Fundamental Physics from CMB: Next Steps

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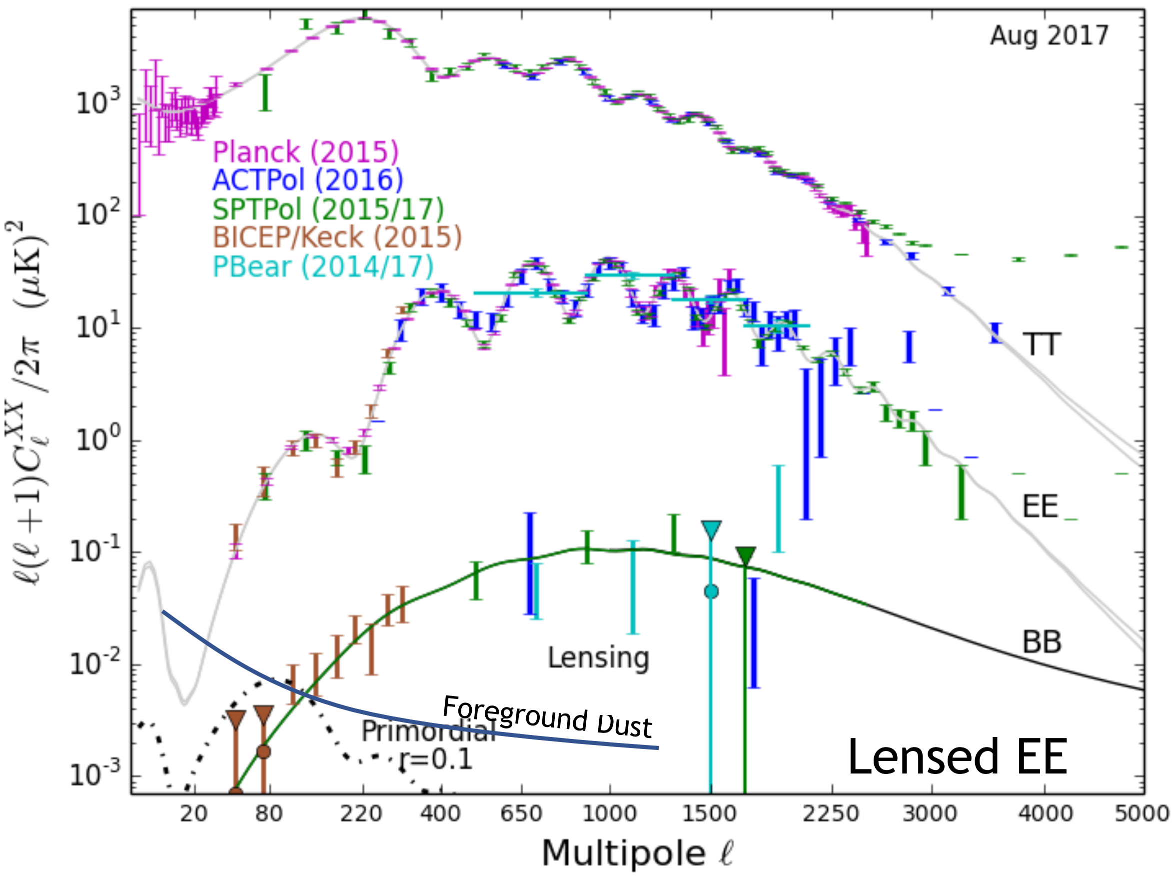
Where are we?

- Over the past 30 years, our measurements of the cosmic microwave background fluctuations continue to improve.
- Planck has measured temperature to the cosmic variance limit on scales dominated by primordial fluctuations
- Precision polarization measurements on both large and small scales are the next frontier
- High resolution temperature measurements will provide ia detailed picture of the large-scale distribution of mass, momentum and pressure

State of the Field

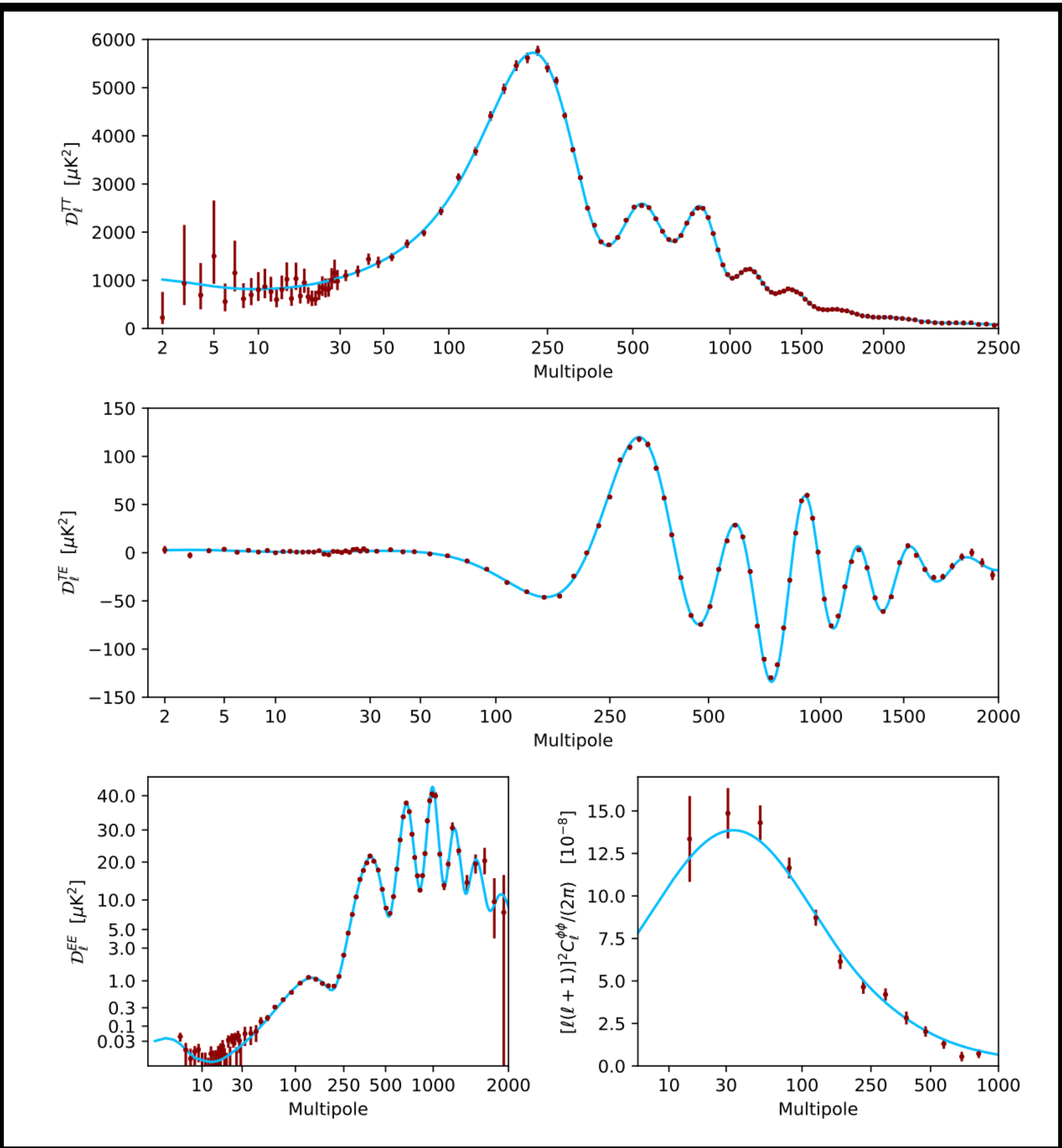


Compiled by L. Page

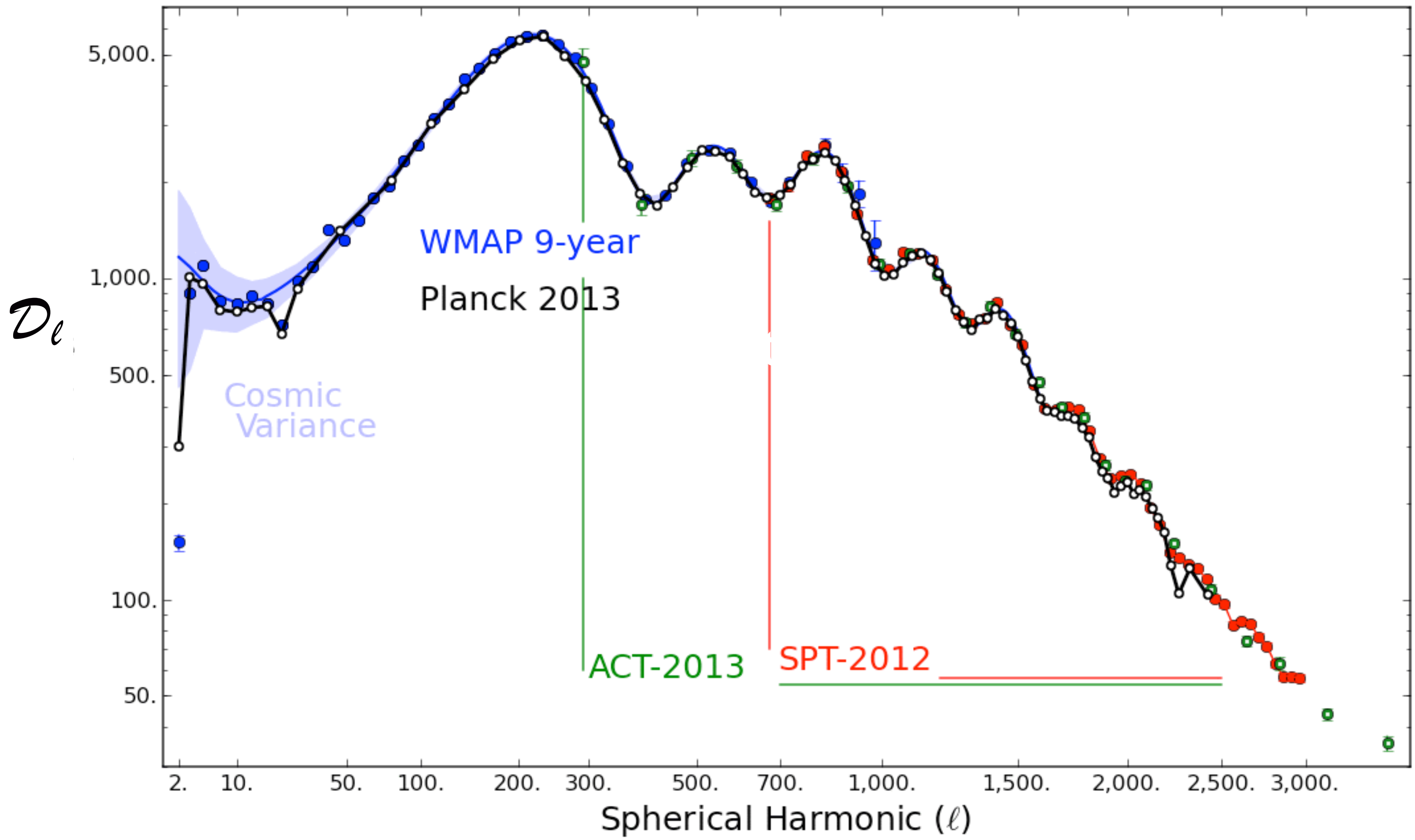
Where do we go from here?

Simplicity!


Happy Birthday
KICC


$\mathcal{D}_\ell^{TT}$ [μK^2]
Multipole
$\mathcal{D}_\ell^{TE}$ [μK^2]
Multipole
$\mathcal{D}_\ell^{EE}$ [μK^2]
Multipole
$[\ell(\ell+1)]^2 C_\ell^{\phi\phi}/(2\pi)$ [10^{-8}]
Multipole

LCDM Model Fits CMB



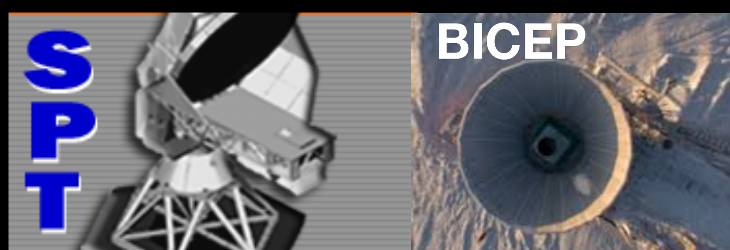
And most other cosmological data*

Fundamental Questions

- How did the universe begin?
- What is it made of?
  - What is the dark matter?
  - What is the dark energy?
- What are its properties?
  - Search for neutrino mass
  - New relativistic species
  - Search for new physics

SIMONS OBSERVATORY

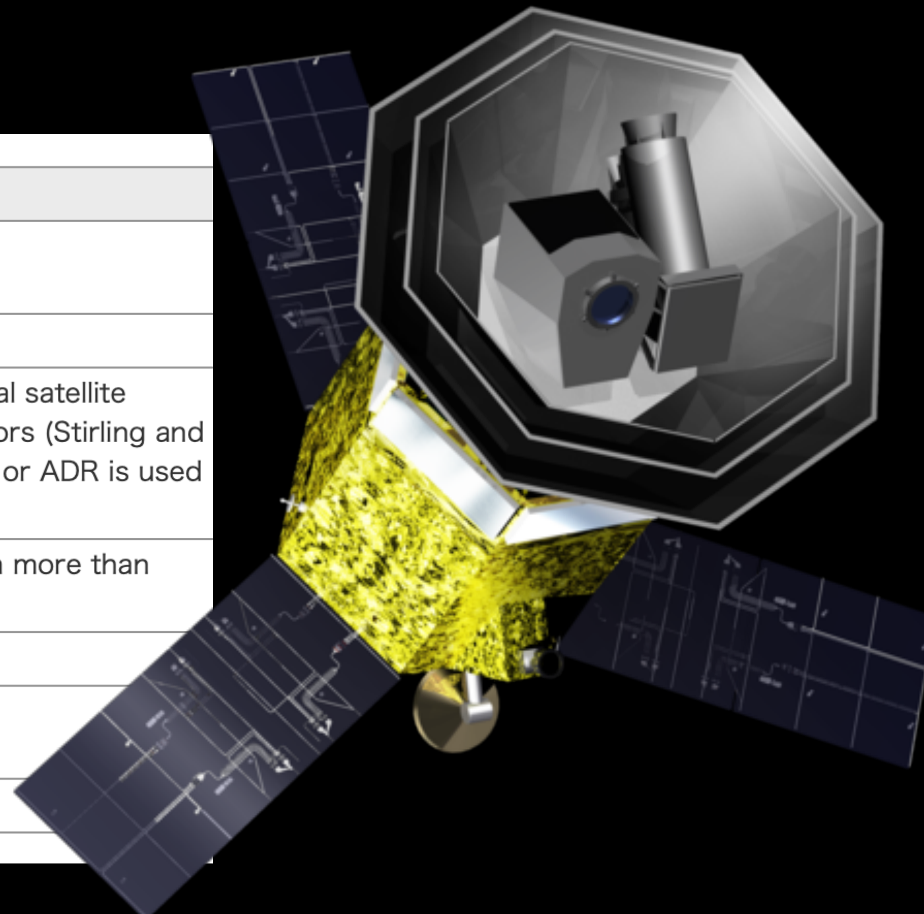
Funded
First light:2021



South Pole Observatory

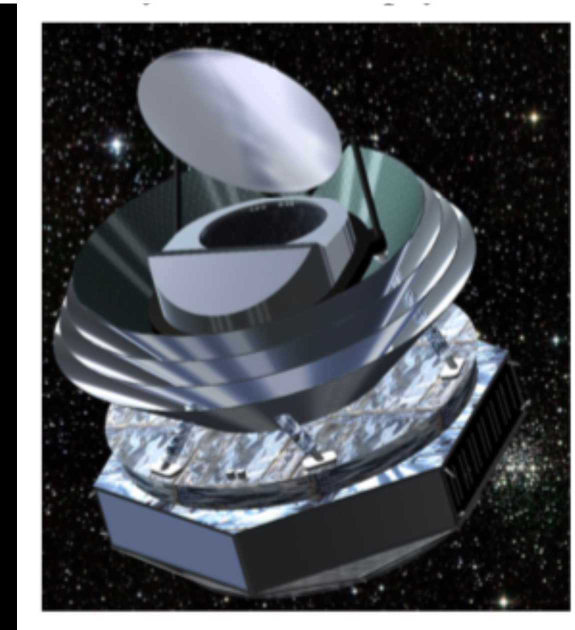
LiteBIRD

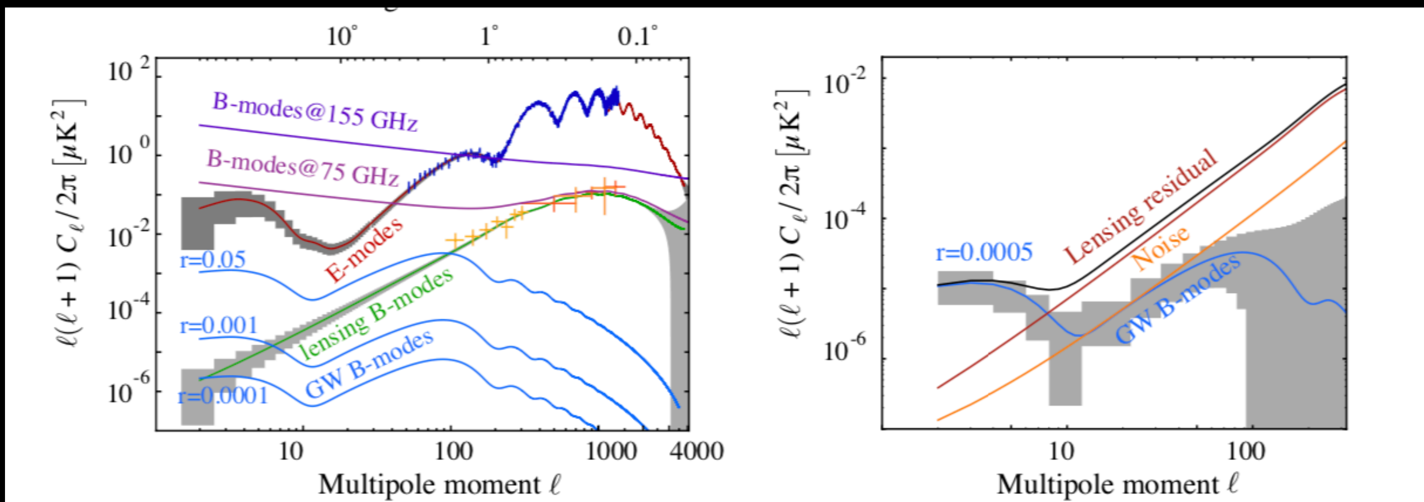
Item	Specification
Observation duration	3 years
Orbit	Sun–Earth L2
Cooling system	Similarly to pre-cooling method of infrared astronomical satellite SPICA, use radiative cooling and mechanical refrigerators (Stirling and JT) without cryogen. Cool in space after launch. CCDR or ADR is used to cool the focal plane down to 0.1 K.
Focal-plane detector	Multi-chroic superconducting detector (TES) array with more than 3000 bolometers
Sensitivity	3 micro-Kelvin x arcmin
Observing frequencies	15 bands between 34 and 448 GHz
Modulation	Satellite spin and half-wave-plate modulation



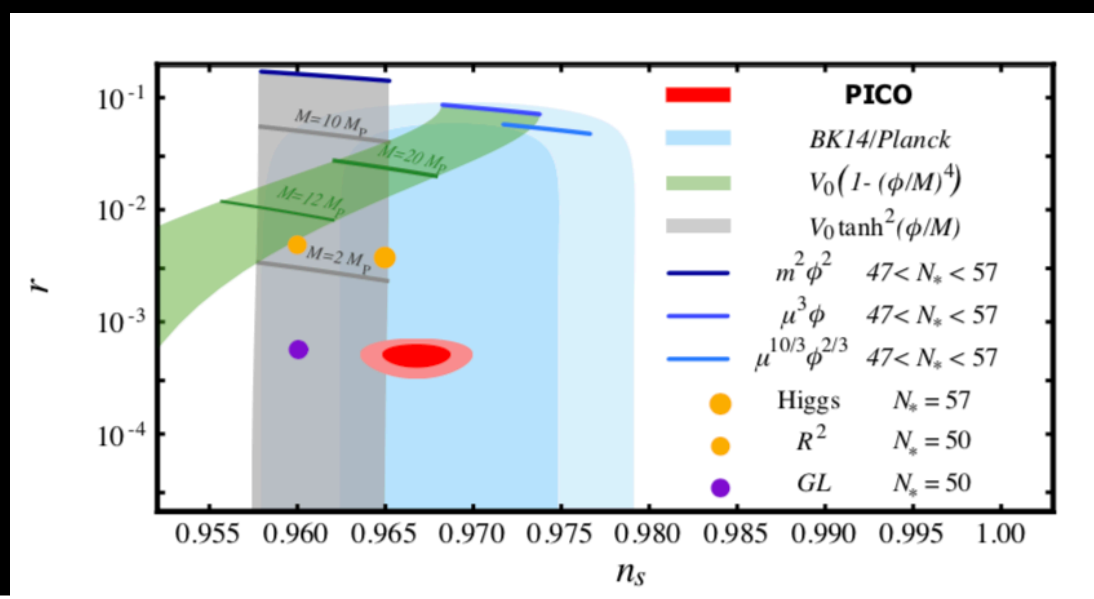
Selected by ISAS as a large strategic mission

PICO





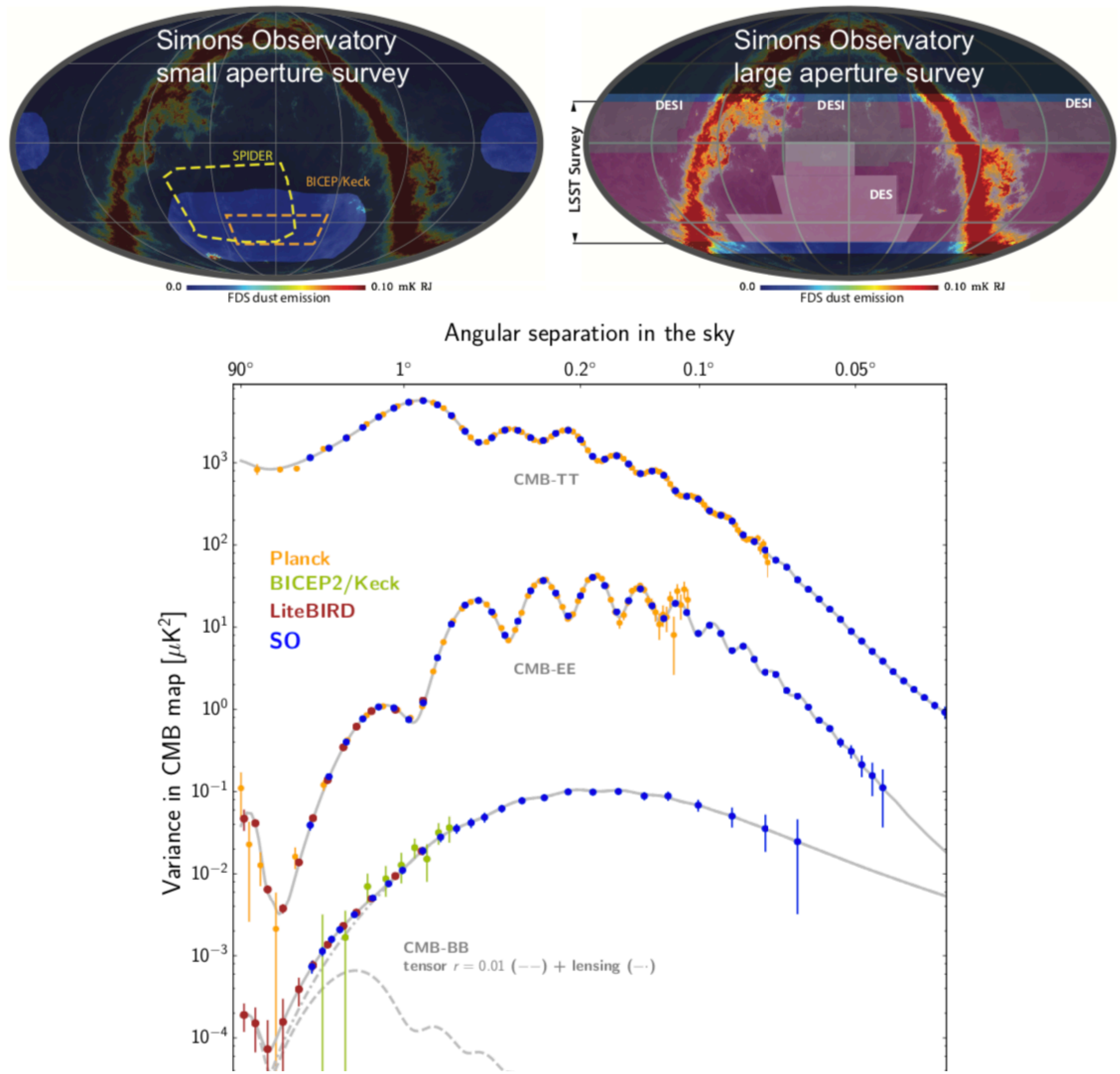
Hanany et al. 2019



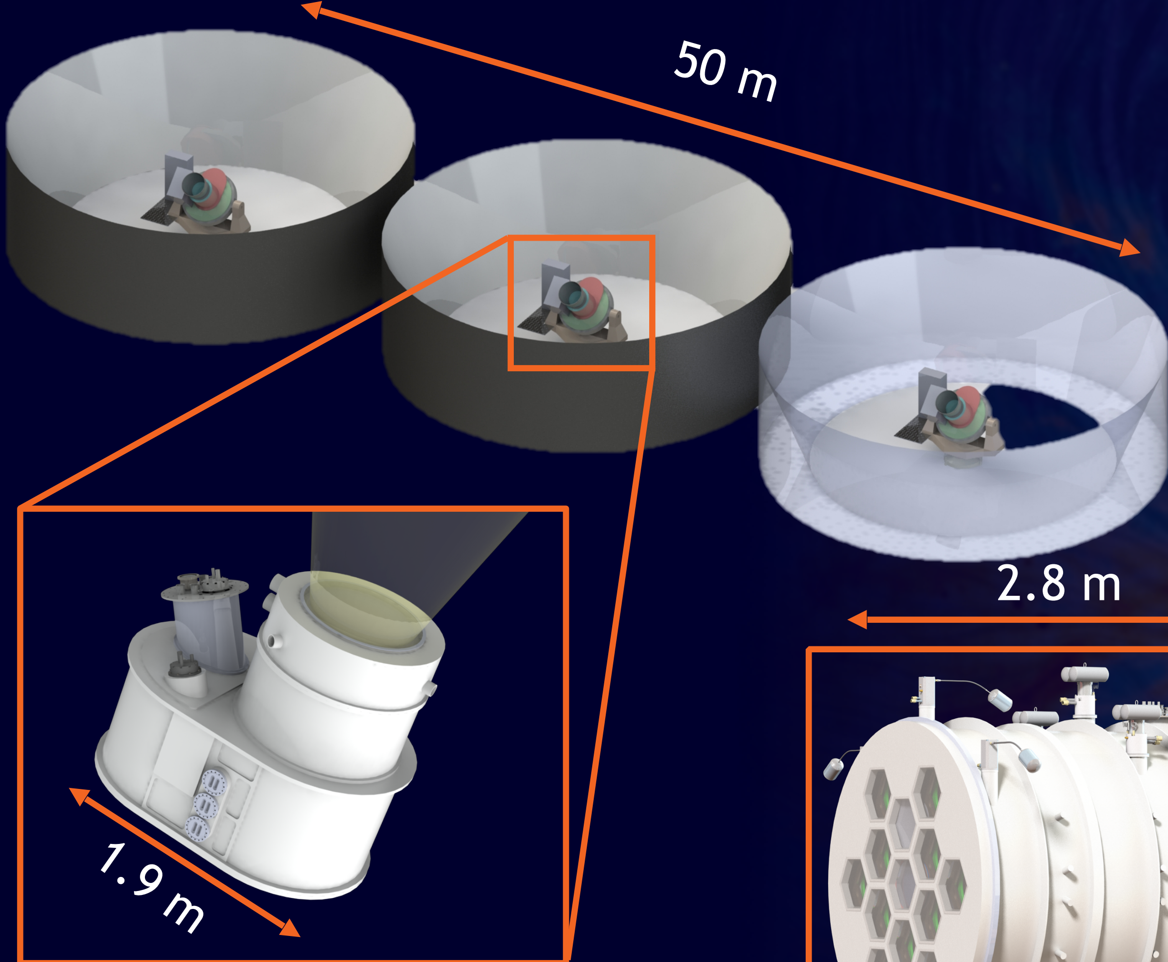
SO - Atacama Desert, Chile

SO is aiming for first light in 2021

SO development is a major step towards CMB-S4 in Chile!


Simons Observatory
small aperture survey
SPIDER
BICEP/Keck
0.0
FDS dust emission
0.10 mK RJ
Simons Observatory
large aperture survey
DESI
DESI
DESI
DES
LSST Survey
0.0
FDS dust emission
0.10 mK RJ
Angular separation in the sky
90°
1°
0.2°
0.1°
0.05°
CMB-TT
Planck
BICEP2/Keck
LiteBIRD
SO
CMB-EE
CMB-BB
tensor $r = 0.01$ (– –) + lensing (-·)
Variance in CMB map [μK^2]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}

SO – Instruments and Technology



Large Aperture Telescope

6 m crossed Dragone telescope coupled to up to 13, 38 cm optics tubes. SO baseline has 7 tubes populated with baseline dichroic pixels:

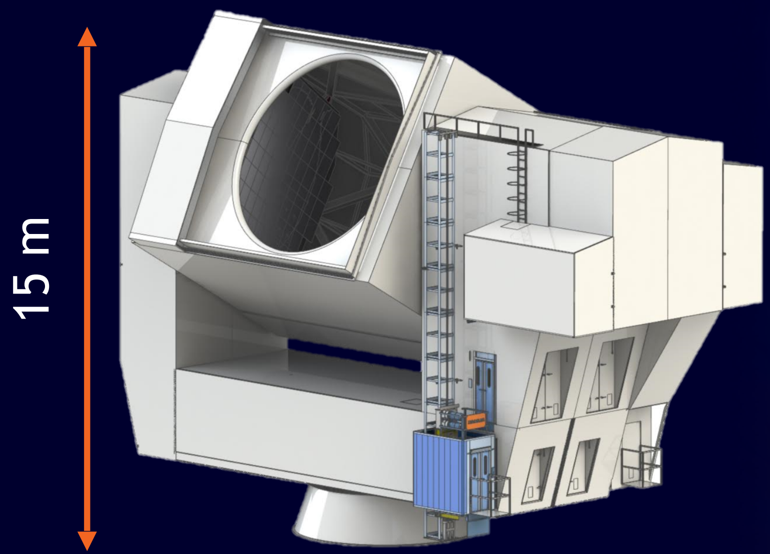
- 1 x 30/40 GHz
- 4 x 90/150 GHz
- 2 x 220/270 GHz

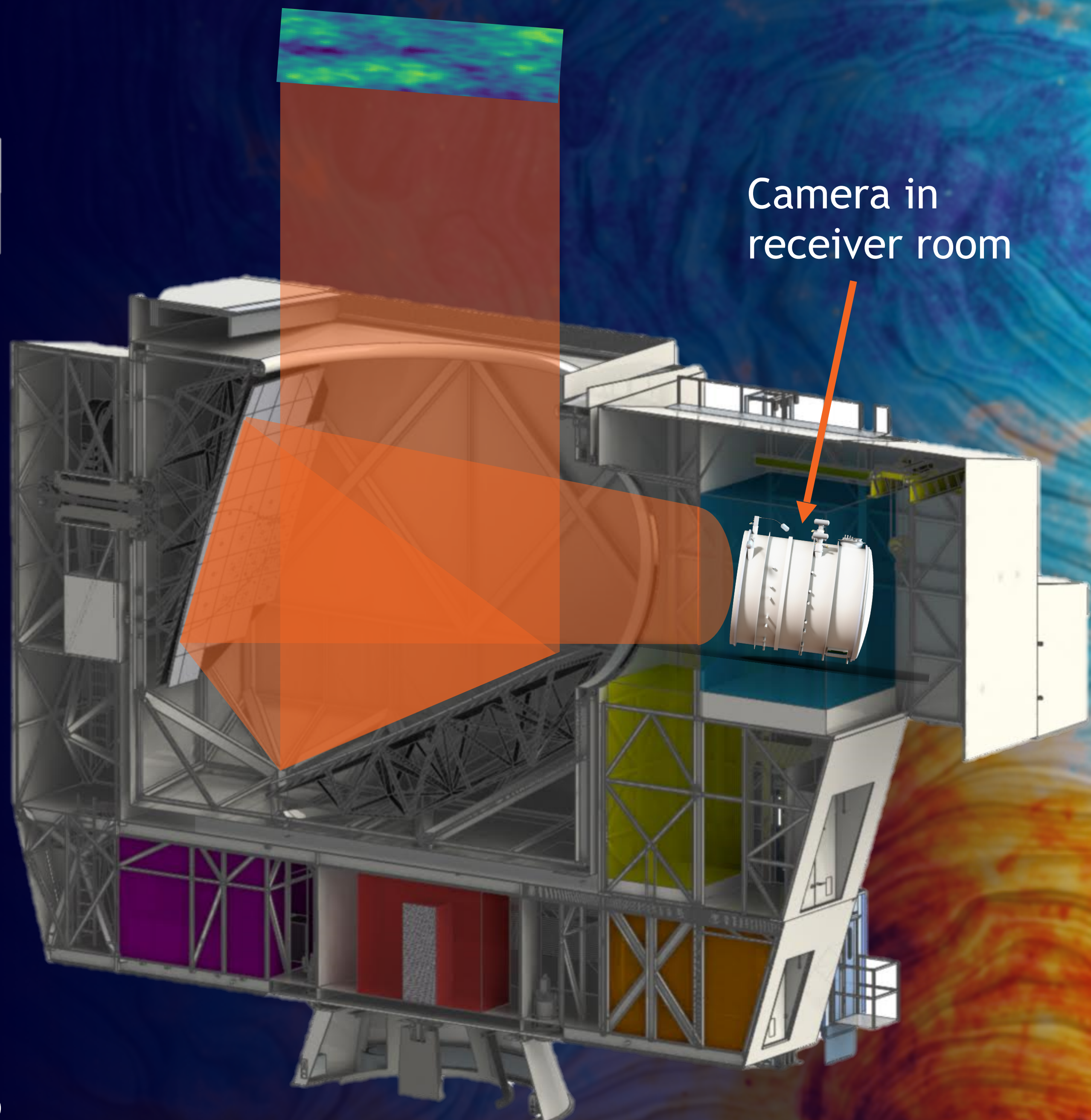
Small Aperture Telescopes

Three 42 cm aperture refractors, baseline dichroic pixels:

30/40 90/150 90/150 220/270 GHz

SO – Large Aperture Telescope

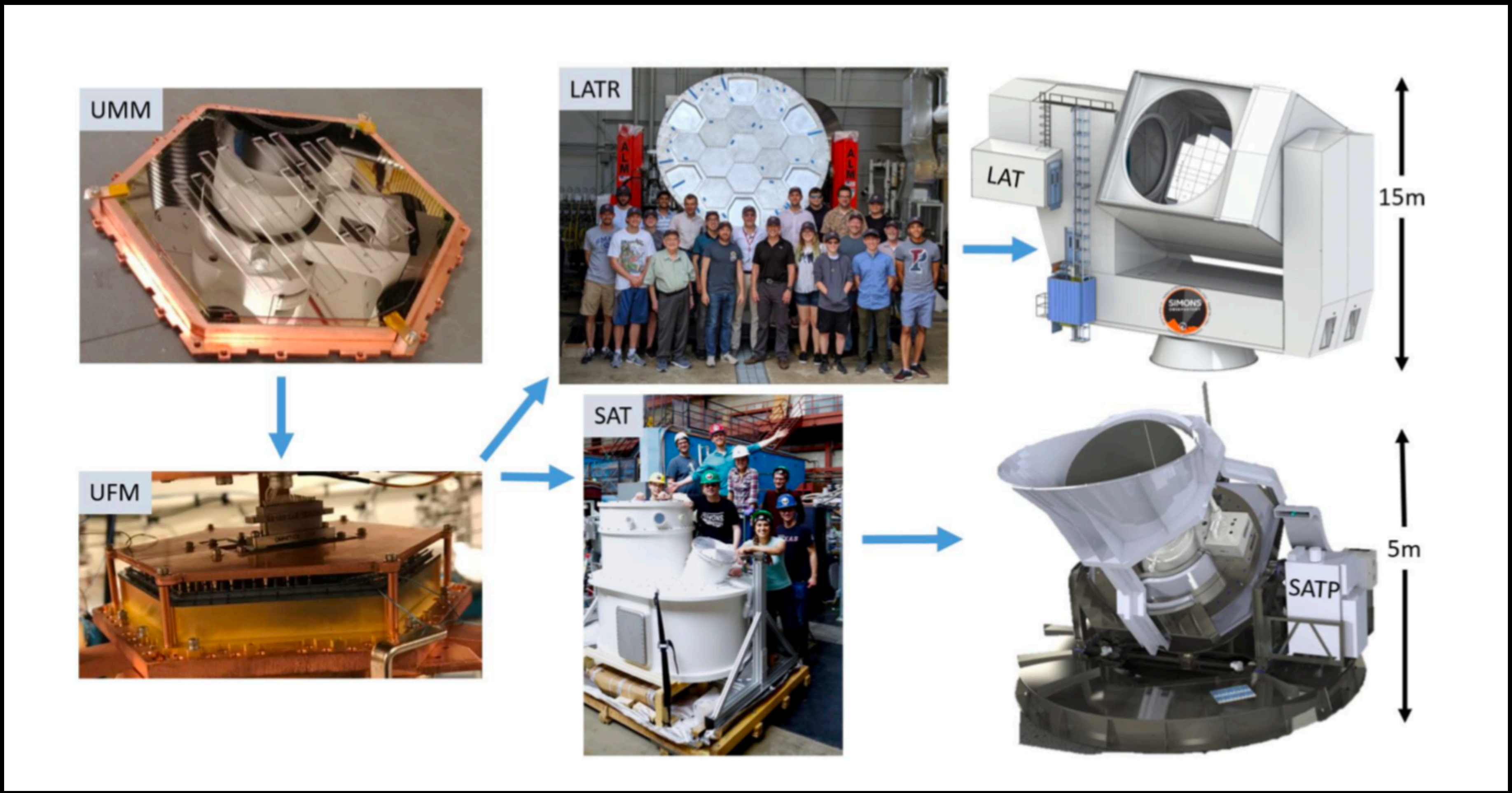




6 meter crossed Dragone telescope

- 2-mirror design with side-looking camera
- Camera rotates only around elevation axis, +/- 47 degrees
- Camera access built in
- Developed in collaboration with CCAT-p with design and manufacture by Vertex
- Telescope capable of coupling to > 100,000 detectors

Simons Observatory: Under Construction



Hopefully with significant UK contribution

CMB-S4

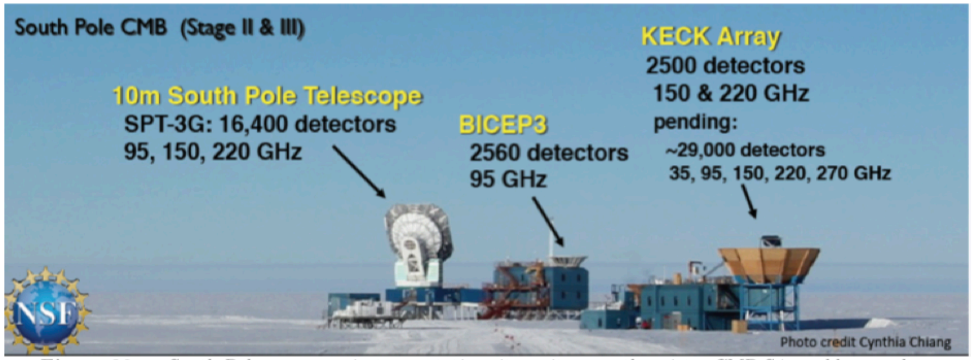


Figure 29. *South Pole mm-wave instrumentation site as it currently exists. CMB-S4 would expand on the existing infrastructure at this site.*

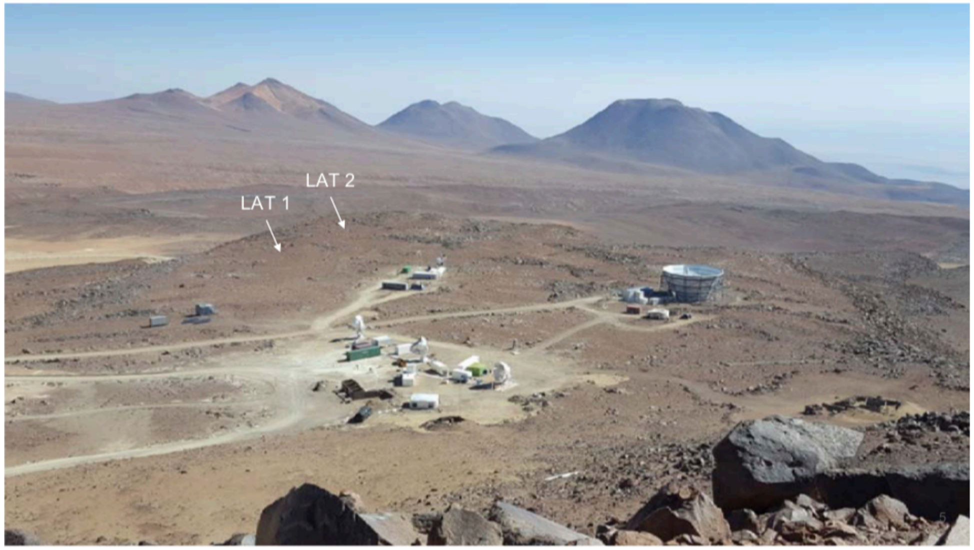


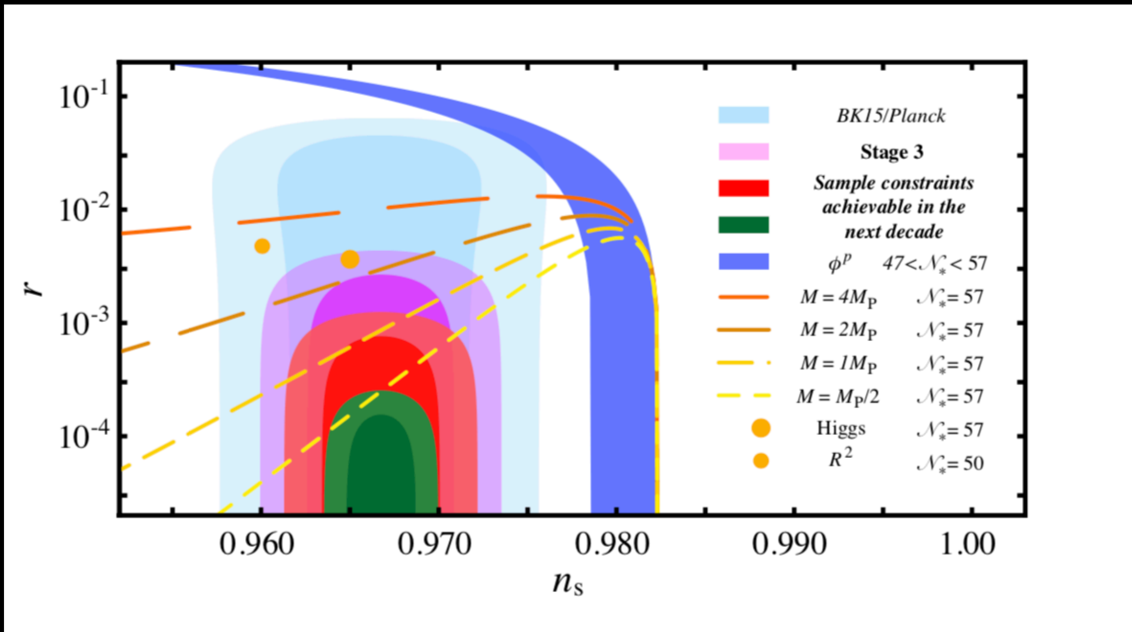
Figure 30. *CMB observatories in Chile are all at this Cerro Toco site. The white arrows indicate possible LAT locations that would not conflict with the preliminary Simons Observatory (SO) instrumentation layout.*

Site	Number of LATs	Number of SAT cryostats	Number of individual SATs
Chile	2	0	0
South Pole	1	6	18

Table 4-1. *Number of LATs and SATs at each site.*

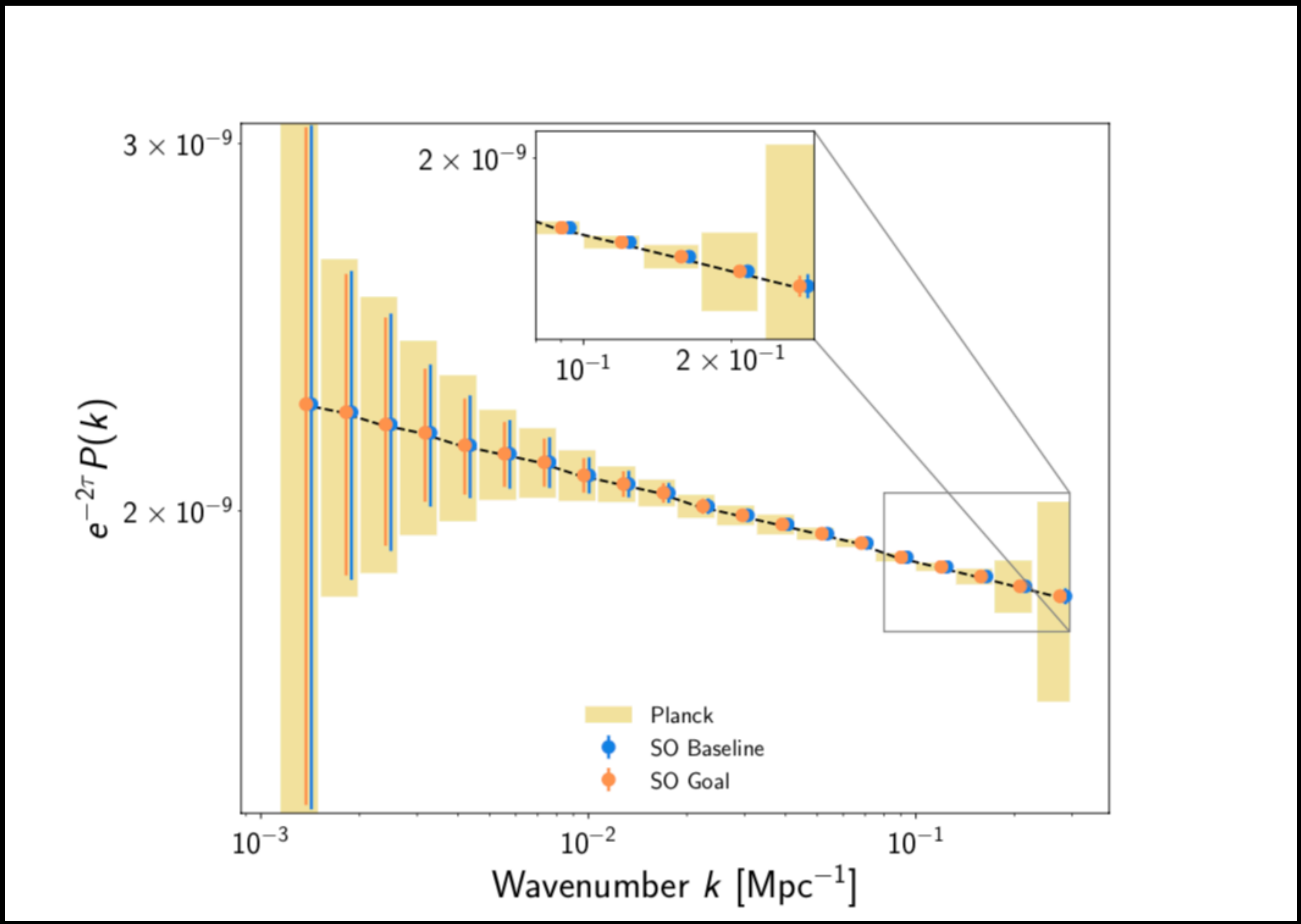
Probing the early universe

- Measuring the primordial power spectrum (scalar fluctuations)
- Detecting and measuring primordial gravitational waves
- Search for non-Gaussianities



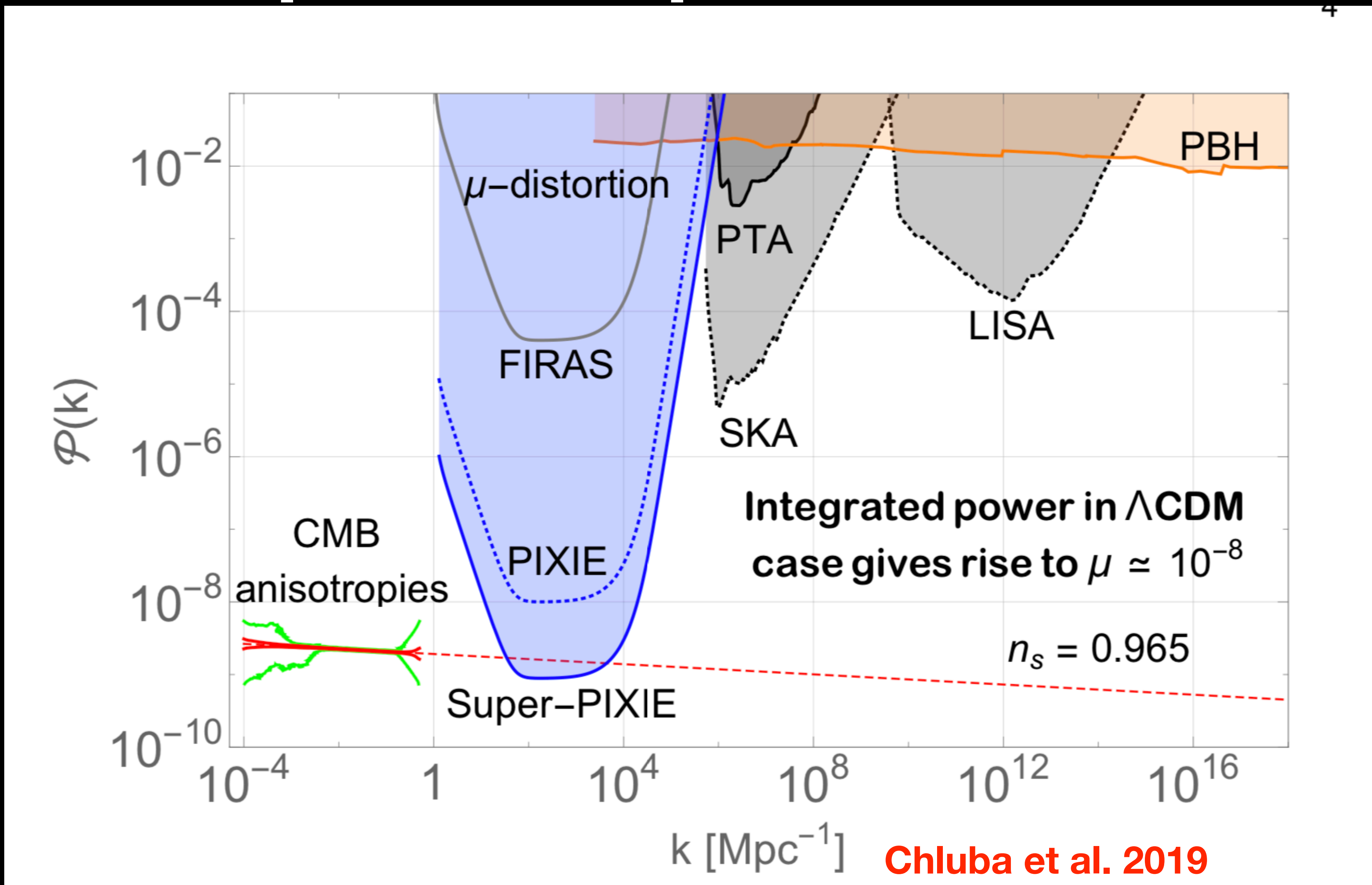
Shandera et al. 2019

Probing the primordial power spectrum

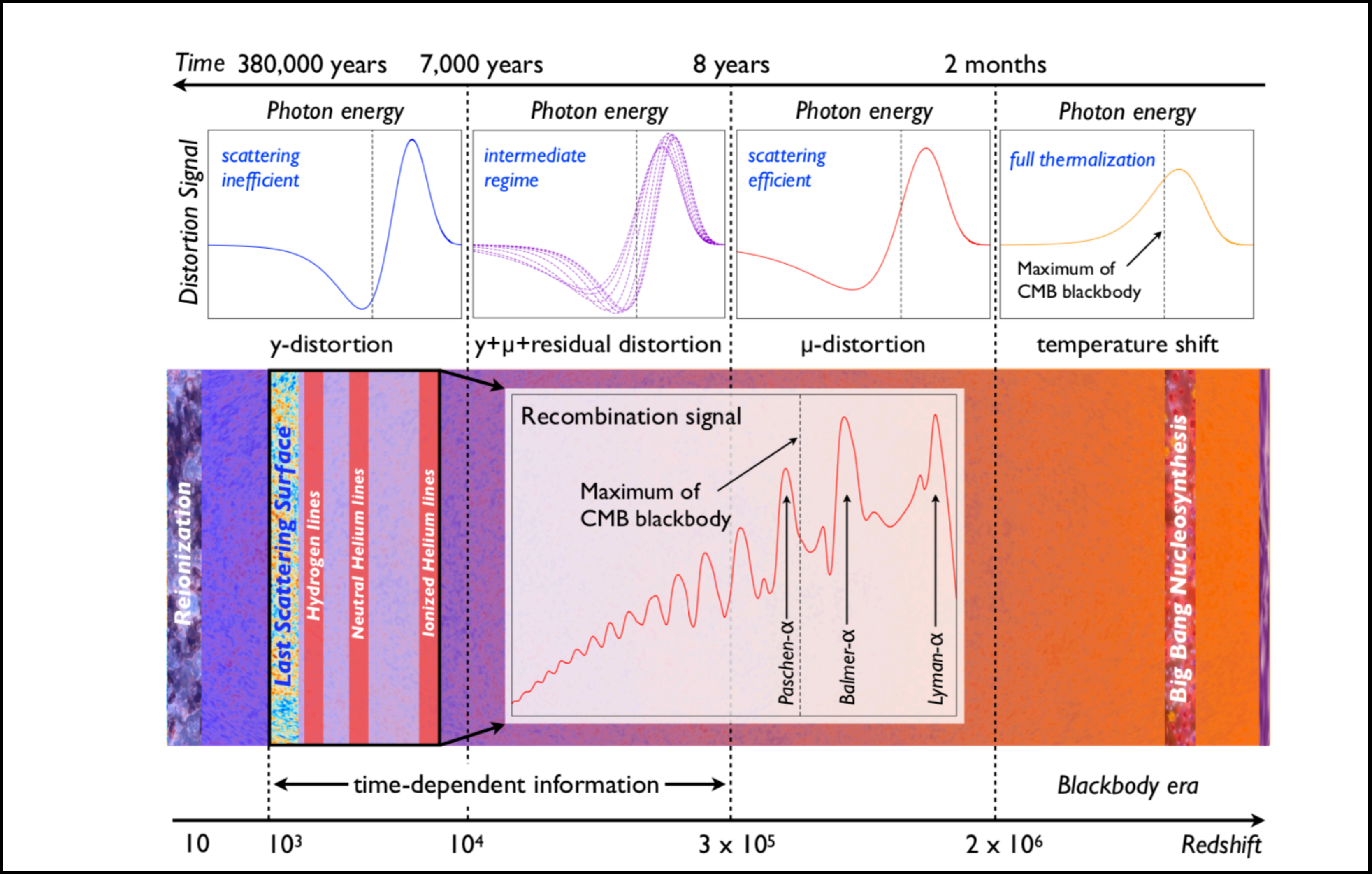


Simons Observatory Collaboration 2019

Probing the primordial power spectrum

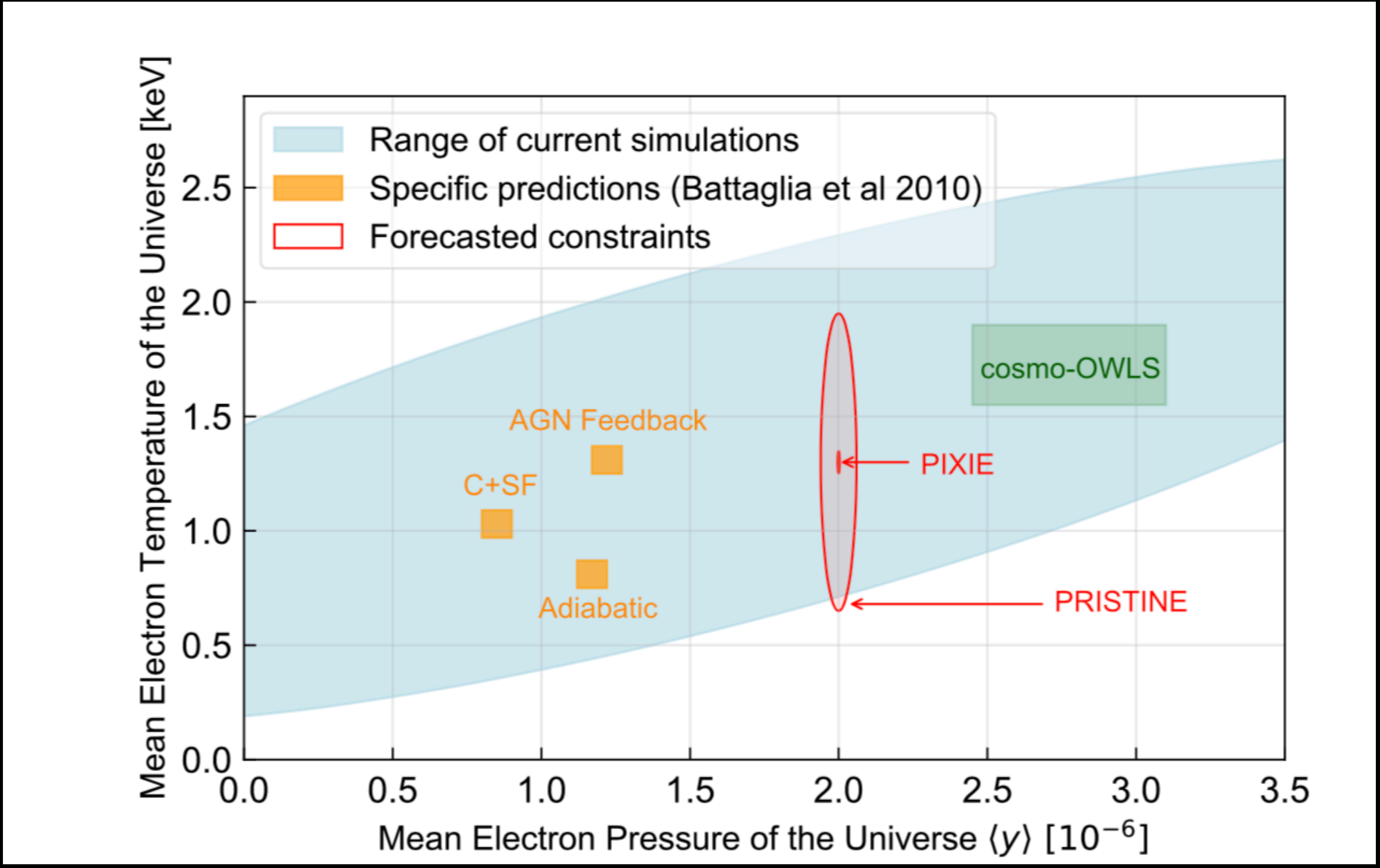


Spectral Distortions

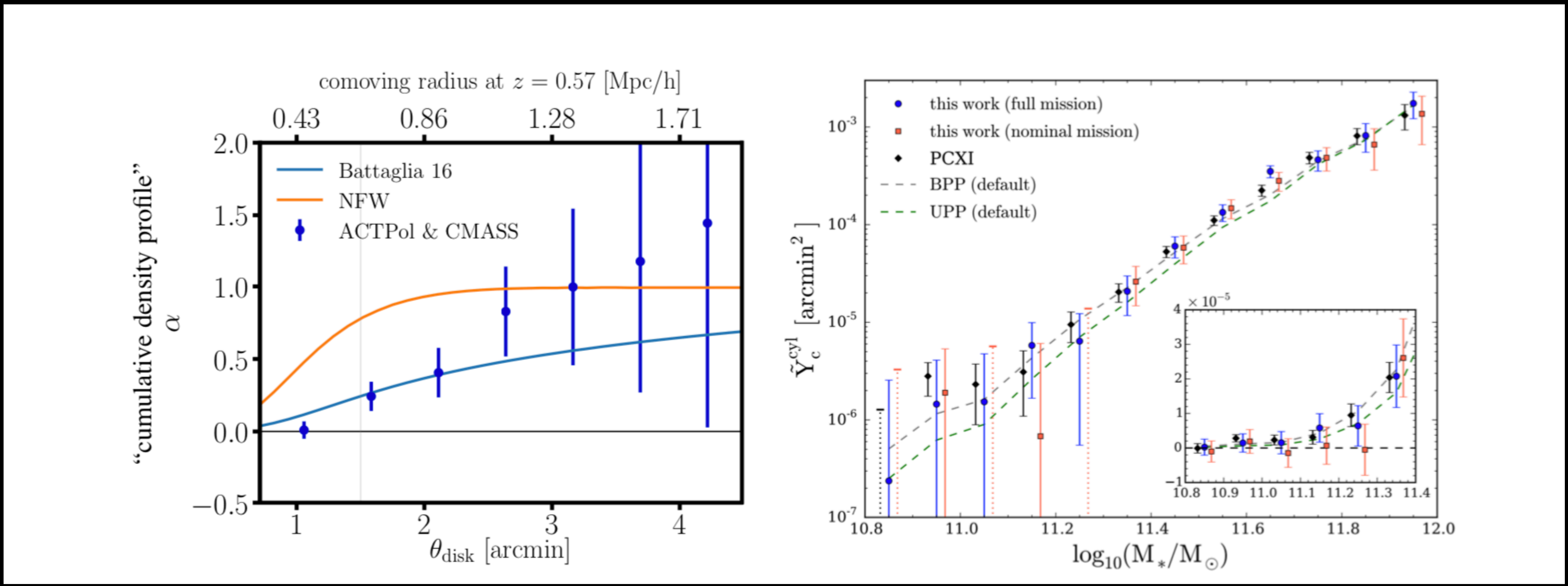


Chluba et al. 2019

Measuring the Universe's Temperature and Pressure



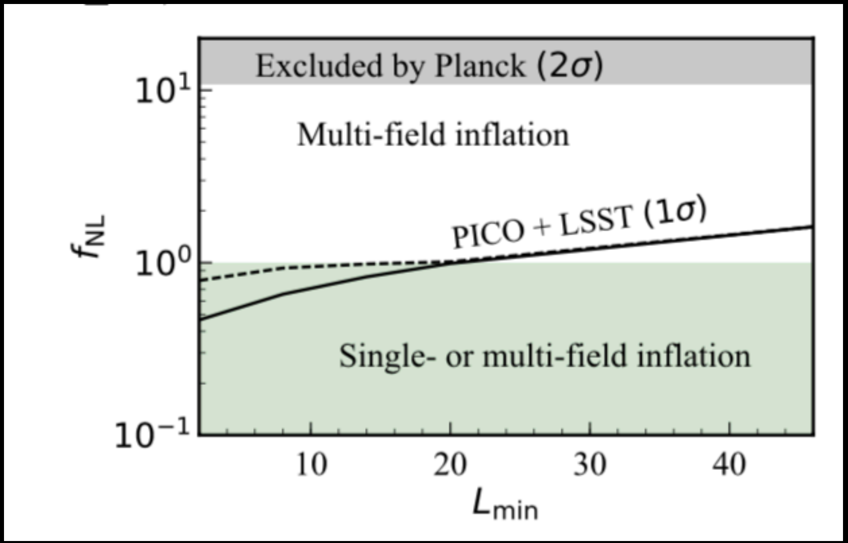
Fluctuations measure Feedback



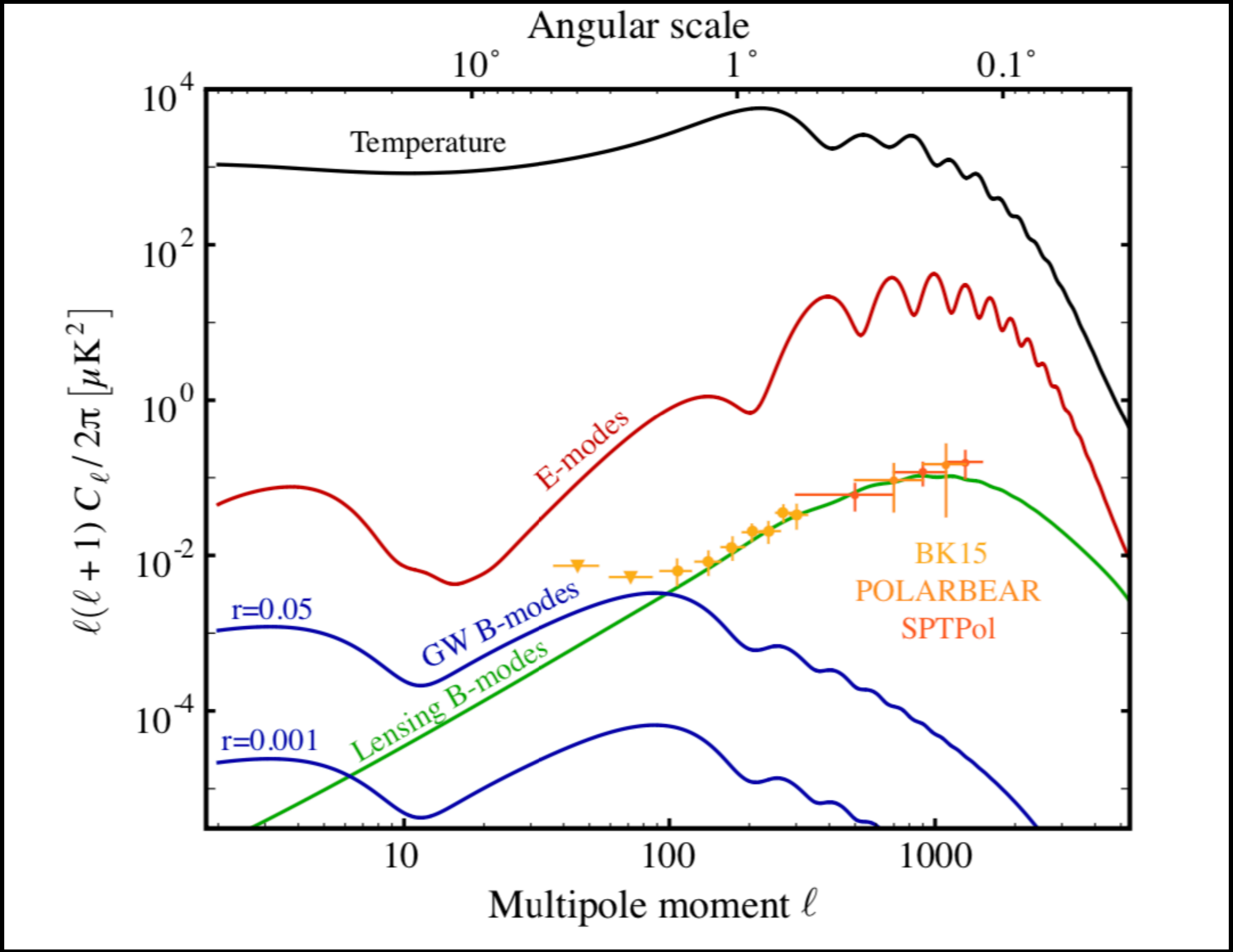
Battaglia, Hill et al. 2019

Searching for non-Gaussianities

- Inflationary self-interactions
- Additional light fields
- Additional heavy fields
- Non-trivial kinetic coupling terms



Searching for gravitational waves



CMB-S4 Collaboration 2019

Simons Observatory:

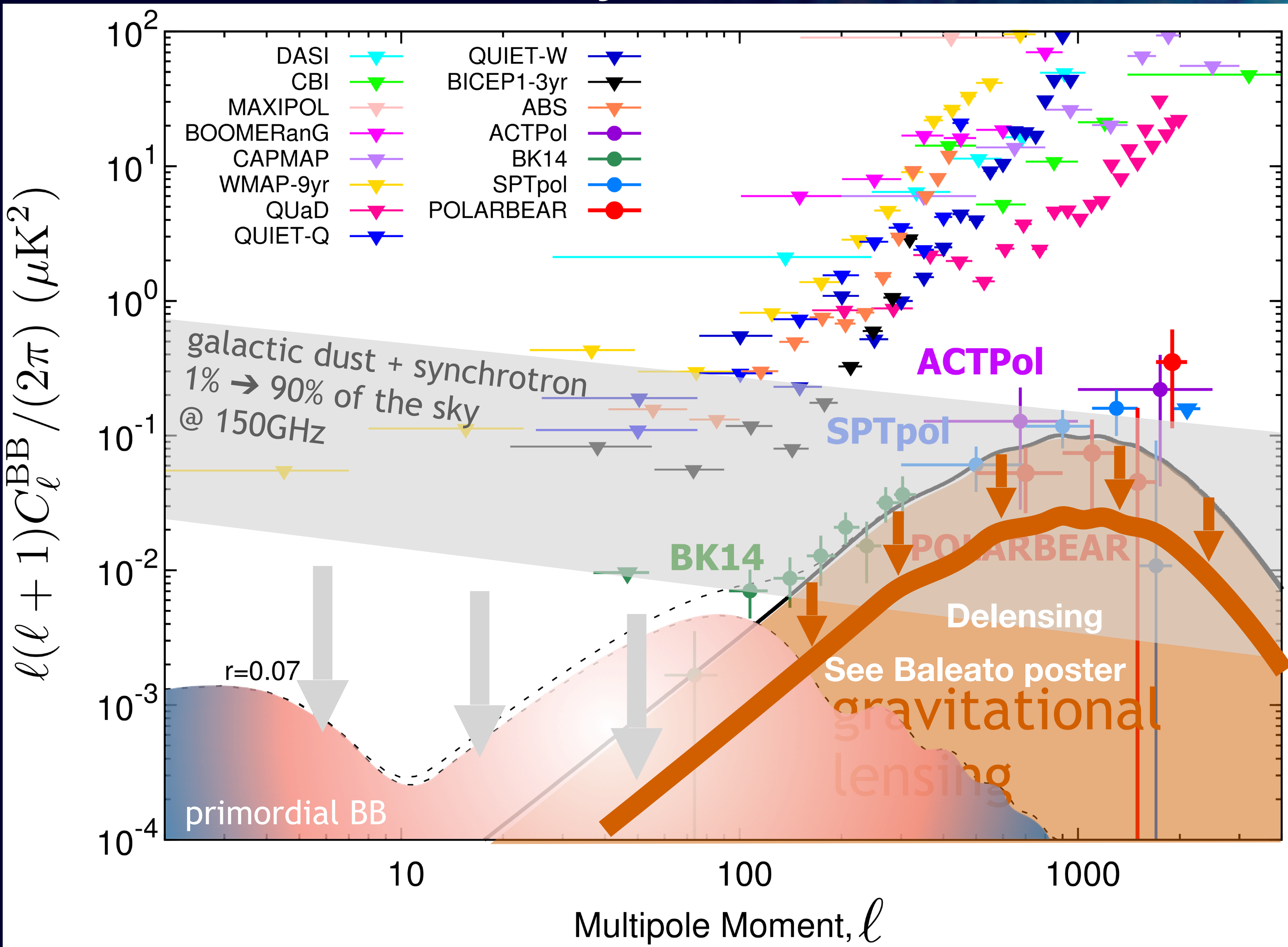


Table 1: Summary of SO-Nominal key science goals[a]

	Current[b]	SO-Nominal (2022-27) Baseline	Goal	Method[d]	SWP
Primordial perturbations (§2.1)					
r ($A_L = 0.5$)	0.03	0.003	0.002[e]	BB + external delensing	[12]
n_s	0.004	0.002	0.002	TT/TE/EE	[12]
$e^{-2\tau}\mathcal{P}(k = 0.2/\mathrm{Mpc})$	3%	0.5%	0.4%	TT/TE/EE	[13]
$f_{\mathrm{NL}}^{\mathrm{local}}$	5	3	1	$\kappa\times$ LSST-LSS	[14]
		2	1	kSZ + LSST-LSS	
Relativistic species (§2.2)					
N_{eff}	0.2	0.07	0.05	TT/TE/EE + $\kappa\kappa$	[15]
Neutrino mass (§2.3)					
Σm_ν (eV, $\sigma(\tau) = 0.01$)	0.1	0.04	0.03	$\kappa\kappa$ + DESI-BAO	[16]
		0.04	0.03	tSZ-N $\times$ LSST-WL	
Σm_ν (eV, $\sigma(\tau) = 0.002$)		0.03[f]	0.02	$\kappa\kappa$ + DESI-BAO + LB	
		0.03	0.02	tSZ-N $\times$ LSST-WL + LB	
Beyond standard model (§2.4)					
$\sigma_8(z = 1-2)$	7%	2%	1%	$\kappa\kappa$ + LSST-LSS	[17]
		2%	1%	tSZ-N $\times$ LSST-WL	
H_0 (km/s/Mpc, ΛCDM)	0.5	0.4	0.3	TT/TE/EE + $\kappa\kappa$	[18]
Galaxy evolution (§2.5)					
η_{feedback}	50-100%	3%	2%	kSZ + tSZ + DESI	[19]
p_{nt}	50-100%	8%	5%	kSZ + tSZ + DESI	[19]
Reionization (§2.6)					
Δz	1.4	0.4	0.3	TT (kSZ)	[20]

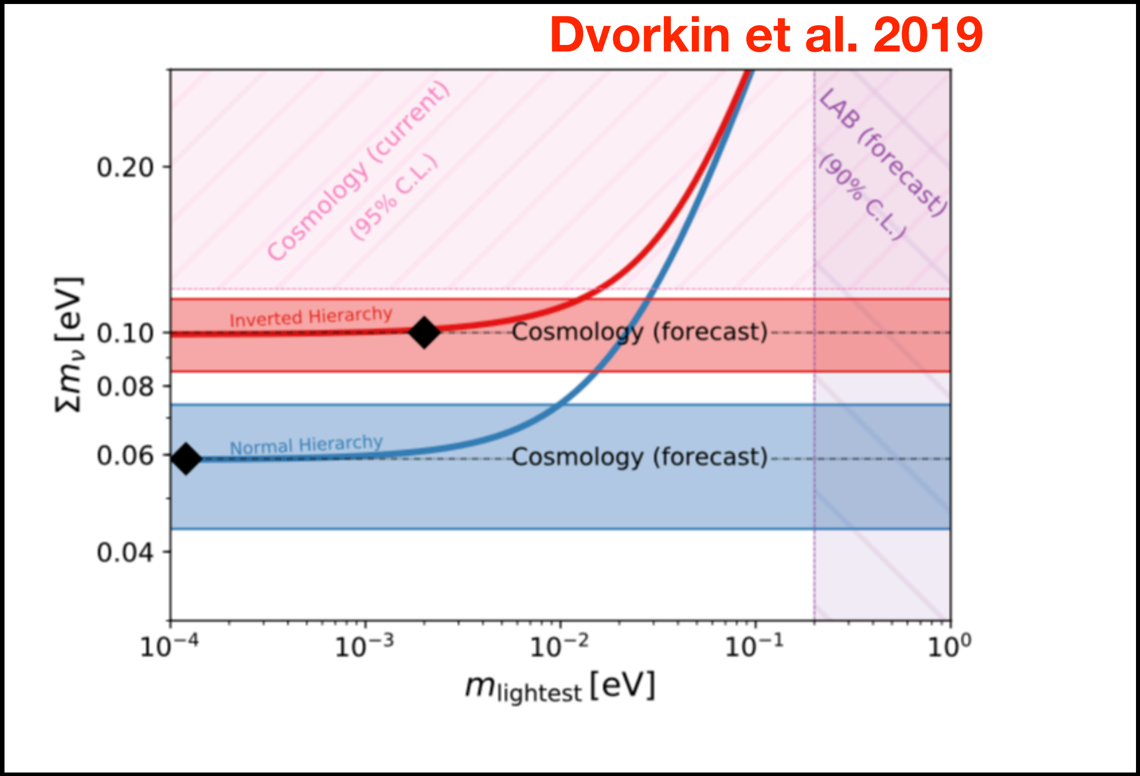
[a] Projected 1σ errors as in [1], with the addition of neutrino mass limits for an optical depth measurement of $\sigma(\tau) = 0.002$, achievable with LiteBIRD soon after SO-Nominal is concluded. Sec. 2 of [1] describes our methods to account for noise properties and foreground uncertainties. A 20% end-to-end observation efficiency is used, matching what has been typically achiev ssume SO is combined with

Neutrino Mass

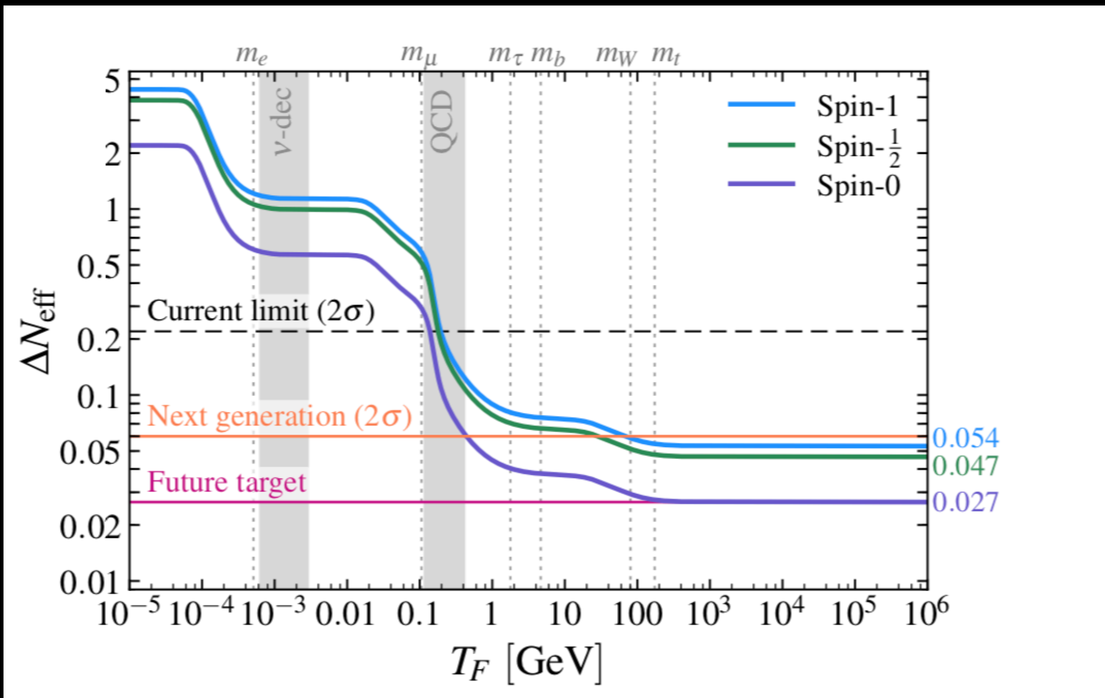
Neutrinos affect the growth of structure

Measure structure growth:

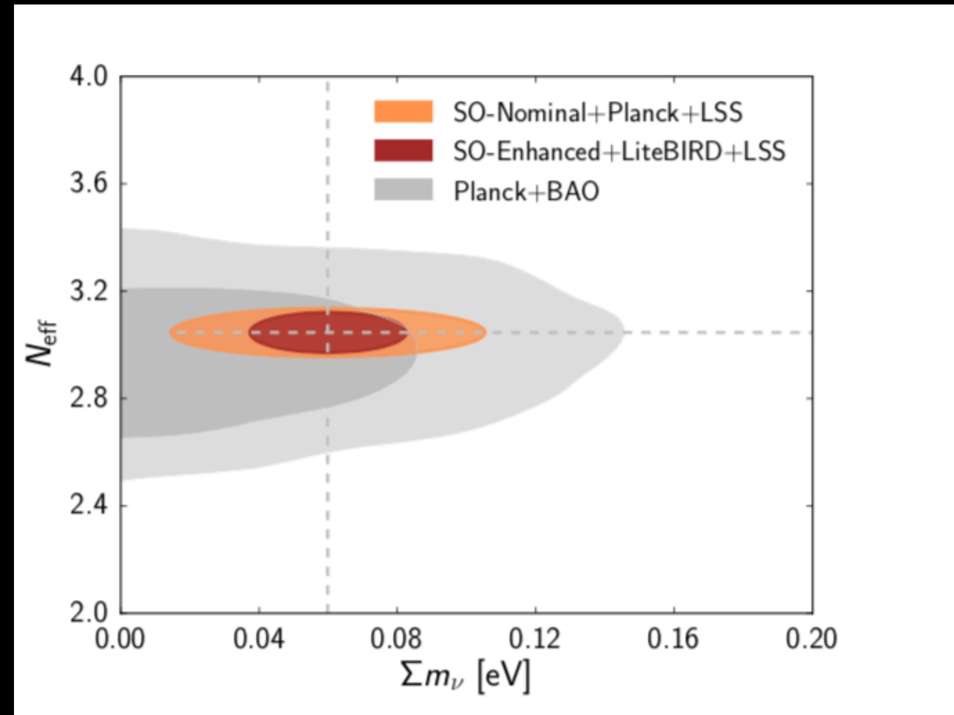
- CMB lensing
- Improve tau measurement
- Optical lensing
- Kinematic SZ effect
- Cosmic Voids
- Clusters
- Lyman alpha forest



Number of Relativistic Species



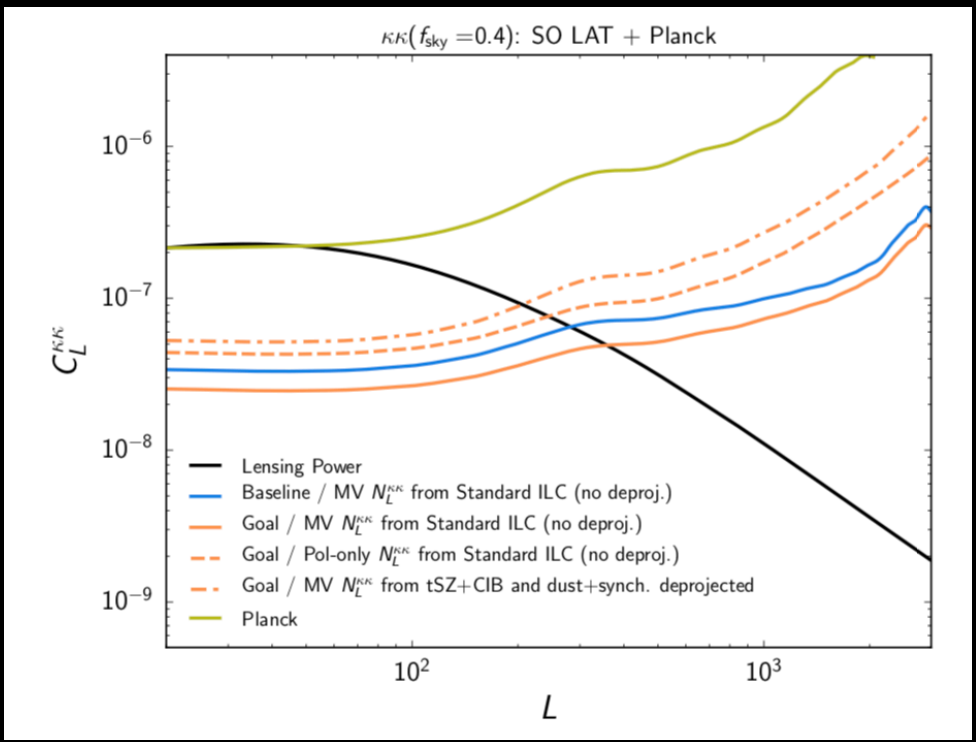
Green et al. 2019

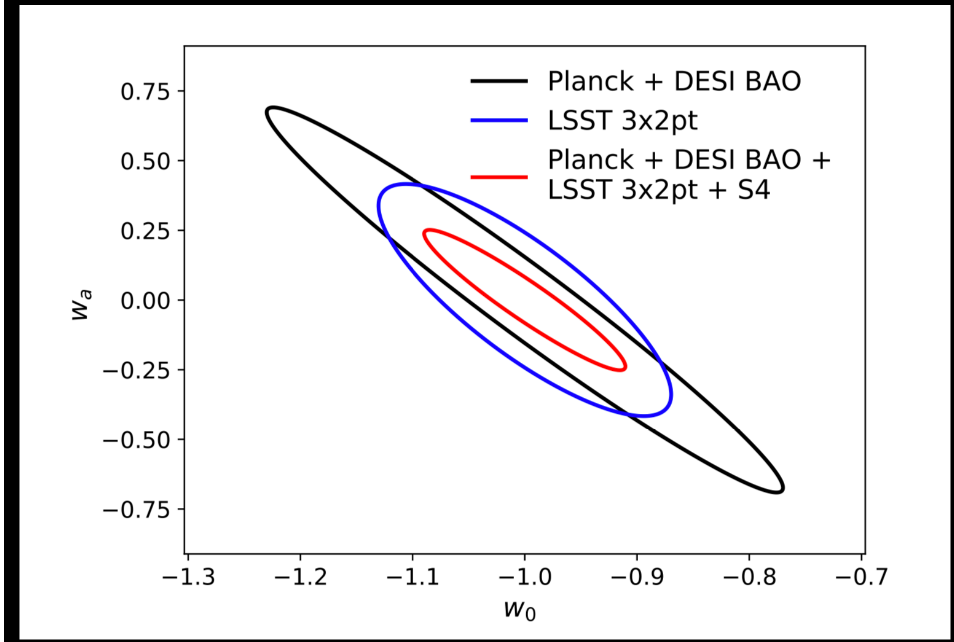


Simons Observatory Collaboration 2019

Early universe was a fabulous accelerator: any stable light particles, even very weakly interacting particles, should have been created in the early universe. They alter the CMB fluctuation spectrum

Dark Energy

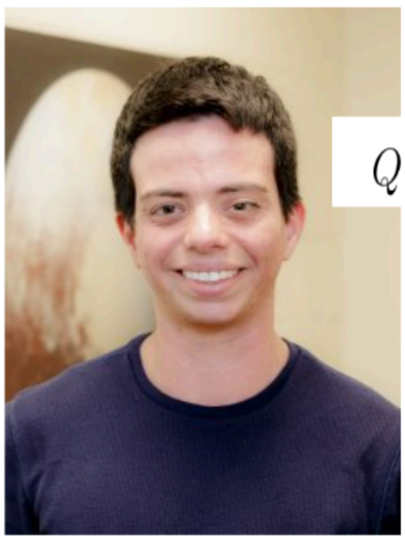




CMB-S4 Collaboration 2019

Simons Observatory

Constraining Alternative Gravity Theories



- CMB polarization power spectrum directly measures velocity field at z =1100

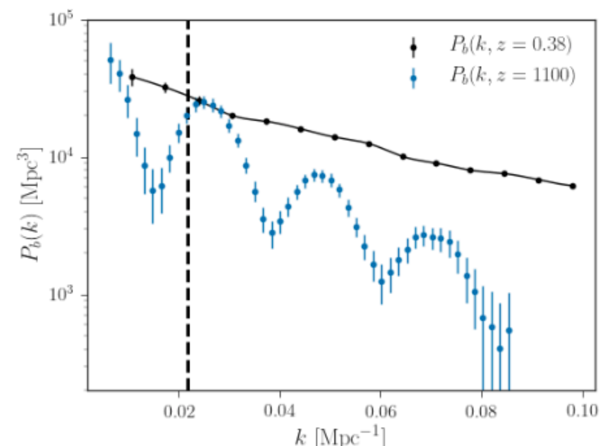
$$Q(\hat{n}) + iU(\hat{n}) \approx 0.17\Delta\tau_* \left[(\partial_x v_x - \partial_y v_y) + i(\partial_x v_y + \partial_y v_x)\right] .$$

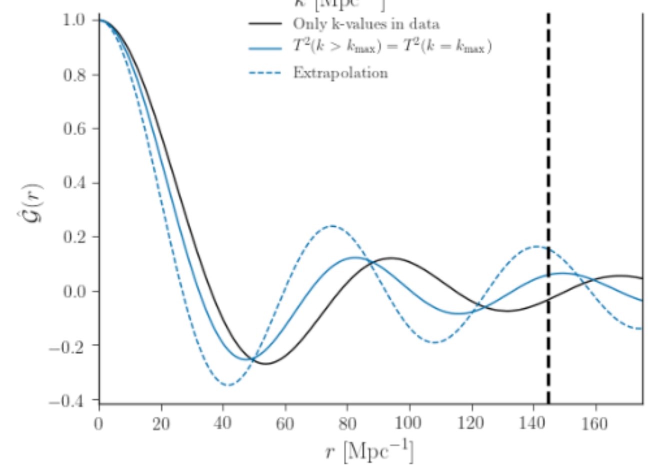
- \+ Continuity equation:

$$P_{bb}(k, z \sim 1100) = \frac{P_{EE}(k)}{(0.17\Delta\tau_*)^2 f_*^2 H_*^2} .$$

- Large scale structure measures power spectrum at z = 0.3

Work with Kris Pardo





CMB + Dark Matter

High Redshift Signatures:

- Baryon-DM interactions
- Neutrino-DM interactions
- Dark energy-DM interactions
- Dark radiation-DM interactions
- DM decay + annihilation

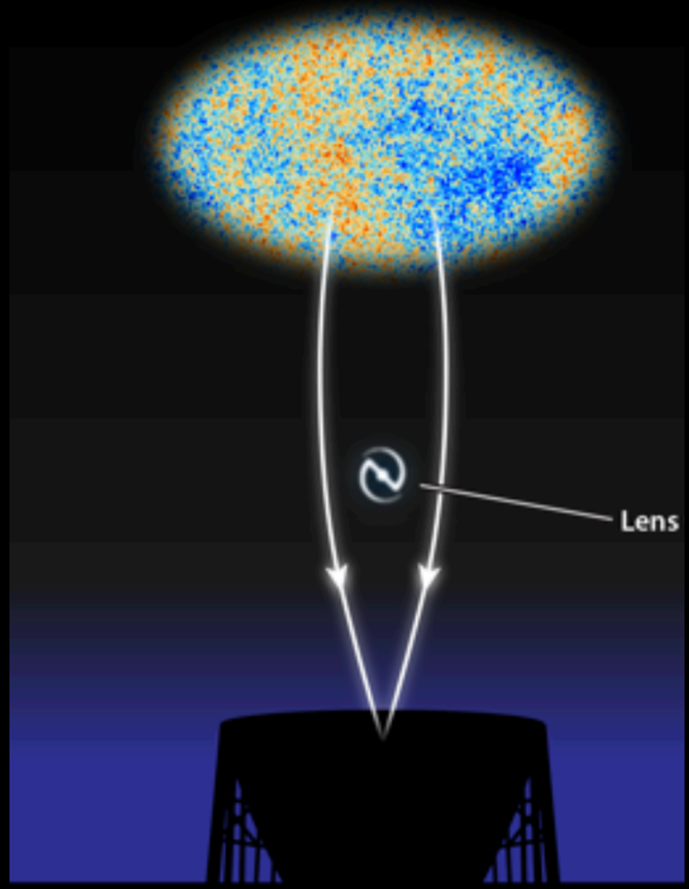
Glusevic et al. 2019

CMB-HD: Ultra-high precision CMB lensing

Ho Nam Nguyen, NS, Mathew Madhavacheril, PRD, 2019, (arXiv:1710.03747)

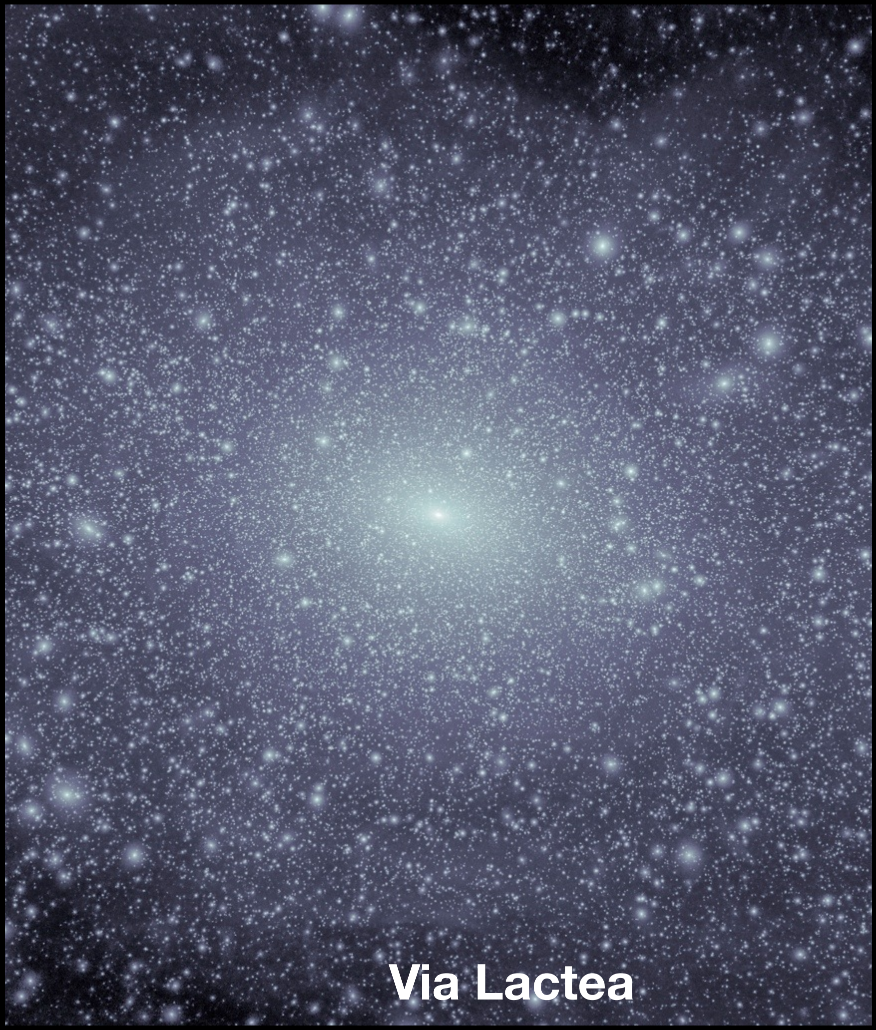
NS et al. 2019, Science White Paper for Astro2020 Decadal (arXiv:1903.03263)

NS et al. 2019, CMB-HD APC White Paper for Astro2020 Decadal (arXiv:1906.10134)

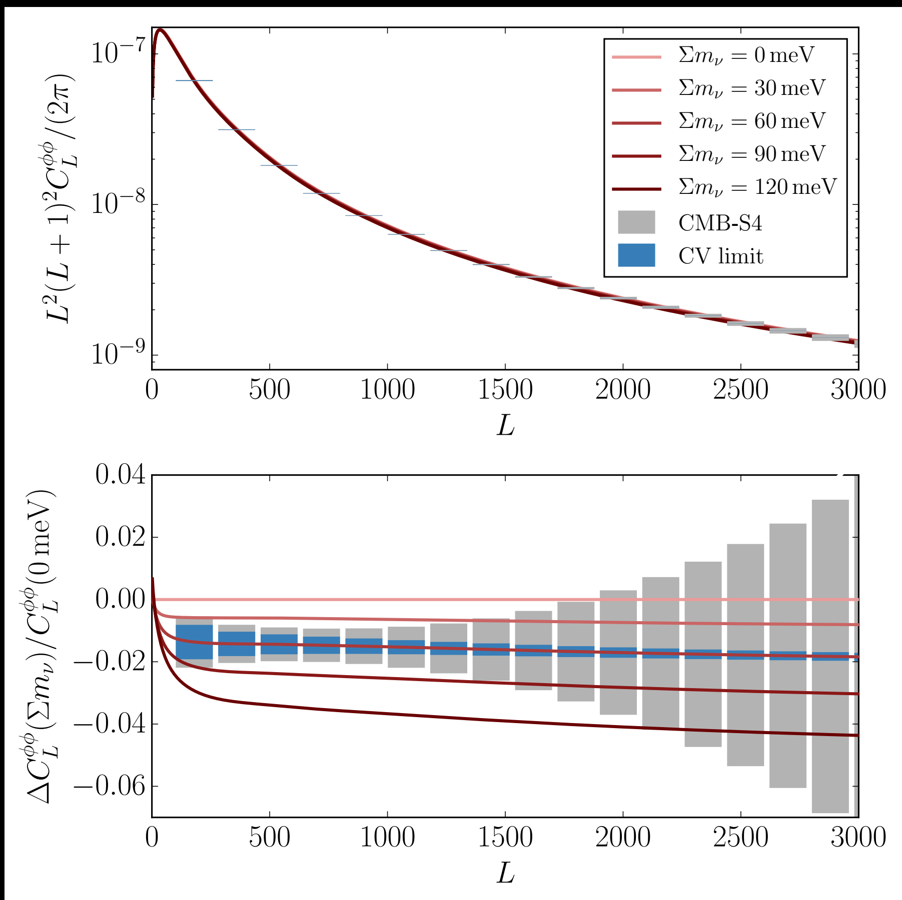


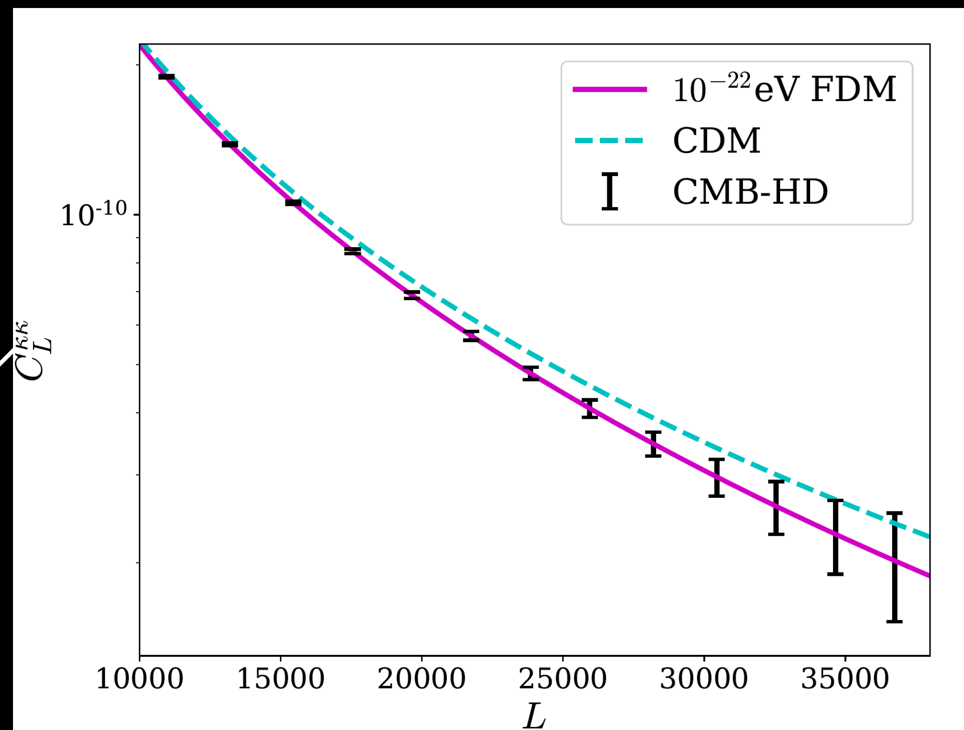
Probing DM substructure

- How does DM cluster on small scales?
- Small-scale CDM “crisis”:
  - missing satellite problem
  - core vs. cusp
  - evidence for interesting DM physics?



Need to push lensing measurements to even smaller scales





CMB-HD

CMB-S4 Collaboration

CMB-HD

Two new 30-meter mm-wave telescopes in Atacama Desert with total sensitivity 3 times deeper than CMB-S4 and 5 times the sensitivity. Aim to survey 50% of the sky

If you must ask, $1.5 Billion

Sehgal et al. 1906.10134

Sub-arcminute CMB measurements

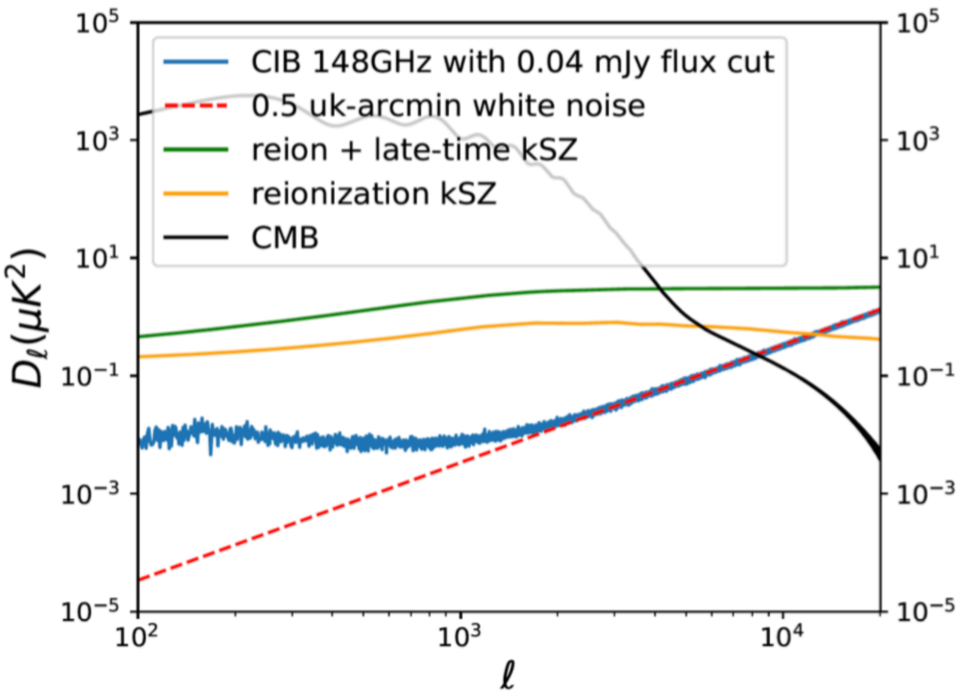


Figure 3: Shown are the CMB temperature power spectrum (black solid) and relevant foregrounds at 150 GHz. The foregrounds are the kSZ effect from the epoch of reionization (orange), reionization kSZ plus the late-time kSZ effect (green), and the CIB (after removing sources above a flux of 0.04 mJy). The CIB flux cut, enabled by frequency channels between 100 and 350 GHz and the 30-meter dish, brings the CIB to the level of 0.5 μK-arcmin (dashed red) on small scales.

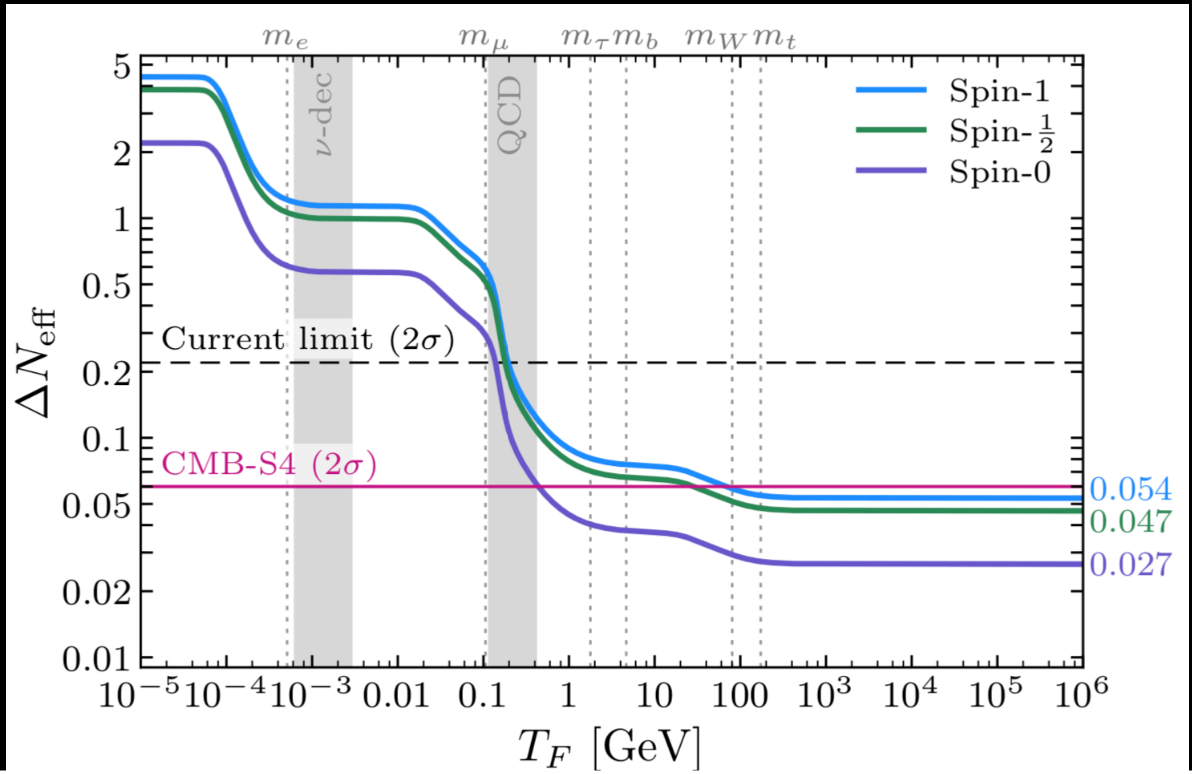
600,000 detectors , 8 frequency 30-350 Ghz

Sehgal et al. 1906.10134

CMB-HD Science

Table 1: Summary of CMB-HD key science goals in fundamental physics

Science	Parameter	Sensitivity
Dark Matter	S/N: Significance in Differentiating FDM/WDM from CDM[a]	S/N = 8
New Light Species	$N_{\rm eff}$: Effective Number of Relativistic Species[b]	$\sigma(N_{\rm eff}) = 0.014$
Inflation	$f_{\rm NL}$: Primordial Non-Gaussianity[c]	$\sigma(f_{\rm NL}) = 0.26$
Inflation	$A_{\rm lens}$: Residual Lensing B-modes[d]	$A_{\rm lens} = 0.1$



Conclusions

- Future CMB Measurements offer the possible of obtaining new insights into fundamental physics
  - dark matter, dark energy, new physics, early universe
- Different observational challenges
  - B mode search at low l
  - High resolution CMB temperature and polarization measurements
  - Spectral distortions