CMB-S4

Next Generation CMB Experiment

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CMB-S4
Next Generation CMB Experiment

Stage 4 CMB experiment: CMB-S4

- A next generation ground-based program to pursue inflation, neutrino properties, dark radiation, dark energy and new discoveries.
- Greater than tenfold increase in sensitivity of the combined Stage 3 experiments (>100x current Stage 2 experiments) to cross critical science thresholds.
- O(500,000) detectors spanning 30 - 300 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), National Labs and the High Energy Physics community.
- International partnerships expected and desired.

Recommended by P5

Moore's Law of CMB sensitivity

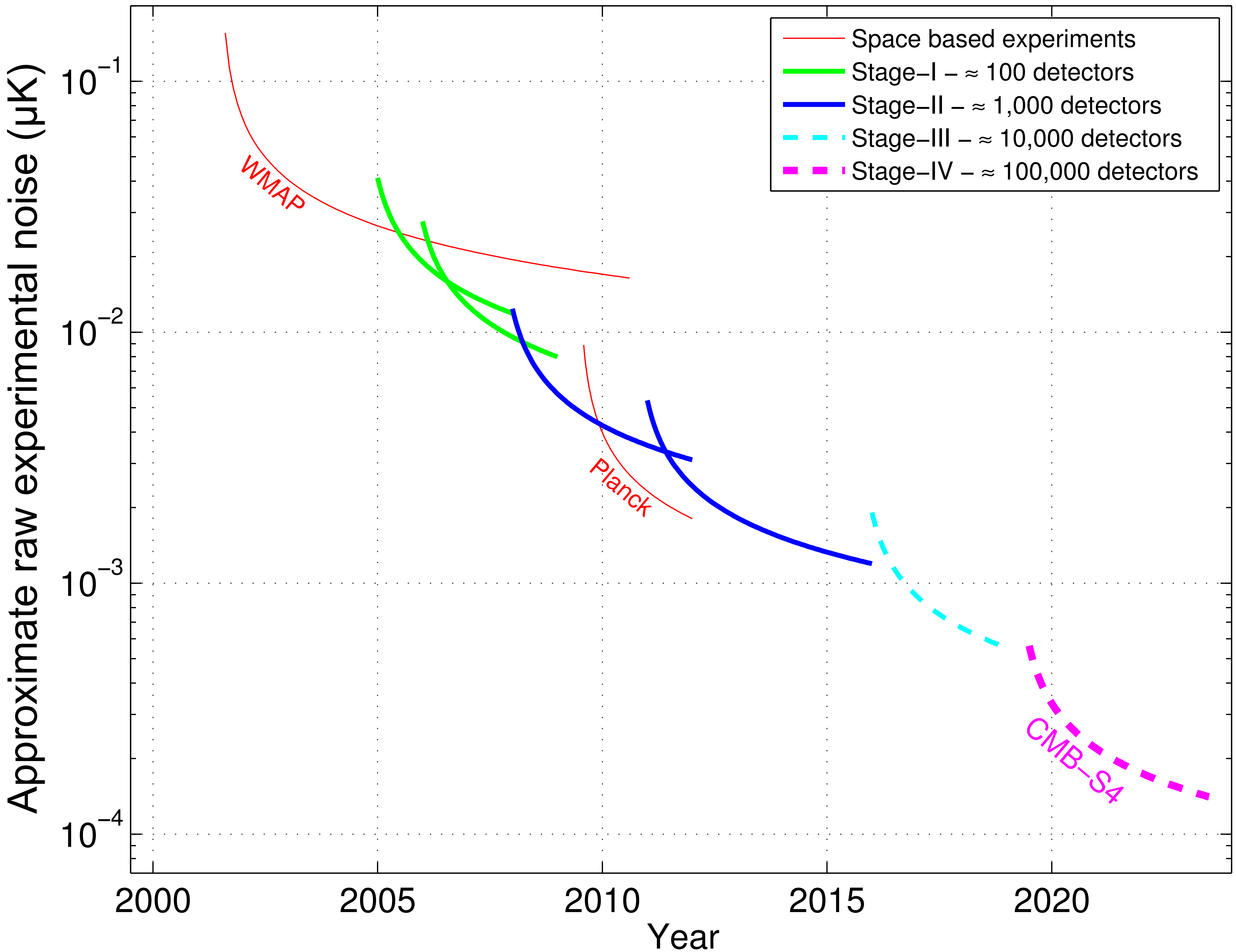

Figure by Clem Pryke for 2013 Snowmass documents

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Next Generation CMB Experiment

"Critical Science Thresholds"

	Stage 2	Stage 3	Stage 4	Top level goal for S4
Inflation: σ_r	≤ 0.1	≤ 0.01	≤ 0.001	Detect or rule out the most natural class of inflationary models.
	single field slow roll			
Light Relativistic Species: σ_{Neff}	0.14	0.06	0.027	Detect or rule out all light relativistic speicies with spin.
	Minimum ΔN_{eff}			
Neutrino Masses: $\sigma_{\Sigma M\nu}$	0.15eV	0.06eV	0.015eV	$>3\sigma$ detection of neutirno mass, potential to determine the neutrino mass hierarchy.
	lower limit Σm_ν			

Part of figure by Jeff McMahon for CMB-S4

CMB-S4
Next Generation CMB Experiment

What about CMB-S4 high-ℓ science?

Is it "for free" or driving the experiment design?

1. **Dark Energy / Modified Gravity / Neutrino masses**
   - SZ galaxy cluster counts (dN/dz) to z~3
   - mass calibration with CMB-lensing at % level
   - evolution of amplitude $\sigma_8(z)$ at % level
2. **The evolution of massive clusters, cluster astrophysics**
   - Unique SZ catalog of clusters at $z > 1.5$
3. **Tracing baryons with kSZ and tSZ**
   - Thermodynamics of the circumgalactic medium out to the peak of cosmic star formation
   - Impact of feedback on the matter power spectrum, P(k)
4. **Patchy Reionization with kSZ**

Continuing series of community 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

Next:
August 24-25 at Harvard

CMB-S4

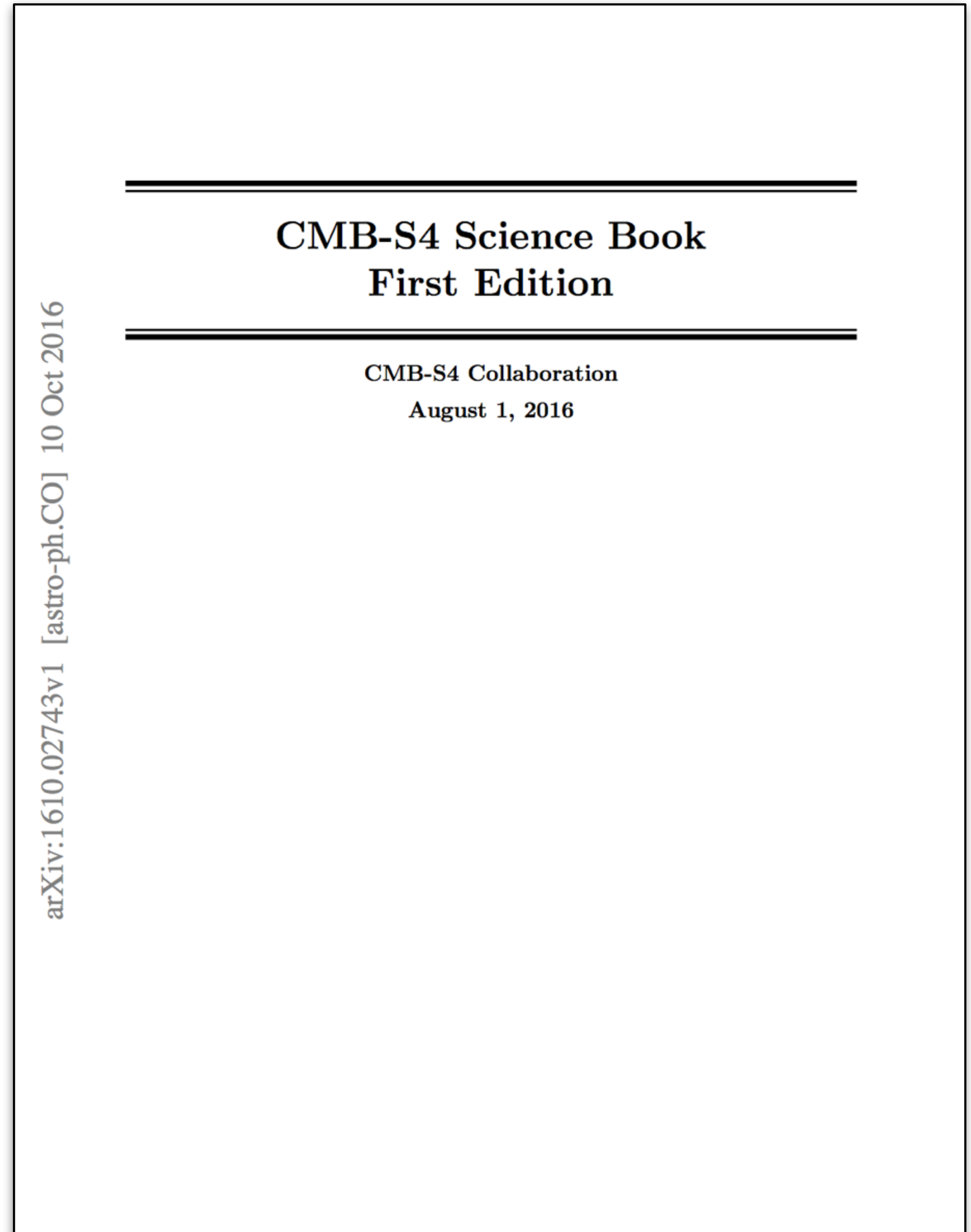
Next Generation CMB Experiment

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):

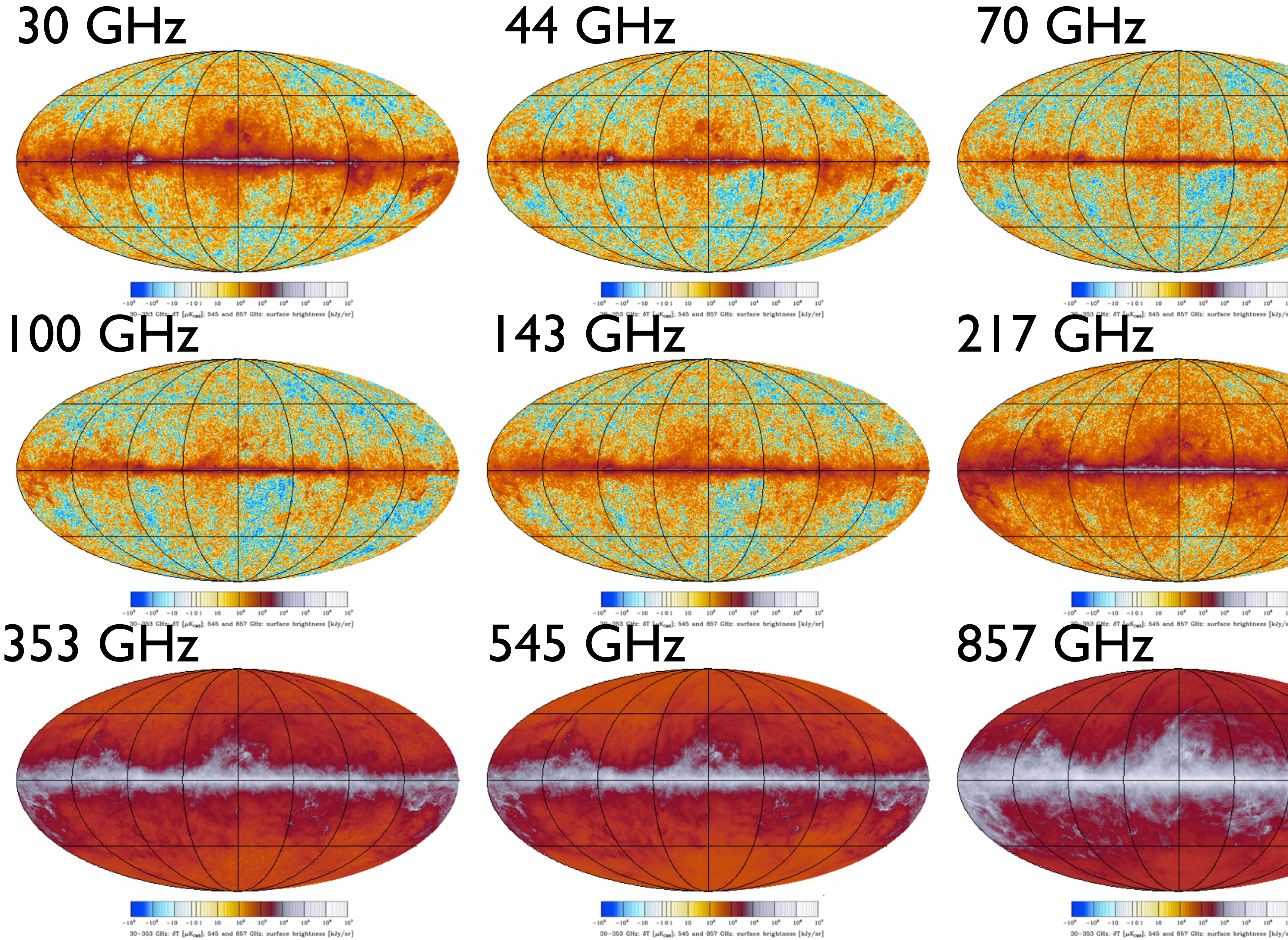
1) Exhortations
2) Inflation
3) Neutrinos
4) Light Relics
5) Dark Matter
6) Dark Energy
7) CMB lensing
8) Data Analysis, Simulations & Forecasting


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

CMB-S4 Science Book
First Edition

CMB-S4 Collaboration
August 1, 2016

Planck Intensity (CMB and foregrounds)

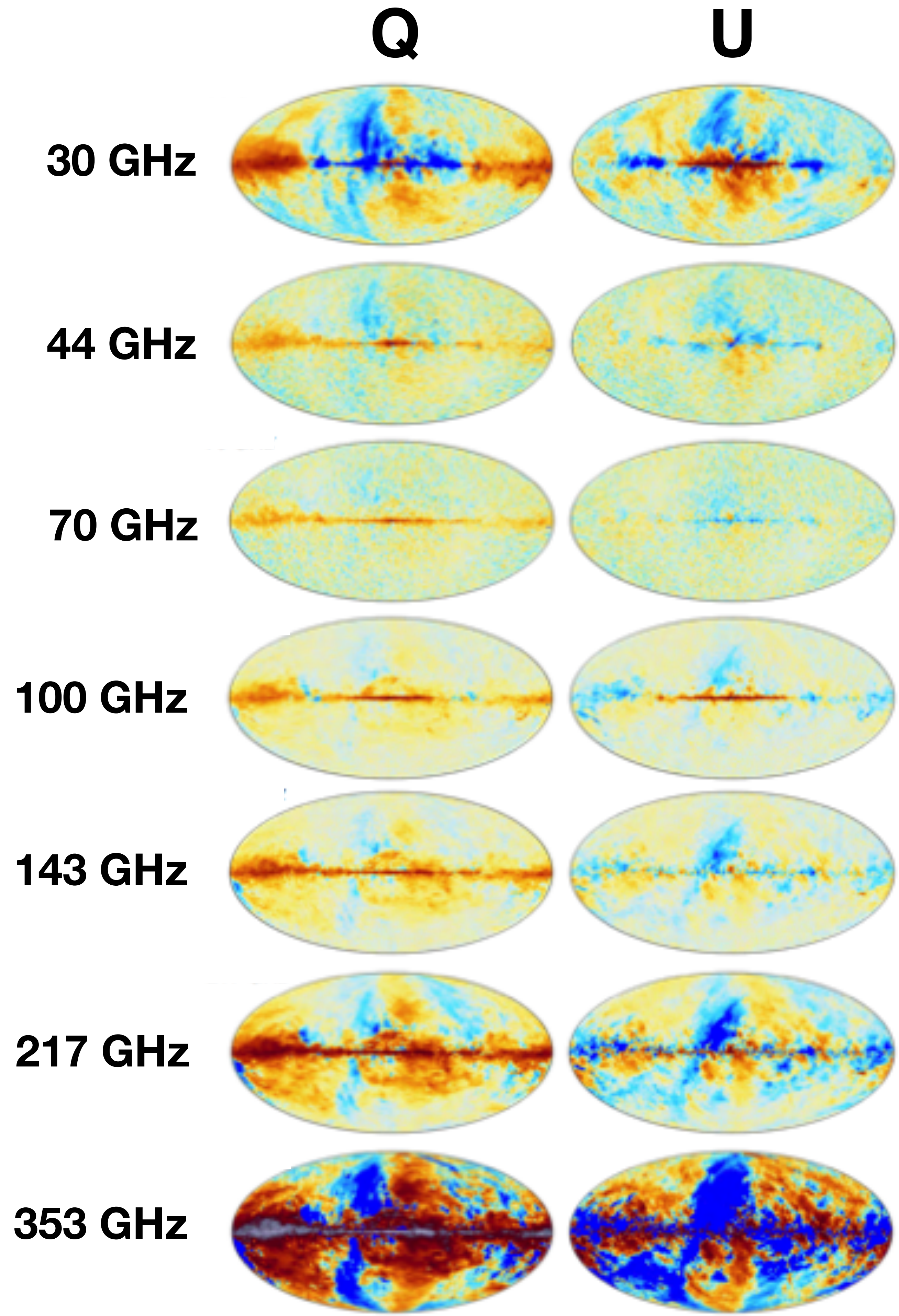


ESA/Planck

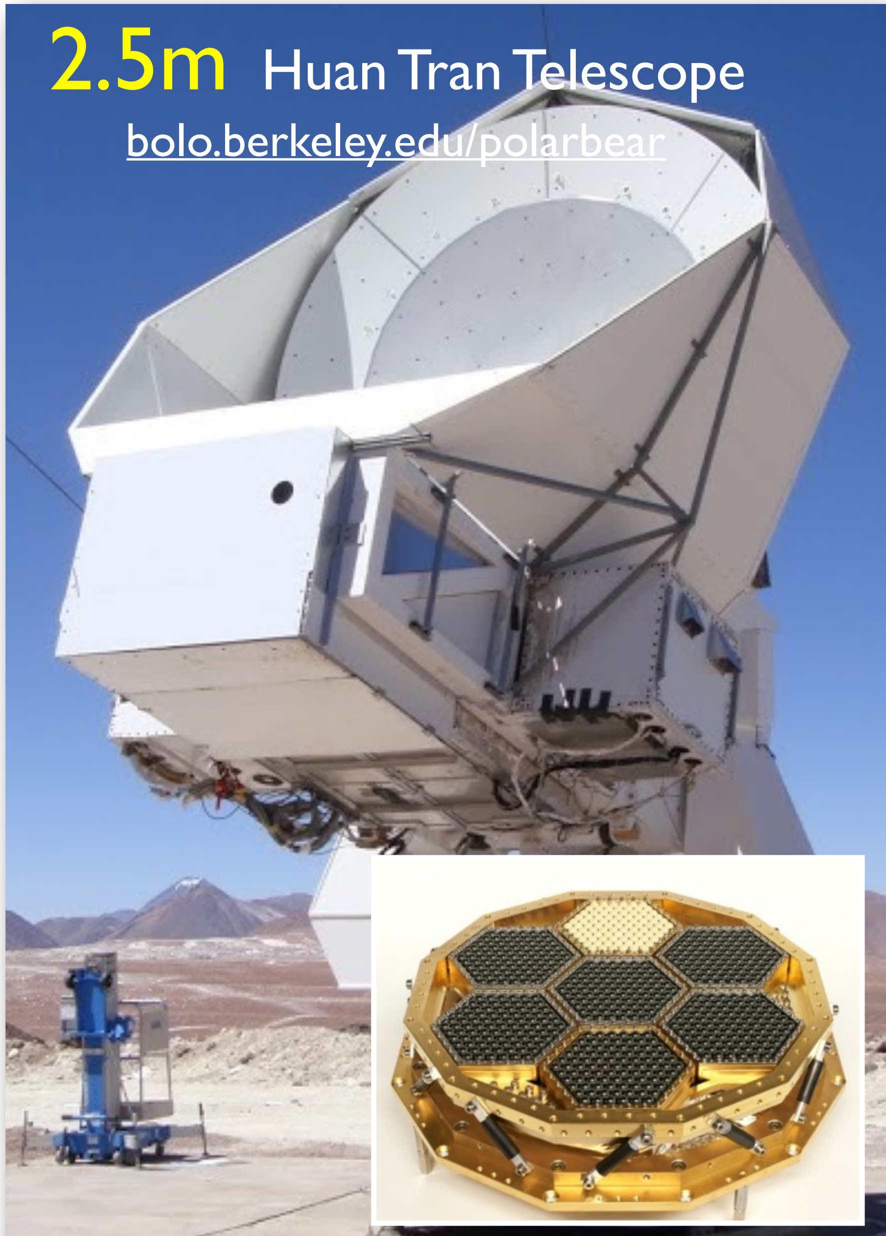
Polarized galactic **synchrotron** dominates at low frequencies

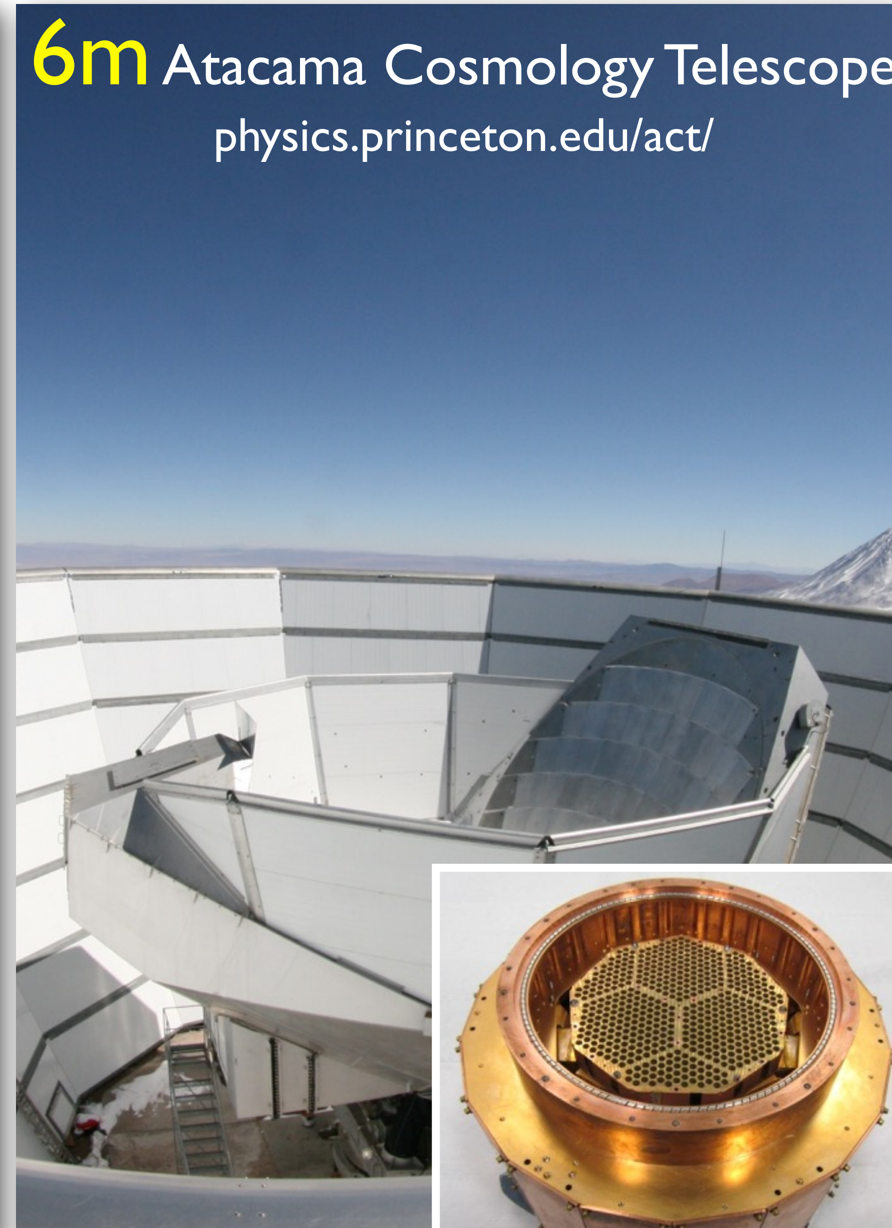
Planck provides <u>polarized</u> maps at 7 frequencies

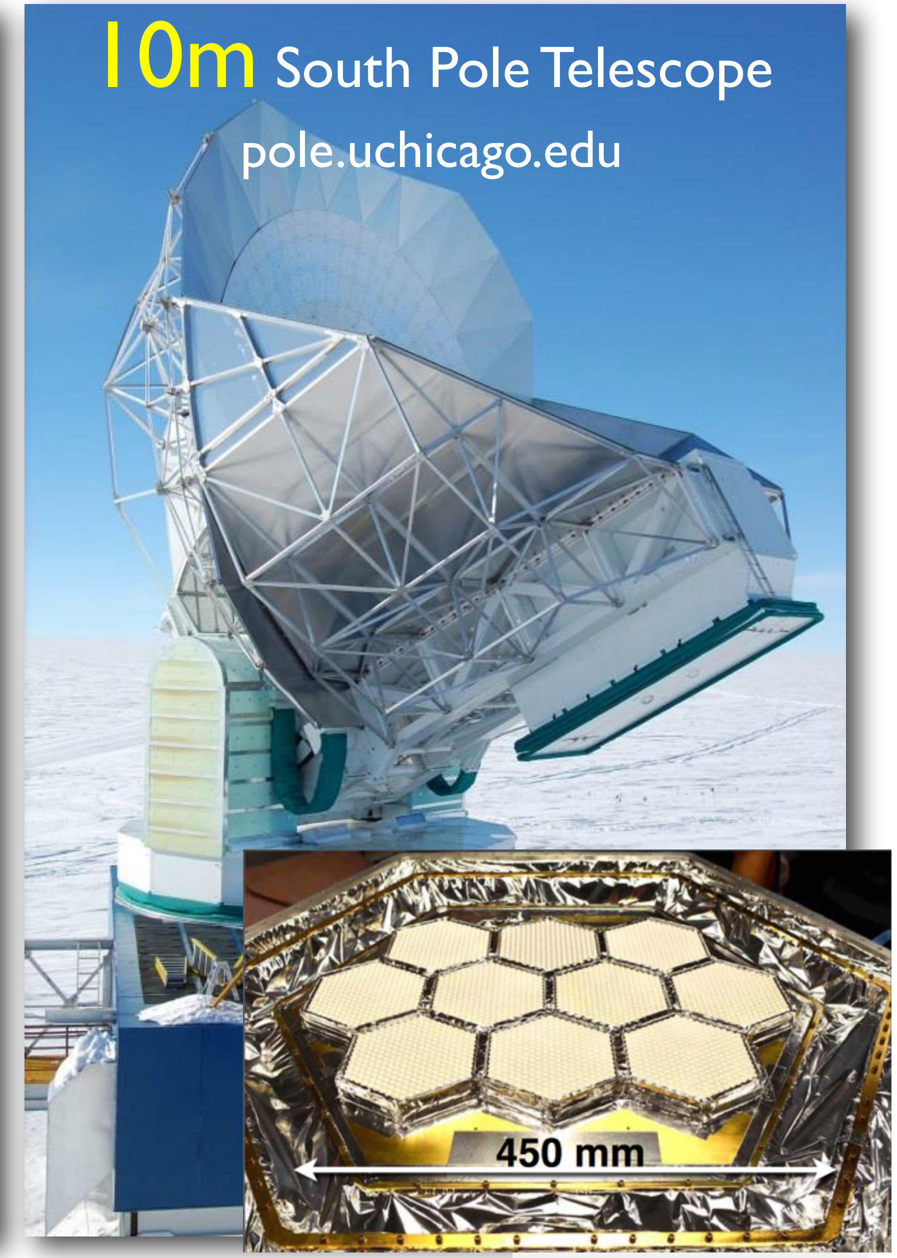
Polarized thermal emission (~20K) from galactic **dust** aligned in magnetic fields dominates at high frequencies



High resolution CMB experiments

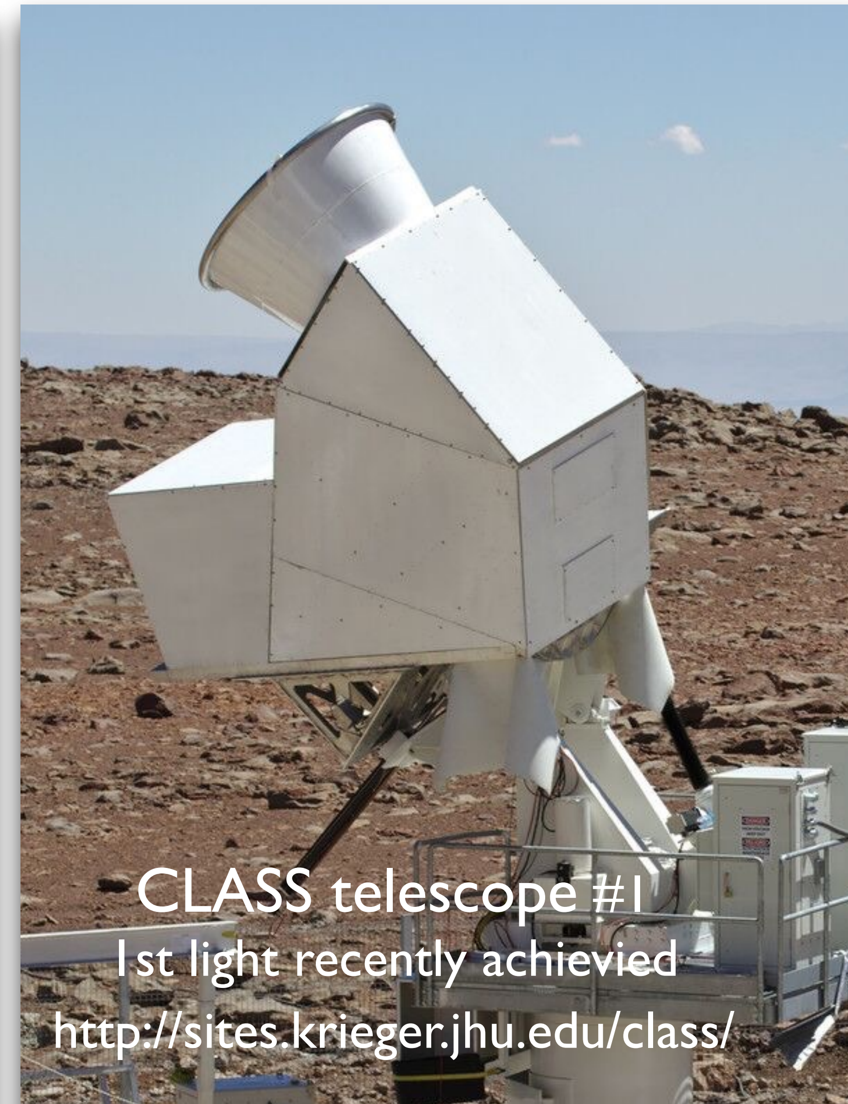


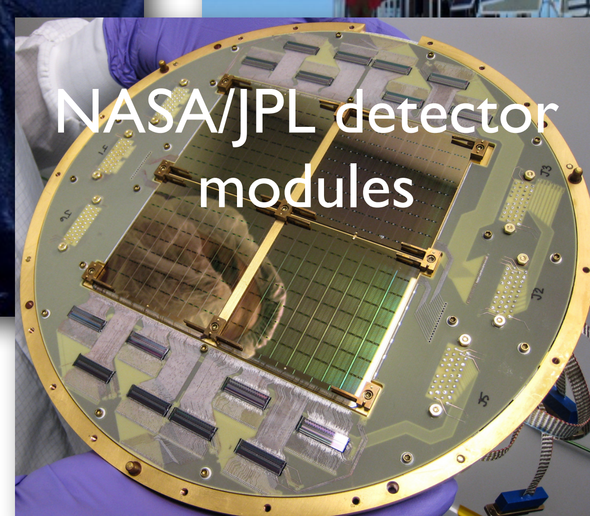




Exceptional high and dry sites for dedicated CMB observations.
Exploiting and driving ongoing revolution in low-noise bolometer cameras

Small aperture (big beam) CMB telescopes



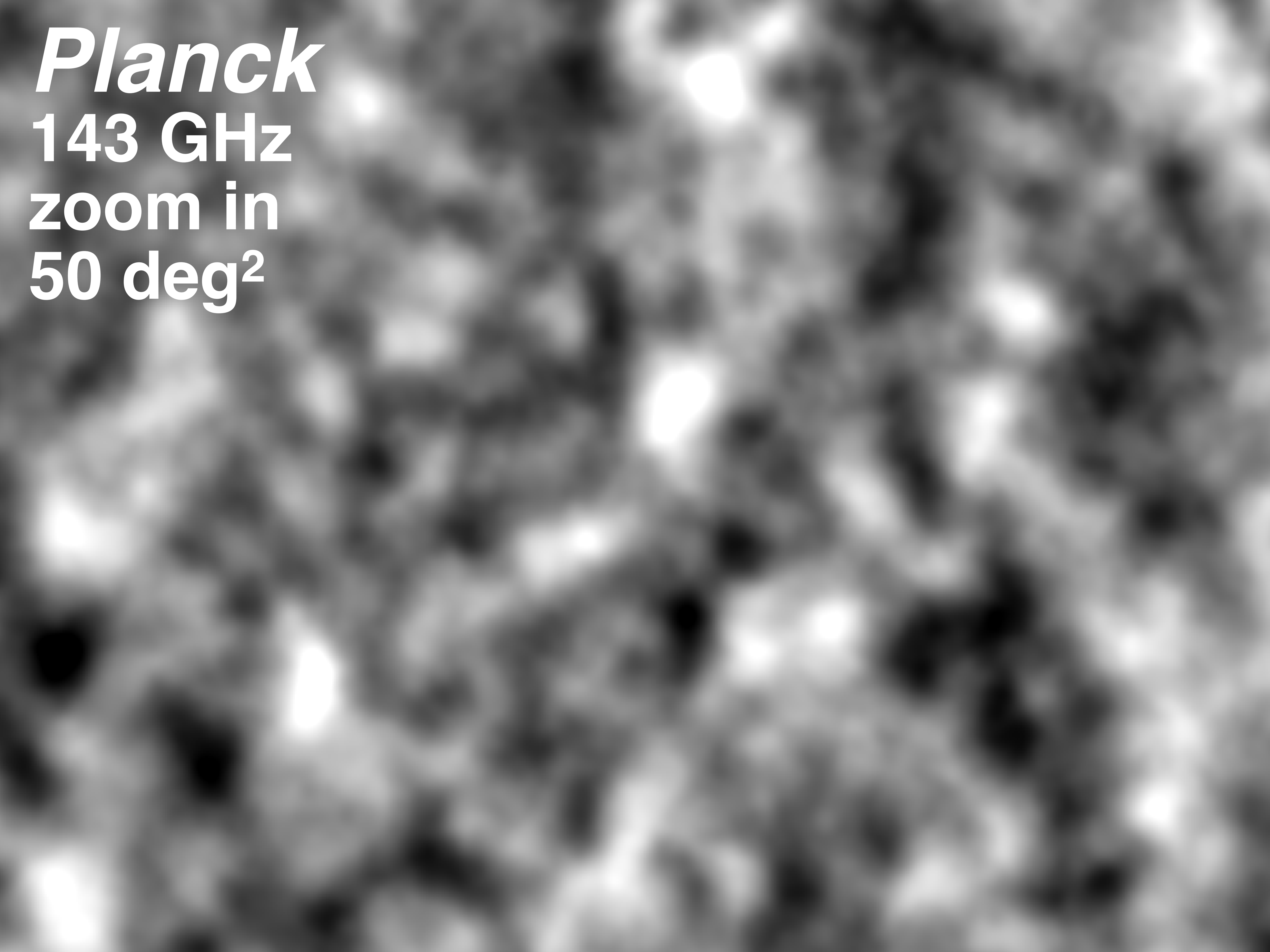


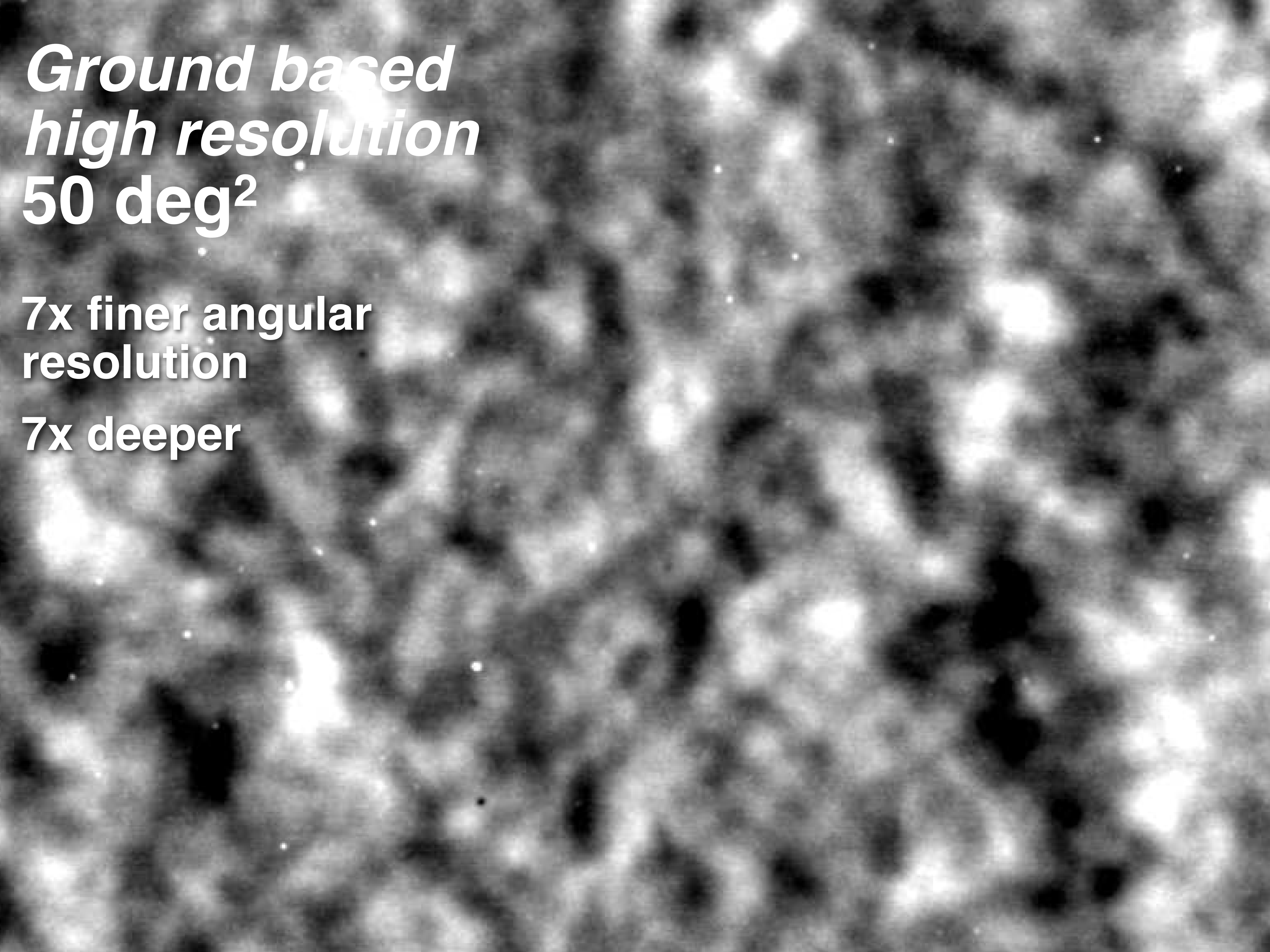
Also

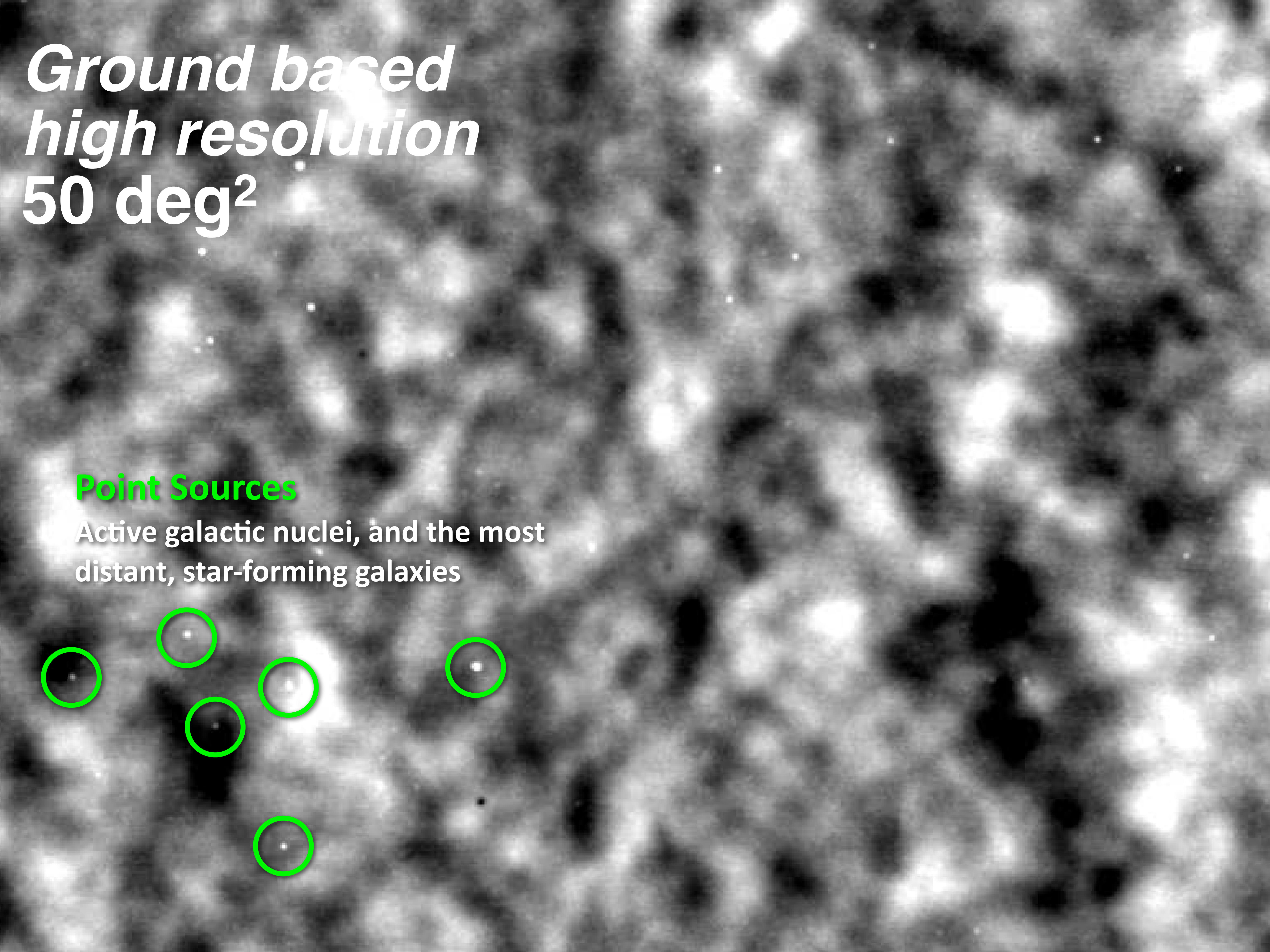
Ground: QUBIC, CBASS, QUIJOTE, GroundBird

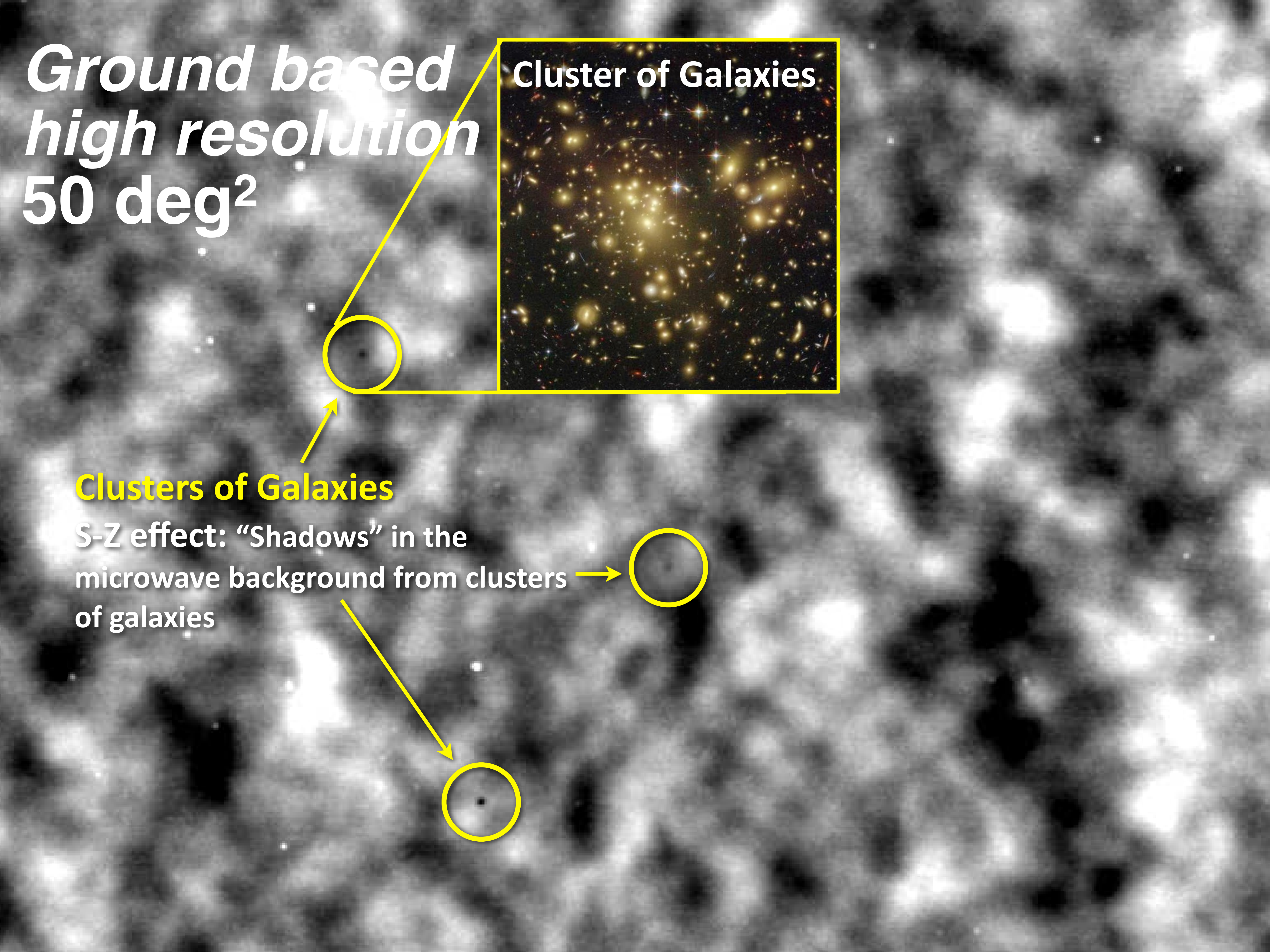
Balloon: PIPER, LSPE, (EBEX, BFORE pending)

Satellite proposals: LiteBIRD, PIXIE (CORE+)

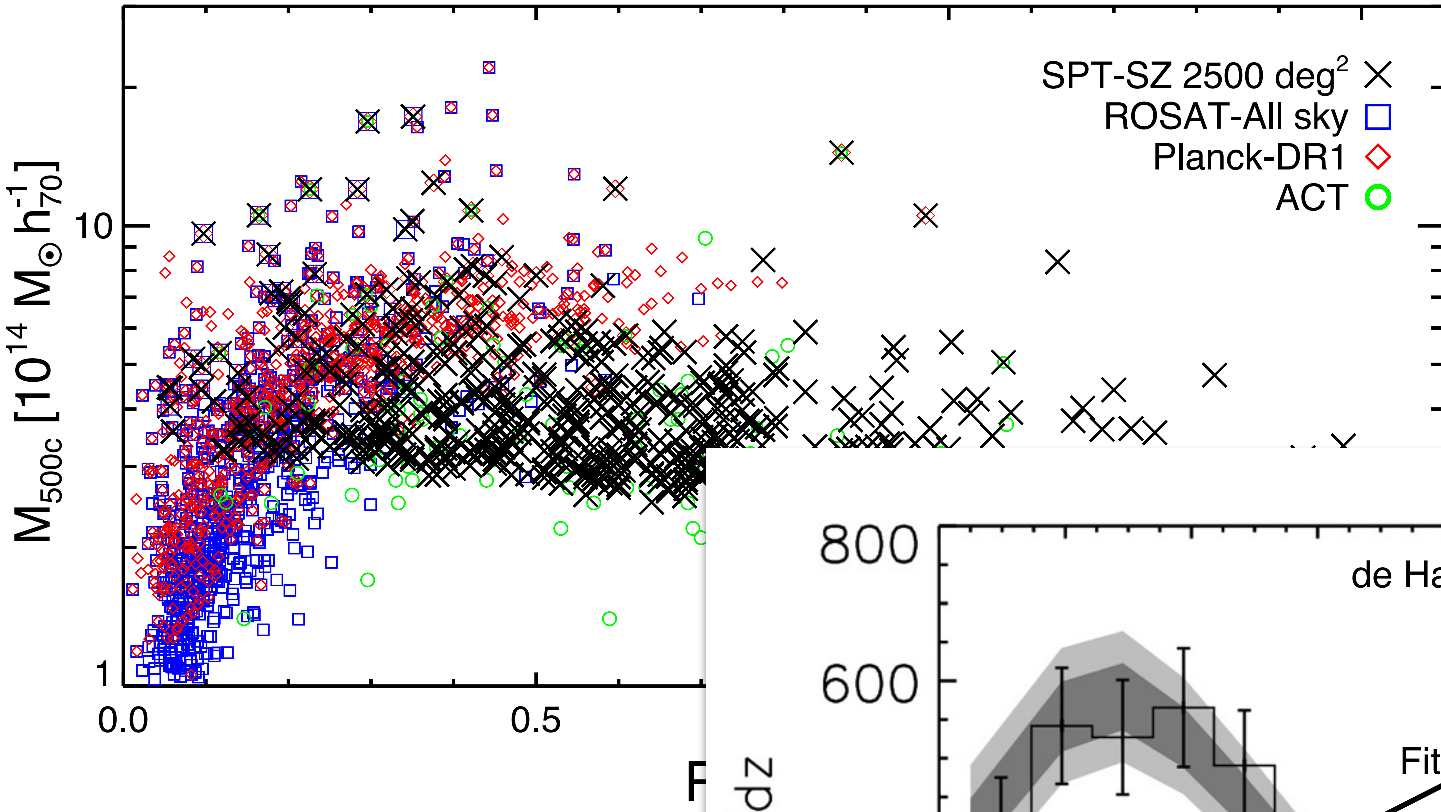

Planck
143 GHz
zoom in
50 deg²

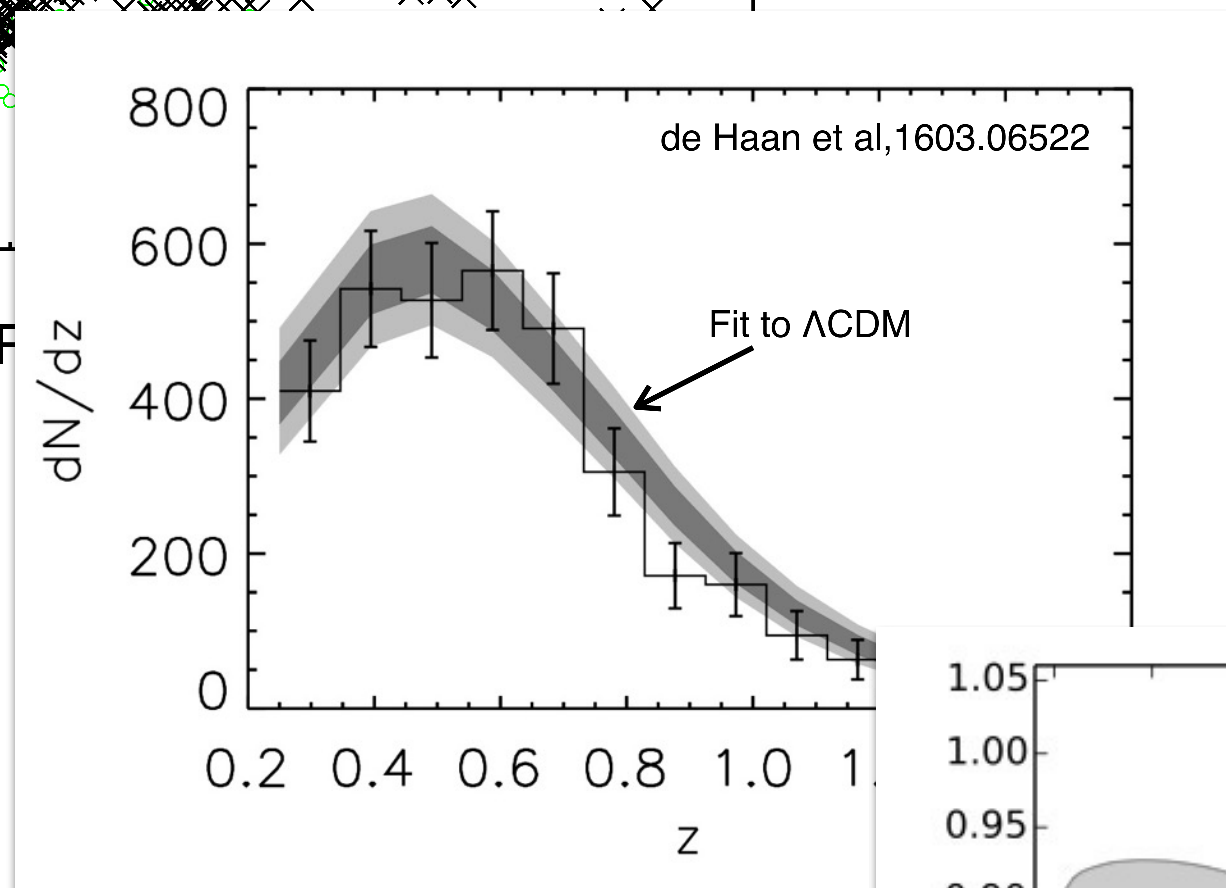

Ground based
high resolution
50 deg²
7x finer angular resolution
7x deeper

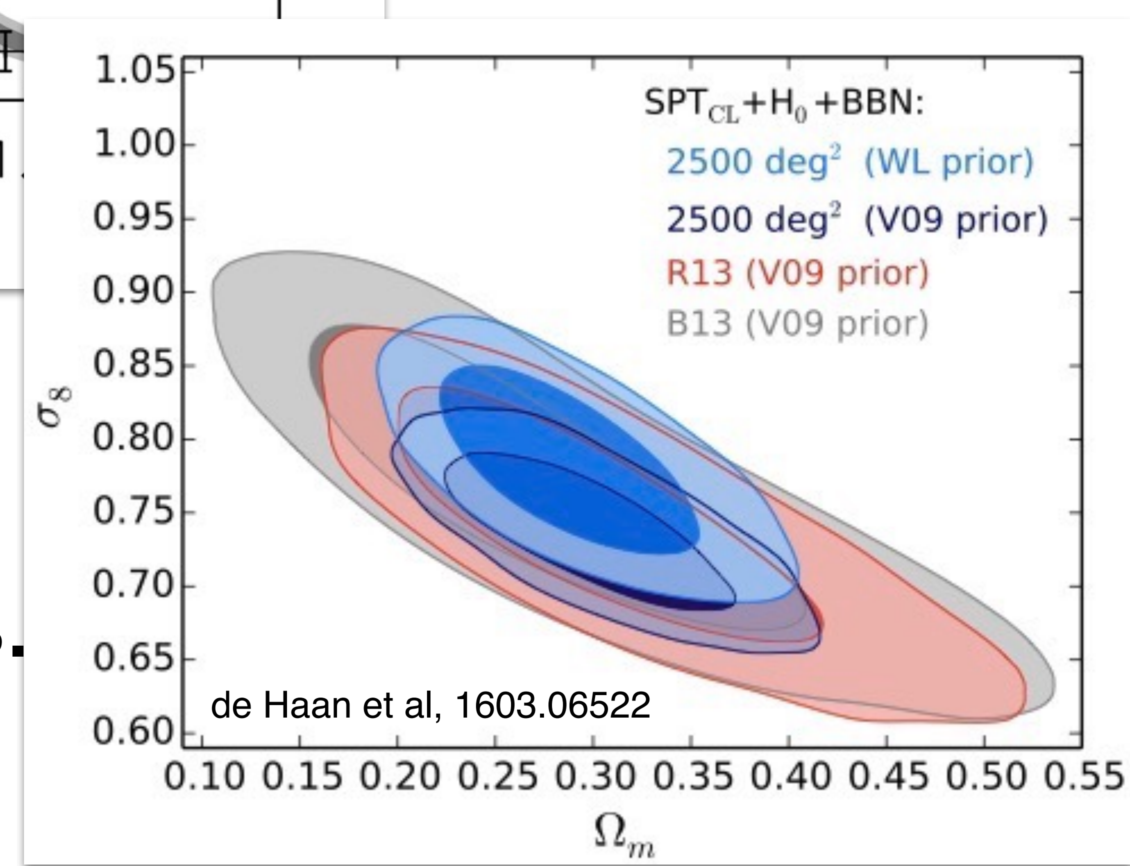

Ground based
high resolution
50 deg²
Point Sources
Active galactic nuclei, and the most distant, star-forming galaxies


Ground based
high resolution
50 deg²
Cluster of Galaxies
Clusters of Galaxies
S-Z effect: "Shadows" in the
microwave background from clusters
of galaxies

Cosmology with SZ clusters

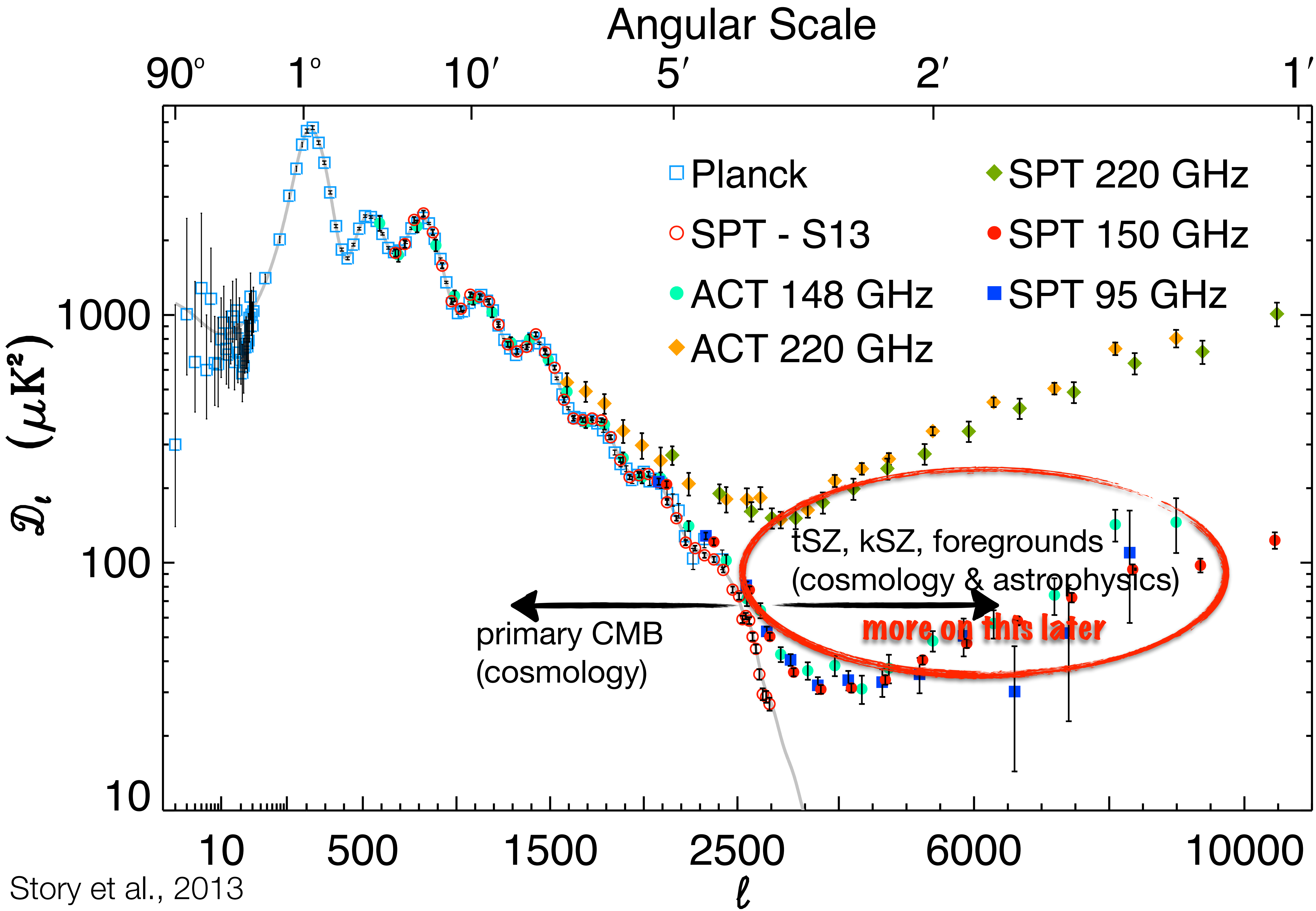






Tracing the growth of structure with evolution of massive galaxy clusters.

<u>Results limited by mass calibration.</u>



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

Status of primary CMB TT measurements

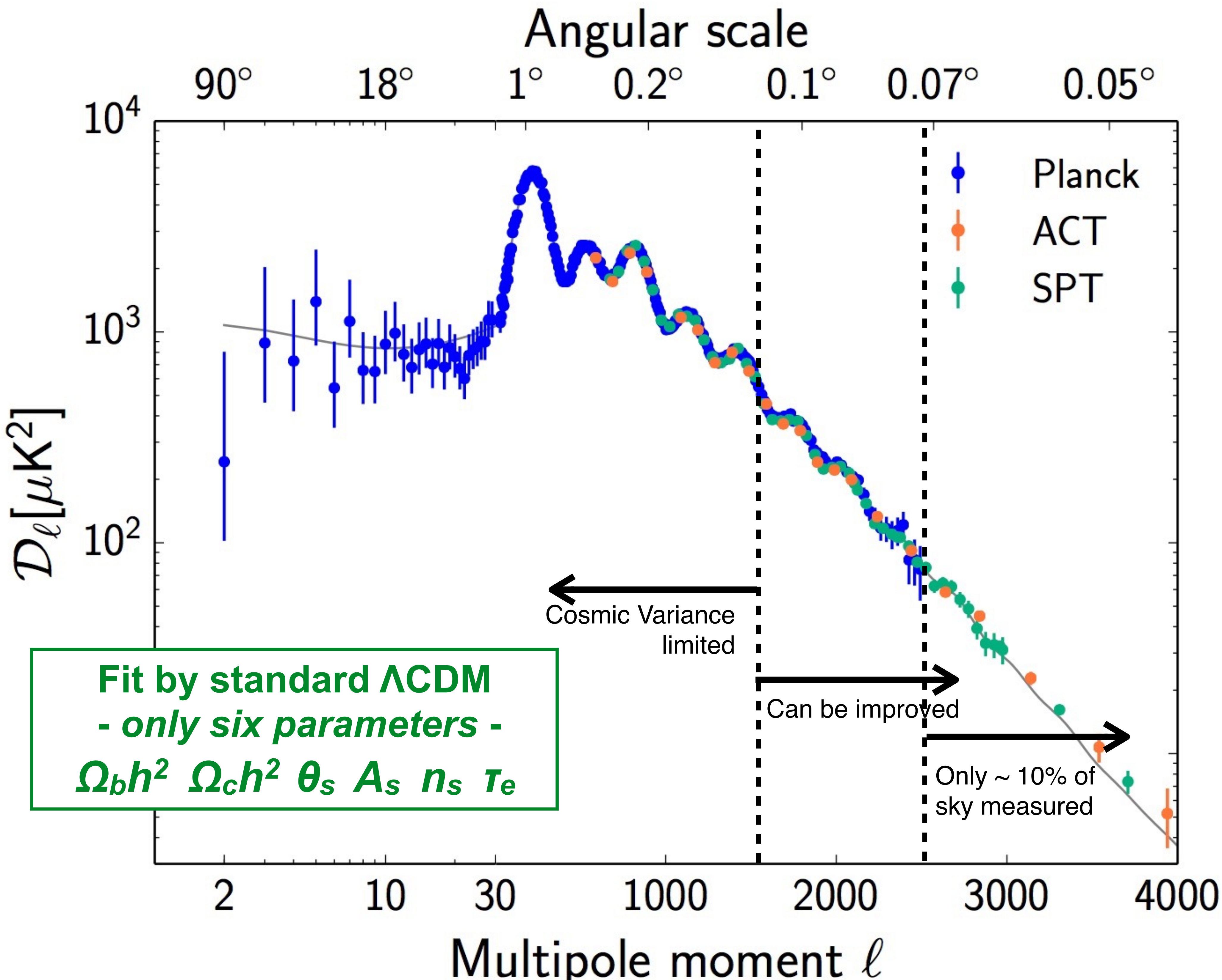
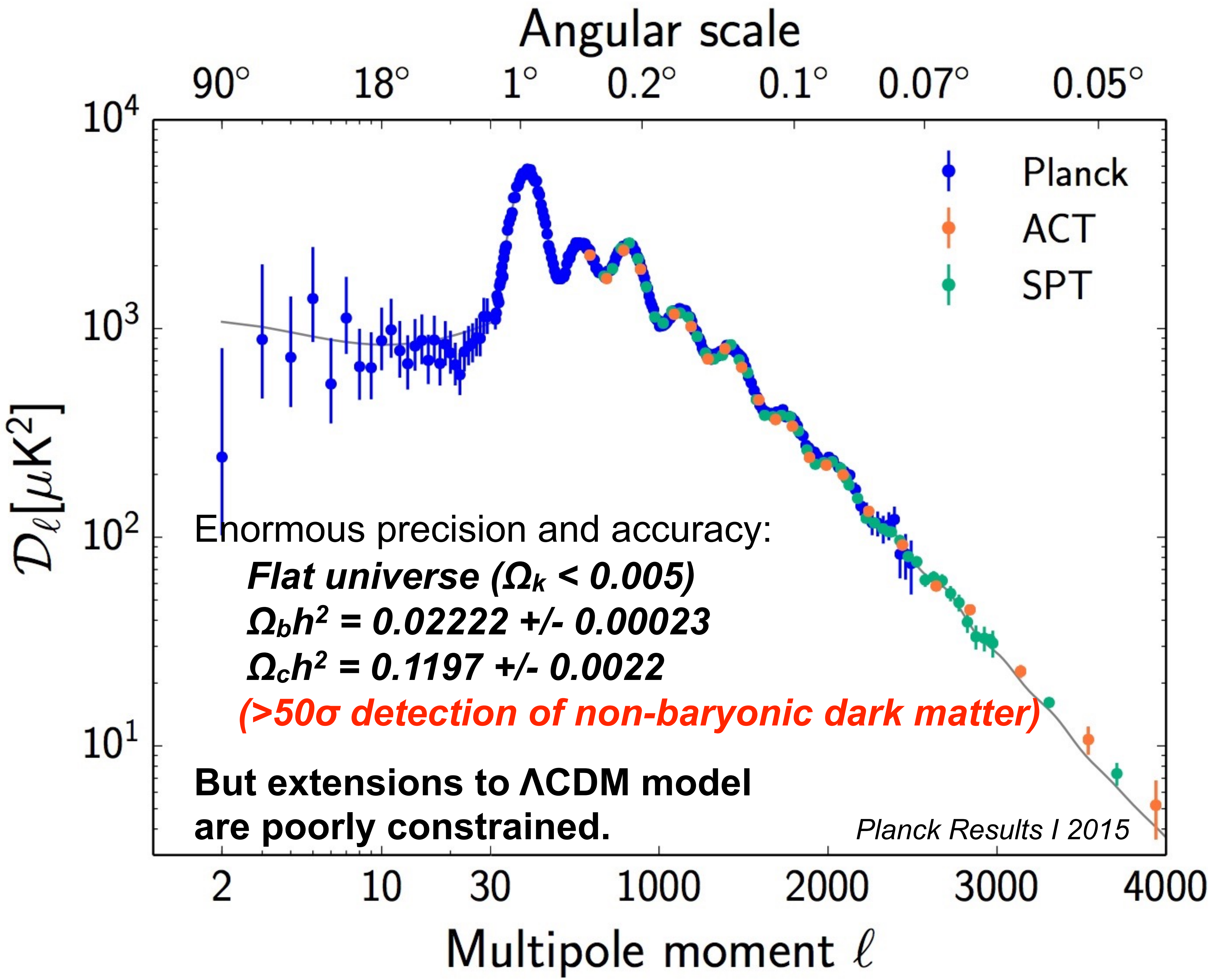


Figure from Planck 2015 Results XI

Constraints on cosmological parameters



Enormous precision and accuracy:

Flat universe (Ω_k < 0.005)

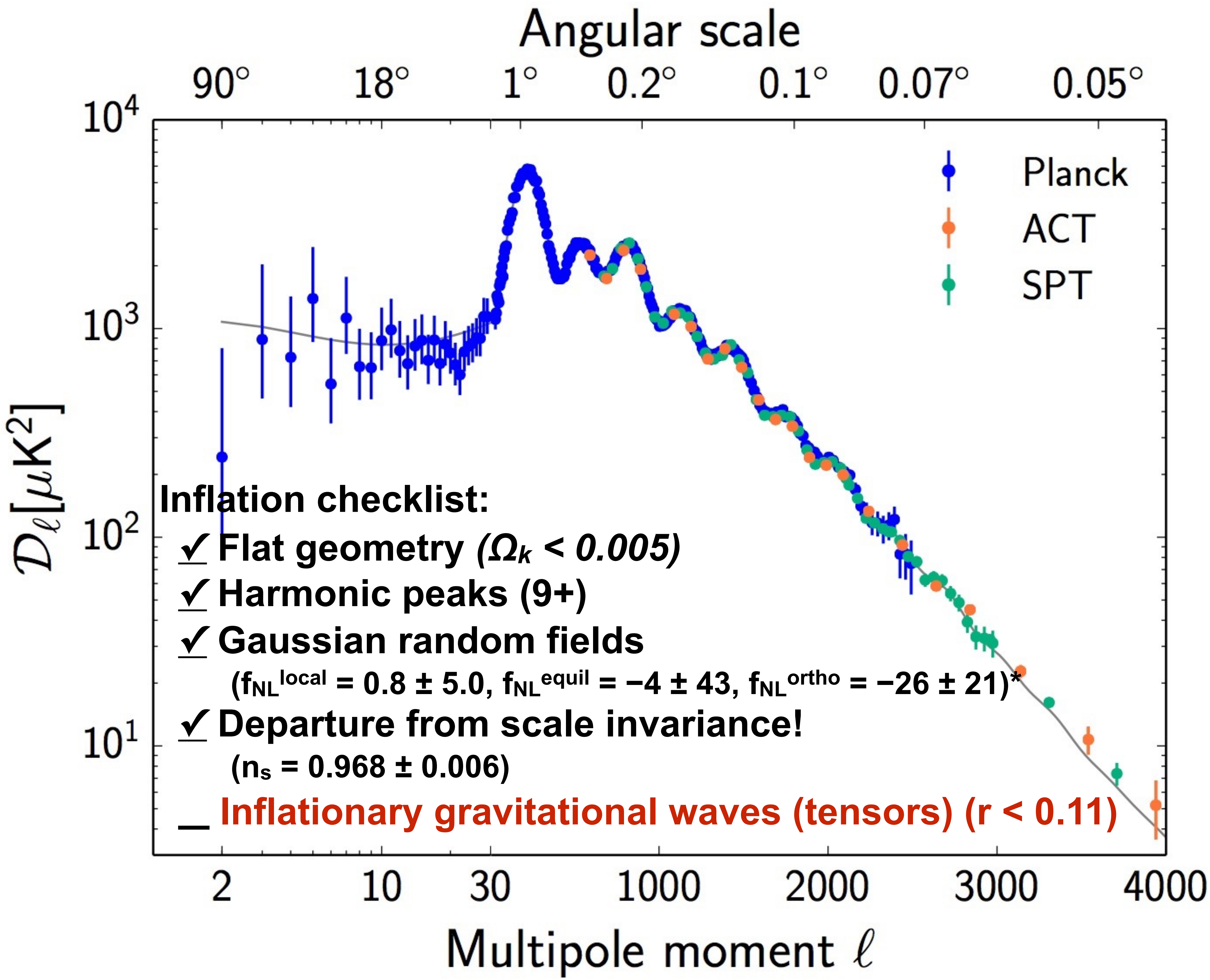
$\Omega_b h^2$ = 0.02222 +/- 0.00023

$\Omega_c h^2$ = 0.1197 +/- 0.0022

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

But extensions to ΛCDM model are poorly constrained.

Constraints on cosmological parameters

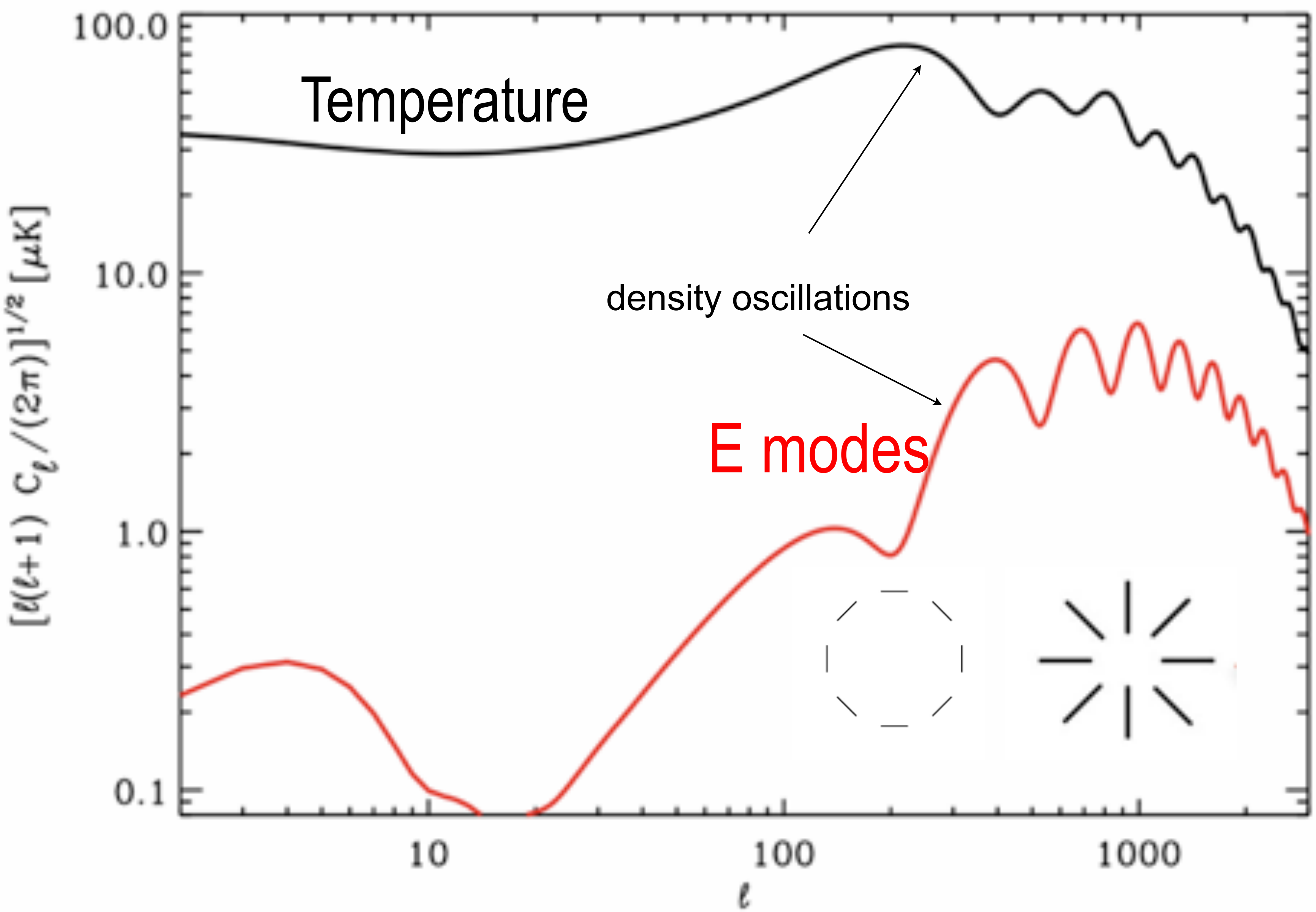


Inflation checklist:

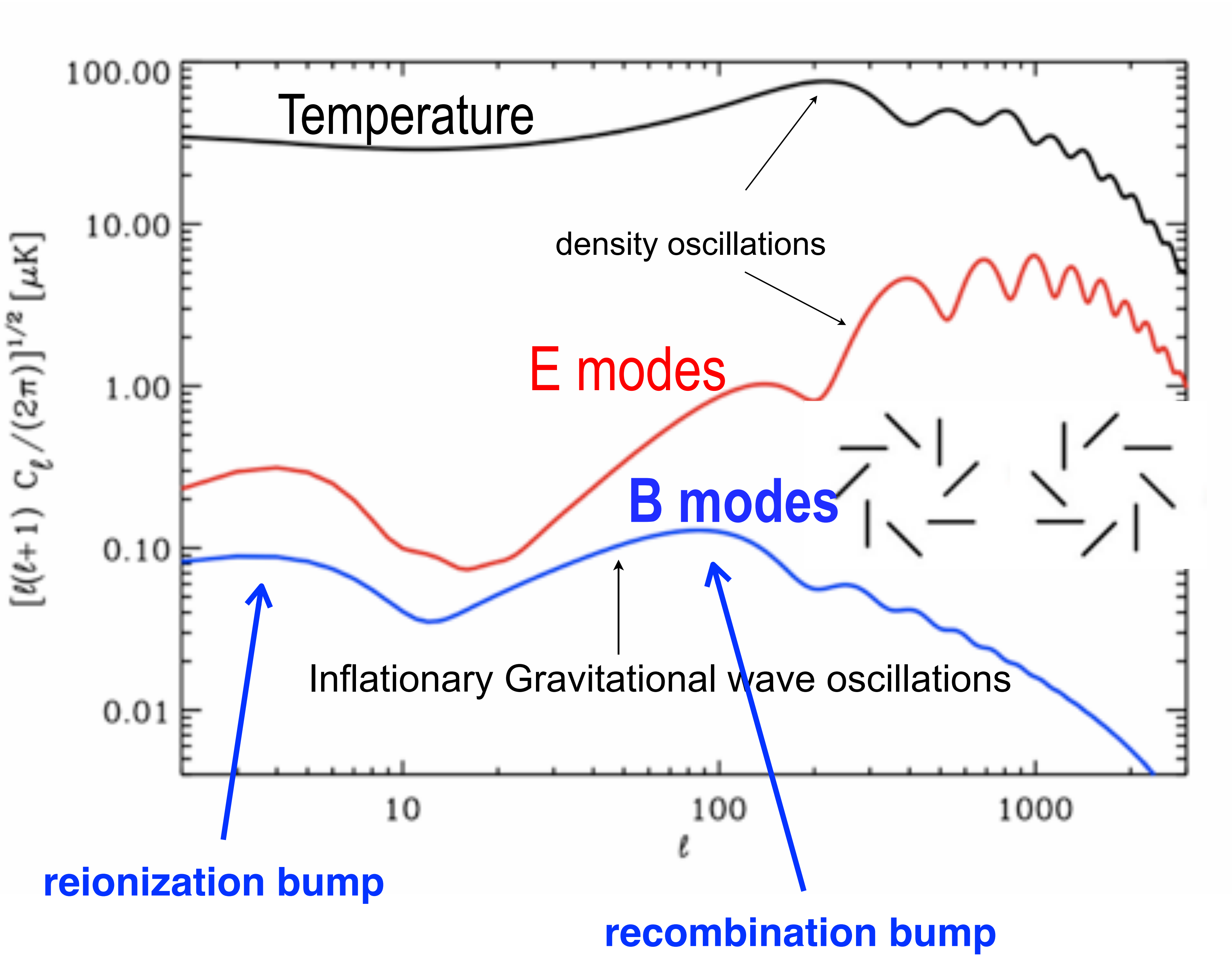
- ✓ **Flat geometry *($\Omega_k < 0.005$)***
- ✓ **Harmonic peaks (9+)**
- ✓ **Gaussian random fields**
  ($f_{NL}^{local} = 0.8 \pm 5.0$, $f_{NL}^{equil} = -4 \pm 43$, $f_{NL}^{ortho} = -26 \pm 21$)*
- ✓ **Departure from scale invariance!**
  ($n_s = 0.968 \pm 0.006$)
- __ **Inflationary gravitational waves (tensors) ($r < 0.11$)**

*constraints include CMB polarization data

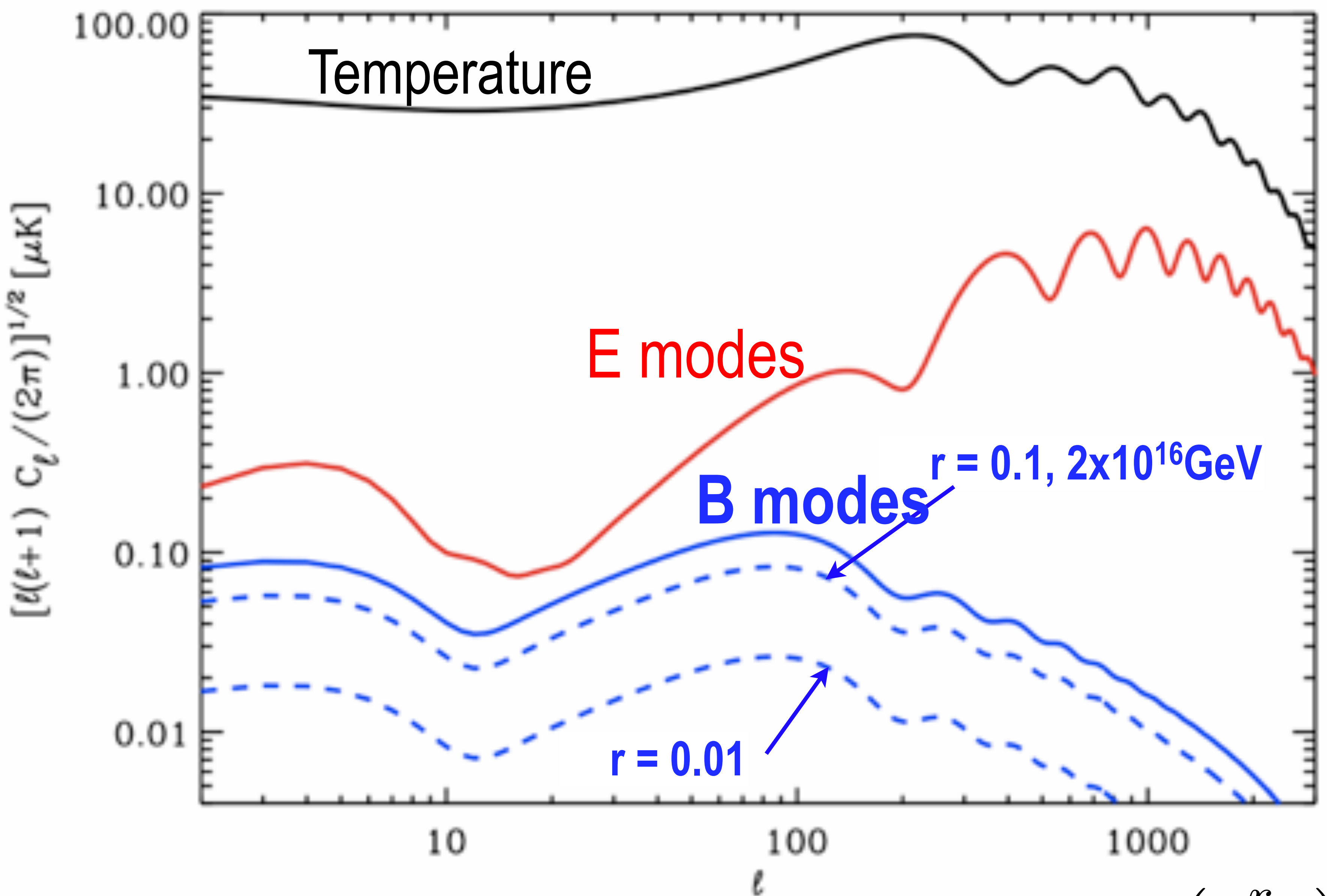
CMB Polarization



CMB Polarization



CMB Polarization

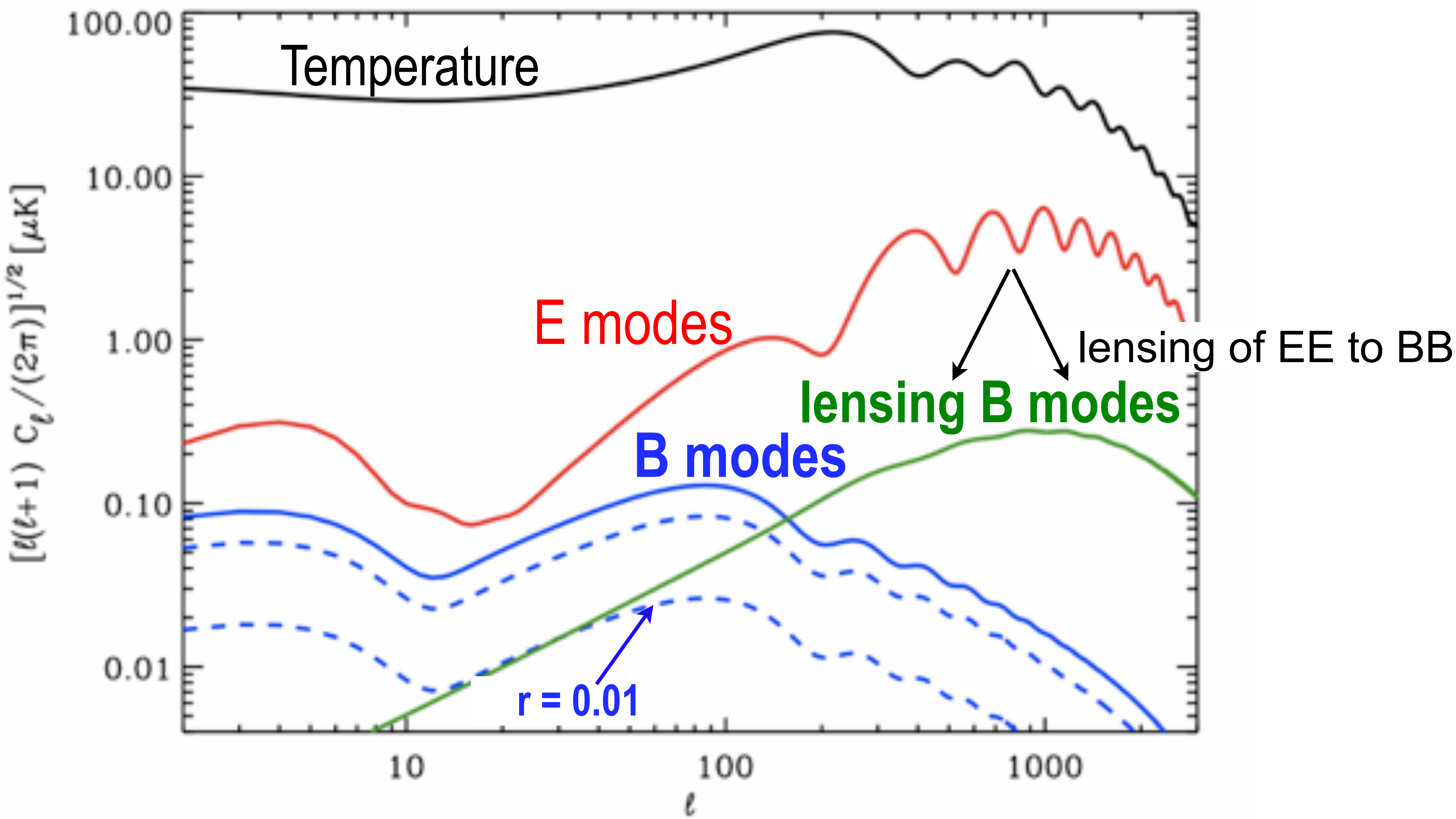


$$r \equiv \frac{\text{Tensor (gravitational) perturbation amplitude}}{\text{Scalar (density) perturbation amplitude}}$$

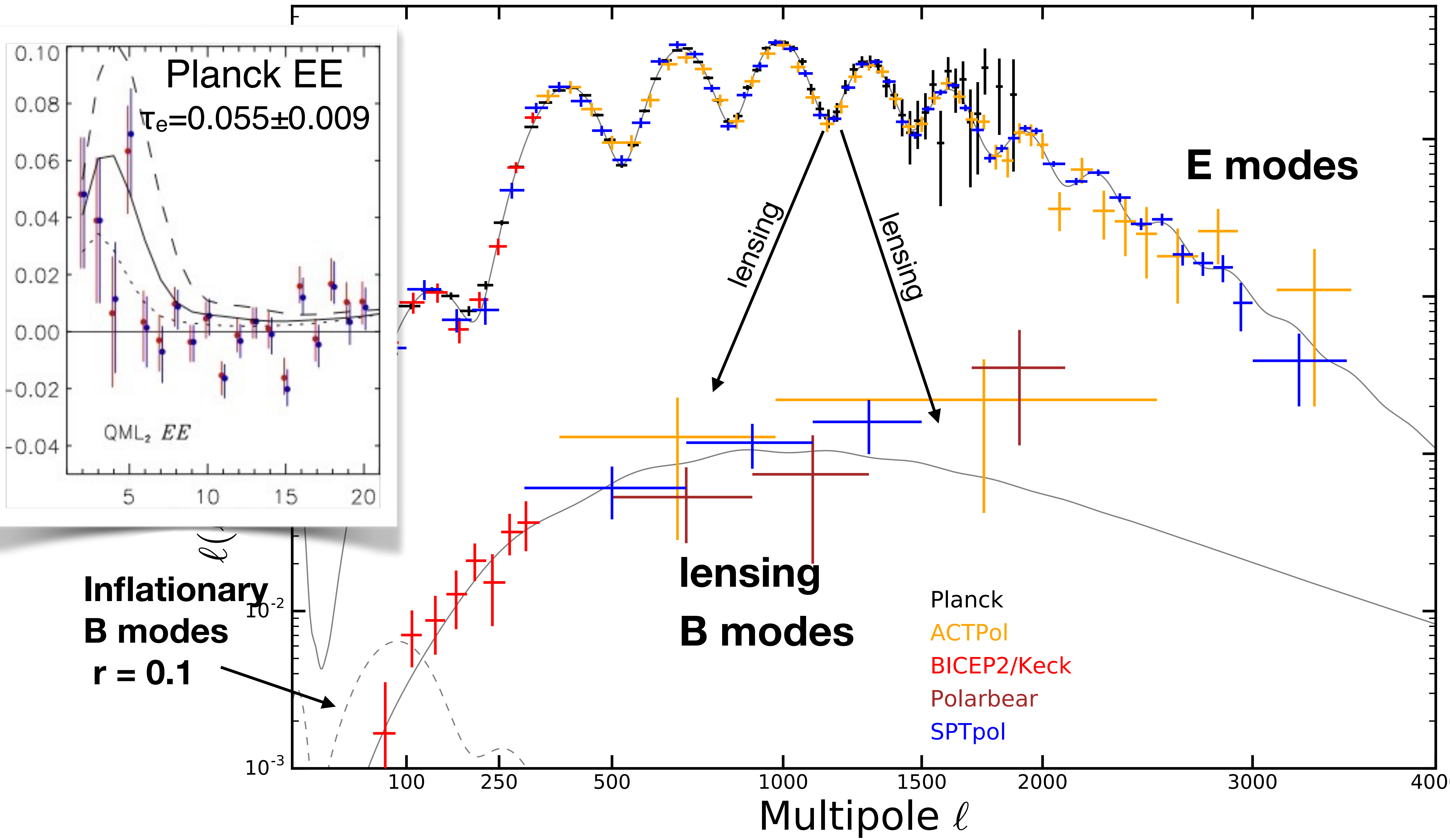
$$\text{energy} = 10^{16}\left(\frac{r}{0.01}\right)^{\frac{1}{4}}\ \text{GeV}$$

$$\text{time} = 10^{-36}\left(\frac{r}{0.01}\right)^{-\frac{1}{2}}\ \text{seconds}$$

CMB Polarization

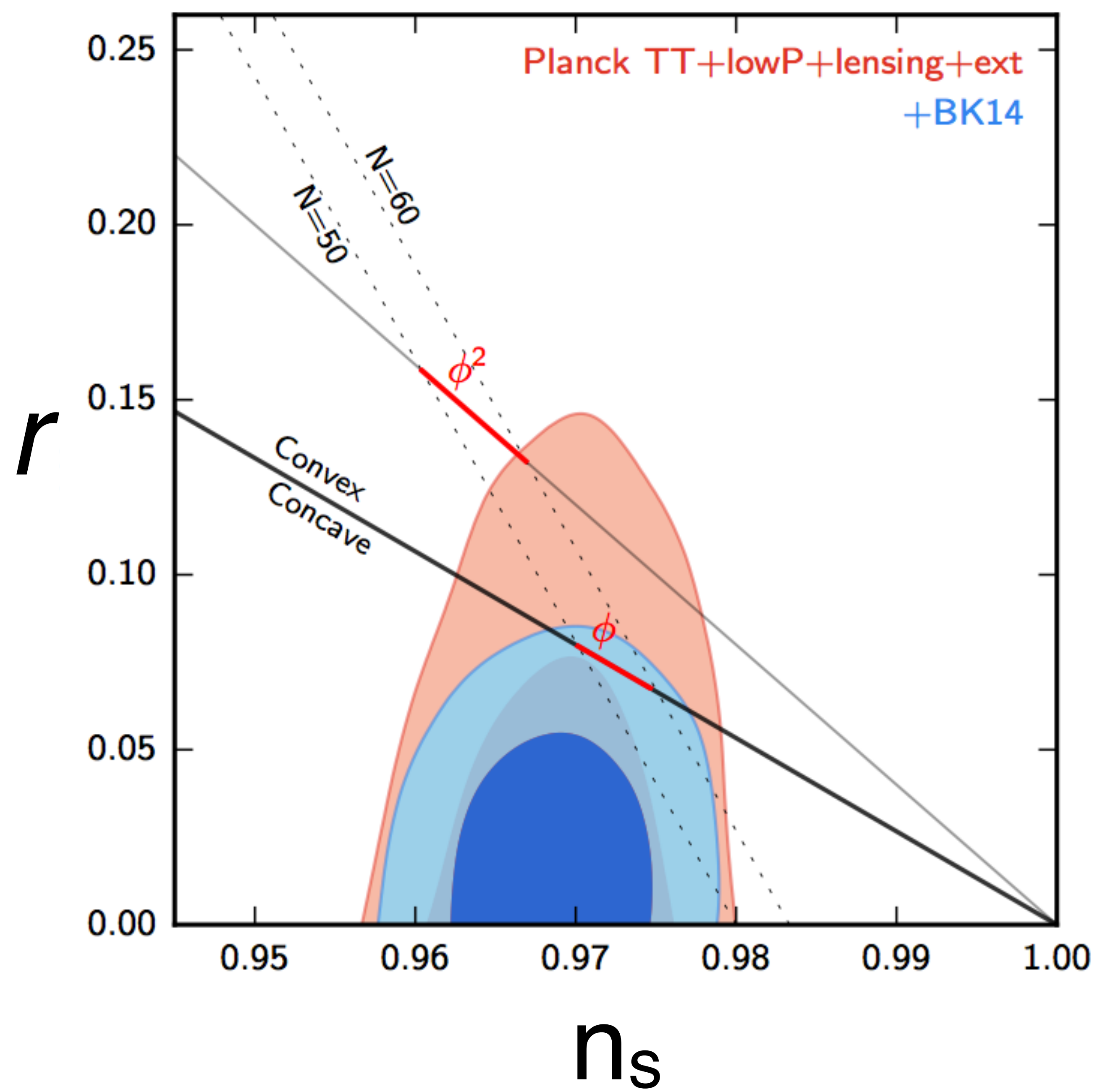


Status of CMB polarization measurements



Rapid progress. All within last few years.

arXiv:1510.09217



The tensor to scalar ratio, r, is now constrained by B-mode polarization measurements

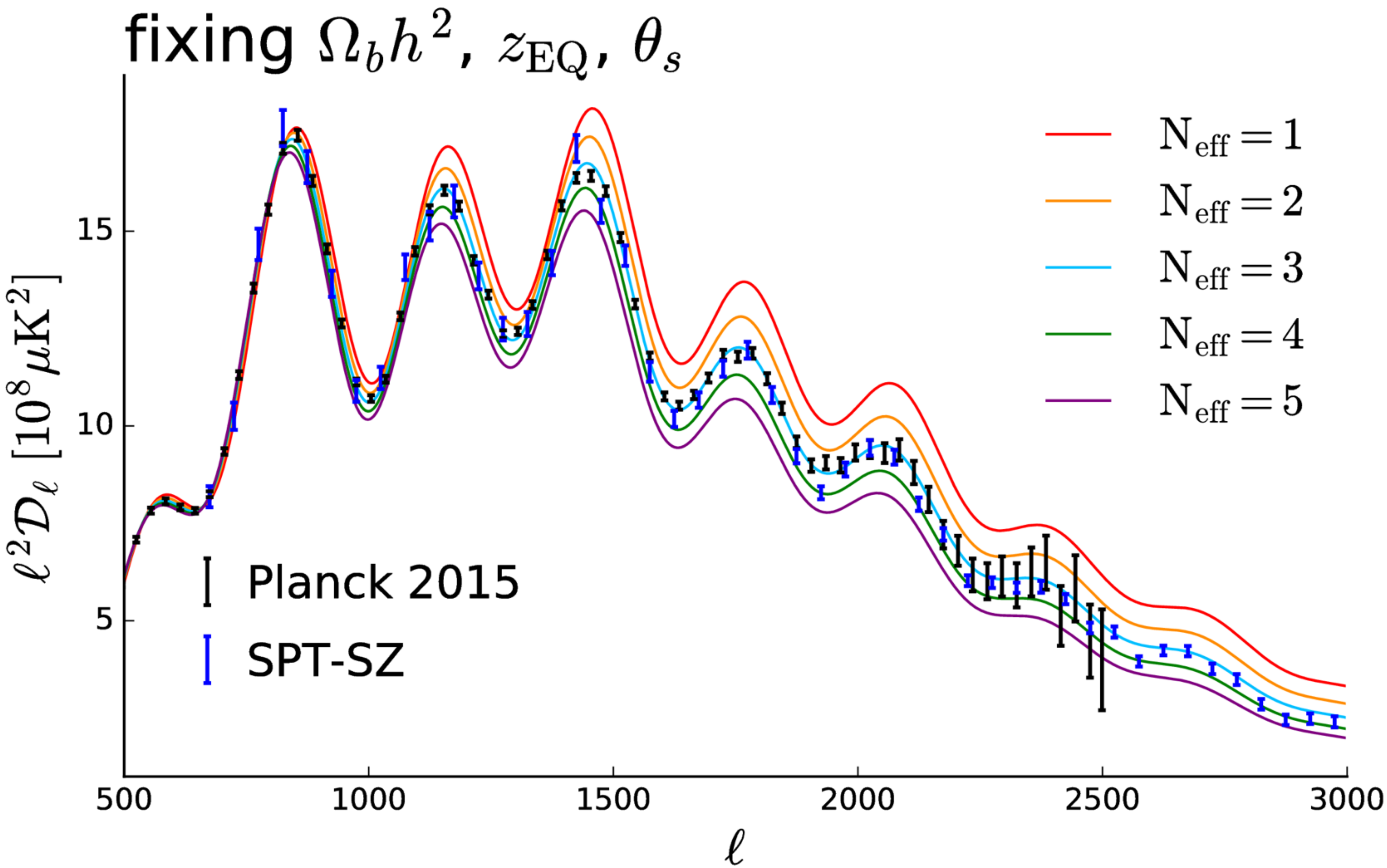
BICEP/Keck & Planck result:

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

Raw sensitivity σ(r) = 0.006

→ *limited by foreground component separation and soon by gravitational lensing distortions of the CMB*

N_{eff} and CMB damping



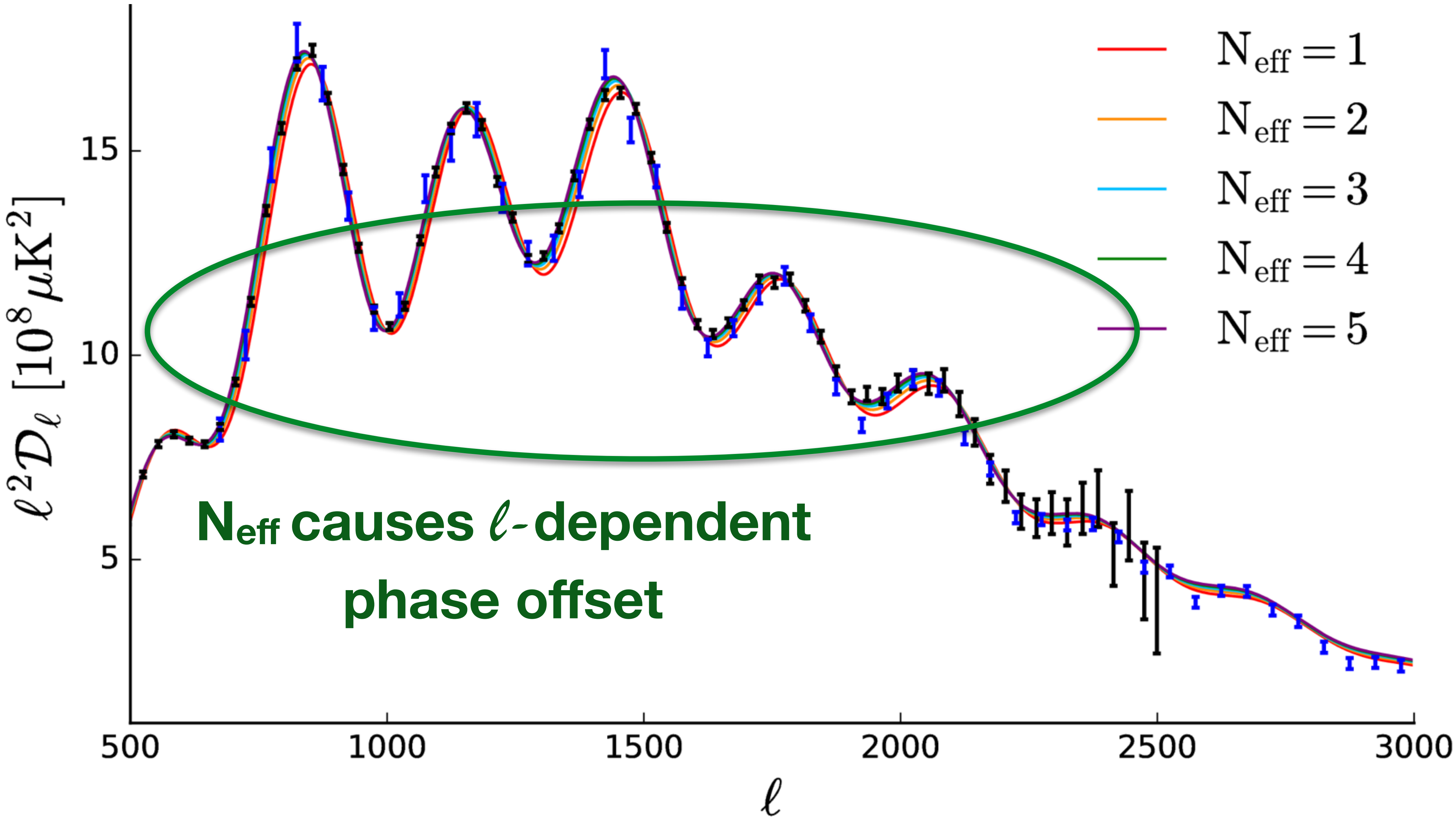
N_{eff} is the effective number of relativistic species.

It measures the extra relativistic energy relative to the photons.

For standard 3 neutrinos N_{eff} =3.046.

Helium fraction & N_{eff} degeneracy

Preserve CMB spectrum with N_{eff} by increasing helium fraction, Y_P



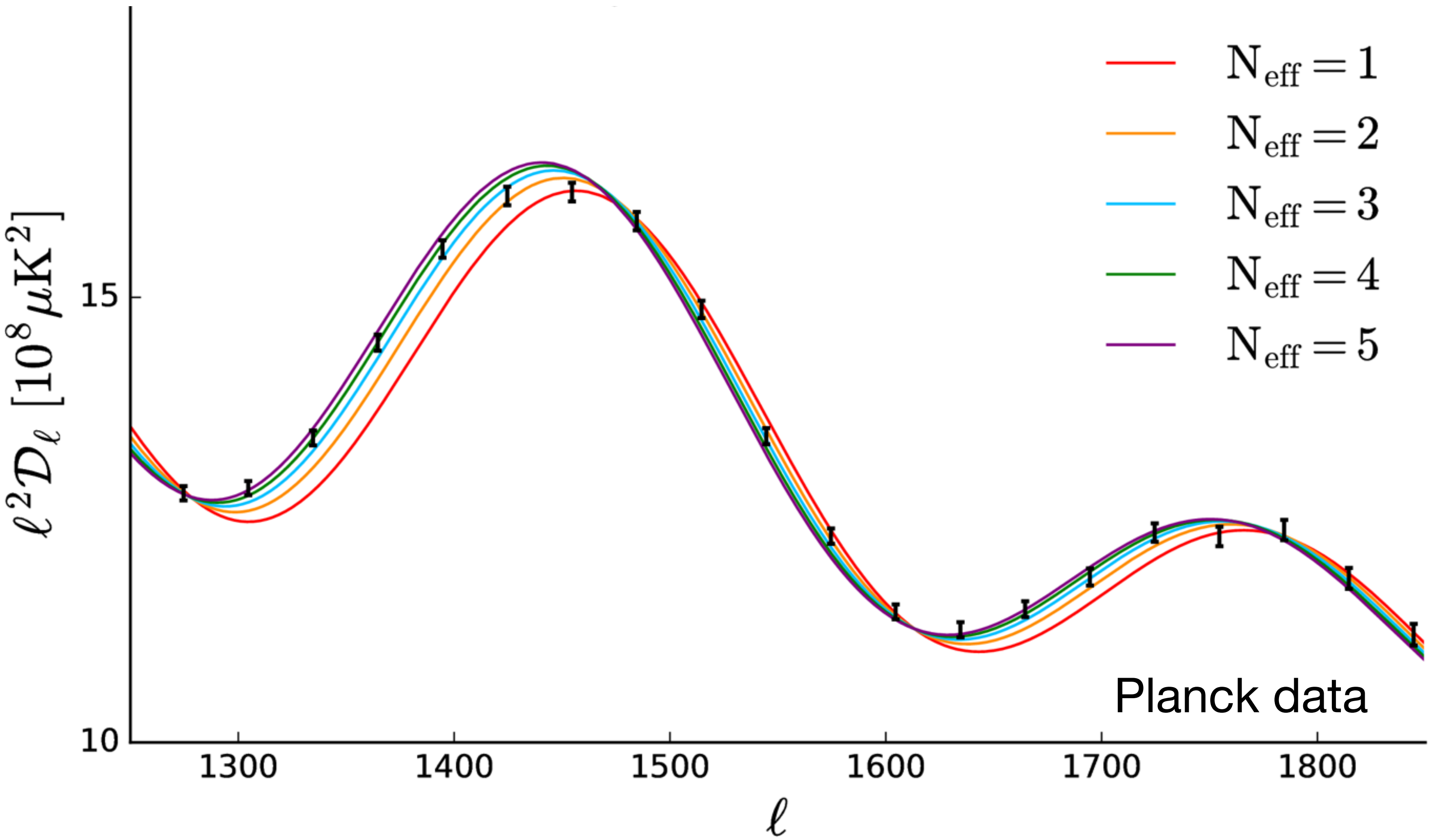
N_{eff} is the effective number of relativistic species.

It measures the extra relativistic energy relative to the photons.

For standard 3 neutrinos N_{eff} =3.046.

Phasing of power spectrum peaks breaks helium fraction & N_{eff} degeneracy

Keep θ_d constant with N_{eff} by increasing helium fraction, Y_P



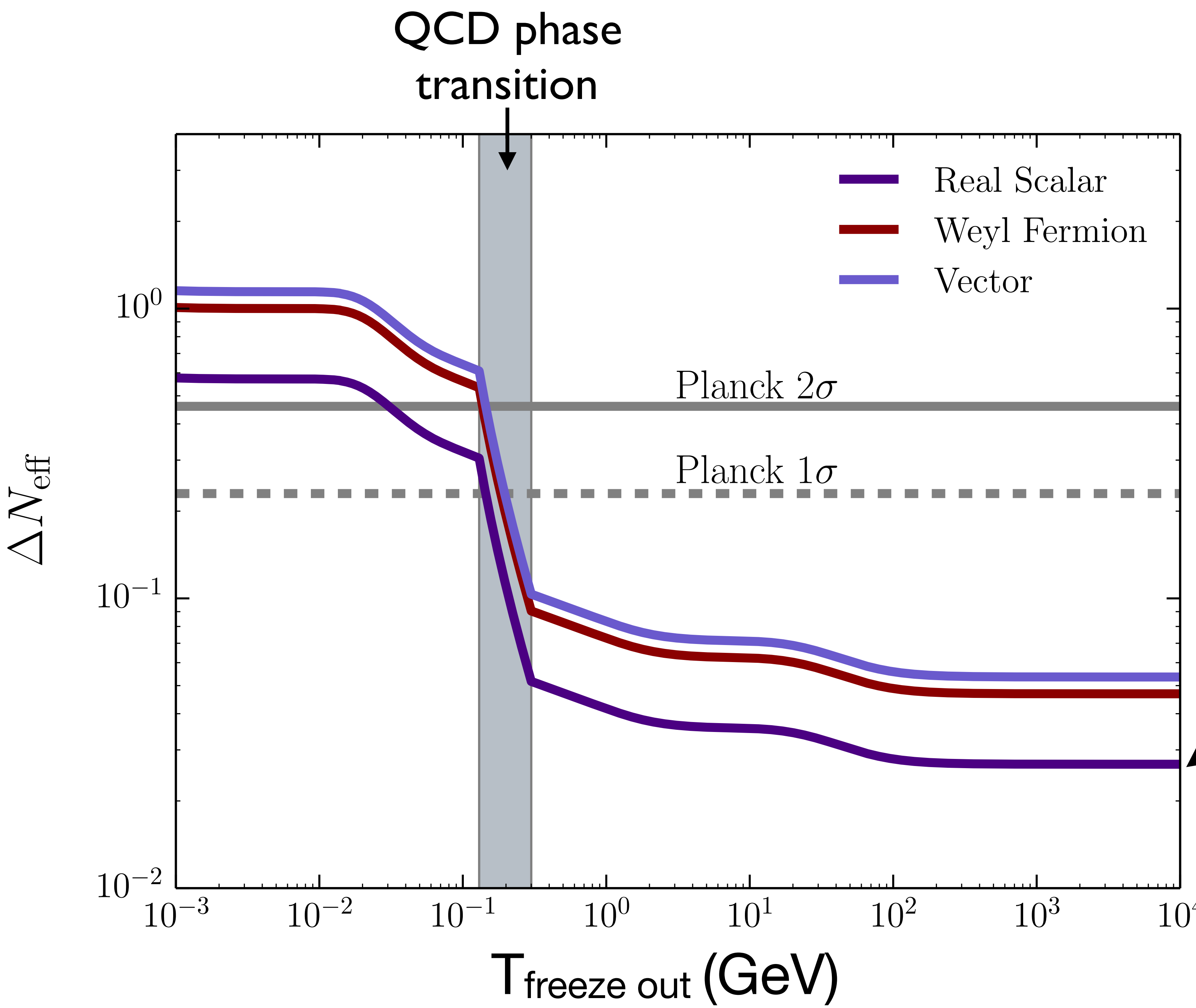
N_{eff} causes ℓ-dependent phase offset

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

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

Highly significant detection of neutrino background

N_{eff} constraints and light thermal relics



N_{eff} measurements constrain light thermal relics

Sets natural, and exceedingly challenging, target of $\Delta N_{eff} = 0.027$ for a relic scalar, 0.054 for a vector.

Green, Meyers in CMB-S4 Science Book (http://CMB-S4.org)
also see Baumann, Green, Wallisch "A New Target for Cosmic Axion Searches" arXiv:1604.08614

Matter power spectrum

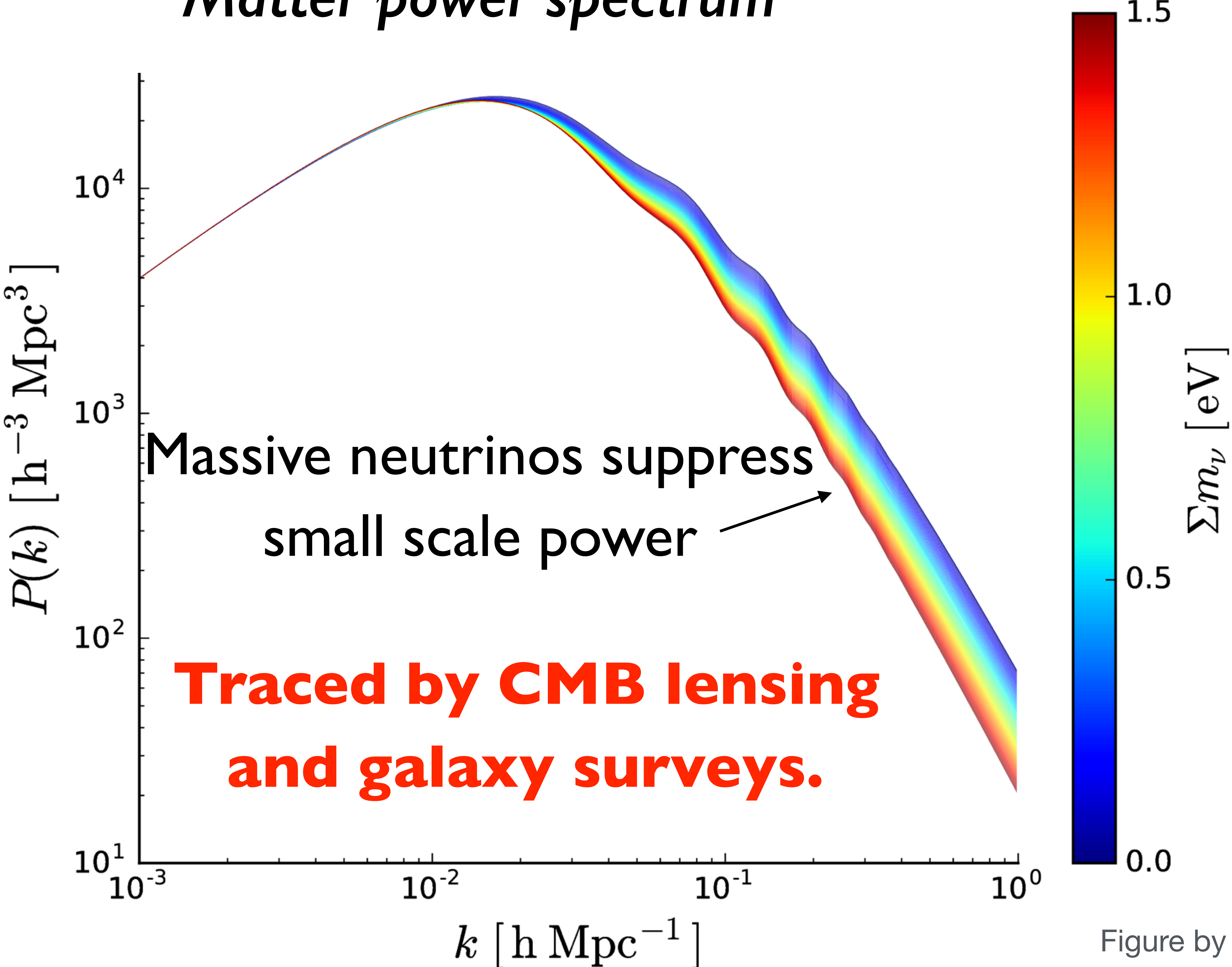
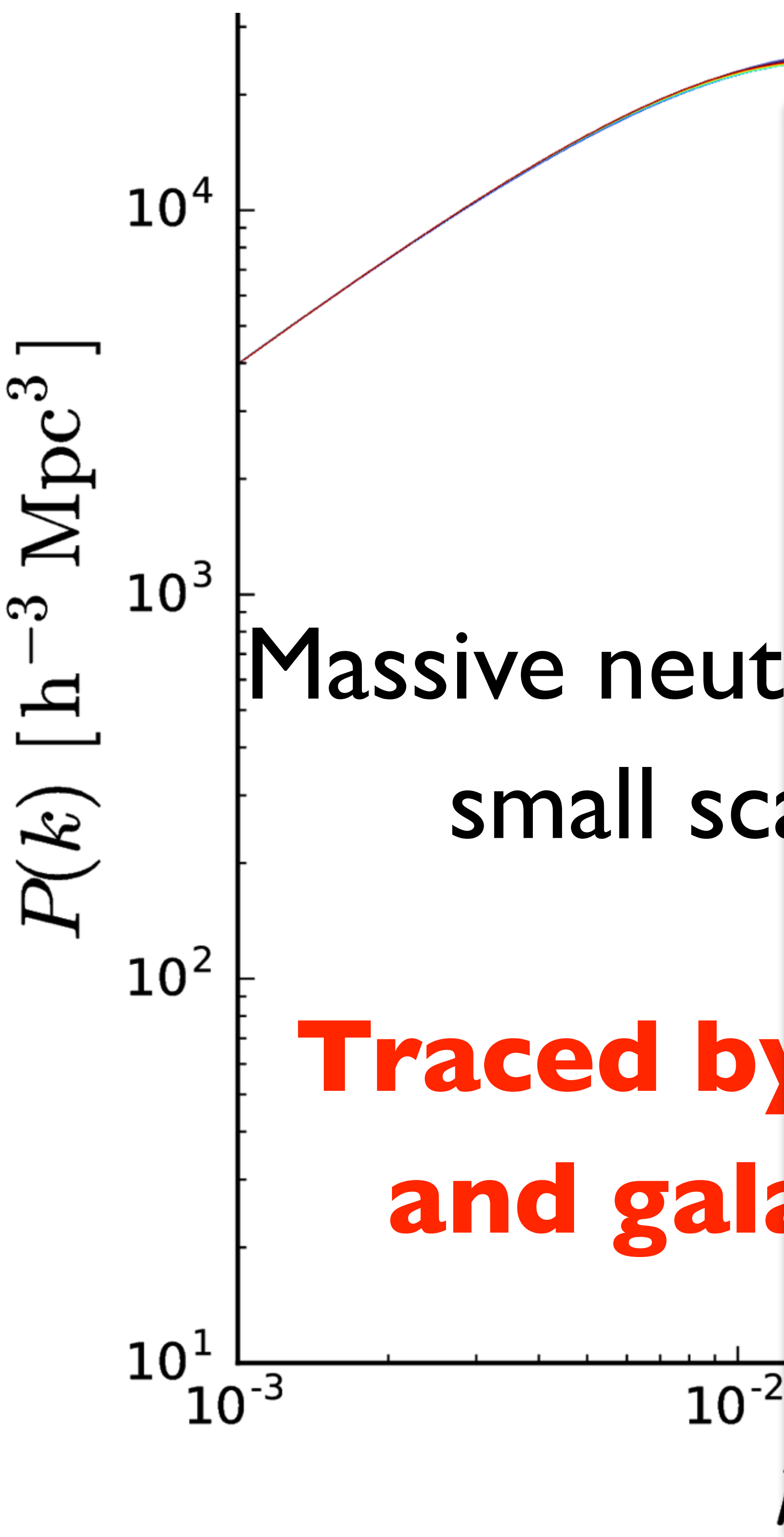


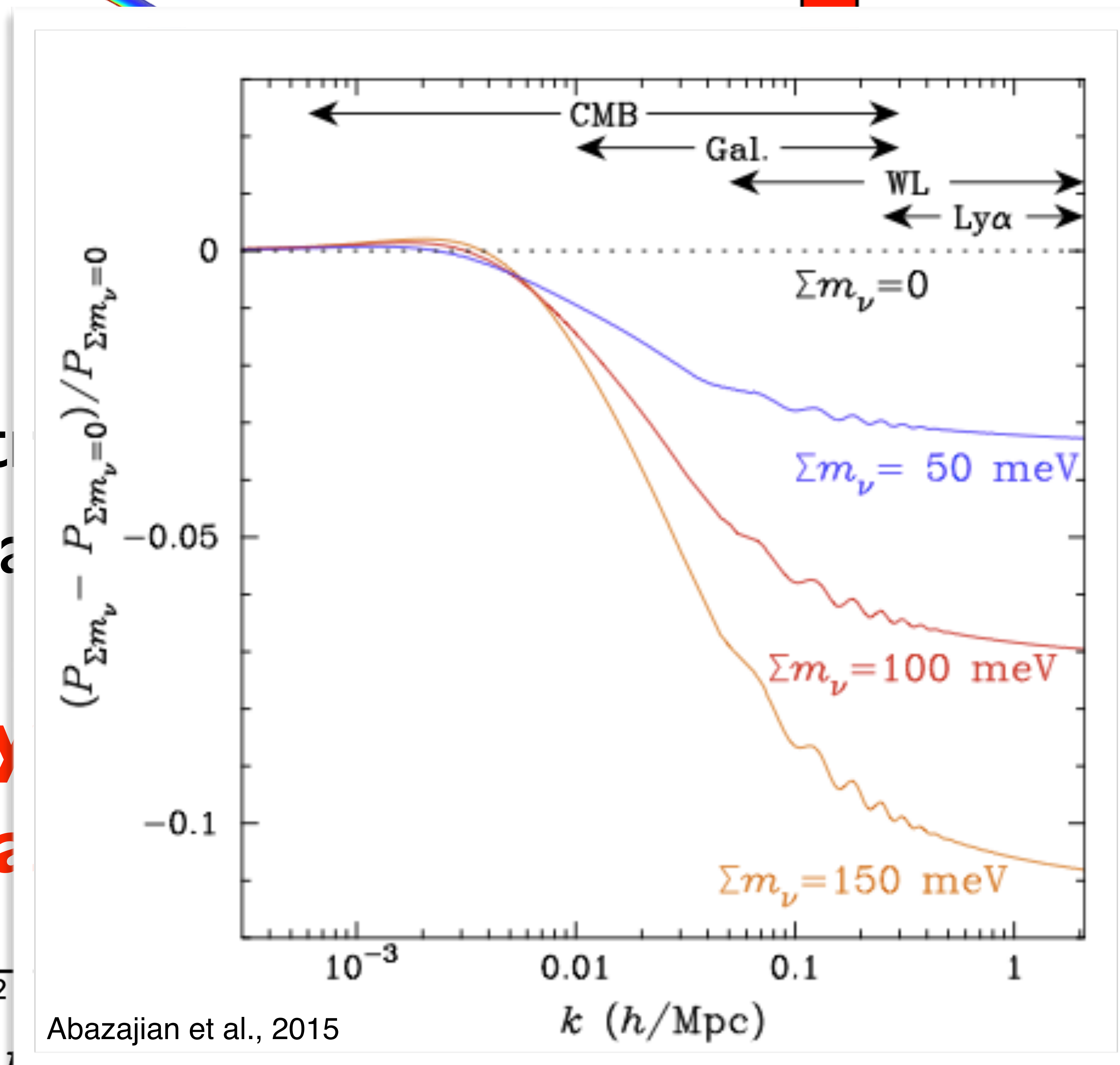
Figure by Zhen Hou

Matter power spectrum

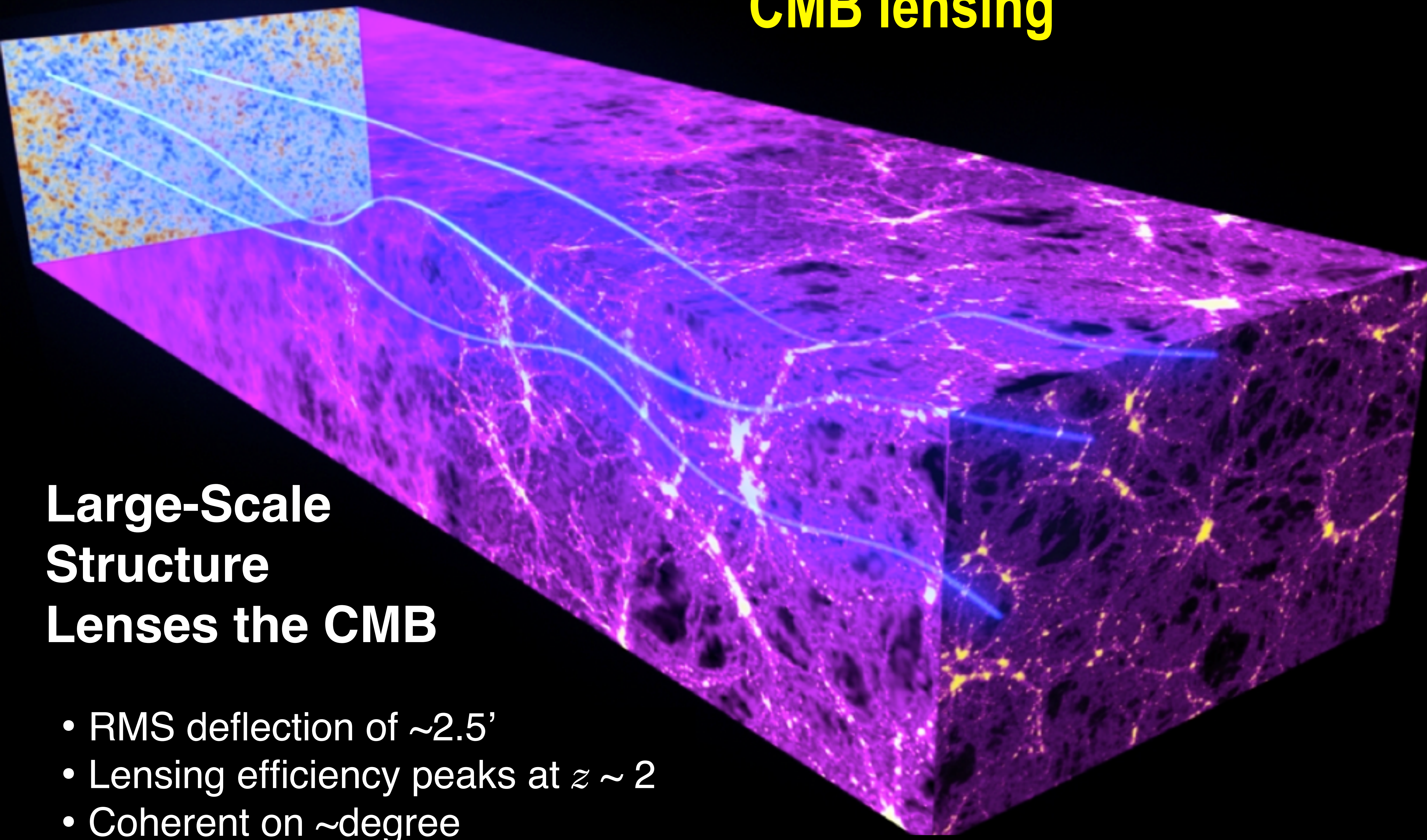


Massive neut
small sca

Traced by
and gala



CMB lensing



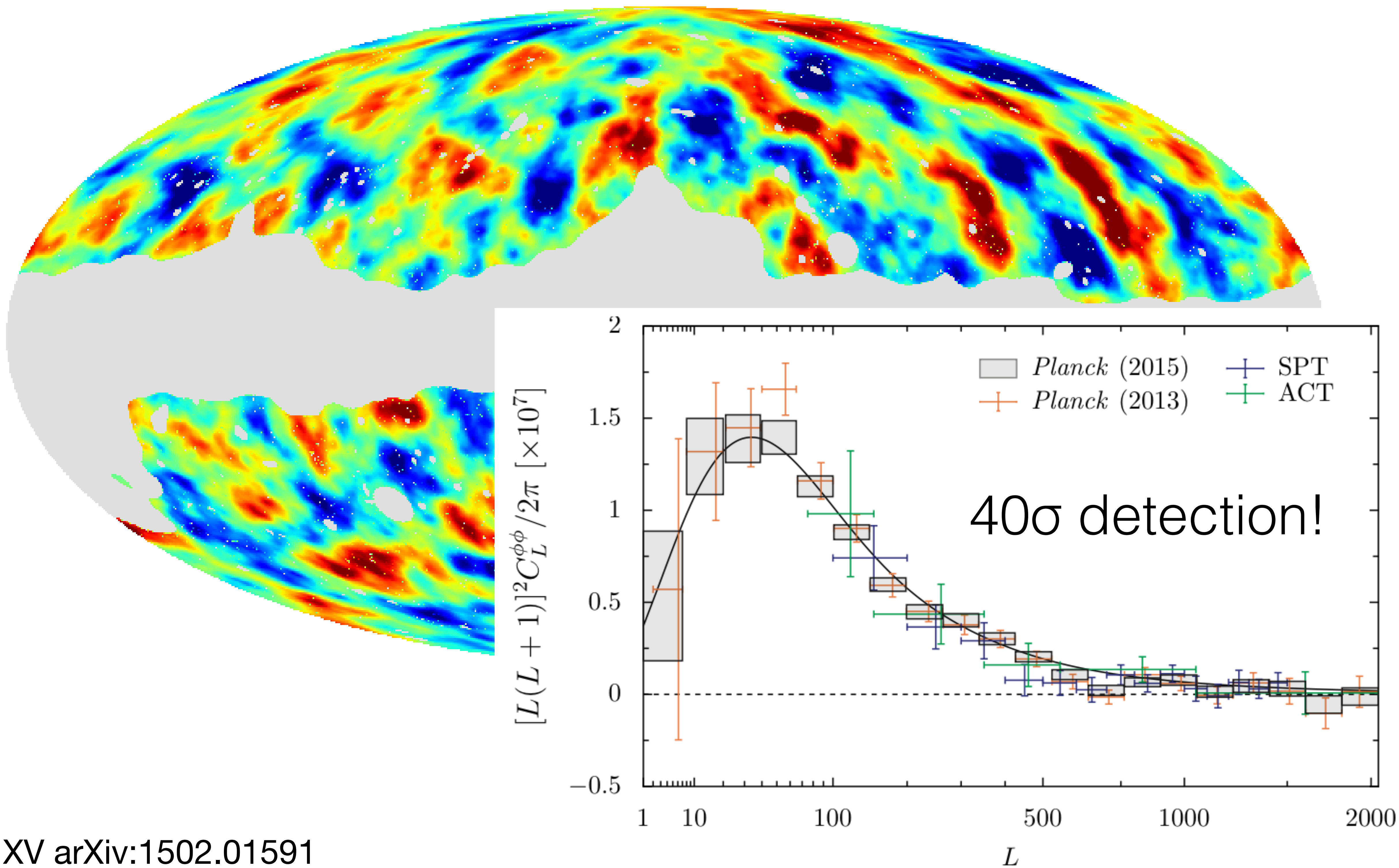
Large-Scale Structure Lenses the CMB

- RMS deflection of ~2.5’
- Lensing efficiency peaks at $z \sim 2$
- Coherent on ~degree (~300 Mpc) scales

graphic from ESA website

CMB lensing

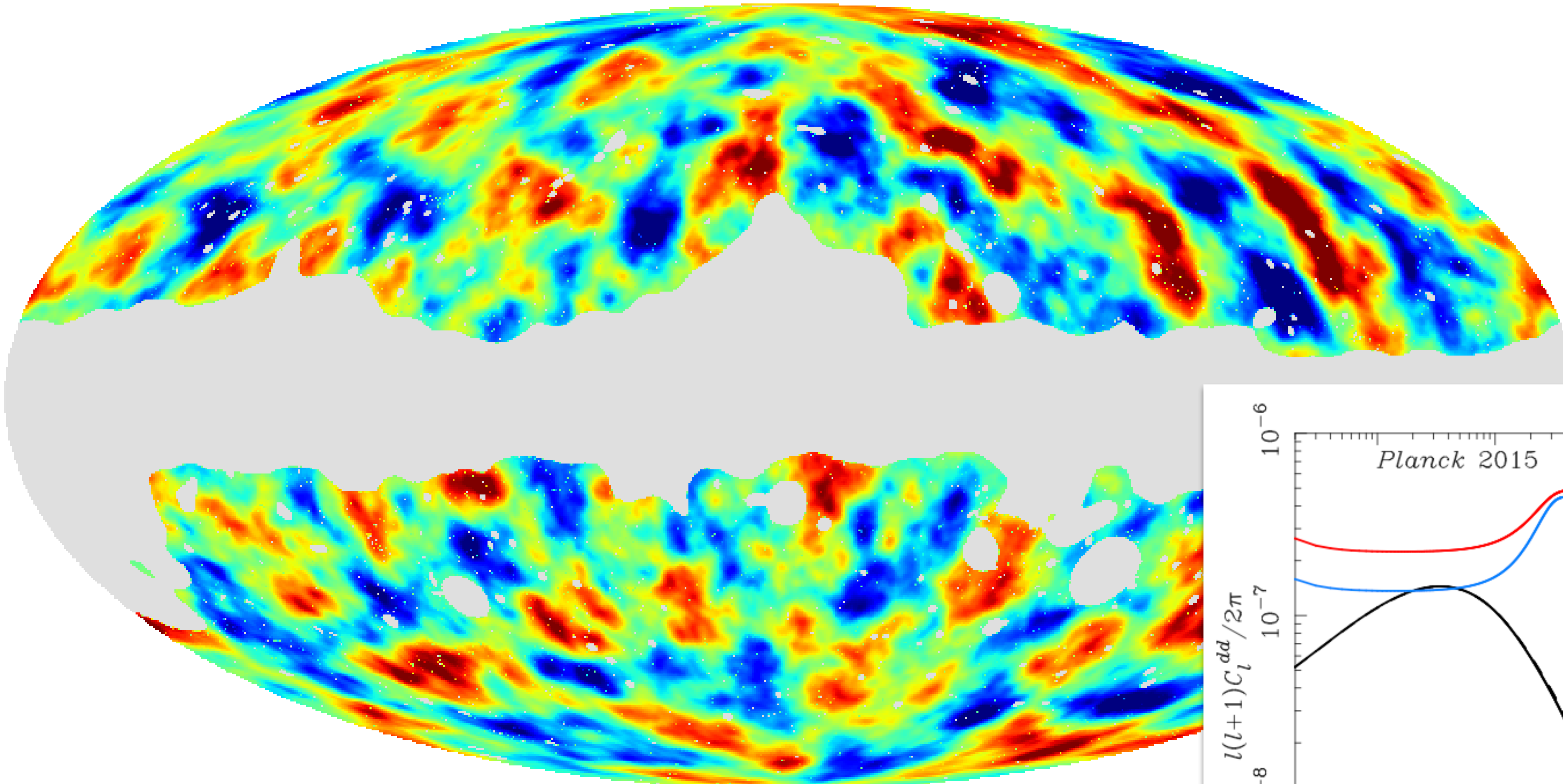
Planck lensing potential reconstruction (projected mass map).

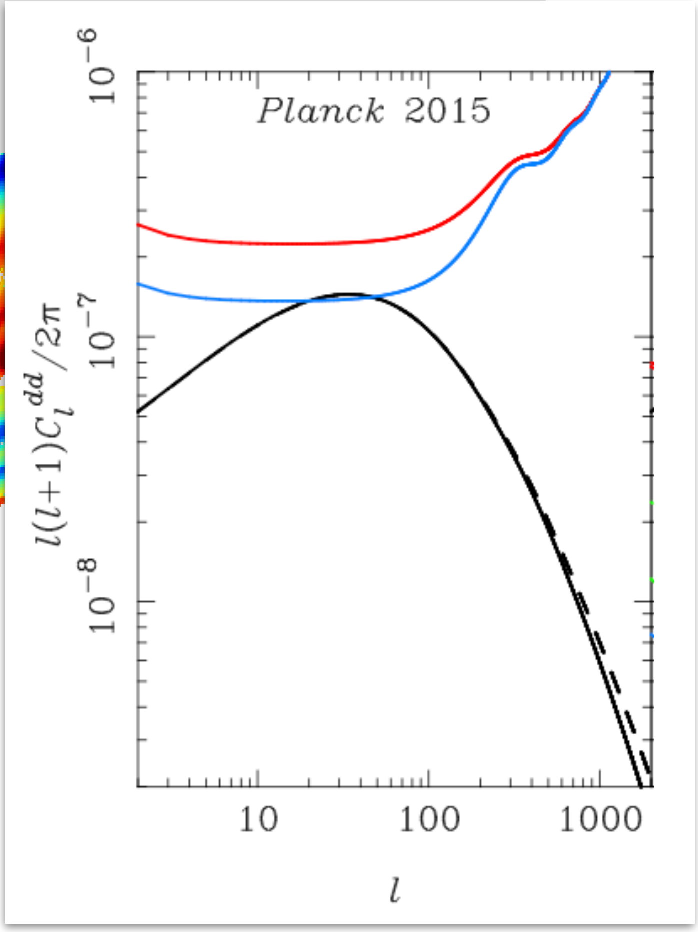


Planck XV arXiv:1502.01591

CMB lensing

Planck lensing potential reconstruction (projected mass map).



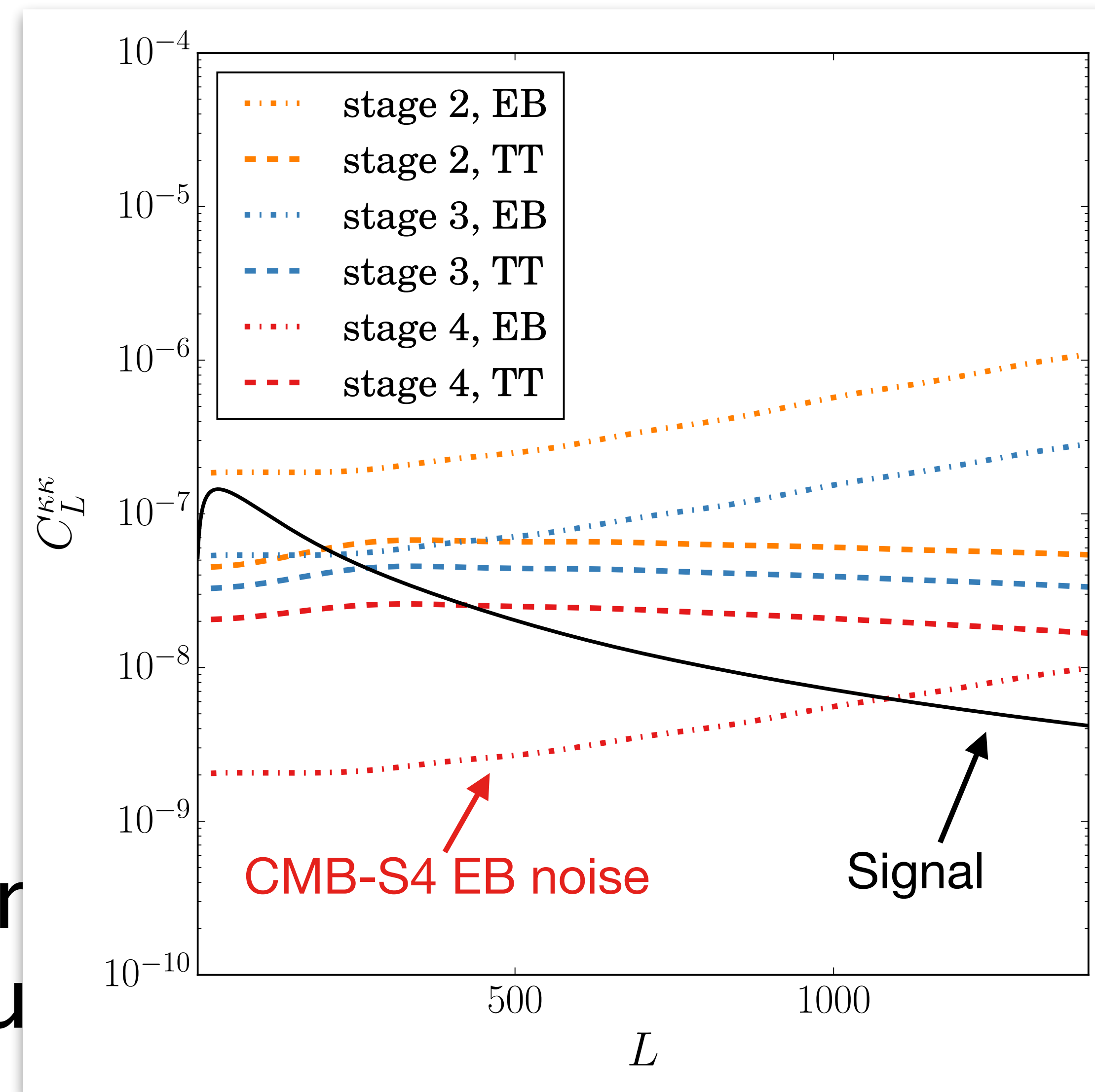


Planck XV arXiv:1502.01591

CMB lensing

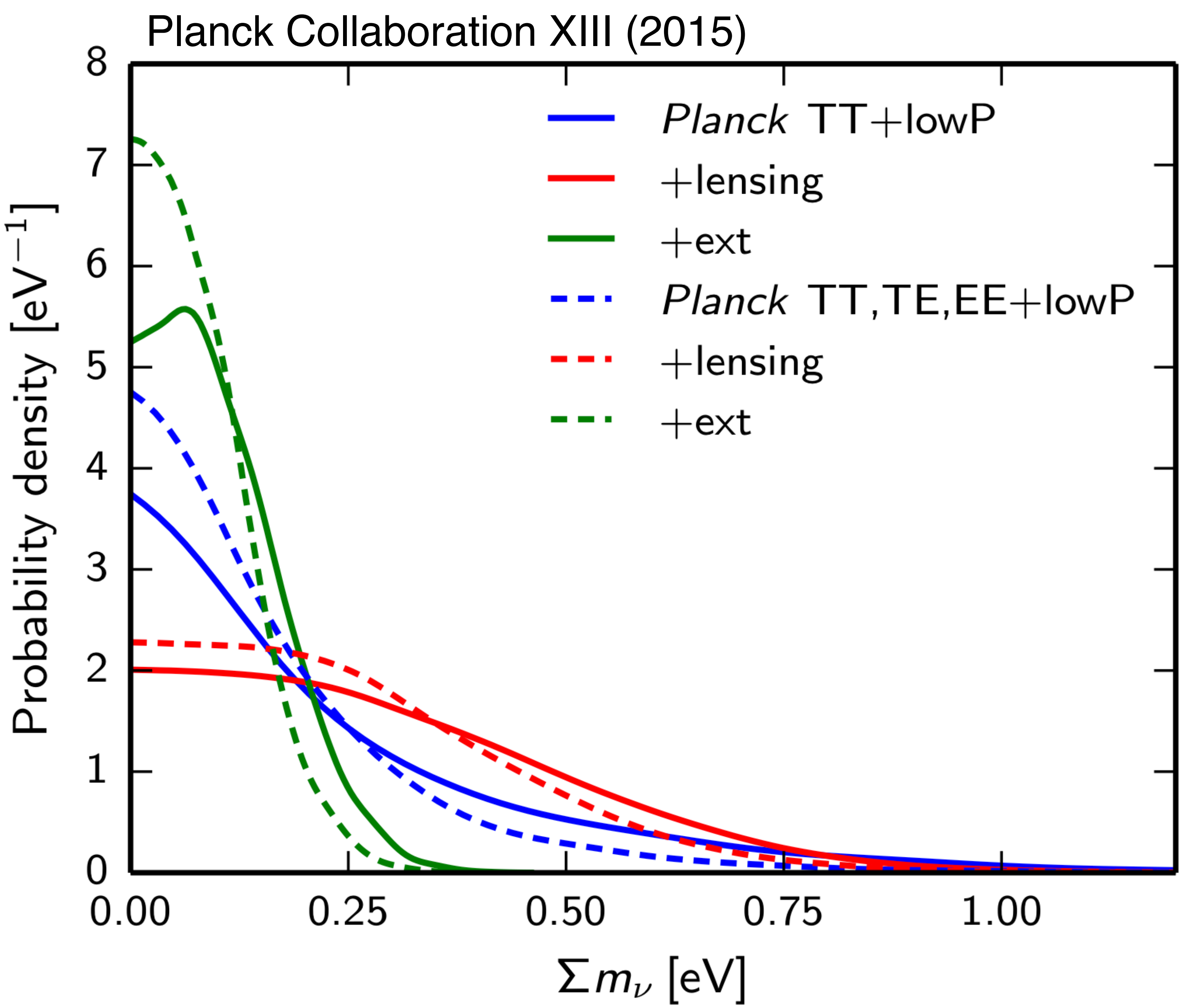
SPTpol 500d lensing potential reconstruction of BICEP field,
L < 250 imaged with s/n > 1.

preliminar
(shown bu



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

Cosmological Neutrino Mass Constraints



CMB alone:

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

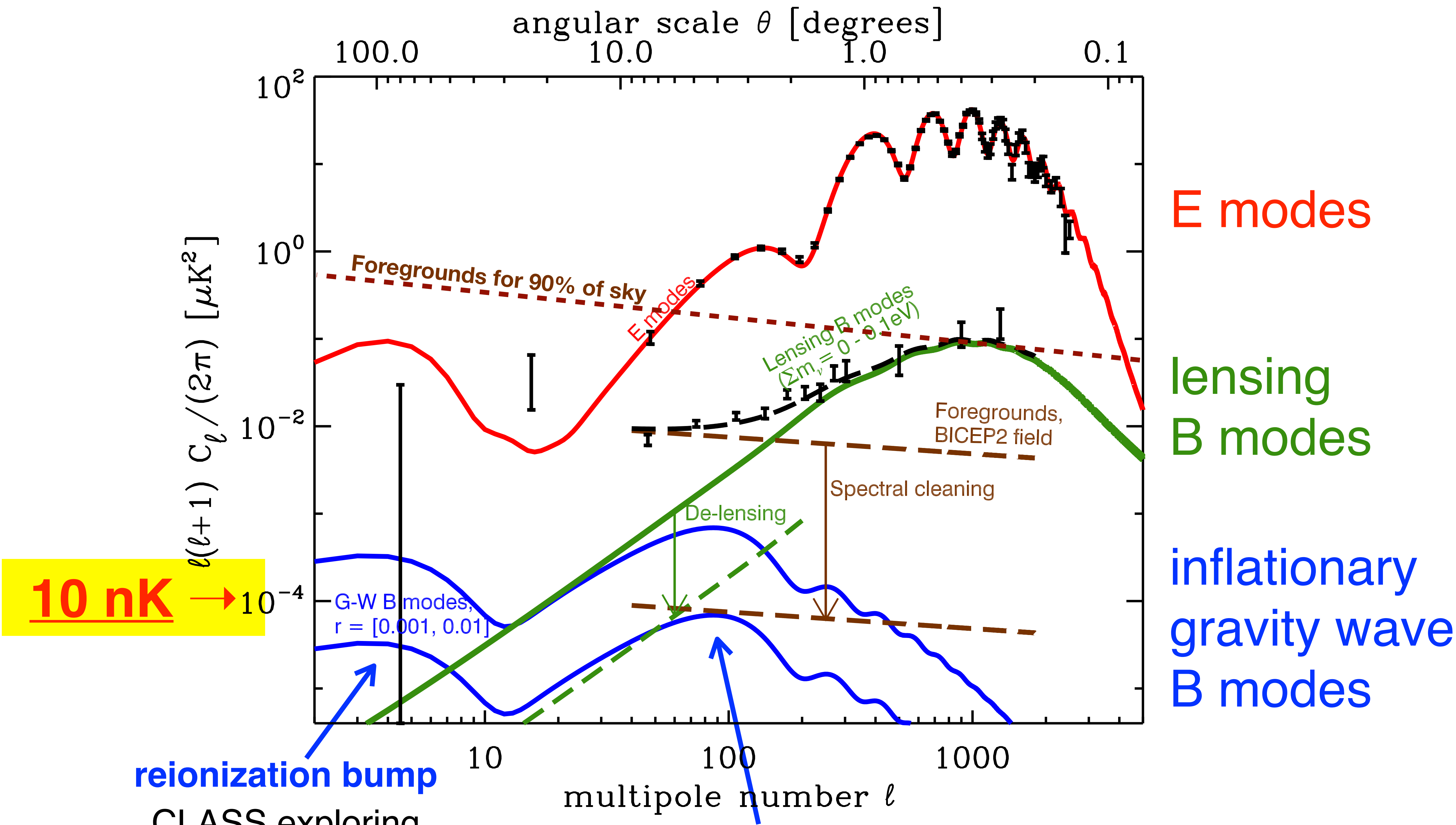
Including other cosmological data:

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

Joint Σm_ν and N_{eff} fit:

$N_{eff} = 3.2 \pm 0.5$
$\Sigma m_\nu < 0.32$ eV
} 95% c.l.

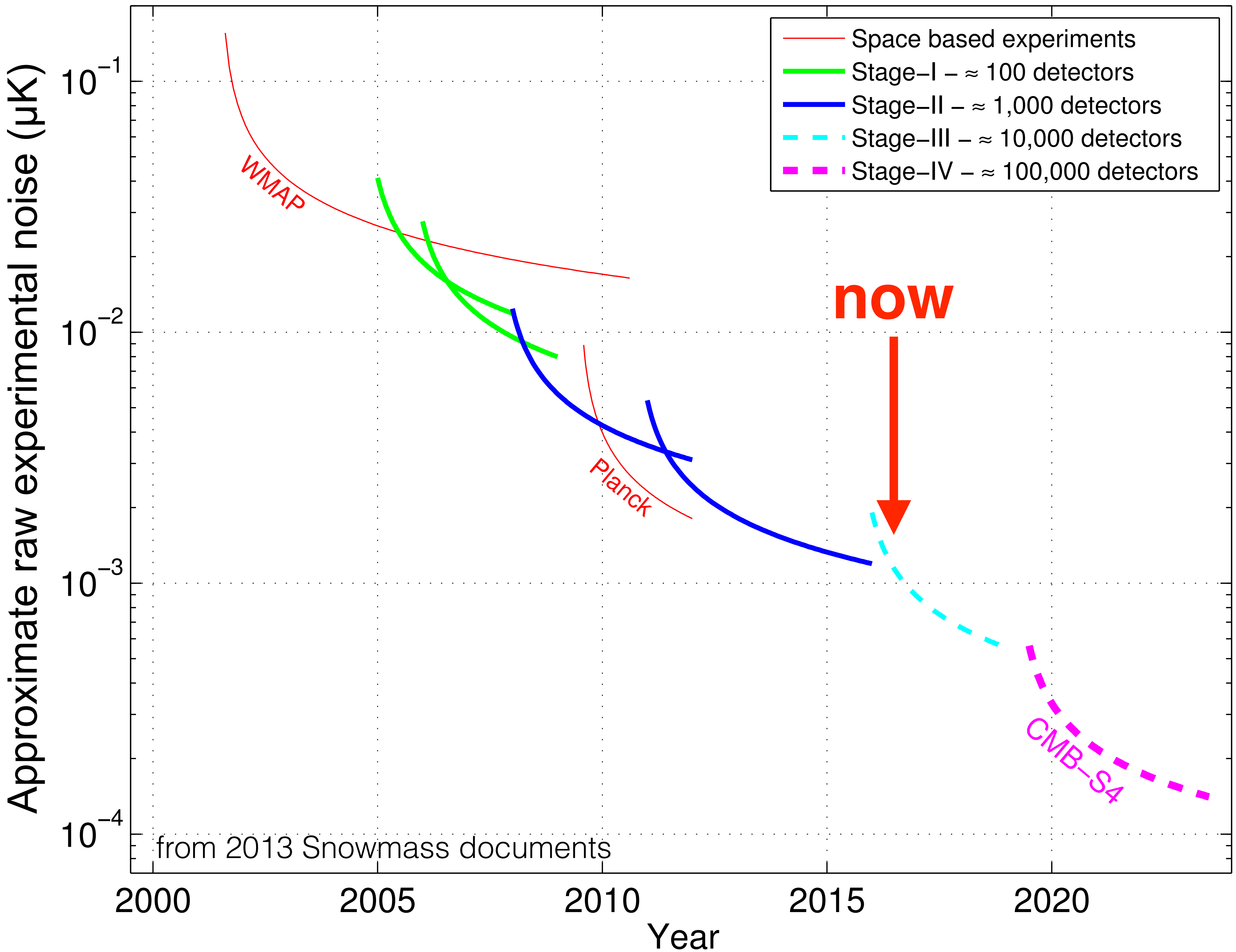
The path forward is through much more sensitive polarization measurements!



reionization bump
CLASS exploring
from the ground;
target of LiteBIRD, PIXIE , CORE
satellites proposals

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

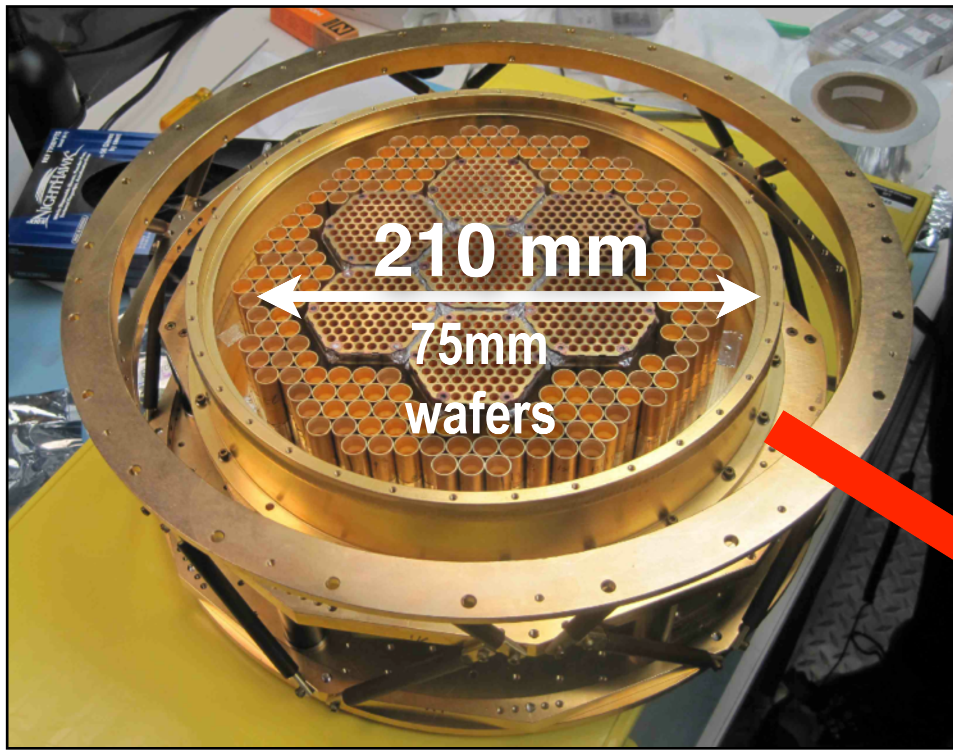
Going to Stage 3

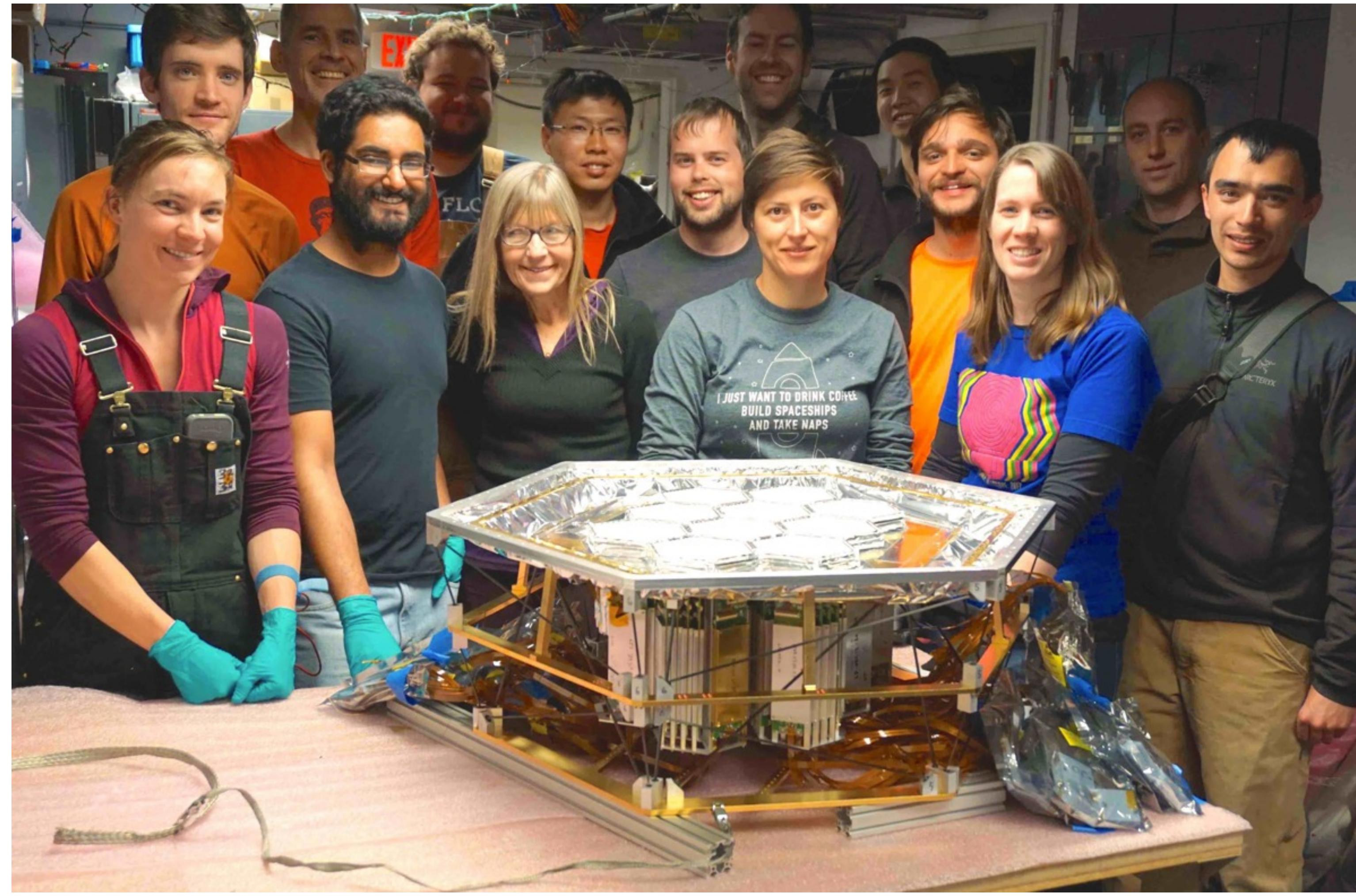


example Stage 2 to Stage 3:

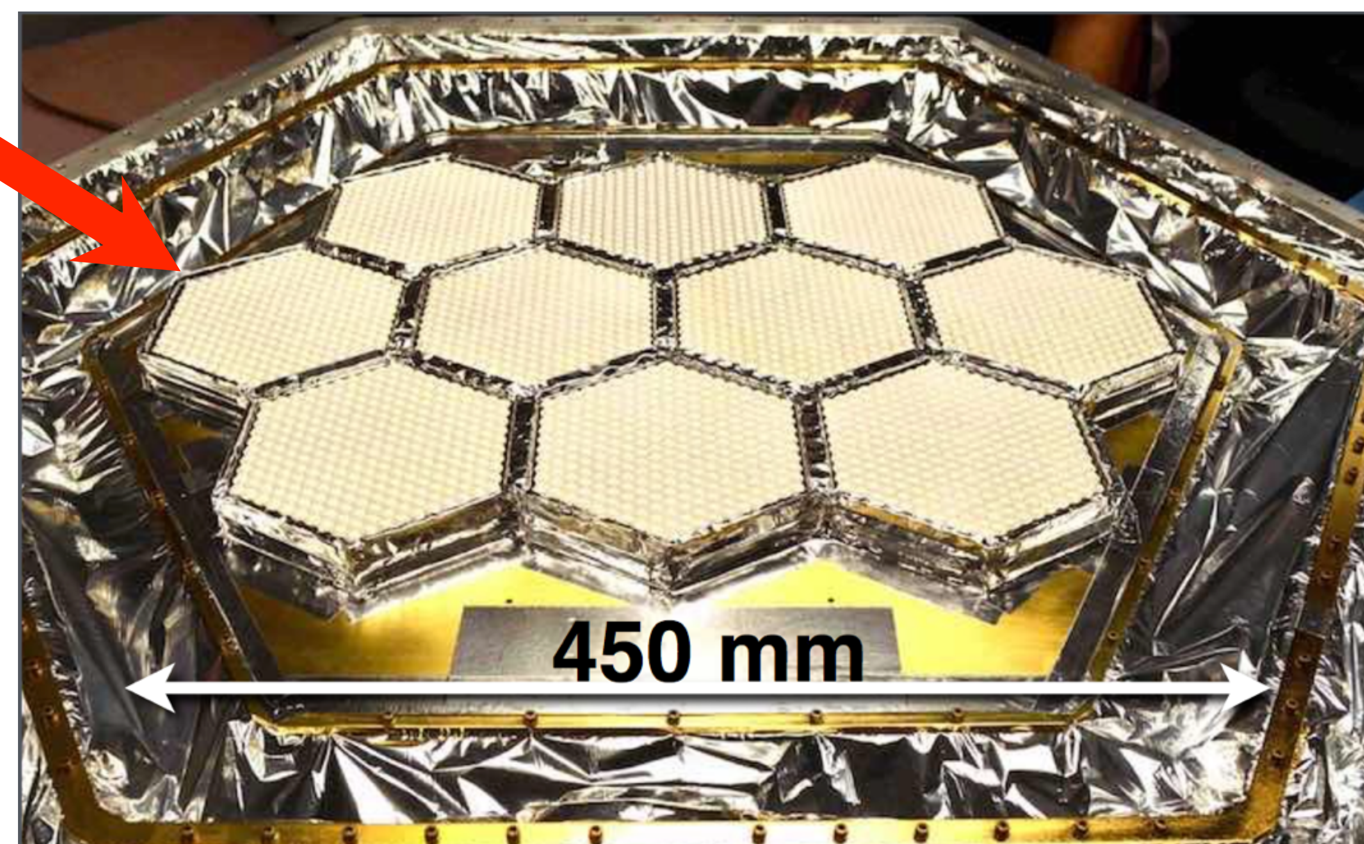
SPTpol → SPT-3G

2012: SPTpol Stage 2
1600 detectors (ANL/NIST)

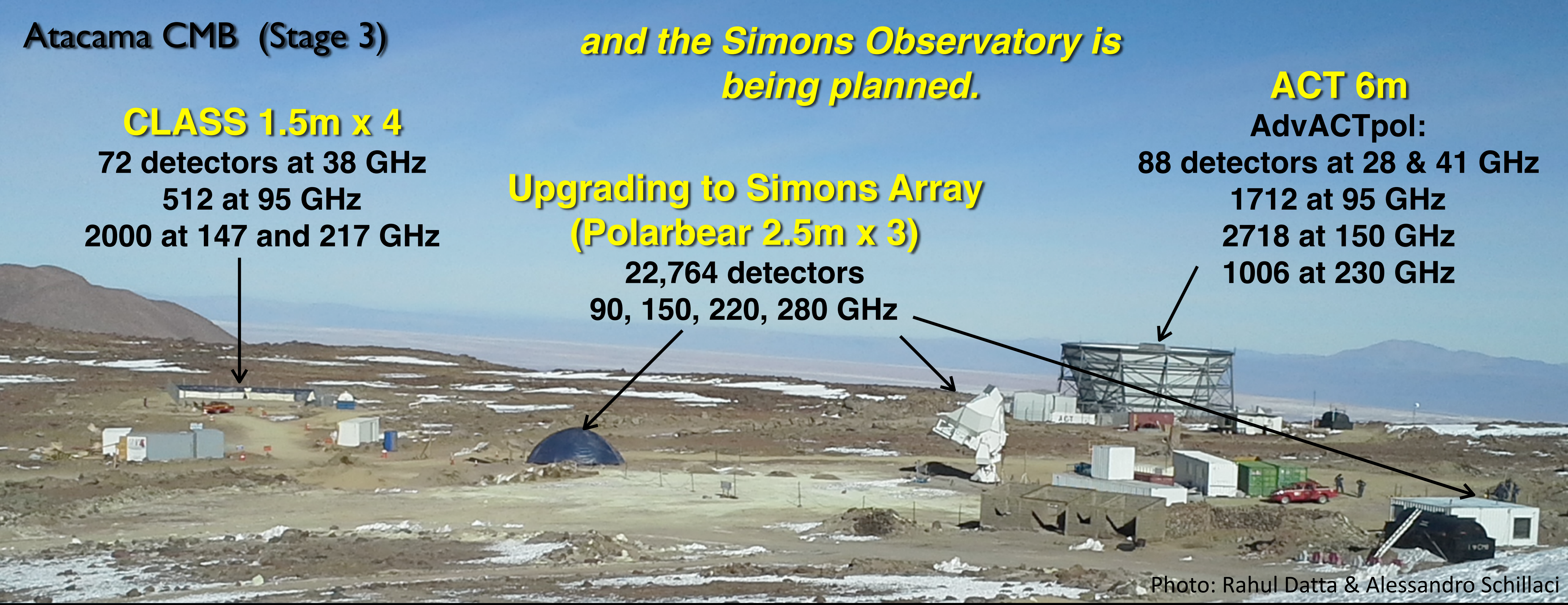


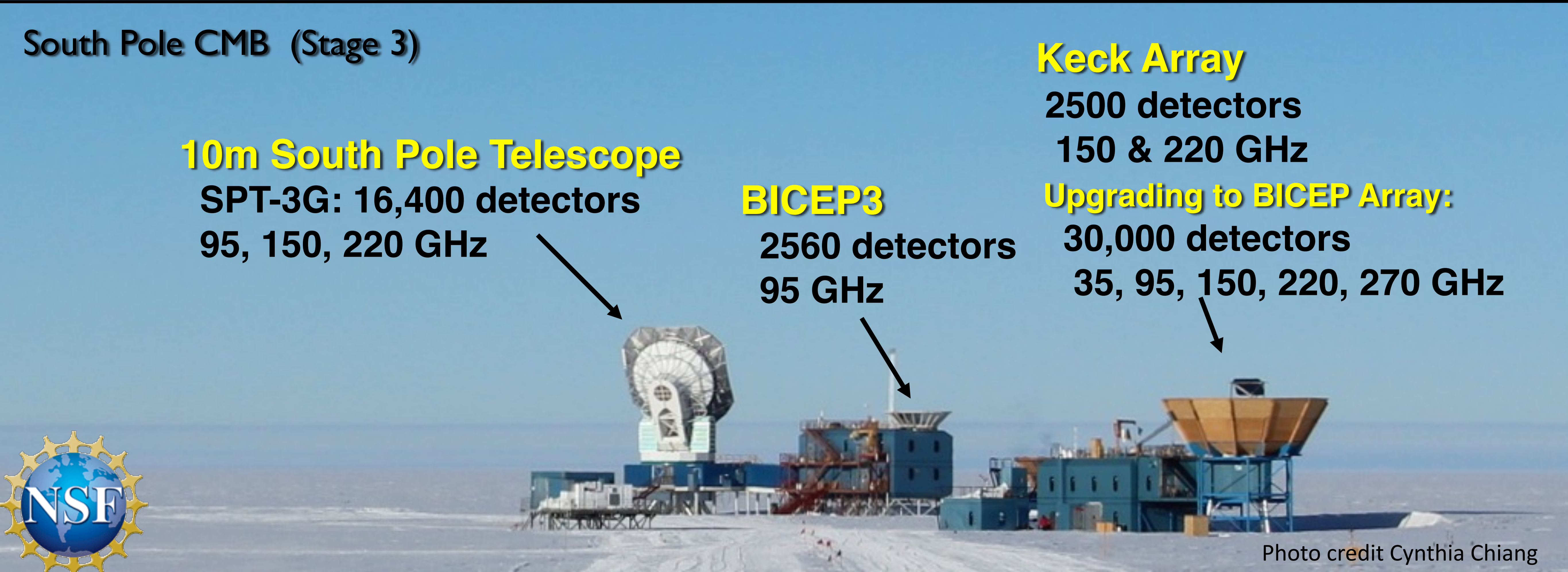


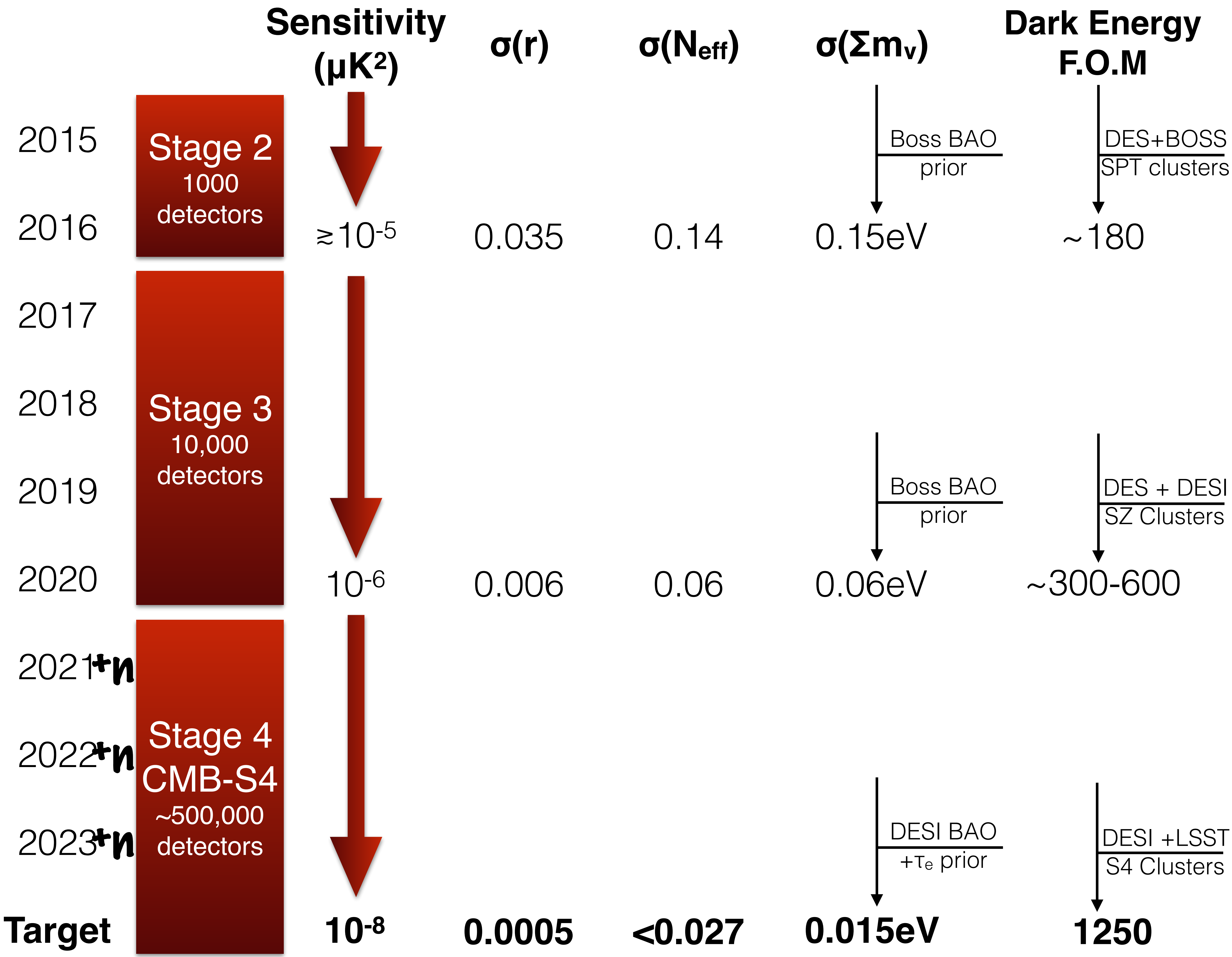
2017: SPT-3G Stage 3 4x larger area
16,000 detectors at T = 250mK



NSF U.S. DEPARTMENT OF ENERGY KAVLI GORDON AND BETTY MOORE FOUNDATION

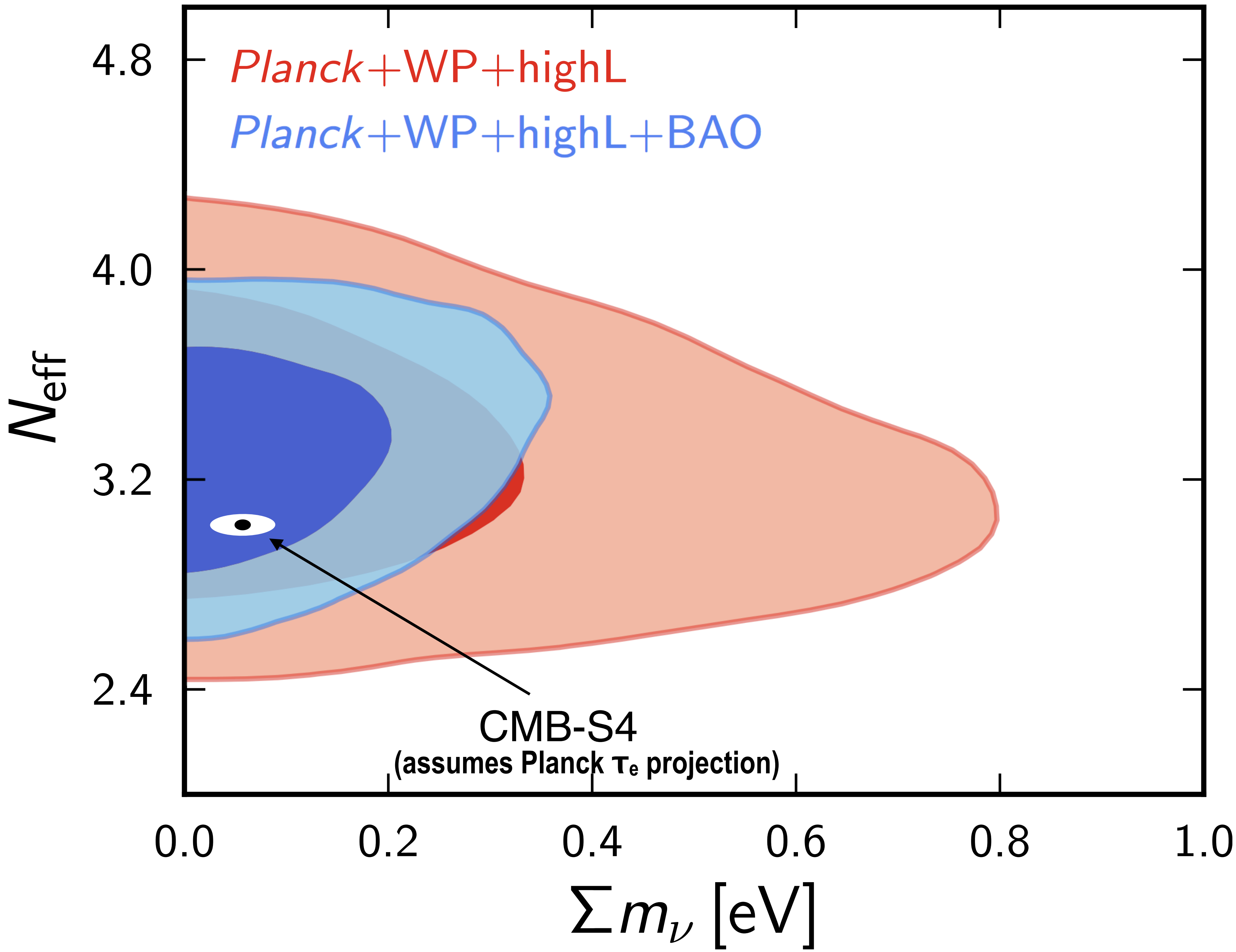

Atacama CMB (Stage 3)
and the Simons Observatory is being planned.
CLASS 1.5m x 4
72 detectors at 38 GHz
512 at 95 GHz
2000 at 147 and 217 GHz
Upgrading to Simons Array
(Polarbear 2.5m x 3)
22,764 detectors
90, 150, 220, 280 GHz
ACT 6m
AdvACTpol:
88 detectors at 28 & 41 GHz
1712 at 95 GHz
2718 at 150 GHz
1006 at 230 GHz
Photo: Rahul Datta & Alessandro Schillaci


South Pole CMB (Stage 3)
Keck Array
2500 detectors
150 & 220 GHz
Upgrading to BICEP Array:
30,000 detectors
35, 95, 150, 220, 270 GHz
10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz
BICEP3
2560 detectors
95 GHz
Photo credit Cynthia Chiang



Sensitivity (μK²)
σ(r)
σ(N_eff)
σ(Σm_ν)
Dark Energy F.O.M
2015
2016
2017
2018
2019
2020
2021+n
2022+n
2023+n
Target
Stage 2
1000 detectors
Stage 3
10,000 detectors
Stage 4
CMB-S4
~500,000 detectors
Boss BAO
prior
DES+BOSS
SPT clusters
≳10-5
0.035
0.14
0.15eV
~180
Boss BAO
prior
DES + DESI
SZ Clusters
10-6
0.006
0.06
0.06eV
~300-600
DESI BAO
+τe prior
DESI +LSST
S4 Clusters
10-8
0.0005
<0.027
0.015eV
1250

Projected CMB-S4 N_{eff} - Σm_ν constraints



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

CMB-S4
Next Generation CMB Experiment

Basic survey and design concept

- **Survey to target r**

  - Array of small-aperture (~1m) telescopes, and separate large-aperture telescopes for de-lensing focused on small (few percent), clean patch of sky

  - 250,000 detectors x 4 years → 10^6 detector years split over several frequency bands

  → optimized split of small and large telescopes effort, sky area, residual lensing noise, detector count, band selection for foreground mitigation

- **Survey to target non-r**

  - Array of large-aperture telescopes, with 10^6 detector years with several frequency bands

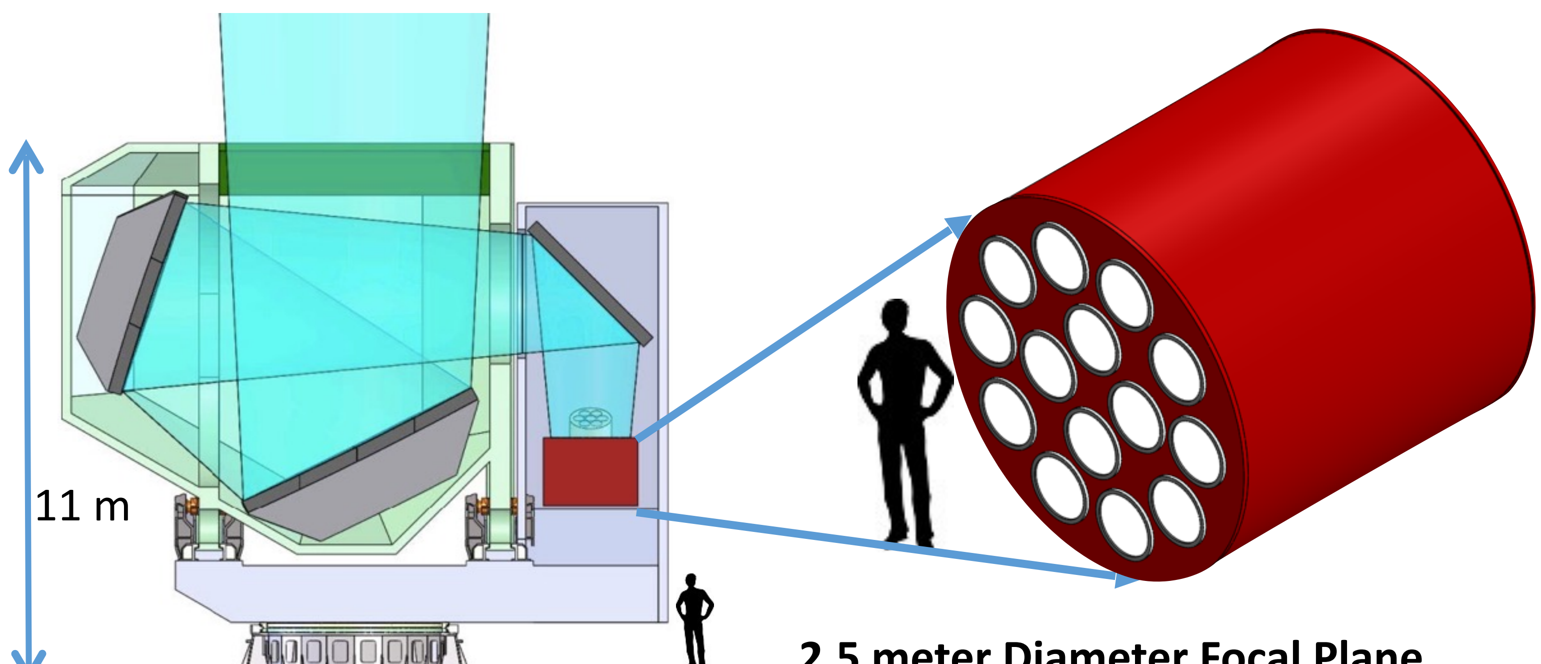
  - useable sky fraction, f_{sky} = 40%

  → provide angular resolution, sky coverage, and detector count for neutrino, light-relic, dark energy, and other science goals

CMB-S4
Next Generation CMB Experiment

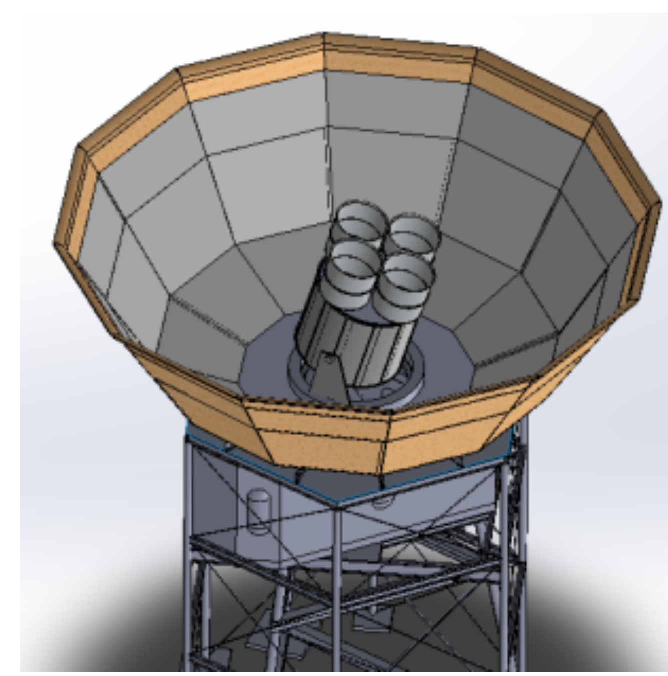
Strawman CMB-S4 configuration

- 500,000 Detectors (Stage 3 experiments have ~10,000 detectors)
- ~8 Frequency Bands for CMB and Foreground Removal
- Telescopes sized to address B-mode, de-lensing and high-ℓ science



e.g., 6 meter Diameter Telescope

2.5 meter Diameter Focal Plane with 100,000+ detectors



High resolution Science + de-lensing:
300,000 Detectors on <u>3-4 large telescopes</u>

Low resolution B-mode Science:
200,000 Det. on ~<u>12 small telescopes</u>

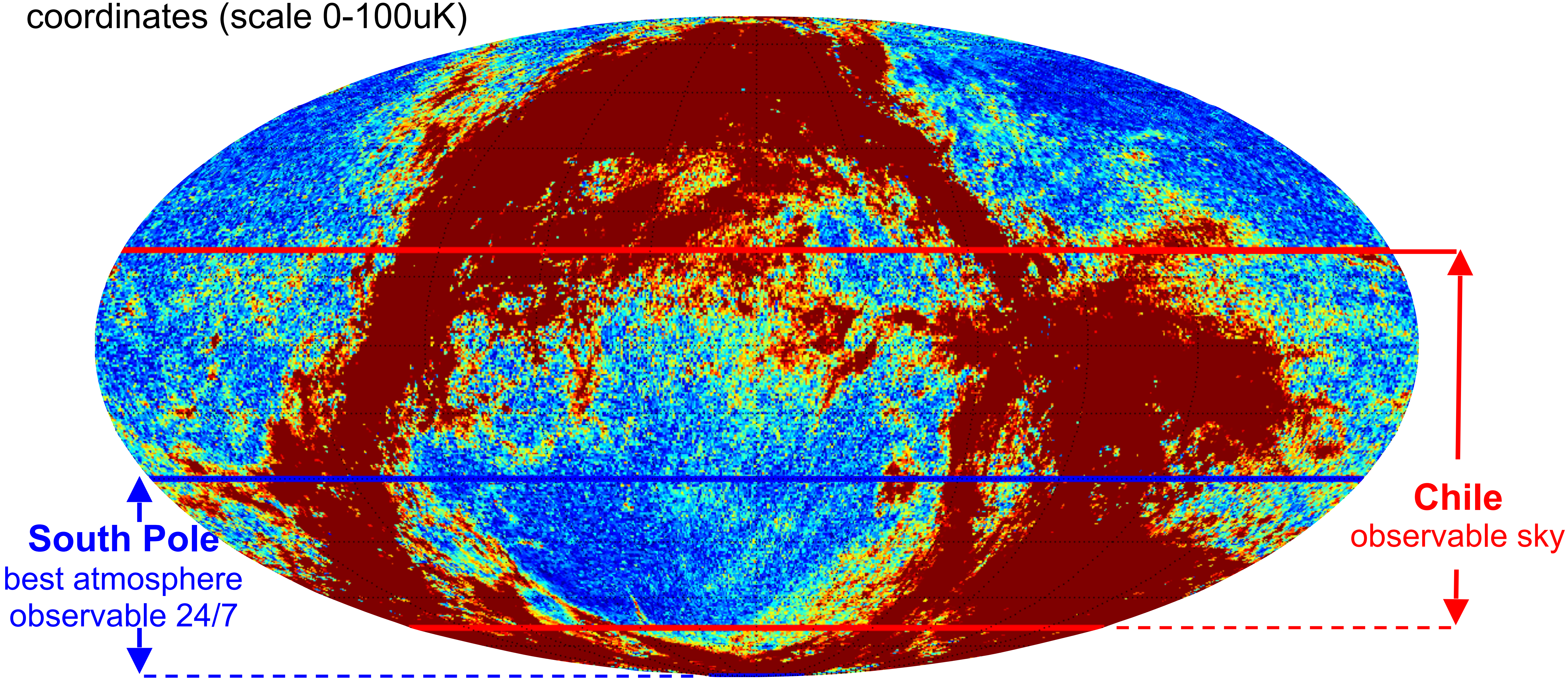
Figure from Mark Devlin / Mike Niemack

Figure from BICEP Array

CMB-S4
Next Generation CMB Experiment

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

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



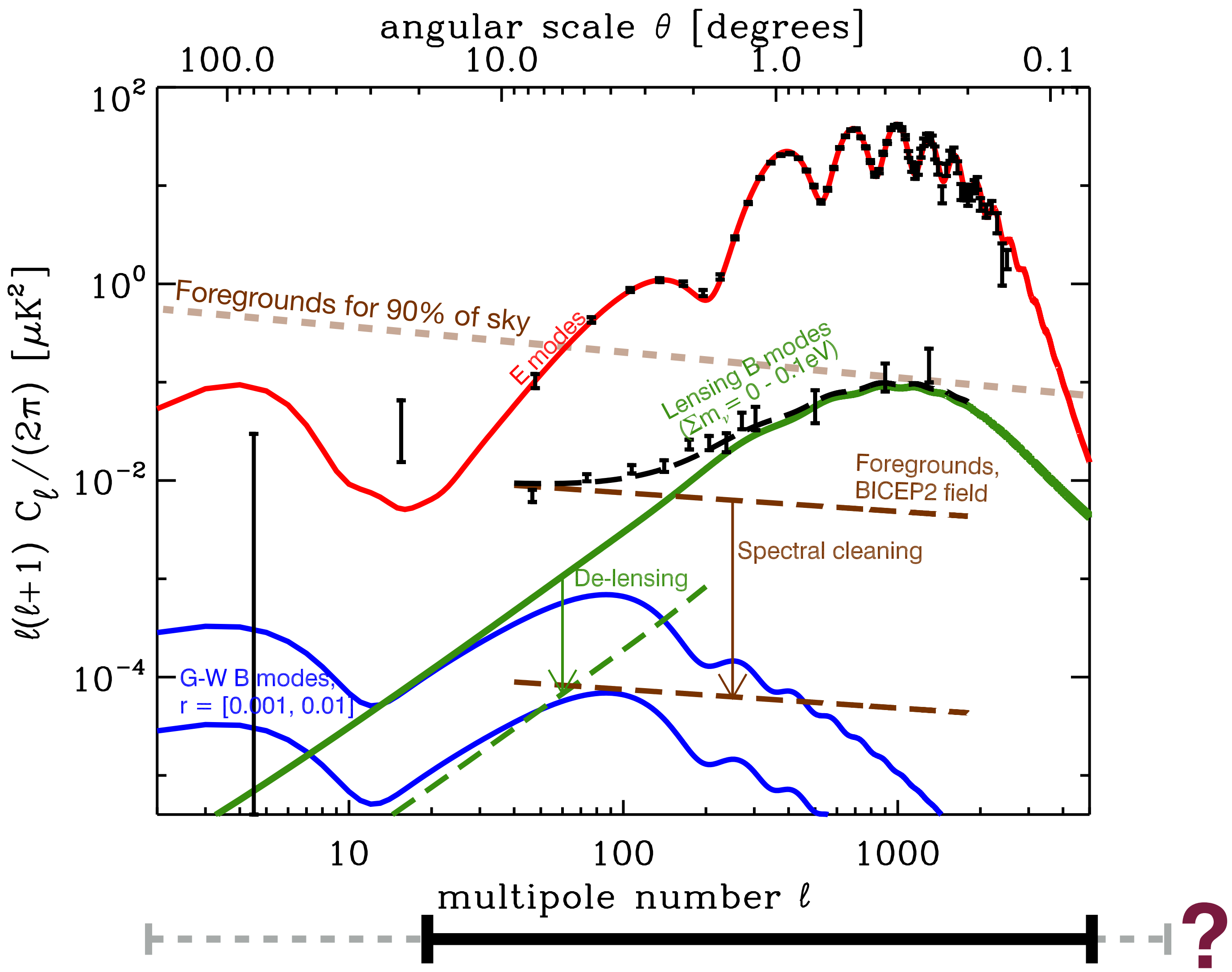
open to adding northern site, e.g., Tibet, Greenland

Figure from Clem Pryke

CMB-S4
Next Generation CMB Experiment

Angular range of CMB-S4

- Inflationary B modes search requires exquisite sensitivity at recombination bump ($\ell \sim 100$) and high-ℓ for de-lensing.
- High-ℓ and large area for CMB lensing cosmic variance limited constraints on neutrino mass and N_{eff}
- <u>Higher-ℓ</u> for clusters, dark energy, gravity tests, reionization, feedback of baryonic physics from SZ effects



ℓ range of CMB-S4

High-ℓ reach still being debated.

Inflation, N_{eff}, Neutrinos only need $\lesssim$ 2 arcm ($\ell_{max} \sim 5000$)

Back to the CMB-S4 high-ℓ science case

1. **Dark Energy / Modified Gravity / Neutrino masses**
   - SZ galaxy cluster counts (dN/dz) to z~3
   - mass calibration with CMB-lensing at % level
   - evolution of amplitude $\sigma_8(z)$ at % level
2. **The evolution of massive clusters, cluster astrophysics**
   - Unique SZ catalog of clusters at z > 1.5
3. **Tracing baryons with kSZ and tSZ**
   - Thermodynamics of the circumgalactic medium out to the peak of cosmic star formation
   - Impact of feedback on the matter power spectrum, P(k)
4. **Patchy Reionization with kSZ**

CMB-S4
Next Generation CMB Experiment

Strawman Specifications for CMB-S4 high-ℓ projections

	Stage-3 CMB	CMB-S4-3.0′	CMB-S4-2.5′	CMB-S4-2.0′	CMB-S4-1.5′	CMB-S4-1.0′
Frequency (GHz)	Beam (arcminutes)					
21	-	21.4	17.9	14.3	10.7	7.1
29	7.1	15.5	12.9	10.3	7.8	5.2
40	4.8	11.2	9.4	7.5	5.6	3.8
95	2.2	4.7	4.0	3.2	2.4	1.6
150	1.3	3.0	2.5	2.0	1.5	1.0
220	0.9	2.0	1.7	1.4	1.0	0.7
270	-	1.7	1.4	1.1	0.8	0.6

	Stage-3 CMB	CMB-S4				
	$f_{\rm sky} = 0.4$	$f_{\rm sky} = 0.7$	$f_{\rm sky} = 0.4$	$f_{\rm sky} = 0.2$	$f_{\rm sky} = 0.1$	$f_{\rm sky} = 0.05$
Frequency (GHz)	Noise RMS (μK-arcmin)					
21	-	10.4	7.9	5.6	4.0	2.8
29	80.0	7.4	5.6	4.0	2.8	2.0
40	70.0	7.2	5.4	3.8	2.7	1.9
95	8.0	2.0	1.5	1.1	0.8	0.5
150	7.0	2.0	1.5	1.1	0.8	0.5
220	25.0	6.9	5.2	3.7	2.6	1.8
270	-	11.8	8.9	6.3	4.5	3.2

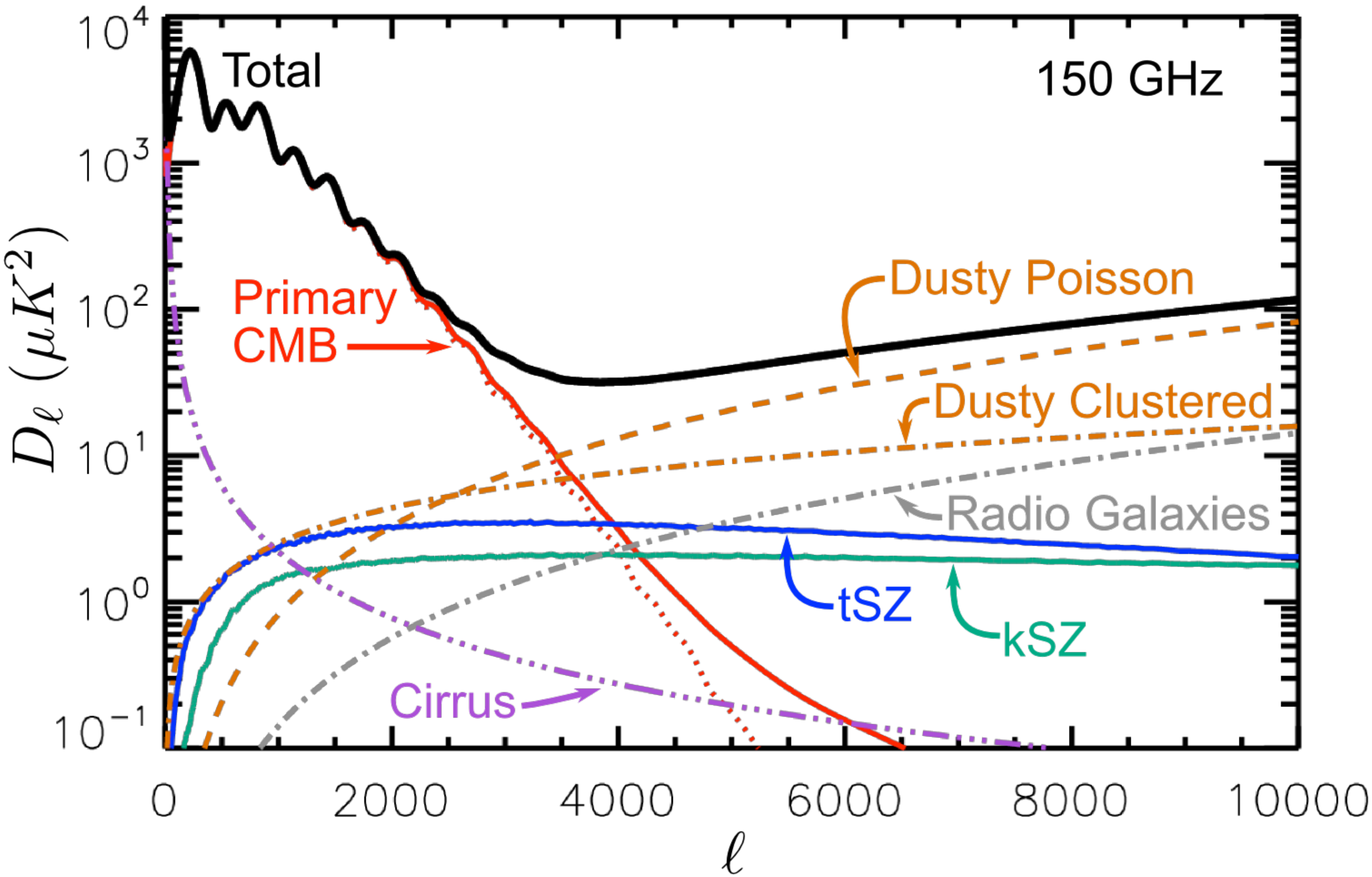
CMB-S4 LSS working group: S. Allen, M.A. Alvarez, J.G. Bartlett, N. Battaglia, B. Benson, L. Bleem, S. Bocquet, J.R. Bond, T. Crawford, S. Ferraro, C. Hill, M. Madhavacheril, A. Mantz, J.-B. Melin, E. Schaan, D. Spergel, D. Rapetti, **ET AL.**

CMB-S4

Next Generation CMB Experiment

Small angular scale anisotropy is dominated by foregrounds.

And desired signal is in TT, not polarization.



Need to use tricks to get the desired signals out; i.e., filtering, multiple frequency bands, cross-correlations, templates…

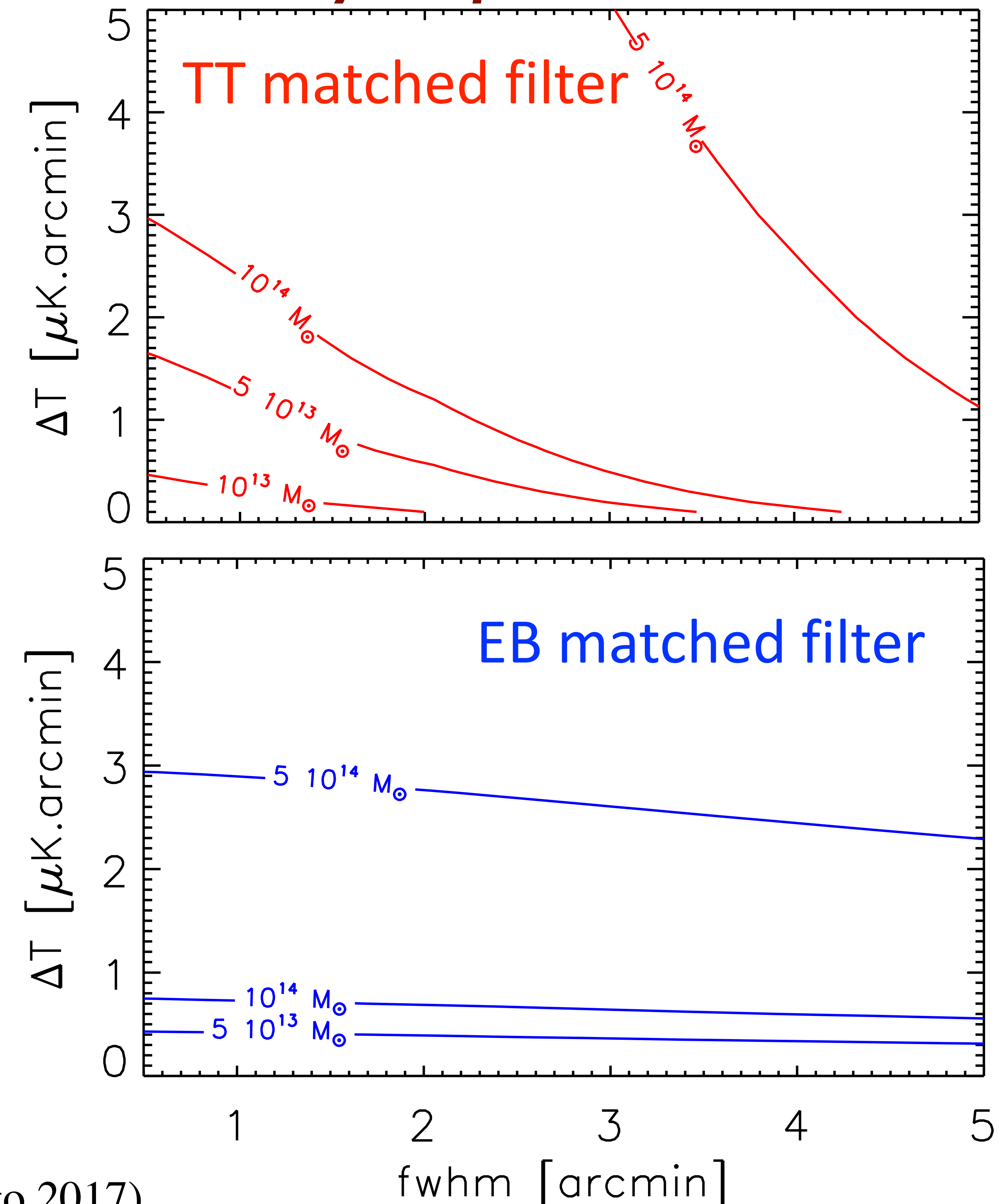
CMB-S4

Next Generation CMB Experiment

Cluster lensing

Resolution & Sensitivity requirements

1-sigma CMB lensing mass contours at z = 0.5 for TT & EB estimators



- TT drives lensing sensitivity at these scales, versus EB at large scales
  - requires high sensitivity and arc minute resolution.
  - requires more freq bands for foreground mitigation than EB

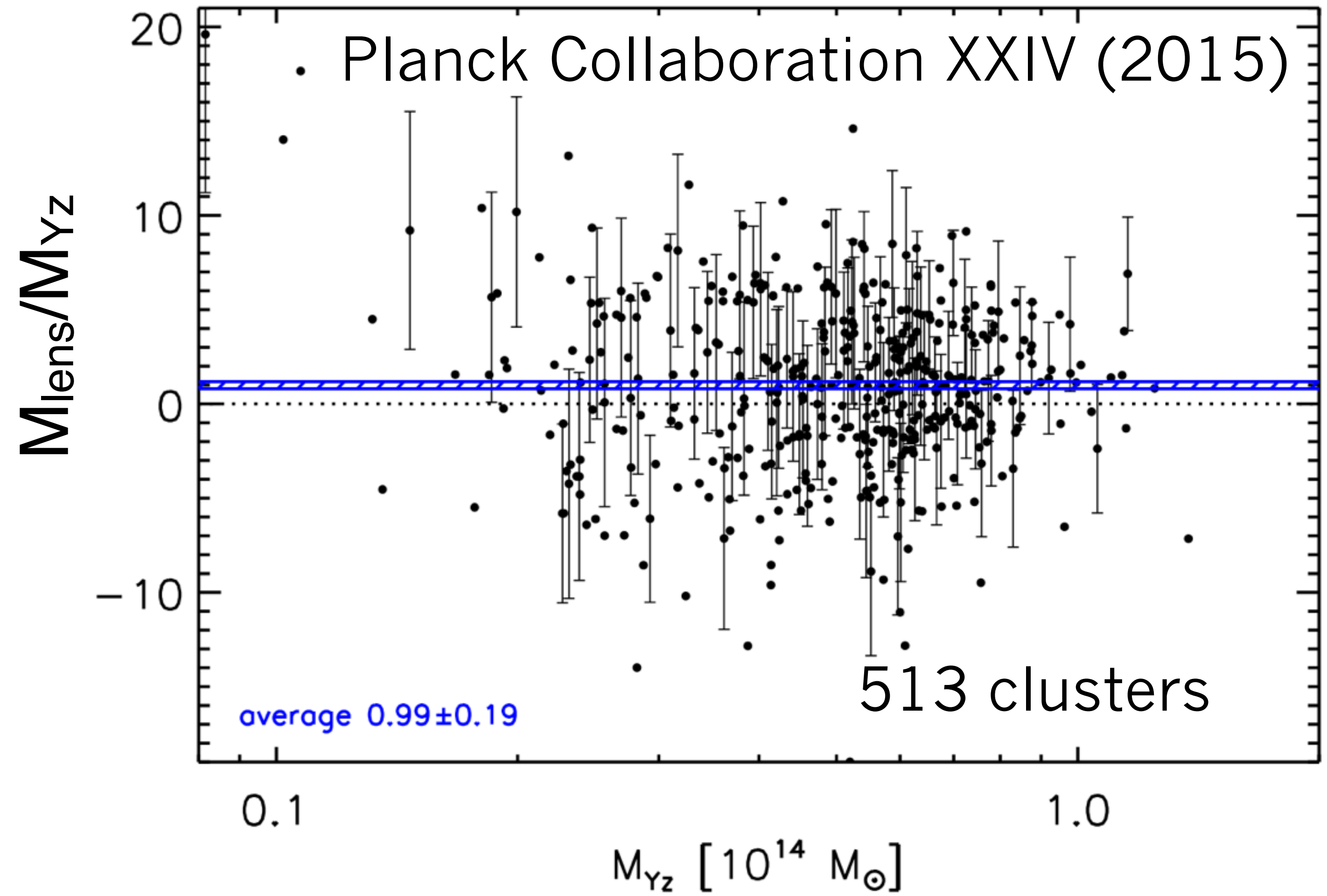
From Melin & Bartlett (CMB-S4 workshop Chicago 2017)

CMB-S4
Next Generation CMB Experiment

CMB-lensing of SZ clusters

439 *Planck* 2015 clusters and CMB-lensing map

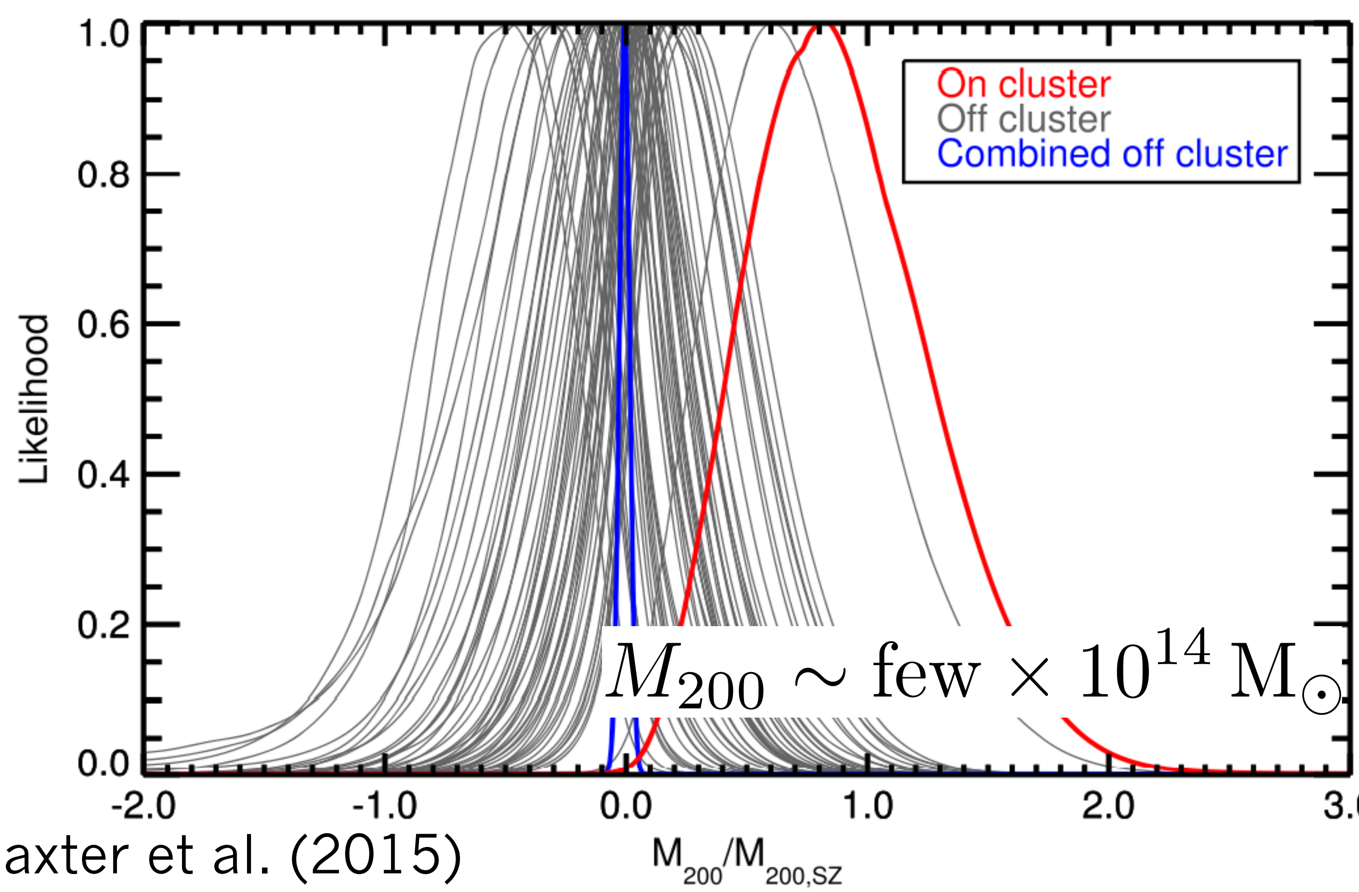
Detection: 5σ



513 SPT clusters

Fit lensing model with noisy tSZ-cleaned CMB map

Detection: 3.1σ



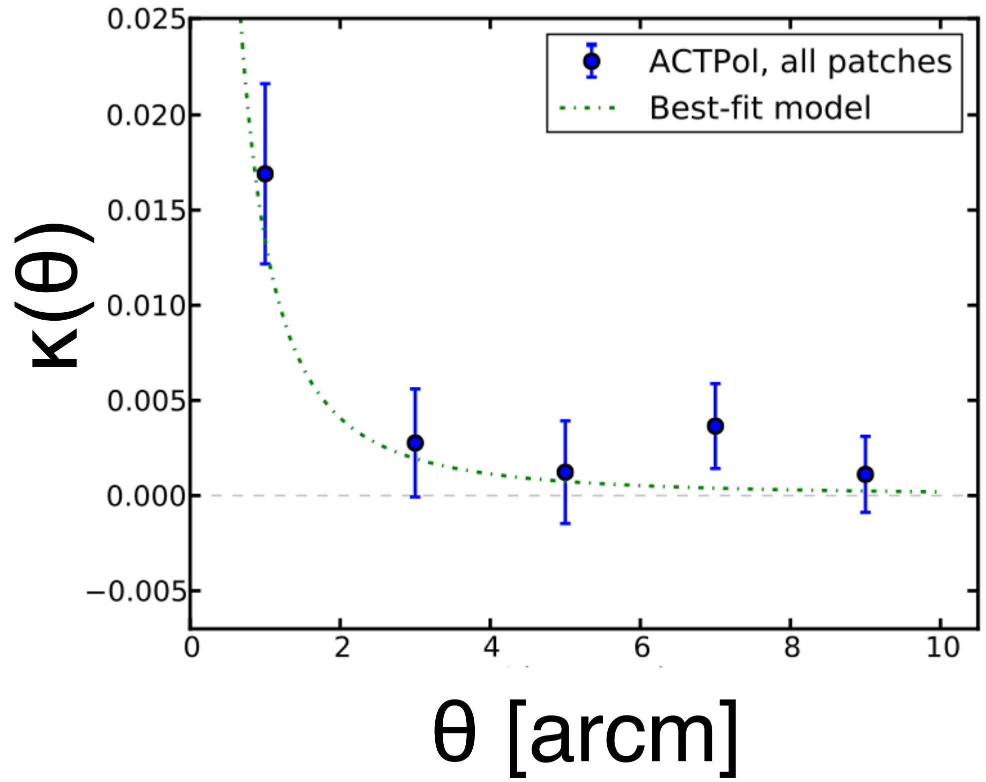
SPT Baxter et al. (2015)

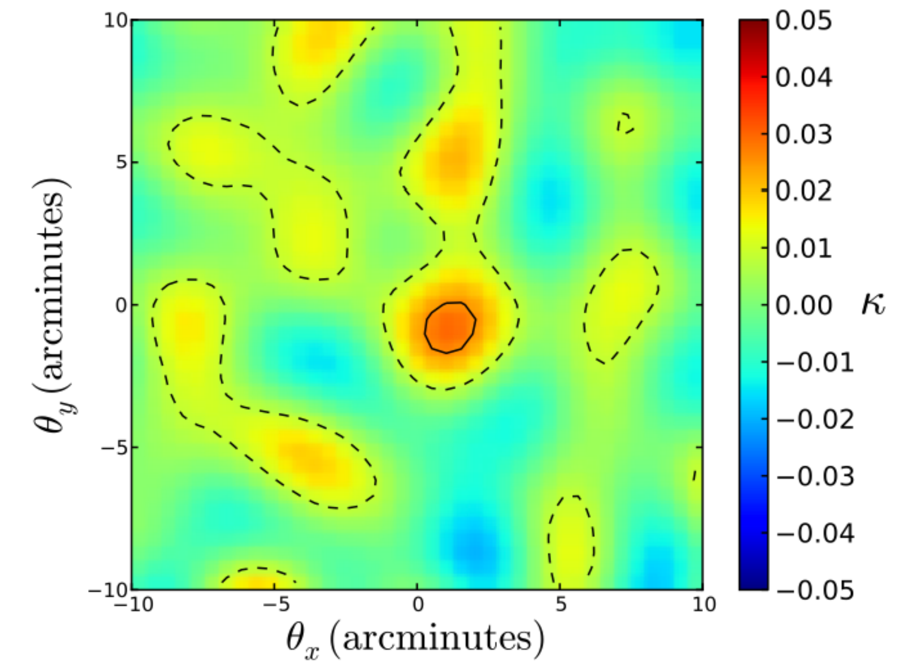
ACT & SPT stacked cluster lensing

ACTPol deep fields CMBlensing stacked on 12,000 CMASS galaxies,
$M_{200} \sim 2\times10^{13}$ halos

Detection: 3.2σ

Madhavacheril et al. (2015)

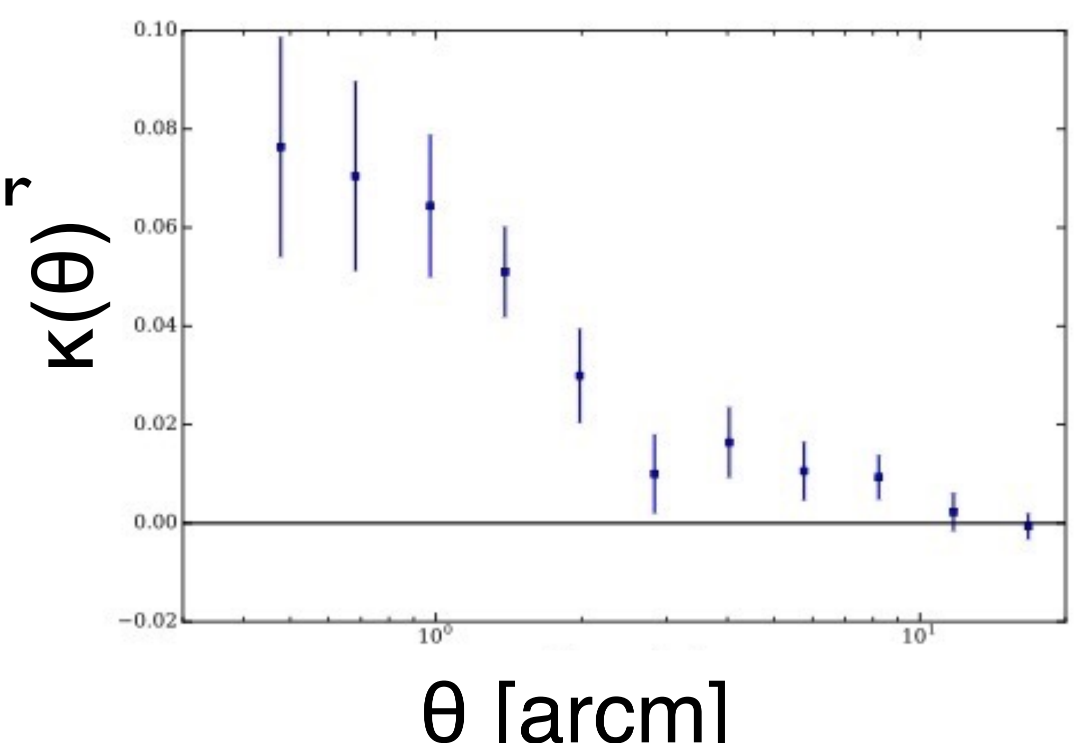


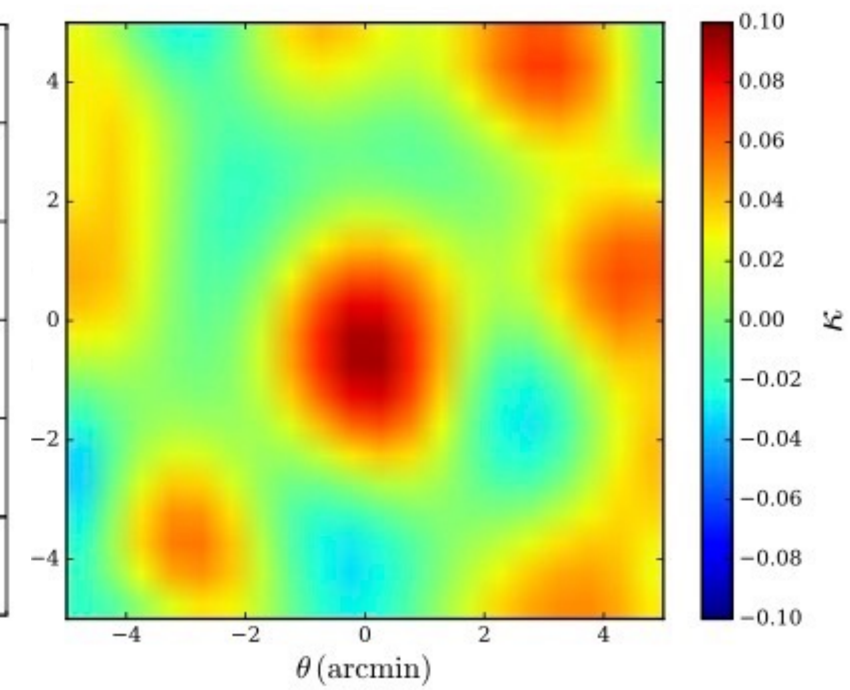


SPT-SZ lensing stacked on 4000 DES redMaPPer
$20 < \lambda < 40$ clusters
$\langle M_{200}\rangle = 1.6\pm0.35 \times10^{14}$

Detection: 6.0 σ

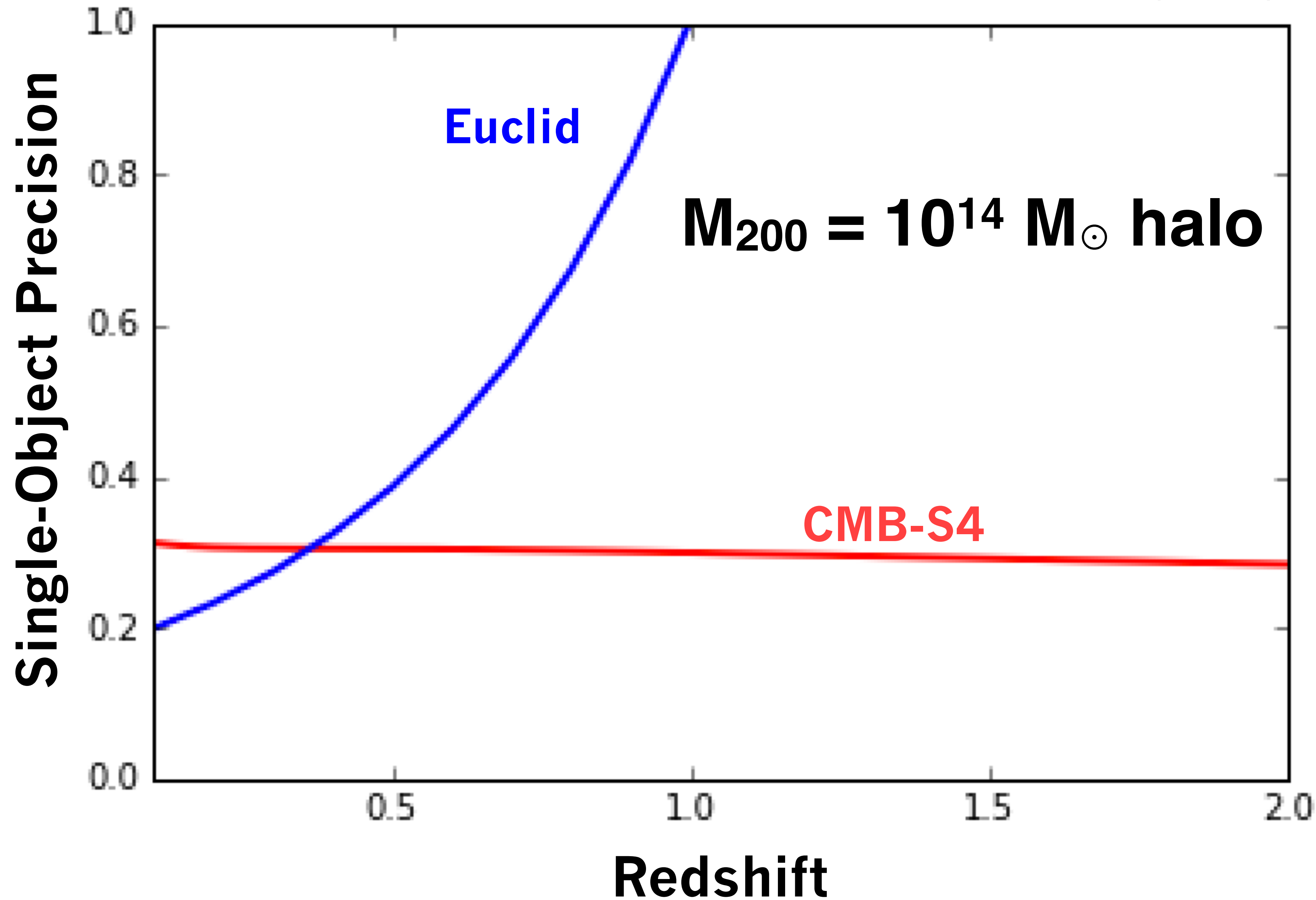
Baxter et al. in prep (2017)





Euclid & CMB-S4 lensing

Melin & Bartlett (2017)



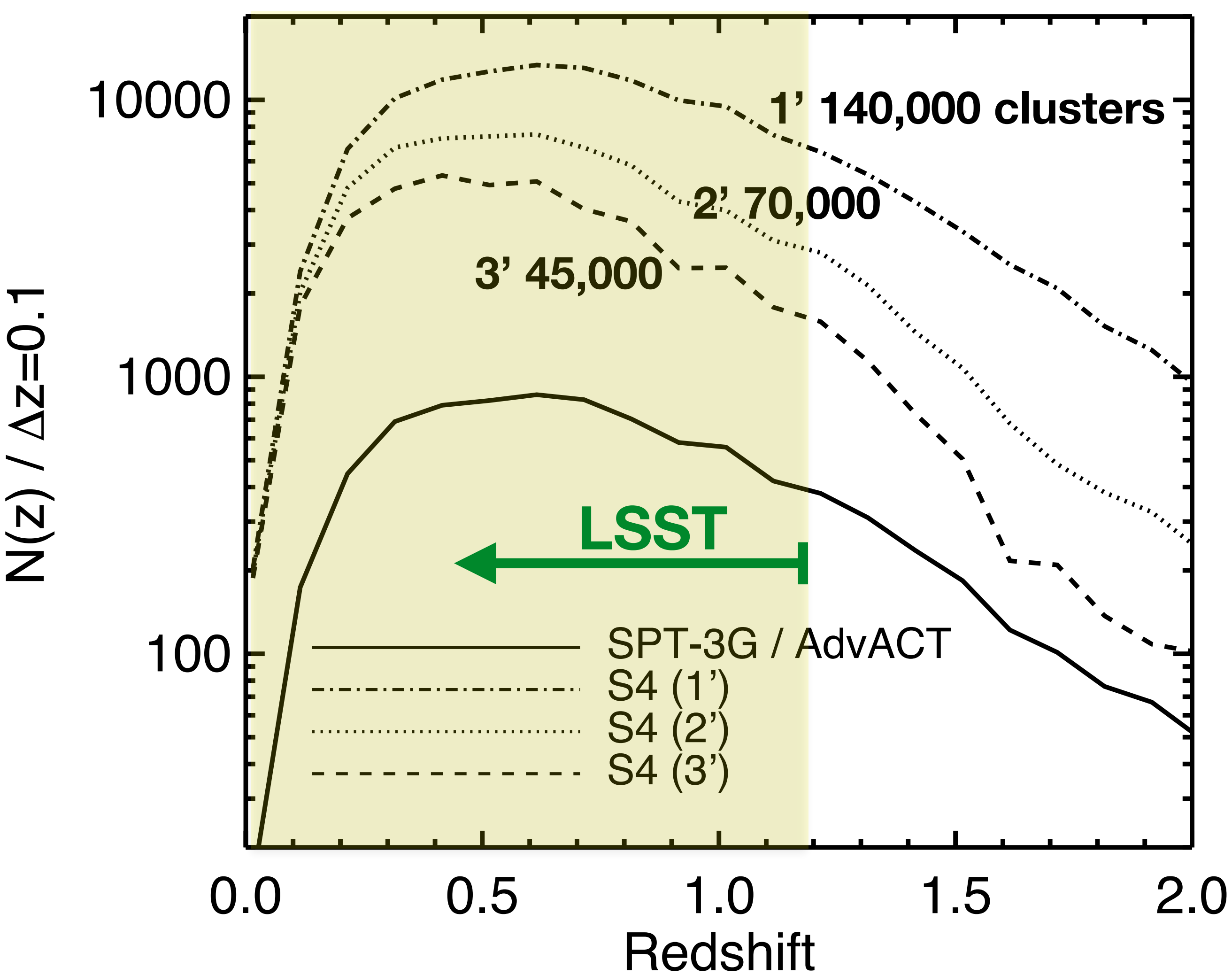
From Melin & Bartlett (CMB-S4 workshop Chicago 2017)

CMB-S4

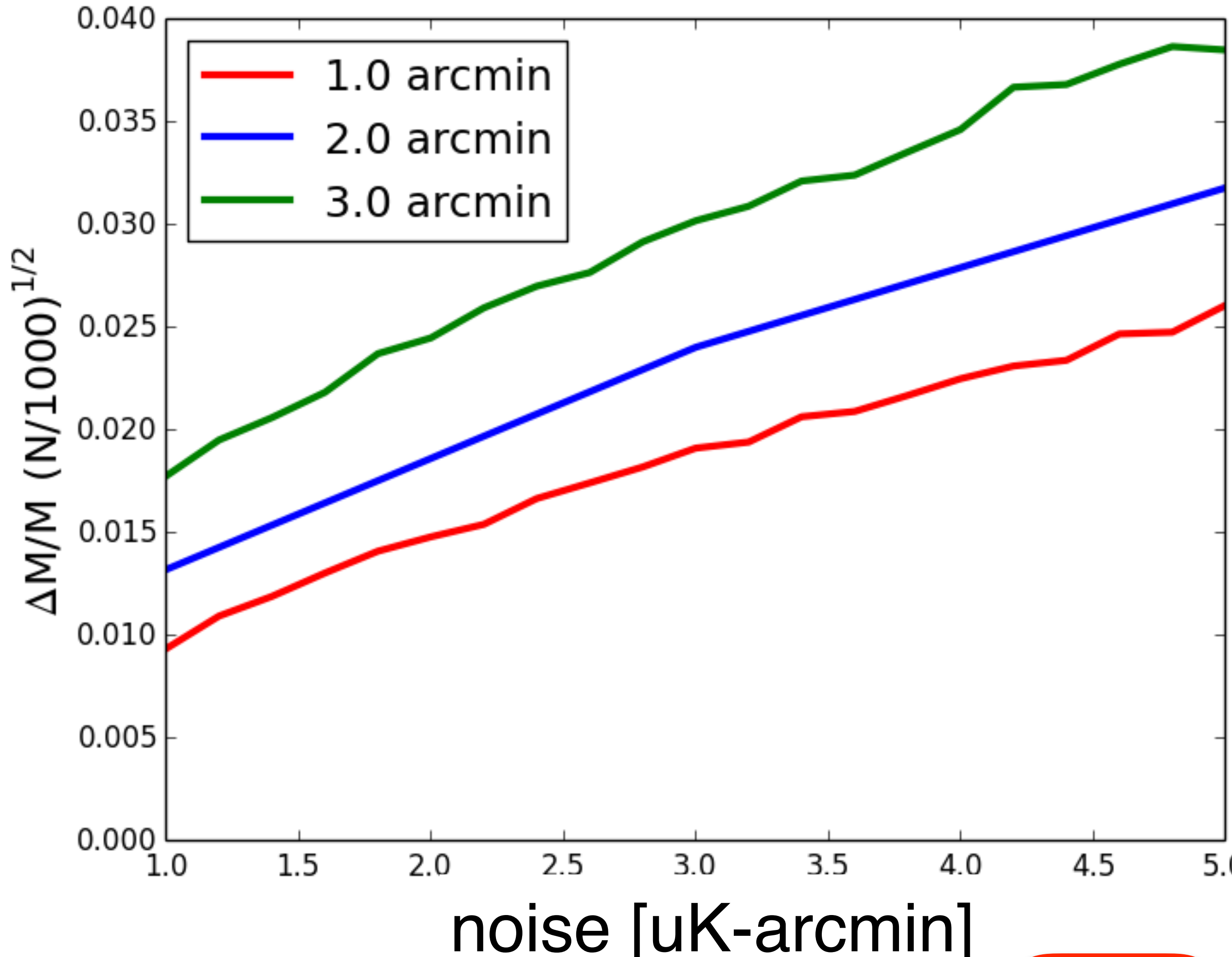
Next Generation CMB Experiment

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



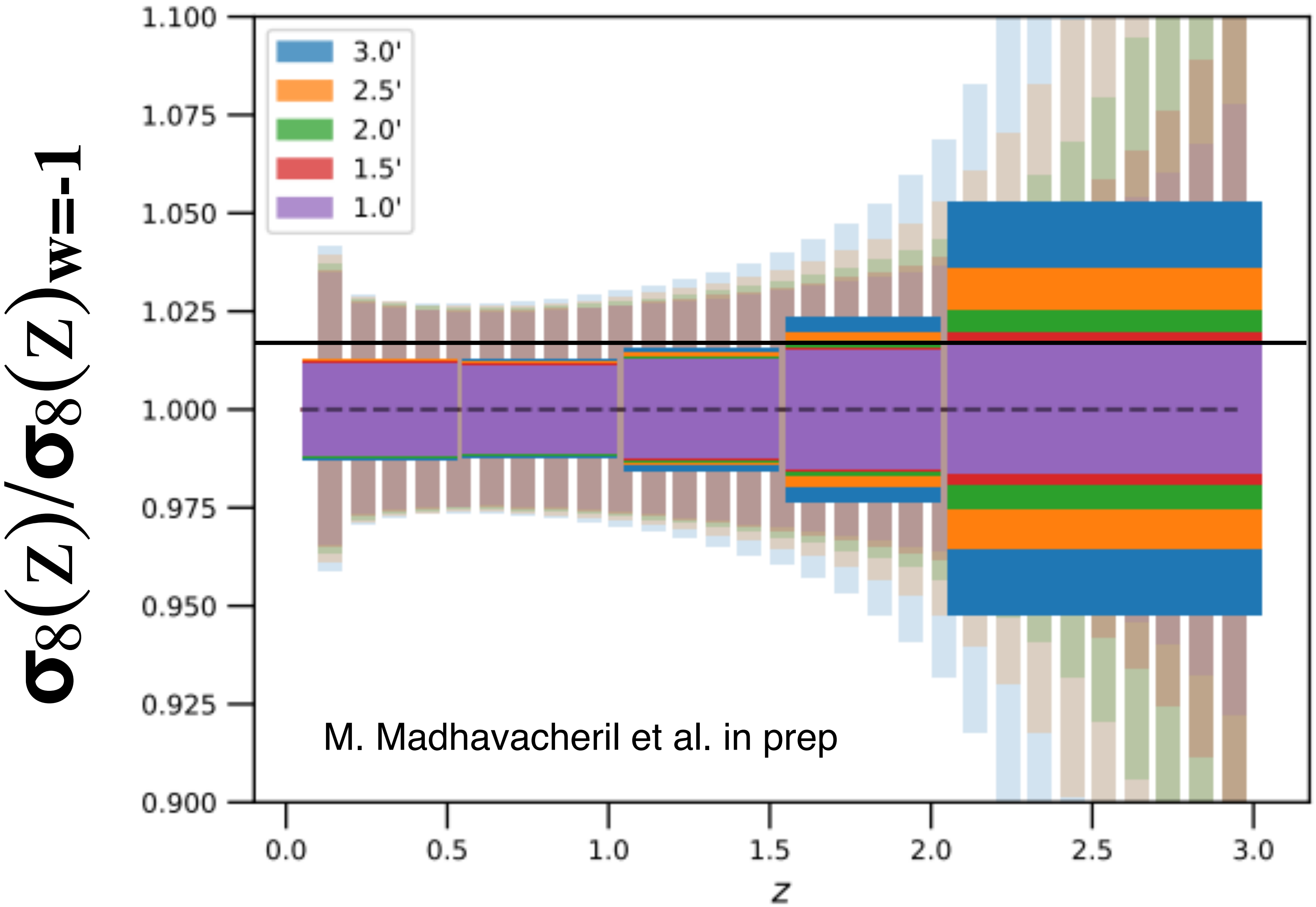
CMB-S4 will provide the definitive survey of massive, high-z clusters (z>1) with “built in” mass calibration

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

CMB-S4
Next Generation CMB Experiment

Growth of Structure, $\sigma_8(z)$



$\sigma_8(z)$ "coupled" case:

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

$\sigma_8(z)$ "decoupled" summary

Fit scaling relation to high z only

	z > 1.2	z > 1.5	1.5 < z <2.0	z > 2.0
3.0'	15%	48%	57%	414%
2.0'	5%	12%	14%	83%
1.5'	3%	6%	7%	
1.0'	2%	4%	5%	18%

From CMB-S4/CDT LSS Working Group

CMB-S4
Next Generation CMB Experiment

Growth of Structure, $\sigma_8(z)$

Provides cluster-based constraints on dark energy, modified gravity, and neutrino mass.
e.g., $\sigma(\Sigma m_\nu)$ ~ 30 meV simultaneously with dark energy equation of state, ***and without other LSS data***.

	1.5'	1.0'	1.5'+ DESI BAO	1'+ DESI BAO
ΛCDM + Σm_ν	**31.9 meV**	**31 meV**	**24.9 meV**	**24.8 meV**
ΛCDM + Σm_ν +w	**33.2 meV**	**32.3 meV**	**30.2 meV**	**29.4 meV**
ΛCDM + Σm_ν +w + w_a	**33.5 meV**	**32.5 meV**	**30.2 meV**	**29.4 meV**

From N. Battaglia and M.Madhavacheril: https://cmb-s4.org/CMB-S4workshops/index.php/SZ_Clusters_update

Cluster Pairwise kSZ

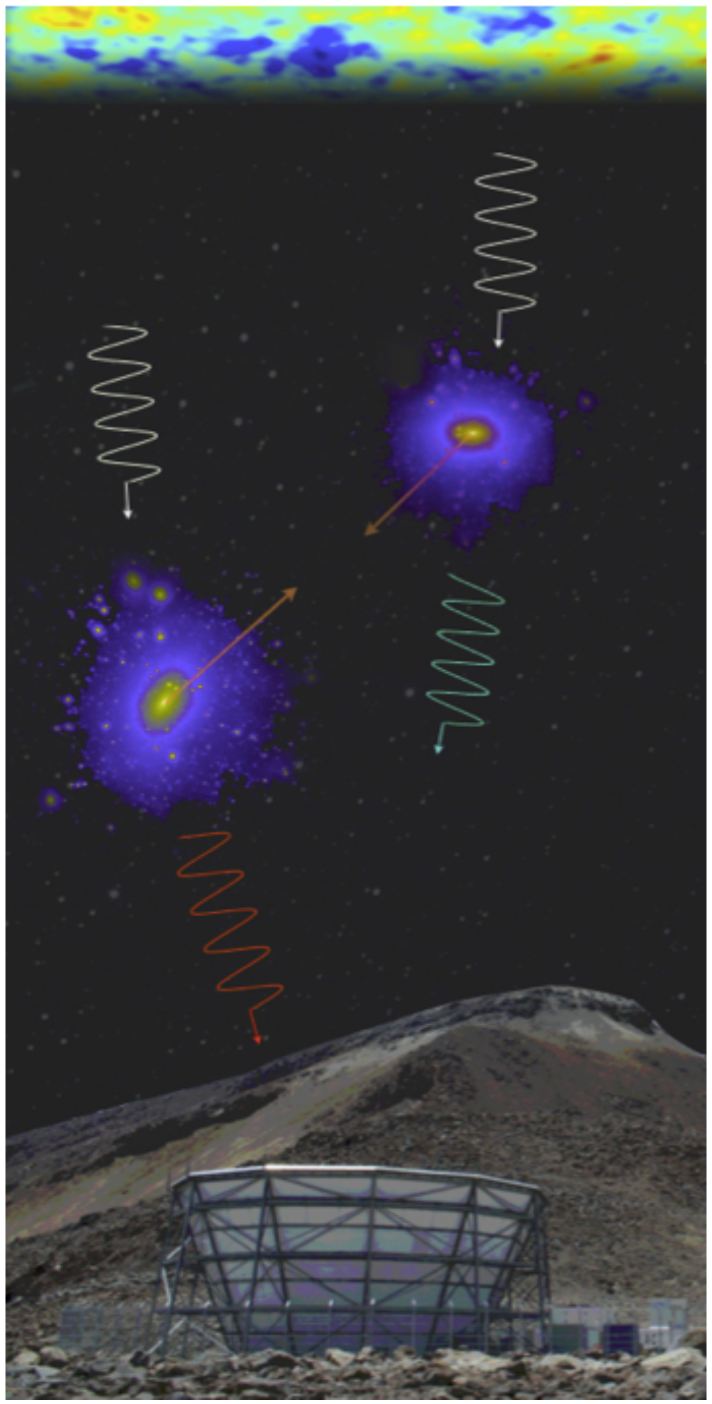


Image from ACT (S. Staggs)

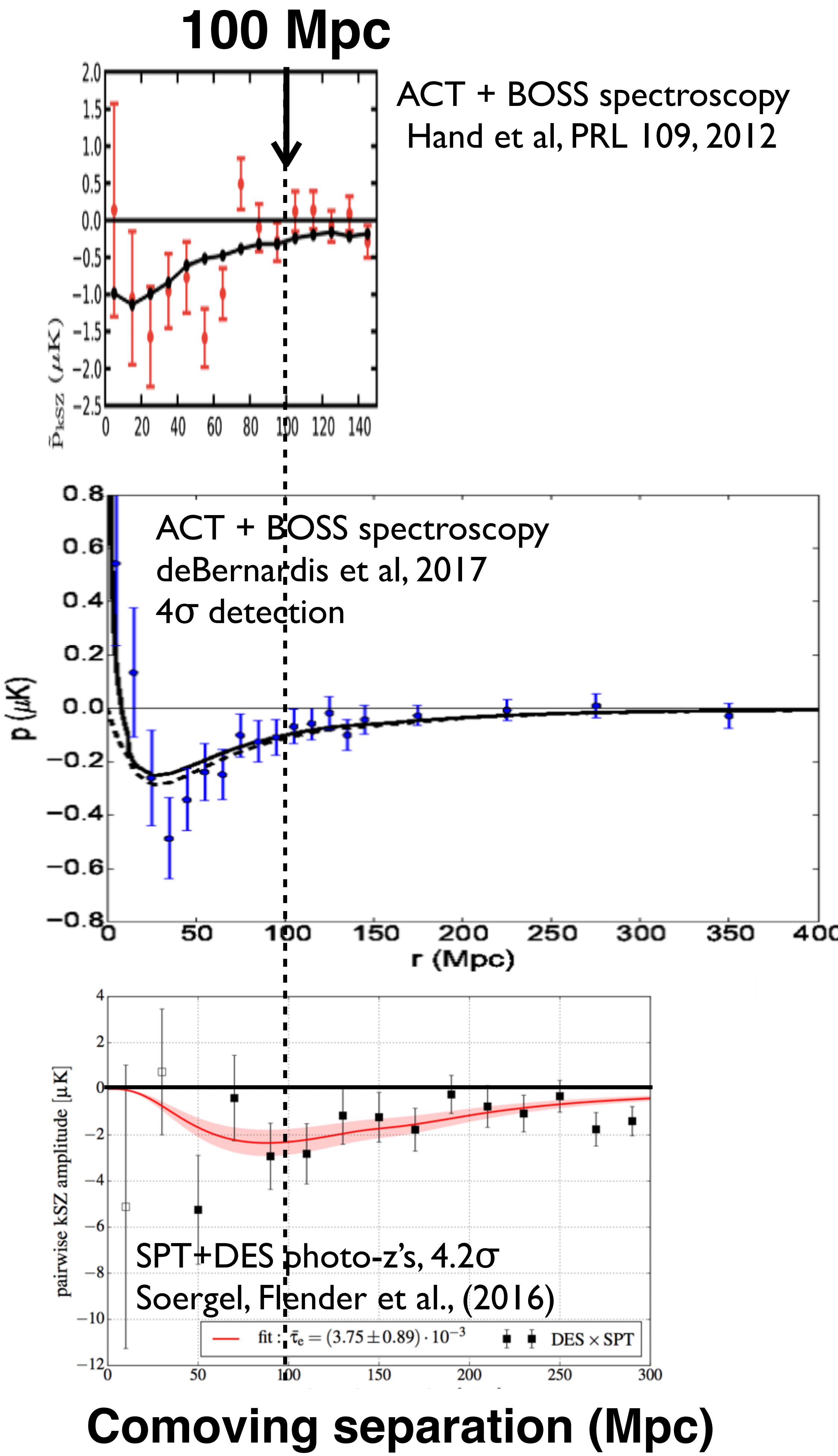
Galaxy clusters tend to fall towards each other (w.r.t. Hubble Flow)

For a given pair there will be a differential CMB signal from the kSZ effect.

Could use to test gravity, probe structure, on large scales (100 Mpc)

First 3-4σ detections achieved

CMB-S4 will make detection of ~500σ



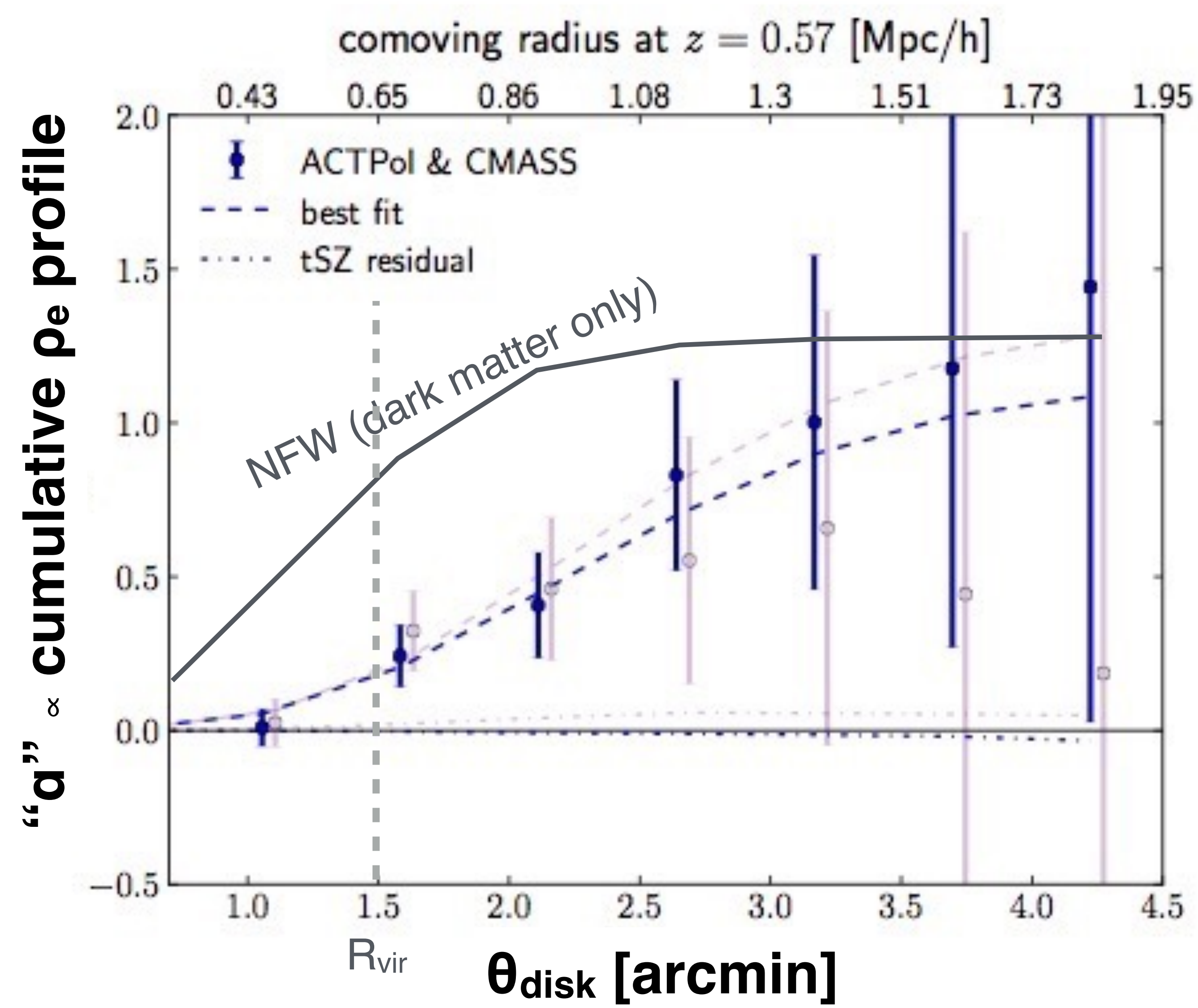
See also Planck kSZ pairwise data (arXiv:1504.03339)

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.

CMB-S4
Next Generation CMB Experiment

Measuring impact of baryon feedback

1. The thermal SZ effect directly probes the thermal energy profiles of the CGM (ICM).

2. The kinematic SZ effect probes the density (tau) profiles of CGM (ICM) (kSZ > tSZ for $M < 10^{13} M_\odot$ and $v_{pec} \sim 100$ km/s)

3. CMB lensing measures total host halo mass.

CMB-S4 stacked tSZ, kSZ and CMB-lensing measurements will allow determination of the

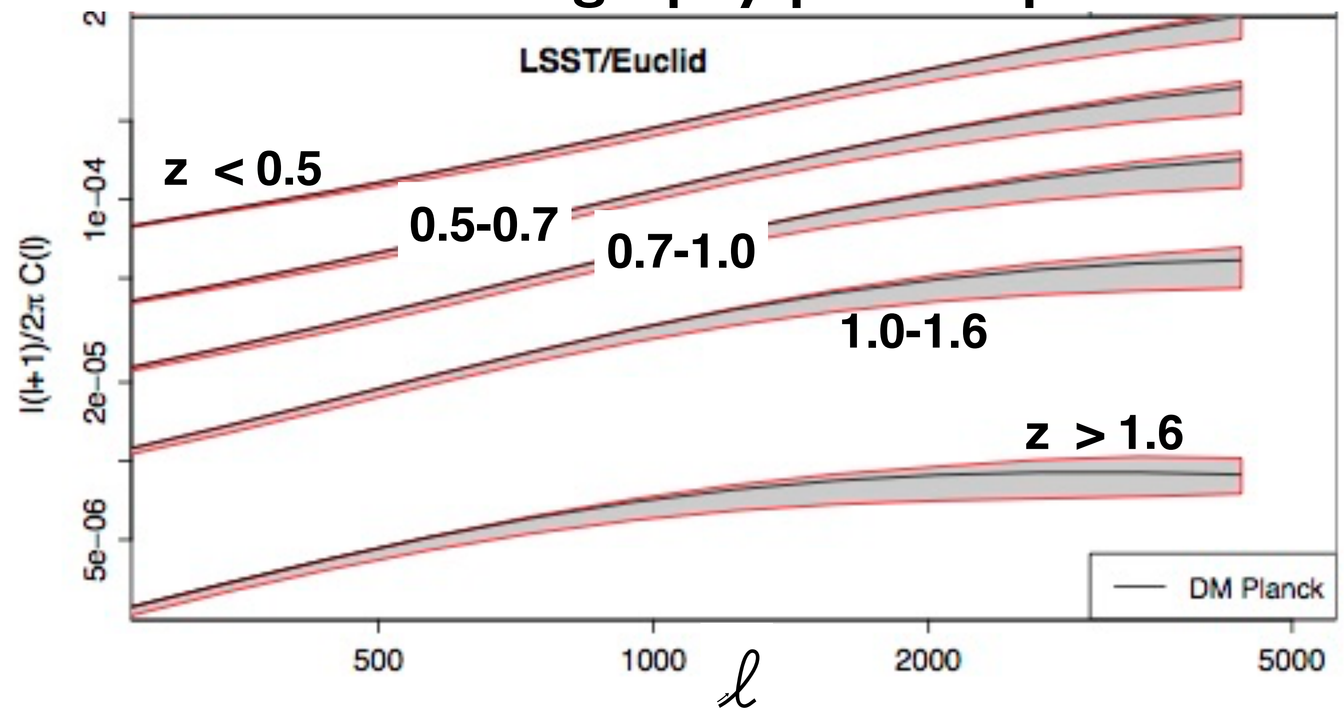
- **impact of feedback processes on the distributions of dark and baryonic matter, critical for both cosmology and galaxy evolution studies**
- **impact of baryon effects for interpreting LSST/Euclid P(k) measurements.**

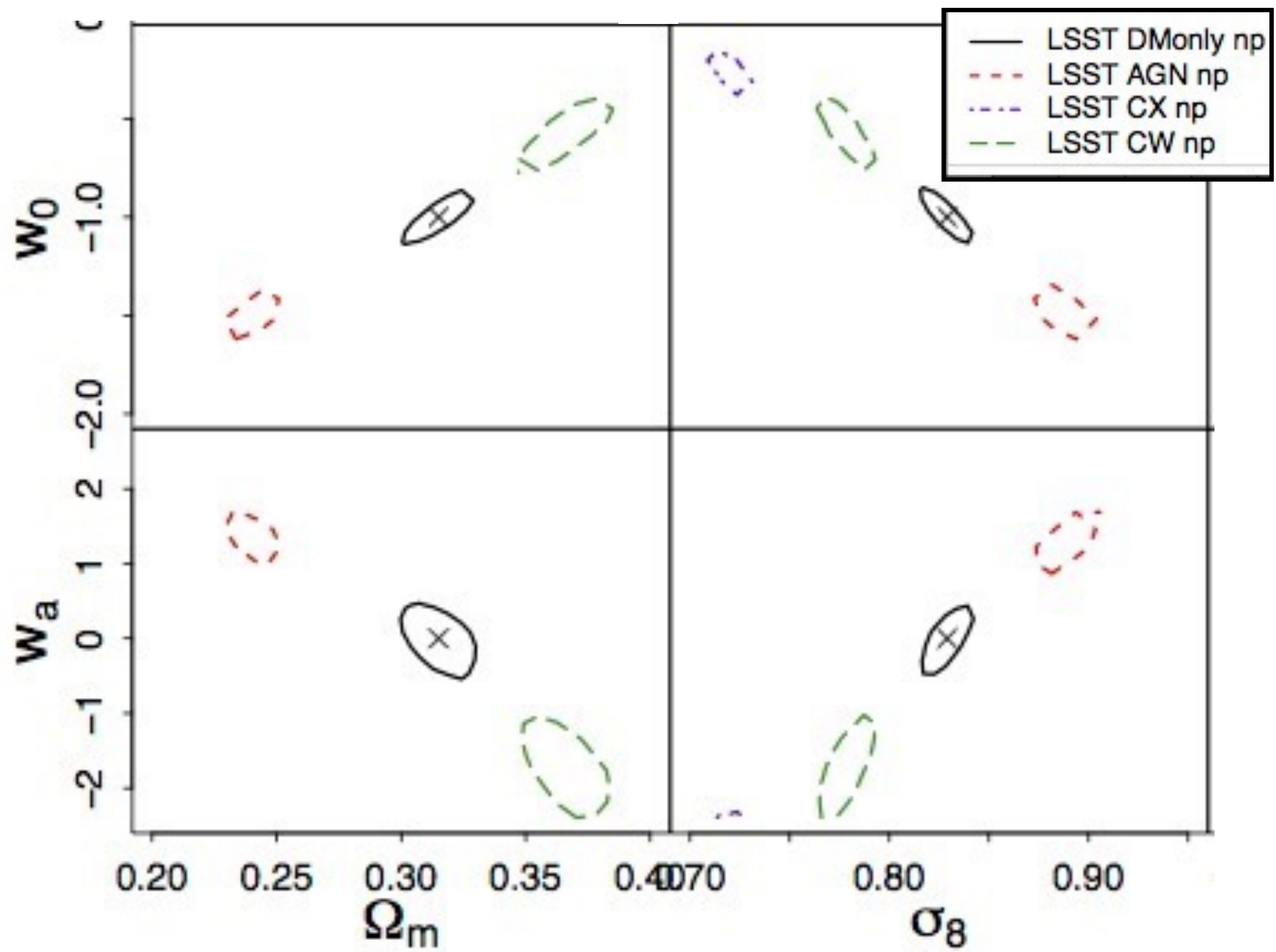
See Schaan et al., arXiv:1510.06442; Flender et al., arXiv:1610.08029; and CMB-S4 LSS log book pages

Cosmological constraints for a LSST/Euclid survey.

Eifler et al. arXiv:1405.7423

Shear tomography power spectra



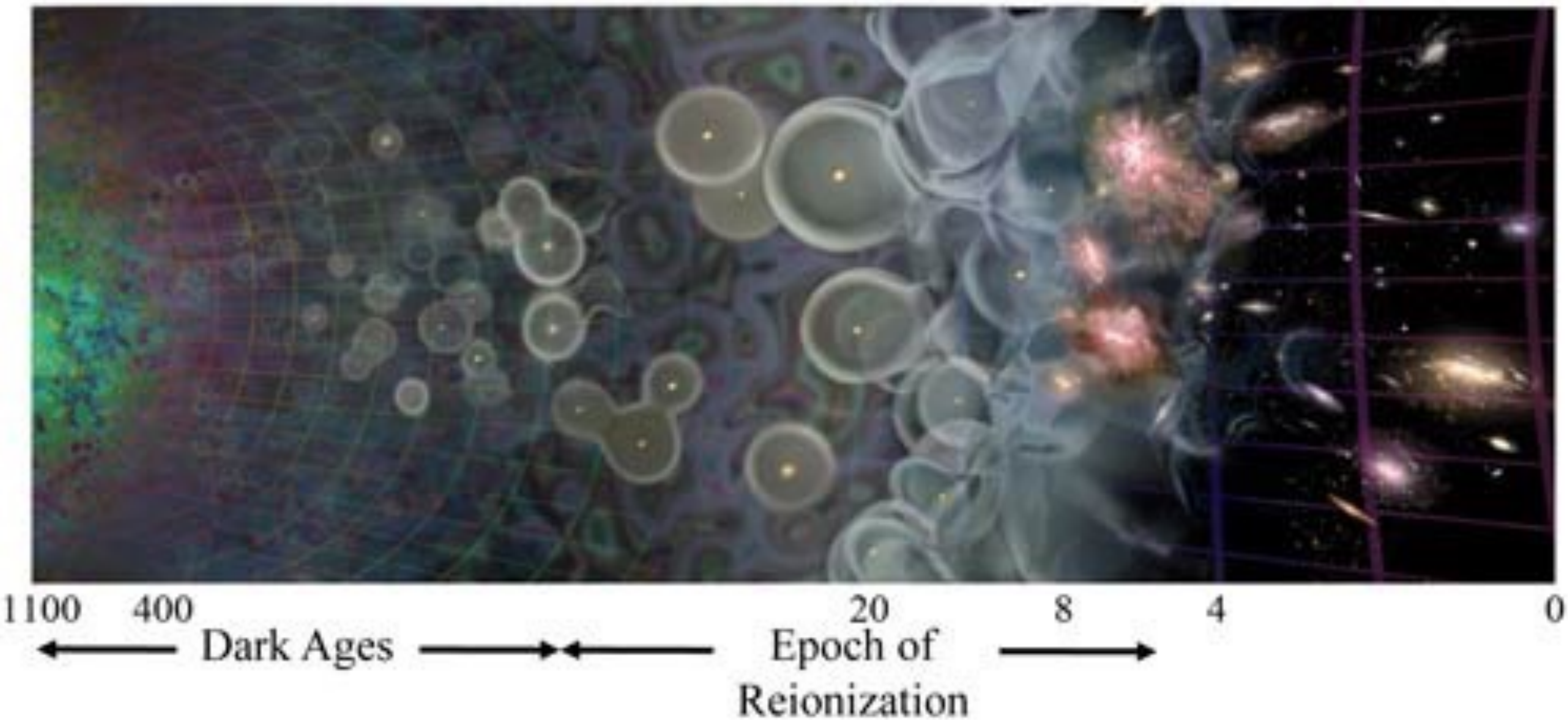


Assuming different underlying baryonic scenarios for our Universe:

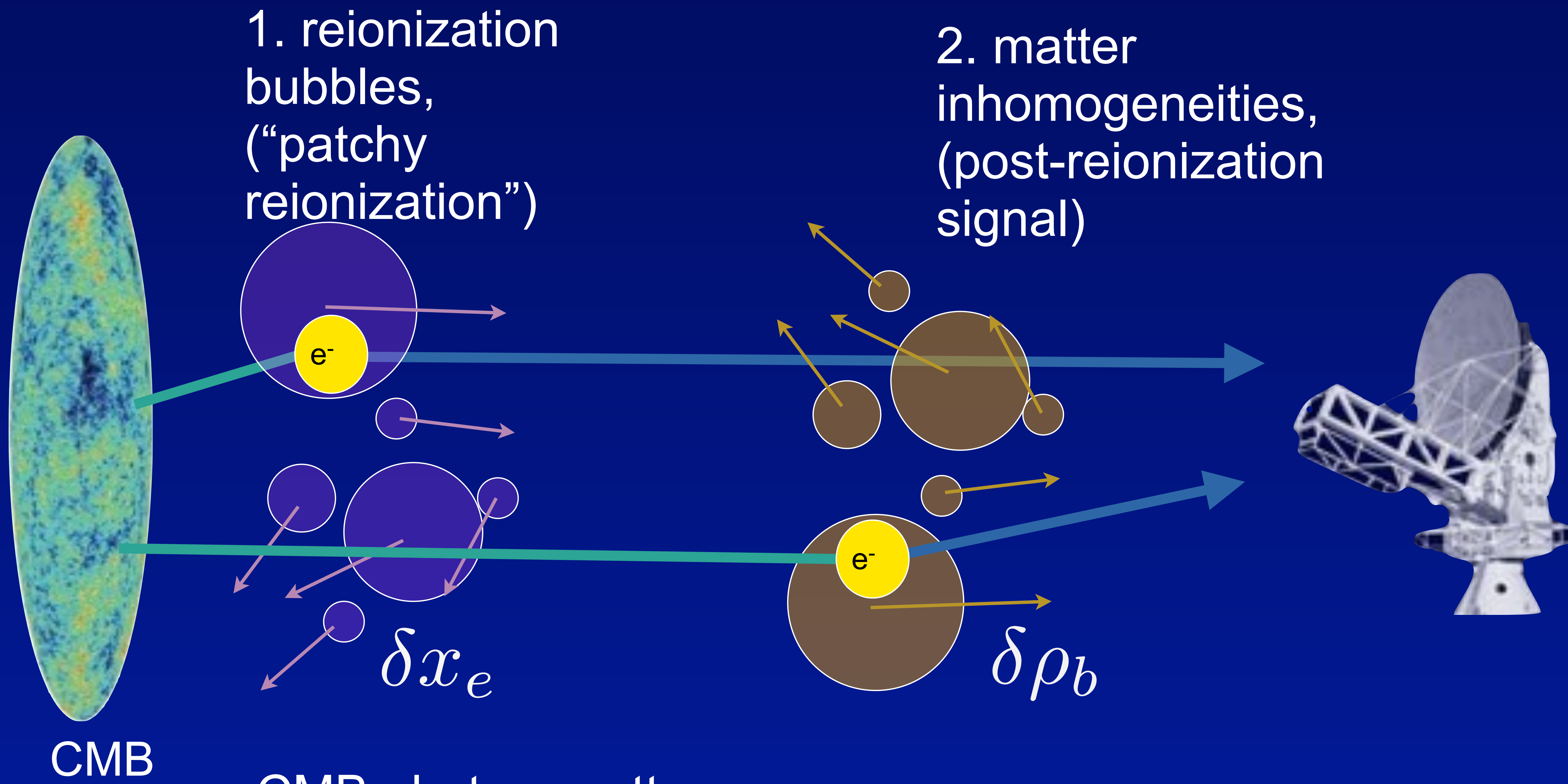
- pure dark matter (black/solid)
- strong AGN feedback (red/dashed)
- extreme cooling (blue/dot-dashed)
- moderate cooling (green dashed)

Reionization

Avi Loeb 2006



kinematic SZ effect and reionization



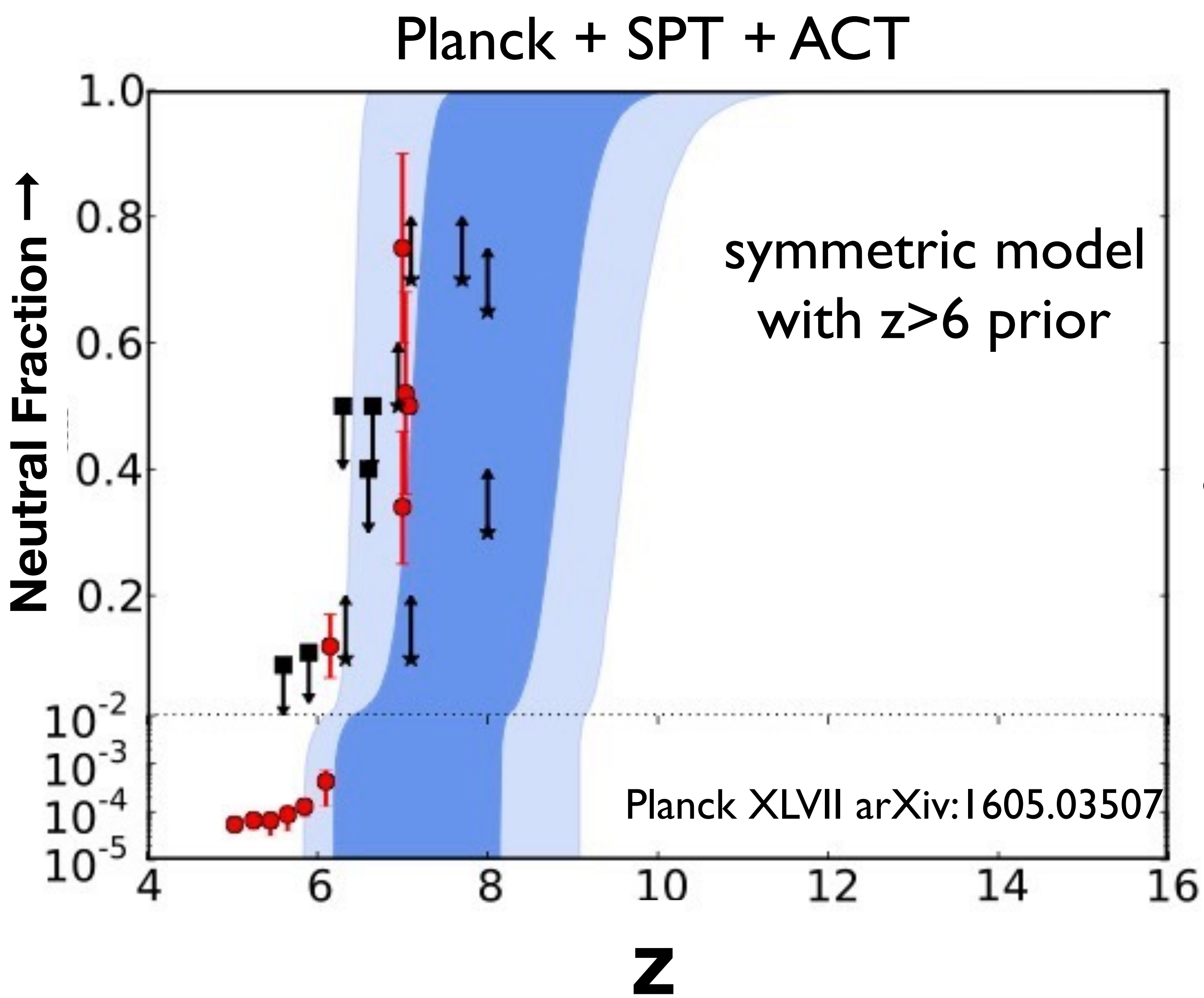
CMB photon scatters on free electrons moving w.r.t the CMB → Doppler shifted

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

from Christian Reichardt

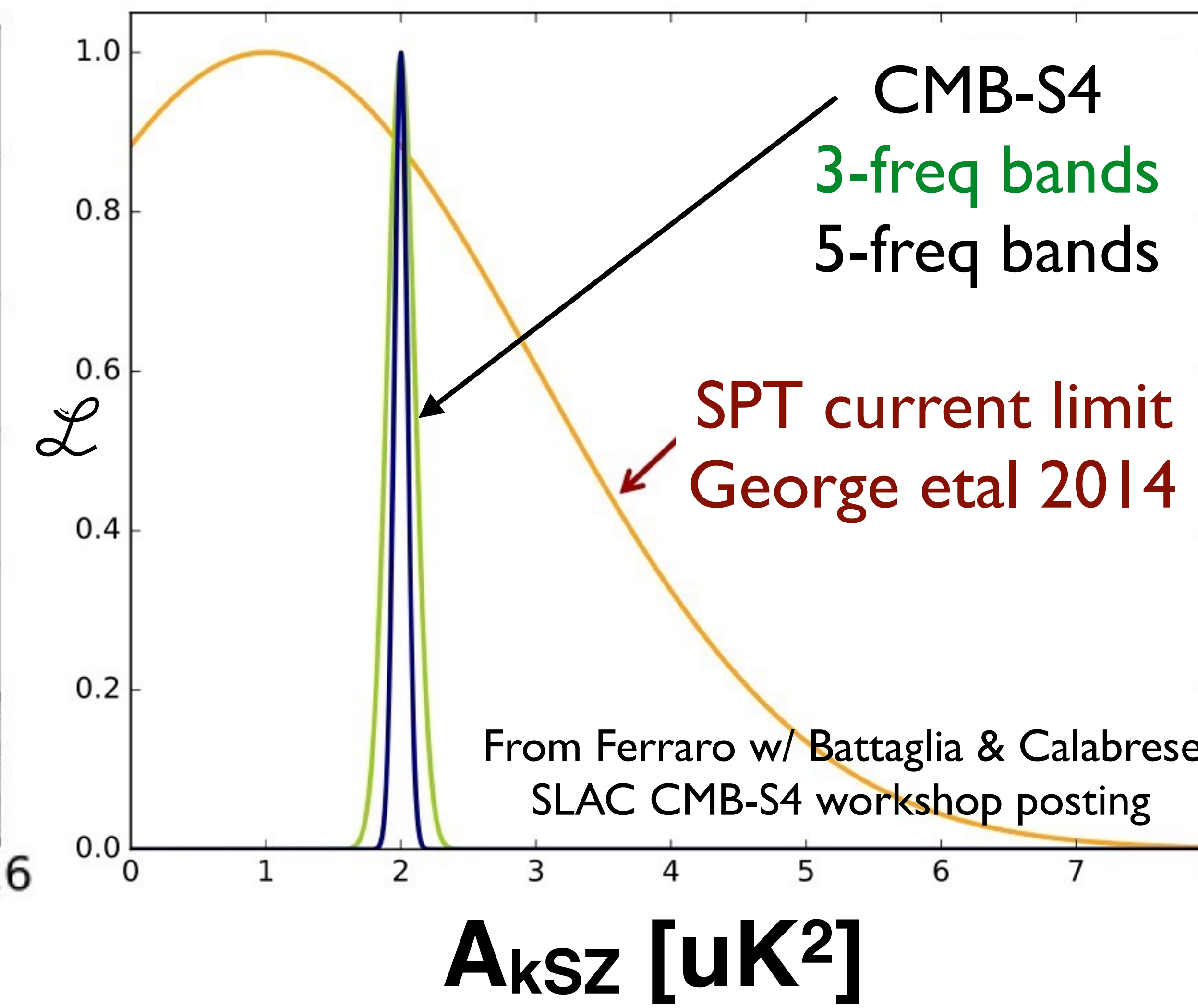
CMB-S4
Next Generation CMB Experiment

Patchy reionization projections



Battaglia et al. 2012:

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



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.

Last words

CMB is the gift that keeps on giving, and CMB-S4 will be an enormous advance for our field.

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