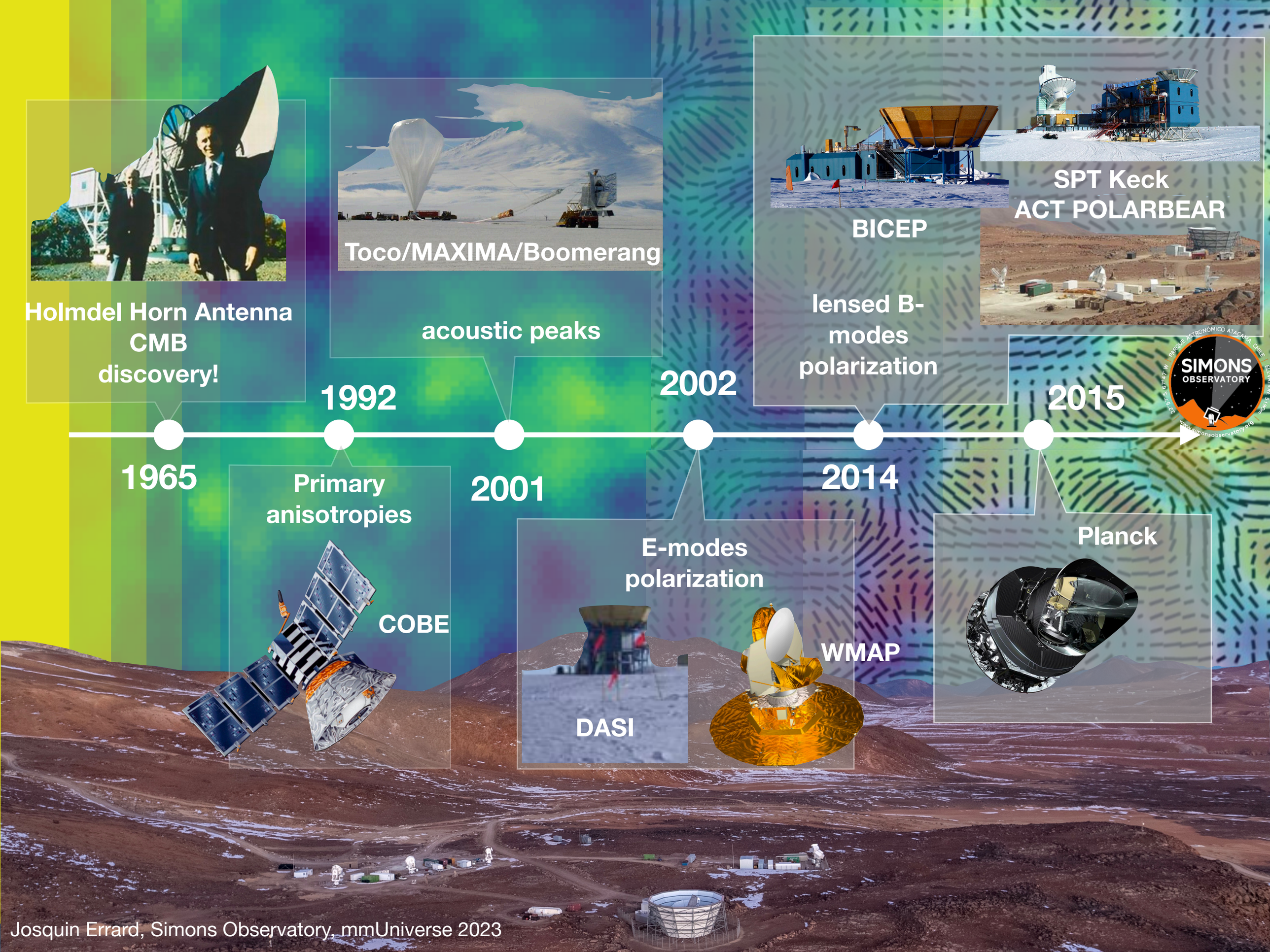
Observing the Universe at mm wavelengths = isotropic signal with a black body spectrum at a 2.7K temperature

zooming at the $\pm 10^{-5}$K

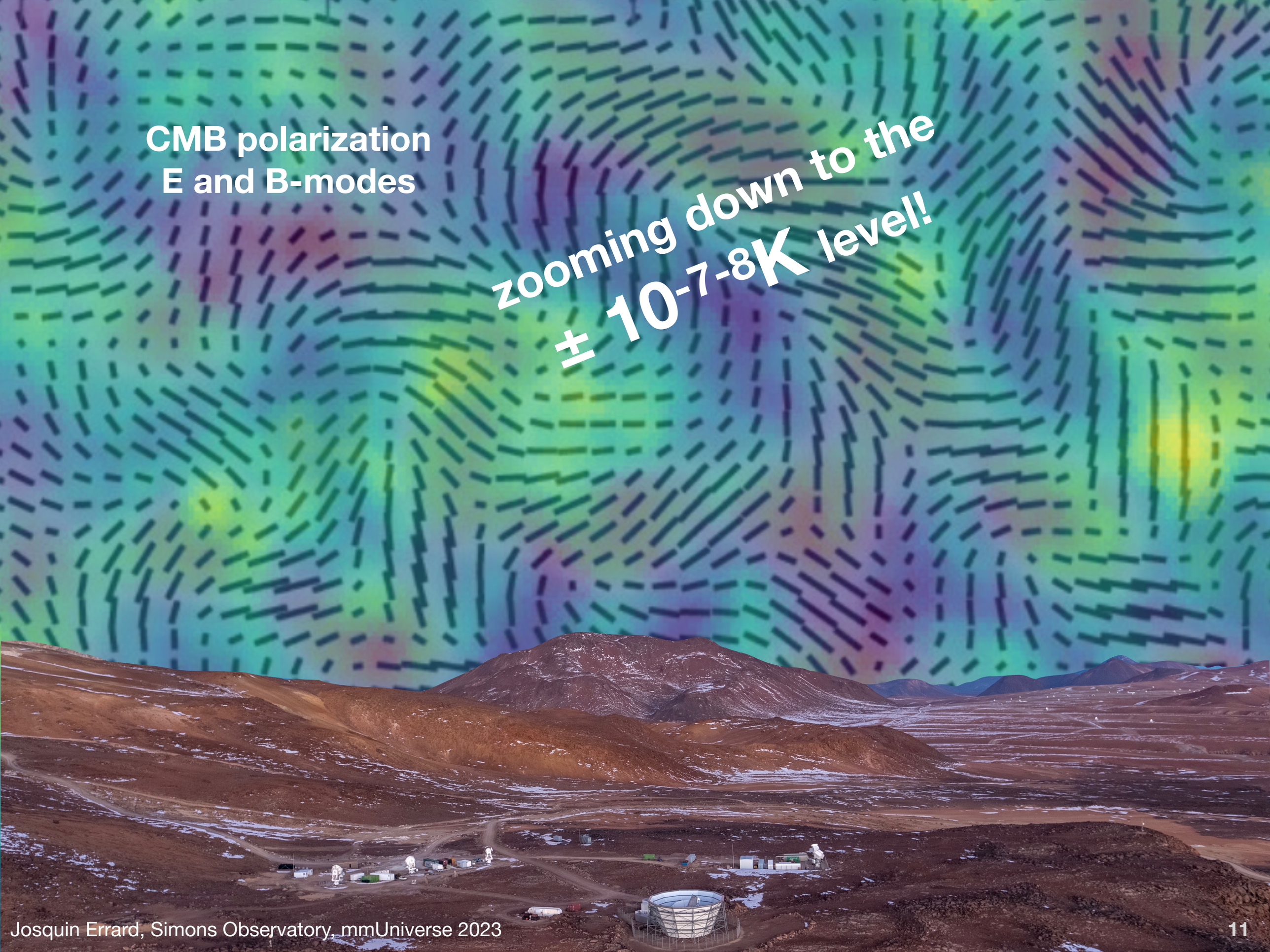




Josquin Errard, Simons Observatory, mmUniverse 2023



Josquin Errard, Simons Observatory, mmUniverse 2023


CMB polarization
E and B-modes
zooming down to the
± 10-7-8K level!

+ galactic
(and extra-galactic)
foregrounds
Josquin Errard, Simons Observatory, mmUniverse 2023

+ atmosphere

+ ground-pickup

+ other instrumental systematics

credits: R. Keskitalo (LBNL)

https://crd.lbl.gov/news-and-publications/news/2017/a-toast-for-next-generation-cmb-experiments/

Errard et al, The Astrophysical Journal, Volume 809, Issue 1, article id. 63, 19 pp. (2015)

+ atmosphere

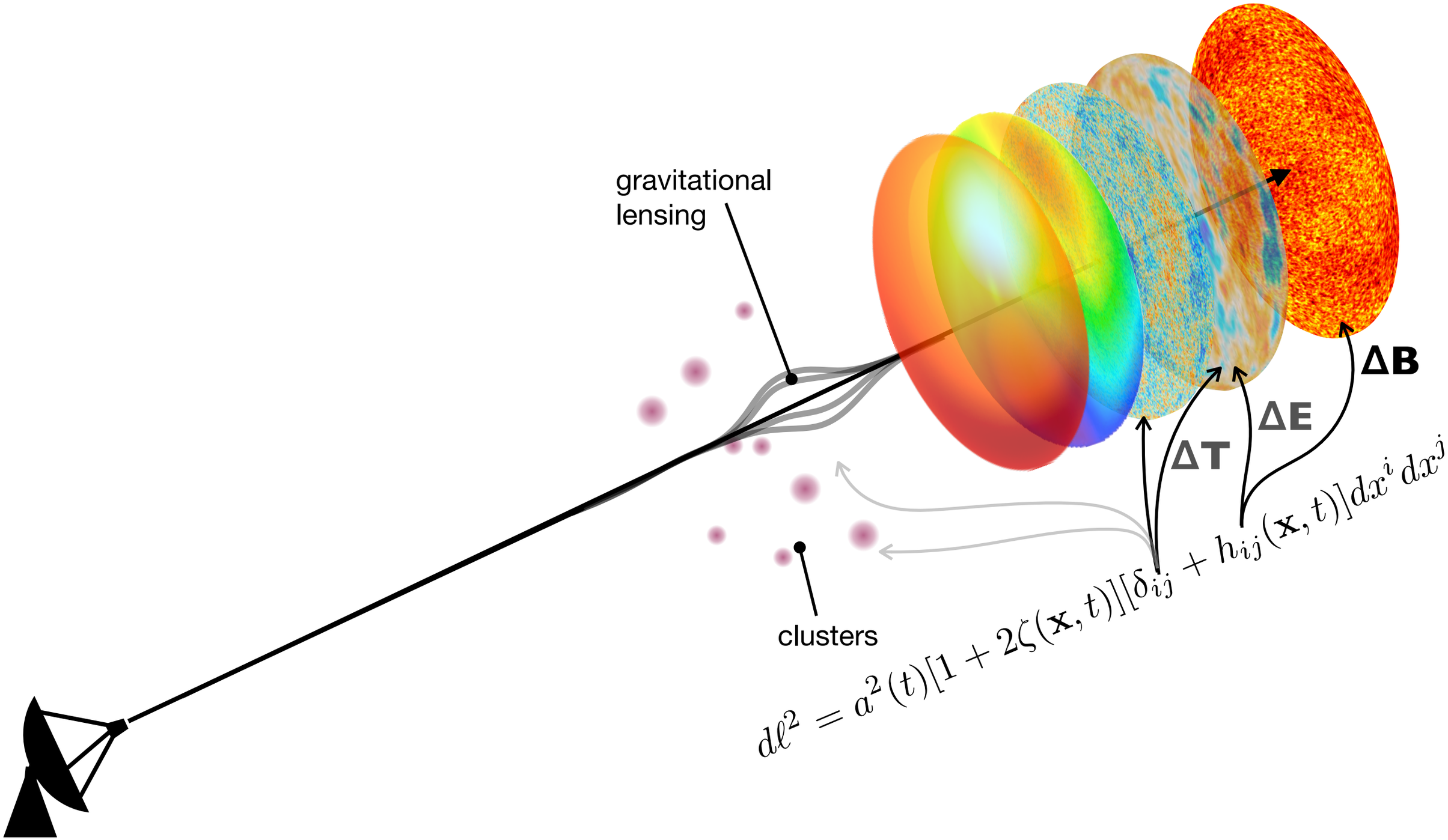
+ ground-pickup

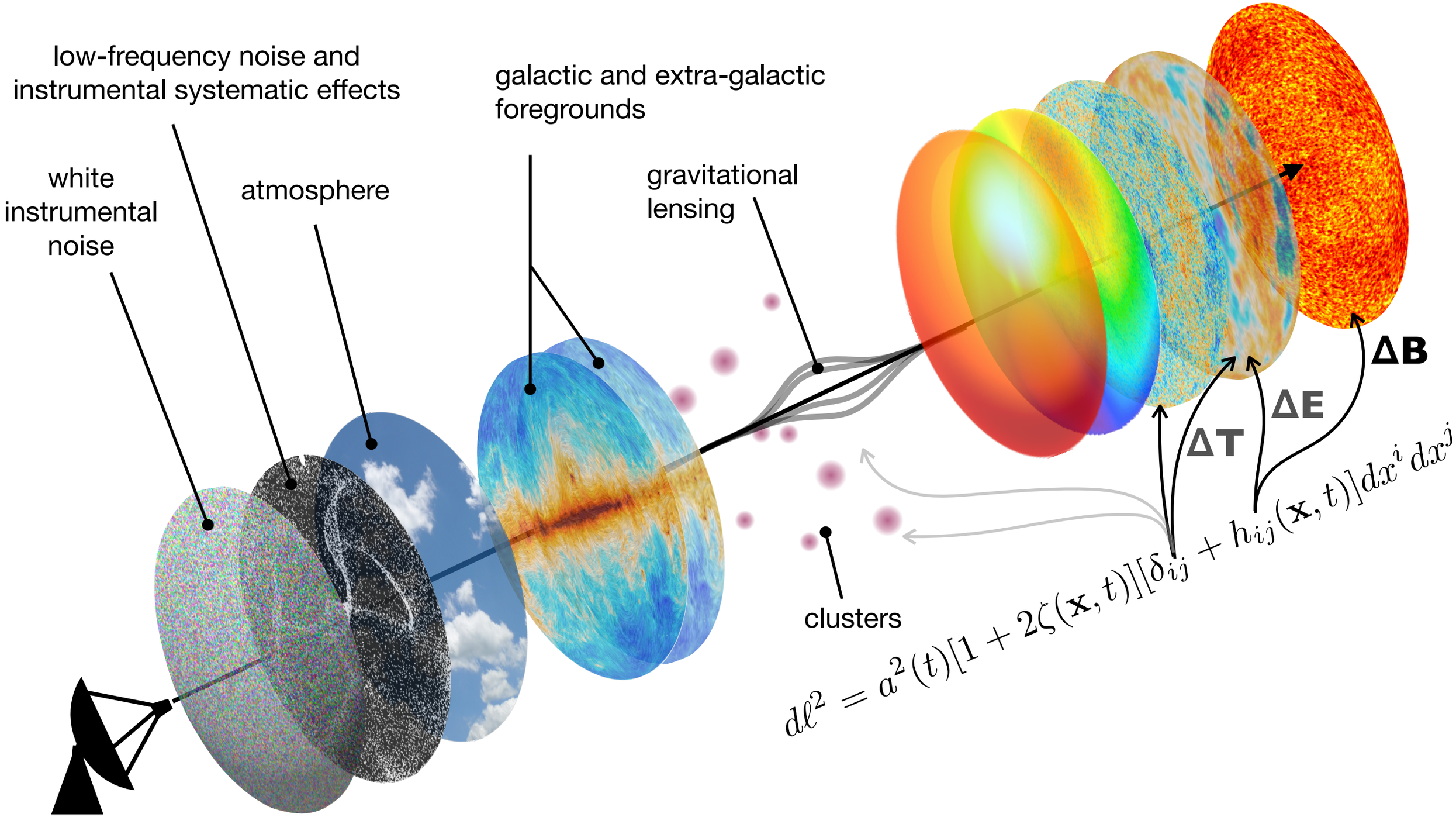
+ other instrumental systematics

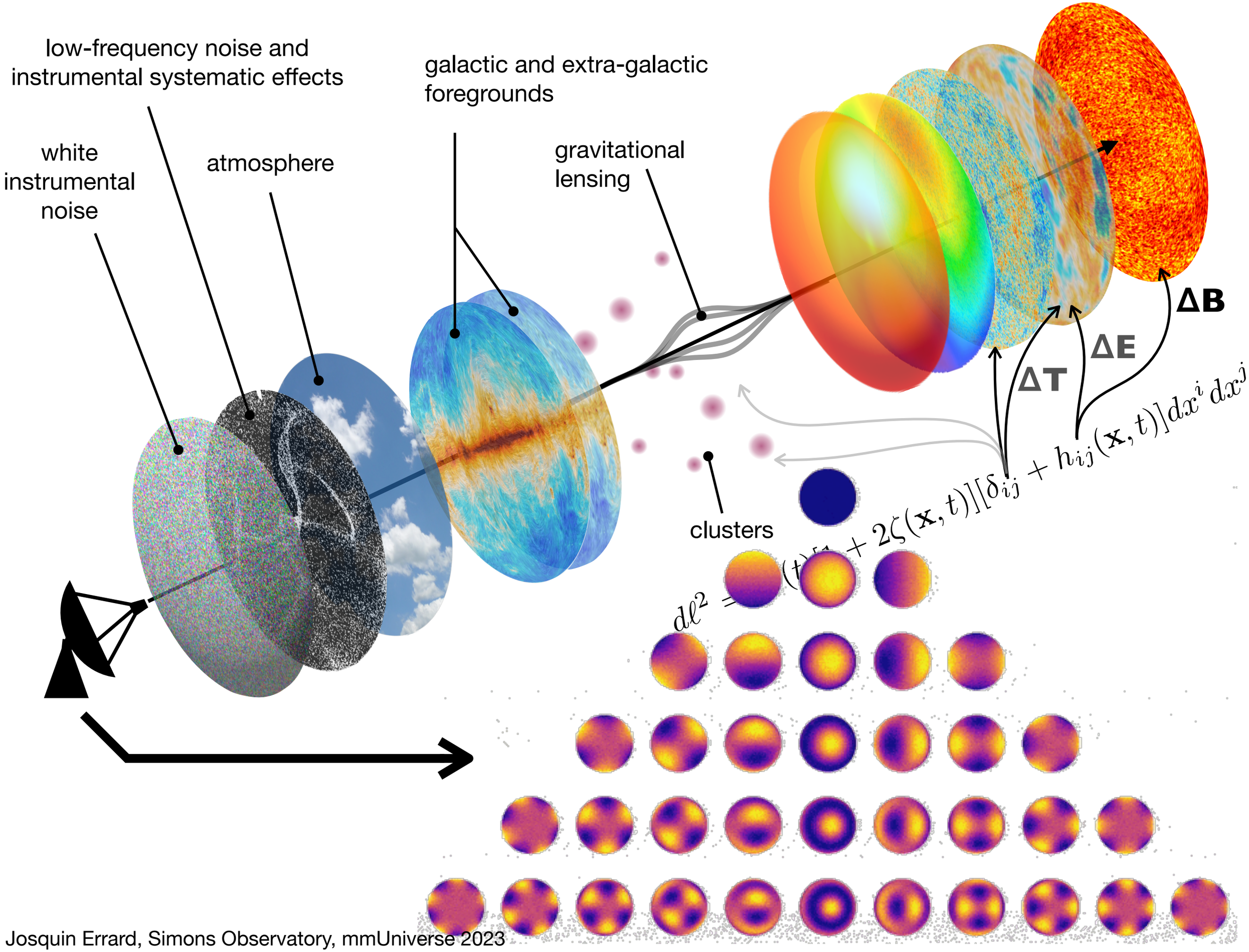
credits: R. Keskitalo (LBNL)

https://crd.lbl.gov/news-and-publications/news/2017/a-toast-for-next-generation-cmb-experiments/

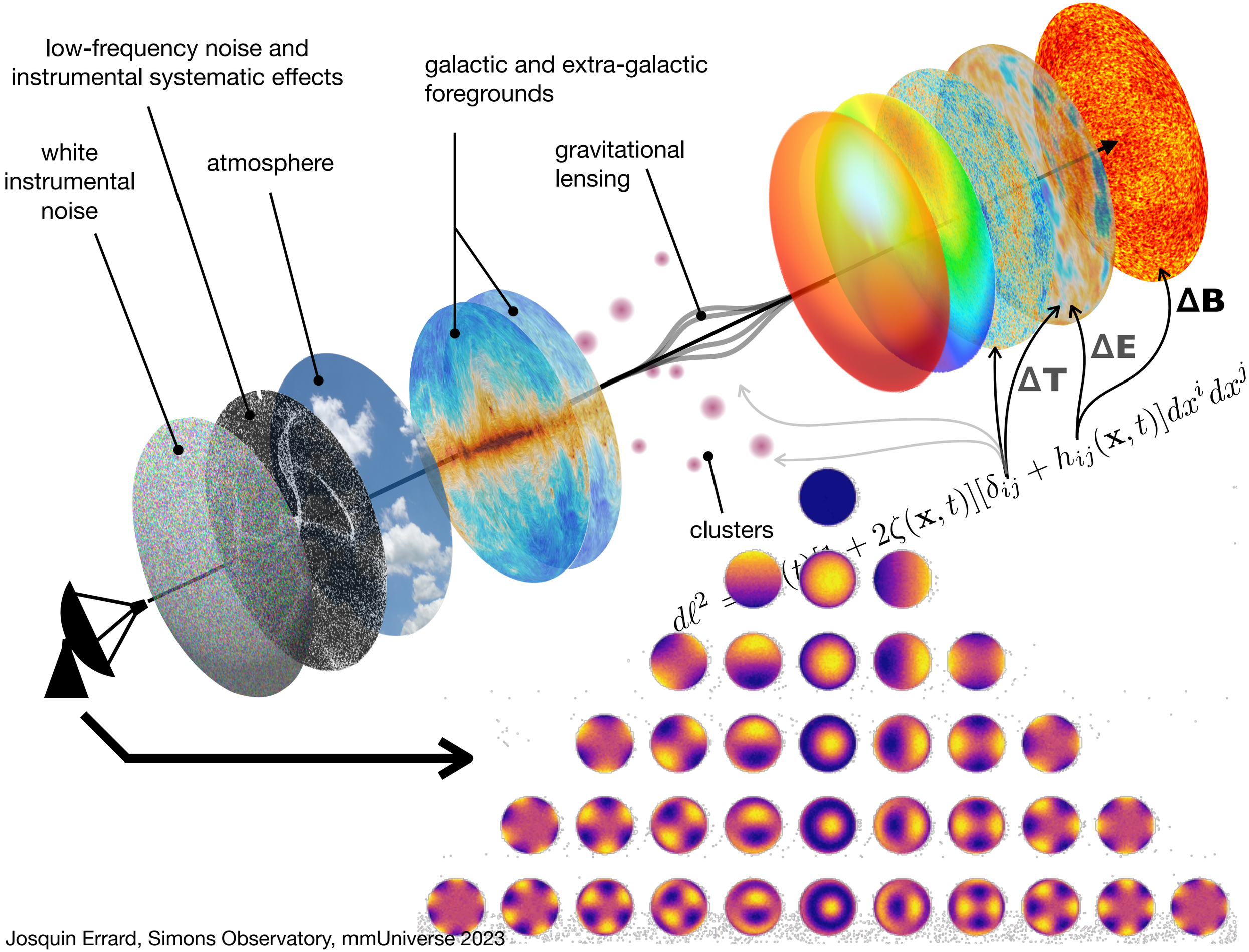
Errard et al, The Astrophysical Journal, Volume 809, Issue 1, article id. 63, 19 pp. (2015)


gravitational
lensing
clusters
ΔT
ΔE
ΔB
$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i\, dx^j$

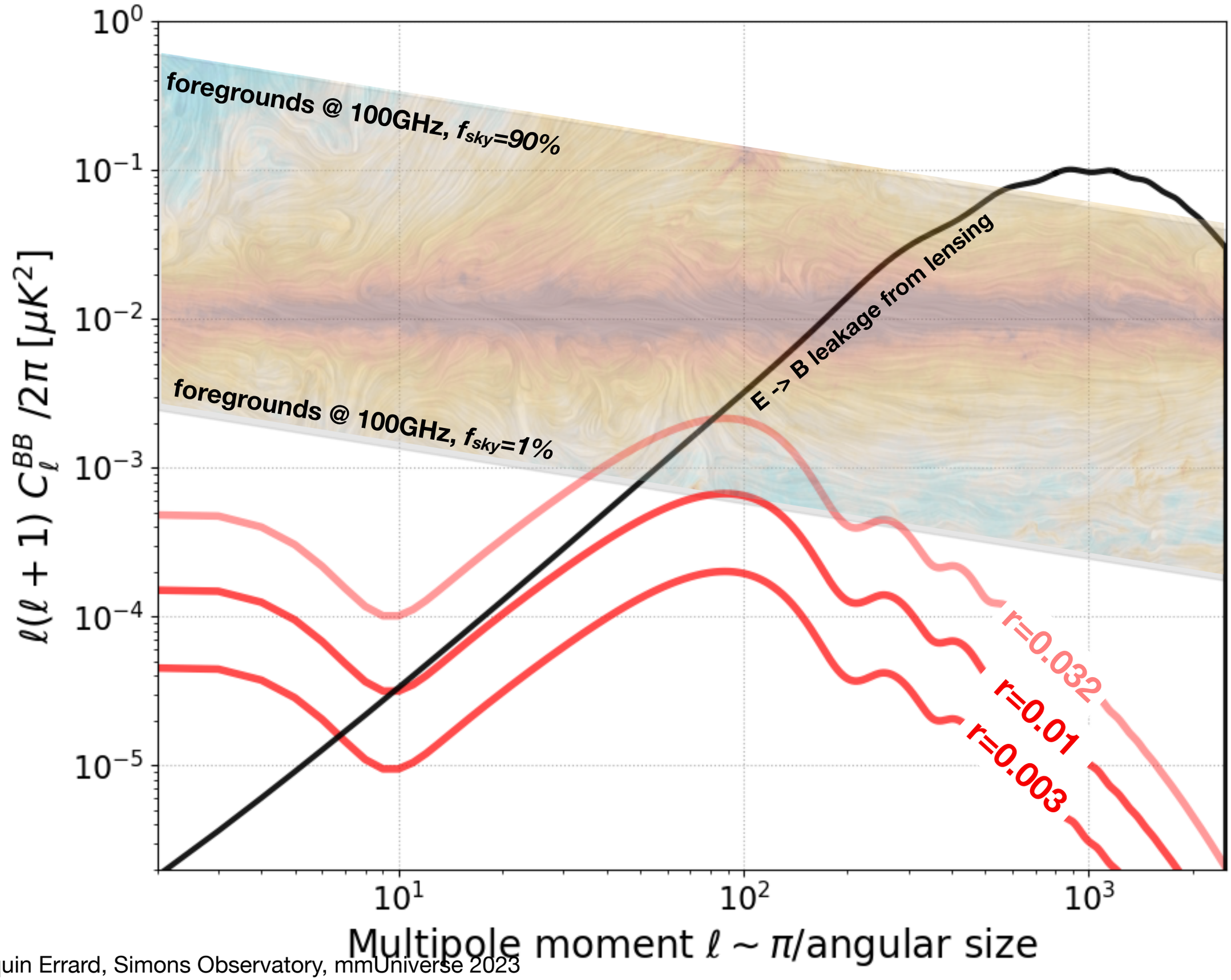

low-frequency noise and
instrumental systematic effects
galactic and extra-galactic
foregrounds
white
instrumental
noise
atmosphere
gravitational
lensing
ΔB
ΔE
ΔT
clusters
$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i\, dx^j$

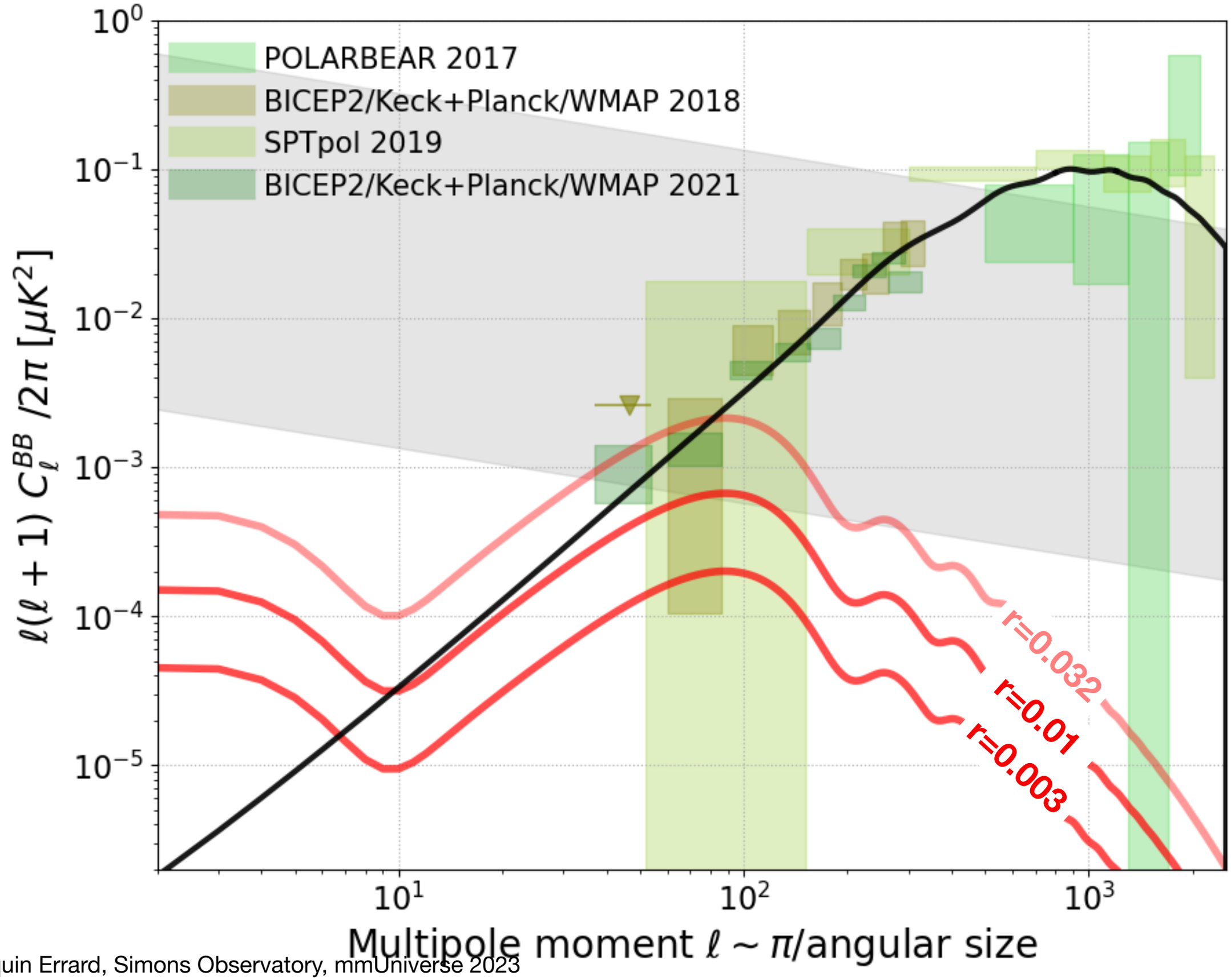


Josquin Errard, Simons Observatory, mmUniverse 2023



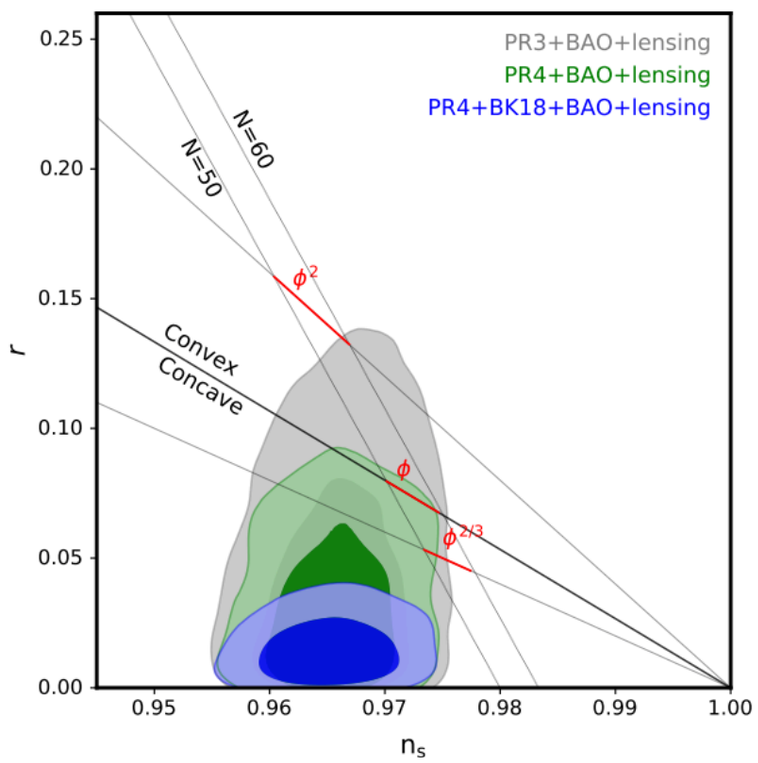
Josquin Errard, Simons Observatory, mmUniverse 2023


foregrounds @ 100GHz, f_{sky}=90%
foregrounds @ 100GHz, f_{sky}=1%
E -> B leakage from lensing
r=0.032
r=0.01
r=0.003
$\ell(\ell+1)\, C_\ell^{BB} /2\pi\ [\mu K^2]$
Multipole moment $\ell \sim \pi$/angular size
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^1
10^2
10^3

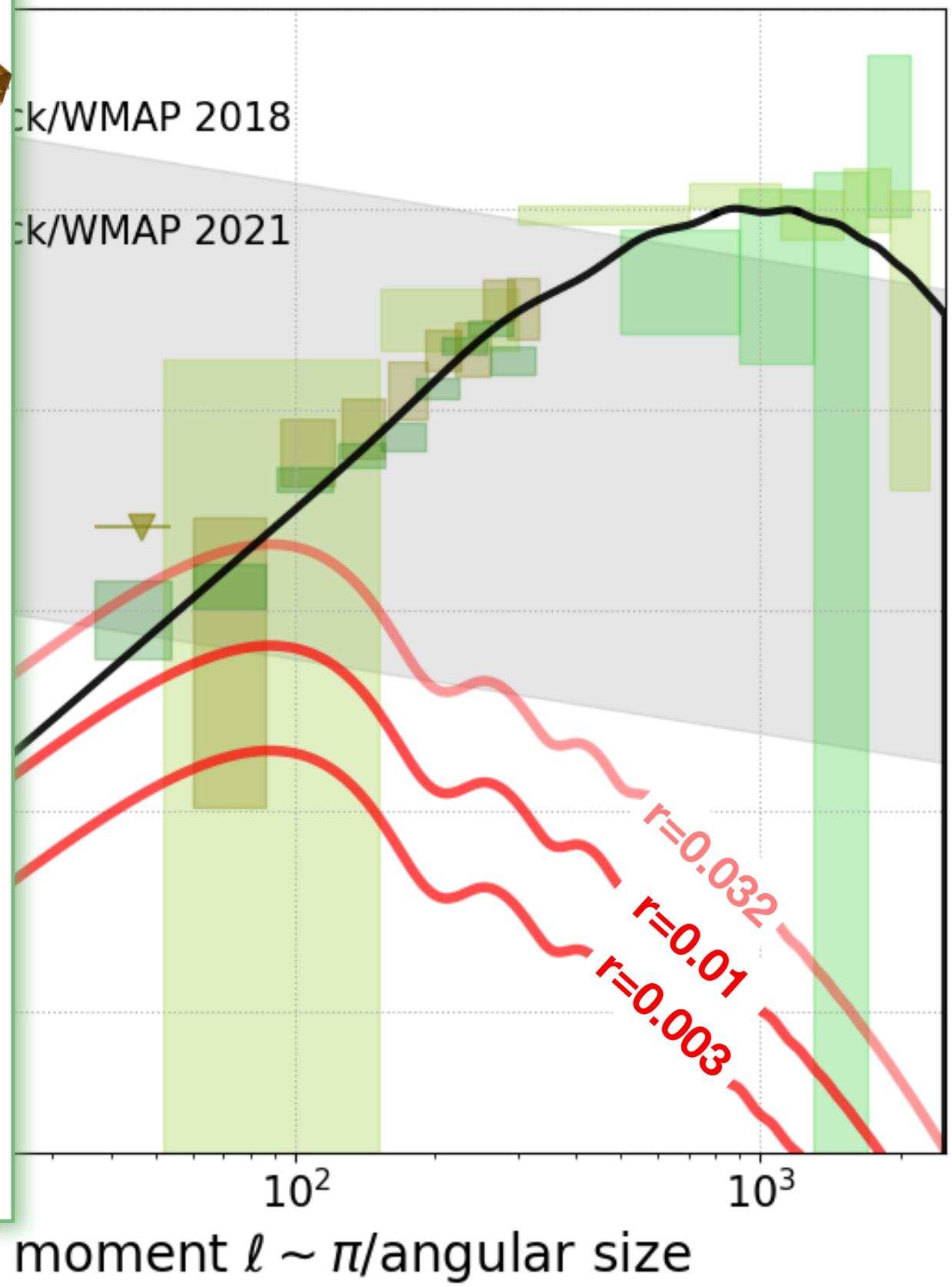

POLARBEAR 2017
BICEP2/Keck+Planck/WMAP 2018
SPTpol 2019
BICEP2/Keck+Planck/WMAP 2021
r=0.032
r=0.01
r=0.003
$\ell(\ell+1)\, C_\ell^{BB}\, /2\pi\ [\mu K^2]$
Multipole moment $\ell \sim \pi$/angular size

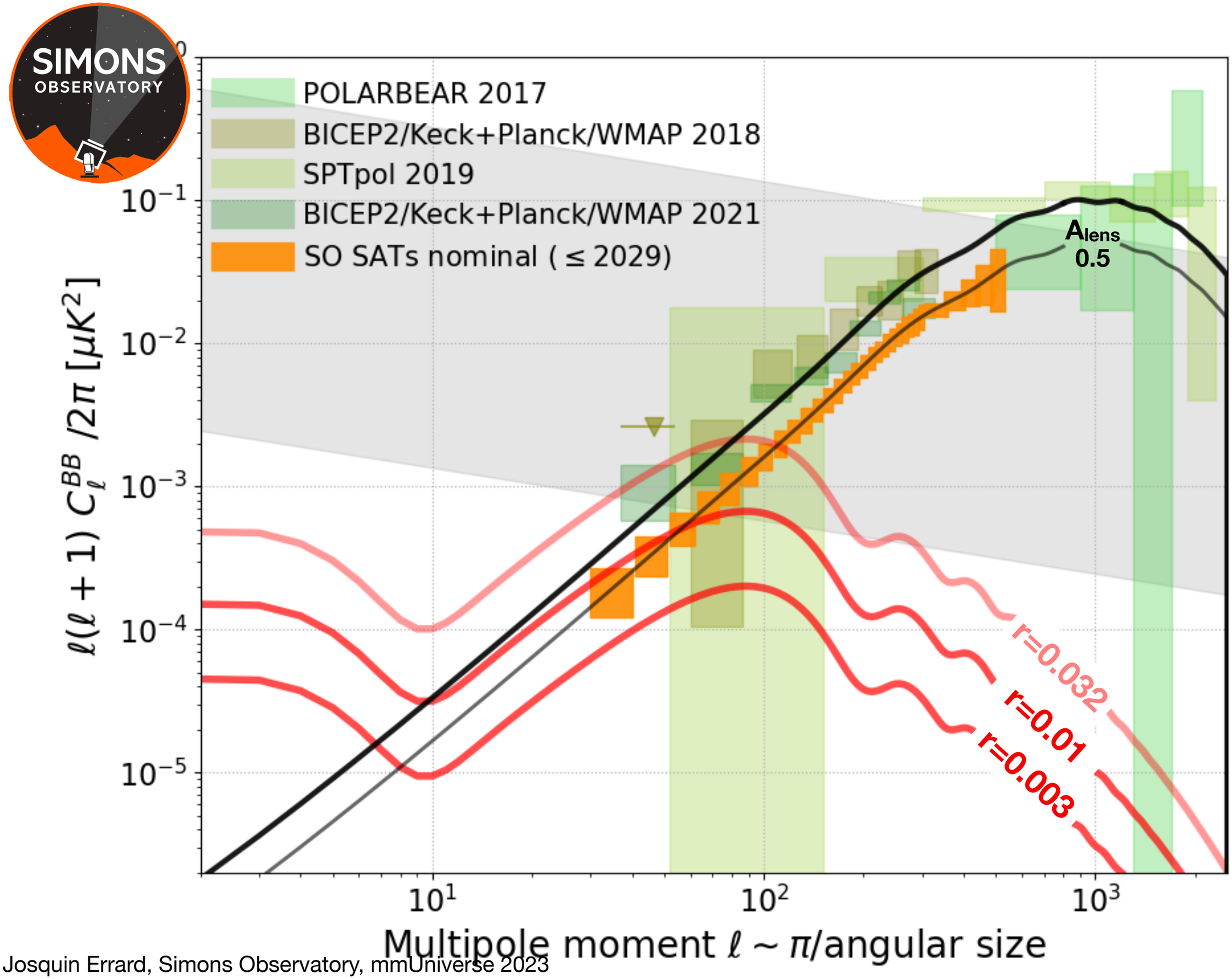
tensor-to-scalar ratio

r<0.032 (95% c.l.)

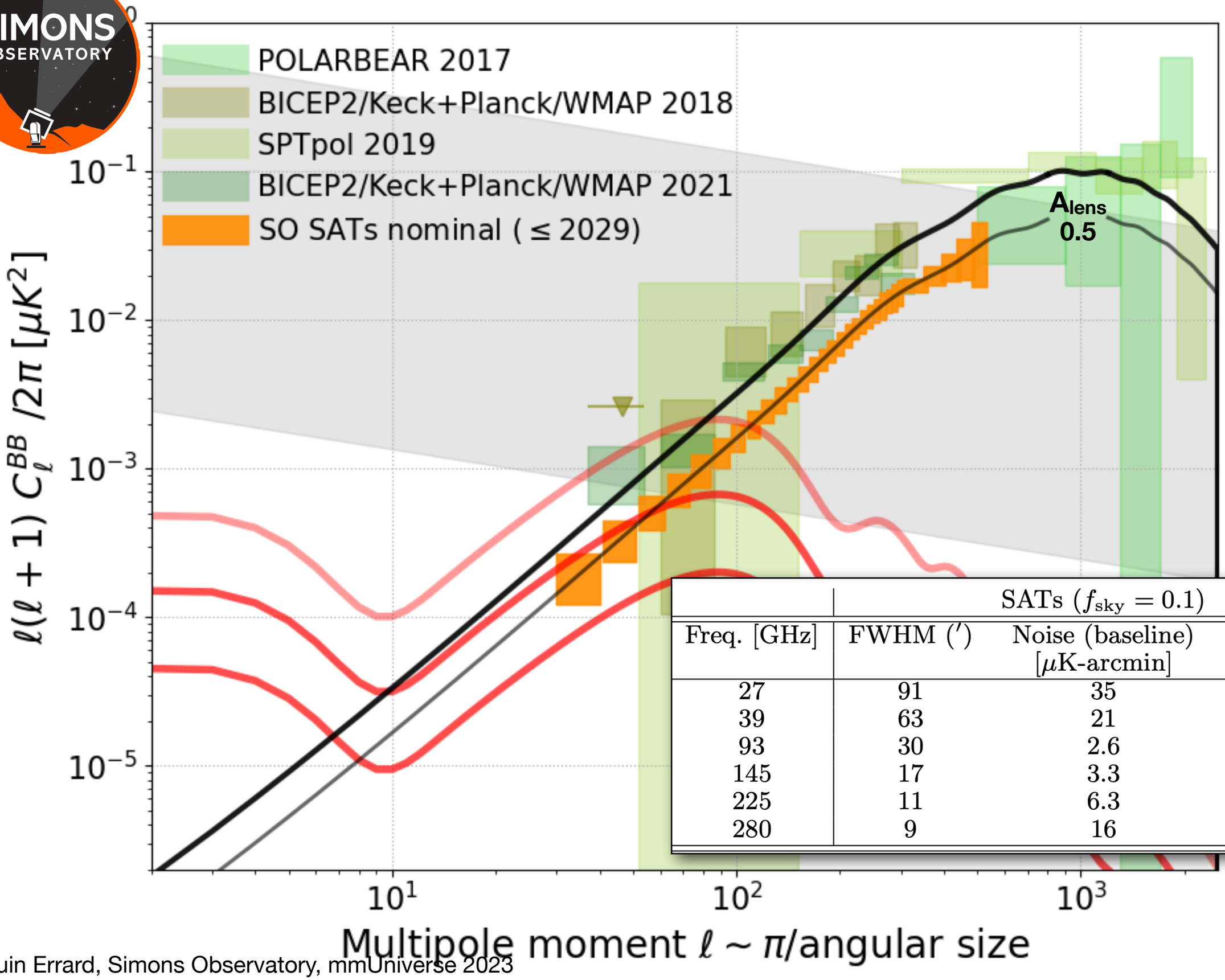


Tristram et al. (2021)



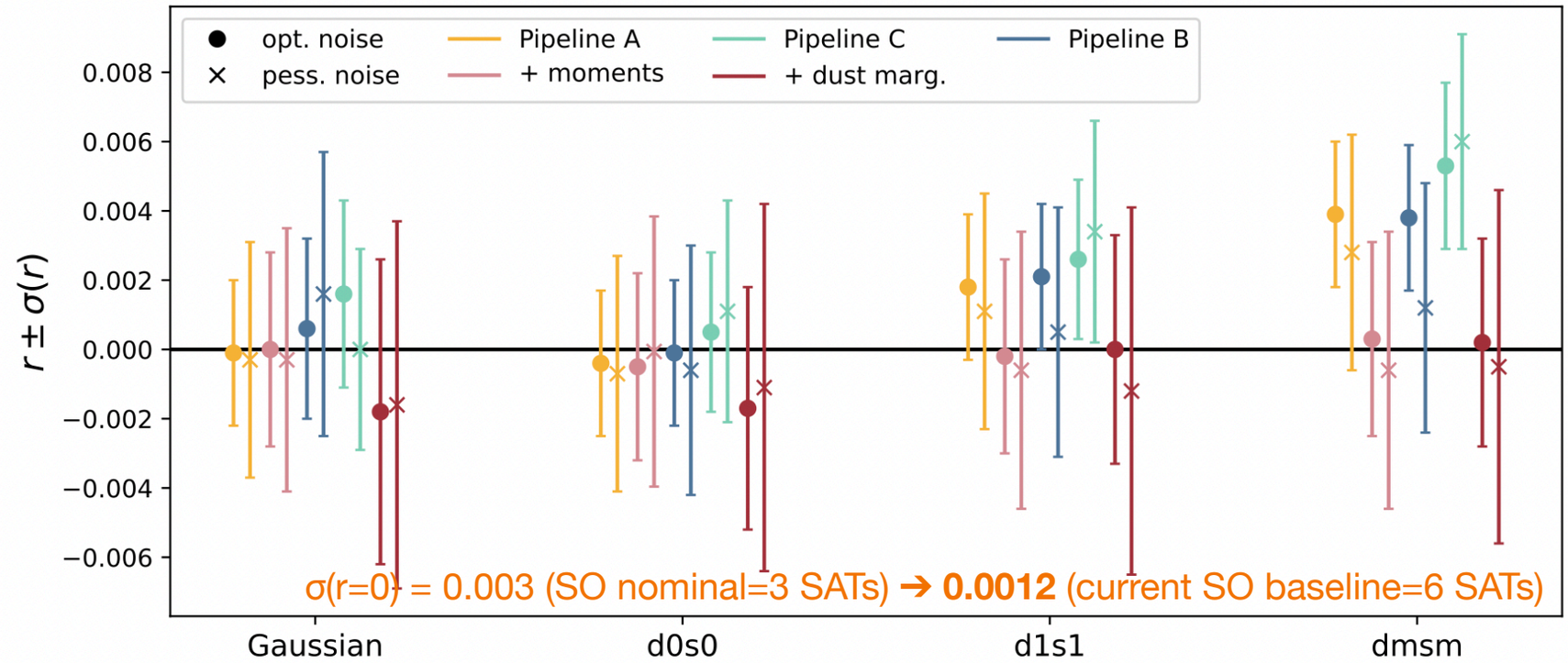


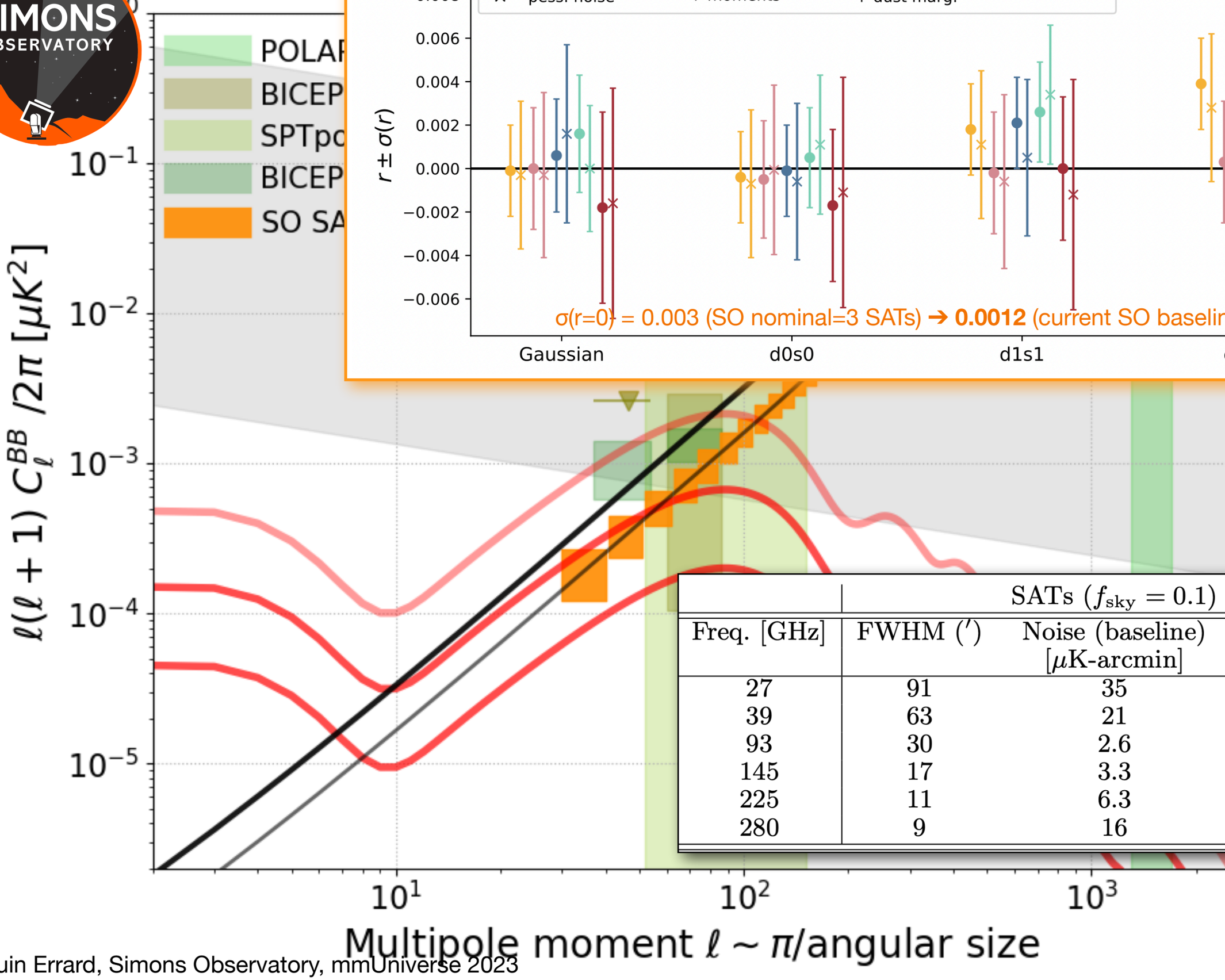
Josquin Errard, Simons Observatory, mmUniverse 2023



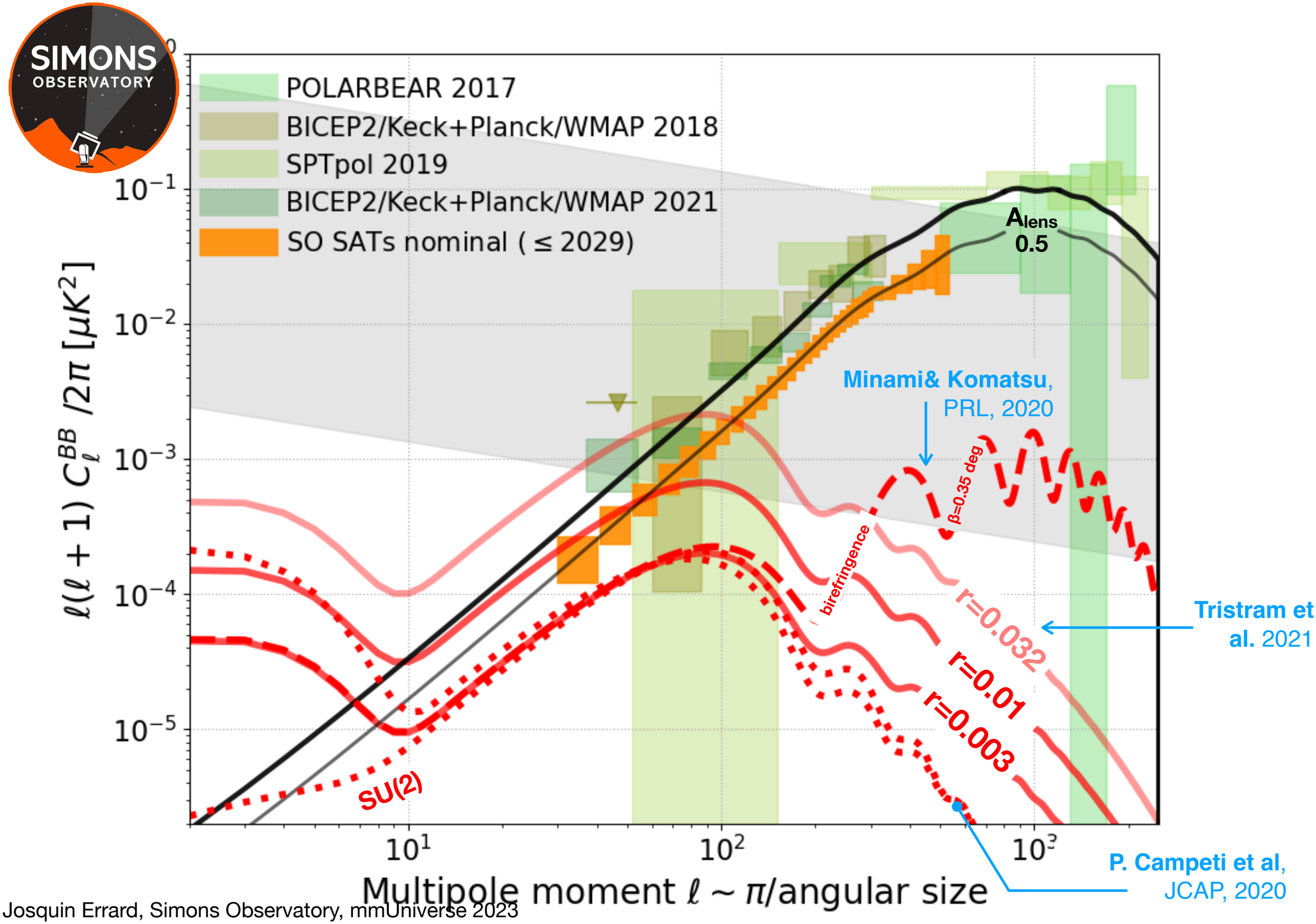
	SATs ($f_{\rm sky} = 0.1$)		
Freq. [GHz]	FWHM ($'$)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
27	91	35	25
39	63	21	17
93	30	2.6	1.9
145	17	3.3	2.1
225	11	6.3	4.2
280	9	16	10

Wolz, Azzoni, Hervias-Caimapo, JE, Krachmalnicoff, Alonso et al. (2023)

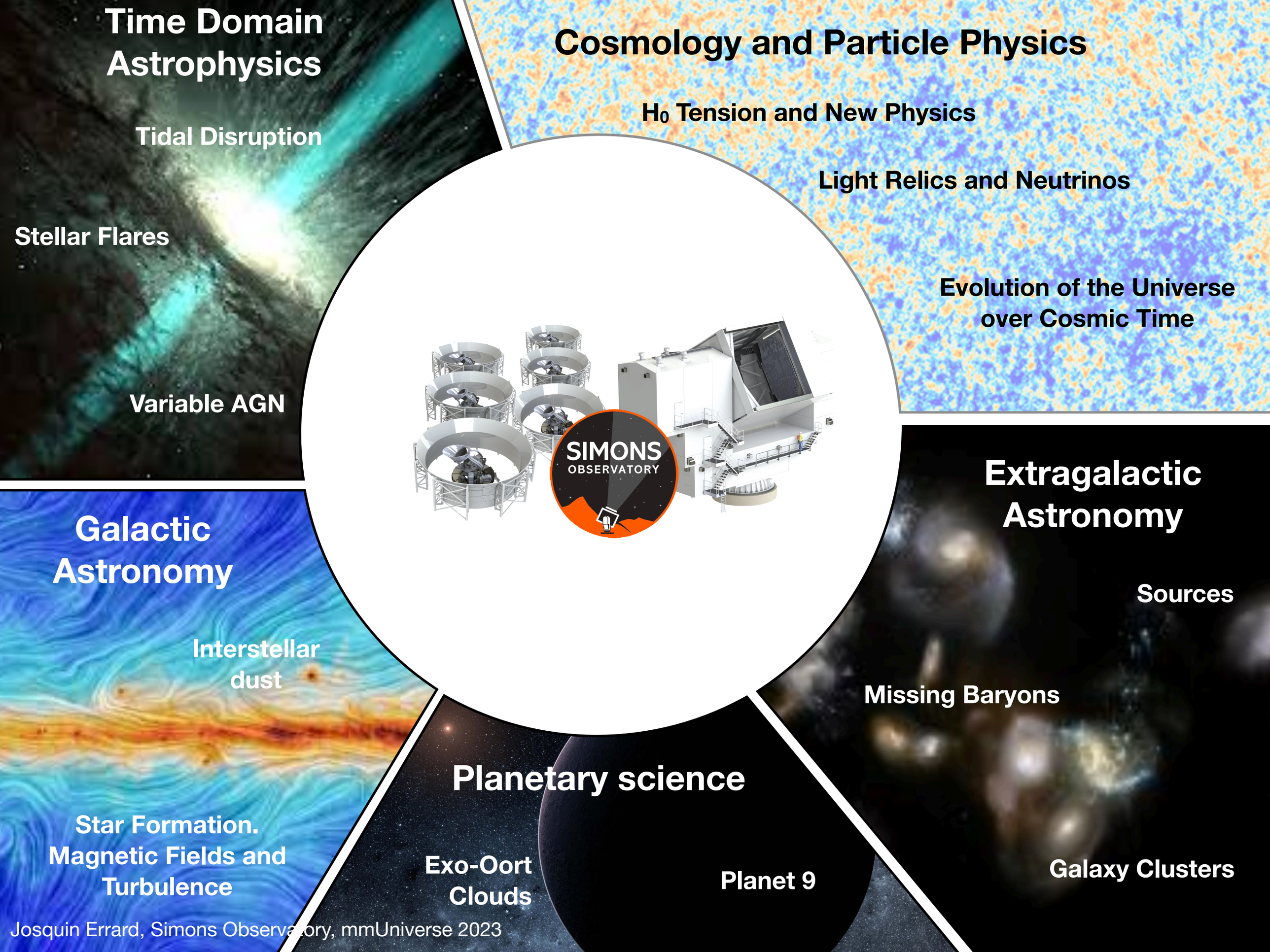




	SATs ($f_{\rm sky} = 0.1$)		
Freq. [GHz]	FWHM ($'$)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
27	91	35	25
39	63	21	17
93	30	2.6	1.9
145	17	3.3	2.1
225	11	6.3	4.2
280	9	16	10

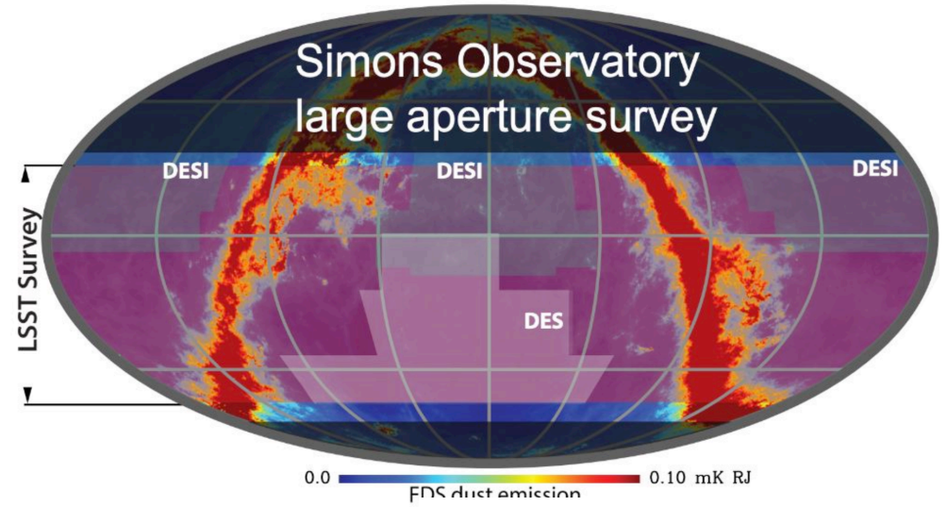


Josquin Errard, Simons Observatory, mmUniverse 2023

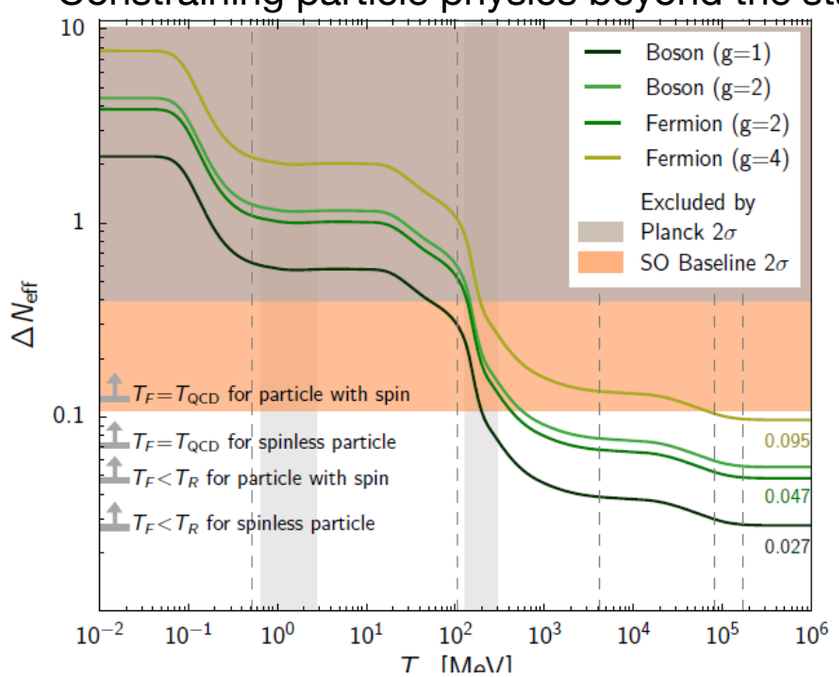


Josquin Errard, Simons Observatory, mmUniverse 2023

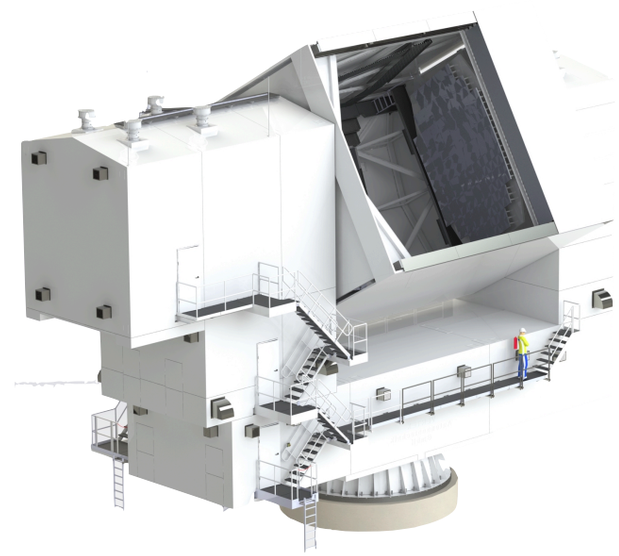
	LAT ($f_{\rm sky} = 0.4$)		
Freq. [GHz]	FWHM ($'$)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
27	7.4	71	52
39	5.1	36	27
93	2.2	8.0	5.8
145	1.4	10	6.3
225	1.0	22	15
280	0.9	54	37

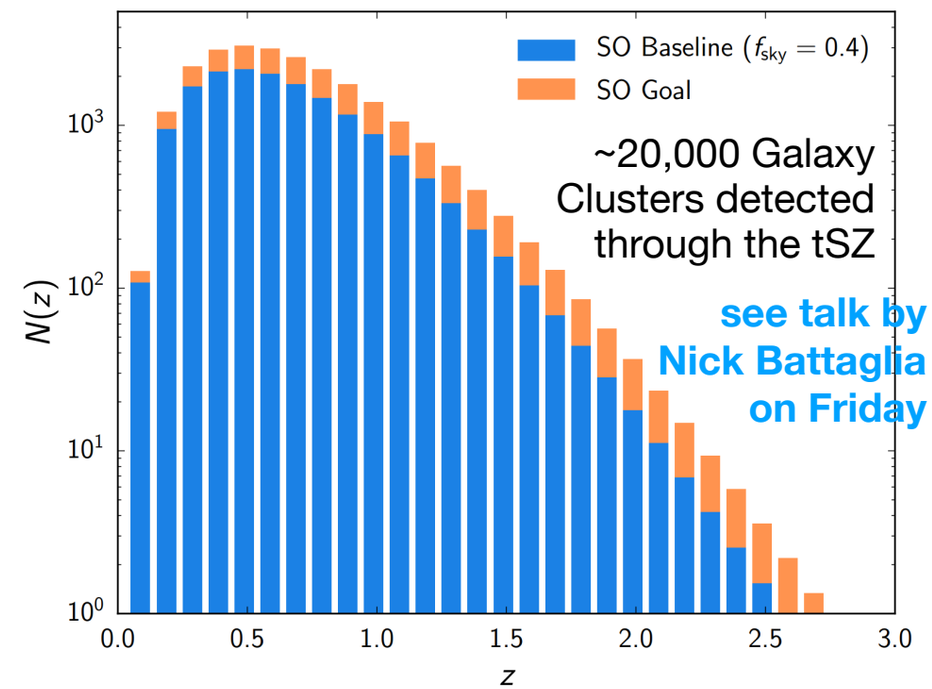


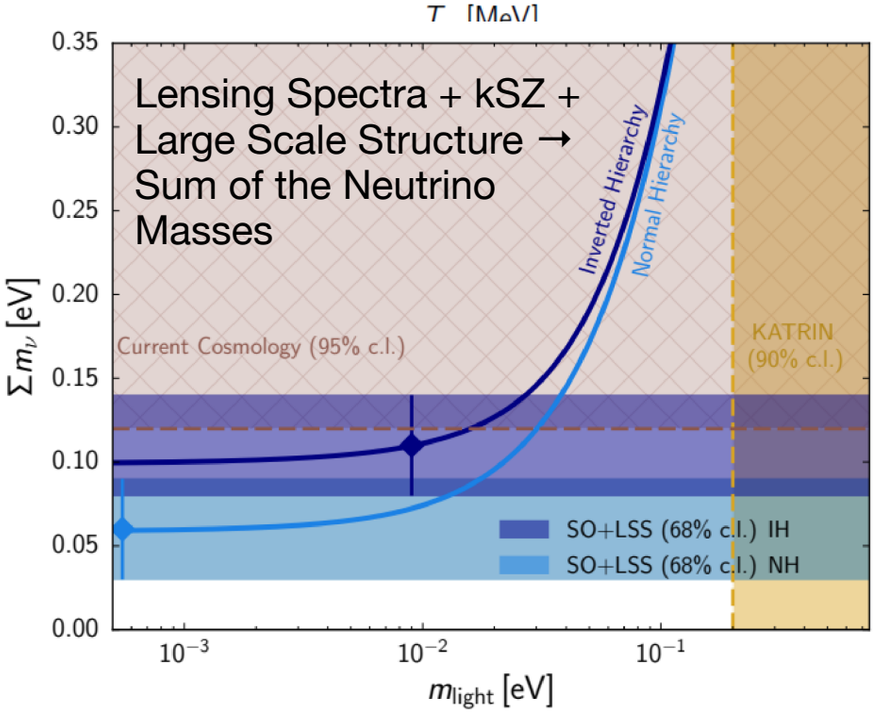
Effective Number of Relativistic Species
→ Constraining particle physics beyond the standard model



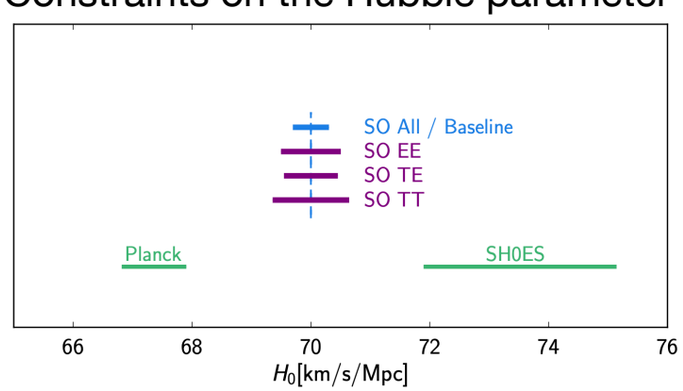
LAT Science

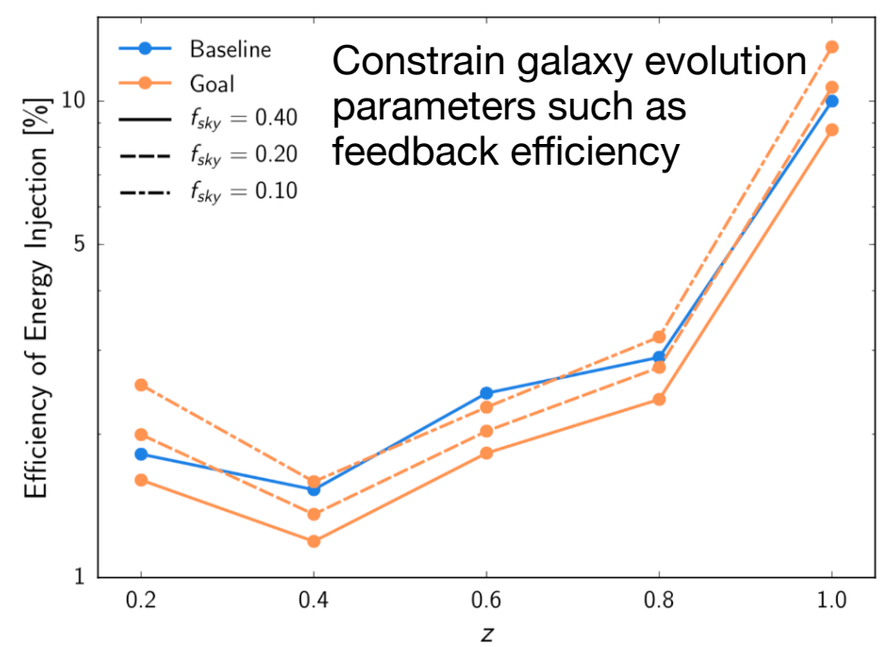




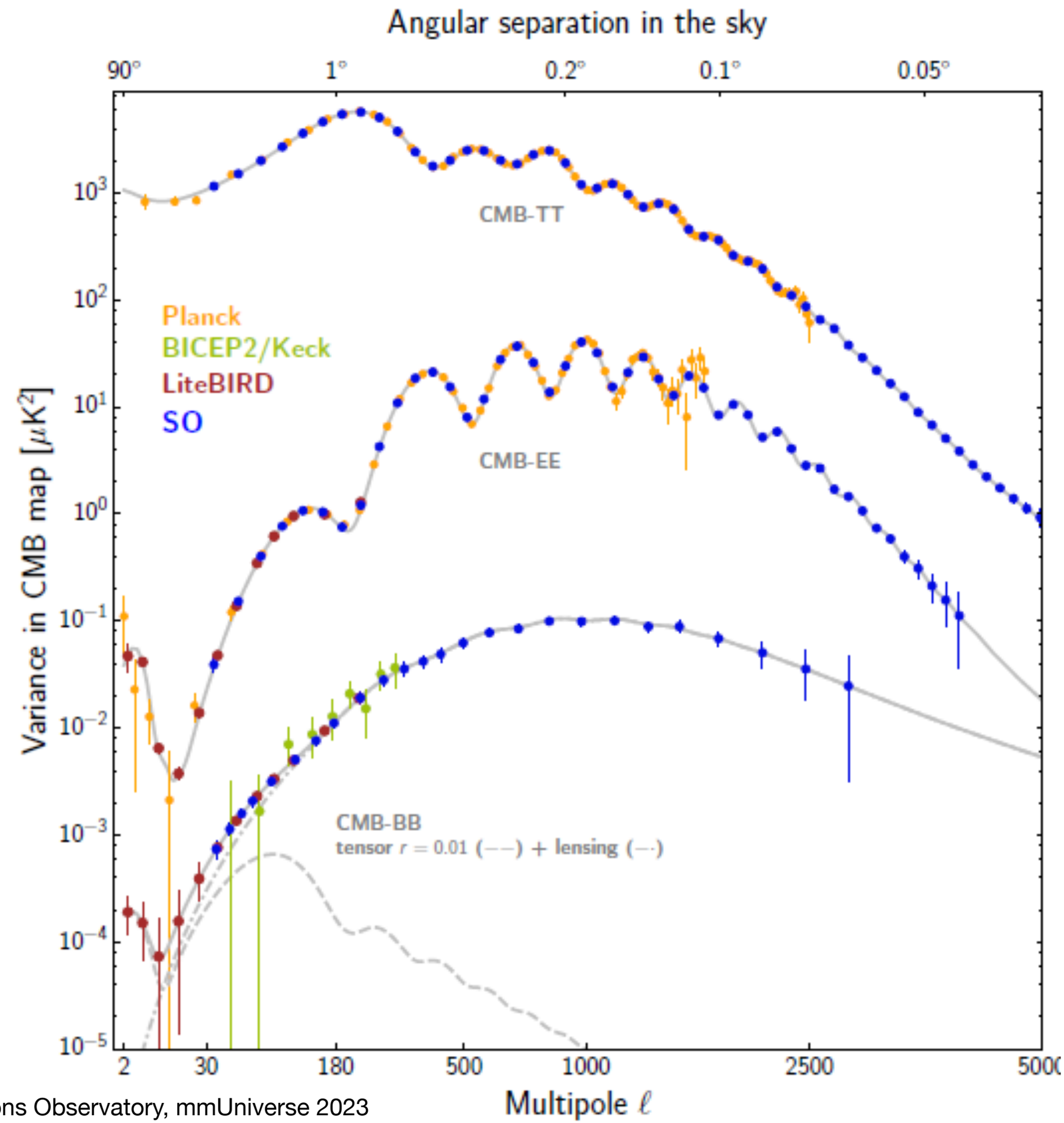


Constraints on the Hubble parameter

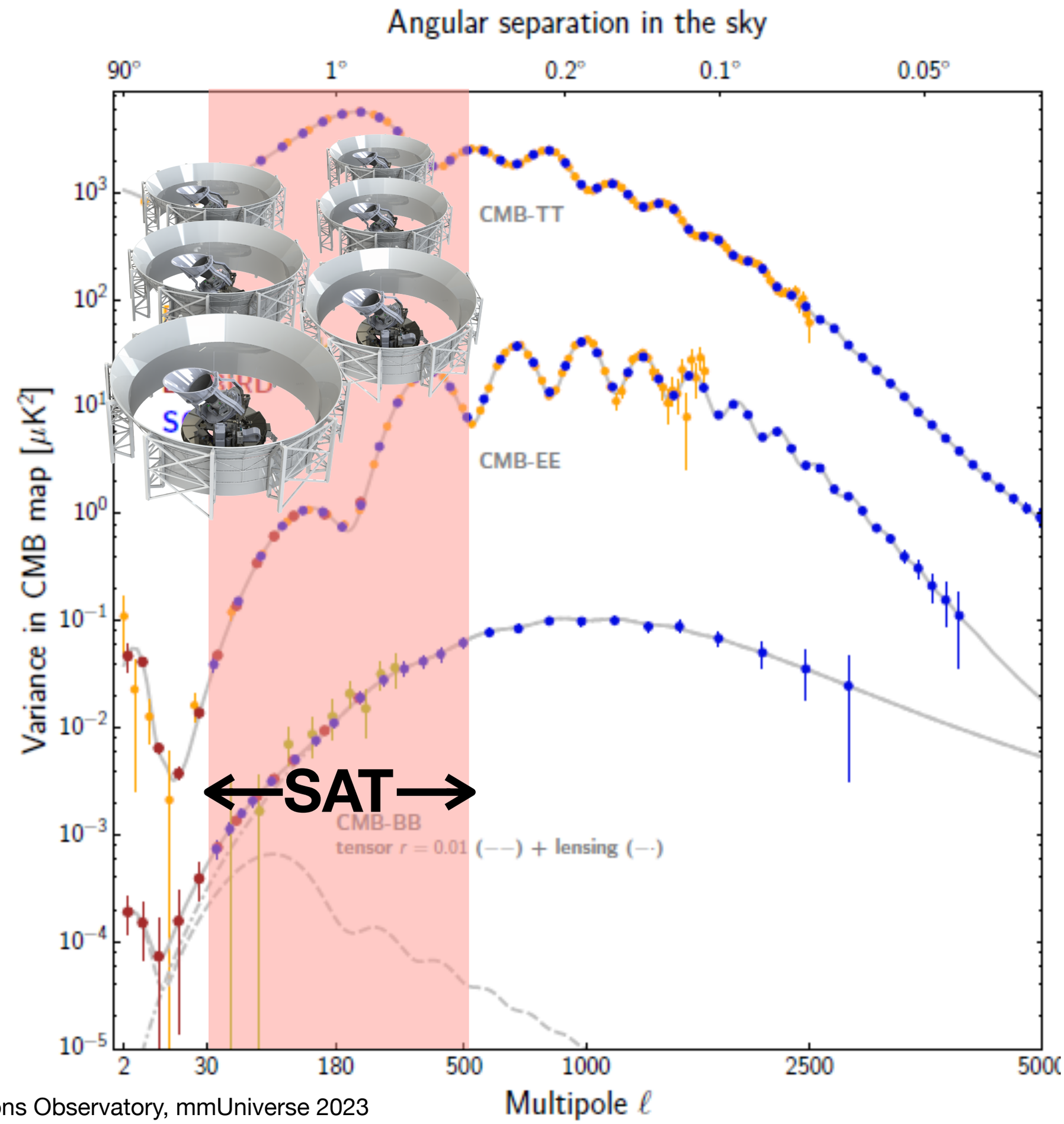




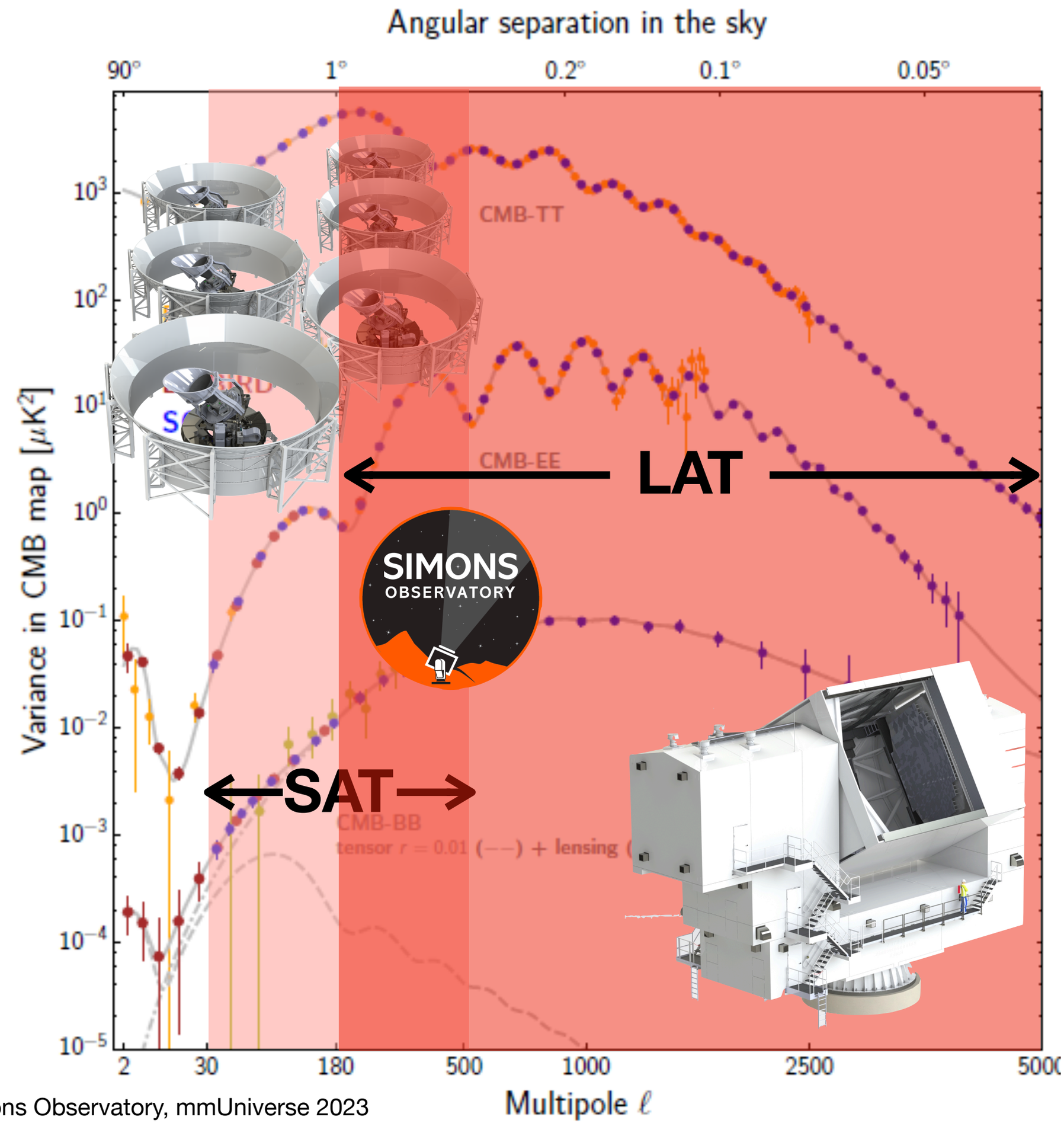
Josquin Errard, Simons Observatory, mmUniverse 2023



Josquin Errard, Simons Observatory, mmUniverse 2023

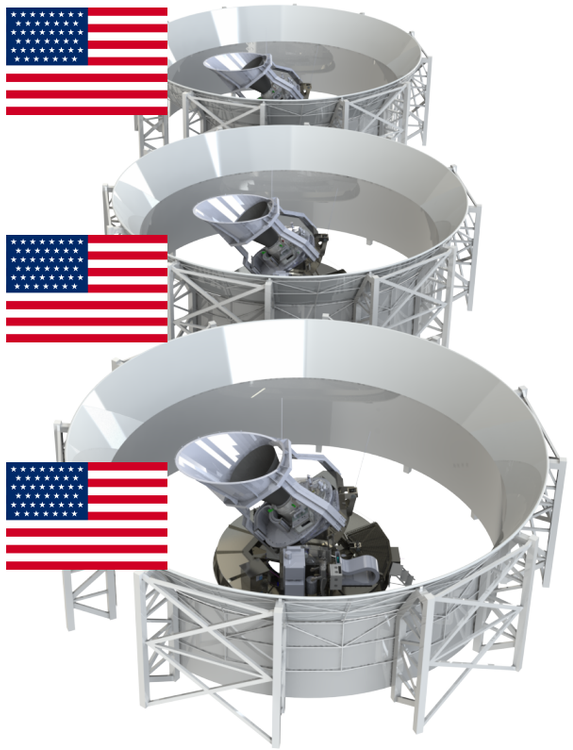


Josquin Errard, Simons Observatory, mmUniverse 2023



Josquin Errard, Simons Observatory, mmUniverse 2023

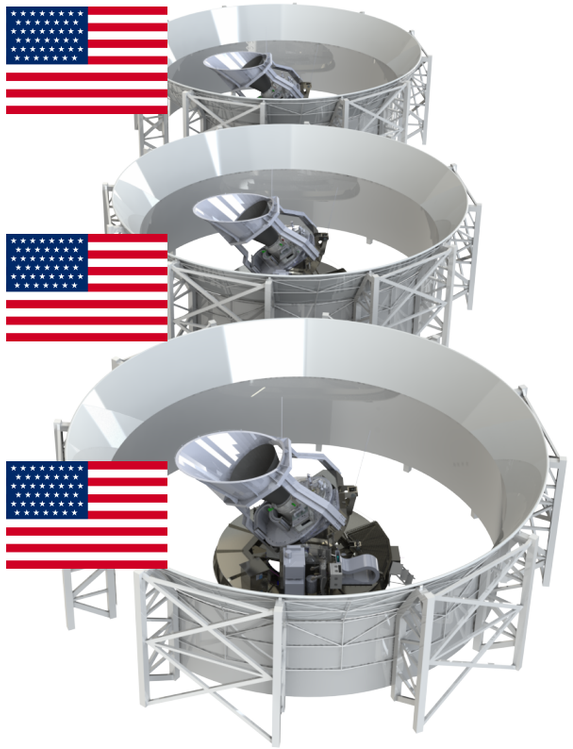
news #1 SO += SO:UK + SO:JP

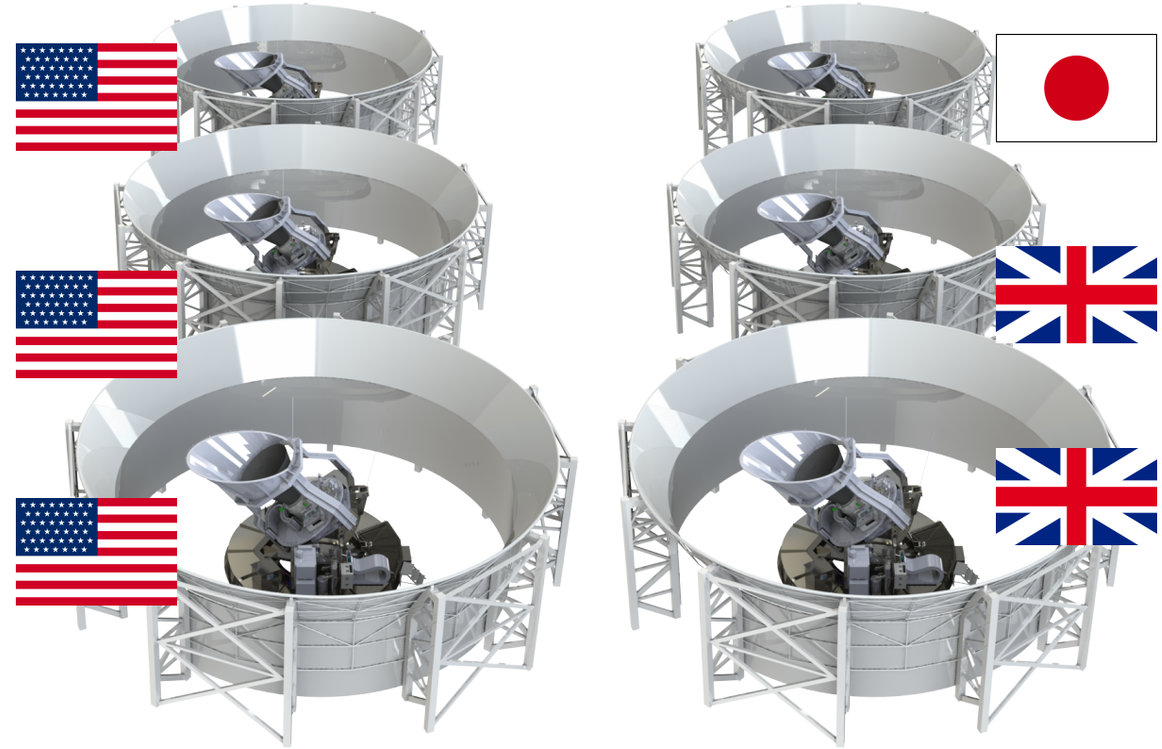


~ 2024

3 SATs
30,000 detectors in total
6 frequency bands

news #1 SO += SO:UK + SO:JP





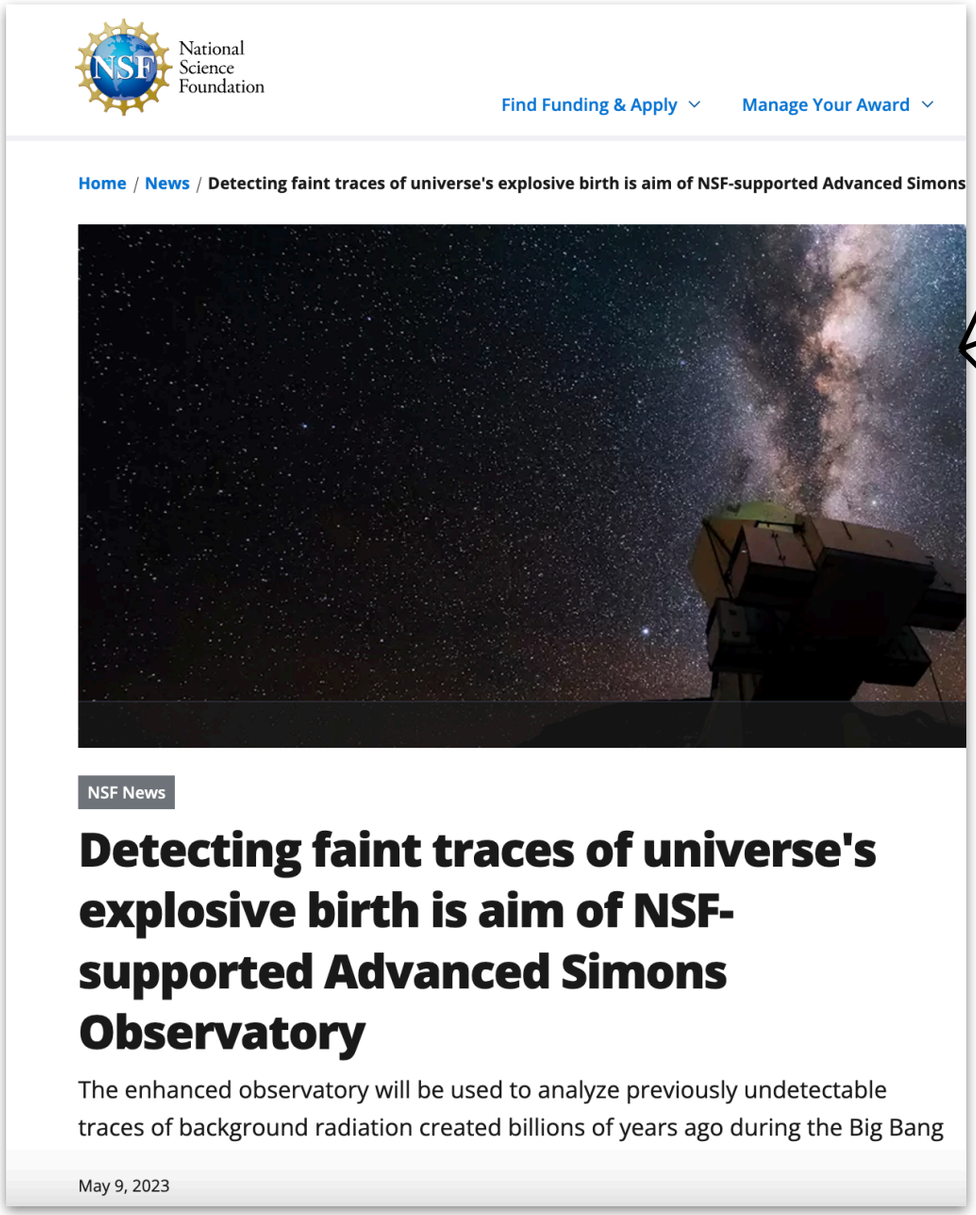
~ 2024

~ 2028

3 SATs
30,000 detectors in total
6 frequency bands

6 SATs
60,000 detectors in total
6 frequency bands

news #2
Advanced-SO


National Science Foundation

Find Funding & Apply Manage Your Award

Home / News / Detecting faint traces of universe's explosive birth is aim of NSF-supported Advanced Simons

NSF News

Detecting faint traces of universe's explosive birth is aim of NSF-supported Advanced Simons Observatory

The enhanced observatory will be used to analyze previously undetectable traces of background radiation created billions of years ago during the Big Bang

May 9, 2023

LAT

- Six New Optics Tubes
- Double Mapping Speed for Delensing and other science
- Enable Transient Detection
- No Development Required

Data Management

- Full Maps Processed in 6 Months
- Daily Transient Alerts
- Verification and Systematics Mitigation
- <u>Community Maps and Tools</u>

Photovoltaic Array

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

	Parameter	SO-Baseline[a] (no syst)	**SO-Baseline**[b]	SO-Goal[c]	Current[d] (2018-19)	Method	Sec.	**Advanced-SO (2024-2032)**
Primordial perturbations	r	0.0024	**0.003**	0.002	0.03	BB + ext delens	3.4	**0.0012**
	$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	0.4%	**0.5%**	0.4%	3%	$TT/TE/EE$	4.2	**0.4%**
	$f_{\mathrm{NL}}^{\mathrm{local}}$	1.8	**3**	1	5	$\kappa\kappa \times$ LSST-LSS + 3-pt	5.3	**1**
		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	**0.045**
Neutrino mass	Σm_ν	0.033	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO	5.2	**0.03**
		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%**
		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	**2%**
	p_{nt}	6%	**8%**	5%	50-100%	kSZ + tSZ + DESI	7.3	**4%**
Reionization	Δz	0.4	**0.6**	0.3	1.4	TT (kSZ)	7.6	**0.3%**

[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.

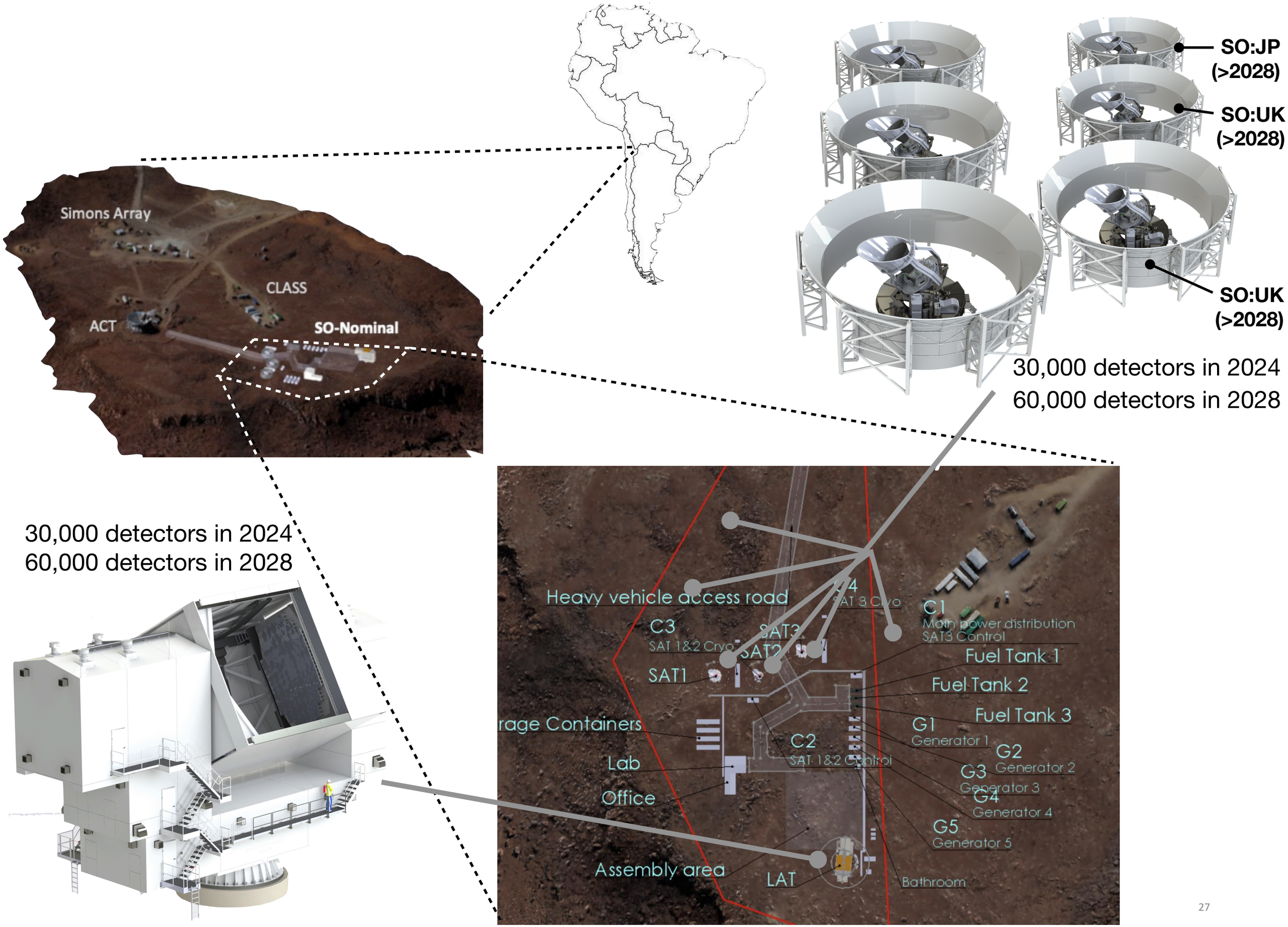
[c] This is the goal forecast, has negligible additional systematic uncertainties, and rounds to 1 s.f.

[d] Primarily from [44] and [287].

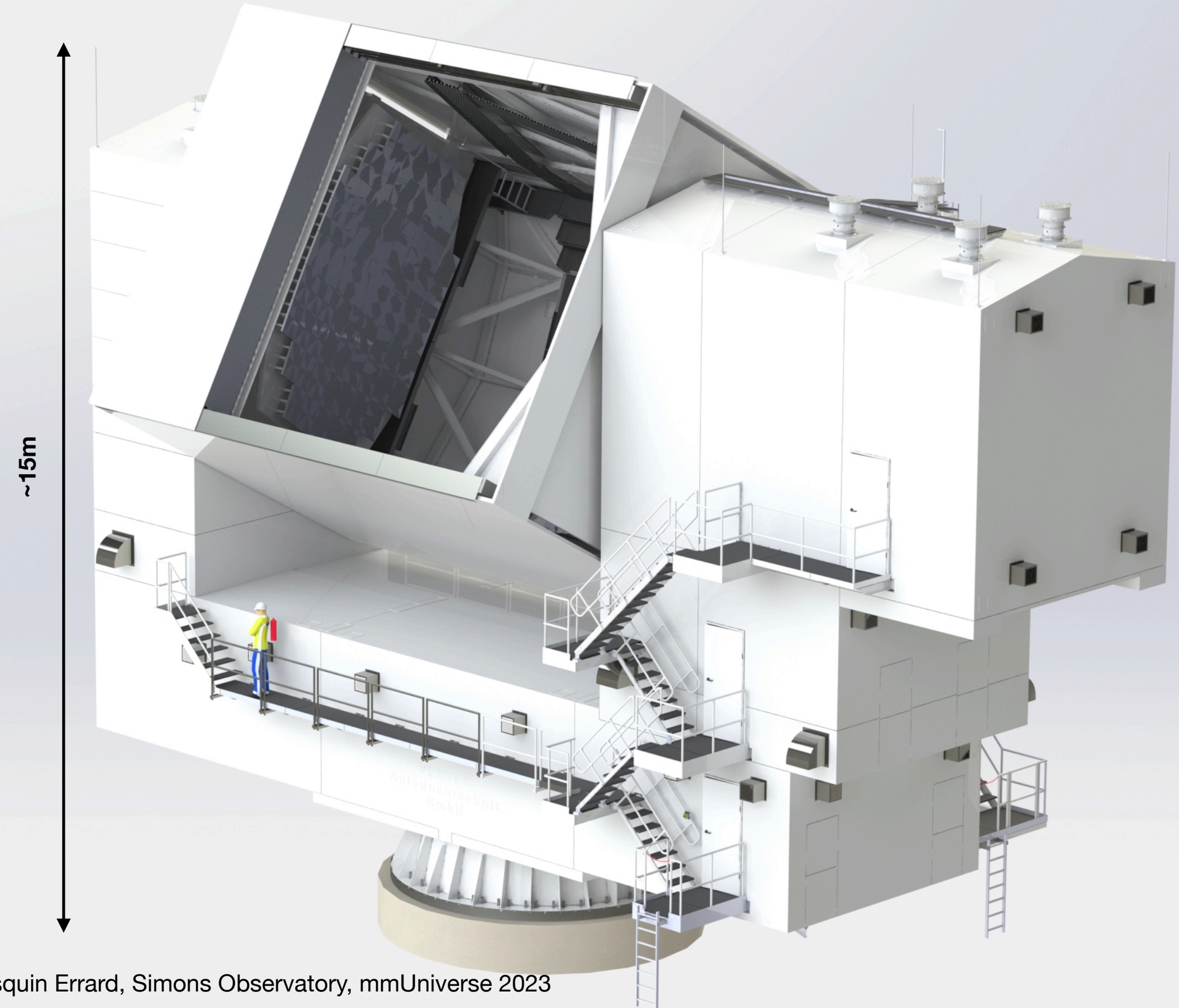
[44] BICEP2 and Planck collaborations, Joint Analysis of BICEP2/Keck Array and Planck Data, Phys. Rev. Lett. 114 (2015) 101301
[287] Planck collaboration, Planck 2018 results. VI. Cosmological parameters

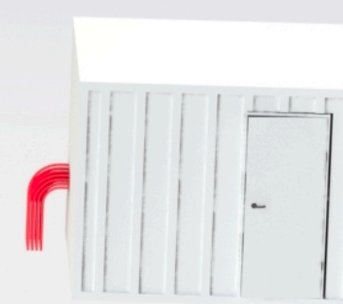
Table 9. Summary of SO key science goals. All of our SO forecasts assume that SO is combined with *Planck* data.

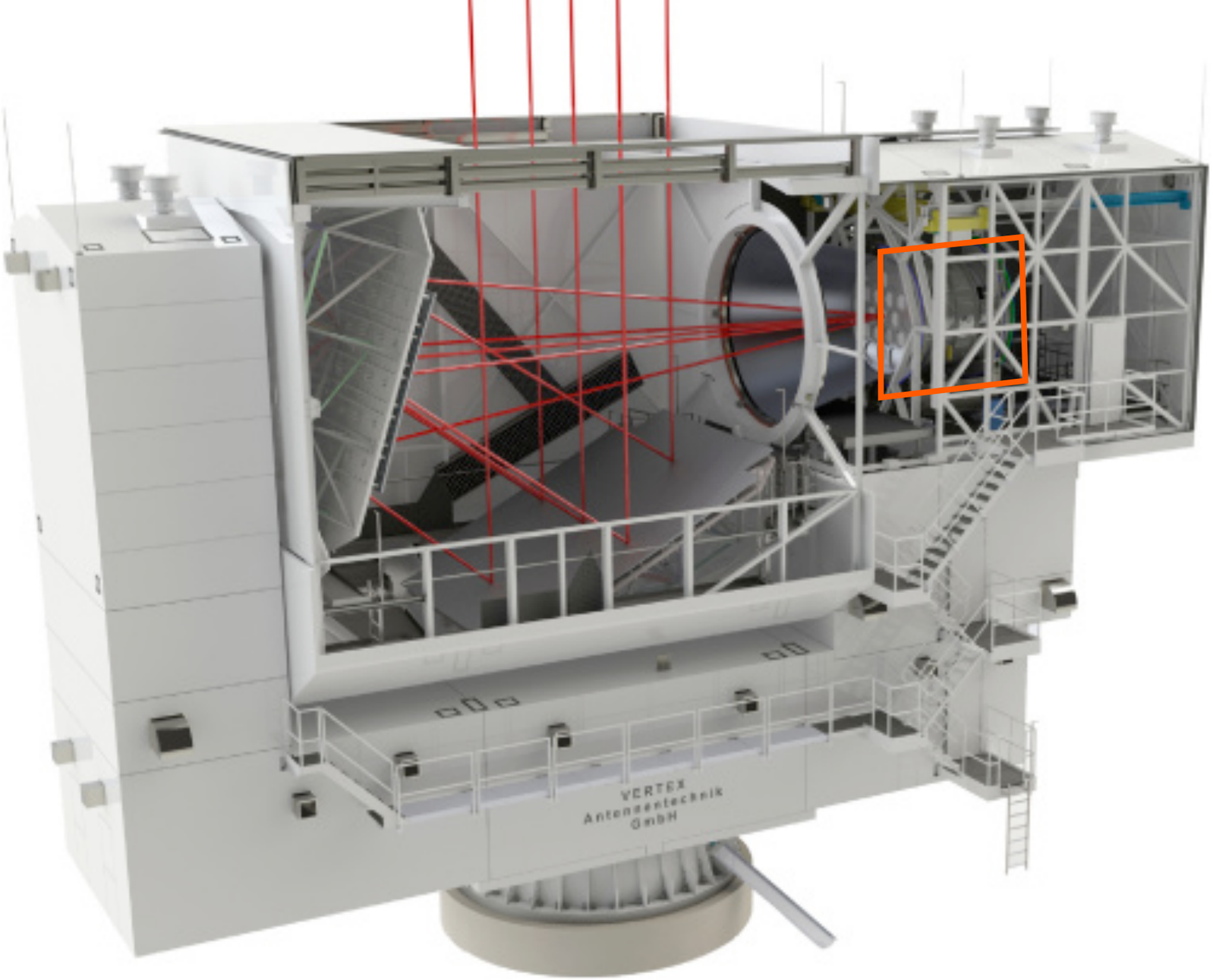
From: The Simons Observatory: science goals and forecasts
Peter Ade et al., JCAP02 (2019) 056
https://ui.adsabs.harvard.edu/abs/2019JCAP...02..056A/abstract

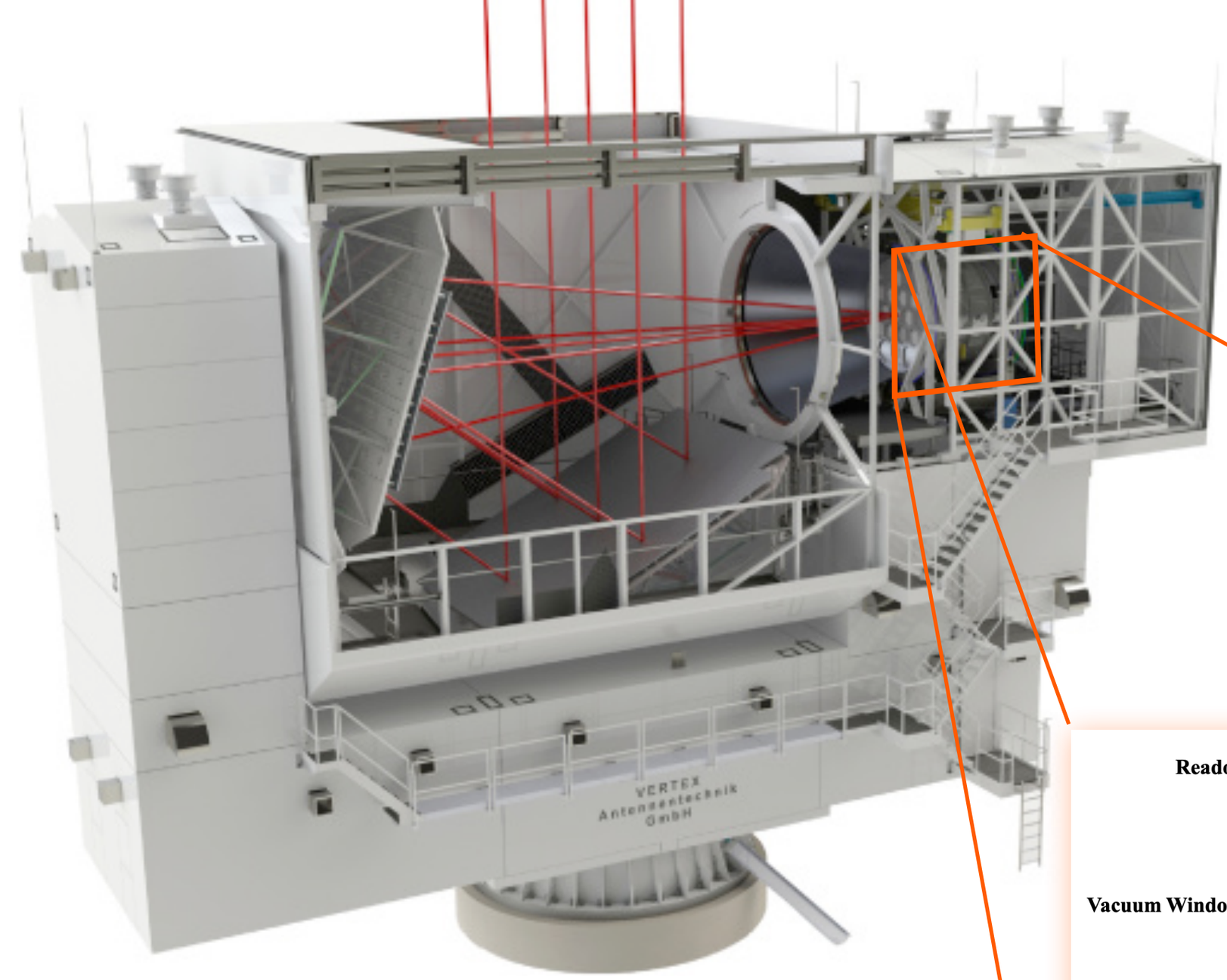


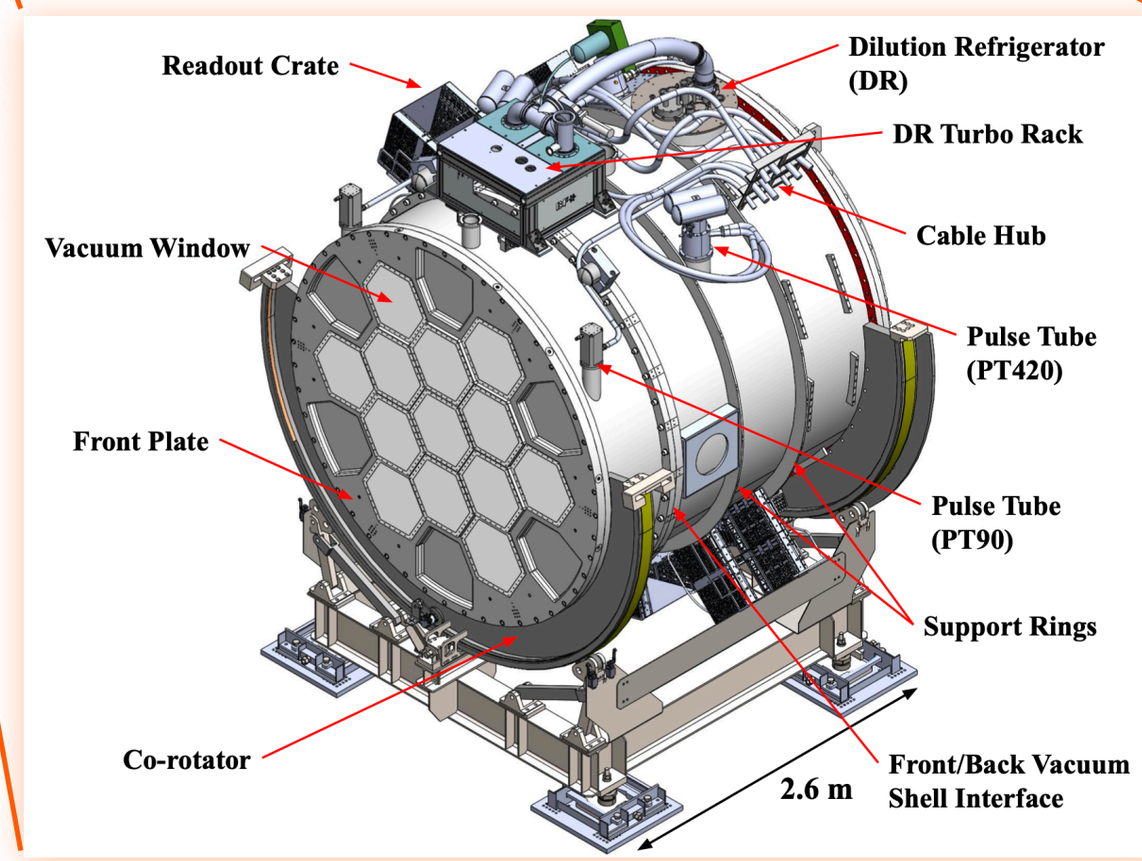
Josquin Errard, Simons Observatory, mmUniverse 2023

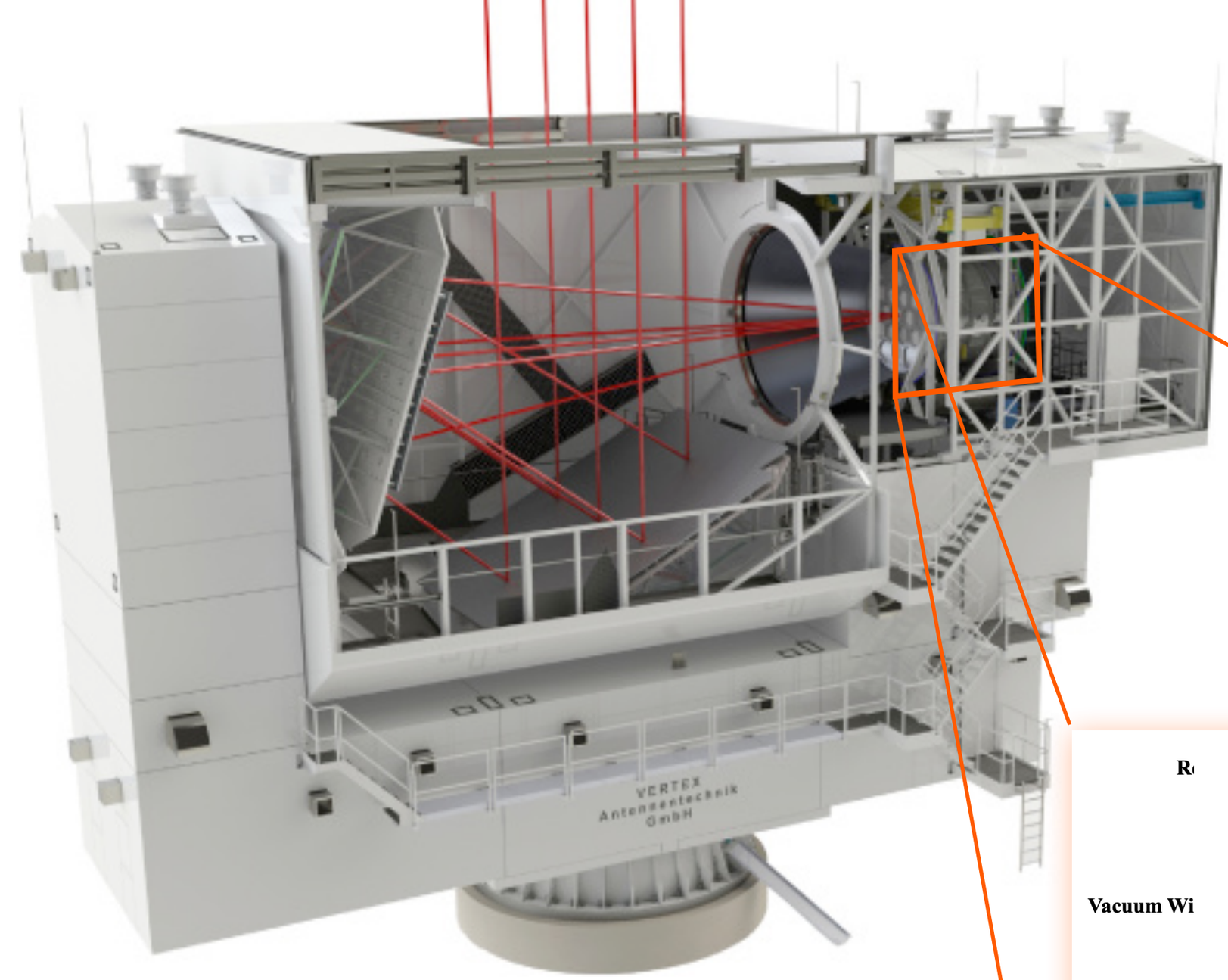

~15m

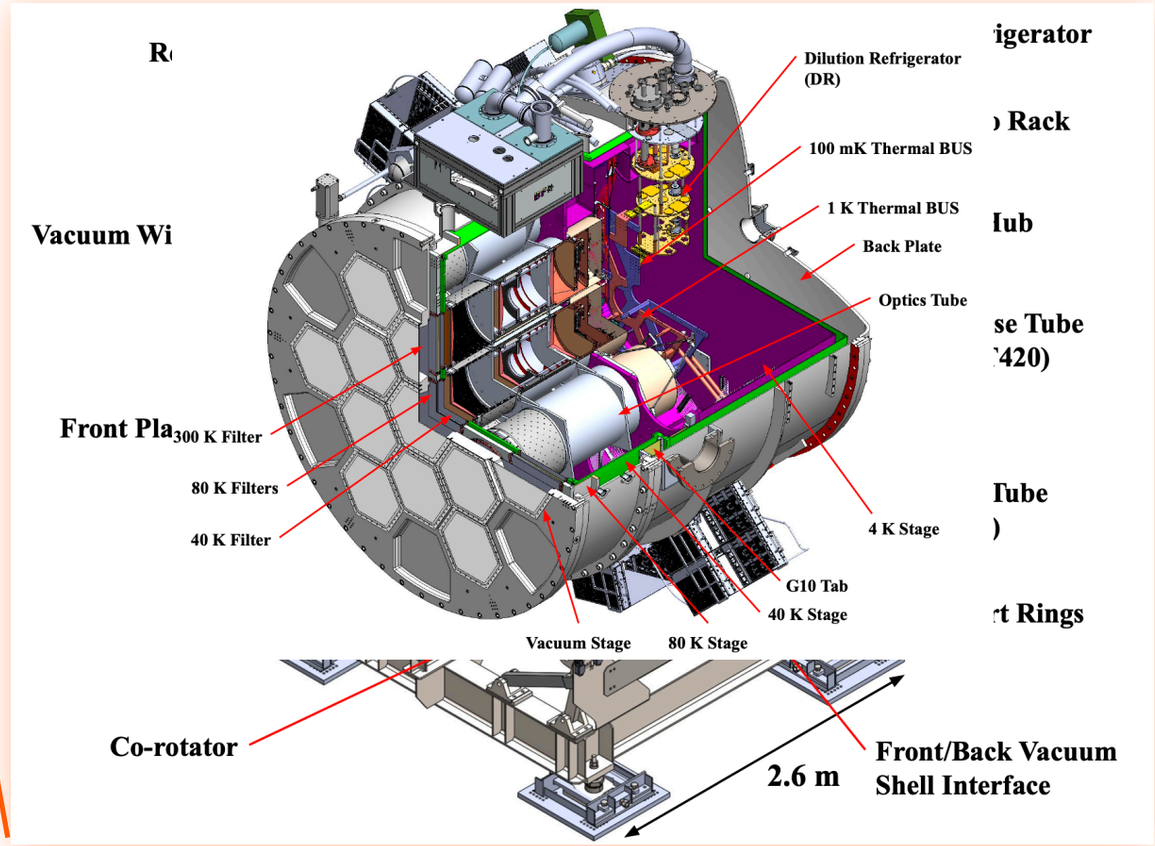


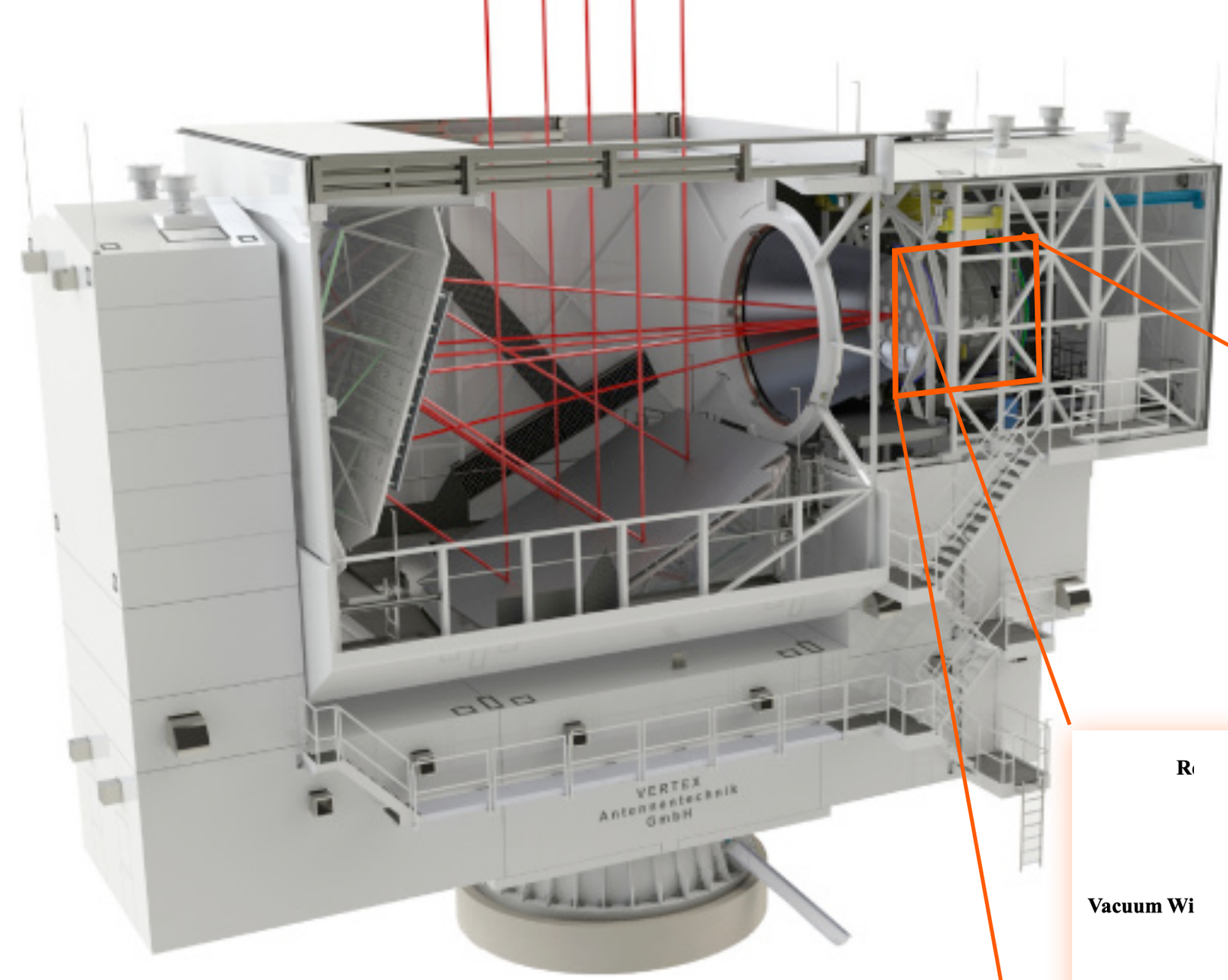

VERTEX
Antennentechnik
GmbH

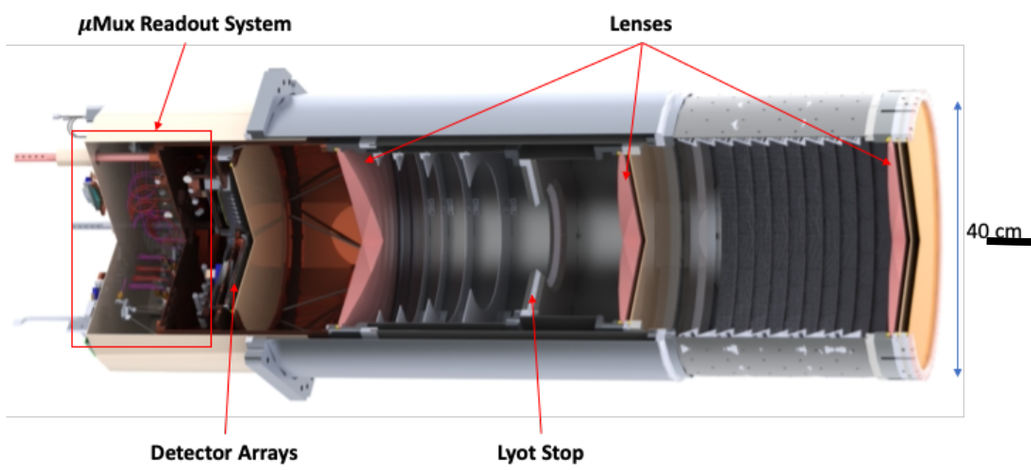

VERTEX
Antennentechnik
GmbH

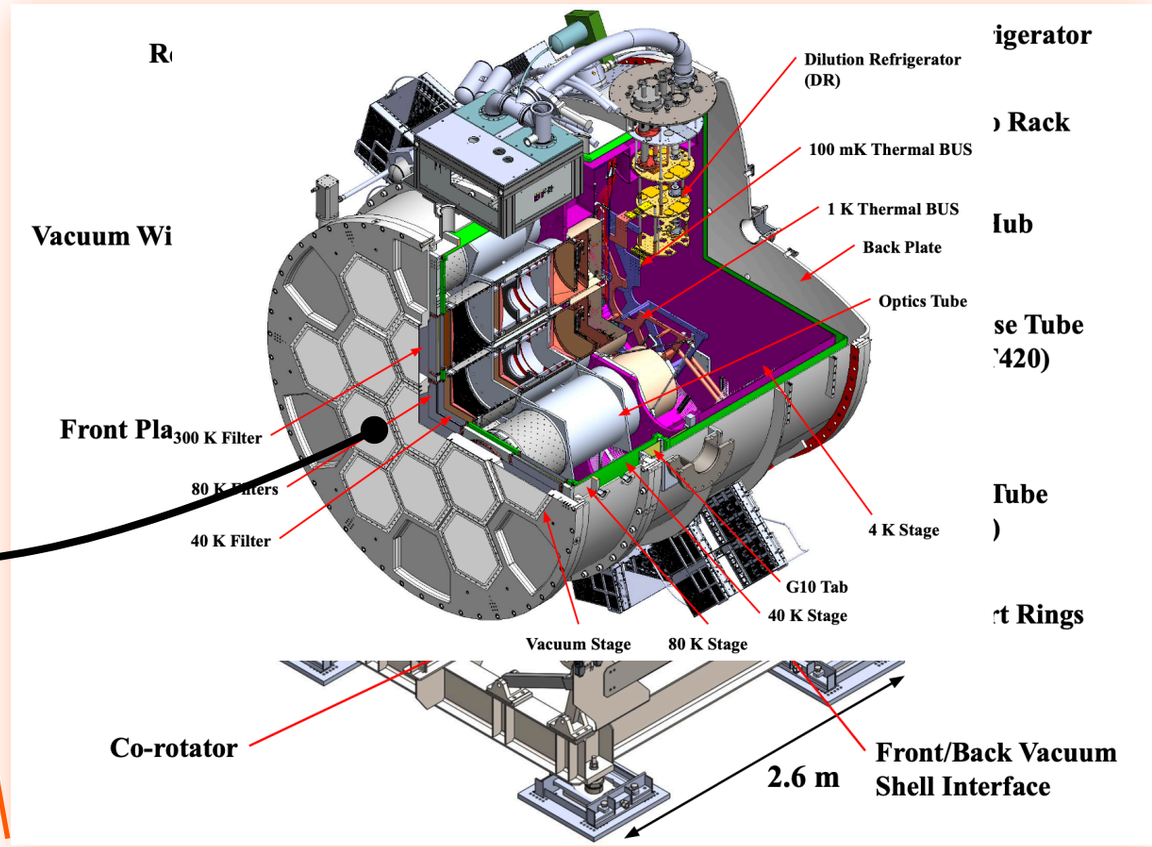

Readout Crate
Dilution Refrigerator (DR)
DR Turbo Rack
Cable Hub
Vacuum Window
Pulse Tube (PT420)
Front Plate
Pulse Tube (PT90)
Support Rings
Co-rotator
2.6 m
Front/Back Vacuum Shell Interface


VERTEX
Antennentechnik
GmbH


Dilution Refrigerator (DR)
100 mK Thermal BUS
1 K Thermal BUS
Back Plate
Optics Tube
300 K Filter
80 K Filters
40 K Filter
4 K Stage
G10 Tab
40 K Stage
Vacuum Stage
80 K Stage
Co-rotator
2.6 m
Front/Back Vacuum Shell Interface


VERTEX
Antennentechnik
GmbH


μMux Readout System
Lenses
40 cm
Detector Arrays
Lyot Stop


Dilution Refrigerator (DR)
100 mK Thermal BUS
1 K Thermal BUS
Back Plate
Optics Tube
300 K Filter
80 K Filters
40 K Filter
4 K Stage
G10 Tab
40 K Stage
Vacuum Stage
80 K Stage
Co-rotator
2.6 m
Front/Back Vacuum Shell Interface

Josquin Errard, Simons Observatory, mmUniverse 2023

LATR
Chile,
January
2023
Josquin Errard, Simons Observatory, mmUniverse 2023

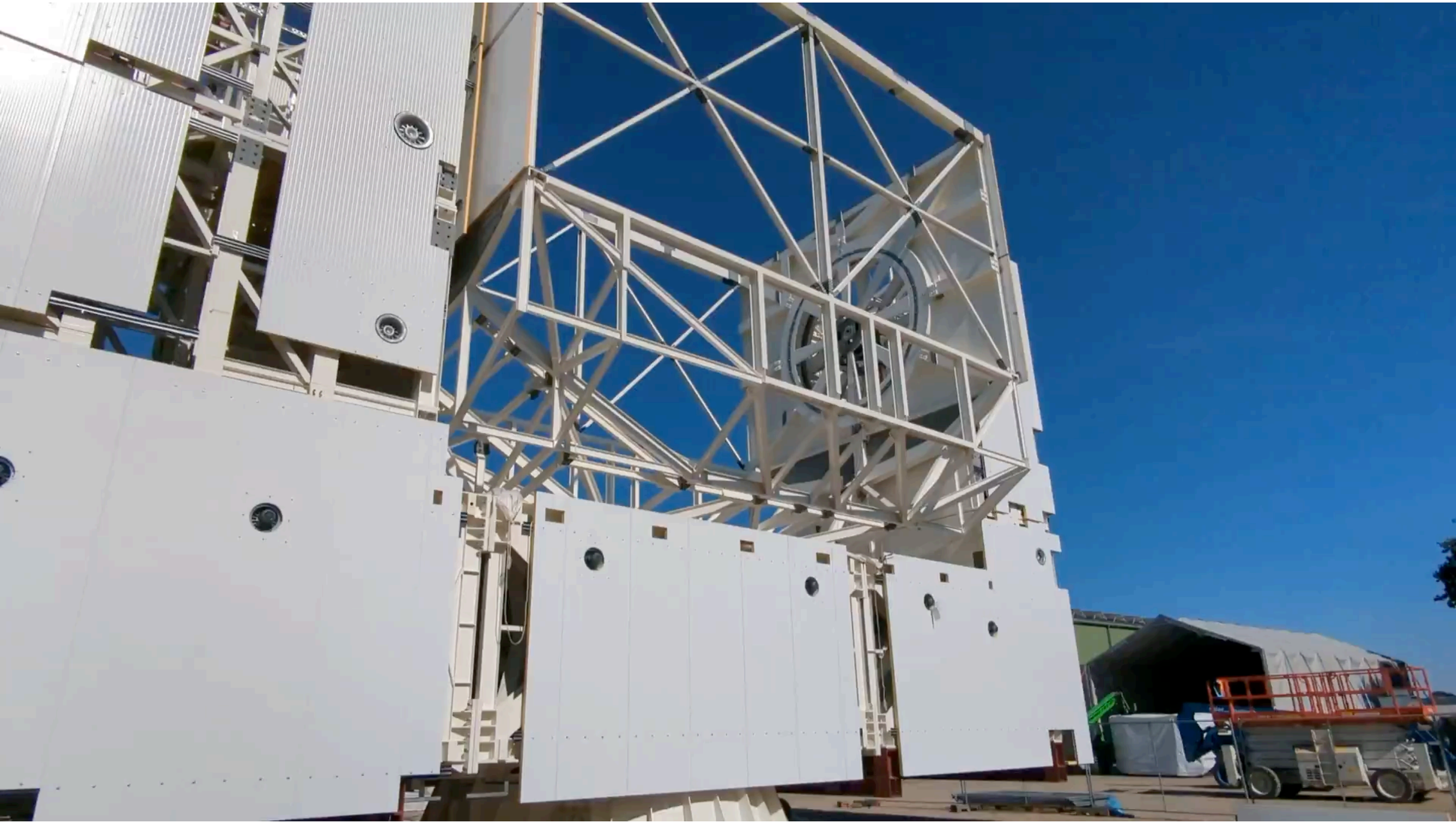
LATR

Chile,
February
2023

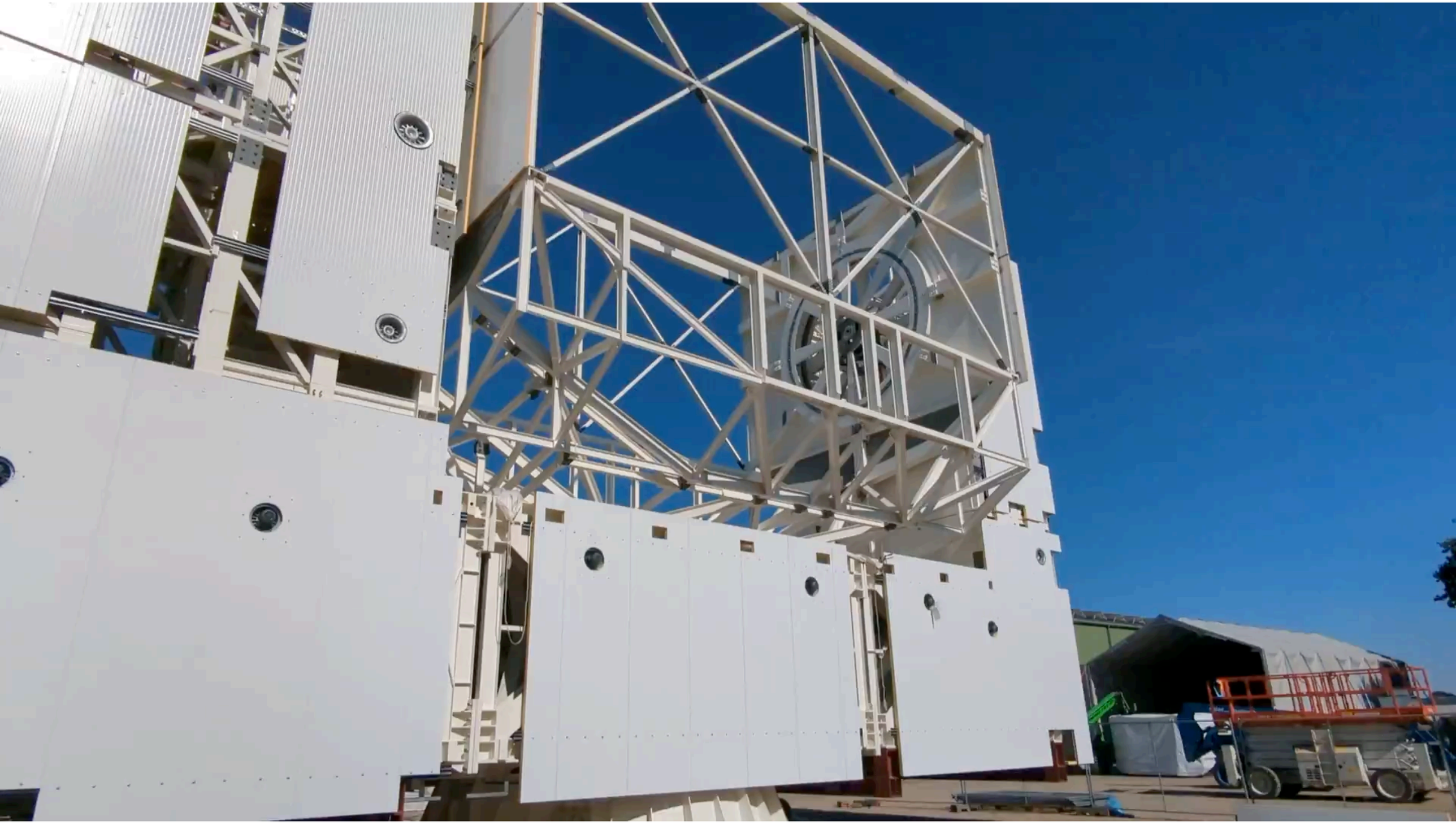
LATR

Chile,
February
2023

LAT in August 2022 (Germany)



LAT in August 2022 (Germany)



LAT in April 2023 (Chile)

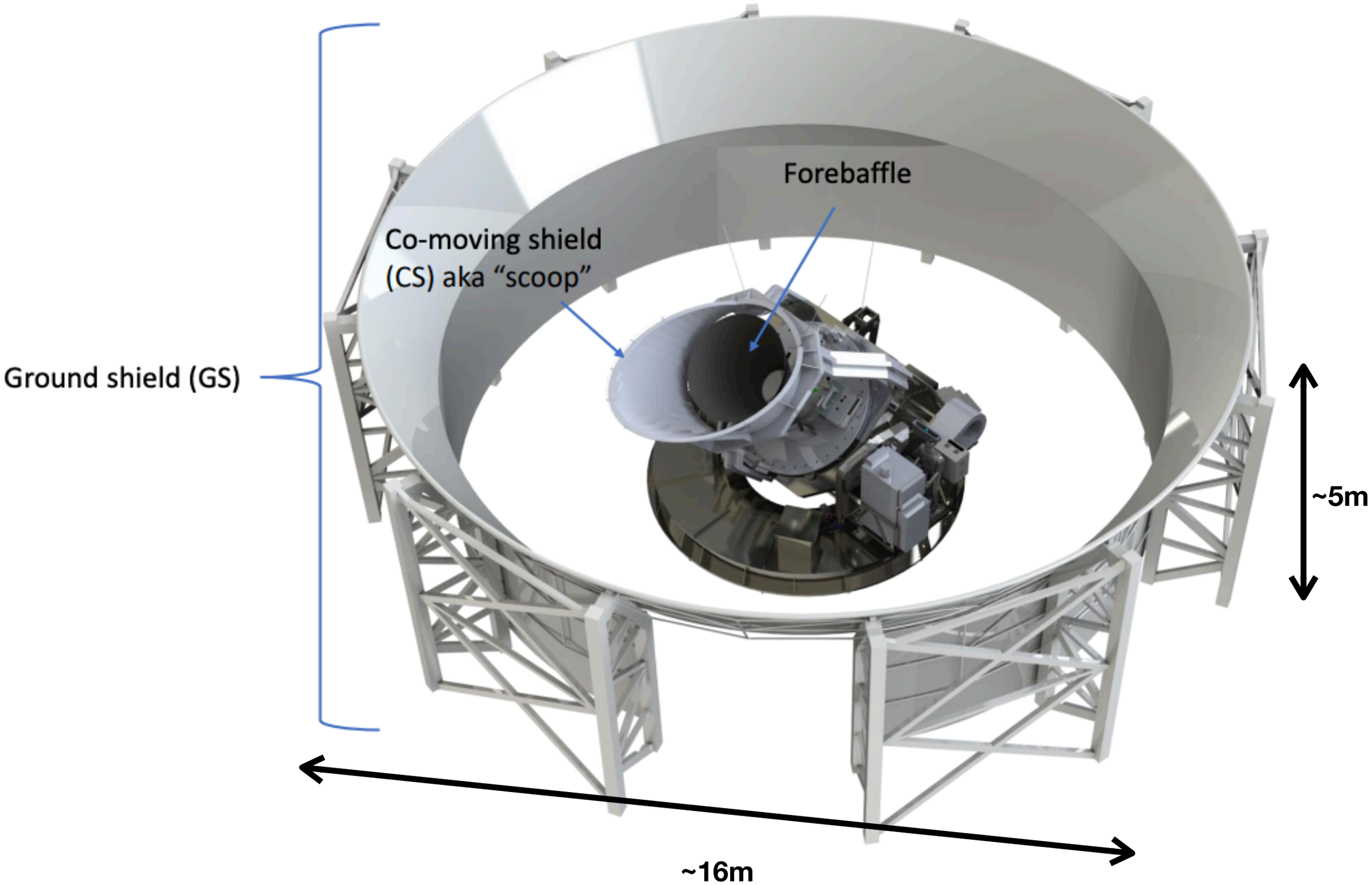
LAT in April 2023 (Chile)

LAT in April 2023 (Chile)

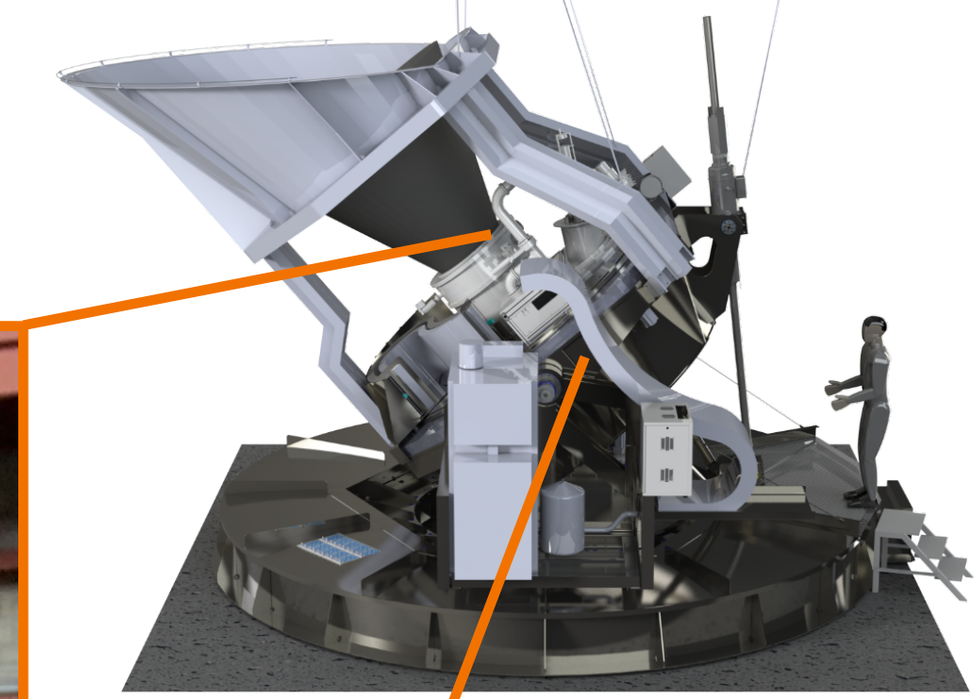
site Feb 2023 (Chile)

Josquin Errard, Simons Observatory, mmUniverse 2023

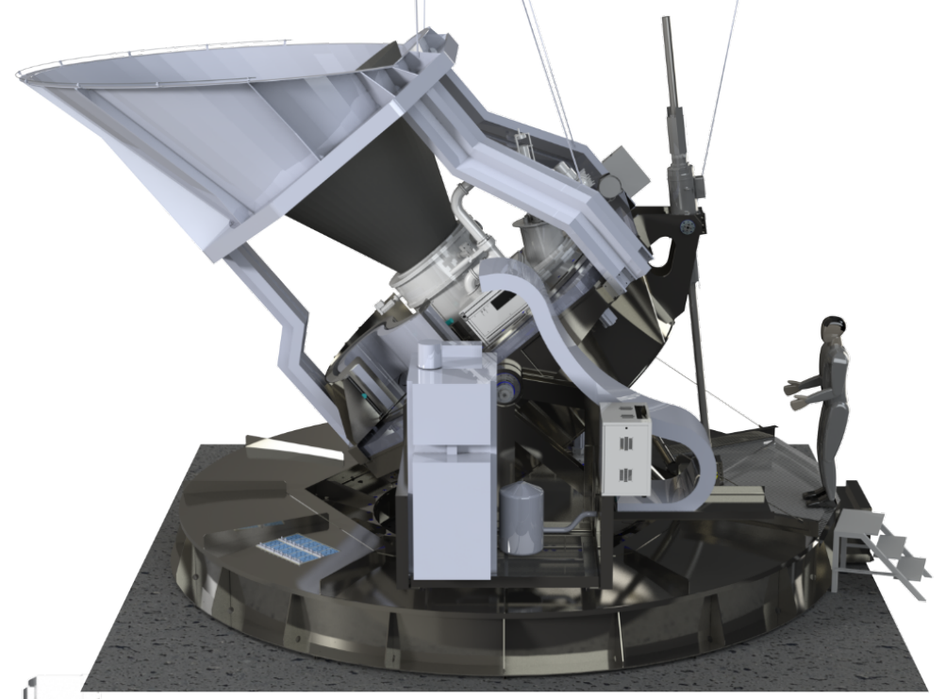
SO SAT

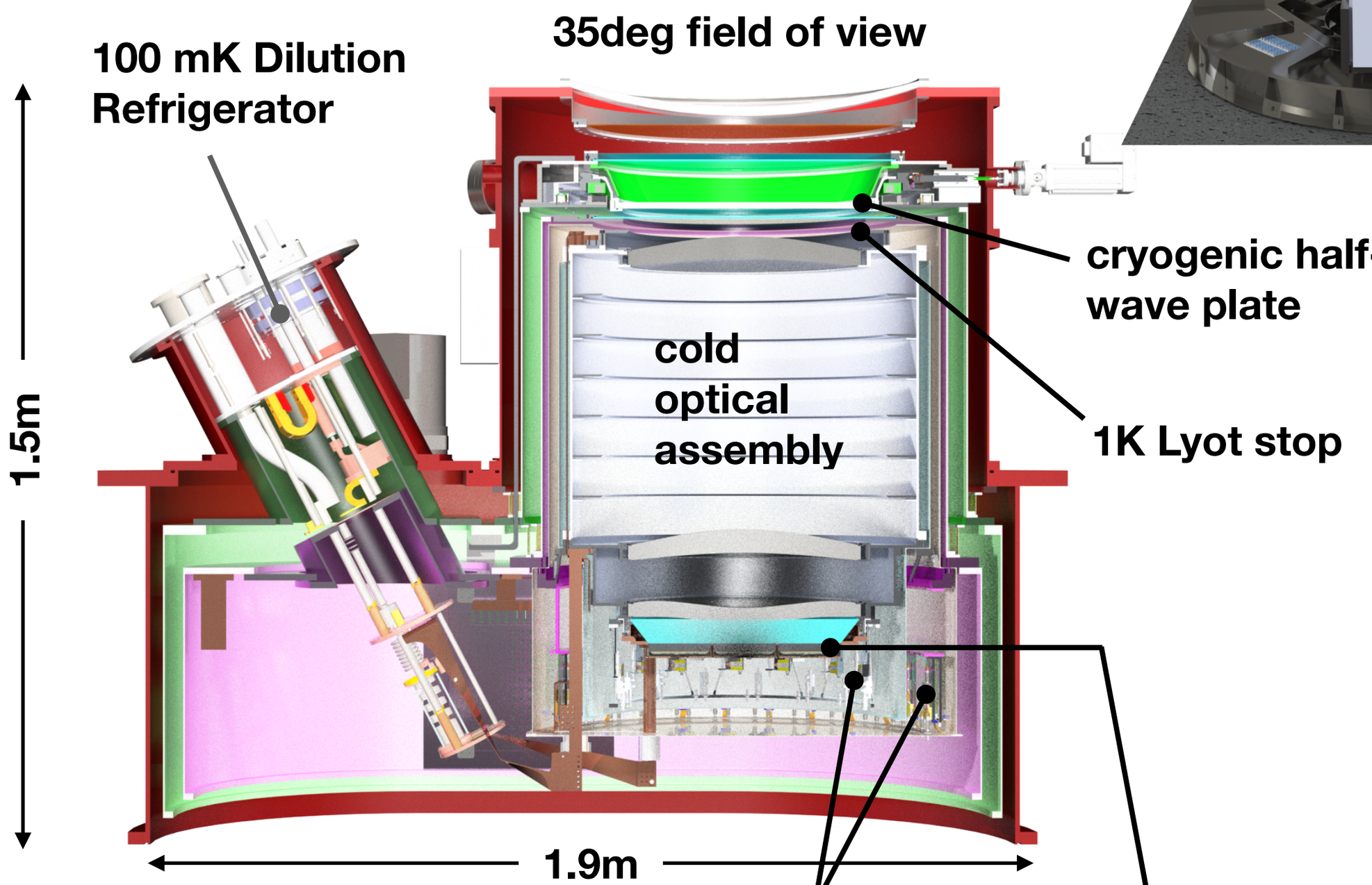

Forebaffle
Co-moving shield
(CS) aka "scoop"
Ground shield (GS)
~5m
~16m

SO SAT

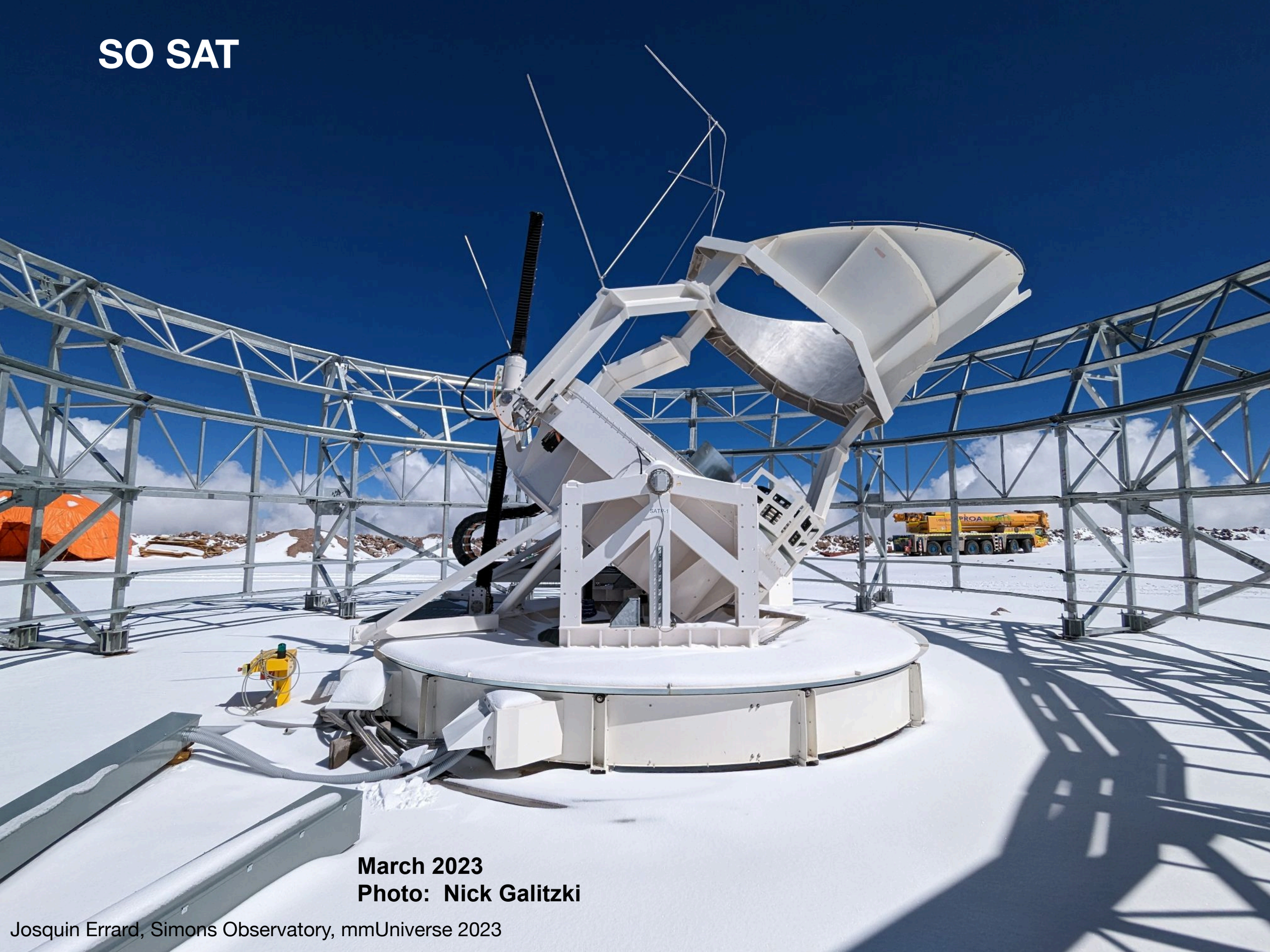


SO SAT




35deg field of view
100 mK Dilution Refrigerator
cryogenic half-wave plate
cold optical assembly
1K Lyot stop
1.5m
1.9m
cold readout assemblies
focal plane assembly
~ 10.000 bolometers

SO SAT



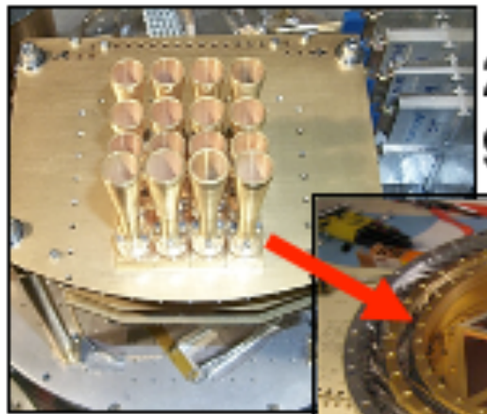
March 2023
Photo: Nick Galitzki

SO SAT

April 2023
Credit: Dave Boettger

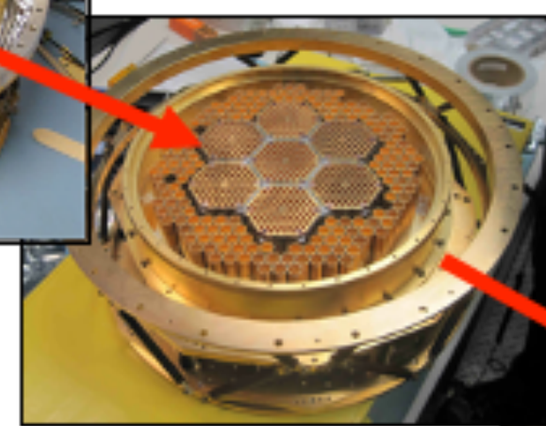
SO sensitivity

2001: ACBAR
16 detectors

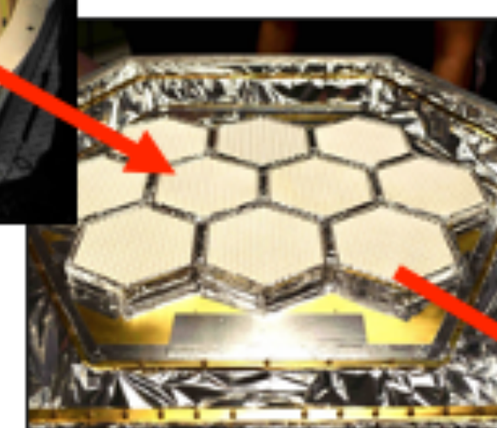


2007: SPT
960 detectors

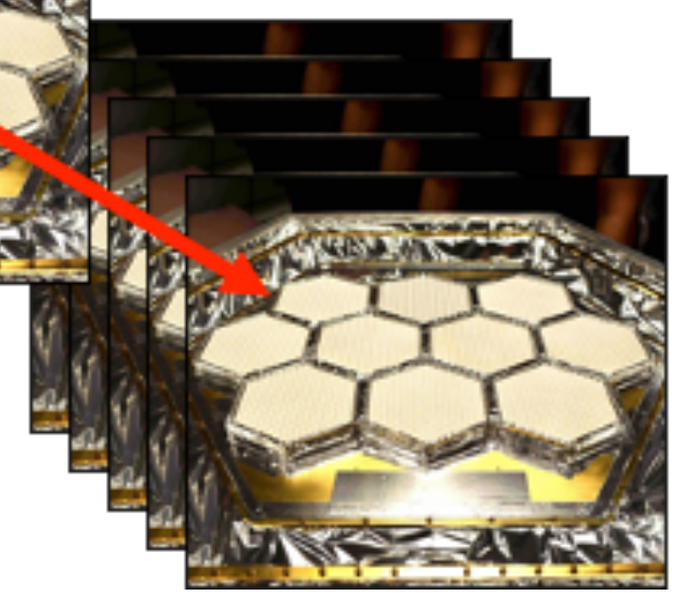
Stage-2
2012: SPTpol
~1600 detectors



Stage-3
2016: SPT-3G
~16,000 detectors



Stage-4
202: CMB-S4
500,000 detectors

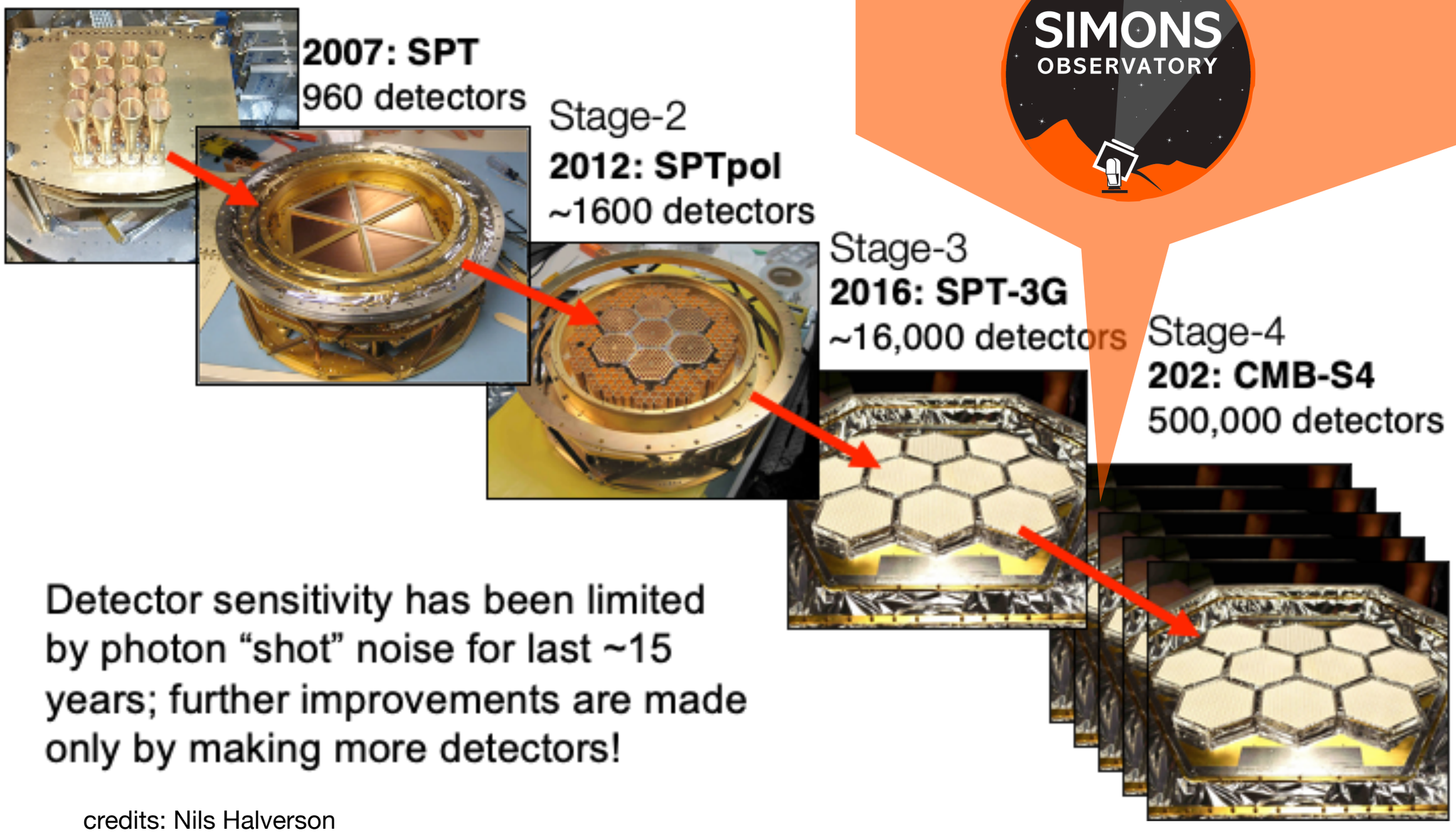


Detector sensitivity has been limited by photon “shot” noise for last ~15 years; further improvements are made only by making more detectors!

credits: Nils Halverson

SO sensitivity

- **2024: 60,000 detectors**
- **2028: 120,000 detectors**



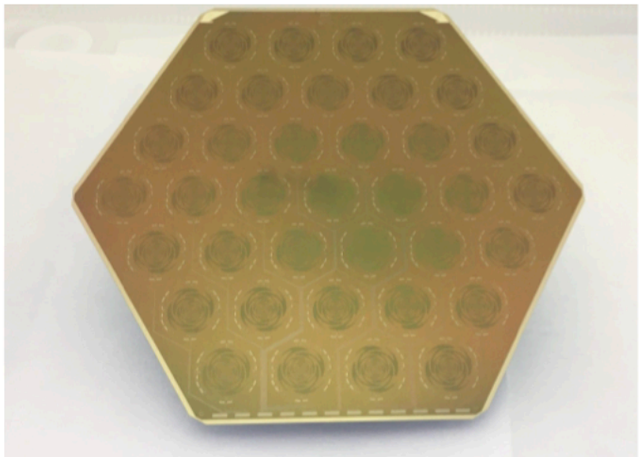
Detector sensitivity has been limited by photon "shot" noise for last ~15 years; further improvements are made only by making more detectors!

credits: Nils Halverson

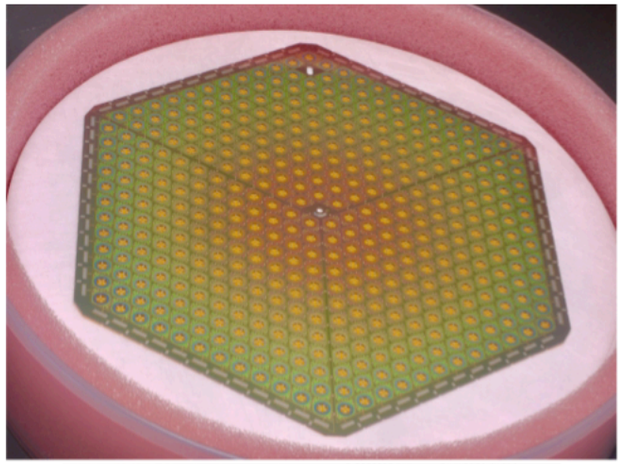
SO sensitivity

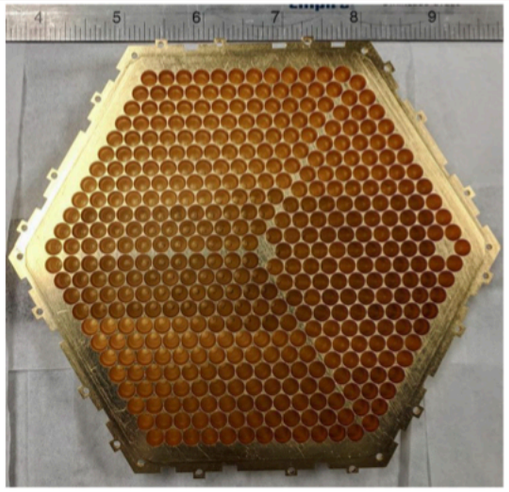
- 2024: 60,000 detectors
- 2028: 120,000 detectors

Low frequency (LF) detector arrays & lenslets



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

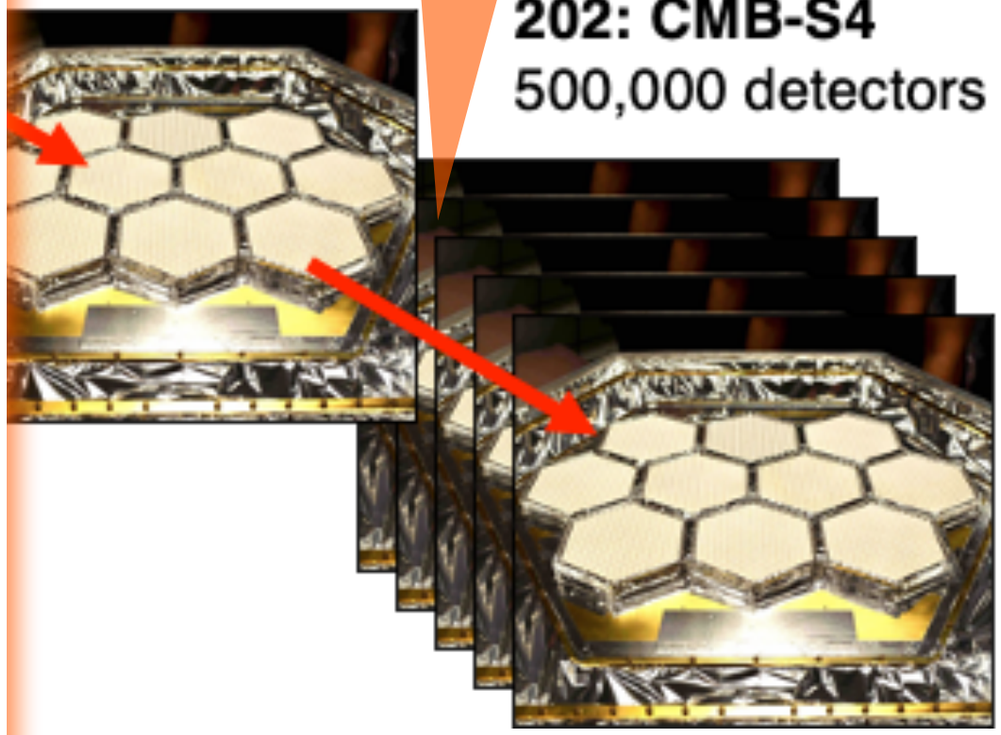




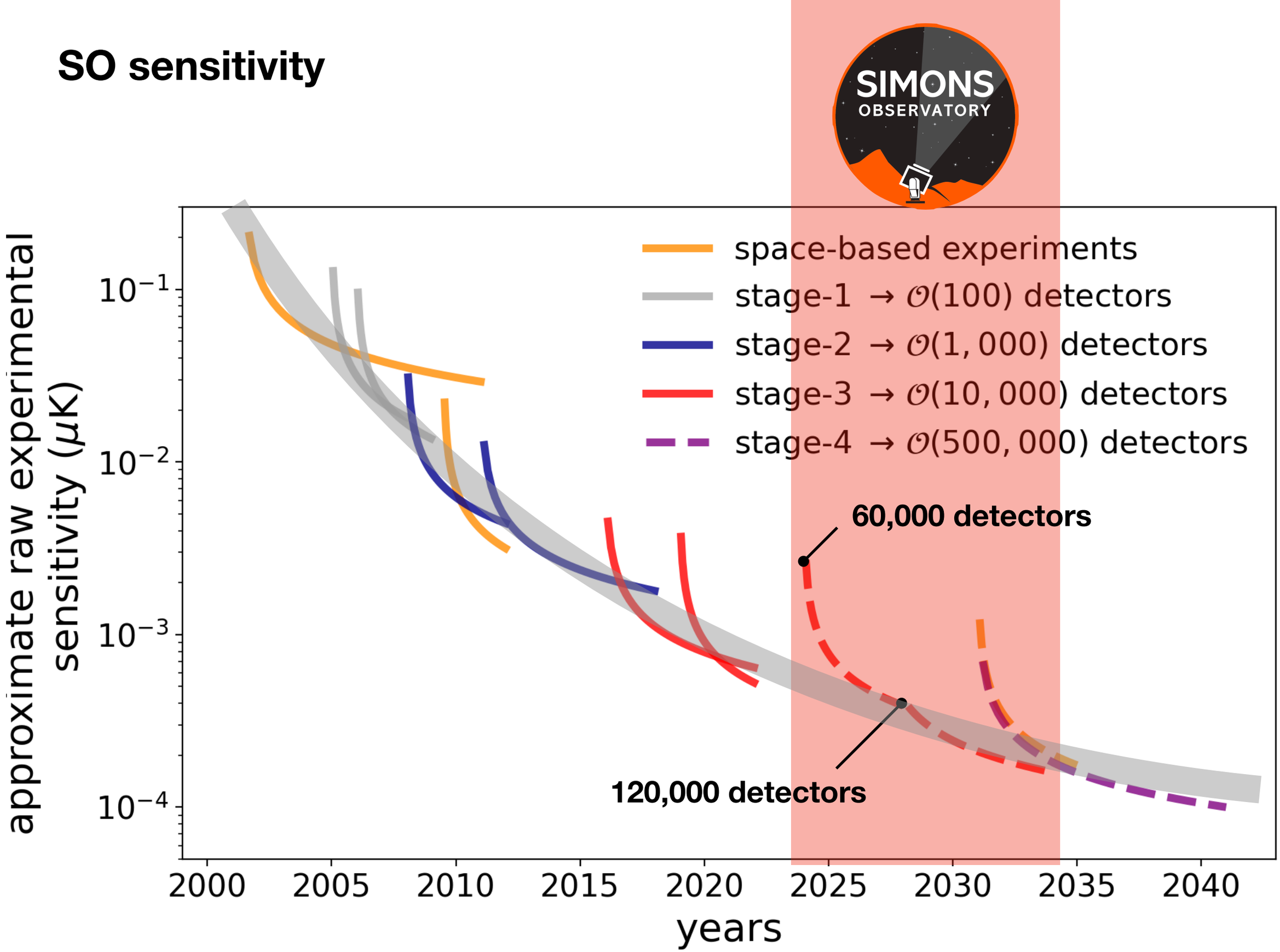
SO will use dual-polarization. dichroic TES bolometer detectors. cooled to 100 mK. The LF detector arrays build on the proven performance of POLARBEAR and the MF and UHF on ACT.

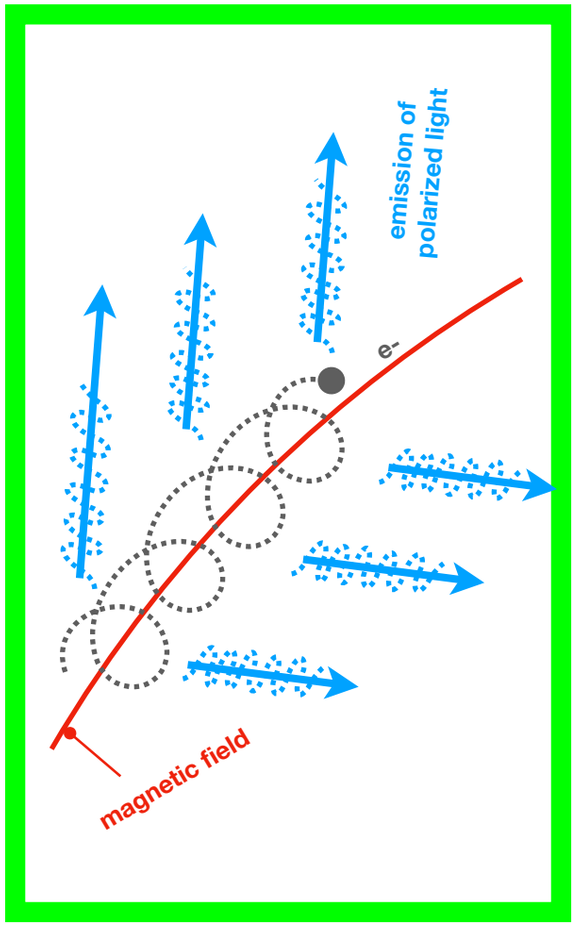
Stage-3
2016: SPT-3G
~16,000 detectors

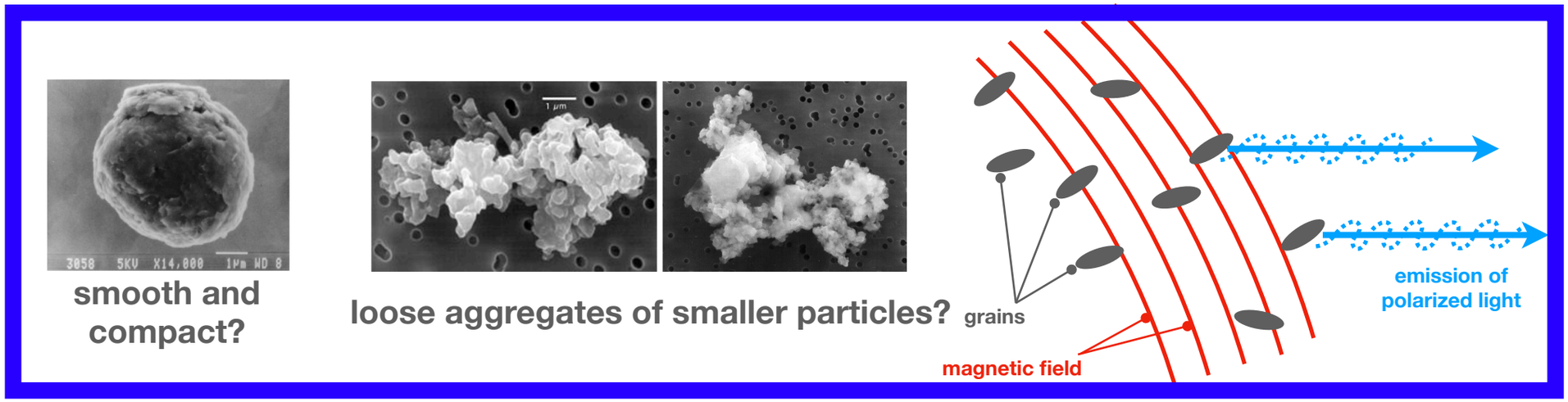
Stage-4
202: CMB-S4
500,000 detectors



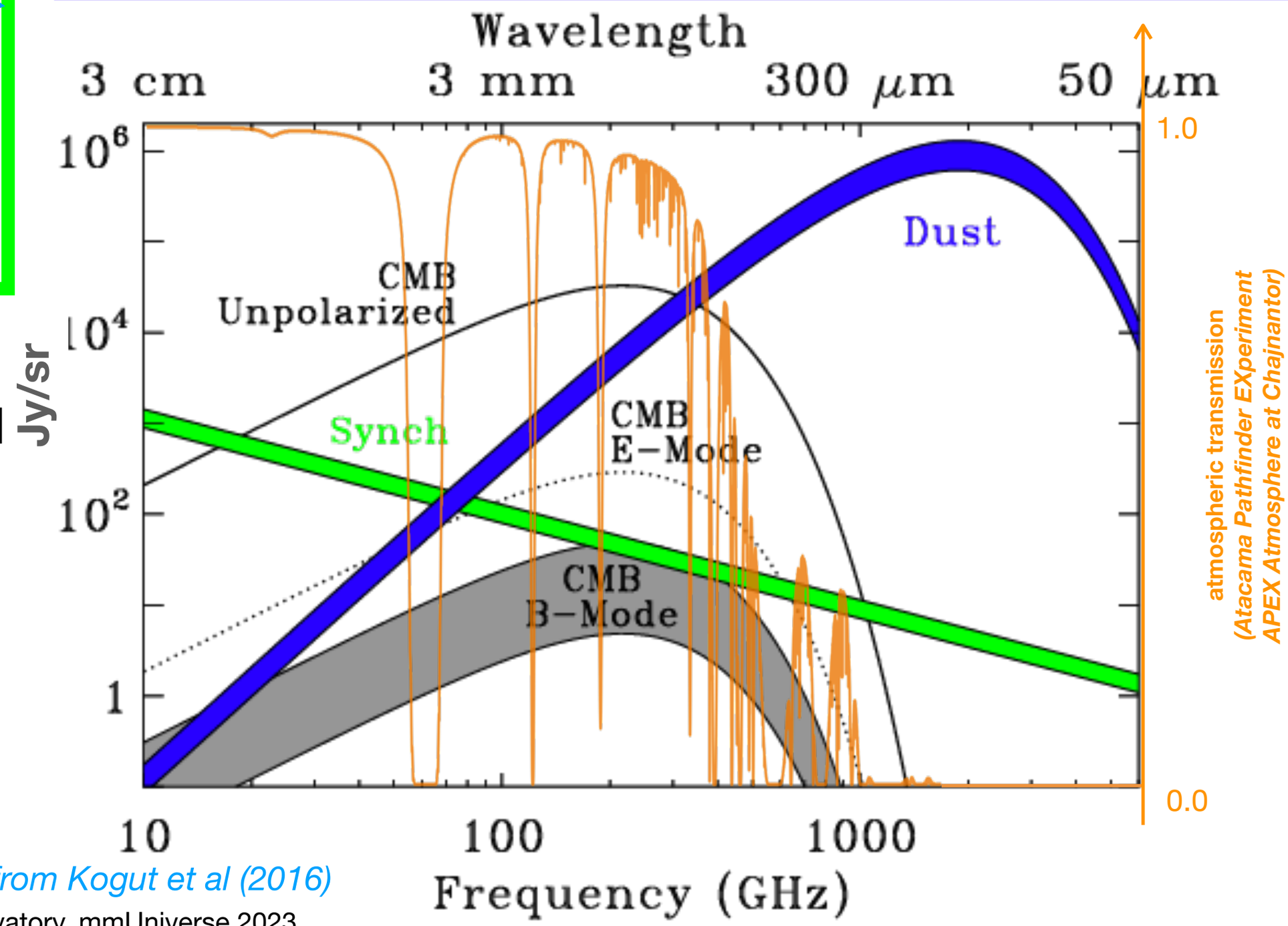
SO sensitivity



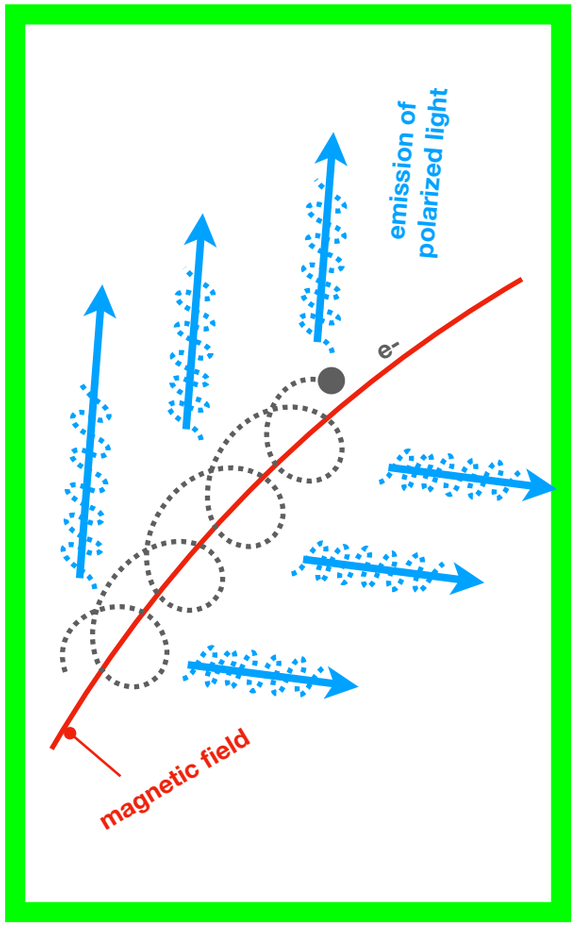


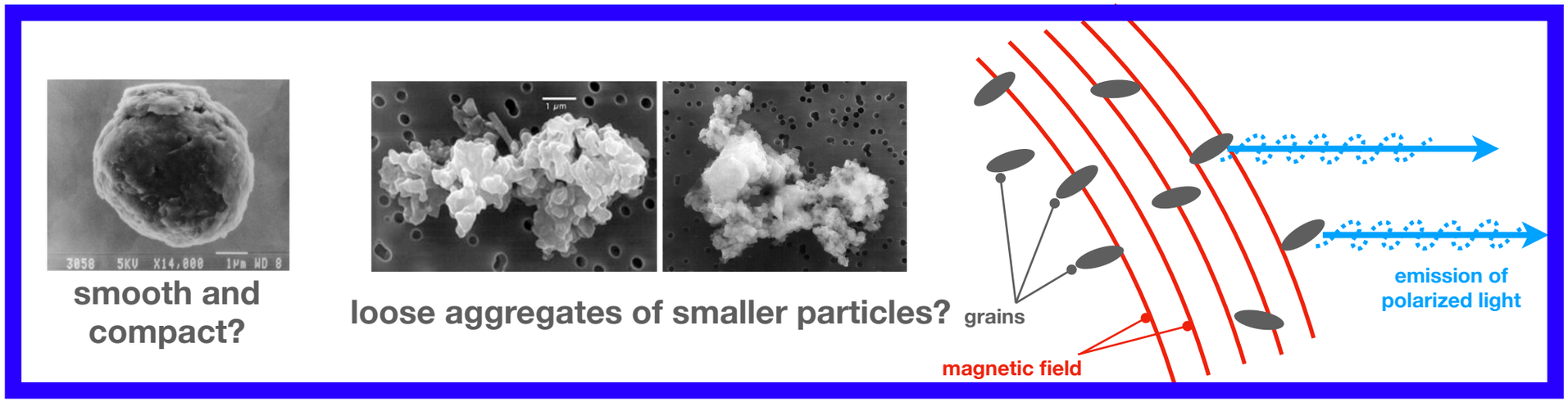


SO observed frequencies



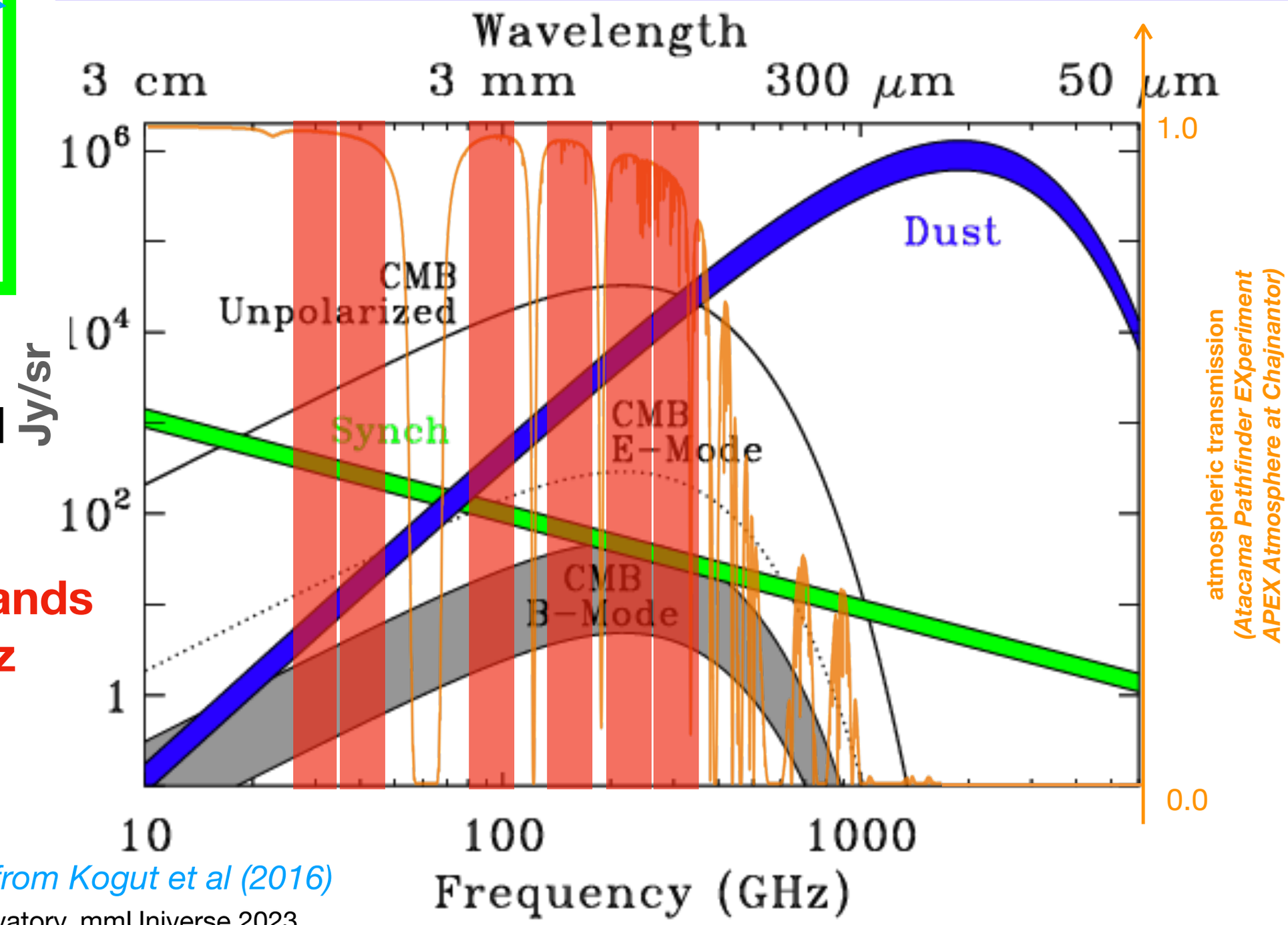
adapted from Kogut et al (2016)





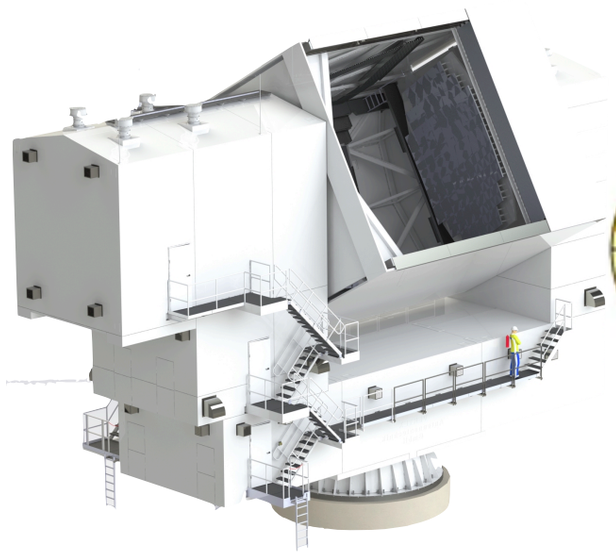
SO observed frequencies

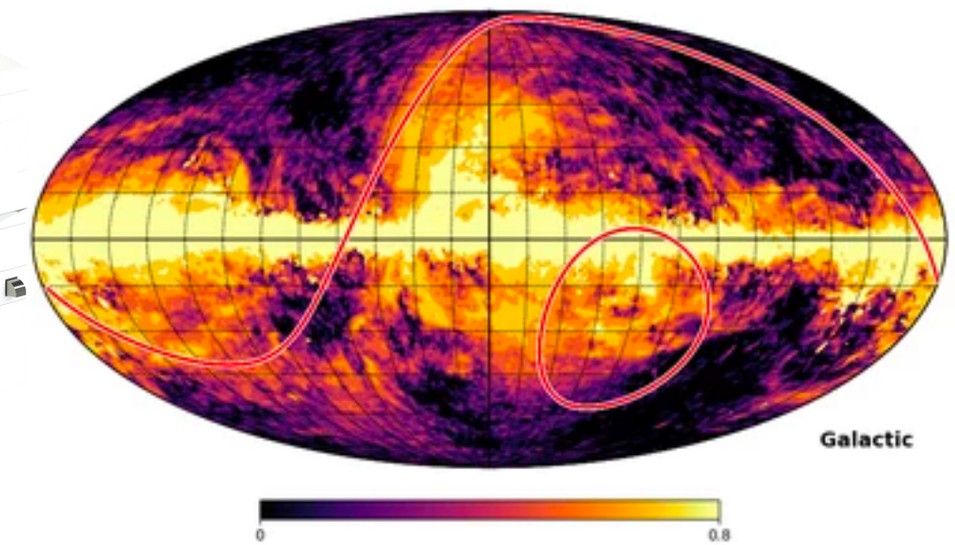
6 frequency bands
27-270 GHz

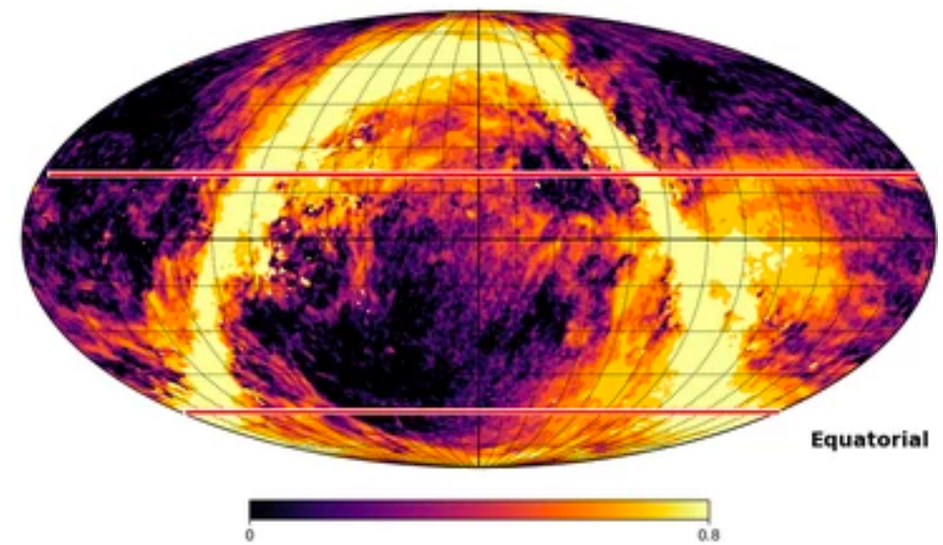


adapted from Kogut et al (2016)

SO observed sky areas

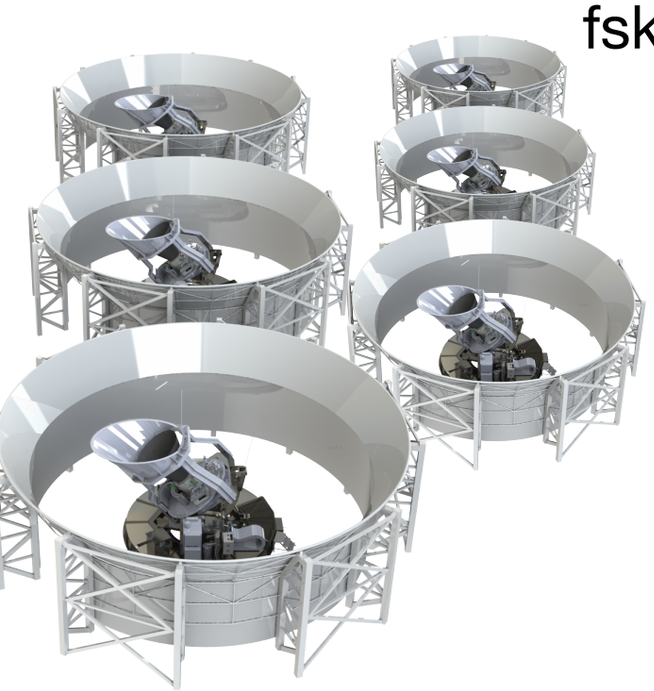


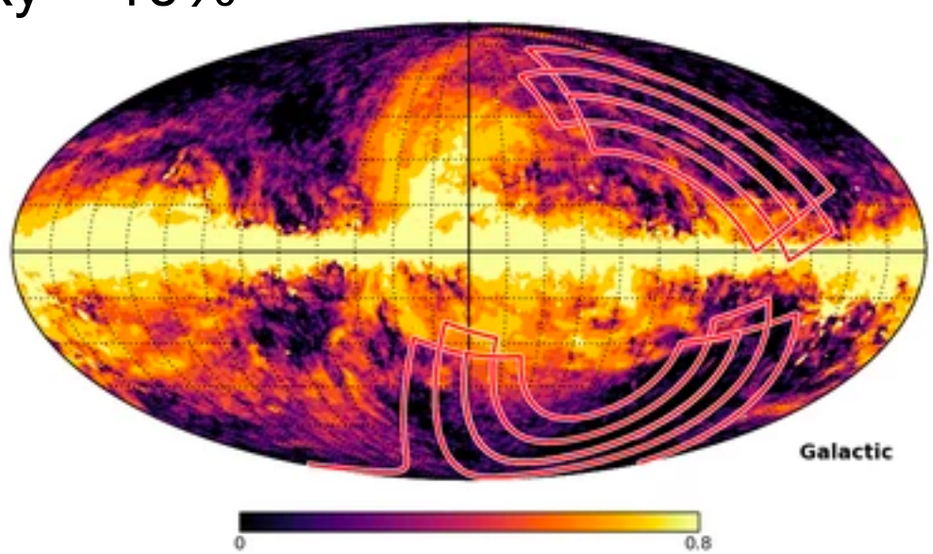


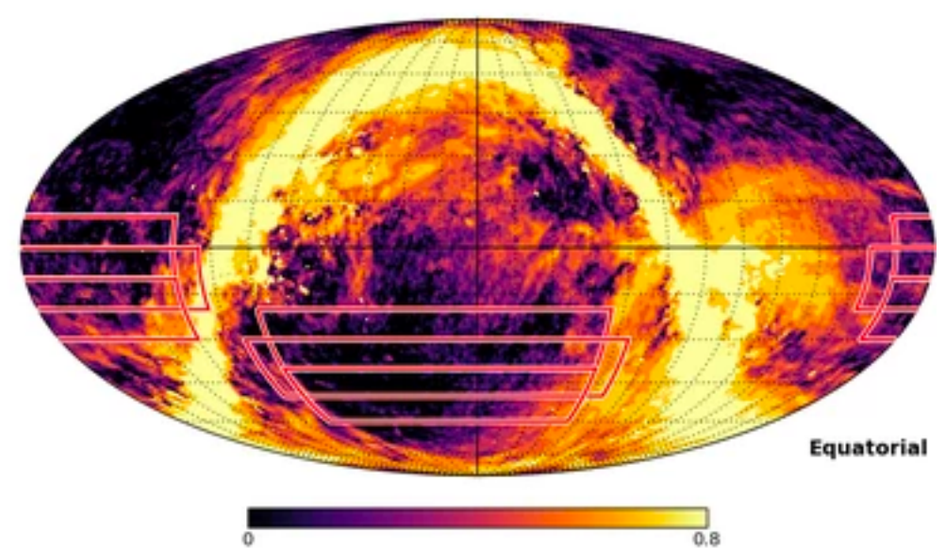


fsky ~ 40%

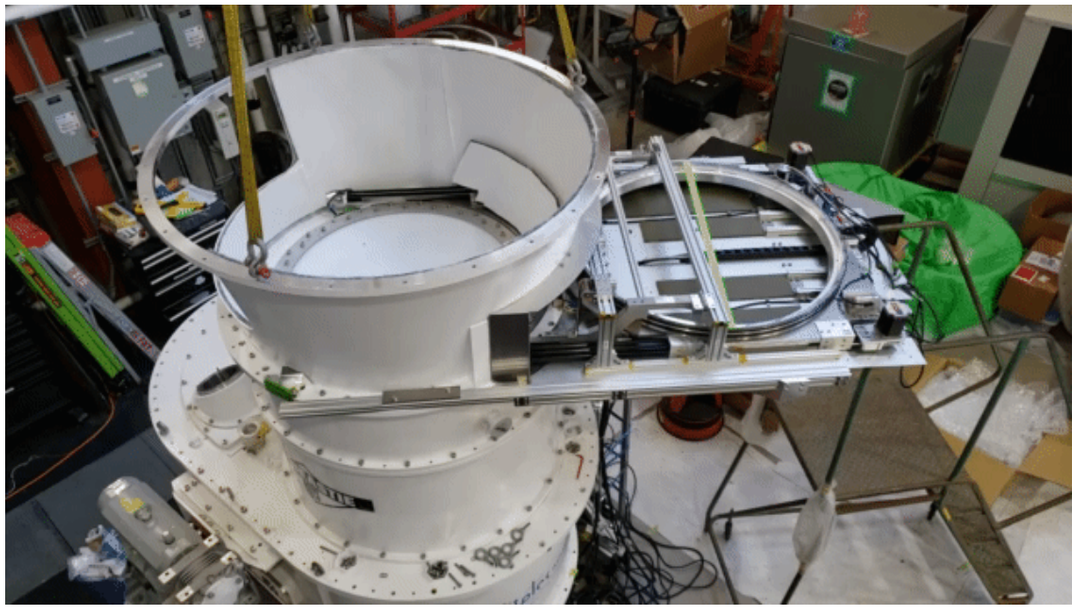
fsky ~ 10%





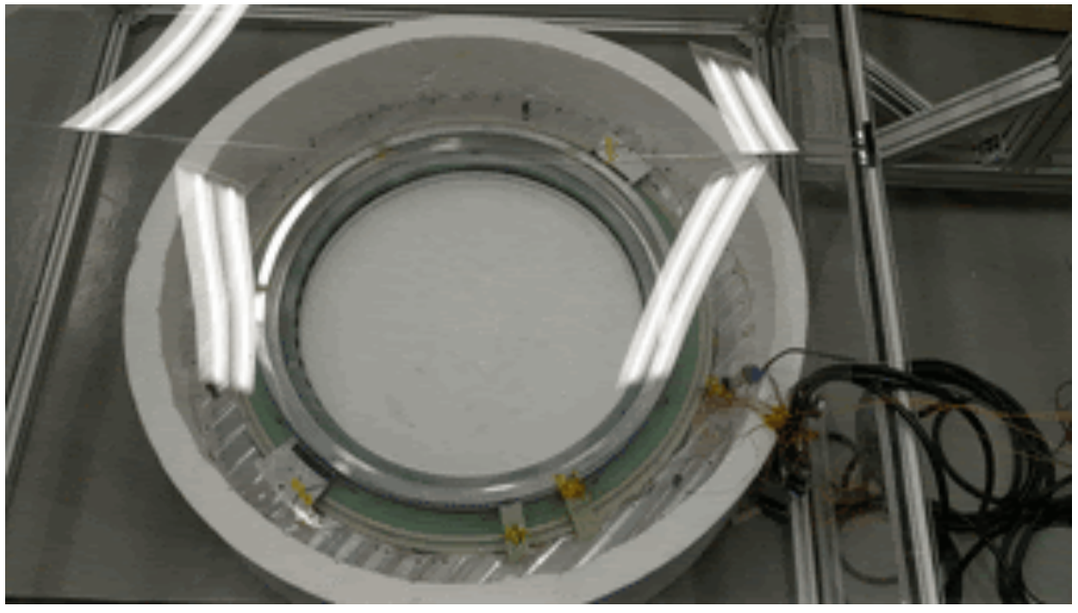


control of instrumental systematics effects: examples



credits: H. Nakata

Polarization grid for relative and absolute polarization angle calibration



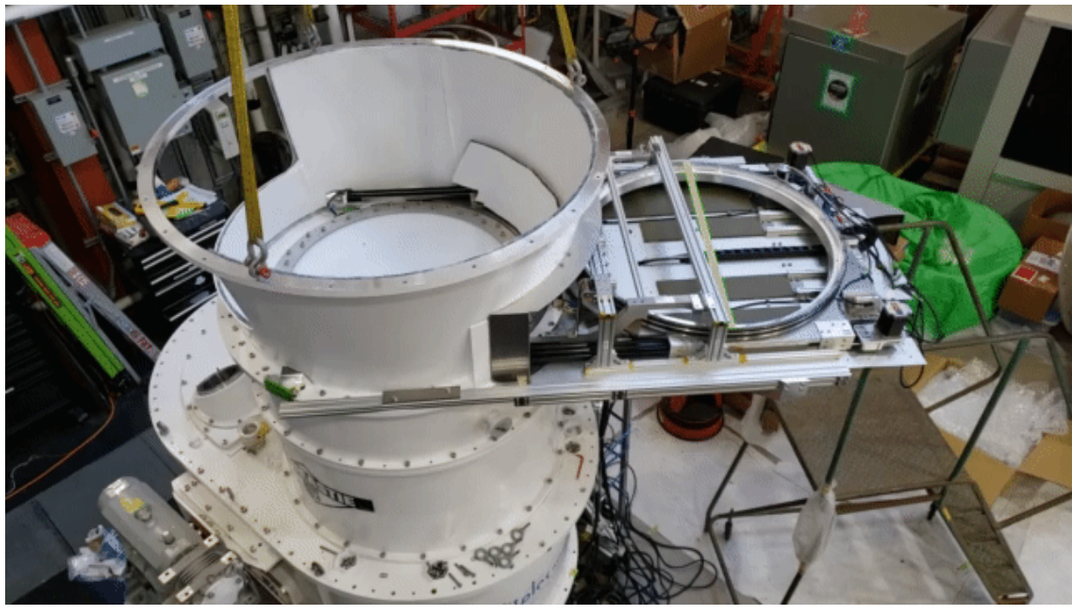
credits: J. Sugiyama

Cryogenic Rotative Half Wave Plate

credits: T. Matsumura

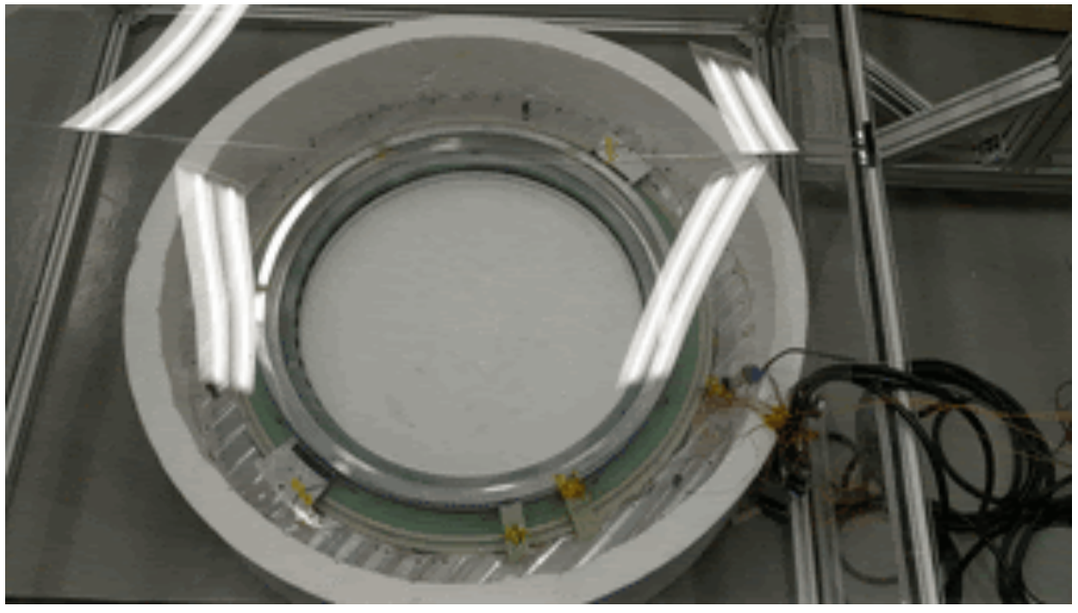
Assembly of Baffles

control of instrumental systematics effects: examples



credits: H. Nakata

Polarization grid for relative and absolute polarization angle calibration



credits: J. Sugiyama

Cryogenic Rotative Half Wave Plate

credits: T. Matsumura

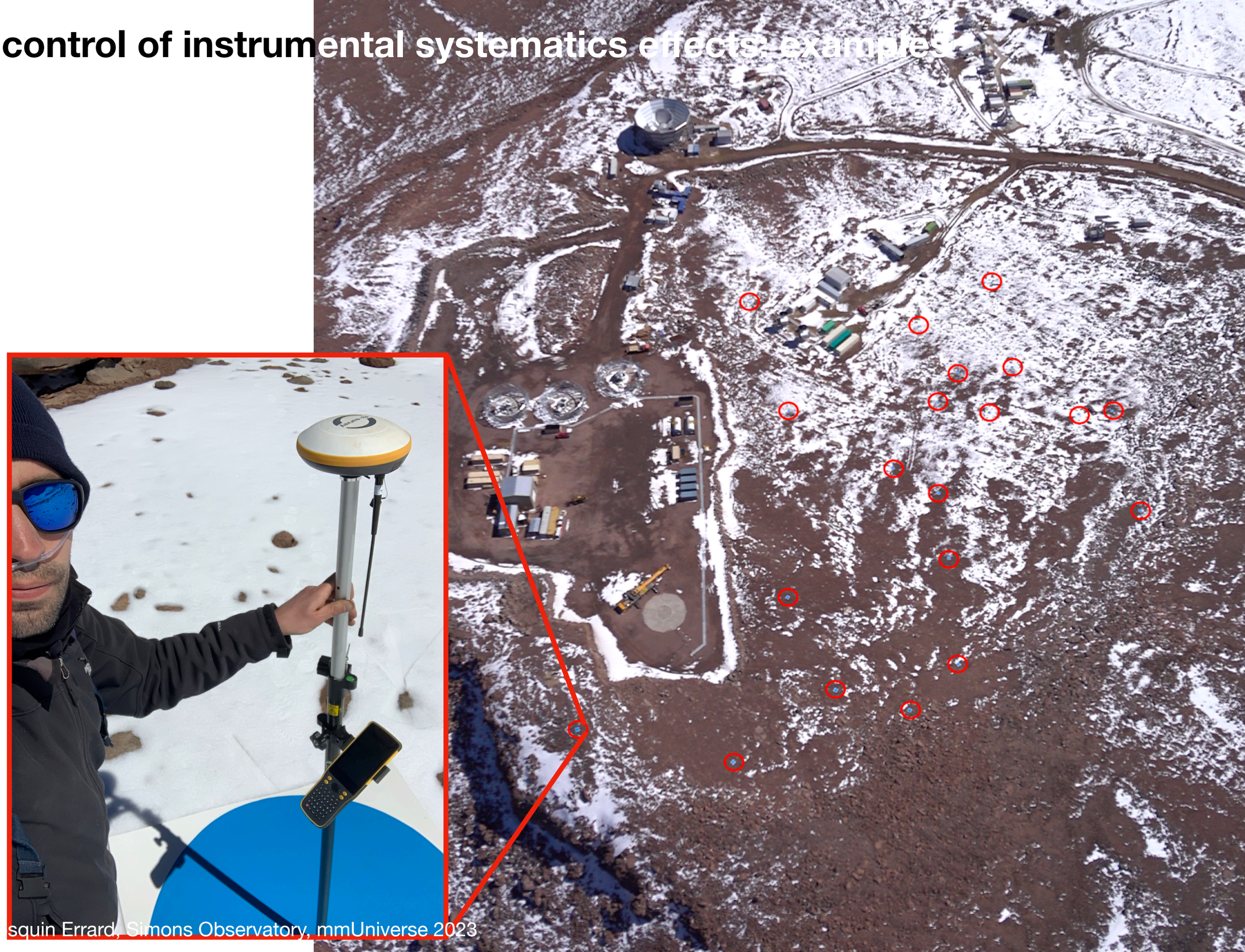
Assembly of Baffles

control of instrumental systematics effects: examples

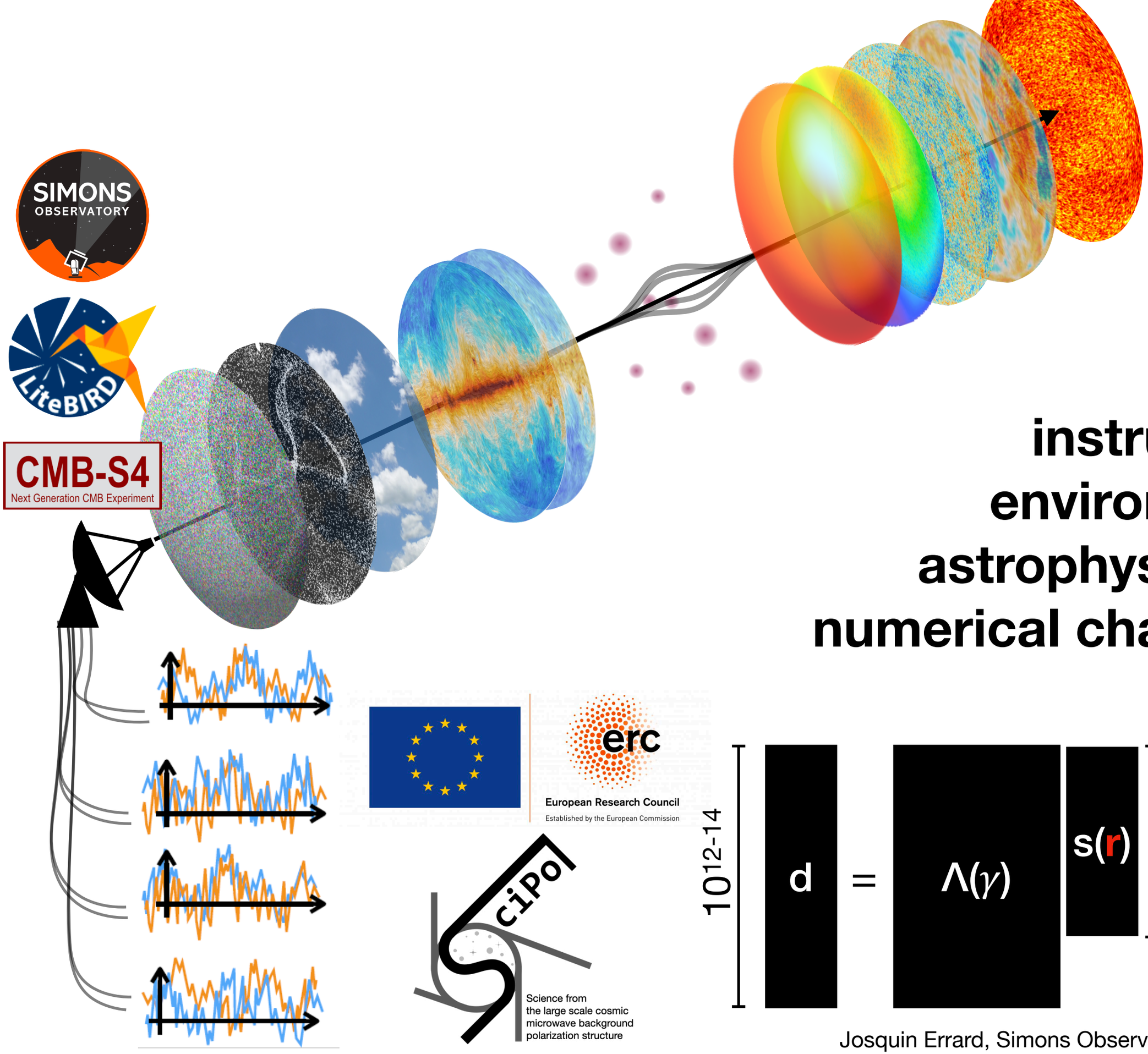
prototype calibration source flying on a drone above CLASS in Feb 2023

see talk by **Gabriele Coppi** this Thursday!

control of instrumental systematics effects: examples



squin Errard, Simons Observatory, mmUniverse 2023

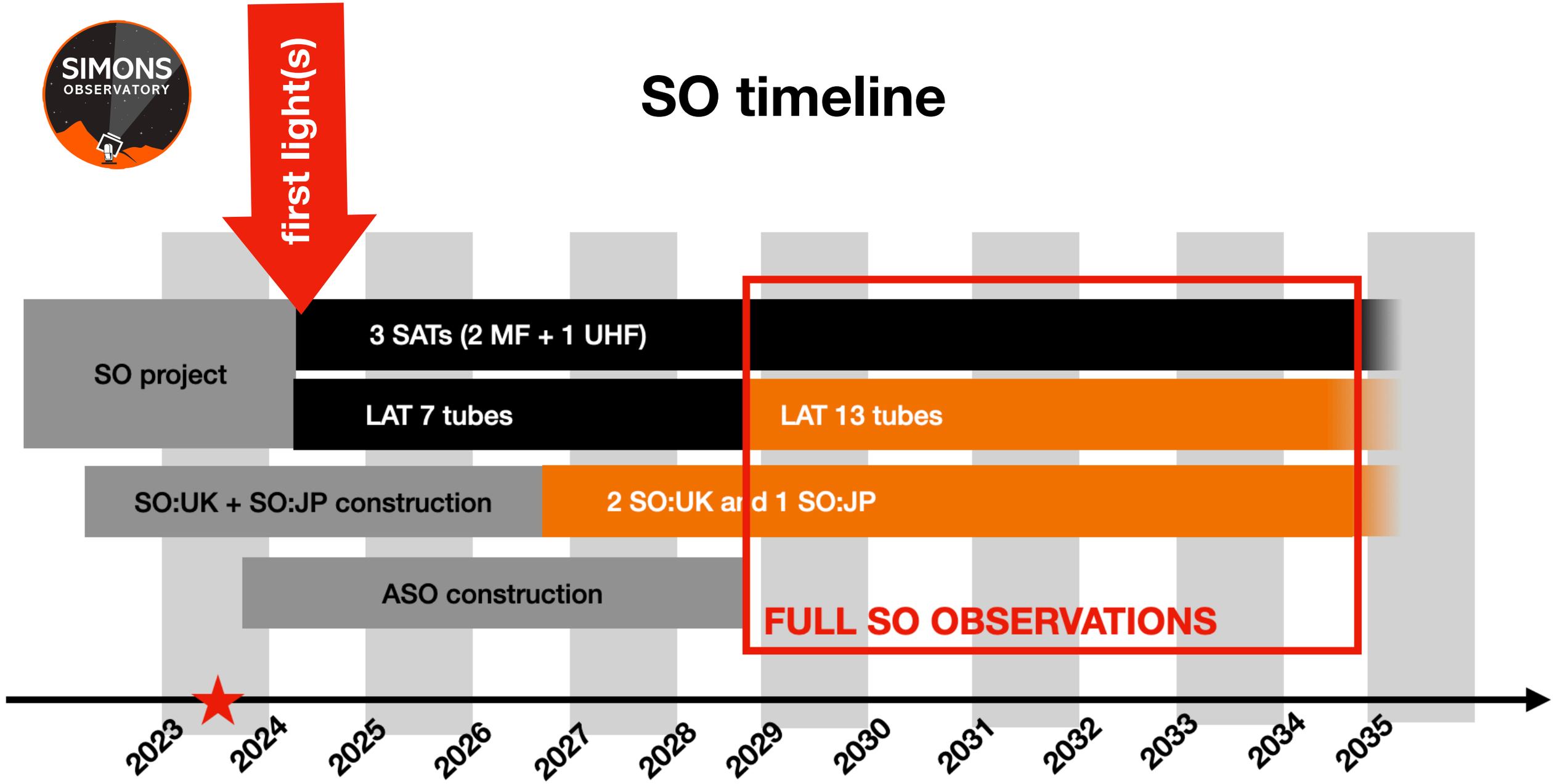


instrumental, environmental, astrophysical and numerical challenges!

$$\underbrace{\mathbf{d}}_{10^{12\text{-}14}} = \Lambda(\gamma)\,\underbrace{\mathbf{s}(\mathbf{r})}_{10^{7}} + \mathbf{n}$$

Josquin Errard, Simons Observatory, mmUniverse 2023

SO timeline



Stay Tuned!