The case for a high resolution all-sky mm survey

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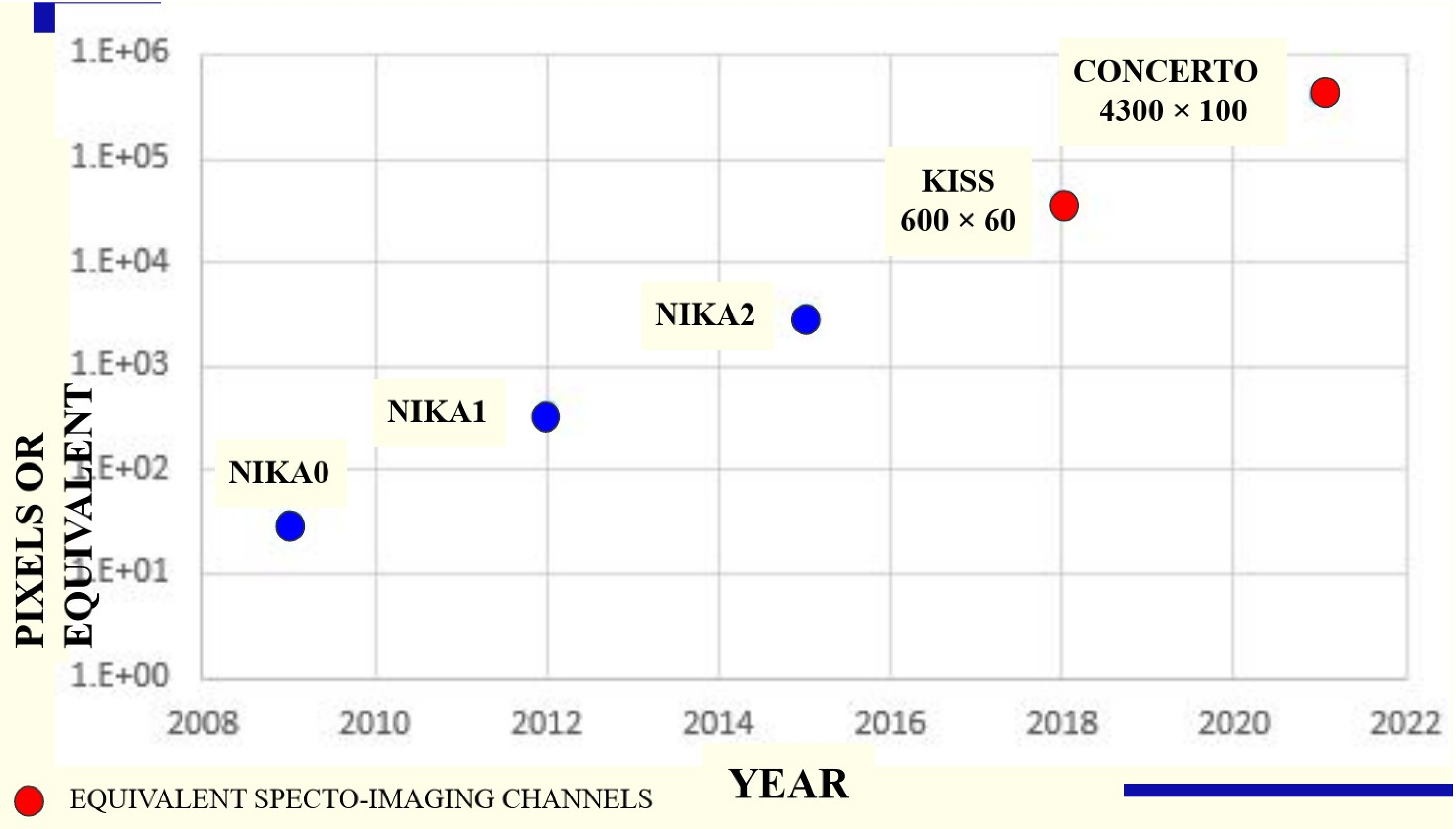
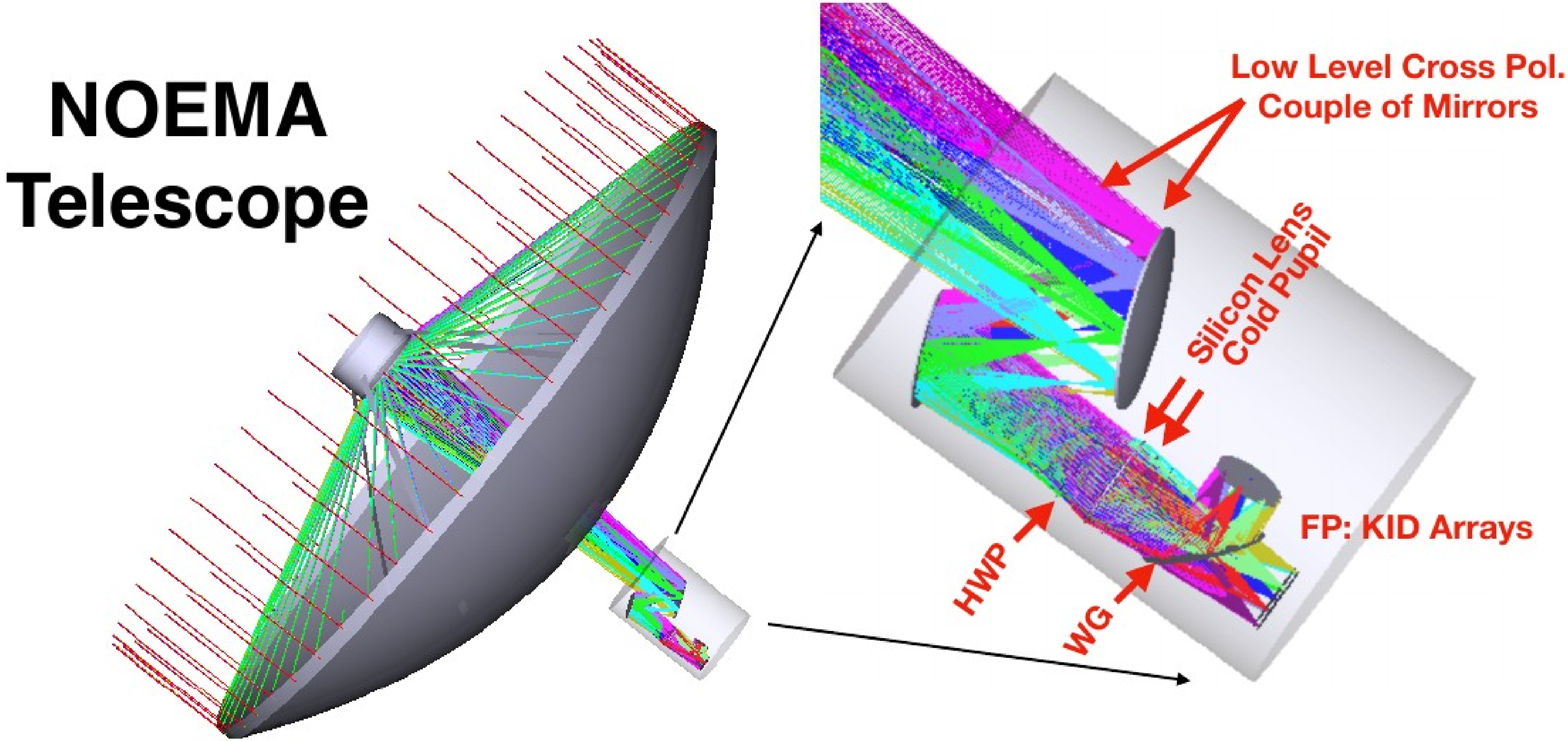
Abstract

A dedicated 15m telescope could map the all-sky in the millimetre, adding 20 arcsecond resolution to Planck all-sky maps. We will present the scientific drivers for that instrument: CMB, lensing, SZ, Cosmic Web, CIB, and Polarized dust. This would provide a European original contribution to the S4 efforts at a moderate cost (20M€).



Monfardini’s presentation PCMI: *The Ascent of Kids*

SynKid15m in a nutshell 1/2



Courtesy of A. Catalano, J. Macias-Perez & S. Leclercq
FOV=1sq degree., HWP, Polarizing Grid Splitter

SynKid15m in a nutshell 2/2

- 15m@ 1-3mm: beam 19-55 arcsec
- FOV 1 sq degree: 30k detectors (Kids) over 4 bands or more
- cold HWP: polarization enabled, Spectroscopy at low resolution would be a very important niche.
- Wide survey (1year, 6k sq. deg) 2-0.4 mJy 1sigma, 0.18-0.004 MJy/sr, beat cosmic variance, 15 uK.arcmin
- Deep survey (1year 300 sq. deg) 0.4-0.1 mJy, 3uK.arcmin, (5 in polarization) ell_max~30,000
- Project cost: 14ME (ERC synergy?) then 1-2ME annual running cost (x 10 years), Need for an observatory and community support
- Cosmological targets (SZ, lensing B-modes), Extragalactic targets (CIB, Galaxies), Galactic (complete mm census, spectral maps, Magnetic field study in cold clouds)
- Initial thinking from Grenoble: A. Catalano, S. Leclercq, N. Ponthieu, J. Macias-Perez, FX Désert, F. Mayet, L. Perotto, A. Monfardini
- Timing: 2023-2027 construction, then 2028 commissionning, 2029- survey
- How about a low cost, fast-track, all sky mm survey at high angular resolution? where ISM meets CMB! Find the needles in the haystack for follow-up by Noema/Alma/30m.

Scientific drivers for a high angular resolution mm observatory

- Secondary anisotropies
  - SZ cluster multiband census tSZ, stacking, lensing :
  - SZ diffuse: cosmic web and kSZ, the missing baryons

    } Goal 1
  - Reionization: kSZ and intensity mapping (C+ if low-resolution spectroscopy)
- CMB-Polarization
  - Lensing B-modes and small-scale matter power spectrum
  - Foreground cleaning for S4 and Litebird

    } Goal 2
- CIB and point-sources
- Neargy galaxy mapping

  } Goal 3
- Magnetic field in the ISM Goal 4, protostellar cores, CO (if spectroscopy), Planet 9
- Serendipity: finding transients
- Stacking and cross-correlating with other wavelengths

  - References for lensing: CMB-HD Sehgal et al. 2019, NGuyen et al, 2019, Phys.Rev.D

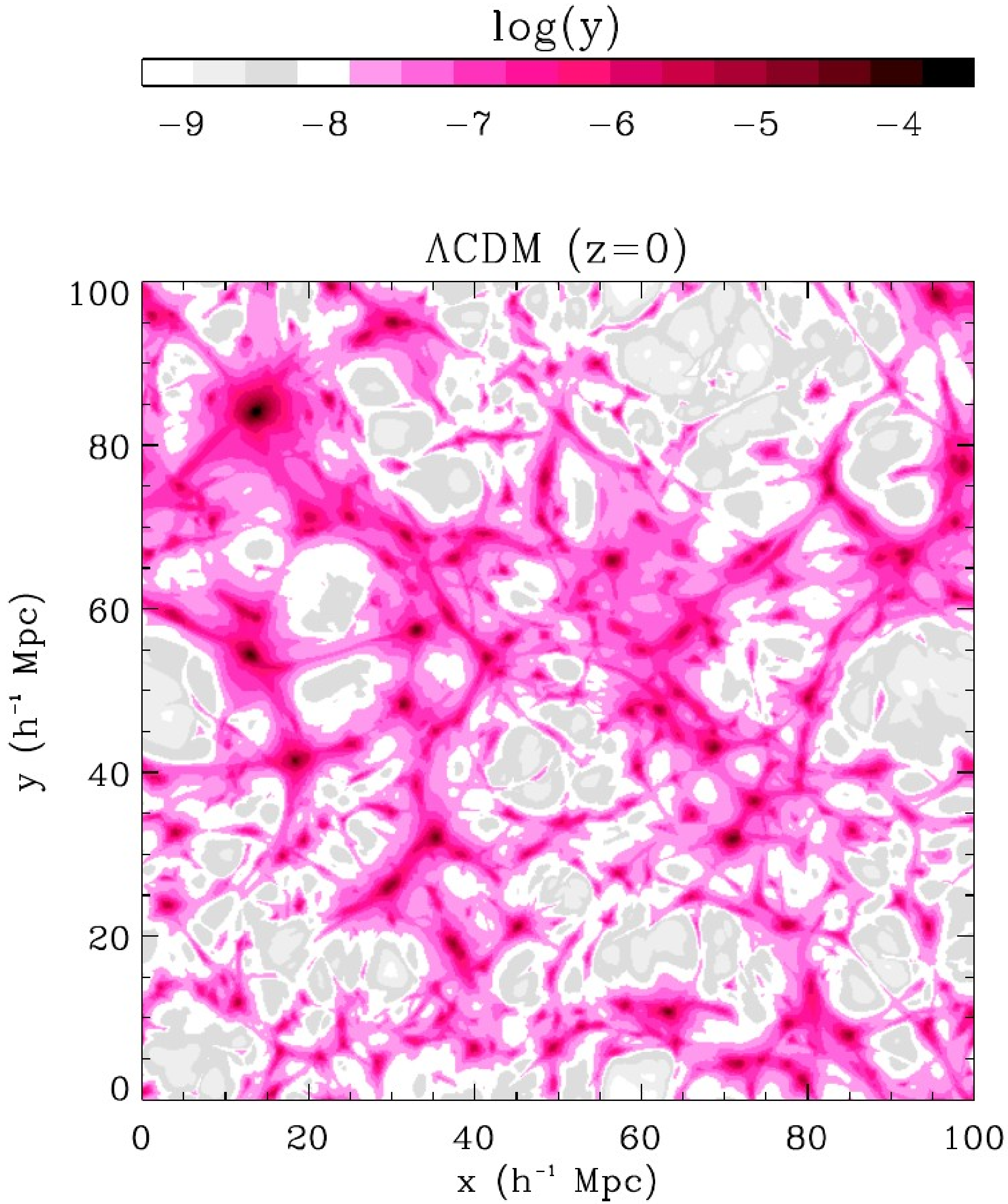


FIG. 2. Comptonization-parameter map for the ΛCDM simulation at $z = 0$.

Refregier et al 2000, 10.1103/PhysRevD.61.123001

2030: Scientific and Political context

- eRosita, Euclid, Rubin-LSST, SKA, Athena, Litebird, Pixie,
  all with big chunks of sky, all in the G€ land.
- CMB-S4 being deployed 1G$ (600M$ + 32 annual ops.)
- CCat-Prime 6m submm surveyor (started)
- ESO ATLAST 50m (Phase A Synergy ERC project) 300 M€
- Astrodecadal survey out, CMB-HD 2*30m= 1.5G$ was proposed (not approved), CMB-S4 is launched
- ESA Voyage 2050 out: an ESA mission, a microwave spectroscopy explorer, with plausible target launch date around 2040, with moderate resolution (R=300) for CMB and intensity mapping
- in France, strong community support, beyond Litebird, to get involved in ground-based CMB polarization experiments (INSU, IN2P3)
- Local Grenoble context: Planck/Archeops, NIKA2, Concerto … (see slide of Moore’s law)
- Key issue (completely open at this time): Telescope site and Observatory operations

Matrix for wide-field CMB experiments

Multiple choices for experiment diversity:
Intensity/Polarization,
Photometry/Spectroscopy,
mm/submm,
10m+ or 6m,
Ground-based/Space

		> 10m		<10m
North	mm photom	This Project		AliCPT
	mm spectro			
	submm	Scuba2/JCMT		
South	mm photom	SPT		CMB-S4, (CMB-HD)
	mm spectro	Concerto/Apex		CCATp
	submm	(AtLast)		CCATp

Additional slides

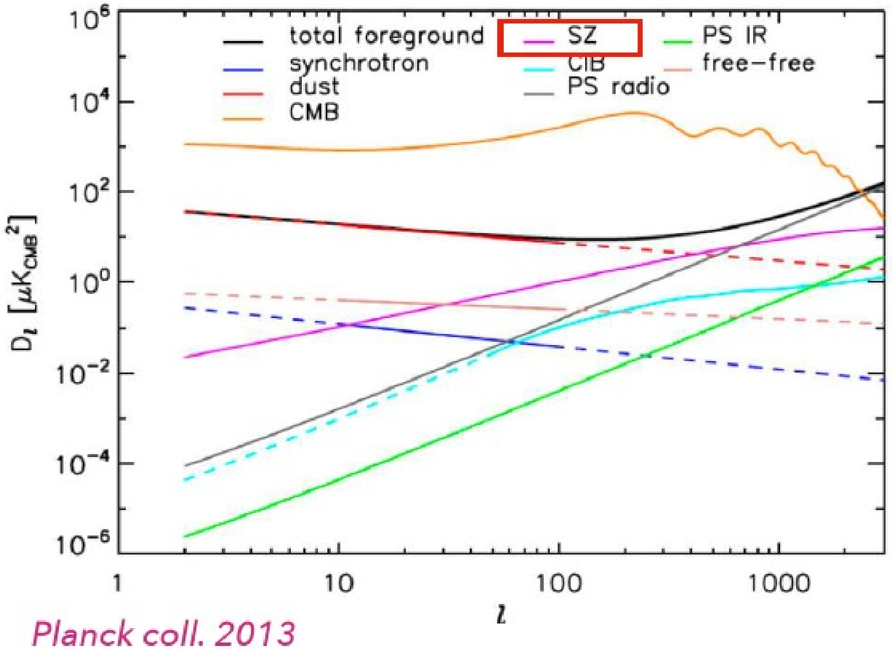
SynKid15m

	Synkid Integration time									
	v1 : initial guess with NIKA2/30m template, **v2 : stick to NOEMA design, polar+4 bands, correct beam approx.**									
	Red=can be changed	Yellow are results								Units
SynKid 15m		Intensity				Polar				
		1.2mm	1.4mm	2mm	3.3mm	1mm	1mm	2mm	3.3mm	
	Central Frequency	260	220	150	90	260	220	150	90	GHz
15	Diameter									m
	Diffraction Beam	19	23	33	55	19	23	33	55	arcsecond
	Effective Beam	19	23	33	55	19	23	33	55	arcsecond
	Opacity for pwv=1	0.076	0.076	0.026	0.026					adim.
	NIKA2 NEFD point source (PS) pwv=2, 60deg Elev *for the current telescope diameter*	40	32	20	12					mJy.s1/2
	NEFD (SynKid)	28.3	22.6	14.1	8.5					mJy.s1/2
	Noise improvement SynKid/NIKA2	2.0	2.0	2.0	2.0					adim.
4	Effective pwv									mm
45	Average elevation									degree
	Zenith opacity	0.30	0.30	0.10	0.10					
	NEFD (PS) Effective	36	29	15	9					mJy.s1/2
						1.41	1.41	1.41	1.41	NefdQ/Nefdl
	Central wavelength	1.15	1.36	2.00	3.33	1.15	1.36	2.00	3.33	mm
0.8	Fraction of good pixels	0.8	0.8	0.8	0.8					
1	*hour on-source integration time*									hour
1	hour 1 sigma PS full FOV	0.68	0.54	0.29	0.17	0.96	0.77	0.41	0.24	mJy
ludgeFact	Sensitivity loss for diffuse emission	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
1	hour 1 sigma diffuse per det	0.070	0.040	0.010	0.0021	0.100	0.057	0.014	0.0030	MJy/sr
1	hour 1 sigma Rayleigh-Jeans	33.9	27.1	14.3	8.6	47.9	38.4	20.3	12.2	uKRJ
	x=hnu/kTCMB	4.577	3.873	2.641	1.584	4.577	3.873	2.641	1.584	
	MJy/sr_to_KCMB	2.19E-03	2.07E-03	2.51E-03	4.93E-03	2.19E-03	2.07E-03	2.51E-03	4.93E-03	
1	hour 1sigma dTCMB per det	154.1	83.4	24.9	10.6	218.0	117.9	35.2	14.9	uKCMB
	MJy/sr_to_y	1.19E-03	2.01E-02	-9.65E-04	-1.13E-03					
1	hour 1sigma y per det	84	812	10	2					micro
60	FOV diameter	38	38	46	46	38	38	46	46	arcmin
	FOV area	1134	1134	1693	1693	1134	1134	1693	1693	arcmin²
30,270	Ndet	12655	9061	6289	2264	12655	9061	6289	2264	
	Ntot					12655	9061	6289	2264	1 array per frequency
	Mapping speed	2455	3835	20488	56912	1227	1918	10244	28456	arcmin²/mJy²/hour
	SOmega	170	170	253	253					cm2.sr
	SURVEY									
0.5	Weather eff									adim.
0.67	Calib overhead									
3.00	hours : Effective Observing Time									
	WIDE SURVEY									
2,920	Observing time on source (hr)									hr
8,760	Effective total observing time (hr)									hr
365	id. (days)									days
0.143	Sky fraction observed									
6,000	(sq. degree)									deg²
19,046	Number of FOV in survey									
	Time per field of view	0.16	0.16	0.23	0.23	0.16	0.16	0.23	0.23	hr
	dTCMB rms per beam	390.1	211.0	51.5	21.9	551.7	298.4	72.8	30.9	uKCMB
	Point source sensitivity (1sigma)	1.72	1.22	0.64	0.39	2.15	1.72	0.91	0.55	mJy
	y sensitivity (1sigma) per beam	212.8	2054.4	19.8	5.0					micro
	1 sigma diffuse emission per beam	0.1782	0.1021	0.0205	0.0044	0.2520	0.1443	0.0290	0.0063	MJy/sr
	1 sec, dTCMB per det	9,248	5,002	1,492	634	13,079	7,074	2,110	896	ukCMB.s1/2
	1 sec, dTRJ per det	2,034	1,627	860	516	2,876	2,301	1,217	730	ukRJ.s1/2
	1 sec, dTCMB array	82	53	19	13	116	74	27	19	ukCMB.s1/2
	mission noise in sqrt(Cl)	117	75	27	19	165	106	38	27	uKCMB.arcmin
	aggregated			15				21		uKCMB.arcmin
100	ell_ref									
	ell(ell+1)DeltaCl/(2pi)	0.518	0.216	0.030	0.020	1.035	0.432	0.061	0.041	uKCMB^2
	DEEP SURVEY									
2920	Observing time on source (hr)									hr
8760	Effective total observing time (hr)									hr
365	id. (days)									days
0.007	Sky fraction observed									
300	(sq. degree)									deg²
2,768	Number of FOV in survey									
	Time per field of view	3.12	3.12	4.66	4.66	3.12	3.12	4.66	4.66	hr
	dTCMB rms per beam	87.2	47.2	11.5	4.9	123.4	66.7	16.3	6.9	uKCMB
	Point source sensitivity (1sigma)	0.38	0.31	0.13	0.08	0.54	0.44	0.19	0.11	mJy
	y sensitivity (1sigma) per beam	47.6	459.4	4.4	1.1					micro
	1 sigma diffuse emission per beam	0.0398	0.0228	0.0046	0.0010	0.0564	0.0323	0.0065	0.0014	MJy/sr
	1 sec, dTCMB per det	9,248	5,002	1,492	634	13,079	7,074	2,110	896	ukCMB.s1/2
	1 sec, dTRJ per det	2,034	1,627	860	516	2,876	2,301	1,217	730	ukRJ.s1/2
	mission noise in sqrt(Cl)	26	17	6	4	37	24	8	6	uKCMB.arcmin
	aggregated			3.4				4.7		uKCMB.arcmin
100	ell_ref									No smoothing, per mode
	ell(ell+1)DeltaCl/(2pi)	0.1157	0.0483	0.0068	0.0046	0.2315	0.0967	0.0136	0.0091	uKCMB^2

tSZ in frequency maps (small scales)

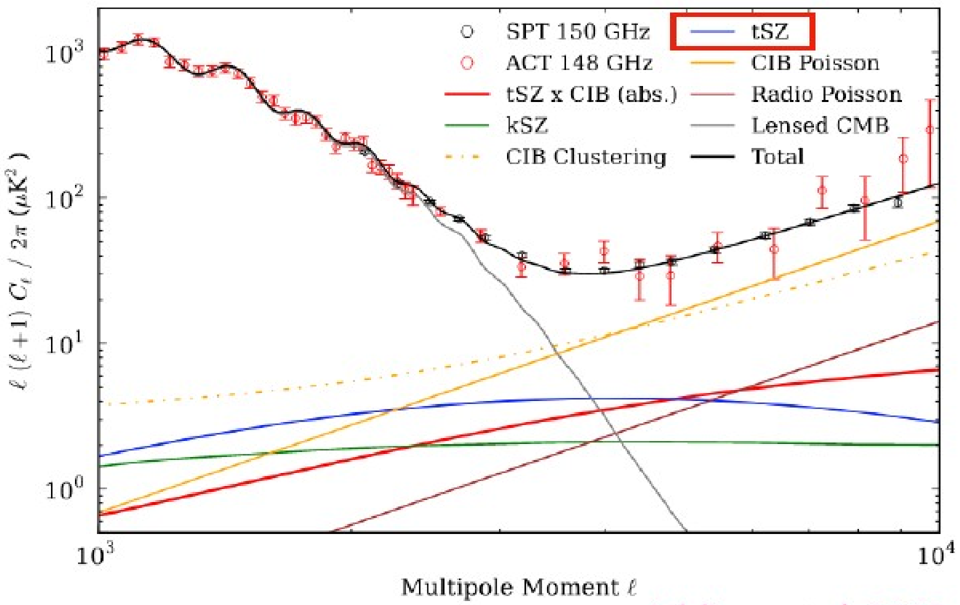
- Primordial CMB becomes negligible
- tSZ is hidden among many other signals

Planck/Large scales



Planck coll. 2013

SPT/small scales



Addison et al. 2012

Additional slides

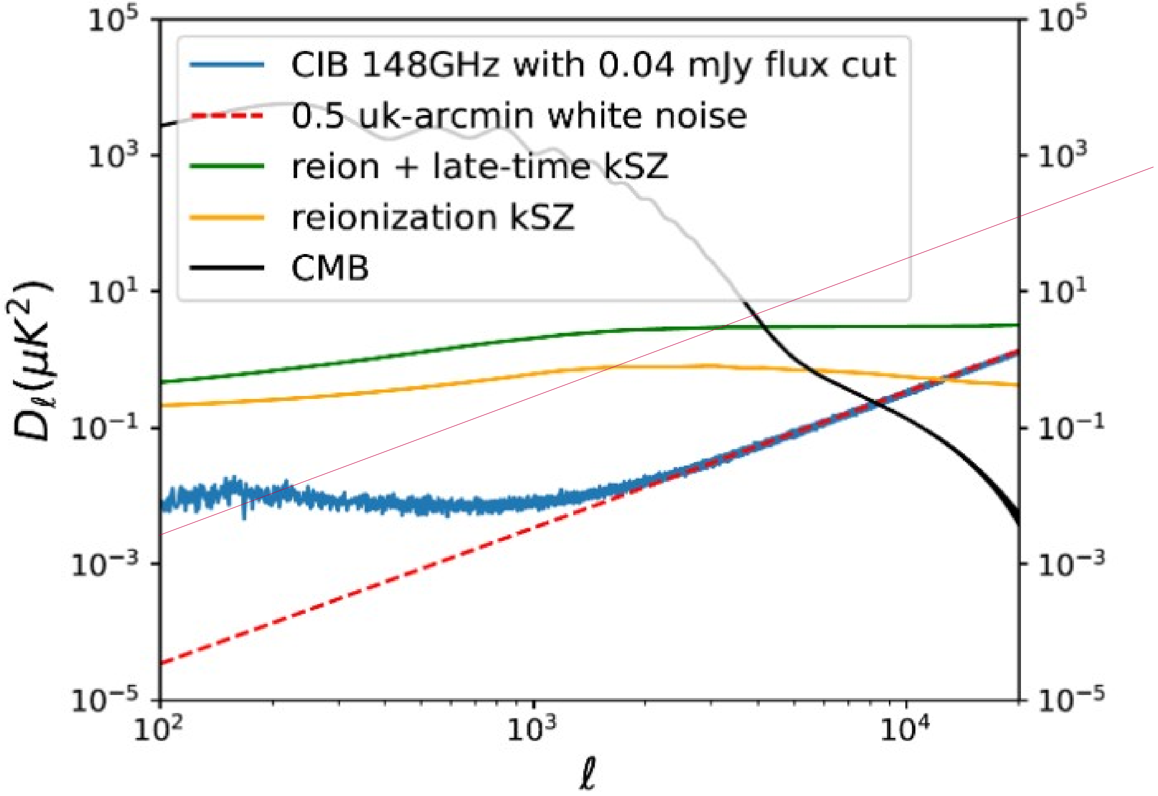
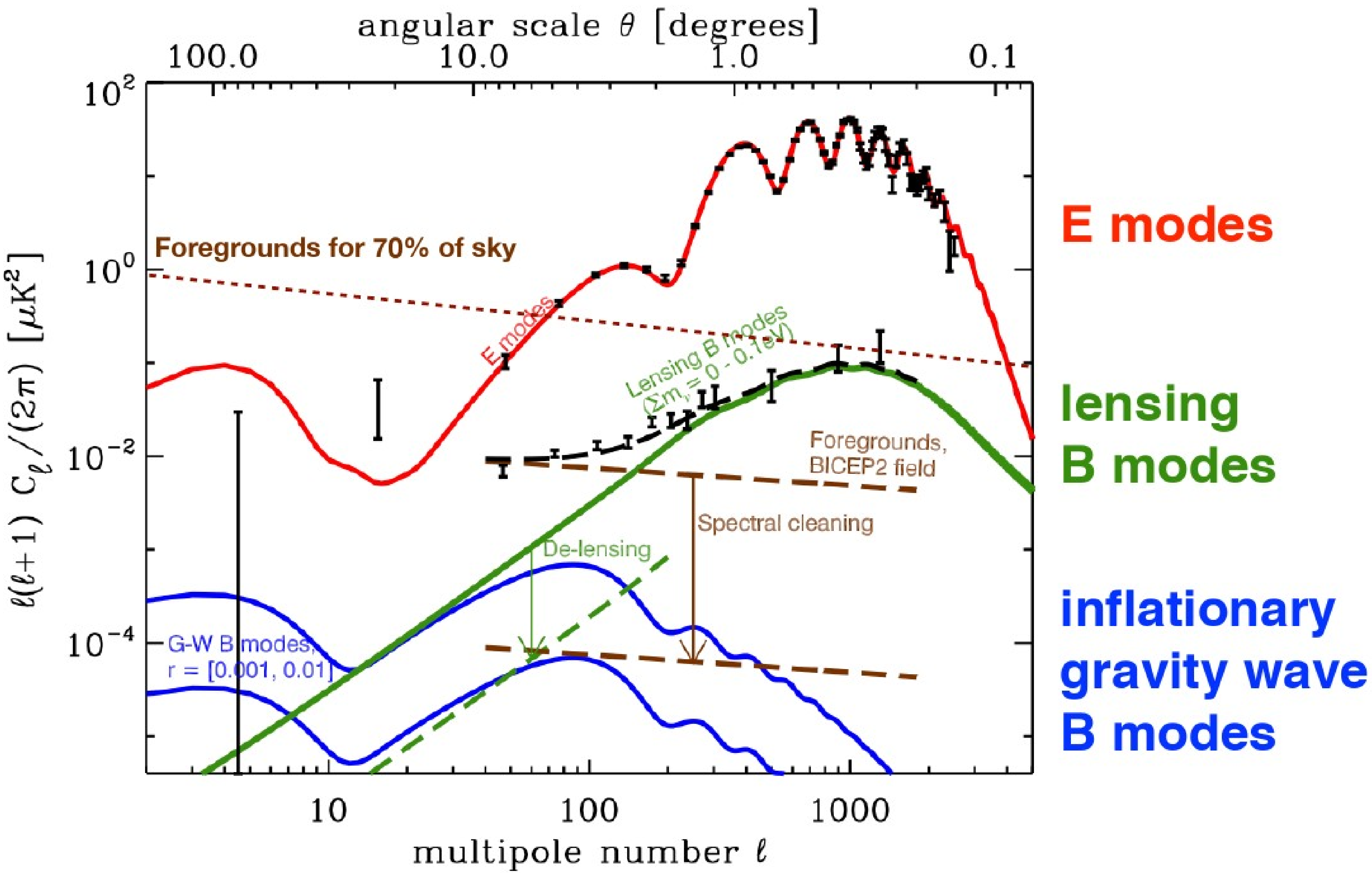


Figure 3: Shown are the CMB temperature power spectrum (black solid) and relevant foregrounds at 150 GHz. The foregrounds are the kSZ effect from the epoch of reionization (orange), reionization kSZ plus the late-time kSZ effect (green), and the CIB (after removing sources above a flux of 0.04 mJy). 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.

Magenta, this project 30k detectors, 1 year, 20M€
CMB-HD Sehgal et al. 2019, 2Mdetectors, 5 years, 1.5 G$.

Additional slides



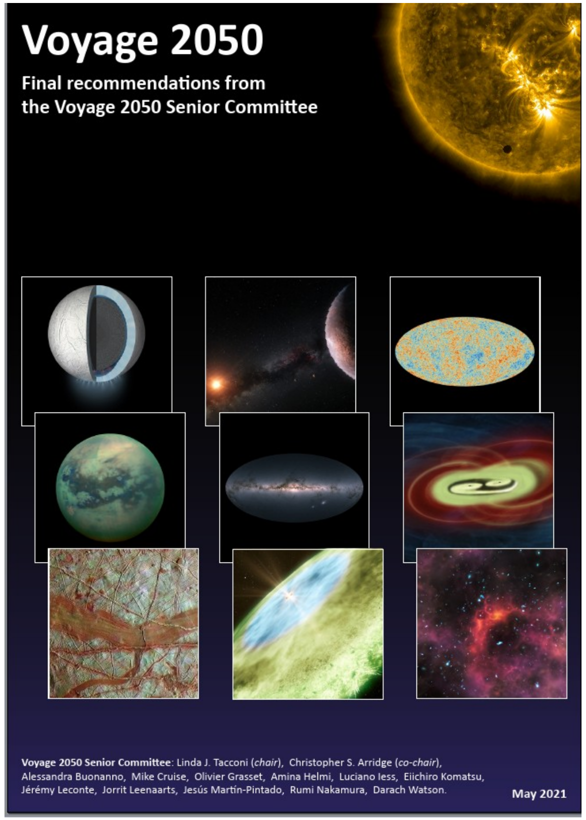
From Carlstrom's presentation 12 Sept 2019, Paris

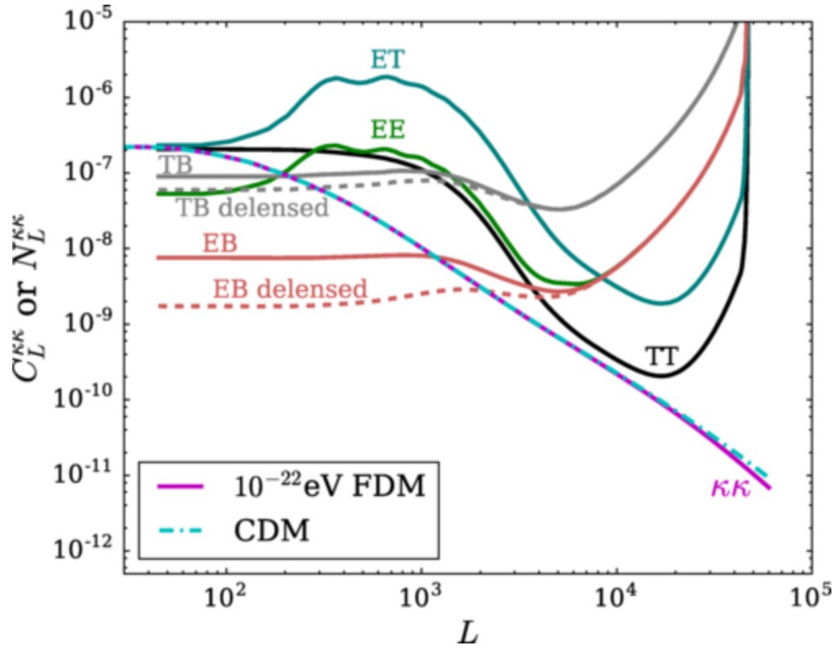
Additional slides

- Voyage 2050 (See Jacques Delabrouille's presentation): ESA Voyage 2050 has a L mission with precision spectrocopic capabilities in the mm range (early Universe, z>8) and a medium mission for high resolution and/or intensity mapping.

- High-resolution CMB and lensing by clusters (cf. e.g. CMB-HD proposal (right))

- kSZ: Calafut 2021 (ACT), Kuruvilla's presentation





Noise on lensing reconstruction:
low-ell: EB, high-ell TT (>5000)

Additional slides

7.6.1.2 Criteria and Decision Rules for Investment in the U.S. ELTs

It will be necessary for NSF to commence with an external review with a target completion in 2023 in order to evaluate the financial and programmatic viability of both proposed U.S. ELT projects, with the level of federal investment in at least one of the projects determined at the end of the review. Federal investment in either project should be predicated on:

1. Demonstration of financial viability with agreed-upon commitments from partners for all of the necessary capital and operations money, pending only NSF investment.
2. Final site selection in the case of the TMT.
3. A public share of telescope time (run through NSF's NOIRLab) roughly equivalent to the total federal investment of construction and operations expenses.
4. Full public archiving of all data taken by the ELTs, after a reasonable proprietary period. This applies to both federal and consortium telescope time.
5. Development of a management plan and governance structure for the joint project, agreed by all parties including the relevant observatory corporations and NSF.

Approval of the project is also subject to the recommendation in Section 5.1.1 that makes the initiation of any new astronomy MREFC project contingent on NSF developing a plan for managing the operations costs of the new facilities within its projected budget envelope.

Recommendation: The National Science Foundation (NSF) should conduct an external review of the U.S. extremely large telescopes, with a target completion date of 2023. If only one of the Giant Magellan Telescope or the Thirty Meter Telescope can meet the conditions enumerated above by the time of NSF's review, NSF should proceed with investment in that project alone.

Depending on the outcome, the decision rules for NSF are the following: In the case that only one project can proceed, NSF's investment of up to a 50 percent share in the project should be undertaken if doing so will ensure that the project has the financial resources to come to fruition. If NSF investment can only fund partnership in one telescope, but both are viable, NSF's investment should factor in complementarity to the ESO ELT, the ability to address the science questions of the Astro2020 survey, and the relative advantages of a larger diameter (D), which increases the sensitivity $\sim D^2$ to D^4 (depending on the science application), versus a larger field of view, which increases survey speed and the number of targets per observation.

7.6.1.3 CMB-S4

Observations of the CMB have not only been central to establishing the standard model of cosmology, but the telescopes designed to undertake them are becoming increasingly important for understanding phenomena ranging from transients to galactic ecosystems to the formation of cosmic structure. The advances possible with a new generation of receivers include searching for polarization signals from gravitational waves from the Big Bang and, when combined with Euclid, Roman, and Rubin Observatory, revealing a detailed picture of our cosmic web, its composition, and its evolution. At the same time, by tracing the electron pressure in halos of galaxies and galaxy clusters, CMB observations can trace feedback between the intergalactic medium, the circumgalactic medium, and the cores of galaxies.

Building on the scientific and technical progress brought about by decades of individual private and public investments by the U.S. community, we are poised in the next decade to make a major step forward in ground-based CMB studies. Over the last two decades, second- and third-generation ground-based CMB experiments, deployed in Antarctica and Chile, have made significant advances, including detecting lensing B-mode signatures in the CMB, and the CMB-galaxy lensing cross power spectrum. The search for the tell-tale signature of cosmic inflation through its imprint on the B-mode polarization pattern of the CMB has pushed to fainter and fainter levels, disentangling foregrounds, and placing tighter constraints on this primordial signal. These observations have informed us how to analyze vast amounts of data and disentangle complex cosmological signals, and how to build theoretical models to extract parameters. The experiments have propelled progress by university groups and government labs to develop ever more sensitive, highly multiplexed bolometer detectors operating over a wide frequency range, and these efforts have informed the community how to design the next-generation facility to push these ground-based observations to their projected limit.

Realizing the ultimate scientific potential of ground-based CMB observations will take an effort far beyond what can be achieved simply by independently scaling up existing experiments. It will require a significant increase in the number of CMB detectors in operation, a wide range of independent frequency bands to separate out foreground contaminations, and it will require probing a combination of both large and small angular scales. While such an effort can be carried out using existing millimeter-wave observing sites in Chile and Antarctica, facilities at both must be carefully designed as part of a systemically planned program. Finally, while the United States has been the unrivaled leader in ground-based CMB observations, the needed project is of a scale that would benefit greatly from international participation in both scientific and technical aspects.

The Panel on Radio, Millimeter and Submillimeter Observations from the Ground (RMS) evaluated a number of CMB projects, and suggested that the CMB-S4 observatory as the compelling and timely next leap for ground-based observations. CMB-S4 is a joint effort of NSF and DOE that includes international participation. It will conduct a 7-year ultra-deep survey of a few percent of the sky from the South Pole with a combination of large and multiple small aperture telescopes observing from 30-270 GHz. This will be done in parallel with a 7-year deep/wide survey of roughly half the sky with additional telescopes sited in the Atacama desert in Chile. A TRACE analysis estimated the cost for design, development and construction to be $660 million (FY2020), within 15 percent of the project team's analysis and within uncertainties for this stage of development. CMB-S4 is well along in planning, and could achieve first-light as early as 2026-27. Although significant scale-up of the detector production is required, plans are in hand to accomplish this. Aerospace evaluated the project risk as medium-low.

This project engages the international cosmology communities, building upon the foundation of decades of ground- and space-based measurements of the CMB to take a major leap that will push CMB science to the next level. The scientific reach of this observatory goes well beyond cosmology. CMB-S4 will produce unprecedented maps of ~50 percent of the sky between wavelengths of 1 mm and 1 cm with a cadence that samples the entire area every other day, opening up discovery space and providing scientific data that will engage a broad swath of the astronomical community. Particularly compelling to the survey is the fact that these observations open the opportunity for systematic time-domain studies in this part of the electromagnetic spectrum for the first time.

Recommendation: The National Science Foundation and the Department of Energy should jointly pursue the design and implementation of the next generation ground-based cosmic microwave background experiment (CMB-S4).

Important to our recommendation is that CMB-S4 is a project with a balanced commitment from both NSF and DOE from inception, to design, implementation, operations and science. NSF nurtures and supports university groups with broad scientific and technical experience who have been leading ground-based CMB efforts both in Chile and in Antarctica, and that have been and will continue to train new generations of talent. DOE brings to bear the technical expertise of its national laboratories, scientific expertise including large scale computation, and importantly systematic management approaches that have proven to be effective for large-scale projects. The agencies have been working jointly and effectively to prepare for initiating this compelling project.

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