SO Science Goals and Forecasts: 1808.07445

see also 2018 SPIE papers

https://simonsobservatory.org/publications.php

Colin Hill (IAS/CCA)

on behalf of the Simons Observatory Collaboration

CMB Foregrounds for B-mode Studies

Tenerife, Spain

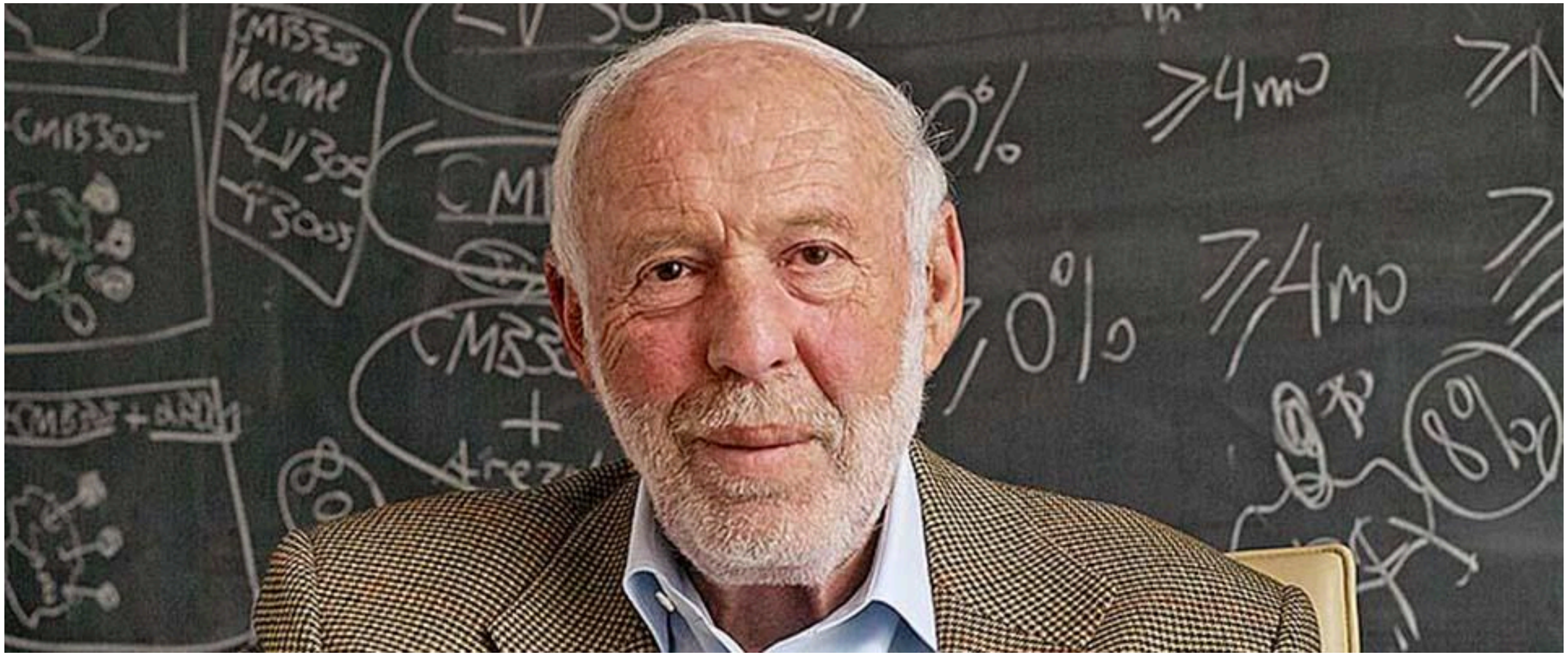
15 October 2018

Colin Hill
IAS/CCA

SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION

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



The Simons Observatory Collaboration

United States

- Arizona State University
- Carnegie Mellon University
- Center for Computational Astrophysics
- Cornell University
- Florida State
- Haverford College
- Lawrence Berkeley National Laboratory
- NASA/GSFC
- NIST
- Princeton University
- Rutgers University
- Stanford University/SLAC
- Stony Brook
- University of California - Berkeley
- University of California – San Diego
- University of Michigan
- University of Pennsylvania
- University of Pittsburgh
- University of Southern California
- West Chester University
- Yale University

Japan

- KEK
- IPMU
- Tohoku
- Tokyo

- **10 Countries**
- **40+ Institutions**
- **160+ Researchers** → **~200**

Canada

- CITA/Toronto
- Dunlap Institute/Toronto
- McGill University
- Simon Fraser University
- University of British Columbia

Chile

- Pontificia Universidad Catolica
- University of Chile

Europe

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

South Africa

- Kwazulu-Natal, SA

Australia

- Melbourne

Middle East

- Tel Aviv

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- Imperial College
- Manchester University
- Oxford University
- SISSA – Italy
- University of Sussex

South Africa

- Kwazulu-Natal, SA

Australia

- Melbourne

Middle East

- Tel Aviv

Simons Observatory Science Goals and Probes

Colin Hill
IAS/CCA

primordial fluctuations

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

damping tail
→ primordial power on small scales (TE, TT, EE)
→ primordial bispectrum (f_{NL} via TTT,TTE,… + lens/kSZ)

relativistic species

damping tail
→ N_{eff} (TE, TT, EE)

reionization

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

neutrino mass

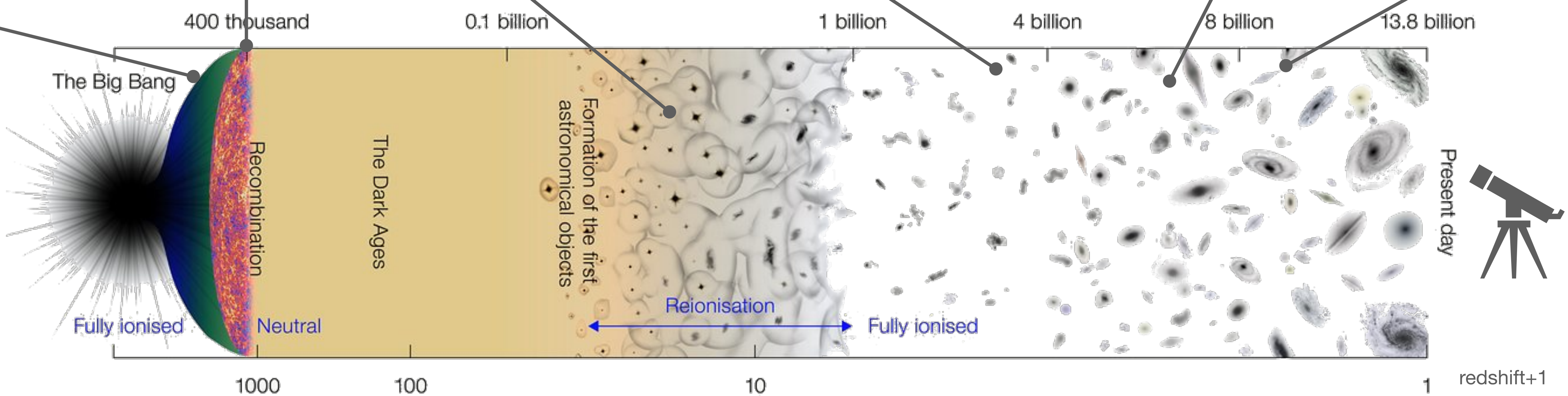
lensing potential (TT+EB), tSZ
→ Σm_ν

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

Additional science includes (but is not limited to):

- helium fraction, cosmic birefringence, primordial magnetic fields
- high-redshift clusters
- dark matter annihilation and interactions
- isocurvature
- calibration of multiplicative shear bias (e.g., for LSST)
- new sample of dusty star-forming galaxies
- transient sources
- cosmic infrared background

THE SIMONS OBSERVATORY: SCIENCE GOALS AND FORECASTS

1808.07445

Simons Observatory Site

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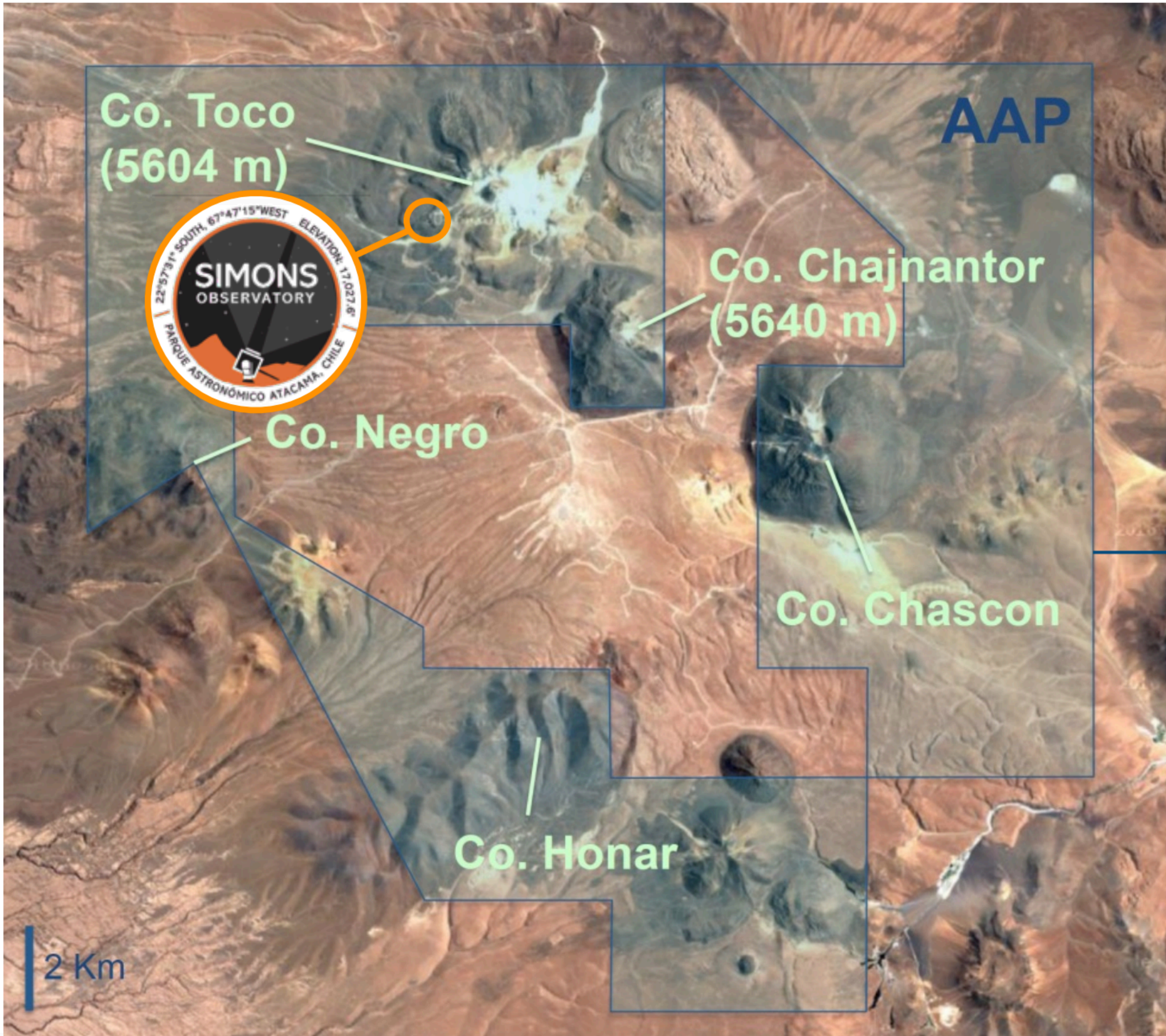
IAS/CCA



Parque Astronómico Atacama

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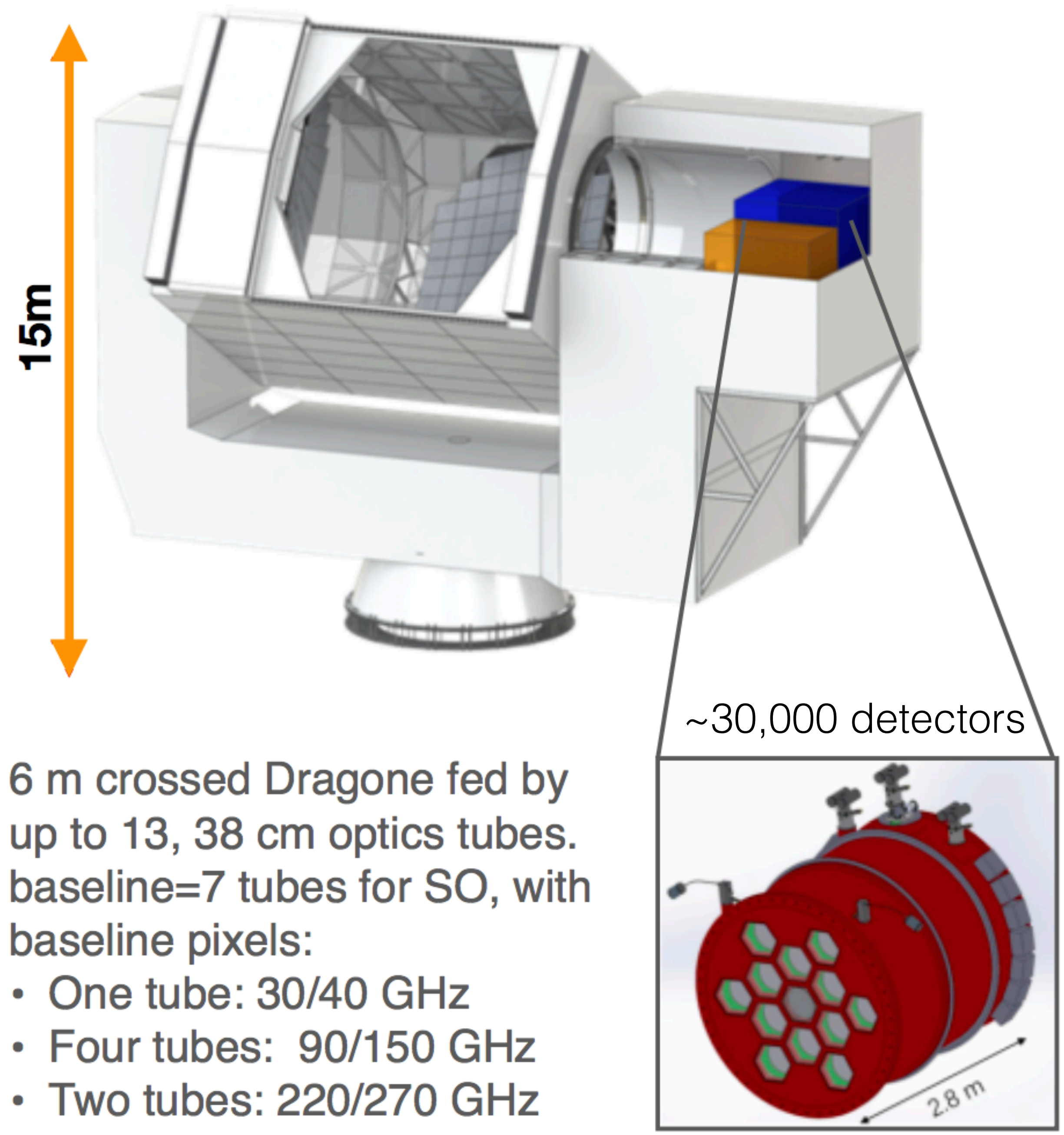
Simons Observatory Instruments & Technology

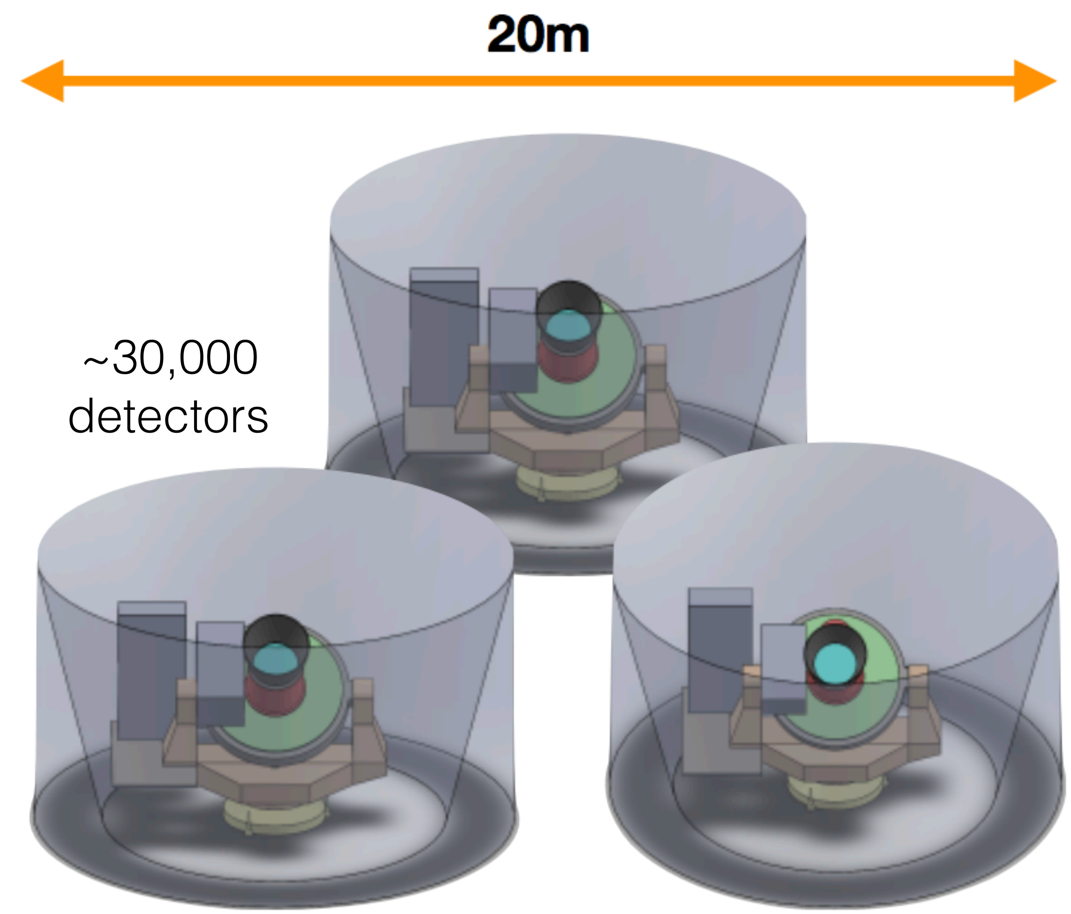
large aperture telescope



6 m crossed Dragone fed by up to 13, 38 cm optics tubes. baseline=7 tubes for SO, with baseline pixels:

- One tube: 30/40 GHz
- Four tubes: 90/150 GHz
- Two tubes: 220/270 GHz

small aperture telescopes



Three 42 cm diameter refractors, baseline dichroic pixels:
30/40 I 90/150 I 90/150 I 220/270 GHz

FIRST LIGHT IN 2021

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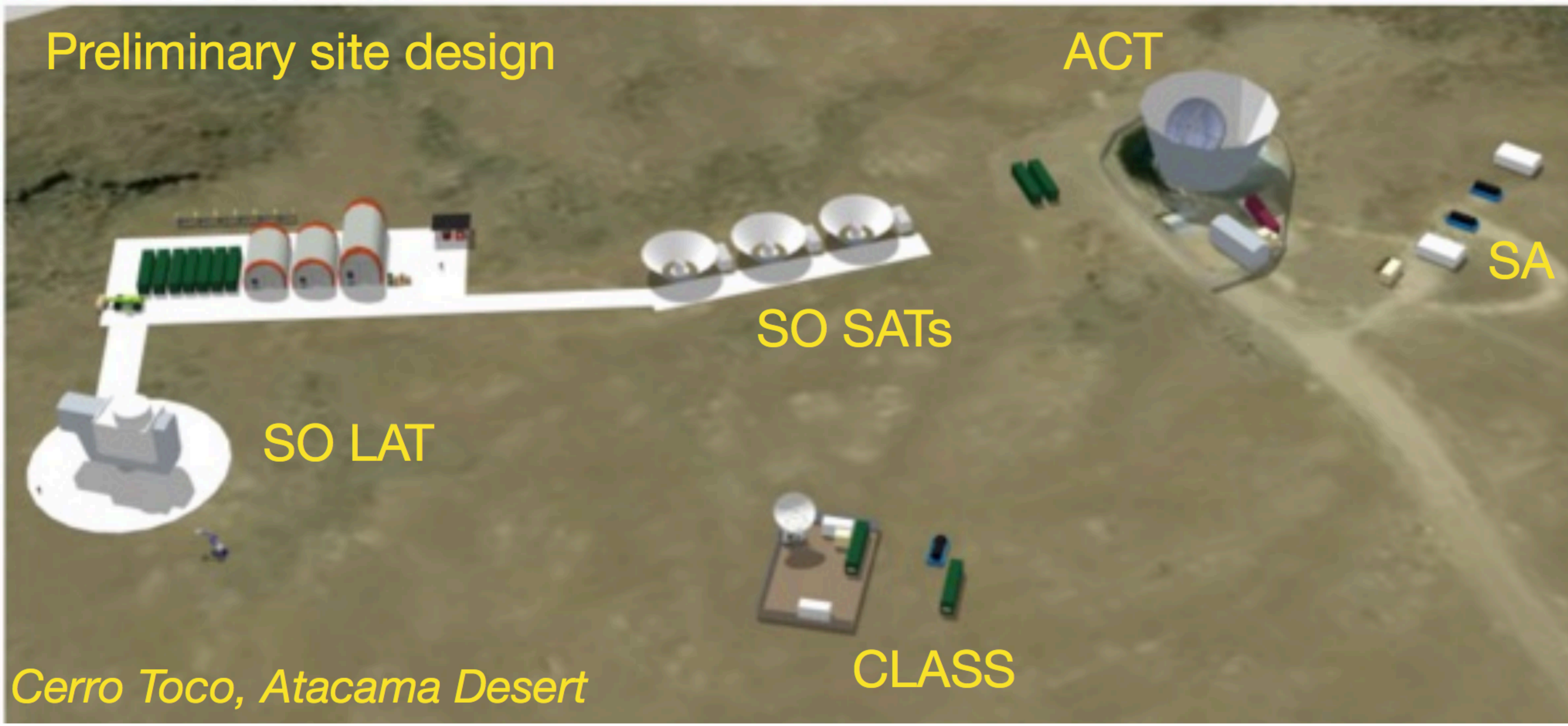
Simons Observatory Layout

One 6m Large Aperture Telescope
Three 0.5m Small Aperture Telescopes
Five-year survey planned 2021-26, six frequencies 30-280 GHz



Large telescope: resolution needed for all science goals except tensor-to-scalar ratio
Small telescopes: lower noise at the few-degree-scale B-mode signal, for tensor-to-scalar ratio

Anticipated Noise Performance

Colin Hill
IAS/CCA

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

White noise levels for 5-yr survey; also include atmospheric noise model and combine with Planck

Anticipated Noise Performance (LAT)

Colin Hill
IAS/CCA

	Freq. [GHz]	SATs ($f_{\rm sky} = 0.1$) FWHM ($'$)	SATs Noise (baseline) [μK-arcmin]	SATs Noise (goal) [μK-arcmin]	LAT ($f_{\rm sky} = 0.4$) FWHM ($'$)	LAT Noise (baseline) [μK-arcmin]	LAT Noise (goal) [μK-arcmin]
LF	27	91	35	25	7.4	71	52
	39	63	21	17	5.1	36	27
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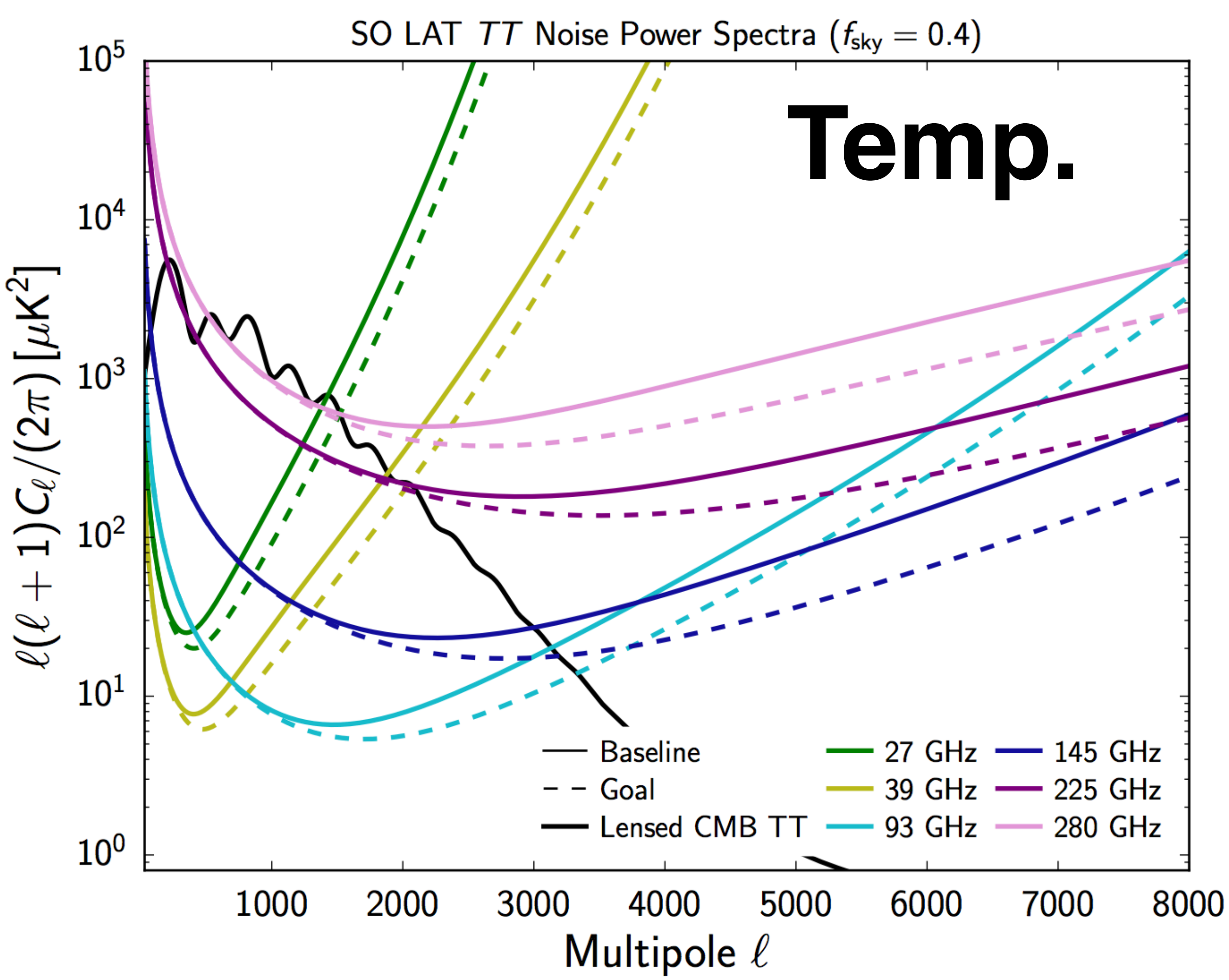

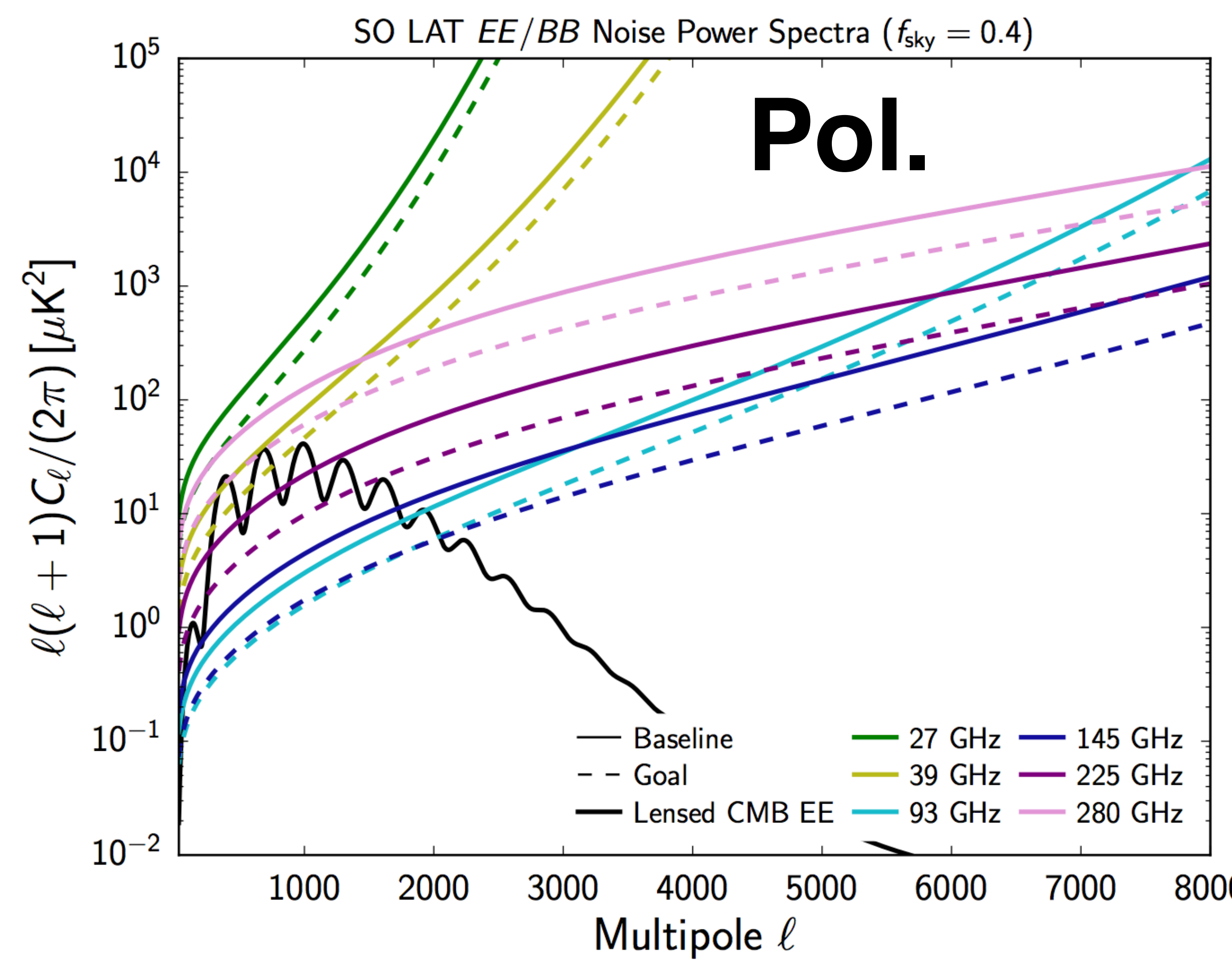

Anticipated Noise Performance (SATs)

Colin Hill
IAS/CCA

	Freq. [GHz]	SATs ($f_{sky} = 0.1$) FWHM (′)	SATs Noise (baseline) [μK-arcmin]	SATs Noise (goal) [μK-arcmin]	LAT ($f_{sky} = 0.4$) FWHM (′)	LAT Noise (baseline) [μK-arcmin]	LAT Noise (goal) [μK-arcmin]
LF	27	91	35	25	7.4	71	52
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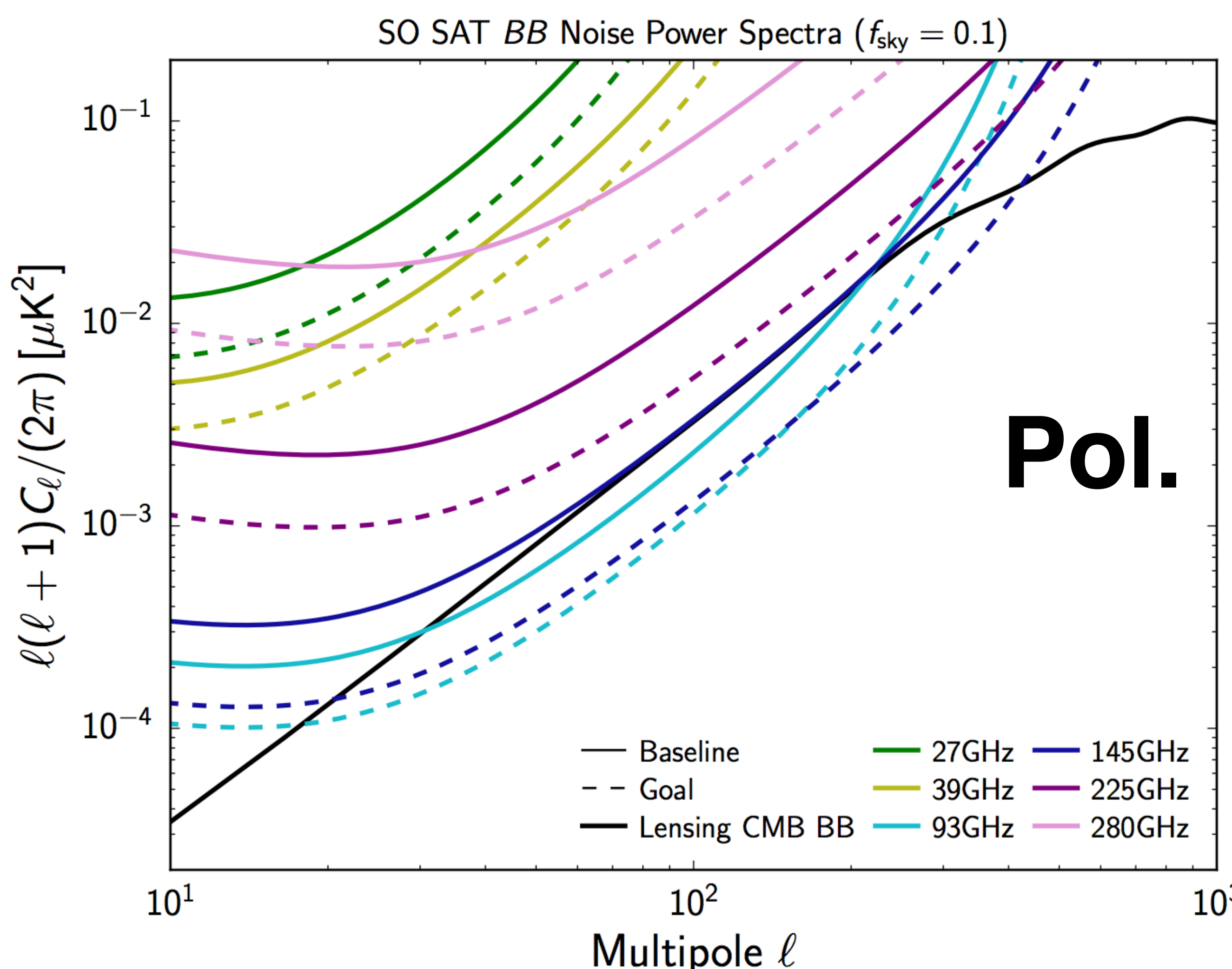
White noise levels for 5-yr survey; also include atmospheric noise model and combine with Planck



also consider two ell_{knee} cases for SATs

Anticipated Sky Coverage

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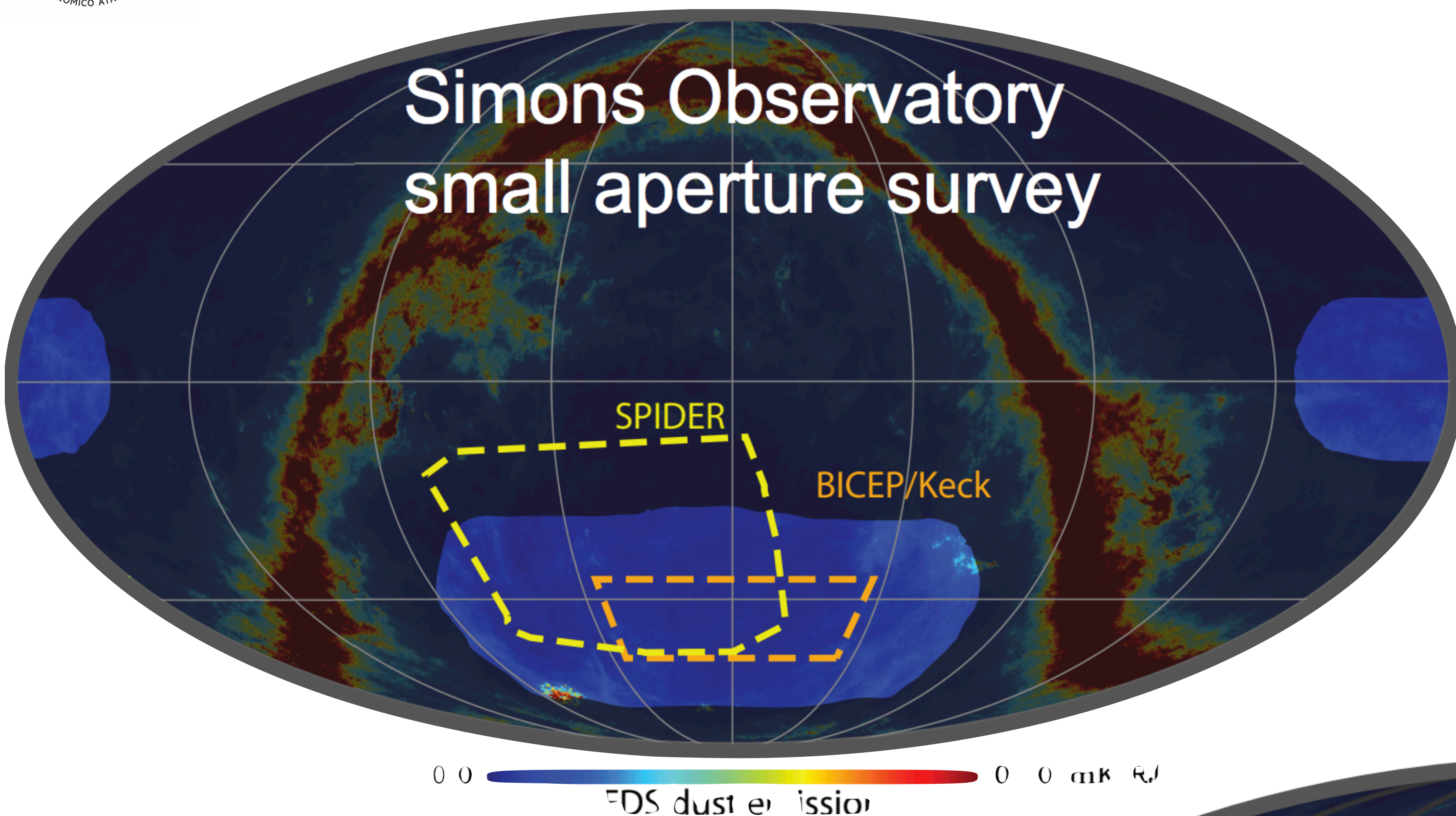
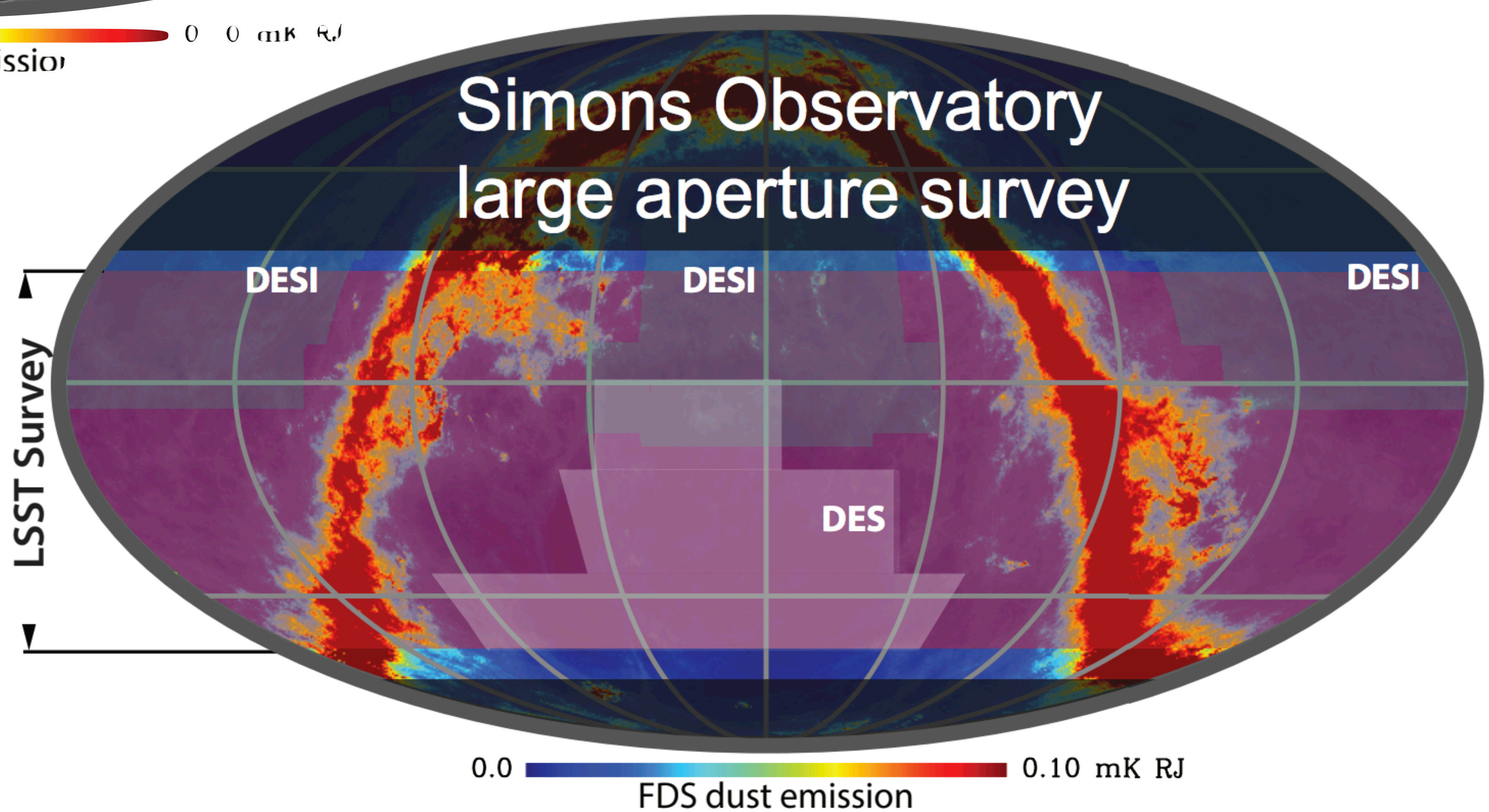
IAS/CCA



effective $f_{sky} \sim 10\%$

for SO noise and coverage, dedicated delensing survey not required



effective $f_{sky} \sim 40\%$

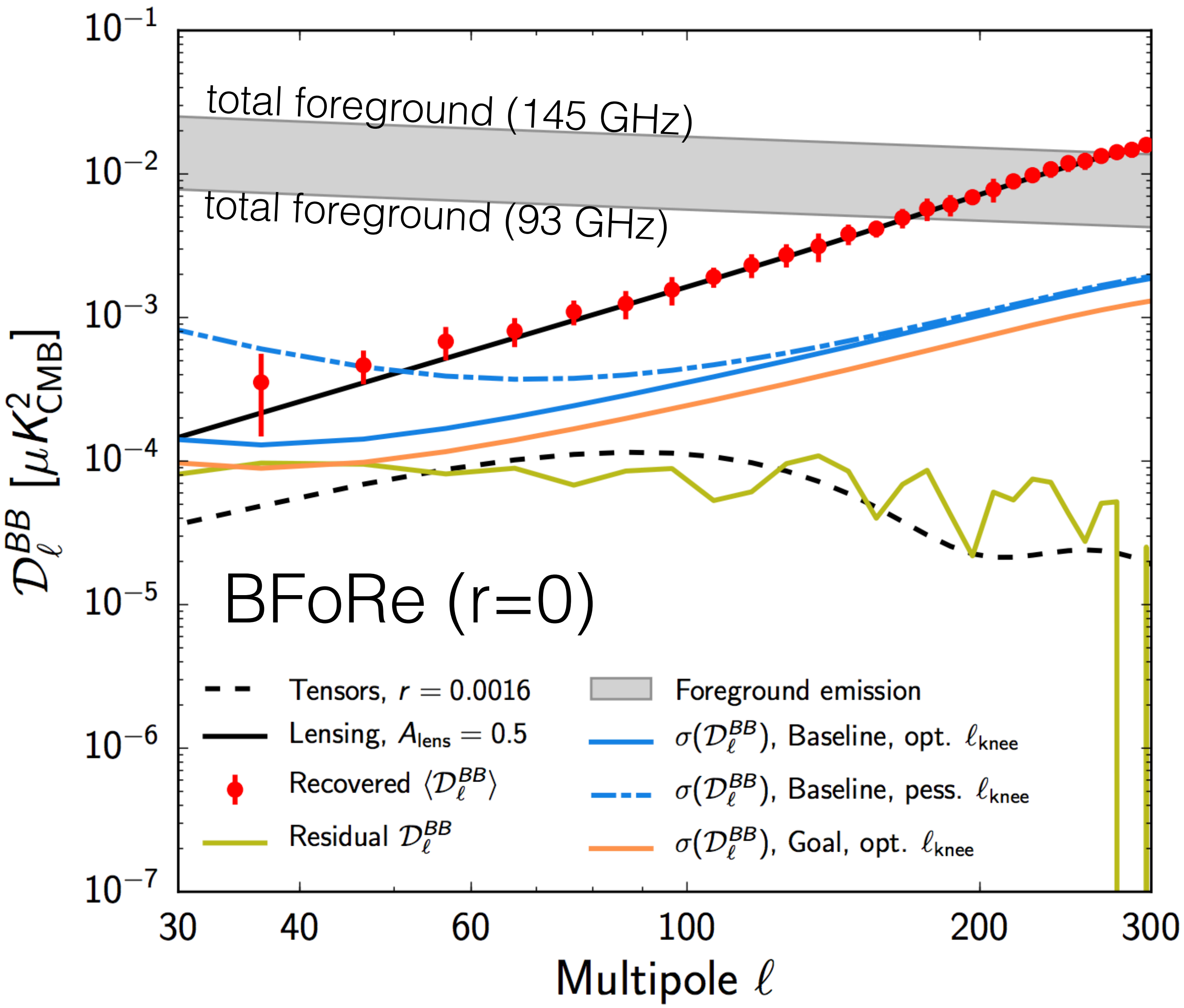
maximal overlap w/ LSST, large overlap w/ DESI

SO SAT Science: Primordial Tensor Modes

Colin Hill
IAS/CCA

SAT BB forecasting based on full-sky simulated maps (PySM) w/ multiple sets of realistic foregrounds

Sky models are combined with SO SAT noise model, then coupled to several foreground mitigation schemes (cross-spectrum analysis, xForecast, BFoRe, harmonic-space ILC) to infer *r*



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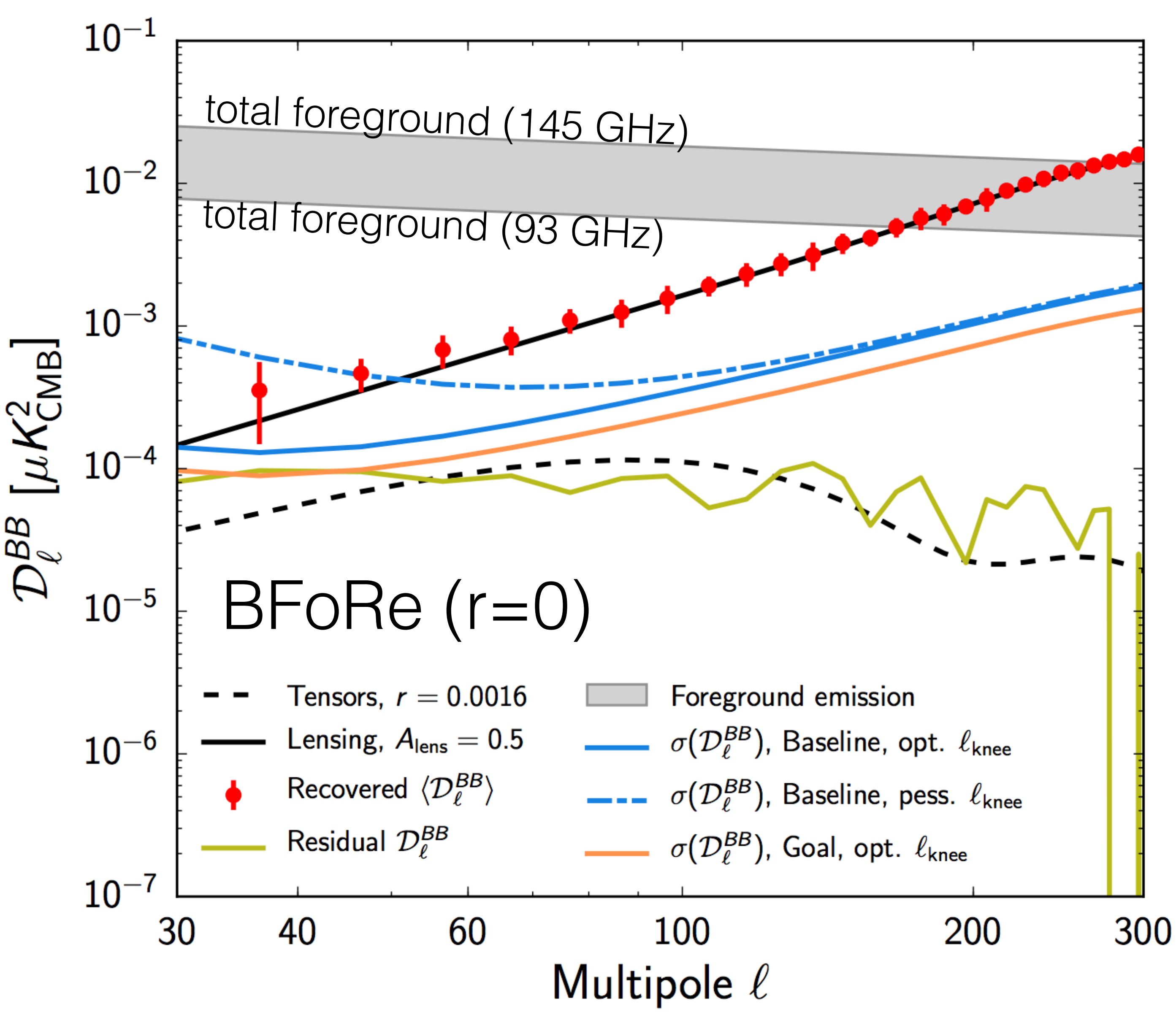
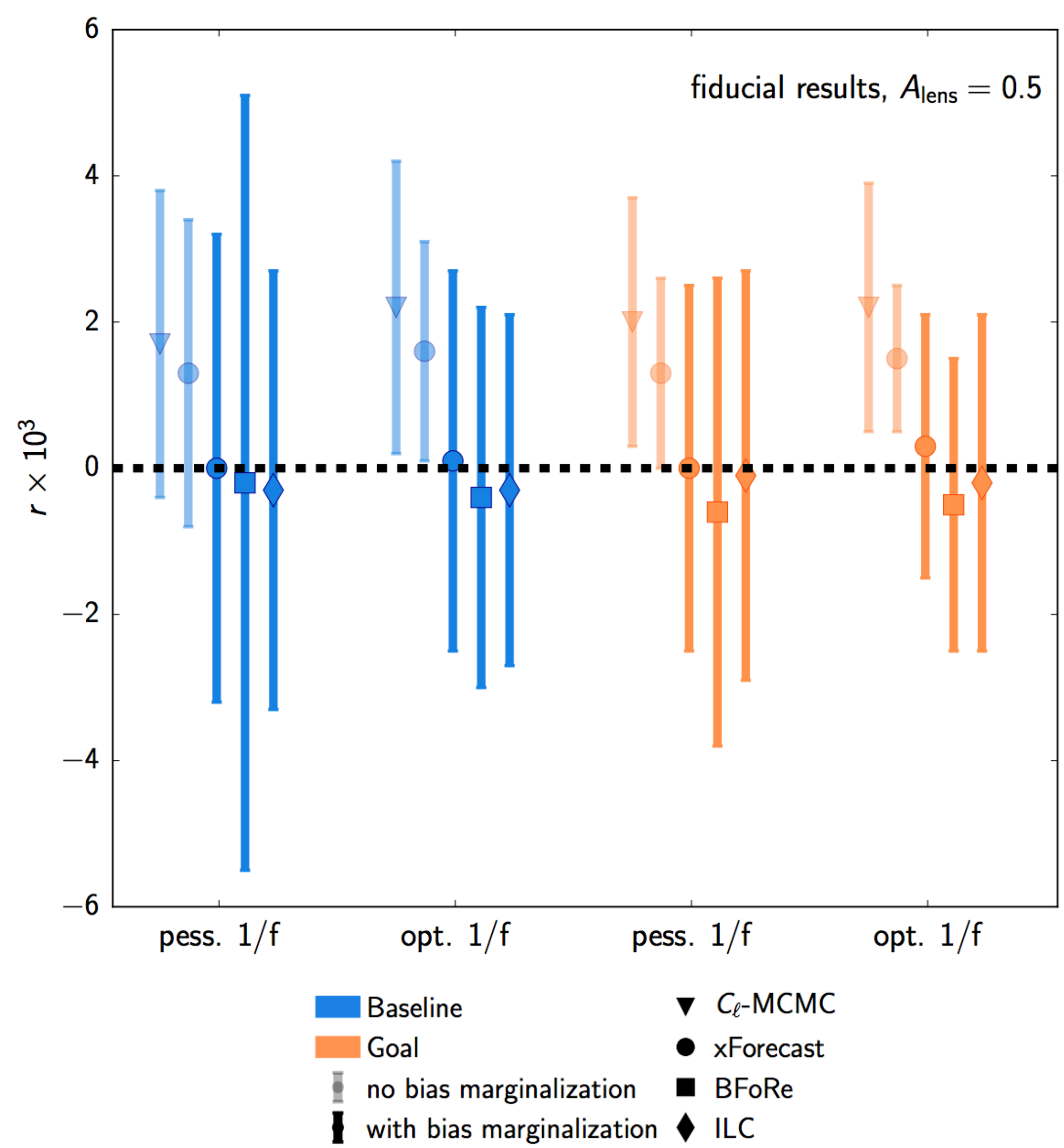
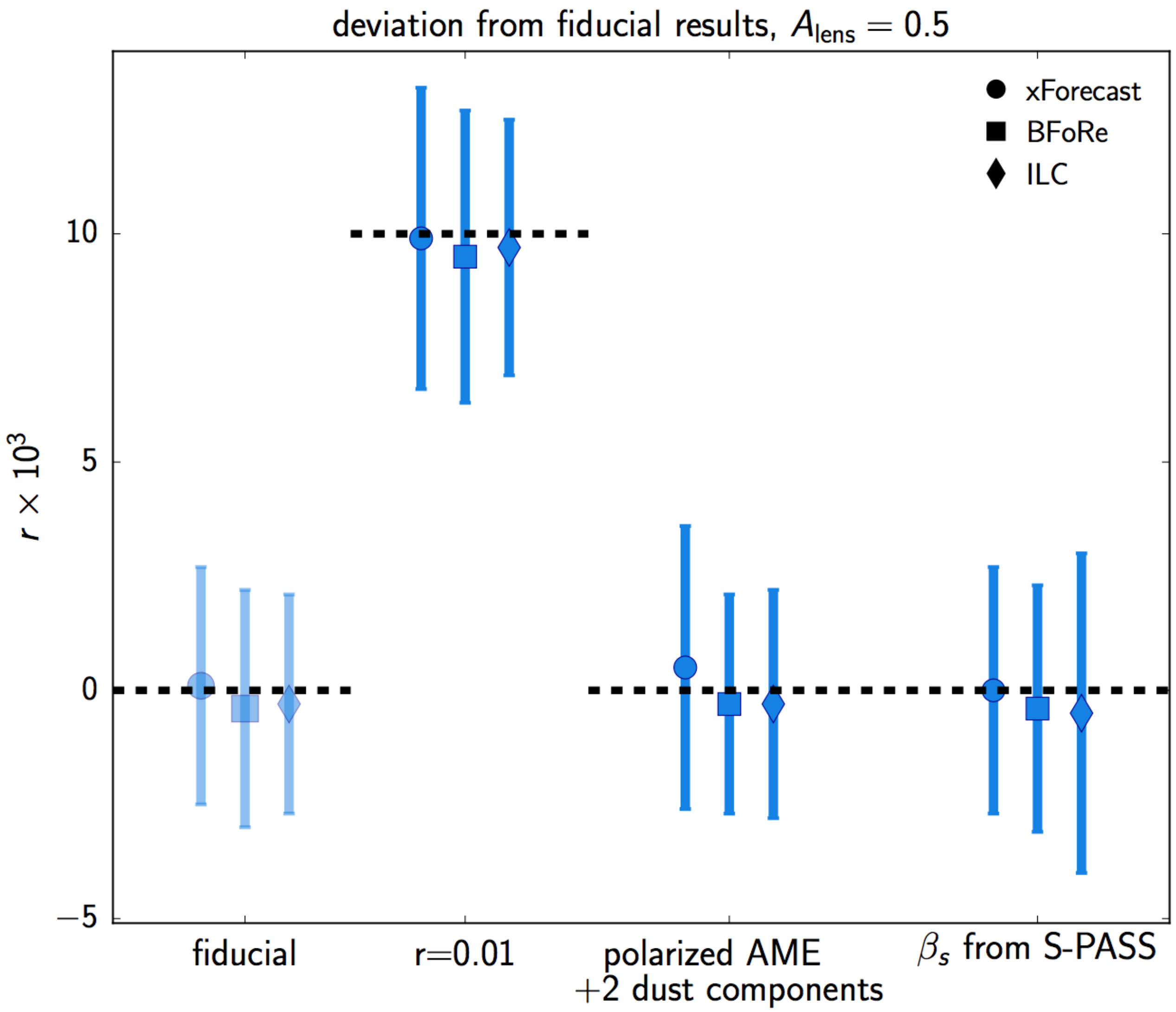




SO SAT Science: Primordial Tensor Modes

Colin Hill
IAS/CCA

Robust to variations in foreground model complexity (within the space of models explored)



SO SAT Science: Primordial Tensor Modes

Colin Hill
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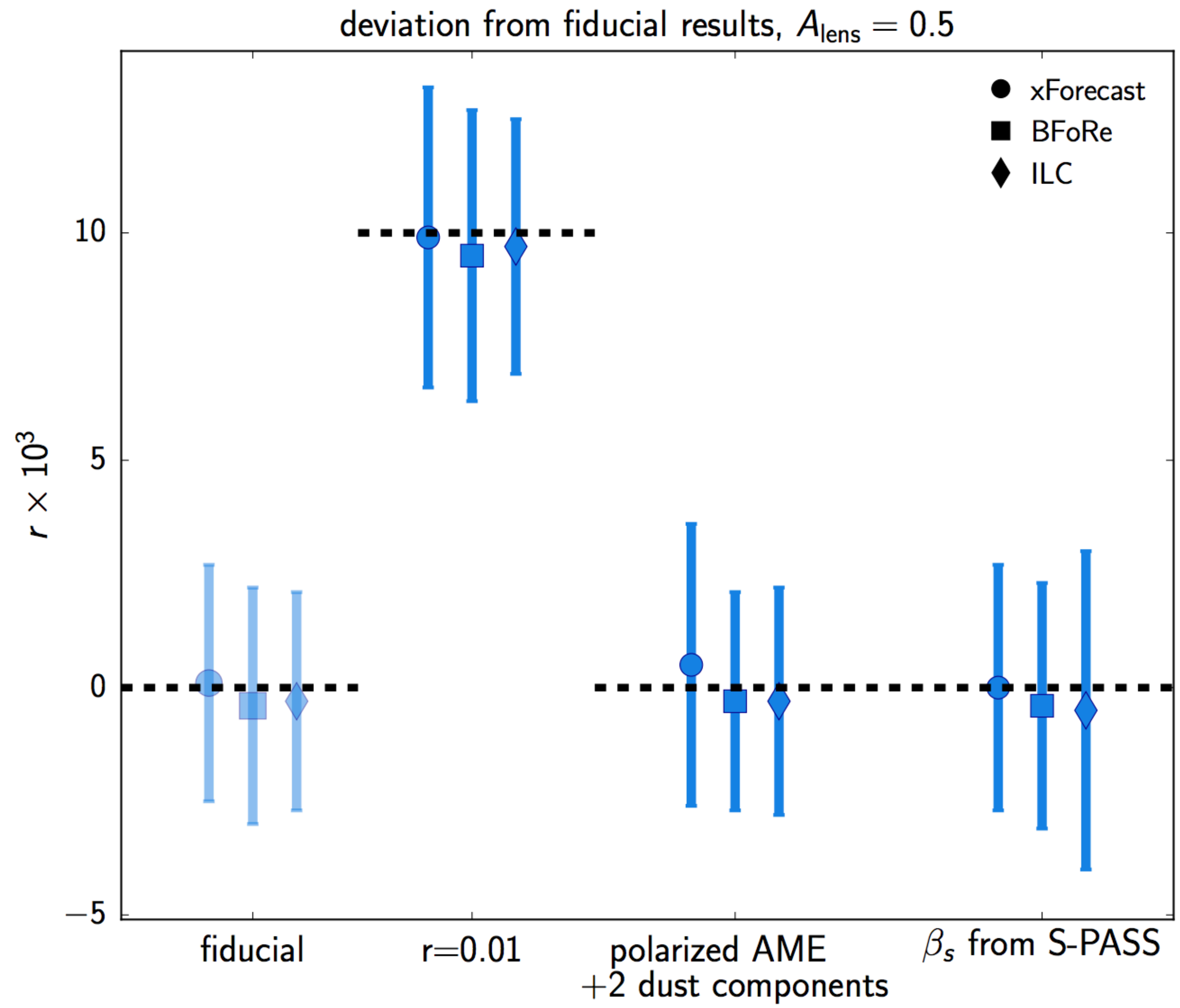
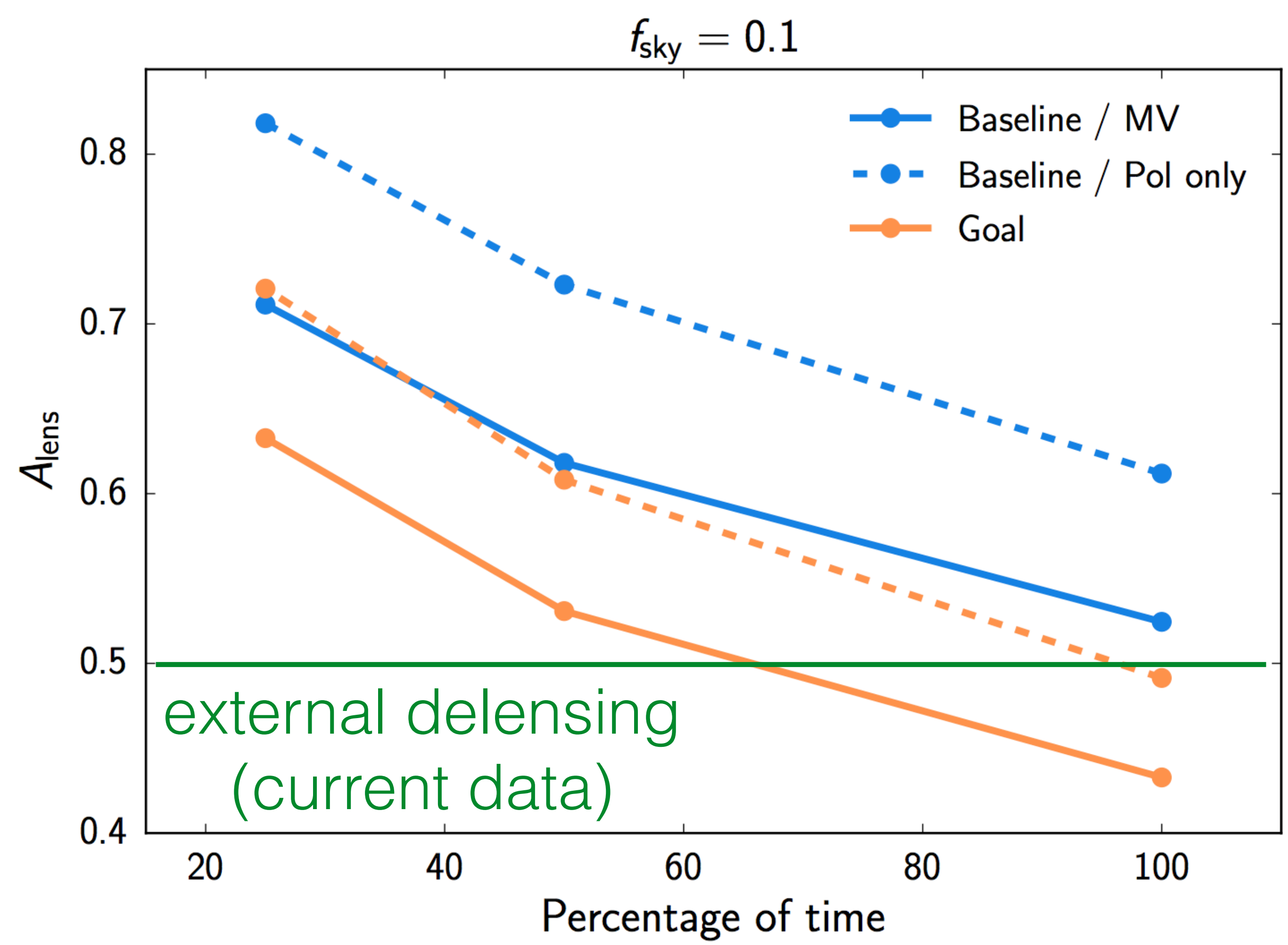


A dedicated delensing survey is not necessary; external delensing suffices

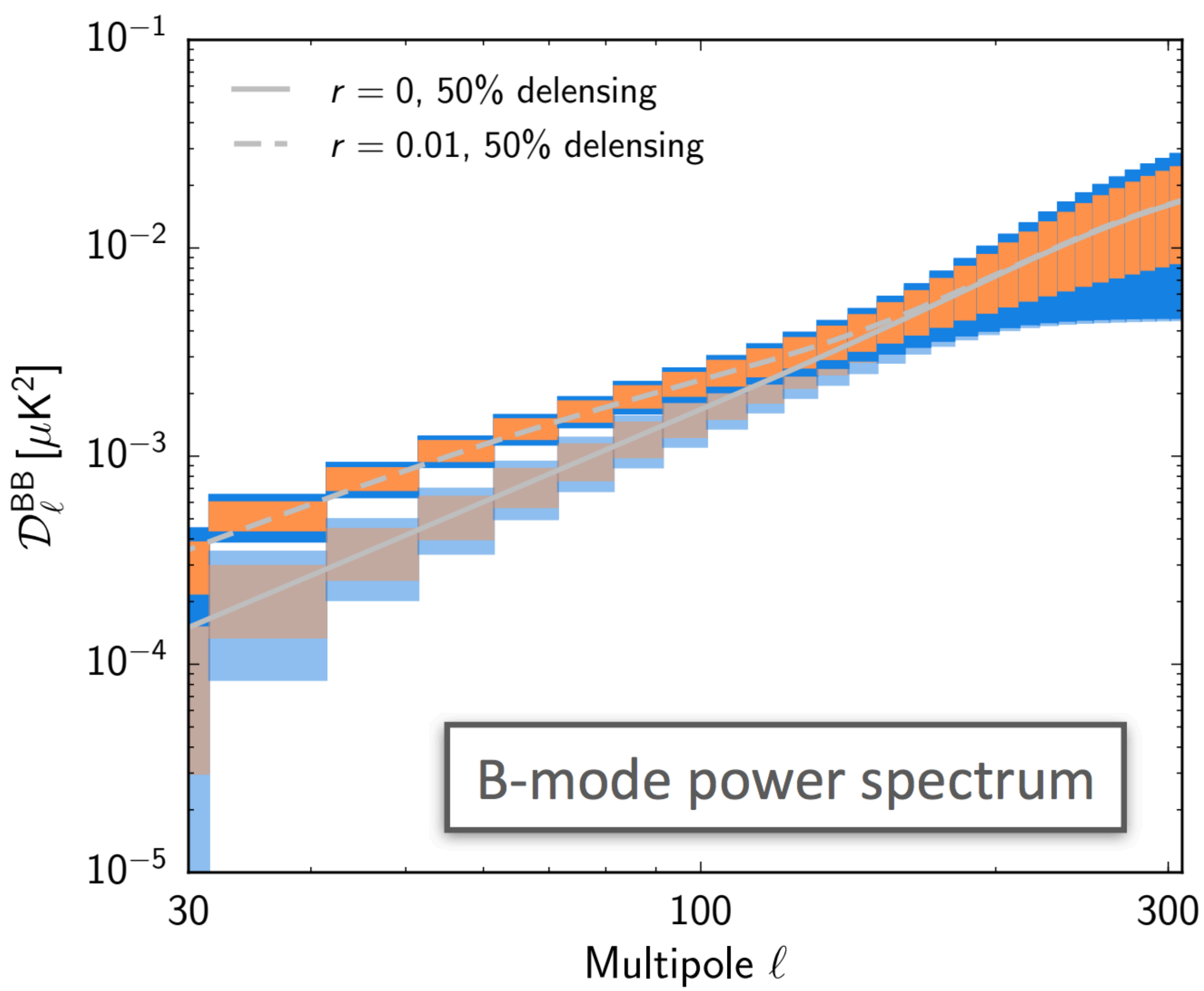


Conclusion: σ(r) = 0.003 (SO Baseline)

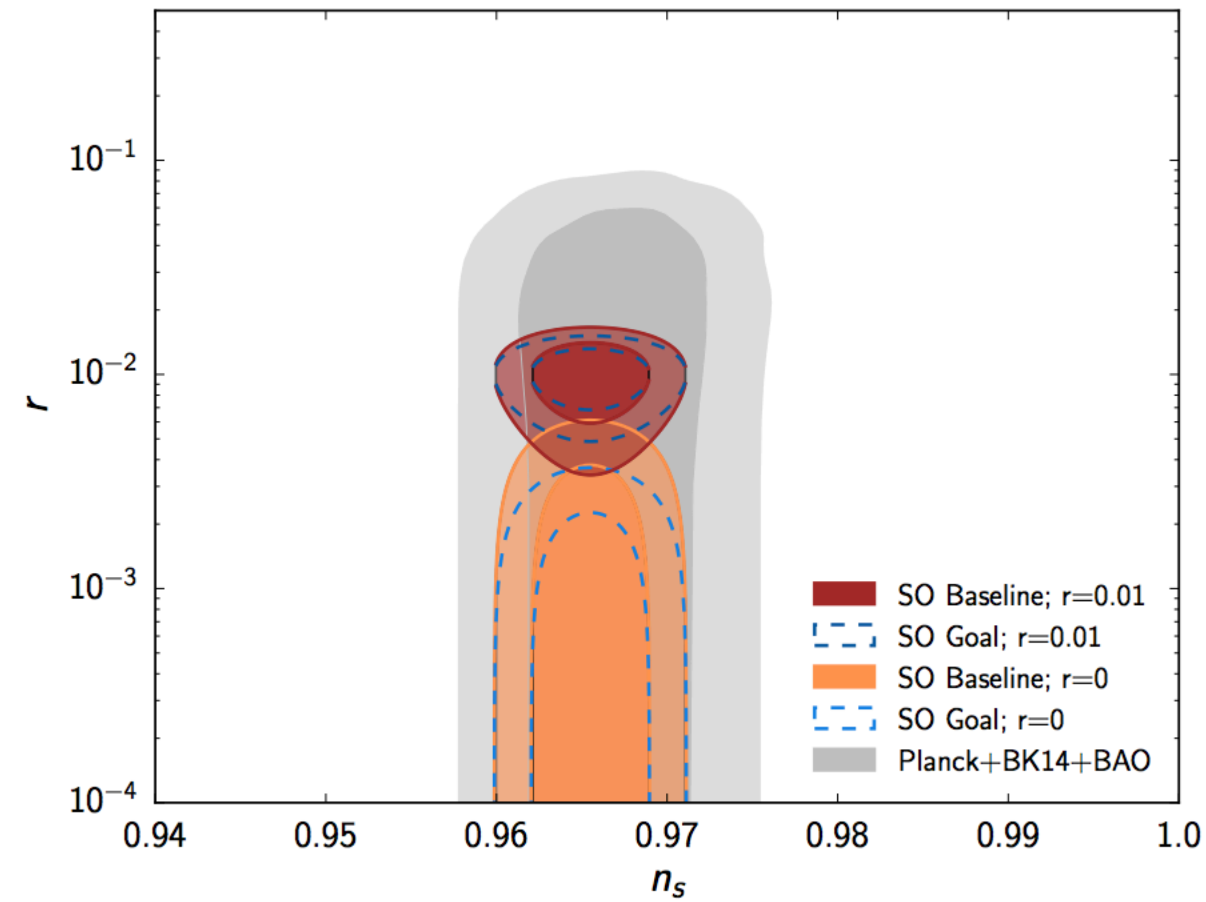
assuming r=0

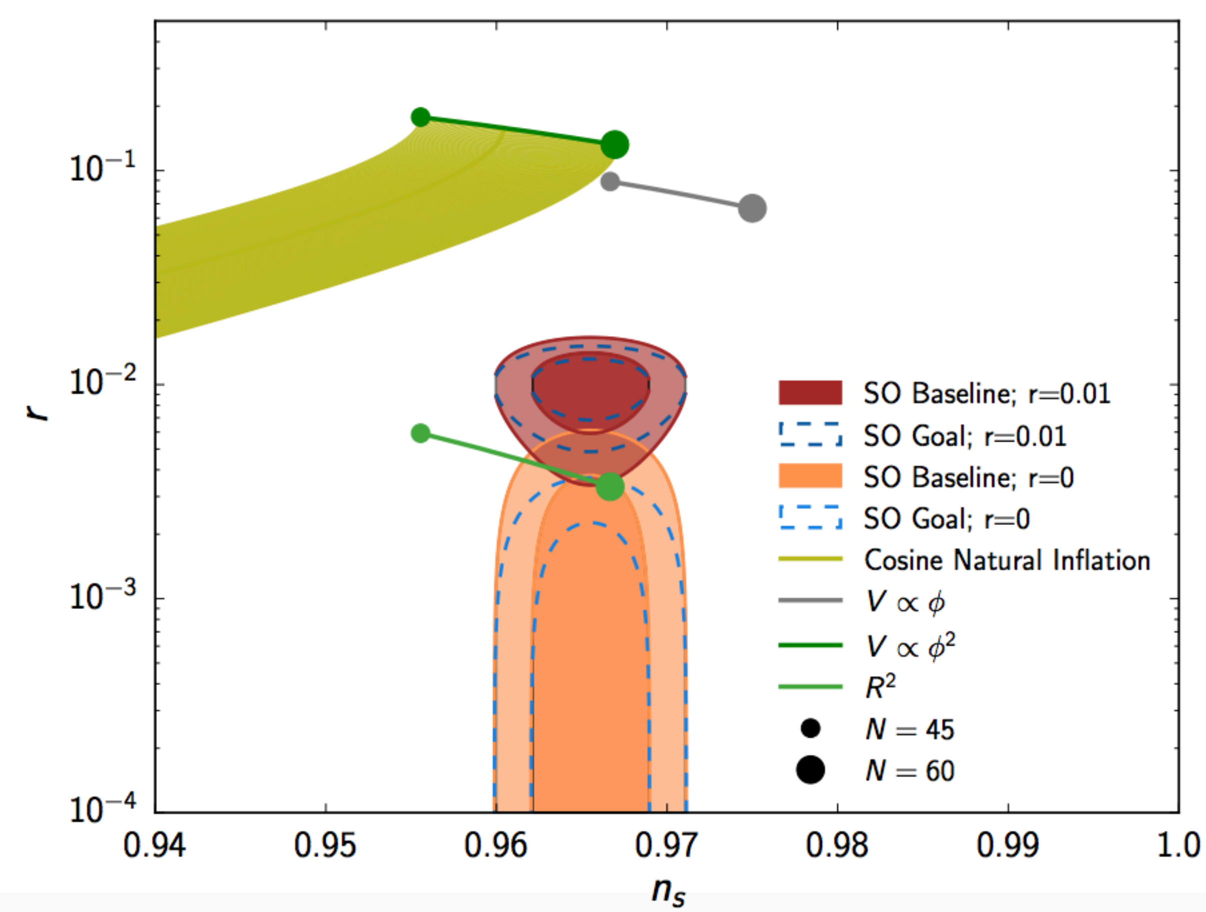
SO SAT Science: Primordial Perturbations

Colin Hill
IAS/CCA



SO will detect or rule out models with r >= 0.01 at 3σ or greater





SO LAT Forecasting Methodology

Colin Hill
IAS/CCA

LAT T forecasting based on high-resolution, full-sky simulated maps w/ realistic foregrounds and signals (e.g., correlated extragalactic fields)

LAT E/B forecasting based on simulated power spectra, calibrated to match SAT BB assumptions at degree scales

SO LAT Forecasting Methodology

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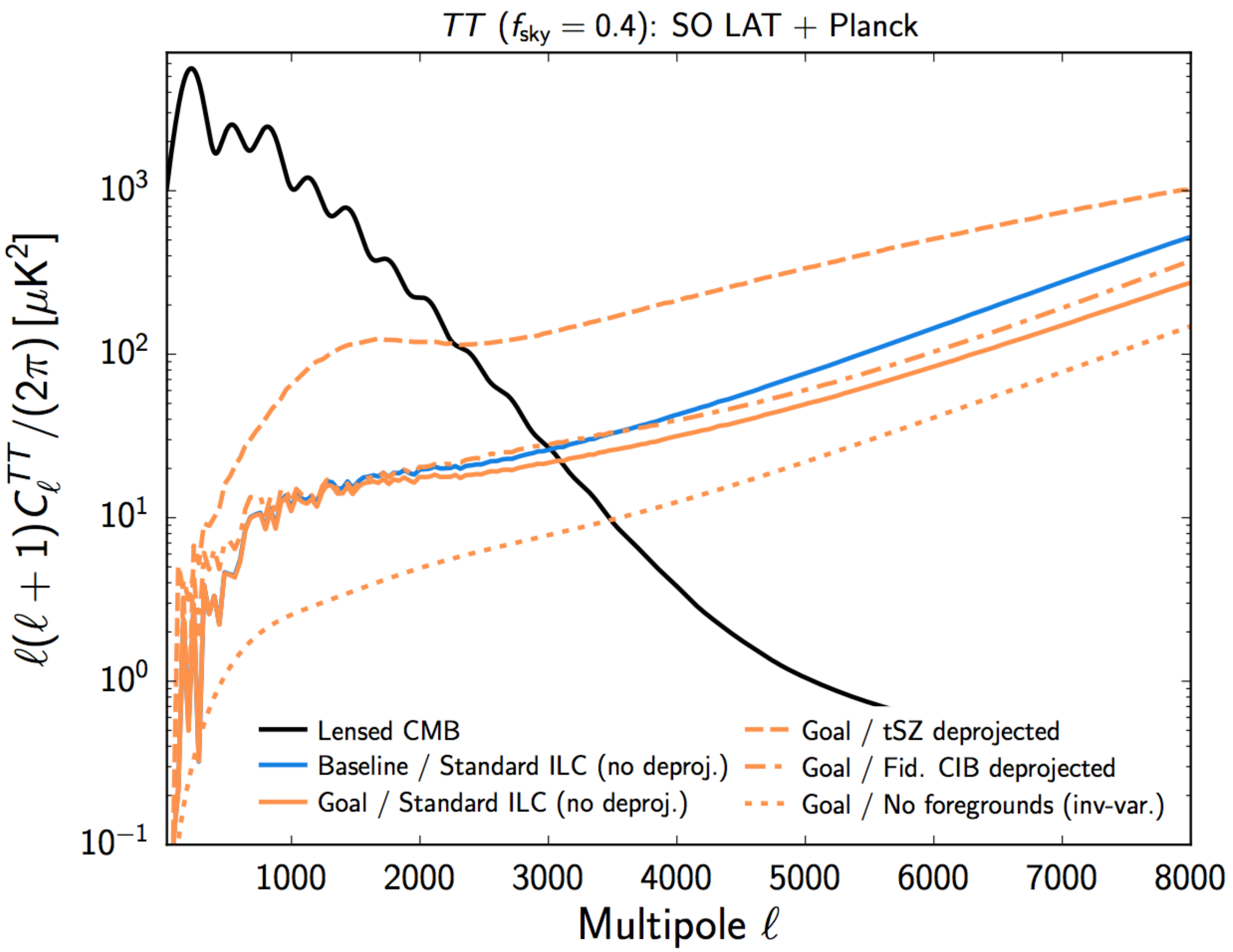
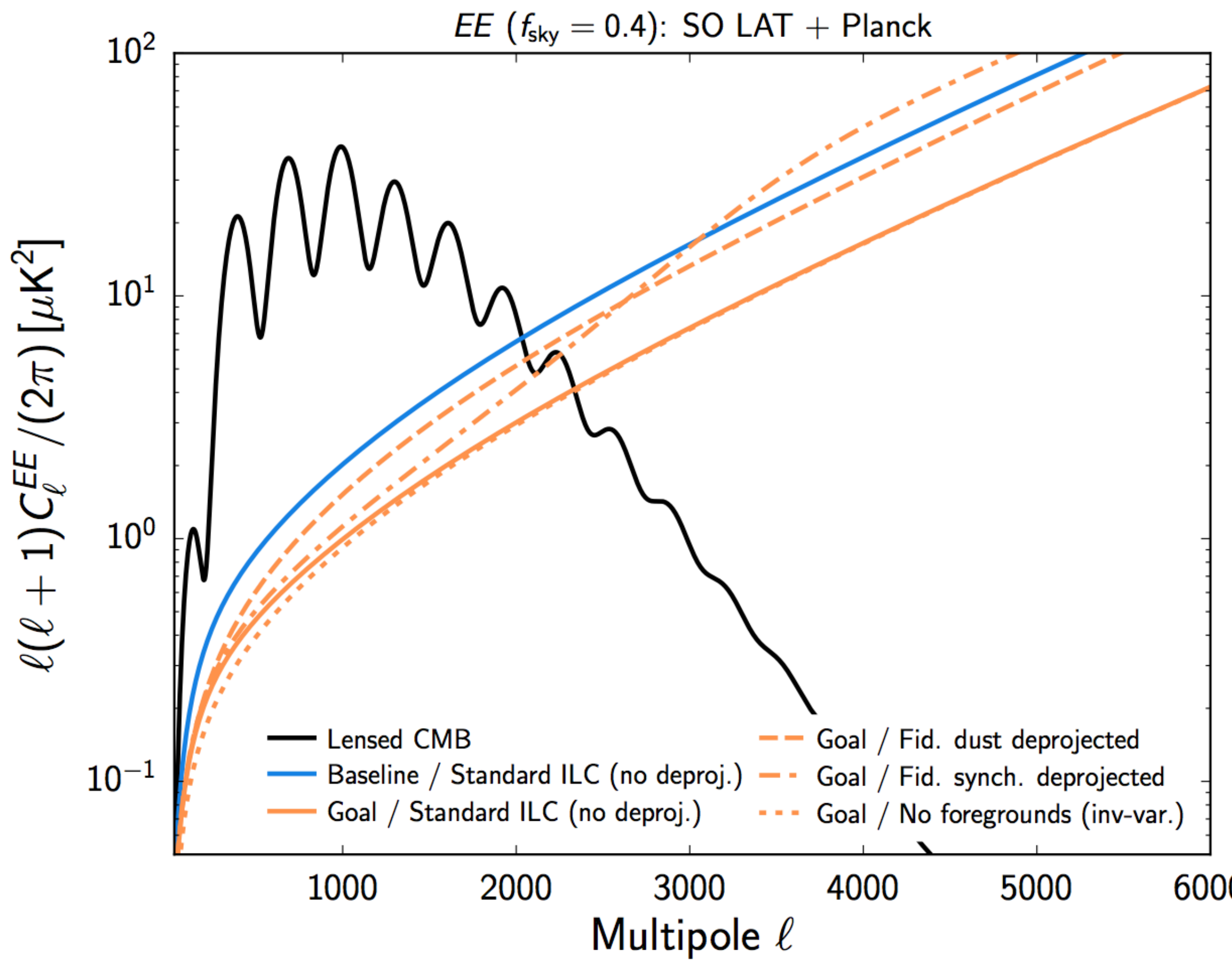
IAS/CCA

LAT T forecasting based on high-resolution, full-sky simulated maps w/ realistic foregrounds and signals (e.g., correlated extragalactic fields)

LAT E/B forecasting based on simulated power spectra, calibrated to match SAT BB assumptions at degree scales

Sky models are combined with SO LAT noise model (and Planck), then coupled to (constrained) harmonic-space internal linear combination (ILC) to derive component-separated noise curves





SO LAT Science Observables

Colin Hill
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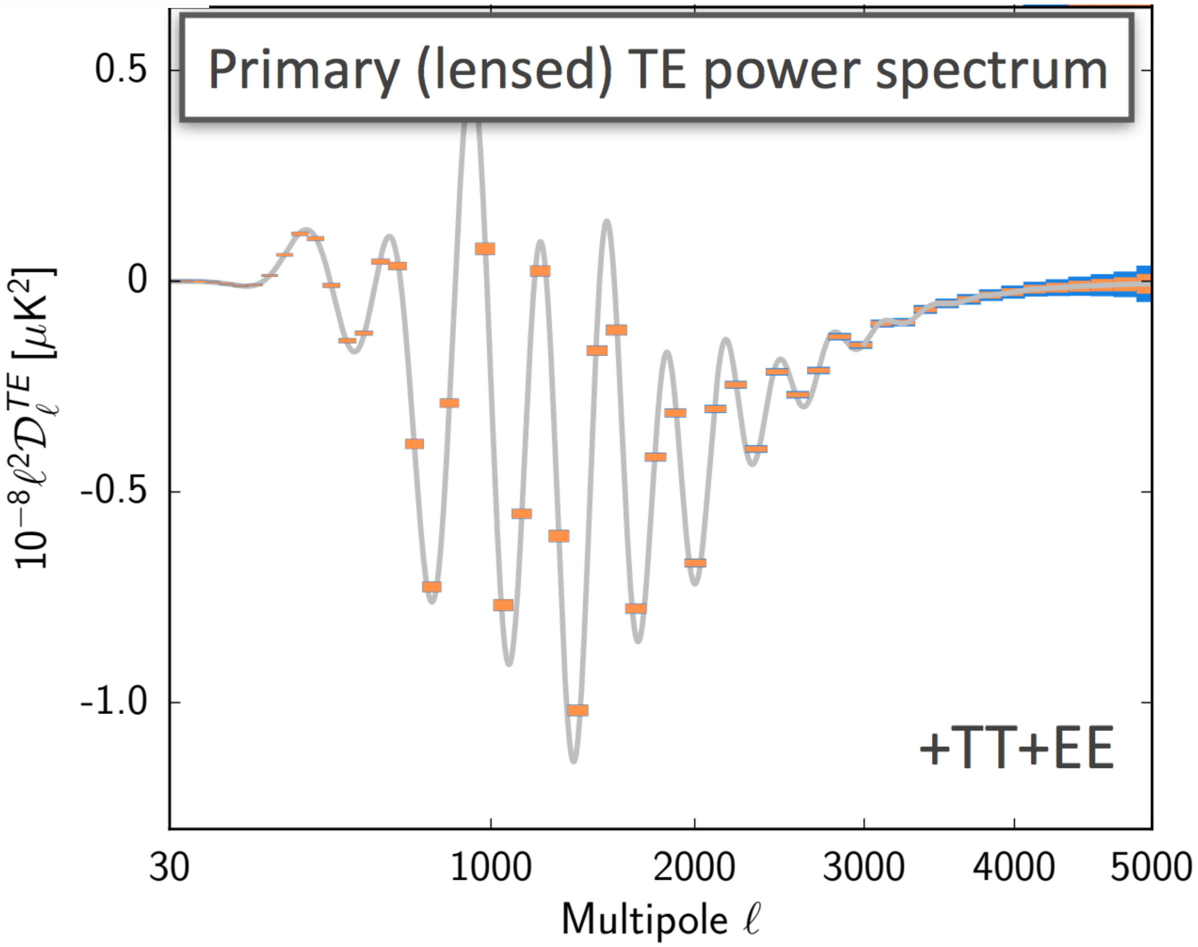
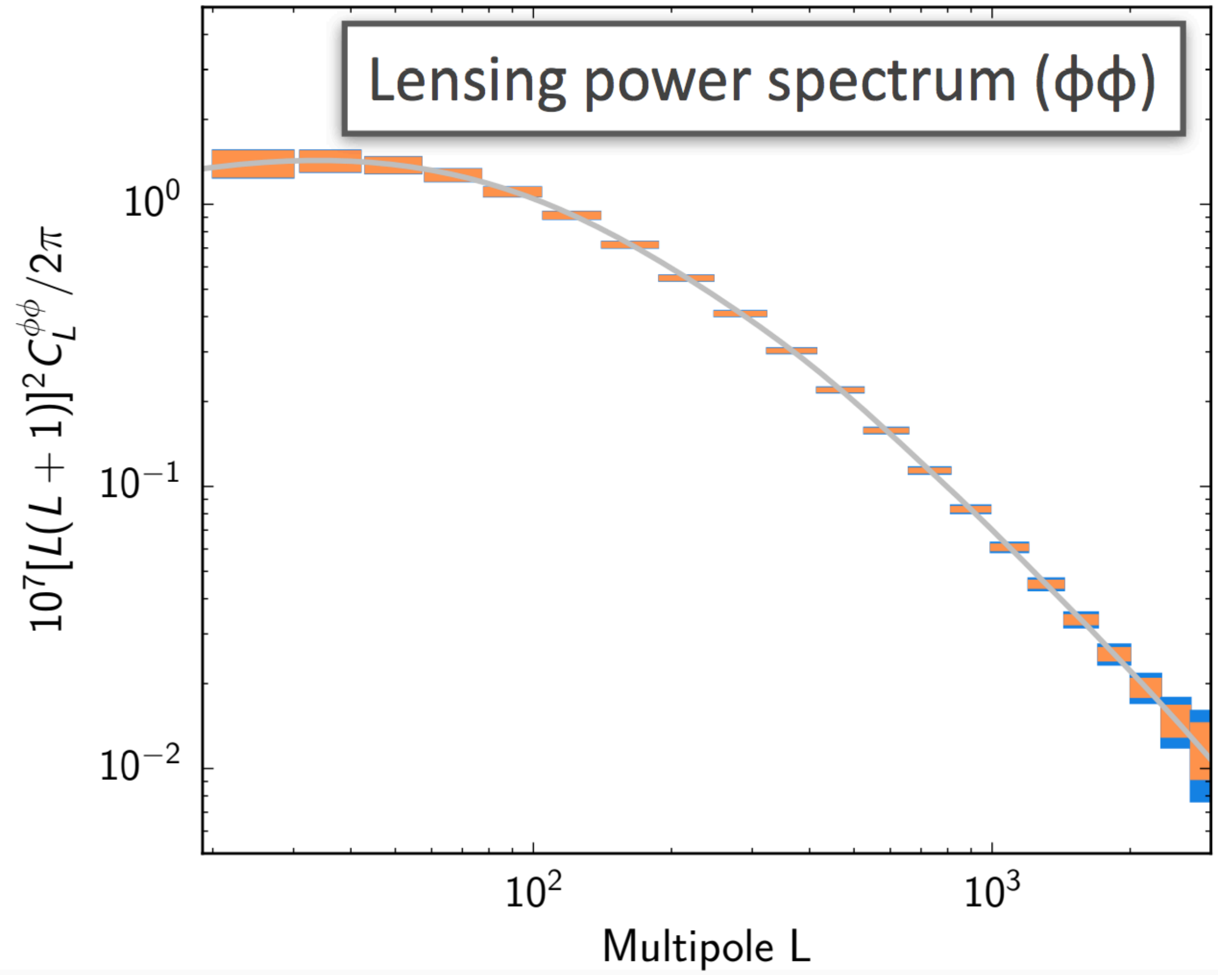
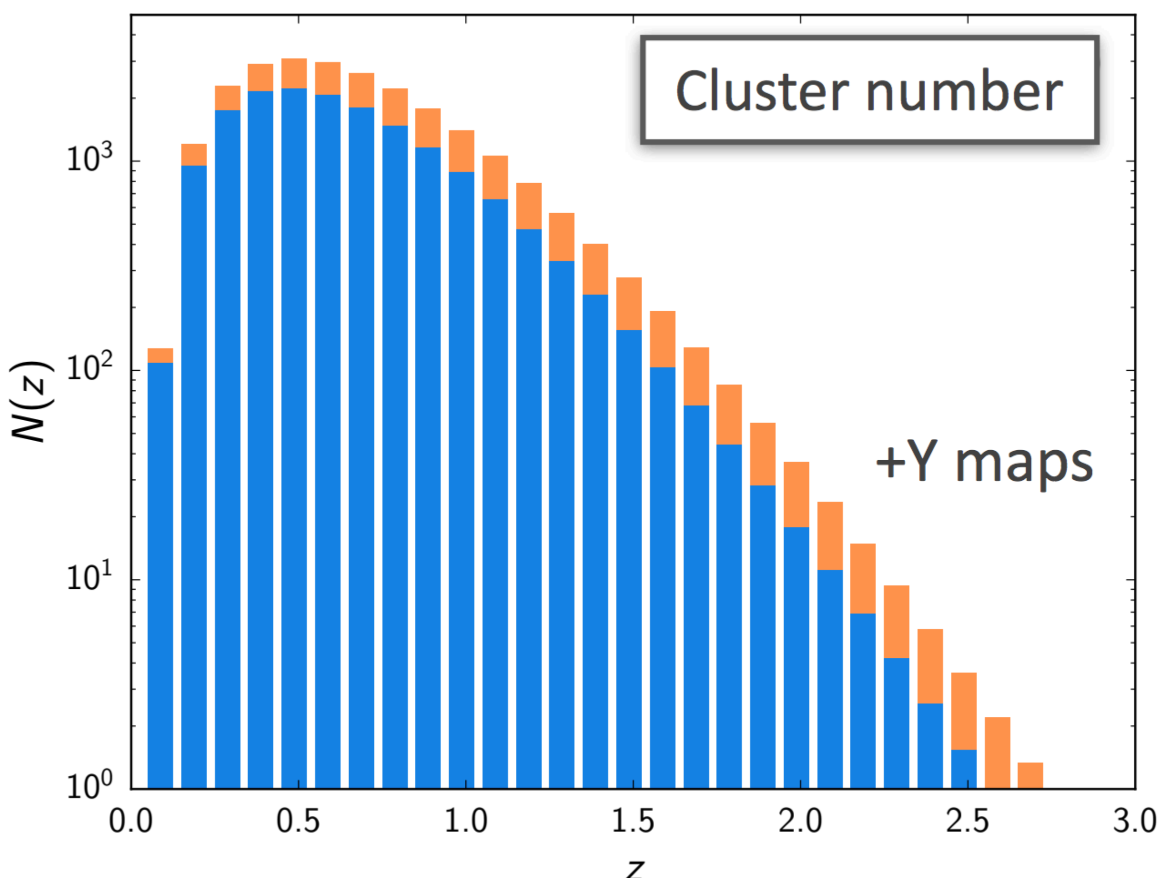






SO Baseline Sensitivity

SO Goal Sensitivity

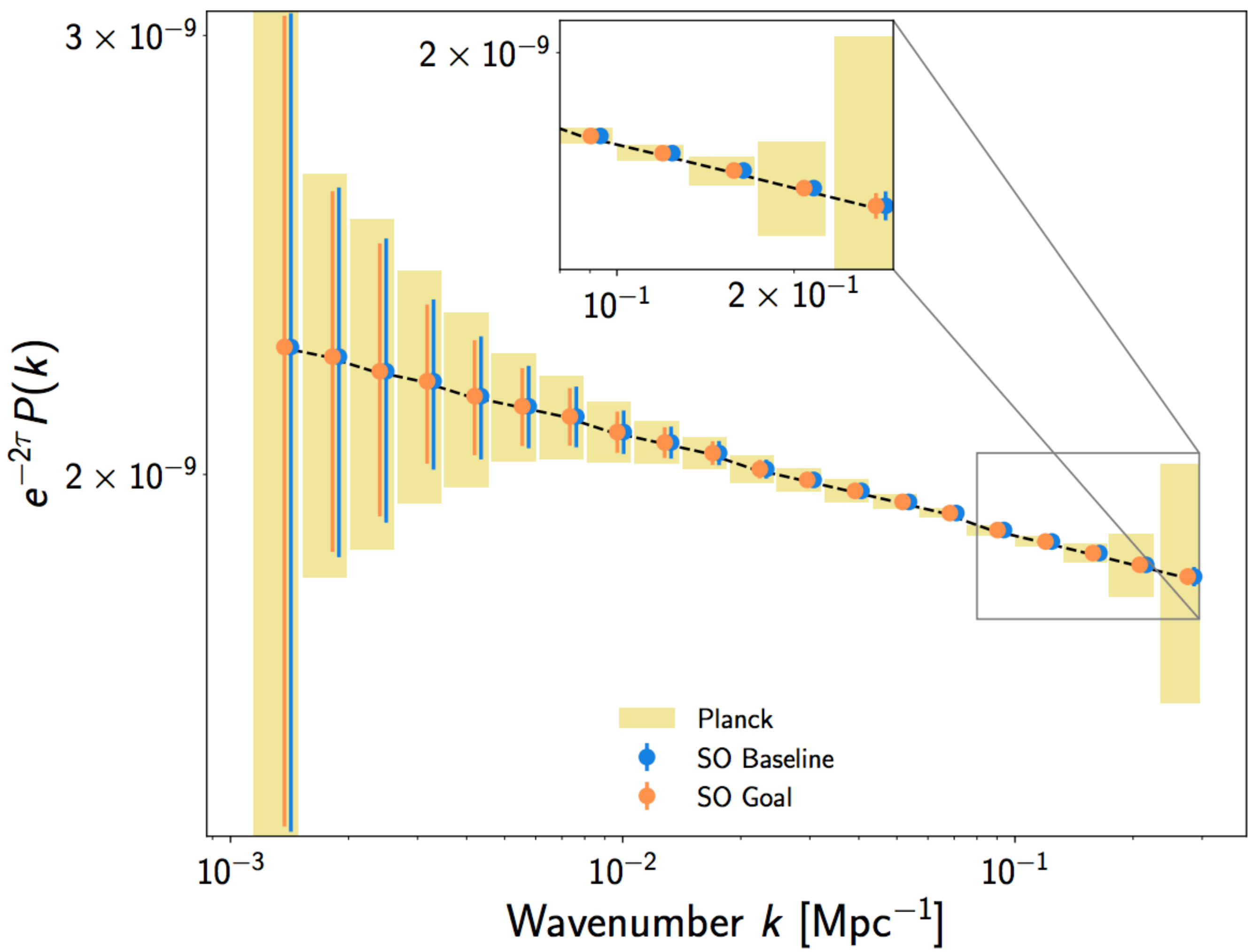
+kSZ signal + bispectrum

+ cross-correlations
+ source counts

SO LAT Science: Primordial Perturbations

Colin Hill
IAS/CCA

Primordial scalar power spectrum



0.4% constraint at k~0.2/Mpc
(10x improvement over Planck)

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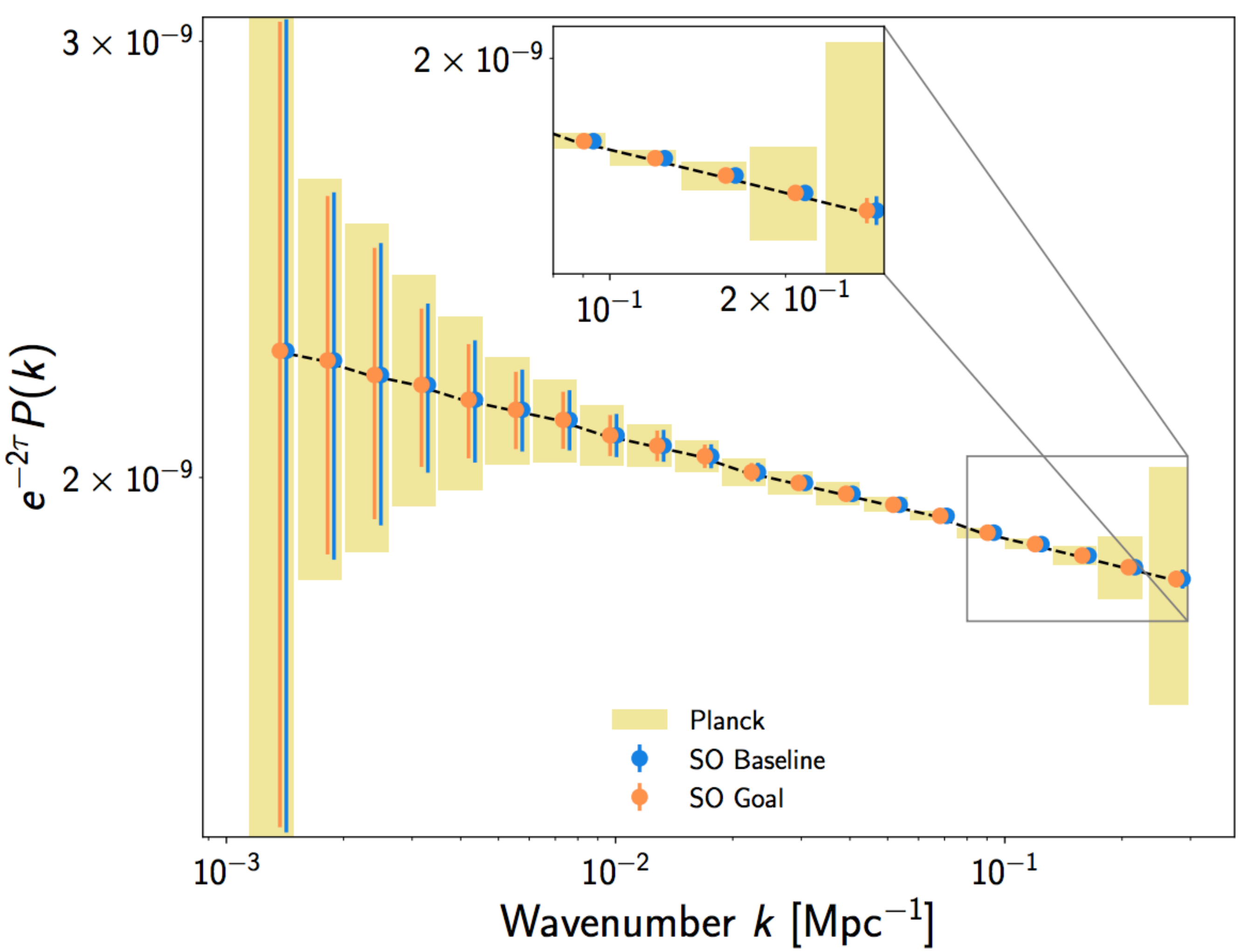
IAS/CCA

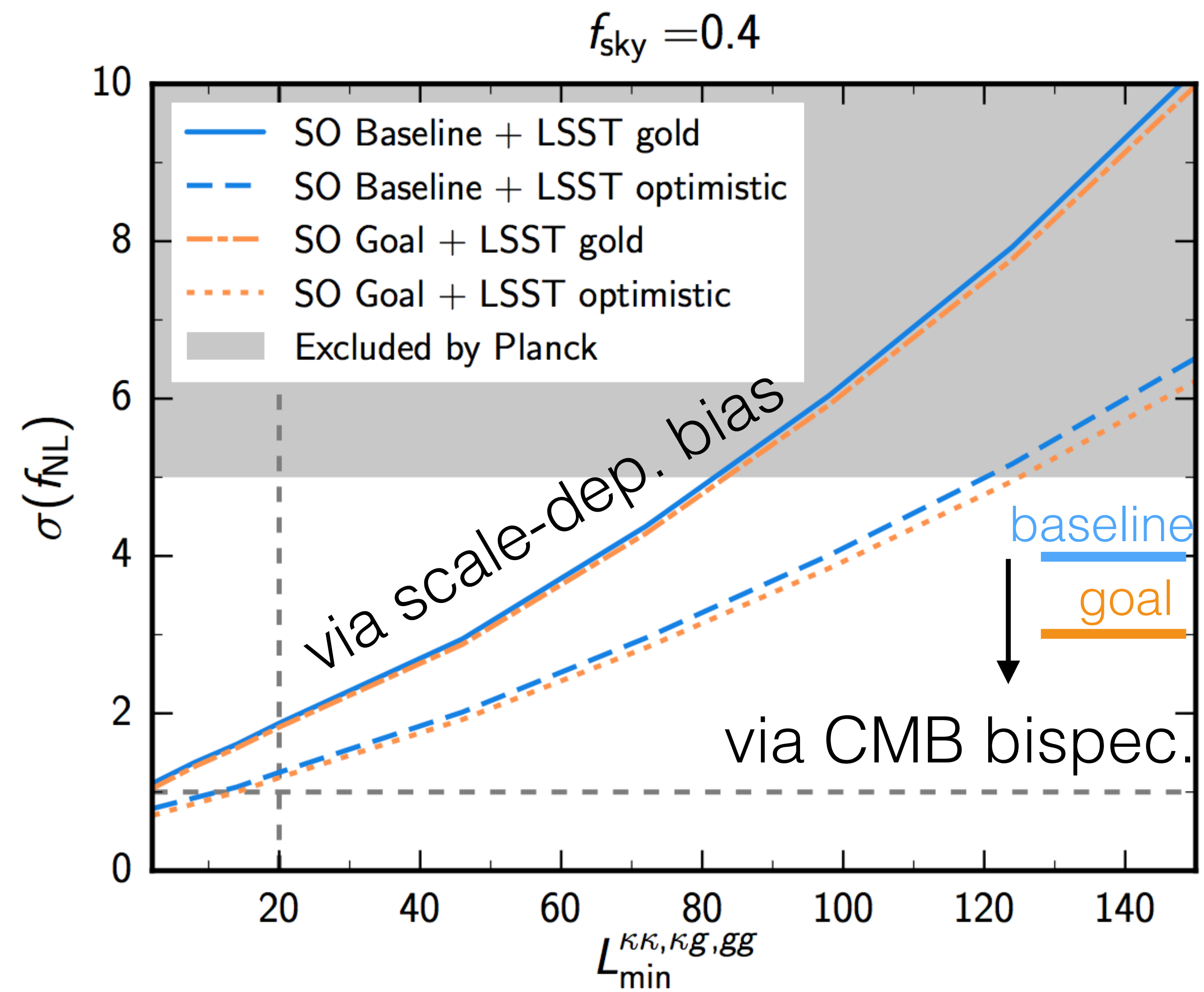
SO LAT Science: Primordial Perturbations

Primordial scalar power spectrum



0.4% constraint at k~0.2/Mpc
(10x improvement over Planck)

Local-type primordial non-Gaussianity

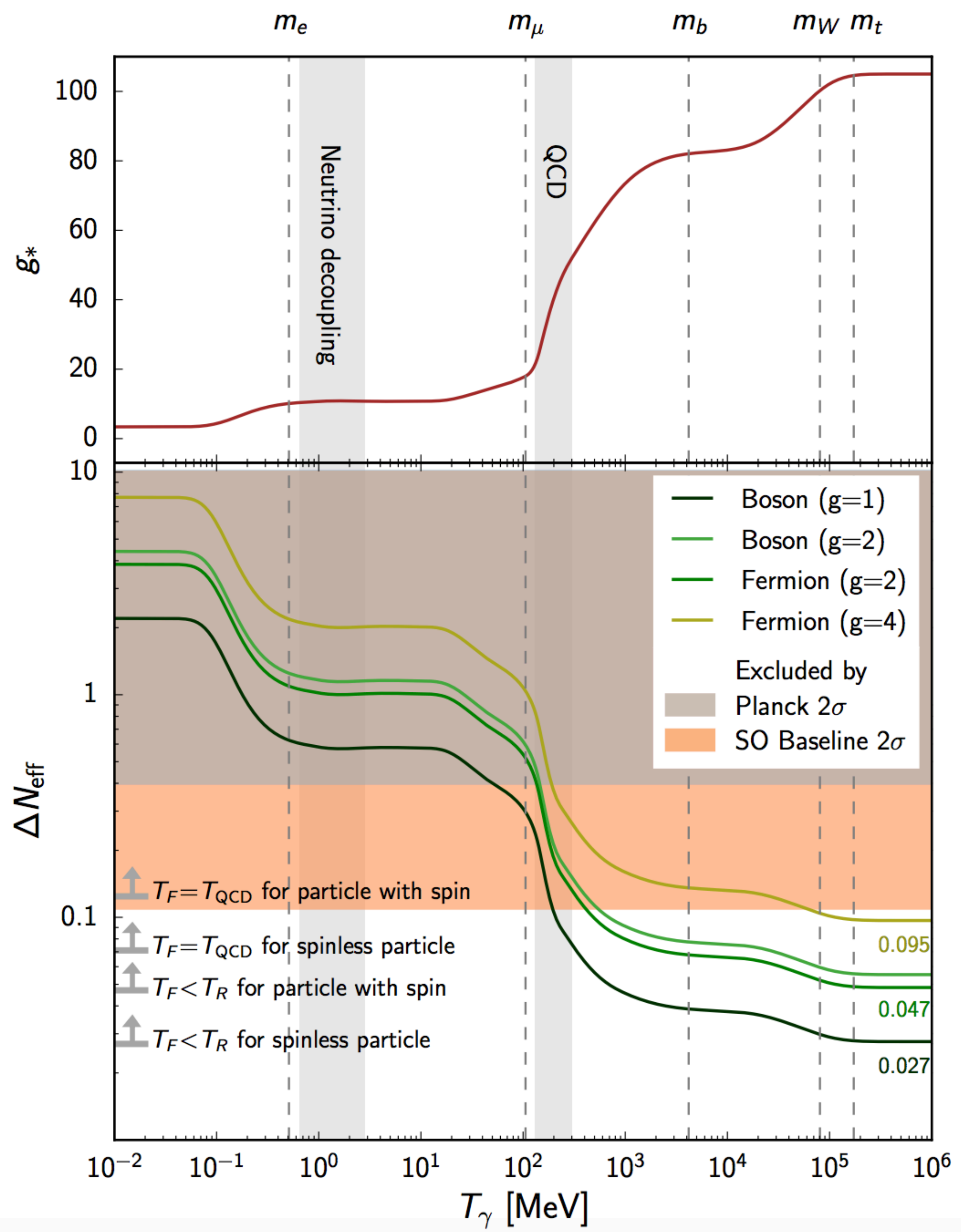


Shape ($\langle\zeta\zeta\zeta\rangle$) $\langle TTT \rangle$,$\langle TTE \rangle$, $\langle TEE \rangle$,$\langle EEE \rangle$	Current (*Planck*)	SO Baseline	SO Goal
local	5	4	3
equilateral	43	27	24
orthogonal	21	14	13

+ tensor NGs

SO LAT Science: Light Relics

Colin Hill
IAS/CCA



SO can detect any particle with spin that decoupled after the start of the QCD phase transition (at 2σ)

$\sigma(N_{\rm eff}) = 0.07$

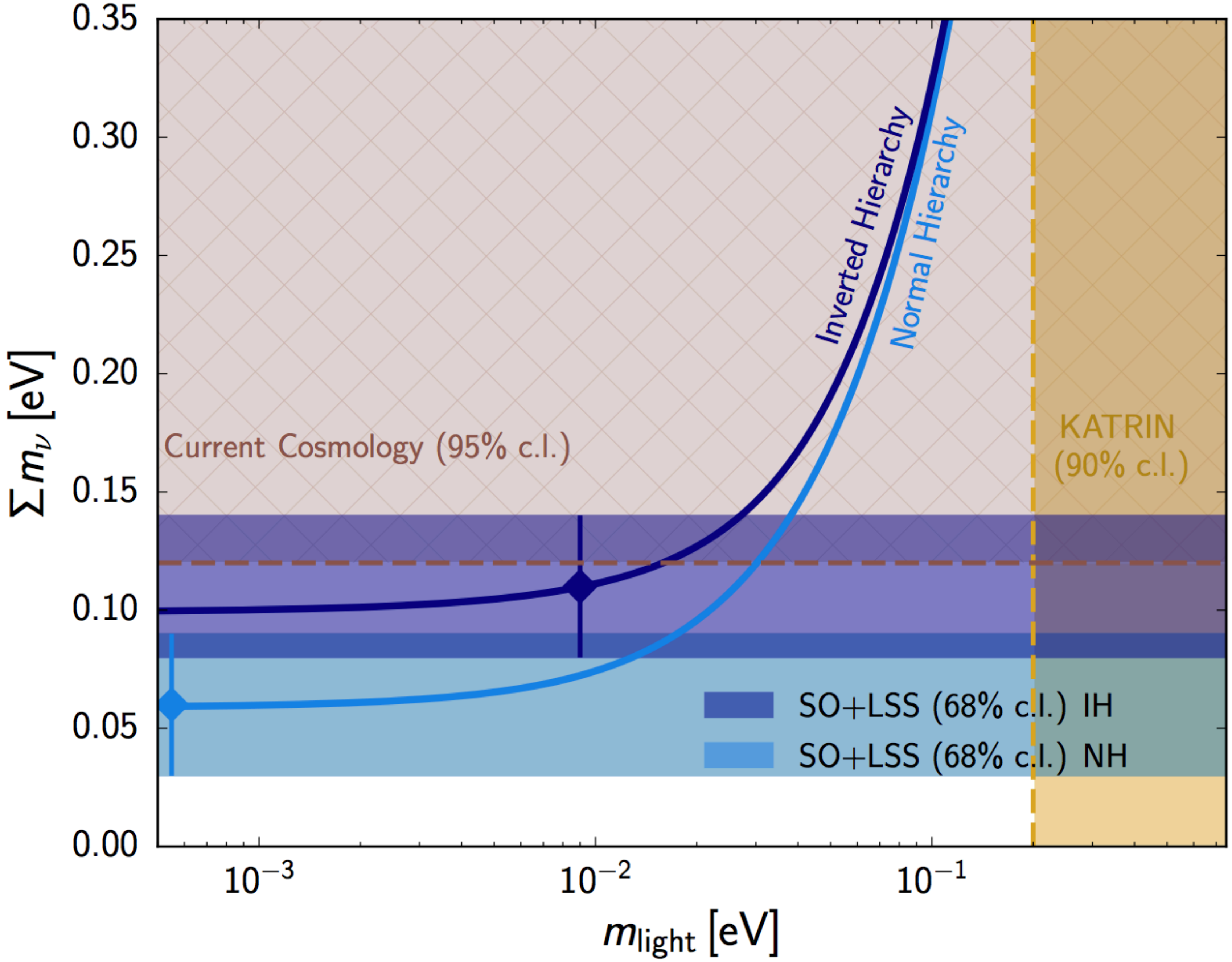
Forecasts are strongly robust to foregrounds (driven by TE + EE)

Other damping tail science:
- BBN (Y_p)
- H_0 improvement (~2x)
- Dark matter interactions
- Ultra-light axions
- and more

SO LAT Science: Neutrino Masses

Colin Hill
IAS/CCA

Constraints derived from CMB lensing power spectrum (+DESI BAO), tSZ cluster counts (+LSST WL), and tSZ power spectrum (+DESI BAO)



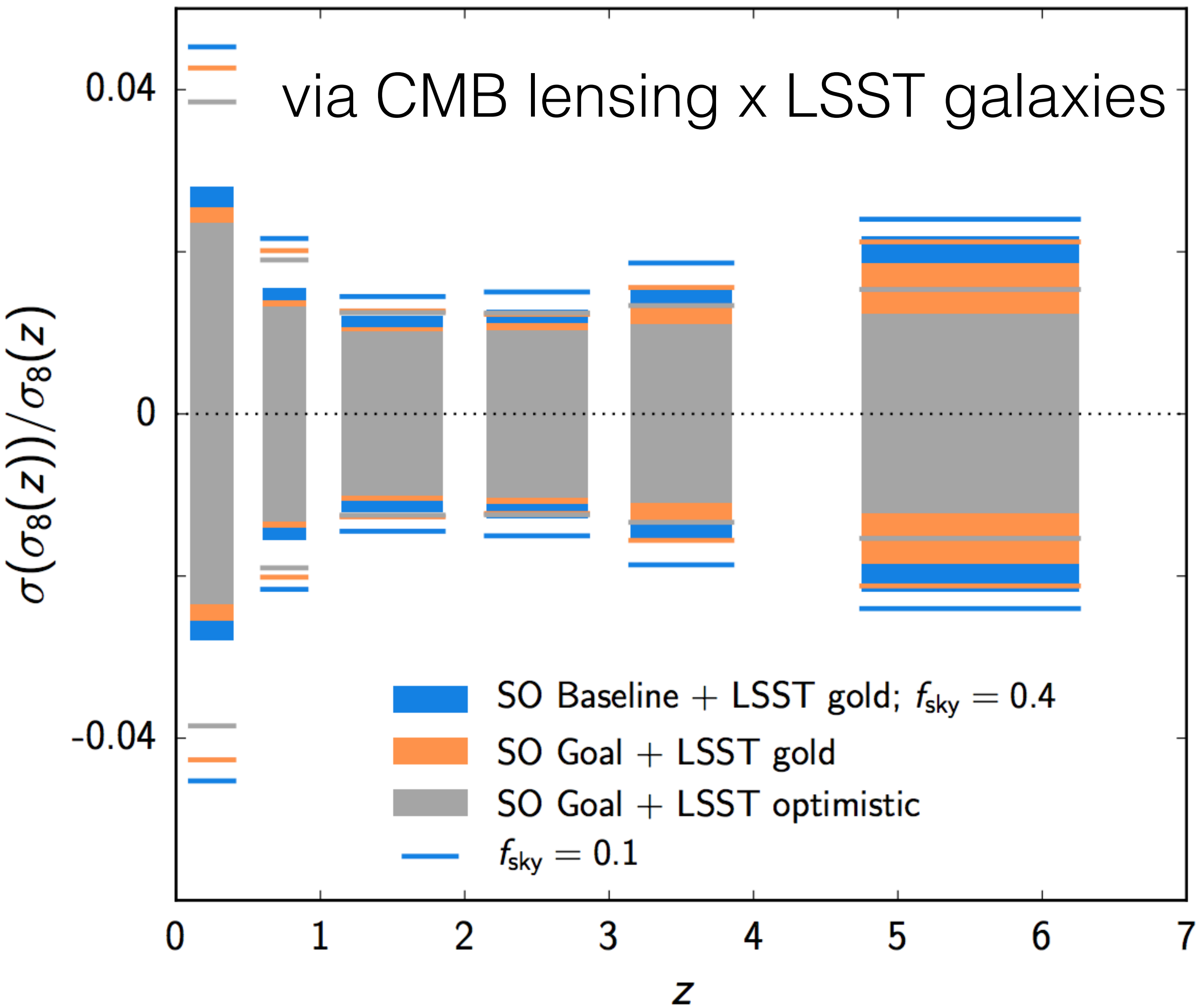
$\sigma(\Sigma M_\nu) = 0.04$ eV ⟶ 0.02 eV w/ CV-limited τ

SO LAT Science: Dark Energy

Colin Hill
IAS/CCA

Constraints derived from tSZ cluster counts (+LSST WL and/or SO CMB lensing), and CMB lensing cross-correlations w/ LSST galaxies

Amplitude of fluctuations as a function of redshift



DE equation of state (via tSZ cluster counts)

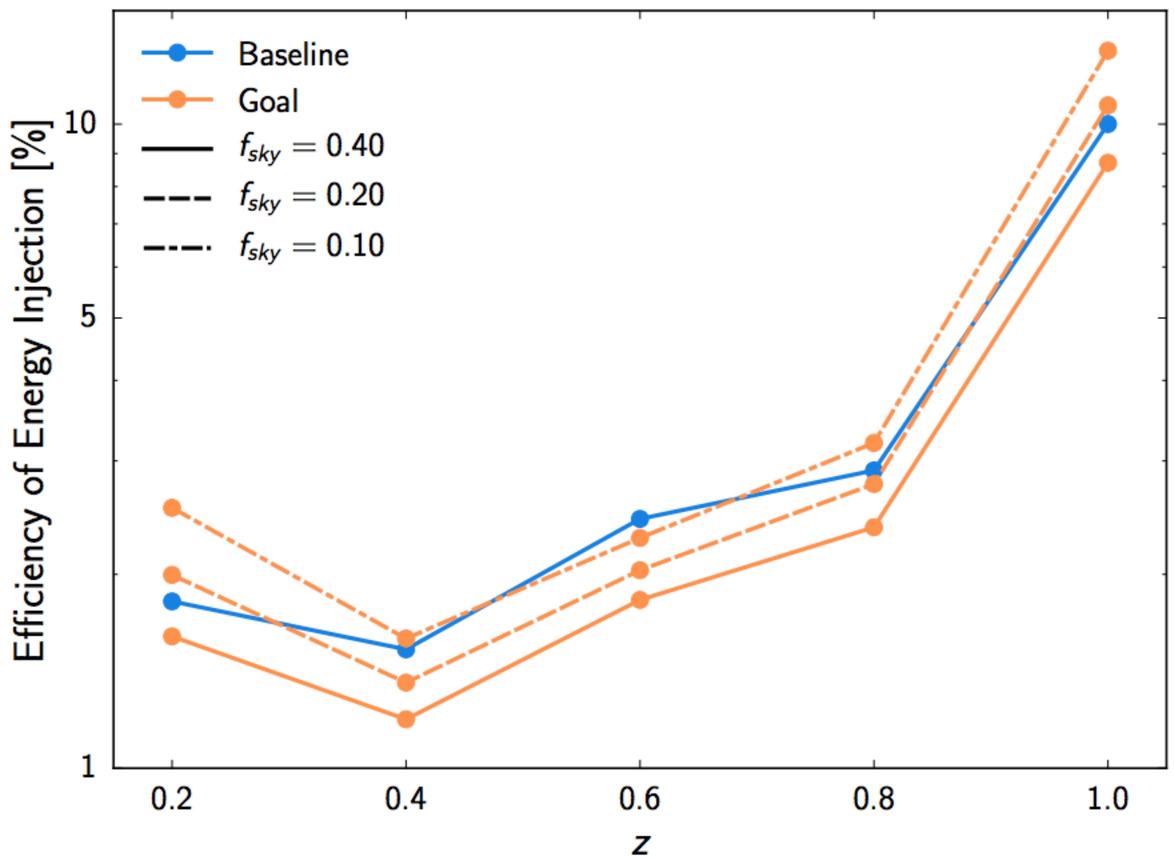
$$\sigma(w_0) = 0.06, \quad \Lambda\mathrm{CDM} + w_0 + w_a$$
$$\sigma(w_a) = 0.20,$$
$$\sigma(w_0) = 0.08, \quad \Lambda\mathrm{CDM} + w_0 + w_a + \Sigma m_\nu$$
$$\sigma(w_a) = 0.32,$$

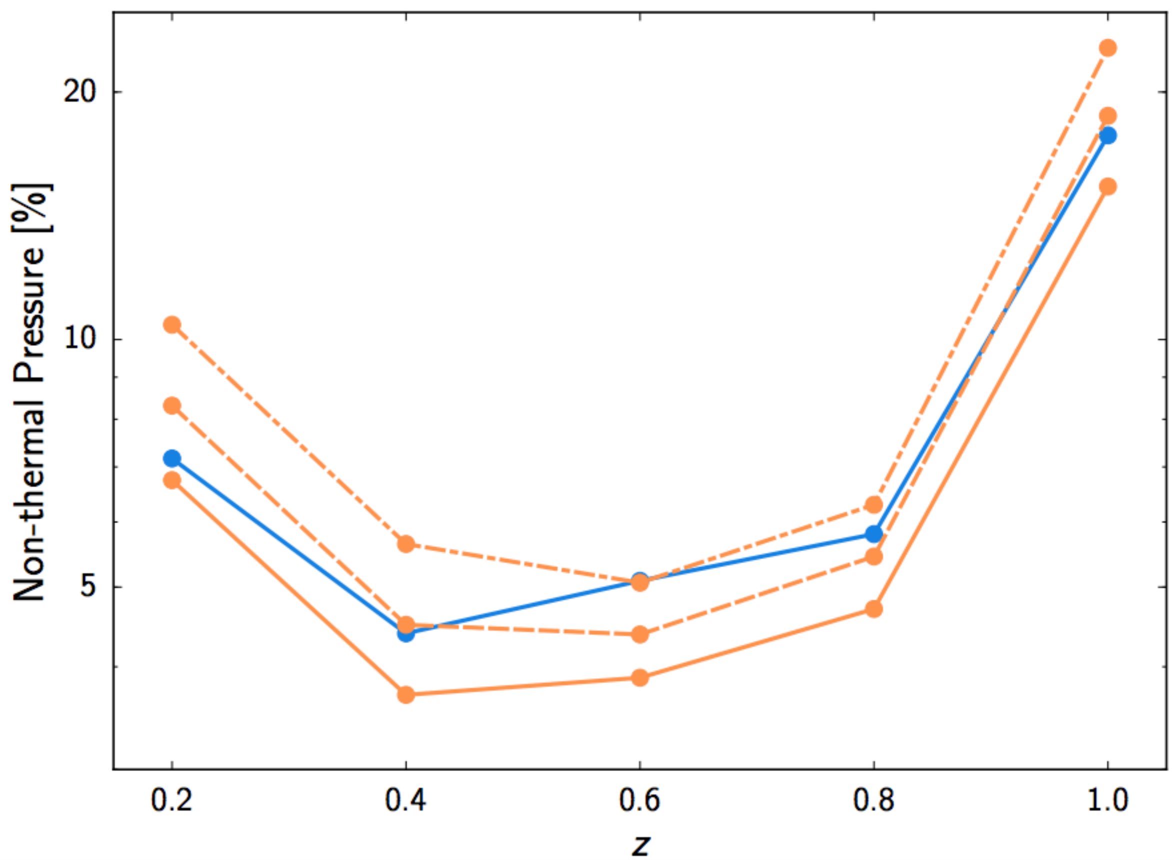
Unique ability to search for deviations from Λ at z > 1 (complementary to lower-redshift WL and galaxy surveys)

c.f. also improved $\sigma(H_0)$

SO LAT Science: Galaxy Formation/Evolution

Colin Hill
IAS/CCA





Constraints derived from joint analysis of tSZ and kSZ measurements of DESI Luminous Red Galaxies (just one example cross-correlation!)

~Few percent constraints on feedback efficiency and non-thermal pressure support

>200σ detection of tSZ PS
>100σ detections of kSZ cross-corrs.

Legacy catalogs

SZ clusters	20000
AGN galaxies	10000
Dusty star-forming galaxies	10000

+transient sources

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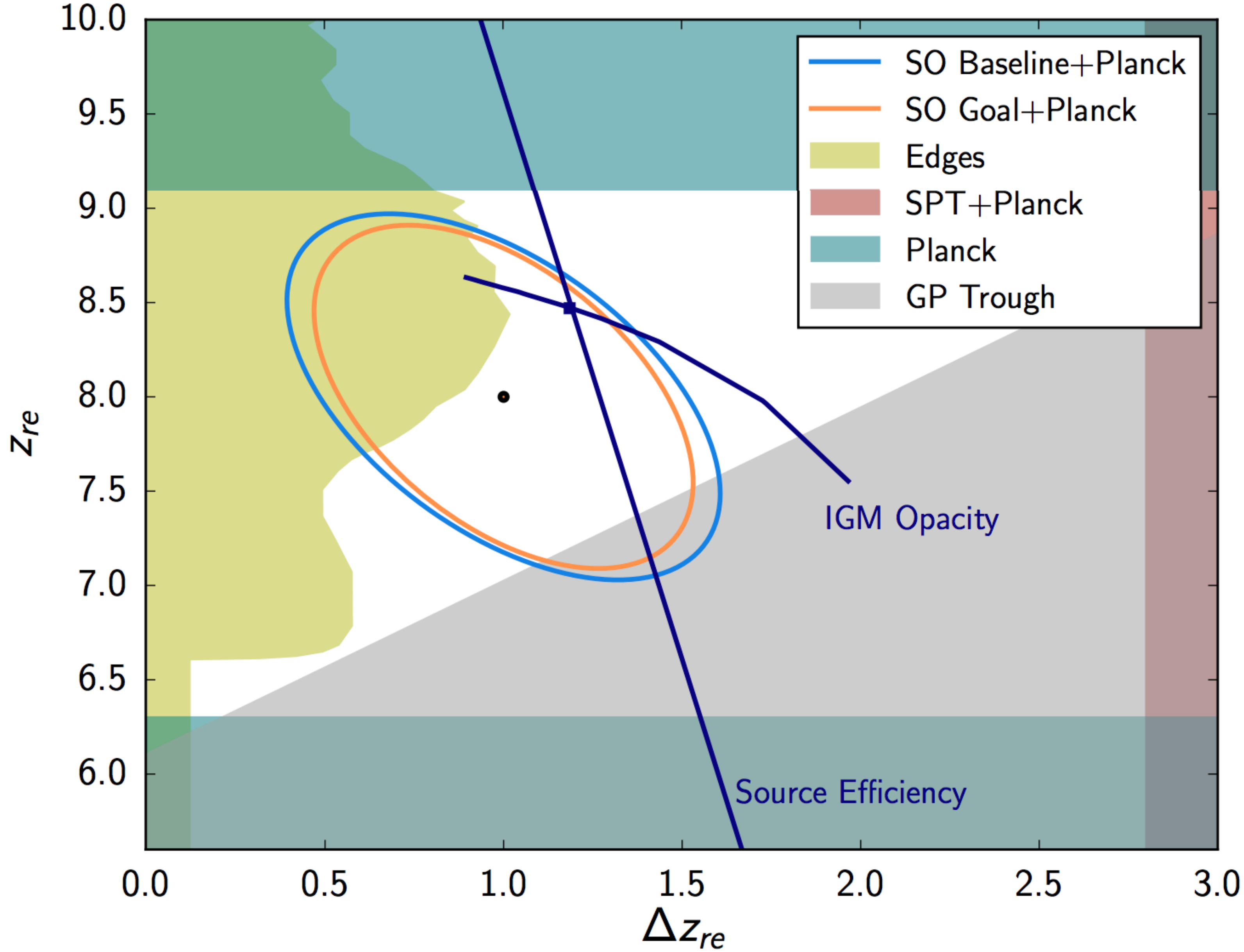
IAS/CCA

SO LAT Science: Reionization

Constraints derived from kSZ power spectrum via TT combined with TE/EE (also, potentially from higher-order kSZ statistics)



$$\sigma(\Delta z_{\rm re}) = 0.40$$

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Simons Observatory Science Goals and Probes

	Parameter	**SO-Baseline**[c]	SO-Goal[d]	Current[e]	Method
Primordial perturbations	r	**0.003**	0.002	0.03	BB + ext delens
	$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	**0.5%**	0.4%	3%	$TT/TE/EE$
	$f_{\mathrm{NL}}^{\mathrm{local}}$	**3**	1	5	$\kappa\kappa \times$ LSST-LSS + 3-pt
		2	1		kSZ + LSST-LSS
Relativistic species	N_{eff}	**0.07**	0.05	0.2	$TT/TE/EE + \kappa\kappa$
Neutrino mass	Σm_ν	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO
		0.04	0.03		tSZ-N $\times$ LSST-WL
		0.05	0.04		tSZ-Y + DESI-BAO
Deviations from Λ	$\sigma_8(z=1-2)$	**2%**	1%	7%	$\kappa\kappa$ + LSST-LSS + DESI-BAO
		2%	1%		tSZ-N $\times$ LSST-WL
	H_0 (ΛCDM)	**0.4**	0.3	0.5	$TT/TE/EE + \kappa\kappa$
Galaxy evolution	η_{feedback}	**3%**	2%	50-100%	kSZ + tSZ + DESI
	p_{nt}	**8%**	5%	50-100%	kSZ + tSZ + DESI
Reionization	Δz	**0.6**	0.3	1.4	TT (kSZ)

All quoted errors are 1σ

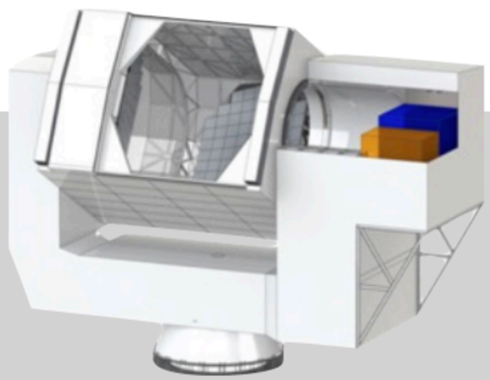
All forecasts assume SO + Planck

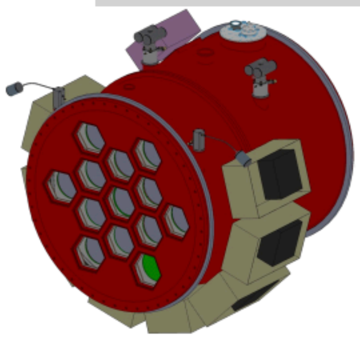
Baseline SO forecasts include systematic error budget

Simons Observatory Outlook

Colin Hill
IAS/CCA

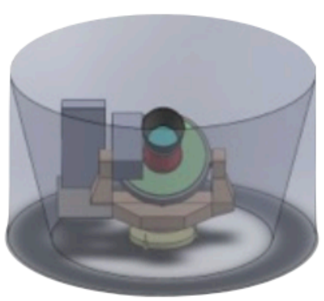
Large Aperture telescope construction by VERTEX





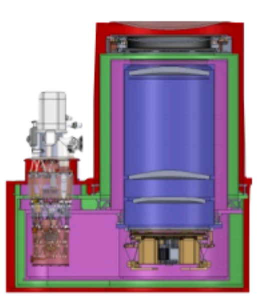
Large Aperture Receiver Design | Manufacture | Cryo-genic test | integration and test | ship and testing | **scientific observations**

2018 — 2019 — 2020 — 2021 2026



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

First SAT on sky 2020



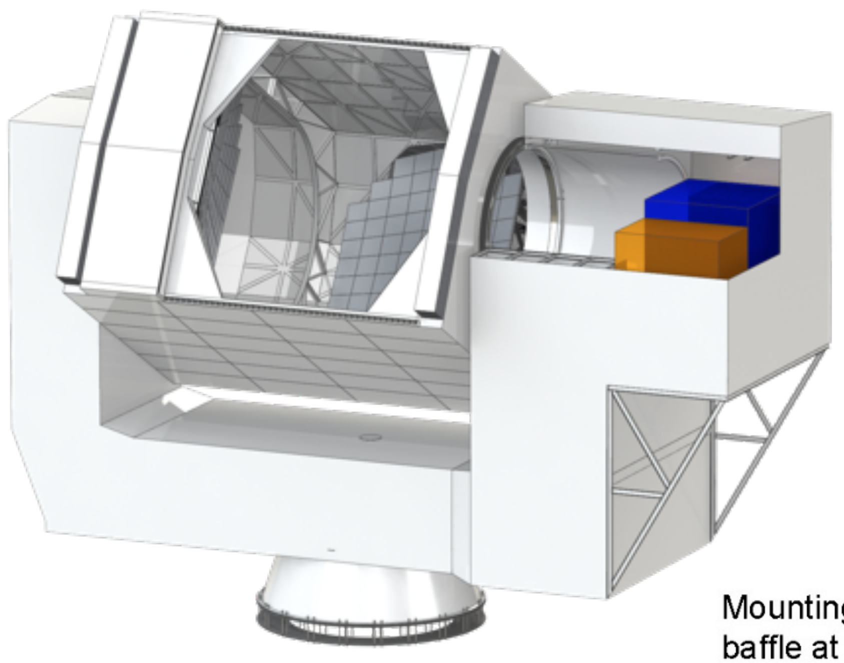
Small Aperture Camera Design | Manufacture | Cryo-genic test | integration and test | ship and testing | **scientific observations**

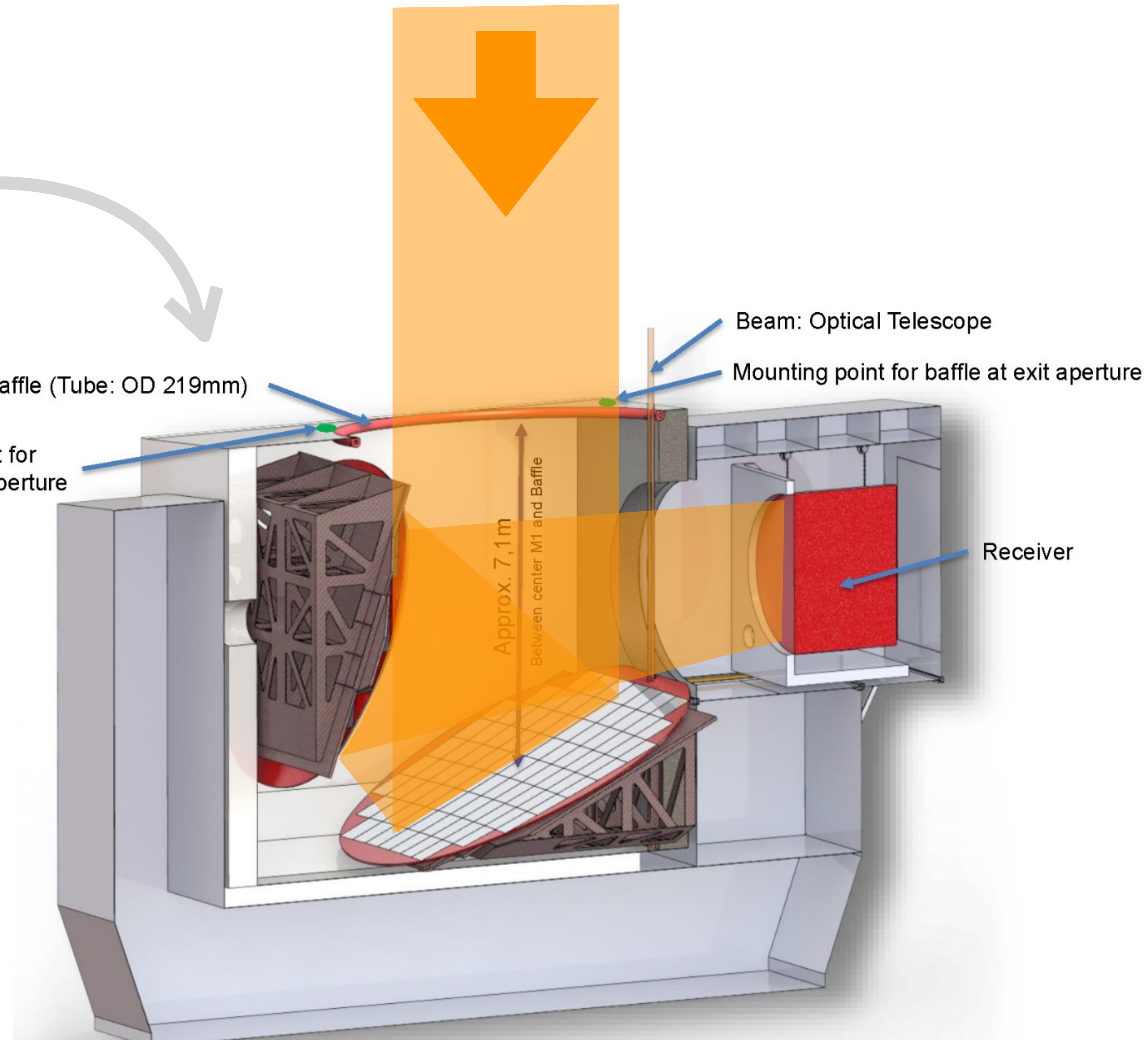
- site design and construction
- analysis pipeline development
- calibration strategy
- etc.

Thanks!

https://simonsobservatory.org/

The Simons Observatory Large Aperture telescope



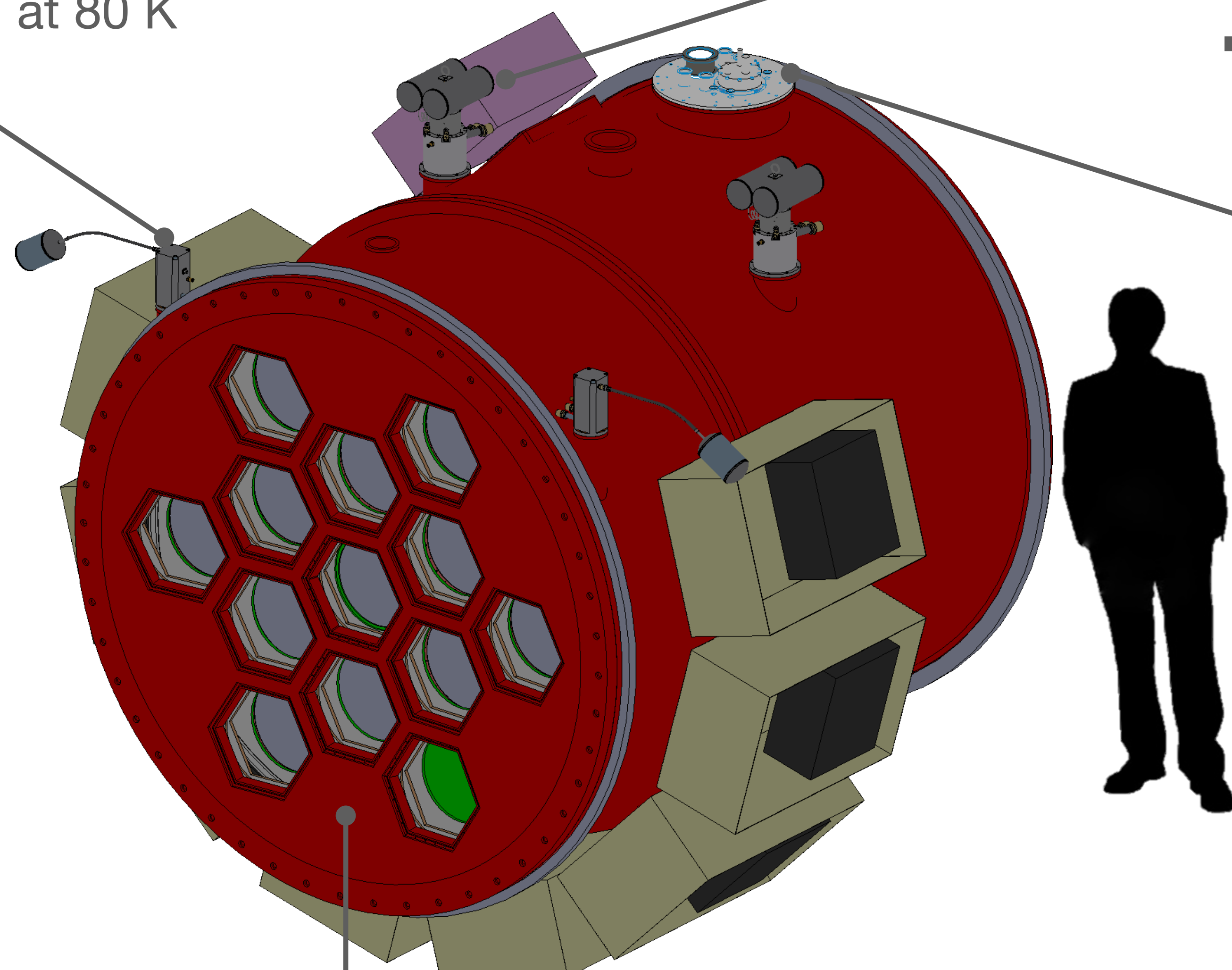


3D Cross-section of Yoke Structure and Elevation Housing (view towards M1)

- The SO will baseline a 6 meter Cross Dragone telescope.
- 2-mirror design with a side-looking camera.
- The camera rotates with the elevation axis.
- The back of the camera can be accessed while installed on the telescope.
- Developed in collaboration with CCAT and built by Vertex
- The telescope is capable of > 100,000 detectors

The Simons Observatory Large Aperture receiver

total weight ~ 5000kg (!) when populated with 13 tubes



2 PT90s

➡180 W of cooling at 80 K

3 PT420 coolers

➡ 165 watts of cooling at 40 K

➡ 6 watts of cooling at 4 K

Dilution Refrigerator

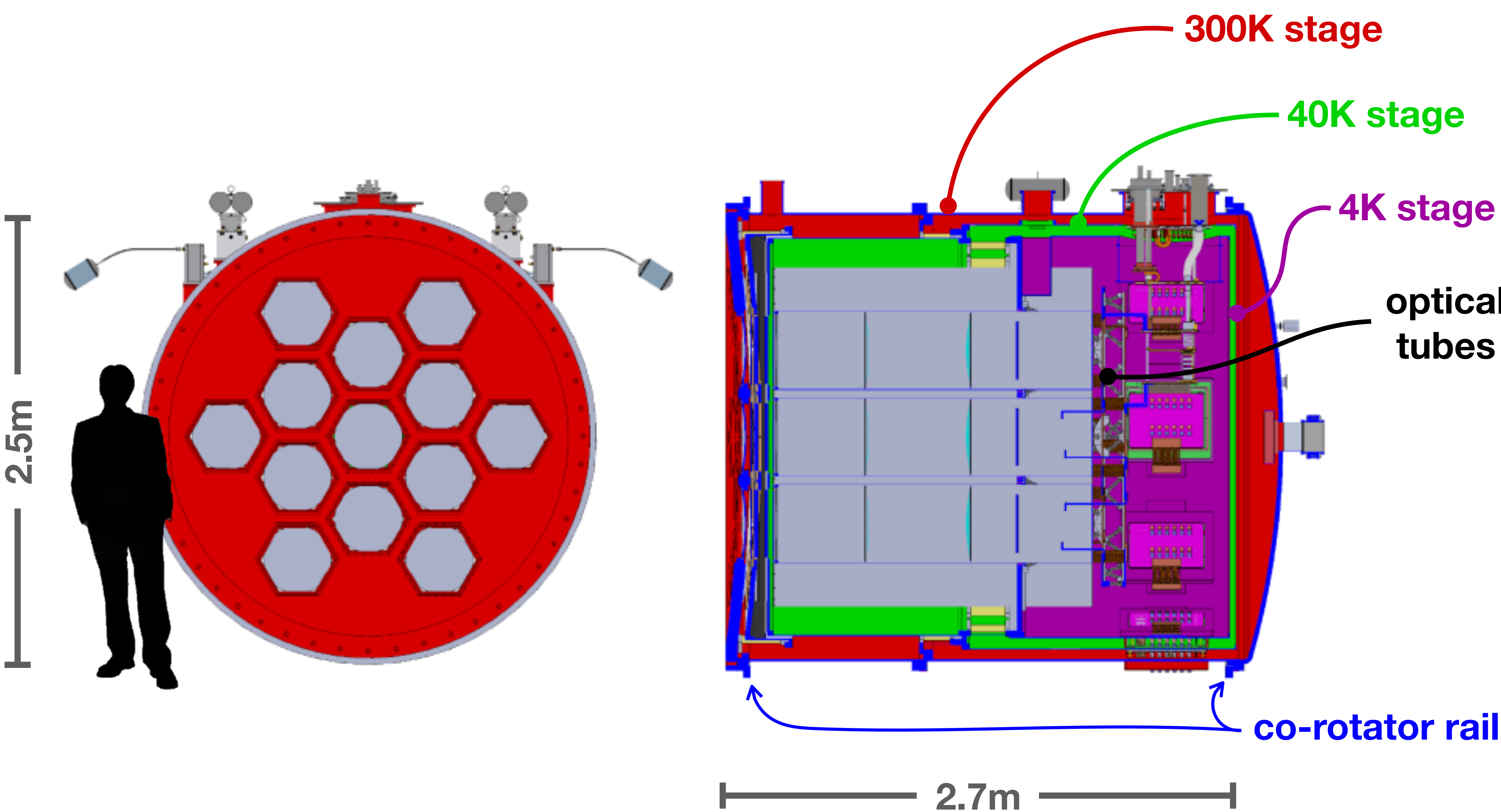
➡17 mW at 1K

➡500 uW at 100 mK

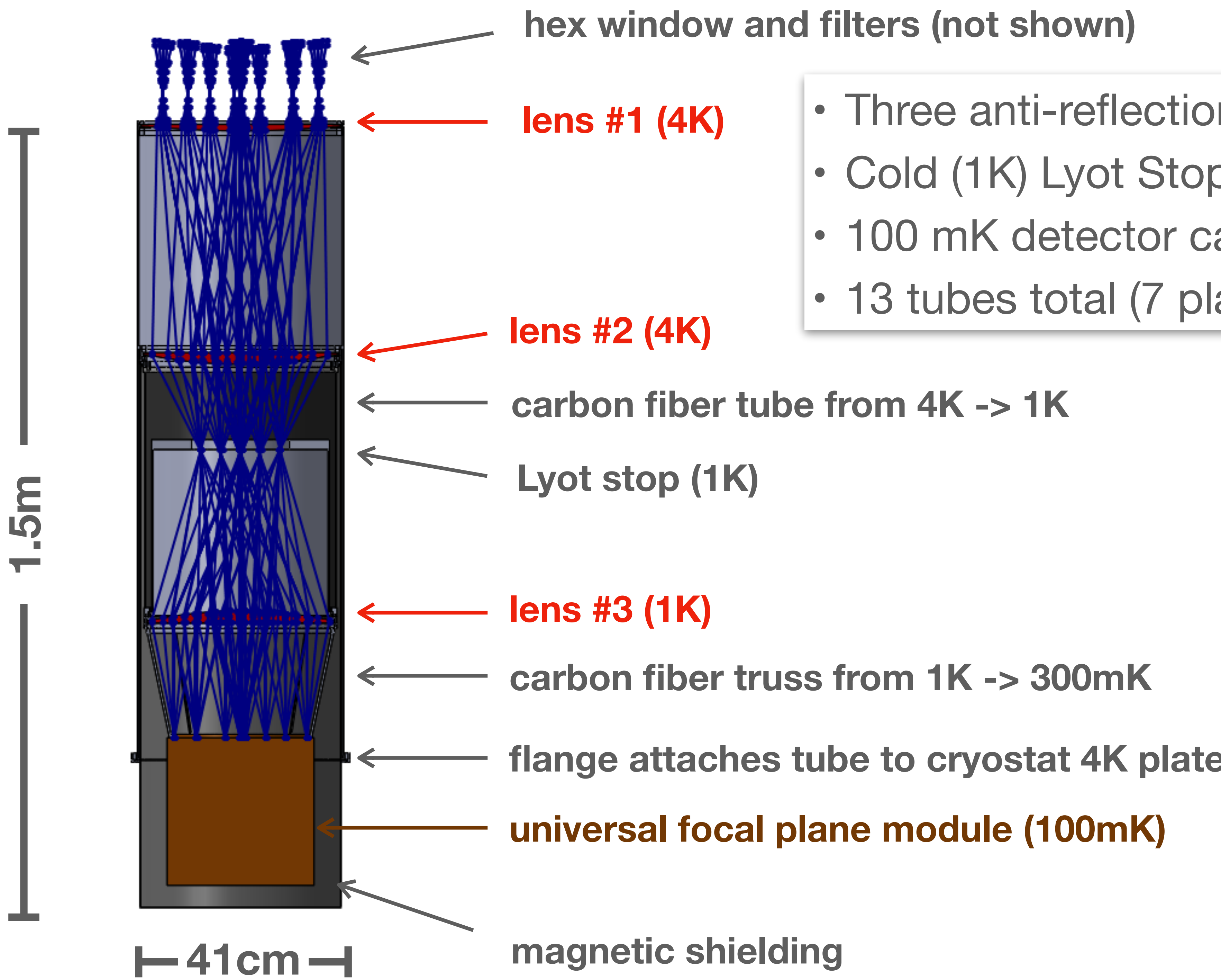
- 1200 kg cooled to 4K
- 200 kg cooled to 100 mK
- **Up to 13 optics tubes**
  - ➡7 currently planned for SO

- **70,000+ detector capacity *in this cryostat***
  - ➡ 30,000 planned for SO
- The optics tubes can be replaced while cryostat is installed.

The Simons Observatory Large Aperture receiver

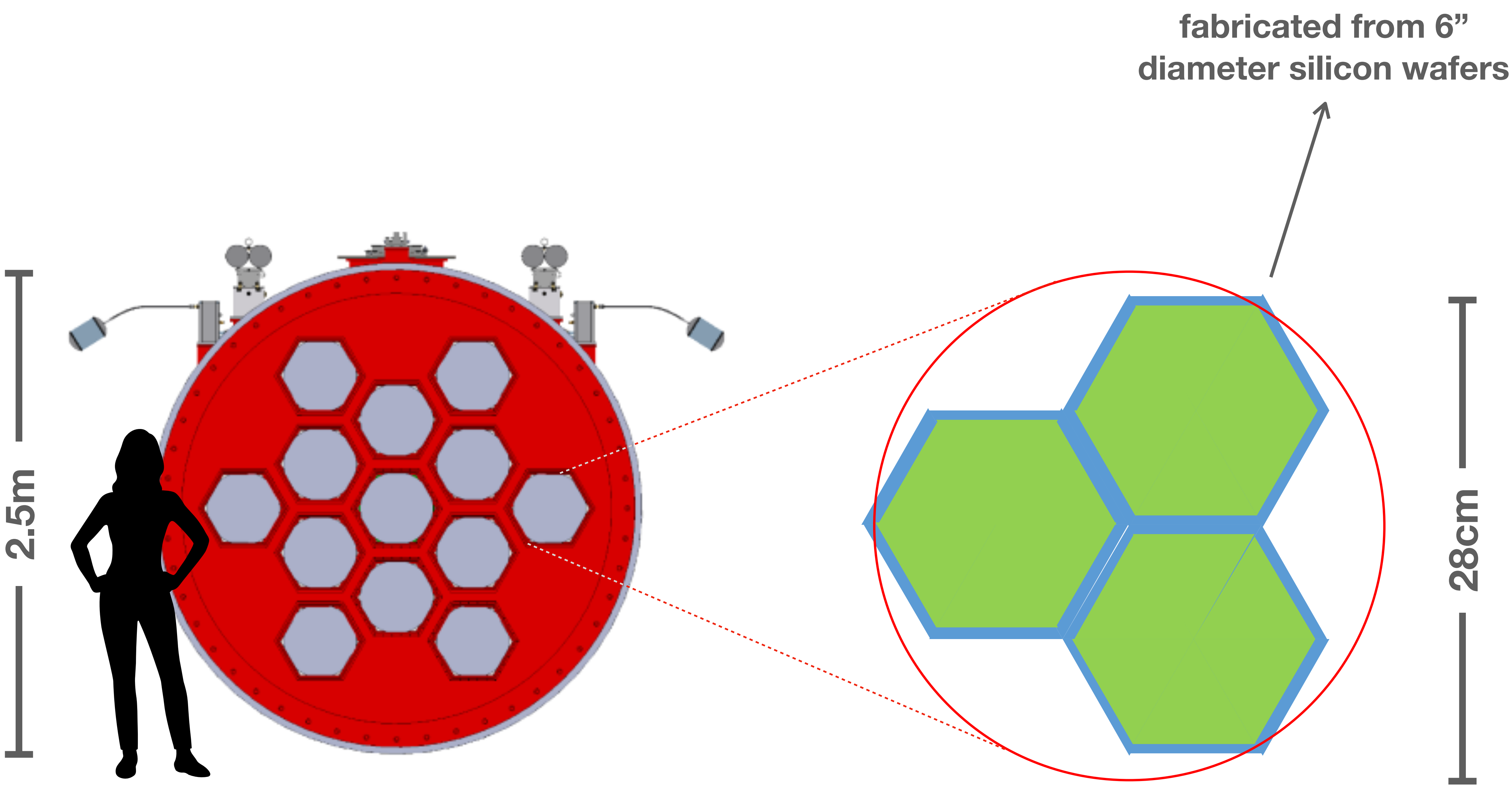


The Simons Observatory Large Aperture receiver



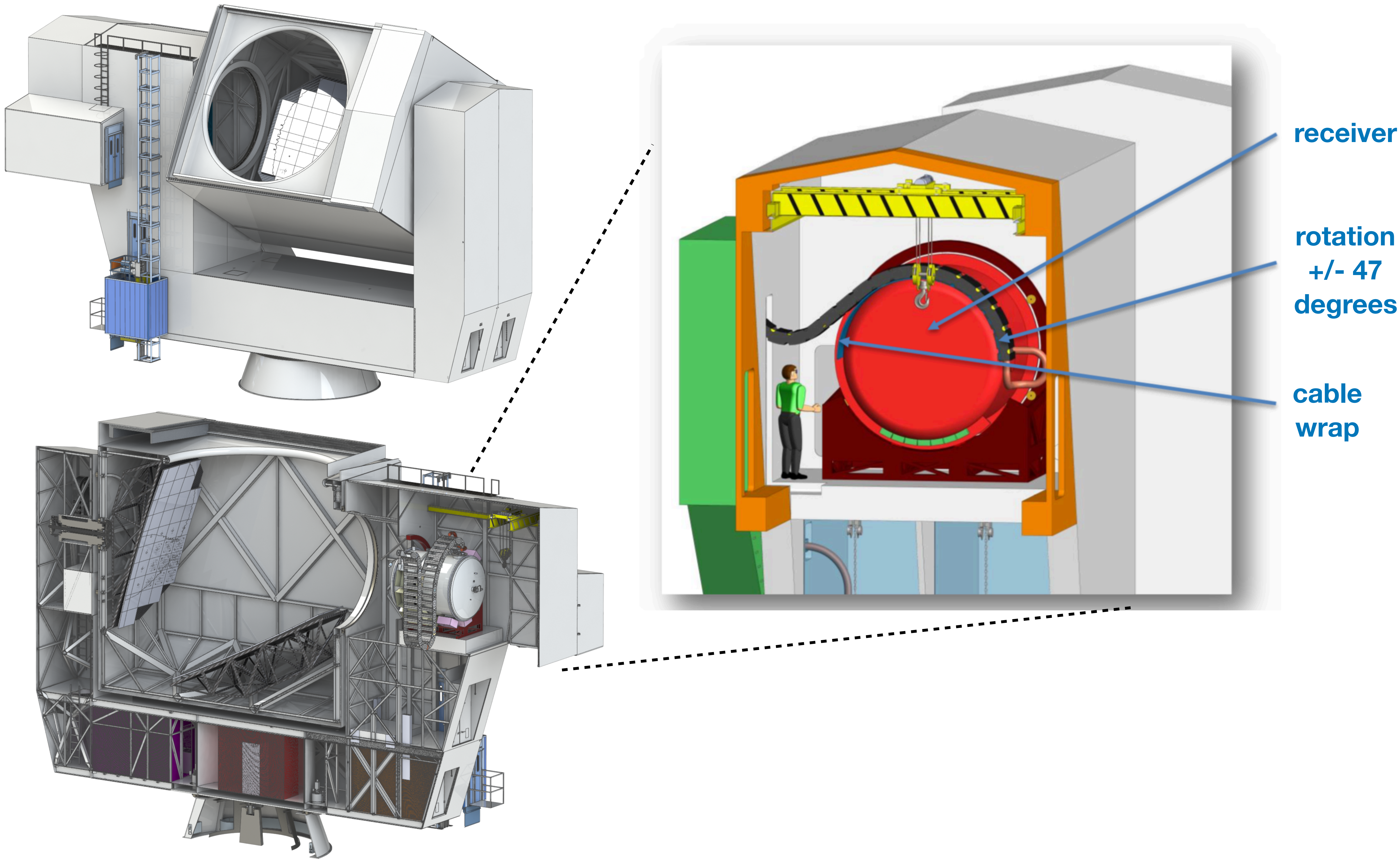
- Three anti-reflection coated silicon lenses
- Cold (1K) Lyot Stop
- 100 mK detector cavity
- 13 tubes total (7 planed for SO)

The Simons Observatory Large Aperture receiver

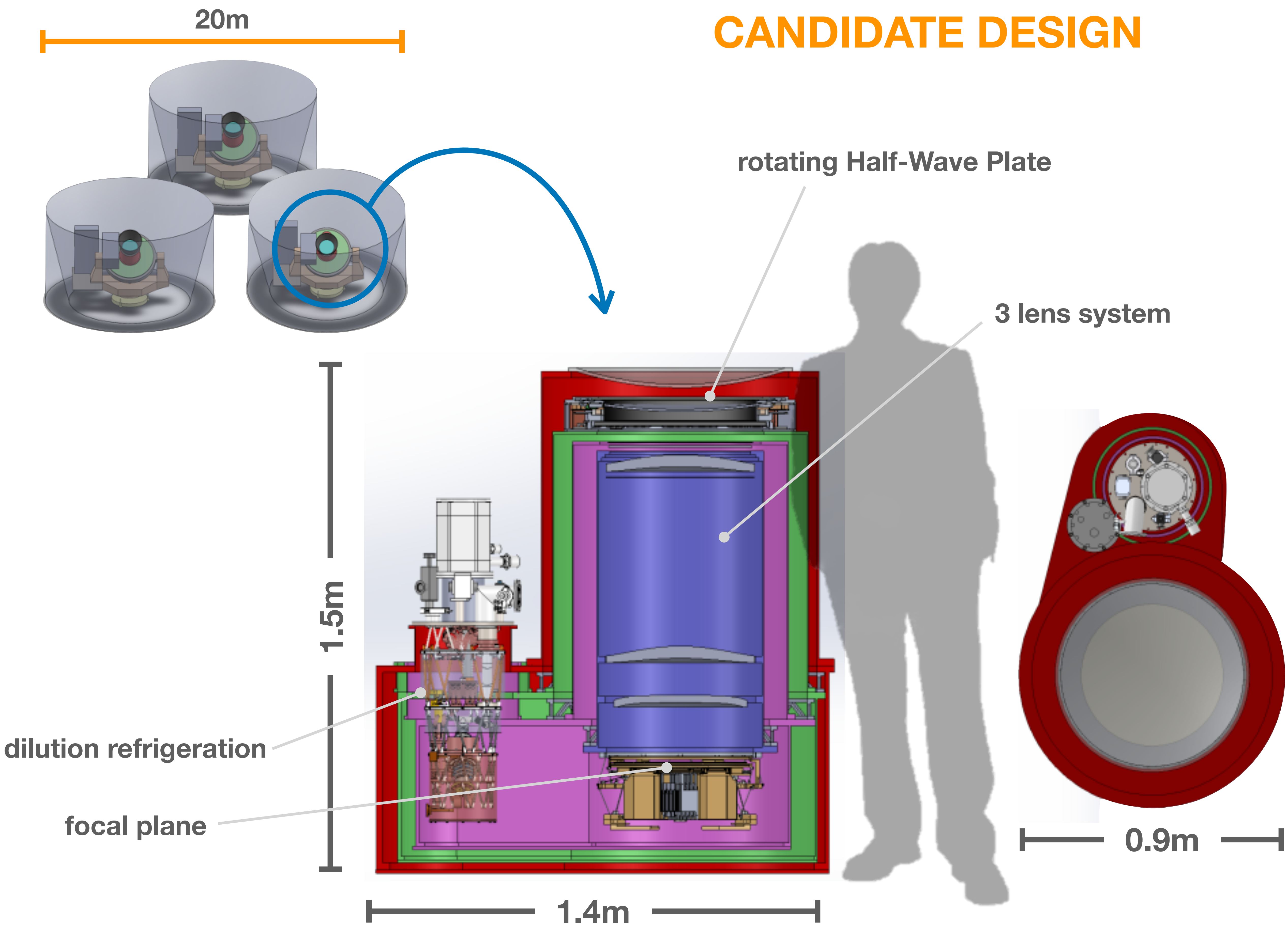


for Simons Observatory Large Aperture:
~21 wafers ➔ ~30,000 detectors

The Simons Observatory Large Aperture receiver

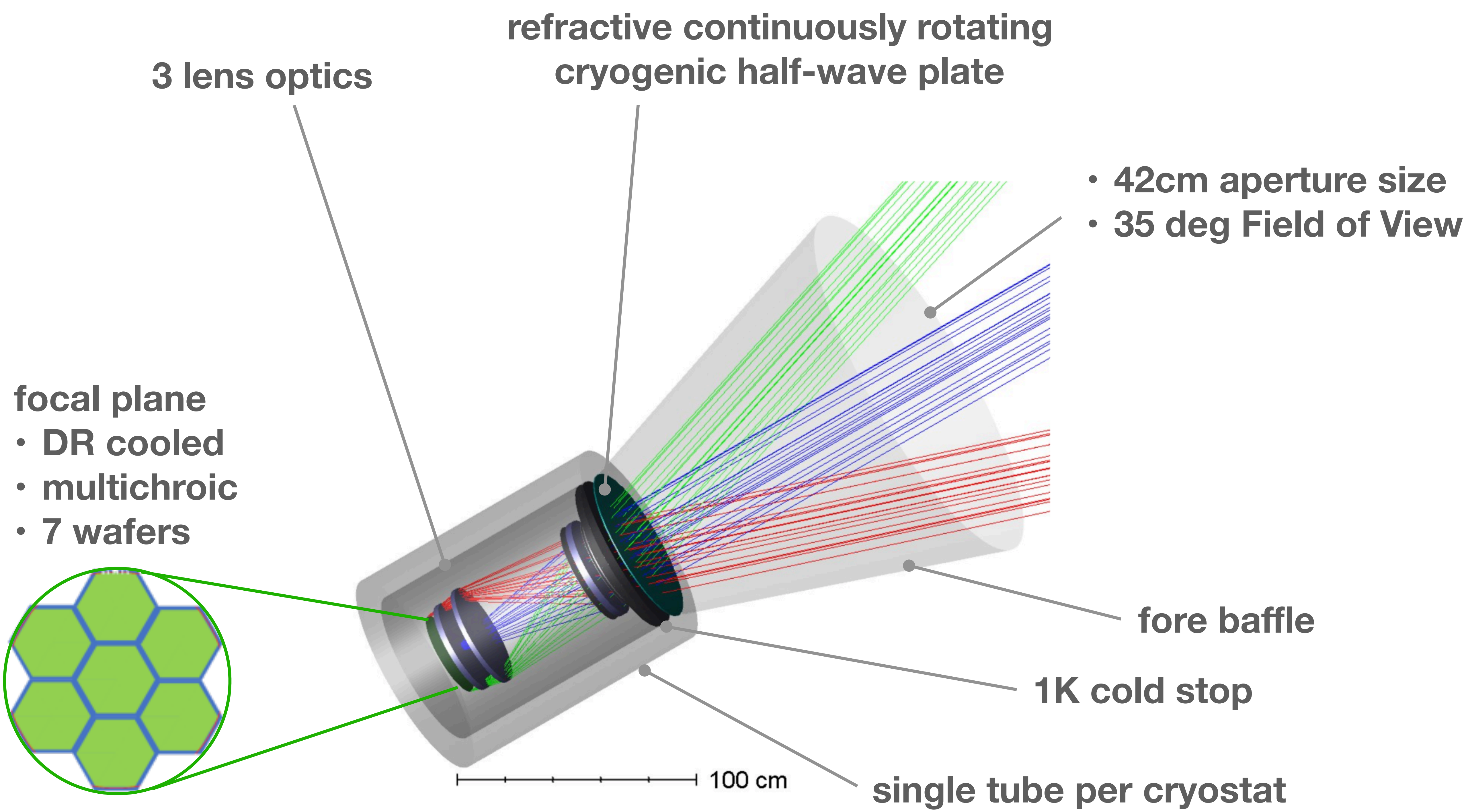


The Simons Observatory Small Aperture Camera



The Simons Observatory Small Aperture Camera

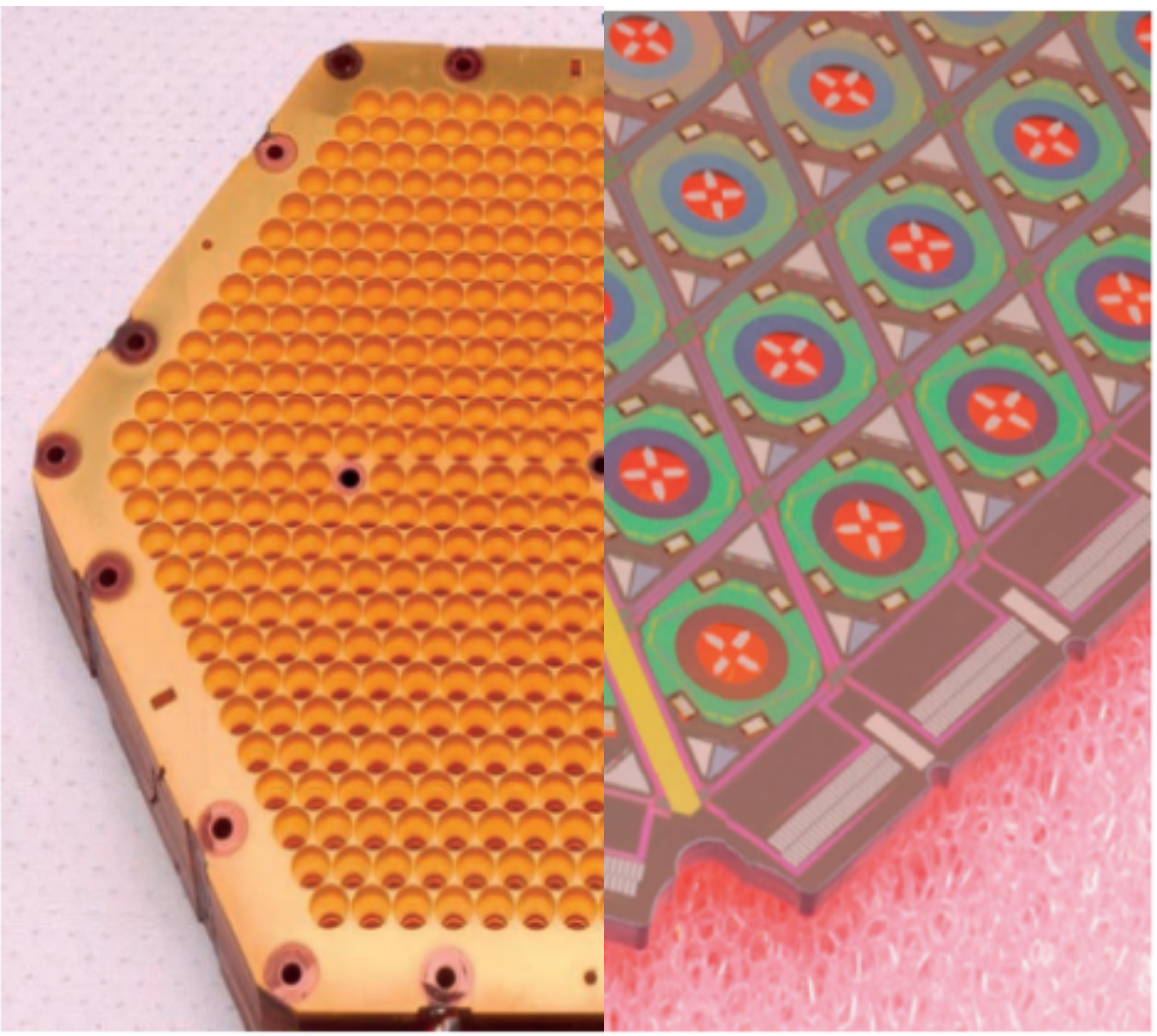
PRELIMINARY DESIGN



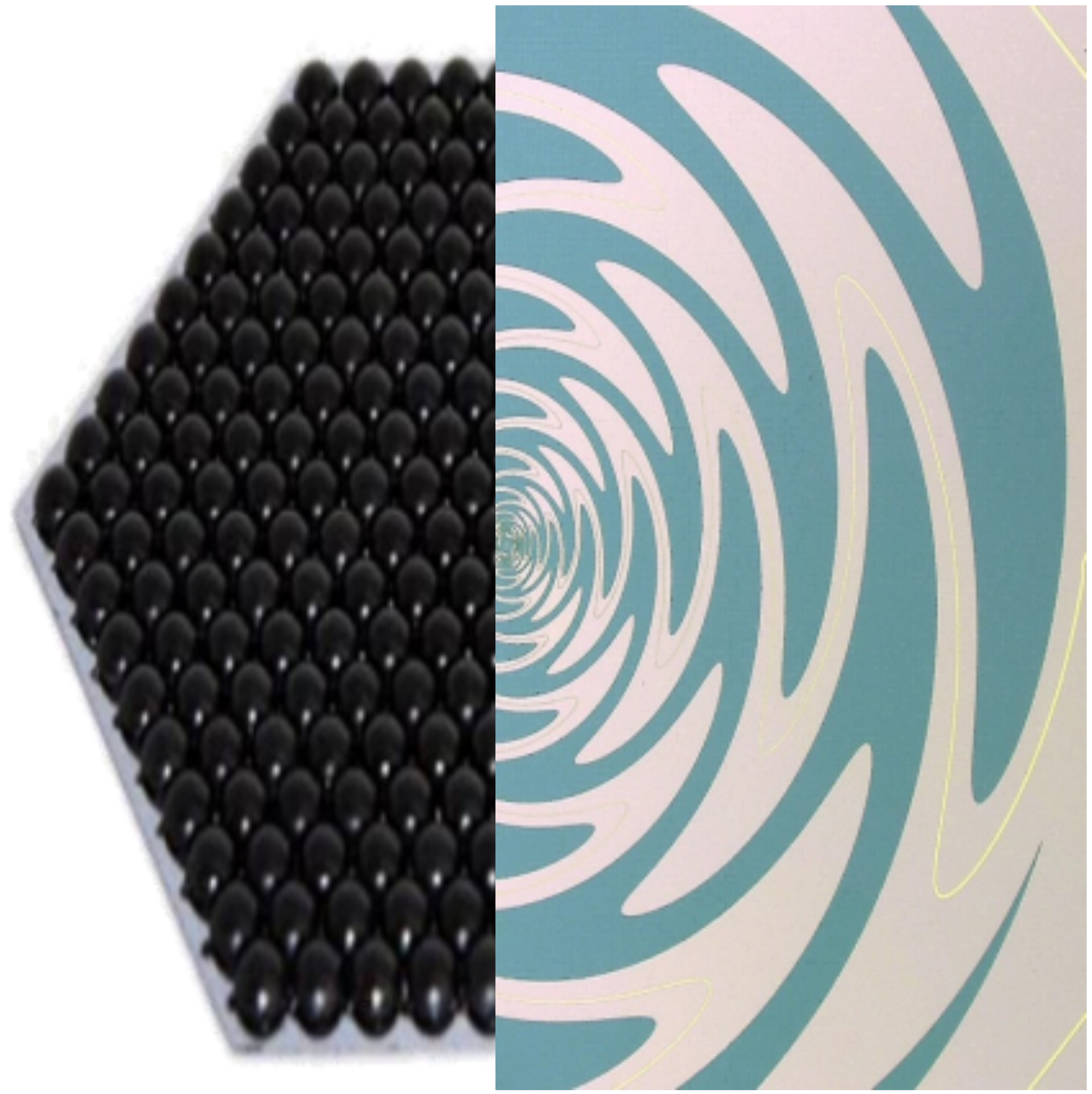
for Simons Observatory: ~21 wafers ➔ ~30,000 detectors

The Simons Observatory Detectors

two detector architectures



Spline Horn Array
(NIST)

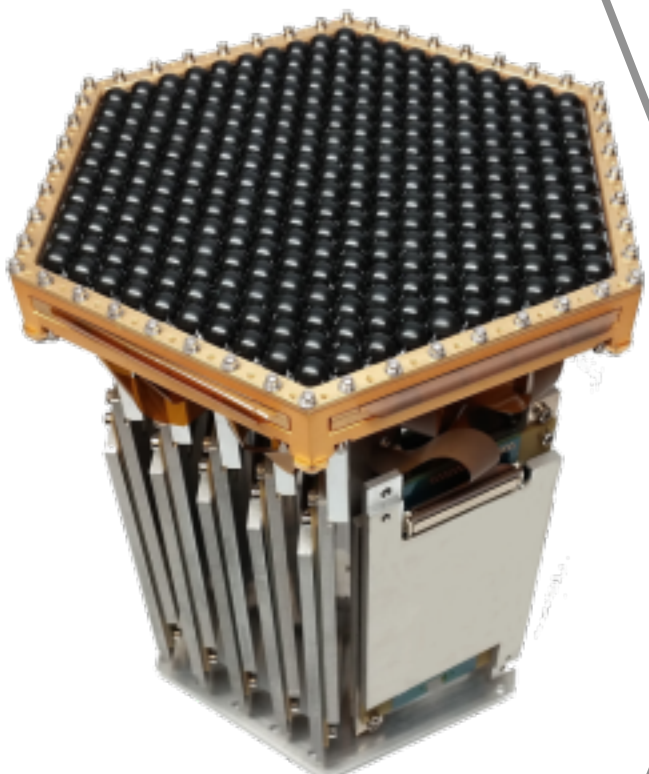


Sinuous antenna + lenslet array
(Berkeley)

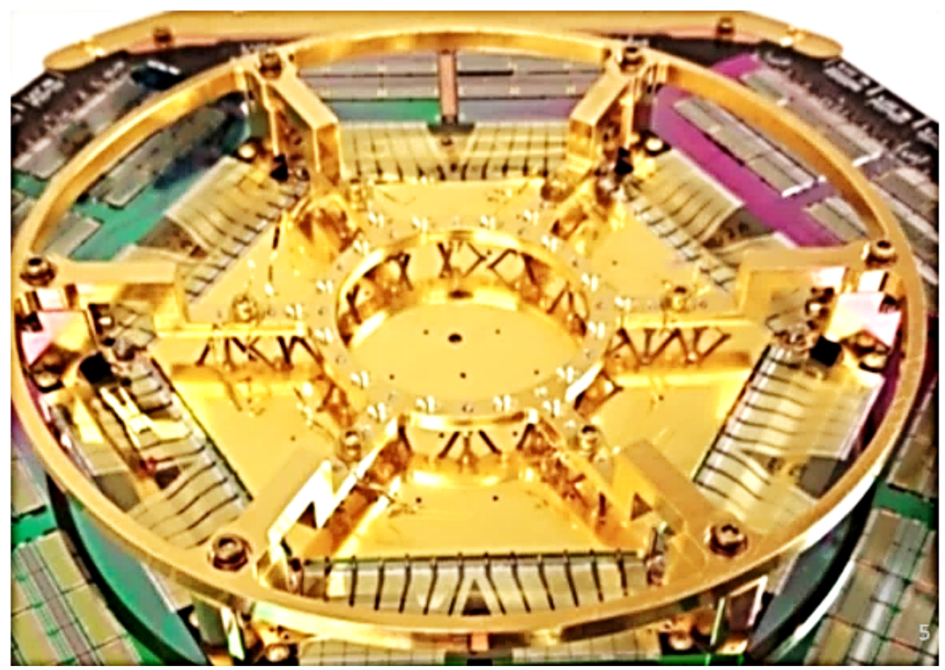
The Simons Observatory Detectors

universal focal plane module (UFM)

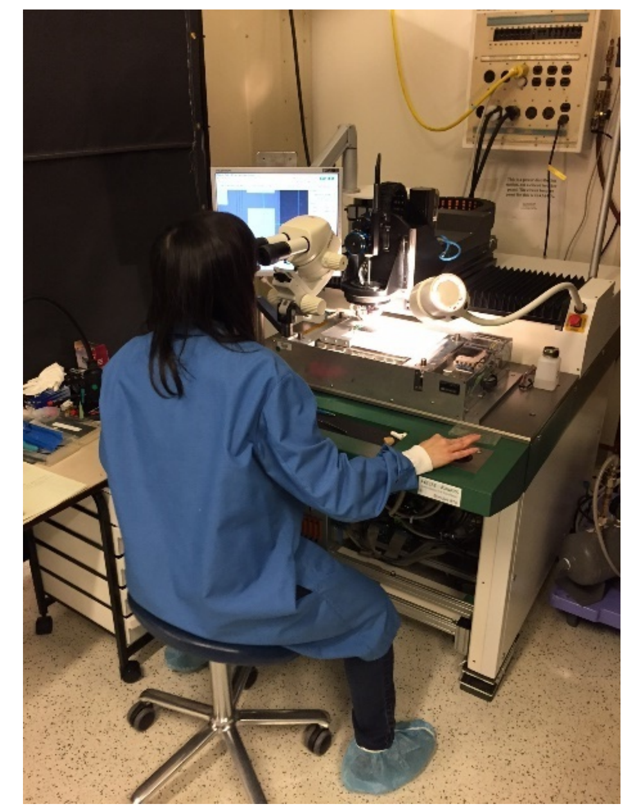
both horn and sinuous/lenslet arrays



detector module



detectors with readout cables

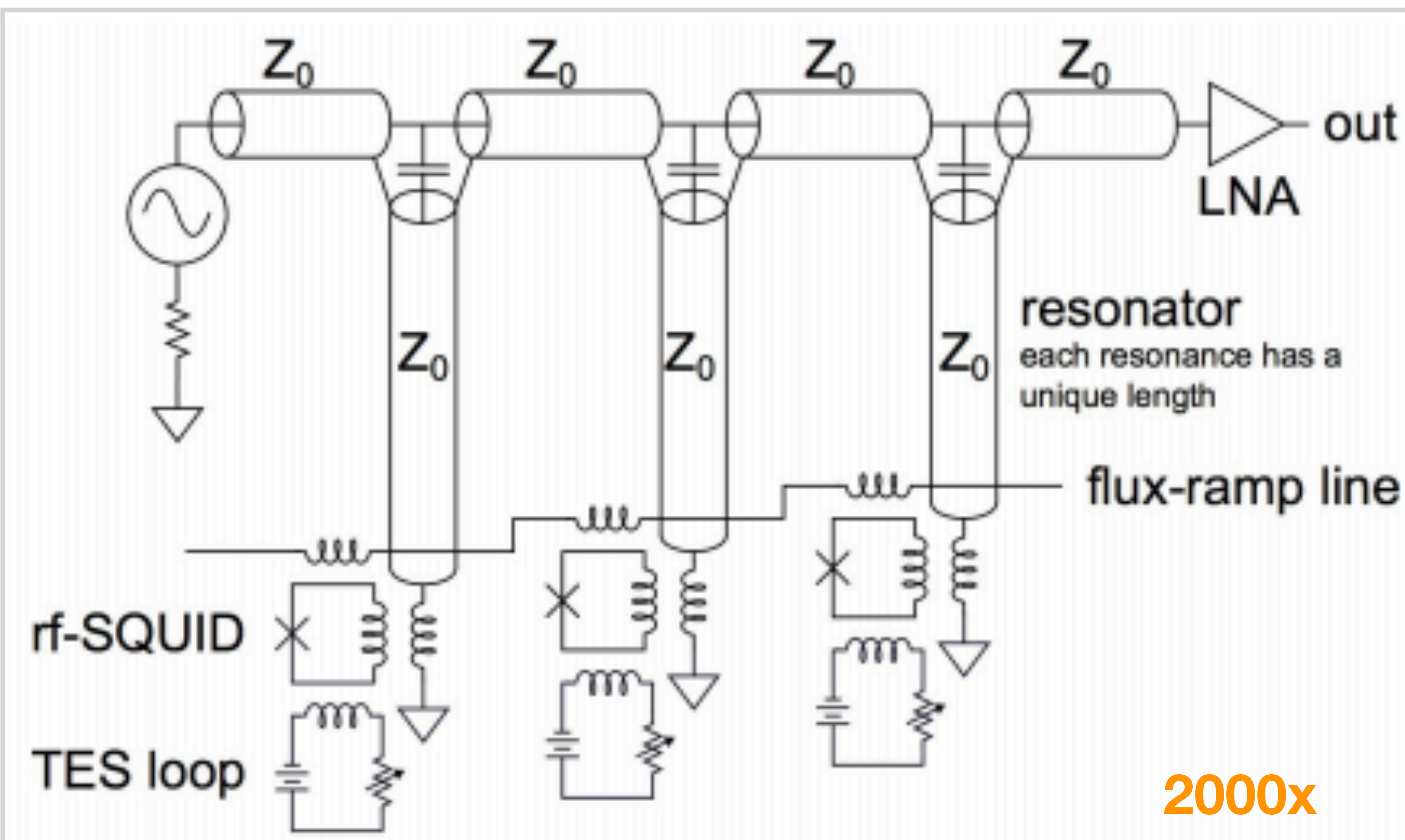


automatic wire bonder

both detector technologies can be read out with the same frequency multiplexing system

The Simons Observatory Detector Readout

- Frequency domain multiplexing
- Send in a comb of narrow frequency bands (tones)
- Each detector is coupled to a resonant circuit such that its output signal is converted to a change in the resonance of the circuit



uMux – current through the TES couples flux into a flux-variable inductor in an LC circuit

The Simons Observatory Calibration

we are working on requirements for bandpass measurements, gain, beams and polarization angles

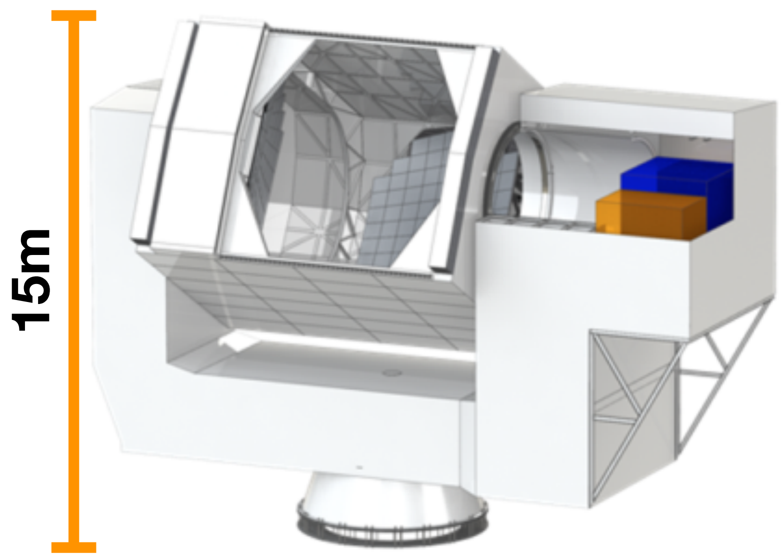
examples of recent studies

POLOCALC: a Novel Method to Measure the Absolute Polarization Orientation of the Cosmic Microwave Background
F. Nati et al (2017)

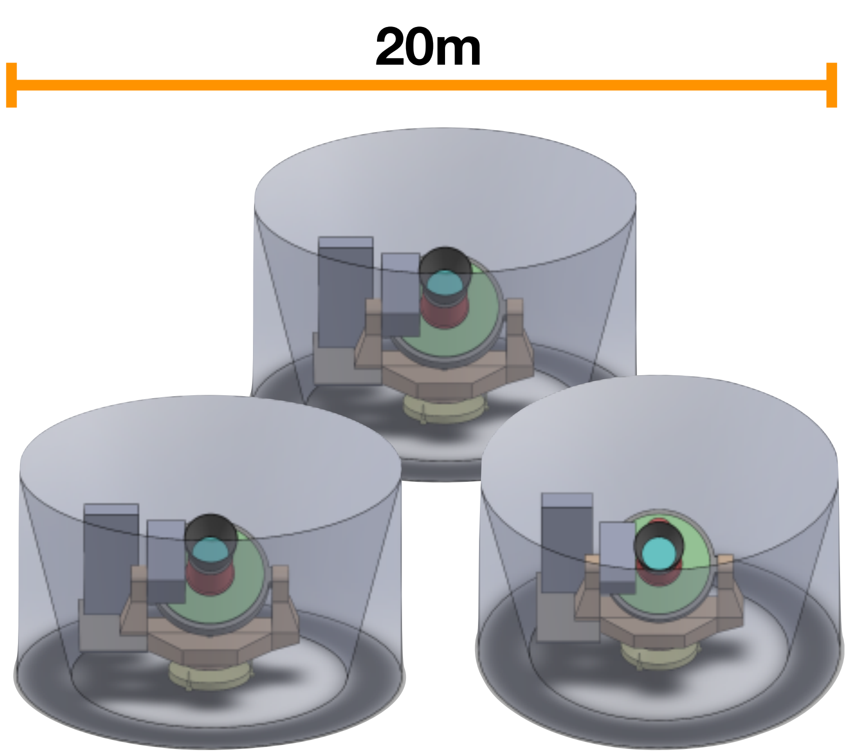
Fig. 1. Three different configurations for POLOCALC (starting from the left): 1) from a ground tripod 2) from a flying drone and 3) from a high-altitude balloon.

The Effects of Bandpass Variations on Foreground Removal Forecasts for Future CMB Experiments
Ward, Alonso, Errard, Devlin, Hasselfield [arXiv:1803.07630]

The Simons Observatory — technical summary



- 6-meter diameter Cross Dragone telescope
- 2-mirror design with a side-looking camera
- the camera rotates with the elevation axis
- the back of the camera can be accessed while installed on the telescope
- constructed by Vertex, in collaboration with CCAT
- 1.4’ FWHM @ 150GHz
- 2.8 m x 2.5 m / 5,000kg cryostat
- 70,000+ detector capacity (30,000 planned for SO)
- modular design receiver for optics tube



- 42 cm aperture size, 35 degree FoV
- 30,000 detectors for SO
- continuously rotating HWP
- 4.2 meter high, 7 meter diameter ground shield

SO deliverables for small + large apertures

~ 42 wafers → 60,000 detectors