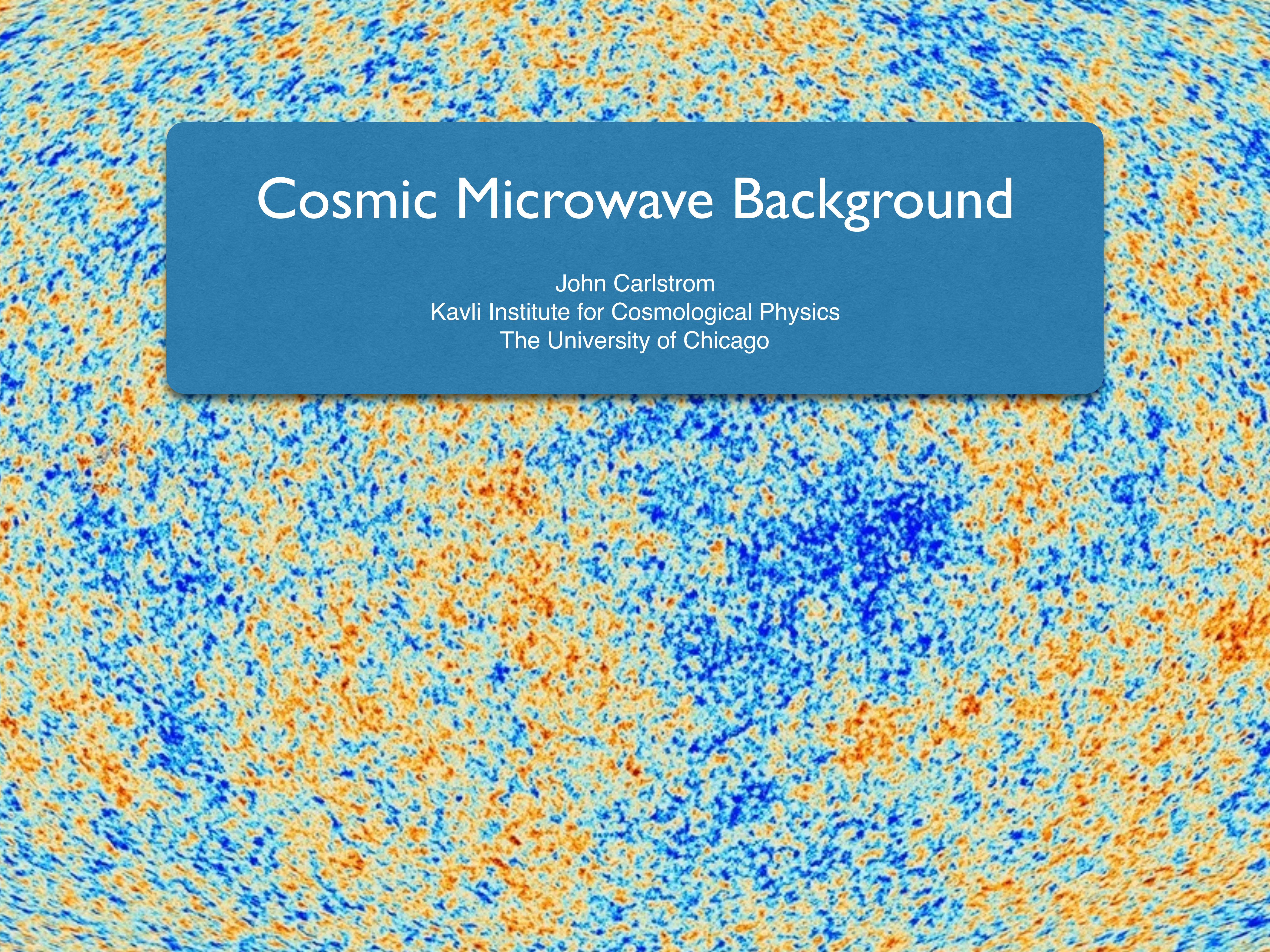
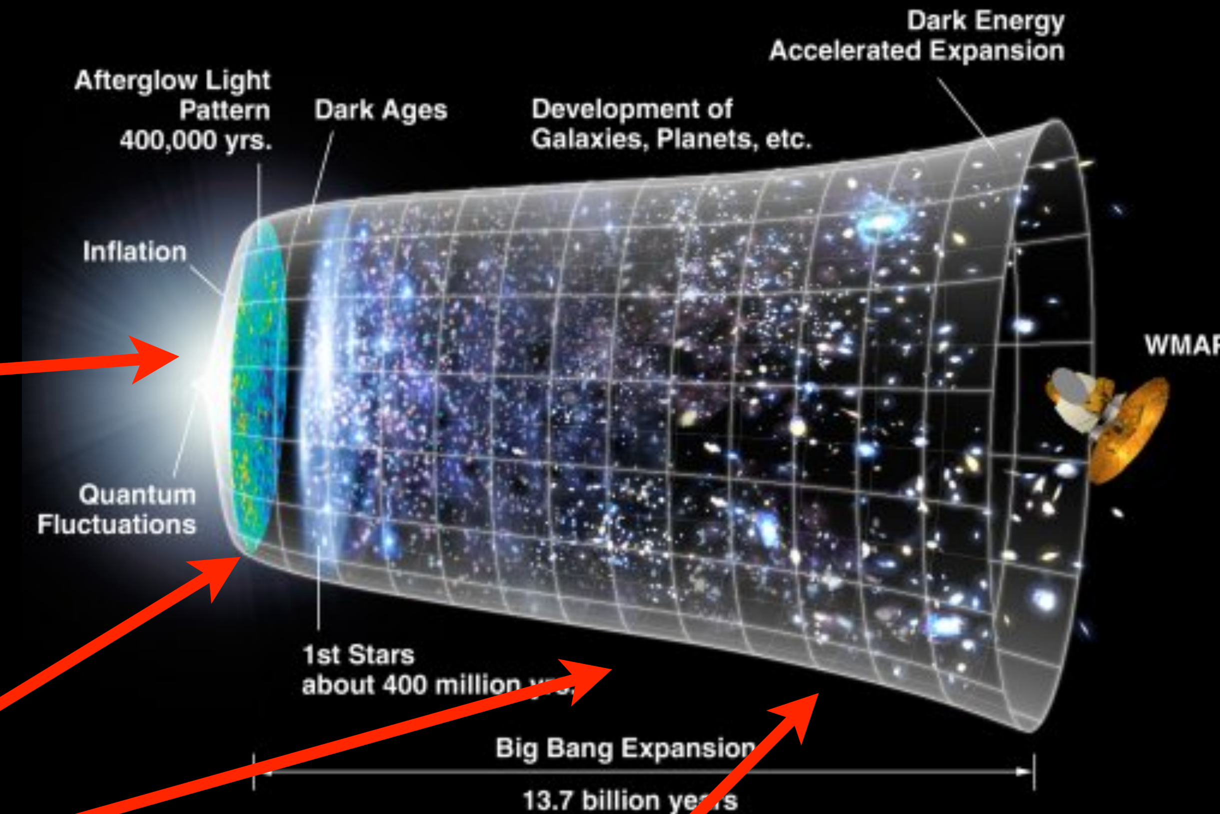
Cosmic Microwave Background

John Carlstrom
Kavli Institute for Cosmological Physics
The University of Chicago



CMB measurements probe cosmology and fundamental physics



Inflation

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

Neutrinos

- Number of relativistic species (Neff or "dark radiation")
- Sum of the neutrino masses, ($\sum m_\nu$) through impact on growth of structure

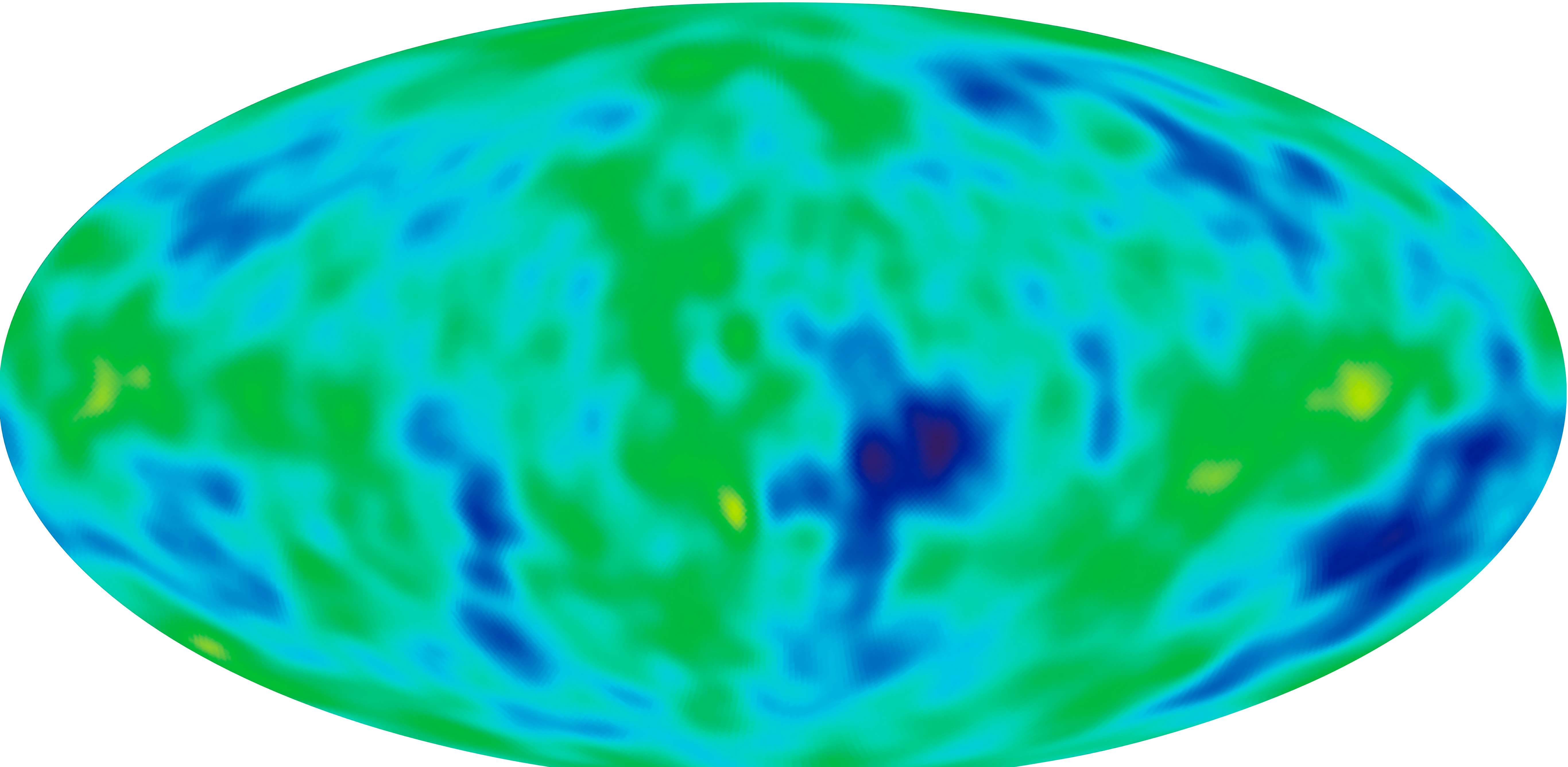
Dark Energy

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

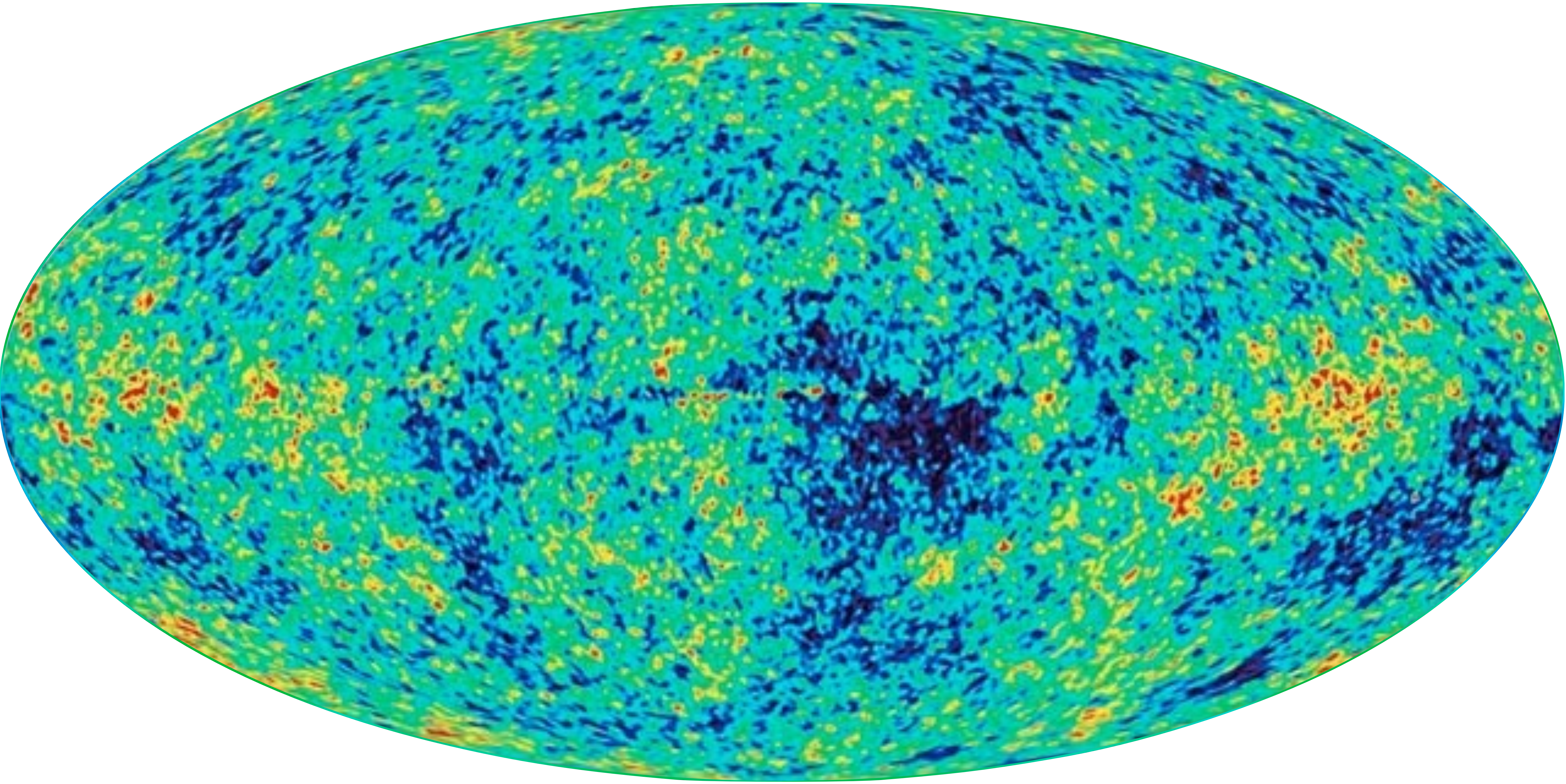
➡ *requires precision CMB measurements of the temperature and polarization CMB anisotropy from degrees to arc minutes*

graphic from NASA website

COBE → WMAP → Planck



COBE → WMAP → Planck



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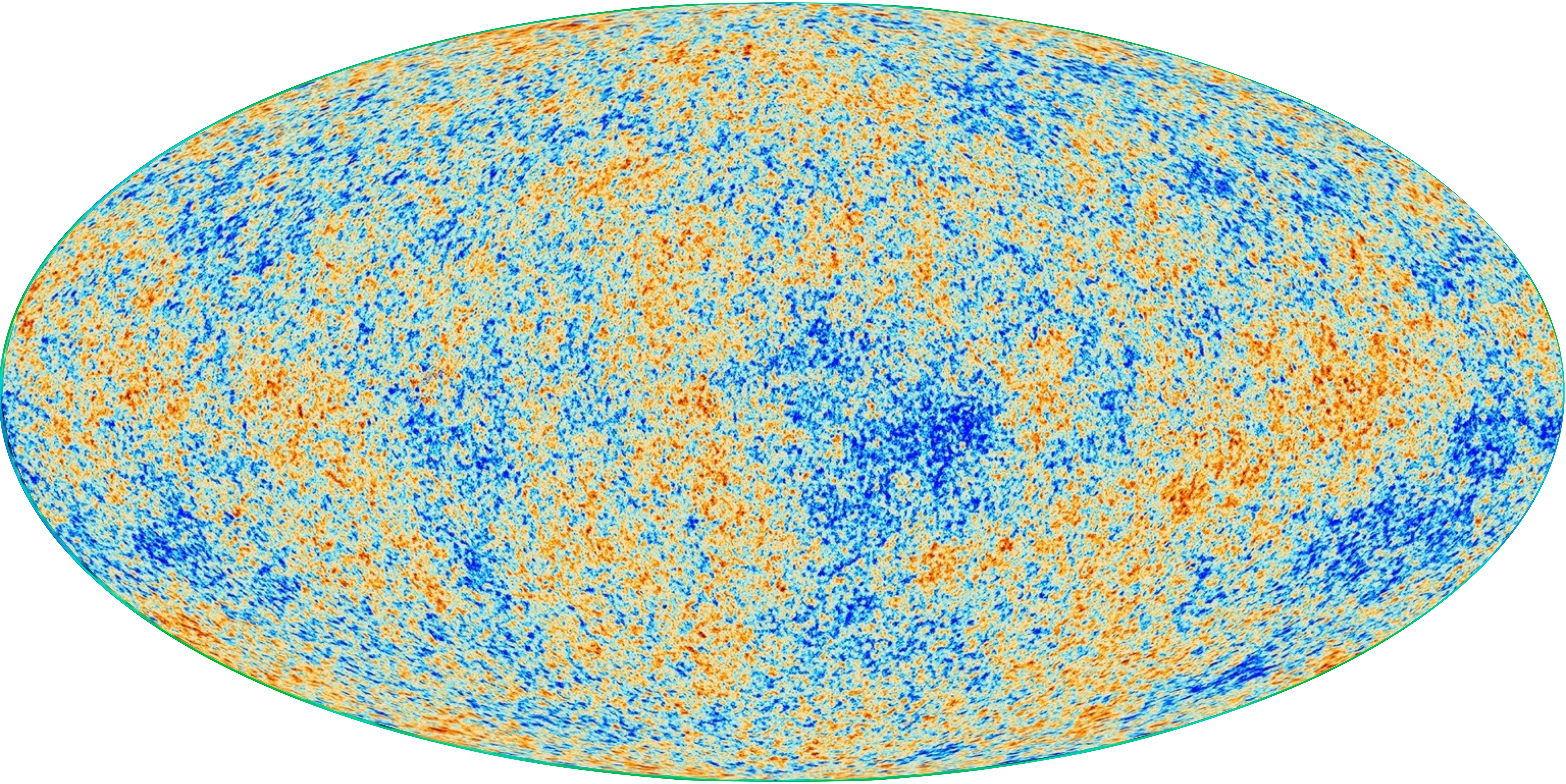
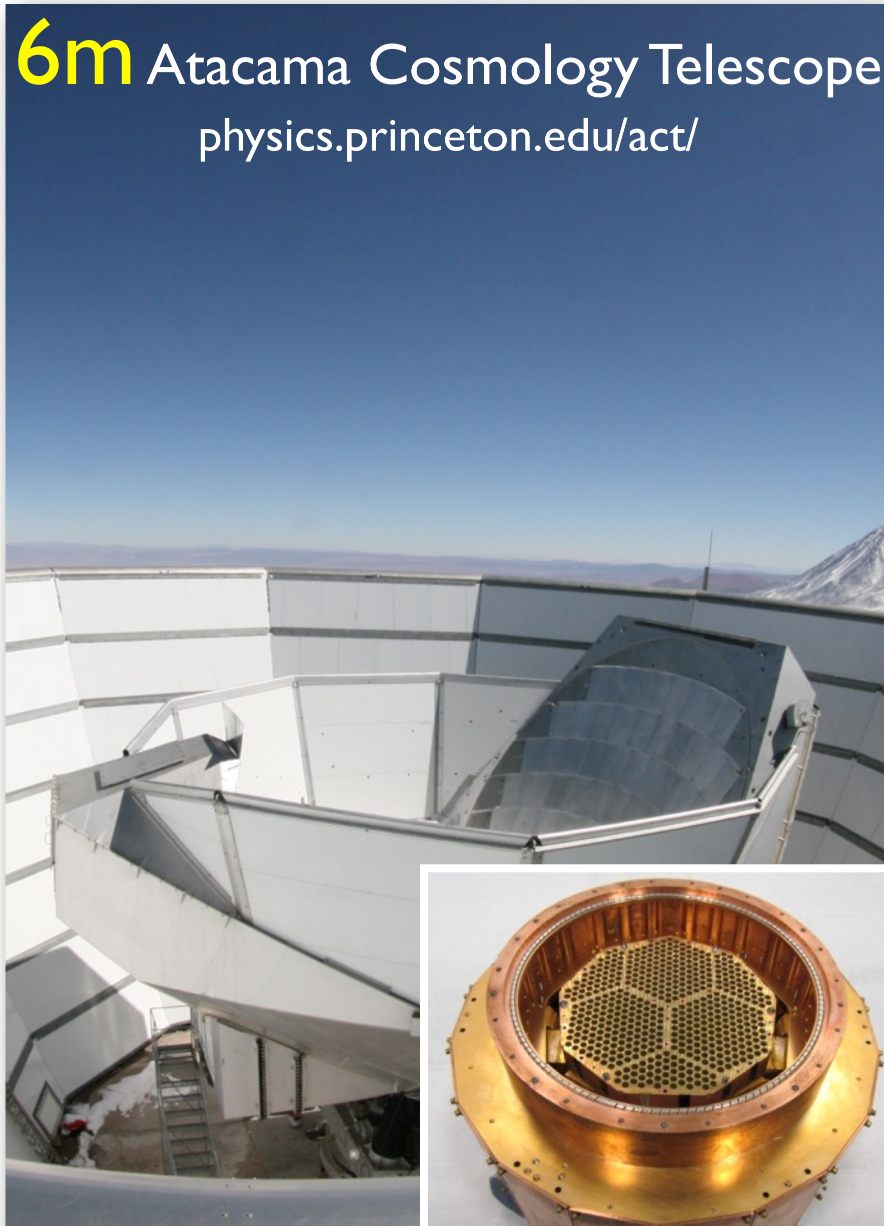
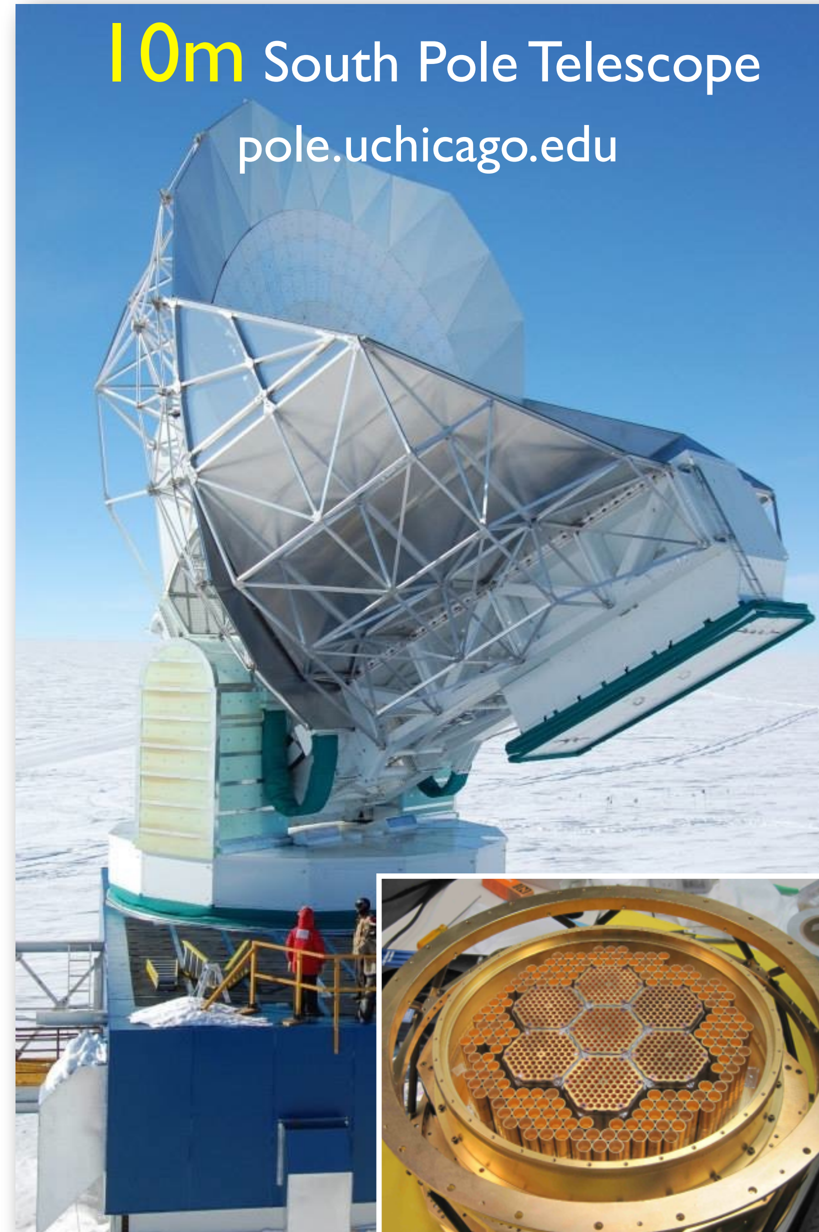
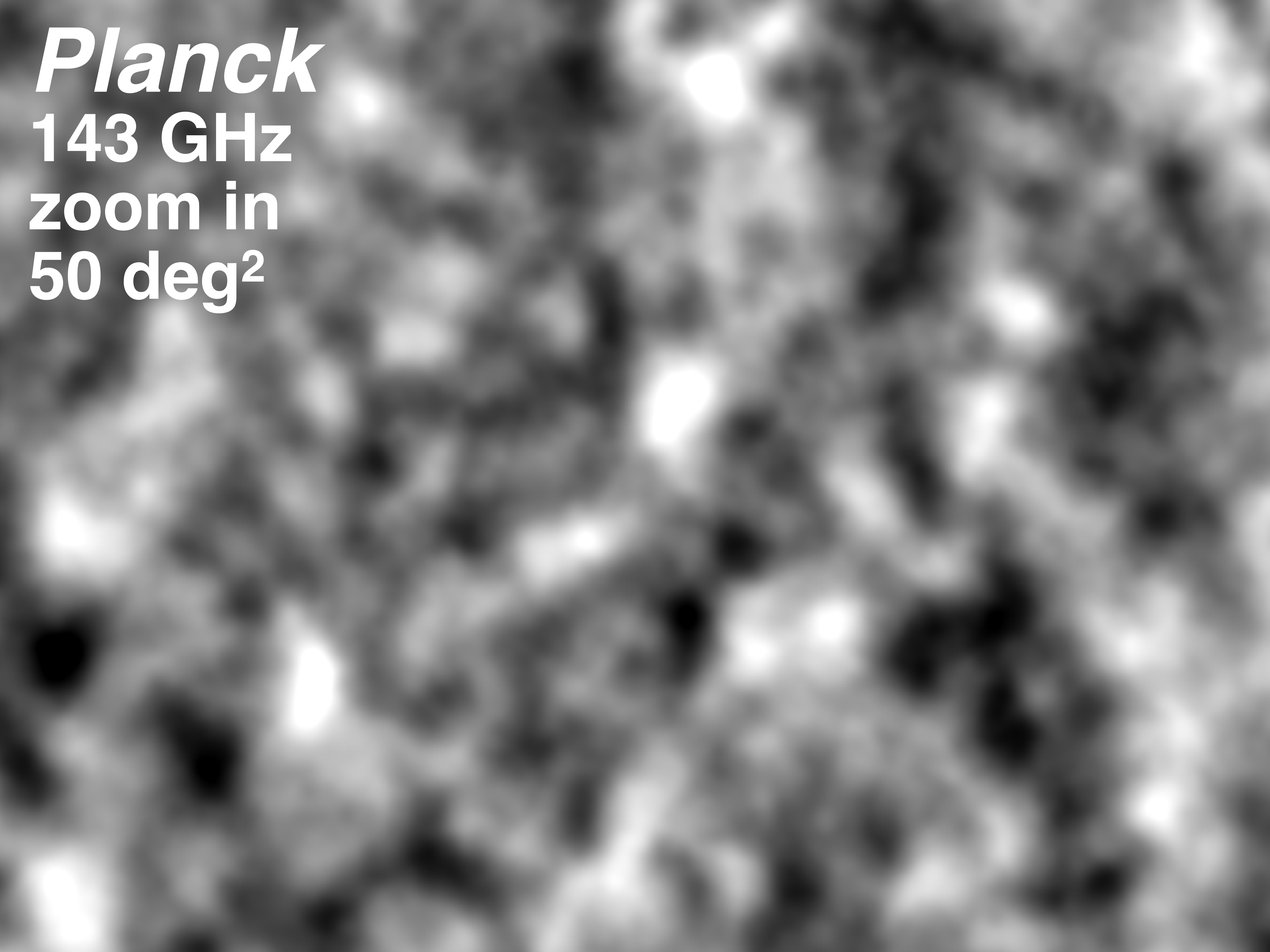


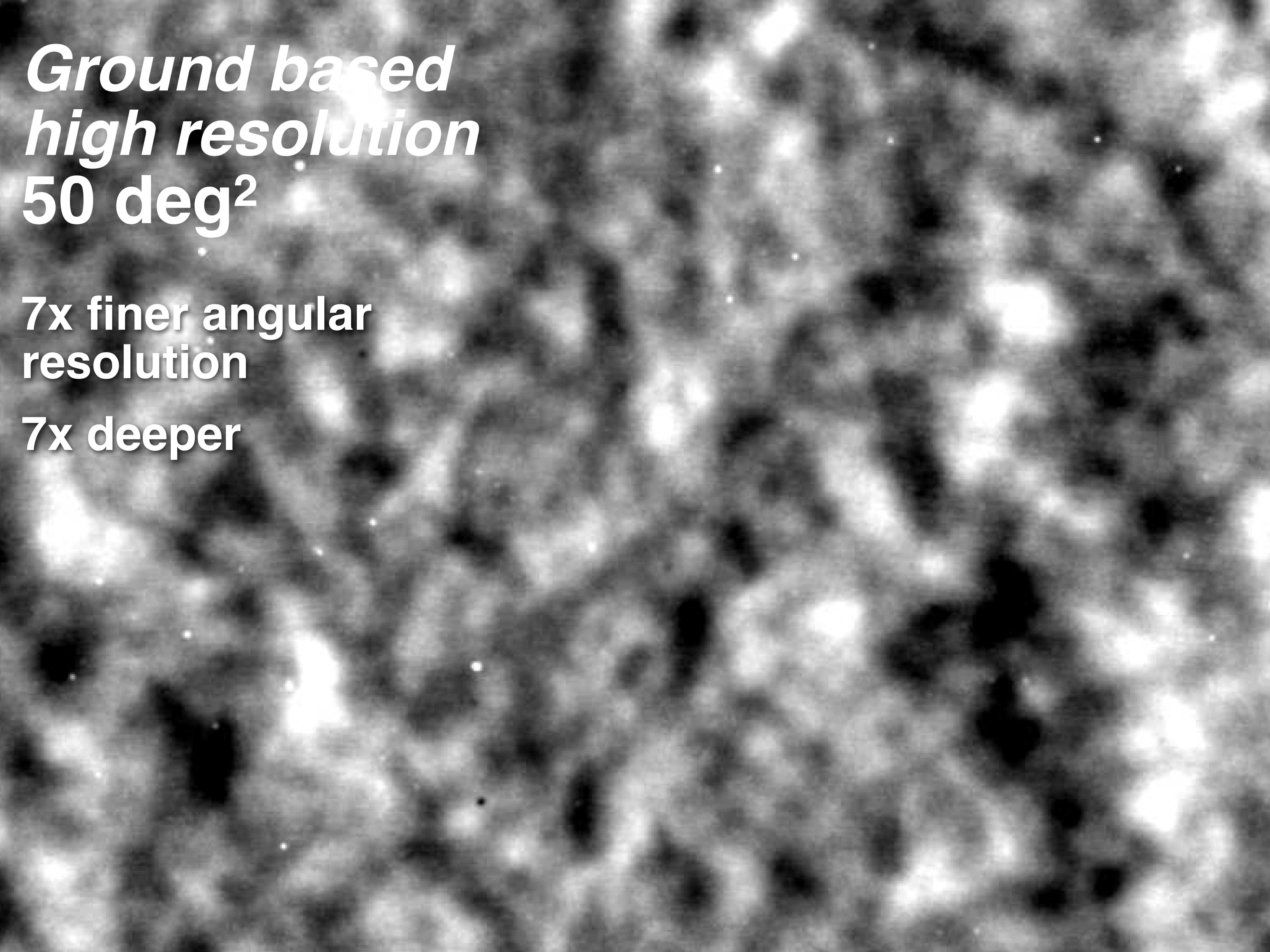
High angular resolution (high-ℓ) CMB measurements

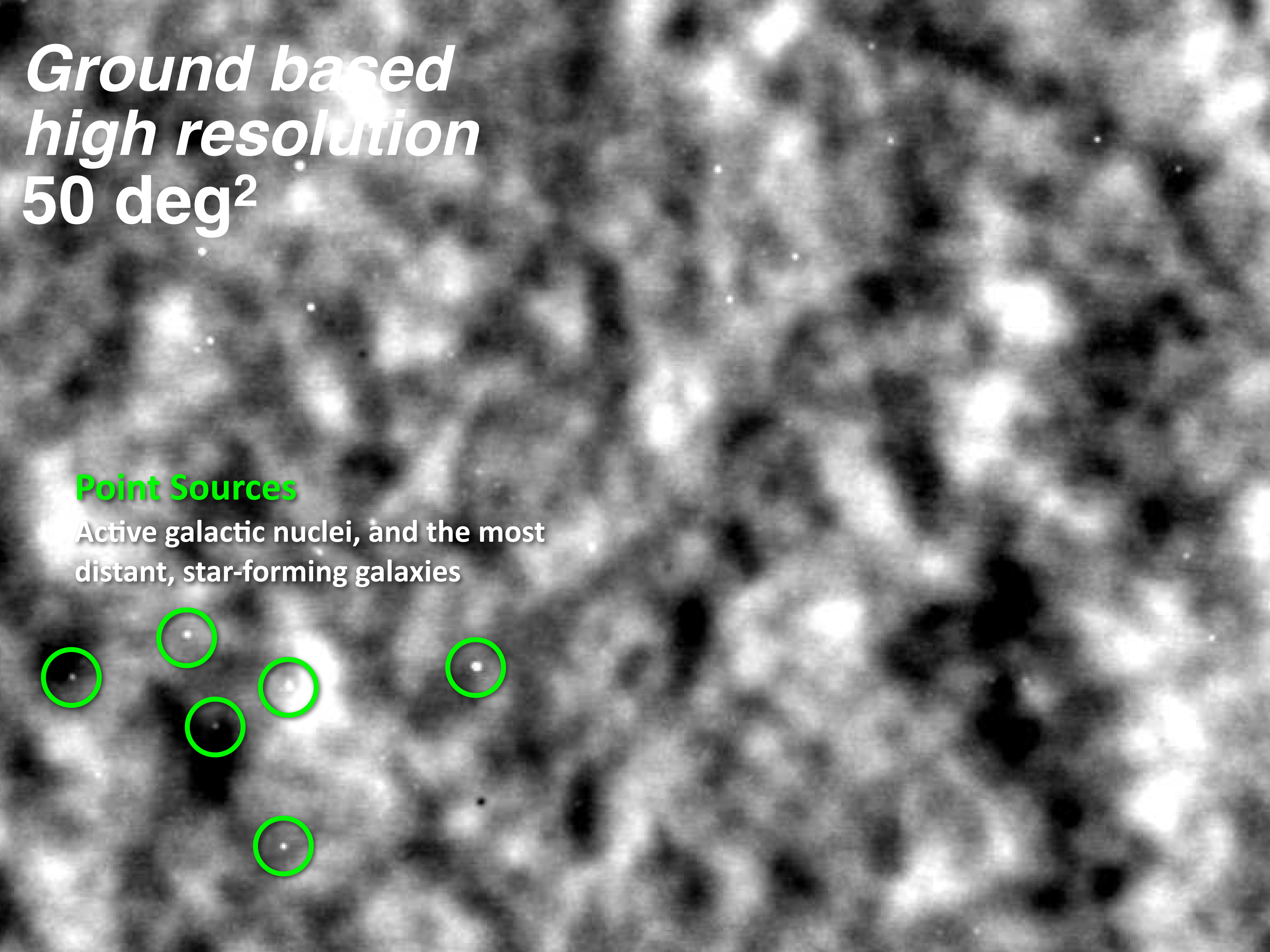


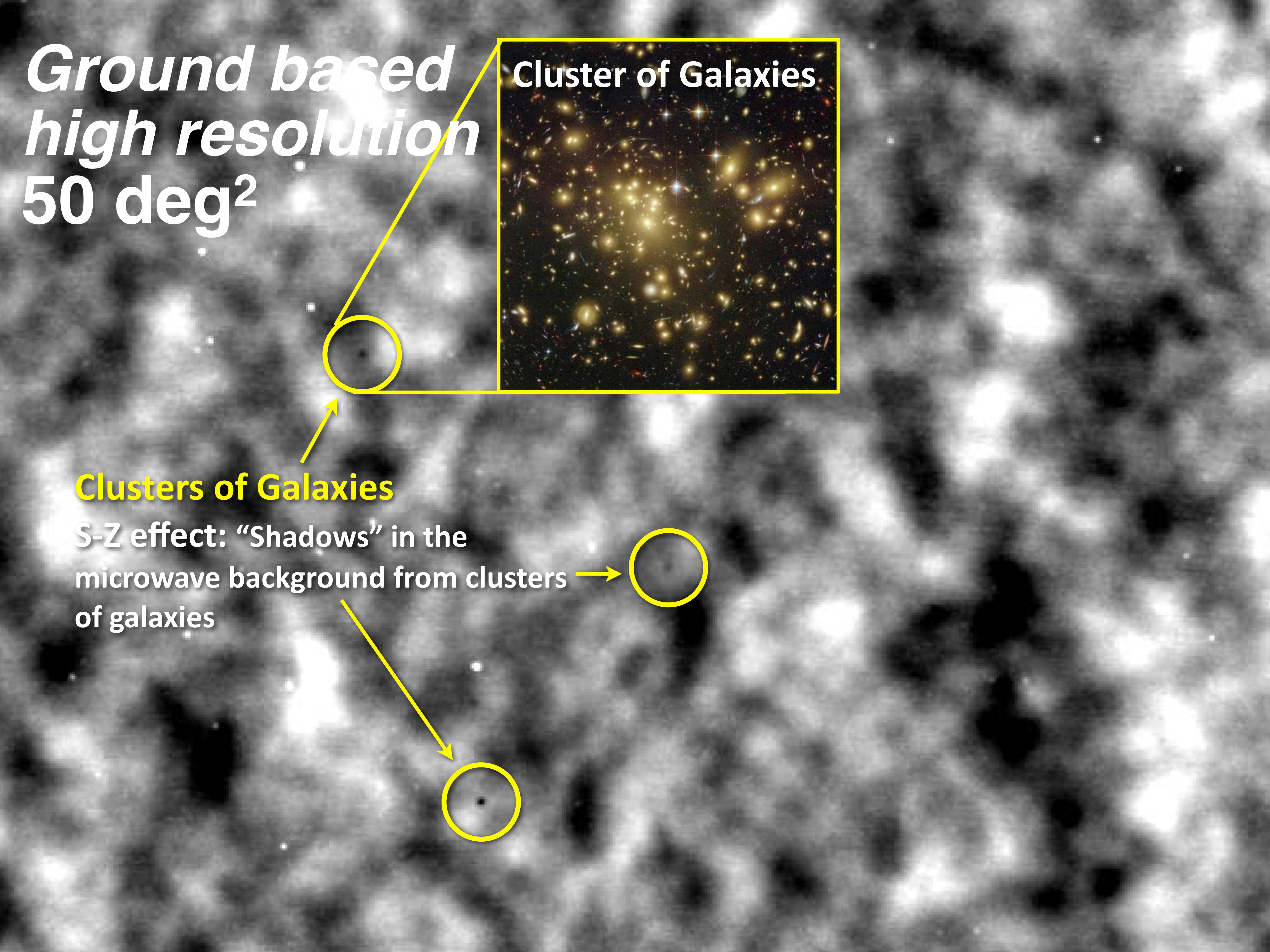


Exceptional high and dry sites for dedicated CMB observations.
Exploiting and driving ongoing revolution in low-noise bolometer cameras

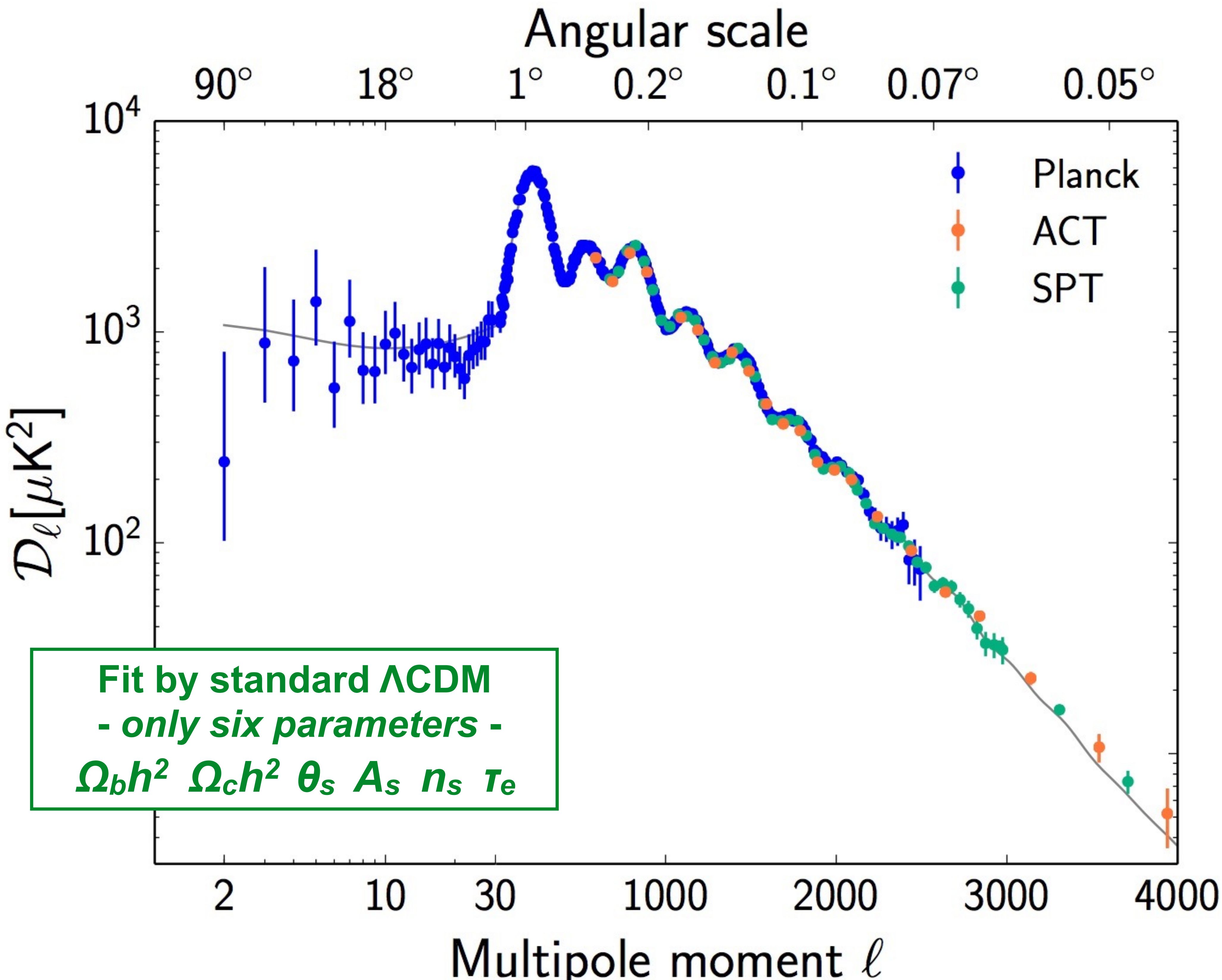

Planck
143 GHz
zoom in
50 deg^2


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 deg^2
Cluster of Galaxies
Clusters of Galaxies
S-Z effect: "Shadows" in the microwave background from clusters of galaxies

Angular power spectrum of primary CMB anisotropy



Fit by standard ΛCDM
- only six parameters -
$\Omega_b h^2$ $\Omega_c h^2$ θ_s A_s n_s τ_e

Figure from Planck 2015 Results XI

So, are we finished with primary CMB Temperature anisotropy measurements?

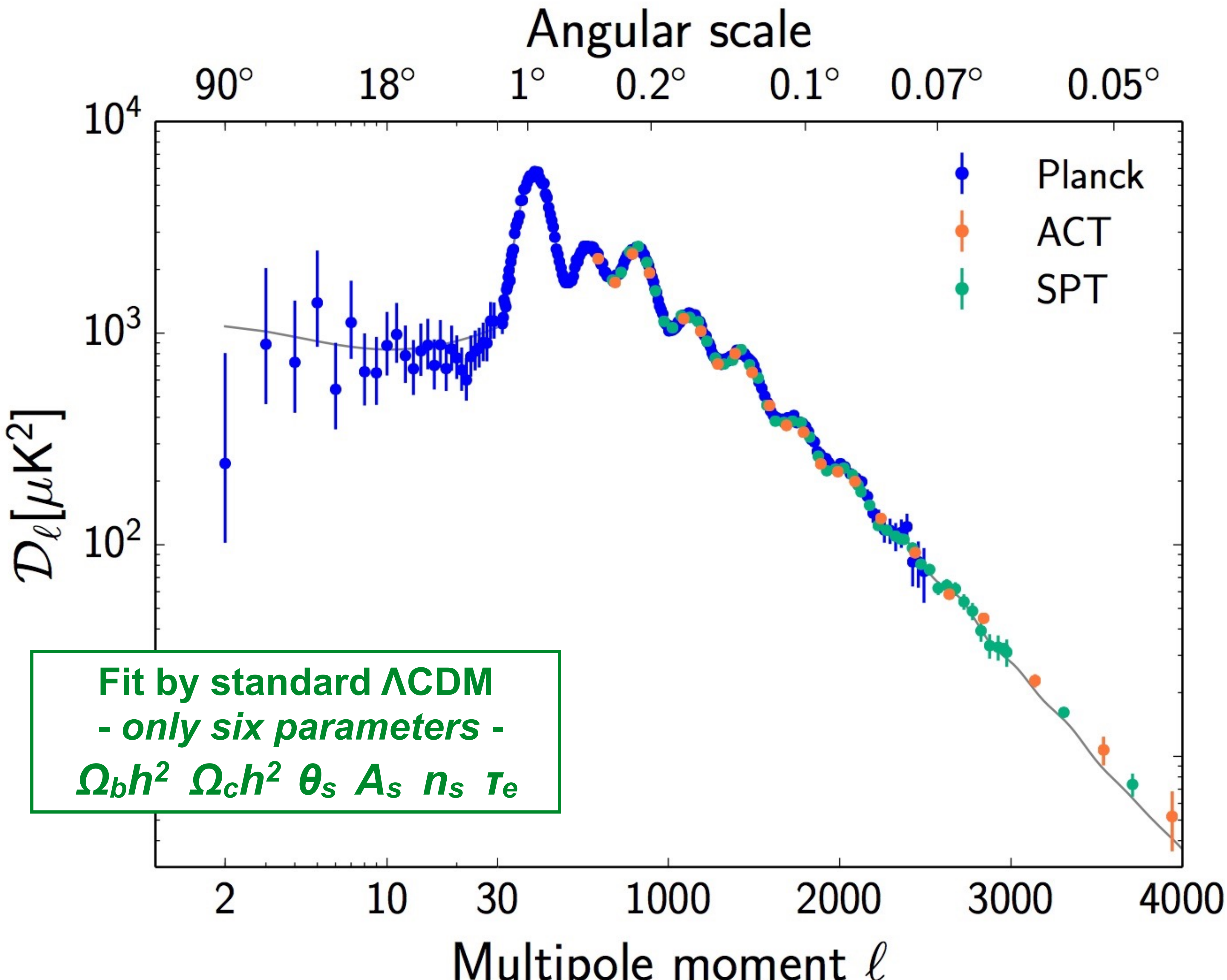


Figure from Planck 2015 Results XI

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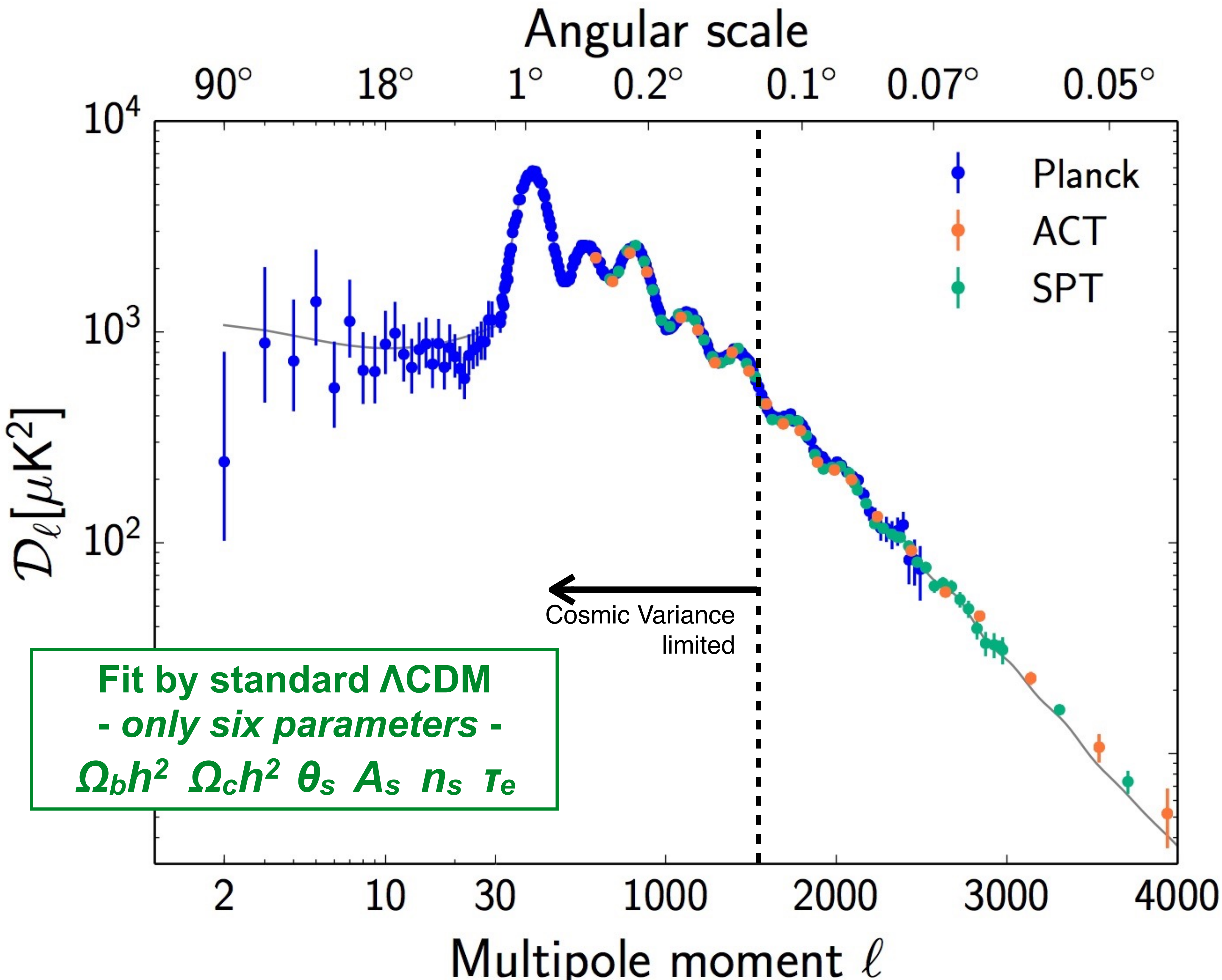

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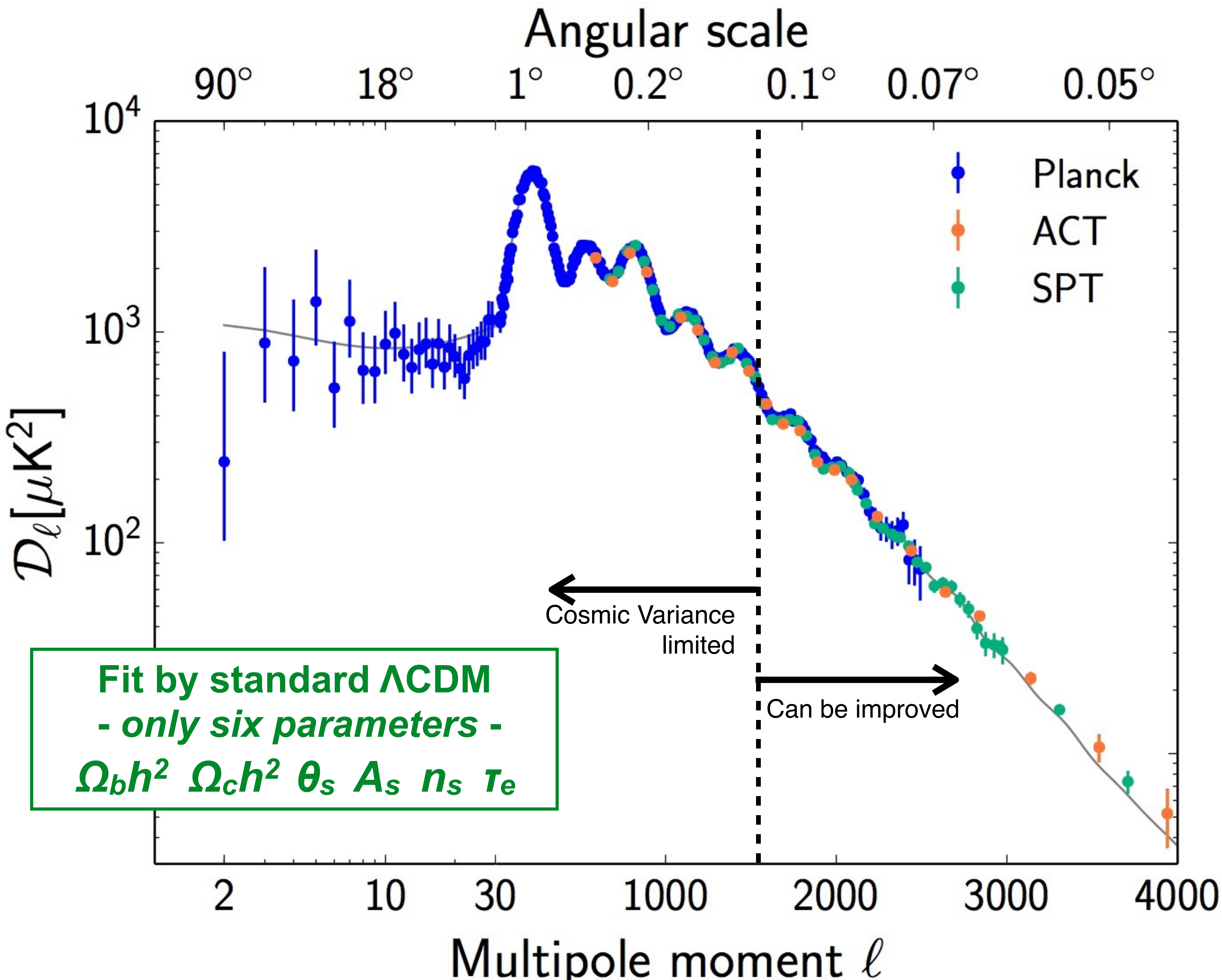

Figure from Planck 2015 Results XI

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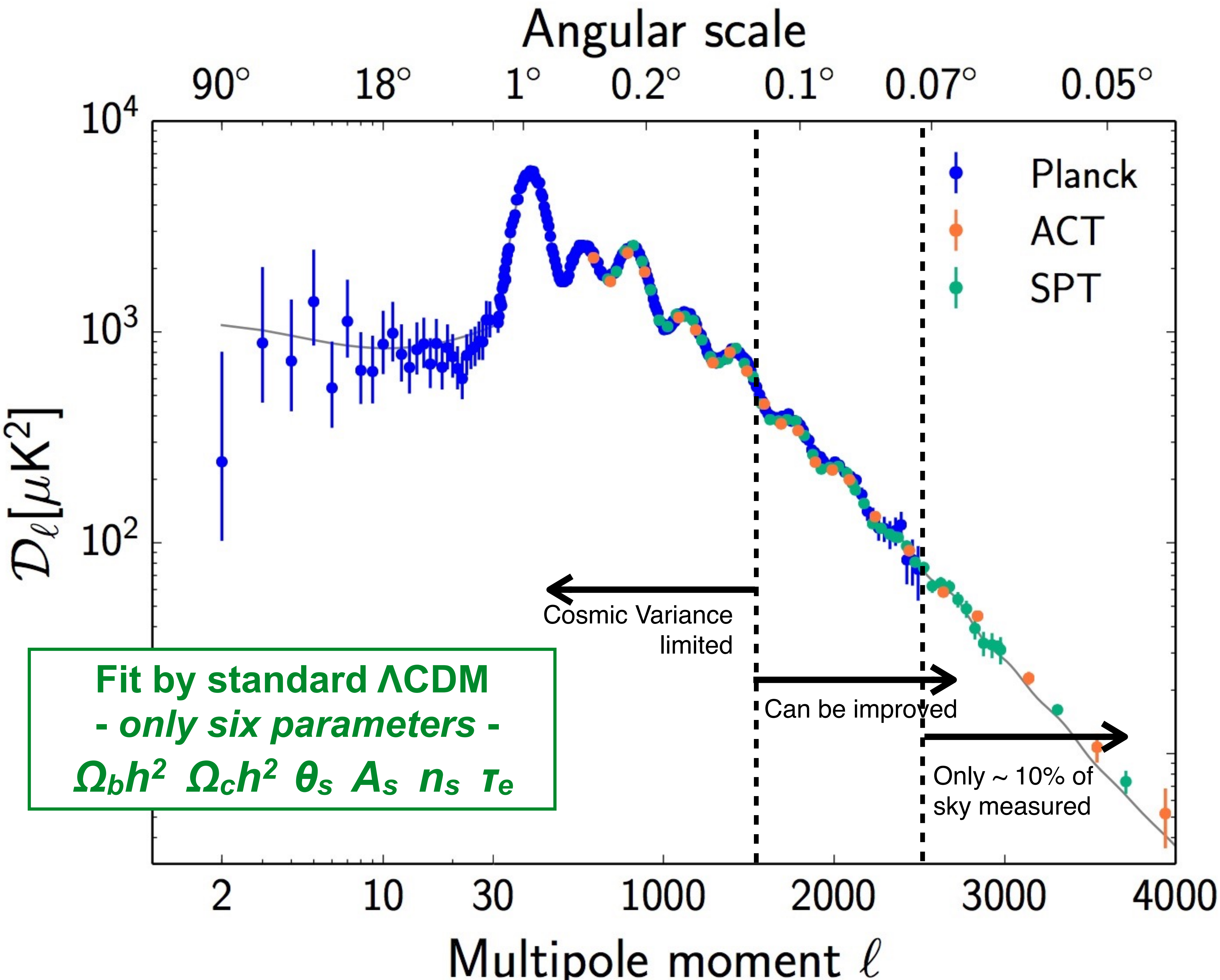

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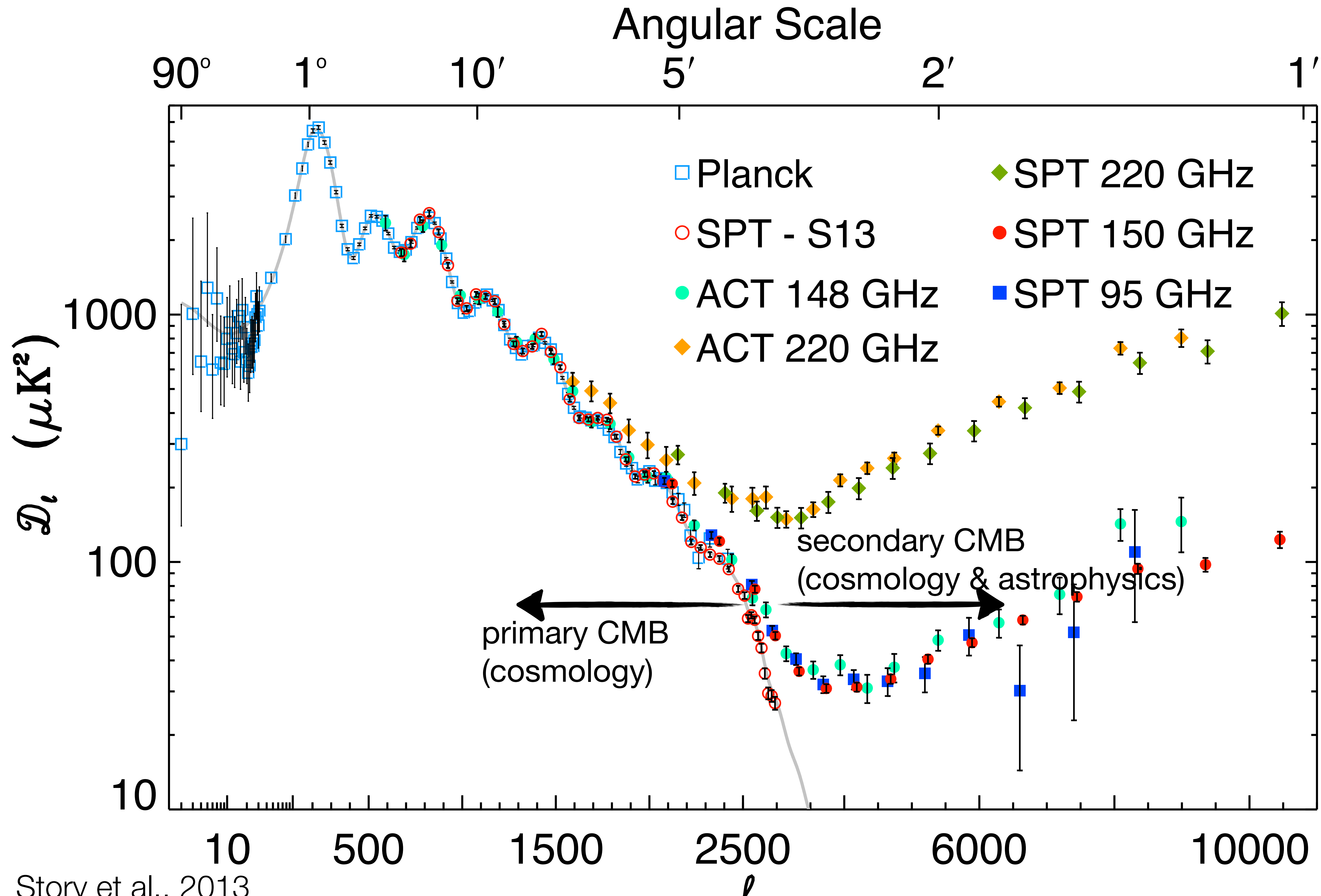
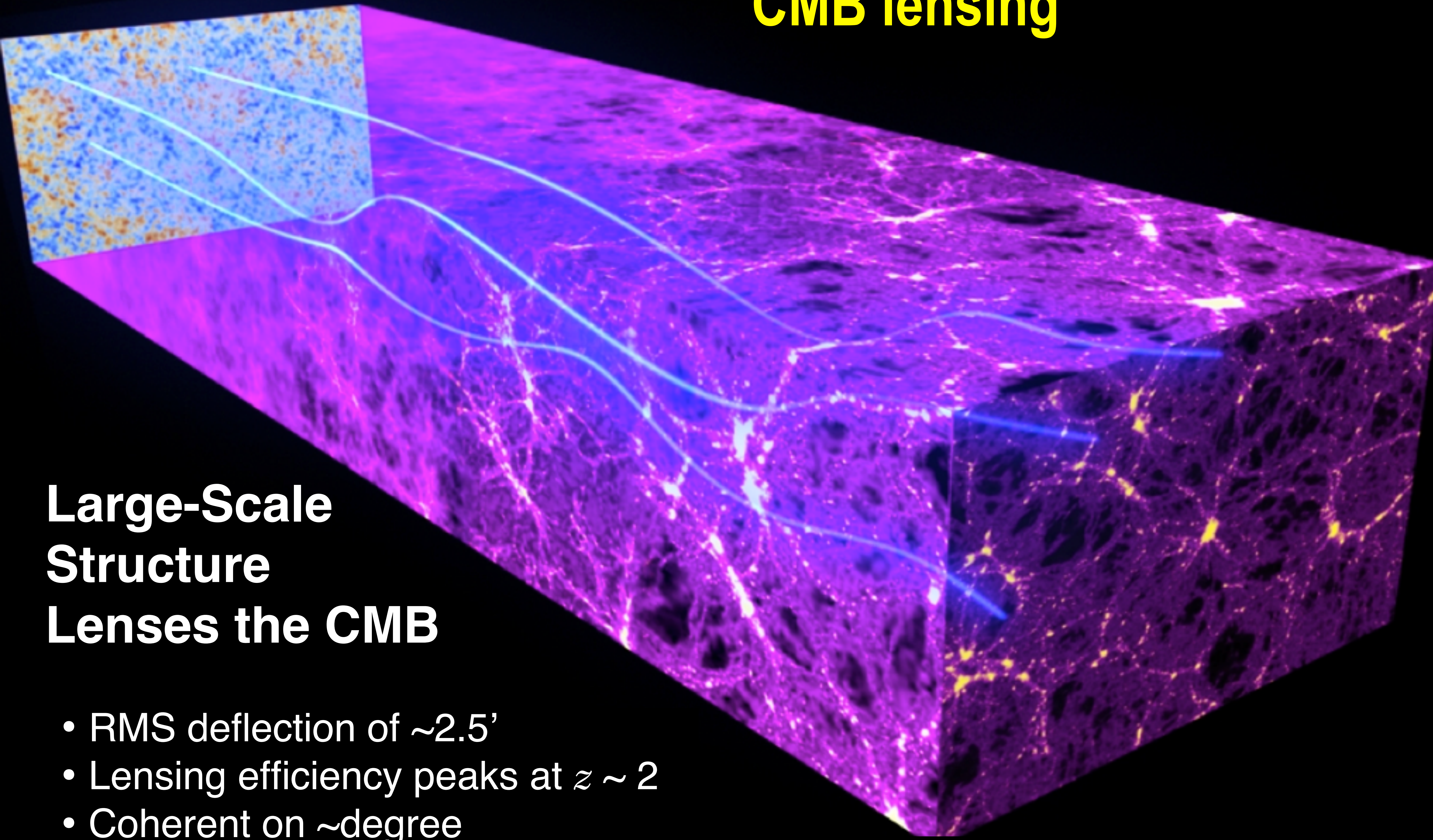


Story et al., 2013
George et al., 2014
Das et al., 2014

CMB lensing



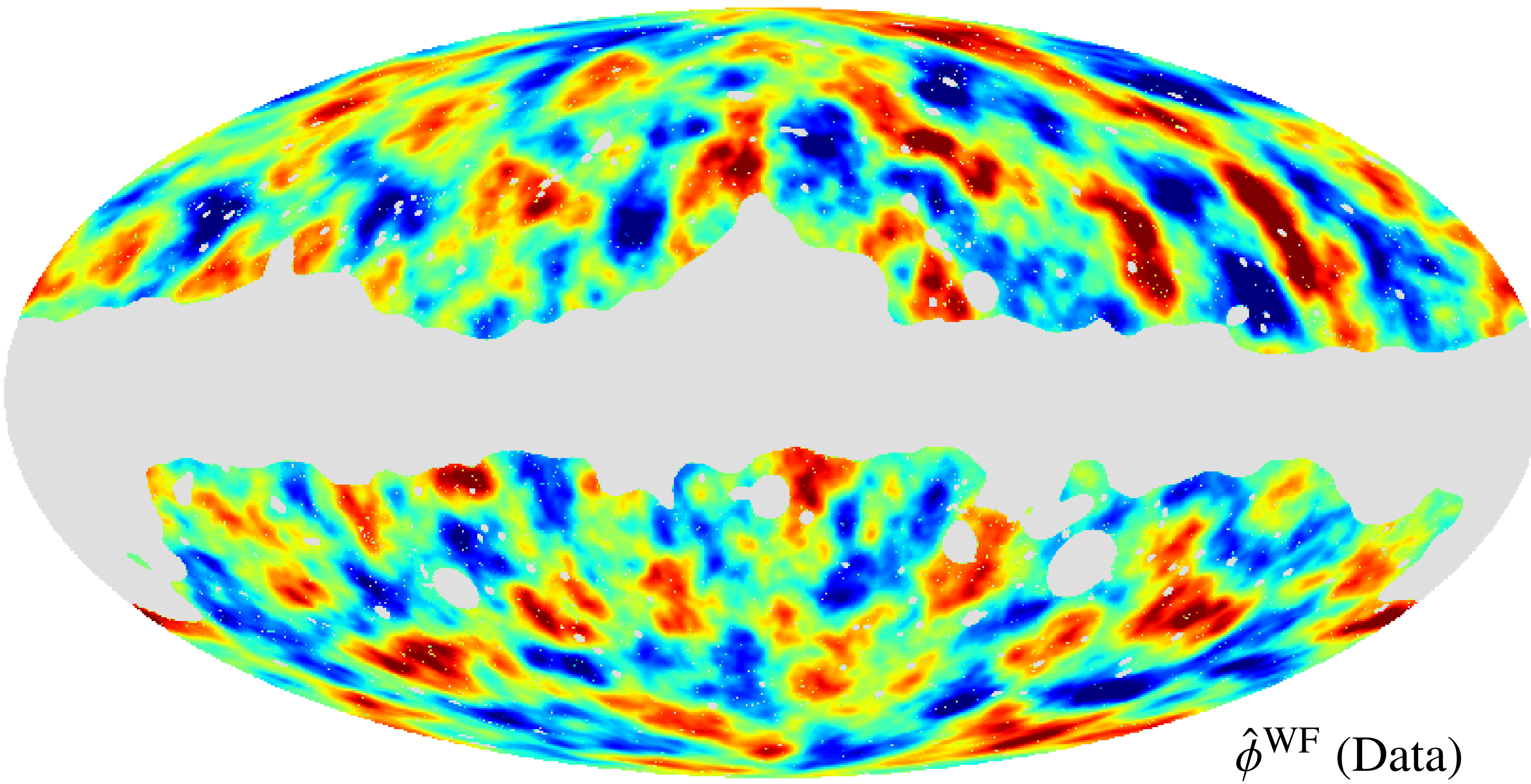
Large-Scale Structure Lenses the CMB

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

graphic from ESA website

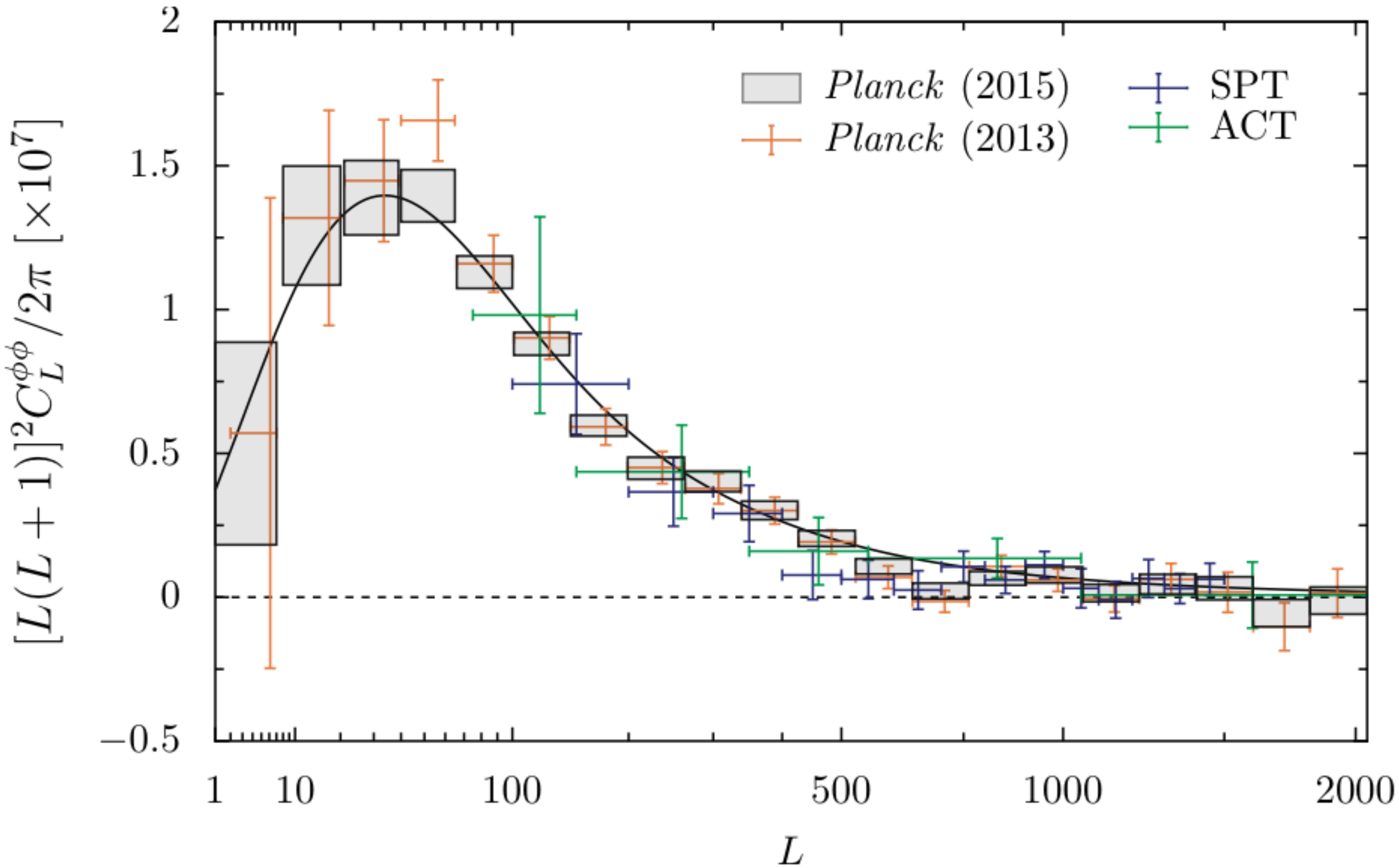
CMB lensing

Planck lensing potential reconstruction (projected mass map).



Planck XV (2015)

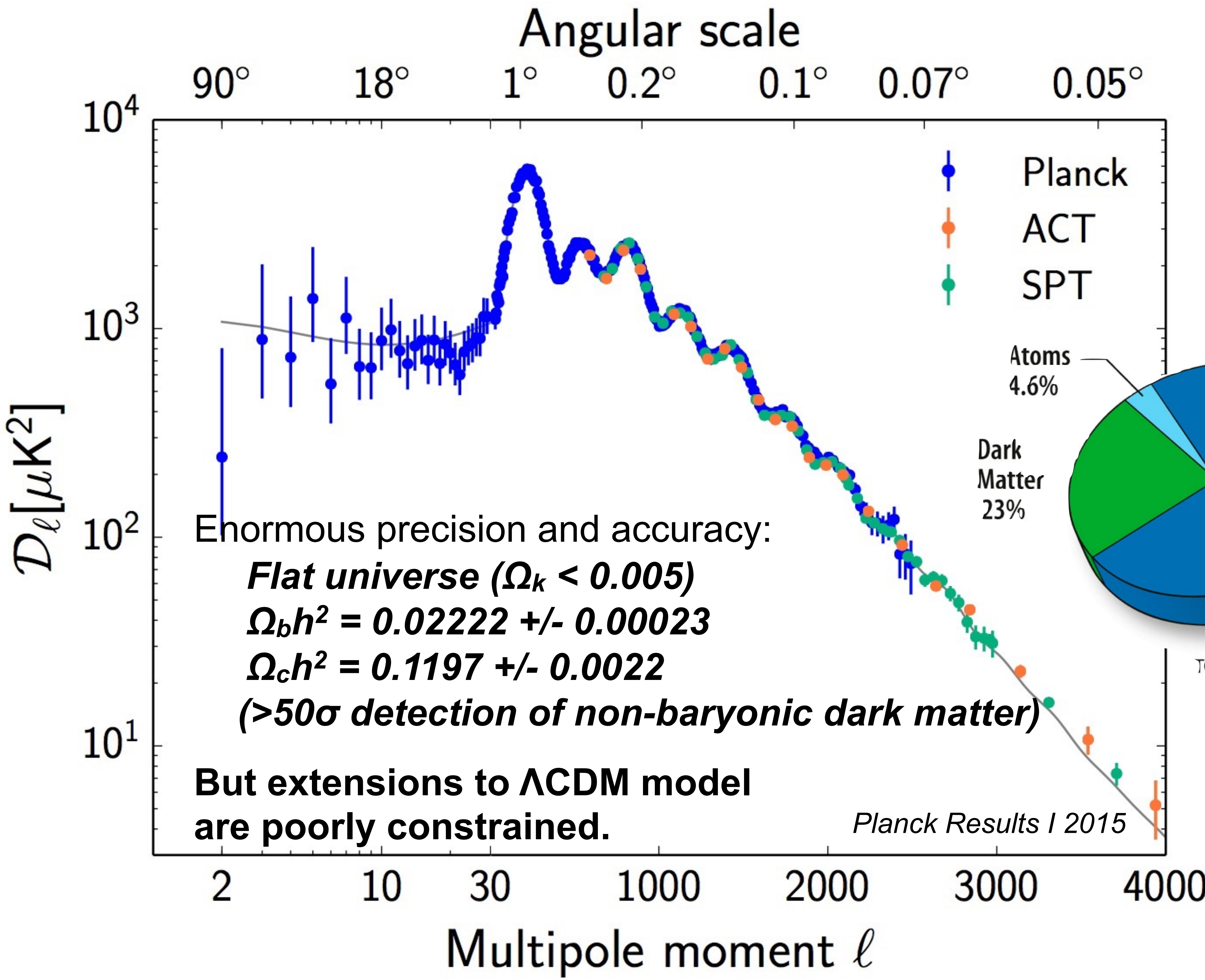
CMB lensing power spectra

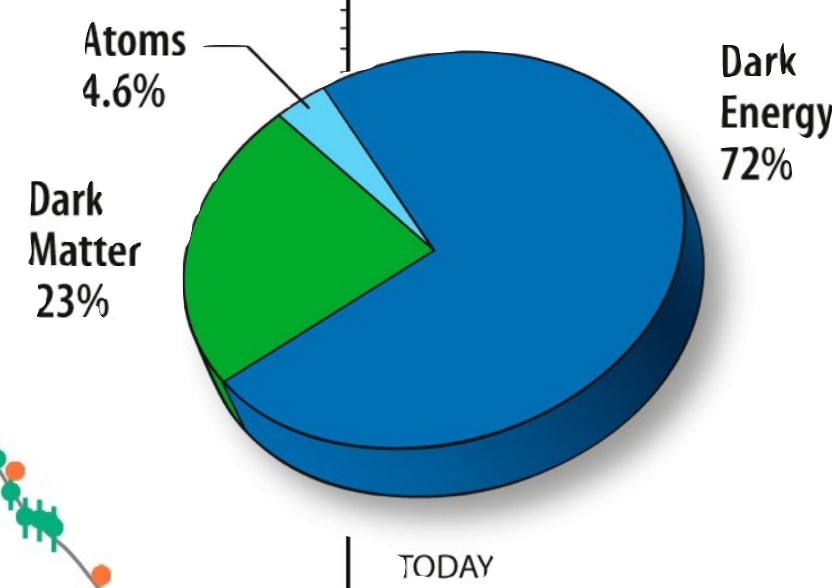


Great progress, but still a long, way to go.

Planck XV (2015)

What about physics constraints? Can they be improved?





Enormous precision and accuracy:

Flat universe ($\Omega_k < 0.005$)

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

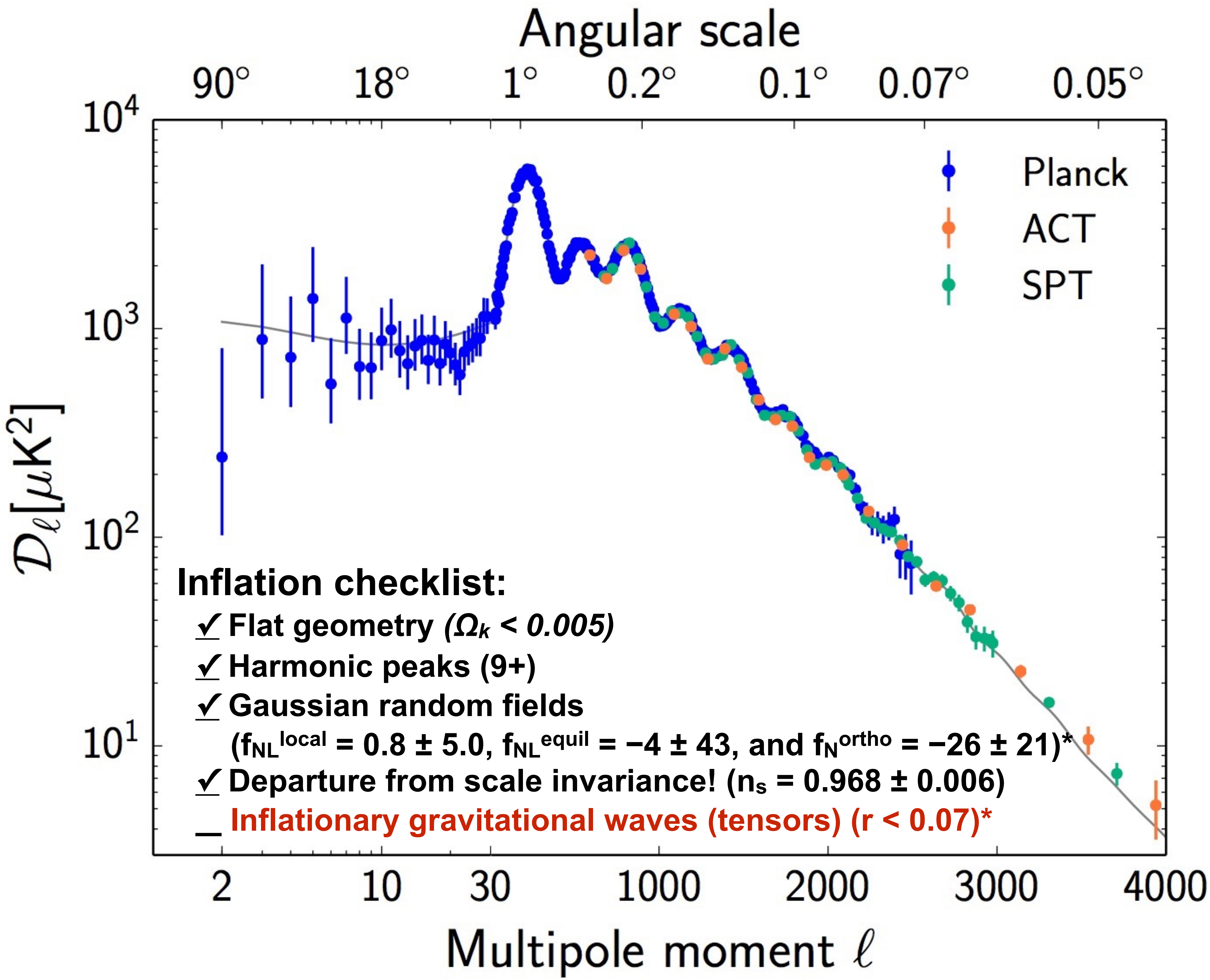
$\Omega_c h^2 = 0.1197 +/- 0.0022$

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

But extensions to ΛCDM model are poorly constrained.

Planck Results I 2015

Inflation?

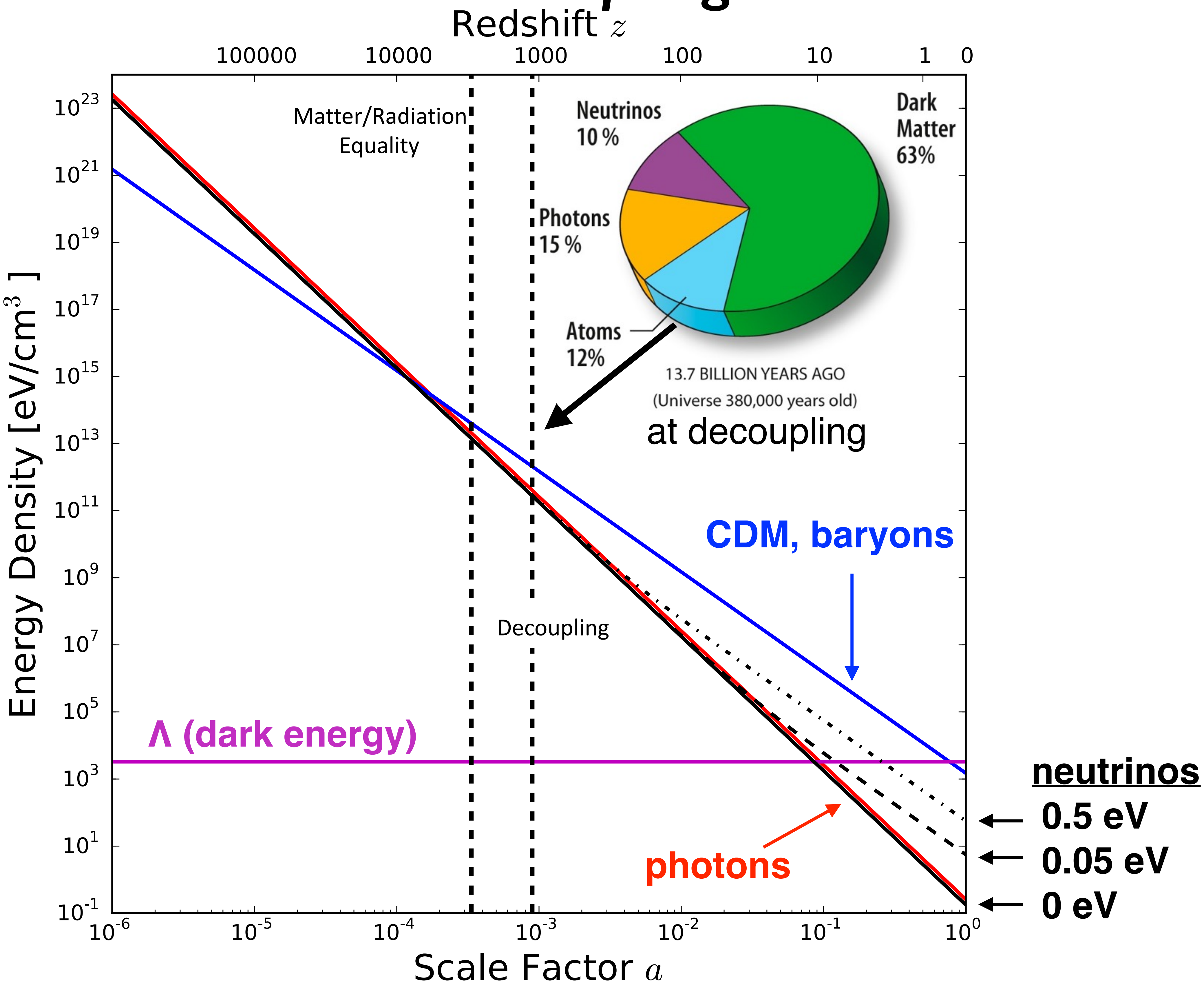


Inflation checklist:

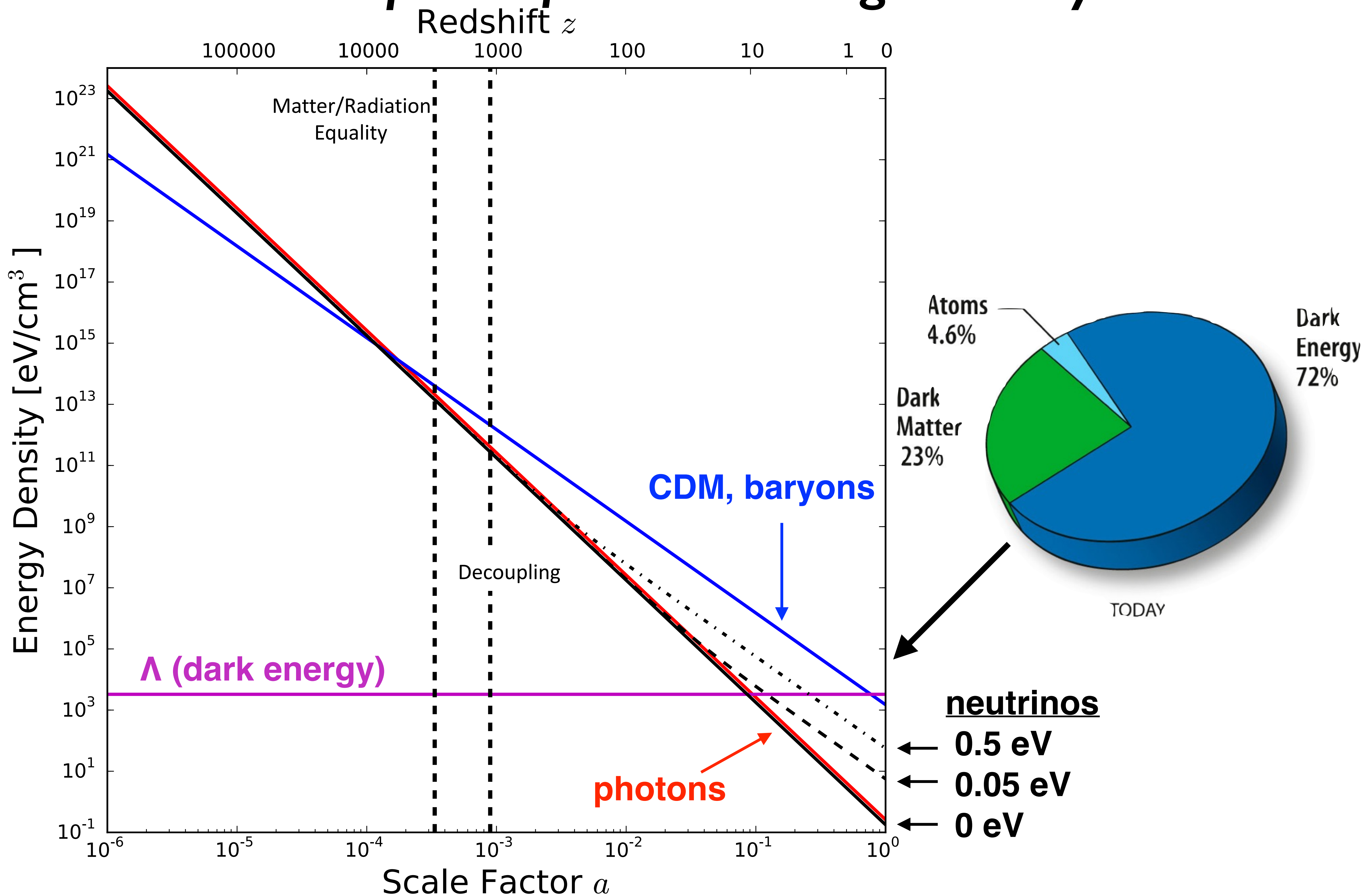
- ✓ **Flat geometry** ***(Ω_k < 0.005)***
- ✓ **Harmonic peaks (9+)**
- ✓ **Gaussian random fields** **($f_{NL}^{local} = 0.8 \pm 5.0$, $f_{NL}^{equil} = -4 \pm 43$, and $f_N^{ortho} = -26 \pm 21$)***
- ✓ **Departure from scale invariance! ($n_s = 0.968 \pm 0.006$)**
- __ **Inflationary gravitational waves (tensors) ($r < 0.07$)***

*constraints include CMB polarization data

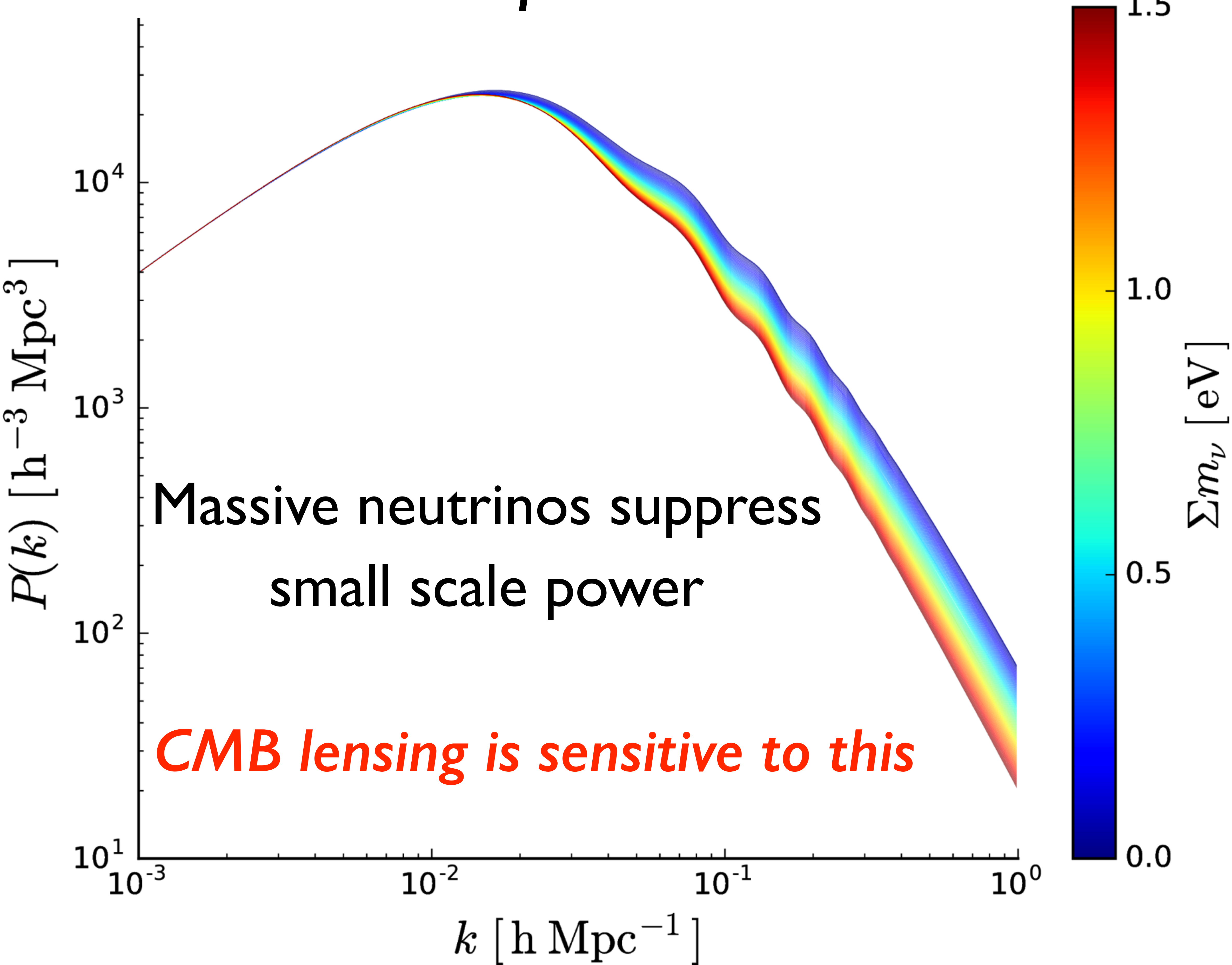
Neutrinos
- relativistic at decoupling



Neutrinos
- transition to part of matter budget today



Matter Power spectrum



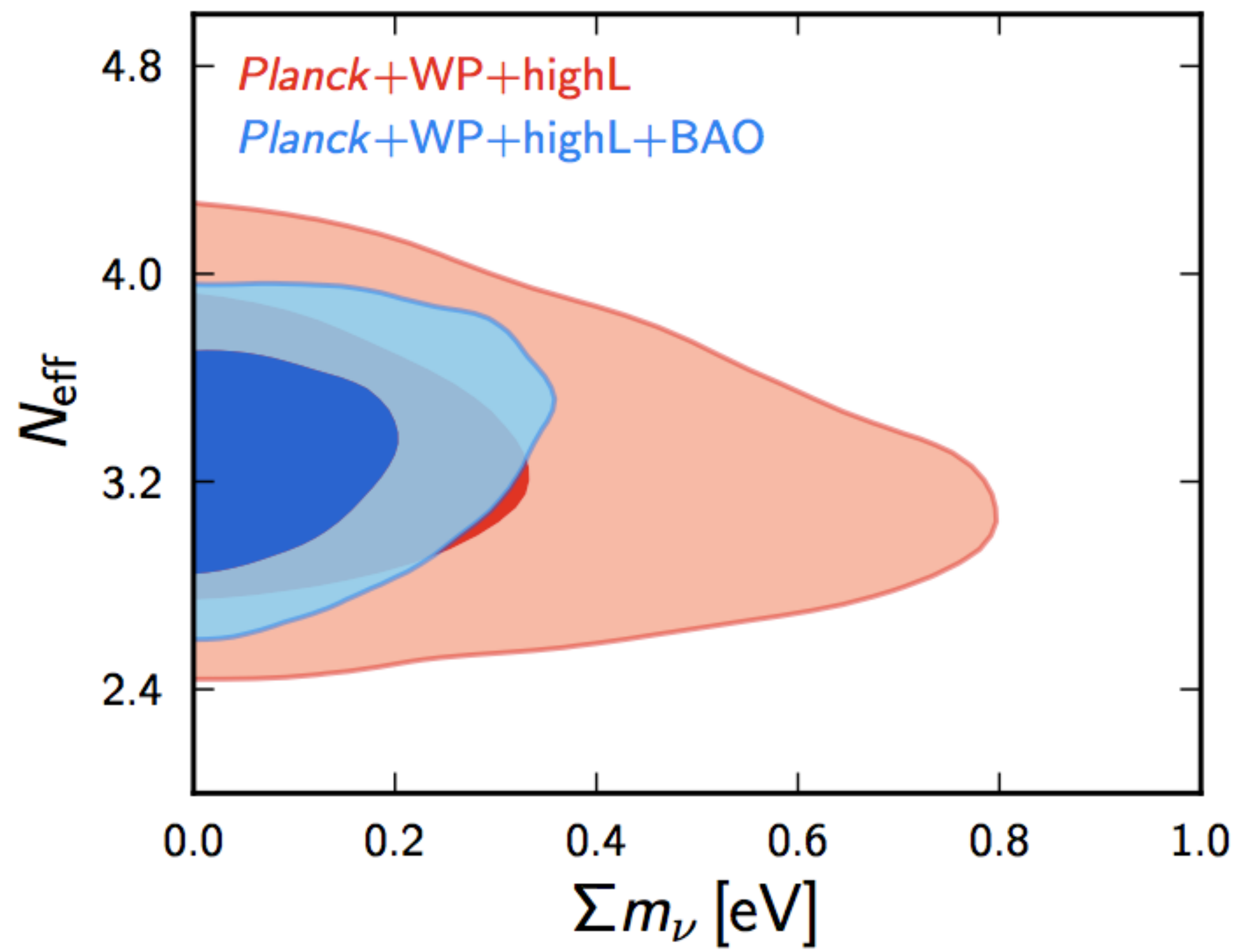
CMB Neutrino Constraints

The non-gamma relativistic energy density of the Universe is parametrized by $\boldsymbol{N_{eff}}$, the effective number of relativistic species, where $\boldsymbol{N_{eff} = 3.046}$ for 3 neutrinos.

N_{eff} = 3.15 +/- 0.23

greater than 10σ detection of cosmic neutrino background!

Planck Collaboration (plot 2013; constraints 2015)



Σm_ν < 0.23 eV at 95% c.l.

Joint Σm_ν and N_{eff} constraints: $N_{eff} = 3.2 \pm 0.5$; $\Sigma m_\nu < 0.32$ eV

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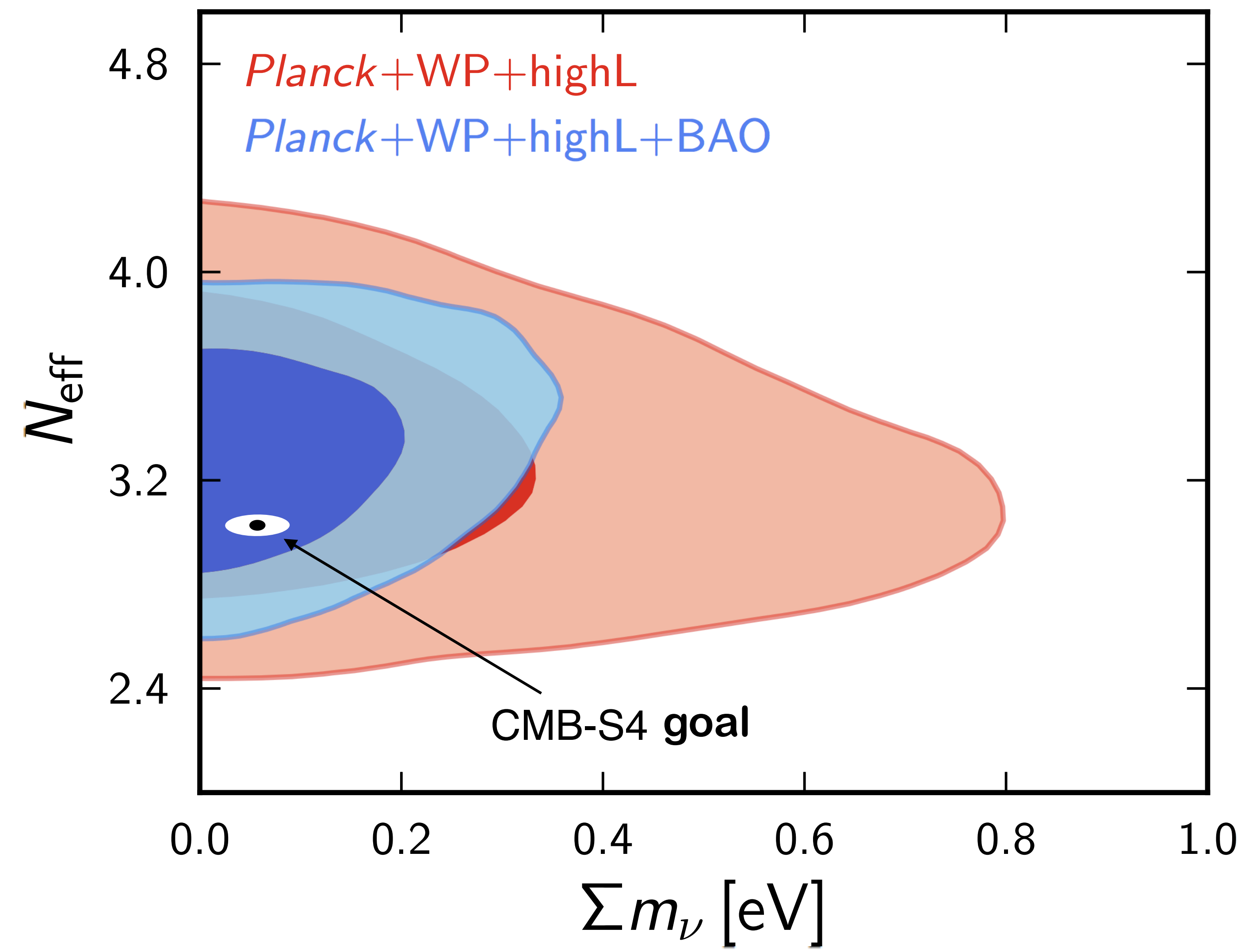

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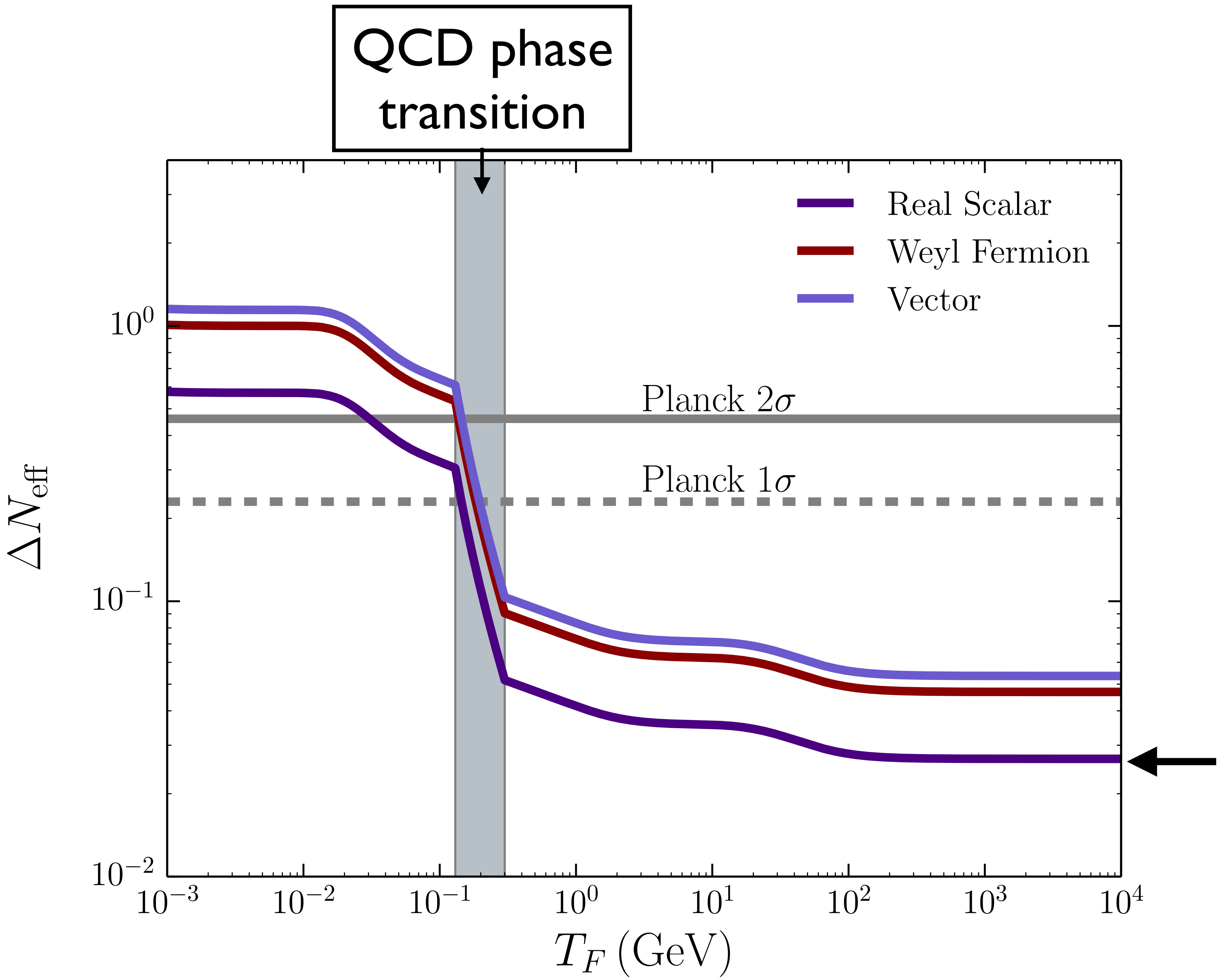
N_{eff} constraints and light relics



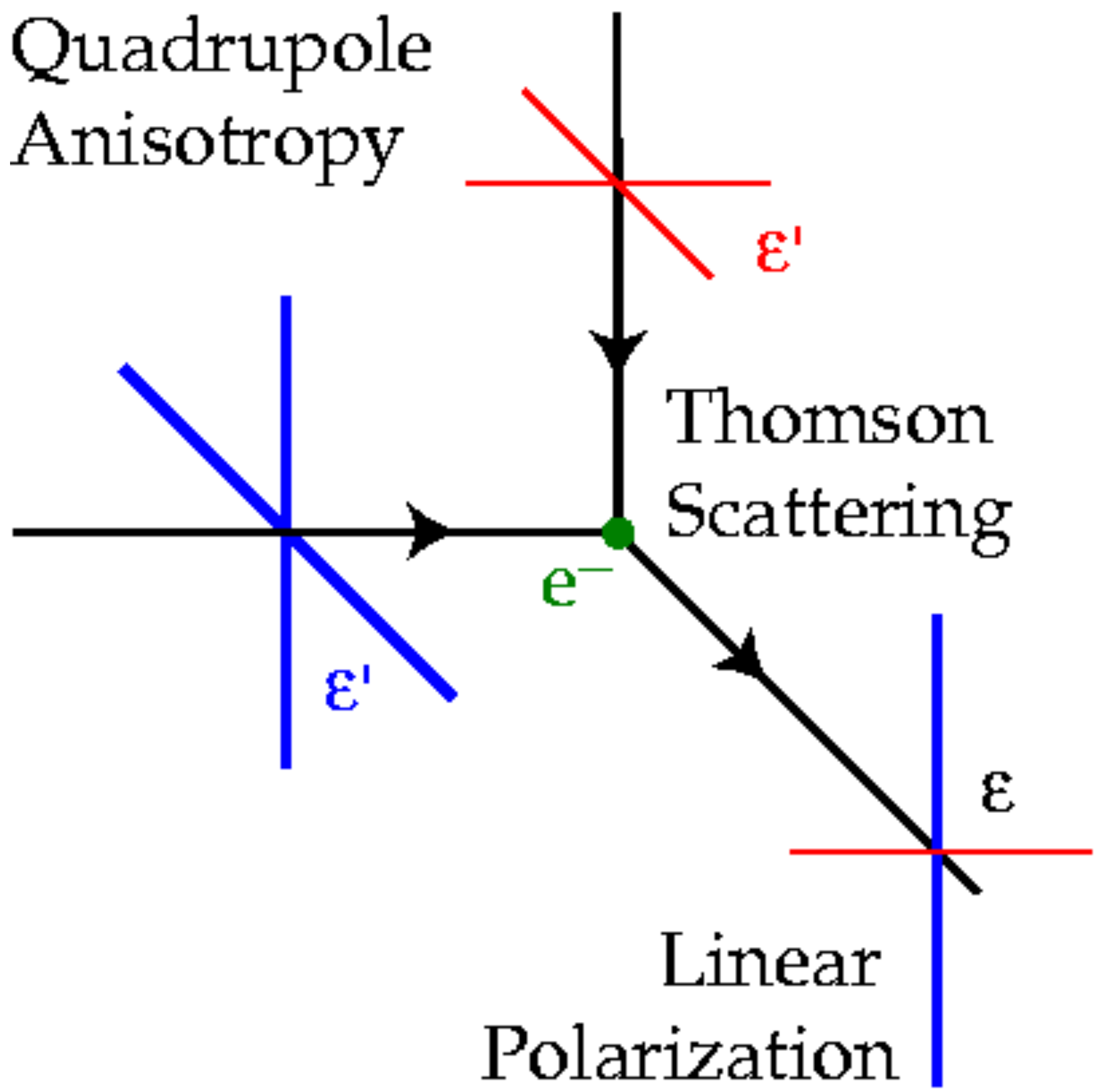
N_{eff} measurements can constrain light thermal relics

Sets experimental target of $\Delta N_{eff} = 0.027$ (goal for CMB-S4)

Baumann, Green, Wallisch arXiv:1604.08614
CMB-S4 Science Book (https://cosmo.uchicago.edu/CMB-S4workshops)

The frontier: CMB Polarization

The frontier is CMB lensing and polarization,
and the future of CMB lensing is polarization.



from W. Hu's web pages

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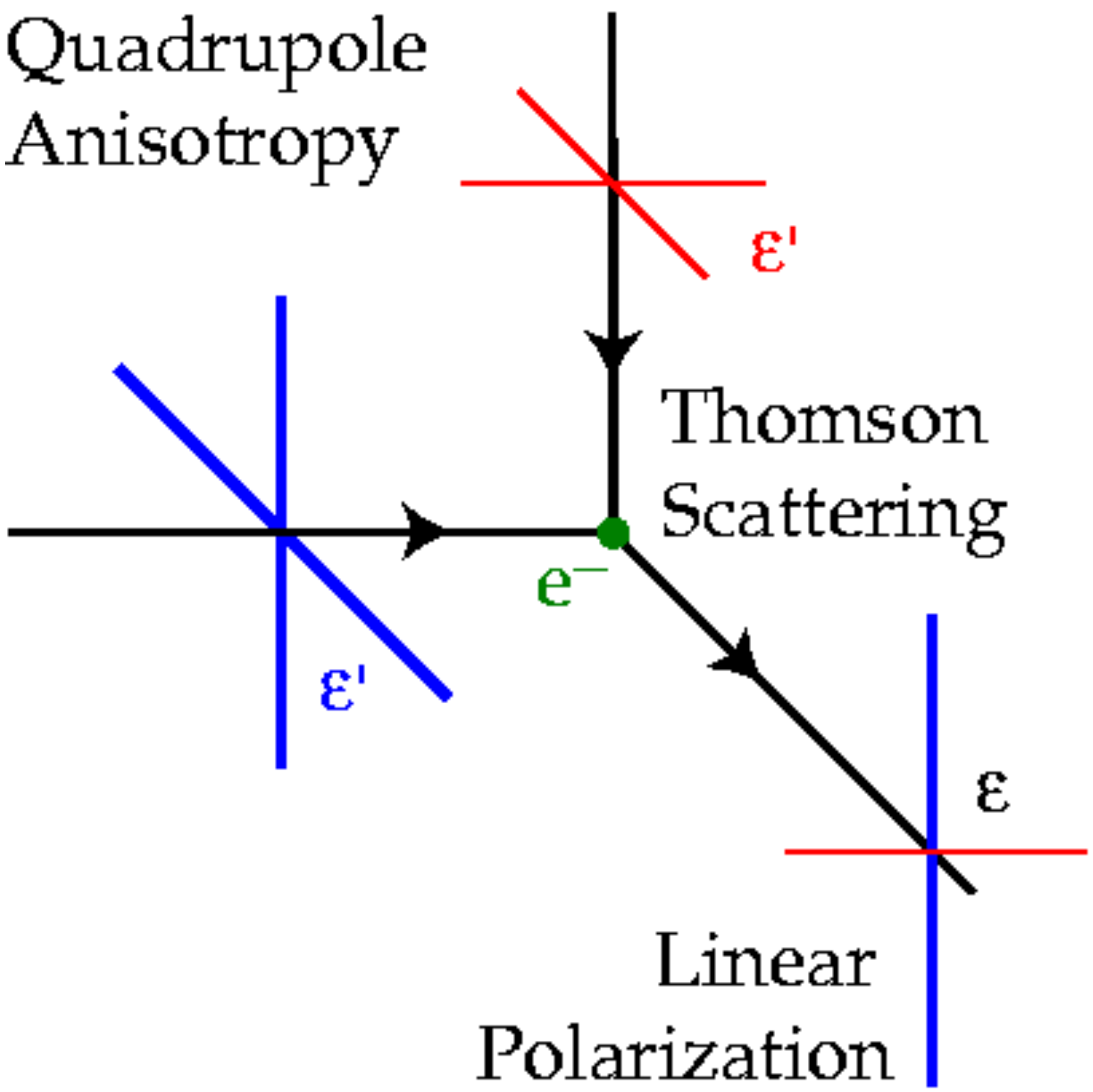

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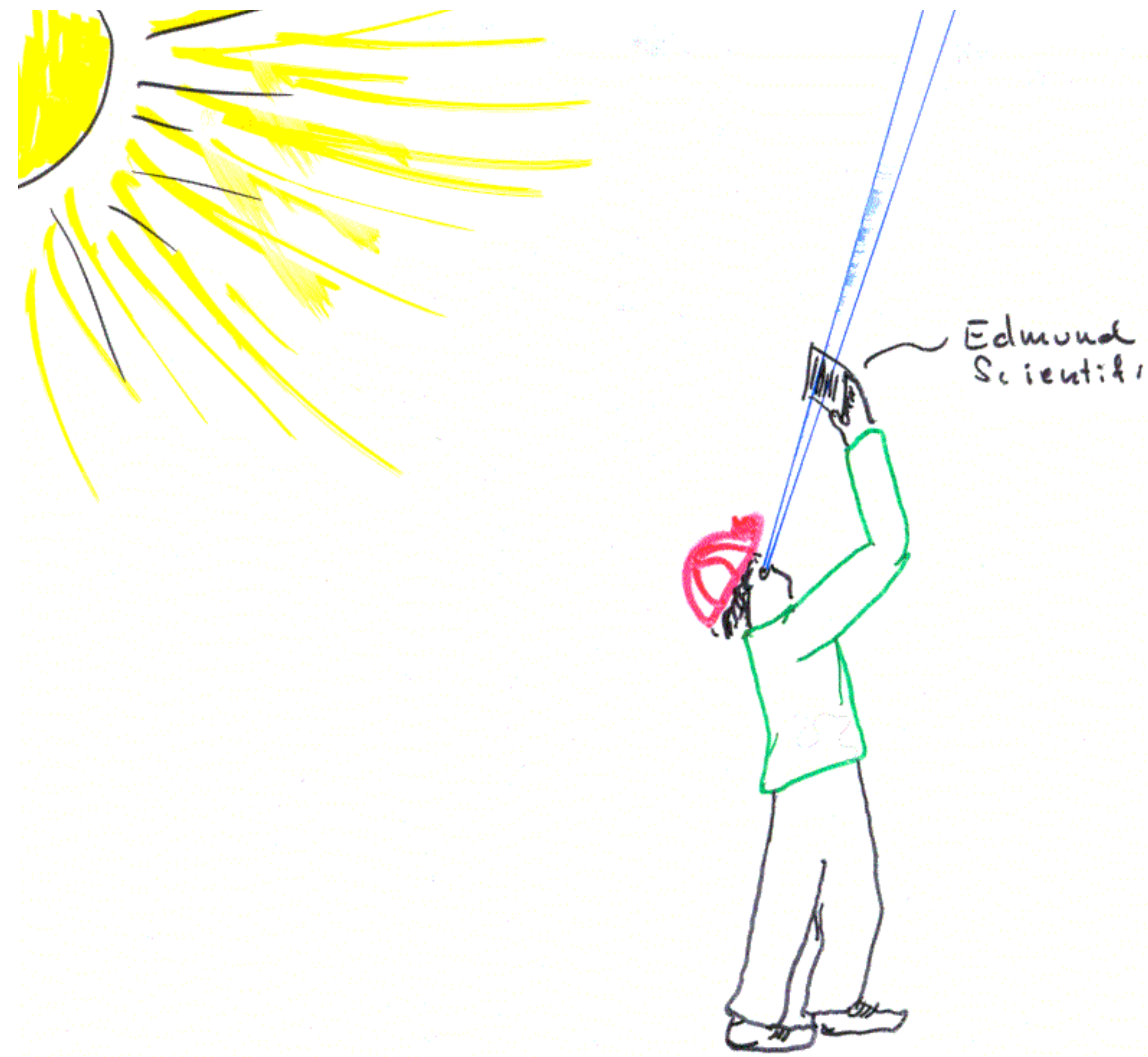
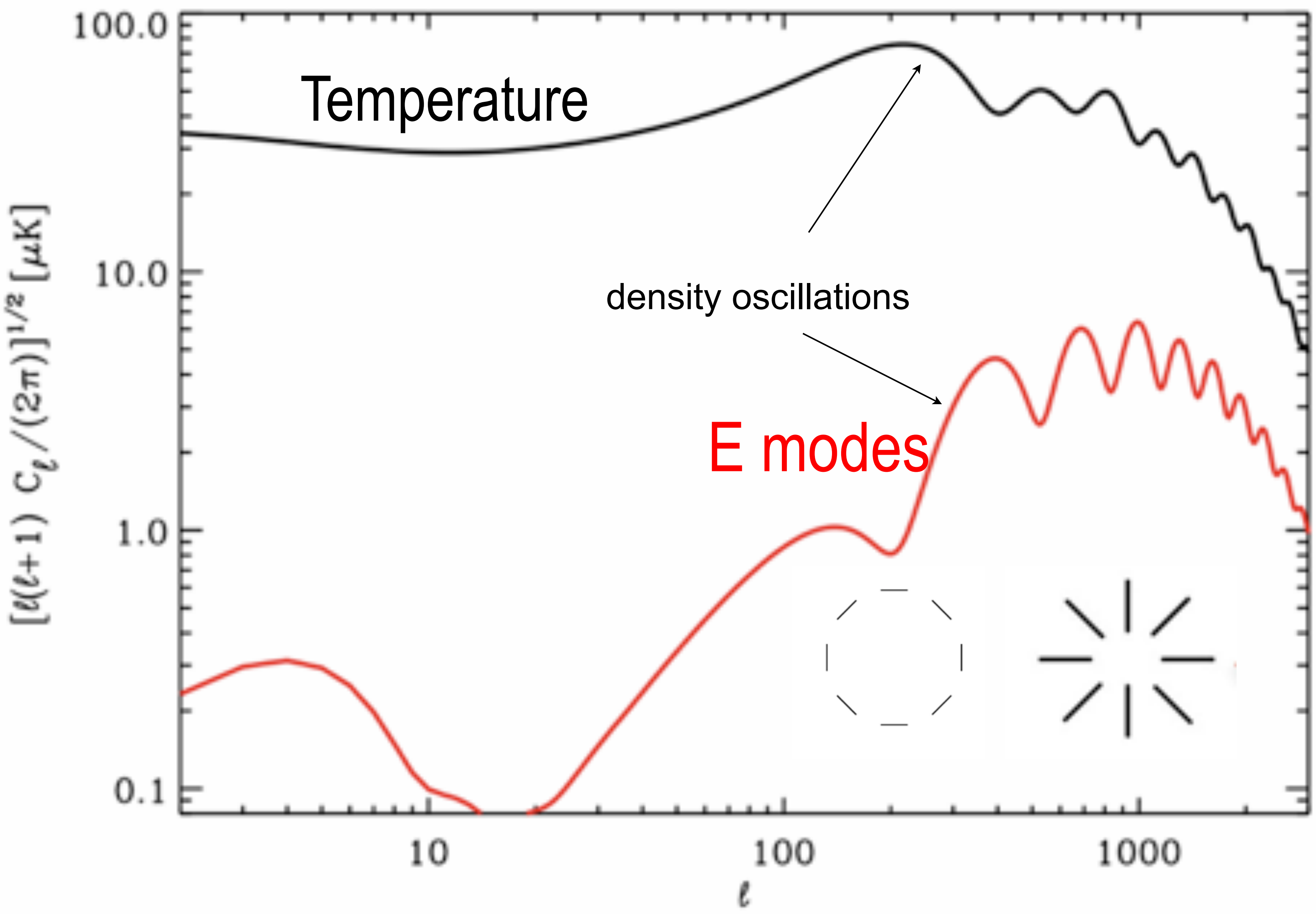
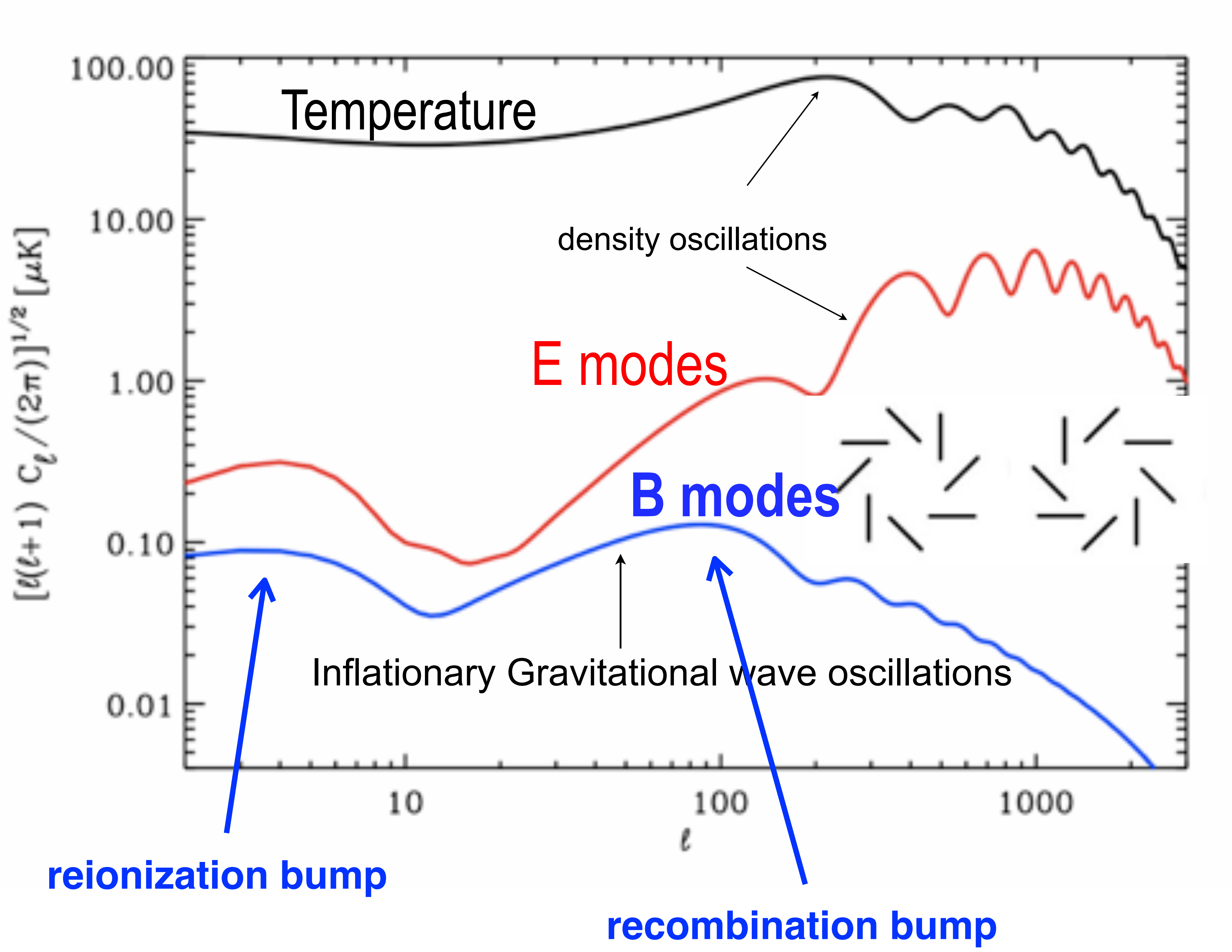


Just like the sky,
the *CMB must be polarized*

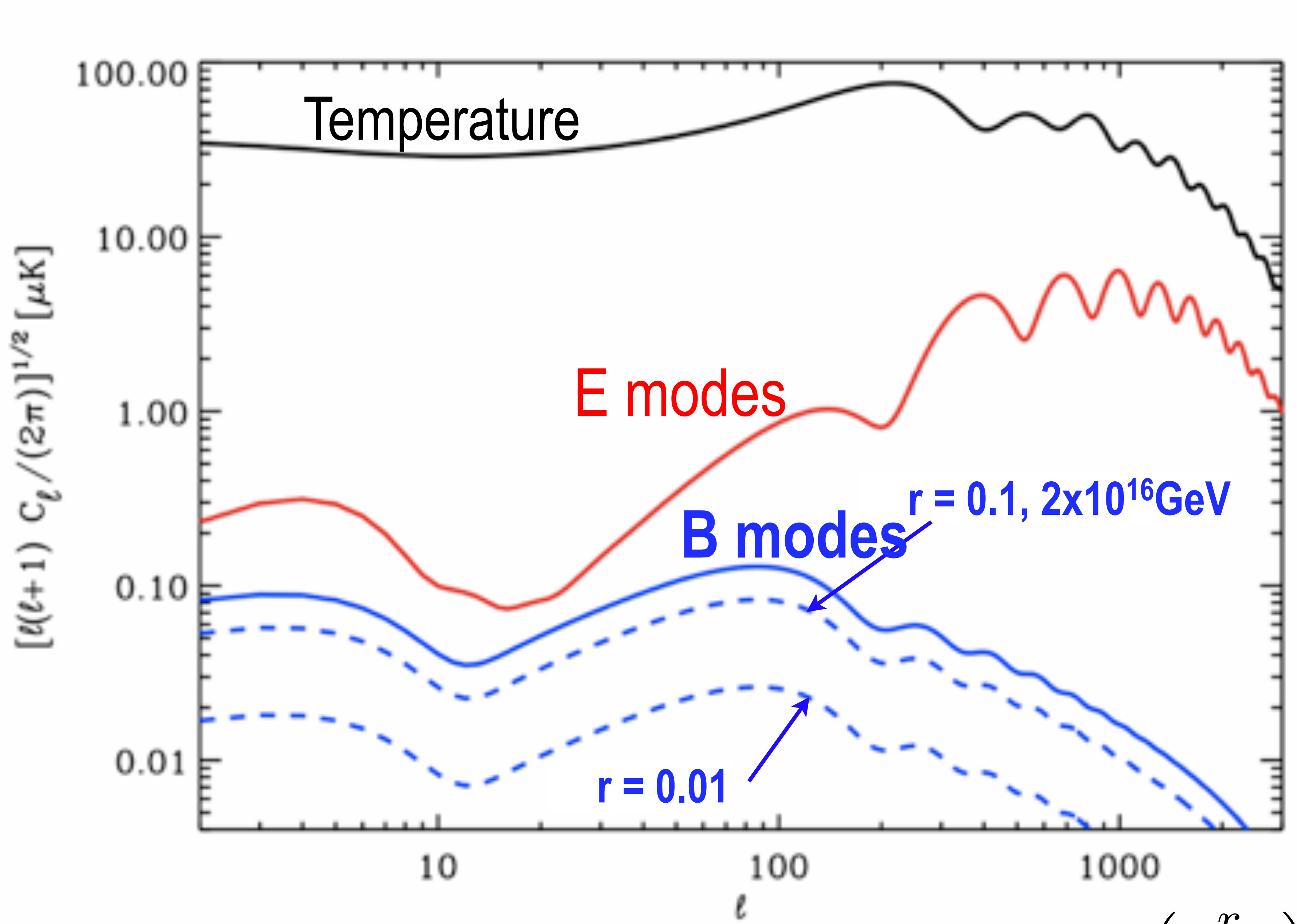
CMB Polarization



CMB Polarization



CMB Polarization

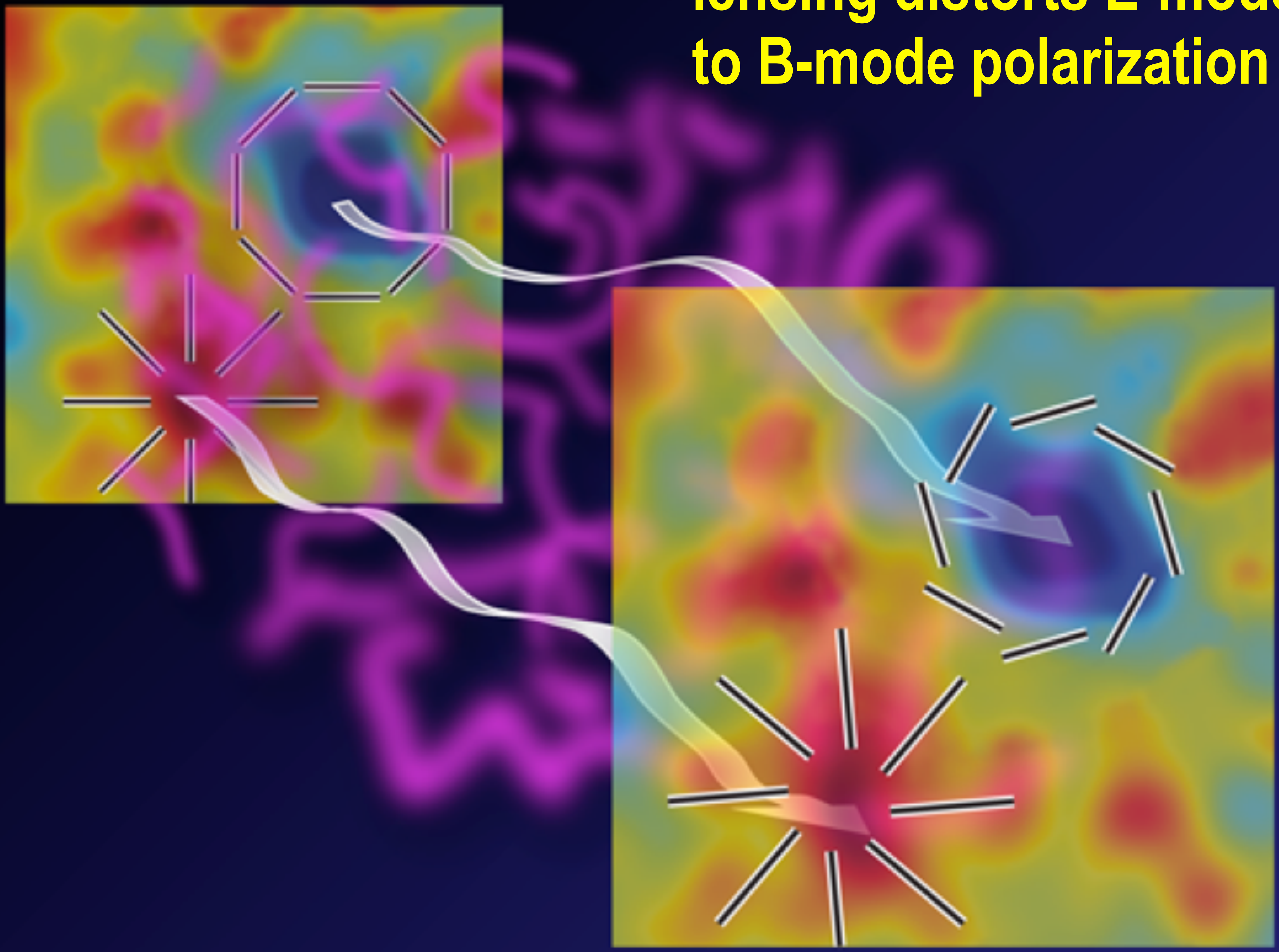


$$r \equiv \frac{\text{Tensor (gravitational) perturbation amplitude}}{\text{Scalar (density) perturbation amplitude}}$$

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

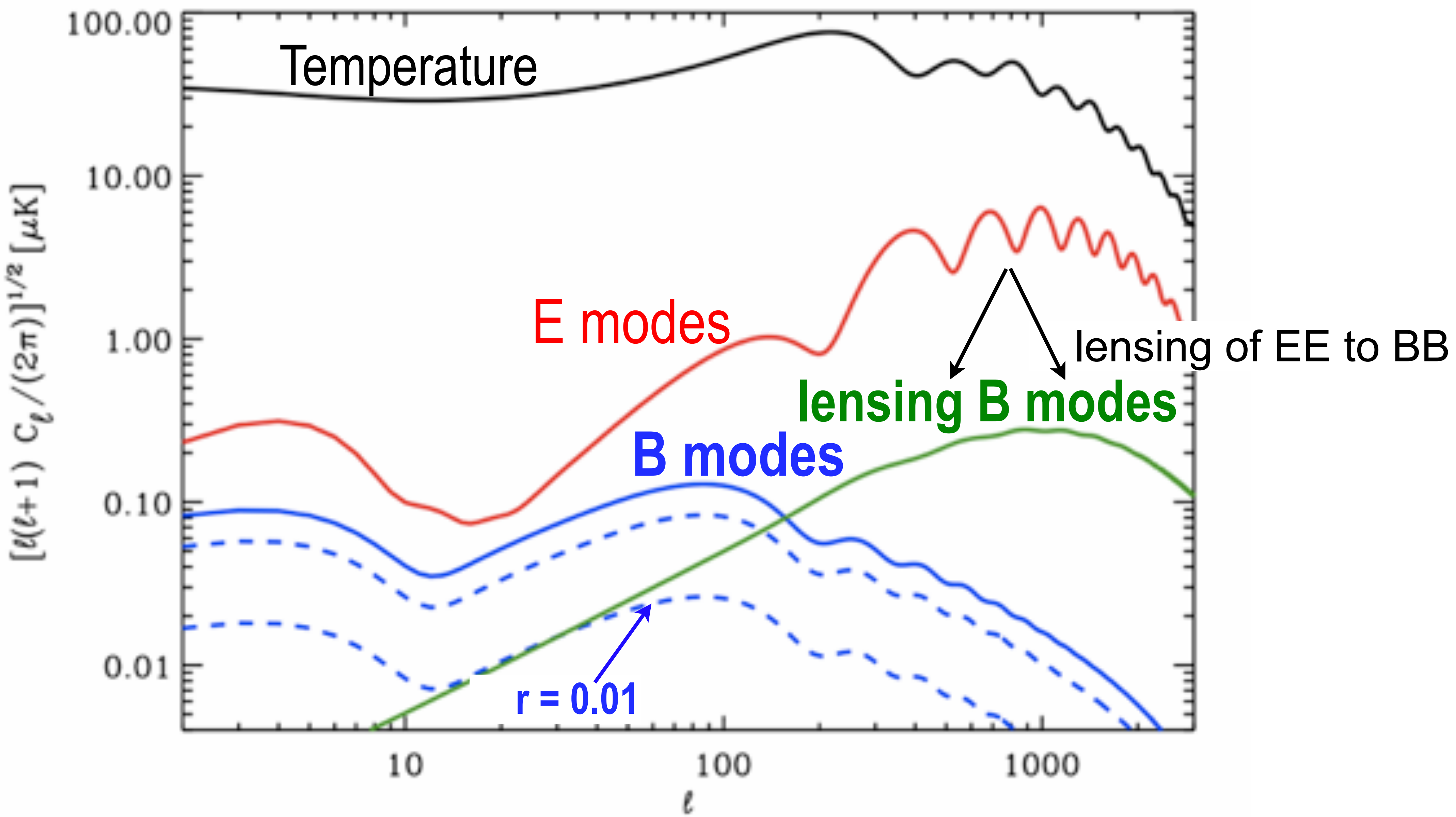
$$\text{time} = 10^{-36} \left(\frac{r}{0.01}\right)^{-\frac{1}{2}} \text{seconds}$$

lensing distorts E-mode to B-mode polarization

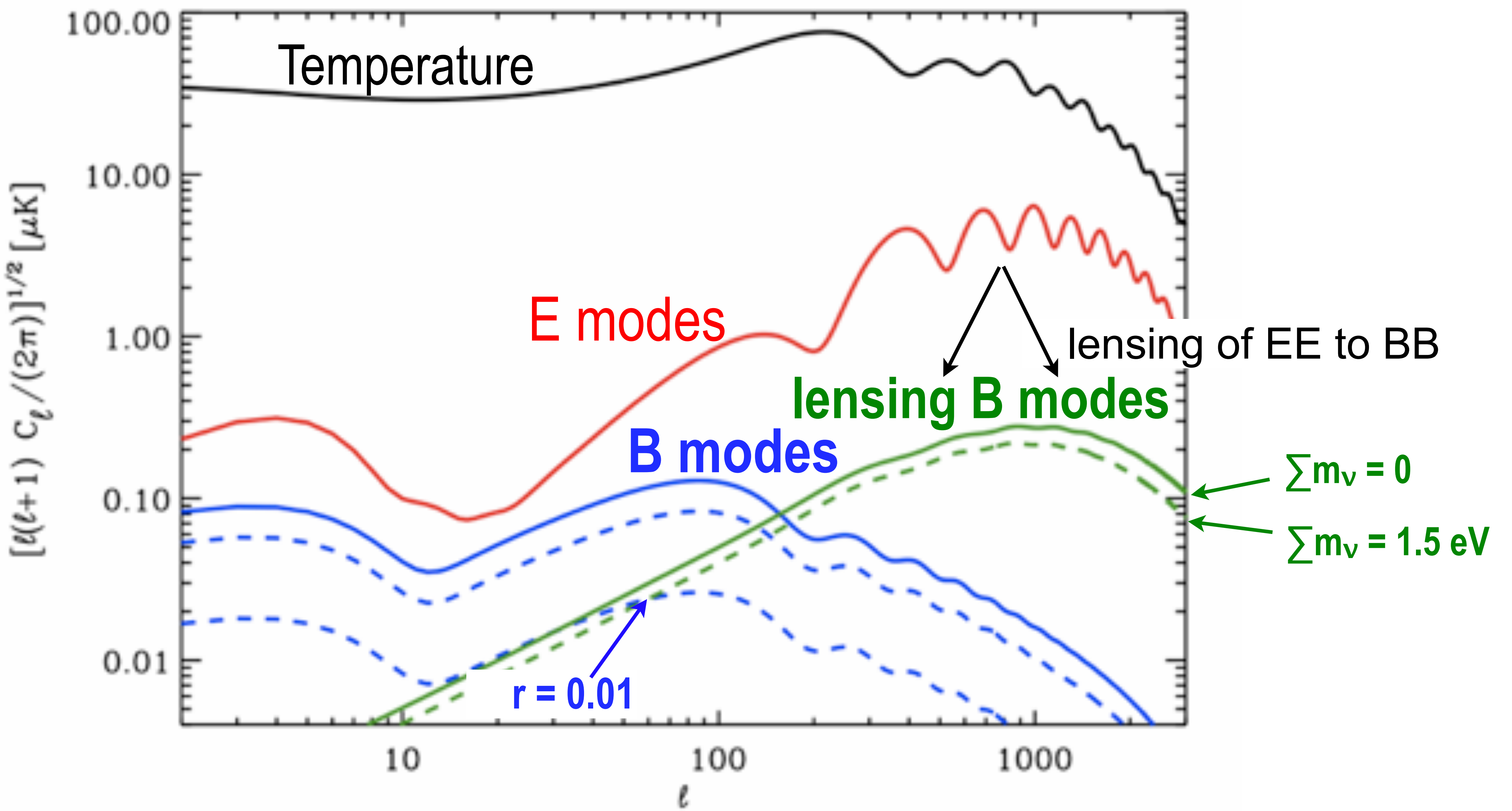


graphic from ESA website

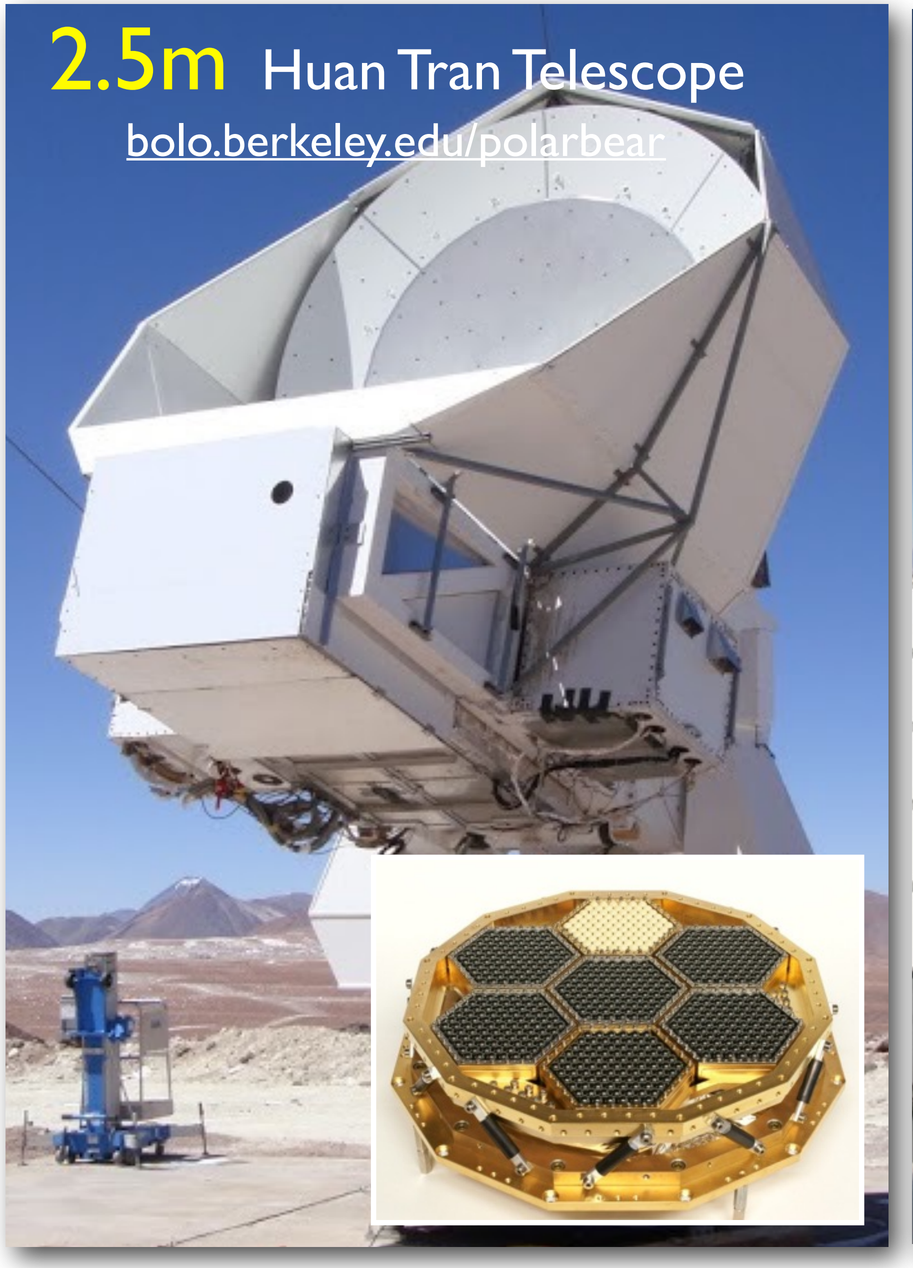
CMB Polarization

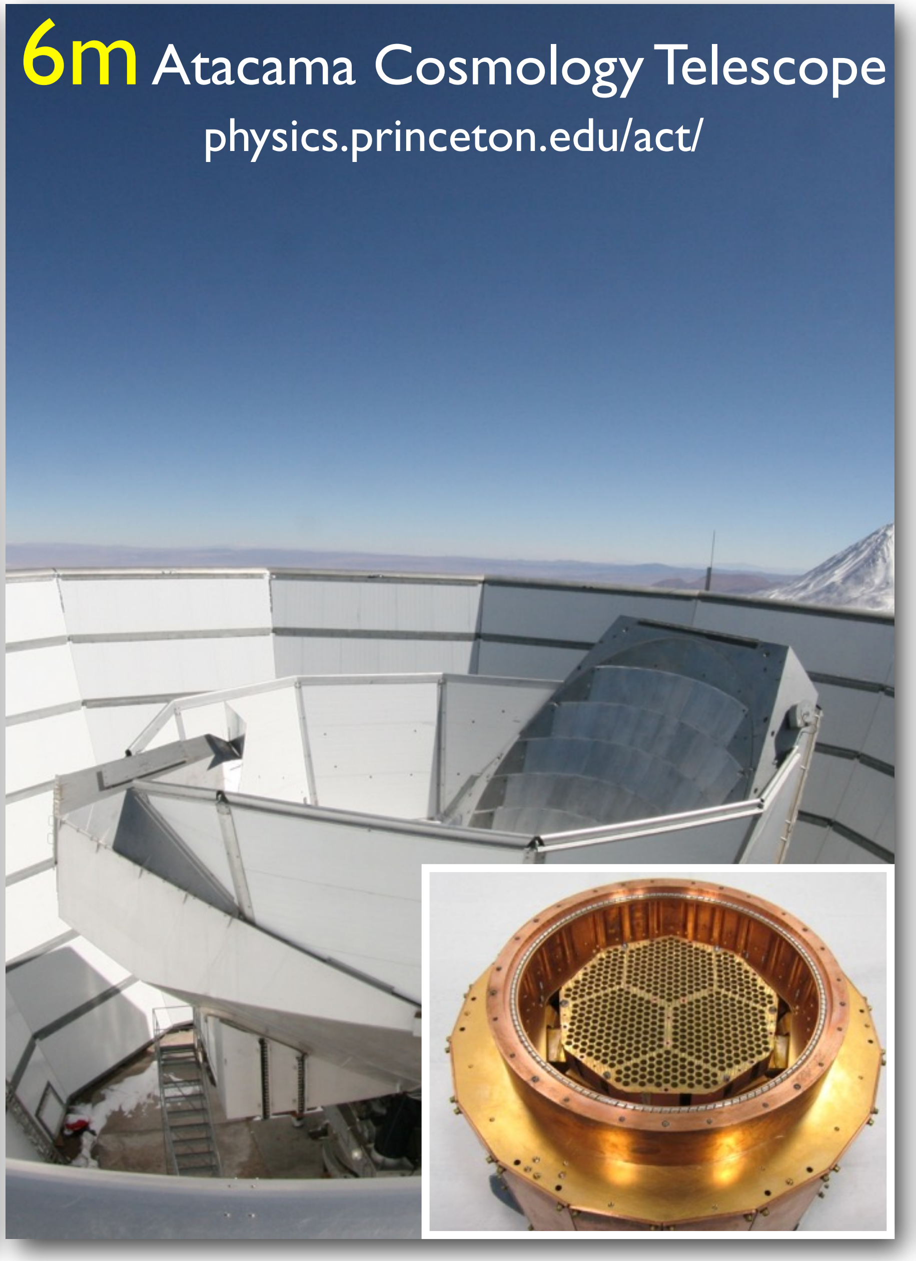


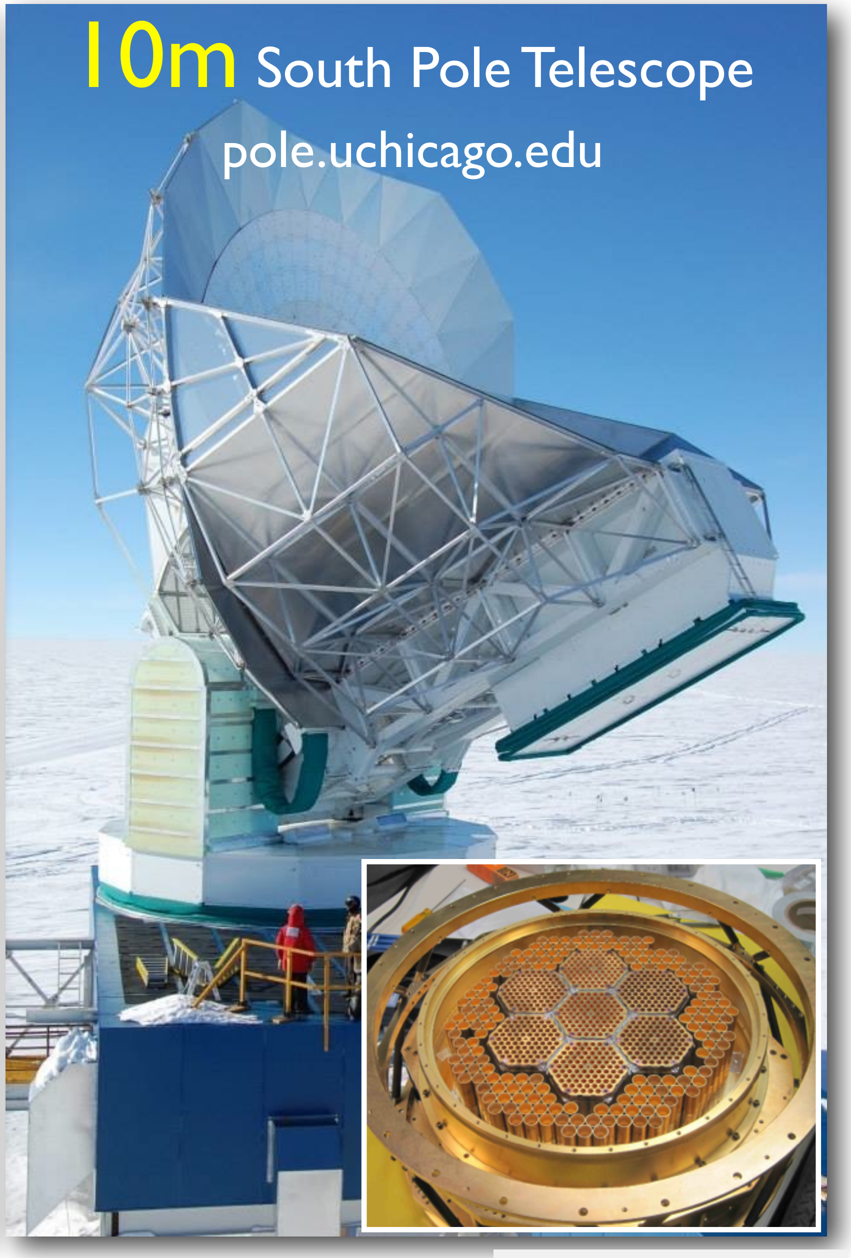
CMB Polarization



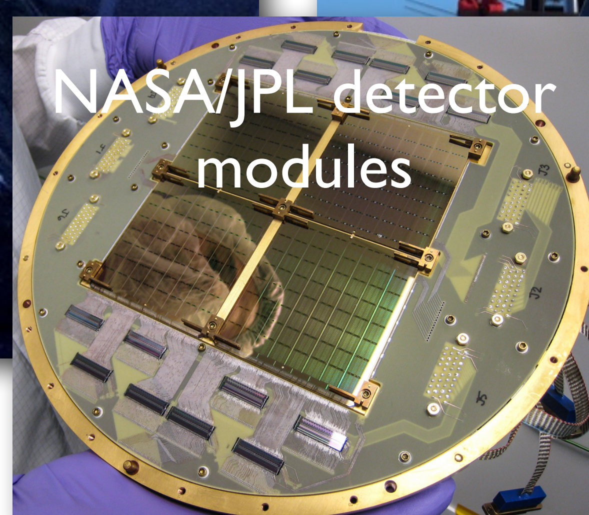
Polarization with mid to large telescopes







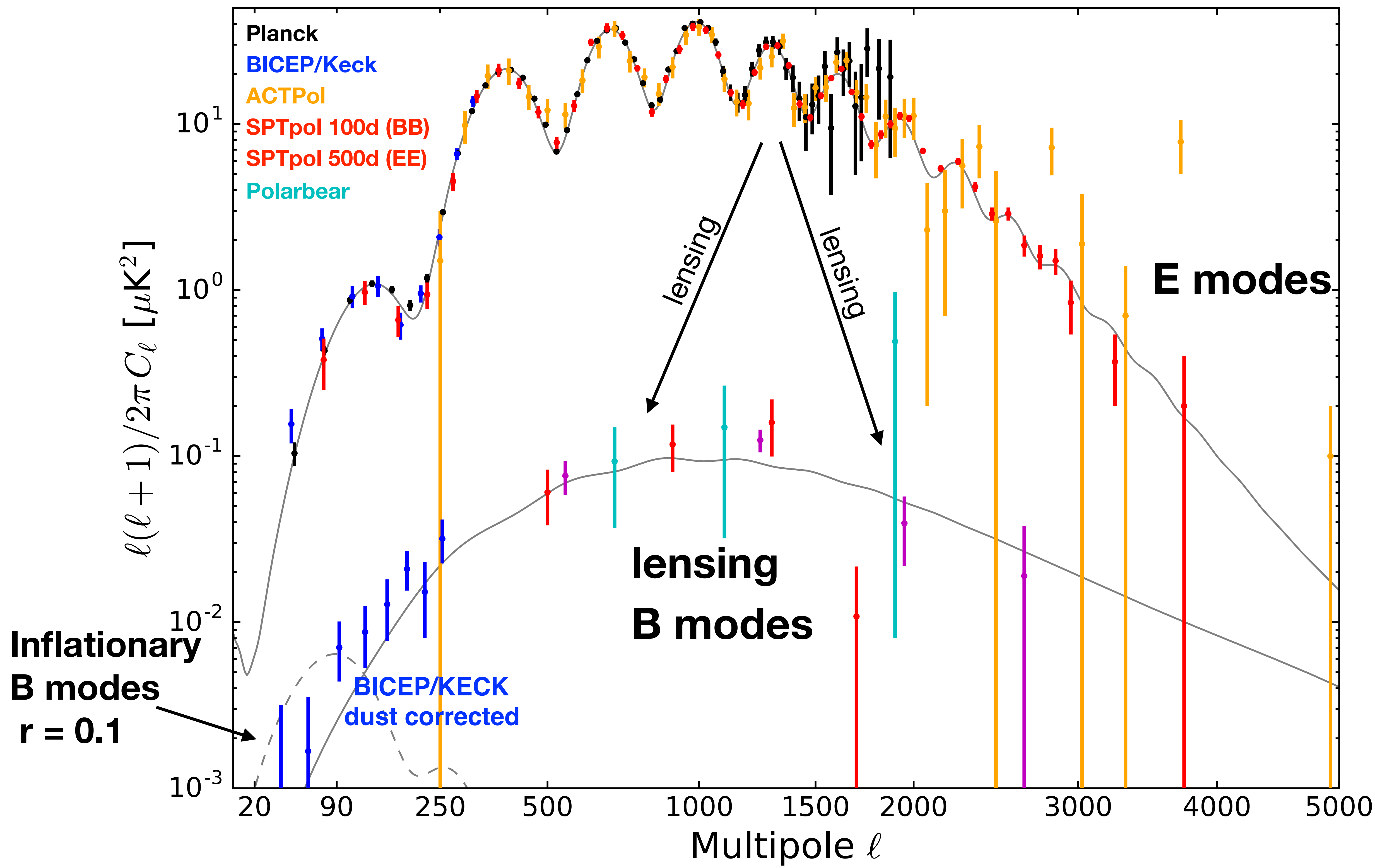
Polarization with small aperture CMB telescopes



Also

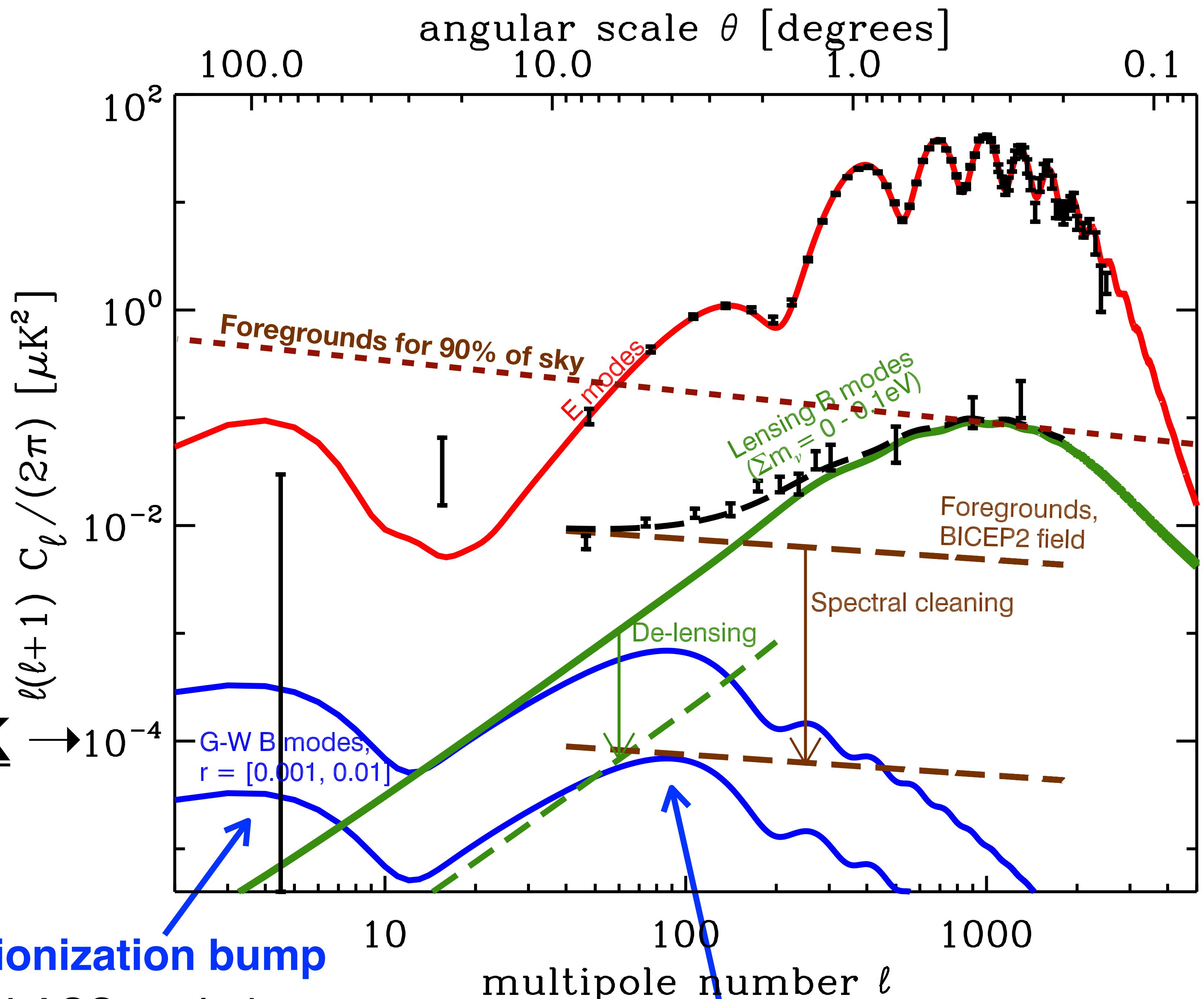
- Ground: ABS, QUBIC, QUIJOTE, GroundBird
- Balloon: EBEX, PIPER, LSPE
- Satellite proposals: LiteBIRD, PIXIE, CORE

Current status CMB polarization



Rapid progress. All within last 3 years.

Polarization status and future challenge



10 nK →

E modes

lensing B modes

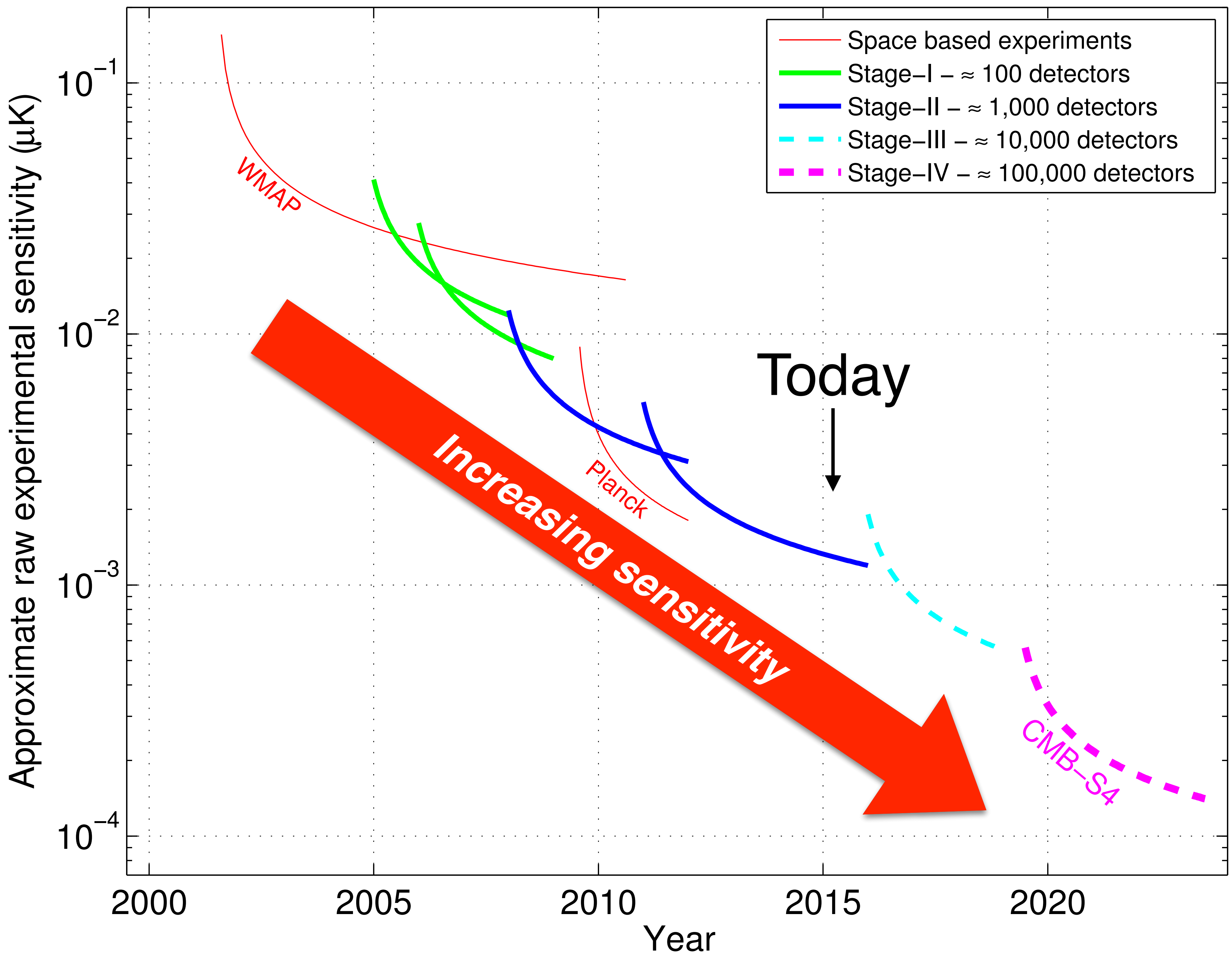
inflationary gravity wave B modes

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

recombination bump
key target of CMB-S4

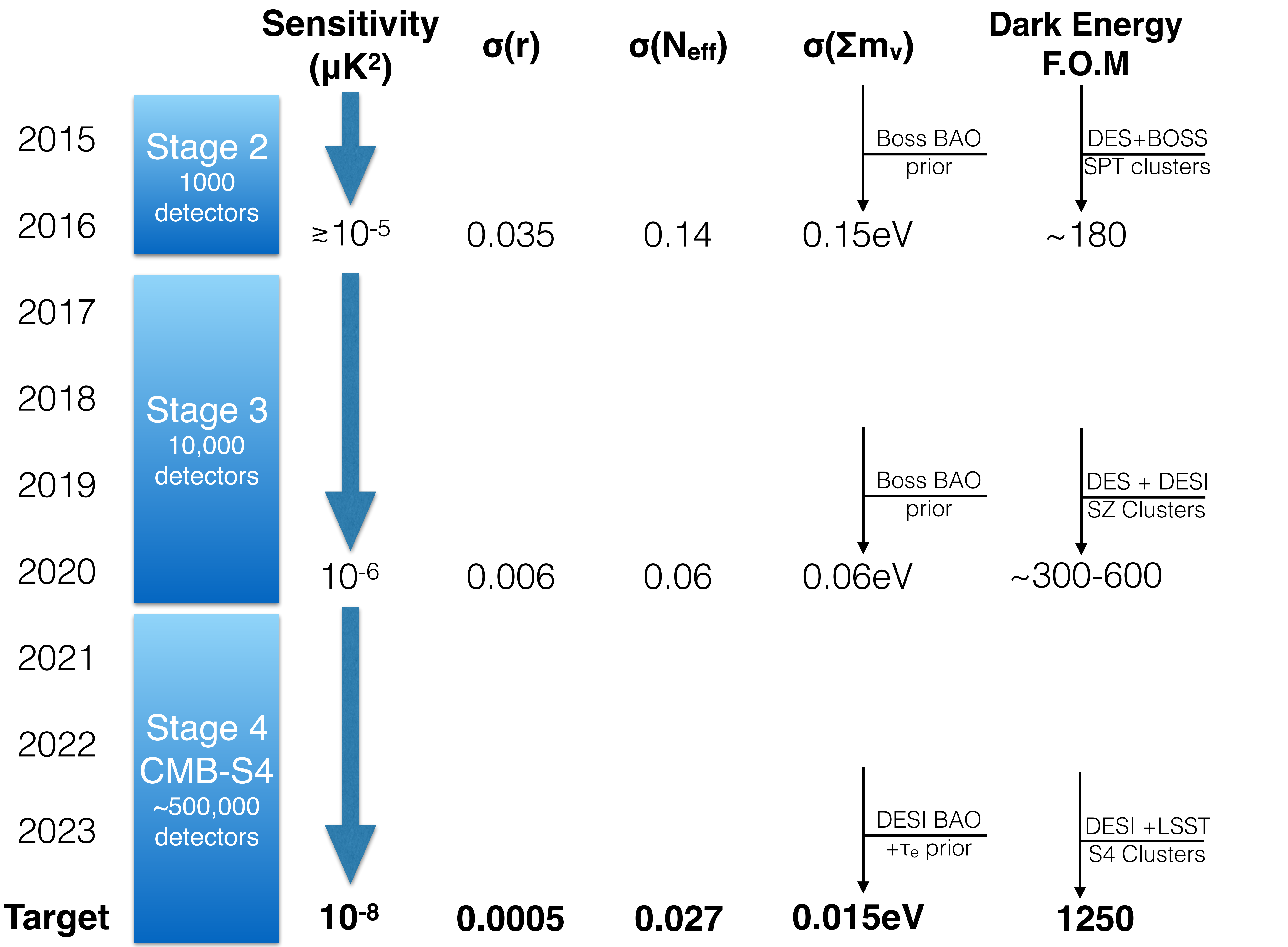
… still a long, long way to go.

The next big steps



A Moore's Law of CMB sensitivity

Snowmass CF5 Neutrinos Document arxiv:1309.5383; figure by Clem Pryke



Sensitivity (μK^2)
$\sigma(r)$
$\sigma(N_{eff})$
$\sigma(\Sigma m_\nu)$
Dark Energy F.O.M
2015
2016
2017
2018
2019
2020
2021
2022
2023
Target
Stage 2
1000 detectors
Stage 3
10,000 detectors
Stage 4
CMB-S4
~500,000 detectors
Boss BAO prior
DES+BOSS
SPT clusters
$\gtrsim 10^{-5}$
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
$+\tau_e$ prior
DESI +LSST
S4 Clusters
10^{-8}
0.0005
0.027
0.015eV
1250

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) to cross critical science thresholds.
- O(500,000) polarization sensitive detectors spanning 30 - 300 GHz using multiple telescopes at South Pole and Chile (and possibly northern sites) to map most of the sky, as well as deep targeted fields.
- Broad participation of the CMB community, including the existing CMB groups, e.g., **ACT, BICEP/KECK, CLASS, Polarbear & SPT,** the National Labs and the High Energy Physics community. International partnerships.

Recommended by P5 & NRC Antarctic reports

Scale of CMB-S4 exceeds capabilities of the University CMB groups.

→ Partnership of CMB community and National labs will do it.

Community workshops to advance CMB-S4

U. Minnesota
Jan 16, 2015

LBNL, Berkeley
March 7-9, 2016

U. Michigan
Sep 21-22, 2015

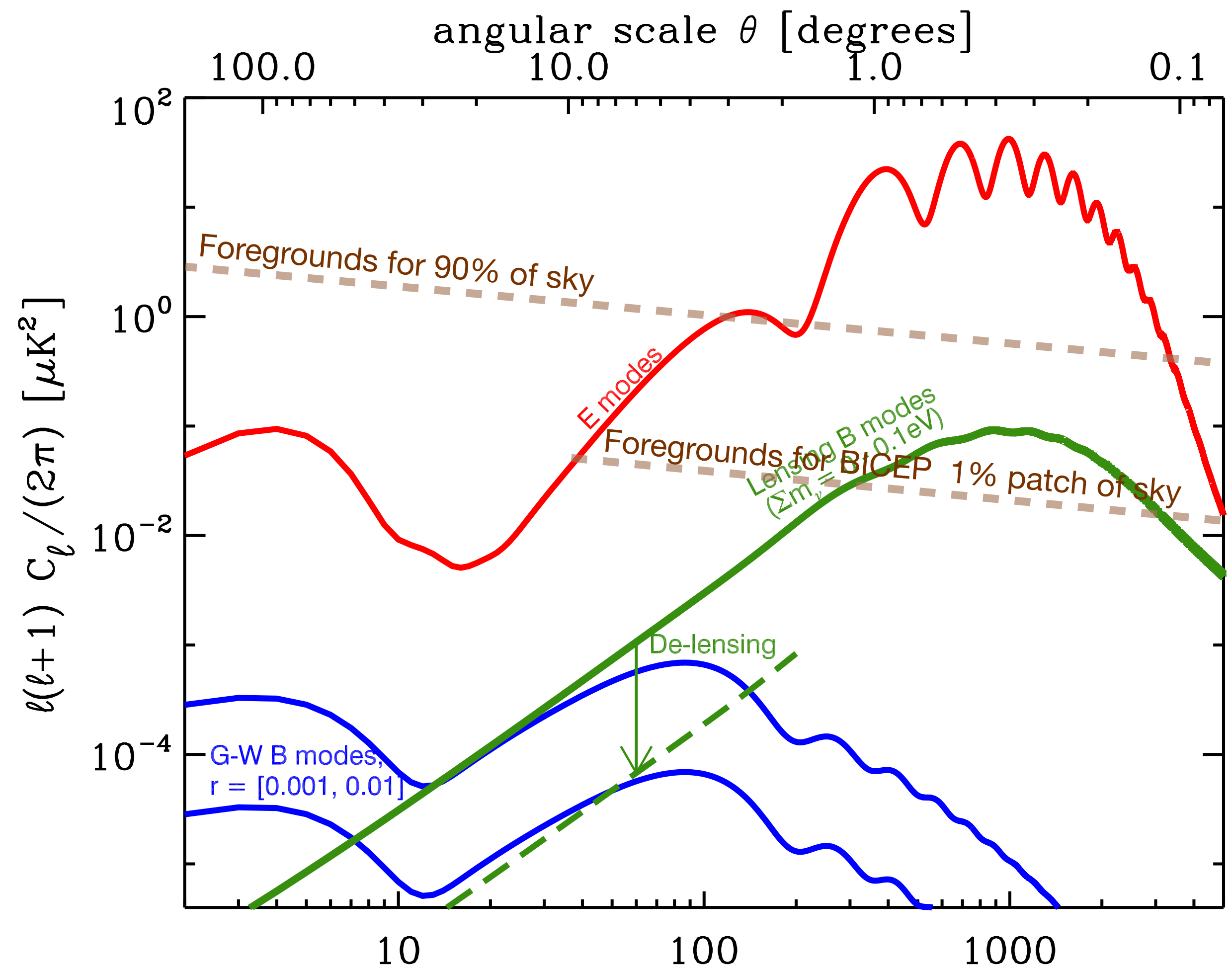
Next: UChicago Sep19-21 2016
Please attend - register at
https://kicp-workshops.uchicago.edu/cmb-s4-2016

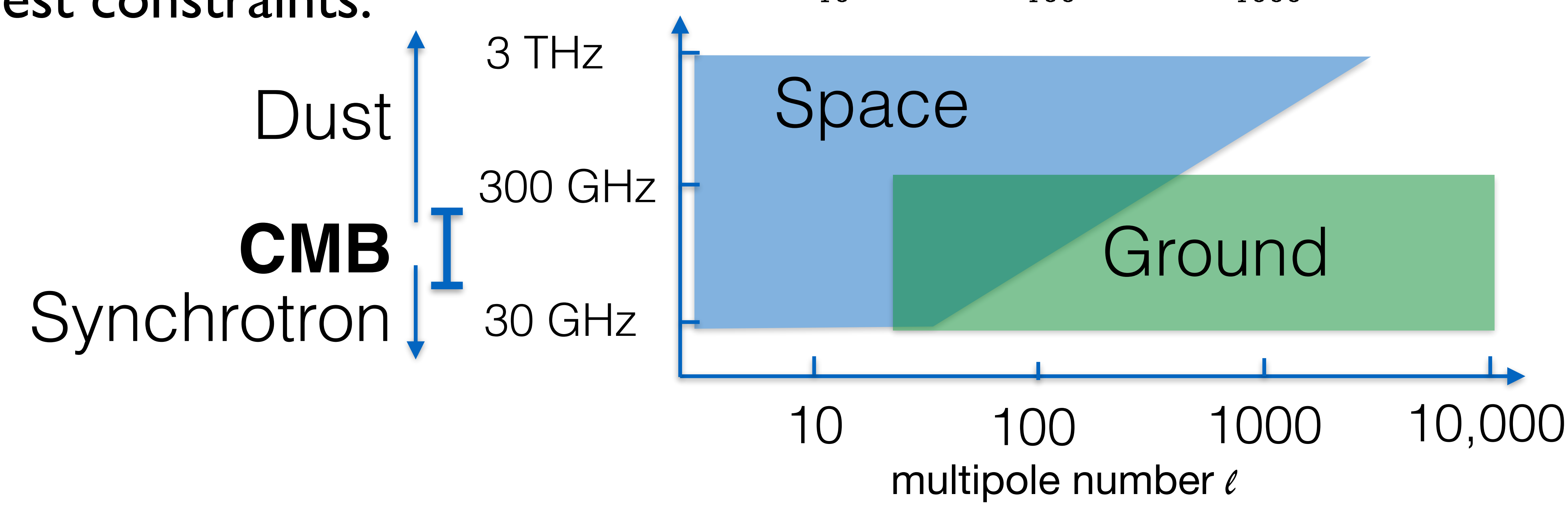
1st edition Science Book complete!
Next: instrument definition and iterate with science goals

CMB-S4
Next Generation CMB Experiment

Complementary strengths of ground and space

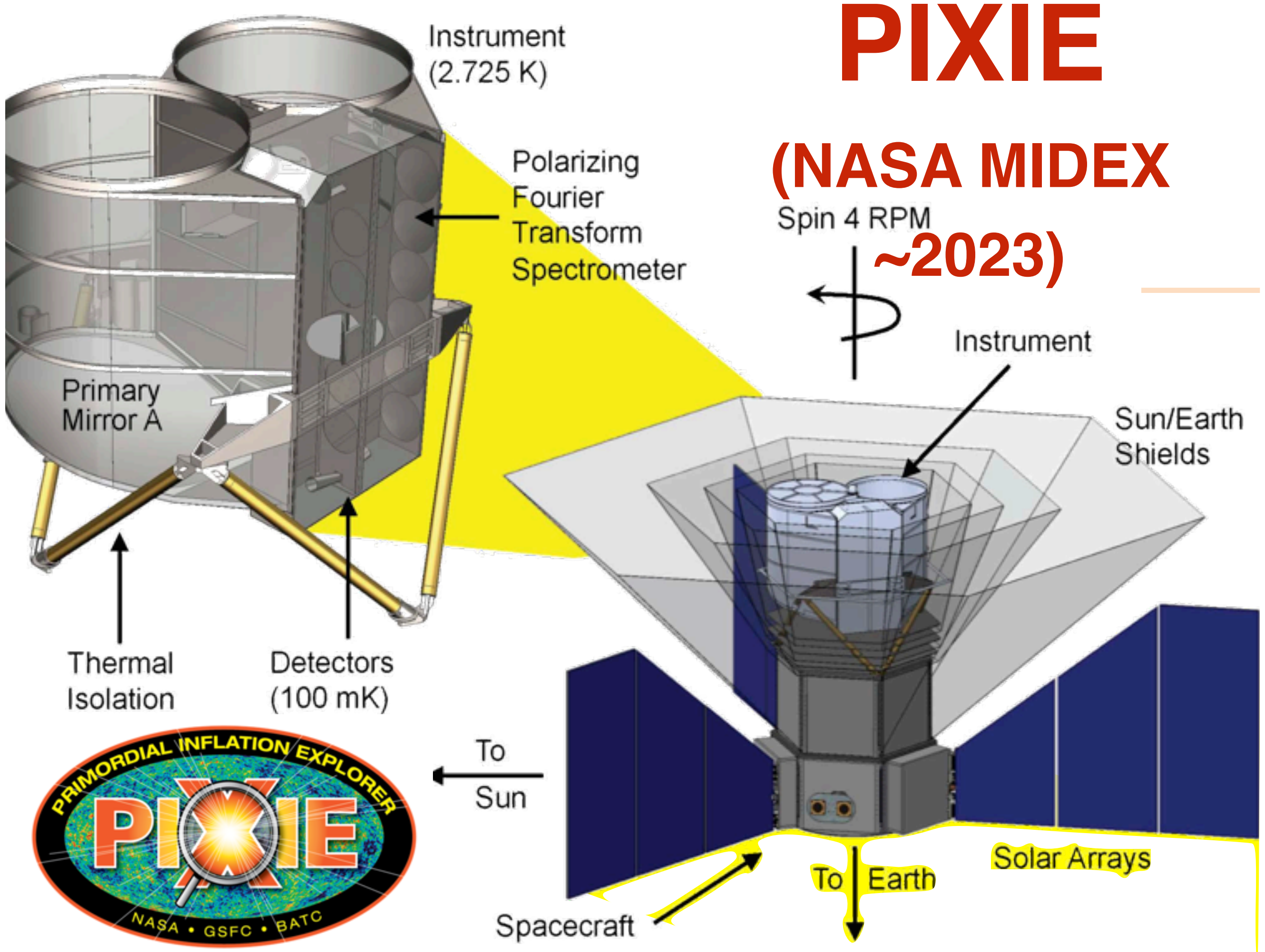
- **Ground:** Angular resolution for CMB lensing (+de-lensing B modes!), damping tail, clusters….
- **Space:** All sky for reionization peak; high frequencies for dust.
- Combined data would provide best constraints.





CMB satellite proposals

PIXIE
(NASA MIDEX ~2023)



LiteCORE
(ESA M5 ~2026-2030)

LiteBIRD (JAXA, ~2025)

Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection

All targeting σ(r) ~ few 10^{-4}

Last words

The CMB is the gift that keeps on giving.

Science is spectacular: we are searching for inflationary gravitational waves and will rigorously test single field slow roll inflation. We will determine the number and masses of the neutrinos, constrain possible new light relic particles, provide precise constraints on the nature of dark energy, test general relativity on large scales, and more…

CMB-S4 will be great leap forward.

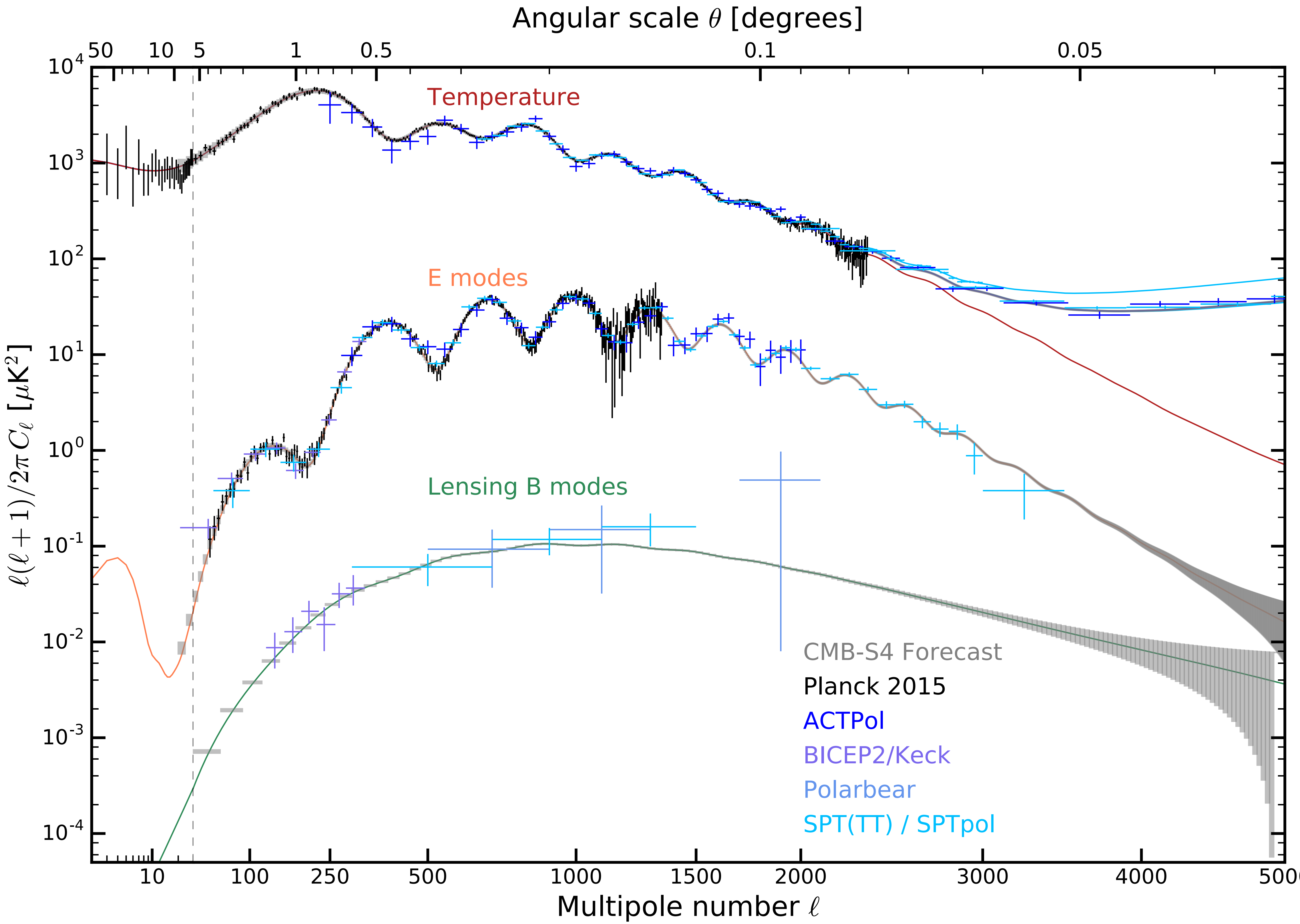
- Science Book available at CMB-S4.org and will be posted on the archive soon.
- NSF and DOE are now requesting applications for CMB-S4 concept design team members (see posting at CMB-S4.org).
- Next workshop September 19-21, 2106 at U. Chicago https://kicp-workshops.uchicago.edu/cmb-s4-2016

backup slides

CMB-S4

Next Generation CMB Experiment

Science Book projection for CMB-S4 strawman configuration



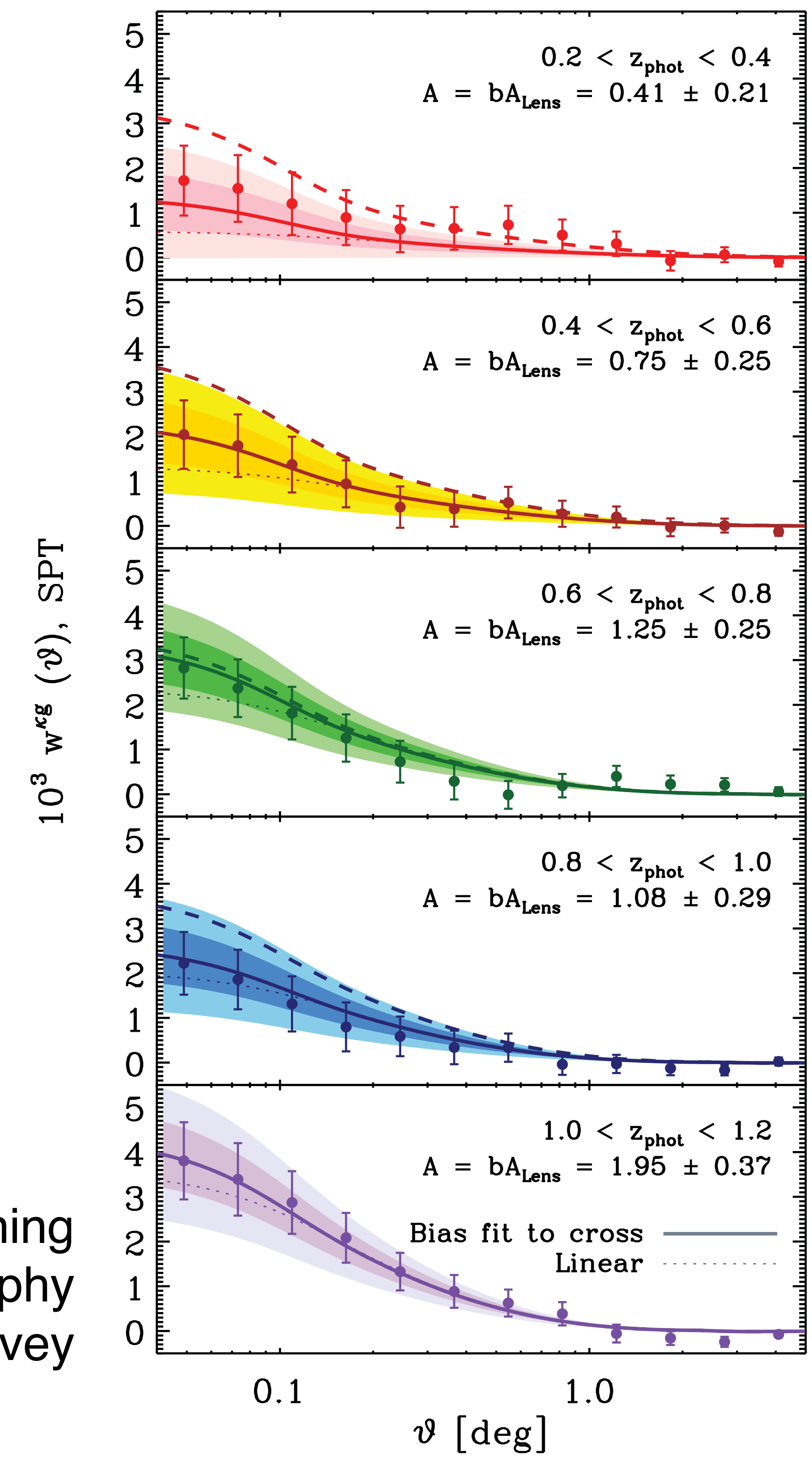
CMB-S4
Next Generation CMB Experiment

CMB lensing and optical surveys

CMB-S4 lensing will complement large optical surveys such as DES, DESI, LSST, Euclid, WFIRST, etc.

The combination leads to better shear-bias calibration and more robust constraints on Dark Energy and the properties of neutrinos. (e.g., Das, Errard, and Spergel, 2013)

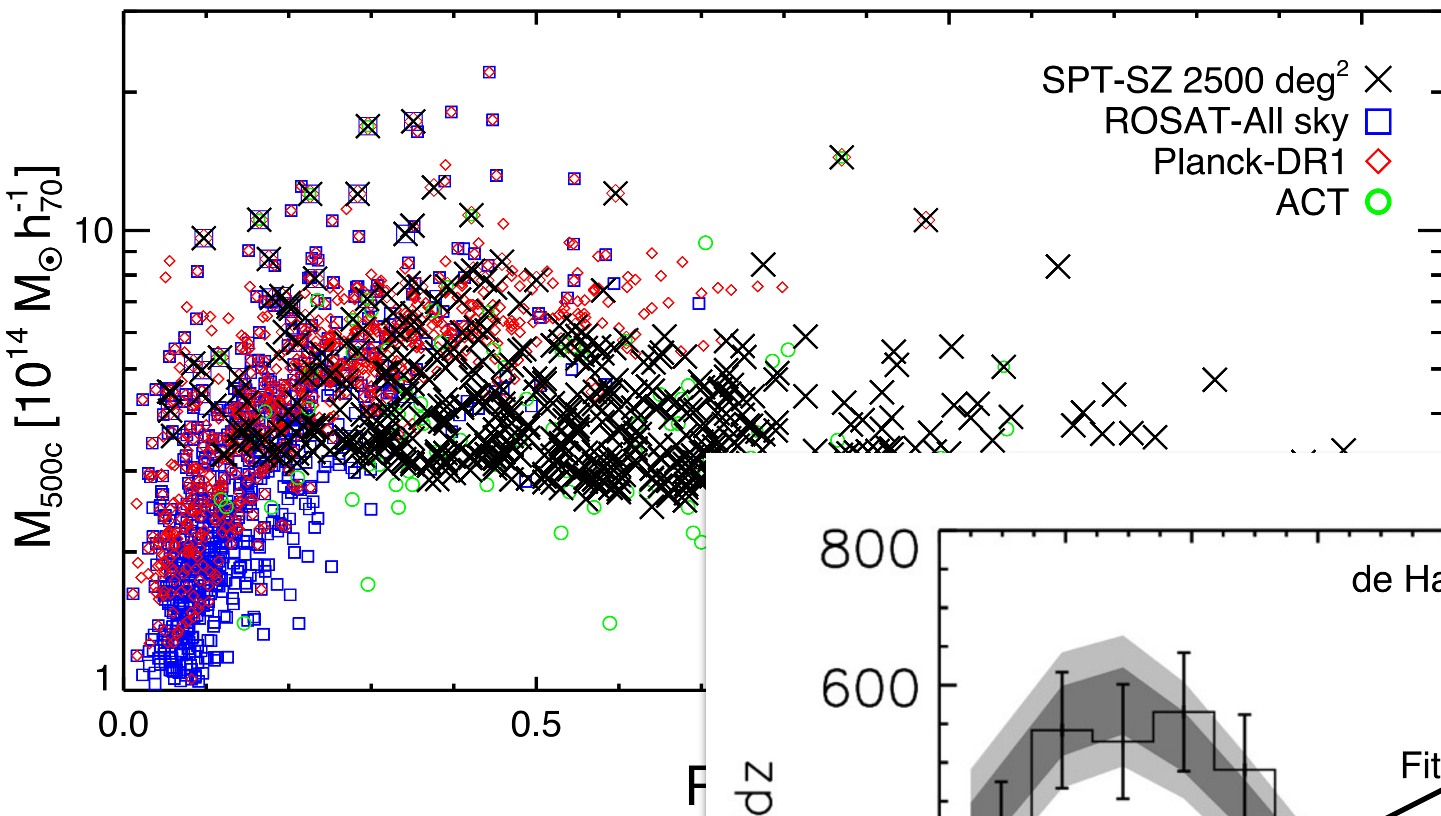
DES Galaxy and SPT CMB-lensing cross-correlation

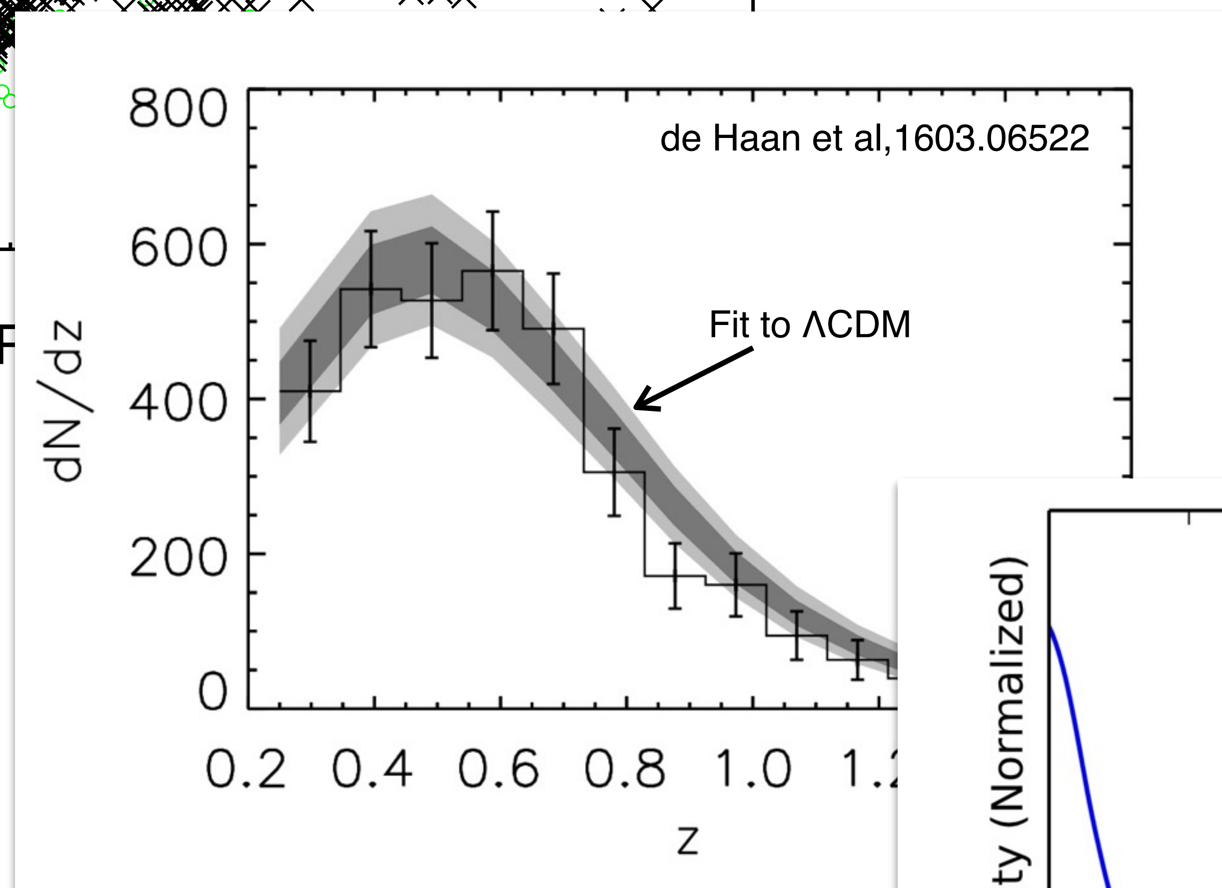


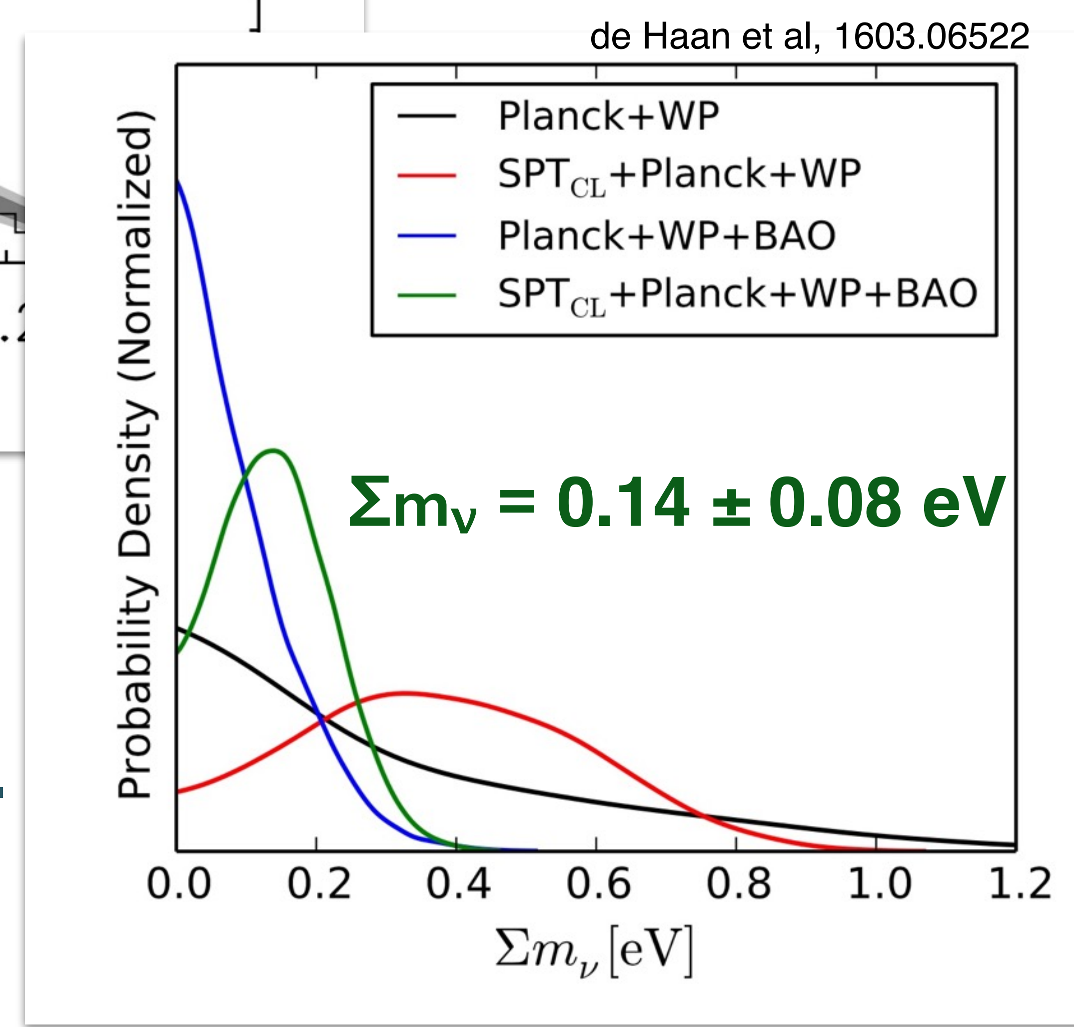
Giannantonio et al., 2016, beginning of CMB lensing tomography using 3% of DES survey

Giannantonio et al., 2016

Cosmology with SZ clusters



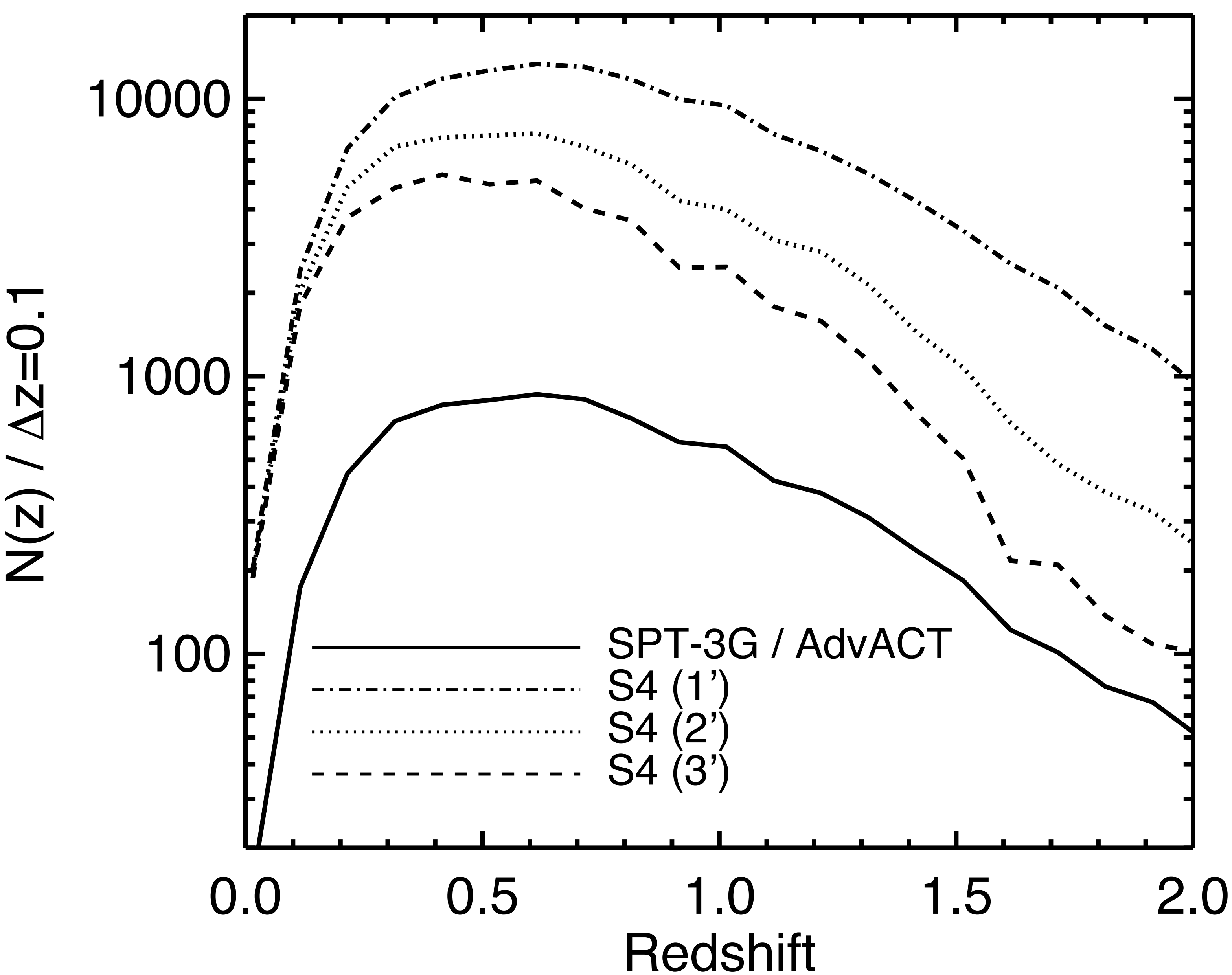




Tracing the growth of structure with evolution of massive galaxy clusters.

CMB-S4
Next Generation CMB Experiment

CMB-S4 SZ cluster projections



CMB-S4 Sunyaev-Zel'dovich (SZ) Cluster Survey:

- Cluster counts will depend on designed beam size, roughly:
  - 1': 140,000 clusters
  - 2': 70,000 clusters
  - 3': 45,000 clusters
- Strong complementarity with LSST cluster survey:
  - Low scatter observable
  - High-redshift: >10,000 clusters at z > 1

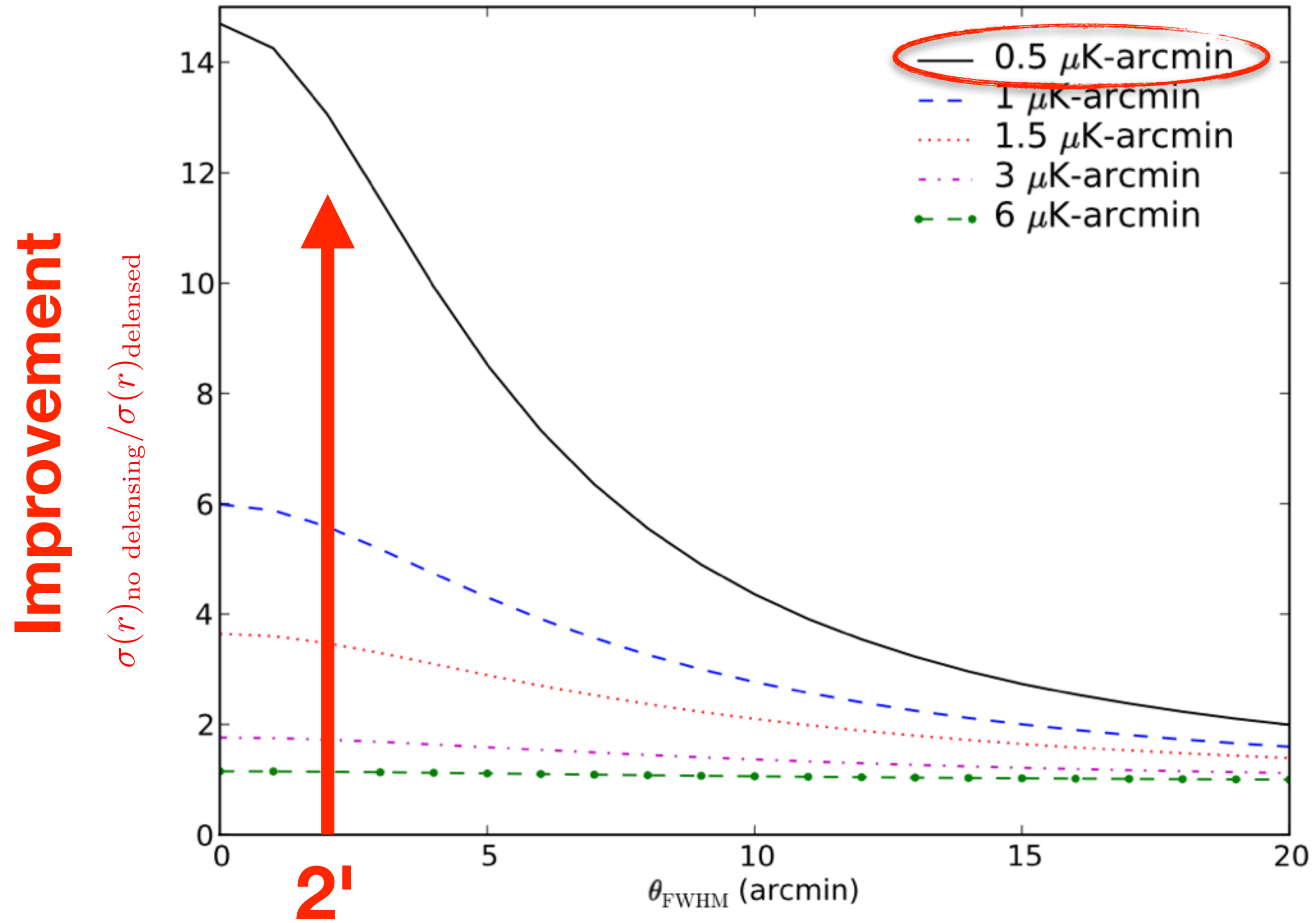
CMB-lensing cluster mass scaling !
σ(M) ~ 2e13 at z > 1 per 1000 clusters

Projection B. Benson

De-lensing B-mode Polarization

High resolution ground-based measurements excellent for de-lensing.

De-lensing Improvement on σ(r) vs Angular Resolution

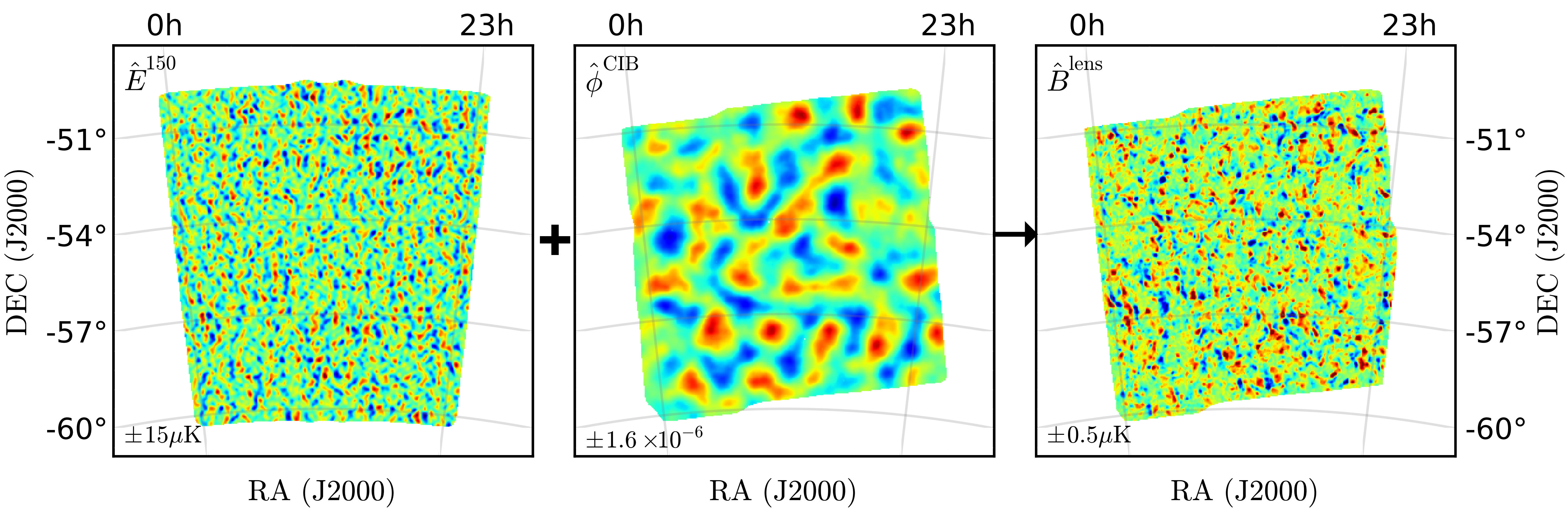


Angular resolution (arcmin)

from Smith et al., CMBpol Mission Study arXiv:0811.2916

SPTpol: 1st Detection of CMB B-mode Polarization

SPTpol Measured E-mode polarization + **Lensing Potential from Herschel CIB** → **Predicted B-mode polarization**

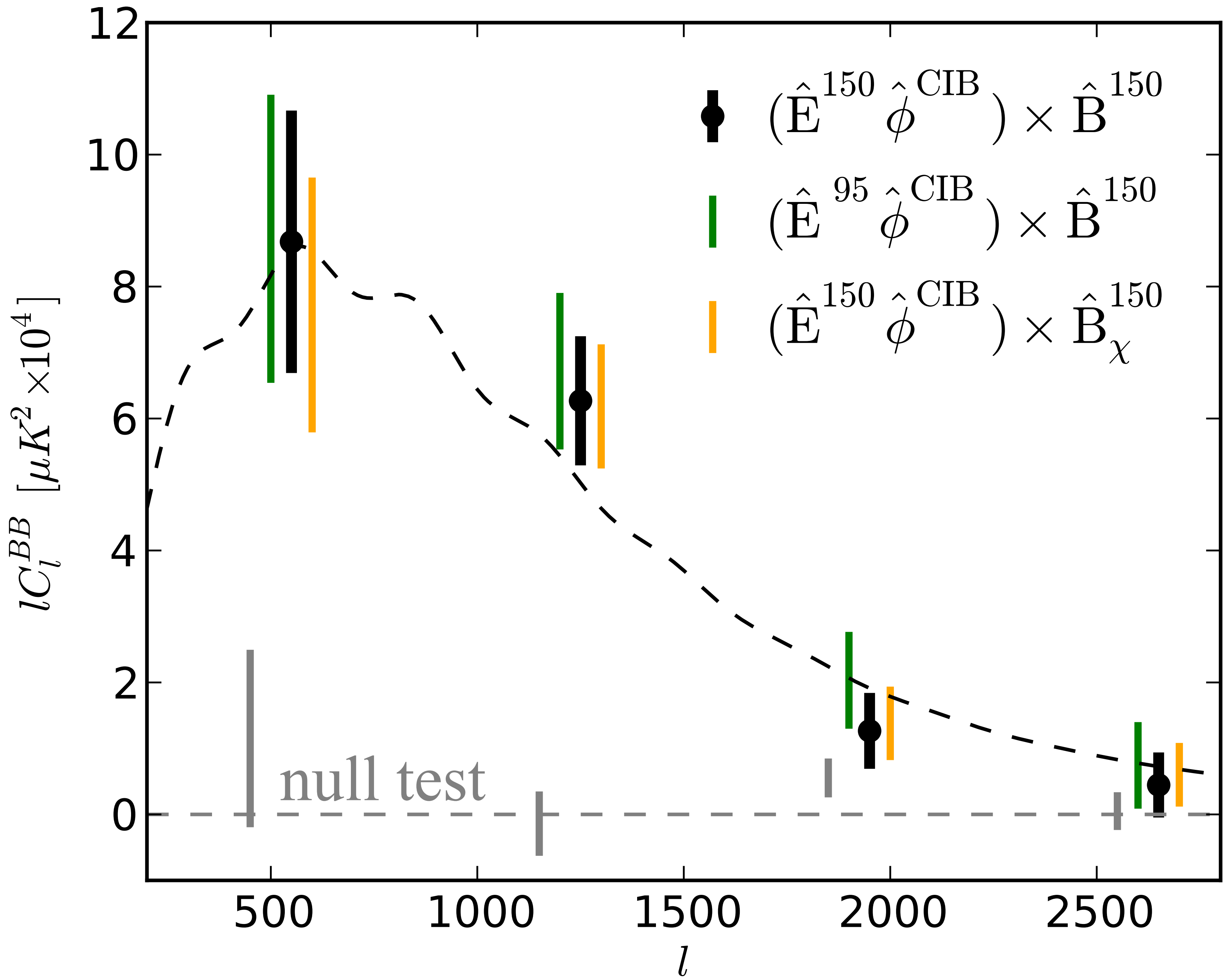


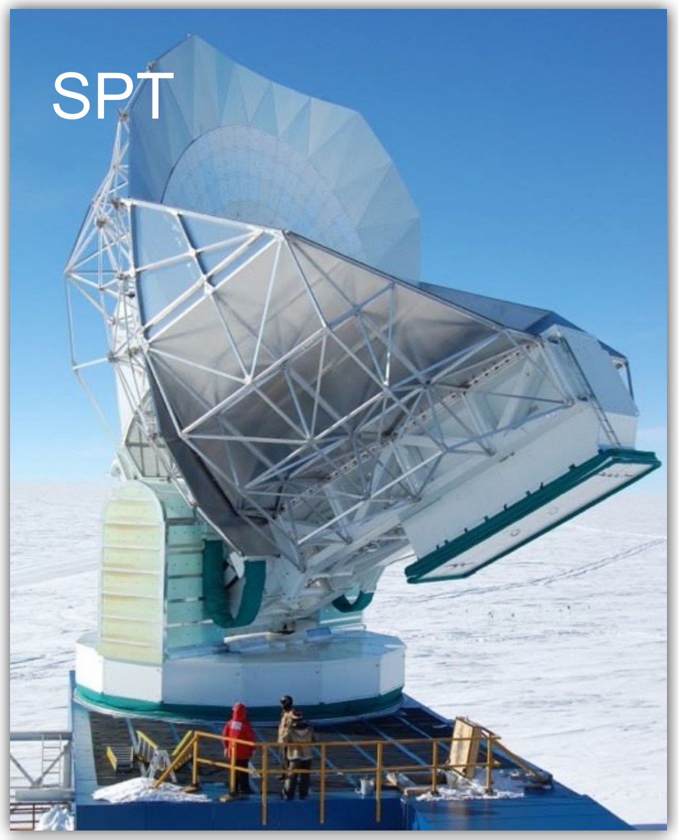
100 deg² survey

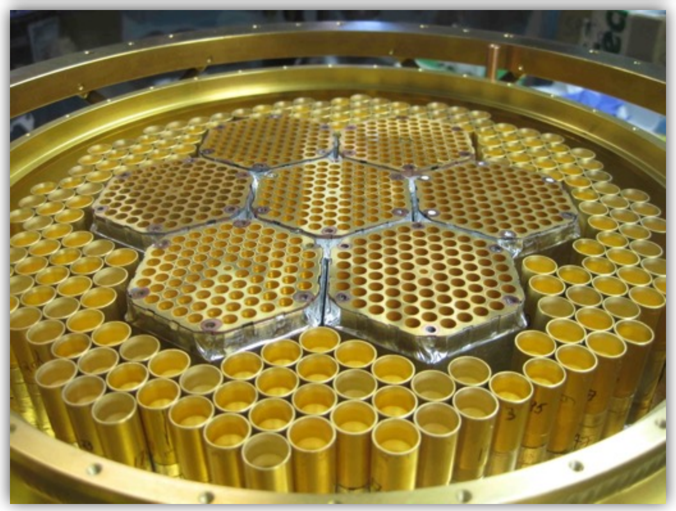
B-mode template to correlate with SPT B-mode map

SPTpol: Hanson et al, Phys.Rev.Lett.111:141301,2013 (arXiv:1307.5830)

SPTpol: 1st Detection of CMB B-mode Polarization



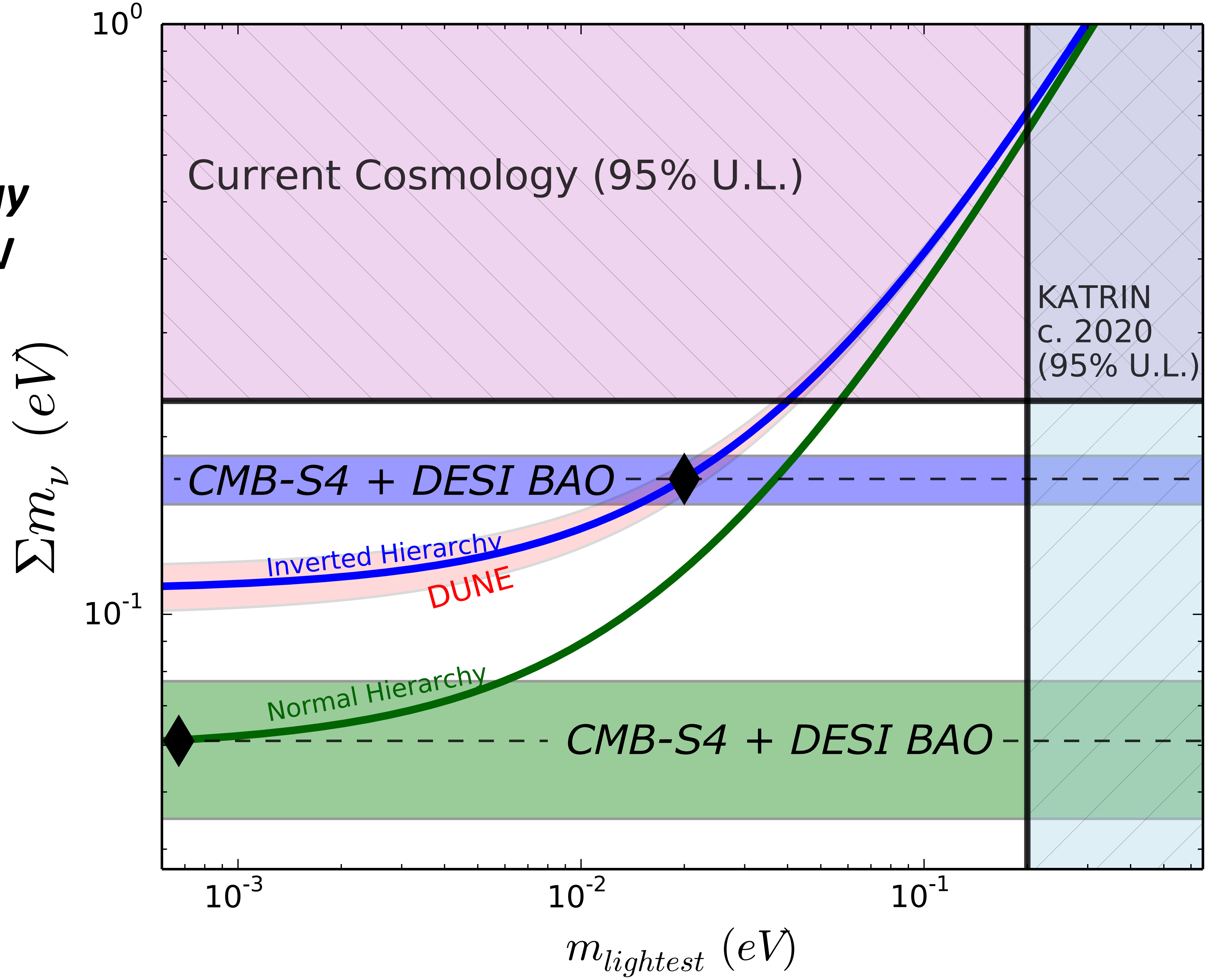




SPTpol: Hanson et al, Phys.Rev.Lett.111:141301,2013 (arXiv:1307.5830)
Also detected by Polarbear arXiv:1312.6645 & 1312.6646

Combined Neutrino mass constraints

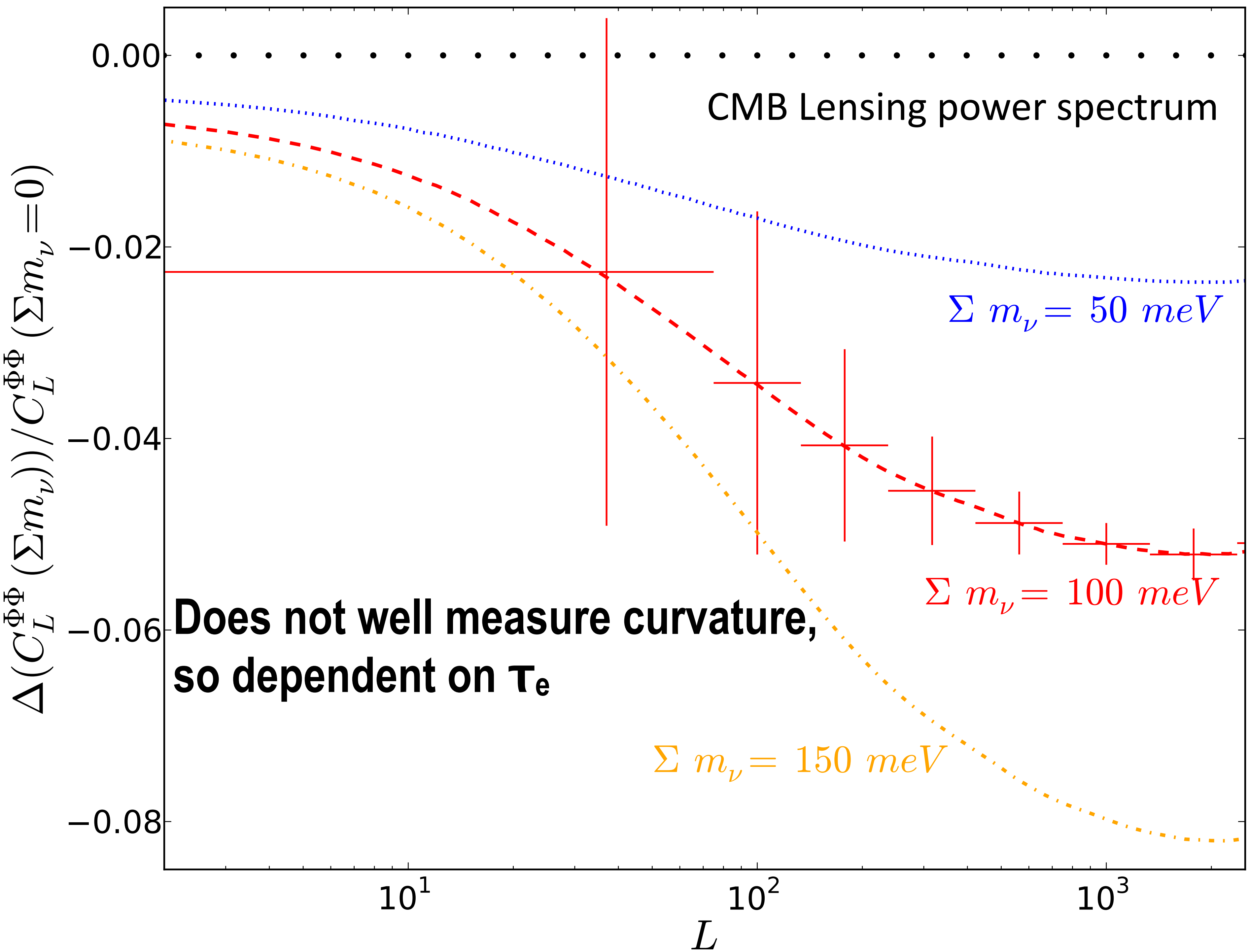
Future Cosmology
σ(Σmν) = 16 meV



"use cosmology to tighten the noose" Boris Kayser

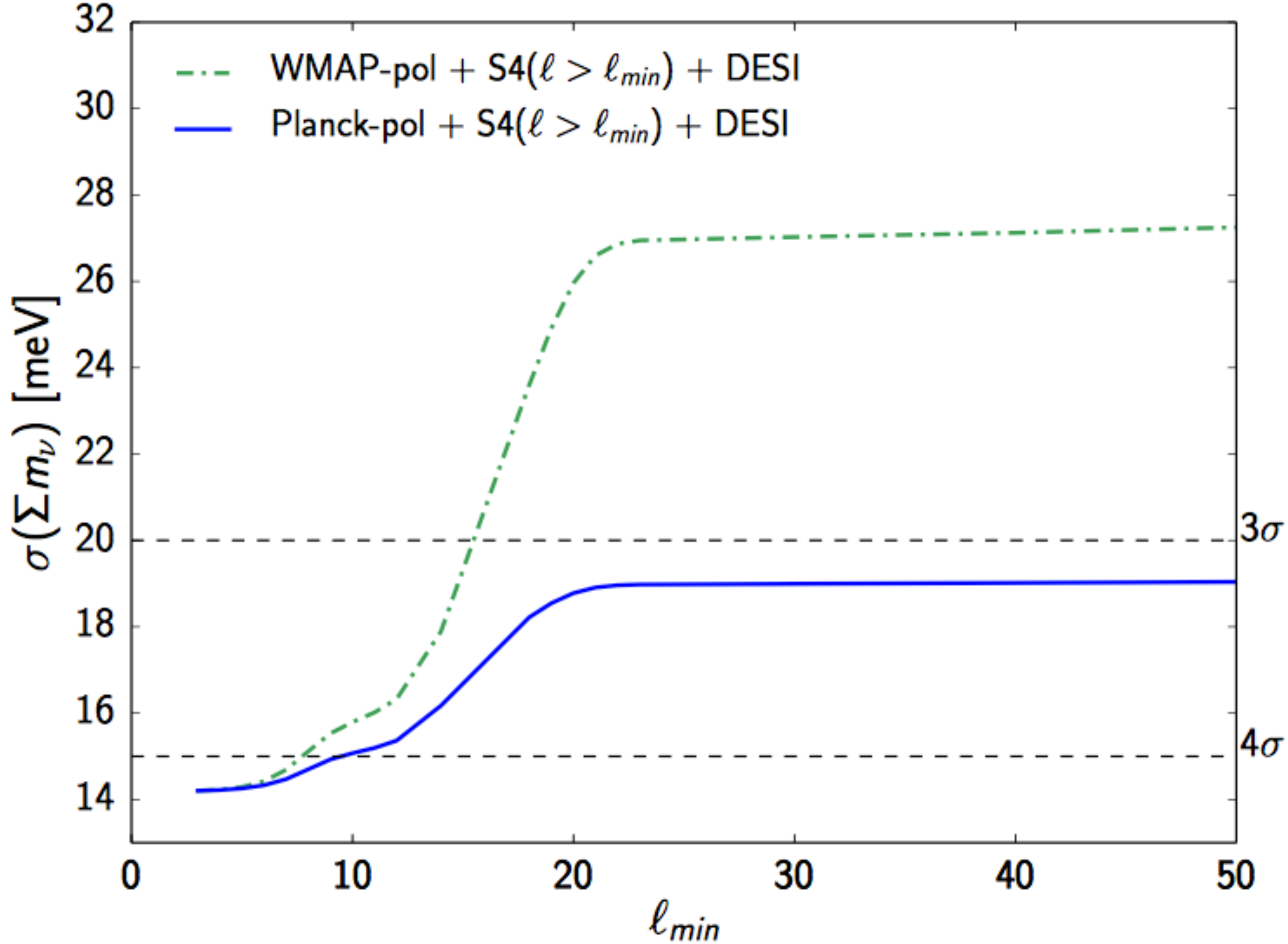
arXiv:1309.5383

CMB-S4 lensing sensitivity to Σm_ν



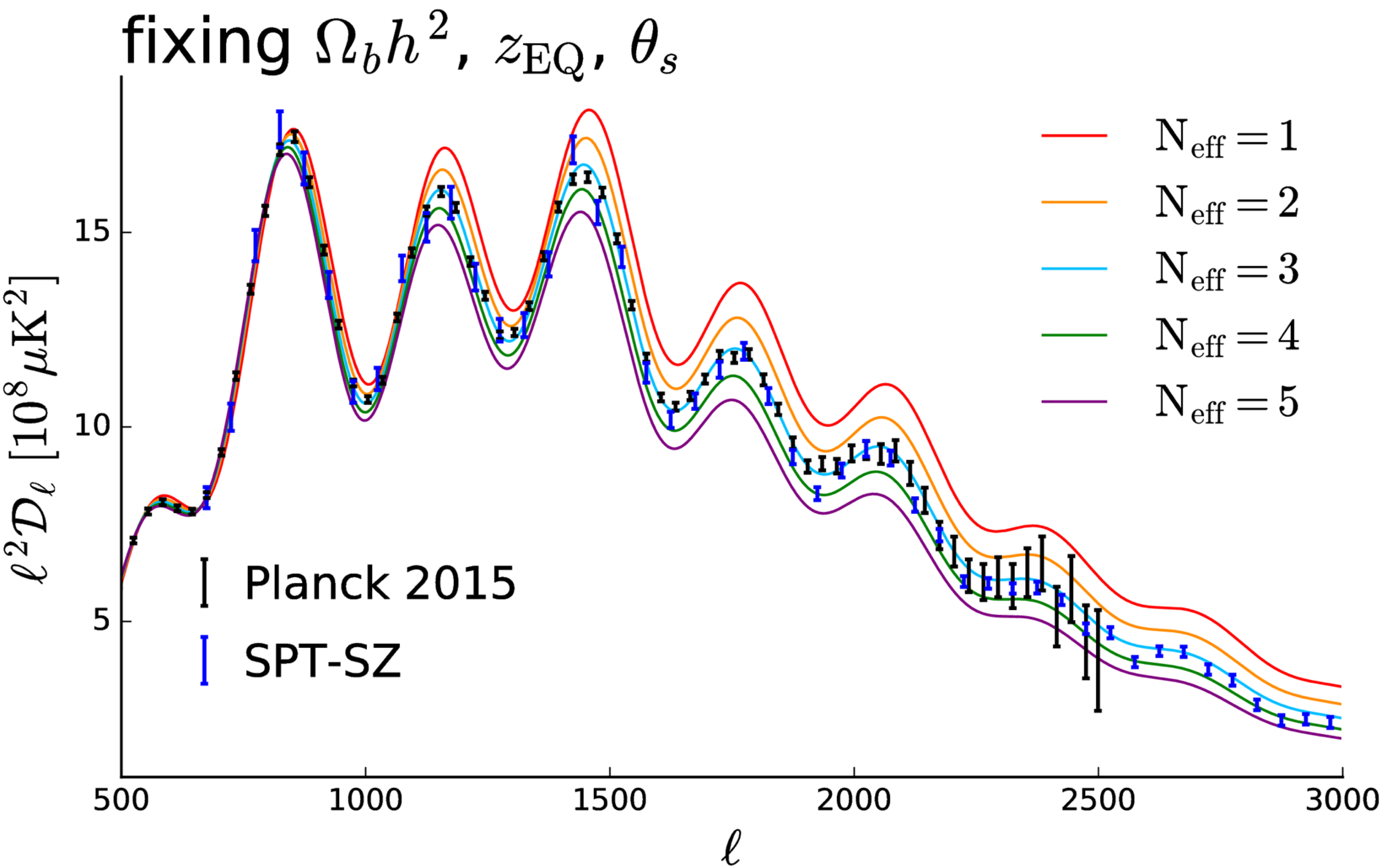
CMB-S4 forecast: arXiv:1309.5383; see also Wu et al, ApJ 788,138 (2014)

need τ_e measurement



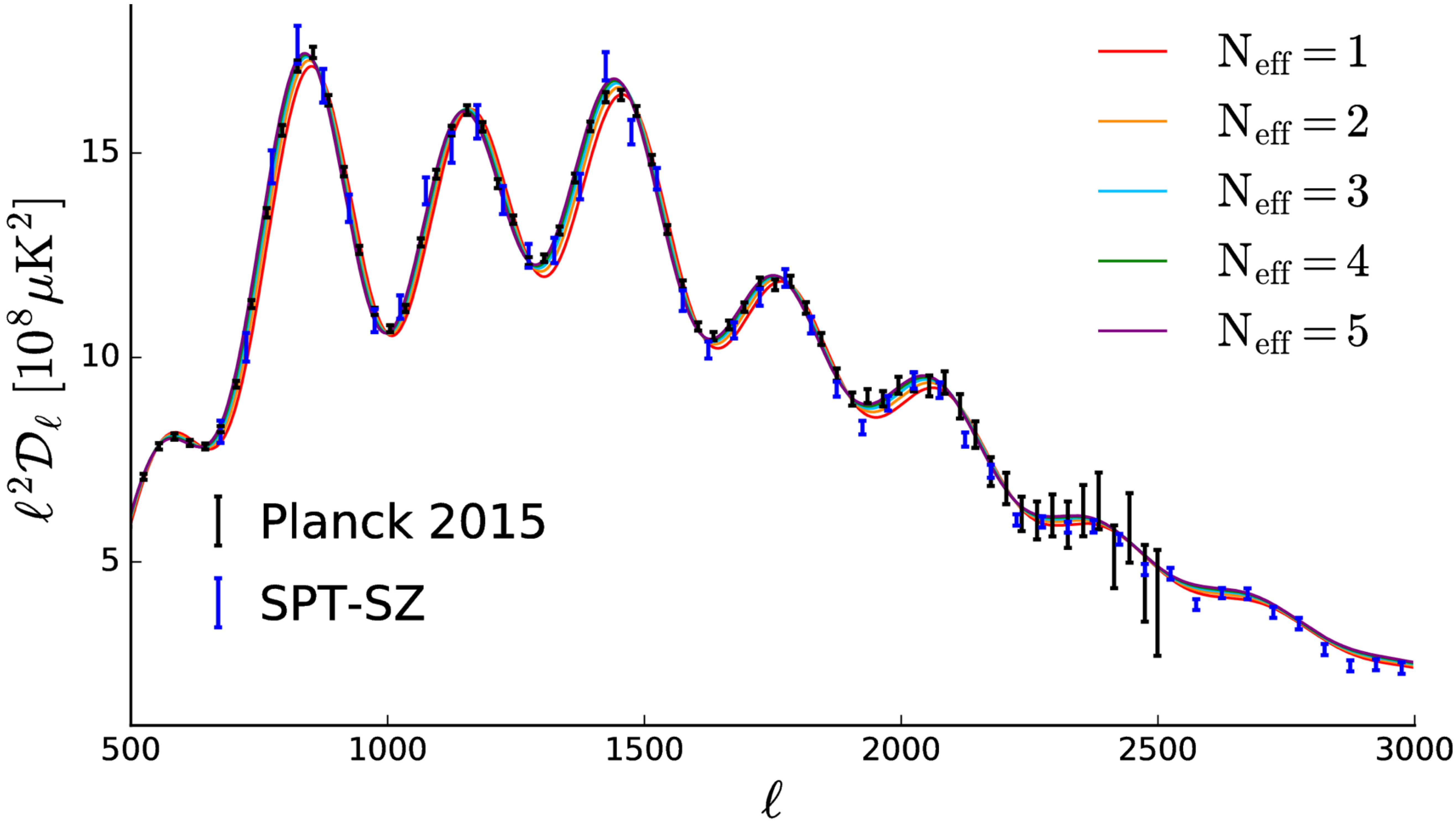
Allison et al arXiv:1509.07471

N_{eff} and CMB damping



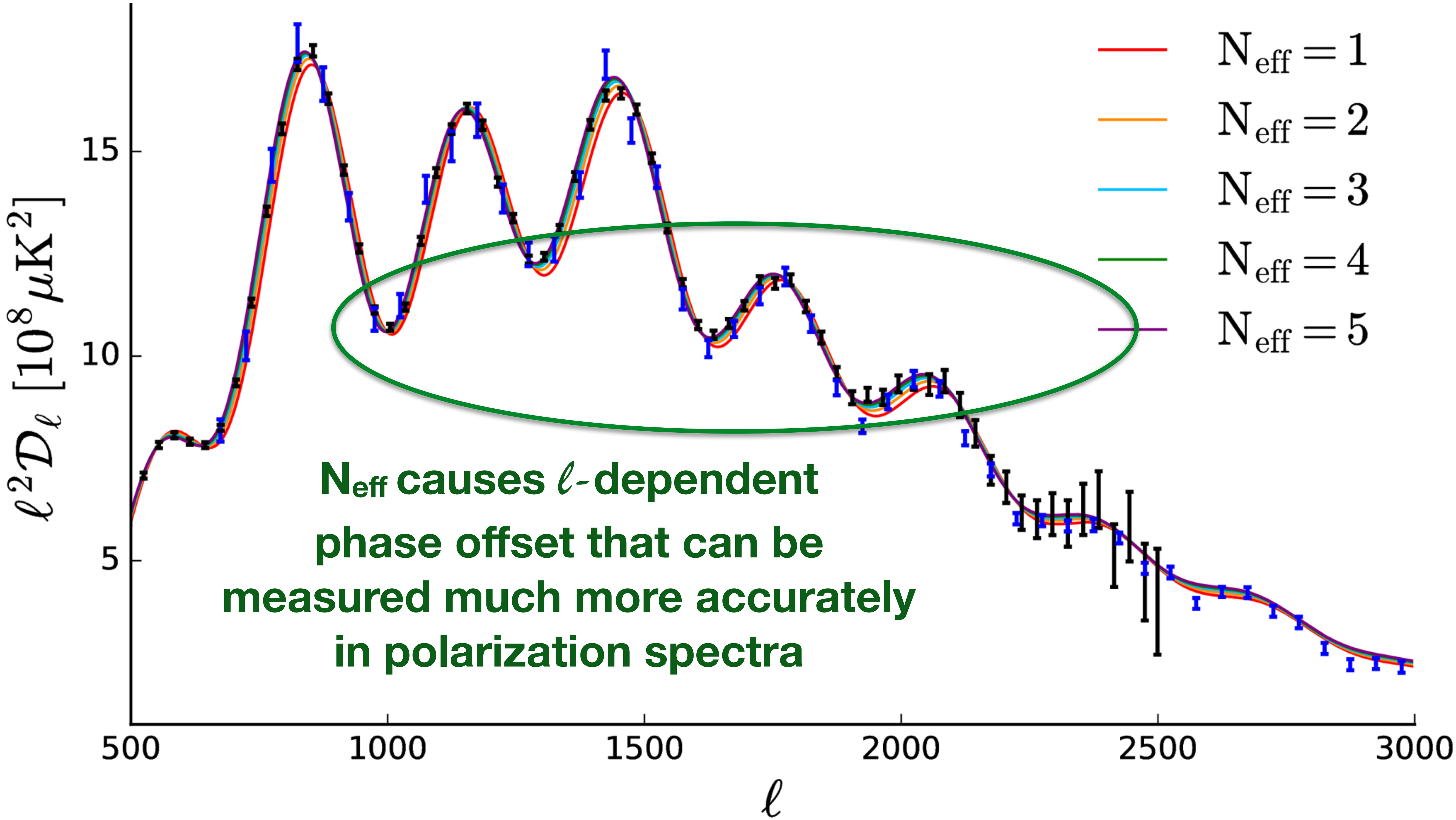
Helium fraction & N_{eff} degeneracy

Artificially keep θ_d constant by increasing helium fraction, Y_P



N_{eff} & Helium fraction degeneracy

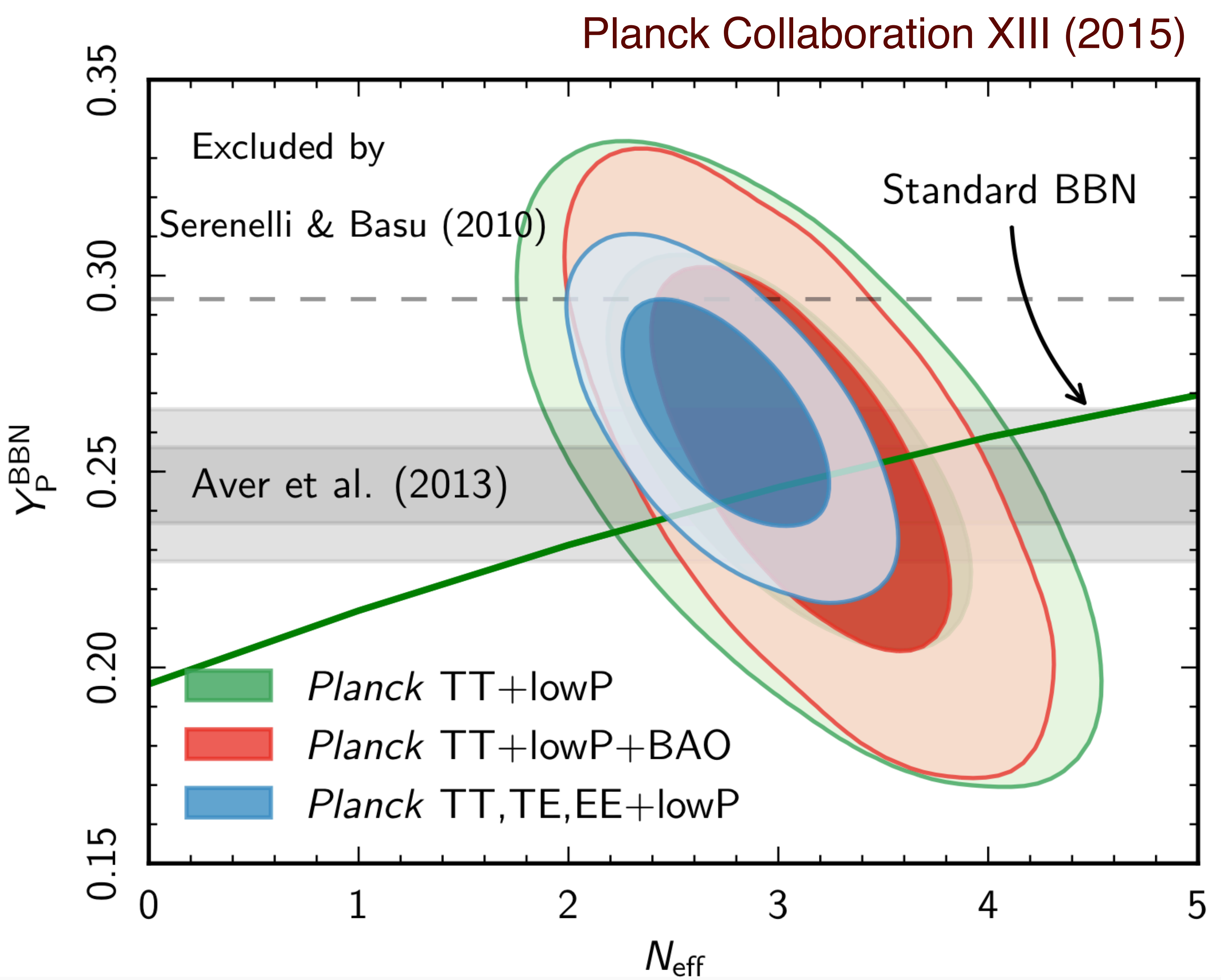
Artificially keep θ_d constant by increasing helium fraction, Y_P



N_{eff} is the extra relativistic energy density compared to photons

For standard 3 neutrinos, N_{eff} = 3.046.

N_{eff} & Helium fraction degeneracy



- Agreement with physics of
  - *1) Cosmic neutrino background at ~1 sec*
  - *2) Light element production at ~3 min*
  - *3) CMB emitted at ~380,000 years*
- ***But we'd like to do much better !***

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

"Pessimistic" ν degeneracy forecasts

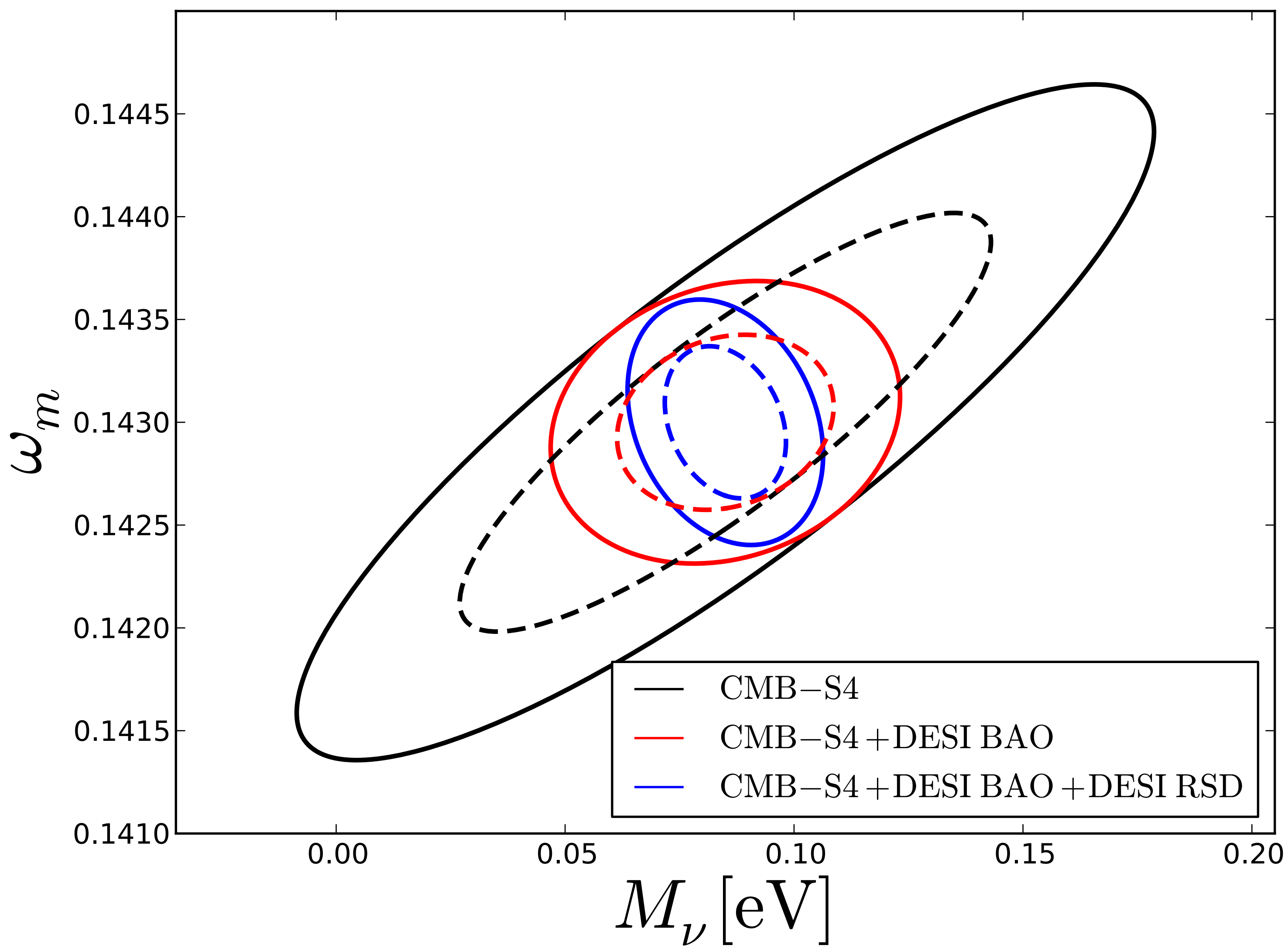
Allison et al., 1509.0747

for CMB-S4 (3 arcm res, $\ell > 20$) + DESI BAO:

$$\Sigma m_\nu = 19\ \text{meV}\quad (\Lambda CDM + \Sigma m_\nu)$$
$$= 30\ \text{meV}\quad (\Lambda CDM + \Sigma m_\nu + \Omega_k)$$
$$= 27\ \text{meV}\quad (\Lambda CDM + \Sigma m_\nu + w_0)$$
$$= 46\ \text{meV}\quad (\Lambda CDM + \Sigma m_\nu + w_0 + w_a)$$
$$= 64\ \text{meV}\quad (\Lambda CDM + \Sigma m_\nu + w_0 + w_a + \Omega_k)$$

“Optimistic” ν forecasts

Pan & Knox 1506.07493



Σm_ν = 9 meV (ΛCDM + Σm_ν)

for CMB-S4 ($\ell > 5$) + DESI BAO + DESI RSD

Complementarity of Neutrino mass constraints

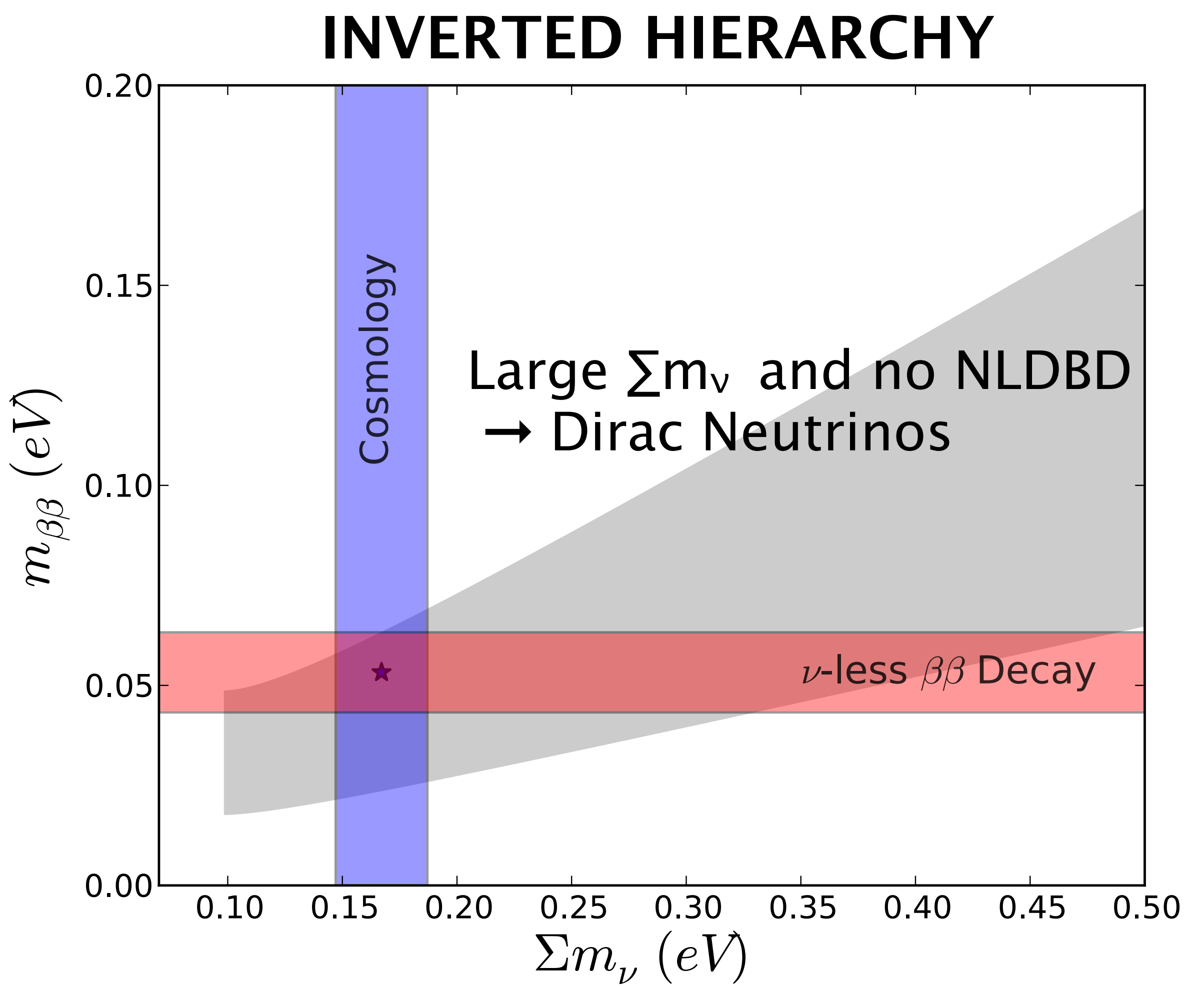


FIG. 1: Projected constraints on neutrino parameters from upcoming cosmic surveys (vertical), neutrino-less double beta decay experiments (horizontal), and all other current measurements (gray) assuming an inverted mass hierarchy and Majorana neutrinos.

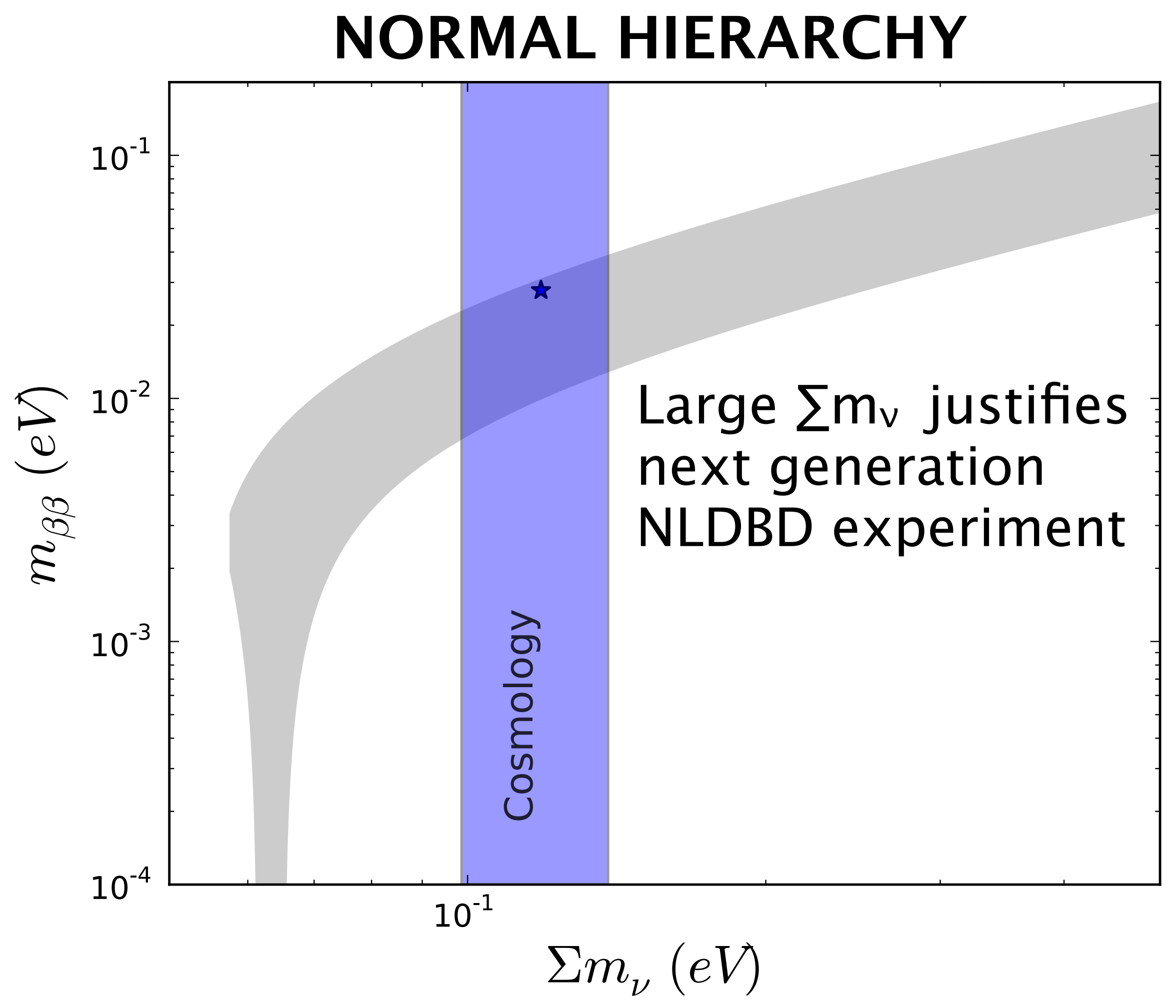


FIG. 3: If the mass hierarchy is normal but the sum of the masses is still relatively large, for example at the value indicated by the star, then there will be a lower limit on $m_{\beta\beta}$, a target for ambitious future double beta decay experiments.

Dodelson and Lykken arXiv:1403.5173