CMB-S4

Next Generation CMB Experiment

Photo provided by Mark Devlin

Update by John Carlstrom
CMB-S4 ICCC Co-Chair
The University of Chicago / ANL

Photo credit Cynthia Chiang

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 <u>critical science thresholds.</u>**
- **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. DOE National Labs and the High Energy Physics community.**
- **<u>International partnerships expected and desired.</u>**

Recommended by P5

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genesis

- Snowmass Physics Planning exercise in 2013
  - Influential CMB community papers for Snowmass:
    - Inflation Physics from the Cosmic Microwave Background and Large Scale Structure, Astroparticle Physics 63, 66 (2015), arXiv:1309.5381
    - Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure, Astroparticle Physics 63, 55 (2015), arXiv:1309.5383
  - CMB "stages" and development of the CMB-S4 concept: What we need to build to obtain our science goals.

- Led to recommendation of Particle Physics Project Priority Panel, P5, in 2014

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CMB Stages

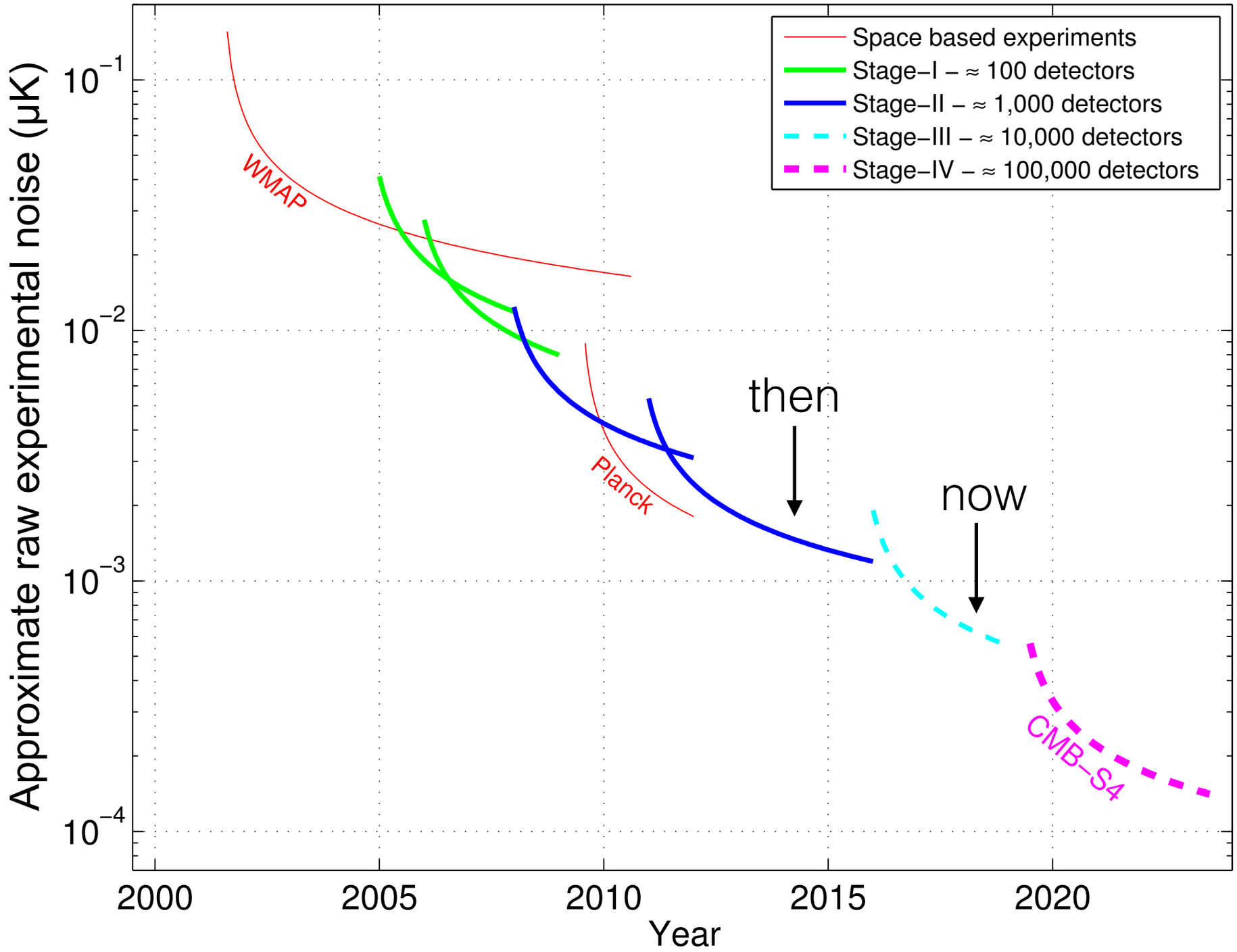

Figure by Clem Pryke for 2013 Snowmass documents

		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		$\approx 10^{-5}$	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

big advance, but not enough….

	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
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Continuing series of open workshops to advance CMB-S4

U. Minnesota
Jan 16, 2015

U. Michigan
Sep 21-22, 2015

LBNL, Berkeley
March 7-9, 2016

U. Chicago
Sep 19-20, 2016

SLAC, Stanford
Feb 27-28, 2017

Continuing series of open workshops to advance CMB-S4

Harvard August 24-25, 2017

Next Workshops:

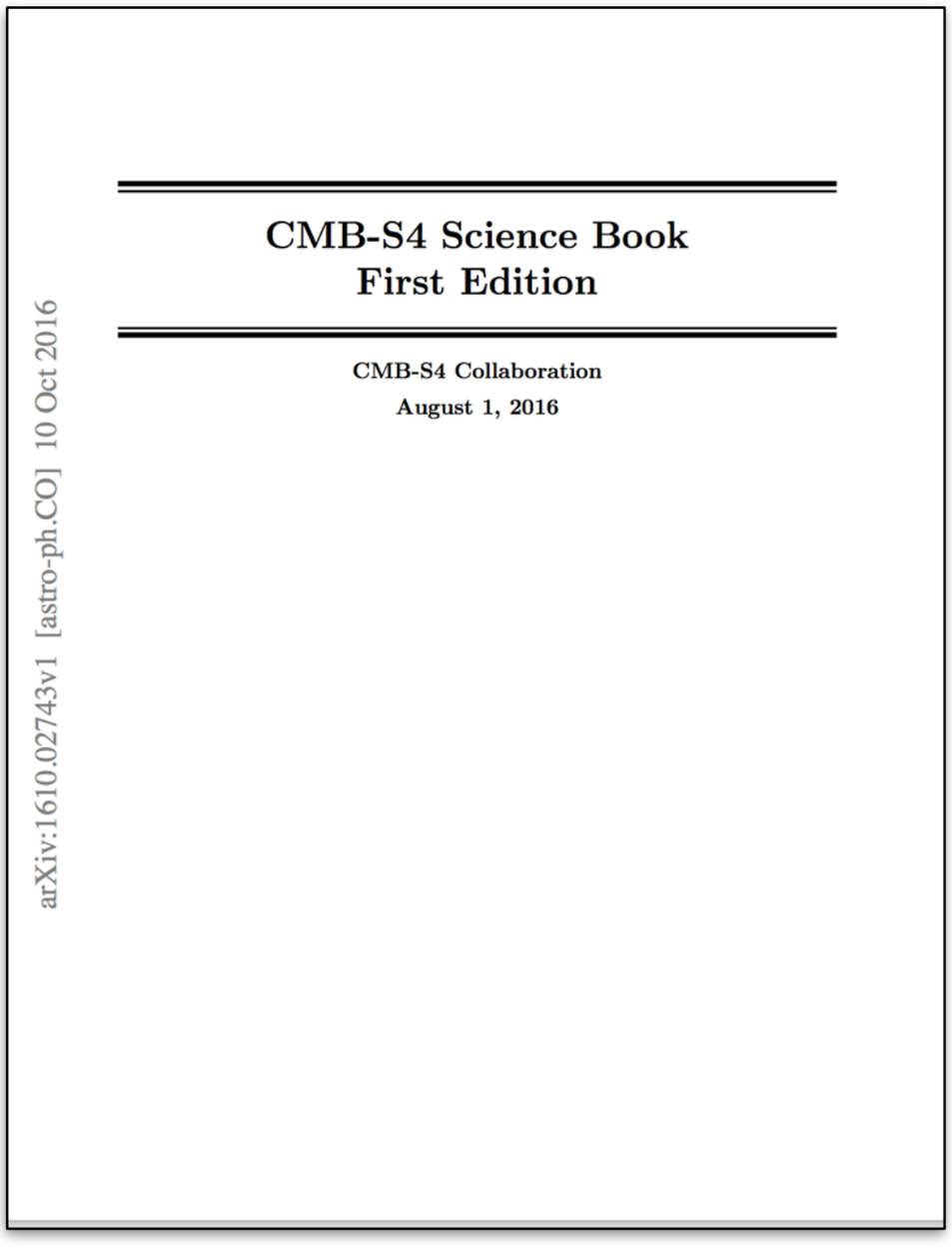
- March 5-6, 2018 at Argonne National Lab registration (free) open now
- September 2018 at Princeton University

CMB-S4 Science Book

First Edition of
CMB-S4 Science Book
available 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



Covers the HEP Cosmic Frontier Science Case and provides a strawman concept based on initial projections

Science Book Figure 3

		Sensitivity (μK^2)	σ(r)	σ(N_{eff})	σ(Σm_ν)	Dark Energy F.O.M
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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
	Stage 4 CMB-S4 ~500,000 detectors					
					DESI BAO +τ_e prior	DESI +LSST S4 Clusters
Target		**10^{-8}**	**0.0005**	**0.027**	**0.015eV**	**1250**

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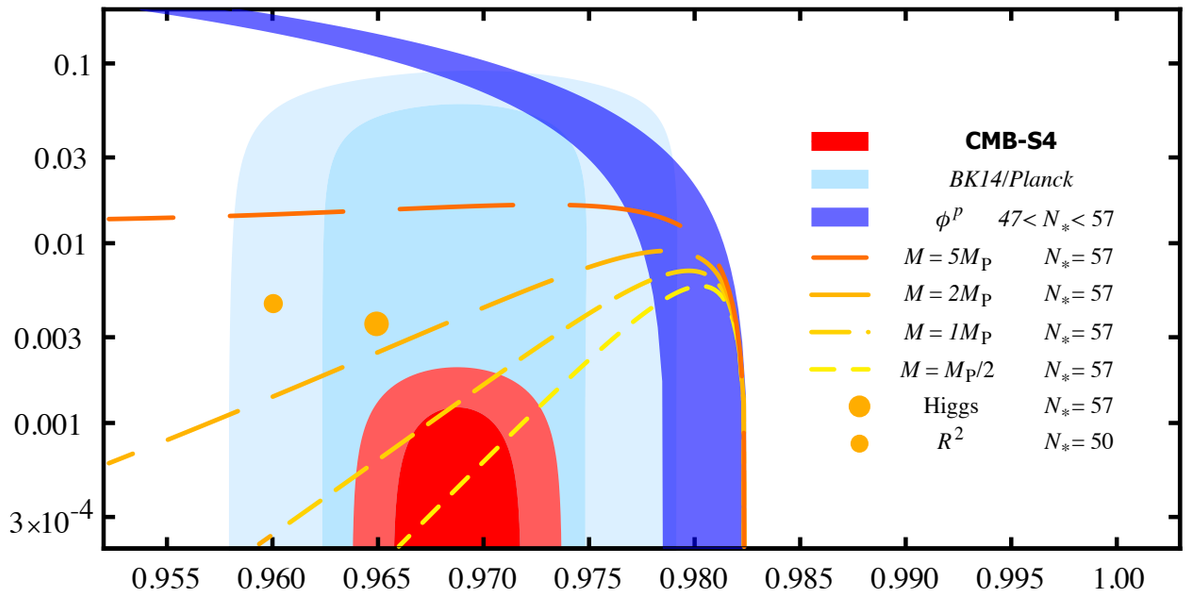
Next Generation CMB Experiment

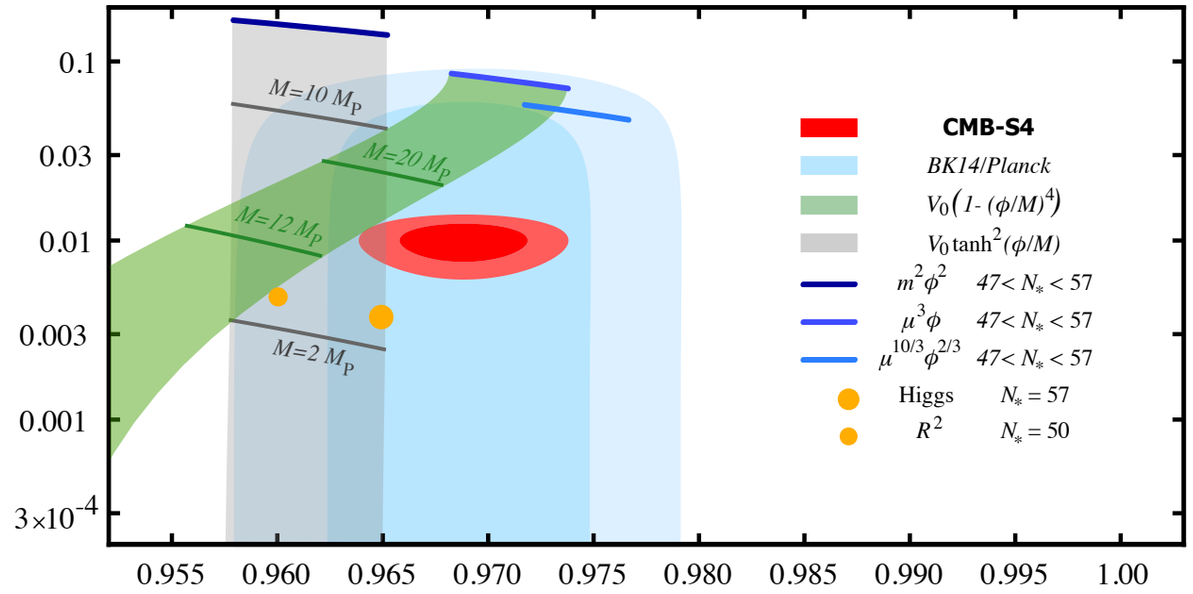
SB projected inflation reach of CMB-S4

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.

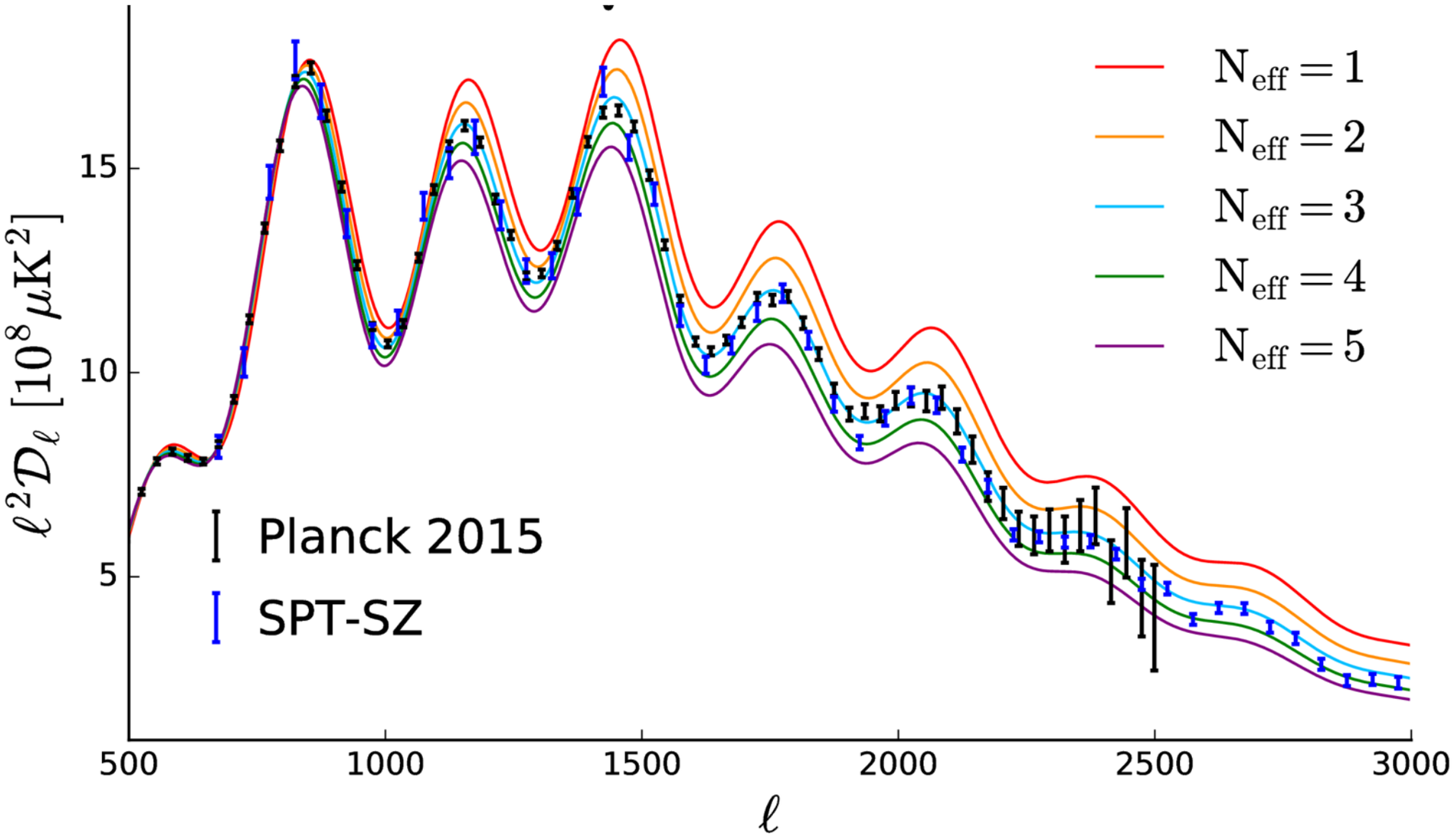
Conversely a non-detection of B modes with CMB-S4 will mean that a large field range is not required.

Targeting r upper limit of 0.001 at 95% C.L.

This is the driving specification for the CMB-S4 deep survey

Light relativistic relics, N_{eff}

Searching for relic particles by their contribution to the energy density



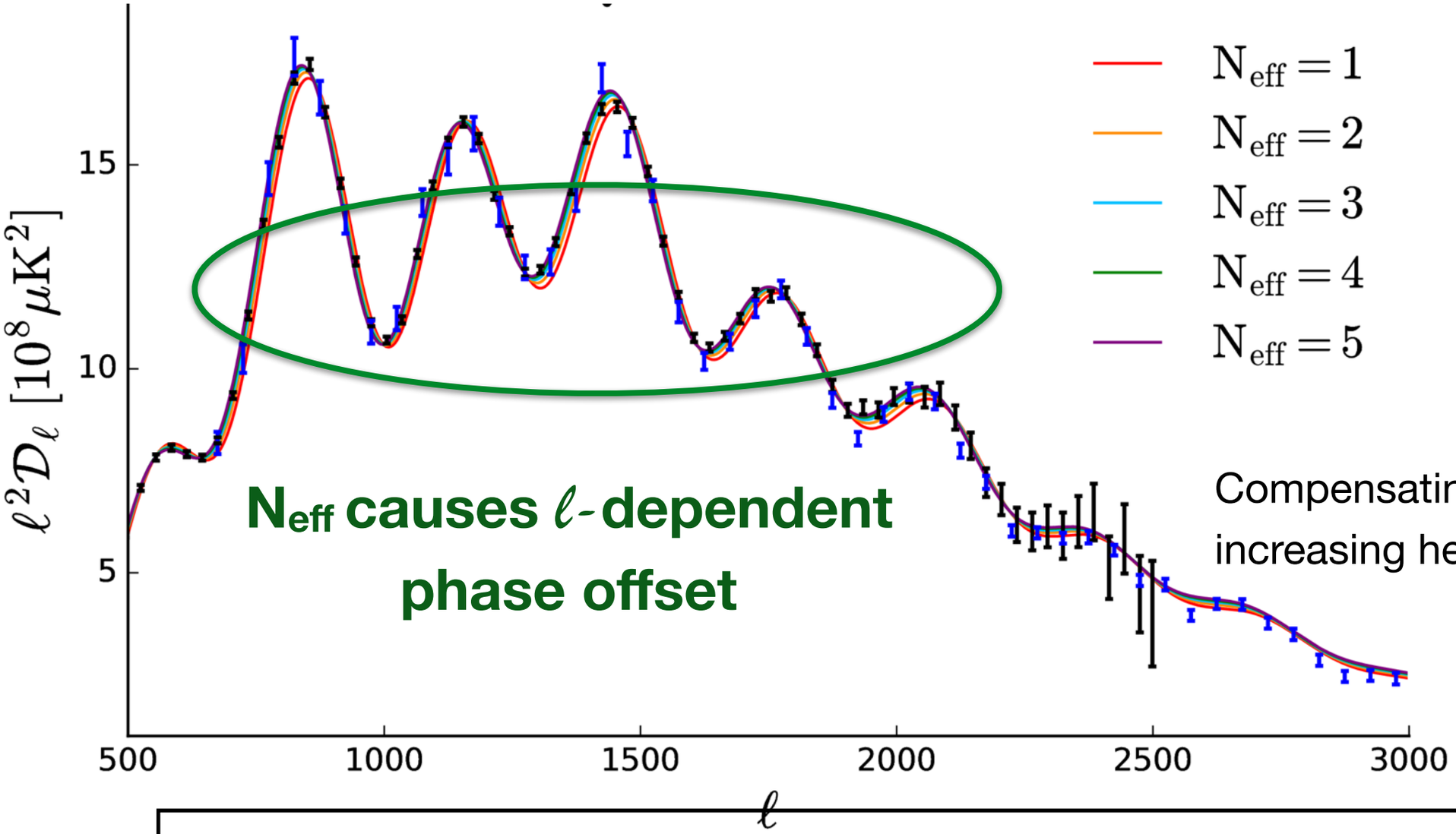
If perfect decoupling and 3 neutrinos, then N_{eff} = 3.00.

Imperfect decoupling and effects of e^+e^- annihilation give

N_{eff} = 3.046

Light relativistic relics, N_{eff}

Searching for relic particles by their contribution to the energy density



Planck constraints:

N_{eff} = 3.15 ± 0.23 (lowP only; along BBN consistency curve)

N_{eff} = 3.14 ± 0.44 (marginalizing over Y_P)

Highly significant detection of neutrino background

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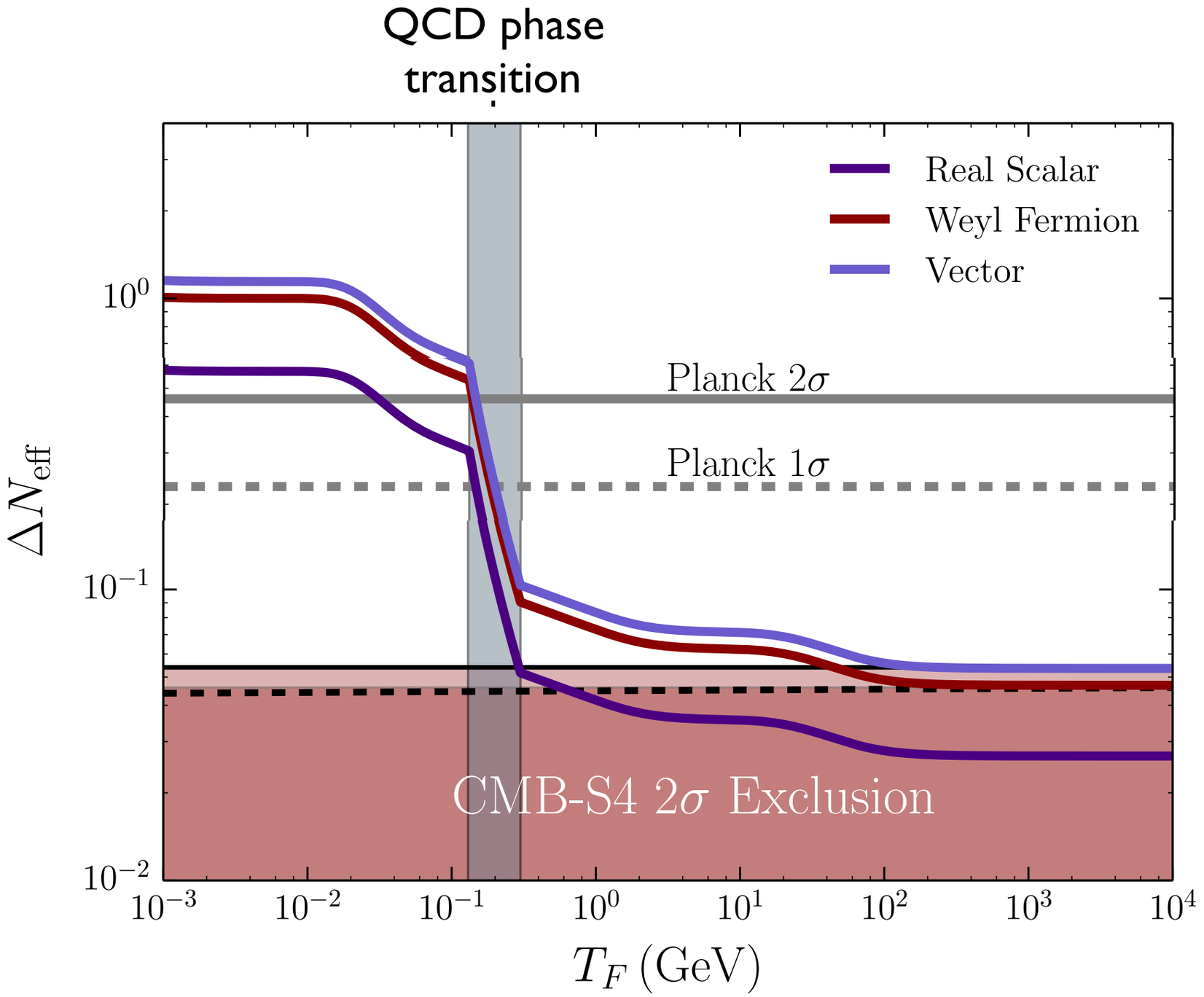
SB N_{eff}, thermal relics projections



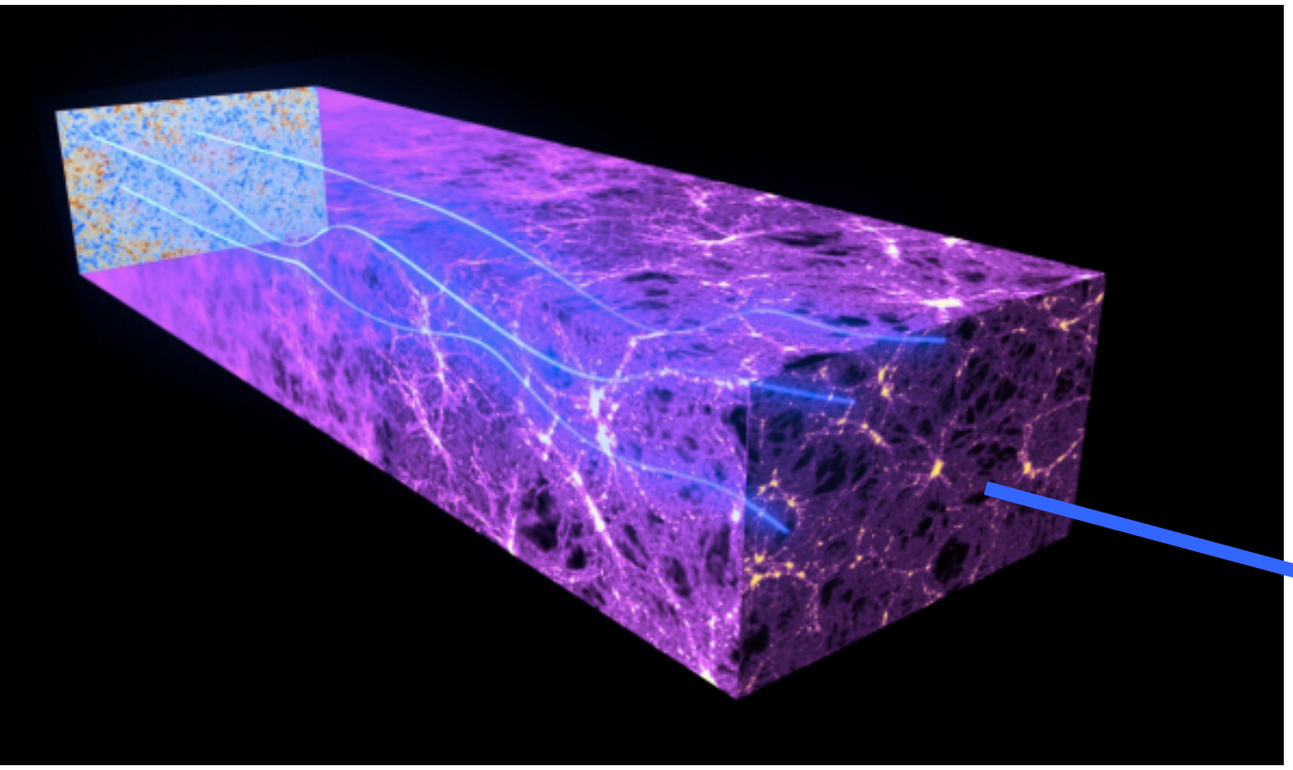
- σ(N_{eff}) constraint leads to orders of magnitude improvement of constraint on the freeze-out temperature of any thermal relic

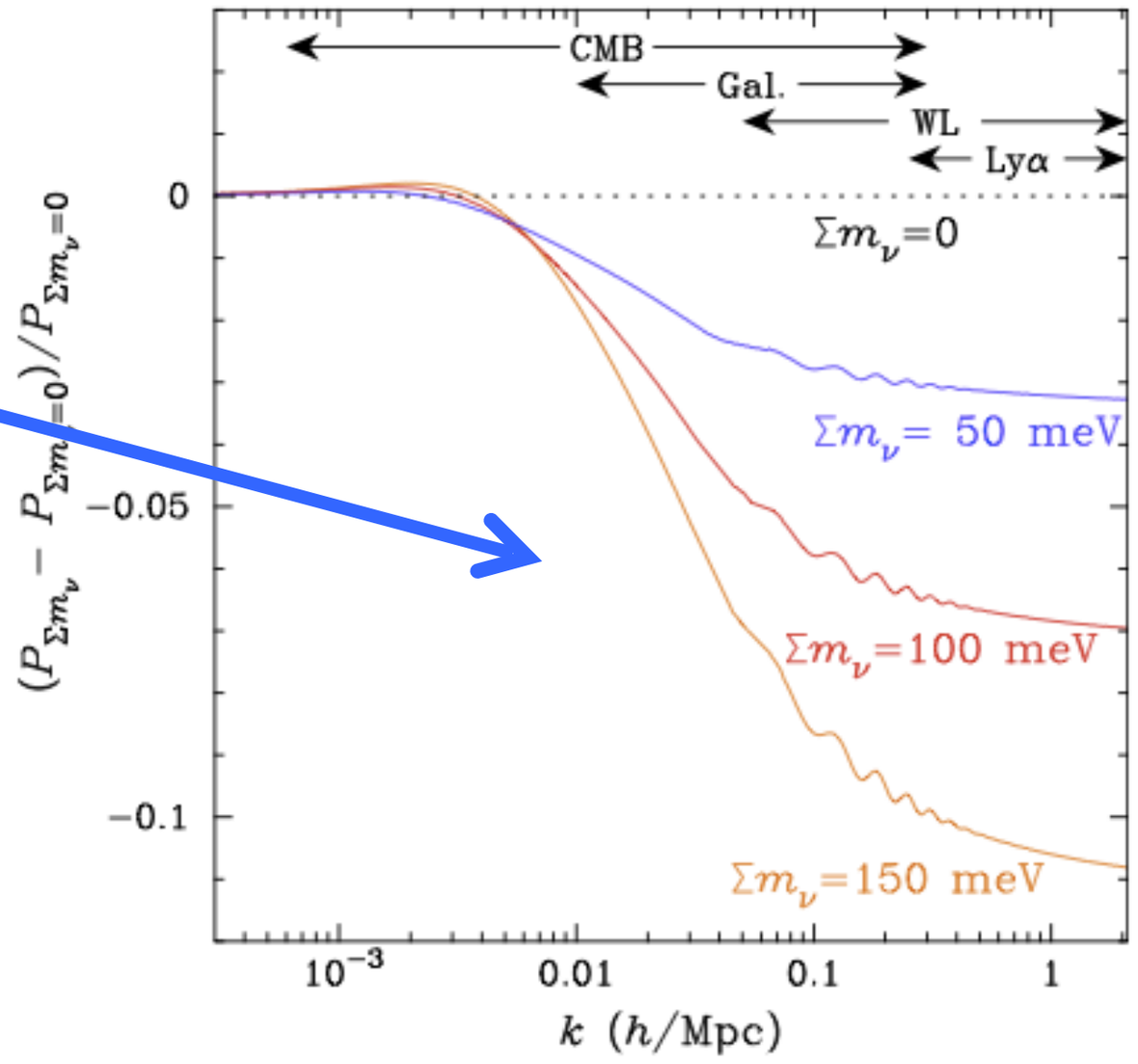
- Natural target:
  $\Delta N_{eff} < 0.027$ limits axion SM couplings for $T_{freeze\text{-}out} < T_{reheat}$

This is the driving specification for the CMB-S4 wide survey

Green, Meyers in CMB-S4 Science Book
Also Baumann, Green & Wallisch, "A New Target for Cosmic Axion Searches" arXiv:1604.08614

Late-time information:
- neutrino masses from gravitational lensing of the CMB





Abazajian et al., 2015

Planck Collaboration XIII (2015) from CMB alone:

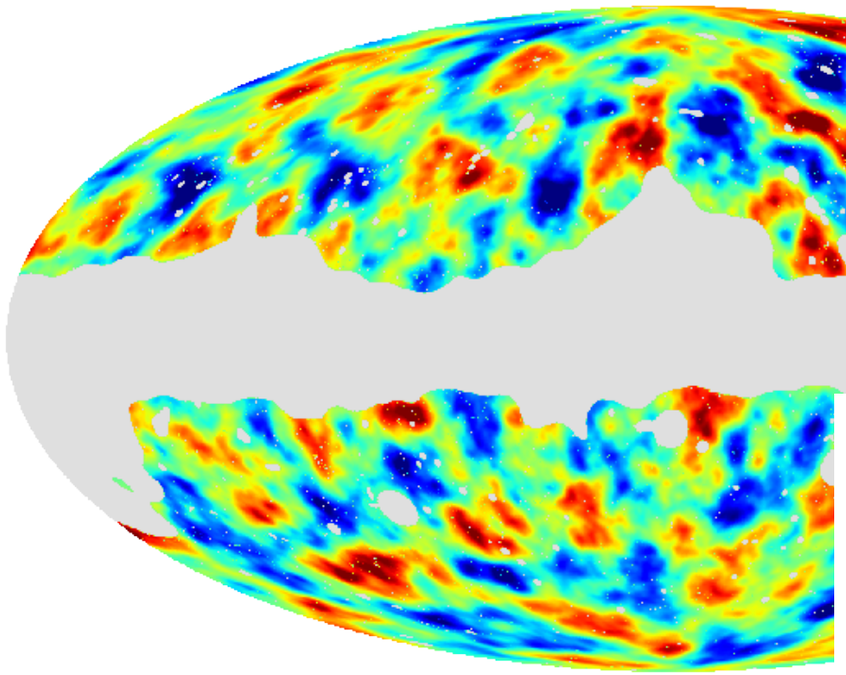
$\Sigma m_\nu < 0.59$ eV at 95% c.l.

Including other cosmological data:

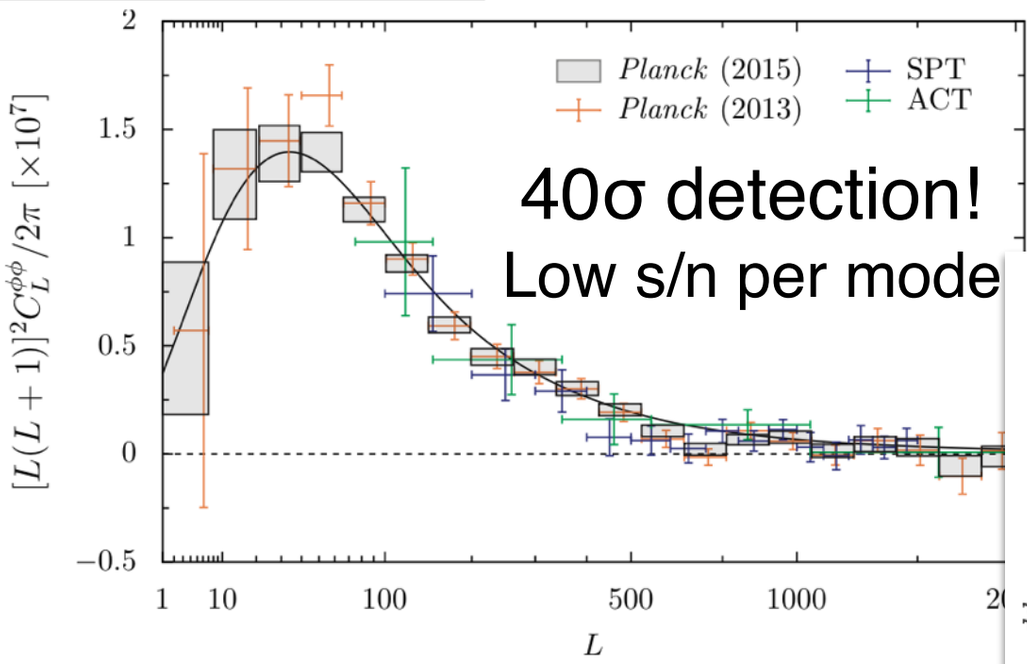
$\Sigma m_\nu < 0.23$ eV at 95% c.l.

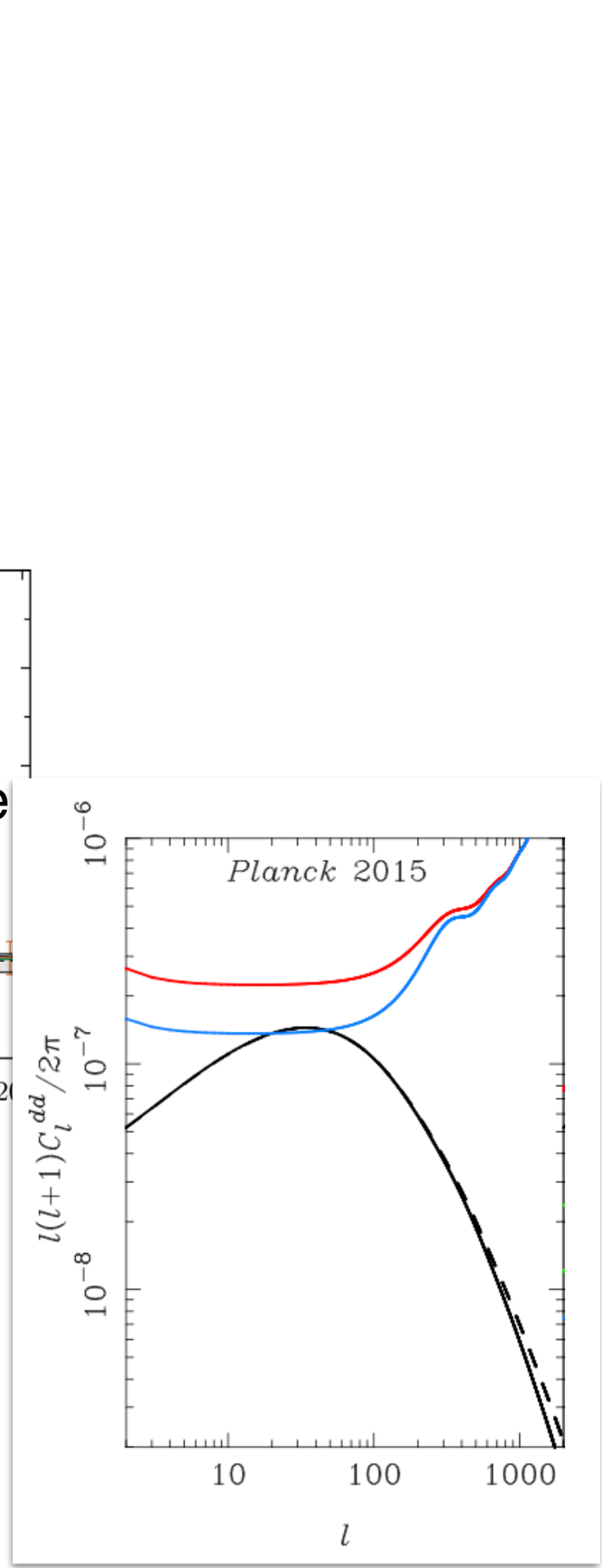
CMB lensing

Planck lensing potential reconstruction
(projected mass map).



Planck XV arXiv:1502.01591





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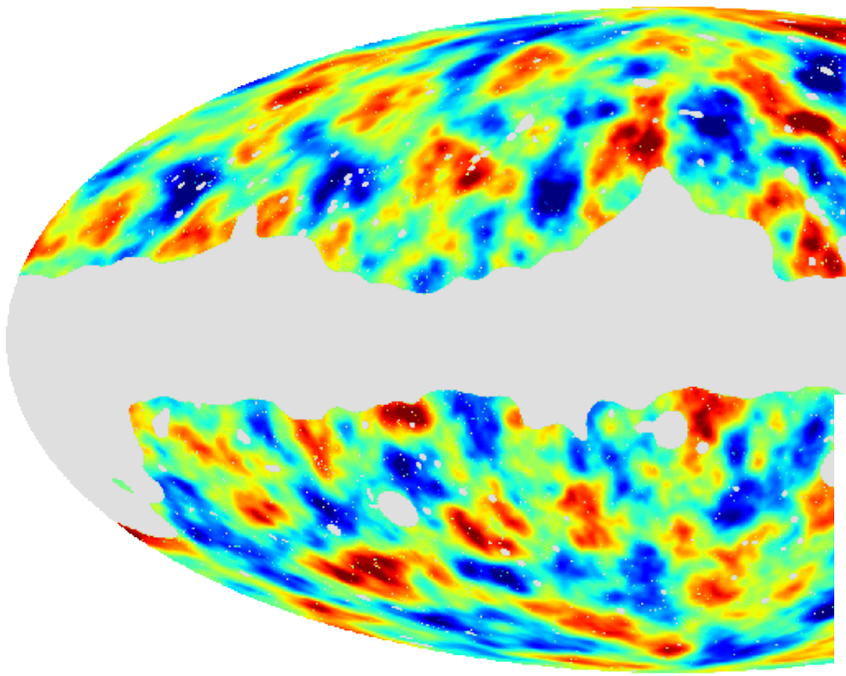

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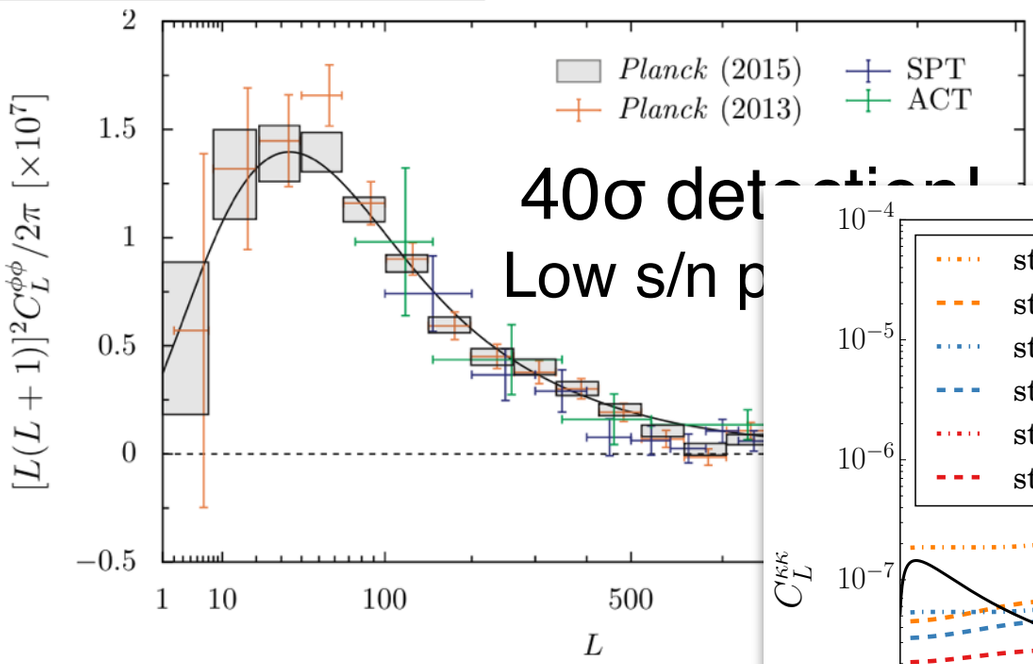
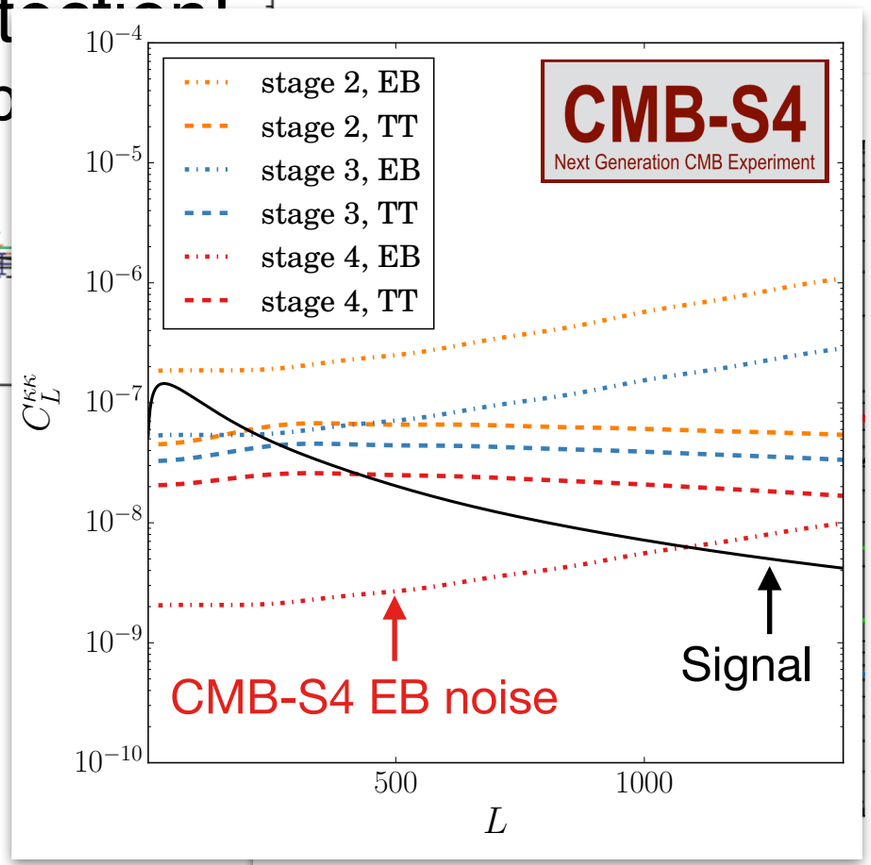


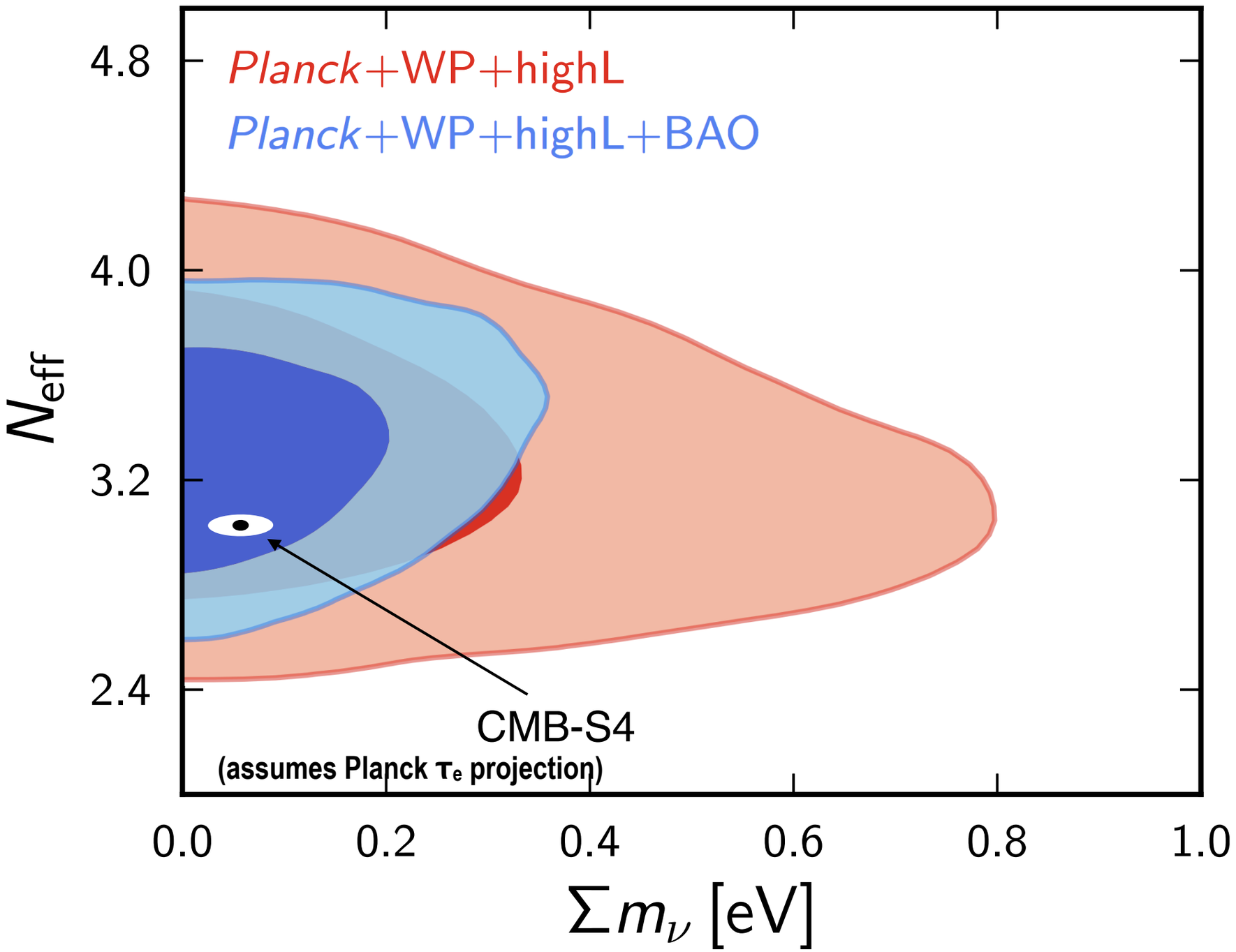
40σ detection!
Low s/n p



CMB-S4 will measure modes with s/n > 1 up to L ~ 1100 over most of the sky.

CMB-S4
Next Generation CMB Experiment

Snowmass CMB-S4 N_{eff} - Σm_ν projections



CMB-S4 forecast: arXiv:1309.5383; see also Wu et al, ApJ 788,138 (2014)

CMB-S4
Next Generation CMB Experiment

CMB-S4 Cosmic Structure Science

(significant effort over last year on CMB-S4 "high-ℓ" science)

- **SZ Cluster Cosmology: Dark Energy / Modified Gravity / Neutrino masses**
  - SZ galaxy cluster counts (dN/dz) to z~3
  - mass scaling calibration with CMB-lensing at % level
  - evolution of amplitude $\sigma_8(z)$ at % level
- **The evolution of massive clusters, cluster astrophysics**
  - Unique SZ catalog of clusters at z > 1.5
- **Tracing baryons with stacked kSZ and tSZ maps**
  - Thermodynamics of the circumgalactic medium out to the peak of cosmic star formation
  - Impact of baryon feedback on the matter power spectrum, P(k)
- **Cross-correlation of CMB lensing maps with galaxy density and shear surveys**
- **Constrain reionization of the universe with kSZ**

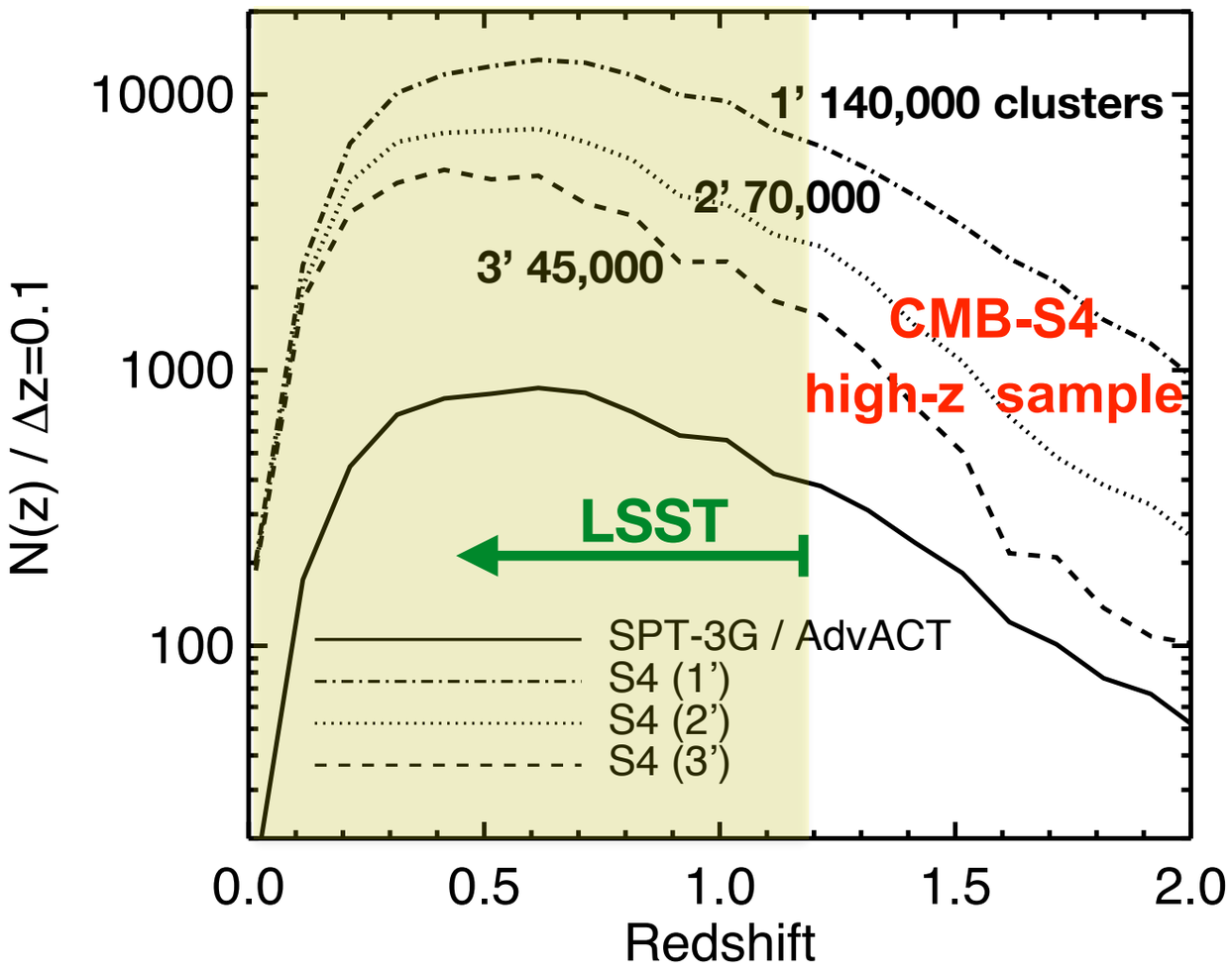
today's 4σ to 6σ results will become > 500σ with CMB-S4

CMB-S4

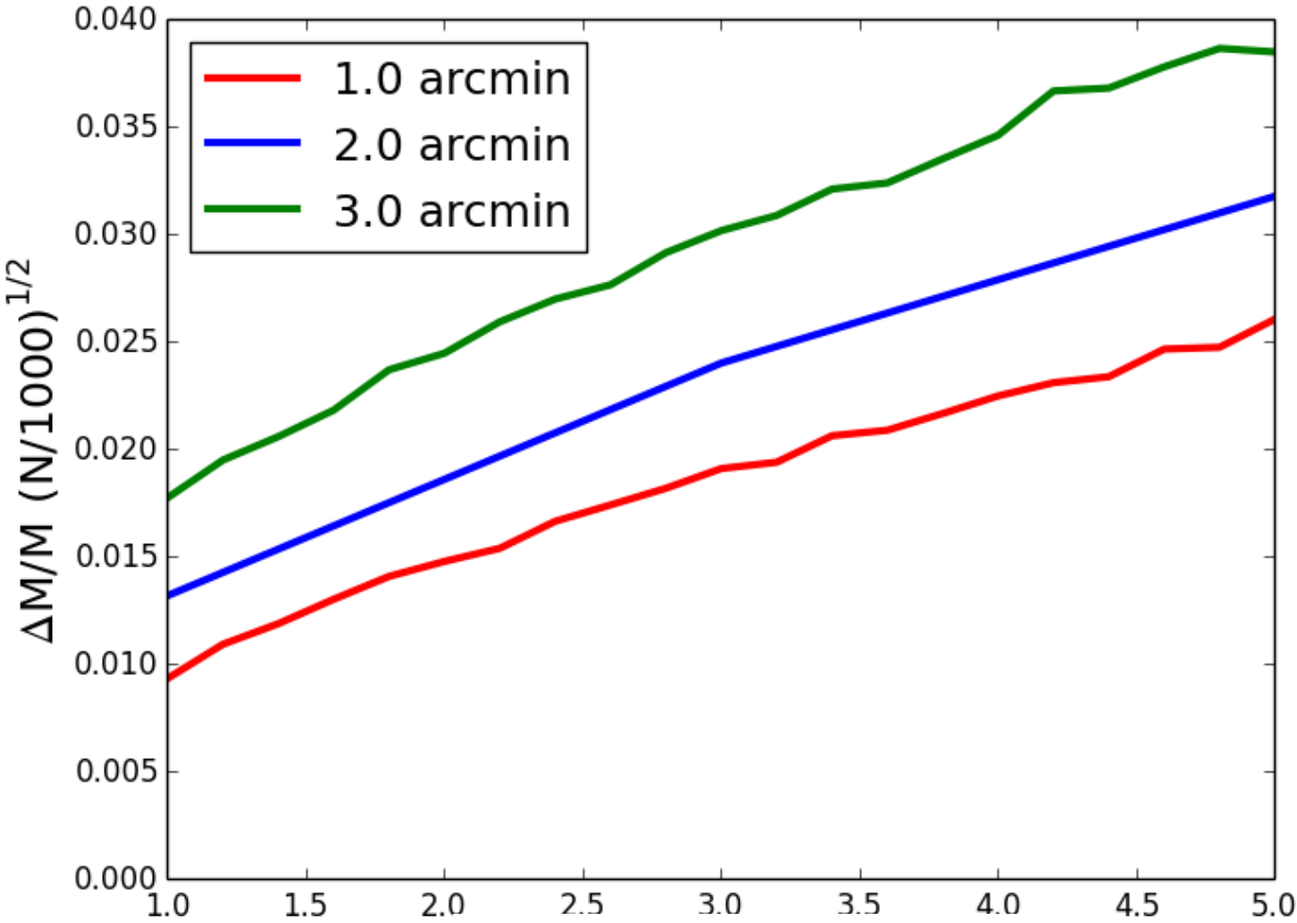
Next Generation CMB Experiment

CMB-S4 SZ cluster projections and lensing mass calibration for dark energy via growth of structure

CMB-S4 cluster count vs redshift



CMB-S4 lensing cluster mass scaling



CMB-S4 will provide the definitive survey of massive, high-z clusters (z>1) with **"built in" mass calibration**

Strong driver for high angular resolution

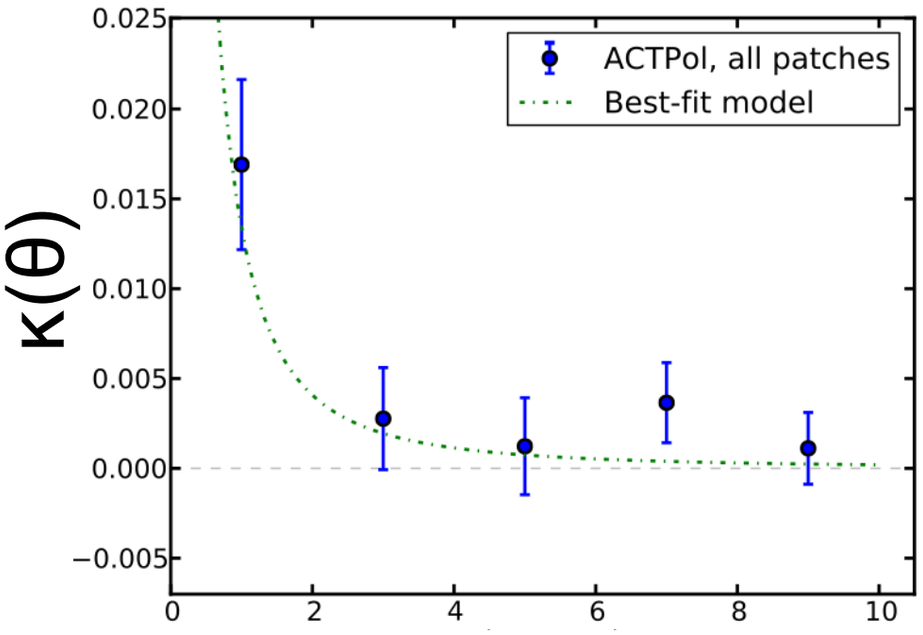
	2.0'	1.5'	1.0'
Total	43800	76800	122800
z >1.5	1420	3640	7850
z > 2.0	180	560	1390

From CMB-S4 Science Book

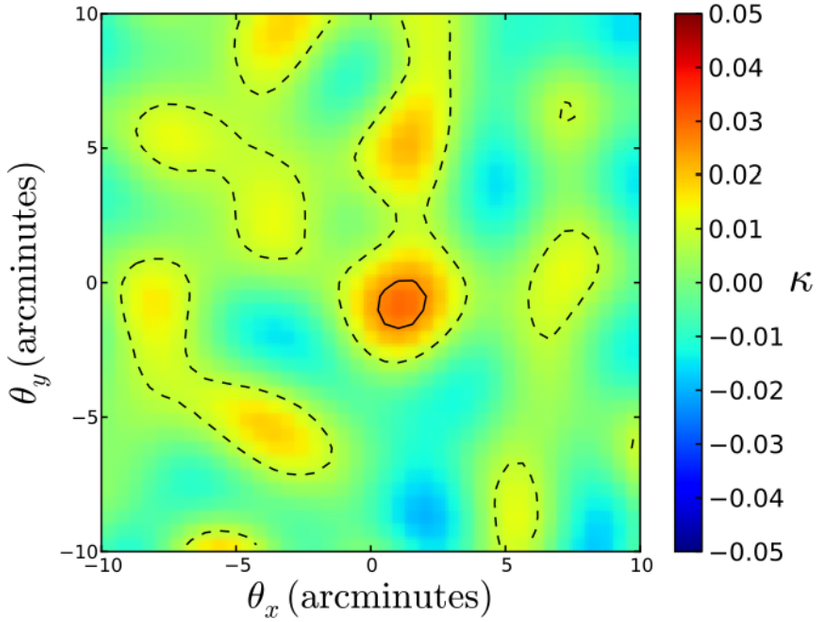
e.g., ACT & SPT stacked cluster lensing

ACTPol deep fields
CMBlensing stacked
on 12,000 CMASS
galaxies,
M_{200} ~2×10^{13} halos

Detection: 3.2σ

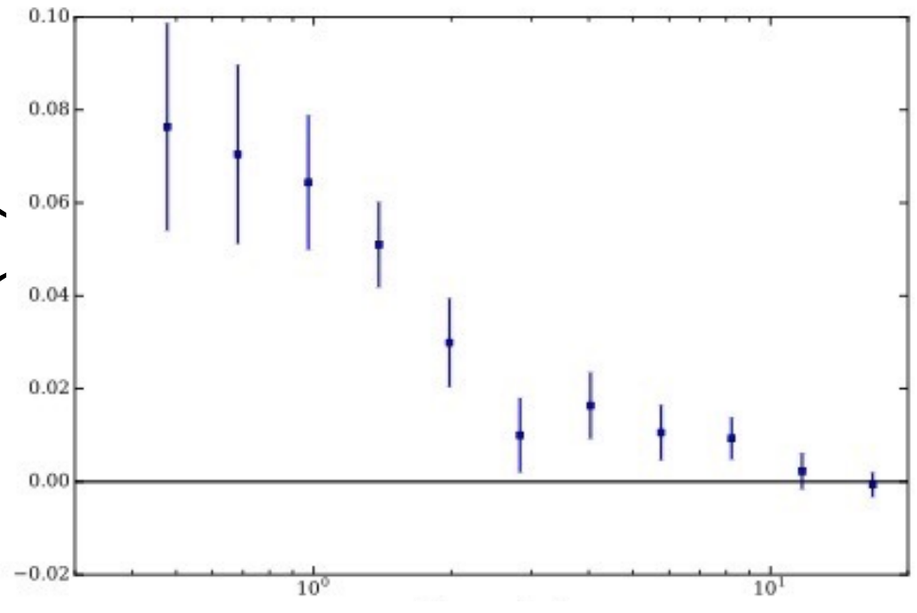


Madhavacheril et al. (2015)

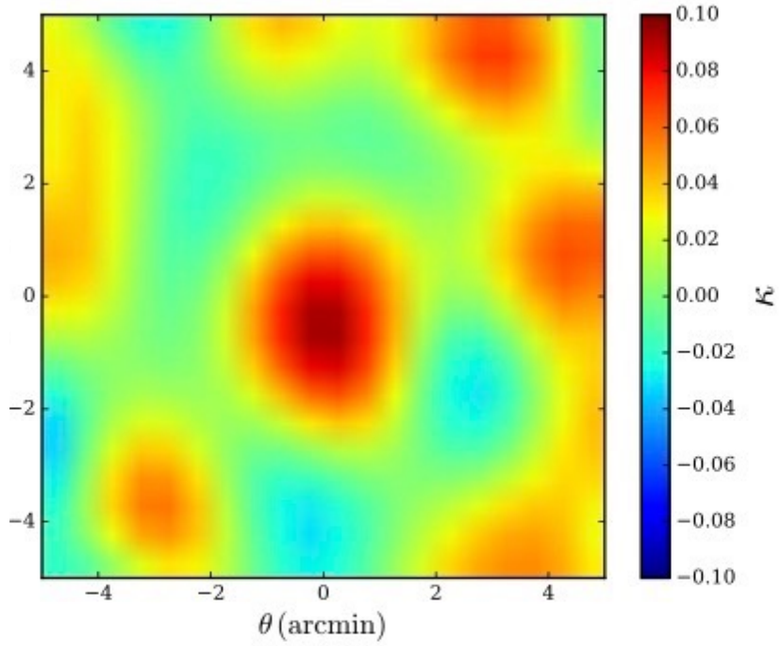


SPT-SZ lensing stacked
on 4000 DES redMaPPer
$20 < \lambda < 40$ clusters
$\langle M_{200}\rangle = 1.6\pm0.35 \times10^{14}$

Detection: 6.0σ



Baxter et al. (2017)

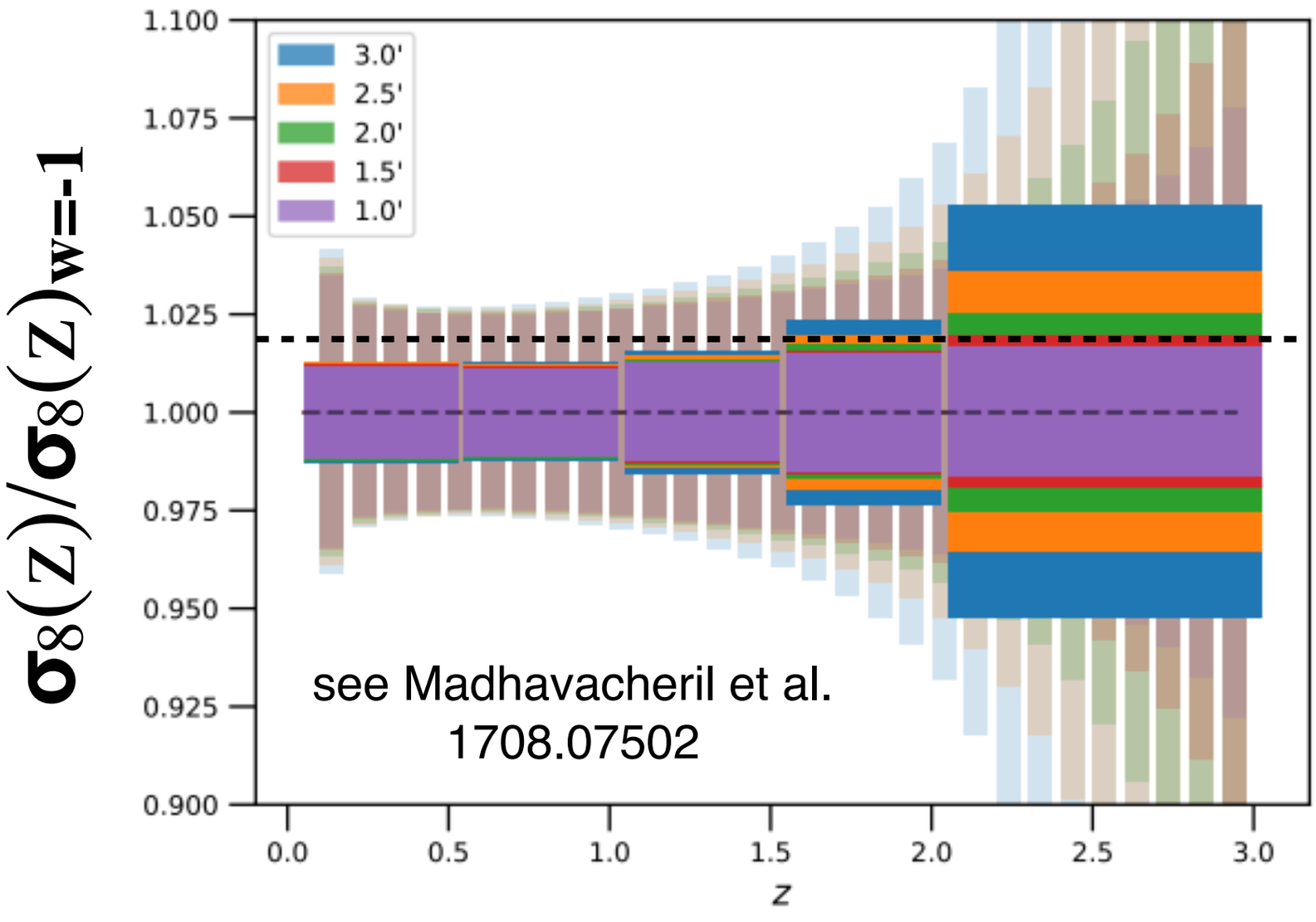


CMB-S4
Next Generation CMB Experiment

Growth of Structure, $\sigma_8(z)$

$\sigma_8(z)$

Fit scaling relation across bins
(< 2% for strawman spec)



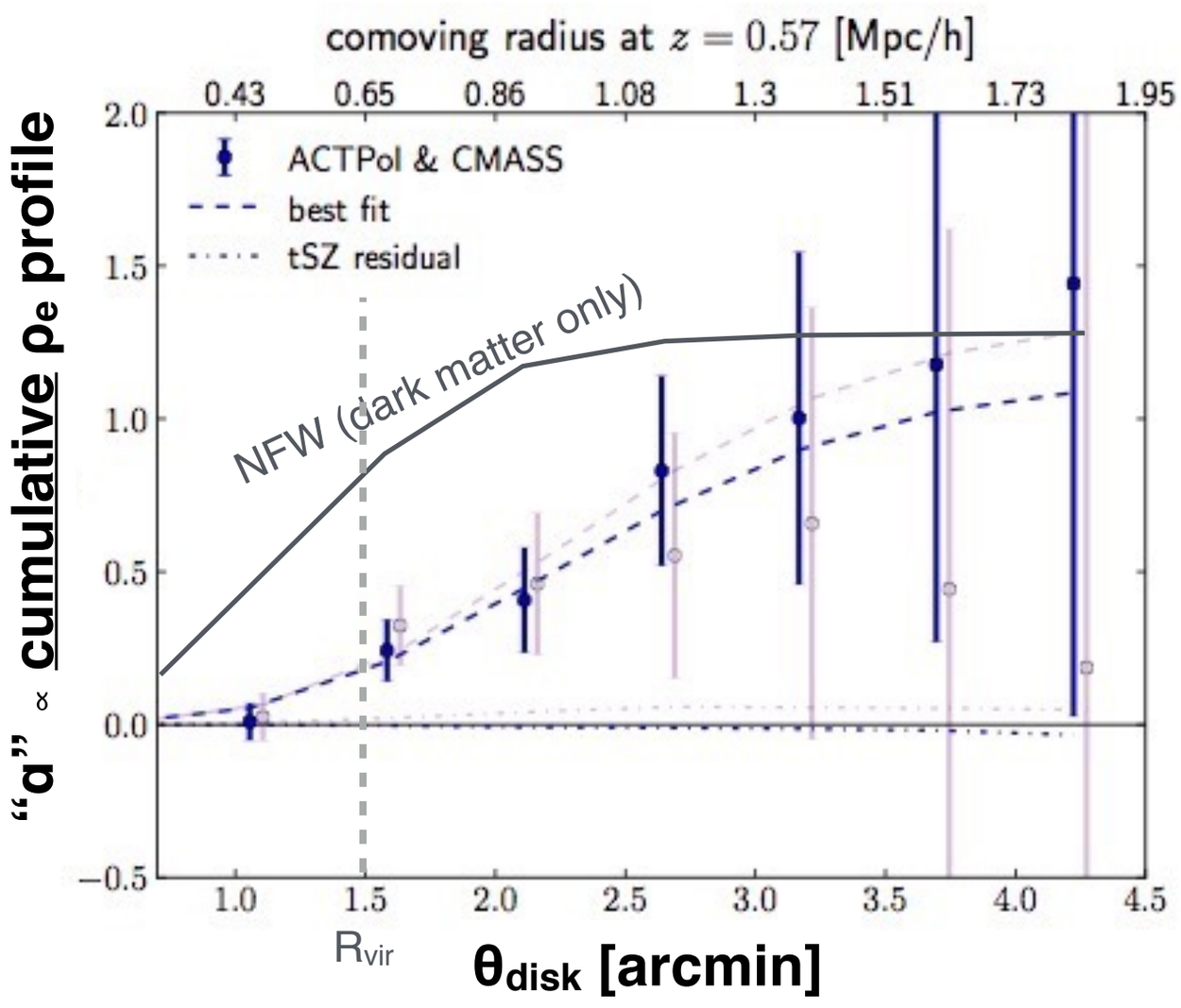
From CMB-S4/CDT LSS Working Group

e.g., Measure gas distribution in halos with stacked kSZ weighted by reconstructed velocity field

Gas density profile measured from BOSS reconstructed velocity field weighting of 25,537 stacked CMASS galaxies positions on ACT CMB maps (e.g., noisy kSZ map)

Detection: 2.9 - 3.3σ

CMB-S4 projection > 500σ



ACT, Schaan, Ferraro et al. 2015

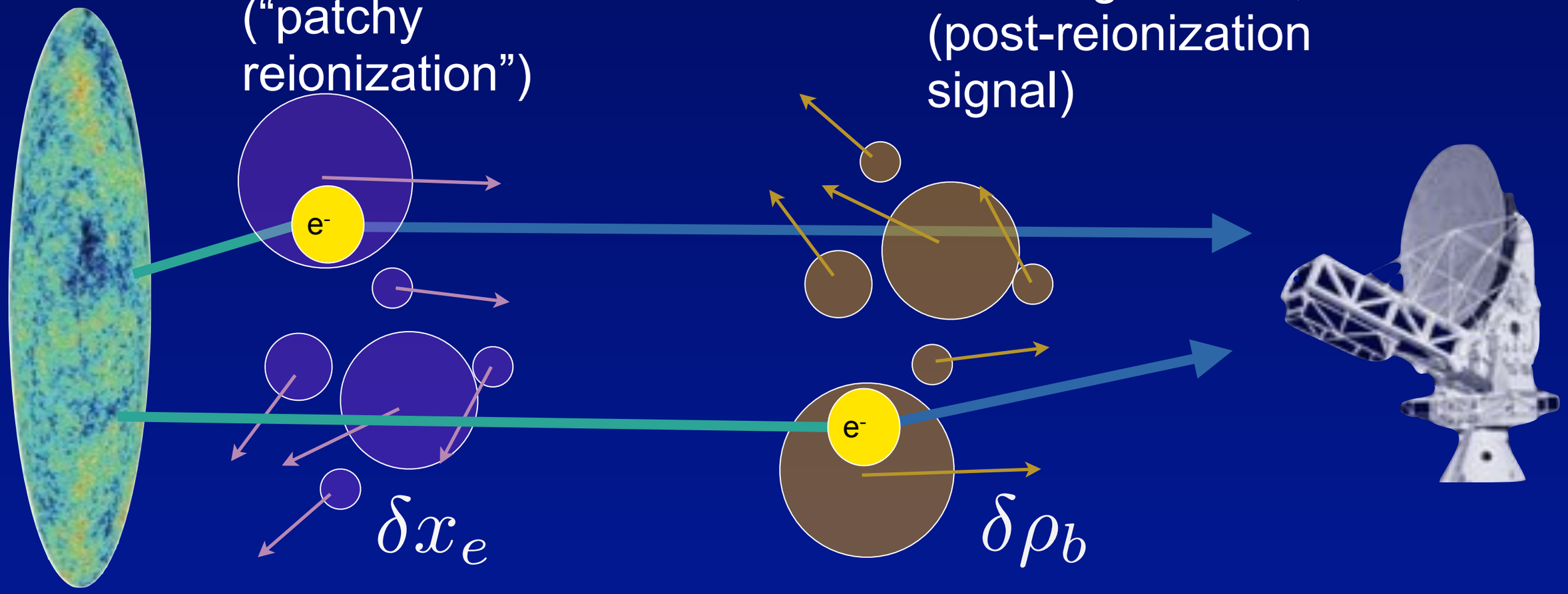
SLIDE EFFECTIVELY STOLEN FROM S. FERRARO'S POSTING ON CMB-S4 LSS LOGBOOK

See also David Olonso's CMB-S4 SLAC workshop posting.

kinematic SZ effect and reionization

1. reionization bubbles, ("patchy reionization")

2. matter inhomogeneities, (post-reionization signal)



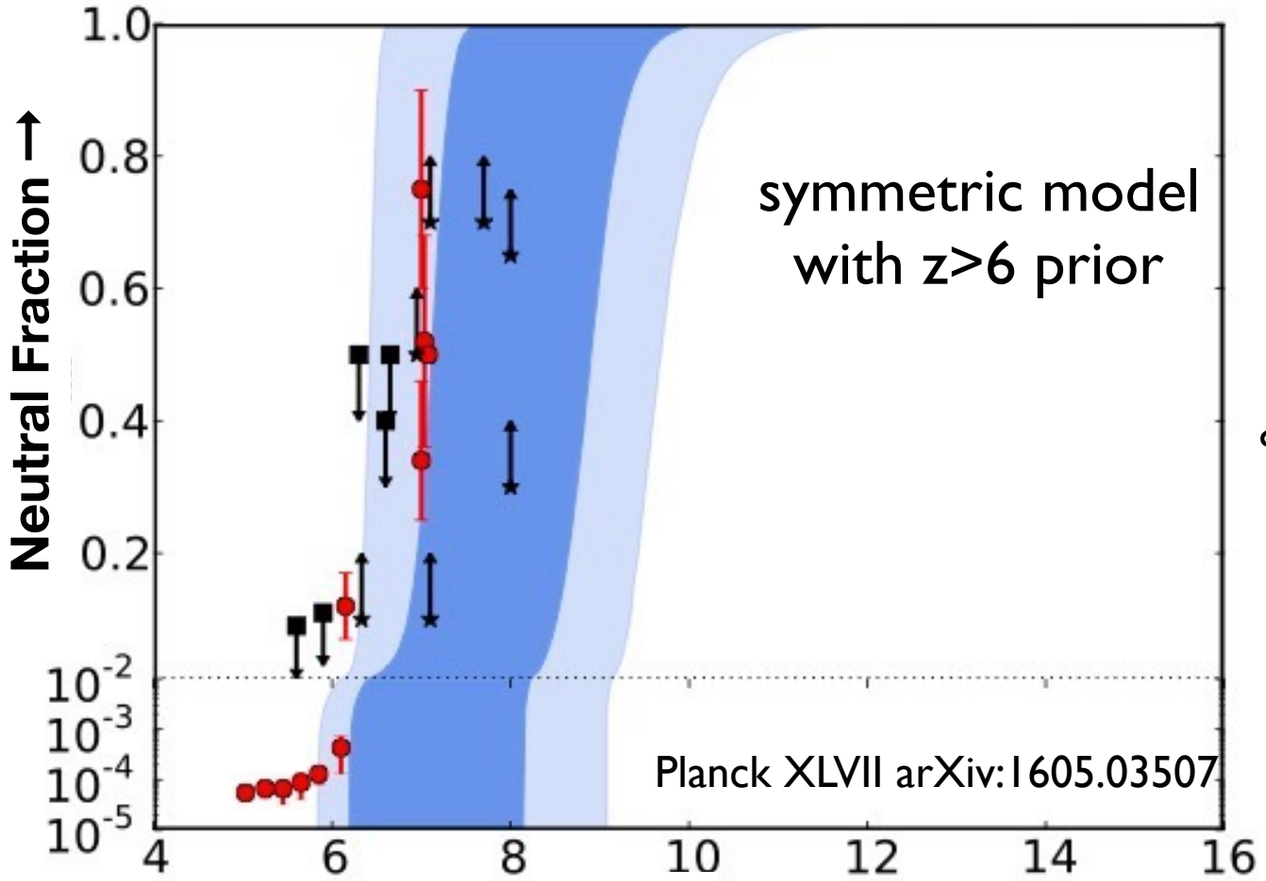
CMB photon scatters on free electrons moving w.r.t the CMB → Doppler shifted

There is a **"kinematic SZ background"** due to both of these effects. Very sensitive to reionization.

from Christian Reichardt

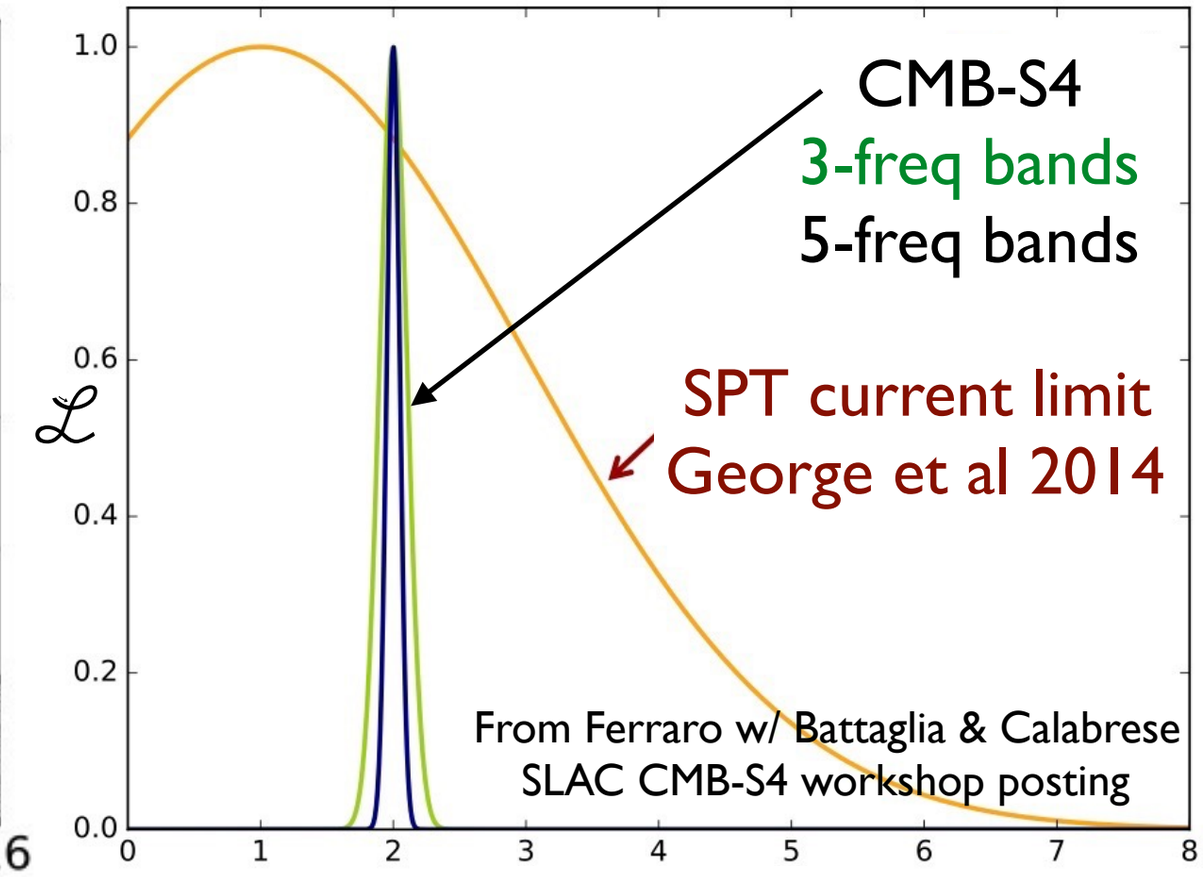
Patchy reionization projections

Planck + SPT + ACT



Battaglia et al. 2012:

$$D^{\rm kSZ}_{\ell=3000} \simeq 2.02\mu{\rm K}^2 \left[\left(\frac{1+\bar{z}}{11}\right) - 0.12\right] \left(\frac{\Delta_{\rm z}}{1.05}\right)^{0.47}$$



Planck τ_e sets z_{reion}, small scale kSZ sets duration Δz_{reion}

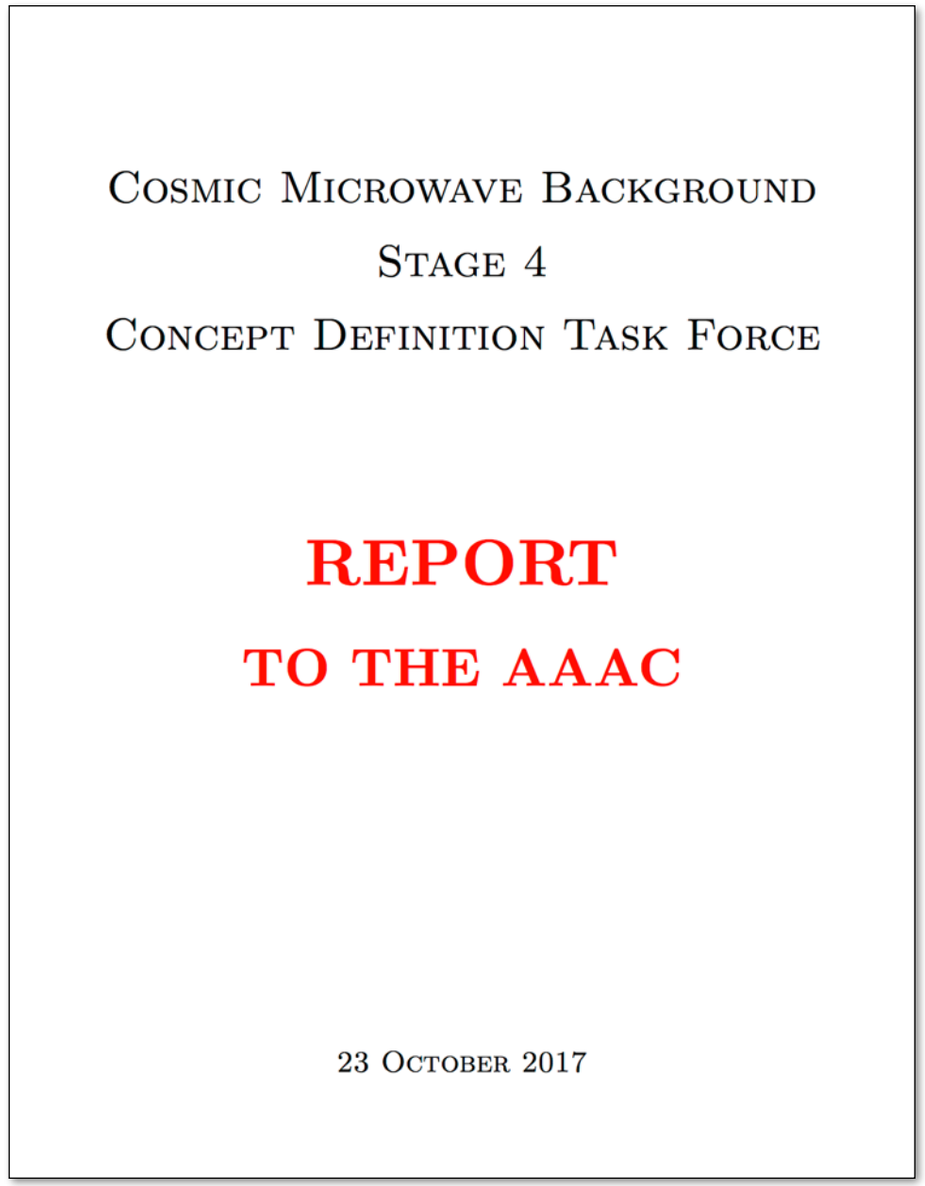
See Smith and Ferraro (2016) for less model dependent kSZ tomography technique, which exploits the high non-Gaussianity of kSZ.

CMB-S4
Next Generation CMB Experiment

Concept Definition Task force (CDT)

Joint NSF & DOE task force report accepted October 2017

- Science requirements
- Measurement requirements,
- Instrument concept that meet requirements, backed by simulations using realized sensitivities and efficiencies
- Cost and schedule



Cosmic Microwave Background

Stage 4

Concept Definition Task Force

REPORT

TO THE AAAC

23 October 2017

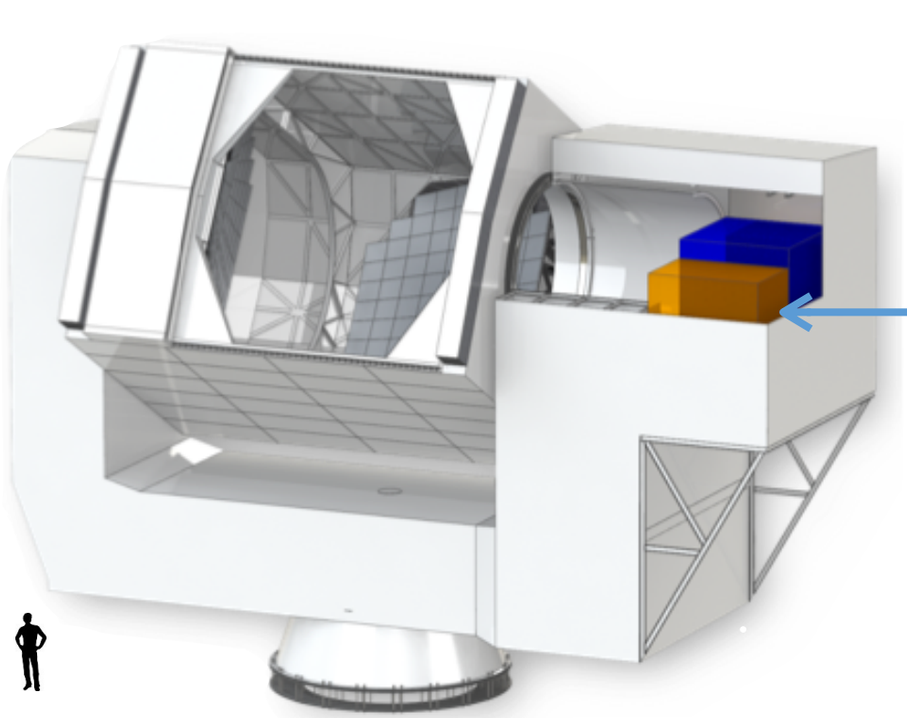
The CDT report is very significant as it enables the agencies to move forward

CMB-S4
Next Generation CMB Experiment

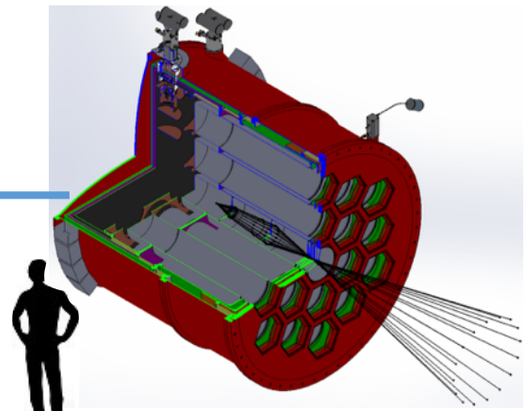
CMB-S4 "concept"

- **One collaboration, one project, with two sites: South Pole and Atacama, Chile**
- Small and large telescopes for B-mode, de-lensing, N_{eff} and cosmic structure science
- O(400,000) detectors (200k on 3 large telescopes; 200k on 14 small telescopes)
- Order 8 frequency bands for CMB and foreground mitigation, 20 - 270 GHz
- Two surveys: 4 yr deep B-mode w/ de-lensing (f_{sky} ~ few %)
  7 yr broad for N_{eff} and cosmic structure science (f_{sky} = 40%)

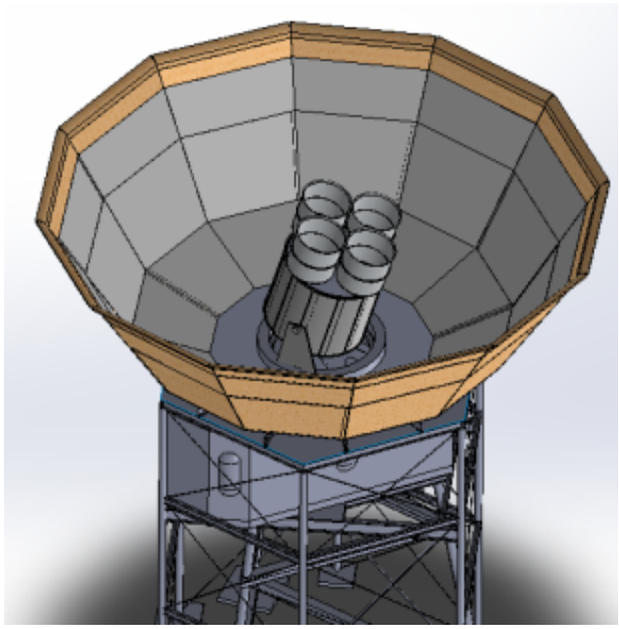
(requires access to 70% of sky)



e.g., 6 meter Diameter Telescope



2.5 meter Diameter Focal Plane with 70,000 detectors



High resolution Science + de-lensing:
200,000 detectors on <u>3 large telescopes</u>

Figure from Simons Obs, Mark Devlin / Mike Niemack

Low resolution B-mode Science:
200,000 det. on <u>14 small telescopes</u>

Figure from BICEP Array

Atacama CMB (Stage 3)

and the Simons Observatory is being planned.

CLASS 1.5m x 4
72 detectors at 38 GHz
512 at 95 GHz
2000 at 147 and 217 GHz

Upgrading to Simons Array (Polarbear 2.5m x 3)
22,764 detectors
90, 150, 220, 280 GHz

ACT 6m
AdvACTpol:
88 detectors at 28 & 41 GHz
1712 at 95 GHz
2718 at 150 GHz
1006 at 230 GHz

Photo: Rahul Datta & Alessandro Schillaci

South Pole CMB (Stage 3)

10m South Pole Telescope
SPT-3G: 16,000 detectors
95, 150, 220 GHz

BICEP3
2560 detectors
95 GHz

Keck Array
2500 detectors
150 & 220 GHz

Upgrading to BICEP Array:
30,000 detectors
35, 95, 150, 220, 270 GHz

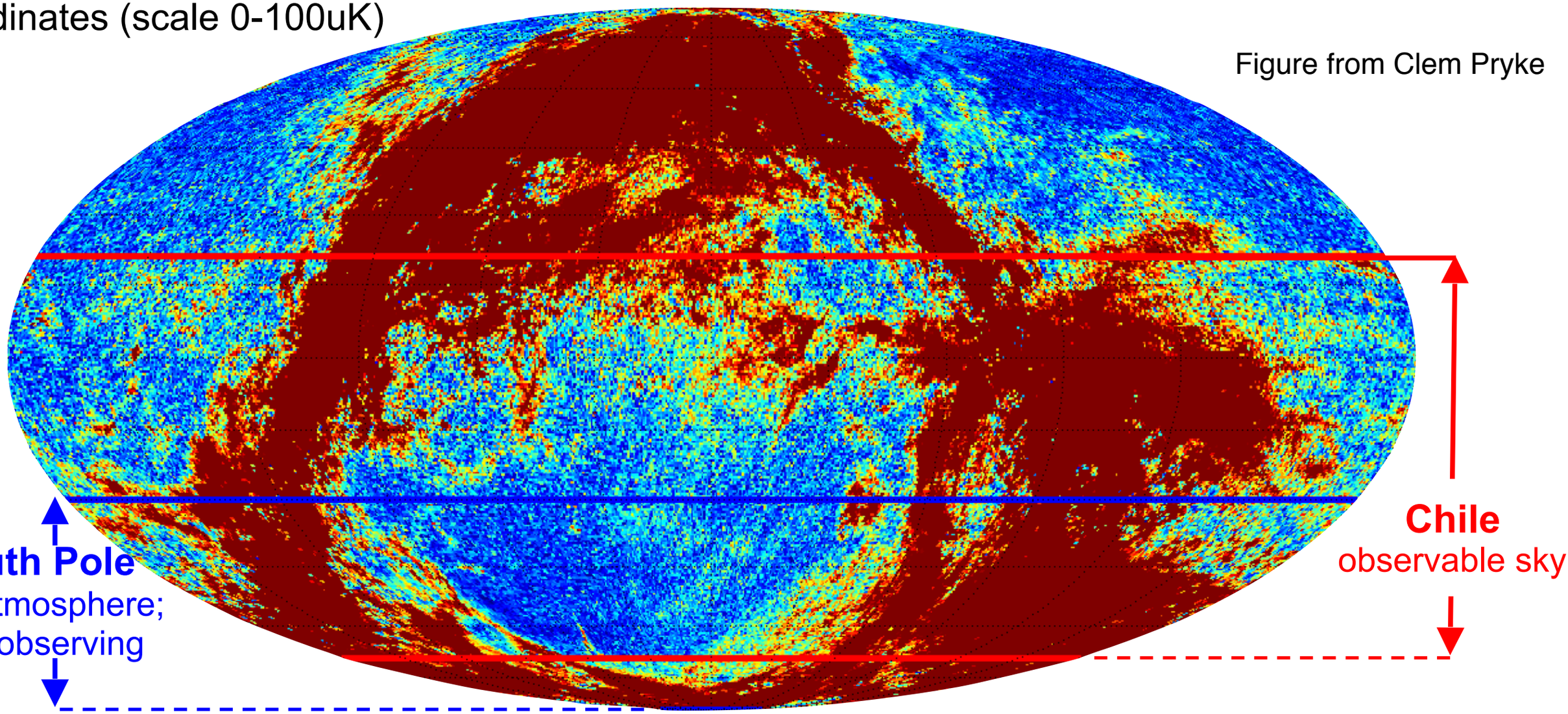
Photo credit Cynthia Chiang

CMB-S4
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 excellent for ultra deep fields

Chile excellent for wide sky coverage

(a northern site would decrease sample variance)

CMB-S4
Next Generation CMB Experiment

Timeline & Cost

Seven year construction project:

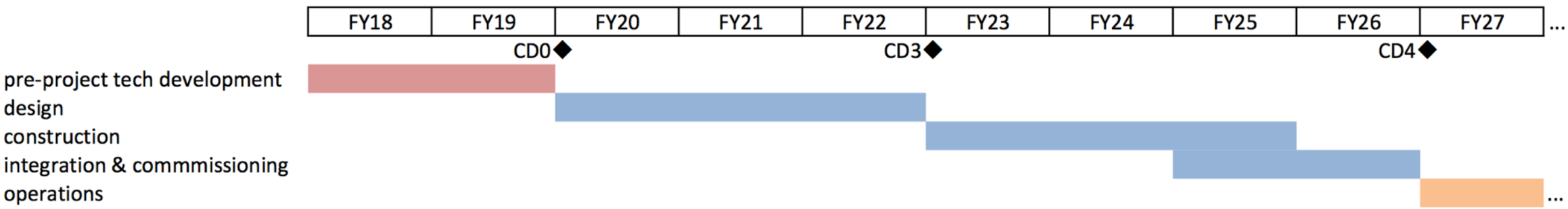


Figure 13: CMB-S4 strawperson schedule.

CDT's total construction project cost vetted by DOE lab budget review is $412M in 2017 equivalent USDs and includes 45% contingency

CMB-S4
Next Generation CMB Experiment

Next Steps

- Establish the official CMB-S4 Science Collaboration
  - Clearly we've been functioning as an effective collaboration, delivering Snowmass docs, P5 input, Science Book, Technology Book, holding workshops, etc., and generally advancing CMB-S4
  - The next step is to make it an official collaboration, with clear organization structure and governance.
  - An elected Interim Collaboration Coordination Committee ICCC is producing governance bylaws before March workshop.

CMB-S4
Next Generation CMB Experiment

Next Steps

- Establish the CMB-S4 Project
  - A pre-Project Development Group (pPDG) with representatives from ICCC and DOE labs has been formed to advance CMB-S4.
  - Prepare for Astronomy and Astrophysics Decadal Survey and for the NSF MREFC* funding line, by
    - articulating the full CMB-S4 science case, not just HEP's, and communicate it to larger astro community
    - developing detailed CMB-S4 conceptual design for input to Decadal Survey

* Major Research Equipment & Facility Construction

last comments

CMB-S4 continues to gain momentum.

Formal CMB-S4 collaboration will soon be established and detailed project is being developed.

Next CMB-S4 workshop March 2018 at Argonne Nat Lab

International partners for CMB-S4 are expected and desired.
The modularity of the concept allows many options.

Go to cmb-s4.org for more information on CMB-S4,
e.g., wiki's for workshops and working groups, join email lists, etc.

Backup Slides

CMB-S4 concept

Science	Item	Frequency [GHz] 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]	$11'$	$7.'0$	$5.'2$	. . .	$2.'2$	$1.'4$	. . .	$1.'0$	$0.'8$	
$N_{\rm eff}$											
	2 x 6-m telescopes										
	# detectors	290	640	1.1 k	. . .	50 k	50 k	. . .	17 k	17 k	136 k
	Angular resolution [FWHM]	$11'$	$7.'0$	$5.'2$	. . .	$2.'2$	$1.'4$	. . .	$1.'0$	$0.'8$	