CMB-S4

Next Generation CMB Experiment

Photo provided by Mark Devlin

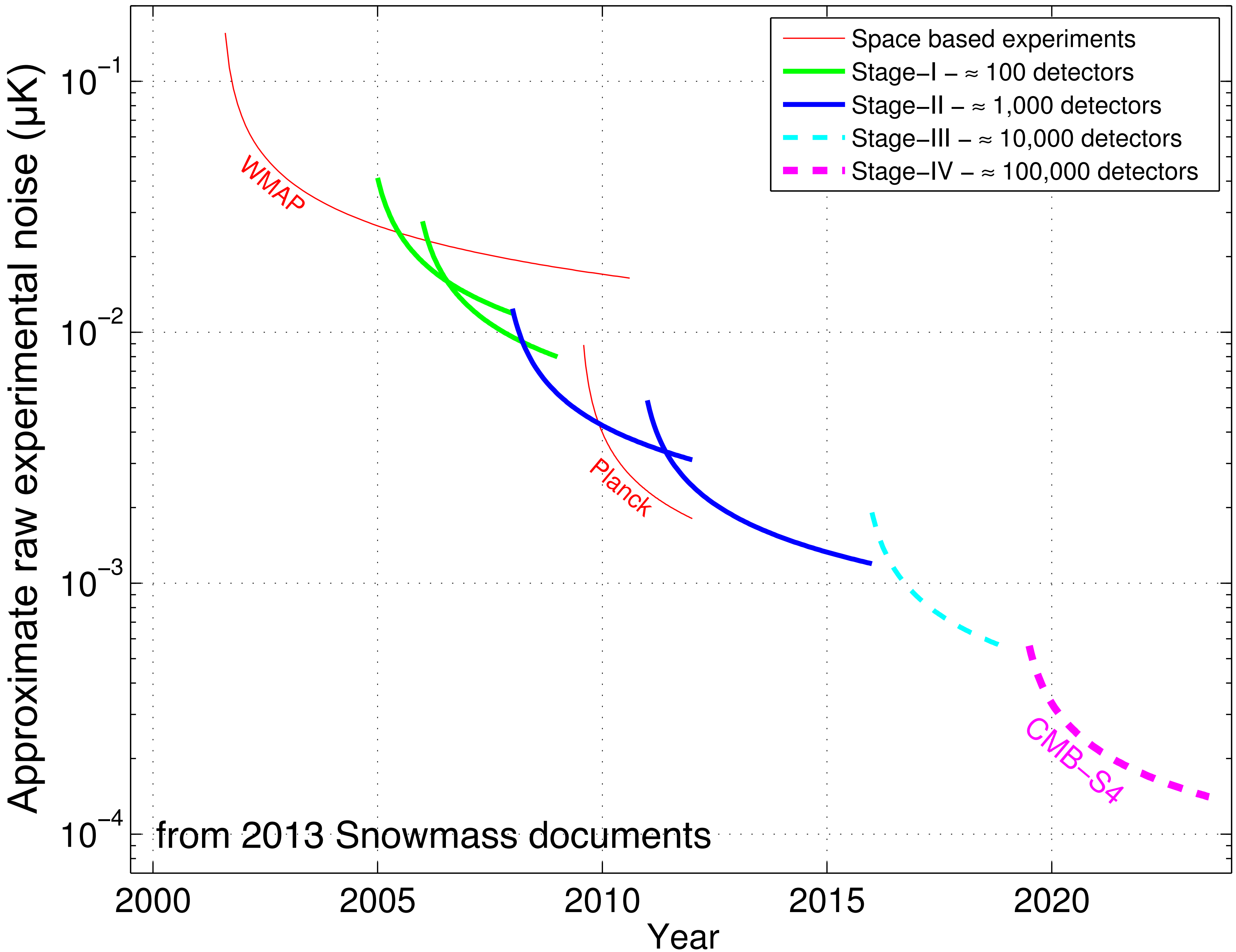
John Carlstrom

CMB-S4 Co-Spokesperson

on behalf of the CMB-S4 Collaboration

Photo credit Cynthia Chiang

“Moore’s Law” of CMB sensitivity



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 those on 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.**

Recommended by P5

CMB-S4
Next Generation CMB Experiment

Twice yearly open community workshops to advance CMB-S4

7th CMB-S4 workshop, Argonne March 5-7, 2017

Next Workshop:

- September 6-8, 2018 at Princeton University registration page available through cmb-s4.org

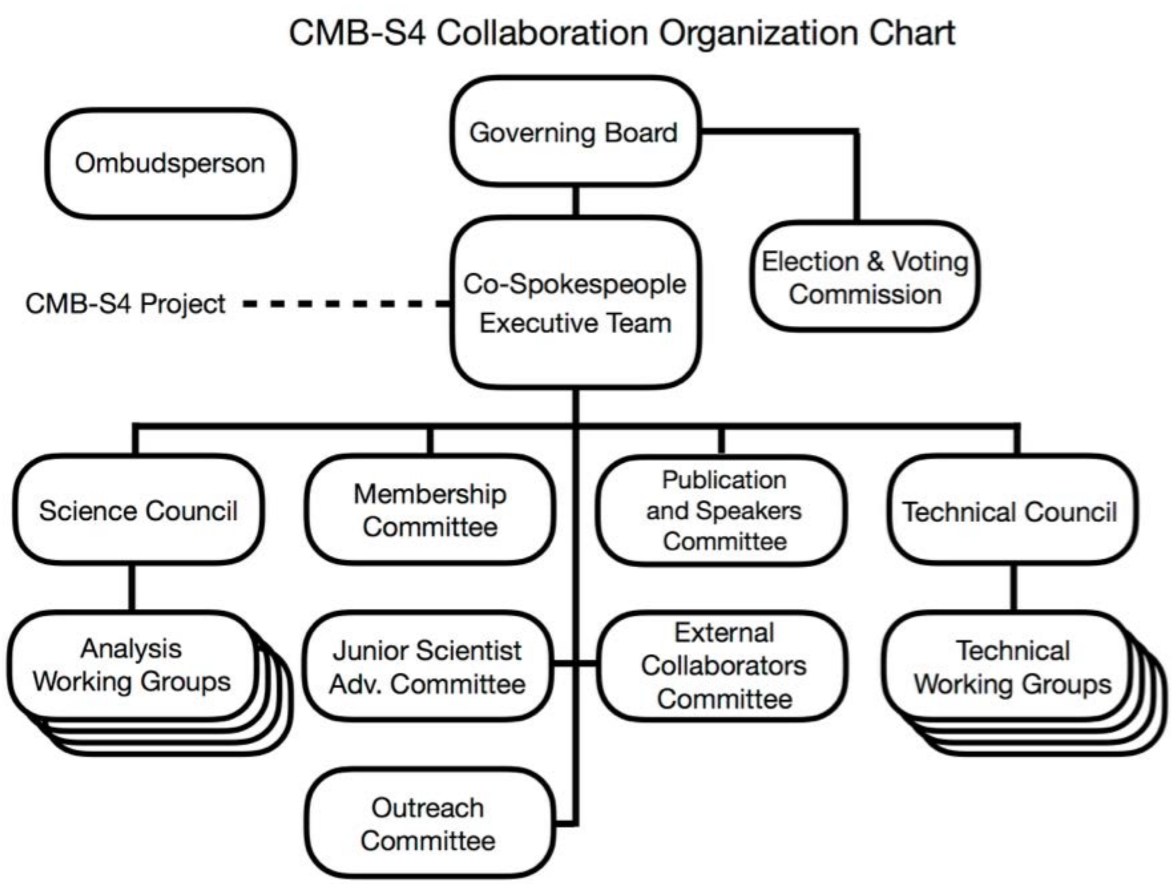
CMB-S4

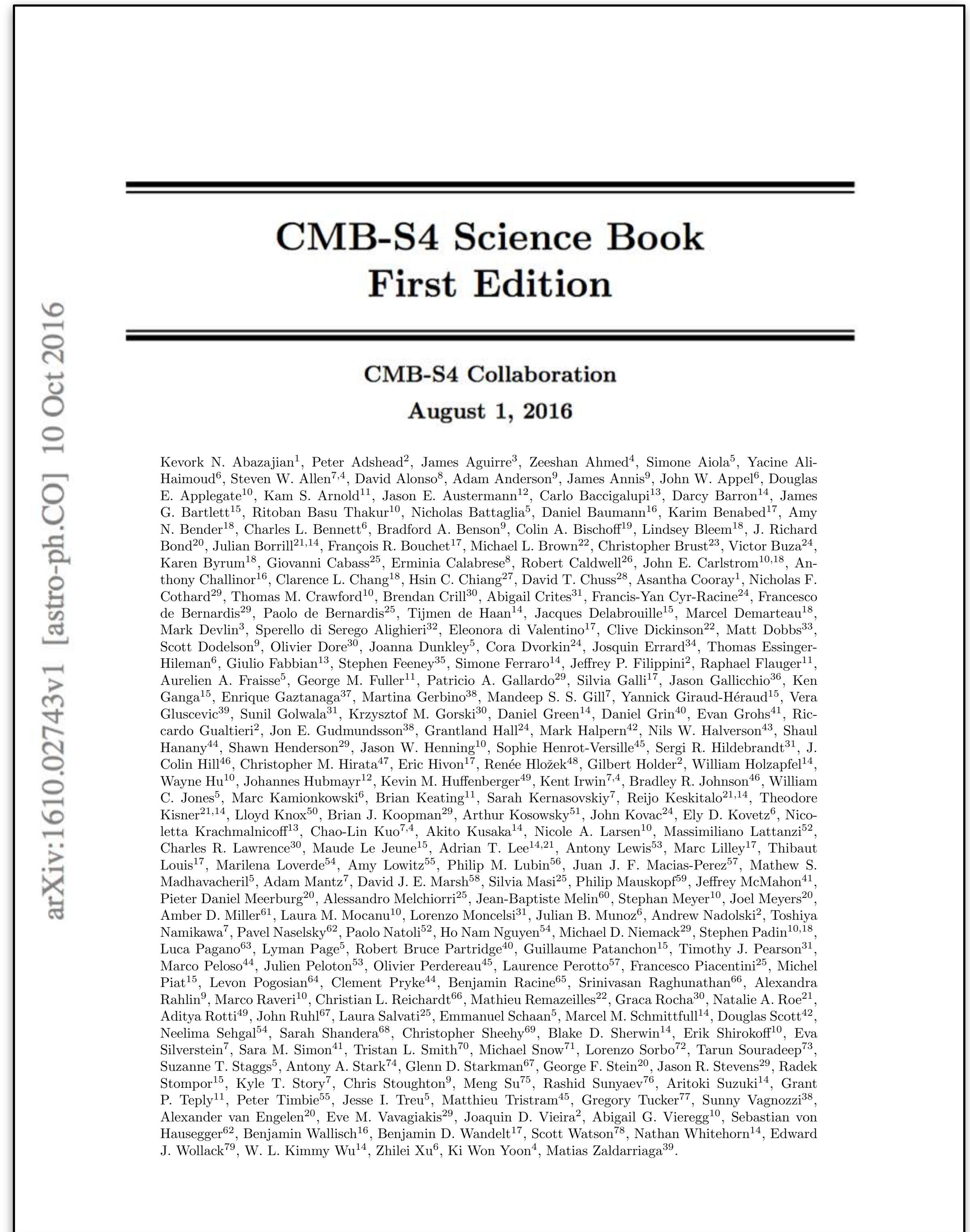
Next Generation CMB Experiment

CMB-S4 Science Collaboration

CMB-S4 Science Collaboration established

Science and Technology Books available at http://cmb-s4.org





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

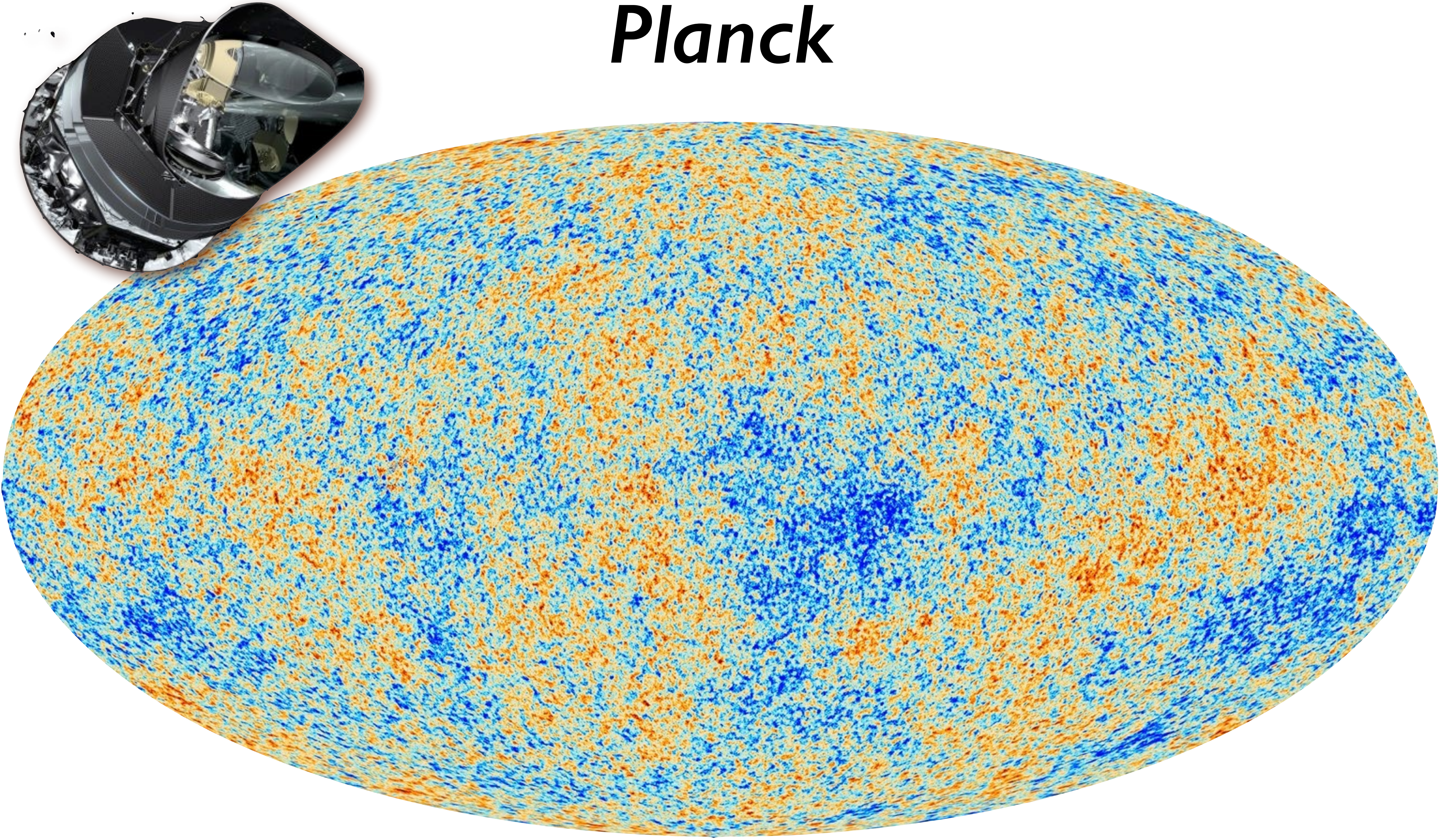
CMB-S4 Science Book First Edition

CMB-S4 Collaboration

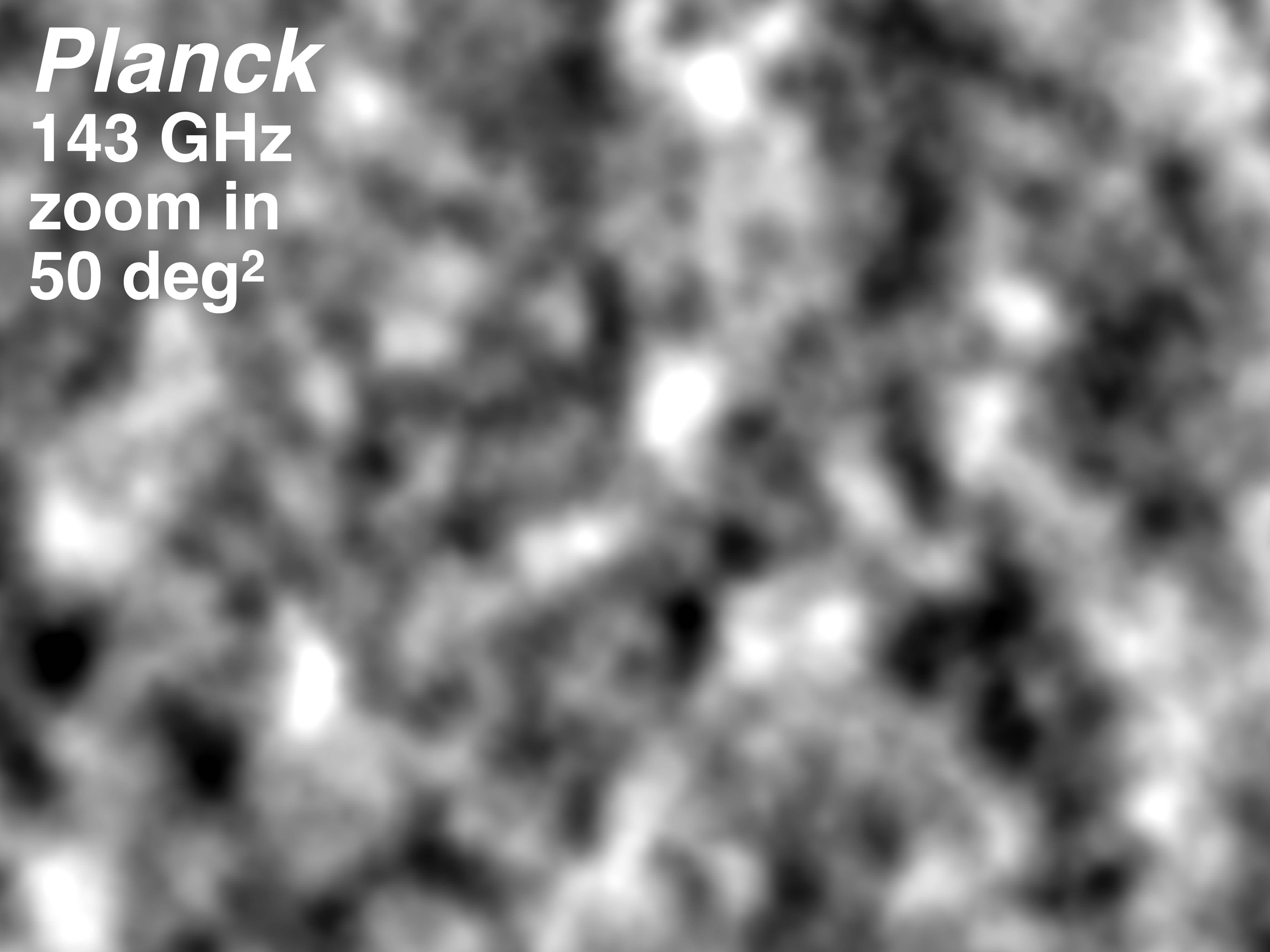
August 1, 2016

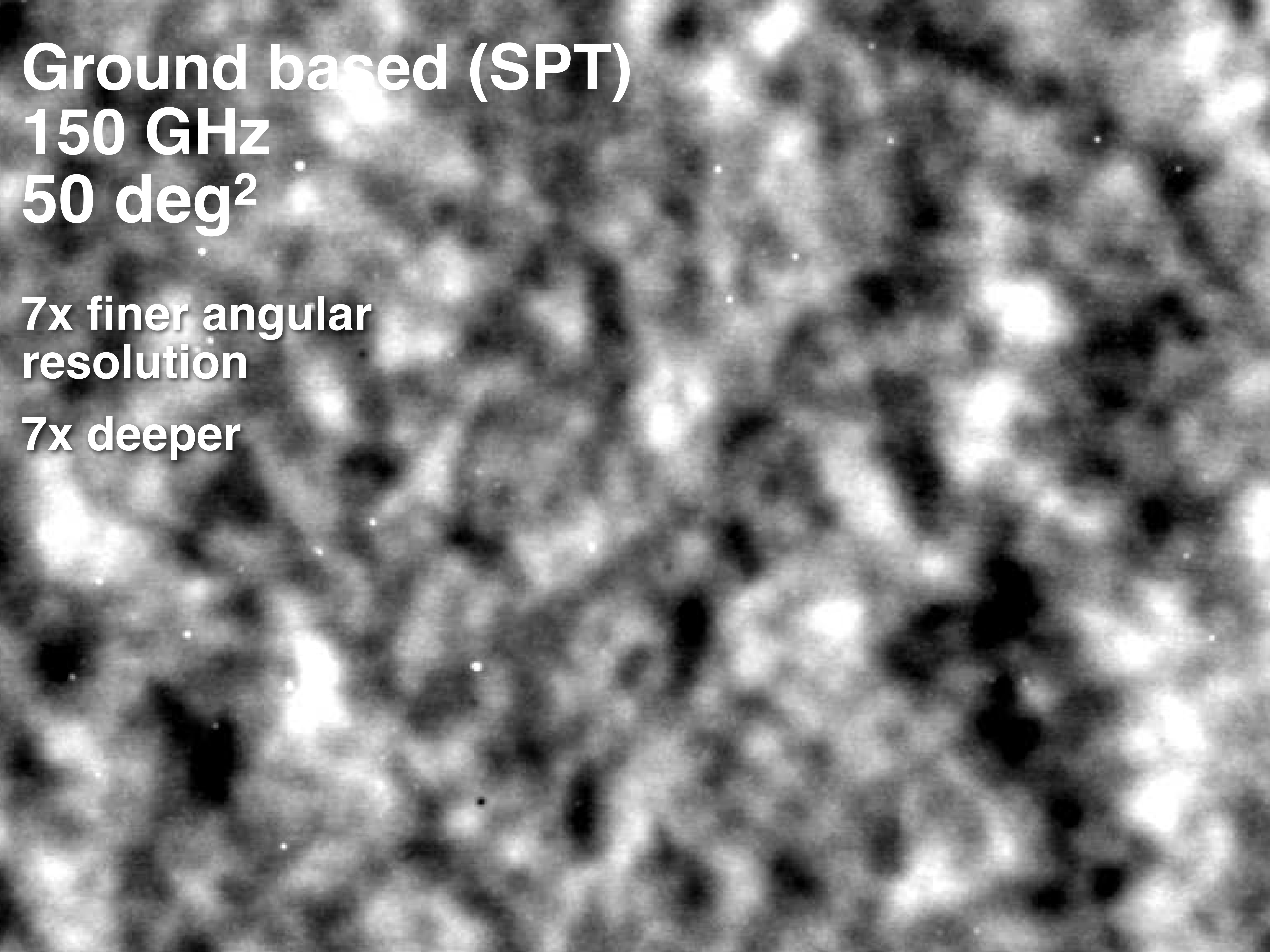
Kevork N. Abazajian[1], Peter Adshead[2], James Aguirre[3], Zeeshan Ahmed[4], Simone Aiola[5], Yacine Ali-Haimoud[6], Steven W. Allen[7,4], David Alonso[8], Adam Anderson[9], James Annis[9], John W. Appel[6], Douglas E. Applegate[10], Kam S. Arnold[11], Jason E. Austermann[12], Carlo Baccigalupi[13], 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].

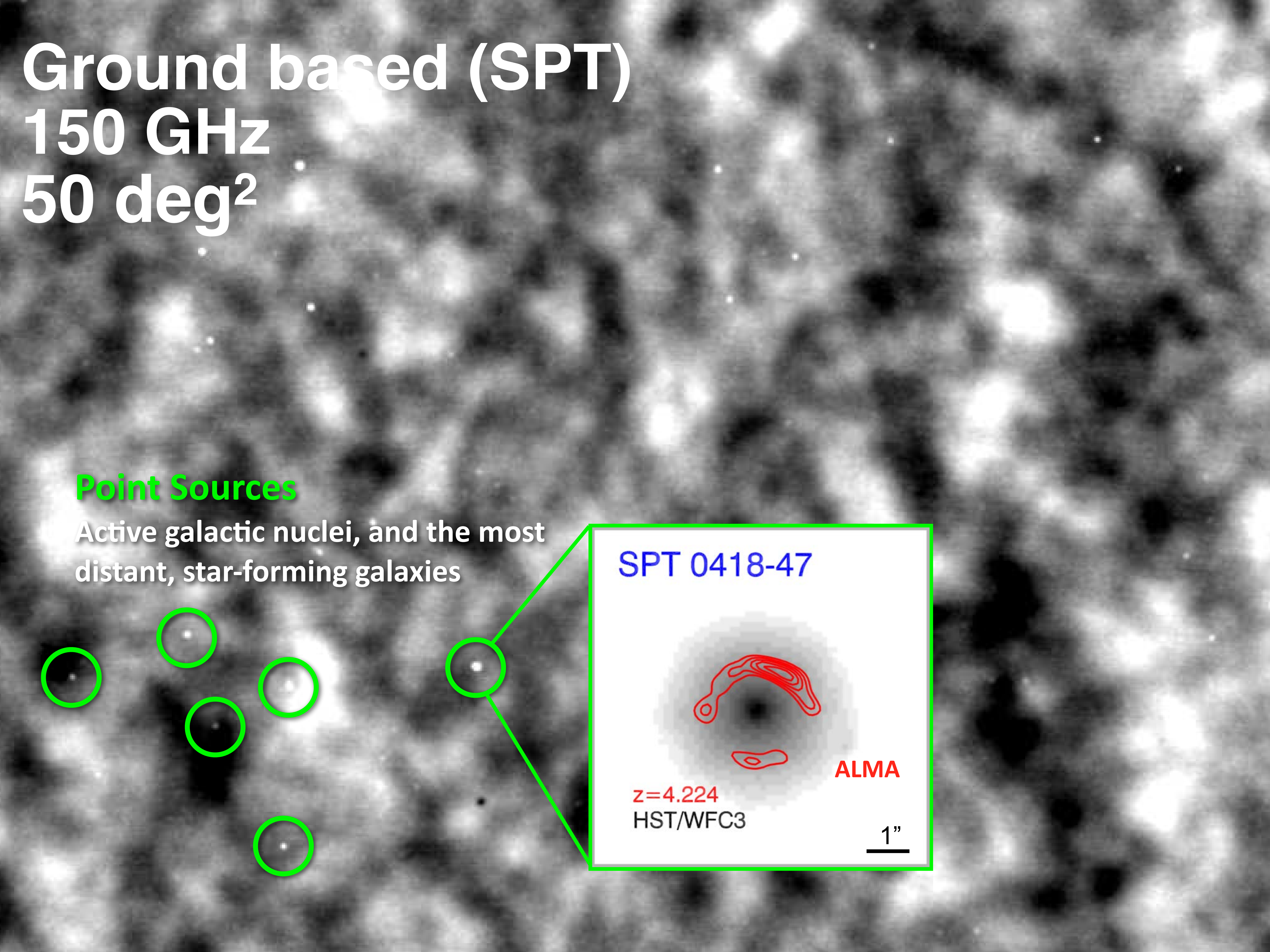
Planck

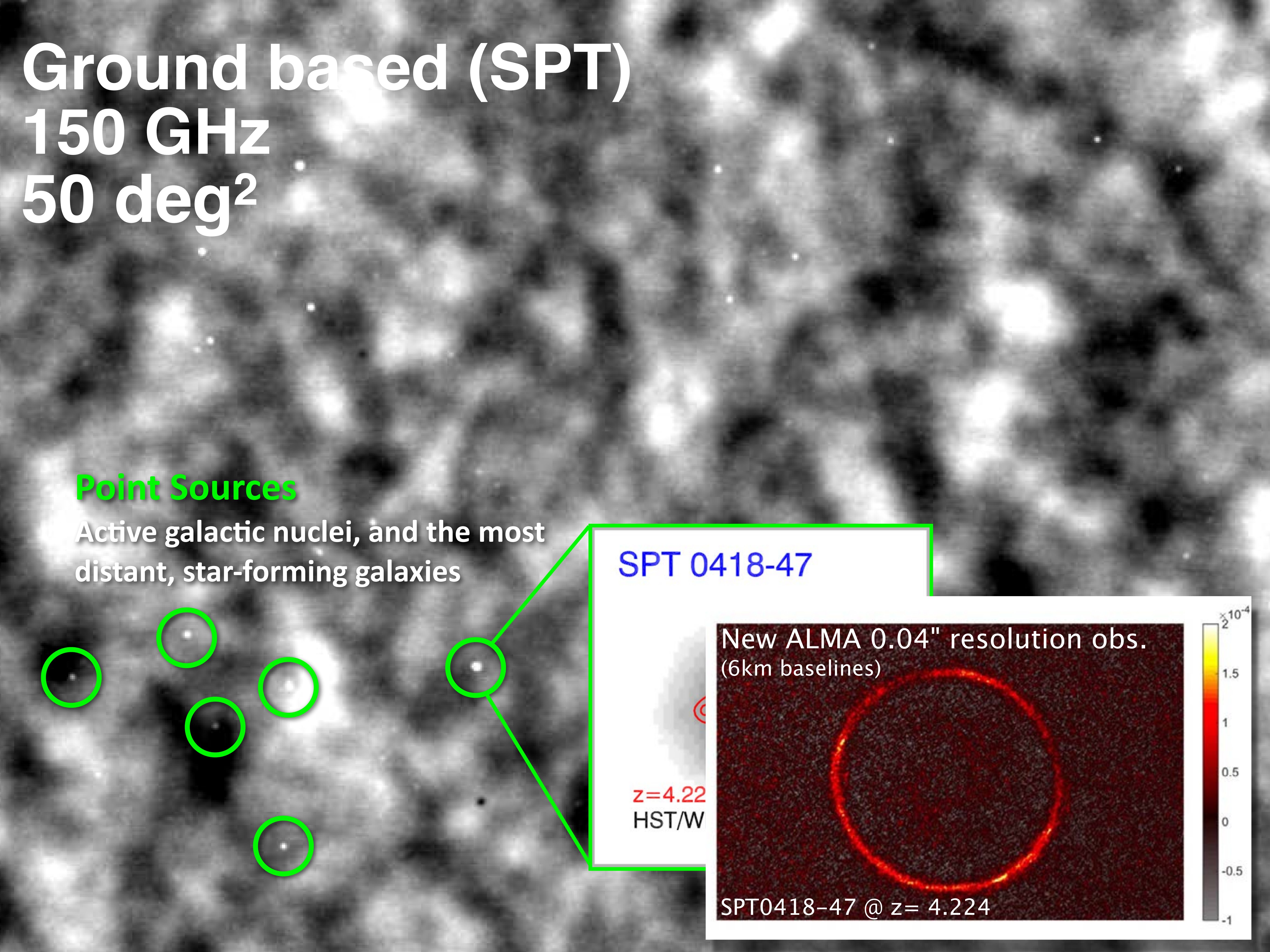


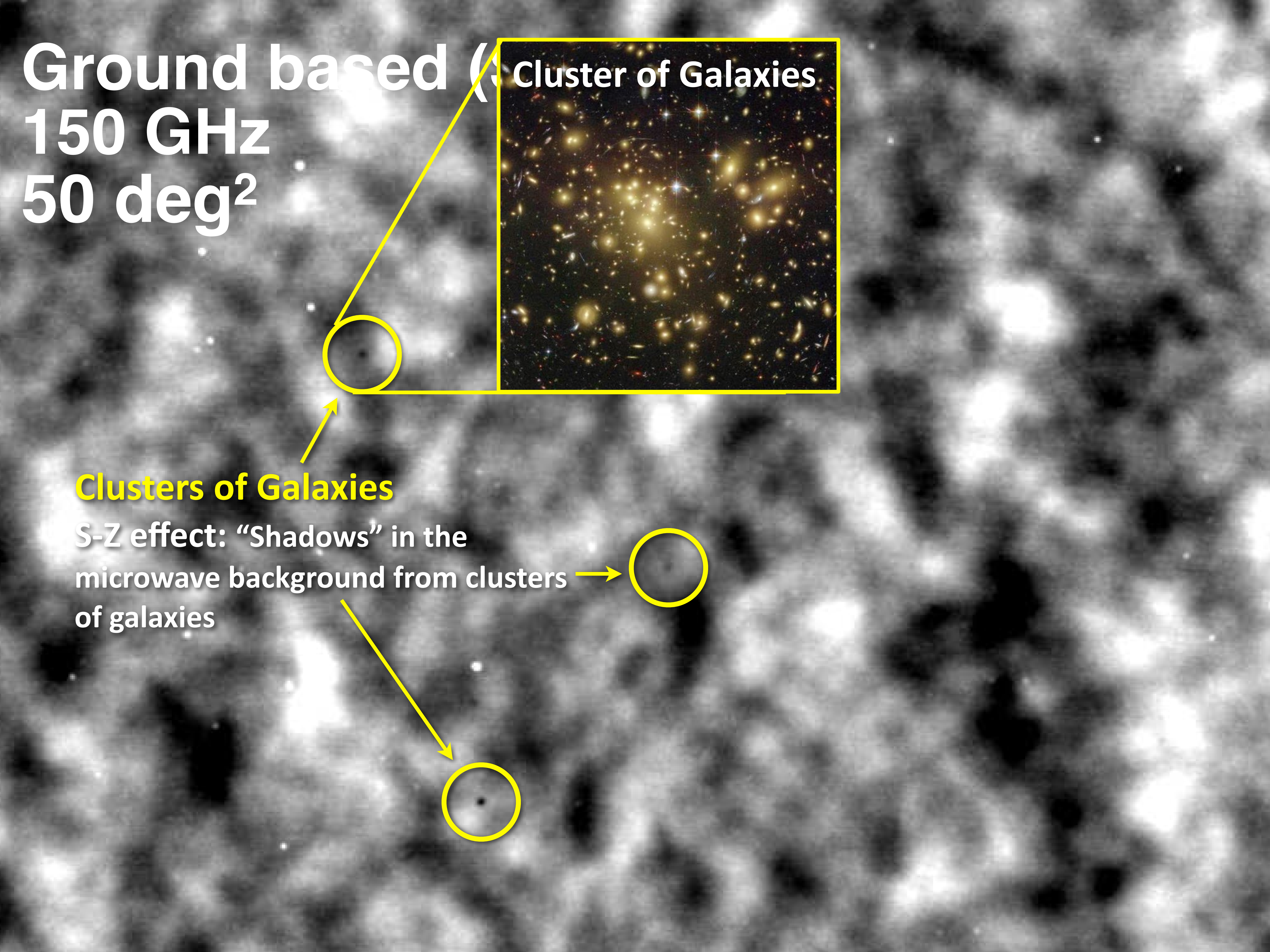
Wow! So, what’s next?


Planck
143 GHz
zoom in
50 deg^2


Ground based (SPT)
150 GHz
50 deg^2
7x finer angular resolution
7x deeper


Ground based (SPT)
150 GHz
50 deg^2
Point Sources
Active galactic nuclei, and the most distant, star-forming galaxies
SPT 0418-47
ALMA
z=4.224
HST/WFC3
1”


Ground based (SPT)
150 GHz
50 deg^2
Point Sources
Active galactic nuclei, and the most distant, star-forming galaxies
SPT 0418-47
z=4.22
HST/W
New ALMA 0.04" resolution obs.
(6km baselines)
SPT0418-47 @ z= 4.224
$\times 10^{-4}$
2
1.5
1
0.5
0
-0.5
-1


Ground ba ed (
150 GHz
50 deg^2
Cluster of Galaxies
Clusters of Galaxies
S-Z effect: "Shadows" in the microwave background from clusters of galaxies

CMB observations probe cosmology, fundamental physics and astrophysics

Inflation

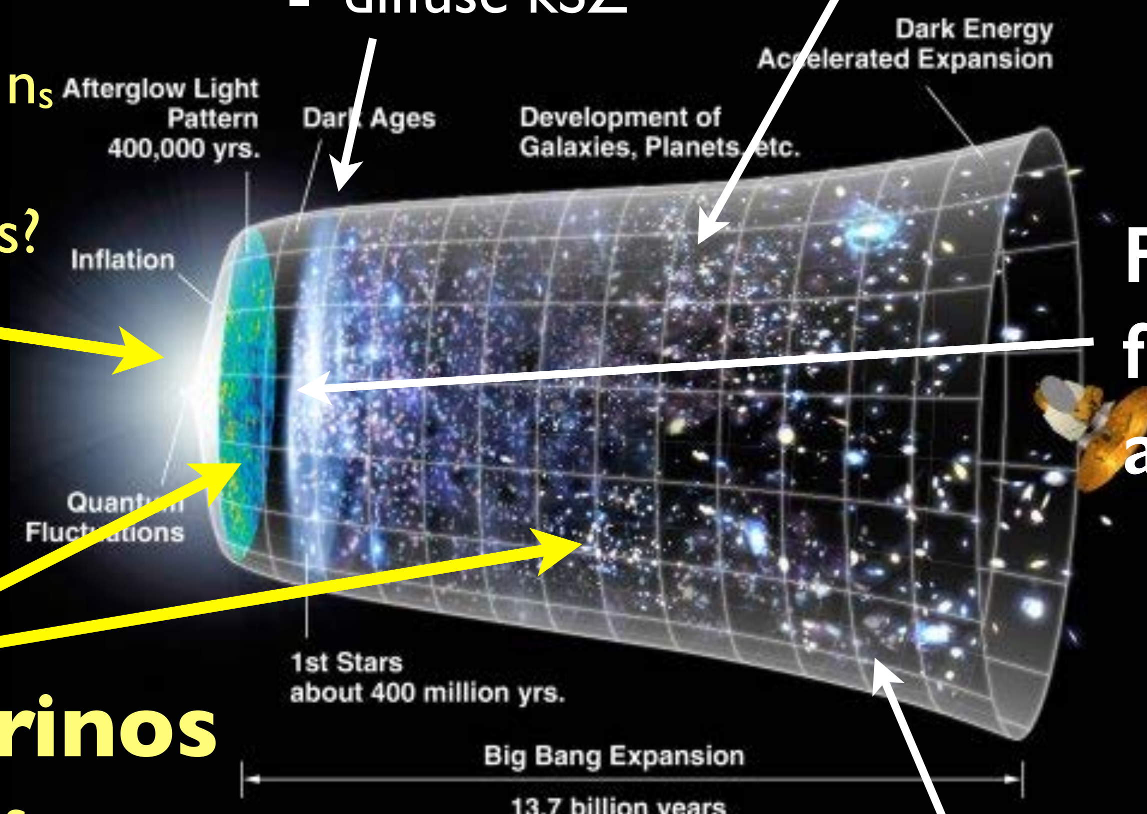
- Spectral index of fluctuations, n_s
- non-Gaussianity
- Inflationary gravitational waves?

Reionization

- diffuse kSZ

Evolution of Structure

- e.g., stacked CMB lensing, thermal and kinematic SZ effects on galaxy positions



First dusty star forming galaxies and proto-clusters

Light relics / Neutrinos

- Number of relativistic species (N_{eff} or “dark radiation”)
- Sum of the neutrino masses, ($\sum m_\nu$) through impact on growth of structure

Dark Energy

- Probe growth with SZ clusters, CMB lensing, correlation with galaxy surveys
- Is GR correct on large scales?

graphic from NASA website

Status of primary CMB TT measurements

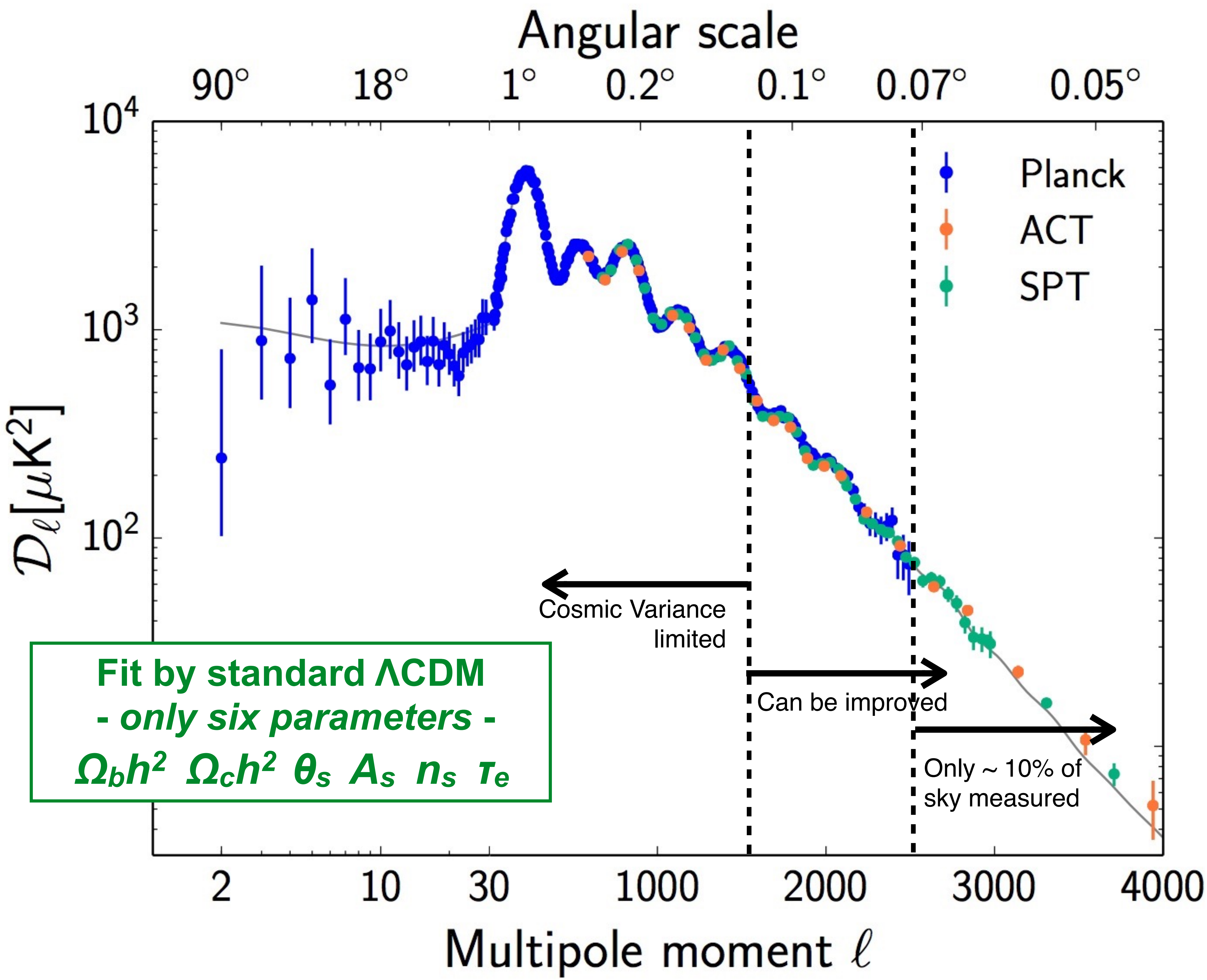
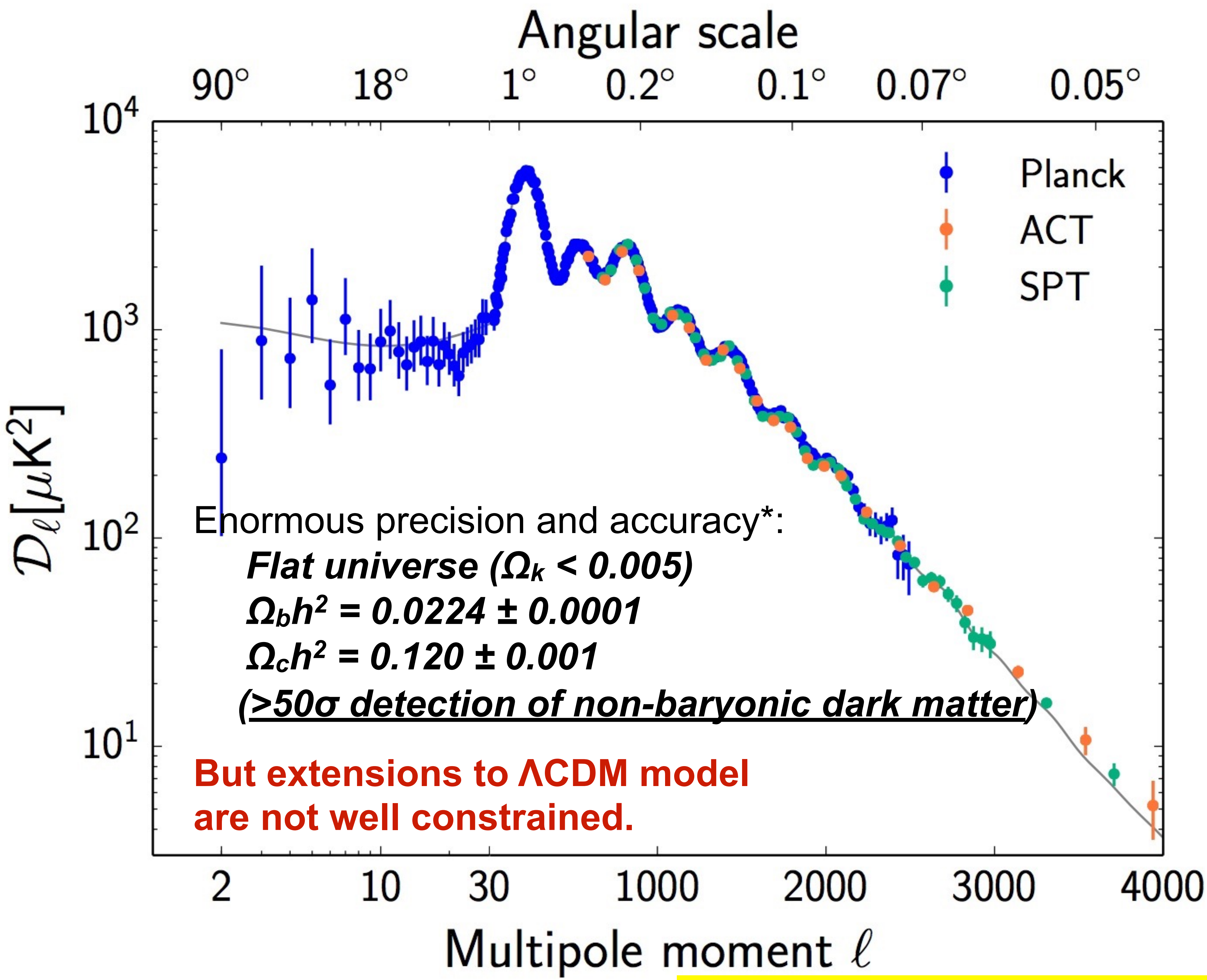


Figure from Planck 2015 Results XI

Constraints on cosmological parameters



Enormous precision and accuracy*:

Flat universe (Ω_k < 0.005)

$\Omega_b h^2$ = 0.0224 ± 0.0001

$\Omega_c h^2$ = 0.120 ± 0.001

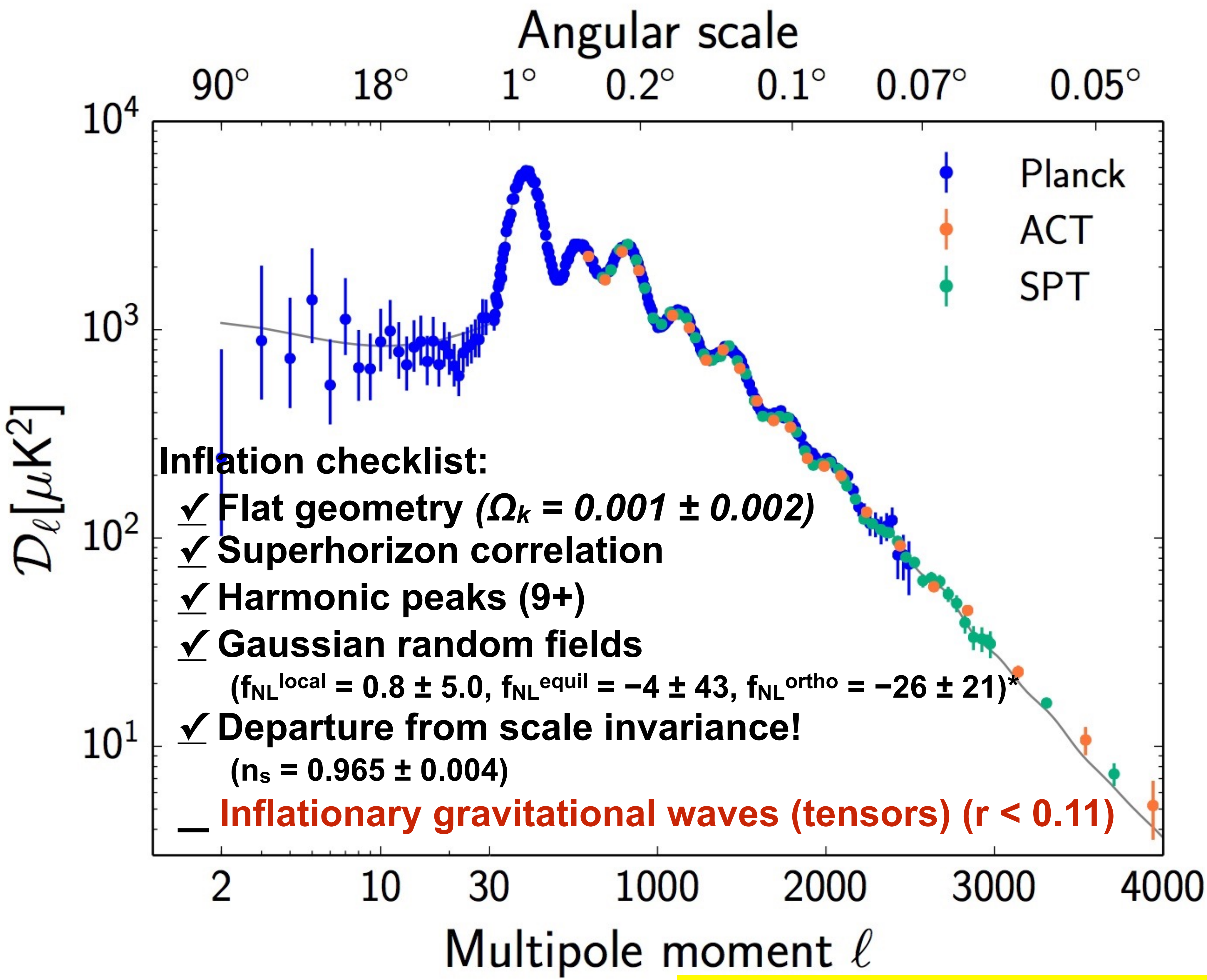
(<u>>50σ detection of non-baryonic dark matter</u>)

But extensions to ΛCDM model are not well constrained.

*Planck 2018 TT,TE,EE+lowE+lensing +BAO

need improved polarization

Constraints on cosmological parameters



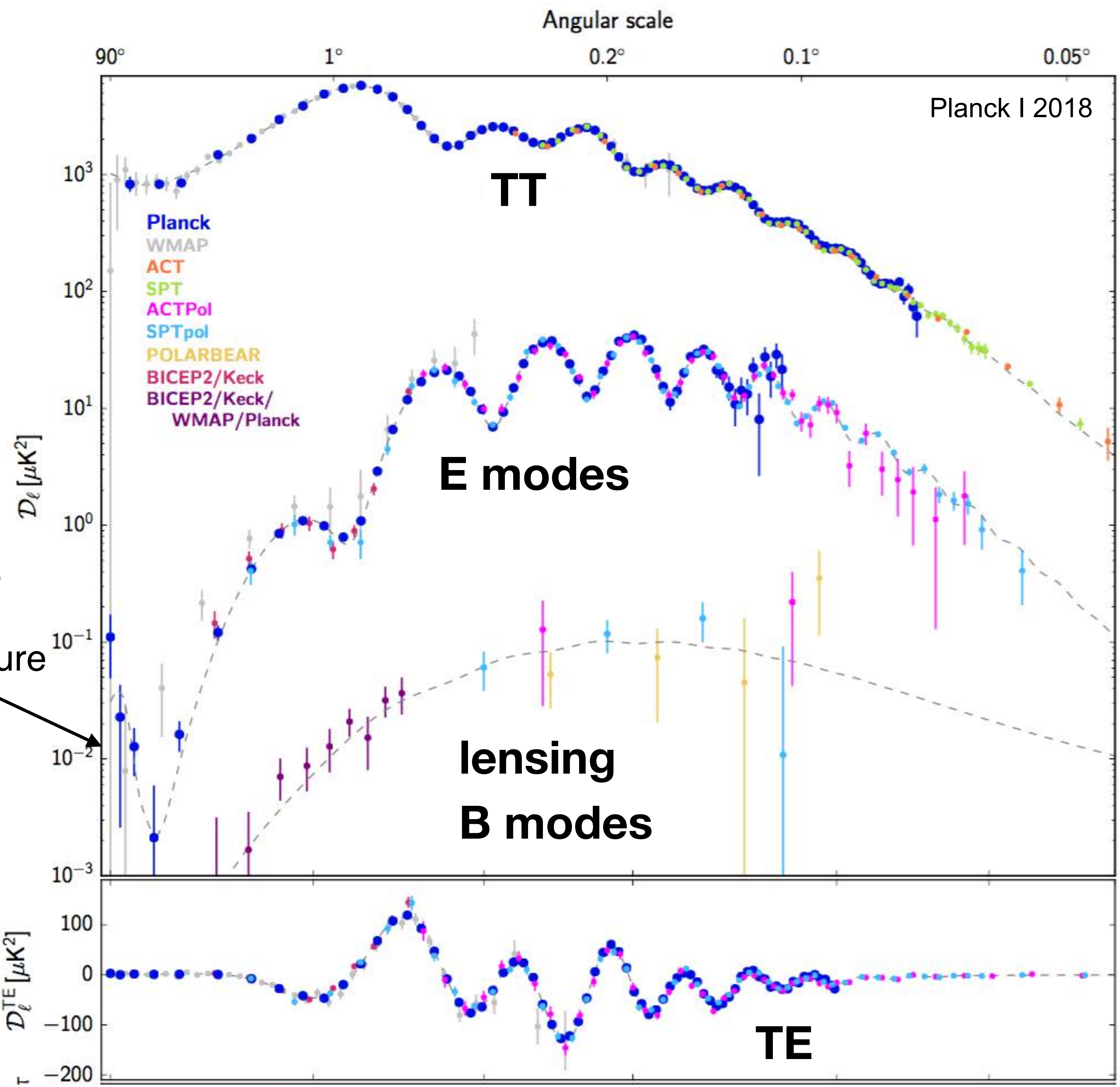
Inflation checklist:

- ✓ **Flat geometry** ***(Ω_k = 0.001 ± 0.002)***
- ✓ **Superhorizon correlation**
- ✓ **Harmonic peaks (9+)**
- ✓ **Gaussian random fields**
  (f_{NL}^{local} = 0.8 ± 5.0, f_{NL}^{equil} = −4 ± 43, f_{NL}^{ortho} = −26 ± 21)*
- ✓ **Departure from scale invariance!**
  (n_s = 0.965 ± 0.004)
- __ **Inflationary gravitational waves (tensors) (r < 0.11)**

*Planck 2018 TT,TE,EE+lowE+lensing +BAO

need improved polarization

Status of CMB polarization measurements

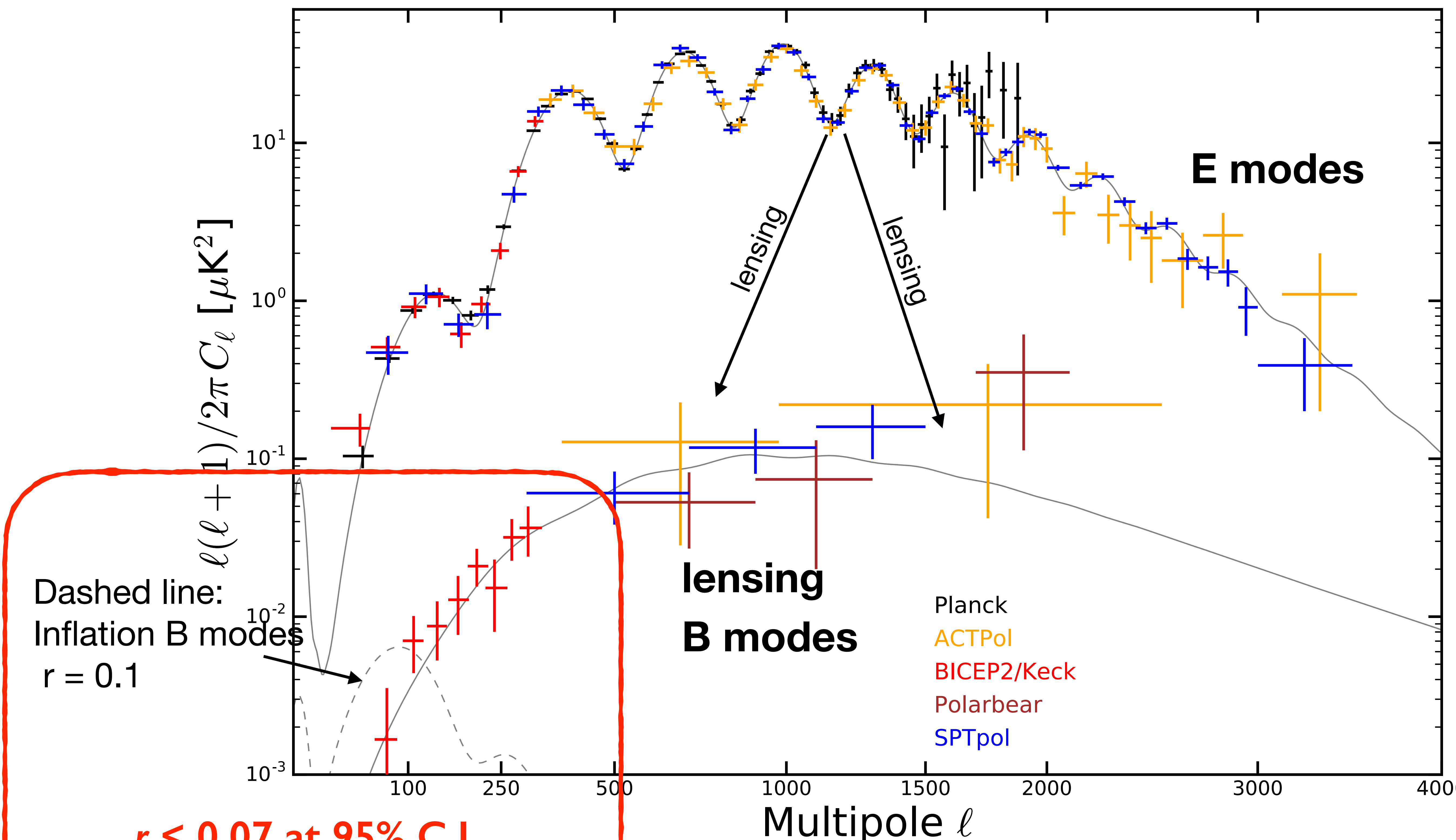


Planck 2018 EE

τ_e=0.054 ± 0.007

from reionization feature

Status of CMB polarization measurements



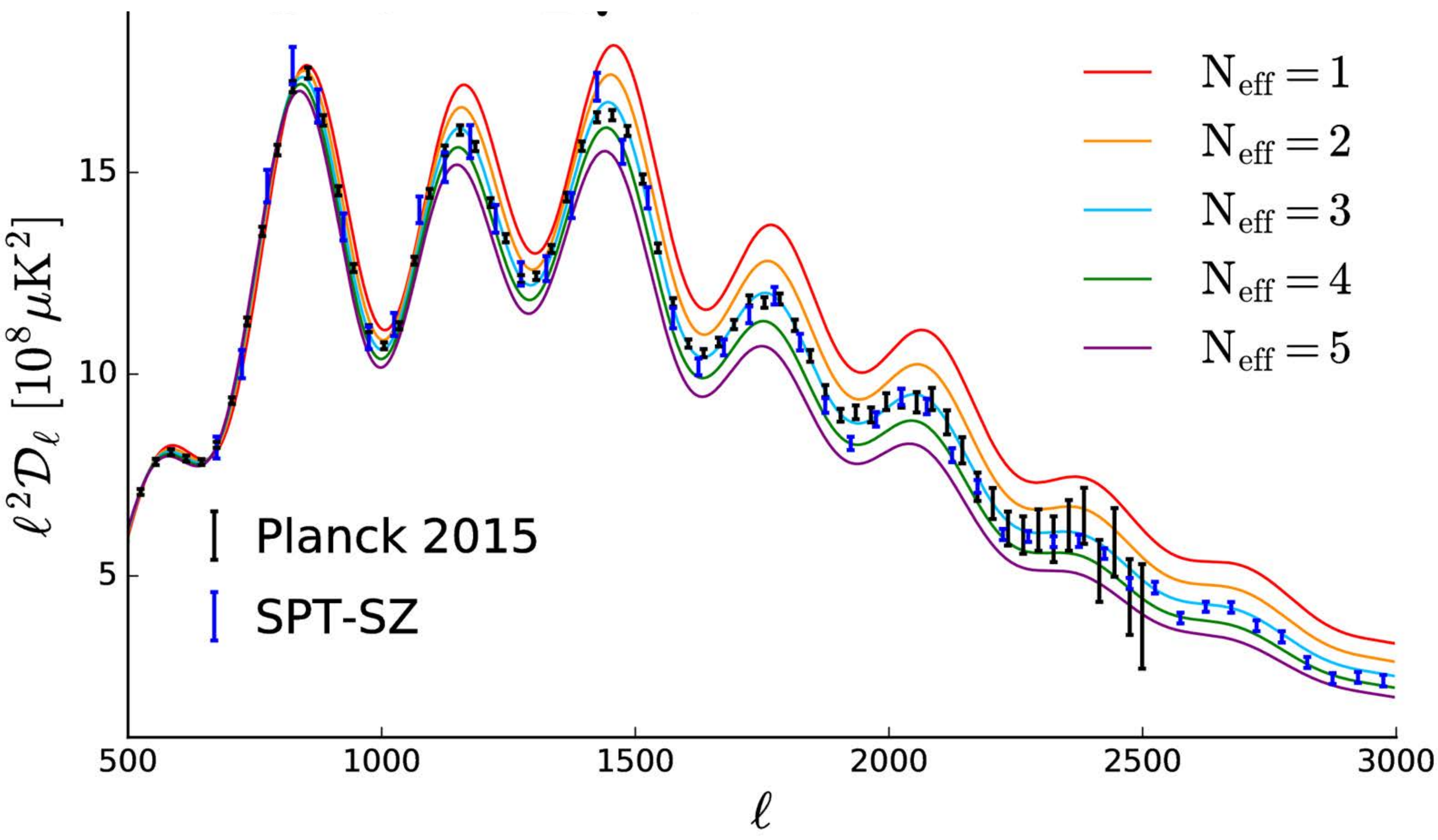
***r* < 0.07 at 95% C.L.**

BICEP/Keck & Planck arXiv:1510.09217

need improved polarization

Light relativistic relics, N_{eff}

Searching for relic particles by their contribution to the energy density



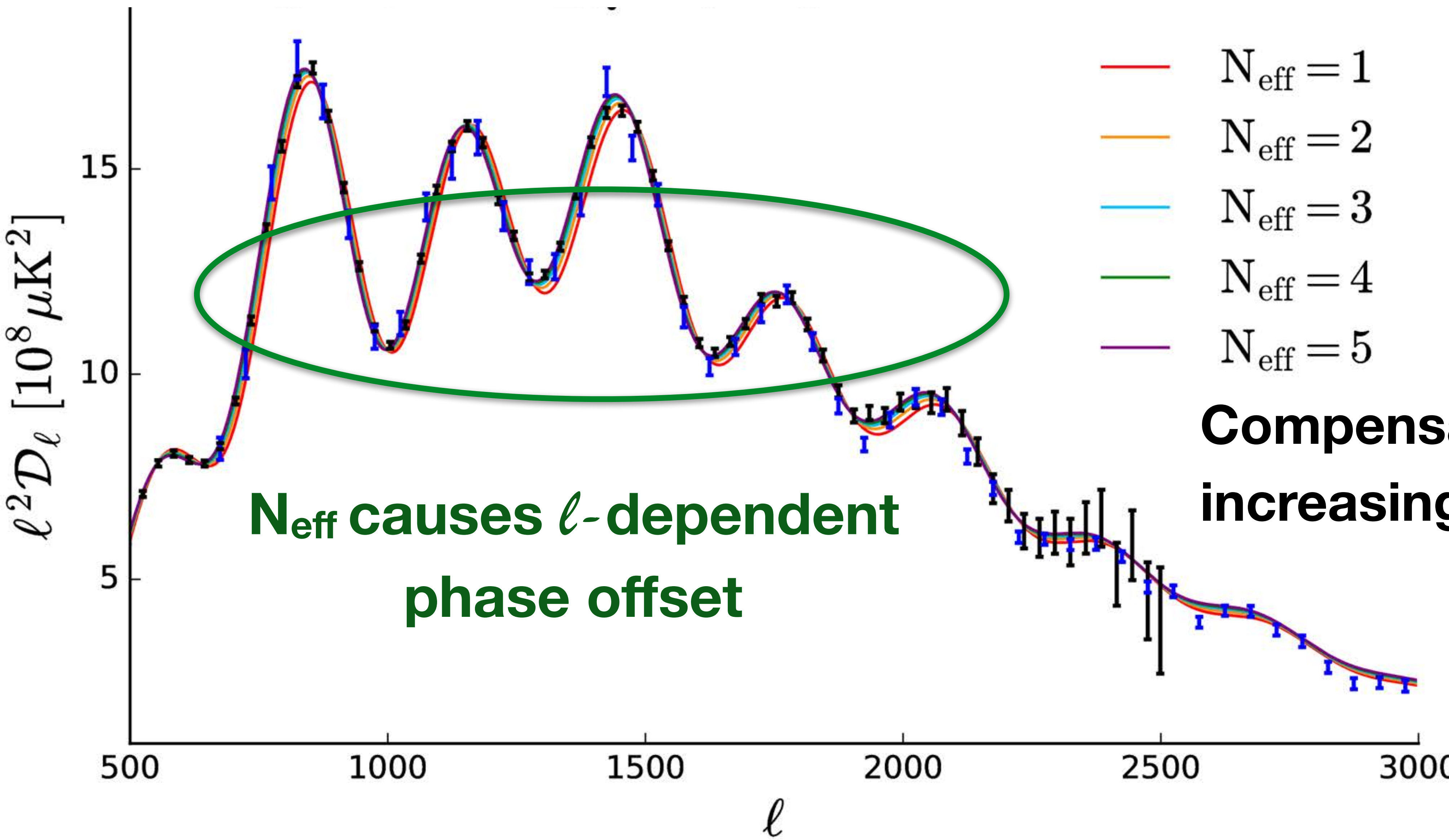
If perfect decoupling and 3 neutrinos, then N_{eff} = 3.00.

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



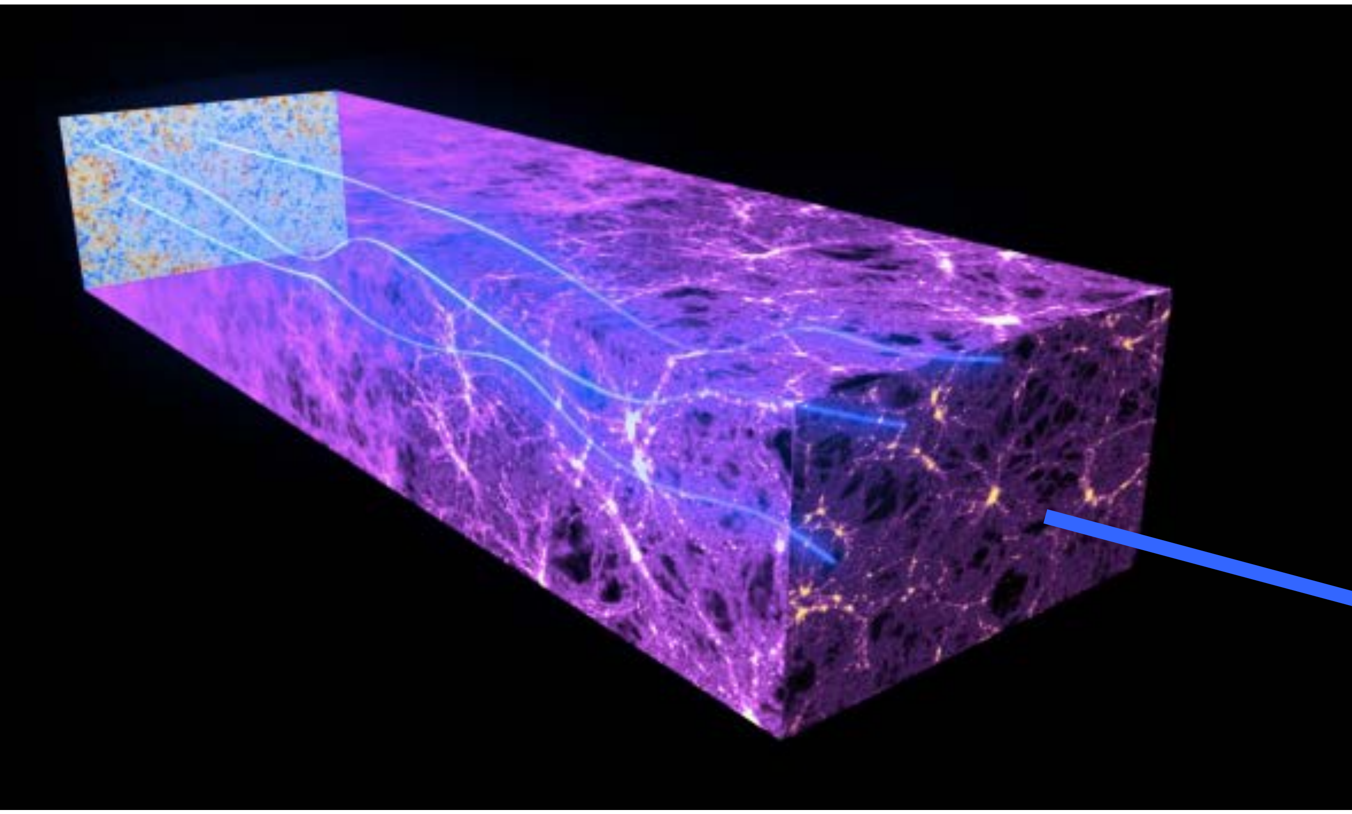
Compensating for N_{eff} by increasing helium fraction, Y_p

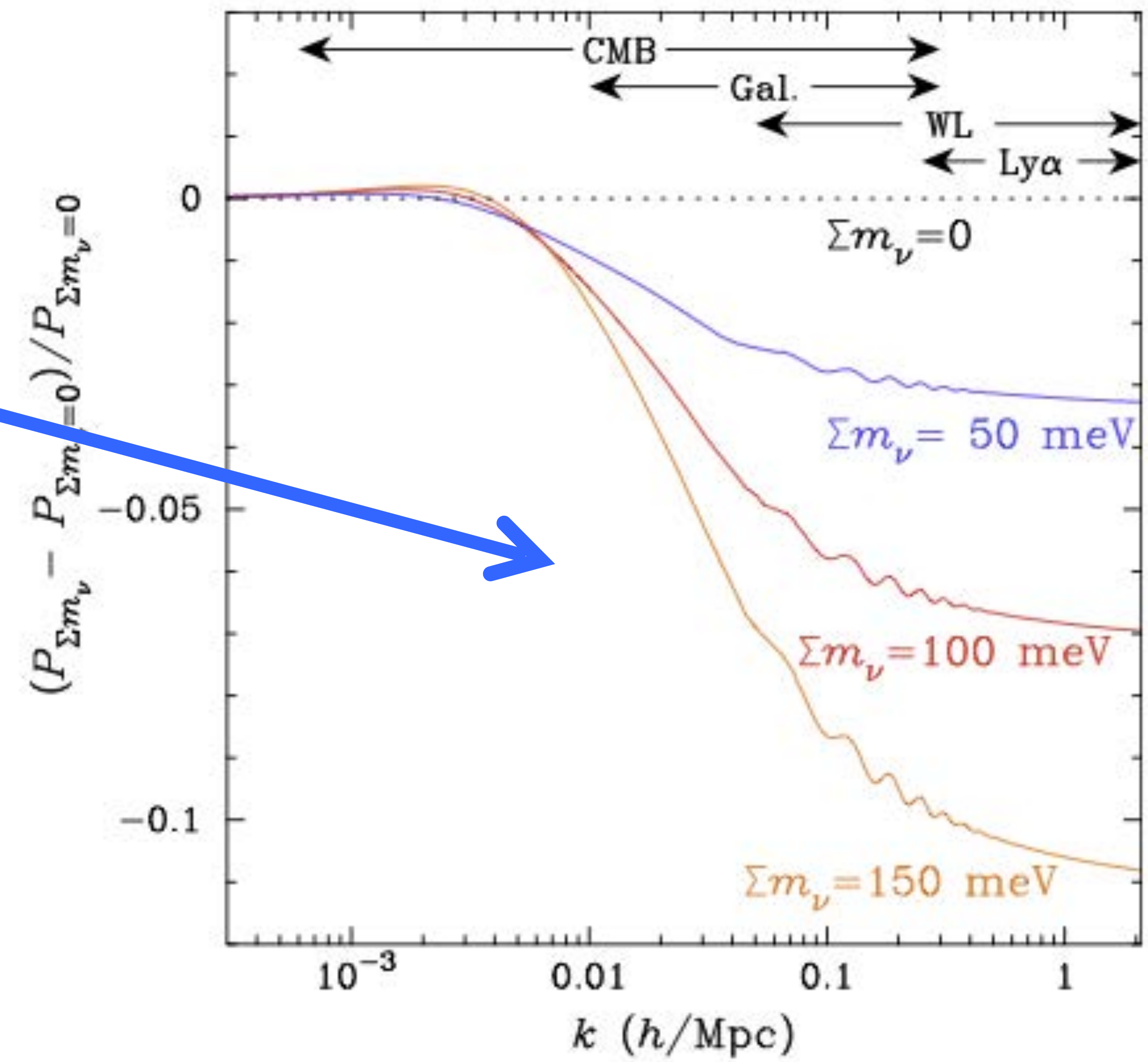
N_{eff} = 2.99 ± 0.17 (Planck TT,TE,EE+lowE+lensing +BAO)

Highly significant detection of neutrino background

need improved polarization

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





Abazajian et al., 2015

Planck 2018:

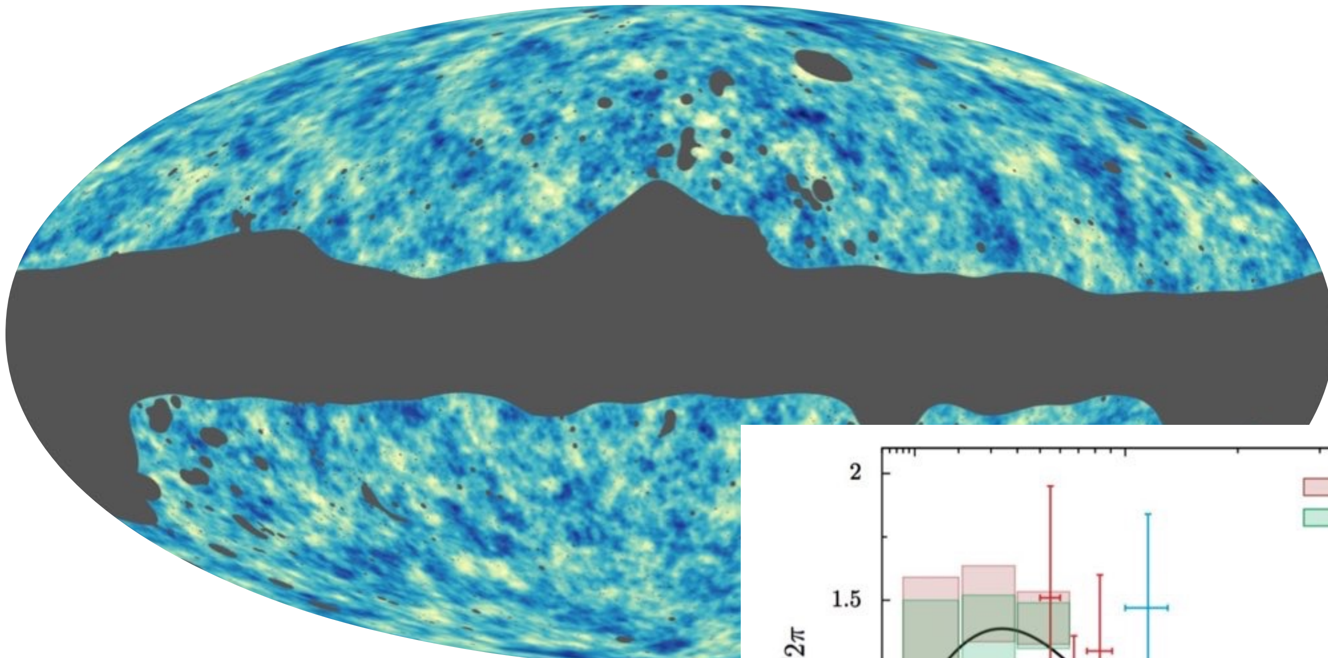
$\Sigma m_\nu <$ 0.12 eV at 95% C.L.

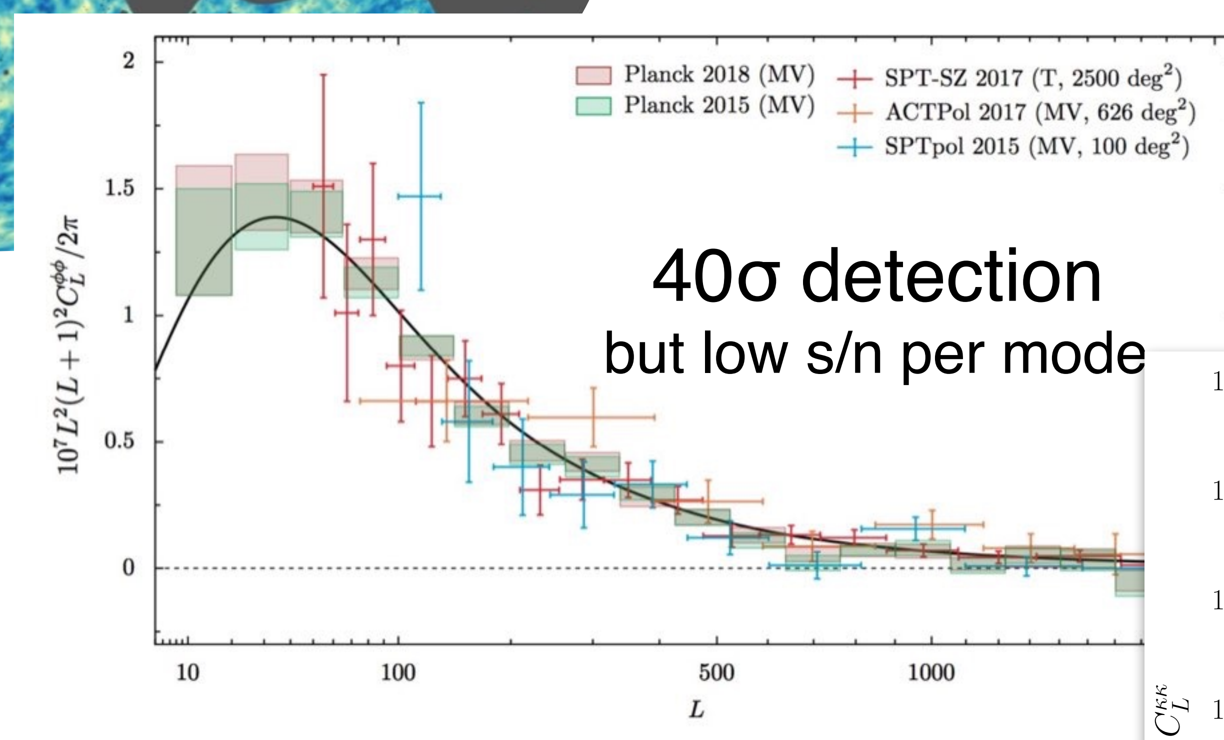
TT,TE,EE+lowE+lensing +BAO

need improved polarization

CMB lensing

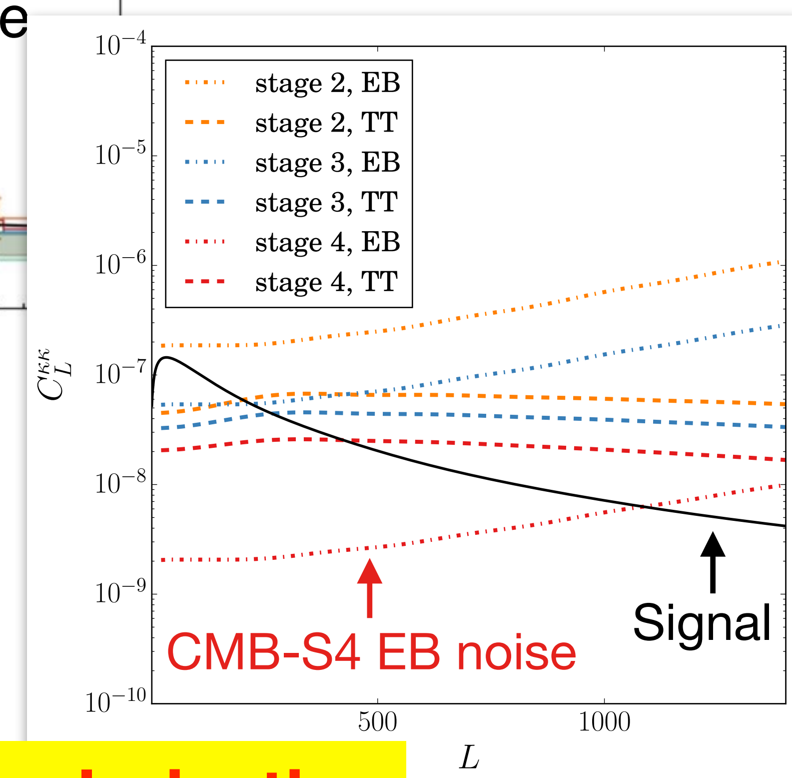
Planck 2018 lensing-deflection reconstruction (projected mass map).





40σ detection

but low s/n per mode



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

from improved polarization

Cosmic Discord ? Hints of new physics?

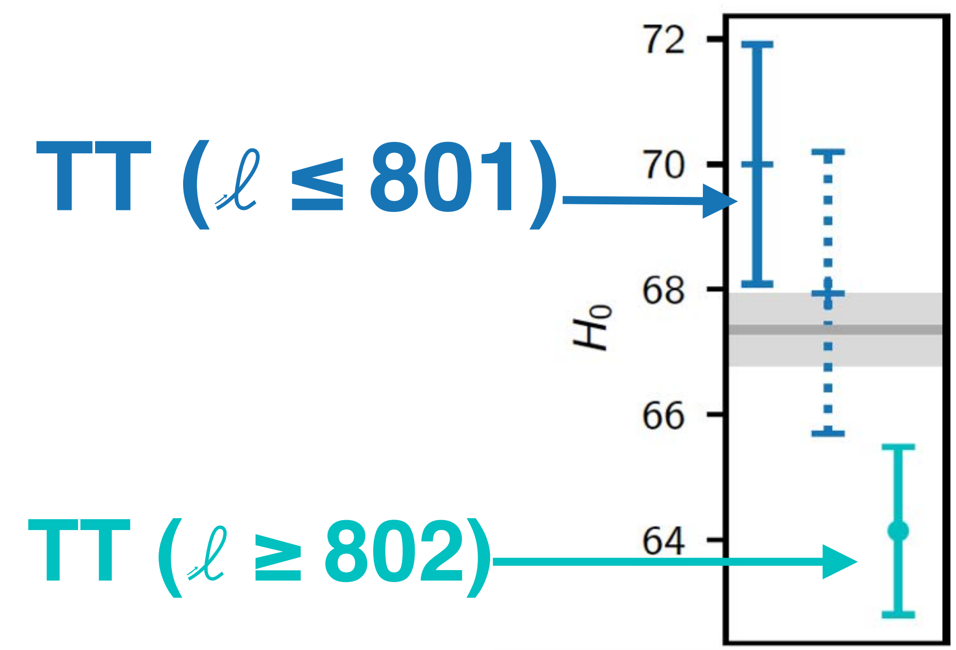
Planck TT spectra are smoother than expected by ~ 3σ

Planck TT + TE + EE + low E

$$A_L = 1.180 \pm 0.065$$

Planck Parameters 2018

Parameter scatter from large to small scales is a bit large compared to expectations (2 to 3σ)



Planck Parameters 2018

(also Addison et al. 2016, Planck LI 2017)

H_0 from CMB and local distance ladder in 3.6σ tension

$$H_0 = (67.27 \pm 0.60)\ \mathrm{km/s/Mpc}$$

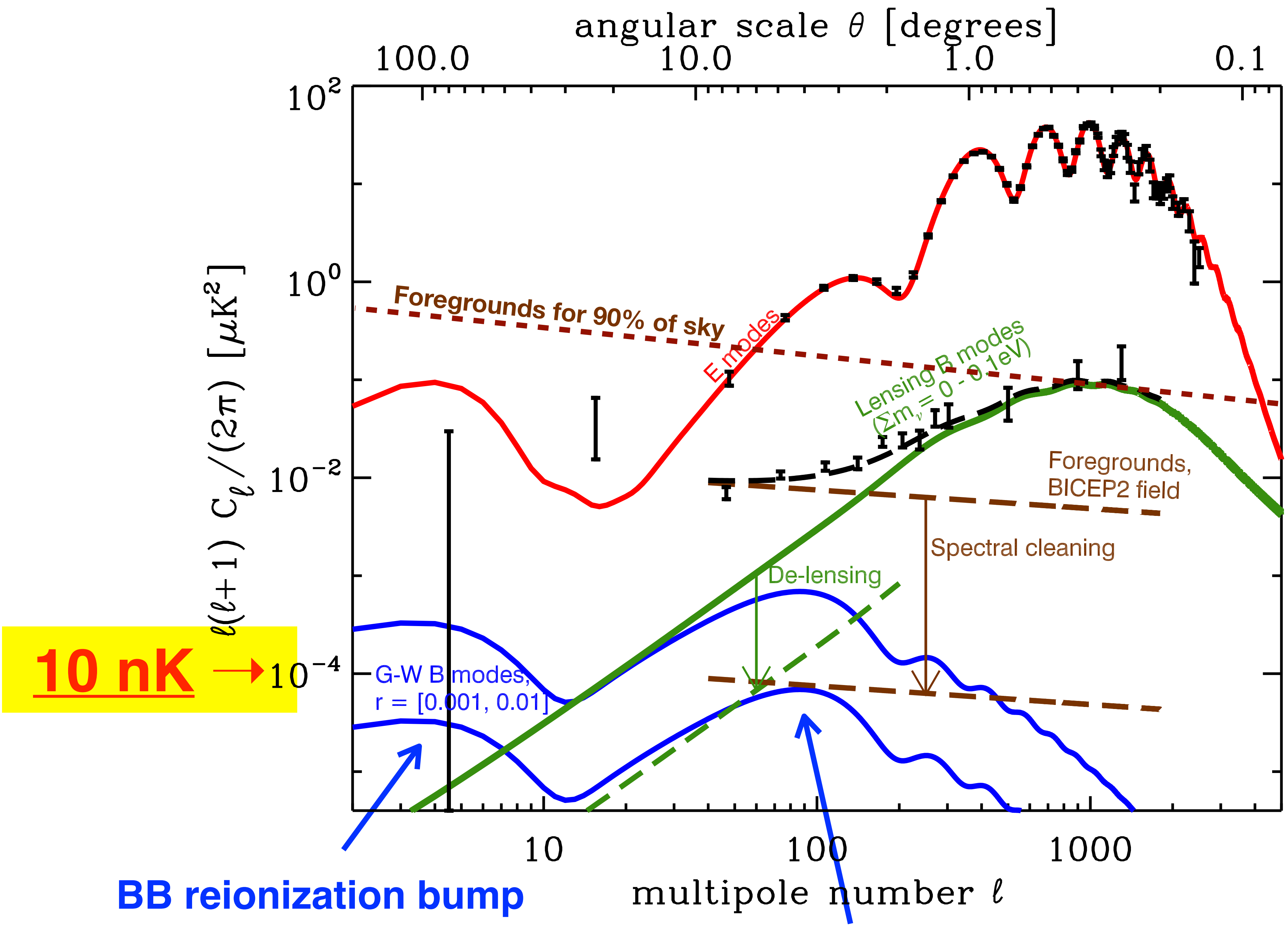
Planck 2018 TT+TE+EE

$$H_0 = (73.48 \pm 1.66)\ \mathrm{km/s/Mpc}$$

Cepheids + SNe, Riess et al. 2018

No sign of systematics, e.g., CMB data sets agree where they overlap → need more data!

The path forward is through extremely challenging multifrequency polarization measurements



E modes

lensing
B modes

inflationary
gravity wave
B modes

BB reionization bump
CLASS exploring
from the ground;
target of LiteBIRD

BB recombination bump
a key target of CMB-S4

CMB-S4
Next Generation CMB Experiment

CMB-S4 Concept
(from CDT report)

- **Three Science Priorities**
  - Inflation: $r < 0.001$ (95% conf.) or detection for $r > 0.003$
  - Light relics: constrain $\Delta N_{eff} < 0.06$ (95% conf.)
  - Legacy Cosmology and Astrophysics Survey

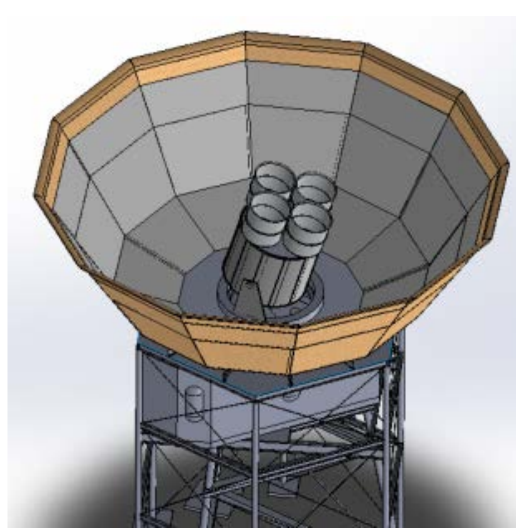
CMB-S4
Next Generation CMB Experiment

CMB-S4 Concept
(from CDT report)

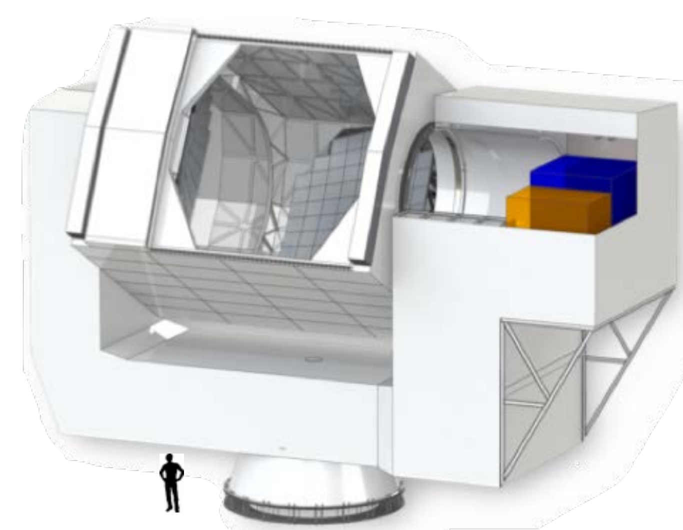
Science	Item	20	30	40	85	95	145	155	220	270	Total
		Frequency [GHz]									
"r" survey	**14 x 0.5-m cameras**										
f_{sky} ~3-8%	# detectors	...	260	470	17 k	21 k	18 k	21 k	34 k	54 k	168 k
	Angular resolution [FWHM]		77′	58′	27′	24′	16′	15′	11′	8.′5	
	1 x 6-m telescope										
	# detectors	130	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} & Legacy survey	**2 x 6-m telescopes**										
f_{sky} = 40%	# 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	

total detectors: 372,000

14x 0.5m small telescopes, e.g., like BICEP Array



3x 6m large telescopes, e.g., like Simons Obs.



CMB-S4

Next Generation CMB Experiment

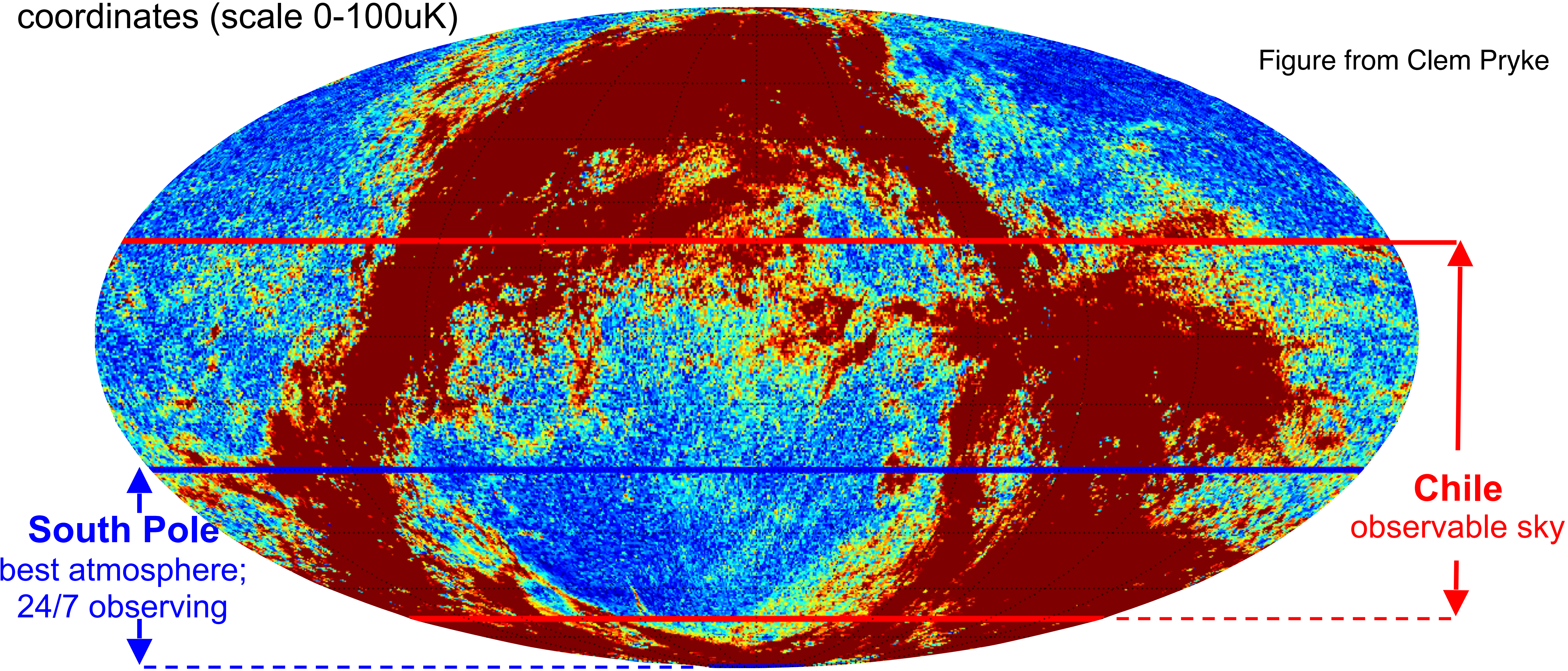
CMB-S4 Concept

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



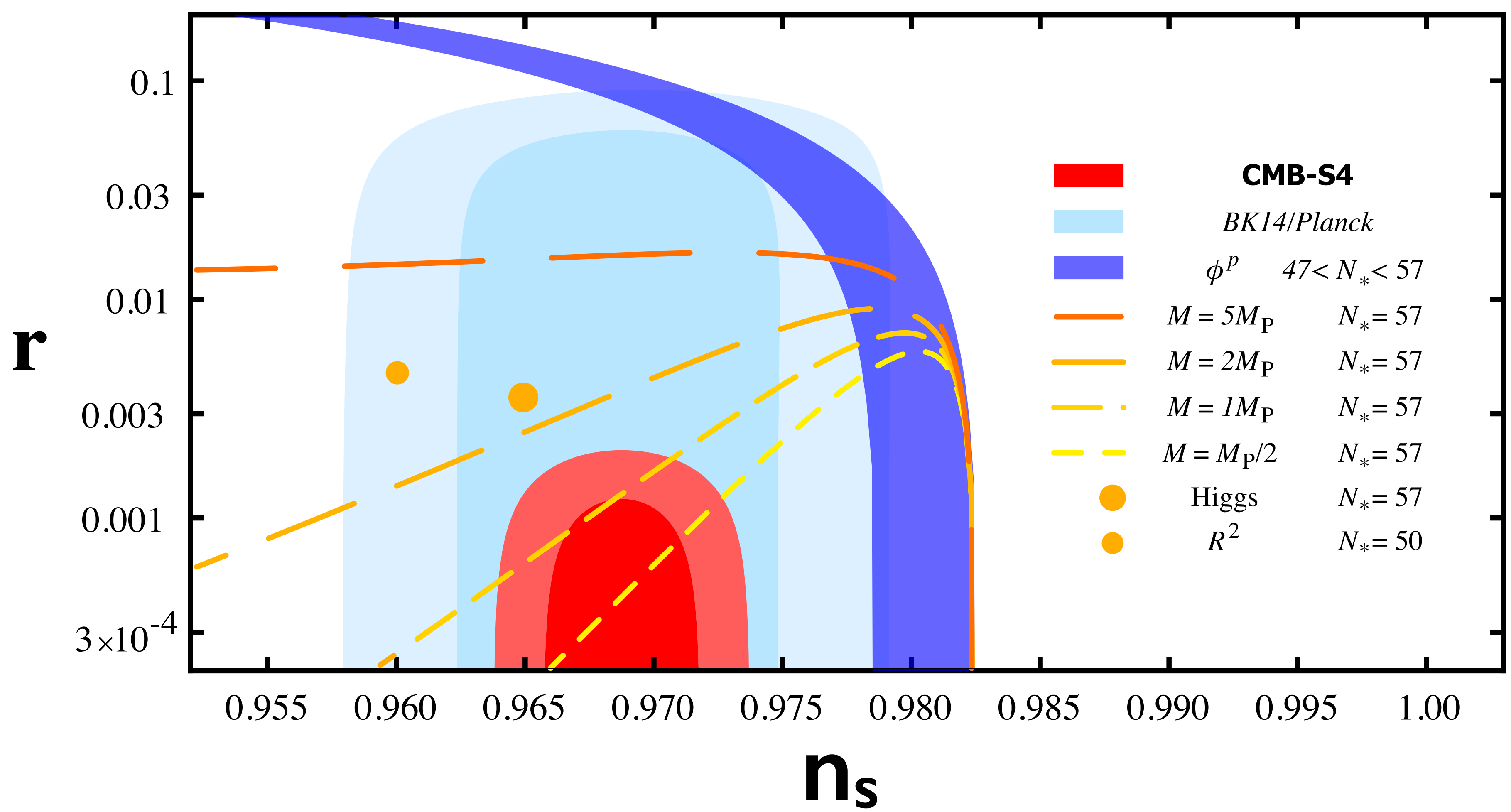
South Pole excellent for ultra deep fields

Chile excellent for wide sky coverage

(Nothern site would allow full sky coverage)

Inflation reach of CMB-S4

for nominal 3% f_{sky} and 10^6 realistic detector years, r = 0



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.

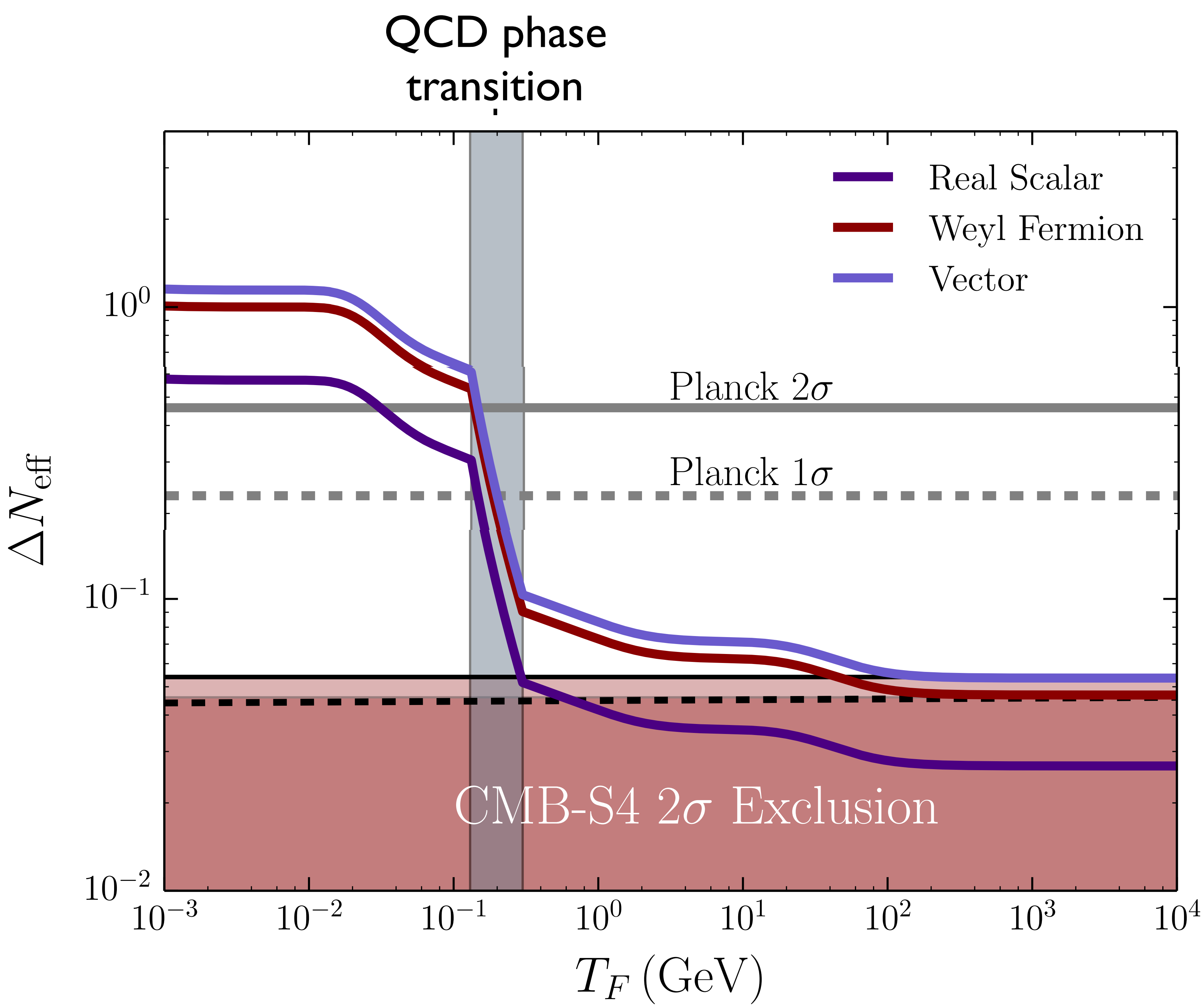
Conversely a non-detection of B modes with CMB-S4 will mean that a large field range is not required.

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,

CMB-S4
Next Generation CMB Experiment

N_{eff} - thermal relics



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

CMB-S4 Requirement:

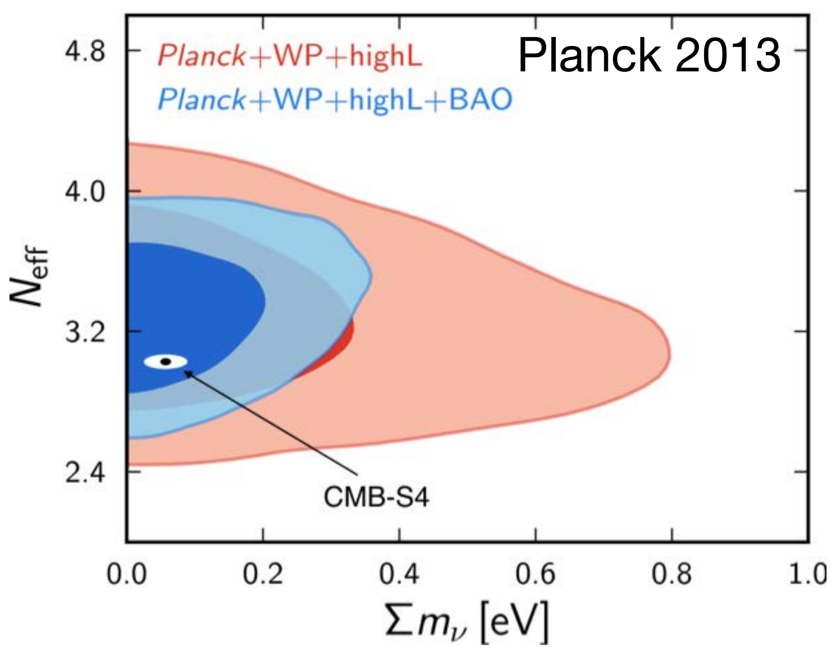
$\Delta N_{eff} < 0.06$
at 95% C.L.

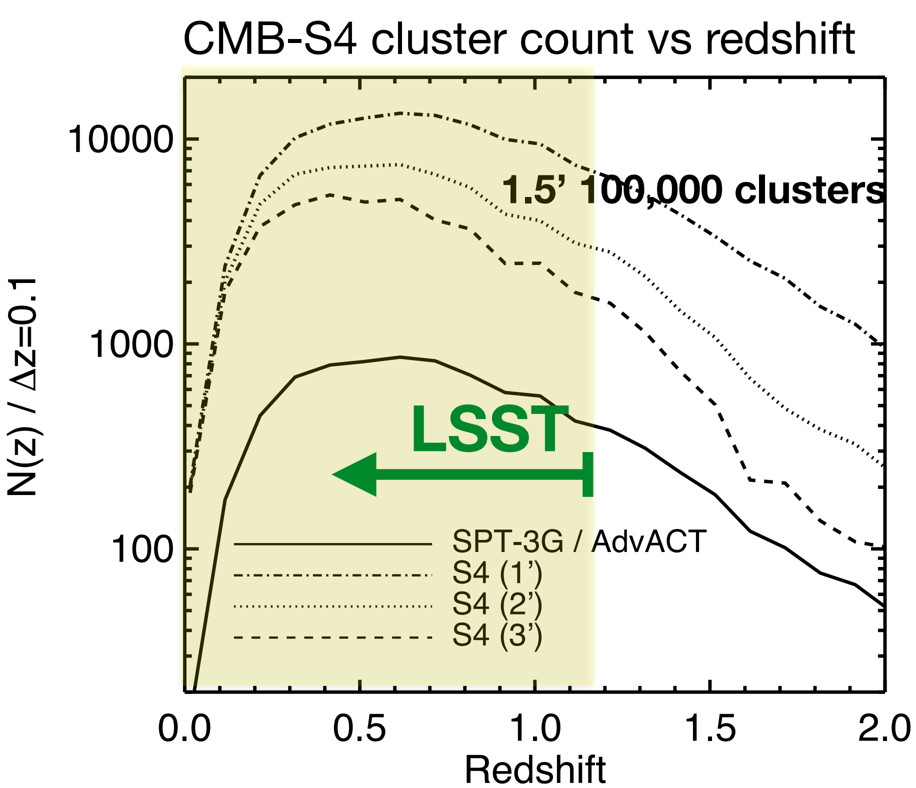
This drives the specifications for the CMB-S4 wide survey

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

CMB-S4
Next Generation CMB Experiment

Cosmology, Astrophysics and Large Scale Structure



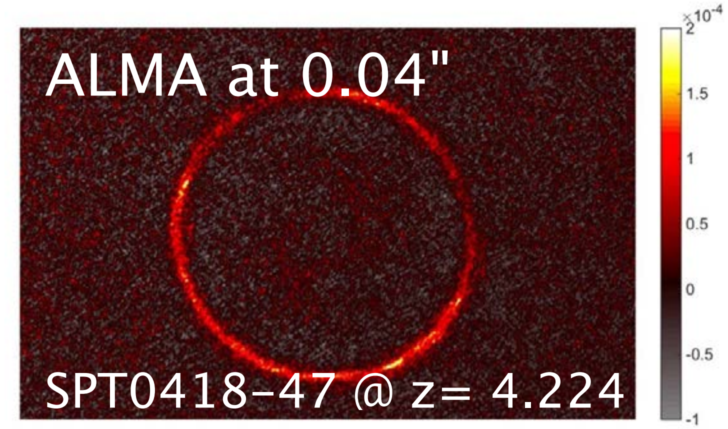


CMB-S4 will lead to transformative advances:

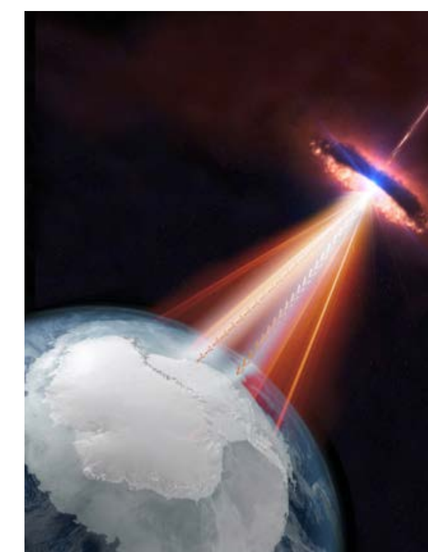
- **CMB-lensing to map the mass distribution of the universe** over a unique redshift range, exploit 3D tomography with optical shear and redshift surveys, and measure **neutrino mass sum**.
- SZ effects to trace all baryons and flows over a range of epochs and **constrain reionization**
- Provide **definitive survey of high-z galaxy clusters** with **"built in" CMB-lensing mass calibration**
- Provide mass profile and gas temperature and density profiles of galaxies as function of type and redshift to determine **role of baryon feedback in galaxy evolution**.
- Tremendous discovery potential and more…

CMB-S4
Next Generation CMB Experiment

A Millimeter Wave Synoptic Survey



- **~1M galaxies**
  - large sky area good for finding rare objects

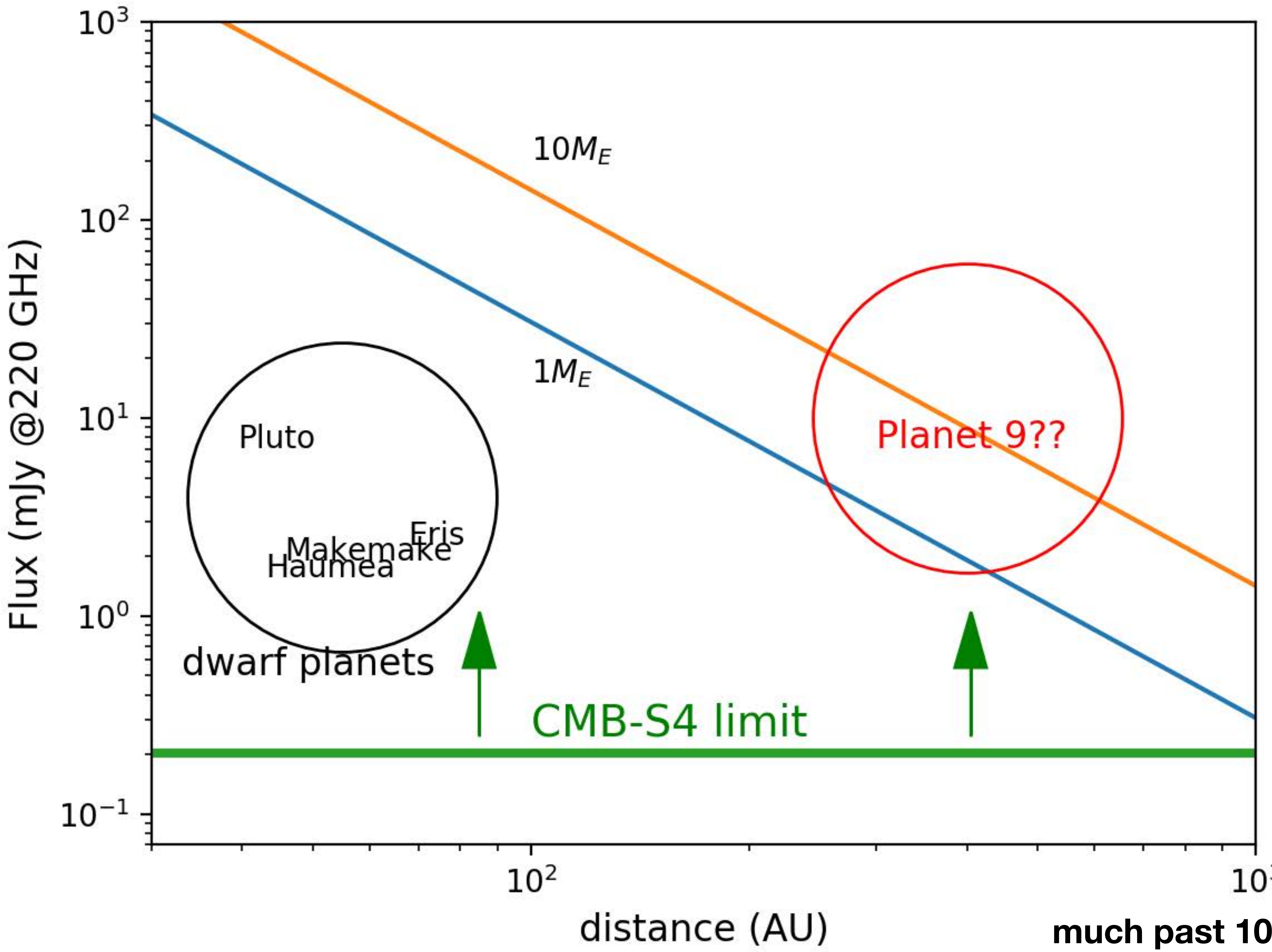

credit: IceCube/NASA

- **Long-term ~daily monitoring of 1000s of square degrees at multiple wavelengths, polarization**
  - always on, can check for GW, neutrino sources
  - ~mJy sensitivity per day for either variation or new transients

- **Thermal detection of Solar System objects**
  - new view / search for outer solar system objects

A Solar System Census

thermal flux from dwarf planets to ~100 AU,
Earth mass planets to ~1000 AU



much past 1000 AU:
parallax & proper motion
become too small to detect

from Gil Holder

CMB-S4
Next Generation CMB Experiment

CDT: Timeline & Cost

Seven year construction project:

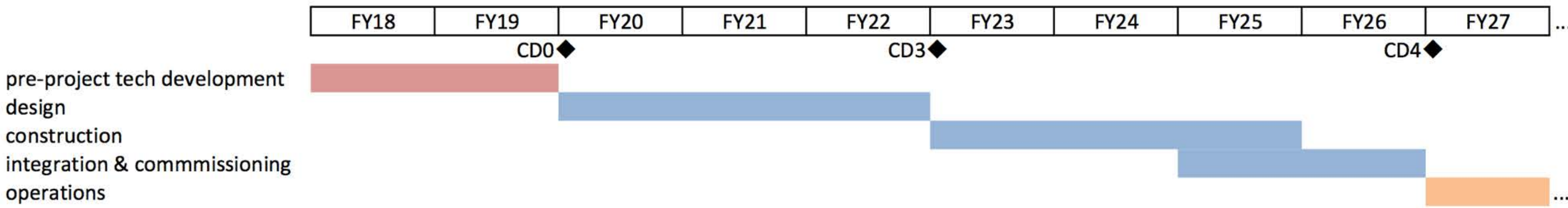


Figure 13: CMB-S4 strawperson schedule.

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

Operations expected to last seven years (FY27-33)

CMB-S4

Next Generation CMB Experiment

Summary

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

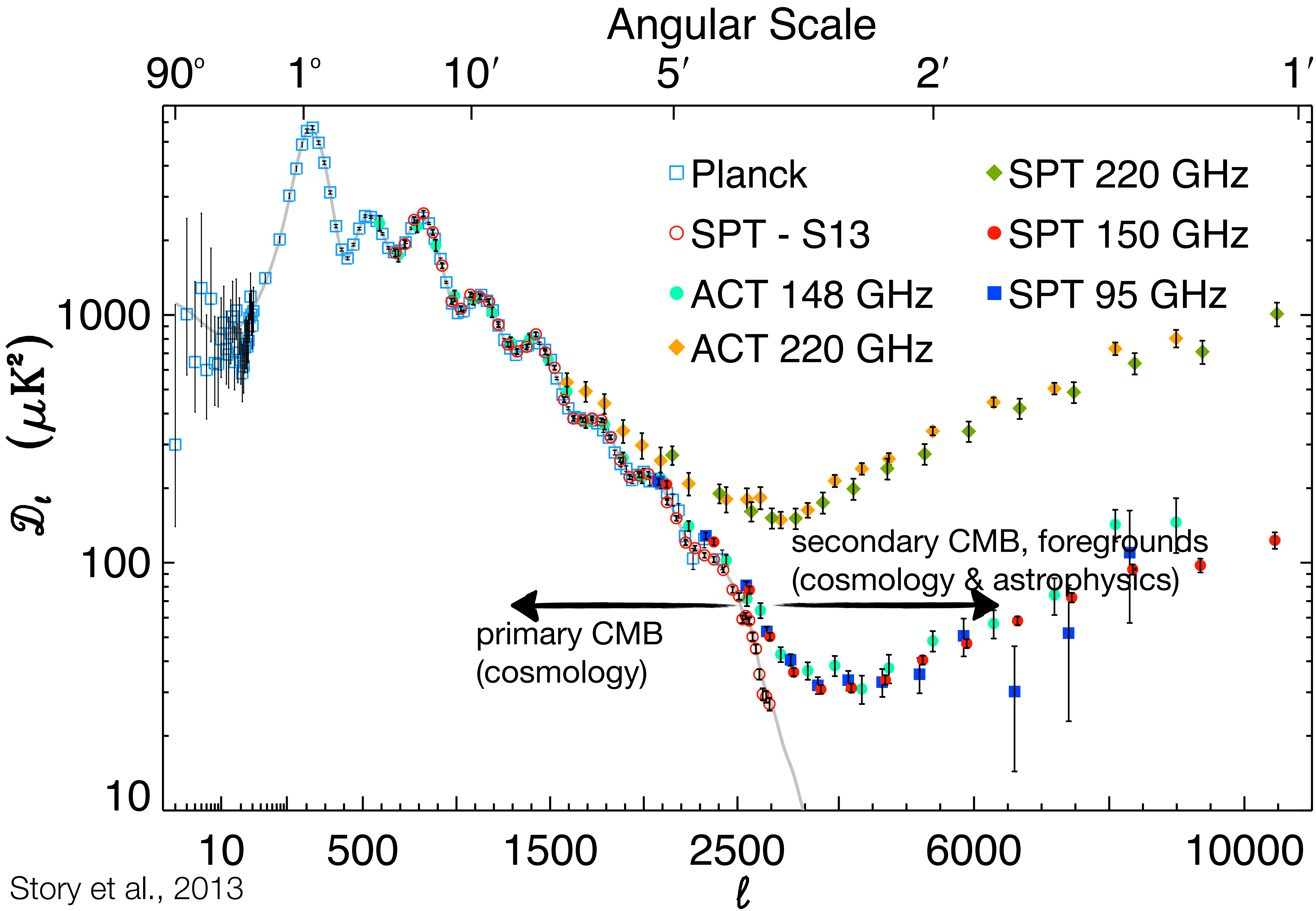
The science is spectacular. We will be searching for primordial gravitational waves and testing single field slow roll inflation, searching for new relics, determining the neutrino masses, mapping the universe in momentum, investigating dark energy, testing general relativity on large scales, measuring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

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

Backup Slides

Science Book Figure 3

		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015–2016	Stage 2 1000 detectors	$\gtrsim 10^{-5}$	0.035	0.14	0.15eV (Boss BAO prior)	~180 (DES+BOSS / SPT clusters)
2017–2020	Stage 3 10,000 detectors	10^{-6}	0.006	0.06	0.06eV (Boss BAO prior)	~300-600 (DES + DESI / SZ Clusters)
Target	Stage 4 CMB-S4 ~400,000 detectors	10^{-8}	**0.0005**	**0.027**	**0.015eV** (DESI BAO +τ_e prior)	**1250** (DESI +LSST / S4 Clusters)



Story et al., 2013
George et al., 2014
Das et al., 2014

CMB-S4
Next Generation CMB Experiment

CMB-S4 power spectra projections