CMB Stage 4 Status

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CMB-S4
Next Generation CMB Experiment

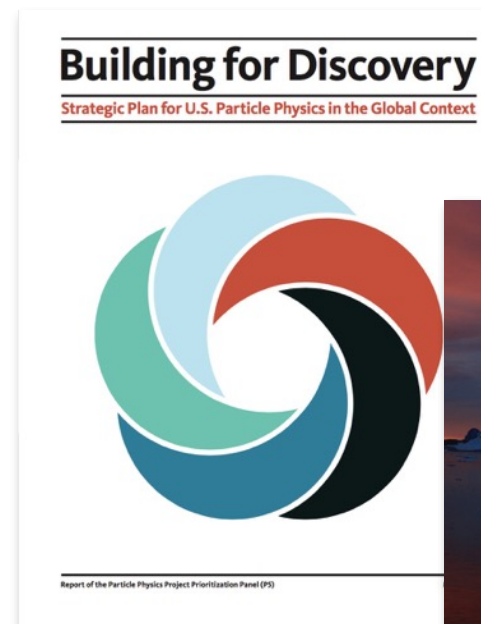
Stage 4 CMB experiment: CMB-S4

- A next generation **ground-based** program to pursue inflation, neutrino properties, dark radiation, dark energy and new discoveries.

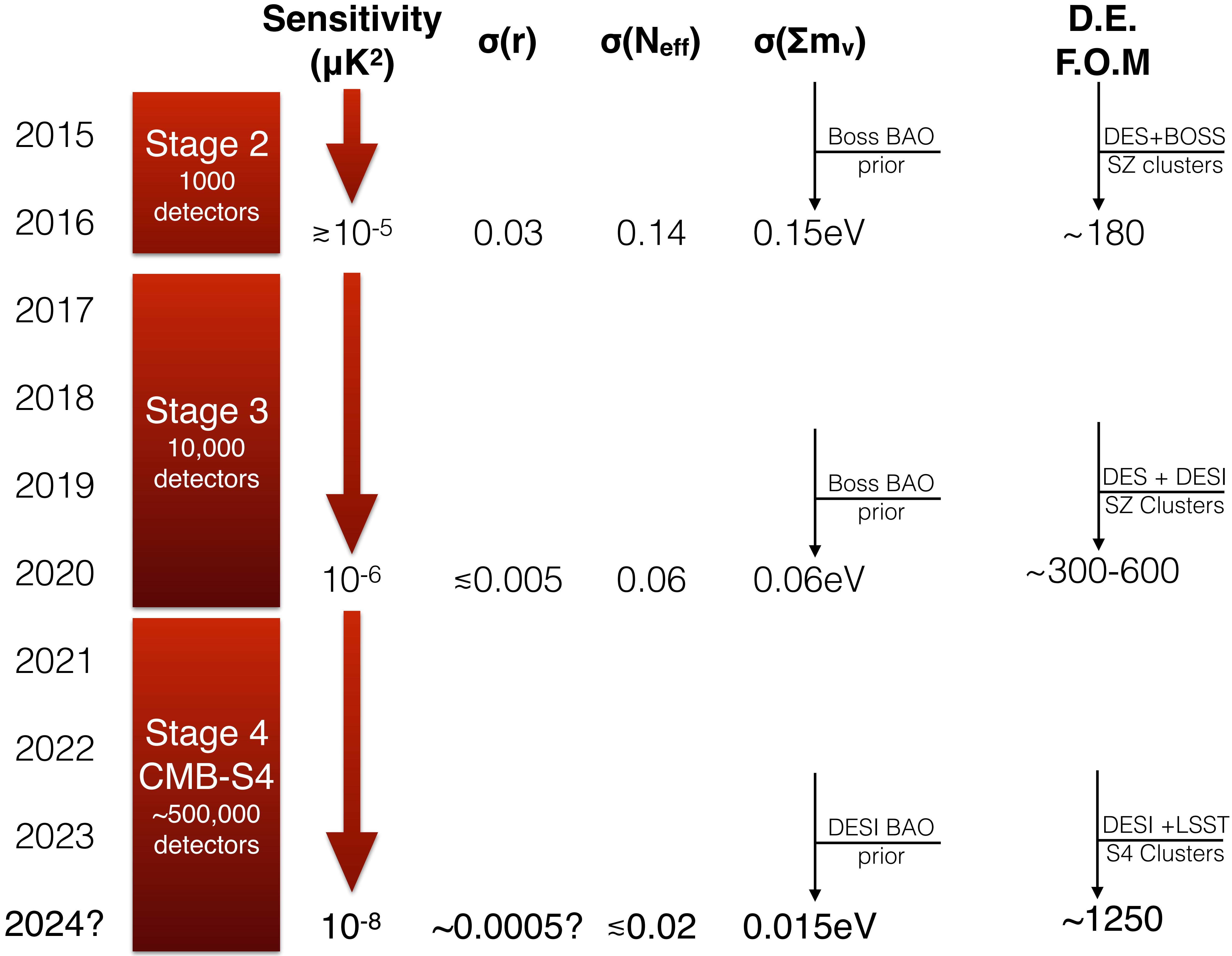
- Greater than tenfold increase in sensitivity of the combined Stage 3 experiments (>100x current Stage 2) to cross critical science thresholds.

- O(500,000) polarization sensitive detectors spanning 30 - 300 GHz using multiple telescopes and sites to map most of the sky, as well as deep targeted fields.

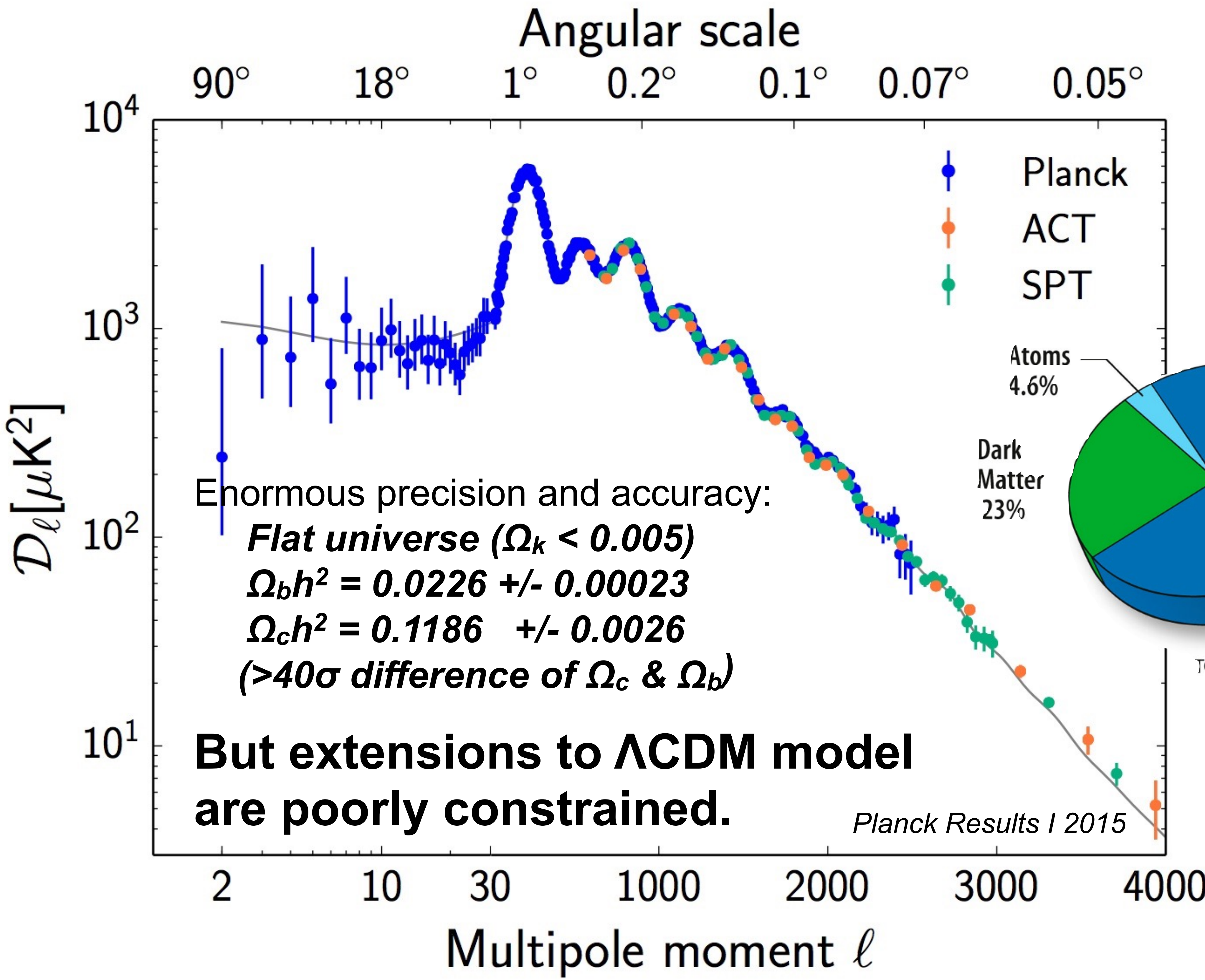
- Broad participation of the CMB community, including the existing CMB groups, e.g., **ACT, BICEP/KECK, CLASS, Polarbear & SPT,** the National Labs and the High Energy Physics community. International partnerships.

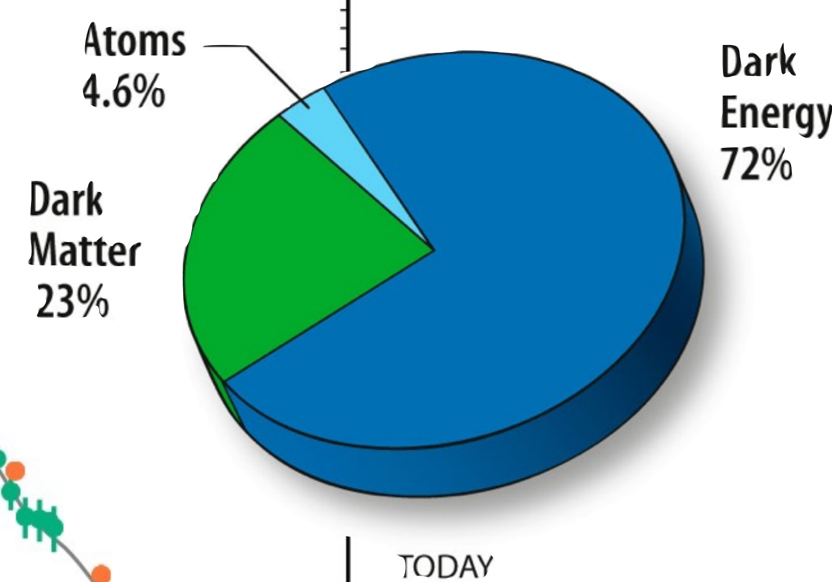


Recommended by P5 & NRC Antarctic reports


Sensitivity (μK²)
σ(r)
σ(N_eff)
σ(Σm_ν)
D.E. F.O.M
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024?
Stage 2
1000 detectors
Stage 3
10,000 detectors
Stage 4
CMB-S4
~500,000 detectors
≳10-5
0.03
0.14
Boss BAO
prior
0.15eV
DES+BOSS
SZ clusters
~180
10-6
≲0.005
0.06
Boss BAO
prior
0.06eV
DES + DESI
SZ Clusters
~300-600
10-8
~0.0005?
≲0.02
DESI BAO
prior
0.015eV
DESI +LSST
S4 Clusters
~1250

CMB temperature anisotropy
Angular power spectrum





Enormous precision and accuracy:

Flat universe ($\Omega_k < 0.005$)

$\Omega_b h^2 = 0.0226$ +/- 0.00023

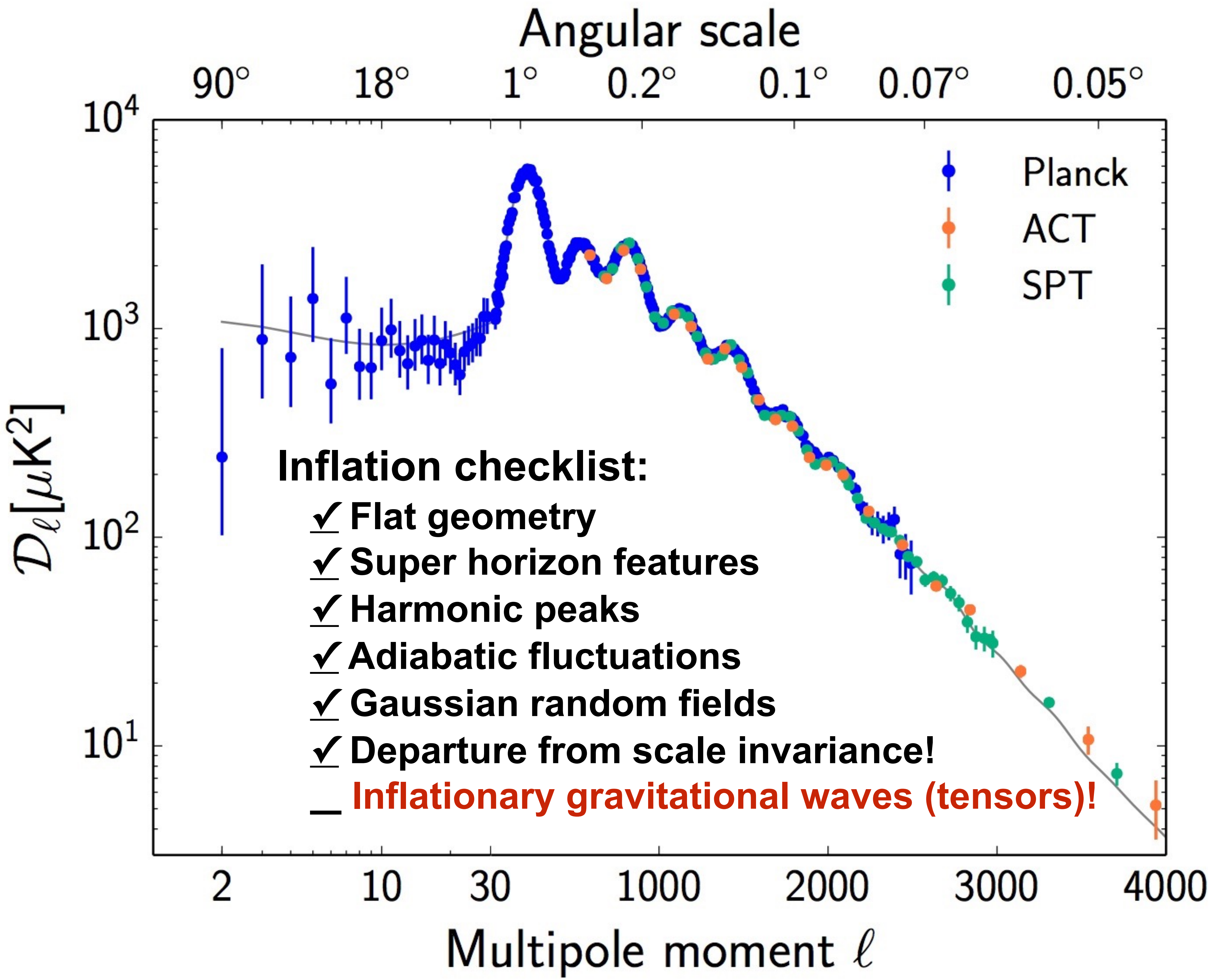
$\Omega_c h^2 = 0.1186$ +/- 0.0026

(>40σ difference of Ω_c & Ω_b)

But extensions to ΛCDM model are poorly constrained.

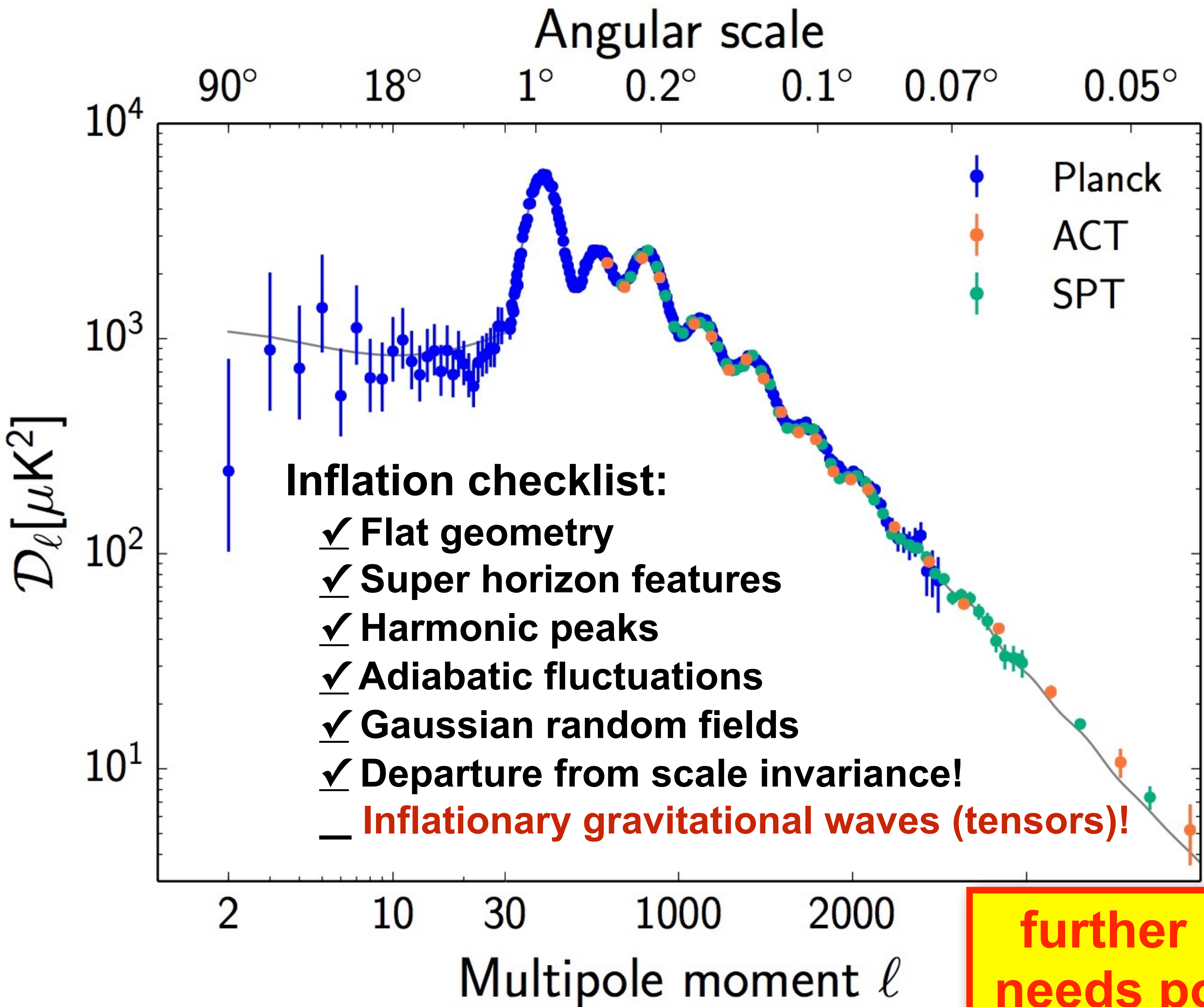
Planck Results I 2015

Inflation?



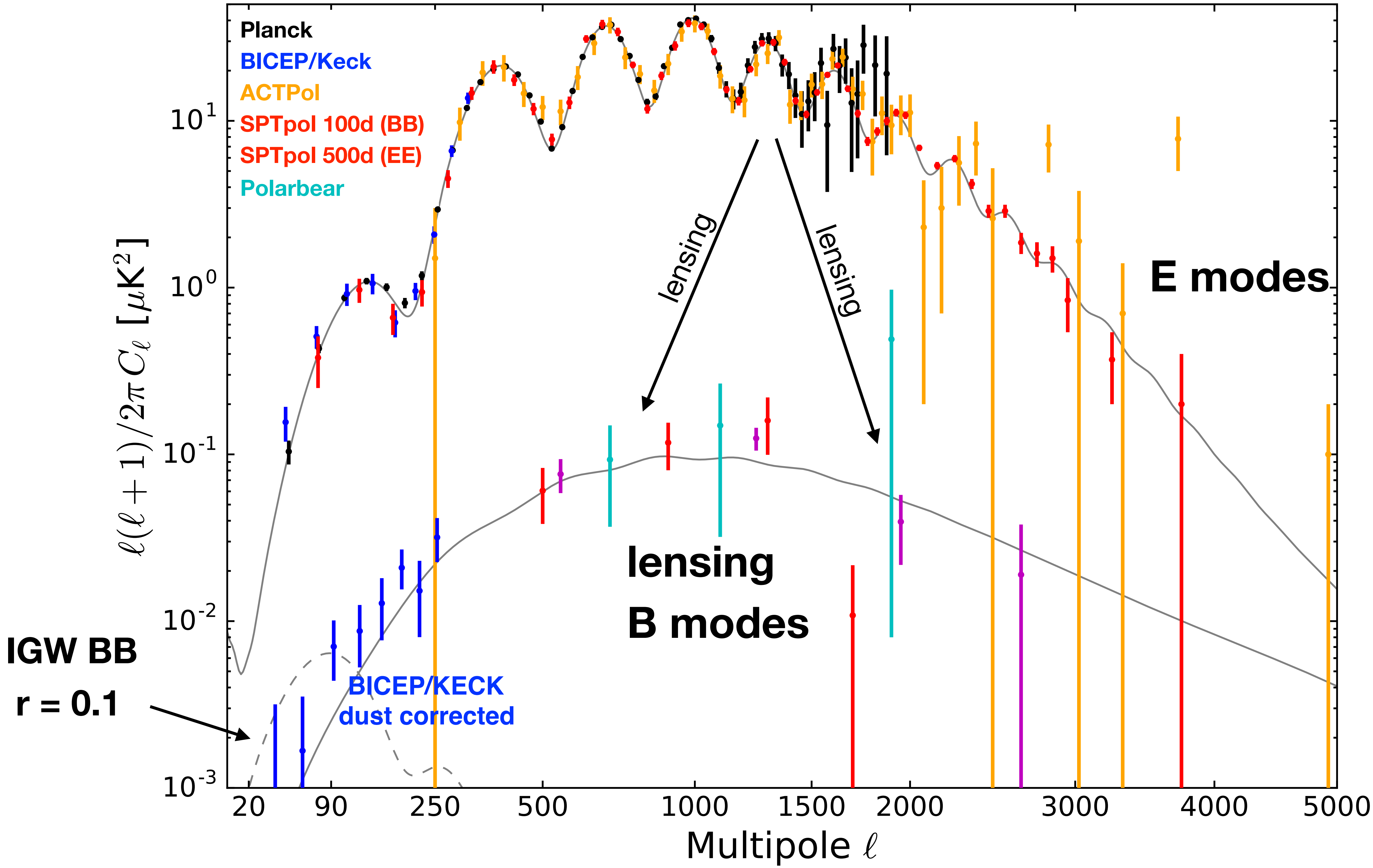
Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
0.05°
10^4
10^3
10^2
10^1
$\mathcal{D}_\ell [\mu K^2]$
Planck
ACT
SPT
2
10
30
1000
2000
3000
4000
Multipole moment ℓ
Inflation checklist:
✓ Flat geometry
✓ Super horizon features
✓ Harmonic peaks
✓ Adiabatic fluctuations
✓ Gaussian random fields
✓ Departure from scale invariance!
_ Inflationary gravitational waves (tensors)!

Inflation?



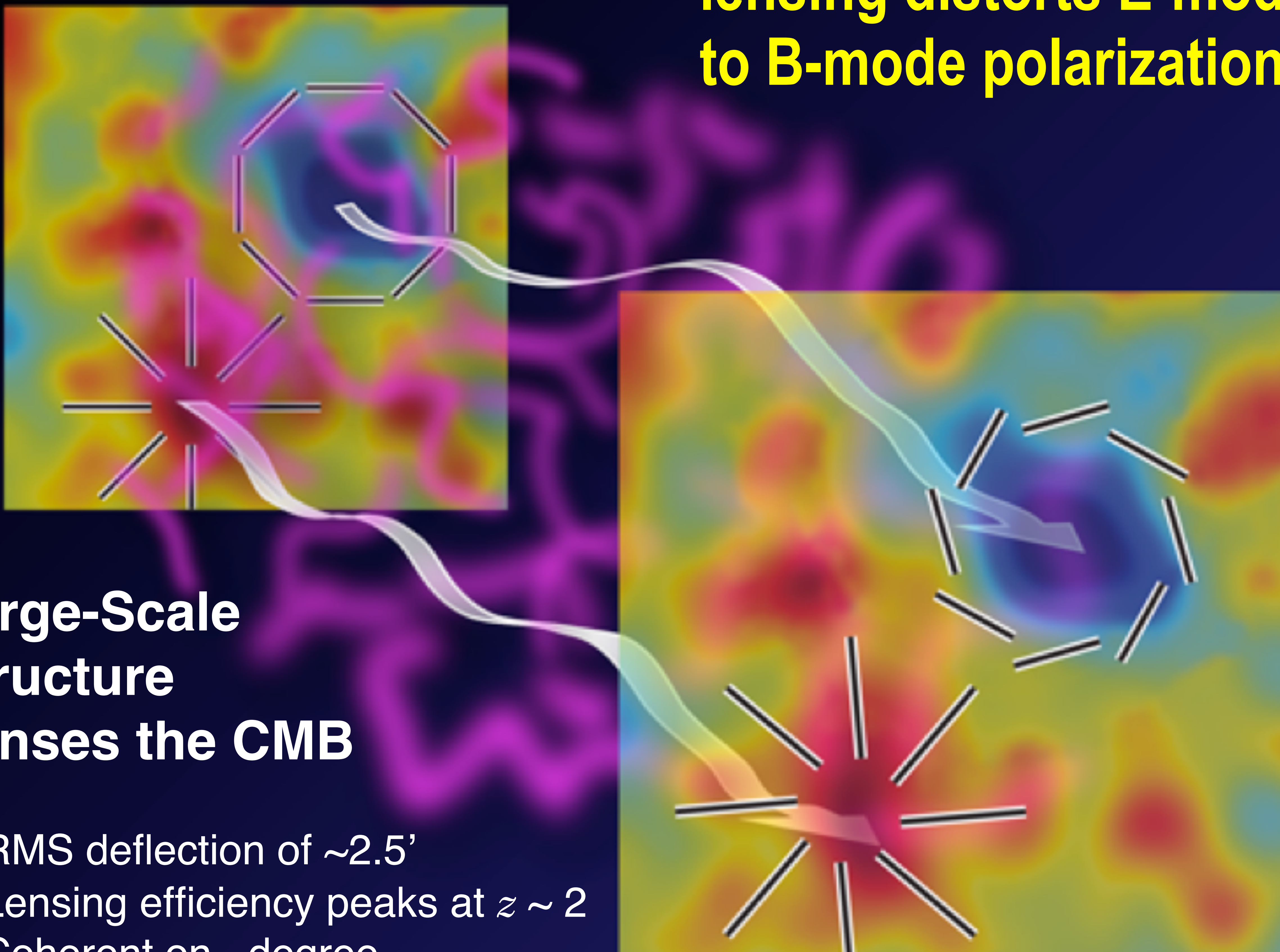
further progress needs polarization

Current status CMB polarization



Rapid progress. All within last 3 years.

lensing distorts E-mode to B-mode polarization

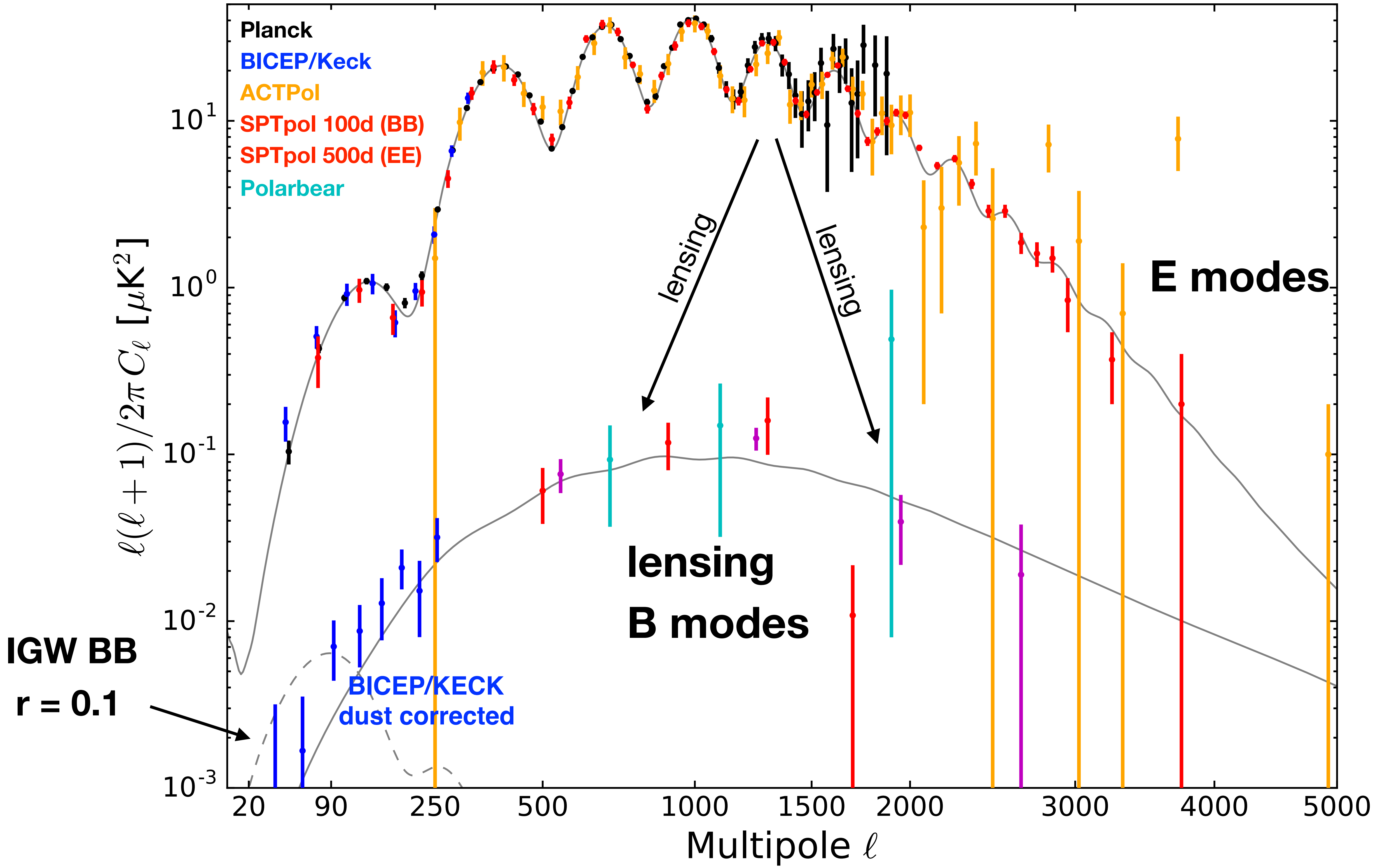


Large-Scale Structure Lenses the CMB

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

graphic from ESA Website

Current status CMB polarization



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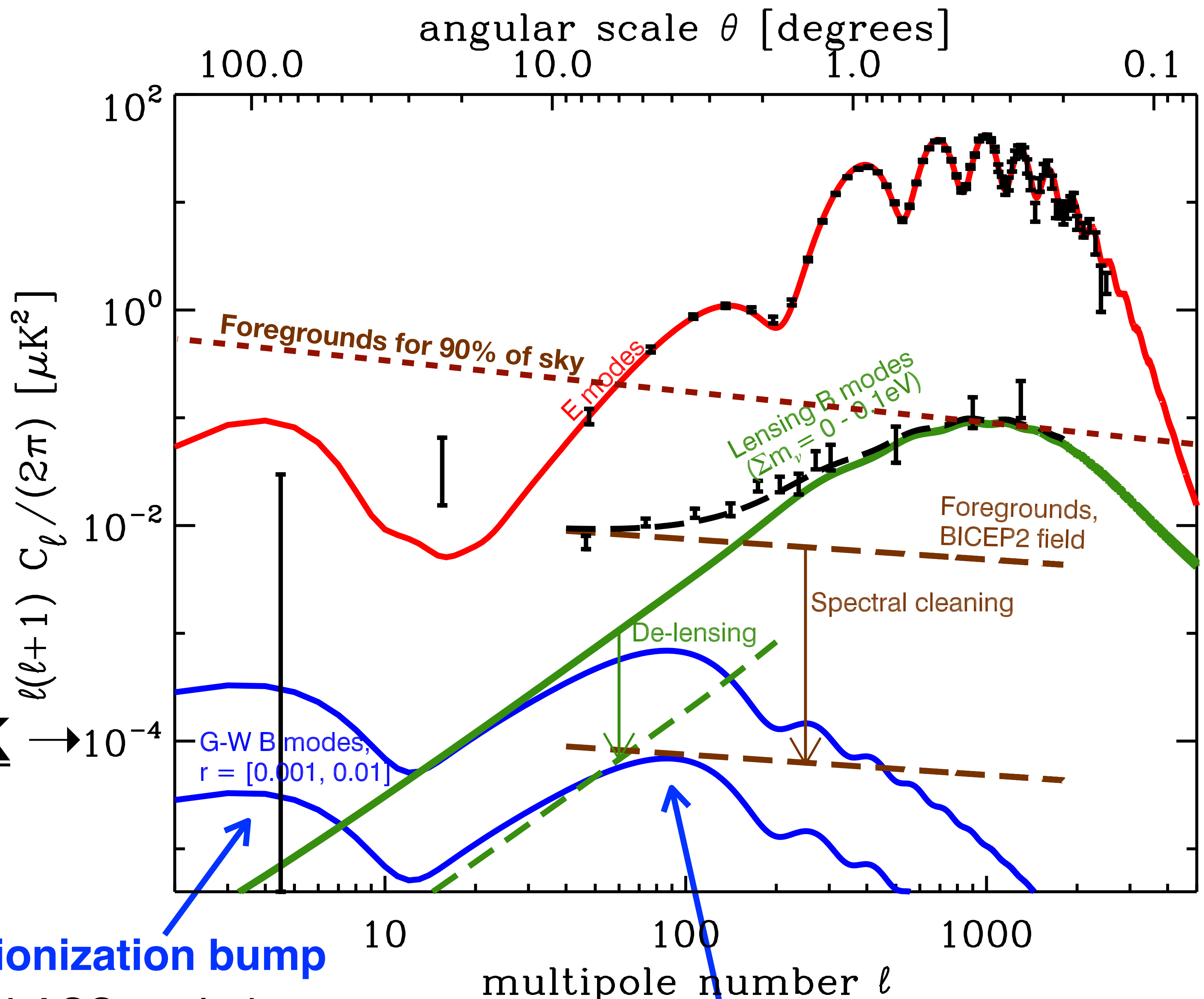
Polarization status and future challenge

10 nK →



E modes

lensing
B modes

inflationary
gravity wave
B modes

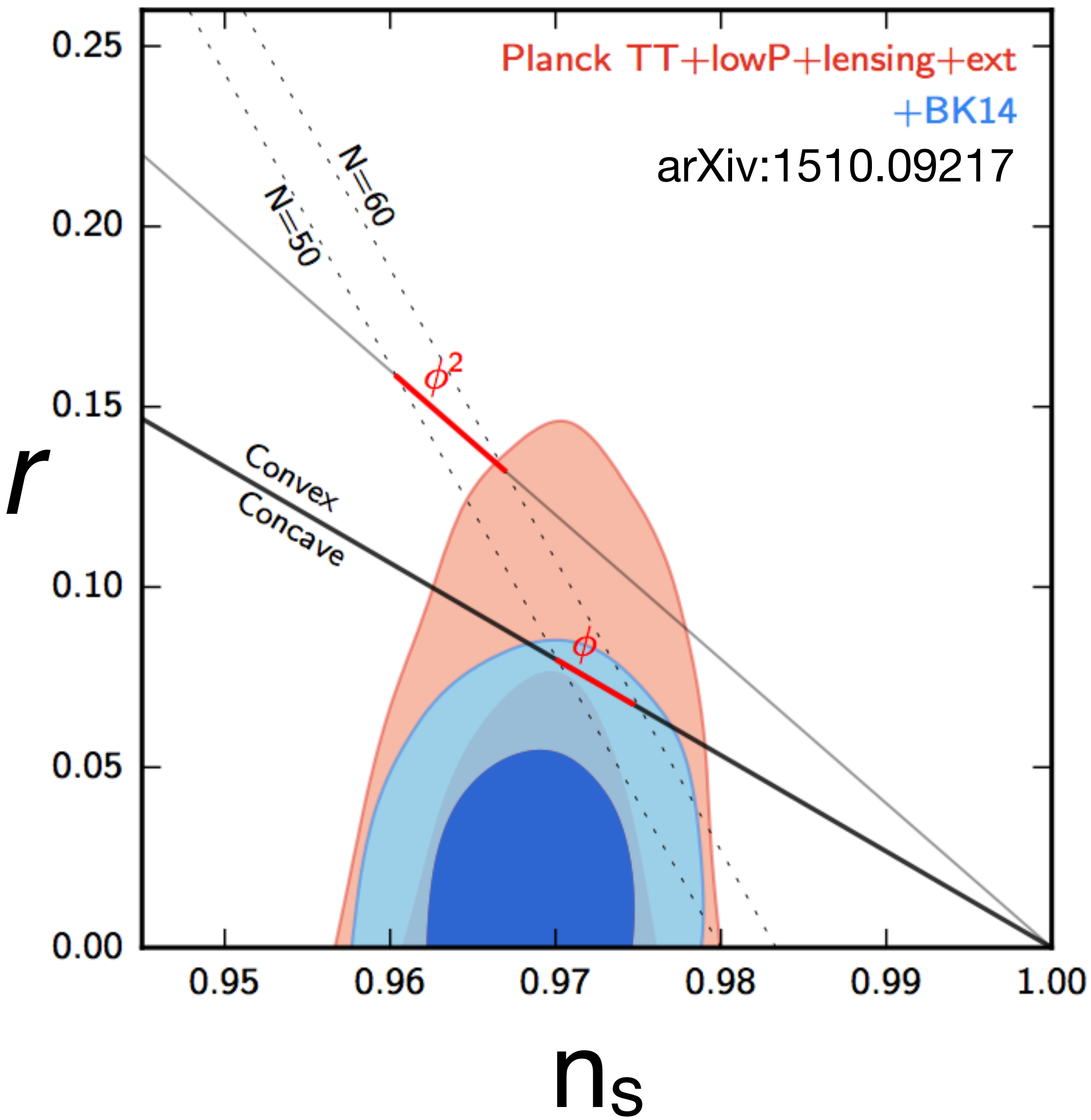
reionization bump

CLASS exploring
from the ground;
LiteBIRD, PIXIE
CORE+

recombination bump

key target of CMB-S4

… still a long, long way to go.



Polarization B-modes are now best limit on tensor to scalar ratio,

r < 0.09 at 95% C.L.

combined with Planck TT

r < 0.07 at 95% C.L.

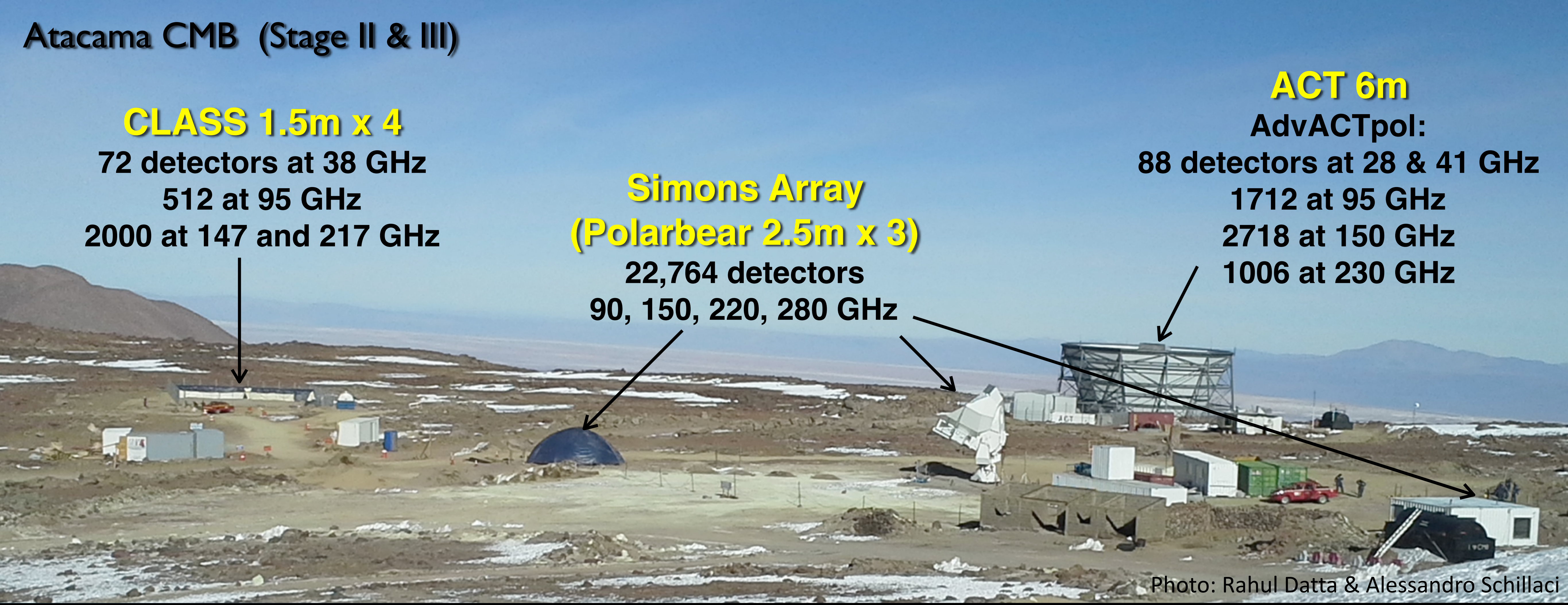
Note BICEP/Keck raw sensitivity is $\sigma(r)$ = 0.006

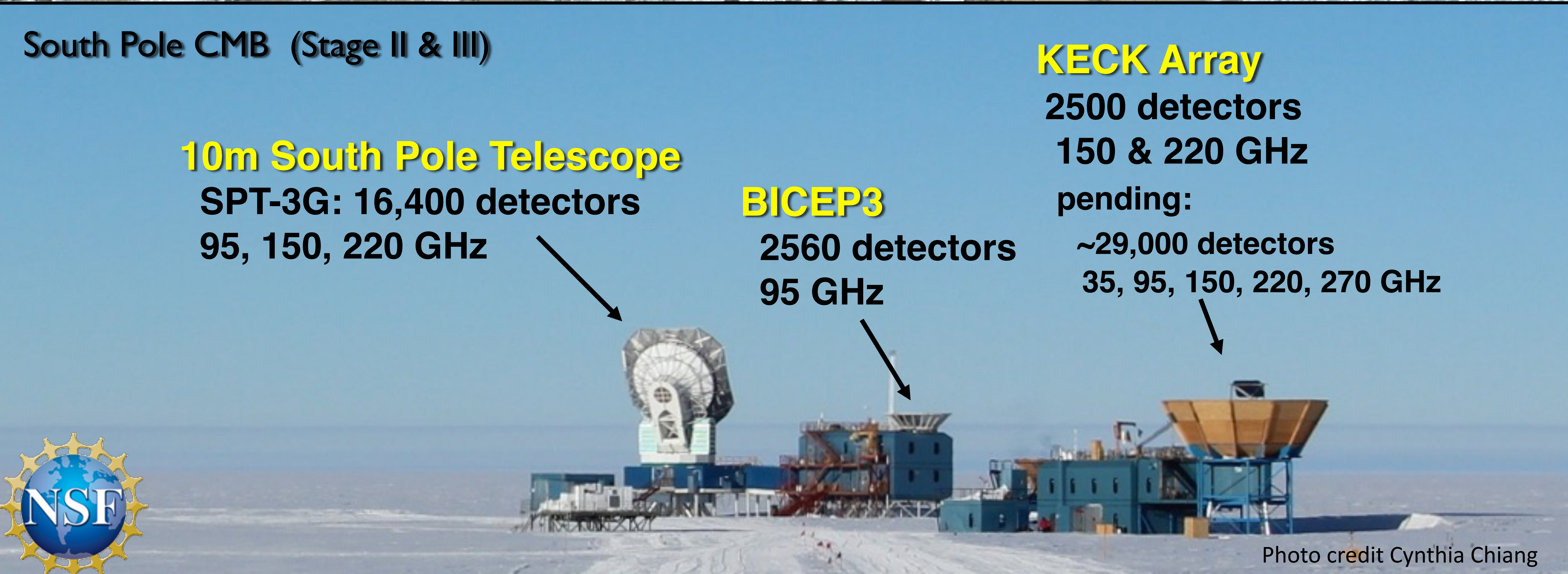
→ ***it is now all about foreground component separation and soon lensing B-mode noise***

Strawman CMB-S4 specifications

CMB-S4
Next Generation CMB Experiment

- **Surveys:**
  - Inflation, Neutrino, and Dark Energy science requires optimized surveys using a range of resolution and sky coverage from deep to wide.
- **Sensitivity:**
  - ~1 uK-arcm over ≳70% of the sky, and considerably deeper on targeted fields.
- **Configuration:**
  - *O*(500,000) detectors on multiple telescopes,
  - **spanning ~ 30 - 300 GHz for foreground mitigation**
- **Resolution:**
  - **exquisite low-ℓ and high-ℓ sensitivity for inflationary B modes with delensing**
  - arc minute for CMB lensing & neutrino science
  - higher resolution improves sensitivity to dark energy, gravity tests, mapping the universe in momentum with SZ effects, and ancillary science.


Atacama CMB (Stage II & III)
CLASS 1.5m x 4
72 detectors at 38 GHz
512 at 95 GHz
2000 at 147 and 217 GHz
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 II & III)
10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz
BICEP3
2560 detectors
95 GHz
KECK Array
2500 detectors
150 & 220 GHz
pending:
~29,000 detectors
35, 95, 150, 220, 270 GHz
NSF
Photo credit Cynthia Chiang

CMB-S4
Next Generation CMB Experiment

Telescopes at Chile and South Pole and possibly Northern sites (e.g., Tibet, Greenland)

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

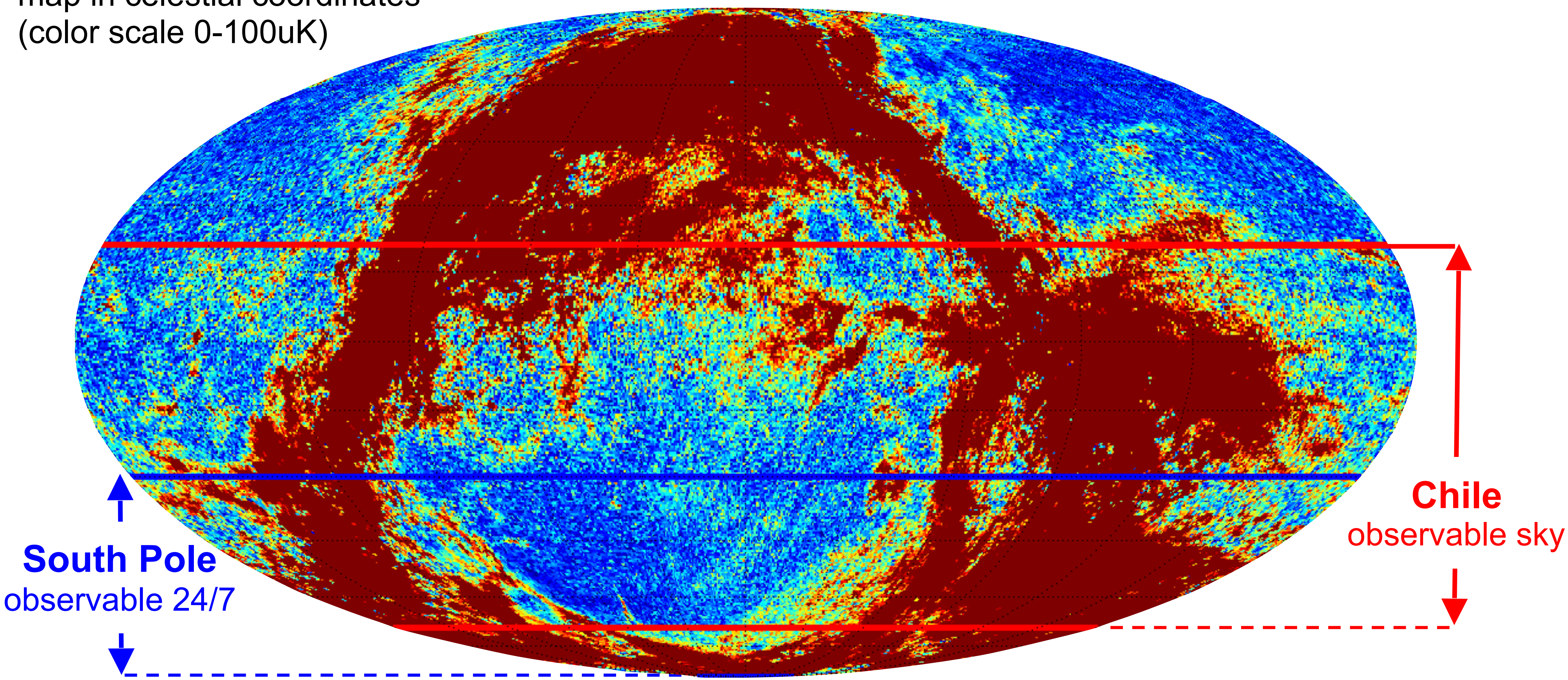


Figure from Clem Pryke

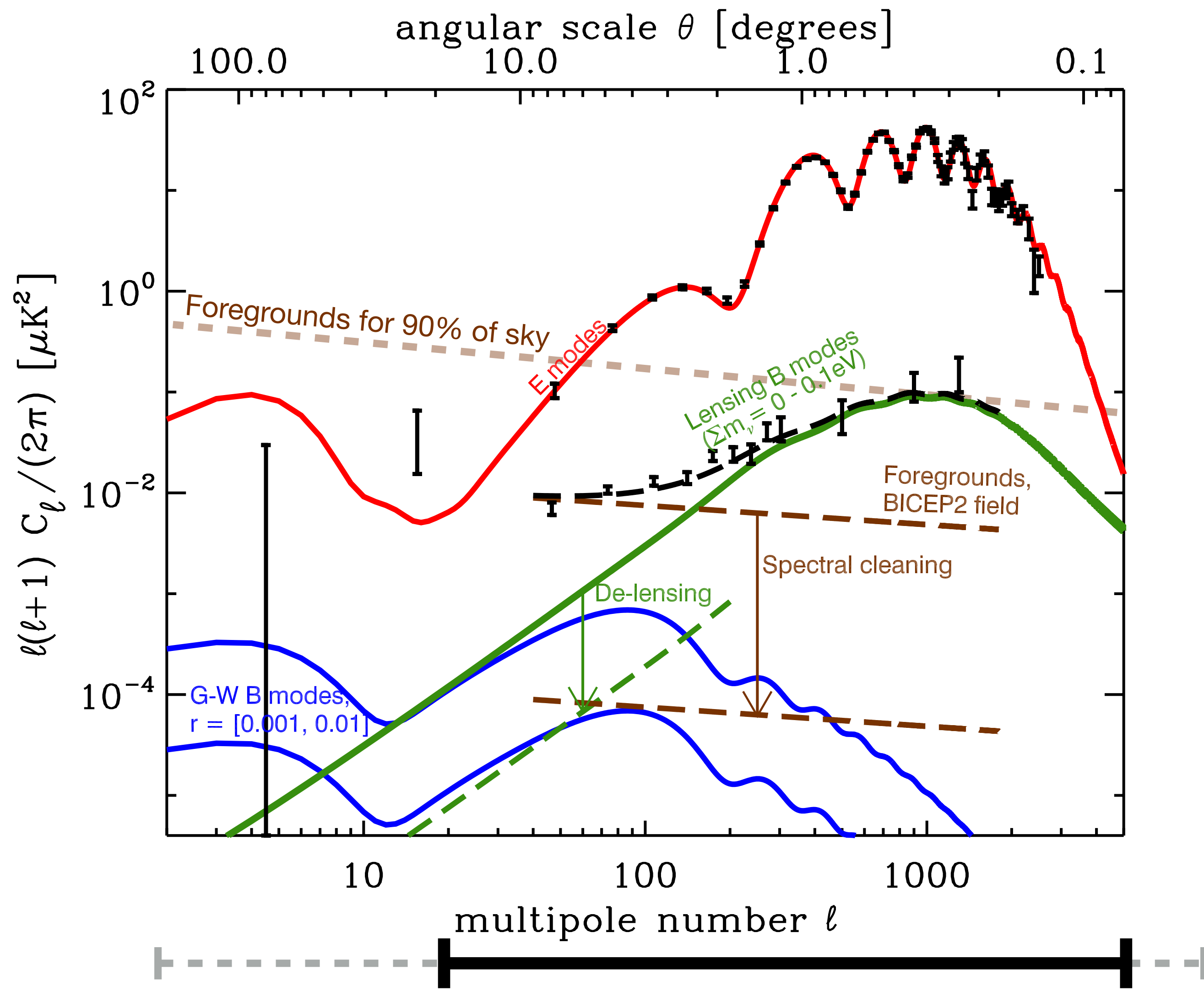
CMB-S4
Next Generation CMB Experiment

Angular range of CMB-S4

- Inflationary B modes search requires exquisite sensitivity **at both low-ℓ and high-ℓ** because of need for **de-lensing**.

Also:

- High-ℓ and large area for CMB lensing cosmic variance limited constraints on neutrino mass and N_{eff}
- Higher-ℓ for dark energy and gravity



ℓ range of CMB-S4

CMB-S4
Next Generation CMB Experiment

De-lensing B-mode Polarization

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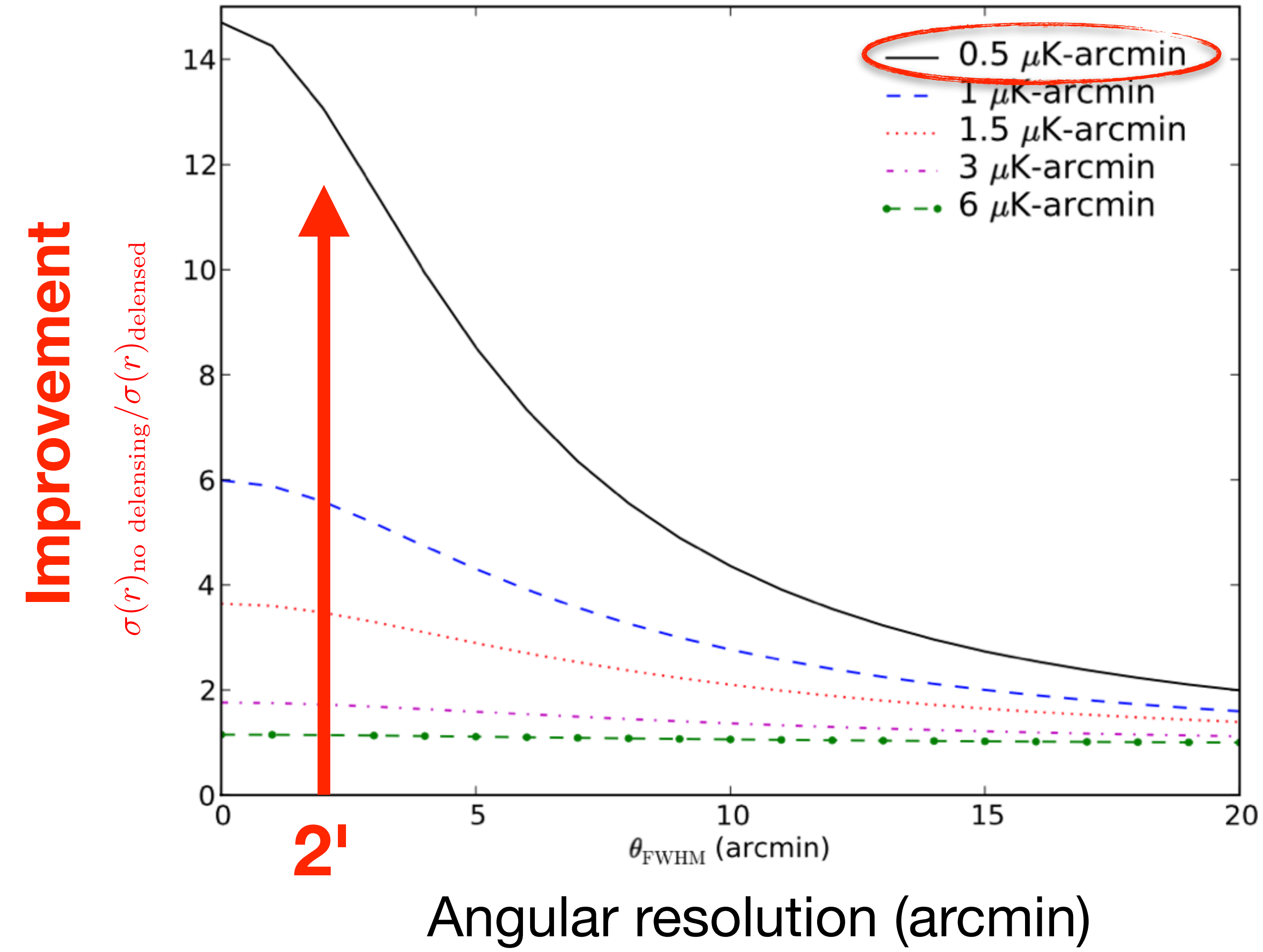
De-lensing Improvement on σ(r) vs Angular Resolution

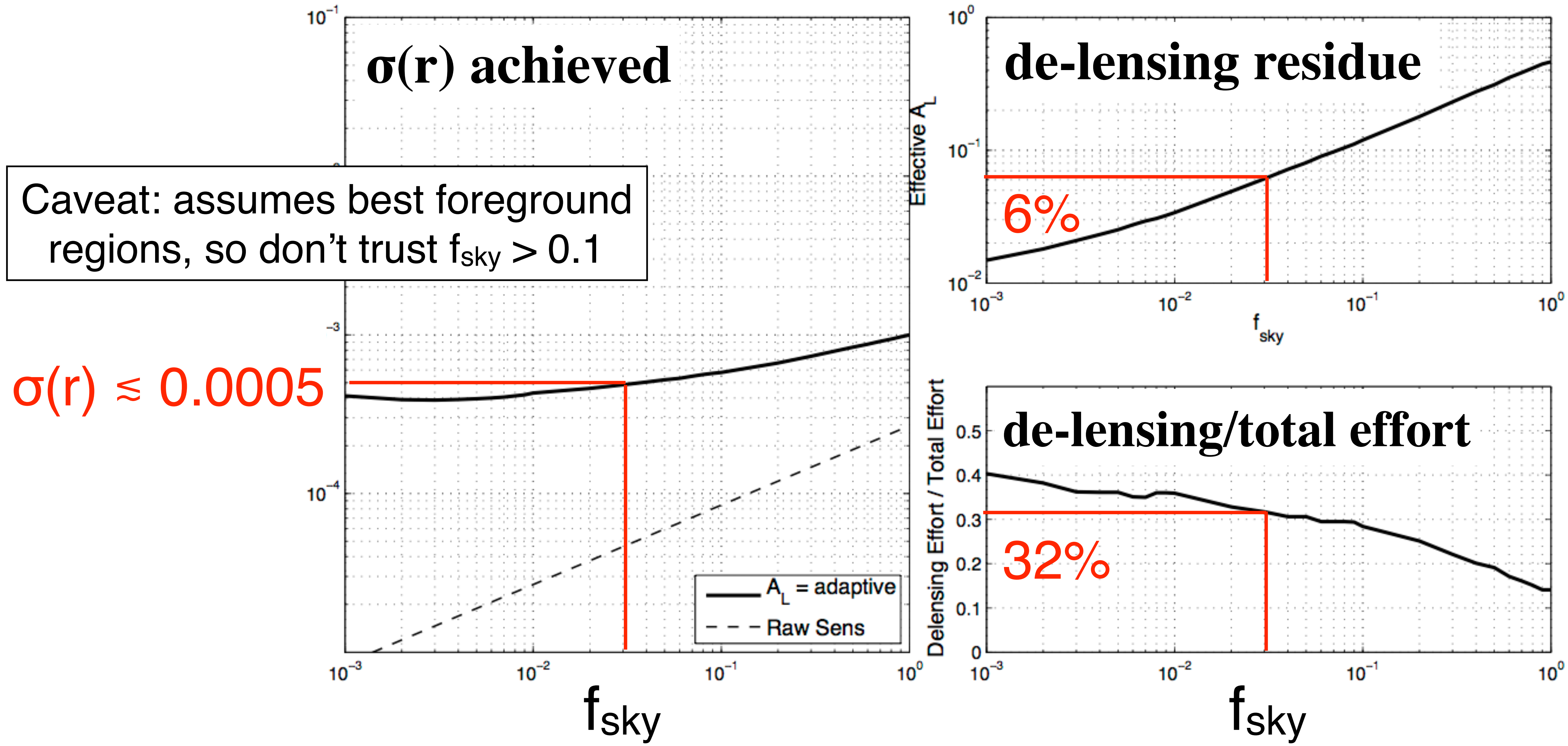


from Smith et al., CMBpol Mission Study arXiv:0811.2916

CMB-S4
Next Generation CMB Experiment

Example of optimization / projection of inflation reach of CMB-S4

Consider f_{sky} = 3% survey using ALL the power of CMB-S4

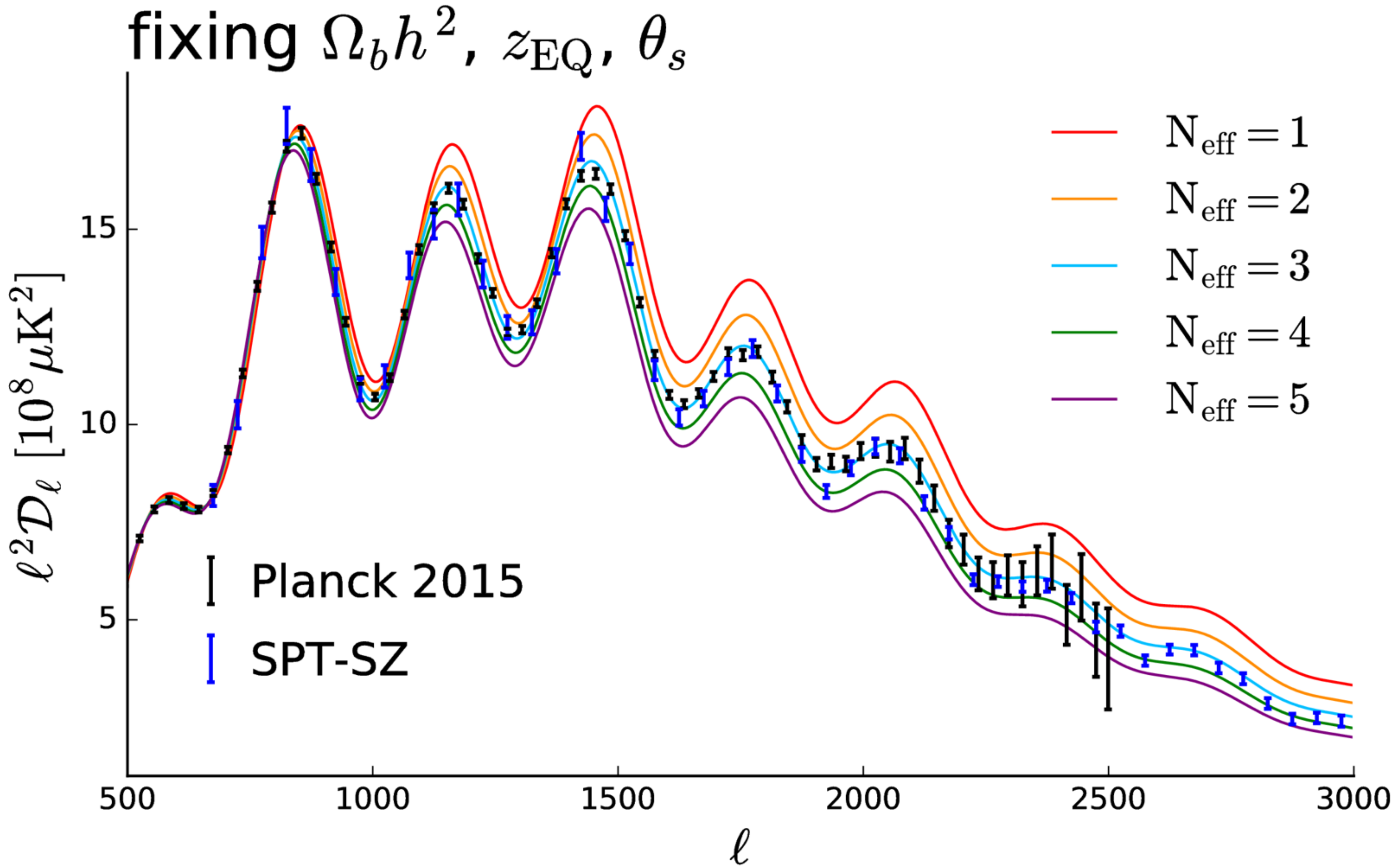


BPCM (Bandpower Covariance Matrix) optimization of

- 8 CMB-S4 frequency bands: 30, 40, 85, 95, 145, 155, 215 & 270GHz
- 13 model parameters (including FG correlations and dust spectral power law index scatter)
- fraction of effort with arc minute telescopes and degree scale telescopes

by V. Buza, C. Bischoff & J. Kovac

Measure N_{eff} from CMB damping

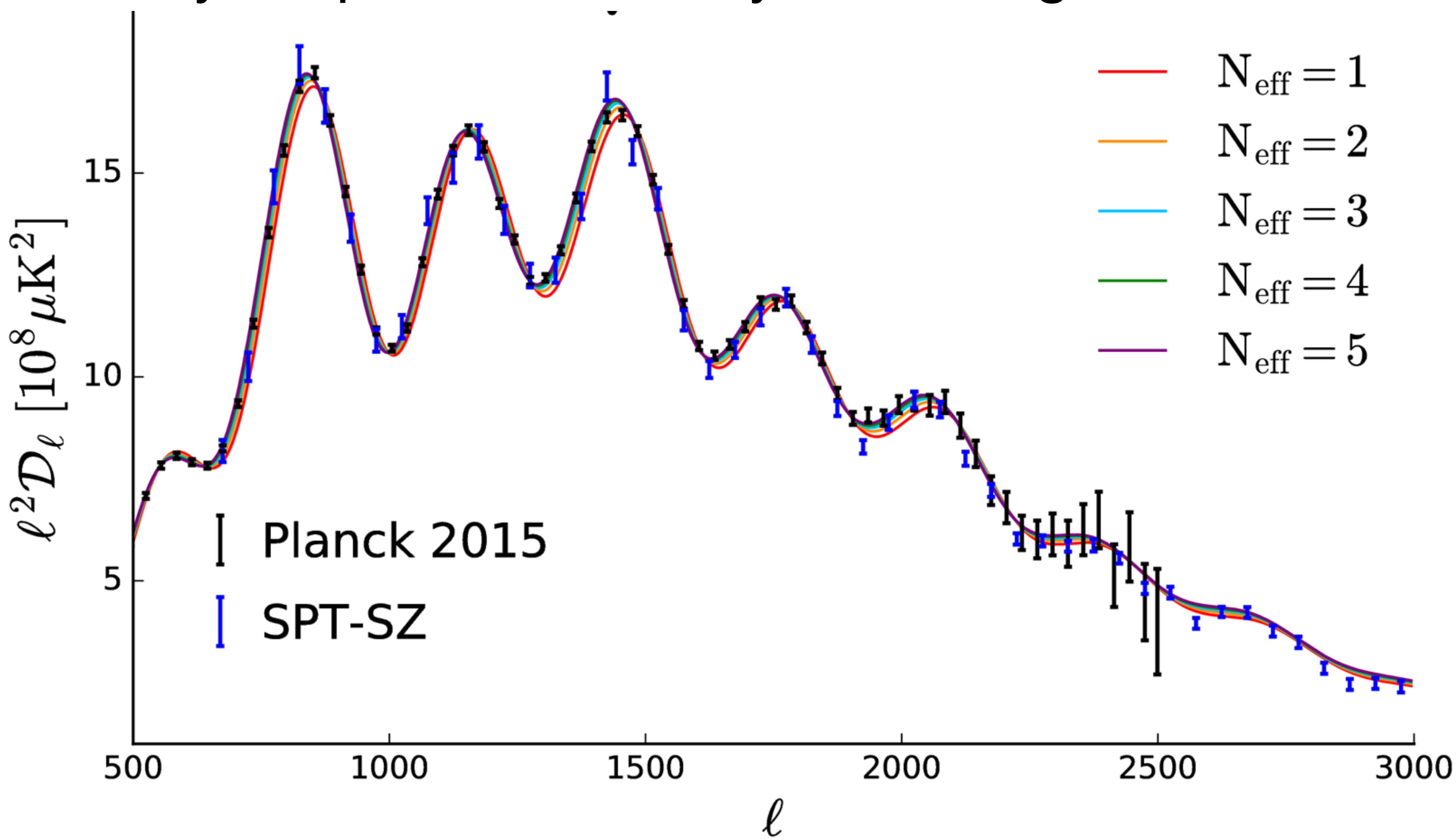


N_{eff} is the extra relativistic energy density compared to photons

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

But, Helium fraction & N_{eff} degeneracy

Artificially keep θ_d constant by increasing helium fraction, Y_P



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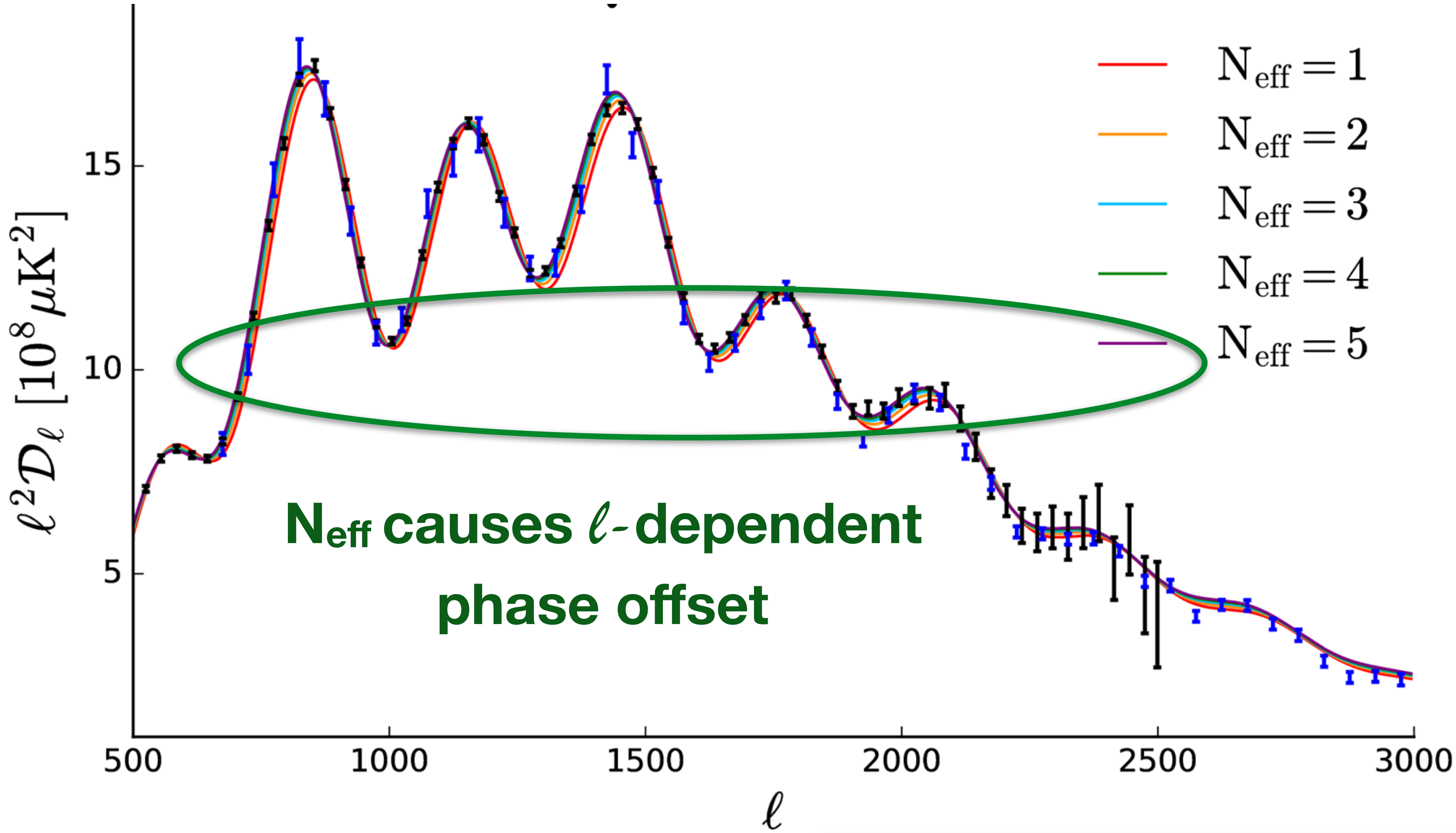
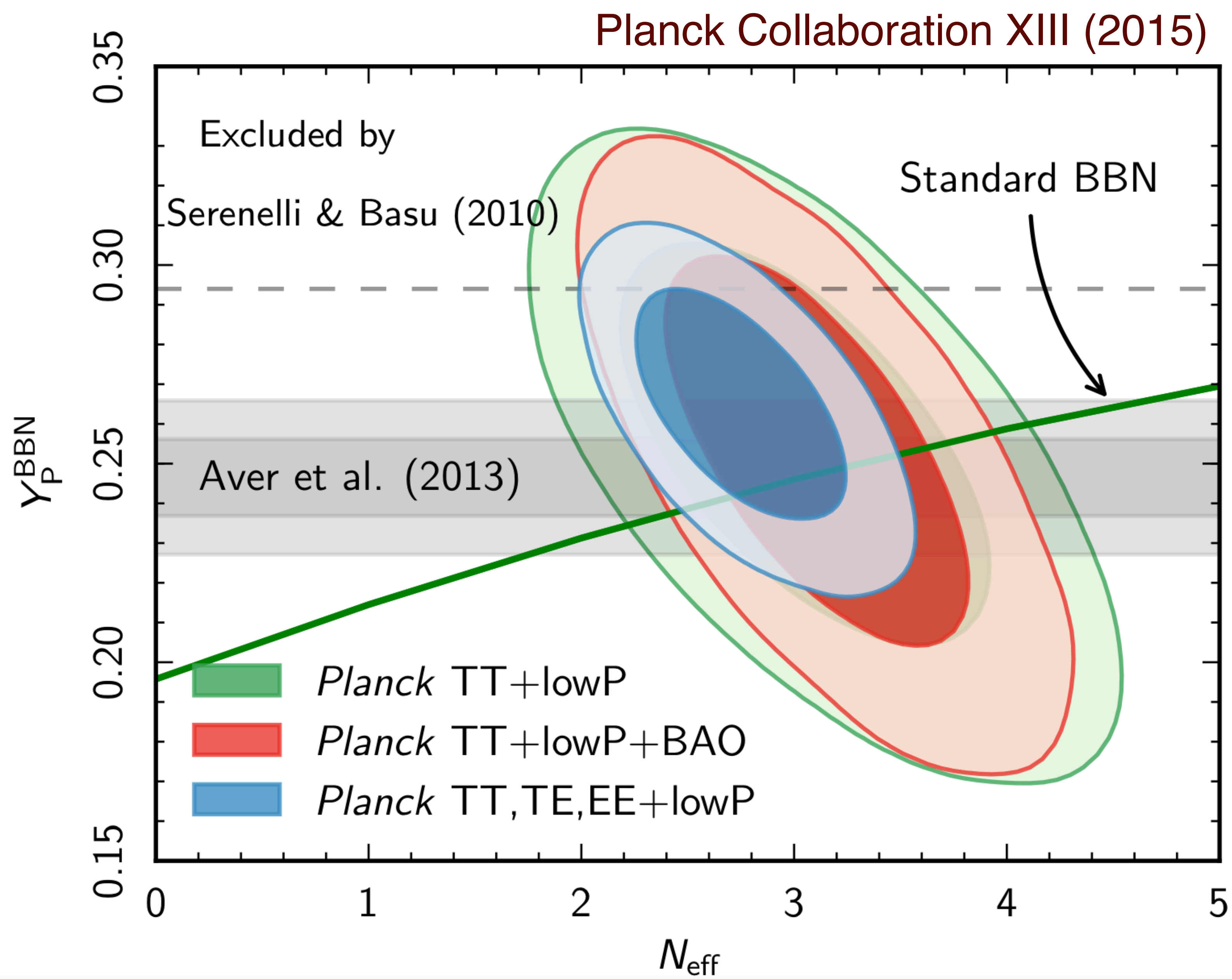


CMB polarization is much more sensitive to N_{eff}

and N_{eff} and Helium are linked through Big Bang Nucleosynthesis



Links physics of

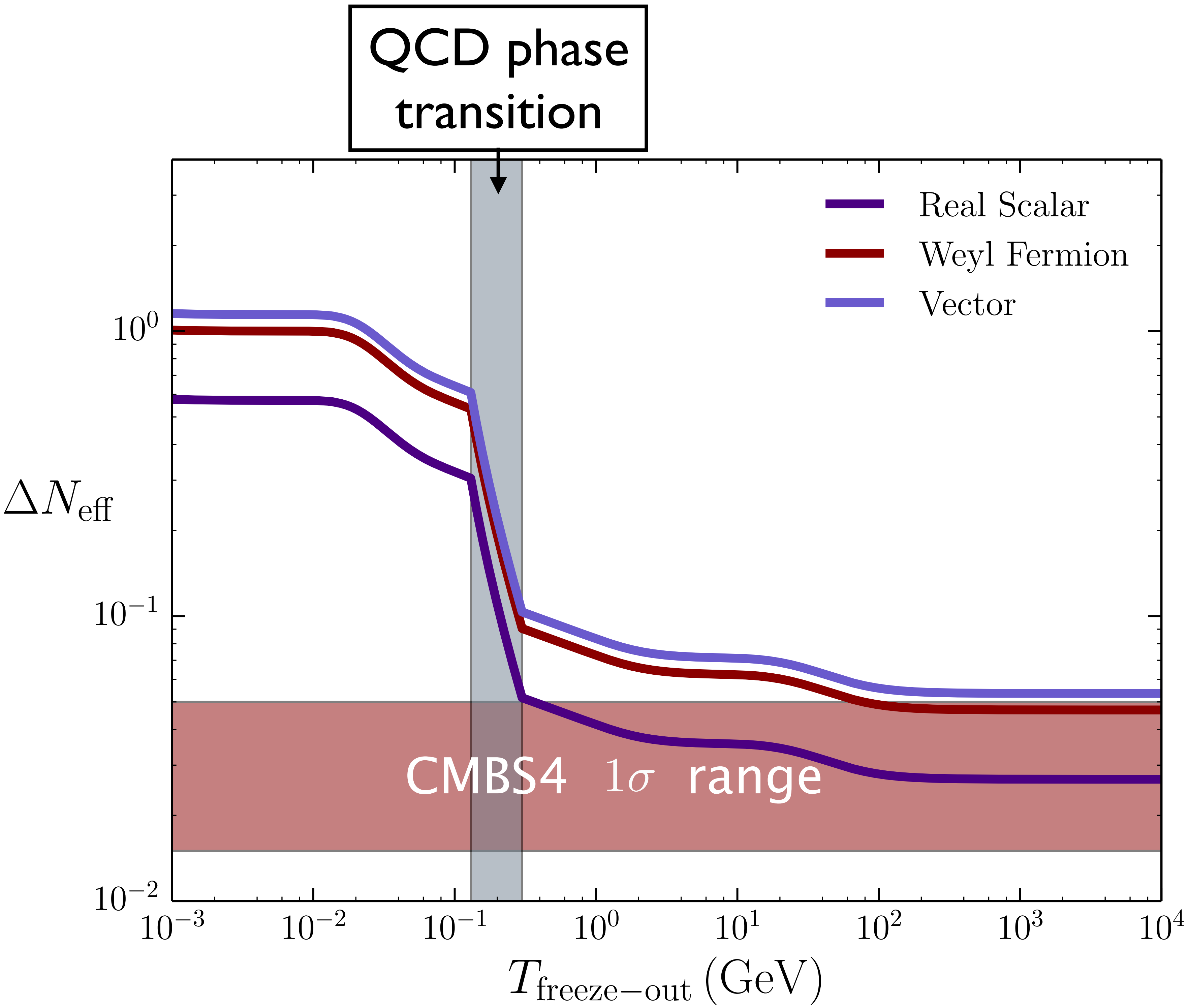
- *Cosmic neutrino background at ~1 sec*
- *Light element production at ~3 min*
- *CMB emitted at ~380,000 years*

Highly significant detection of neutrino background! But we need to do much better

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

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

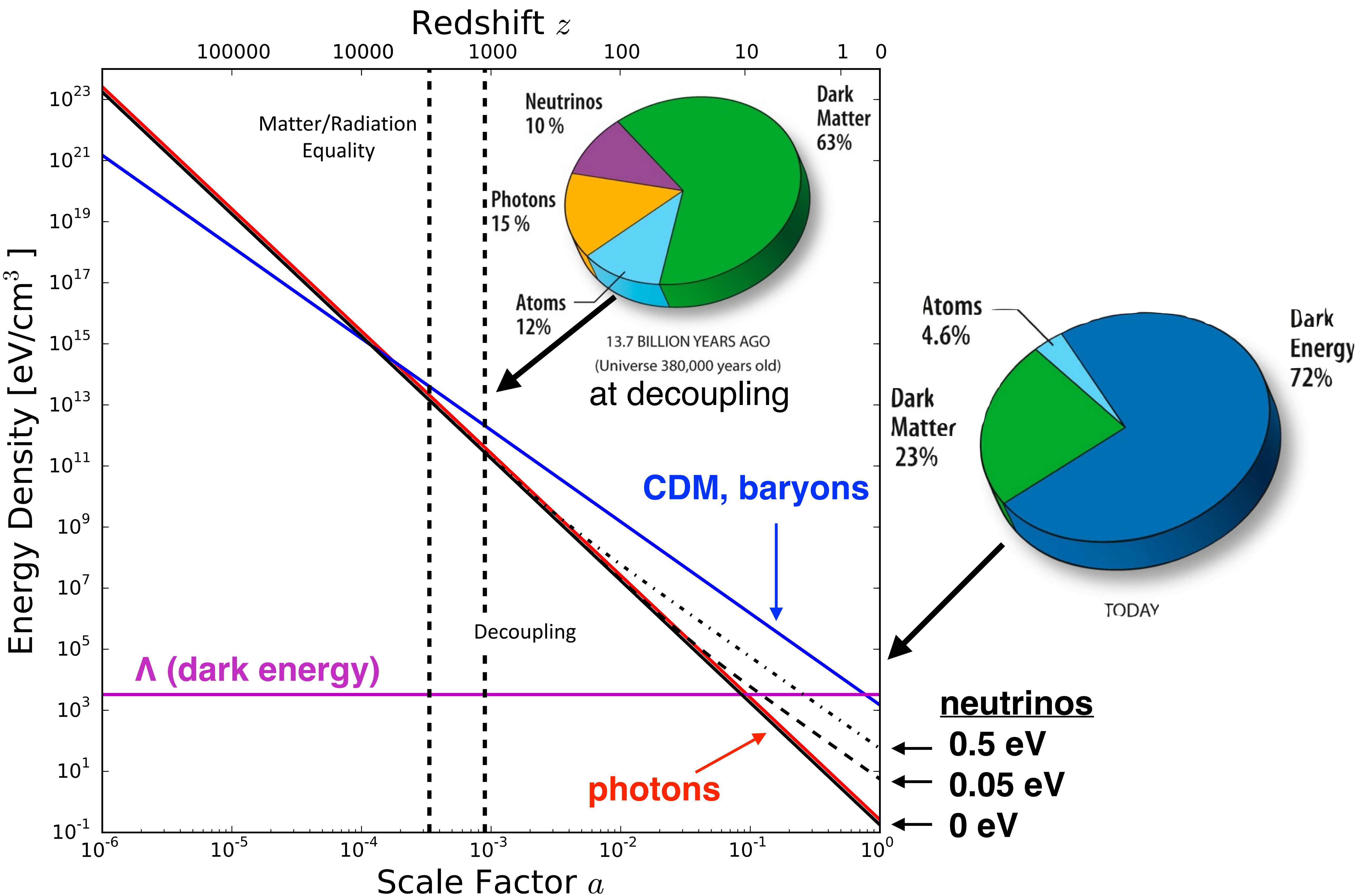
N_{eff} can constrain thermal relics



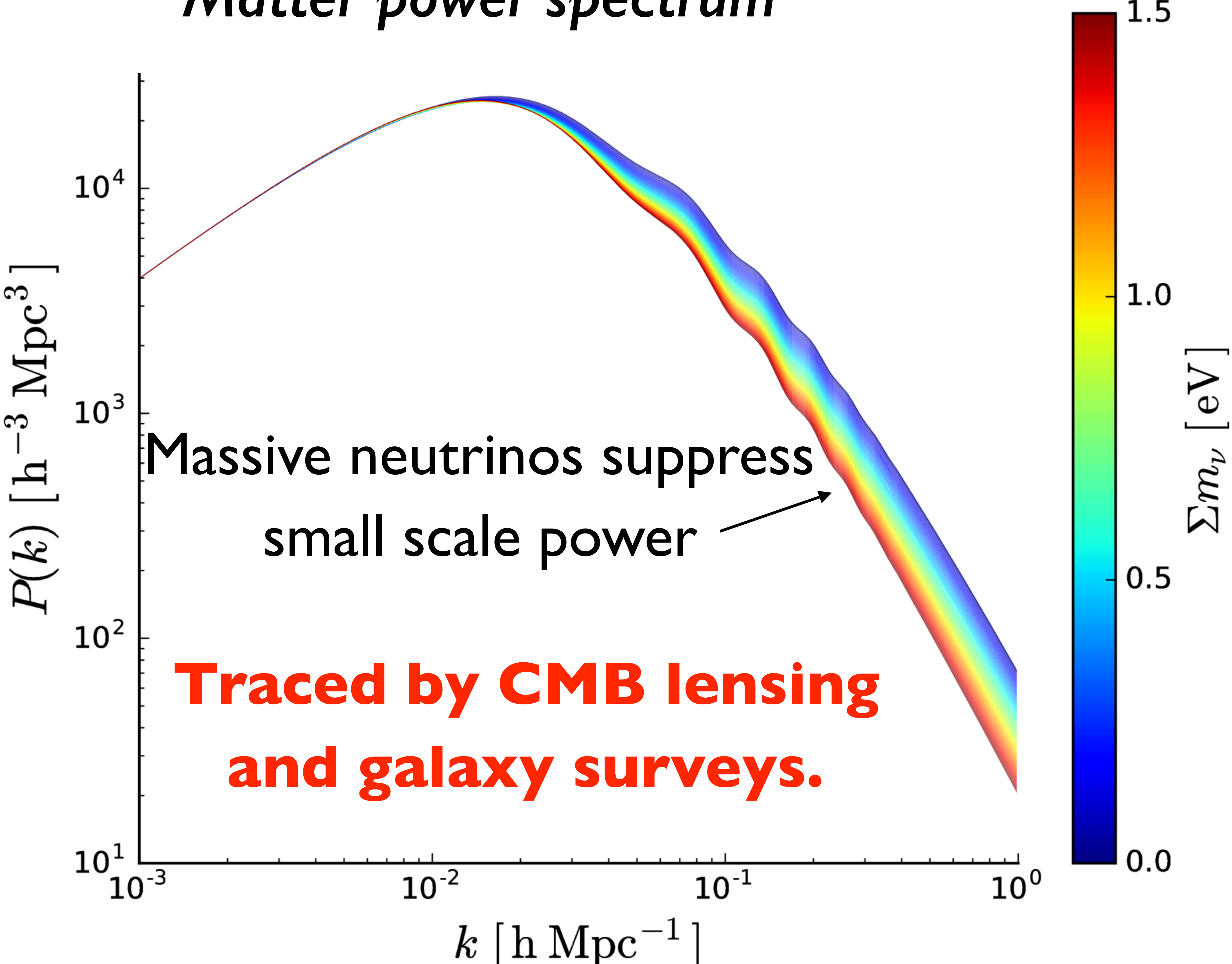
- reduction in $\sigma(N_{eff})$ leads to orders of magnitude improvement of constraint on the freeze-out temperature for any light thermal relic

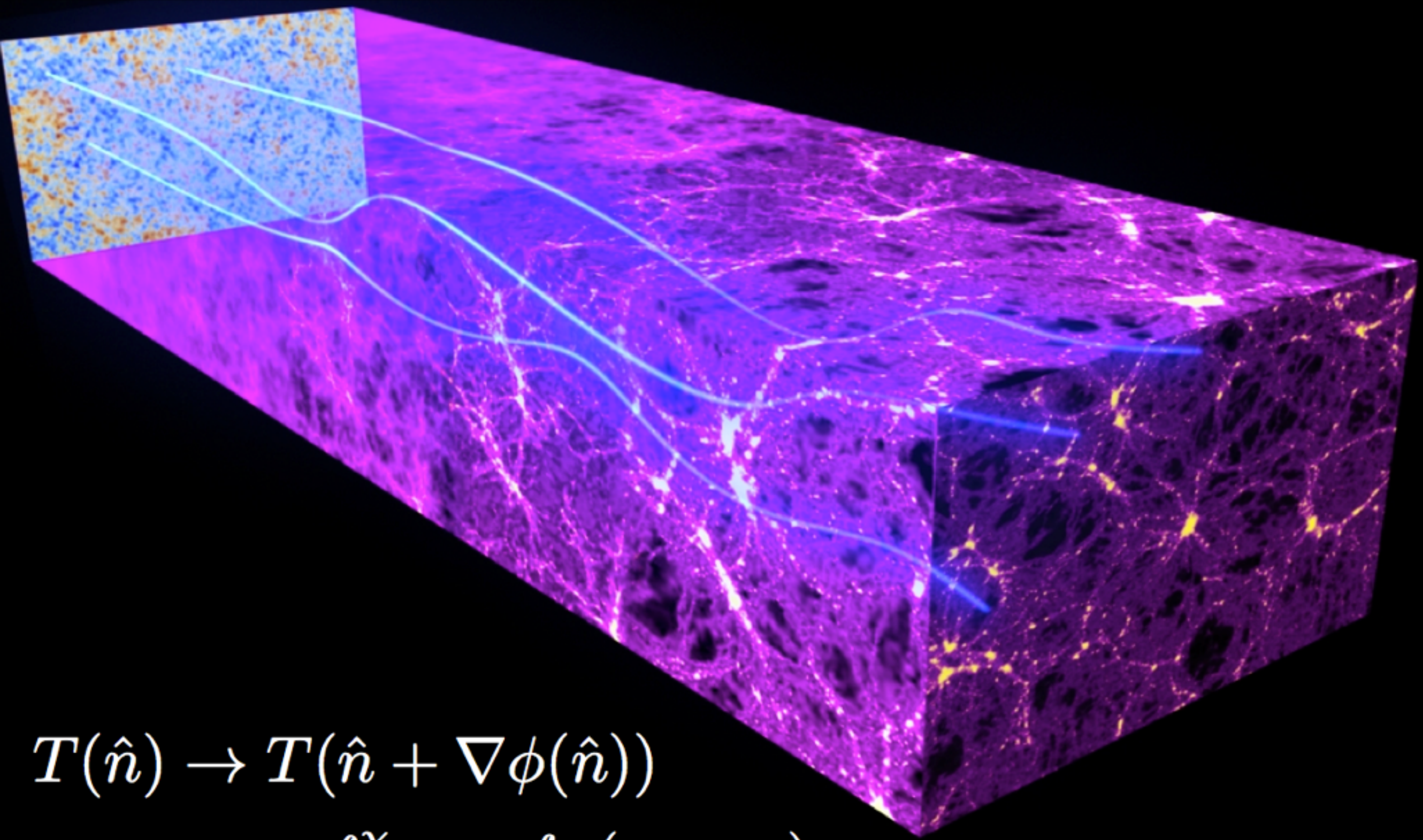
Green, Meyers CMB-S4 Science Book draft (https://cosmo.uchicago.edu/CMB-S4workshops)

Neutrinos transition from relativistic at decoupling to part of matter budget today



Matter power spectrum

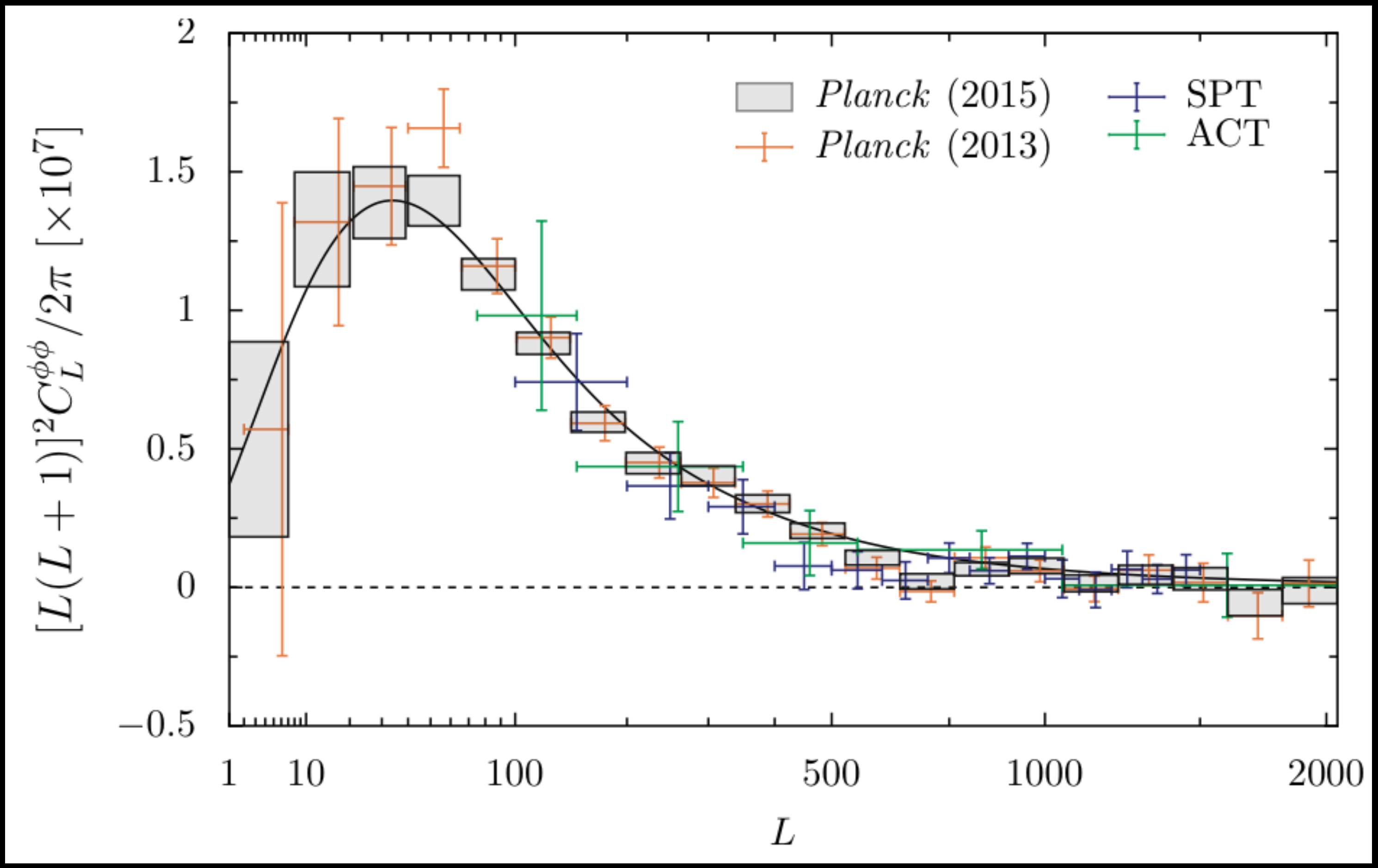




CMB lensing - also great progress, and also a long, long way to go

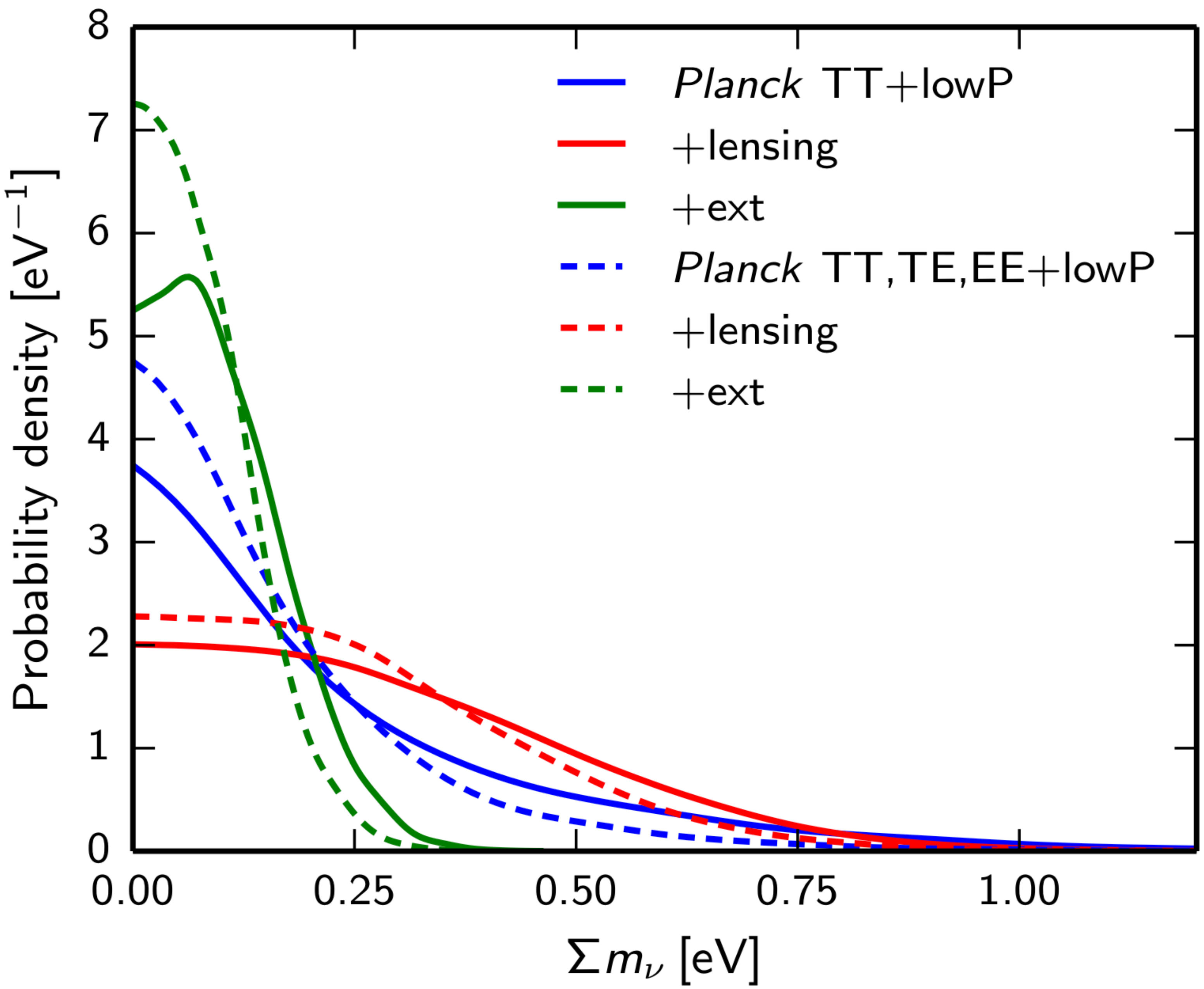
$$T(\hat{n}) \rightarrow T(\hat{n} + \nabla\phi(\hat{n}))$$

$$\phi(\hat{n}) = -2\int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*)f_K(\chi)} \Psi(\chi\hat{n}; \eta_0 - \chi)$$



graphic from ESA Website

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.

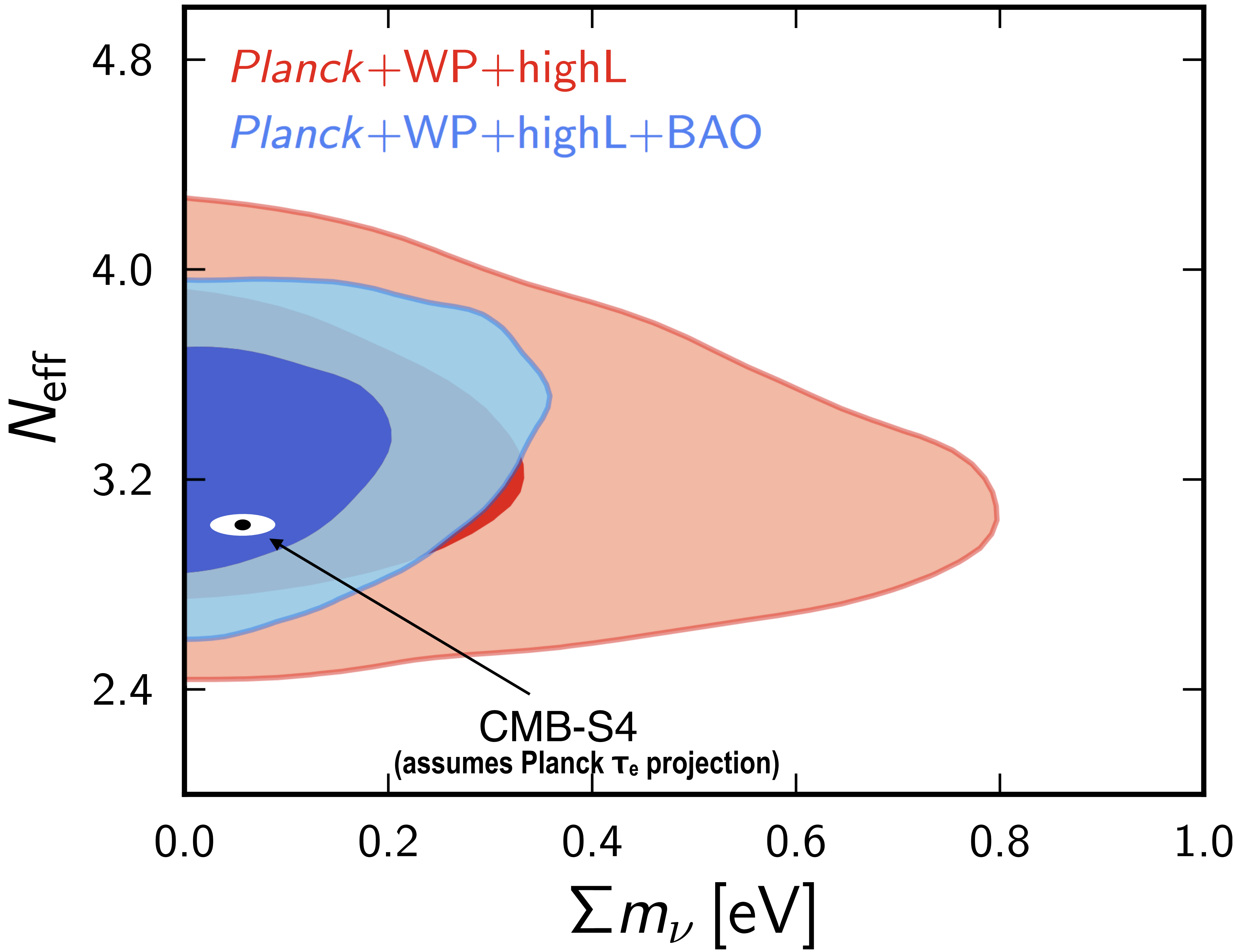
Joint Σm_ν and N_{eff} fit:

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

We can and need to do much better

Planck Collaboration XIII (2015)

Projected CMB-S4 N_{eff} - Σm_ν constraints



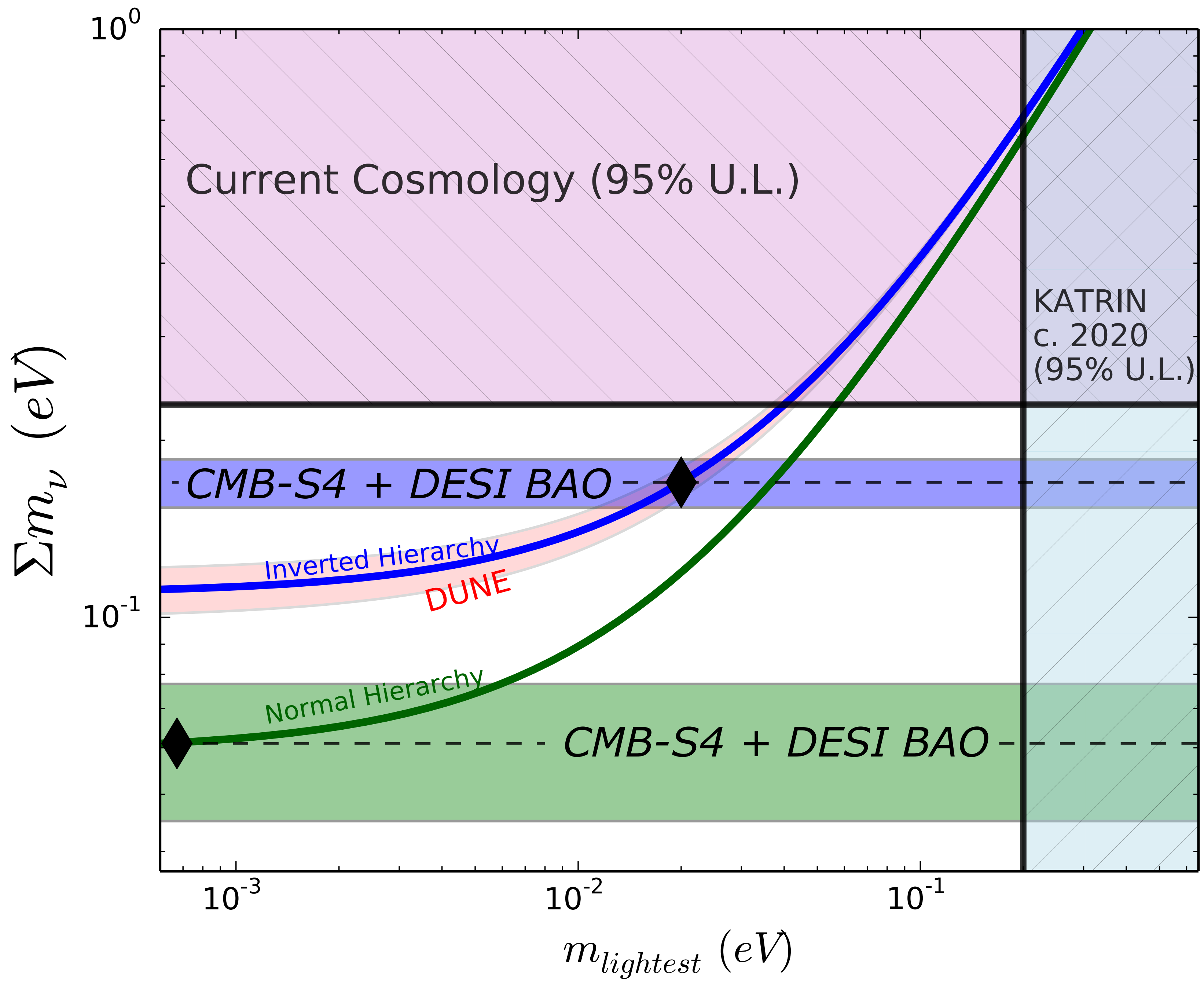
$\sigma(\Sigma m_\nu)$ = 15 meV
(with DESI BAO)

$\sigma(N_{eff})$ = 0.016*
CMB uniquely probes N_{eff}

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

Complementarity of Cosmic Neutrino Constraints

"use cosmology to tighten the noose"
- Boris Kayser



Cosmic N_{eff} and Σm_ν constraints also complement Short Baseline Neutrino experiments and Neutrinoless Double Beta Decay experiments

arXiv:1309.5383

Cosmology with CMB-S4 community workshops

U. Minnesota
Jan 16, 2015

U. Michigan
Sep 21-22, 2015

LBNL, Berkeley
March 7-9, 2016

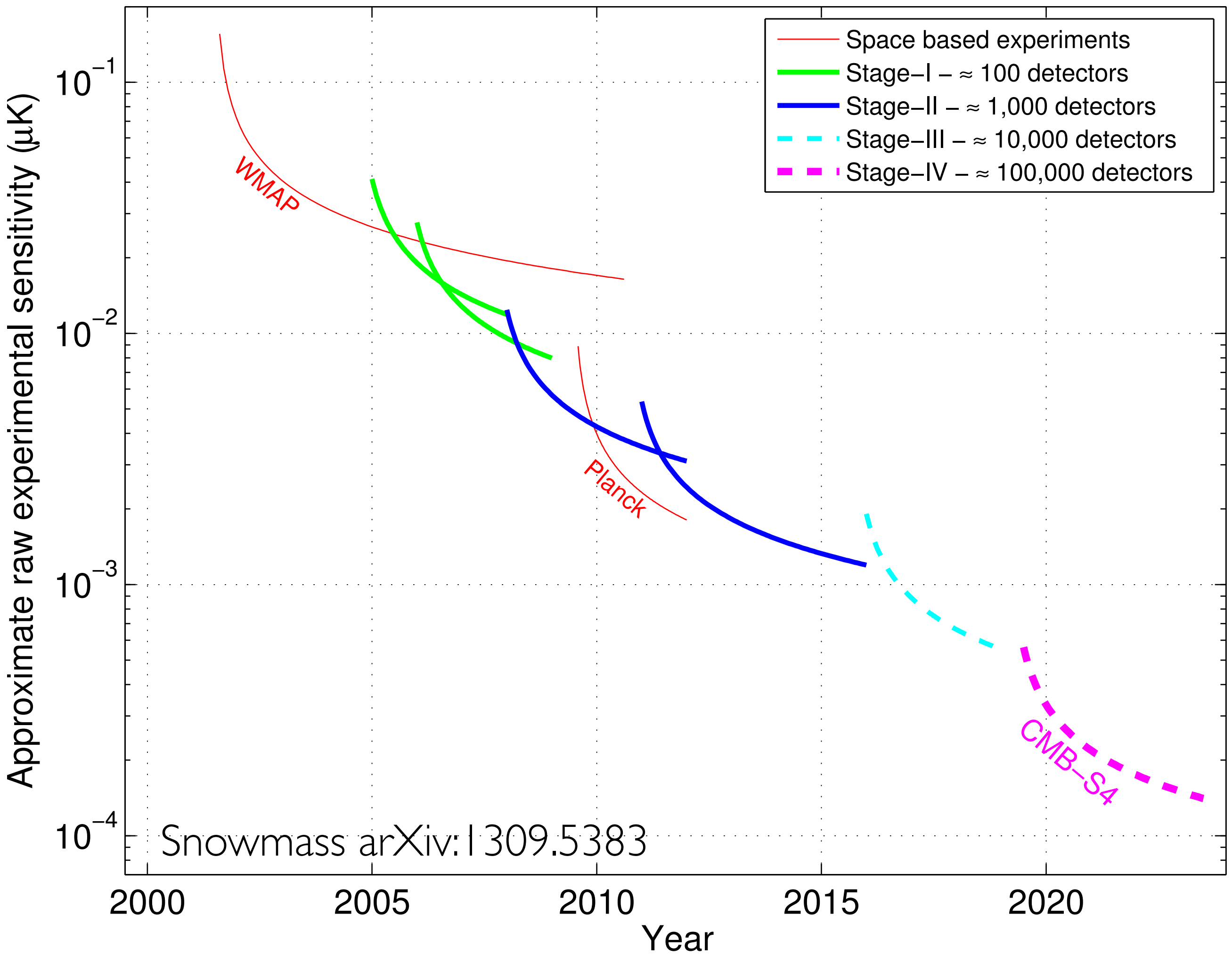
NEXT: U. Chicago Sep19-21 2016
please participate

Refining the science goals and instrument definition. Science Book nearly complete
(web pages moving to CMB-S4.org)

CMB-S4 What's needed to realize CMB-S4

Next Generation CMB Experiment

- **Scaling up:**
  - detectors, focal planes
  - sky area and frequency coverage
  - multiple telescopes; new designs
  - computation, data analysis, simulations
  - project organization, management
- **Systematics:**
  - improved control, especially of foreground mitigation
- **Theory/phenomenology:**
  - Increased precision for analysis; new methods

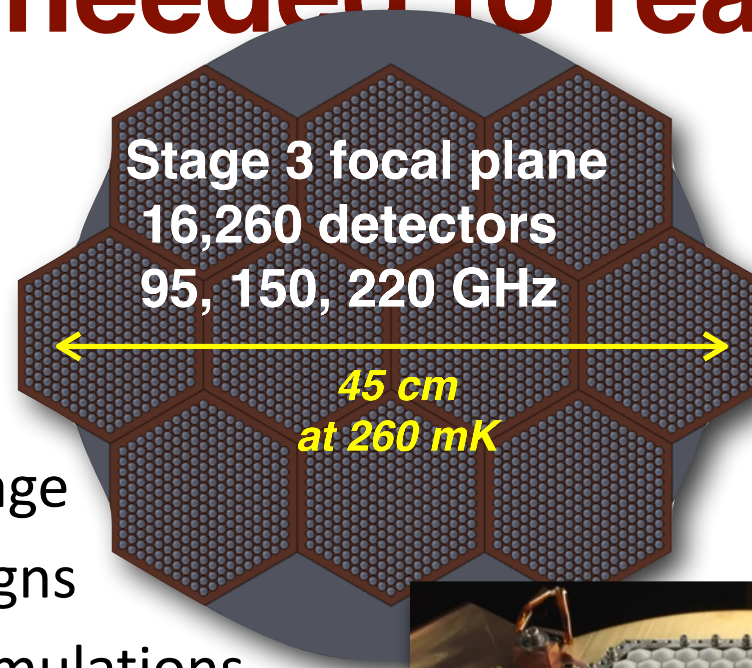


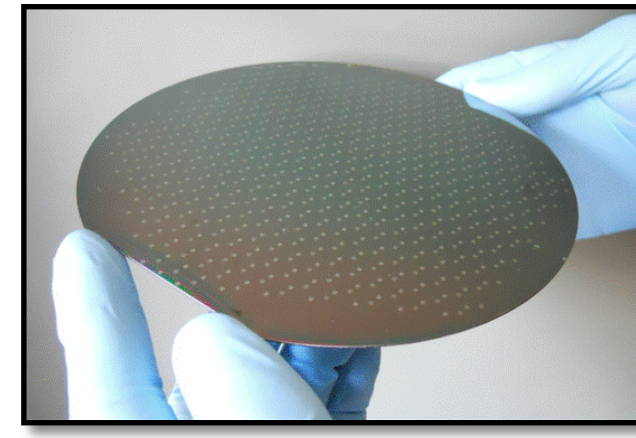
Scale of CMB-S4 exceeds capabilities of the University CMB groups.

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

CMB-S4
Next Generation CMB Experiment

What's needed to realize CMB-S4





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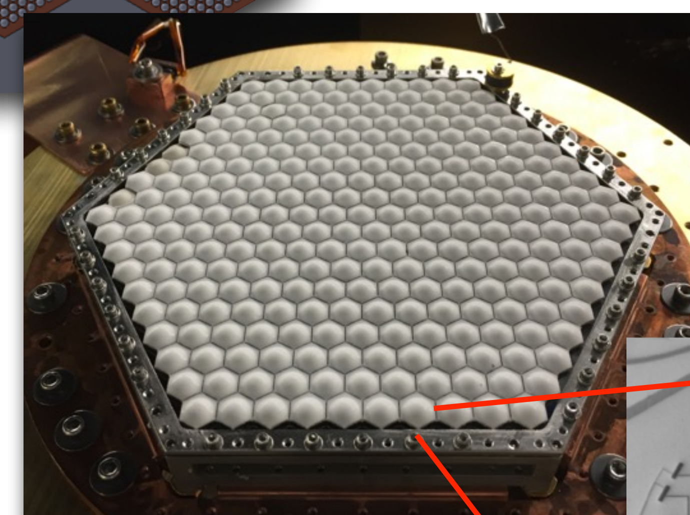

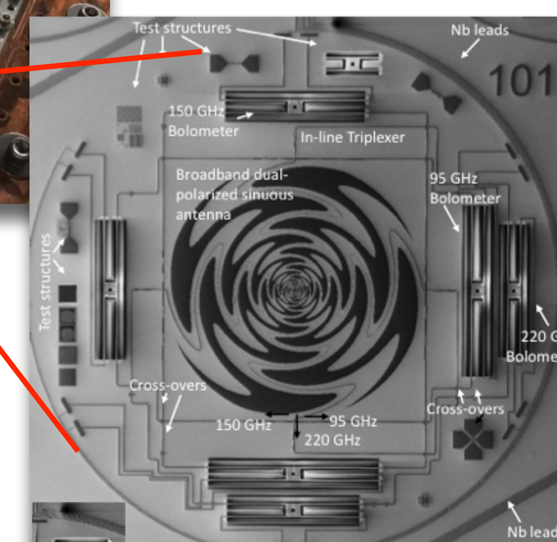

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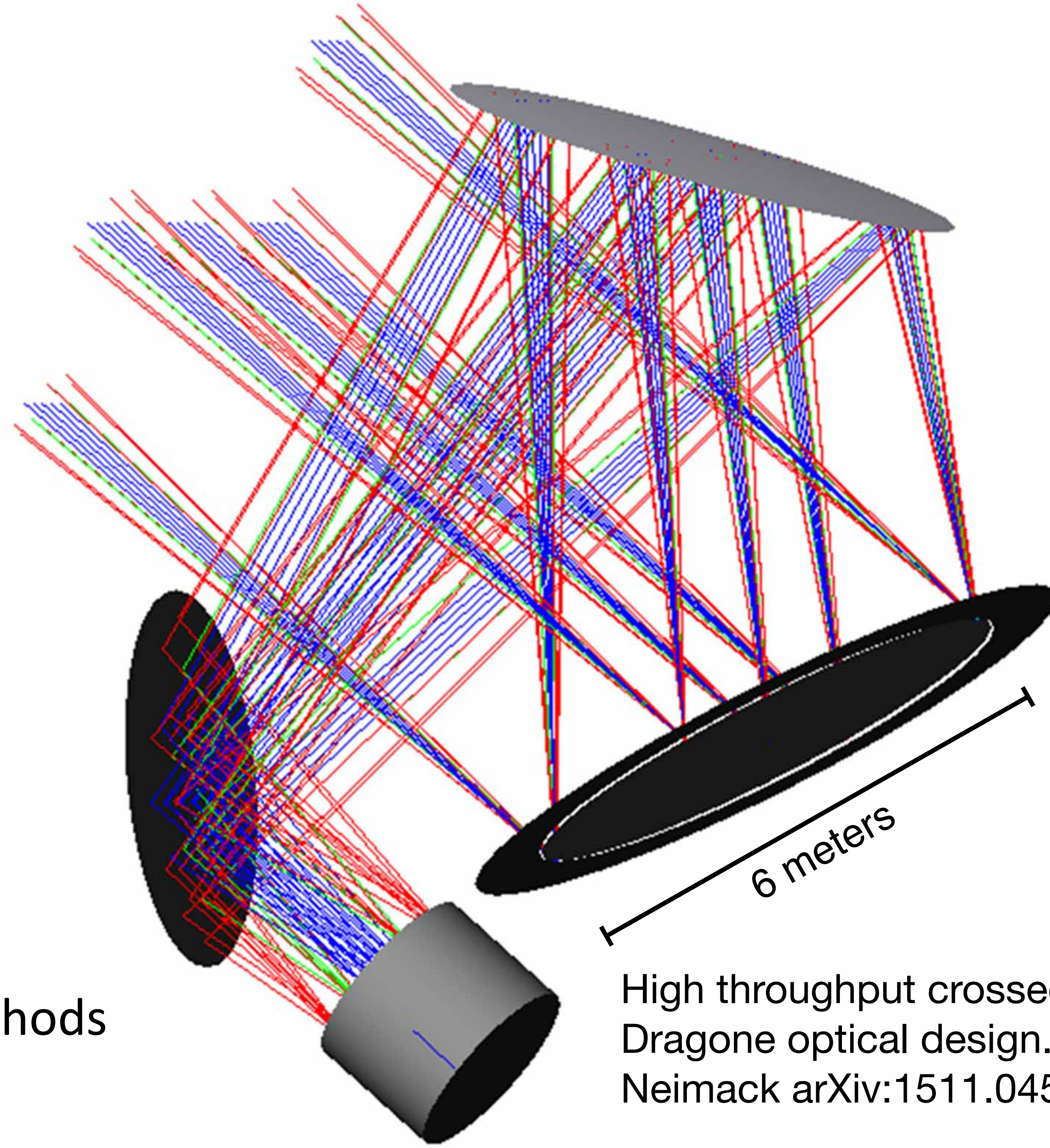

High throughput crossed Dragone optical design. Neimack arXiv:1511.04506

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CMB-S4
Next Generation CMB Experiment

DOE Lab Involvement

- Science!
- High Volume Fabrication of Detector Arrays
- Multiplexed Superconducting Readout Electronics
- High Volume Assembly and testing of Detector Modules
- Receiver Development (Optics, Polarization Modulators, …)
- High Performance Computing / Analysis and Simulations
- Project Management

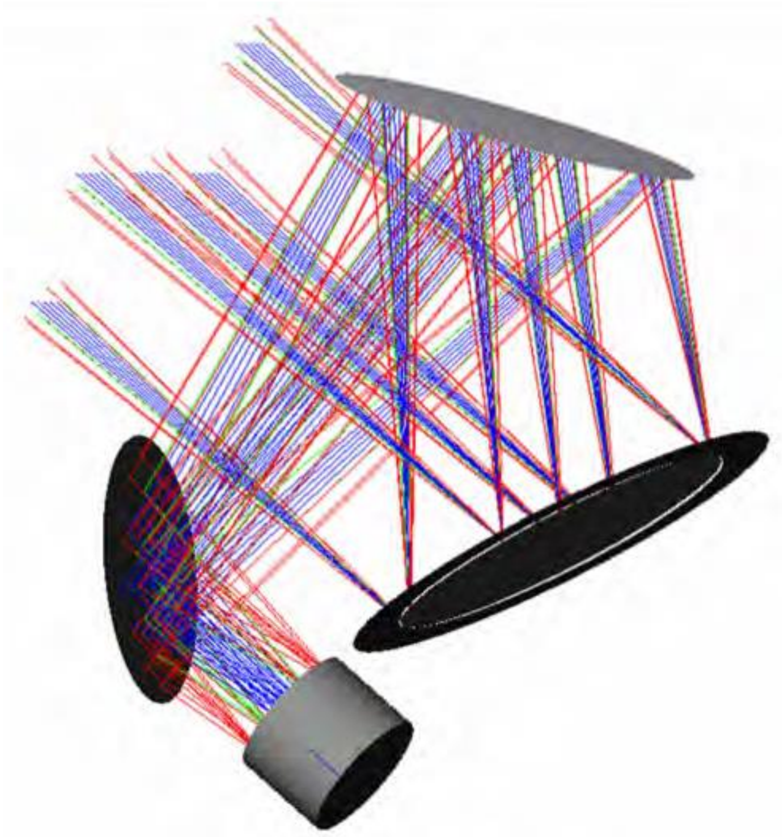
Argonne NATIONAL LABORATORY BERKELEY LAB Fermilab SLAC NATIONAL ACCELERATOR LABORATORY

Cosmic Frontier Highlight:
CMB-S4 Collaboration Workshop

- As recommended by P5, HEP is planning to participate in a CMB Stage 4 (CMB-S4) experiment
  - HEP will coordinate efforts within HEP program and consider possible HEP roles
  - Will work with NSF to coordinate planning and a path forward


CMB-S4 Collaboration Workshop Participants

- *Cosmology with CMB-S4 Collaboration Workshop* was held March 7-9, 2016, at LBNL
  - 180 participants
  - Produced first draft Science Book (149 pages)
    - https://cosmo.uchicago.edu/CMB-S4workshops/index.php/Main_Page
- Community-based planning aiming towards ground-based experiment to:
  - Gain insight into the inflationary epoch
  - Probe dark energy and neutrino properties from CMB lensing
  - Map B-mode polarization power spectrum
  - Probe high energy environment of early universe
- Notional CMB-S4 experiment is array of several telescopes with on the order of 0.5 M detectors total in Chile and South Pole
  - Involving ANL, FNAL, LBNL, SLAC, universities
  - Partnership may include NSF-AST, NSF-PLR, NSF-PHY, international agencies
  - Technology ready, but needs scale-up of detector fabrication, testing, and readout
  - Cost models under development with considerations for possible international contributions

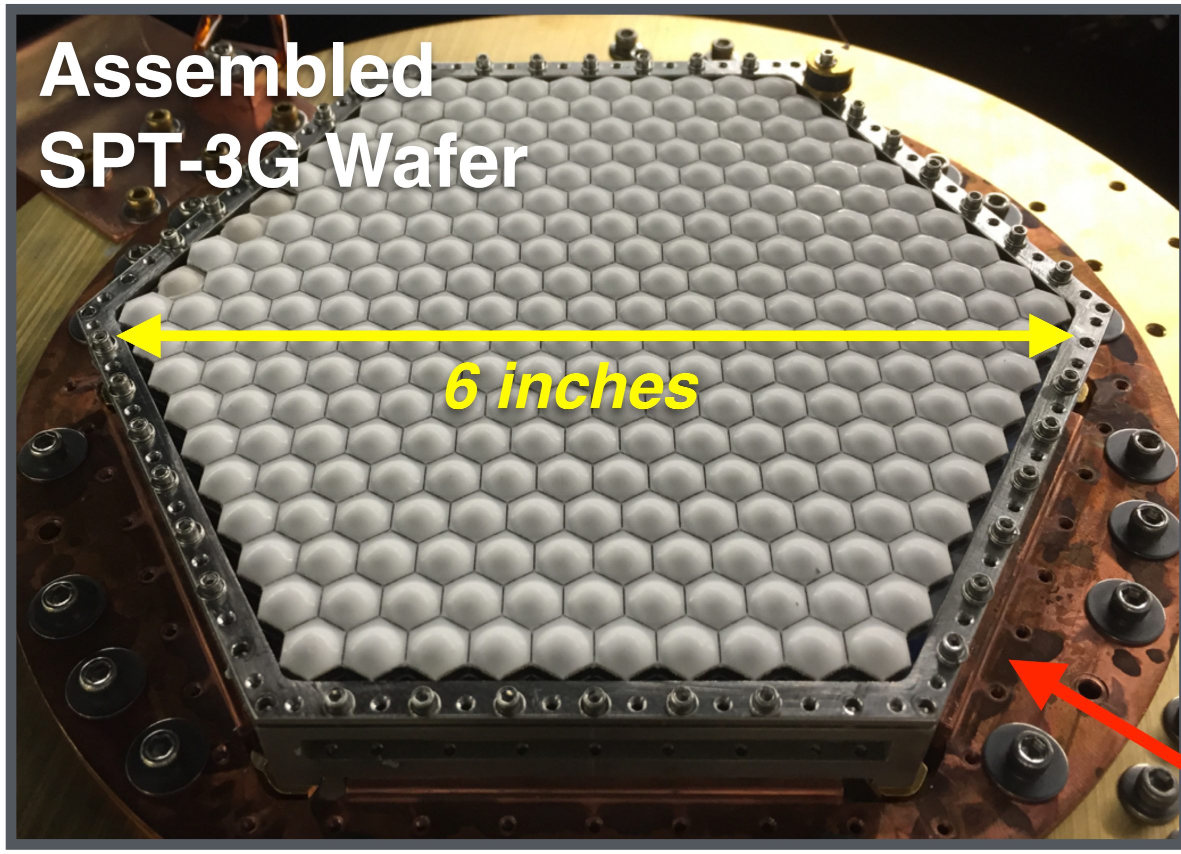

Prototype Large Aperture Telescope design with 10x mapping speed improvement (Niemack 2016)

CMB-S4
Next Generation CMB Experiment

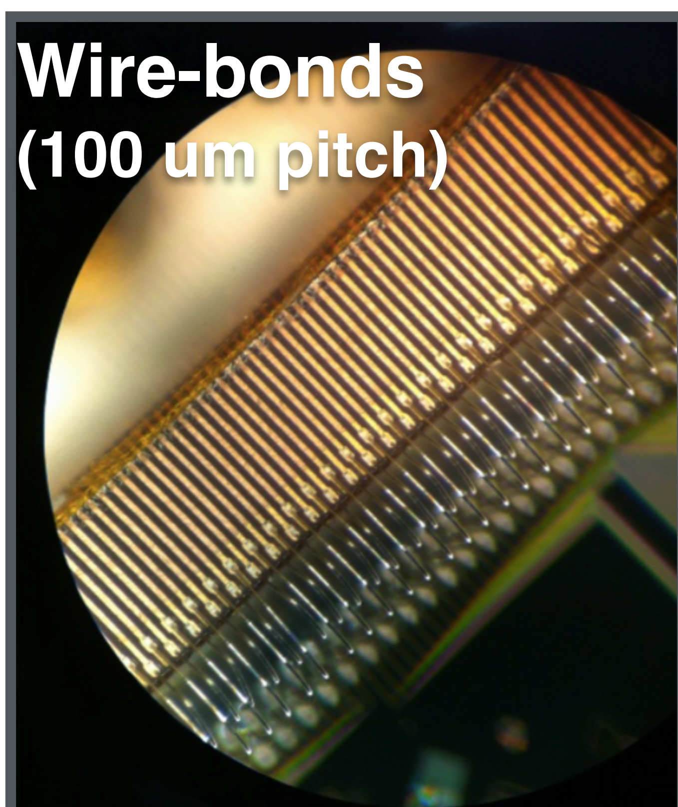
Fermilab and CMB-S4

- Strong leadership in the science
  - Seminal paper of B-modes as tracer of IGW (Kamionkowski, Kosowsky, and Stebbins, Phys. Rev. Lett. 78, 2058 (1997)
  - DES, DES⊗SPT analysis, CMB lensing; CMB-S4 will greatly enhance DES, DESI and LSST science, i.e., **Scott Dodelson's presentation to PAC**
- Played major role in QUIET CMB polarization experiment
- Major role in SPT-3G experiment carries directly to CMB-S4:
  - Detector packaging and readout: leverage existing resources at Sidet for silicon detector development and packaging.
  - Detector development and characterization: Use new sub-Kelvin facilities, RF, and electronics expertise to develop and characterize these new large arrays of CMB detectors.
  - Systems engineering, receiver design and integration: Large cryogenic systems will be required for future CMB cameras
- Deep project management experience
- Integral part of Chicagoland CMB efforts (ANL and UChicago), and tightly connected with those at SLAC and LBNL. (*I can't imagine FNAL not being involved*)

Fermilab Roles on SPT-3G:
Detector Packaging and Characterization

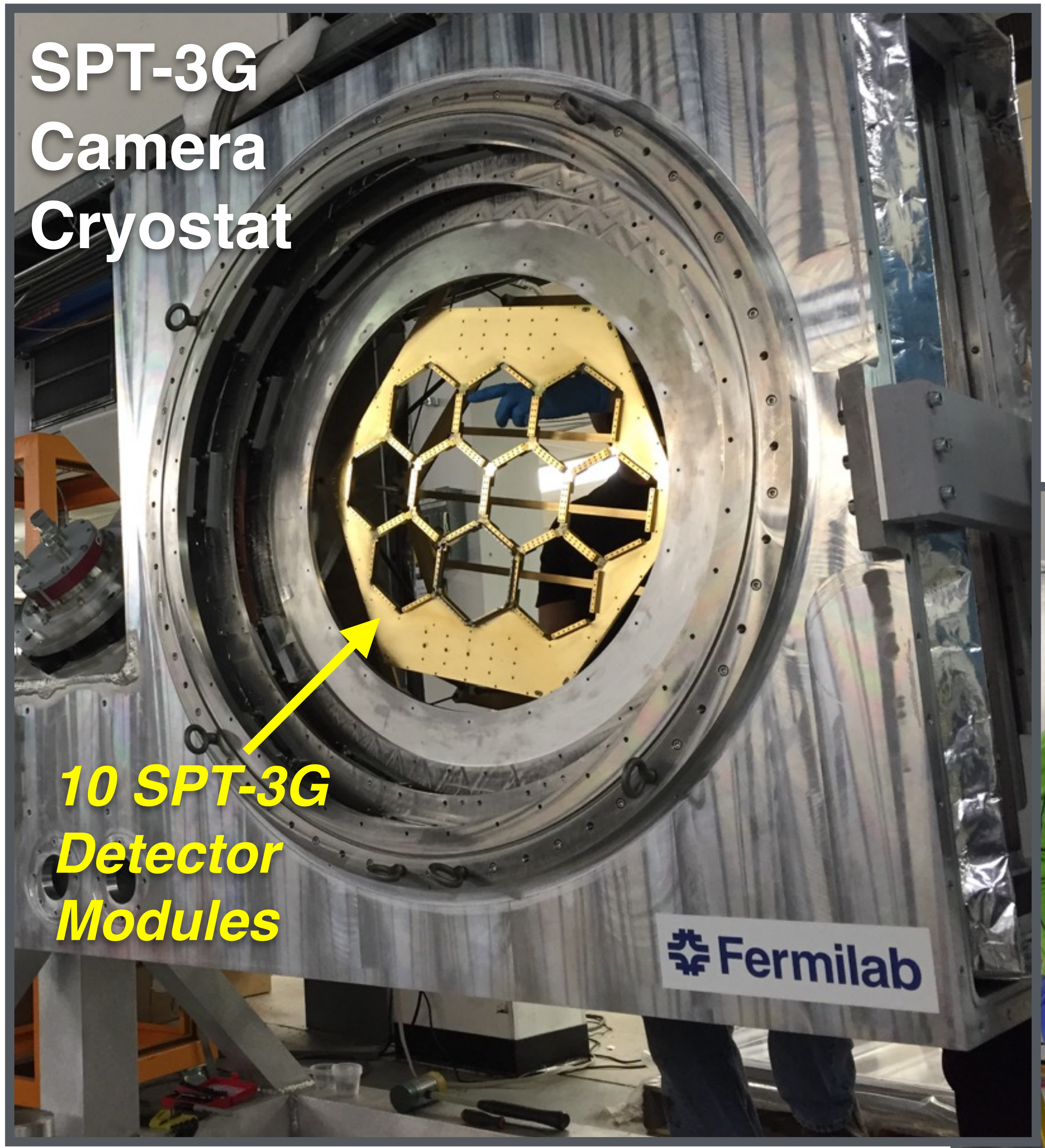


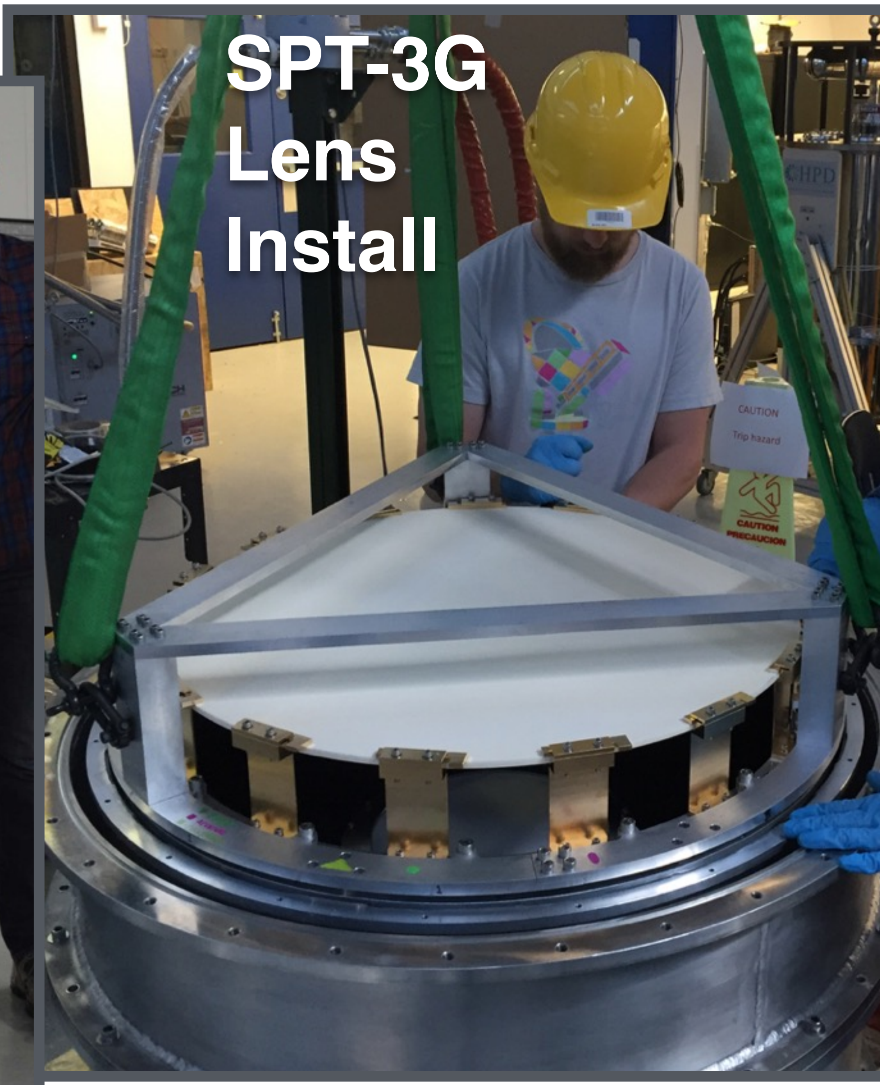
- ***Packaging SPT-3G detector wafers***
  - Precision alignment of detector and lenslet wafers
  - Over 60,000 wire-bonds on the SPT-3G focal plane (10 detector wafers and 120 boards of 136 LC channel)
  - Builds off experience and infrastructure on DES, DAMIC, CMS
- ***Detector Development & Characterization***
  - Microwave simulations
  - Cryogenic detector characterization
  - Multiplexed readout electronics development



Fermilab Roles on SPT-3G:
Receiver Design and Integration

- ***SPT-3G Camera Design and Integration***
  - Camera mechanical and cryogenic design:
    - Detectors cooled to 250 mK
    - Lenses (720 mm diameter) cooled to 4 K
    - Integrated camera nearly 2300 lbs, 8 feet long
  - Integration of the camera cryogenics, readout, and detectors at SiDet





CMB-S4
Next Generation CMB Experiment

Collaboration

- Community — university and labs — working well together on Science Book and on path toward instrumentation choices. Several science and technical working groups.

- Interactions with DOE through DOE's CMB Cosmic-Vision group. Working on R&D and Project timeline and budget. Goal is CD1 FY19 and CD2 FY20.

- DOE and NSF have begun discussions. NSF responds to proposals.

- Need to proceed with formation of formal collaboration and CMB-S4 project
  - addressing issues on nature of project organization
  - maintain constructive competition between sites?

- International partnerships in development: European partnership discussed at CERN CMB meeting last month. China IHEP pursuing Tibet site with possible partnership with BICEP/KECK and/or CMB-S4.

Last words

CMB-S4 is moving forward and will deliver great science aligned with DOE's HEP mission.

CMB-S4 results will complement and enhance FNAL's science program.

FNAL is positioned both scientifically and technically to make key contributions to CMB-S4.

FNAL contributions key to scaling up to CMB-S4.

CMB-S4
Next Generation CMB Experiment

extra slides

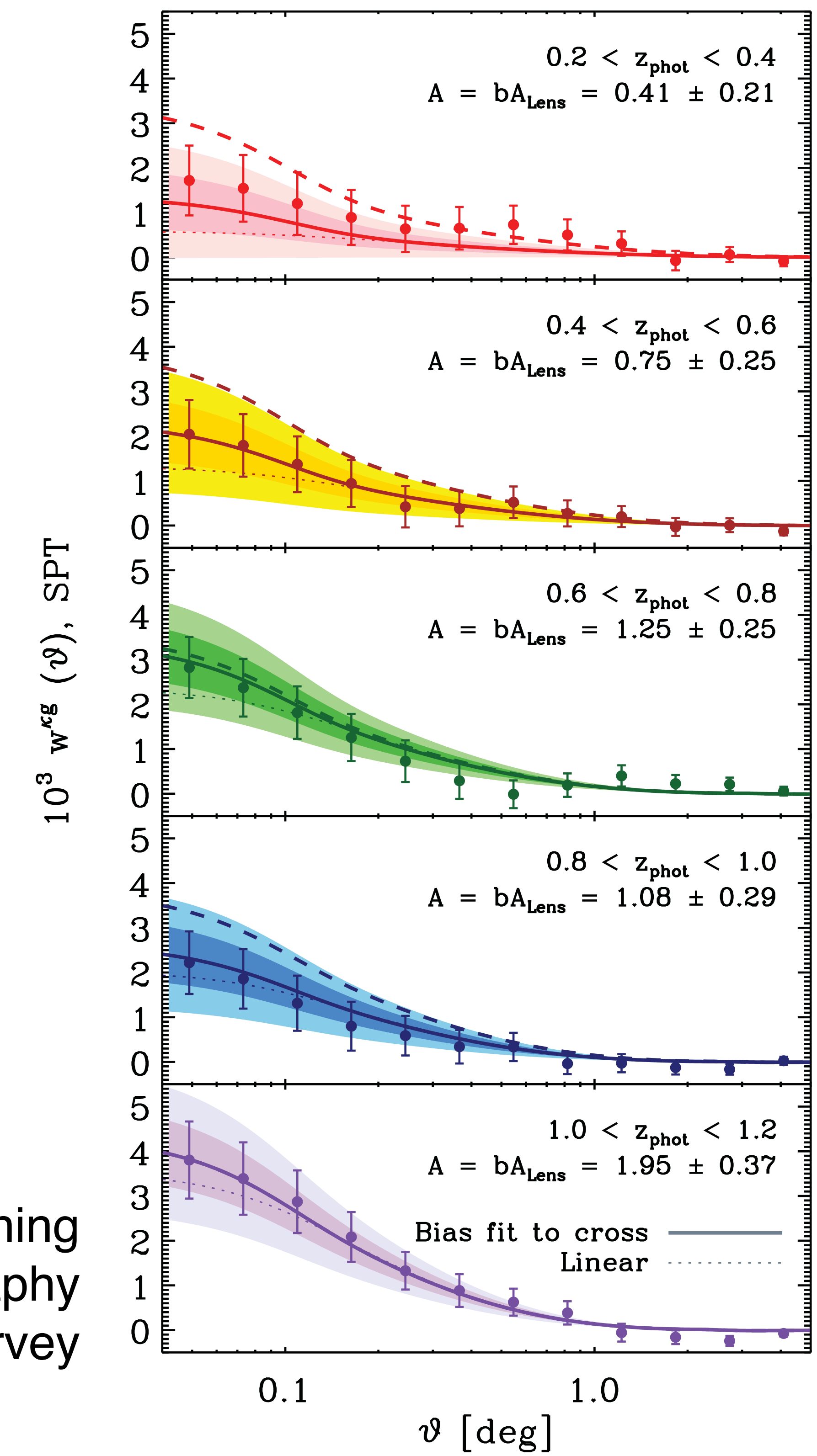
CMB-S4
Next Generation CMB Experiment

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)

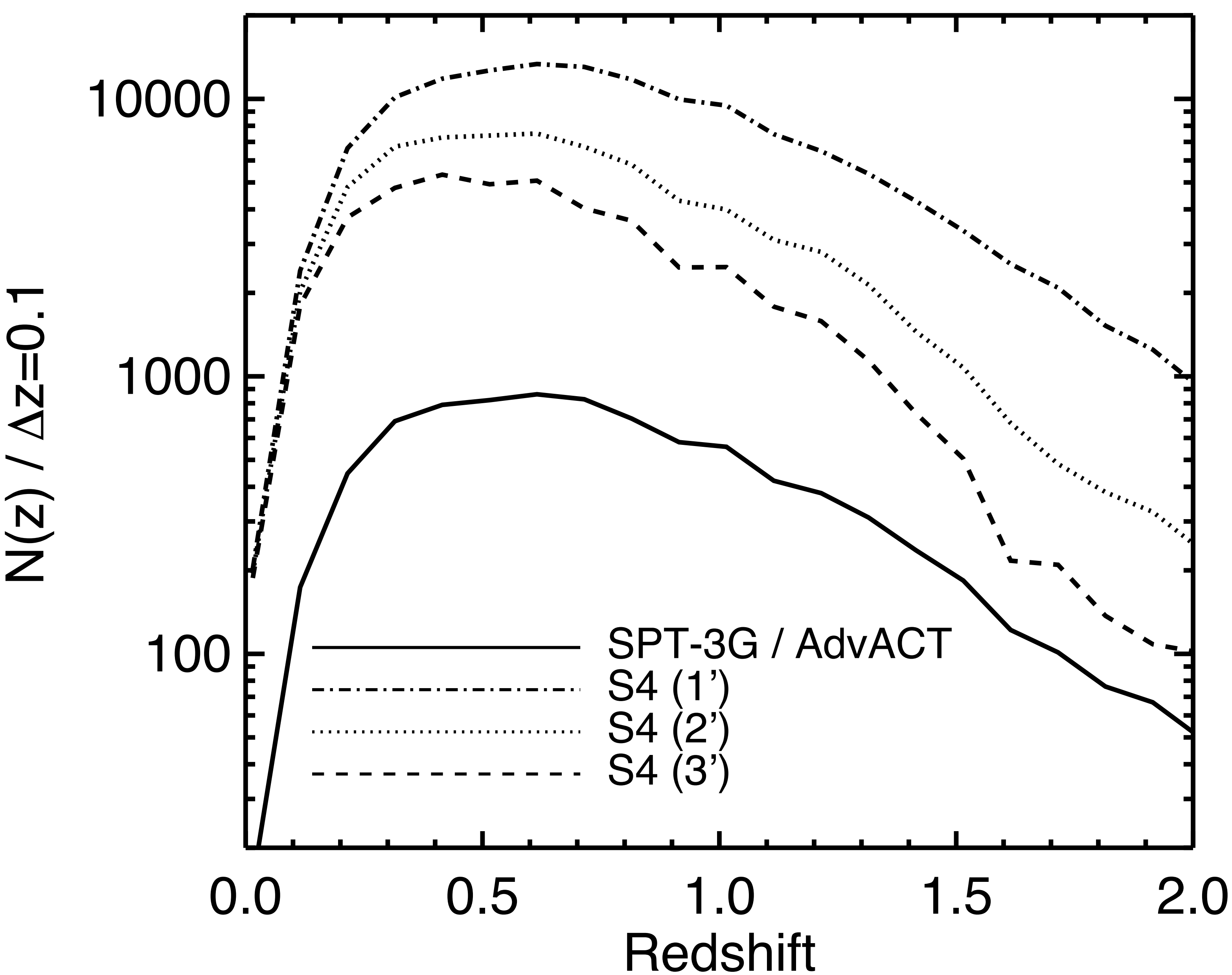
Galaxy and CMB-lensing cross-correlation



Giannantonio et al., 2016

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

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

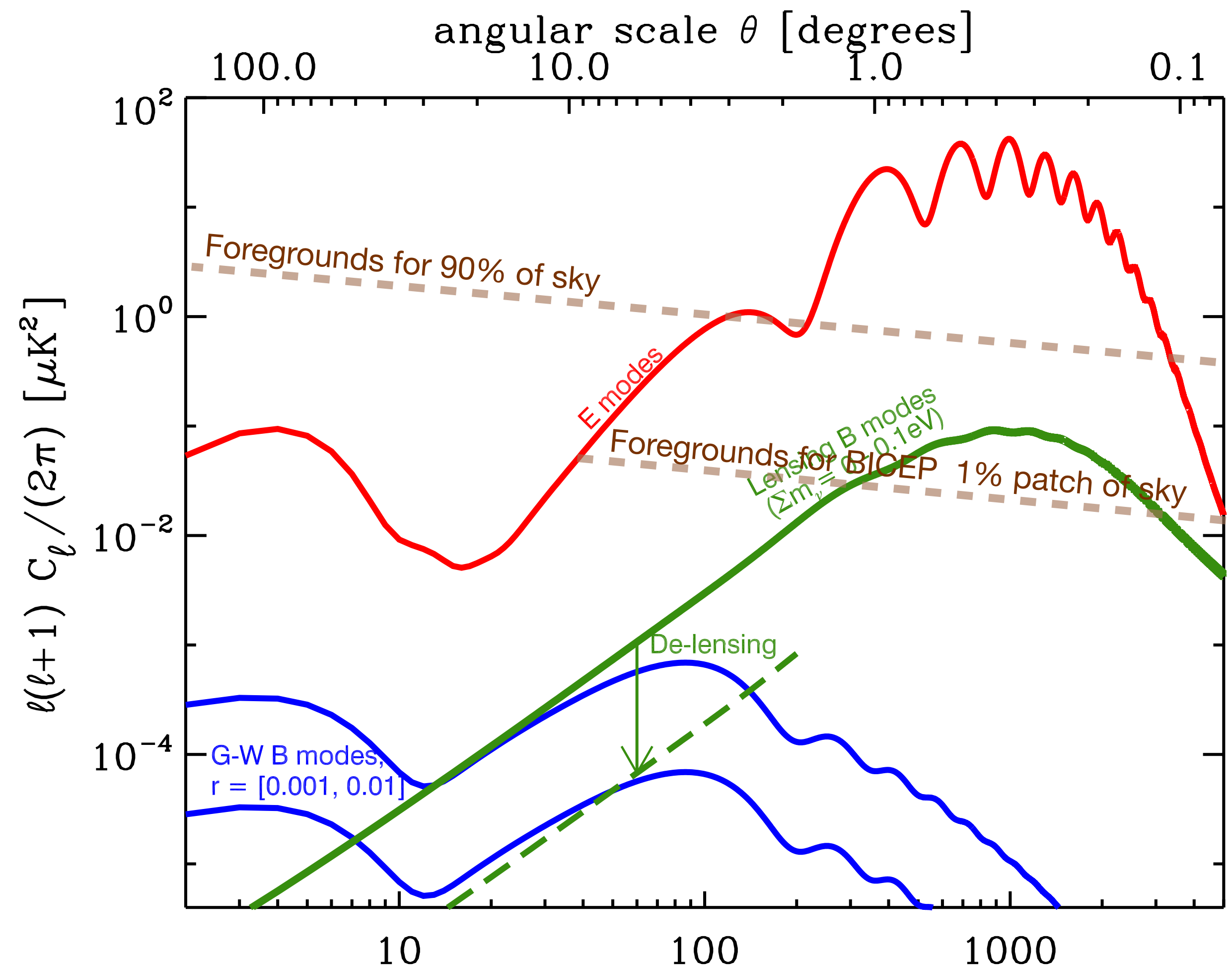
CMB-lensing cluster mass scaling !
$\sigma(M) \sim 2e13$ at $z > 1$ per 1000 clusters

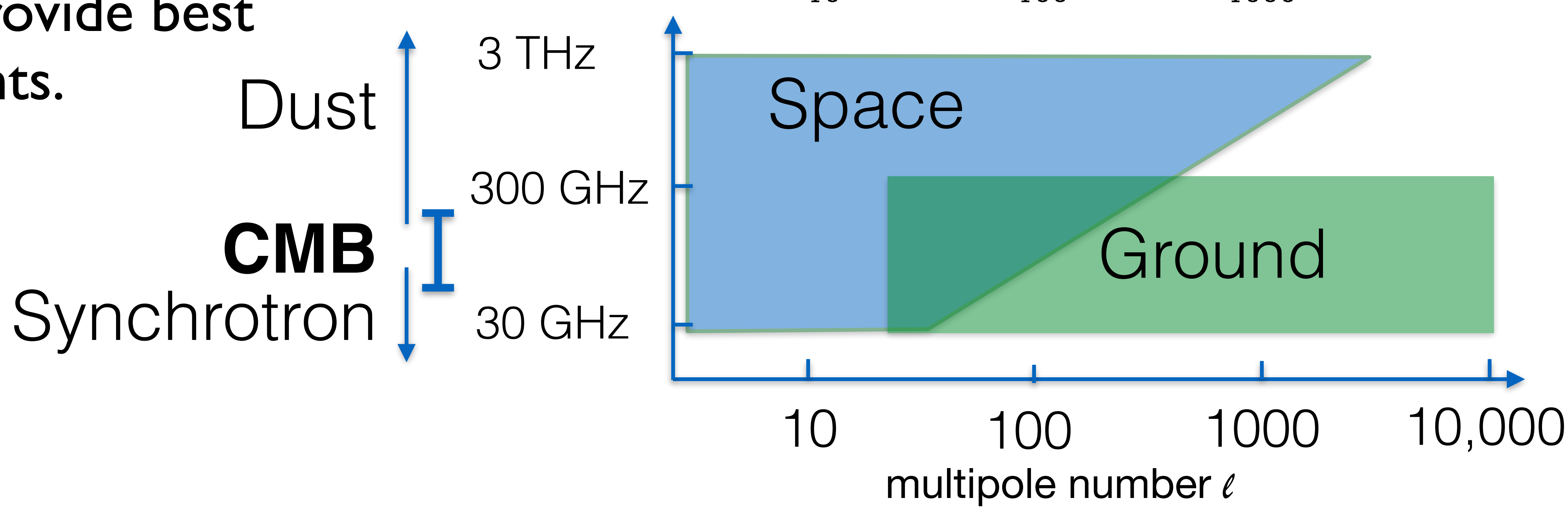
Projection B. Benson

CMB-S4
Next Generation CMB Experiment

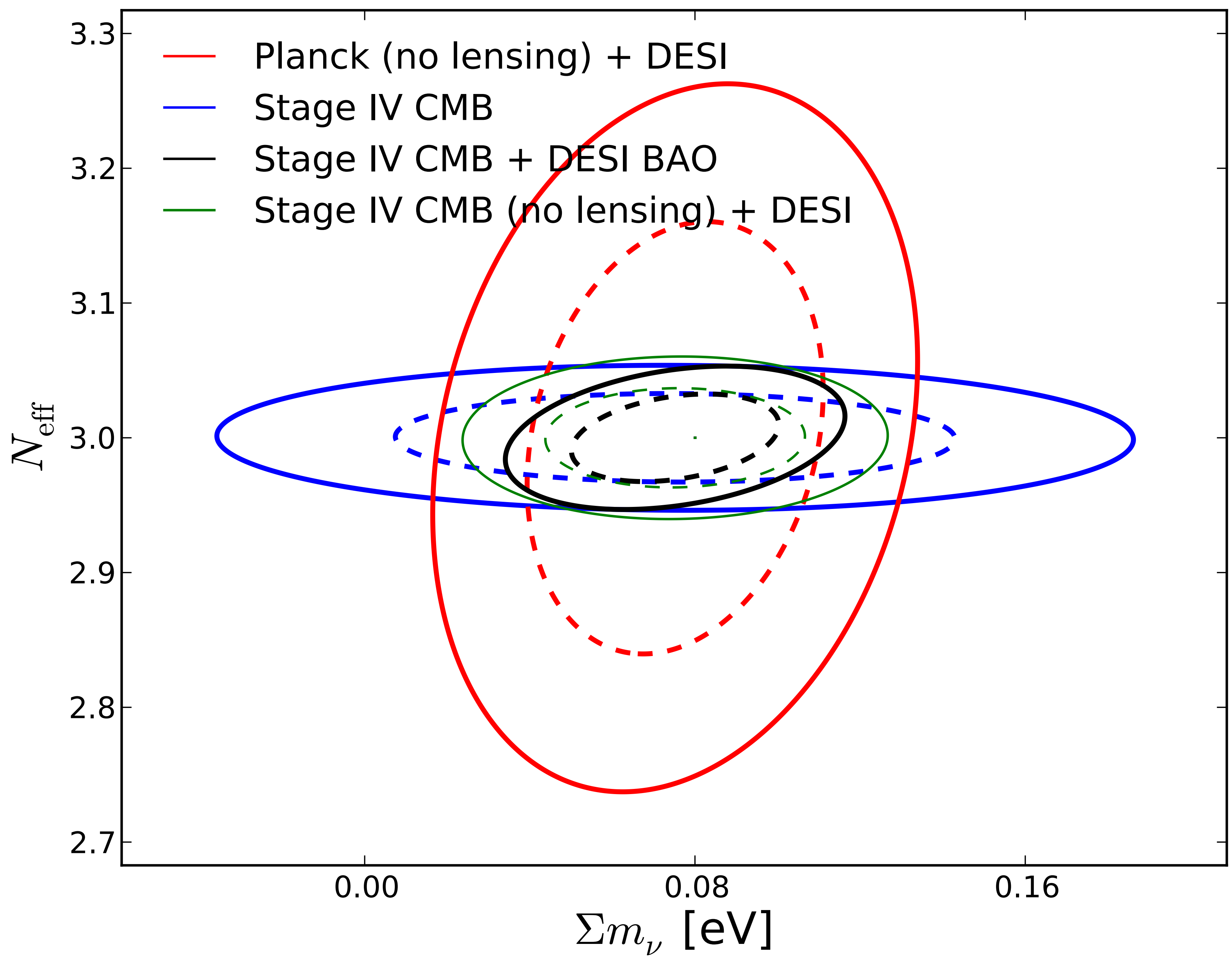
Complementary strengths of ground and space

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





Snowmass CMB-S4 N_{eff} - Σm_ν constraints



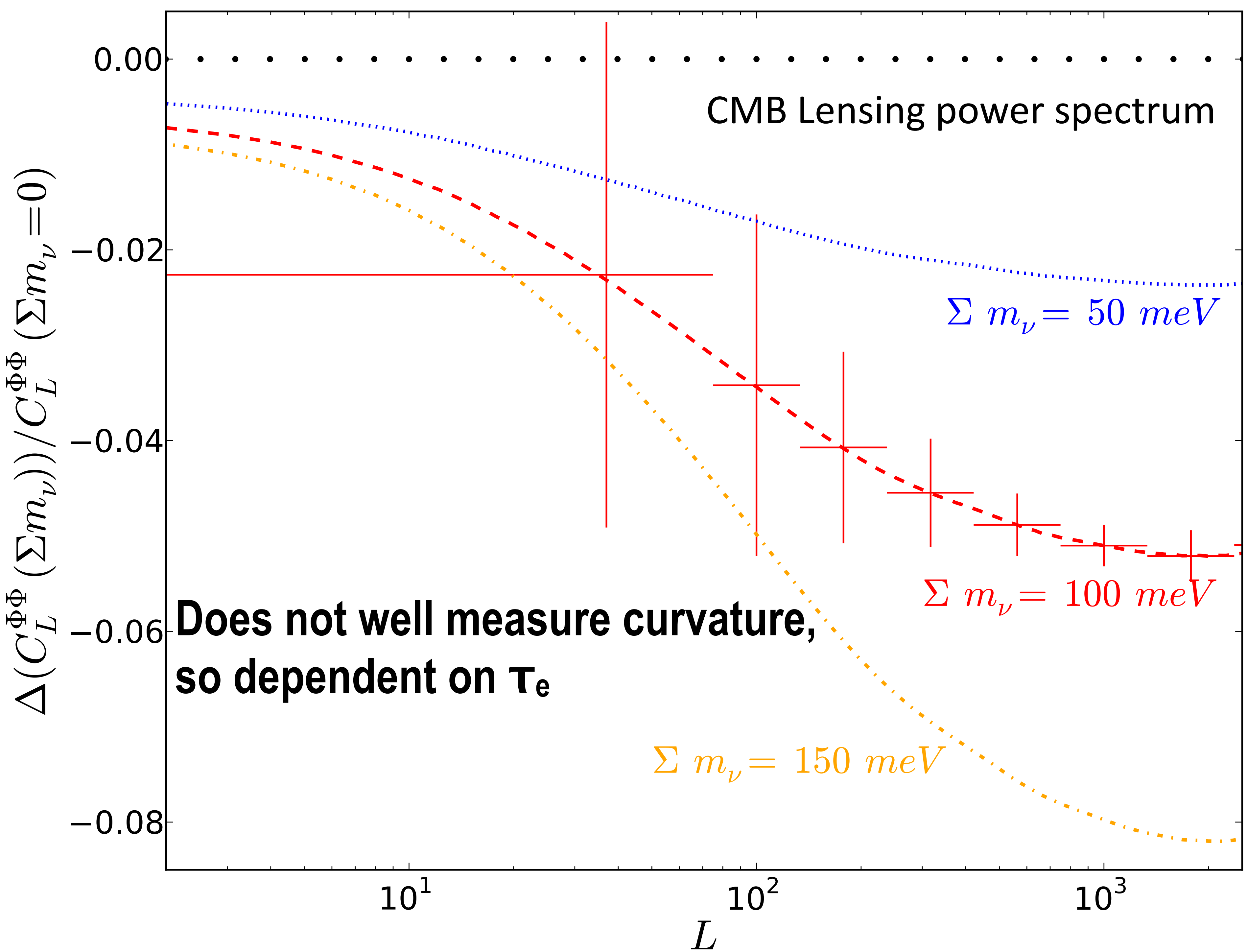
$\sigma(\Sigma m_\nu)$ = 15 meV (with DESI BAO)

$\sigma(N_{eff})$ = 0.020

CMB uniquely probes N_{eff}

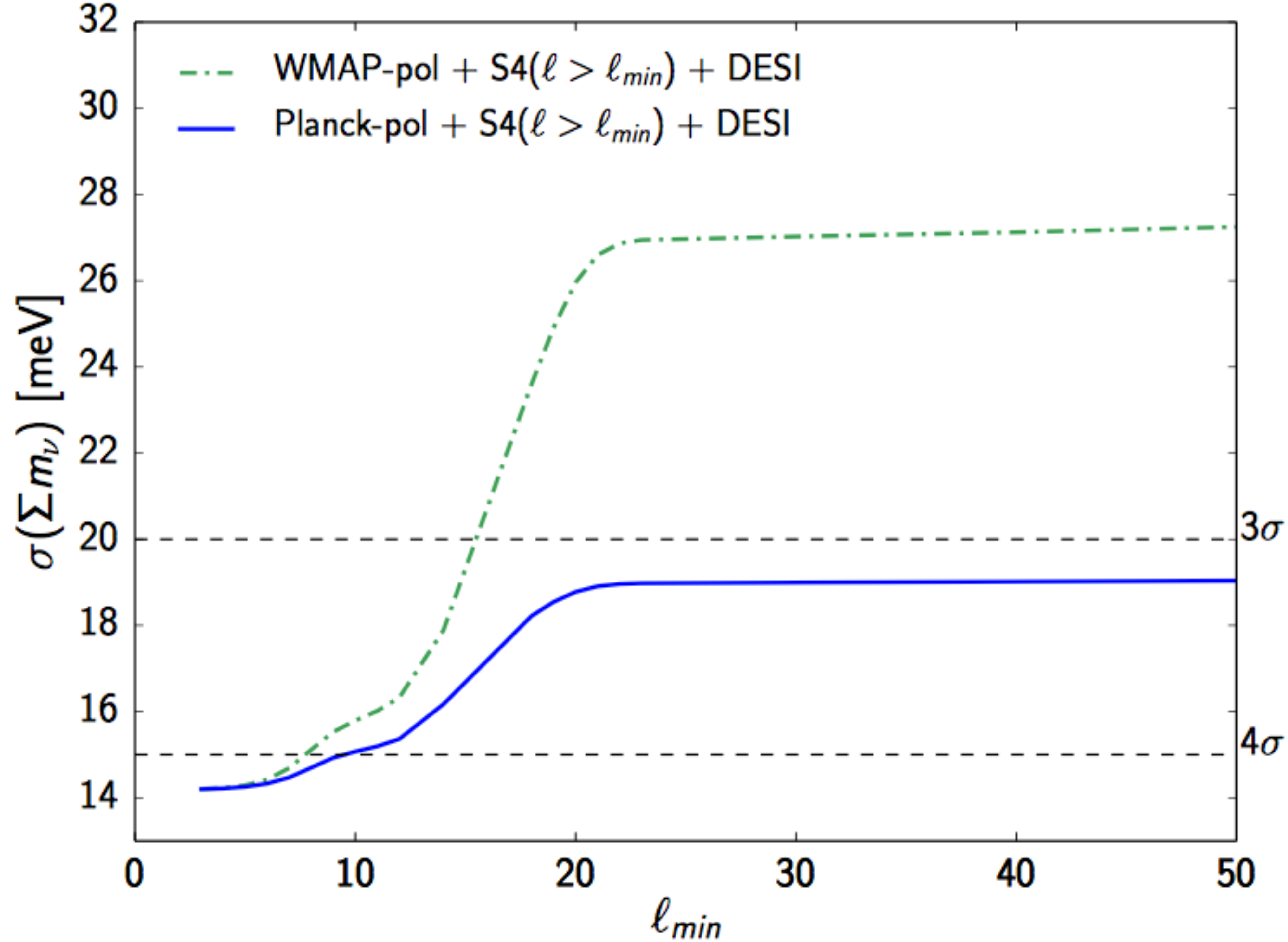
CMB-S4 forecast: arXiv:1309.5383; see also Wu et al, ApJ 788,138 (2014)

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

"Pessimistic" ν degeneracy forecasts

Allison et al., 1509.0747

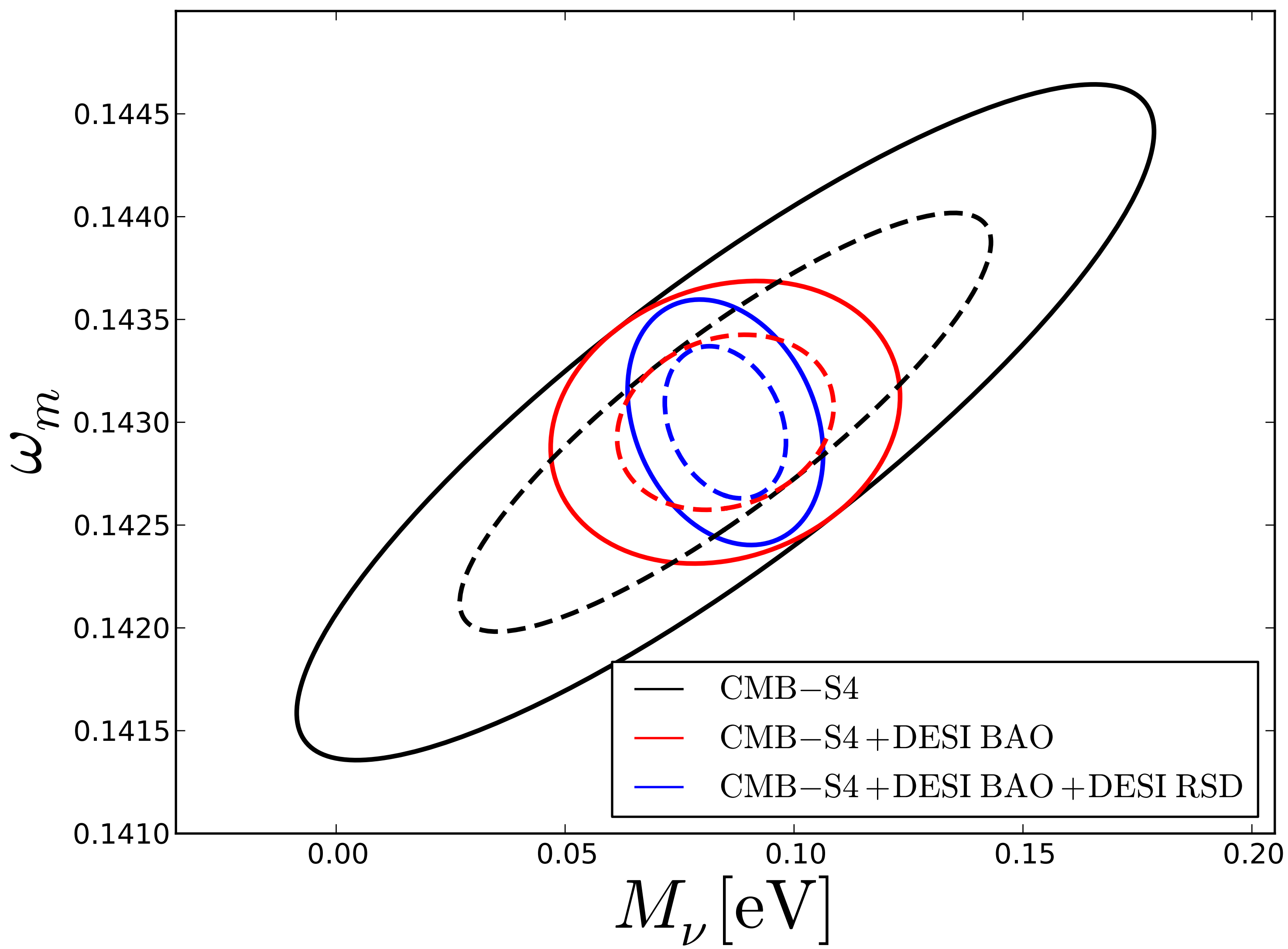
for CMB-S4 (3 arcm res, $\ell > 20$) + DESI BAO:

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

but, we break these degeneracies with other probes

“Optimistic” ν forecasts

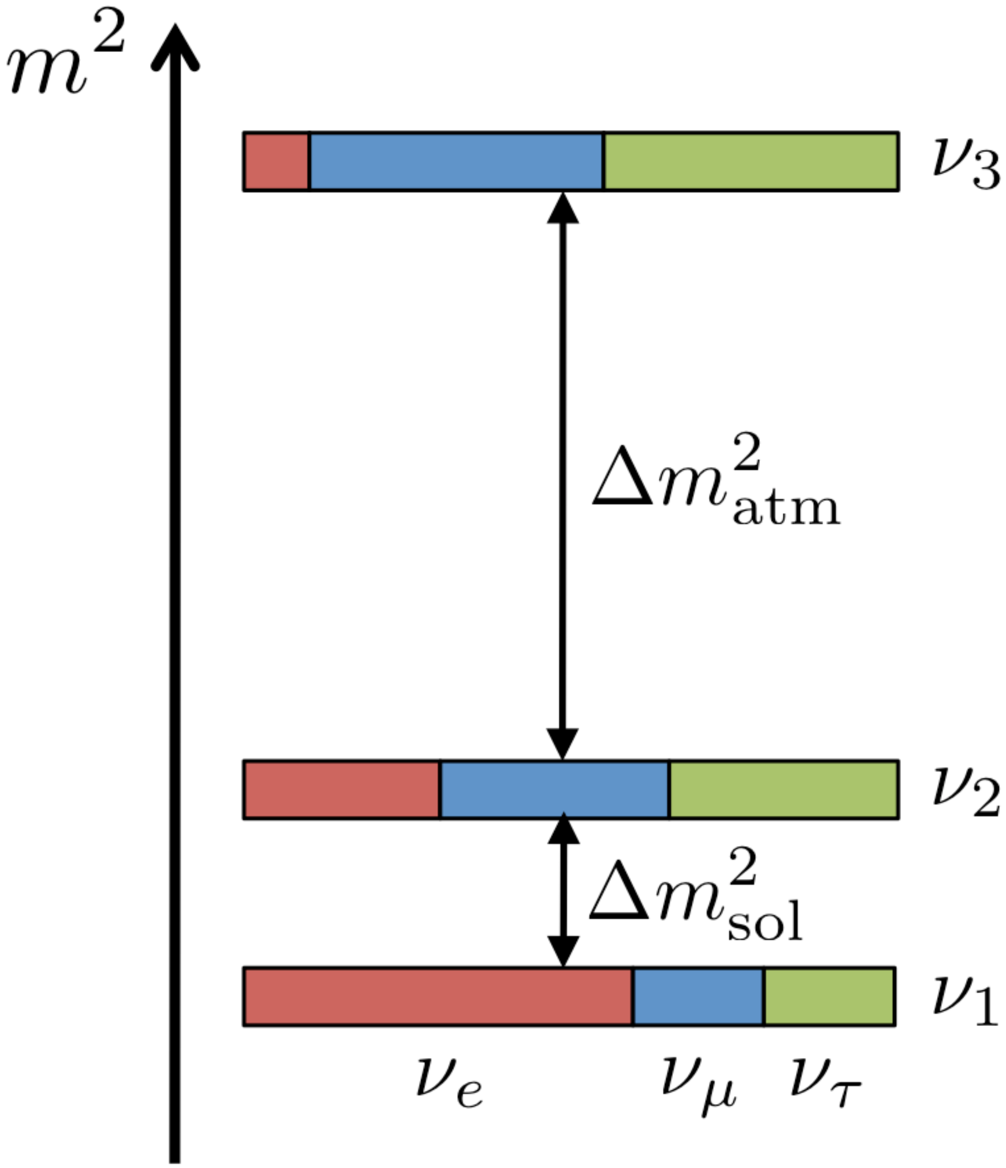
Pan & Knox 1506.07493



Σm_ν = 9 meV (ΛCDM + Σm_ν)

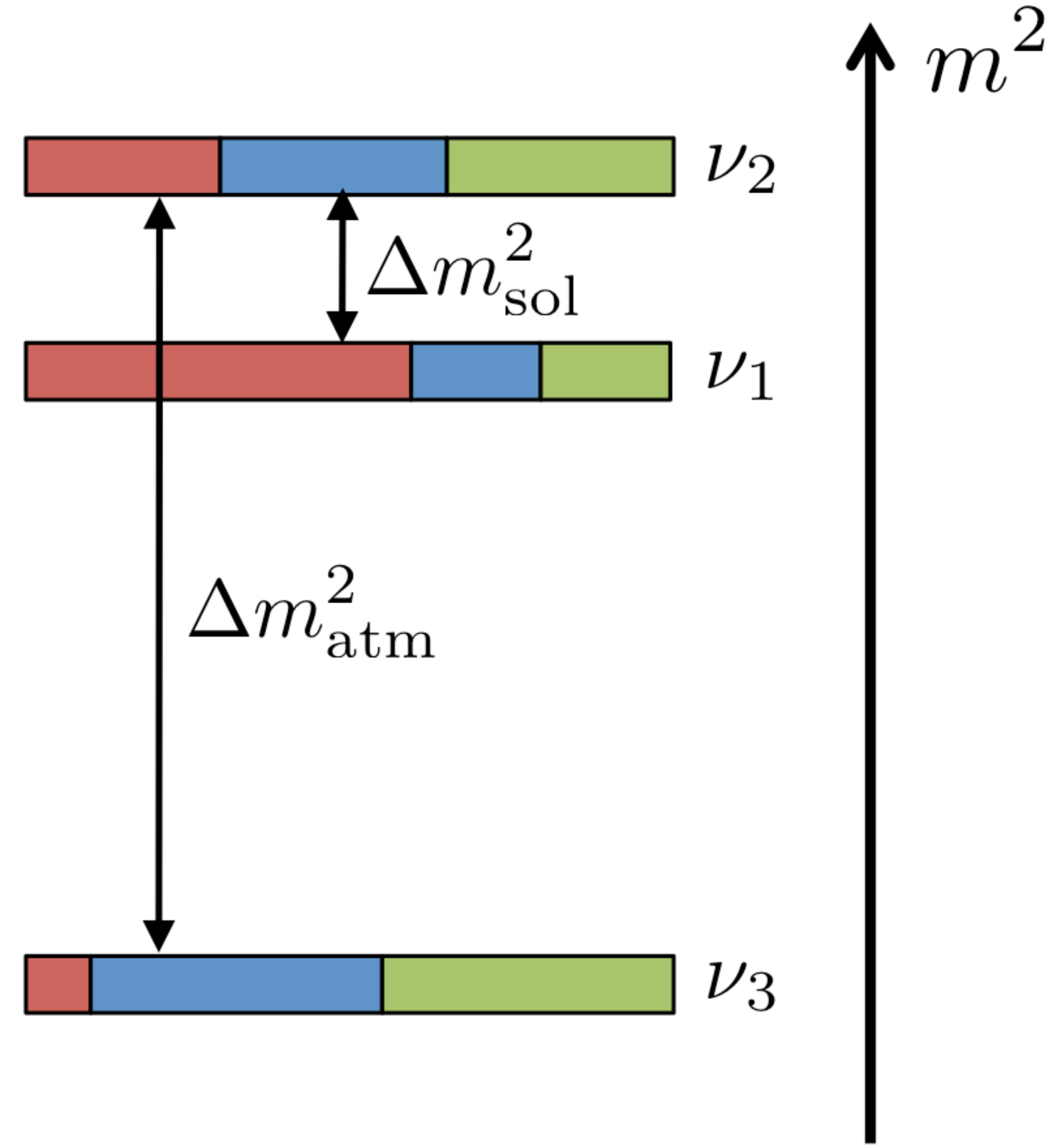
for CMB-S4 (ℓ > 5) + DESI BAO + DESI RSD

normal hierarchy (NH)



$\sum m_\nu \geq 58$ meV

inverted hierarchy (IH)



$\sum m_\nu \geq 100$ meV

Complementarity of Neutrino mass constraints

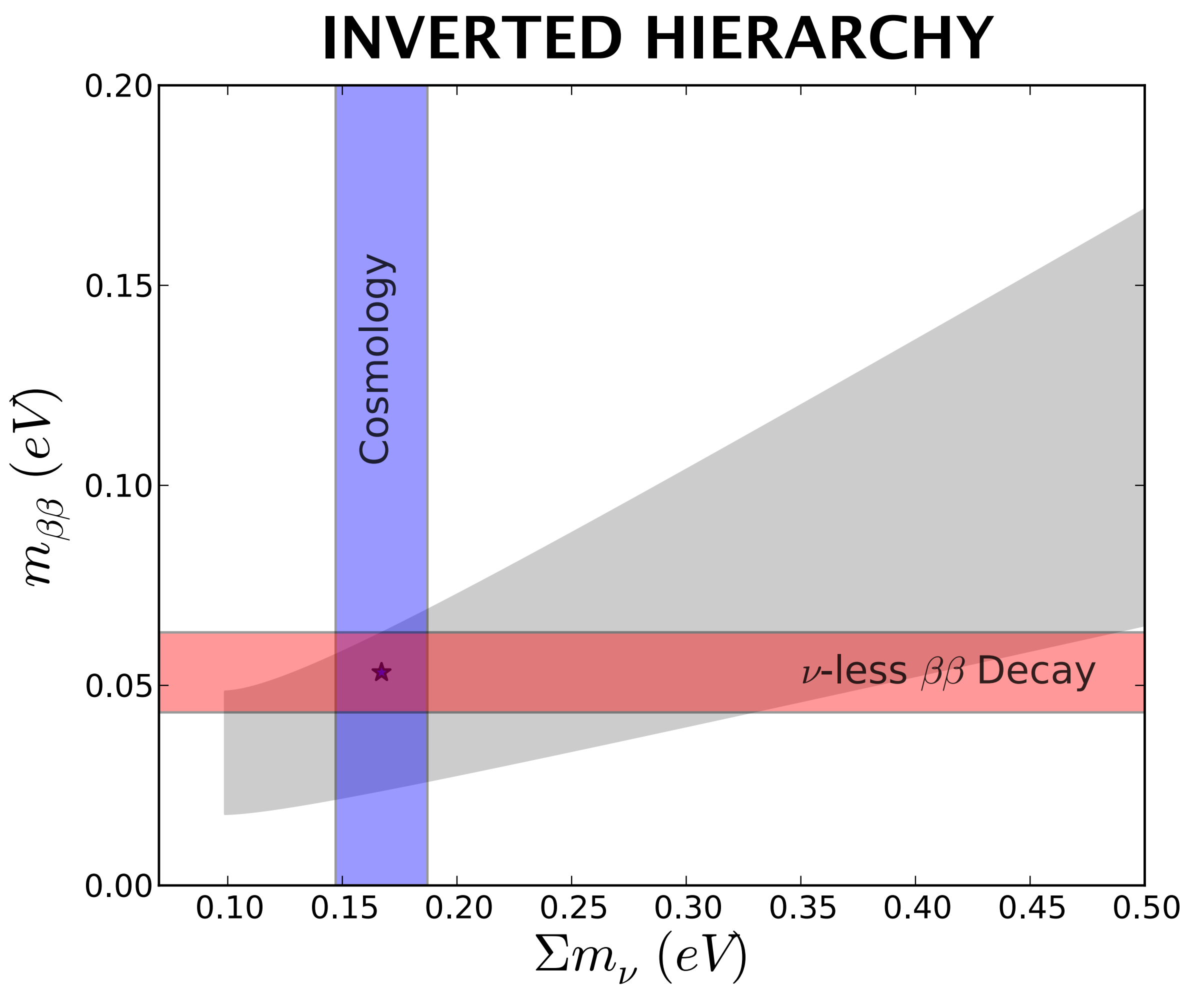


FIG. 1: Projected constraints on neutrino parameters from upcoming cosmic surveys (vertical), neutrino-less double beta decay experiments (horizontal), and all other current measurements (gray) assuming an inverted mass hierarchy and Majorana neutrinos.

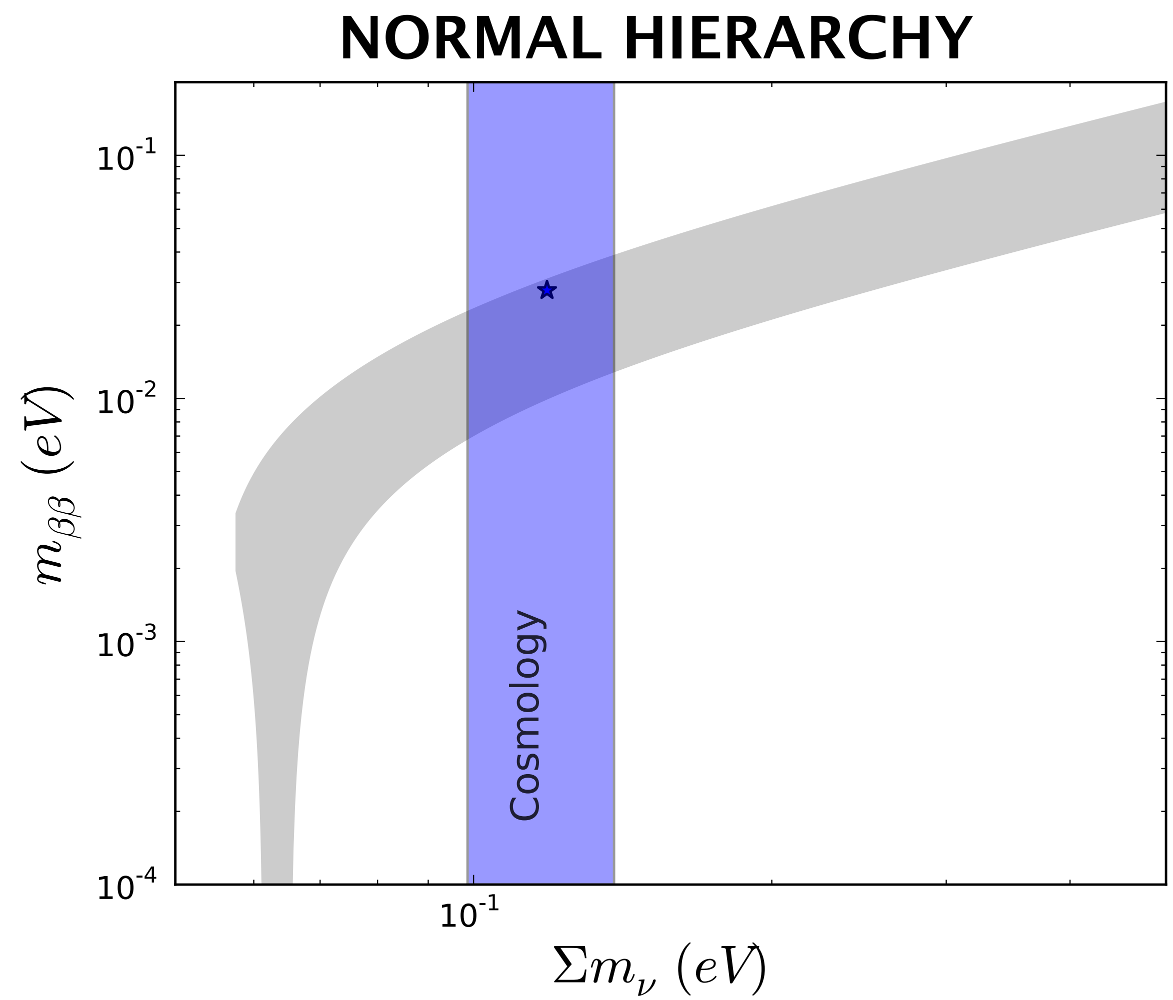
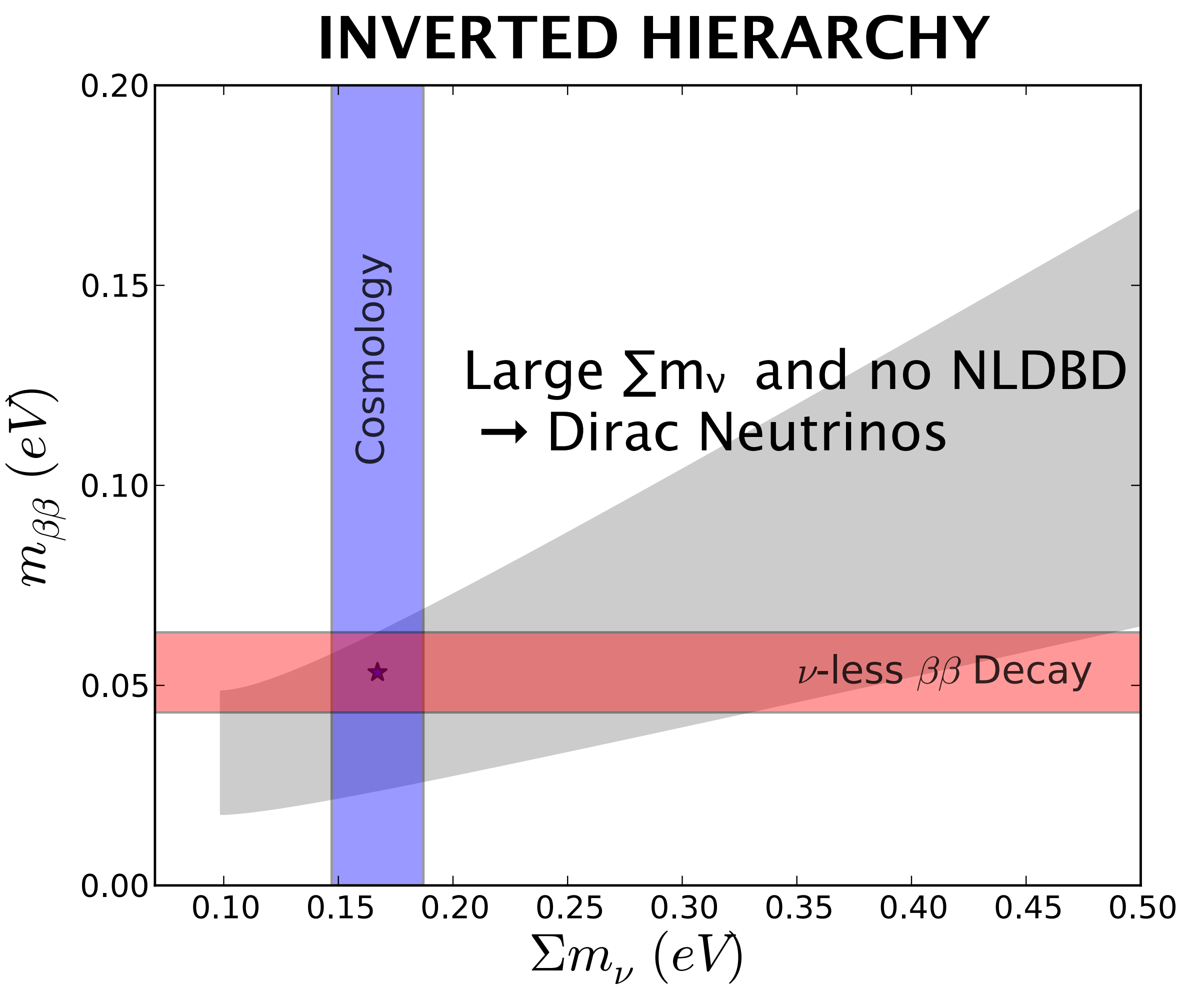


FIG. 3: If the mass hierarchy is normal but the sum of the masses is still relatively large, for example at the value indicated by the star, then there will be a lower limit on $m_{\beta\beta}$, a target for ambitious future double beta decay experiments.

Dodelson and Lykken arXiv:1403.5173

Complementarity of Neutrino mass constraints



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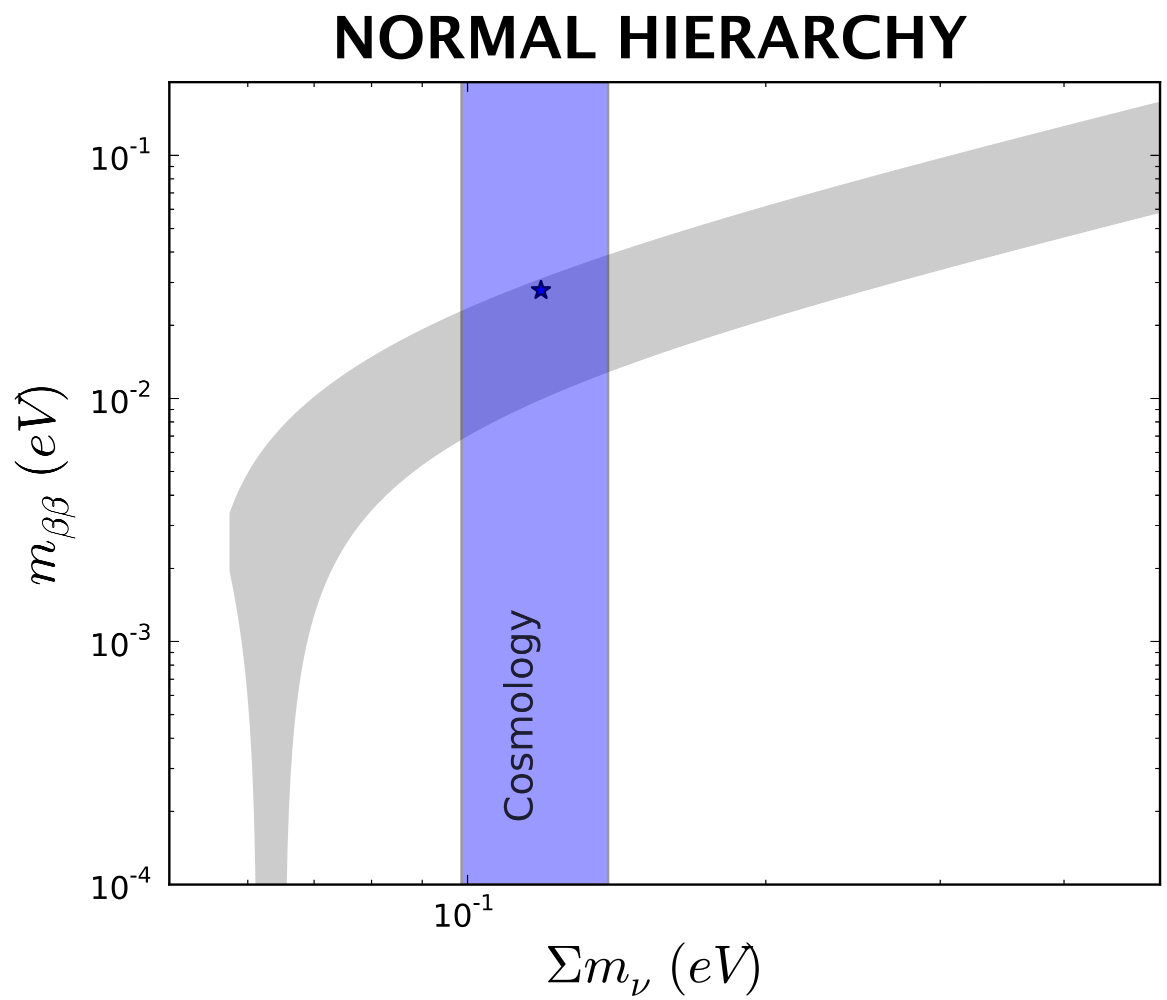

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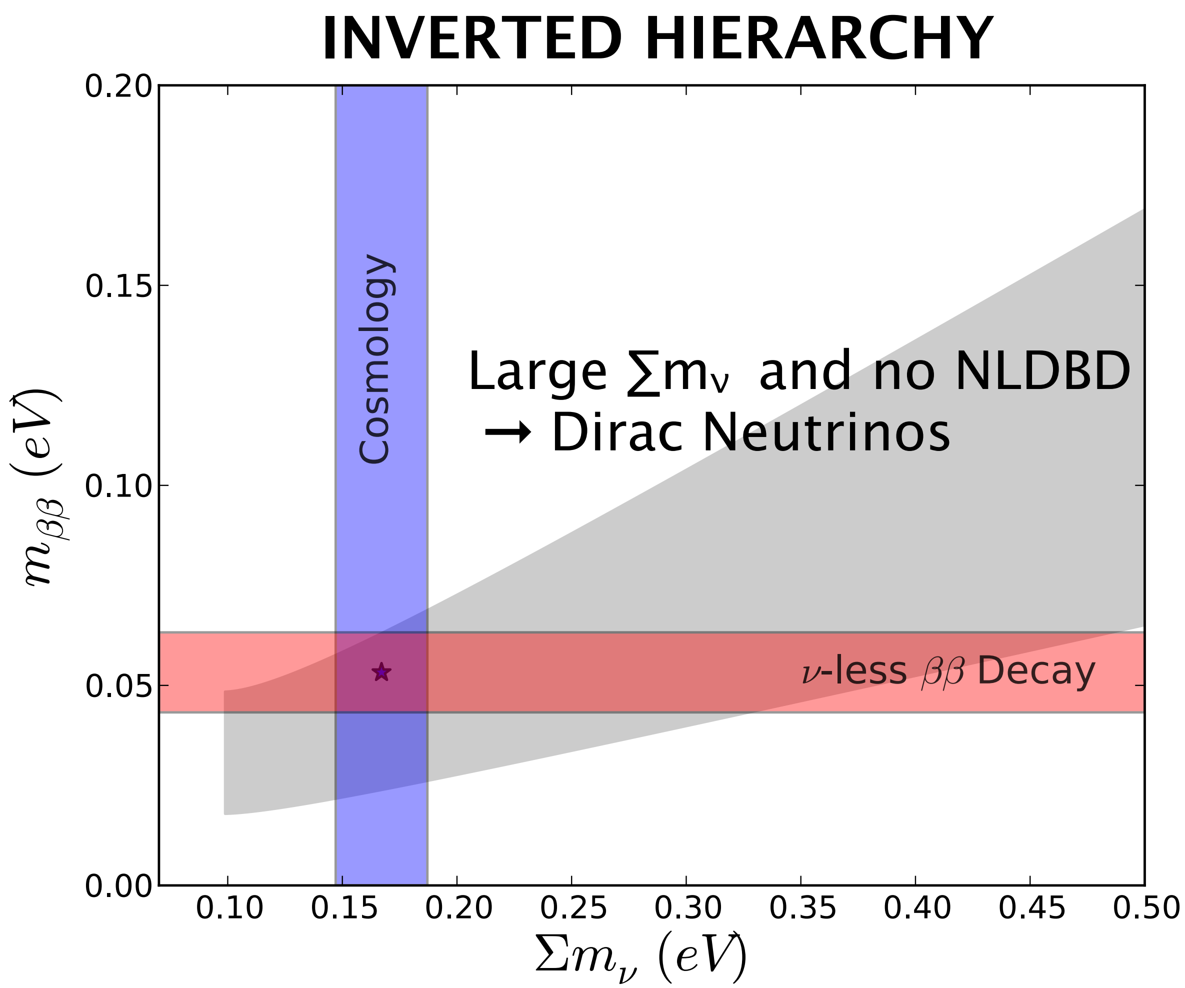

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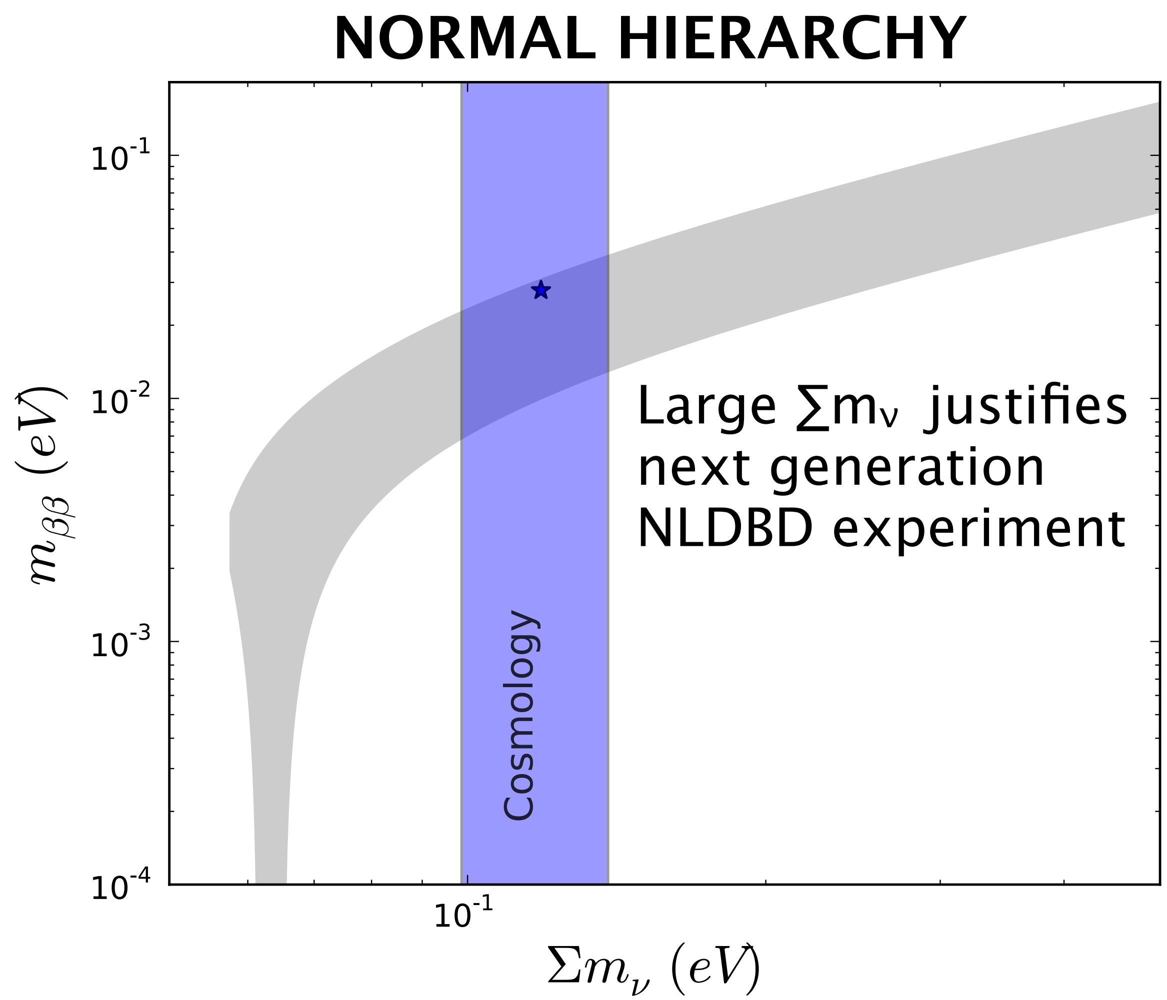

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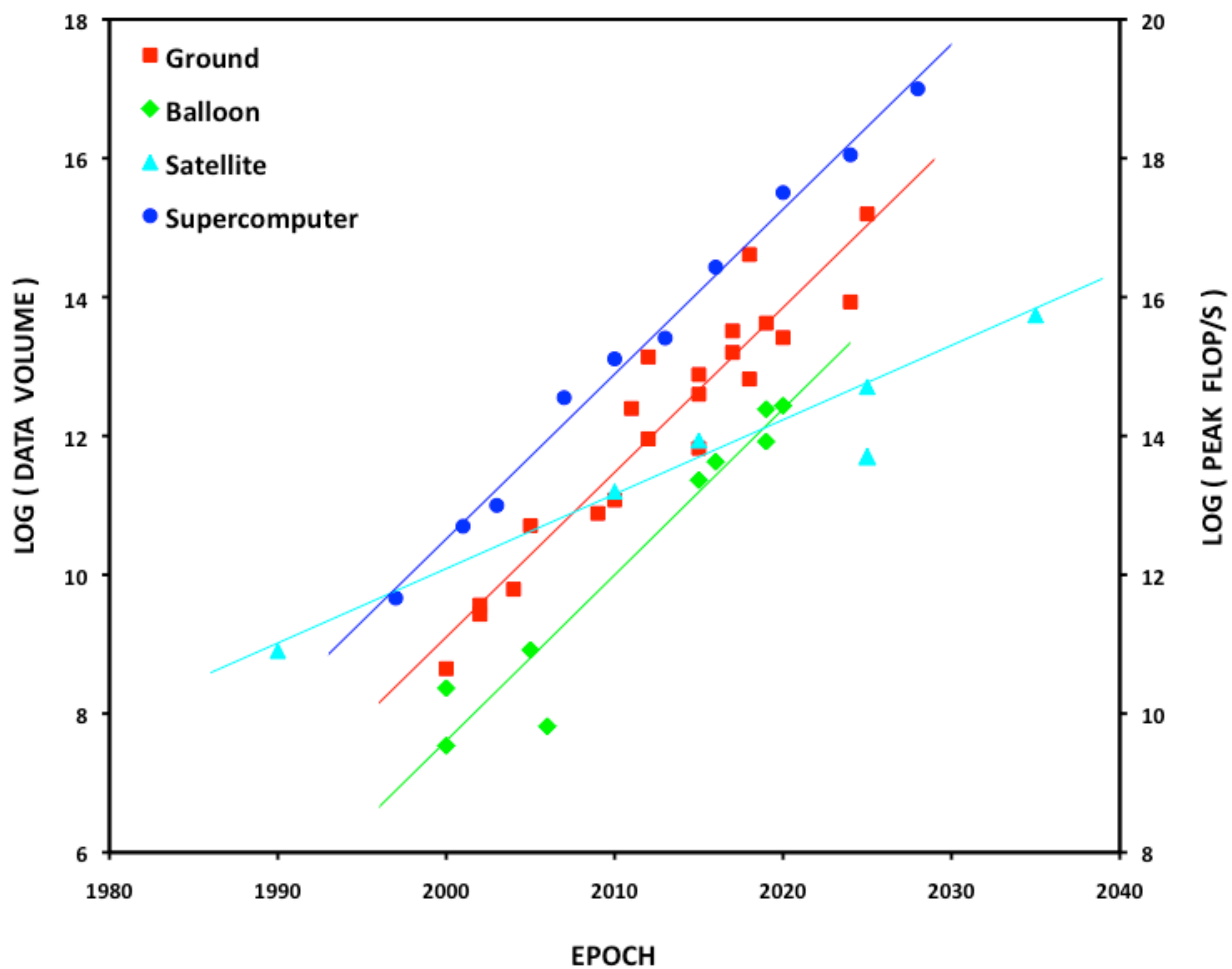
Big Data & High Performance Computing



Exponential data growth tracking Moore's Law

P5 timeline

CMB-S4 ramps up as LSST ramps down