CMB-S4

Next Generation CMB Experiment


Photo provided by Mark Devlin

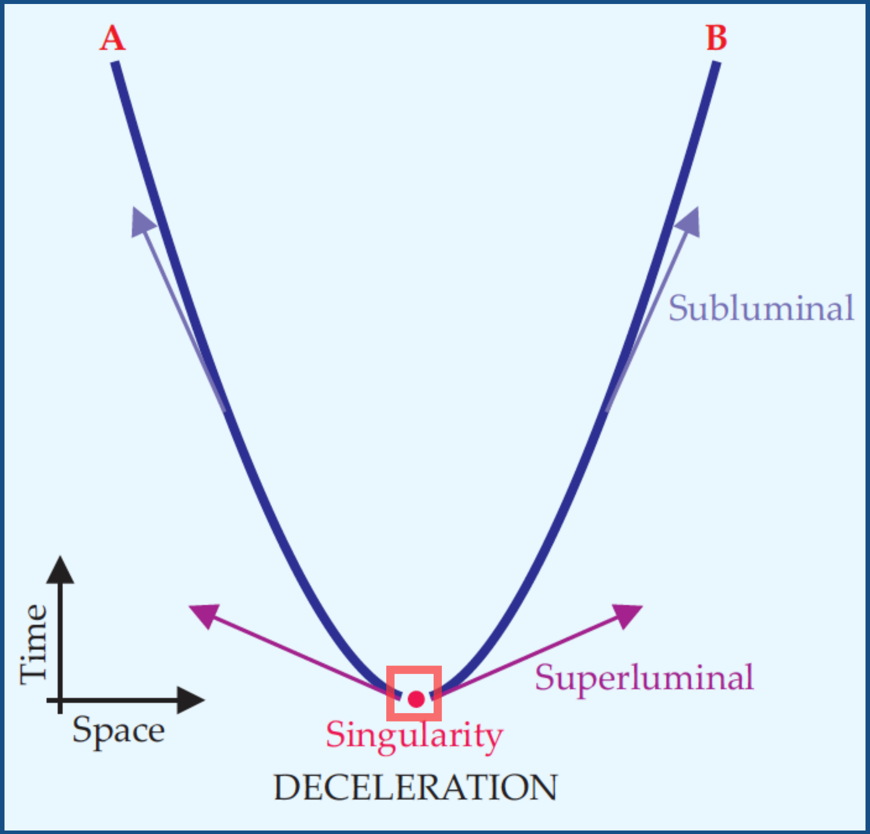
Lloyd Knox

University of California, Davis

On Behalf of the CMB-S4 Collaboration


Photo credit Cynthia Chiang

Carlstrom, Crawford, and Knox March 2015 Physics Today
“Particle Physics and the Cosmic Microwave Background”



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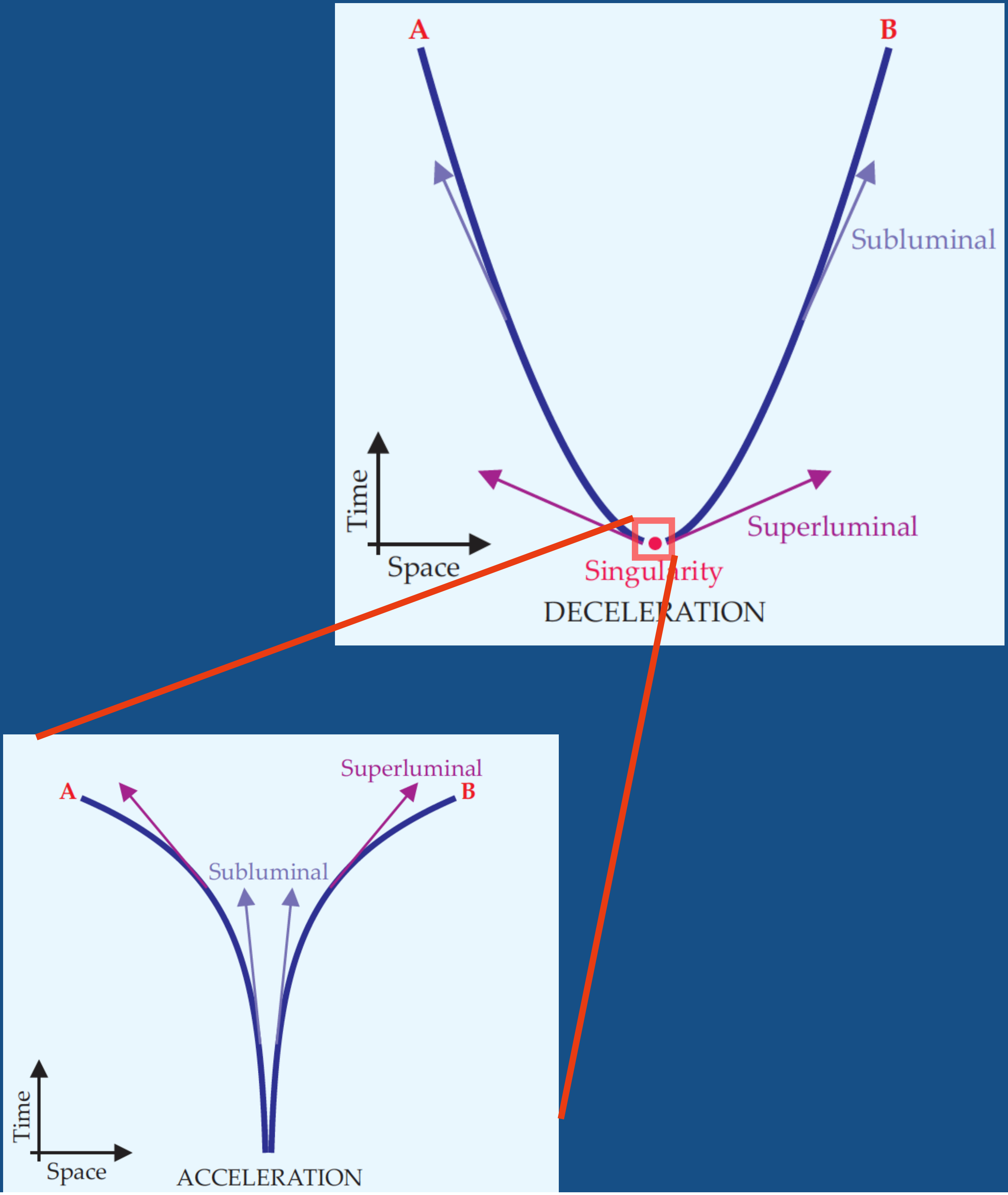

Carlstrom, Crawford, and Knox March 2015 Physics Today
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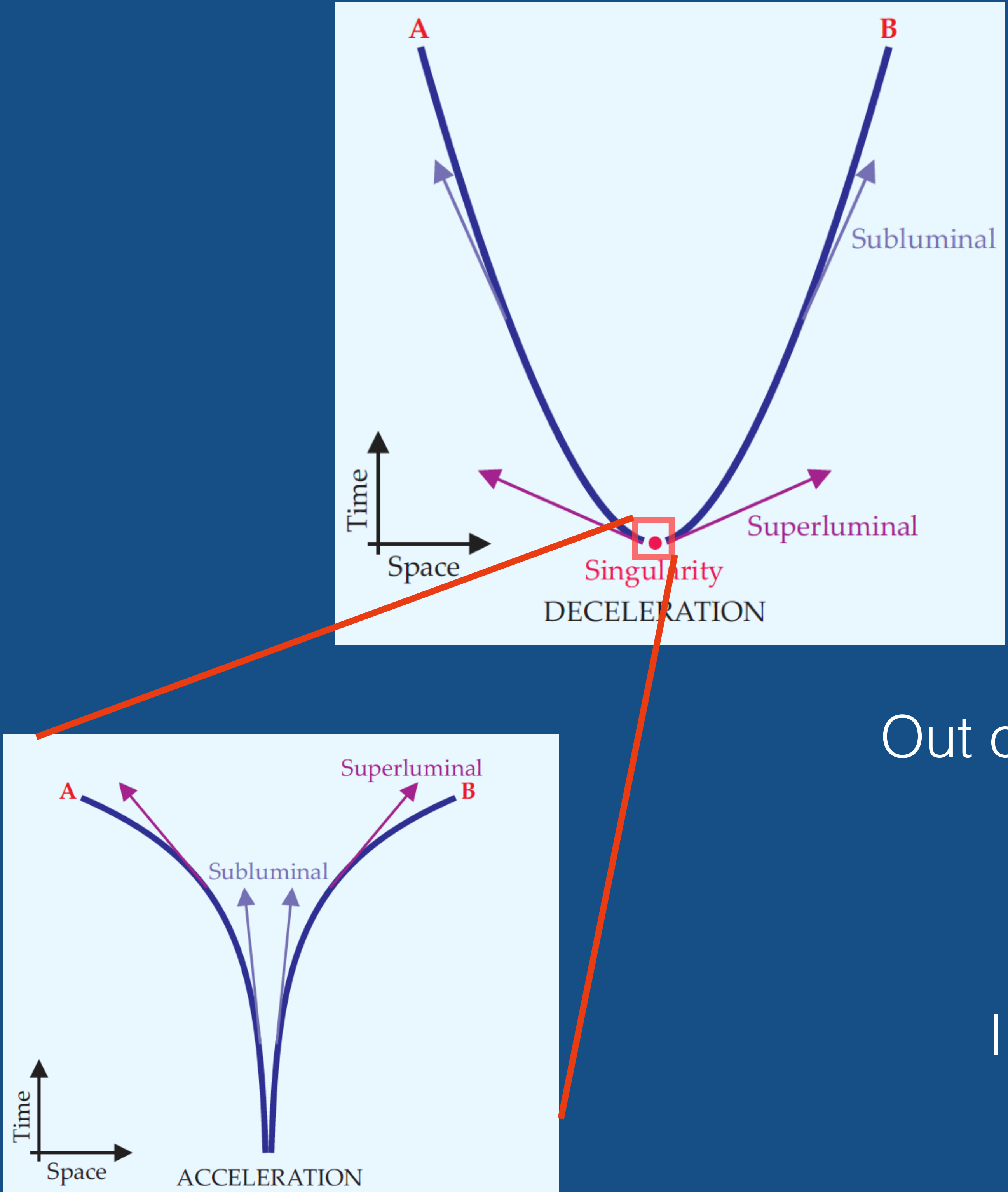
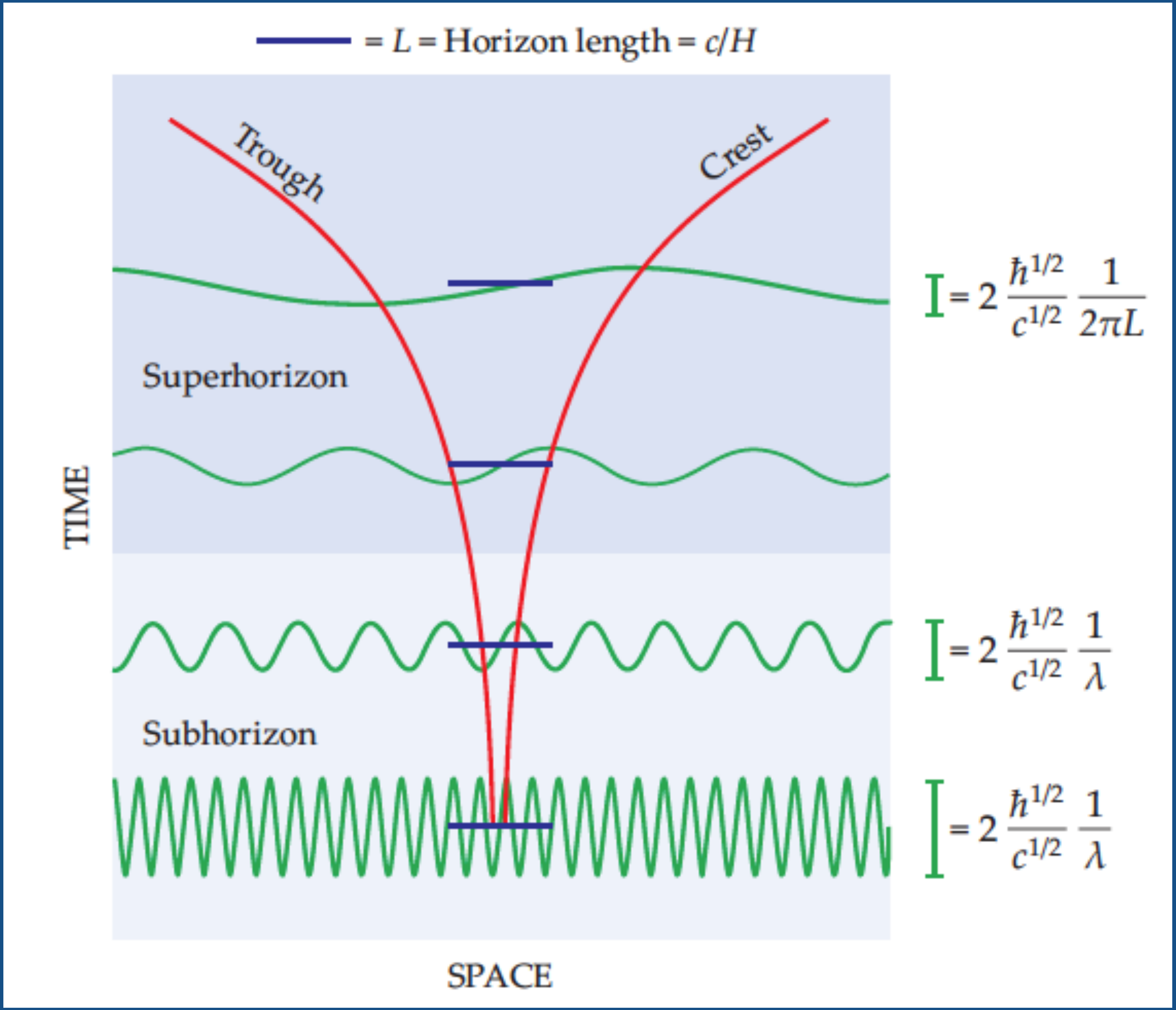


In causal contact

Out of causal contact

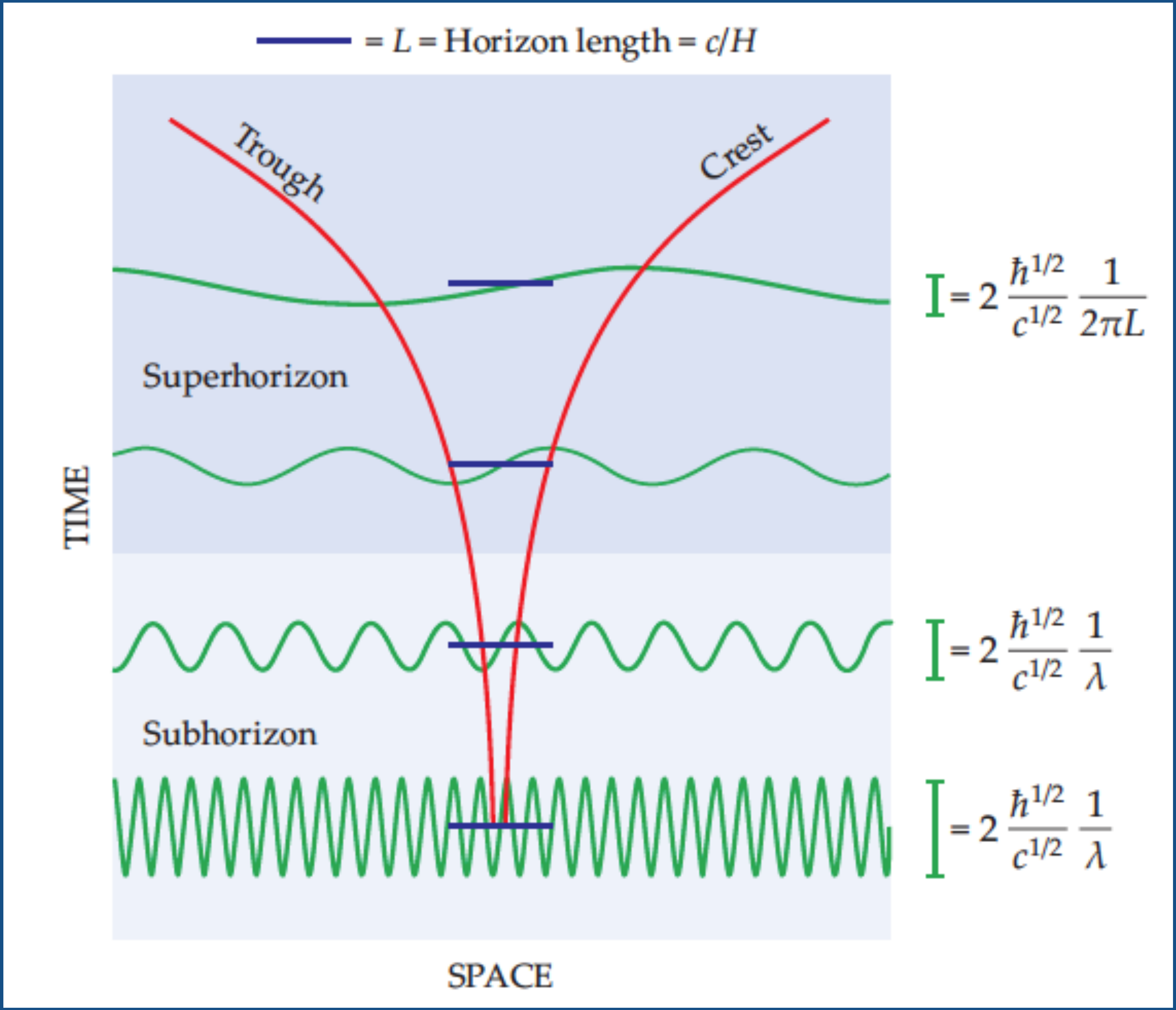
In causal contact

Carlstrom, Crawford, and Knox March 2015 Physics Today
“Particle Physics and the Cosmic Microwave Background”



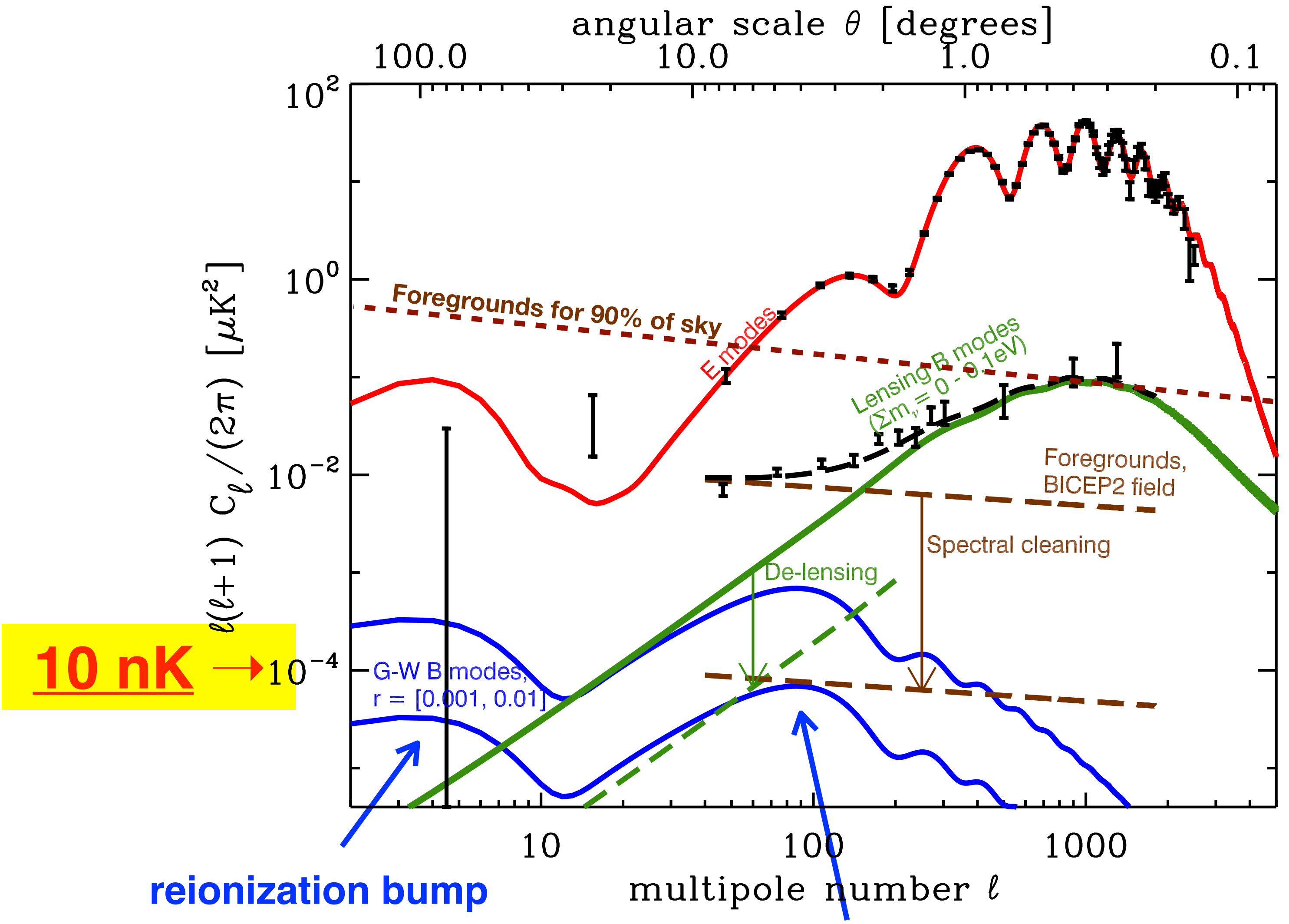
Acceleration + Lots of Expansion ==> Sensitivity to small-scale ground-state quantum fluctuations

Carlstrom, Crawford, and Knox March 2015 Physics Today
“Particle Physics and the Cosmic Microwave Background”



Ground-state fluctuations in the metric tensor ==> gravitational waves

The path forward is through much more sensitive polarization measurements



E modes

lensing
B modes

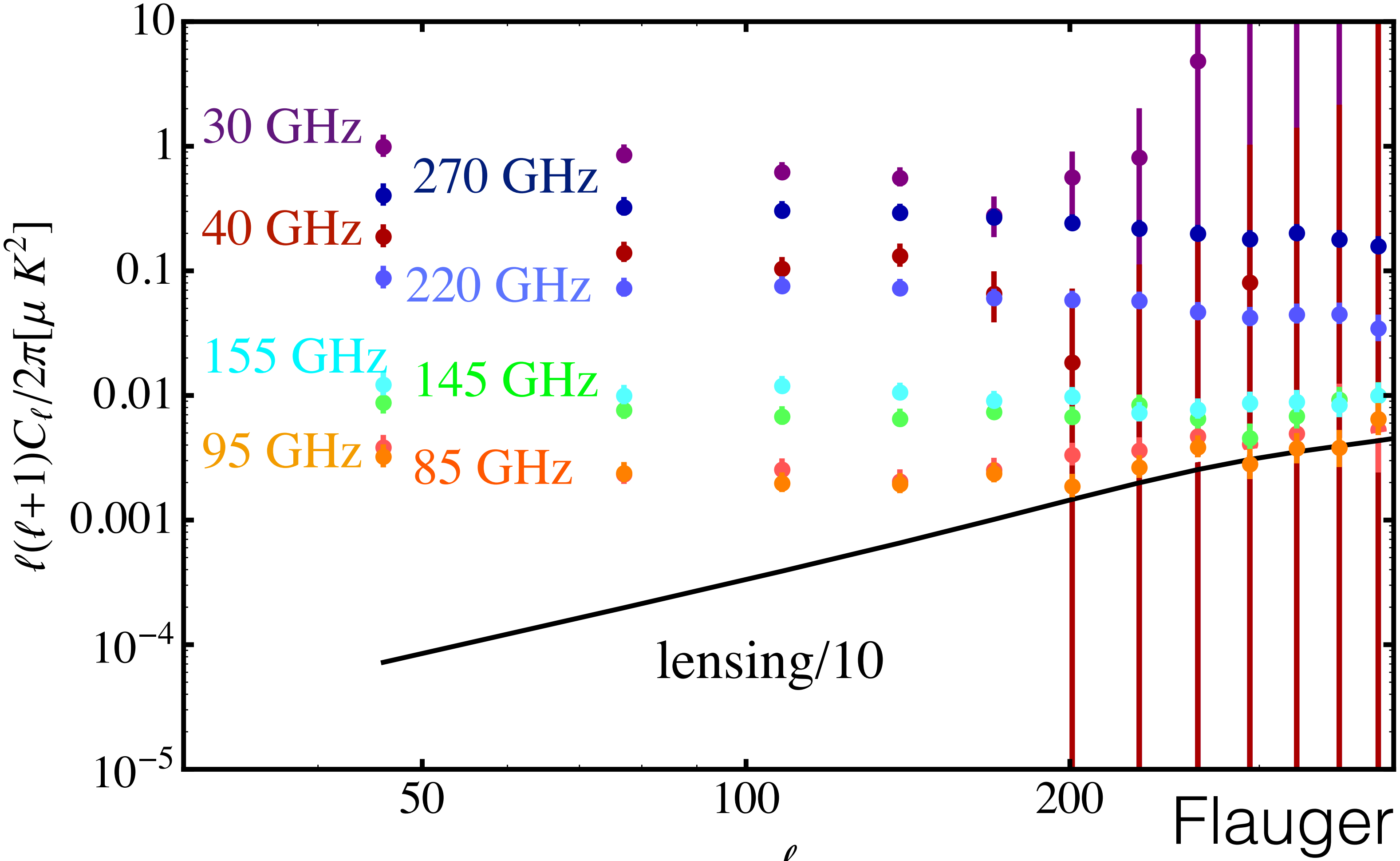
inflationary
gravity wave
B modes

reionization bump
CLASS exploring
from the ground;
target of LiteBIRD

recombination bump
key target of ground experiments, incl. CMB-S4

A Challenging Proposition

The challenge is to use maps with auto-spectra below to tell the difference between...

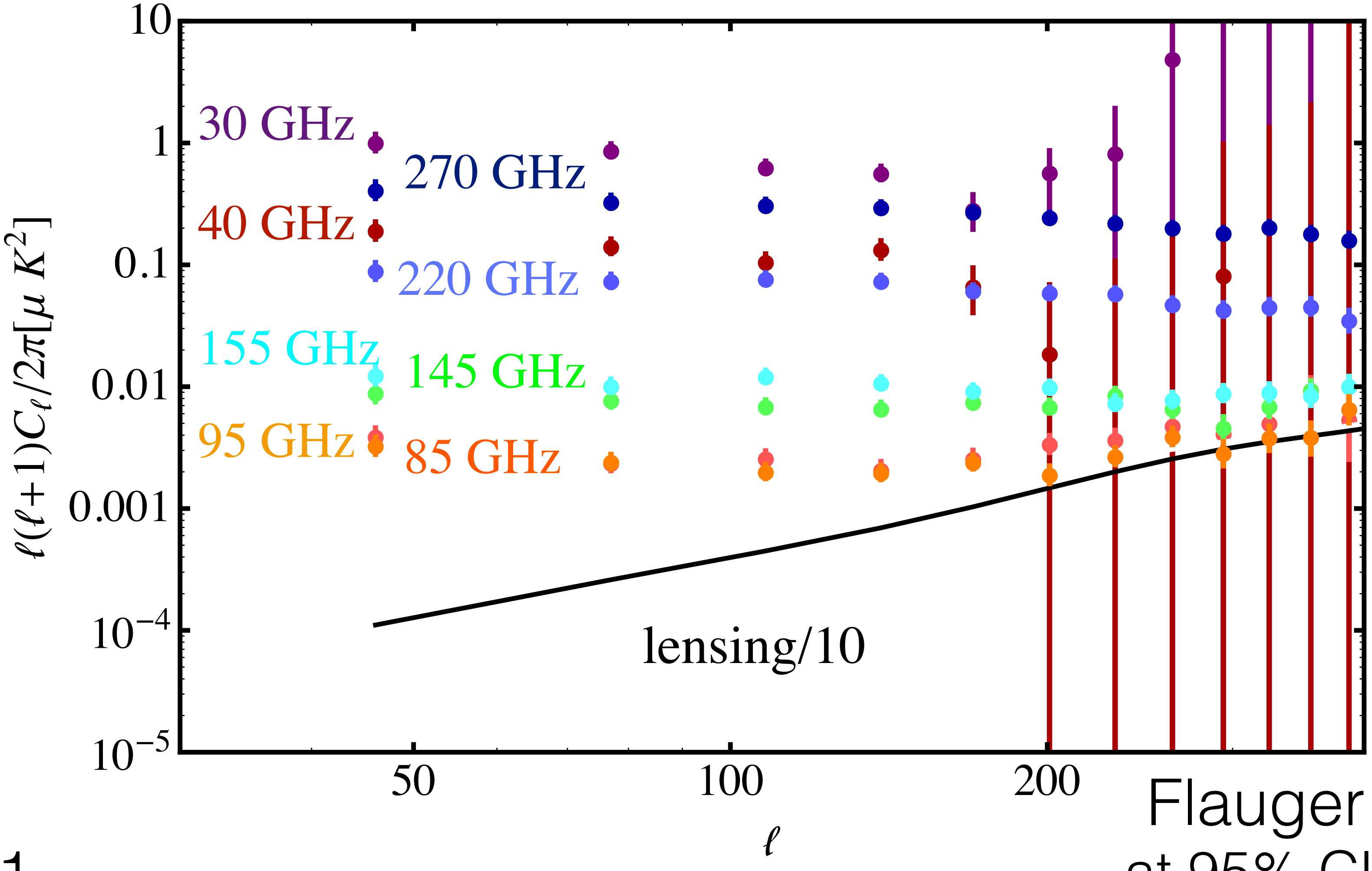


Flauger

r=0.000

A Challenging Proposition

and...



Flauger
at 95% CL

r=0.001

CMB-S4
Next Generation CMB Experiment

Next generation experiment: CMB-S4

- A next generation, Stage 4, ground-based experiment to pursue inflation, relic particles, neutrino properties, dark energy, galaxy and structure evolution and new discoveries.
- Enormous increase in sensitivity over the combined Stage 3 experiments now being deployed (>100x current Stage 2) to enable CMB-S4 to cross critical science thresholds.
- O(400,000) detectors spanning 20 - 270 GHz using multiple telescopes, large and small, at South Pole and Chile to map most of the sky, as well as deep targeted fields.
- Broad participation of the CMB community, including the existing CMB experiments (e.g., ACT, BICEP/Keck, CLASS, POLARBEAR/Simons Array, Simons Obs & SPT), U.S. National Labs and the High Energy Physics community.
- International partnerships expected and desired.


Building for Discovery
Strategic Plan for U.S. Particle Physics in the Global Context
Report of the Particle Physics Project Prioritization Panel (P5) May 2014

Recommended by P5

CMB-S4
Next Generation CMB Experiment

Twice yearly open community workshops to advance CMB-S4

6th CMB-S4 workshop, Harvard August 24-25, 2017

Next Workshops:

- March 5-7, 2018 at Argonne National Laboratory
- September 2018 at Princeton University

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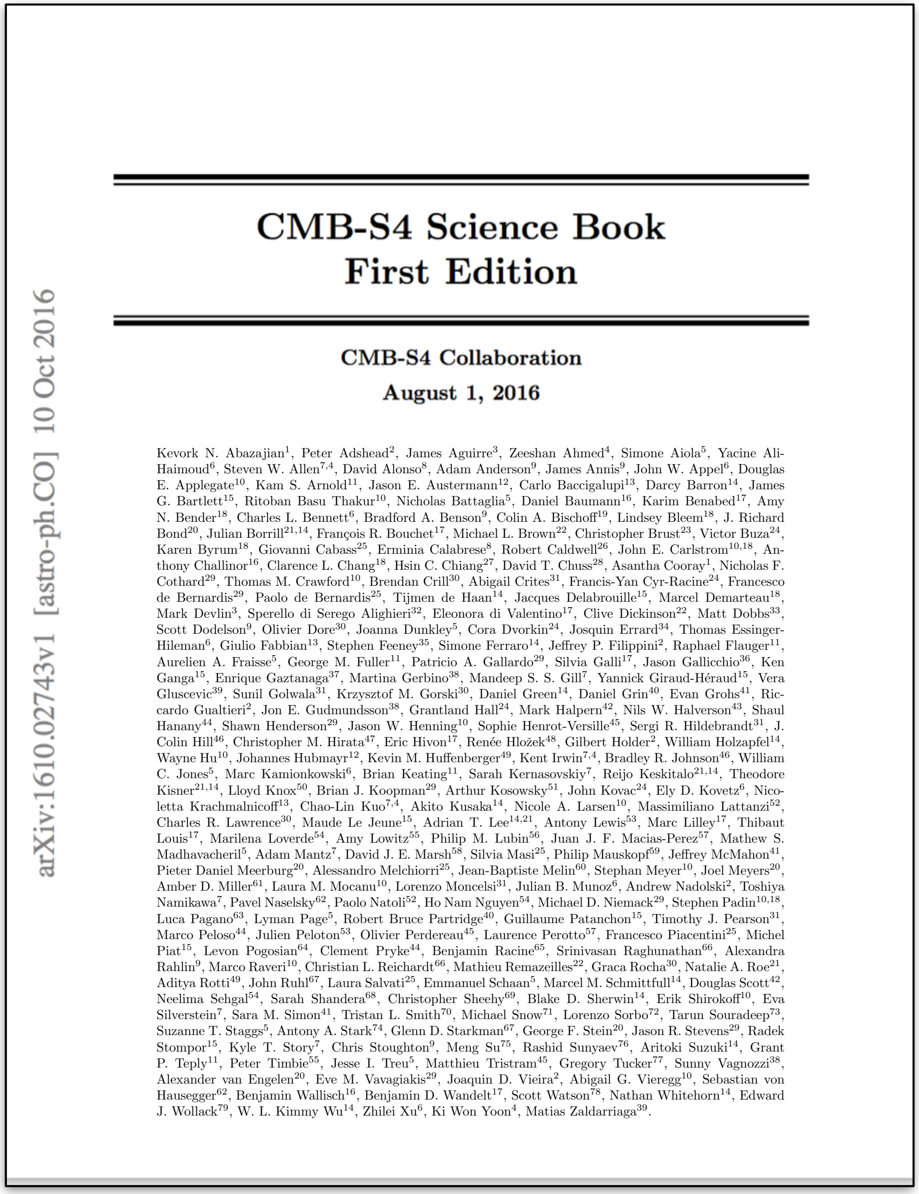
Next Generation CMB Experiment

CMB-S4 Science Book

CMB-S4 Science Book
and Technology Book
available at web site
http://cmb-s4.org

Science Book: 8 chapters (220 pages):

1) Exhortations
2) Inflation
3) Neutrinos
4) Light Relics
5) Dark Matter
6) Dark Energy
7) CMB lensing
8) Data Analysis, Simulations & Forecasting



arXiv:1610.02743v1 [astro-ph.CO] 10 Oct 2016

CMB-S4 Science Book
First Edition

CMB-S4 Collaboration

August 1, 2016

Kevork N. Abazajian[1], Peter Adshead[2], James Aguirre[3], Zeeshan Ahmed[4], Simone Aiola[5], Yacine Ali-Haimoud[6], Steven W. Allen[7,4], David Alonso[8], Adam Anderson[9], James Annis[9], John W. Appel[6], Douglas E. Applegate[10], Kam S. Arnold[11], Jason E. Austermann[12], Carlo Baccigalupi[13], Darcy Barron[14], James G. Bartlett[15], Ritoban Basu Thakur[10], Nicholas Battaglia[5], Daniel Baumann[16], Karim Benabed[17], Amy N. Bender[18], Charles L. Bennett[6], Bradford A. Benson[9], Colin A. Bischoff[19], Lindsey Bleem[18], J. Richard Bond[20], Julian Borrill[21,14], François R. Bouchet[17], Michael L. Brown[22], Christopher Brust[23], Victor Buza[24], Karen Byrum[18], Giovanni Cabass[25], Erminia Calabrese[8], Robert Caldwell[26], John E. Carlstrom[10,18], Anthony Challinor[16], Clarence L. Chang[18], Hsin C. Chiang[27], David T. Chuss[28], Asantha Cooray[1], Nicholas F. Cothard[29], Thomas M. Crawford[10], Brendan Crill[30], Abigail Crites[31], Francis-Yan Cyr-Racine[24], Francesco de Bernardis[29], Paolo de Bernardis[25], Tijmen de Haan[14], Jacques Delabrouille[15], Marcel Demarteau[18], Mark Devlin[3], Sperello di Serego Alighieri[32], Eleonora di Valentino[17], Clive Dickinson[22], Matt Dobbs[33], Scott Dodelson[9], Olivier Dore[30], Joanna Dunkley[5], Cora Dvorkin[24], Josquin Errard[34], Thomas Essinger-Hileman[6], Giulio Fabbian[13], Stephen Feeney[35], Simone Ferraro[14], Jeffrey P. Filippini[2], Raphael Flauger[11], Aurelien A. Fraisse[5], George M. Fuller[11], Patricio A. Gallardo[29], Silvia Galli[17], Jason Gallicchio[36], Ken Ganga[15], Enrique Gaztanaga[37], Martina Gerbino[38], Mandeep S. S. Gill[7], Yannick Giraud-Héraud[15], Vera Gluscevic[39], Sunil Golwala[31], Krzysztof M. Gorski[30], Daniel Green[14], Daniel Grin[40], Evan Grohs[41], Riccardo Gualtieri[2], Jon E. Gudmundsson[38], Grantland Hall[24], Mark Halpern[42], Nils W. Halverson[43], Shaul Hanany[44], Shawn Henderson[29], Jason W. Henning[10], Sophie Henrot-Versille[45], Sergi R. Hildebrandt[31], J. Colin Hill[46], Christopher M. Hirata[47], Eric Hivon[17], Renée Hložek[48], Gilbert Holder[2], William Holzapfel[14], Wayne Hu[10], Johannes Hubmayr[12], Kevin M. Huffenberger[49], Kent Irwin[7,4], Bradley R. Johnson[46], William C. Jones[5], Marc Kamionkowski[6], Brian Keating[11], Sarah Kernasovskiy[7], Reijo Keskitalo[21,14], Theodore Kisner[21,14], Lloyd Knox[50], Brian J. Koopman[29], Arthur Kosowsky[51], John Kovac[24], Ely D. Kovetz[6], Nicoletta Krachmalnicoff[13], Chao-Lin Kuo[7,4], Akito Kusaka[14], Nicole A. Larsen[10], Massimiliano Lattanzi[52], Charles R. Lawrence[30], Maude Le Jeune[15], Adrian T. Lee[14,21], Antony Lewis[53], Marc Lilley[17], Thibaut Louis[17], Marilena Loverde[54], Amy Lowitz[55], Philip M. Lubin[56], Juan J. F. Macias-Perez[57], Mathew S. Madhavacheril[5], Adam Mantz[7], David J. E. Marsh[58], Silvia Masi[25], Philip Mauskopf[59], Jeffrey McMahon[41], Pieter Daniel Meerburg[20], Alessandro Melchiorri[25], Jean-Baptiste Melin[60], Stephan Meyer[10], Joel Meyers[20], Amber D. Miller[61], Laura M. Mocanu[10], Lorenzo Moncelsi[31], Julian B. Munoz[6], Andrew Nadolski[2], Toshiya Namikawa[7], Pavel Naselsky[62], Paolo Natoli[52], Ho Nam Nguyen[54], Michael D. Niemack[29], Stephen Padin[10,18], Luca Pagano[63], Lyman Page[5], Robert Bruce Partridge[40], Guillaume Patanchon[15], Timothy J. Pearson[31], Marco Peloso[44], Julien Peloton[53], Olivier Perdereau[45], Laurence Perotto[57], Francesco Piacentini[25], Michel Piat[15], Levon Pogosian[64], Clement Pryke[44], Benjamin Racine[65], Srinivasan Raghunathan[66], Alexandra Rahlin[9], Marco Raveri[10], Christian L. Reichardt[66], Mathieu Remazeilles[22], Graca Rocha[30], Natalie A. Roe[21], Aditya Rotti[49], John Ruhl[67], Laura Salvati[25], Emmanuel Schaan[5], Marcel M. Schmittfull[14], Douglas Scott[42], Neelima Sehgal[54], Sarah Shandera[68], Christopher Sheehy[69], Blake D. Sherwin[14], Erik Shirokoff[10], Eva Silverstein[7], Sara M. Simon[41], Tristan L. Smith[70], Michael Snow[71], Lorenzo Sorbo[72], Tarun Souradeep[73], Suzanne T. Staggs[5], Antony A. Stark[74], Glenn D. Starkman[67], George F. Stein[20], Jason R. Stevens[29], Radek Stompor[15], Kyle T. Story[7], Chris Stoughton[9], Meng Su[75], Rashid Sunyaev[76], Aritoki Suzuki[14], Grant P. Teply[11], Peter Timbie[55], Jesse I. Treu[5], Matthieu Tristram[45], Gregory Tucker[77], Sunny Vagnozzi[38], Alexander van Engelen[20], Eve M. Vavagiakis[29], Joaquin D. Vieira[2], Abigail G. Vieregg[10], Sebastian von Hausegger[62], Benjamin Wallisch[16], Benjamin D. Wandelt[17], Scott Watson[78], Nathan Whitehorn[14], Edward J. Wollack[79], W. L. Kimmy Wu[14], Zhilei Xu[6], Ki Won Yoon[4], Matias Zaldarriaga[39].

CMB-S4
Next Generation CMB Experiment

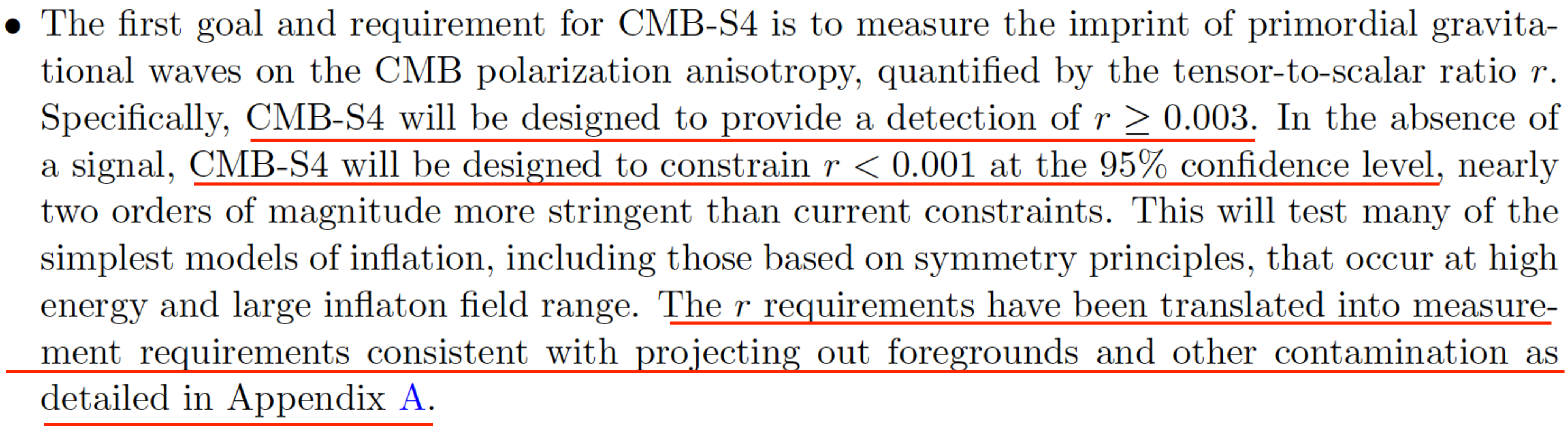
Concept Definition Task force (CDT)

Working from CMB-S4 Science Book, earlier documents, and new simulation work, the NSF & DOE-sponsored Concept Definition Task force submitted its report in October 2017

Concept defined and costed.
Formal CMB-S4 collaboration now being established and working with the agencies and national laboratories on next steps.

https://cmb-s4.org/CMB-S4workshops/index.php/File:CMBS4_CDT_final.pdf

From the Executive Summary of the CDT Report



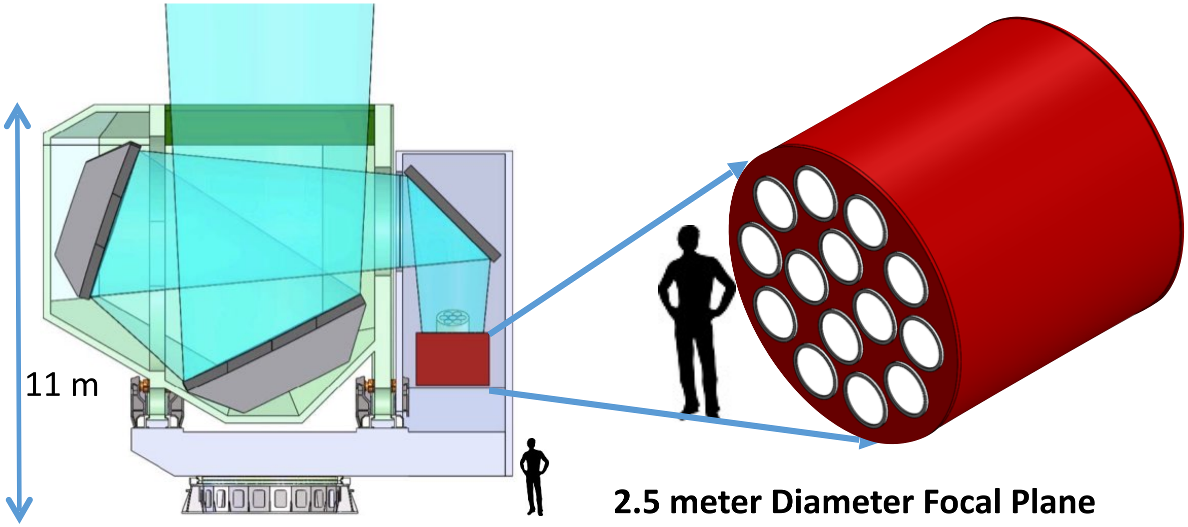
- The first goal and requirement for CMB-S4 is to measure the imprint of primordial gravitational waves on the CMB polarization anisotropy, quantified by the tensor-to-scalar ratio r. Specifically, CMB-S4 will be designed to provide a detection of $r \geq 0.003$. In the absence of a signal, CMB-S4 will be designed to constrain $r < 0.001$ at the 95% confidence level, nearly two orders of magnitude more stringent than current constraints. This will test many of the simplest models of inflation, including those based on symmetry principles, that occur at high energy and large inflaton field range. The r requirements have been translated into measurement requirements consistent with projecting out foregrounds and other contamination as detailed in Appendix A.

https://cmb-s4.org/CMB-S4workshops/index.php/File:CMBS4_CDT_final.pdf

CMB-S4
Next Generation CMB Experiment

CMB-S4 concept

- One collaboration, one project, with two sites: South Pole and Atacama, Chile
- 14 small (0.5 m) and 3 large (≥6m) telescopes for B-mode, de-lensing, N_{eff} and cosmic structure science
- Total of ~400,000 detectors with 9 frequency bands spanning 20-270 GHz.
- Two surveys:
  - 4 yr deep B-mode w/ de-lensing (f_{sky} ~3-8%) with 1 large & 14 small telescopes
  - 7 yr broad for N_{eff} and cosmic structure science (f_{sky} = 40%) with 2 large telescopes

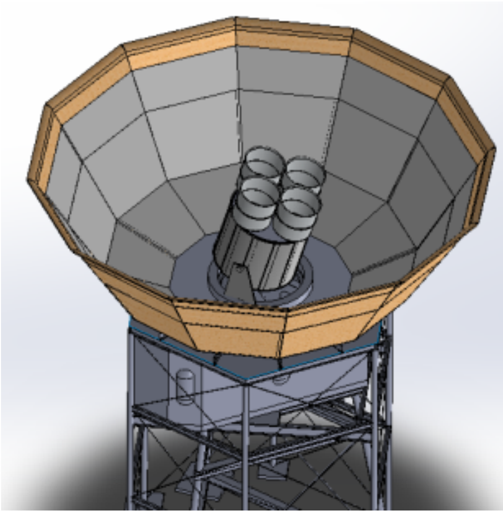


e.g., 6 meter Diameter Telescope

2.5 meter Diameter Focal Plane with 70,000 detectors

High resolution Science + de-lensing:
210,000 detectors on <u>3 large telescopes</u>

Figure from Simons Obs, Mark Devlin / Mike Niemack



Low resolution B-mode Science:
170,000 det. on <u>14 small telescopes</u>

Figure from BICEP Array

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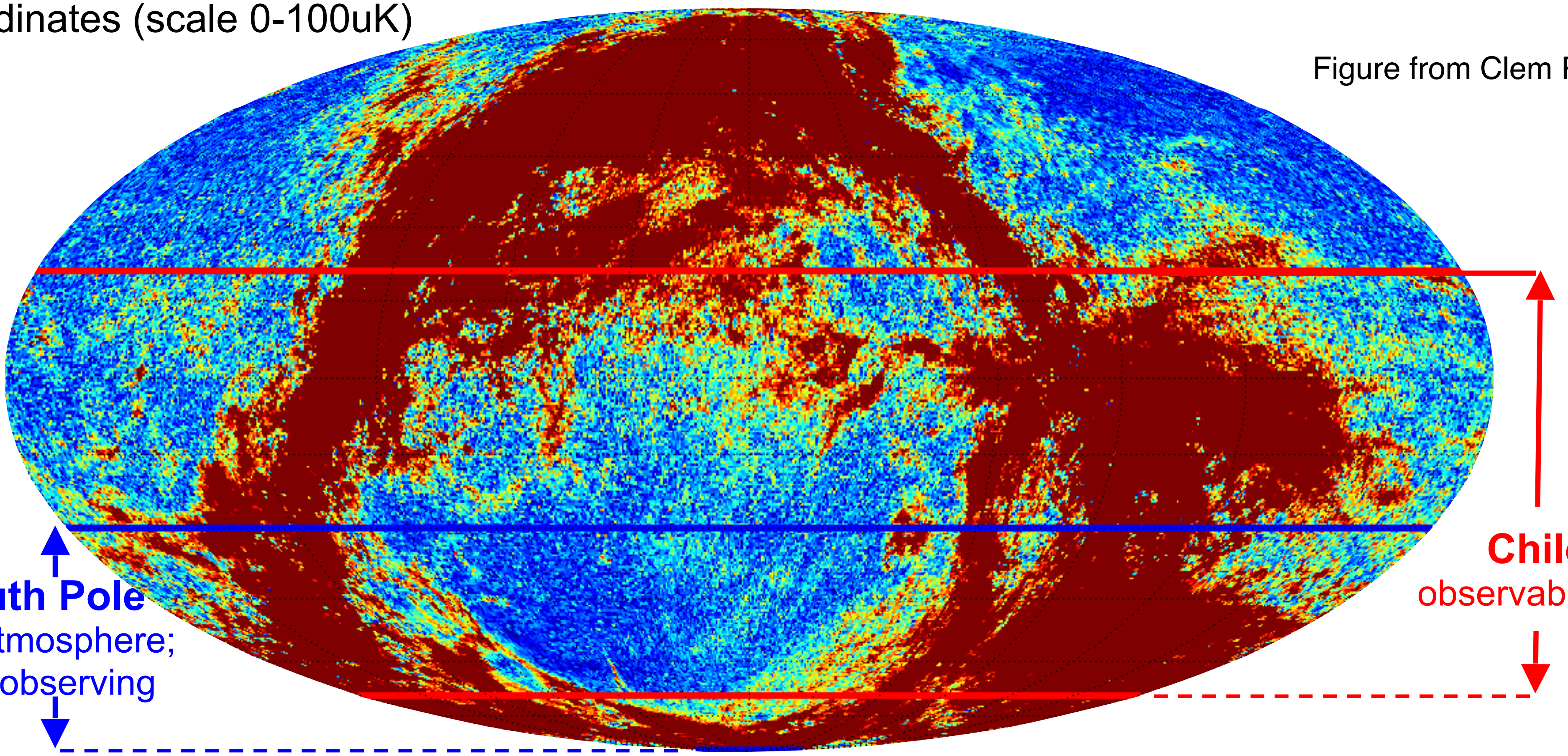
Next Generation CMB Experiment

Telescopes at Chile and South Pole (established, proven CMB sites)

Planck 353 GHz polarized intensity map in celestial coordinates (scale 0-100uK)

Figure from Clem Pryke



South Pole
best atmosphere;
24/7 observing

Chile
observable sky

South Pole excellent for ultra deep fields

Chile excellent for wide sky coverage

(Ali site in Tibet would allow full sky coverage)

Main contributors to Appendix A:

Colin Bischoff, Julian Borrill, Victor Buza, Tom Crawford, Raphael Flauger, Brandon Hensley, LK, John Kovac, Charles Lawrence, Clem Pryke, Justin Willmert
+
de-lensers: Collin Hill, Neelima Sehgal, Blake Sherwin, Kyle Story, Alex van Engelen, Kimmy Wu

Important optimization study that also informed CDT thinking:
Barron et al. (2017)

Forecasting Methodology

1. Start with particular sky model.

2. Use the (semi-)analytic spectral forecasts, based on achieved map noise power and full BPCM, for optimization forecasting.

3. Determine baseline “checkpoints” in survey definition space.

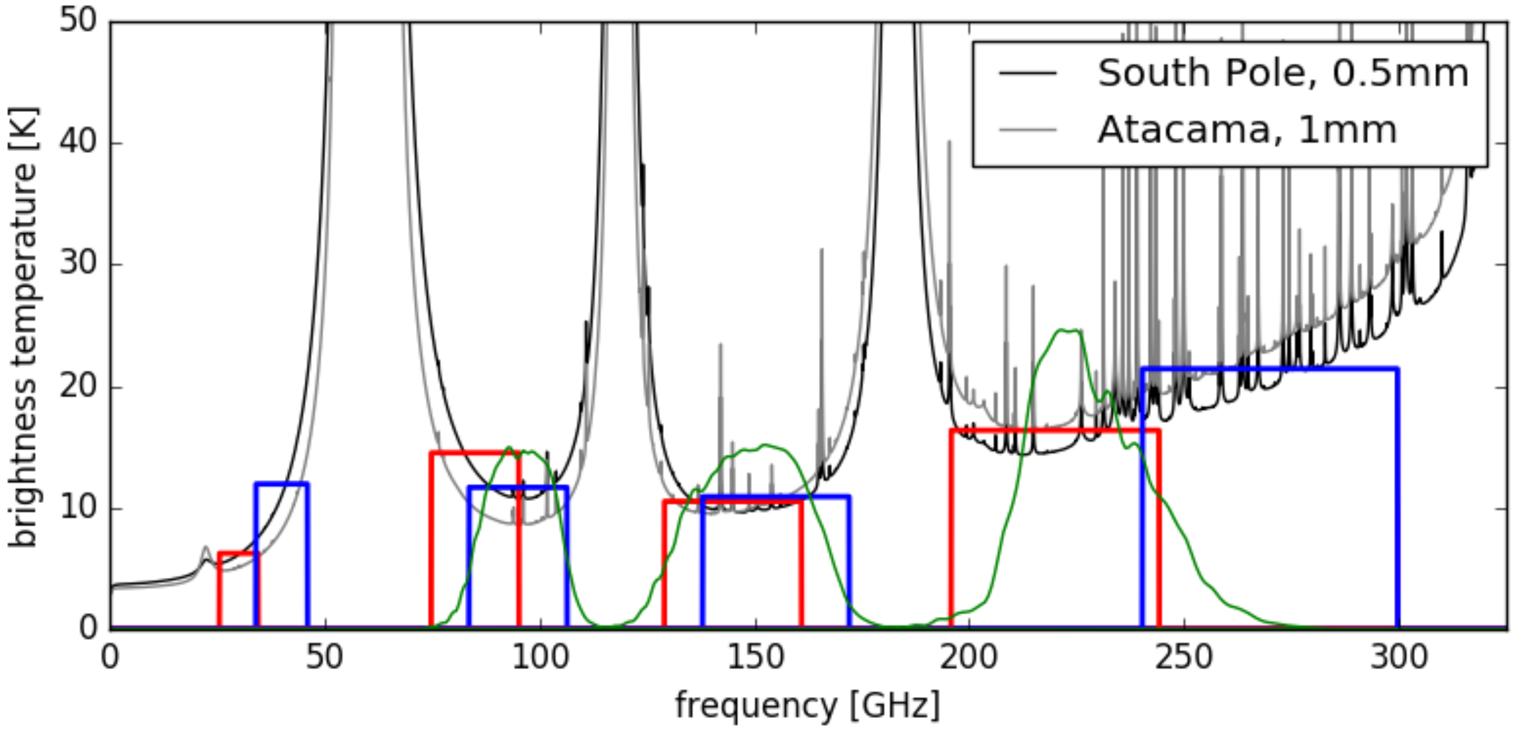
4. Validate checkpoint configurations with standardized, version-numbered map-based data challenges.

5. Increase complexity: model / band selection / systematic effects / unmodeled residuals

6. Analyses of real experiments from timestreams are used to validate the form, parameterization and likely amplitude of systematics, as well as guiding the scaling of the noise.

7. Iterate

Basis of our r forecasts in the Science Book

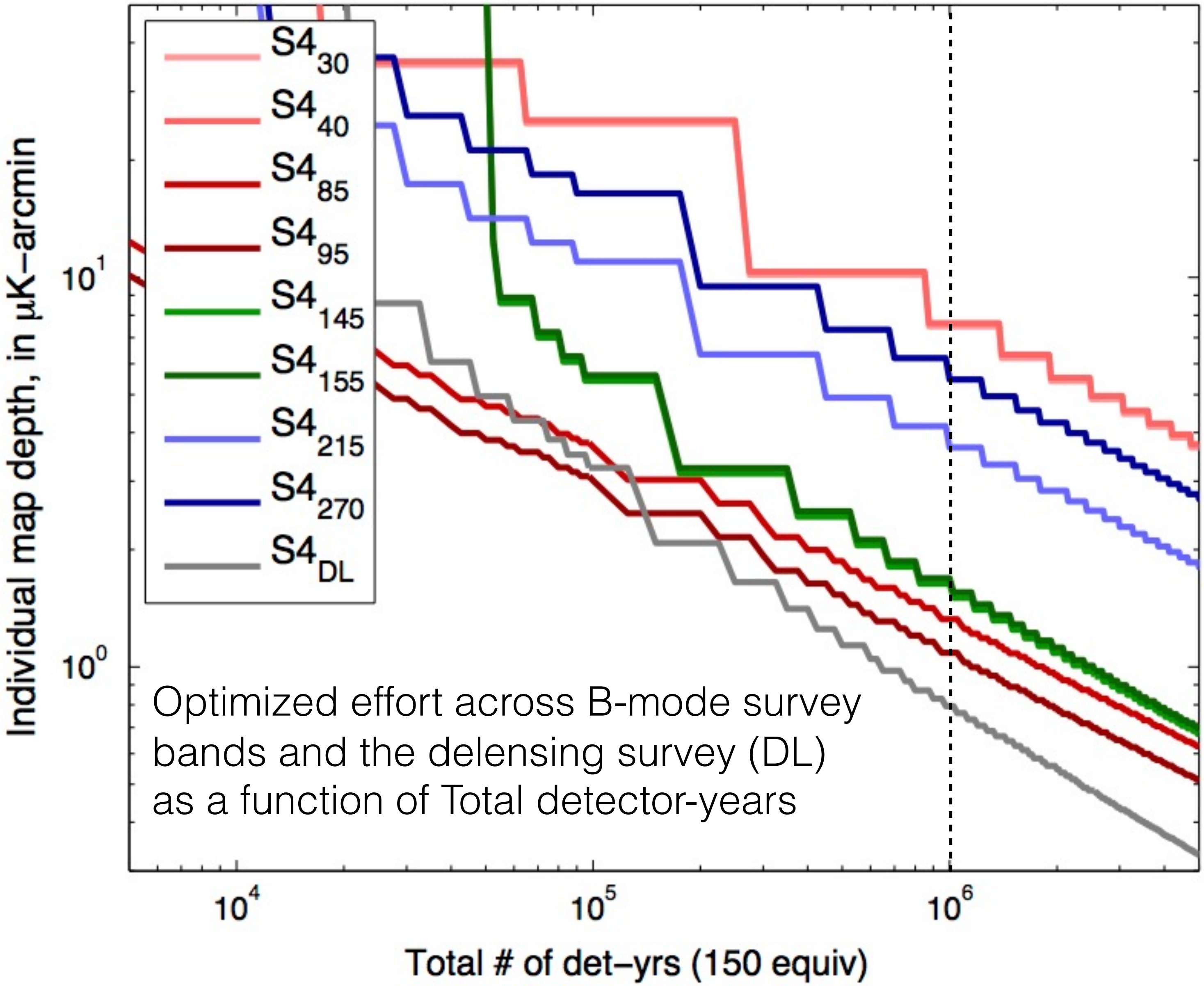


Science Book Low-res Survey Bands
Chosen to cover atmospheric windows

A simple foreground model and power spectrum Fisher analysis was used to optimize detector allocation across these bands (Buza, Bischoff, Kovac)

Optimization example for r = 0 and fsky = 3% (with band split)

From work on Science Book

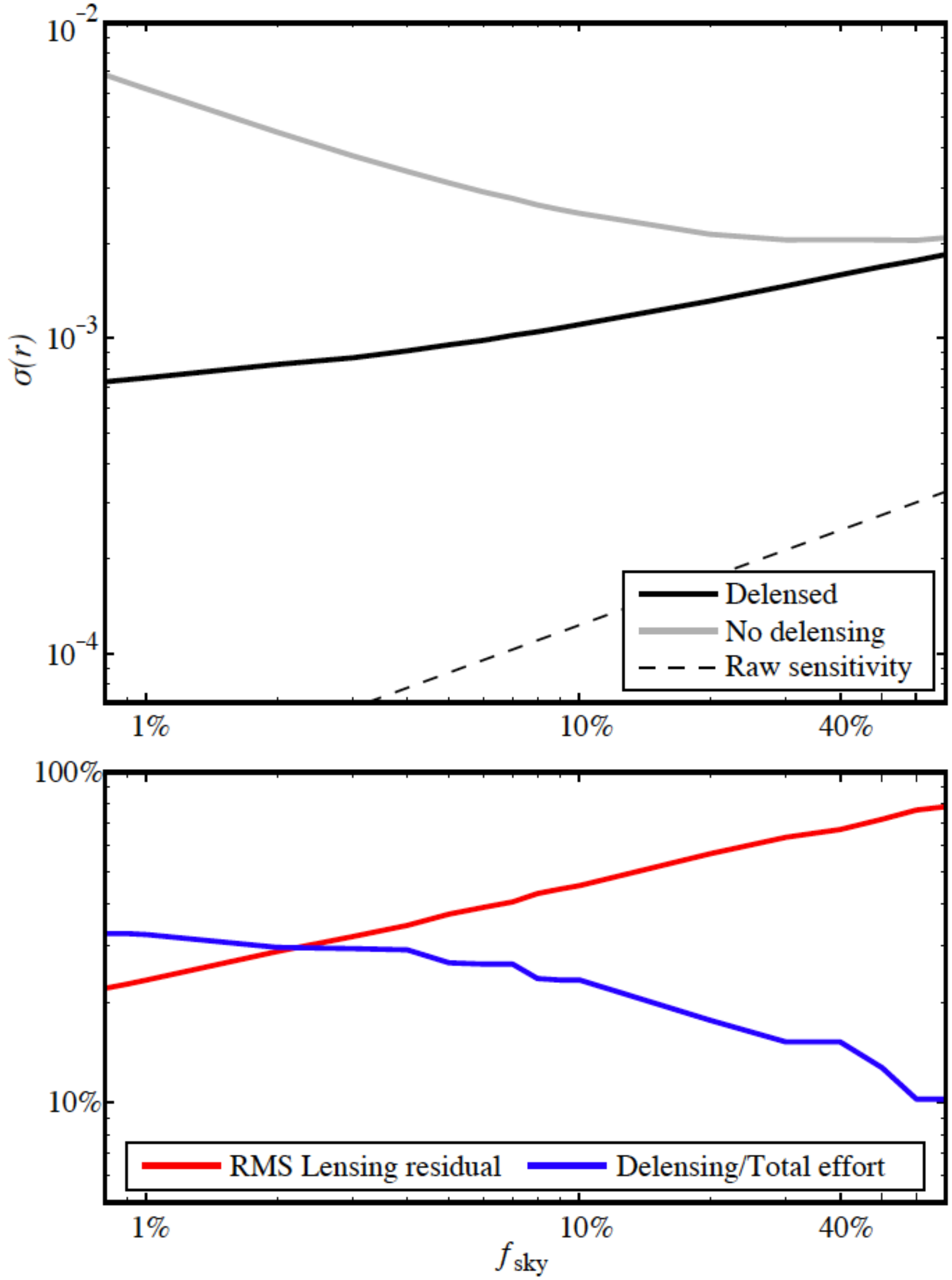


Optimized effort across B-mode survey bands and the delensing survey (DL) as a function of Total detector-years

Forecasted map depths based on scaling from achieved BICEP/Keck performance

DL map depth —> lensing power removed based on Smith et al. (2012)

Figure from CMB-S4 Science Book



(Assuming r=0)

Results from Spectral-based Fisher Forecasting with Optimization of Frequency Allocation

- For fixed total effort (focal plane area times observing time), at a given fsky, the detector allocation is chosen to minimize sigma(r)
  - across surveys (degree-scale vs. de-lensing)
  - across frequency in the degree-scale survey
- Note raw sensitivity line: foregrounds have huge impact

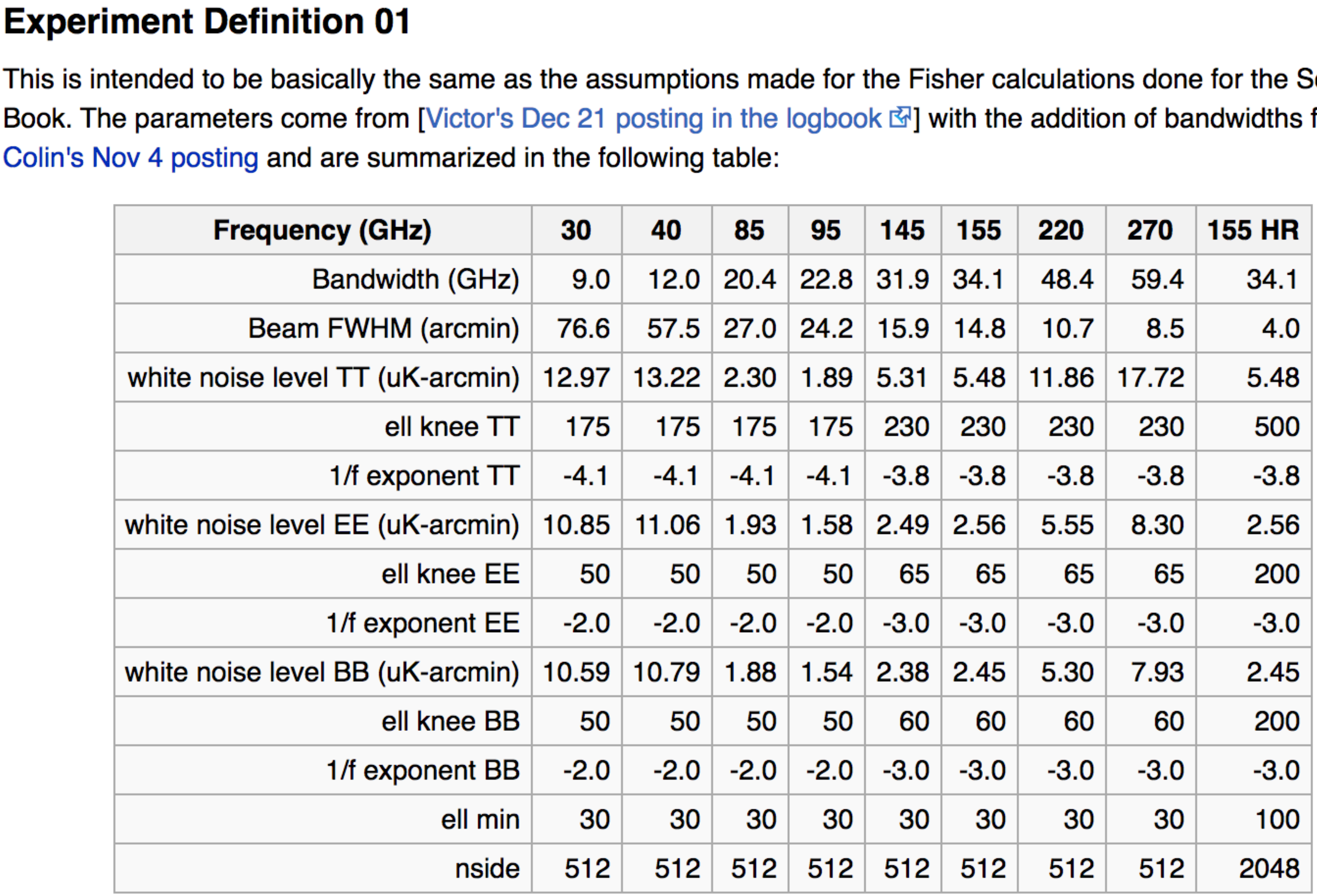
Forecasting Methodology

1. Start with particular sky model.
2. Use the (semi-)analytic spectral forecasts, based on achieved map noise power and full BPCM, for optimization forecasting.
3. Determine baseline “checkpoints” in survey definition space.
4. Validate checkpoint configurations with standardized, version-numbered map-based data challenges.
5. Increase complexity: model / band selection / systematic effects / unmodeled residuals
6. Analyses of real experiments from timestreams are used to validate the form, parameterization and likely amplitude of systematics, as well as guiding the scaling of the noise.
7. Iterate

Simulations Require:
1) Experiment Model
2) Sky Model

From the Data Challenge region of the S4 wiki

(https://cmb-s4.org/CMB-S4workshops/index.php/Data_Challenges)



Experiment Definition 01

This is intended to be basically the same as the assumptions made for the Fisher calculations done for the Science Book. The parameters come from [Victor's Dec 21 posting in the logbook] with the addition of bandwidths from Colin's Nov 4 posting and are summarized in the following table:

Frequency (GHz)	30	40	85	95	145	155	220	270	155 HR
Bandwidth (GHz)	9.0	12.0	20.4	22.8	31.9	34.1	48.4	59.4	34.1
Beam FWHM (arcmin)	76.6	57.5	27.0	24.2	15.9	14.8	10.7	8.5	4.0
white noise level TT (uK-arcmin)	12.97	13.22	2.30	1.89	5.31	5.48	11.86	17.72	5.48
ell knee TT	175	175	175	175	230	230	230	230	500
1/f exponent TT	-4.1	-4.1	-4.1	-4.1	-3.8	-3.8	-3.8	-3.8	-3.8
white noise level EE (uK-arcmin)	10.85	11.06	1.93	1.58	2.49	2.56	5.55	8.30	2.56
ell knee EE	50	50	50	50	65	65	65	65	200
1/f exponent EE	-2.0	-2.0	-2.0	-2.0	-3.0	-3.0	-3.0	-3.0	-3.0
white noise level BB (uK-arcmin)	10.59	10.79	1.88	1.54	2.38	2.45	5.30	7.93	2.45
ell knee BB	50	50	50	50	60	60	60	60	200
1/f exponent BB	-2.0	-2.0	-2.0	-2.0	-3.0	-3.0	-3.0	-3.0	-3.0
ell min	30	30	30	30	30	30	30	30	100
nside	512	512	512	512	512	512	512	512	2048

Experiment Definitions

- 01: Science Book (slightly modified)
- 02: addition of 20 GHz and (slight) changes to allocation across bands
  - 02b: fsky = 1% and 02c: fsky = 10%
- 03 (and 03b, 03c): same as 02 + 8 different systematic error contributions
- 04: very similar to 02 but with noise levels tweaked down by sqrt(7/6) to hit our r science target and 20 GHz resolution increased by placing it on a 6m telescope

Sky Models

- 00: Gaussian dust + Gaussian Sync set to levels found in BICEP/Keck field, LCDM CMB but with lensing scaled down so A_L = 0.1 (Science Book sky model)

- 01: This is PySM run in a1d1f1s1 mode - i.e. with the default settings for AME, dust, free-free and synchrotron. [a = AME, d = dust, f = free-free, s = synchrotron, with numbers indicating number of parameters in the model.]

- 02: This is PySM run in a2d4f1s3 mode

- 03: ~02 but with Hensley/Draine dust model

- 04: like above but w/ Tuhin Ghosh dust model

- 05: toy dust model with (probably) unphysically high dust decorrelation

- 06: Flauger/Hensley based on MHD sims for naturally correlated dust and synchrotron

Experiment Definition 02: Results for our suite of sky models

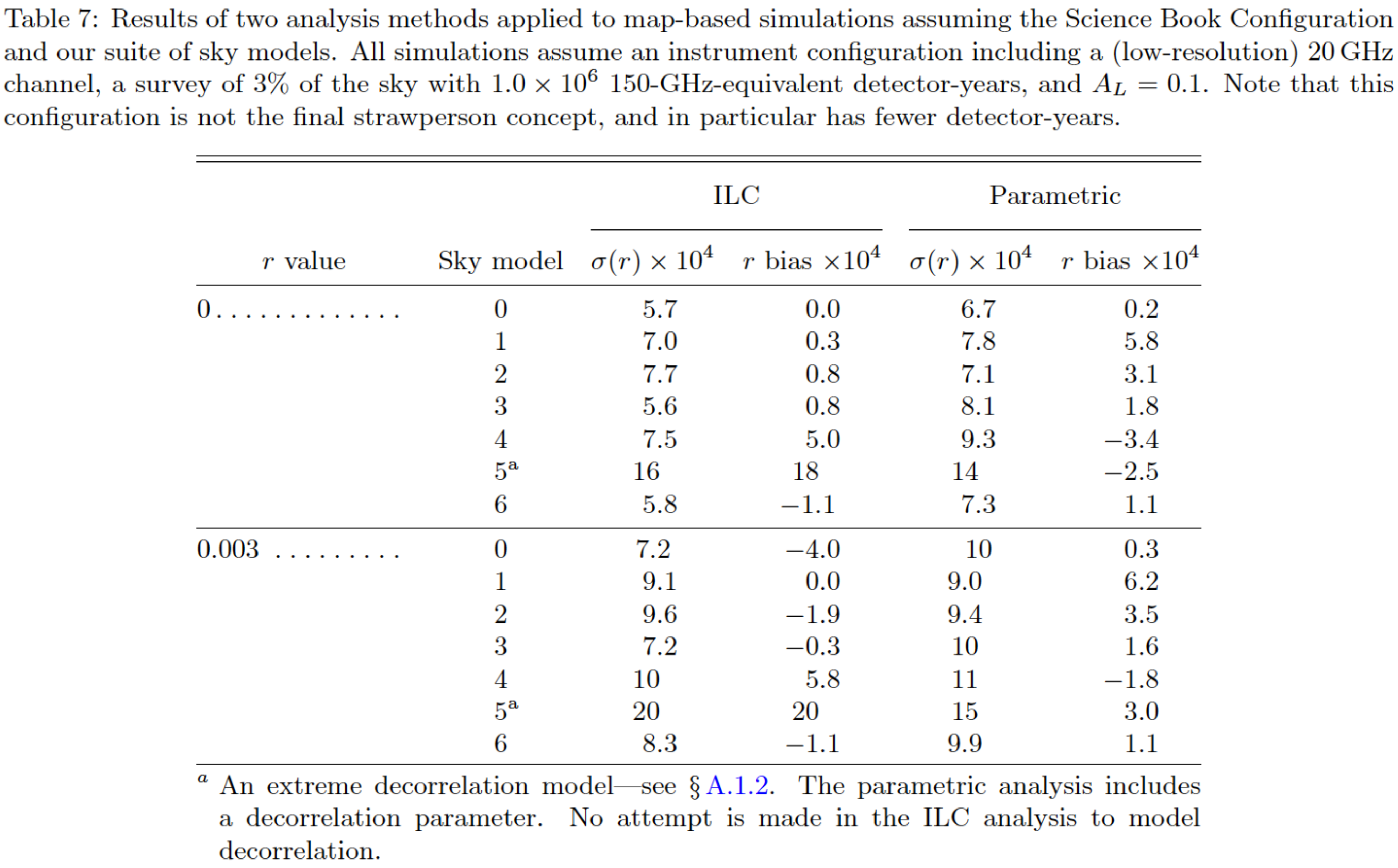


Table 7: Results of two analysis methods applied to map-based simulations assuming the Science Book Configuration and our suite of sky models. All simulations assume an instrument configuration including a (low-resolution) 20 GHz channel, a survey of 3% of the sky with 1.0×10^6 150-GHz-equivalent detector-years, and $A_L = 0.1$. Note that this configuration is not the final strawperson concept, and in particular has fewer detector-years.

		ILC		Parametric	
r value	Sky model	$\sigma(r) \times 10^4$	r bias $\times 10^4$	$\sigma(r) \times 10^4$	r bias $\times 10^4$
0	0	5.7	0.0	6.7	0.2
	1	7.0	0.3	7.8	5.8
	2	7.7	0.8	7.1	3.1
	3	5.6	0.8	8.1	1.8
	4	7.5	5.0	9.3	−3.4
	5[a]	16	18	14	−2.5
	6	5.8	−1.1	7.3	1.1
0.003	0	7.2	−4.0	10	0.3
	1	9.1	0.0	9.0	6.2
	2	9.6	−1.9	9.4	3.5
	3	7.2	−0.3	10	1.6
	4	10	5.8	11	−1.8
	5[a]	20	20	15	3.0
	6	8.3	−1.1	9.9	1.1

[a] An extreme decorrelation model—see § A.1.2. The parametric analysis includes a decorrelation parameter. No attempt is made in the ILC analysis to model decorrelation.

Key Points From Sims

- Sky Model 0 analytic forecast results (Science Book forecasts) were reproduced with map-based simulations via two analysis methods

- With one exception, different foreground models increase error on r only by 1.1 - 1.4.

- The one exception is Sky Model 05, with the highly decorrelated dust, increasing error by factor of 2 to 3. Consistent with observations in CMB channels, but highly unexpected. But does serve as warning: unexpected foreground properties can impact us.

- Experiment Definition 02 + Sky Model 6 analyzed in the most conservative manner has high bias due to synchrotron residuals at ell ~ 100 to 150. Experiment Definition 04 (Strawperson concept) thus puts 20 GHz channel on the 6-m telescope.

Results for the strawperson concept
(Experiment Definition 04)

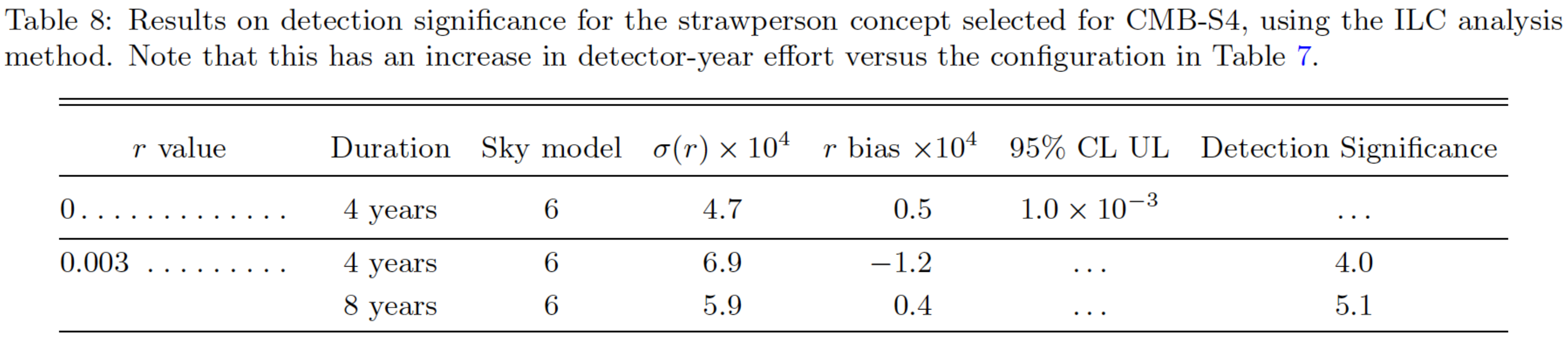
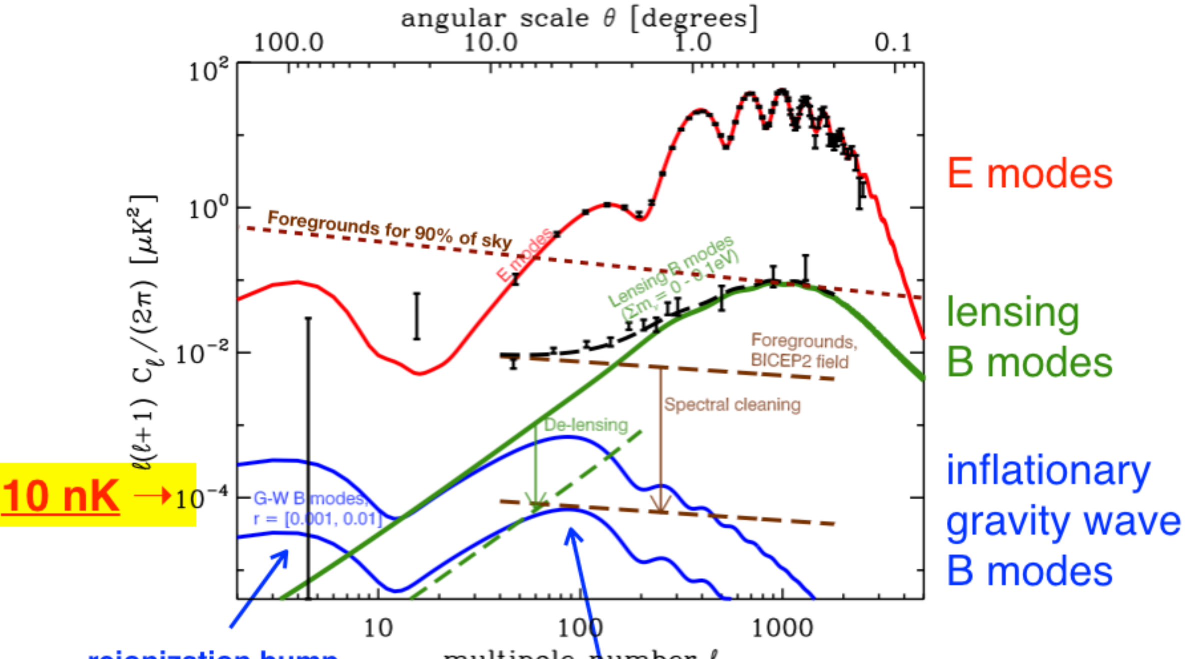


Table 8: Results on detection significance for the strawperson concept selected for CMB-S4, using the ILC analysis method. Note that this has an increase in detector-year effort versus the configuration in Table 7.

r value	Duration	Sky model	$\sigma(r) \times 10^4$	r bias $\times 10^4$	95% CL UL	Detection Significance
0	4 years	6	4.7	0.5	1.0×10^{-3}	. . .
0.003	4 years	6	6.9	−1.2	. . .	4.0
	8 years	6	5.9	0.4	. . .	5.1

Risk Areas

The path forward is through much more sensitive polarization measurements



reionization bump
CLASS exploring
from the ground;
target of LiteBIRD

recombination bump
key target of ground experiments, incl. CMB-S4

- Foregrounds: Clean maps by a factor of 10
- De-lensing: Forecasts assume can reduce lensing B-mode power to 10% (30% in maps).
- Systematics: Very important, most difficult to model. Somewhat crudely done so far. Need to do better to provide feedback for instrument design choices.

CMB-S4
Next Generation CMB Experiment

Twice yearly open community workshops to advance CMB-S4

6th CMB-S4 workshop, Harvard August 24-25, 2017

Next Workshops:

- March 5-7, 2018 at Argonne National Laboratory
- September 2018 at Princeton University

Lots of well-organized information here: https://cmb-s4.org

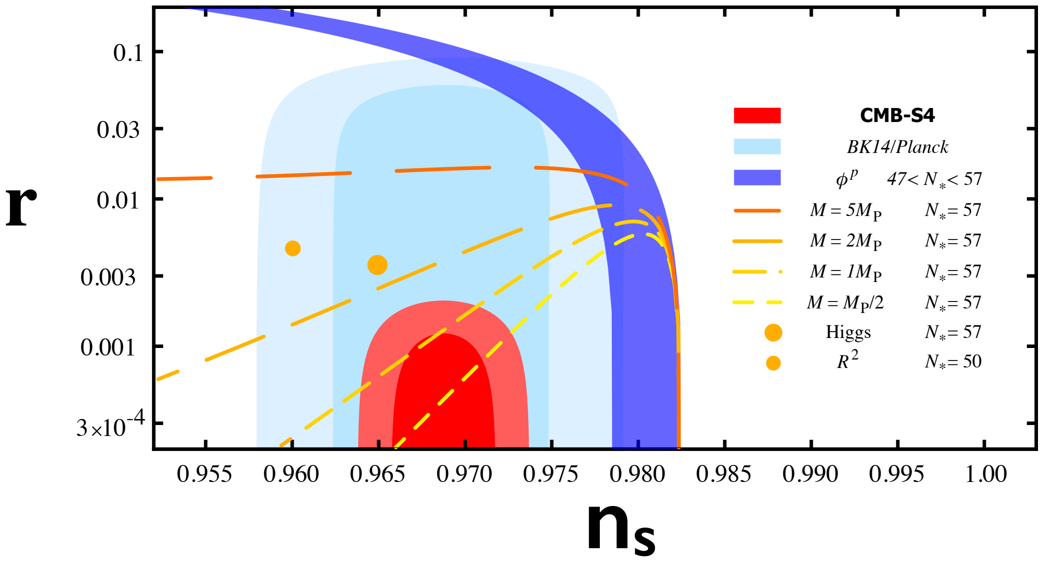
(workshop agendas and presentations, data challenges, Science Book, CDT report)

STOP

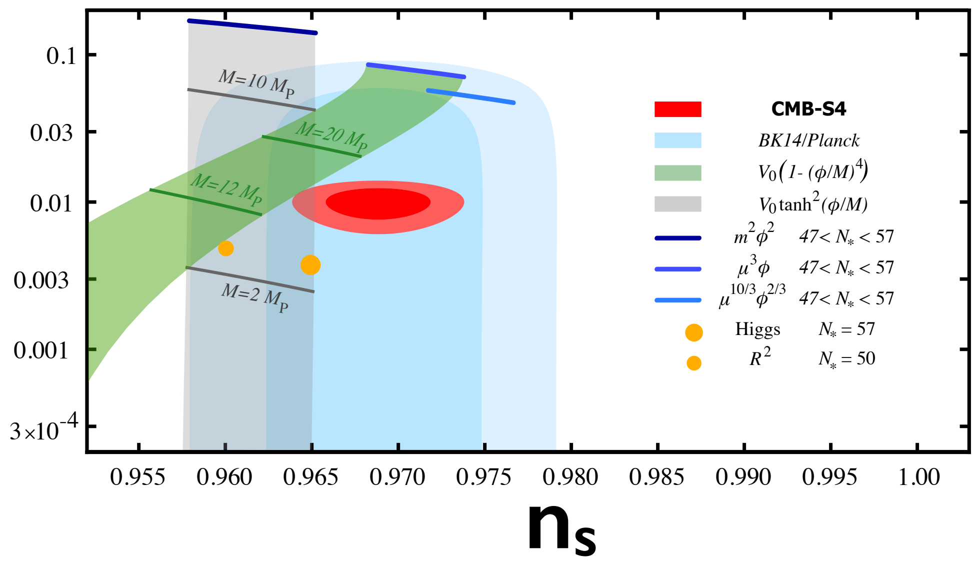
Inflation reach of CMB-S4

for nominal 3% f_{sky} and 10^6 realistic detector years

r = 0



r = 0.01



A detection of primordial B modes with CMB-S4 would provide evidence that the theory of quantum gravity must accommodate a Planckian field range for the inflaton.

Conversely a non-detection of B modes with CMB-S4 will mean that a large field range is not required.

Requirement: upper limit of r < 0.001 at 95% c.l., or detection for r > 0.003

This drives the specifications for the CMB-S4 deep survey, supported by detailed simulations (see Appendix A of CDT report).

CMB-S4
Next Generation CMB Experiment

Summary

The CMB has a lot to offer and we have a plan to get it, CMB-S4

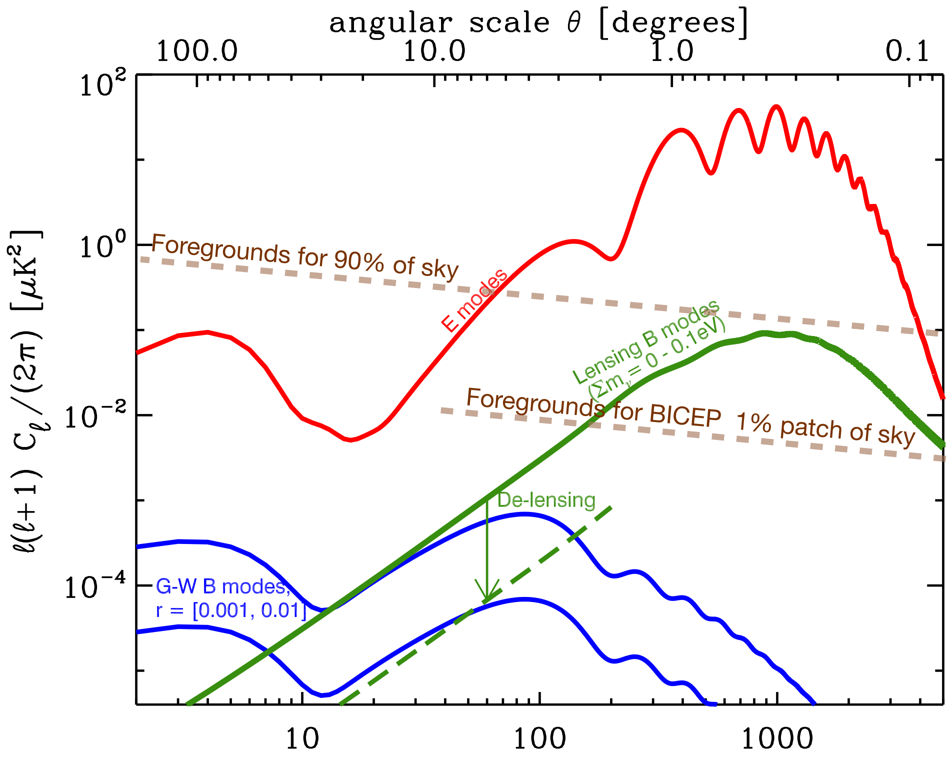
The science is spectacular. We will be searching for primordial gravitational waves and testing single field slow roll inflation, searching for new relics, determining the neutrino masses, mapping the universe in momentum, investigating dark energy, testing general relativity on large scales, measuring the impact of baryon feedback in structure evolution and much more.

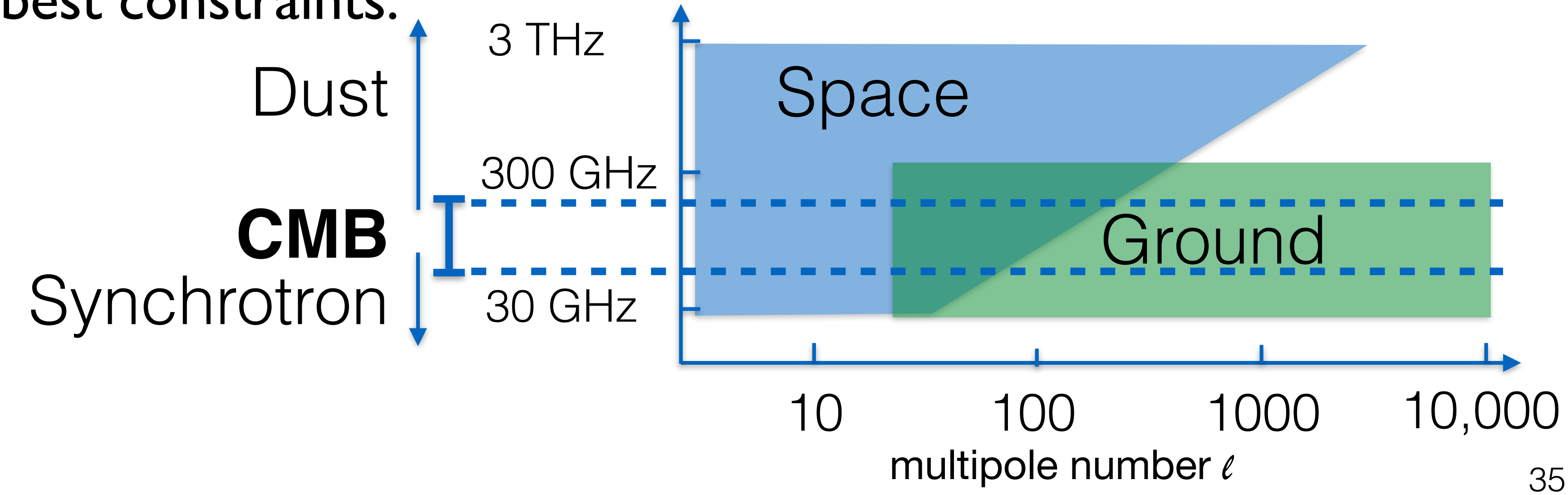
Go to **cmb-s4.org** for more information, including documents, reports, workshops, wiki's, join email lists, etc.

CMB-S4
Next Generation CMB Experiment

Complementary strengths of ground and space

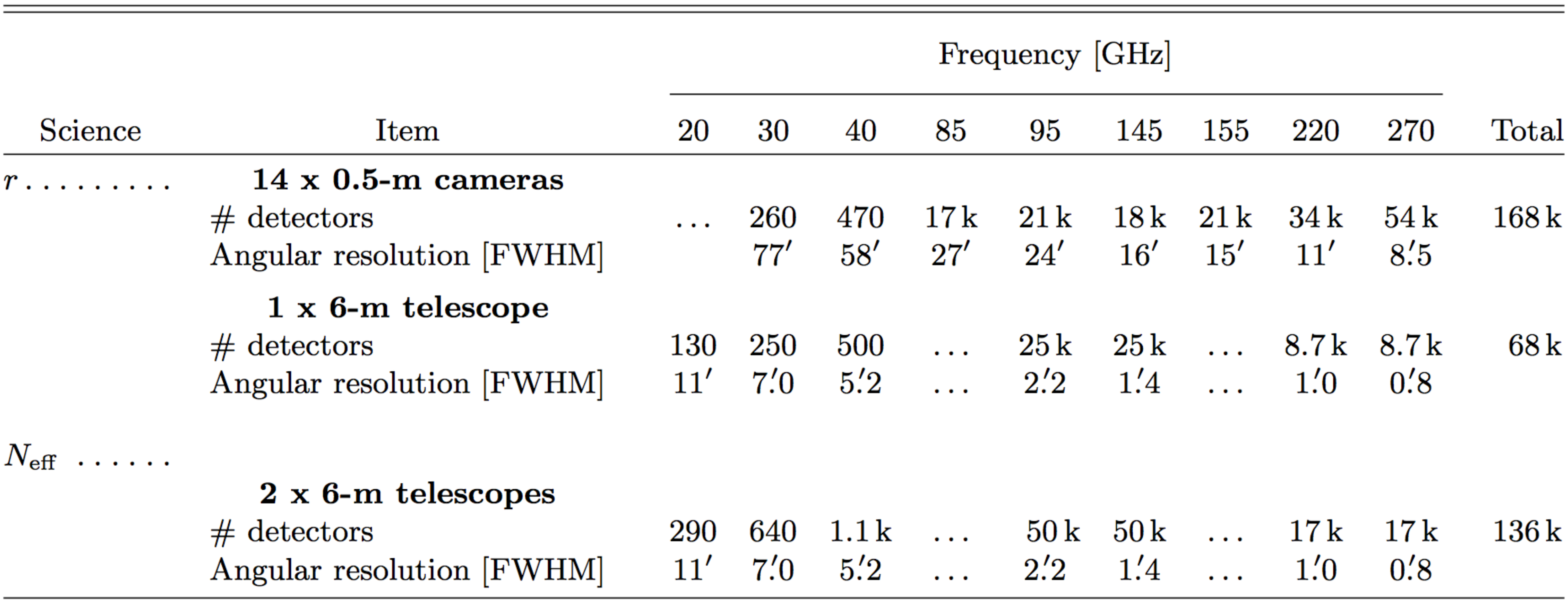
- **Ground:** Resolution required for CMB lensing (+de-lensing!), damping tail, clusters….
- **Space:** All sky for reionization peak; high frequencies for dust.
- Combined data will provide best constraints.





CMB-S4
Next Generation CMB Experiment

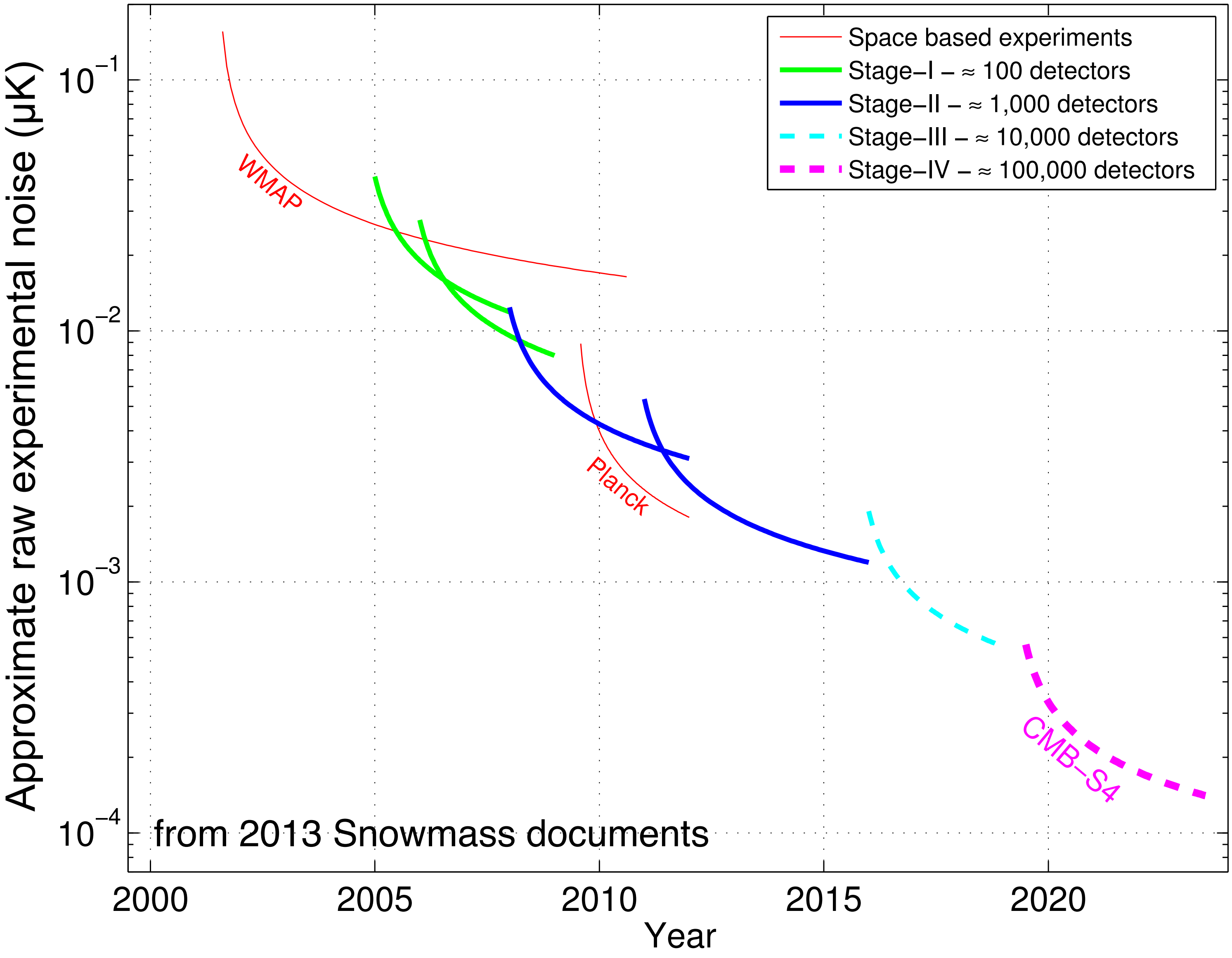
CMB-S4 concept



		Frequency [GHz]									
Science	Item	20	30	40	85	95	145	155	220	270	Total
r	**14 x 0.5-m cameras**										
	# detectors	. . .	260	470	17 k	21 k	18 k	21 k	34 k	54 k	168 k
	Angular resolution [FWHM]		$77'$	$58'$	$27'$	$24'$	$16'$	$15'$	$11'$	$8'.5$	
	1 x 6-m telescope										
	# detectors	130	250	500	. . .	25 k	25 k	. . .	8.7 k	8.7 k	68 k
	Angular resolution [FWHM]	$11'$	$7'.0$	$5'.2$	. . .	$2'.2$	$1'.4$	. . .	$1'.0$	$0'.8$	
N_{eff}											
	2 x 6-m telescopes										
	# detectors	290	640	1.1 k	. . .	50 k	50 k	. . .	17 k	17 k	136 k
	Angular resolution [FWHM]	$11'$	$7'.0$	$5'.2$	. . .	$2'.2$	$1'.4$	. . .	$1'.0$	$0'.8$	

That the “r” survey can achieve the science goals is backed up in Appendix A of the CDT report

More Background limited Detectors



but it will take much more to achieve our goals.

		Sensitivity (μK^2)	**$\sigma(r)$**	**$\sigma(N_{eff})$**	**$\sigma(\Sigma m_\nu)$**	**Dark Energy F.O.M**
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	0.006	0.06	0.06eV	~300-600

CMB-S4

Next Generation CMB Experiment