CMB-S4

Next Generation CMB Experiment

John Carlstrom
on behalf of CMB-S4 collaboration

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 from Stage 3 to cross critical science thresholds.
- O(500,000) 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 experiments, National Labs and the High Energy Physics community. International partnerships expected and desired.

Recommended by P5 & NRC Antarctic reports

Year	Stage	Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	D.E. F.O.M
2015–2016	Stage 2 1000 detectors	$\gtrsim 10^{-5}$	0.03	0.14	0.15eV (Boss BAO prior)	~180 (DES+BOSS / SZ clusters)
2017–2020	Stage 3 10,000 detectors	10^{-6}	$\lesssim$0.005	0.06	0.06eV (Boss BAO prior)	~300-600 (DES + DESI / SZ Clusters)
2021–2024?	Stage 4 CMB-S4 ~500,000 detectors	10^{-8}	~0.0005?	$\lesssim$0.02	0.015eV (DESI BAO prior)	~1250 (DESI +LSST / S4 Clusters)

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Measurements needed

- Science goals require much improved CMB polarization and CMB-lensing
  - Inflation: B-mode polarization and de-lensing
  - Neutrinos: N_{eff} or "dark radiation" requires de-lensed polarization spectra; $\sum m_\nu$ requires CMB-lensing (and τ_e).
  - Dark Energy: Galaxy survey correlation with CMB-lensing; SZ cosmology from high-ℓ TT with CMB-lensing mass calibration

- and CMB-lensing requires much improved CMB polarization.

→ we need CMB polarization!

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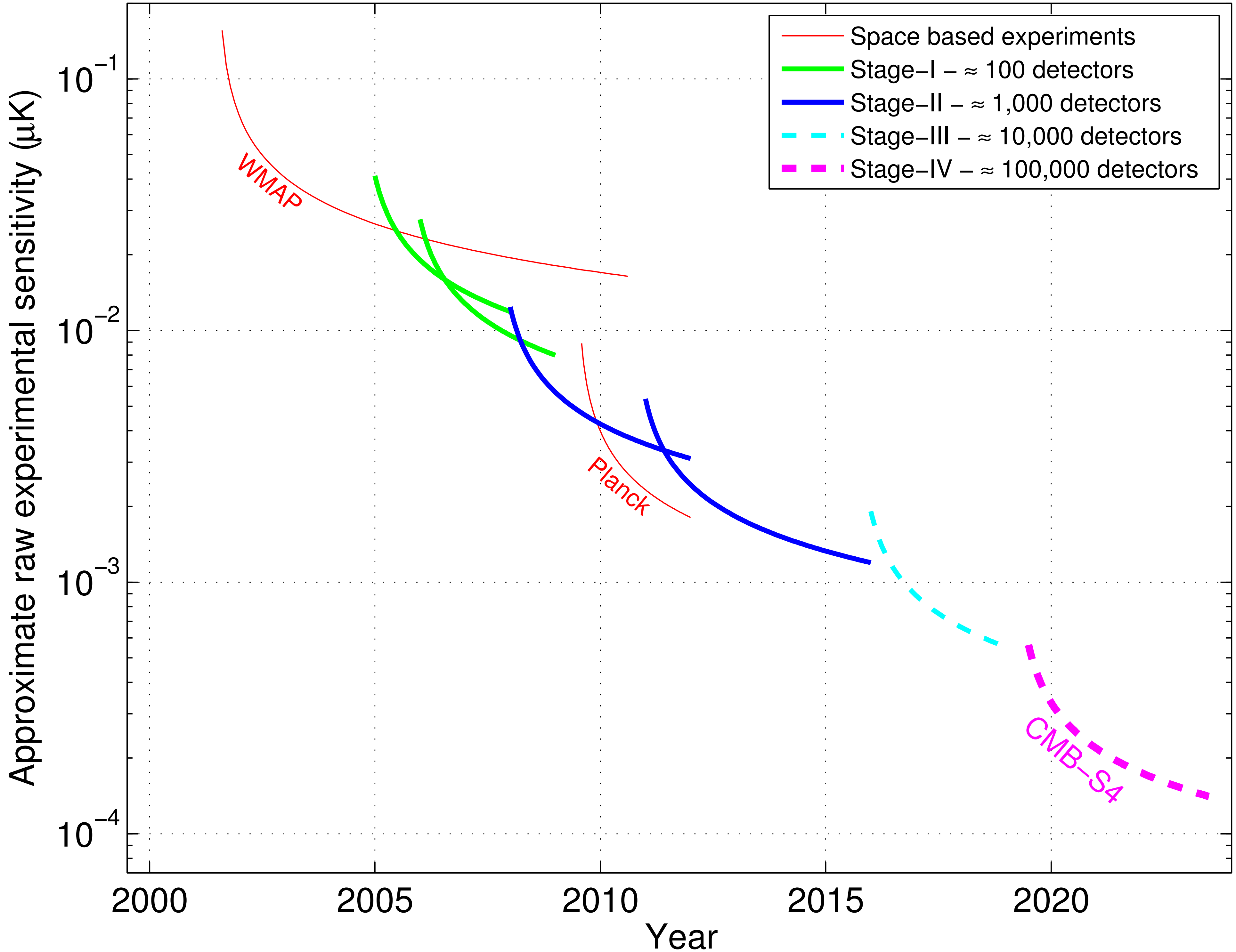
Detectors are a big challenge,



but it will take much more to achieve our goals.

What's needed to realize CMB-S4

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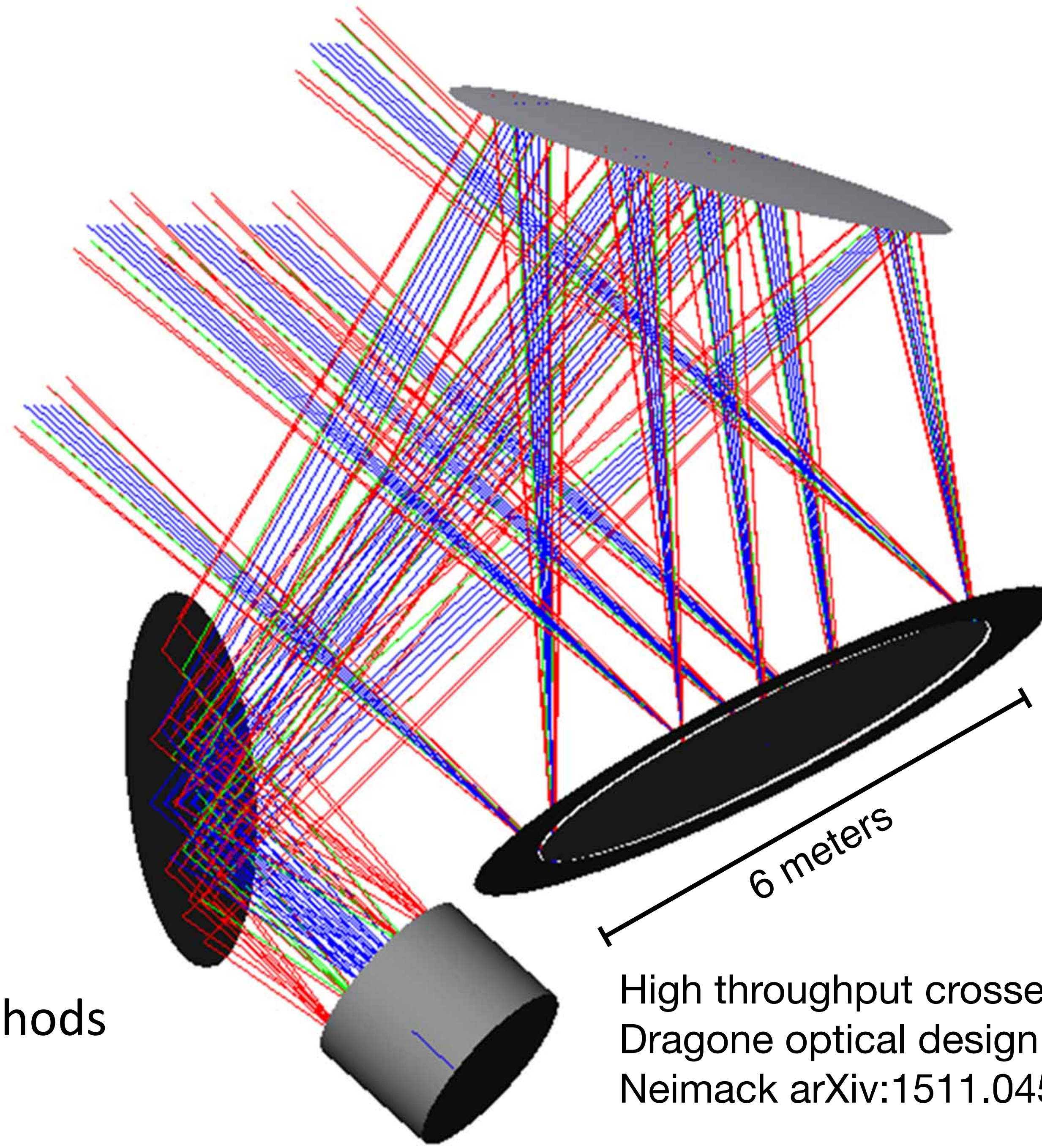
Next Generation CMB Experiment

- **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



High throughput crossed Dragone optical design. Neimack arXiv:1511.04506

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

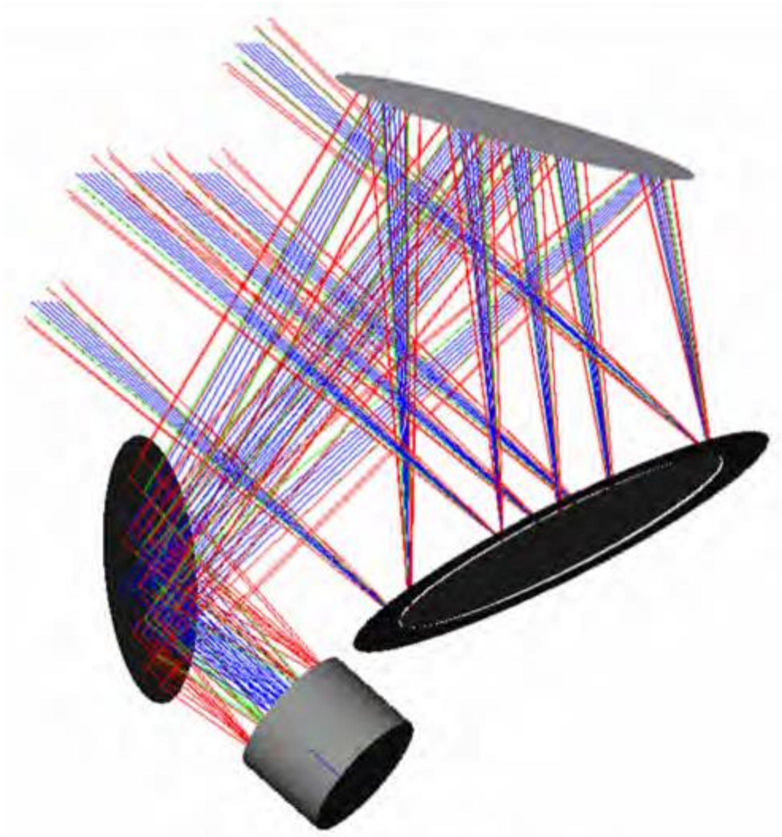
→ Partnership of CMB community and National labs will do it.

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
- ***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

CMB-S4 Collaboration Workshop Participants



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

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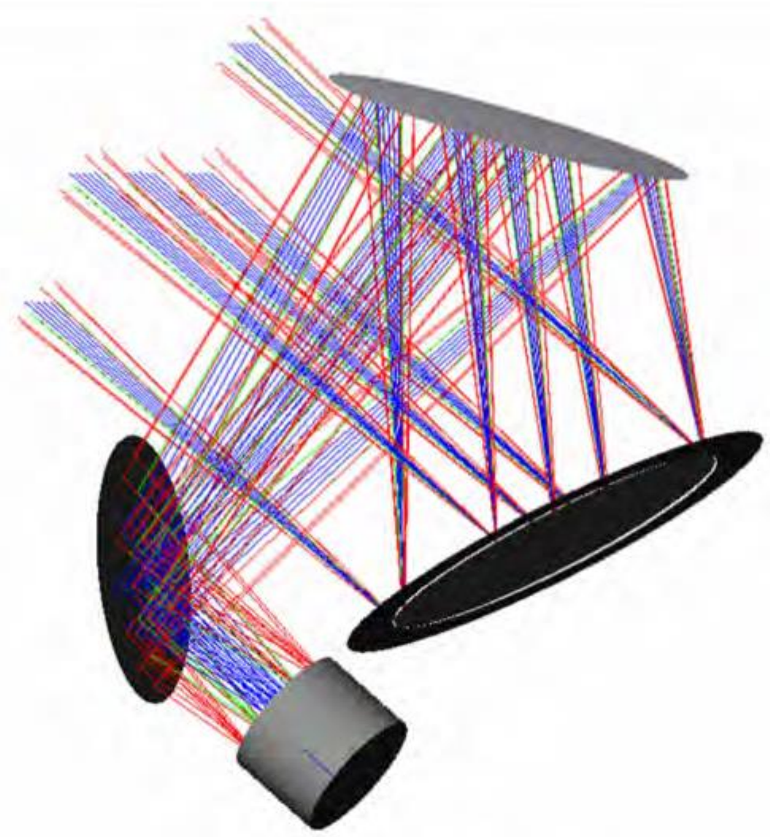

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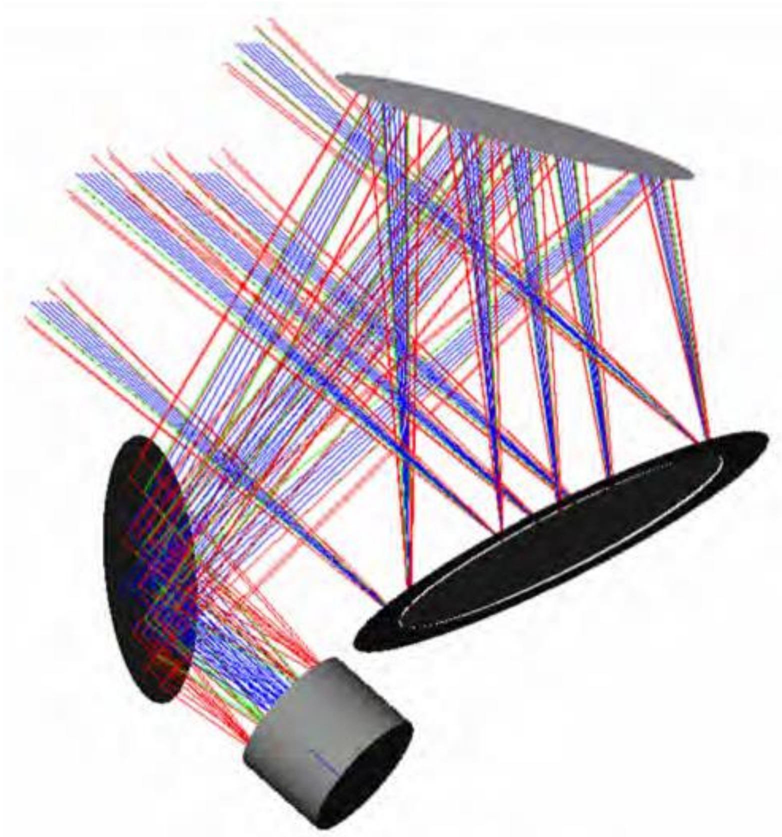
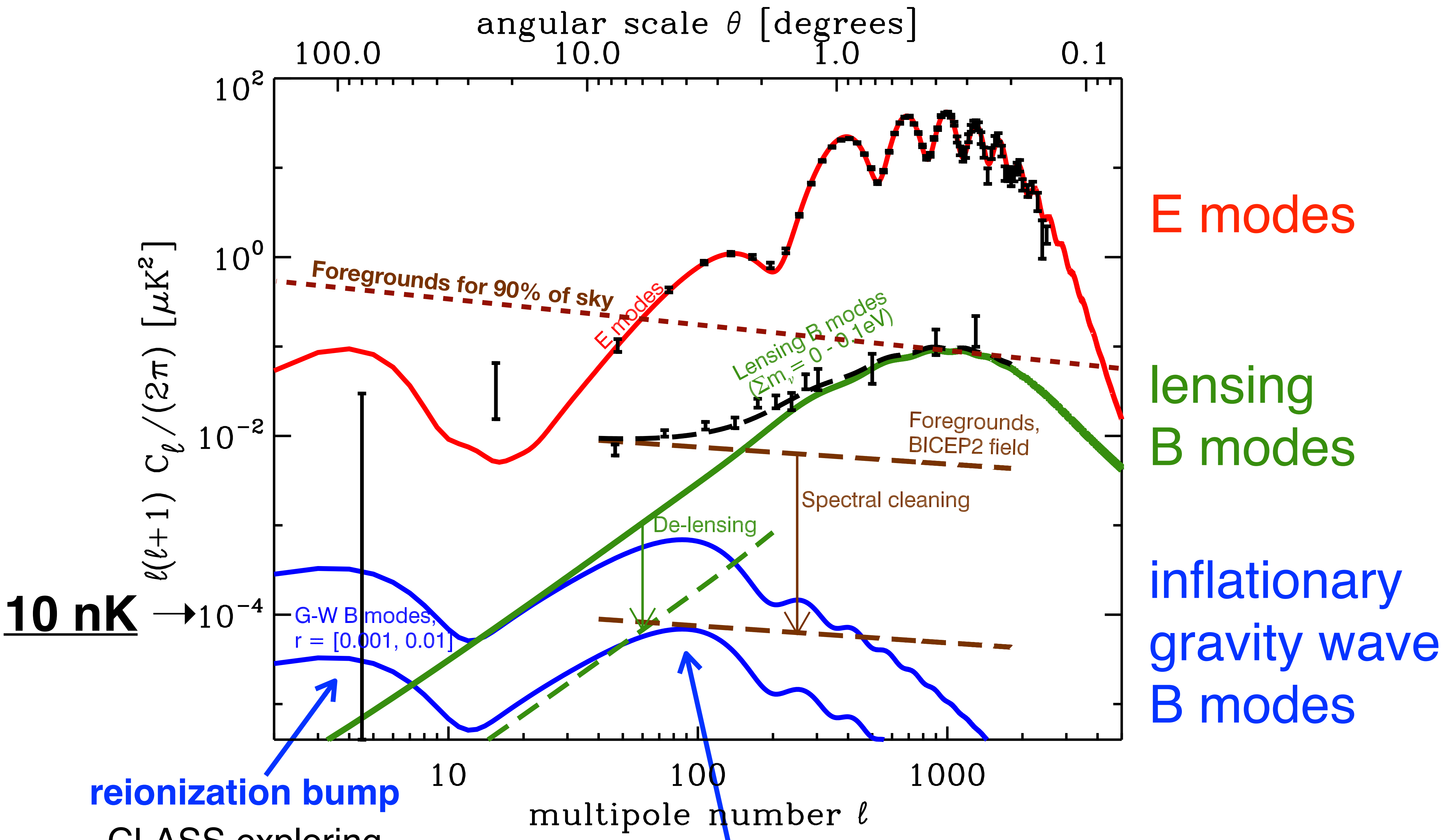


Prototype Large Aperture Telescope design with 10x mapping speed improvement (Niemack 2016)

Polarization status and future challenge

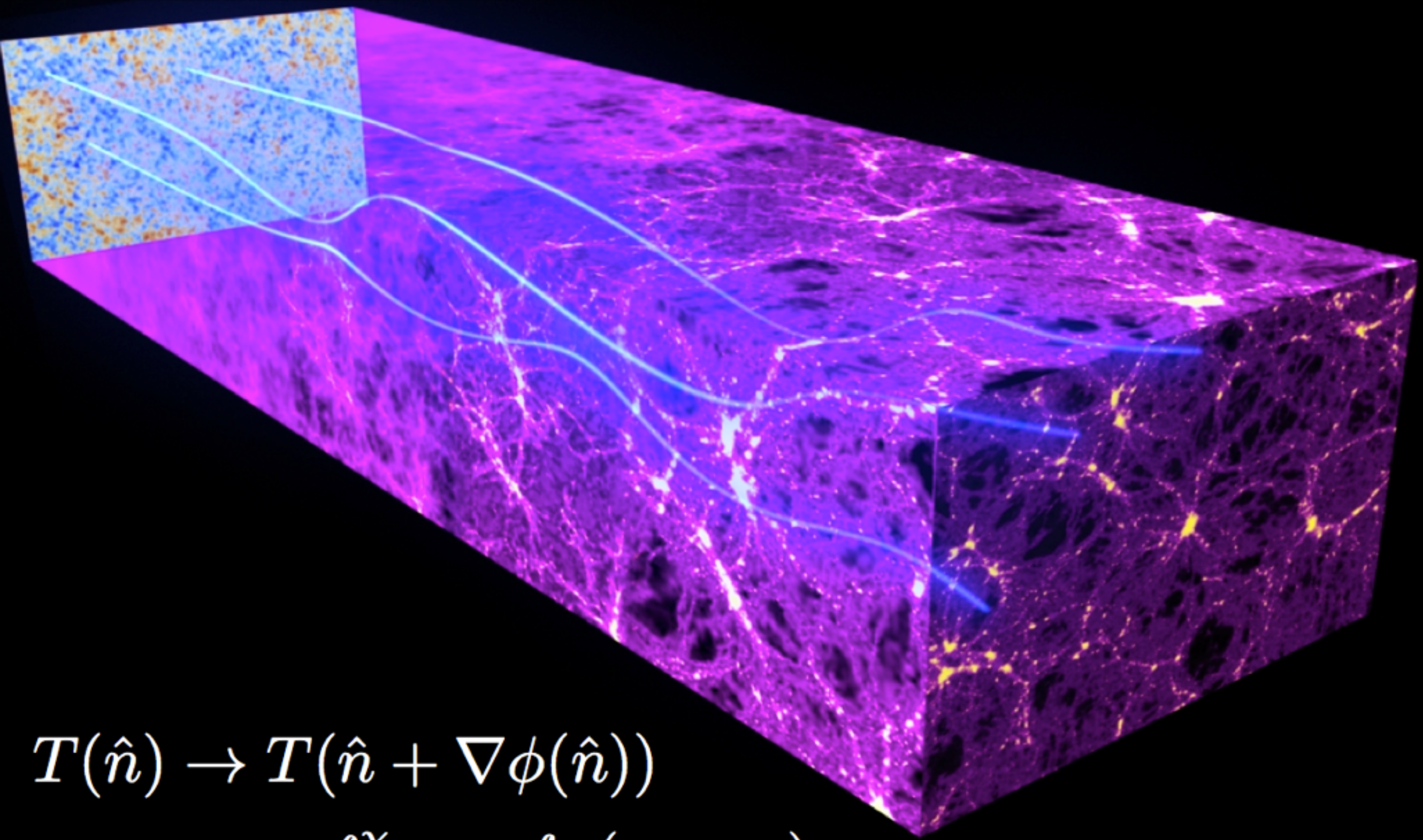


CLASS exploring from the ground; **LiteBIRD, PIXIE CORE+**

key target of ground based experiments

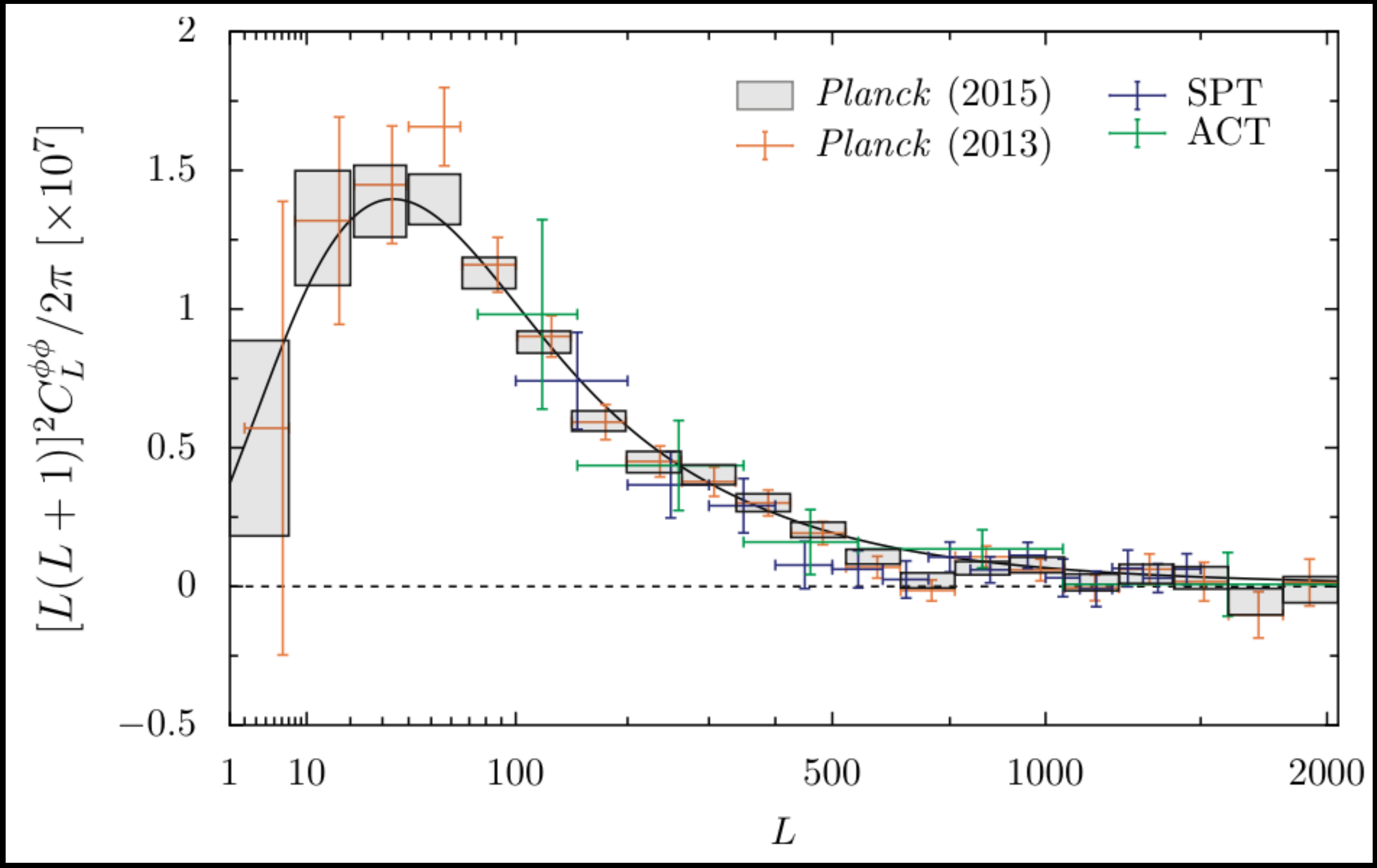
… still a long, long way to go.

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



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

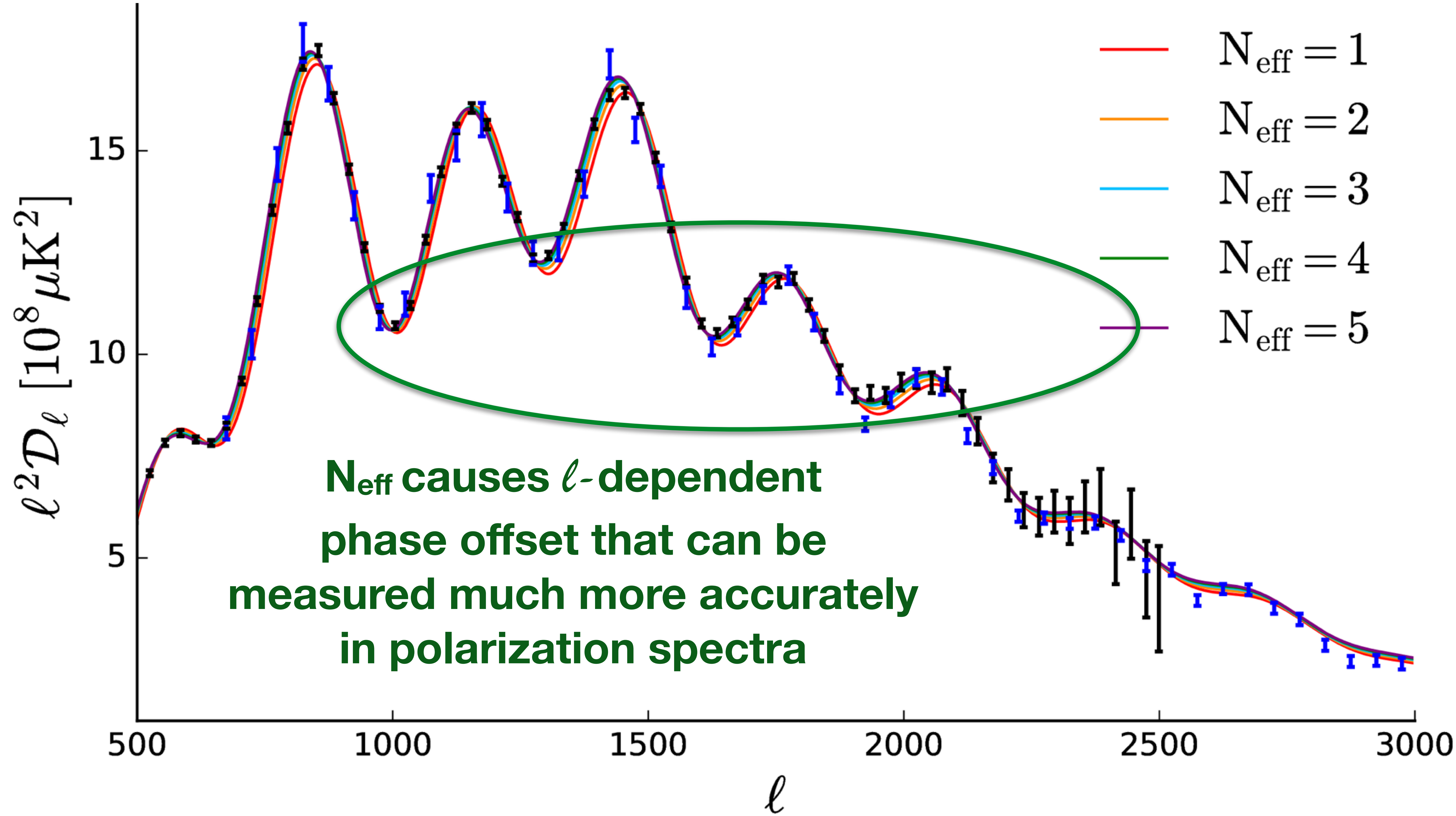
$$\phi(\hat{n}) = -2 \int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{n}; \eta_0 - \chi)$$



graphic from ESA Website

N_{eff} & Helium fraction degeneracy

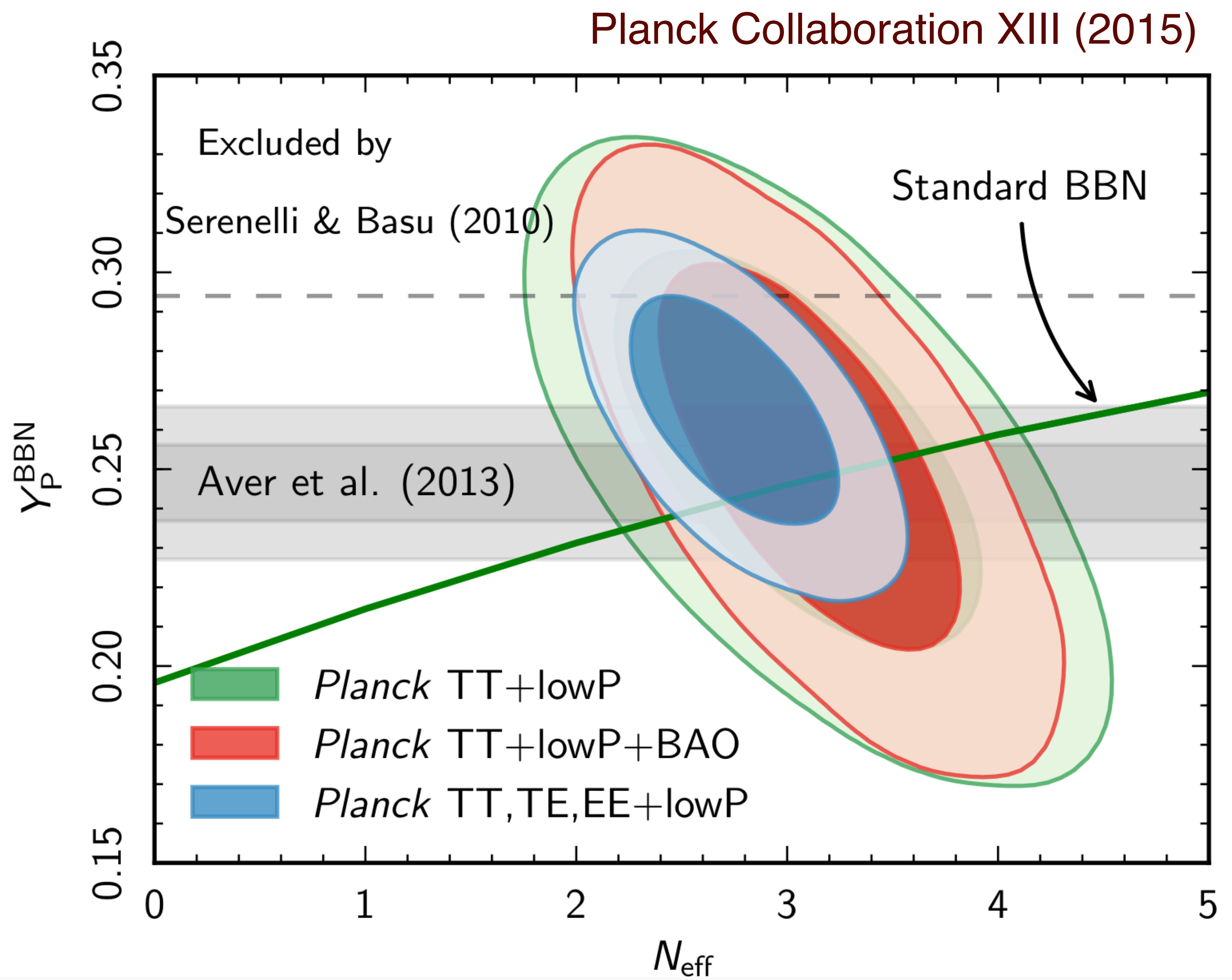
Artificially keep θ_d constant by increasing helium fraction, Y_P



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

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

N_{eff} & Helium fraction degeneracy

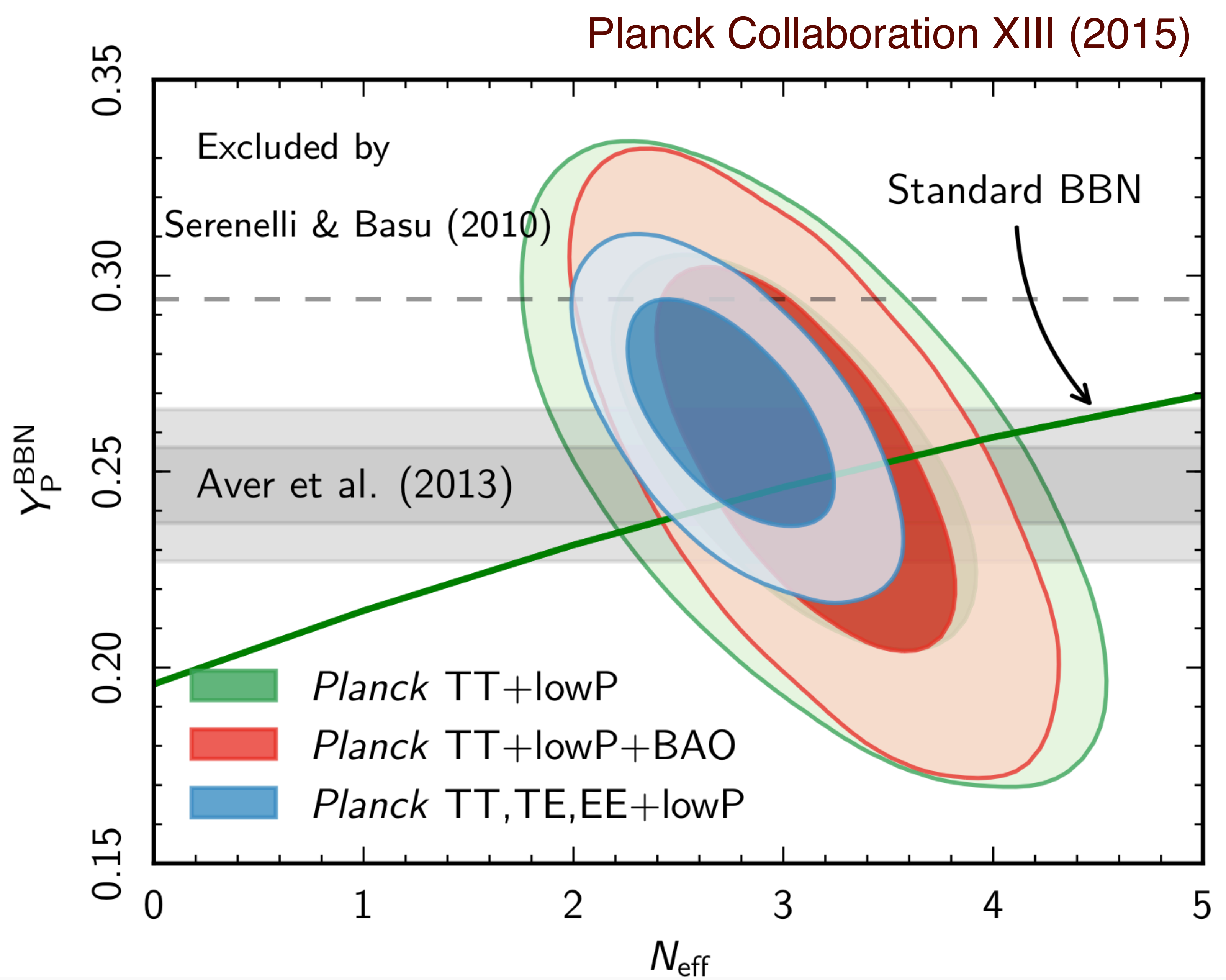


- Agreement with physics of
  1) Cosmic neutrino background at ~1 sec
  2) Light element production at ~3 min
  3) CMB emitted at ~380,000 years

- ***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

N_{eff} & Helium fraction degeneracy



- Agreement with physics of
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- ***But we'd like to do much better !***

need de-lensed polarization spectra

N_{eff} = 3.15 ± 0.23 (along BBN consistency curve)
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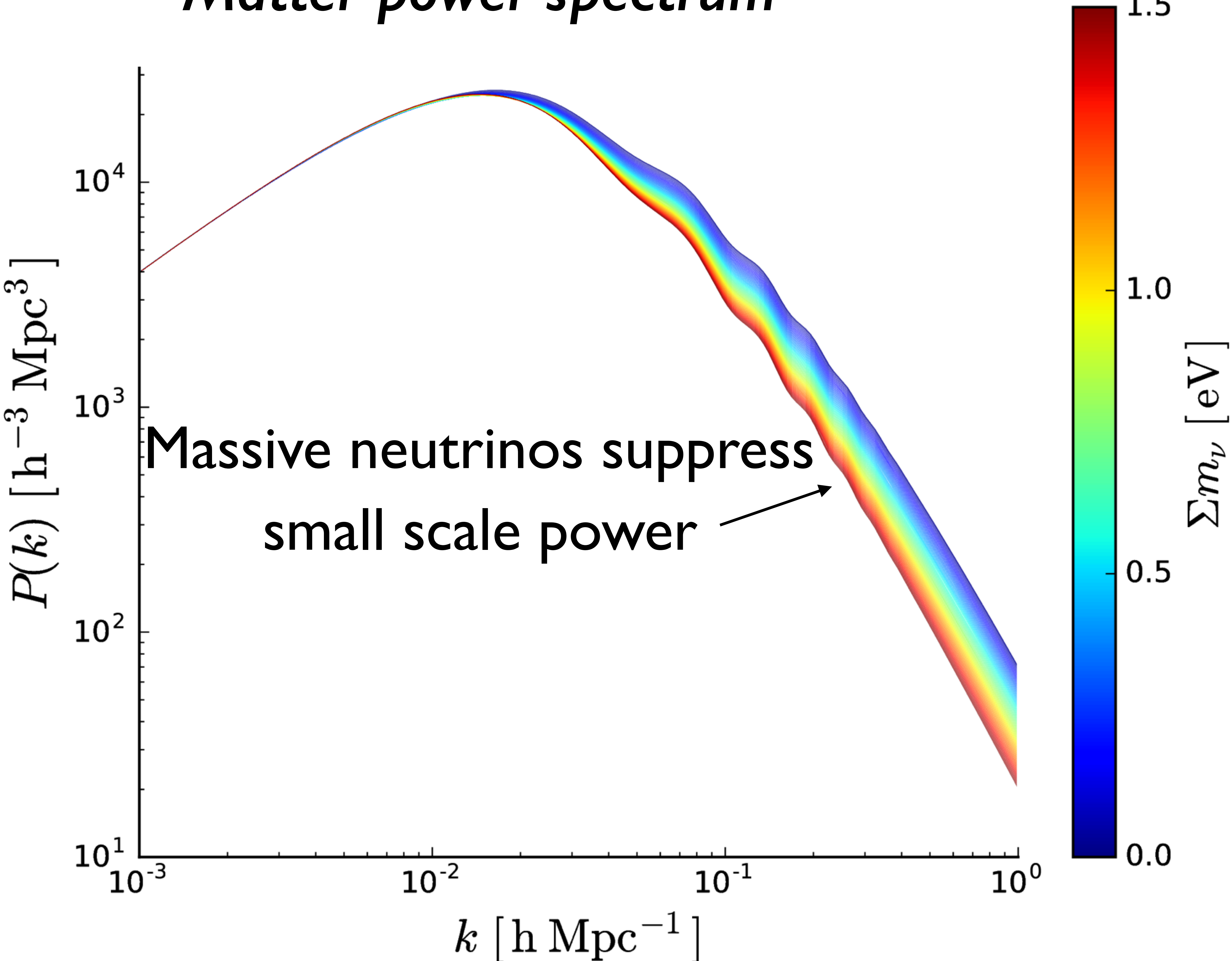
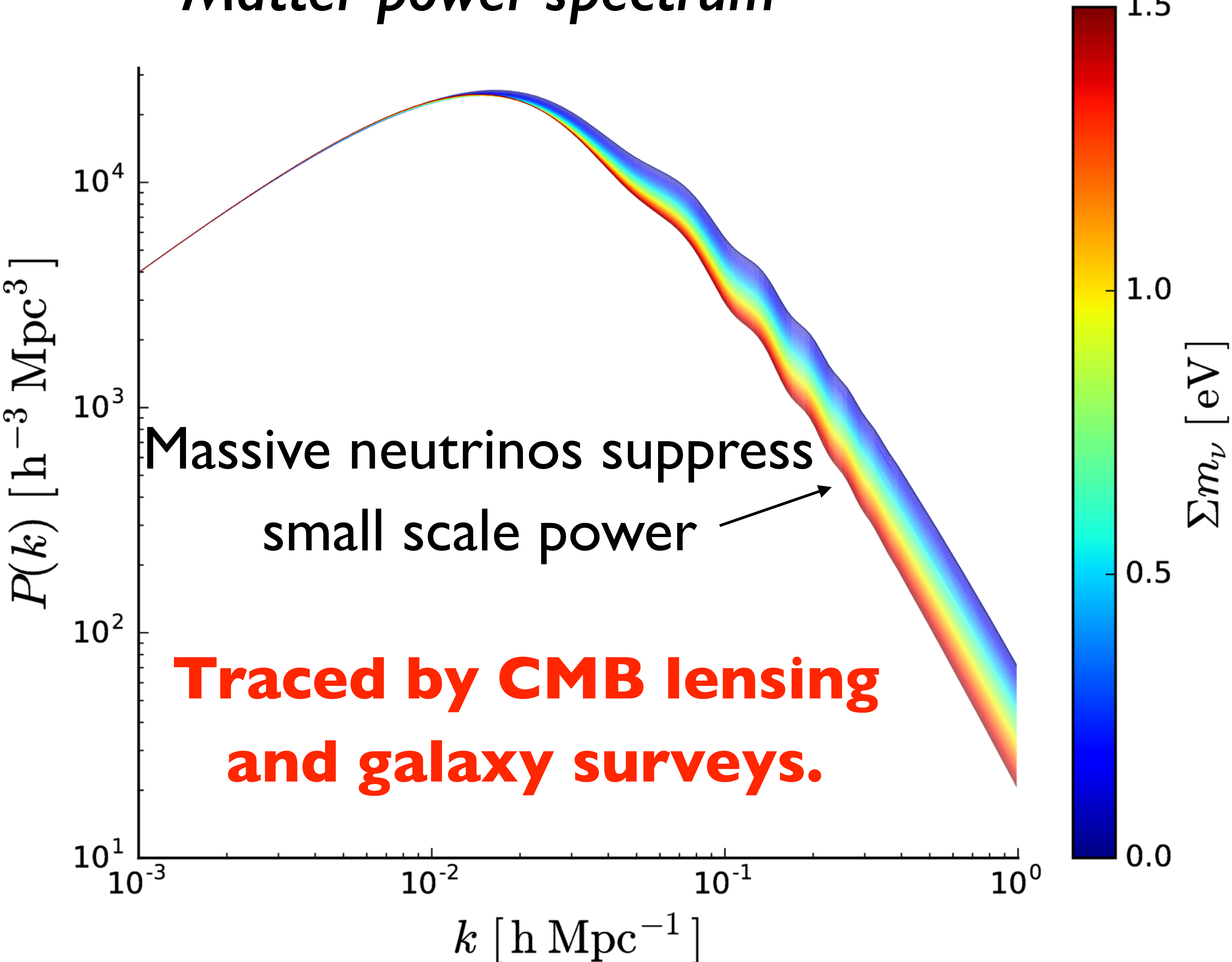
Highly significant detection of neutrino background

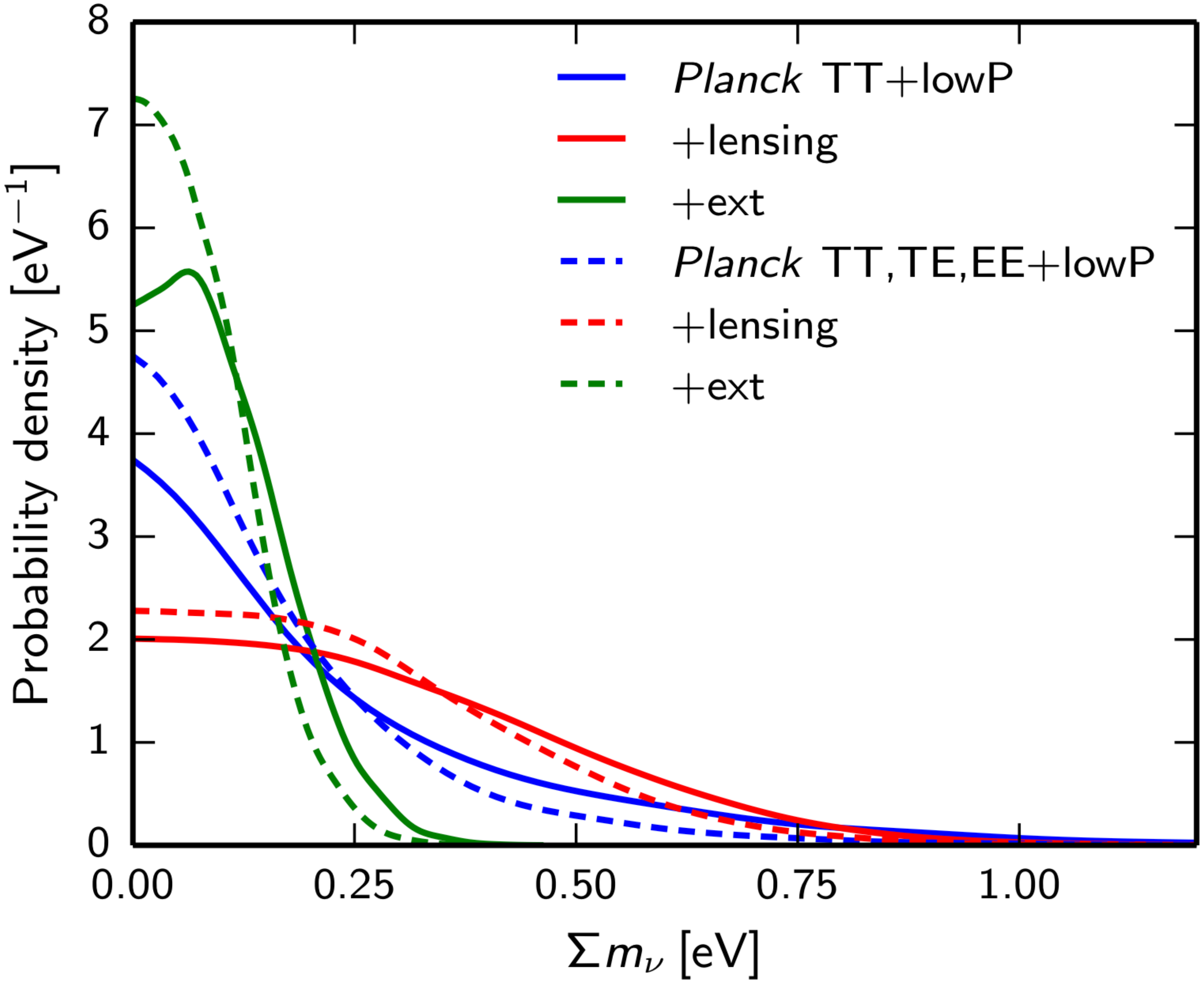
Matter power spectrum



Matter power spectrum



Cosmological Neutrino Mass Constraints



CMB alone:

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

Including other cosmological data:

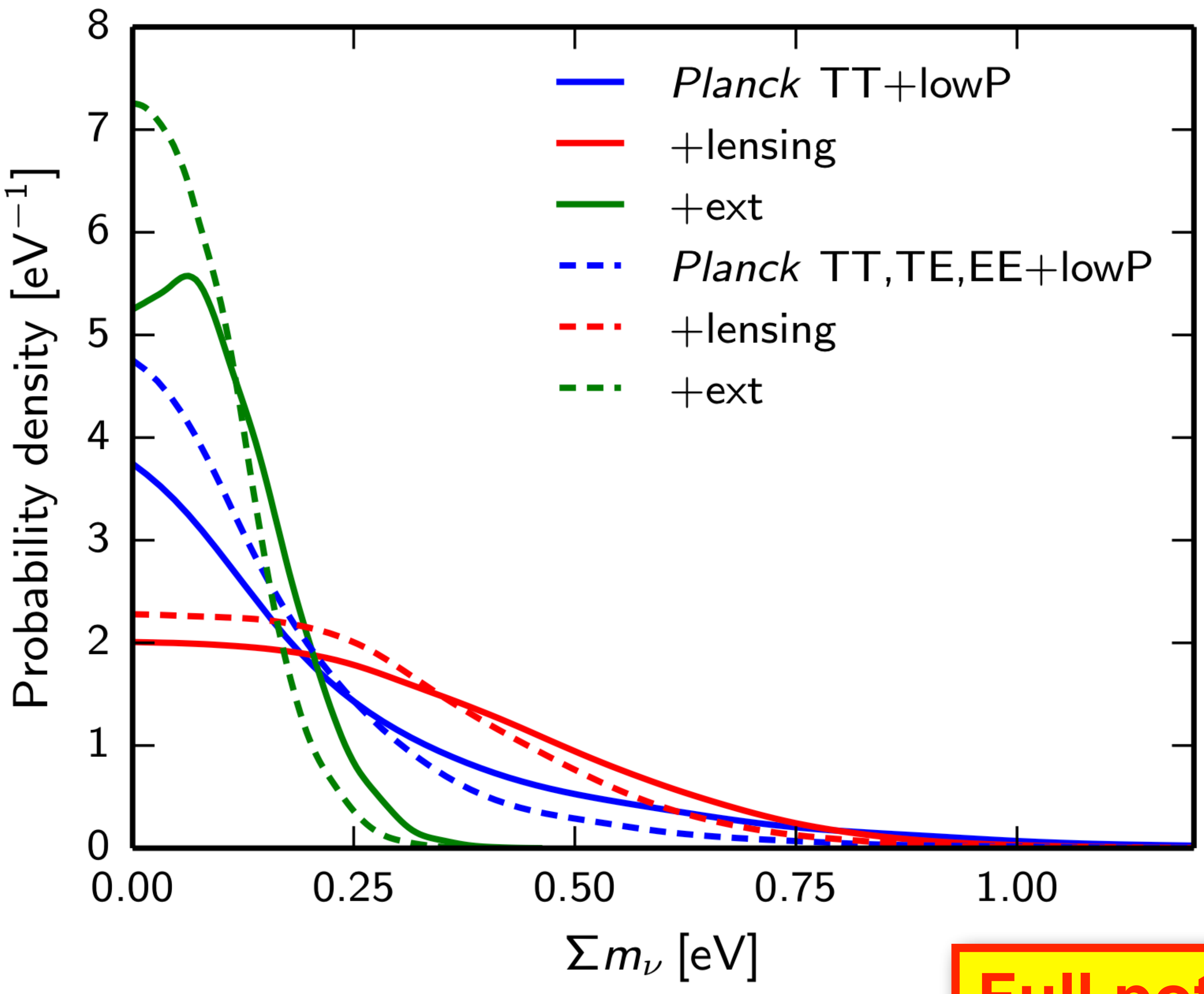
$\Sigma m_\nu < 0.23$ eV at 95% c.l.

Joint Σm_ν and N_{eff} fit:

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

Planck Collaboration XIII (2015)

Cosmological Neutrino Mass Constraints



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Full potential of CMB lensing and best N_{eff} and Σm_ν constraints require better polarization data

Planck Collaboration XIII (2015)

Moving CMB-S4 forward

Community coming together to refine the science goals and instrument definition. Science Book in progress

(https://cosmo.uchicago.edu/CMB-S4workshops)

Strawman CMB-S4 specifications

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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 <u>multiple</u> 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.

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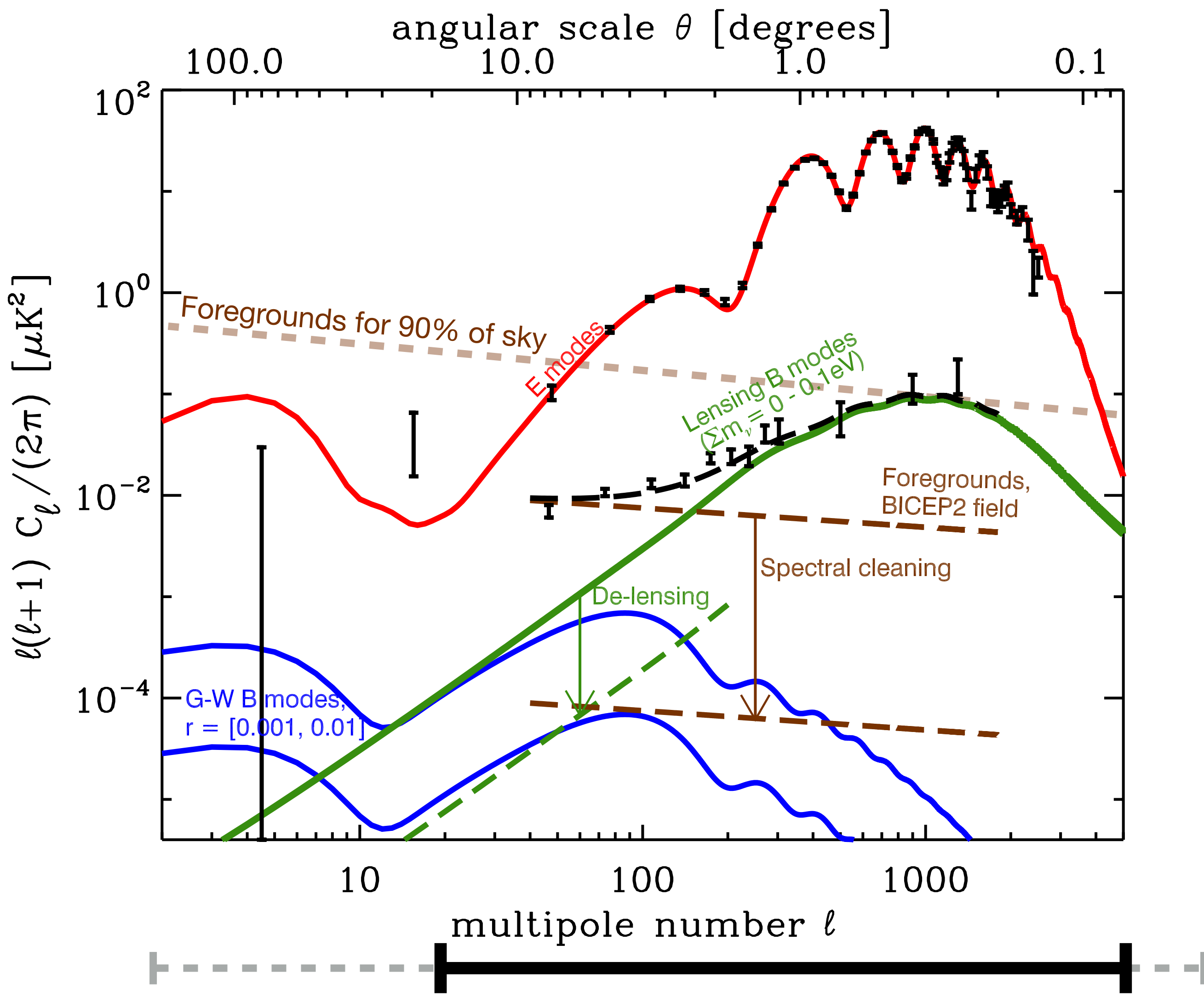
Next Generation CMB Experiment

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

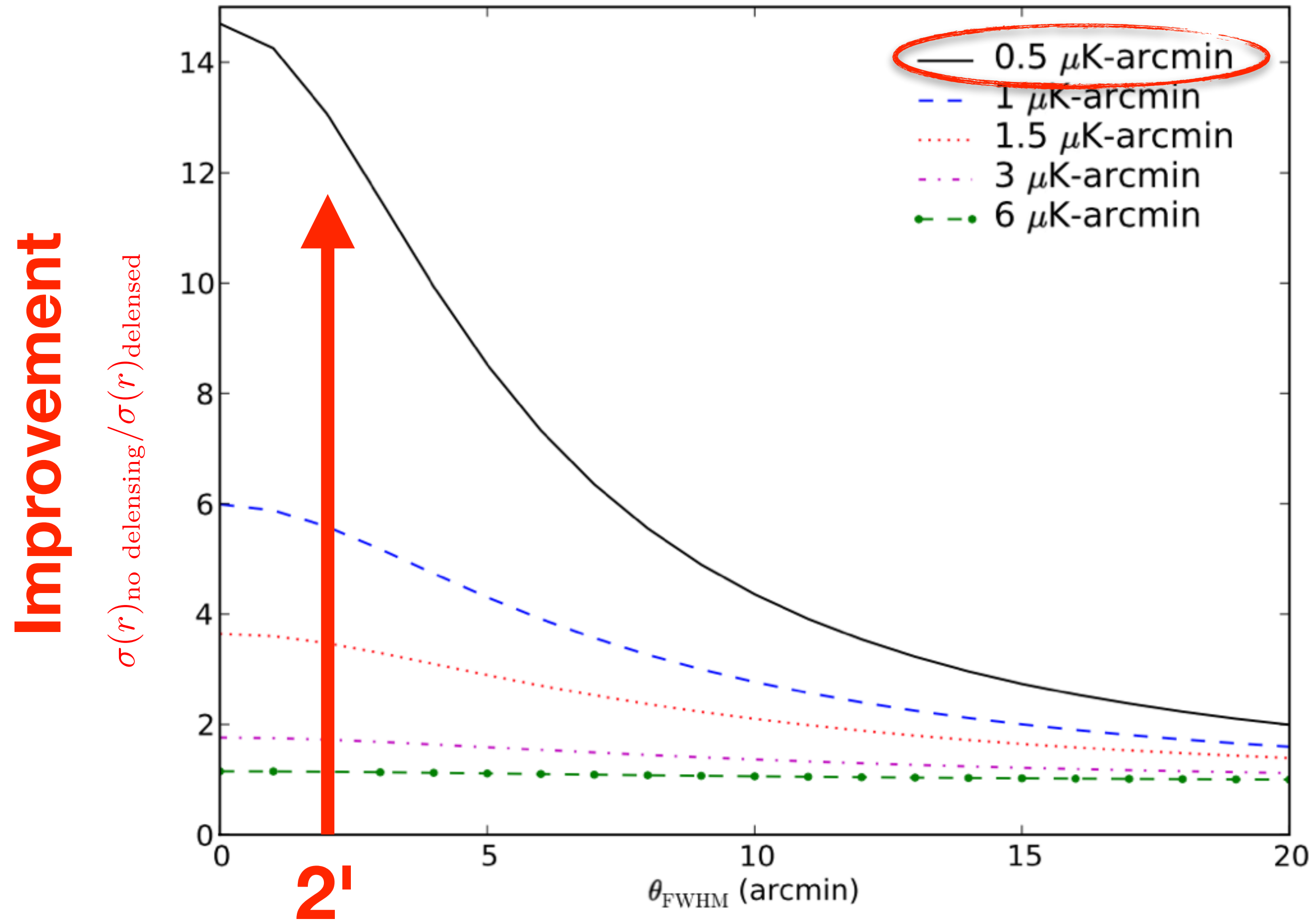


ℓ range of CMB-S4

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

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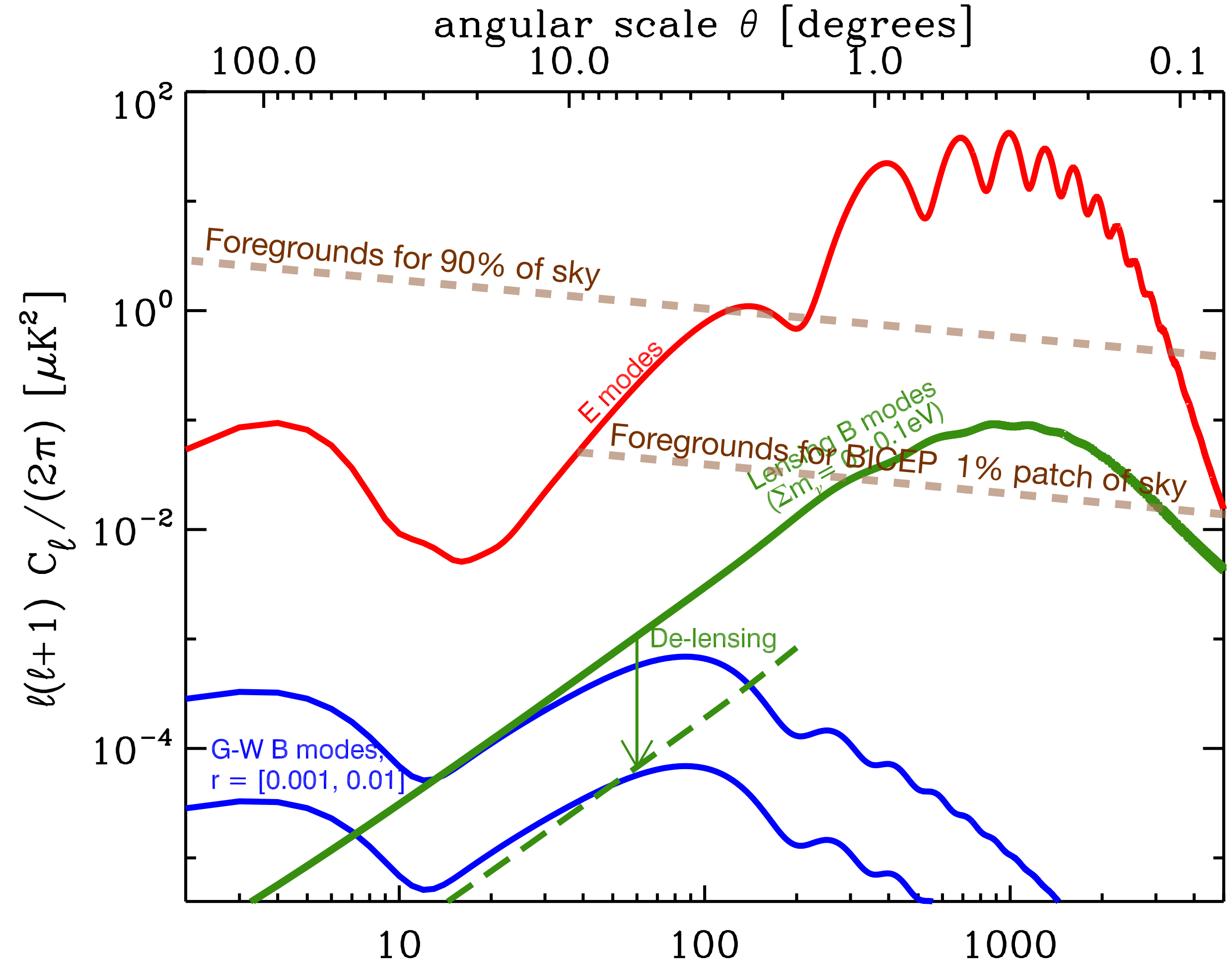
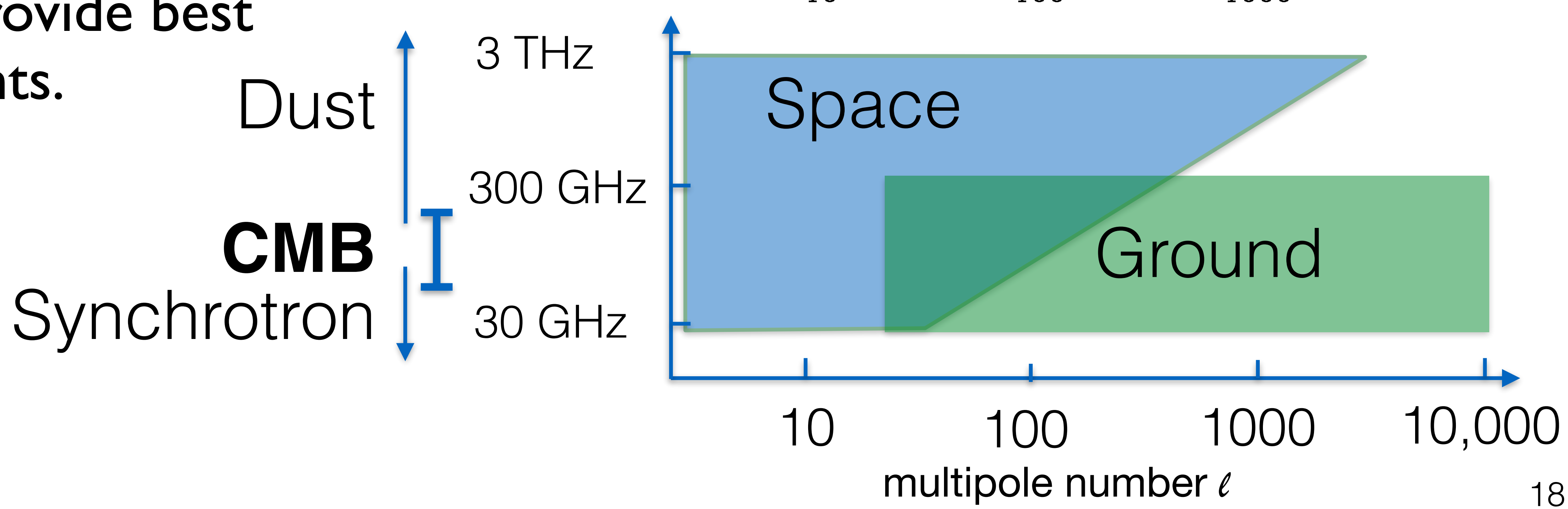
Complementary strengths of ground and space

- **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.





initial Snowmass projection of Inflation reach of CMB-S4

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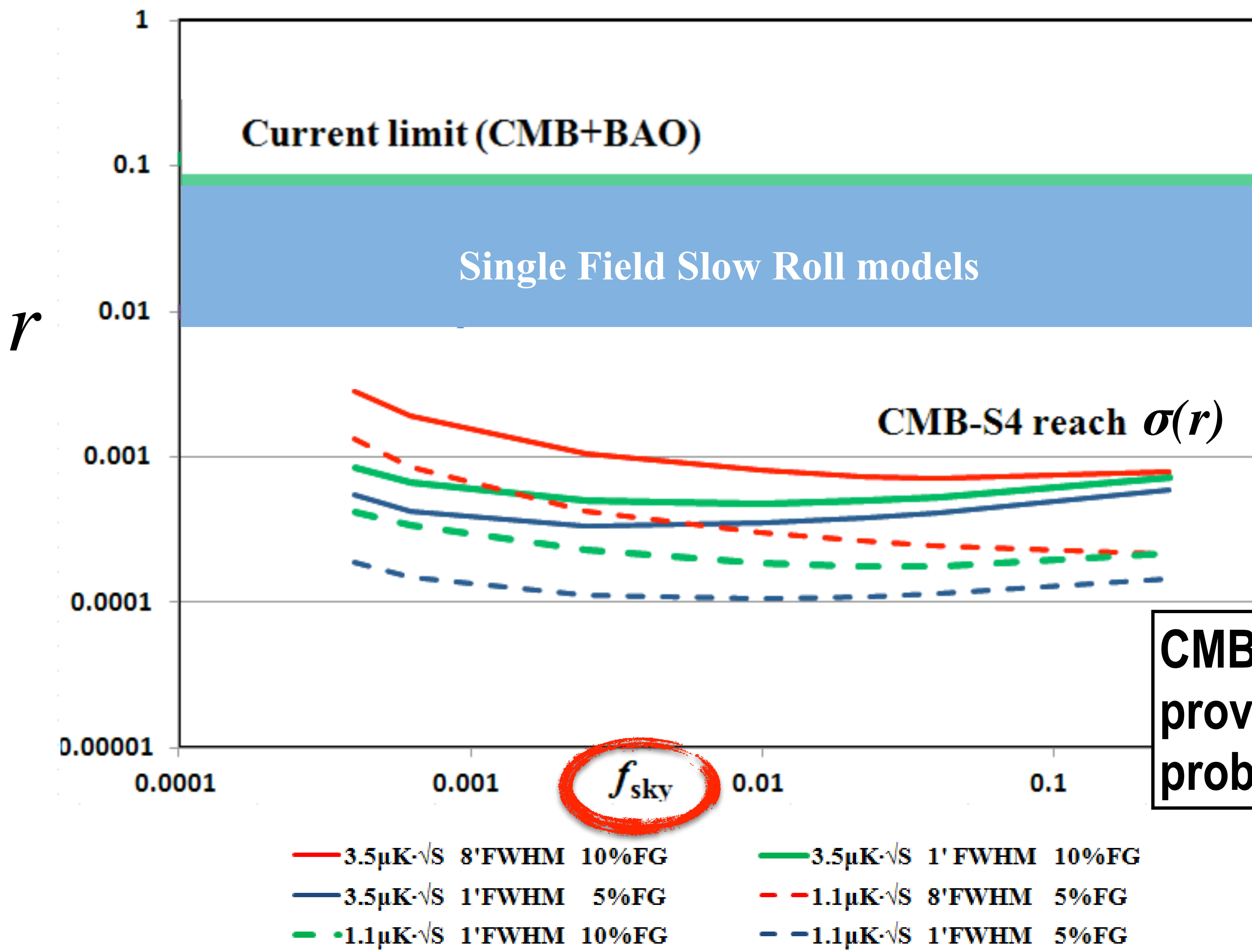

CMB polarization provides the only probe for r < 0.1

arXiv:1309.5381

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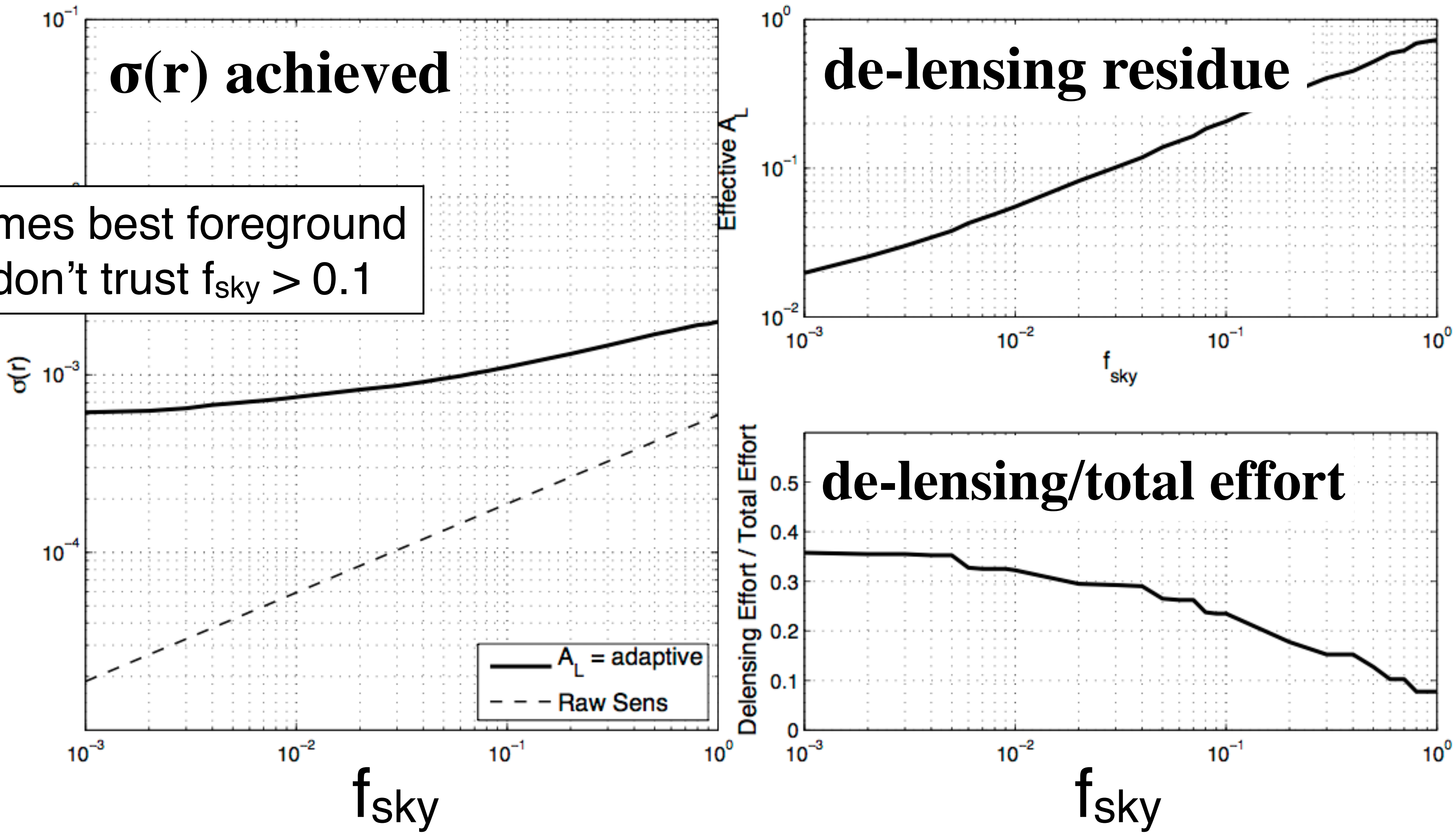
Next Generation CMB Experiment

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

Caveat: assumes best foreground regions, so don't trust $f_{sky} > 0.1$



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

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

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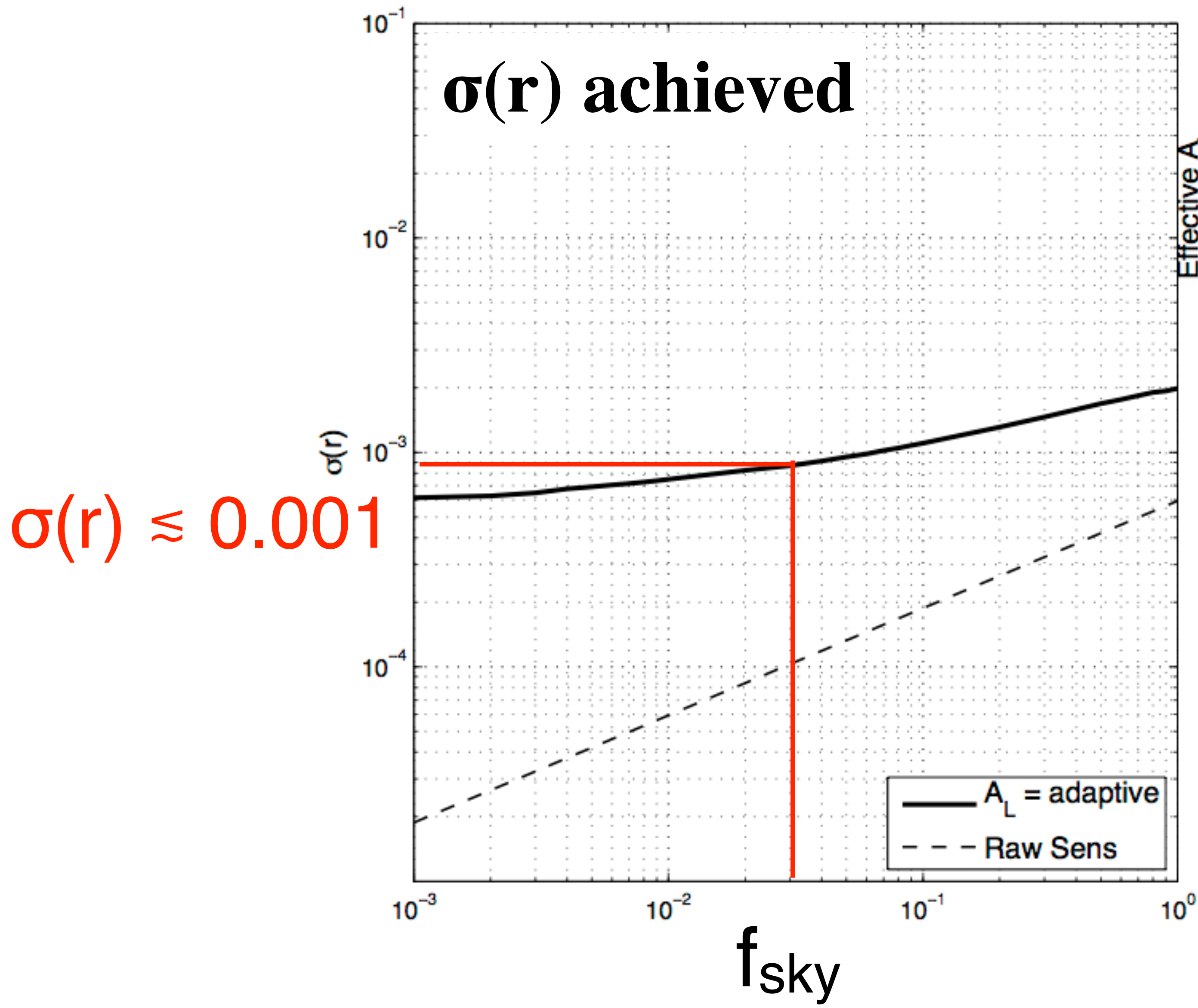
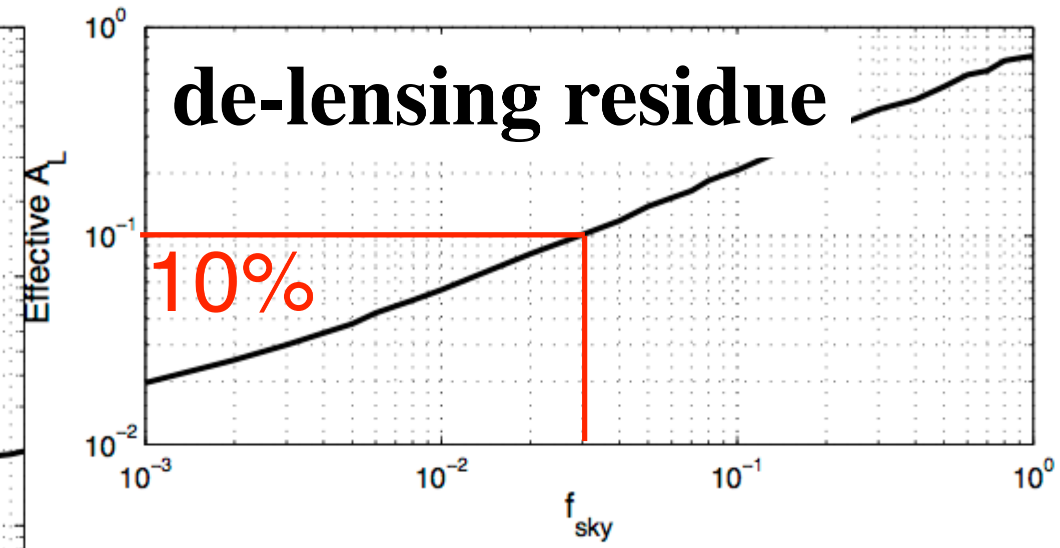
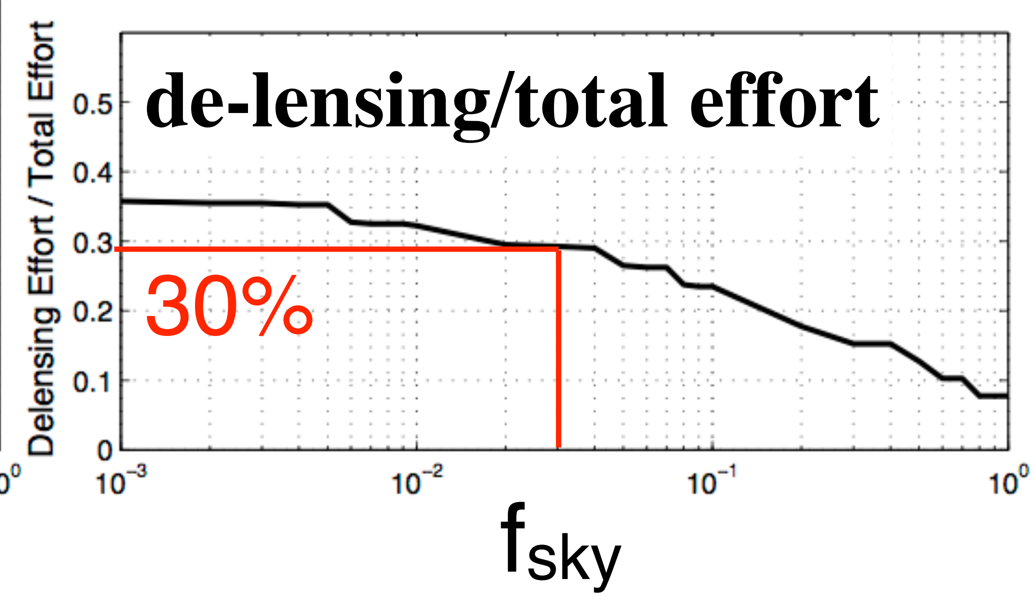
Consider f_{sky} = 3% survey using half the power of CMB-S4







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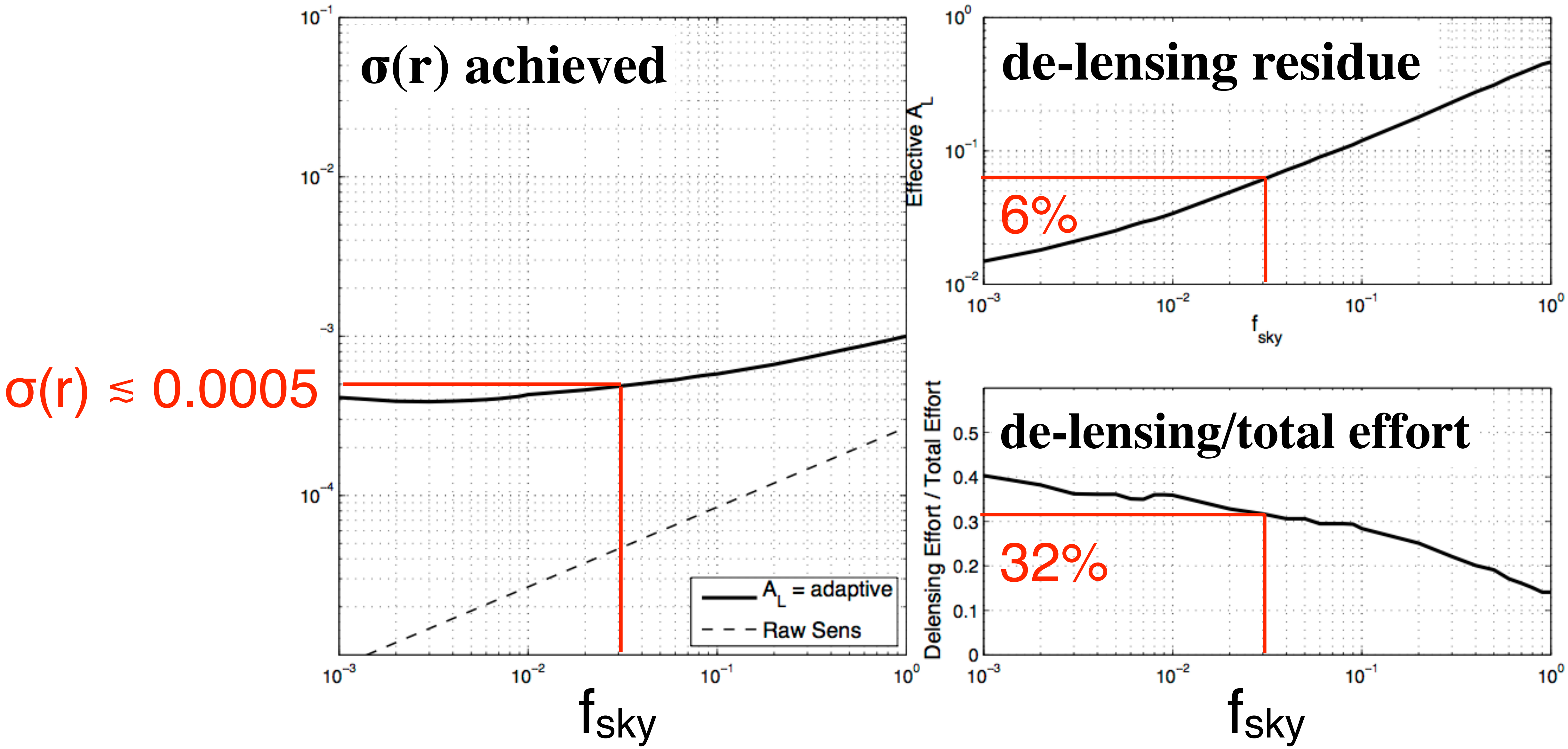
Next Generation CMB Experiment

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

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



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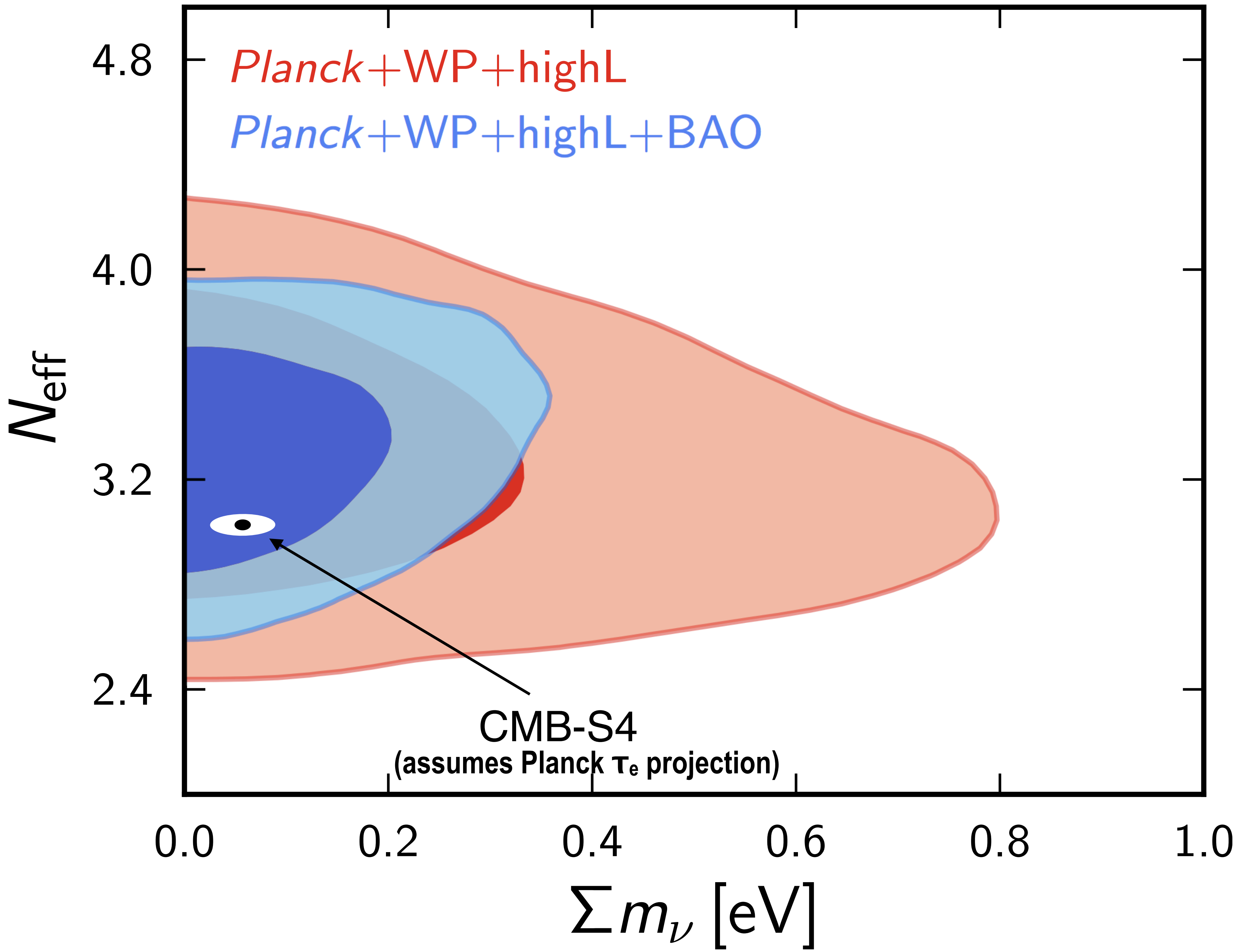
Projected CMB-S4 N_{eff} - Σm_ν constraints



$\sigma(\Sigma m_\nu)$ = 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)*

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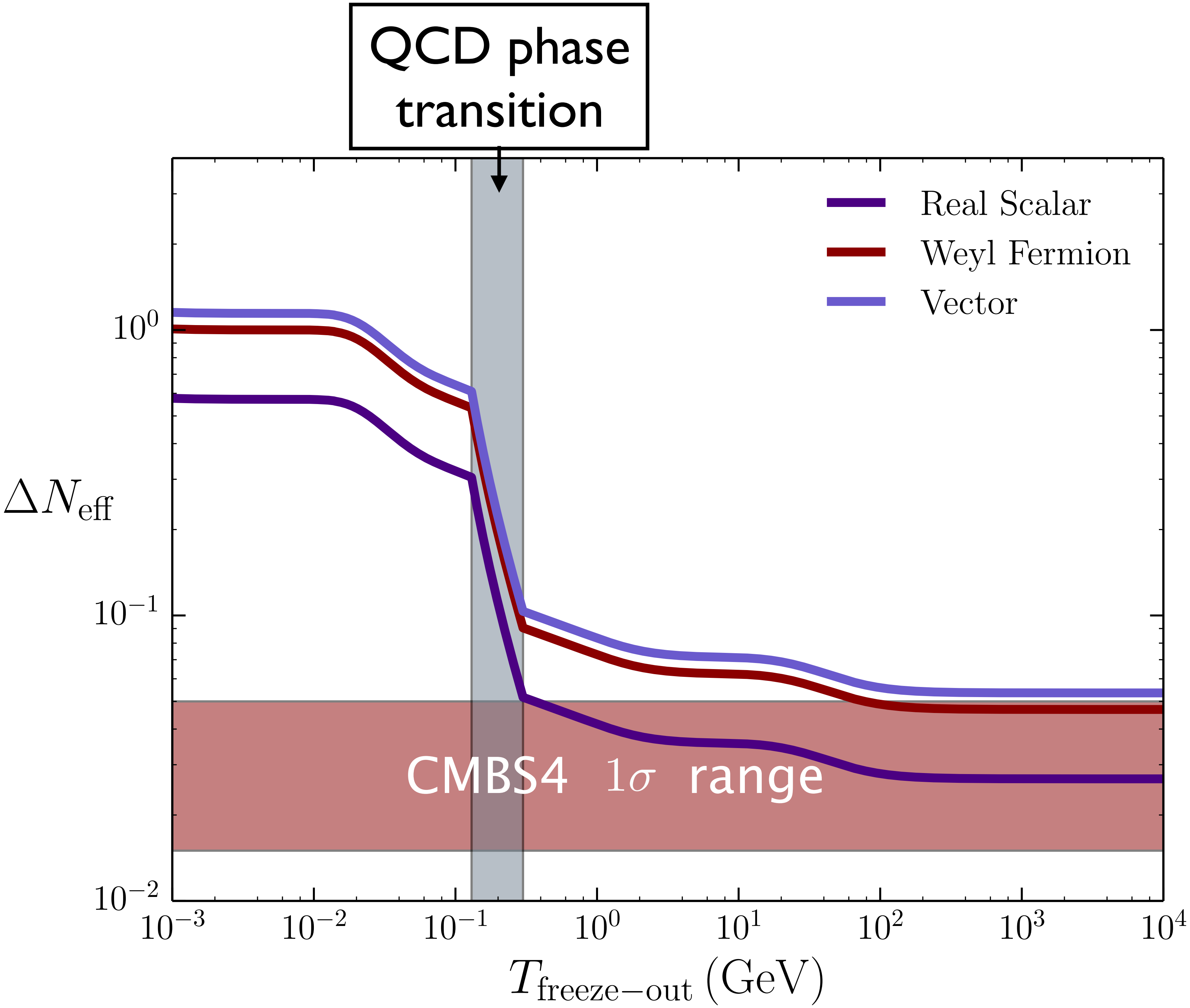
N_{eff}: thermal relics



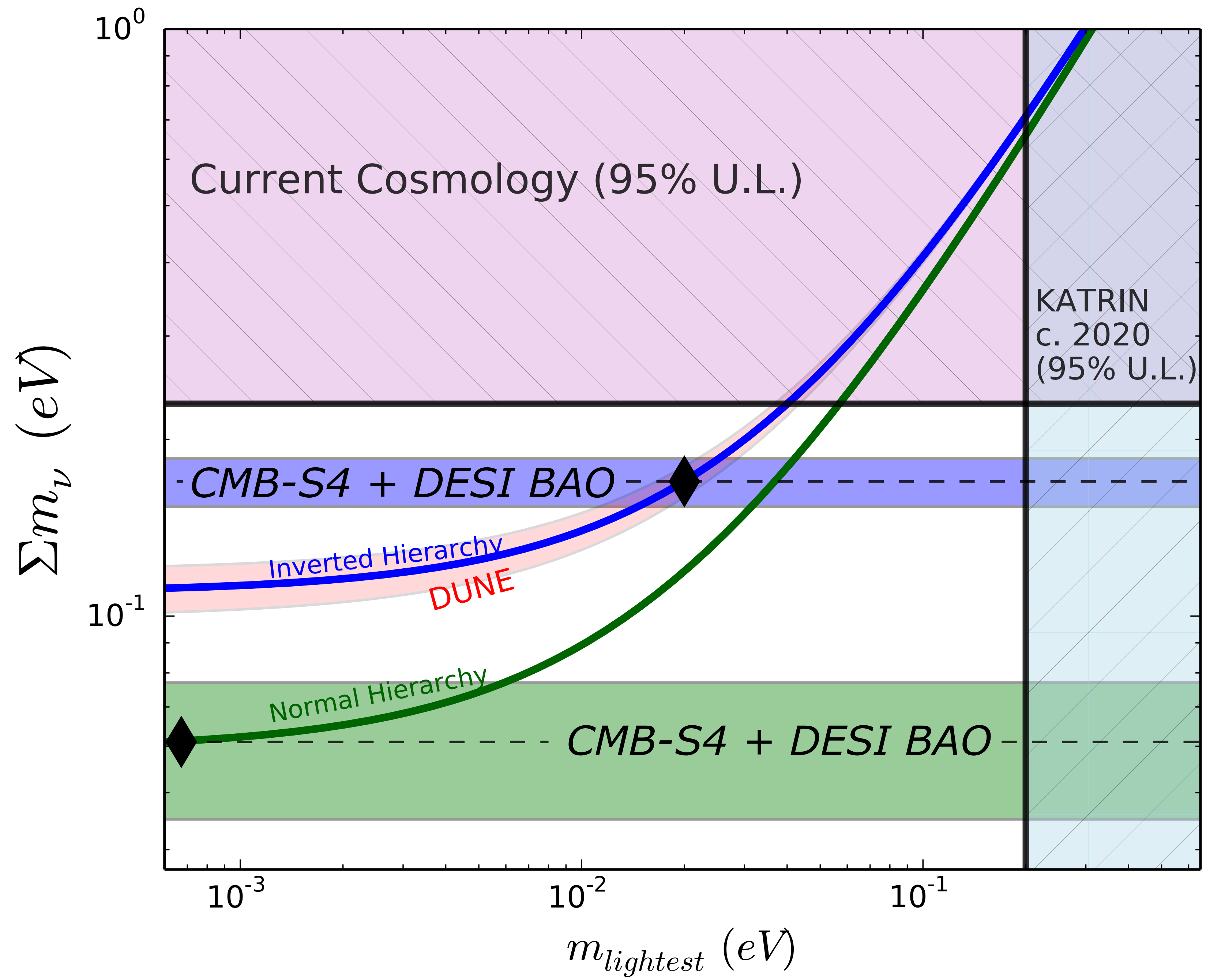
- reduction in $\sigma(N_{eff})$ leads to orders of magnitude improvement of constraint on the freeze-out temperature for any thermal relic

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

Green, Meyers CMB-S4 Science Book draft (https://cosmo.uchicago.edu/CMB-S4workshops)
Also Baumann, Green & Wallisch, "A New Target for Cosmic Axion Searches" arXiv:1604.08614

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

CMB lensing and optical surveys

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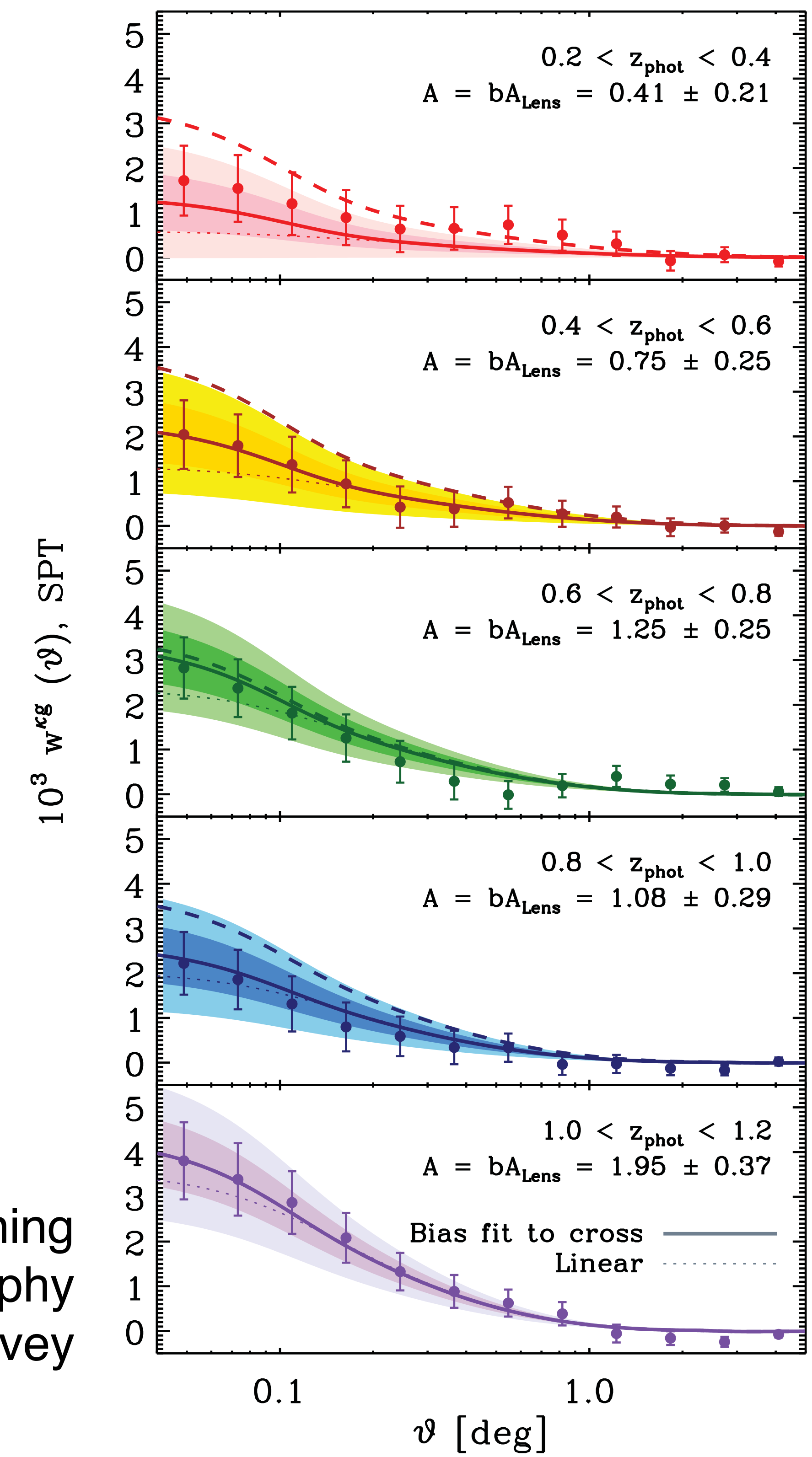
Next Generation CMB Experiment

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

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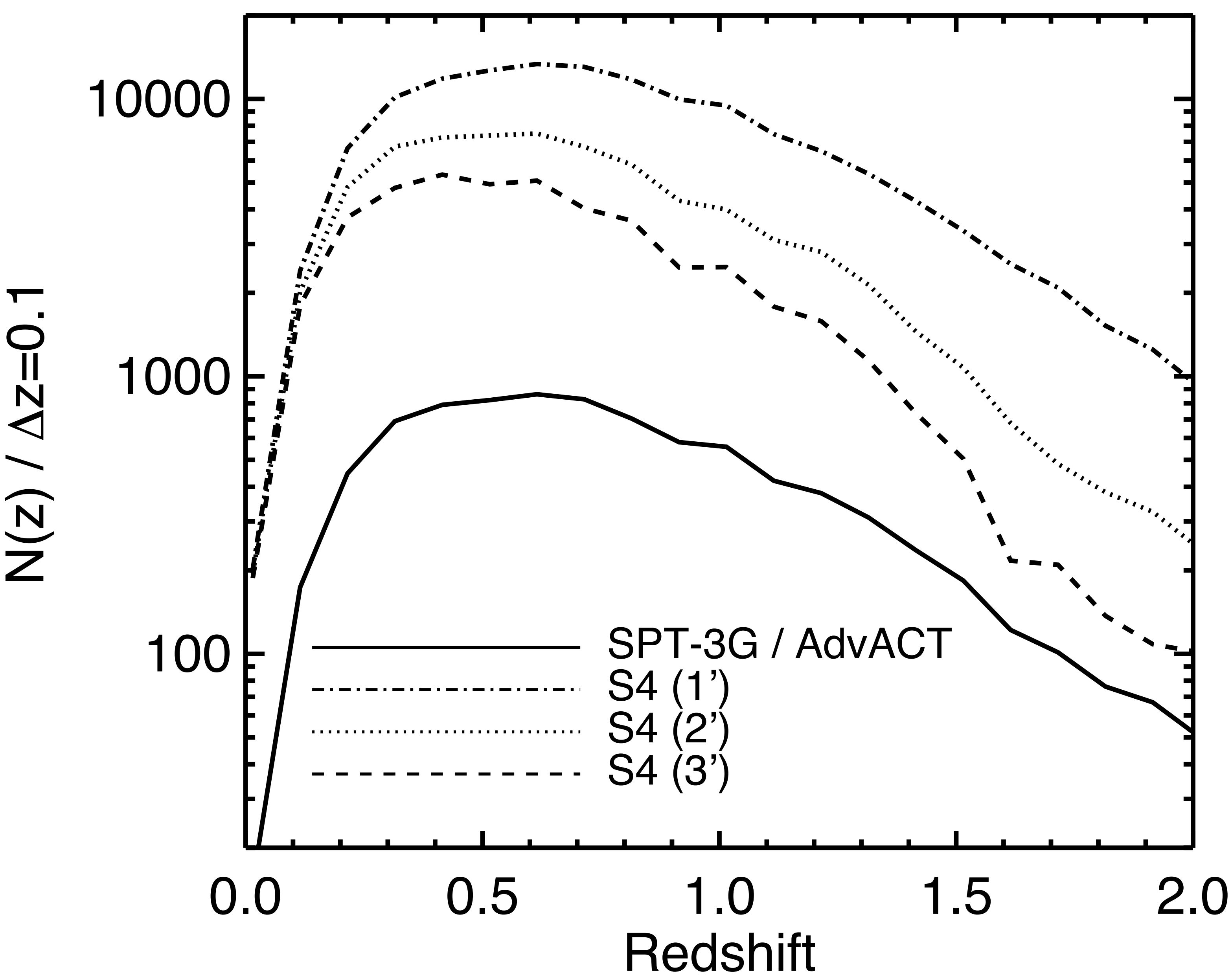
CMB-S4 SZ cluster projections



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

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)

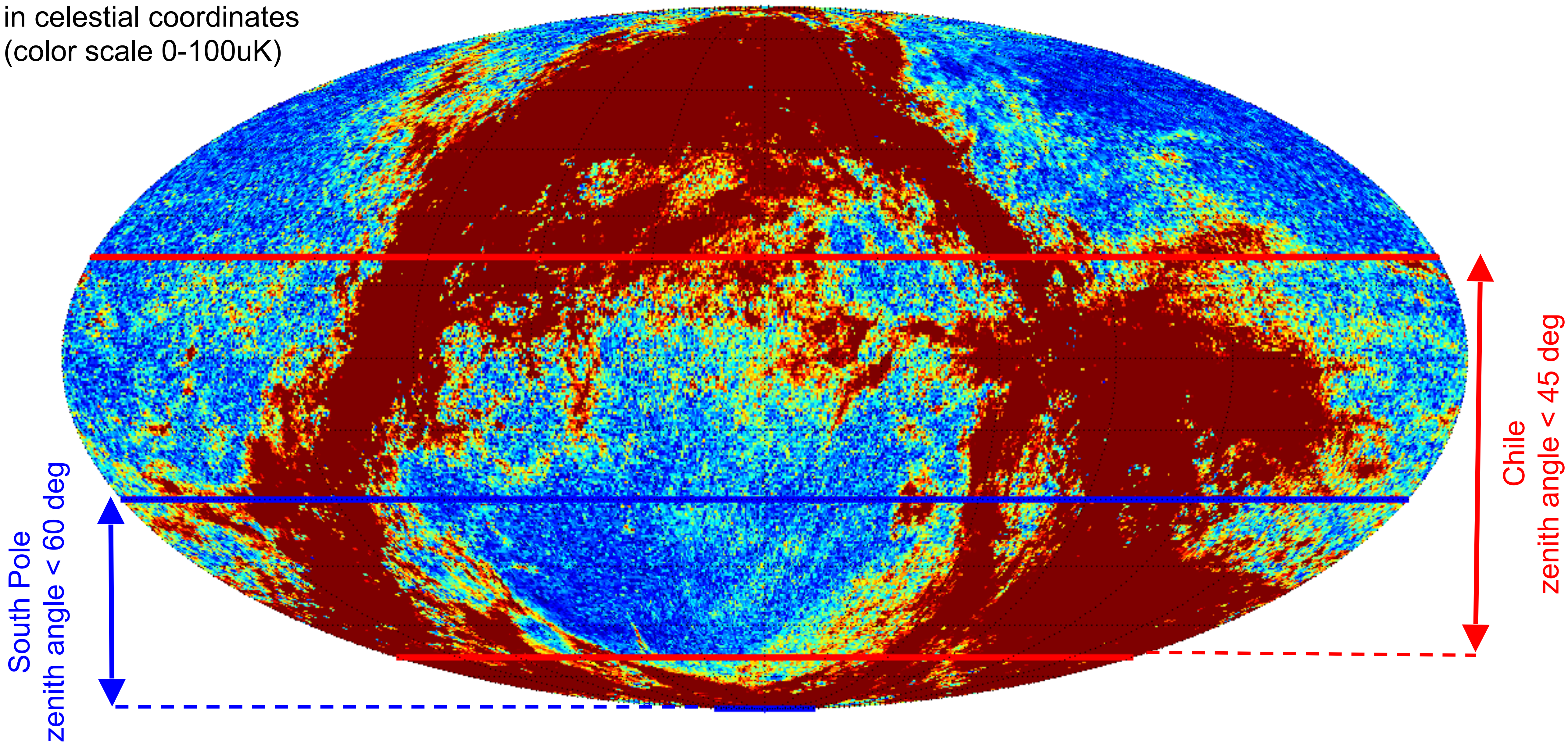


Figure from Clem Pryke

Greatly enhance DES, DESI and LSST science by overlapping coverage

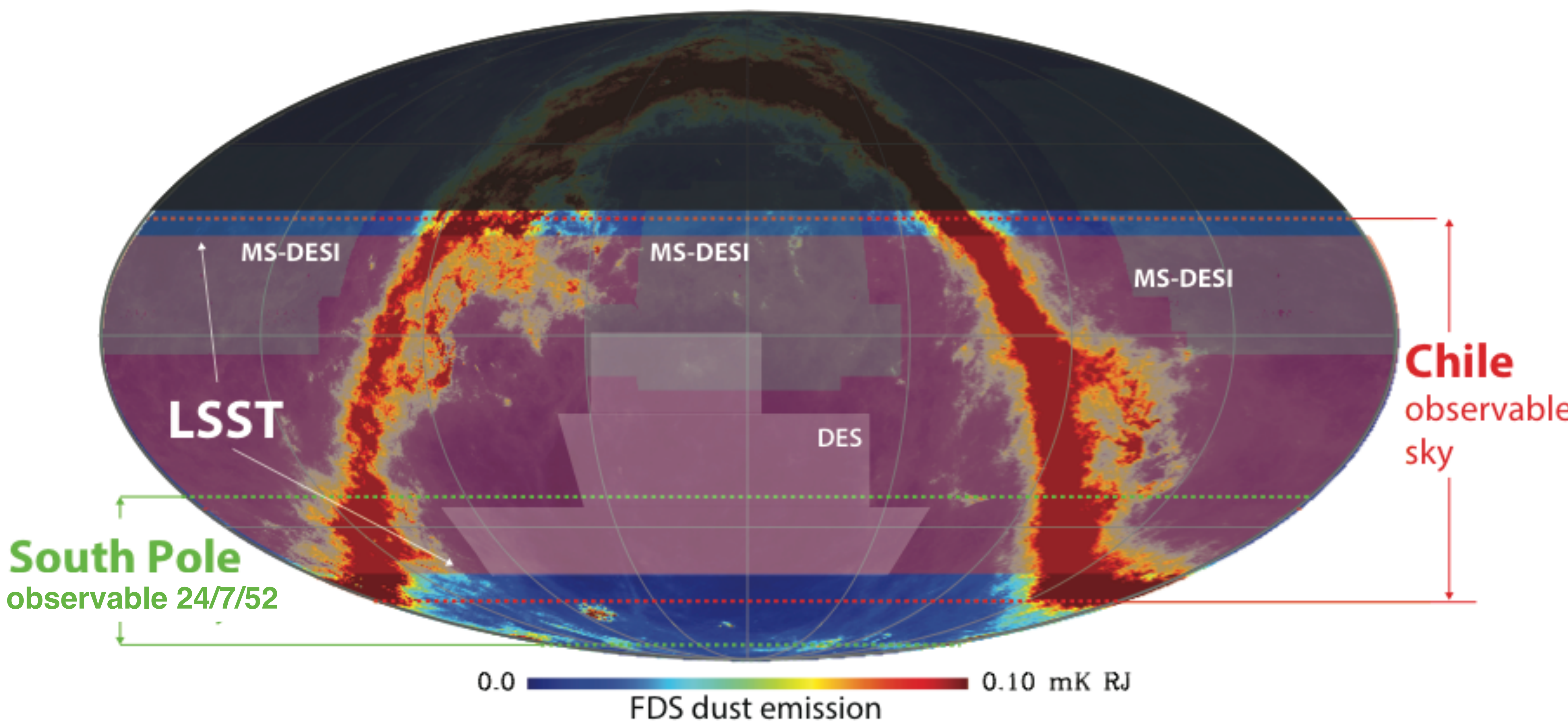


Figure from Jeff McMahon

Ongoing and upcoming South Pole CMB experiments (Stage II & III)

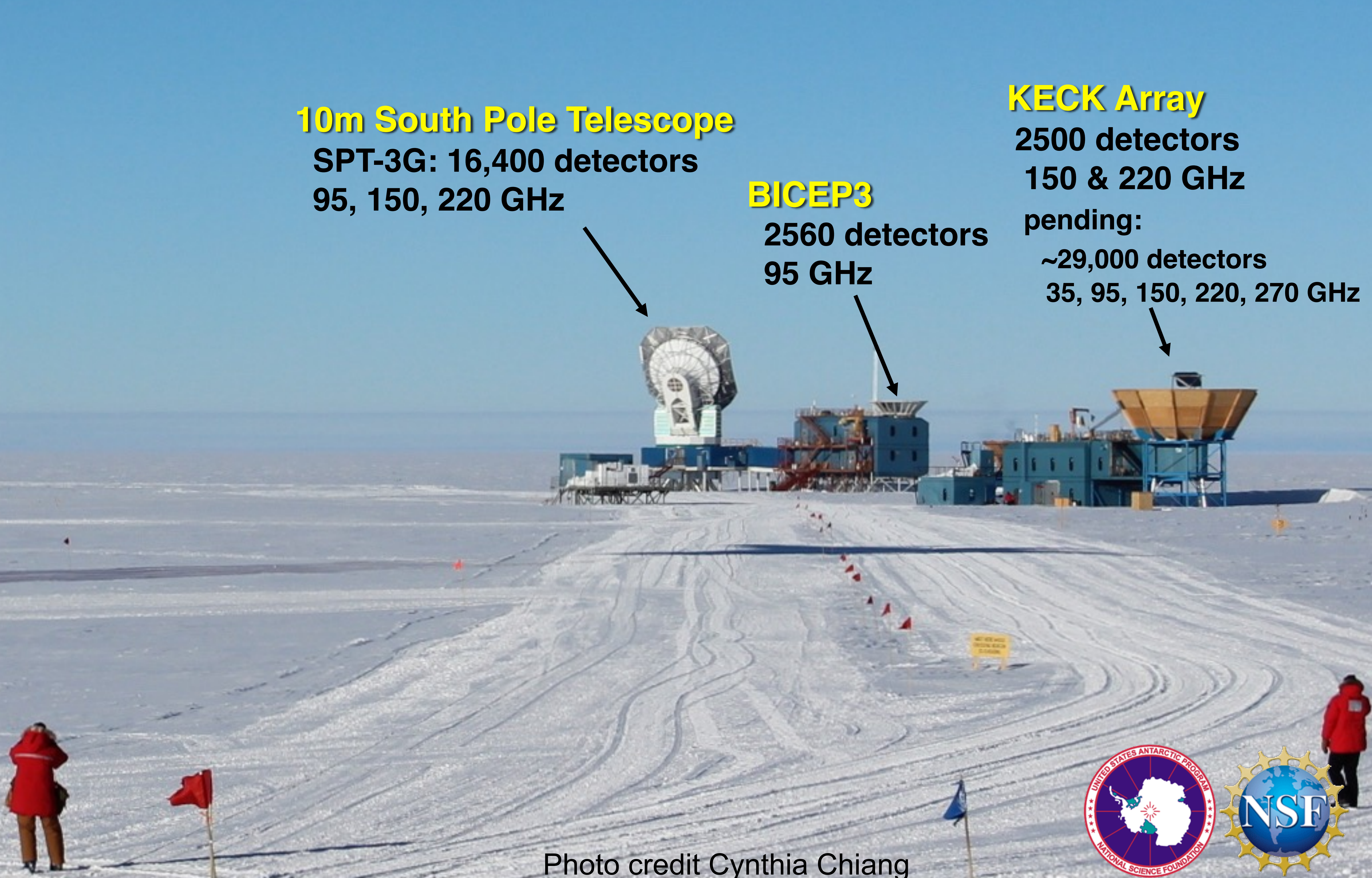


Photo credit Cynthia Chiang

Ongoing and upcoming Atacama CMB experiments (Stage II & III)

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Collaboration

- Community — university and labs — working very well together on Science Book and on path toward instrumentation choices.
- Interactions with DOE through DOE’s CMB Cosmic-Vision group
- NSF responds to proposals. NSF interactions with CMB-S4 through their award PI’s
- Addressing issues on nature of project organization
  - bottoms up versus top down
  - maintain constructive competition between sites?
- Proceeding with formation of formal collaboration and formal CMB-S4 project

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Next Generation CMB Experiment

Last words

CMB-S4 will be a great leap for cosmology and astrophysics. CMB is the gift that keeps on giving.

The science is spectacular. We will be searching for inflationary gravitational waves and rigorously testing single field slow roll inflation, determining the neutrino masses, searching for new relics, mapping the universe in momentum, investigating dark energy, testing general relativity and more.

The community is behind CMB-S4 and we are moving forward.

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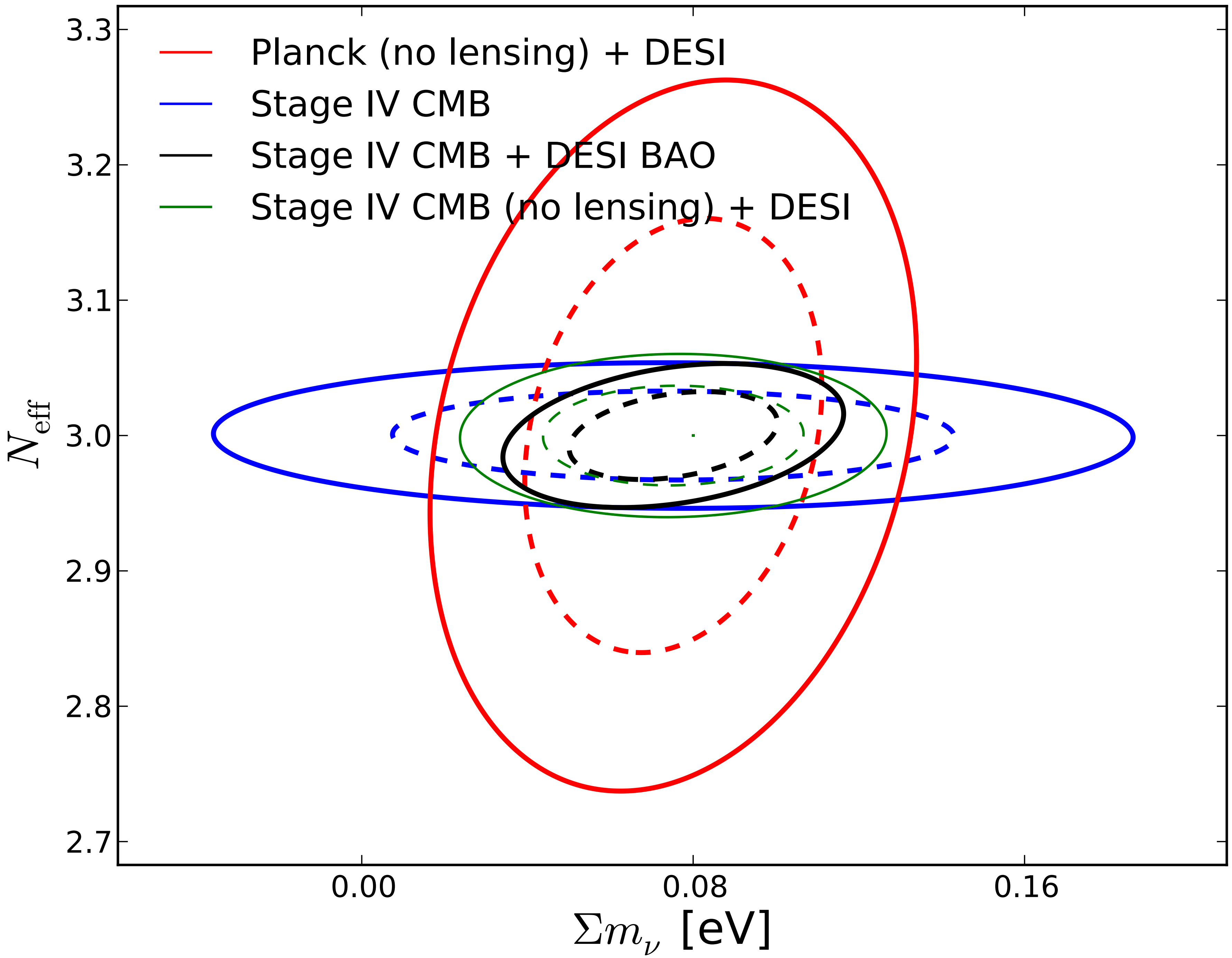
extra slides

Snowmass CMB-S4 N_{eff} - Σm_ν constraints



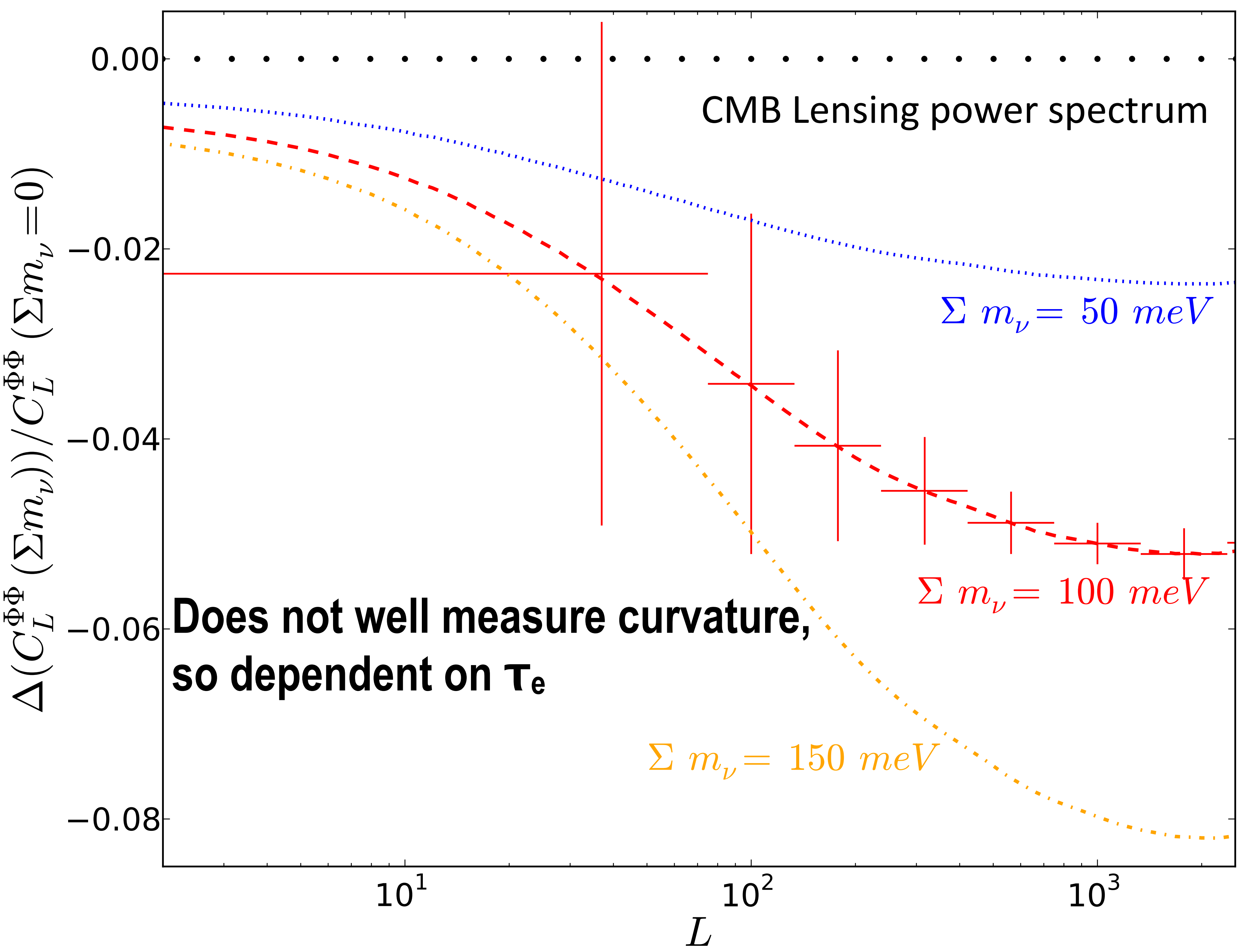
$\sigma(\Sigma m_\nu)$ = 15 meV (with DESI BAO)

$\sigma(N_{eff})$ = 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



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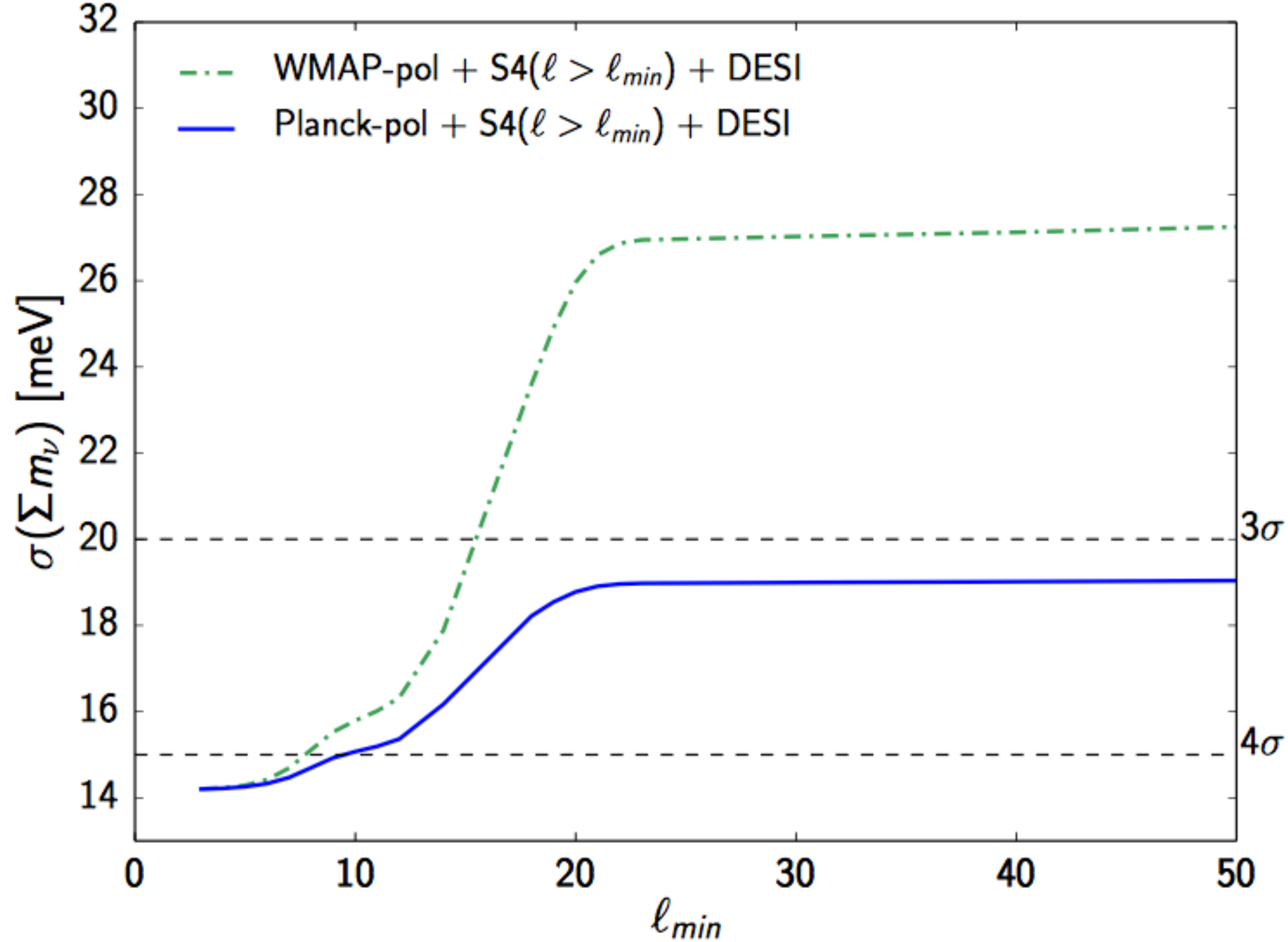
need τ_e measurement



Allison et al arXiv:1509.07471

"Pessimistic" ν degeneracy forecasts

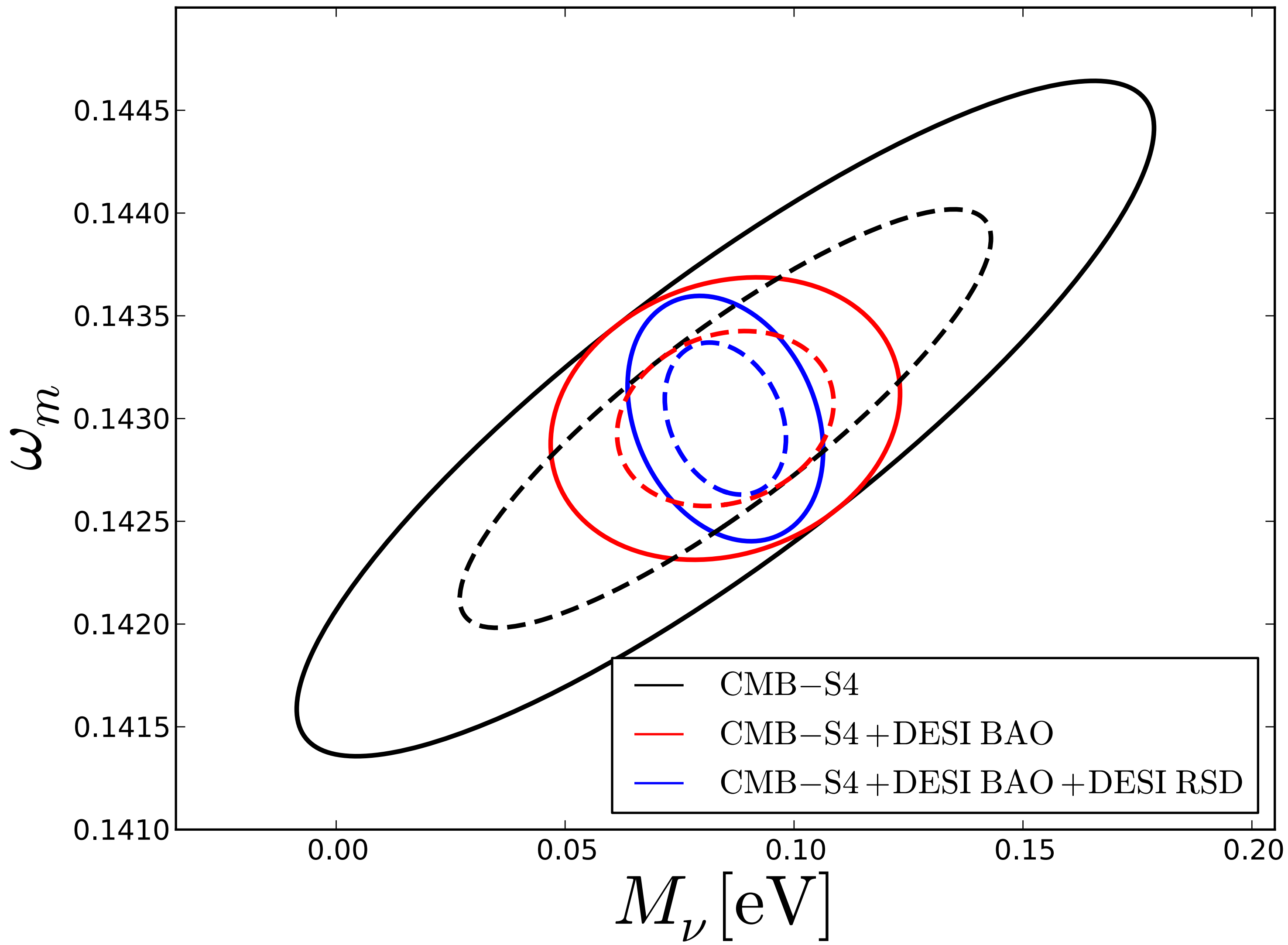
Allison et al., 1509.0747

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

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

“Optimistic” ν forecasts

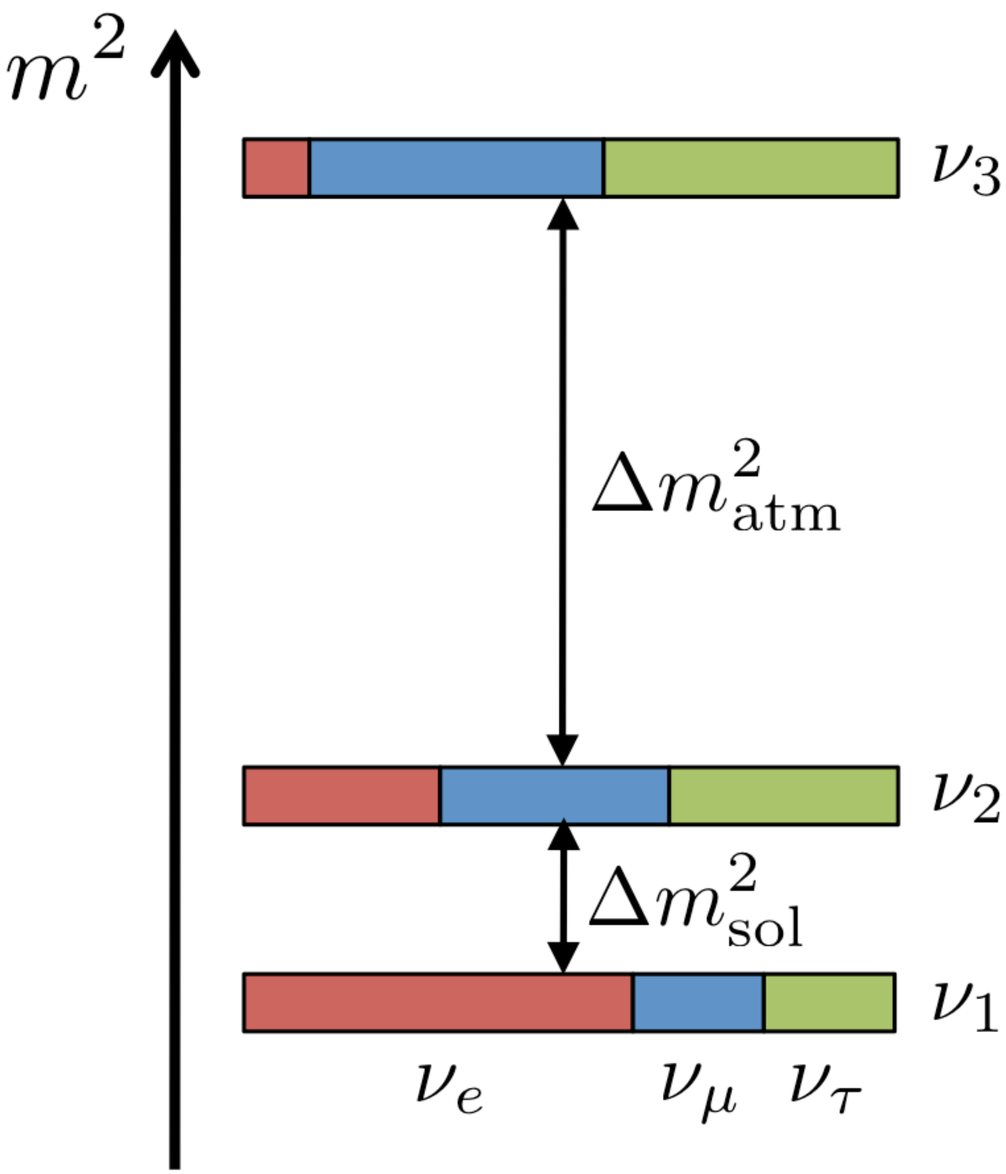
Pan & Knox 1506.07493



Σm_ν = 9 meV (ΛCDM + Σm_ν)

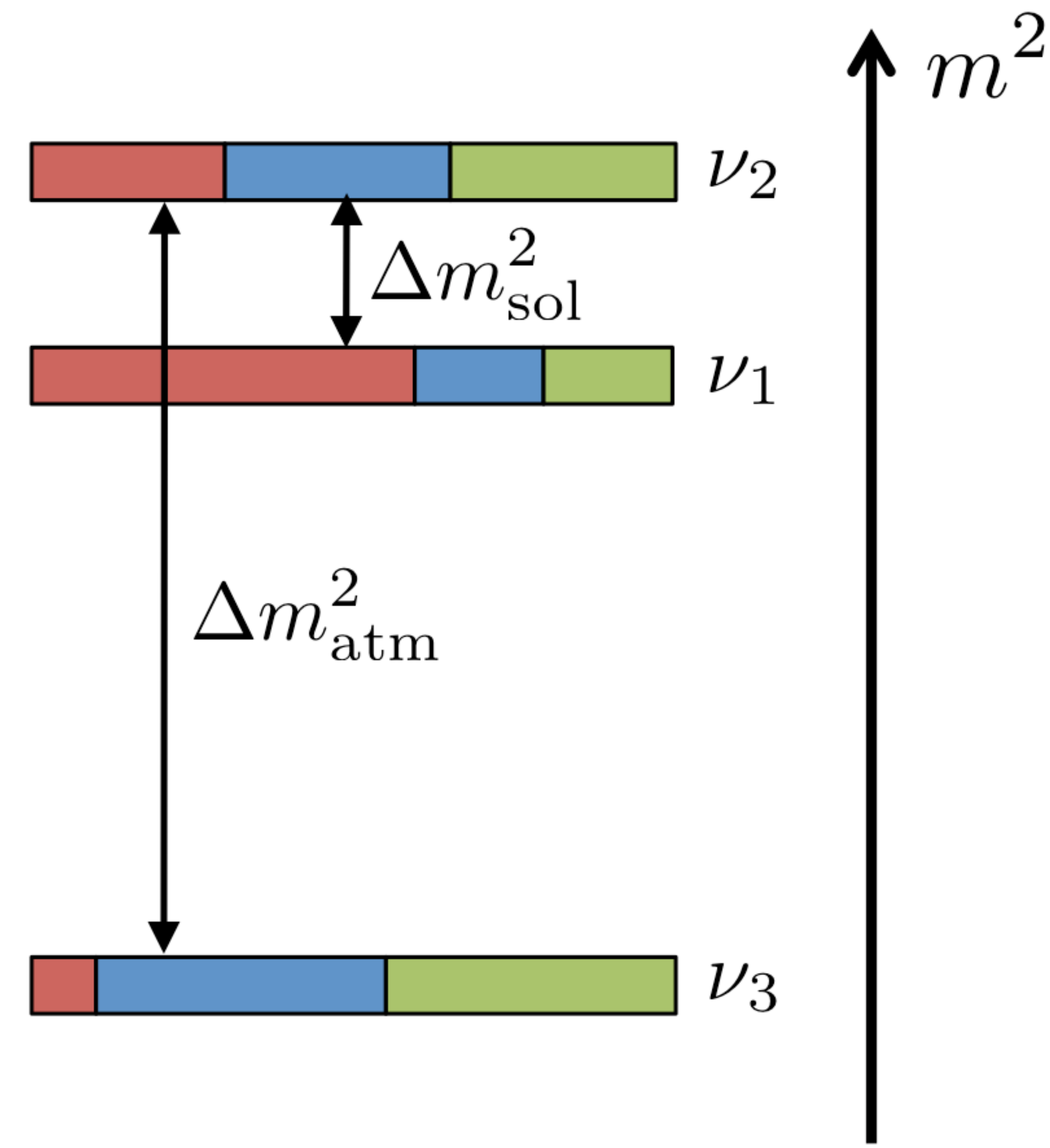
for CMB-S4 ($\ell > 5$) + DESI BAO + DESI RSD

normal hierarchy (NH)



$\sum m_\nu \geq 58$ meV

inverted hierarchy (IH)



$\sum m_\nu \geq 100$ meV

Complementarity of Neutrino mass constraints

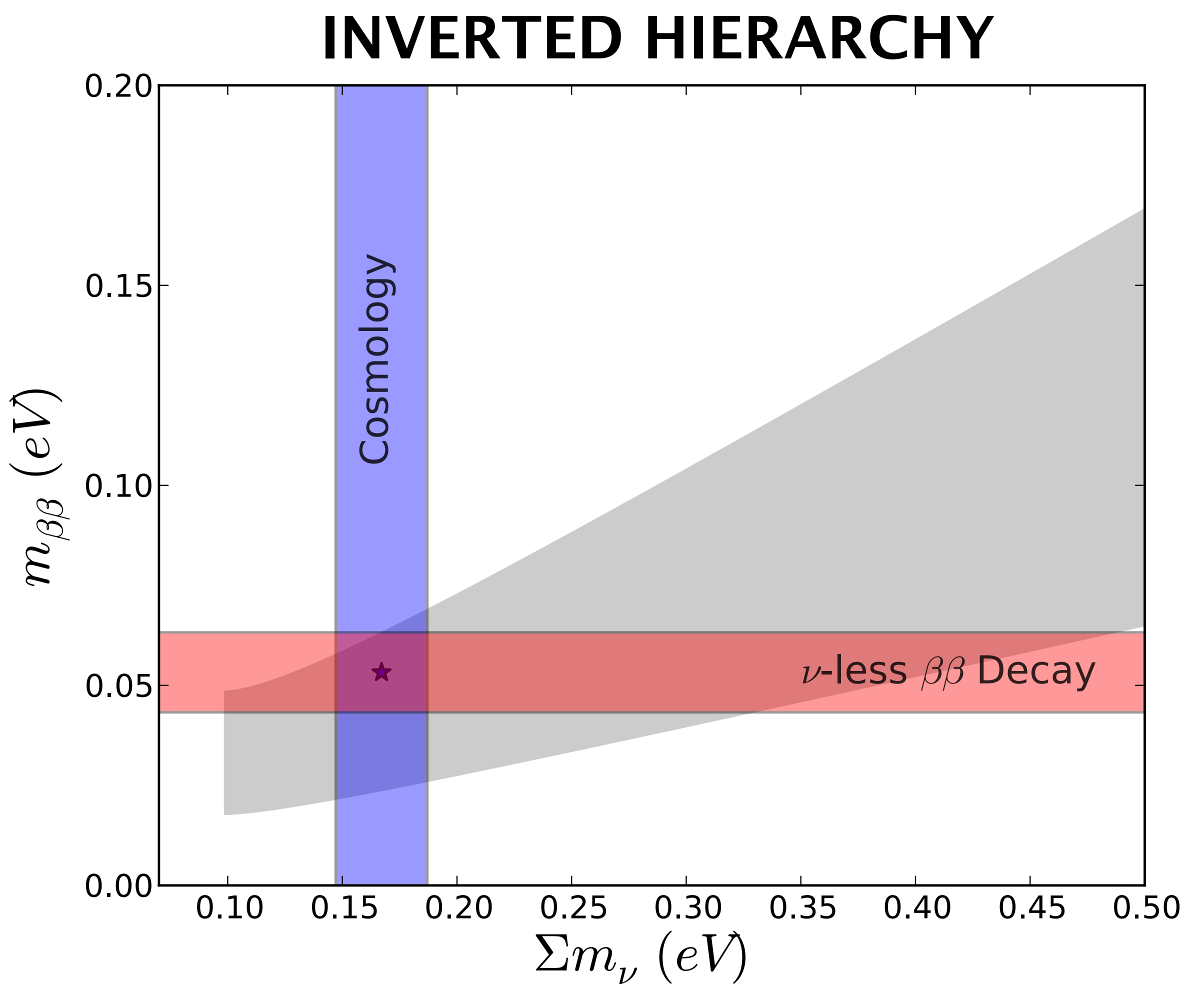


FIG. 1: Projected constraints on neutrino parameters from upcoming cosmic surveys (vertical), neutrino-less double beta decay experiments (horizontal), and all other current measurements (gray) assuming an inverted mass hierarchy and Majorana neutrinos.

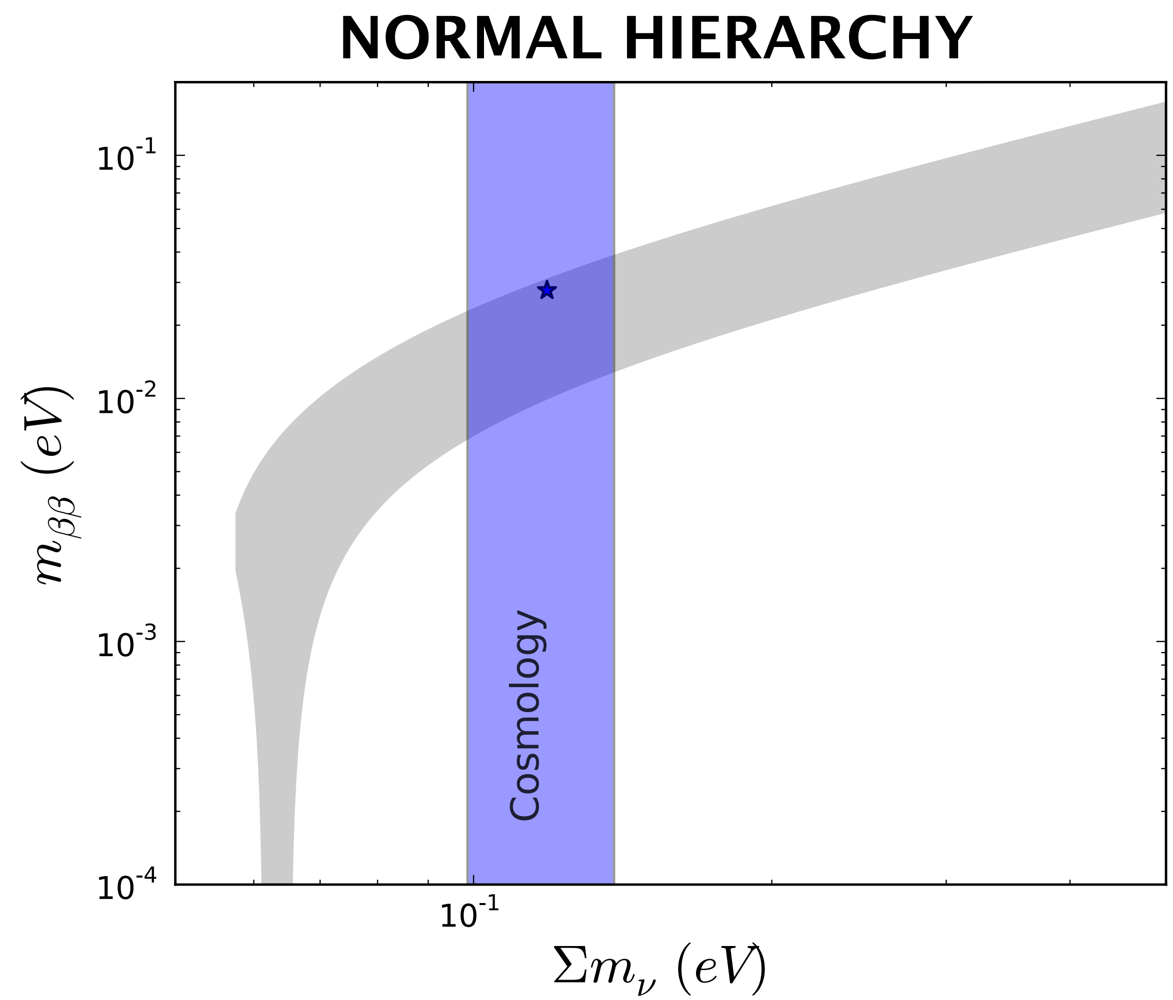
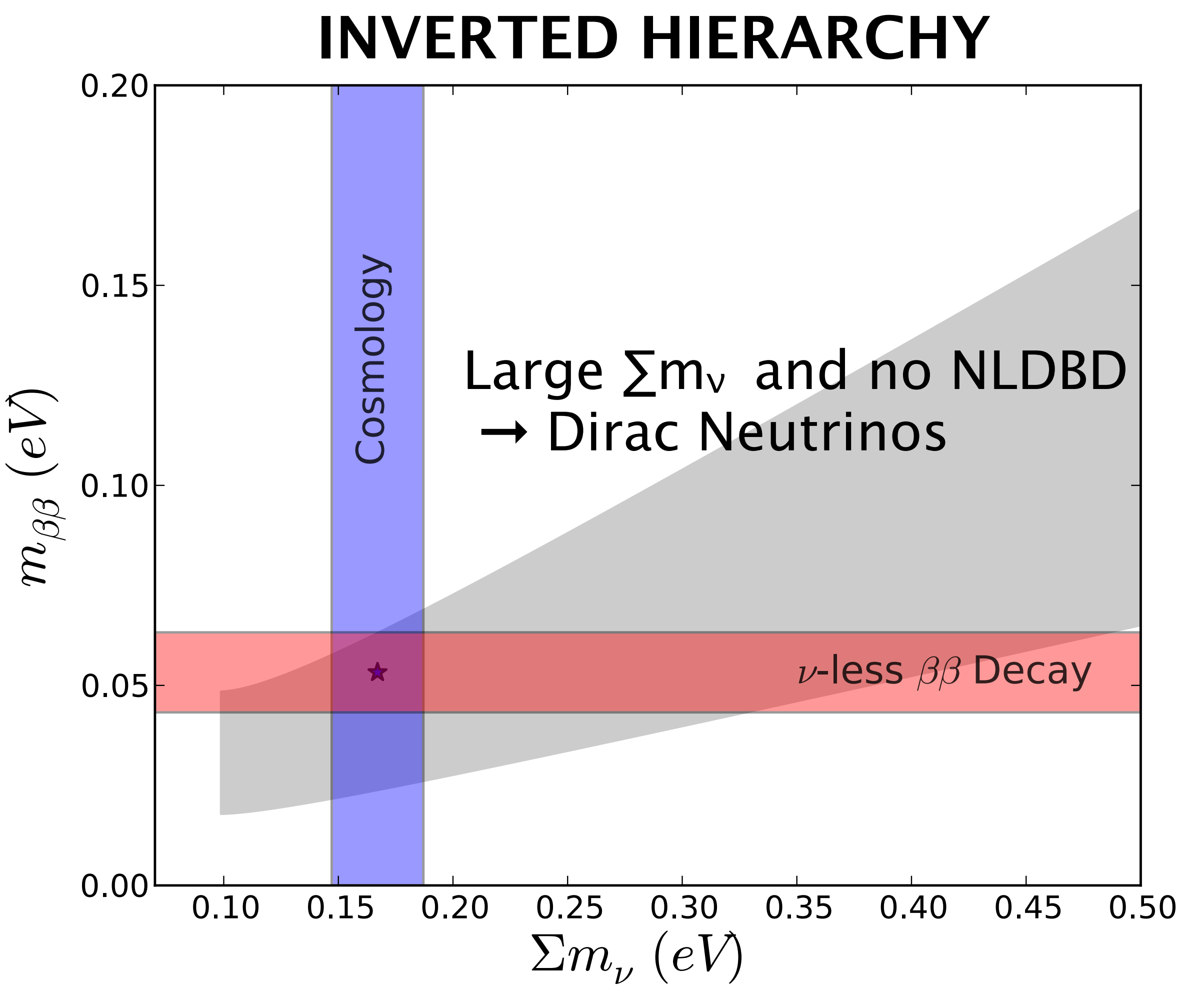


FIG. 3: If the mass hierarchy is normal but the sum of the masses is still relatively large, for example at the value indicated by the star, then there will be a lower limit on $m_{\beta\beta}$, a target for ambitious future double beta decay experiments.

Dodelson and Lykken arXiv:1403.5173

Complementarity of Neutrino mass constraints



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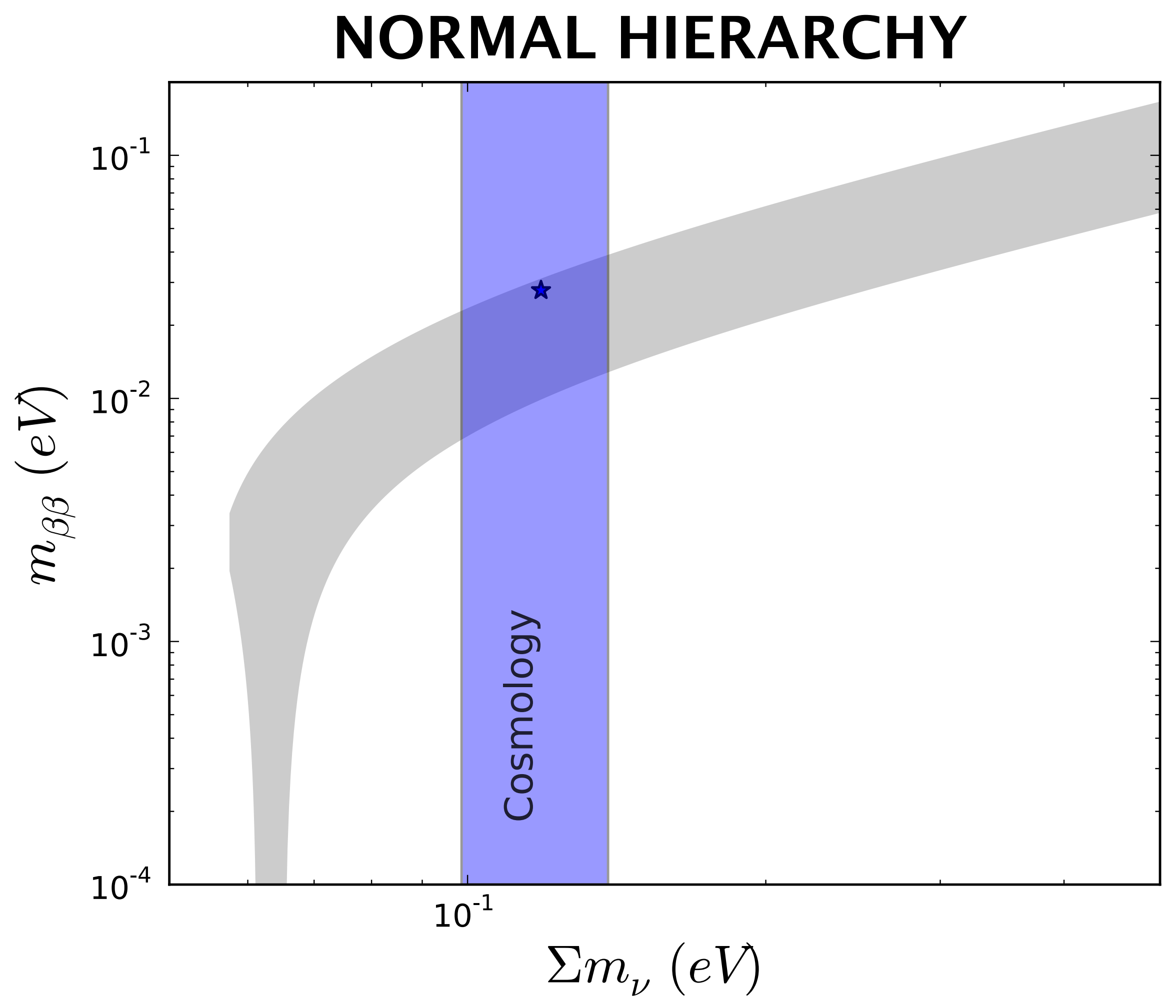

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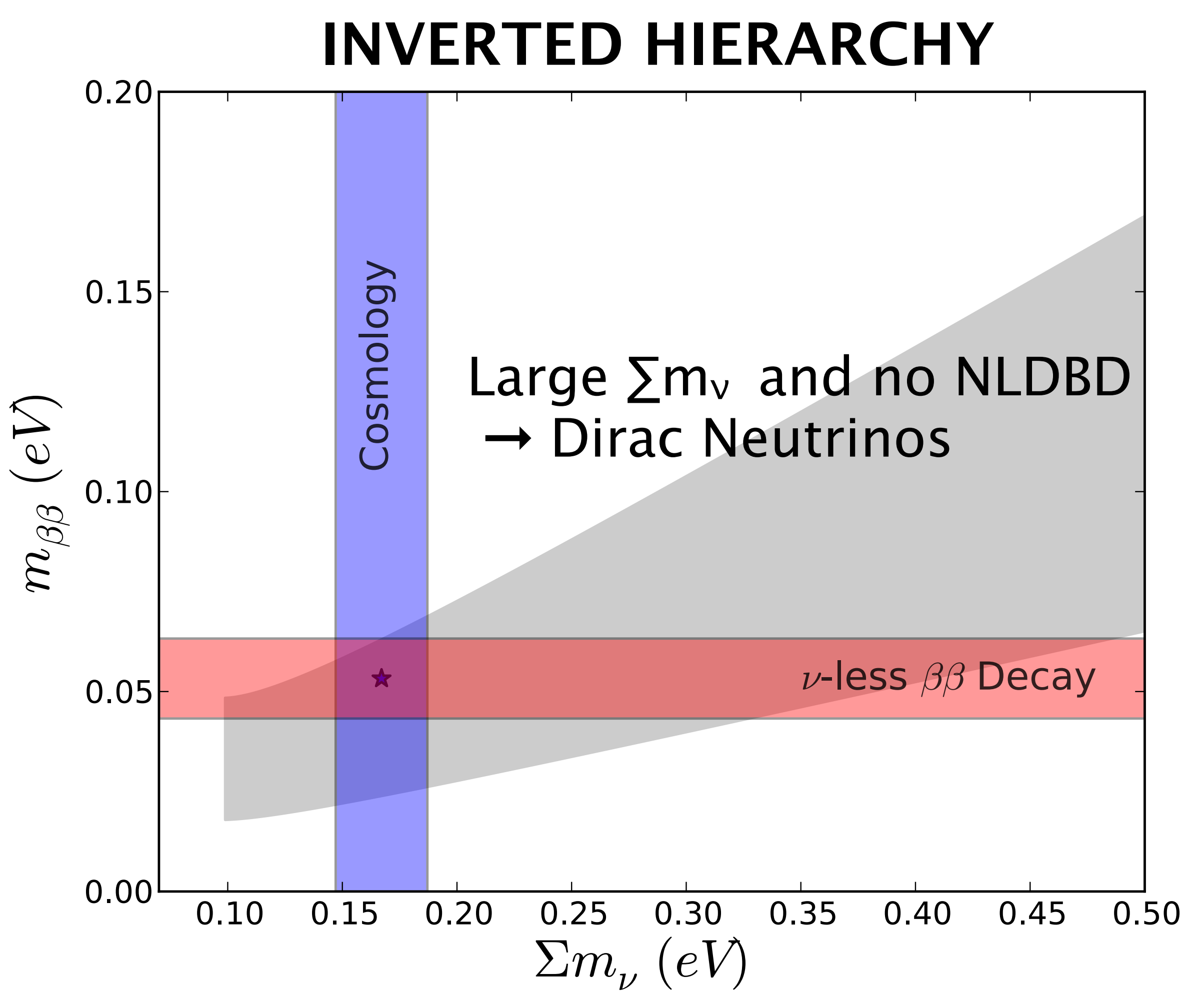

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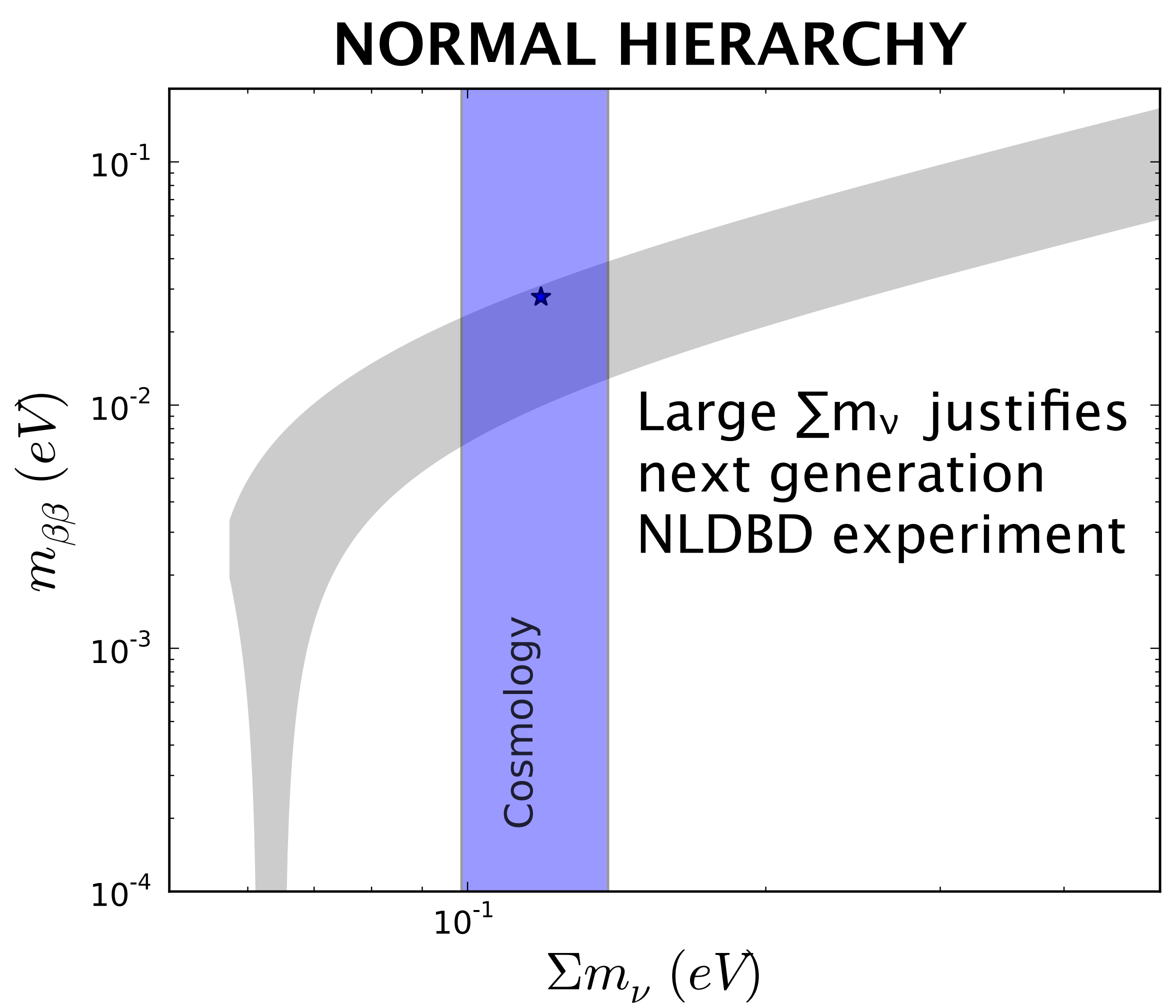

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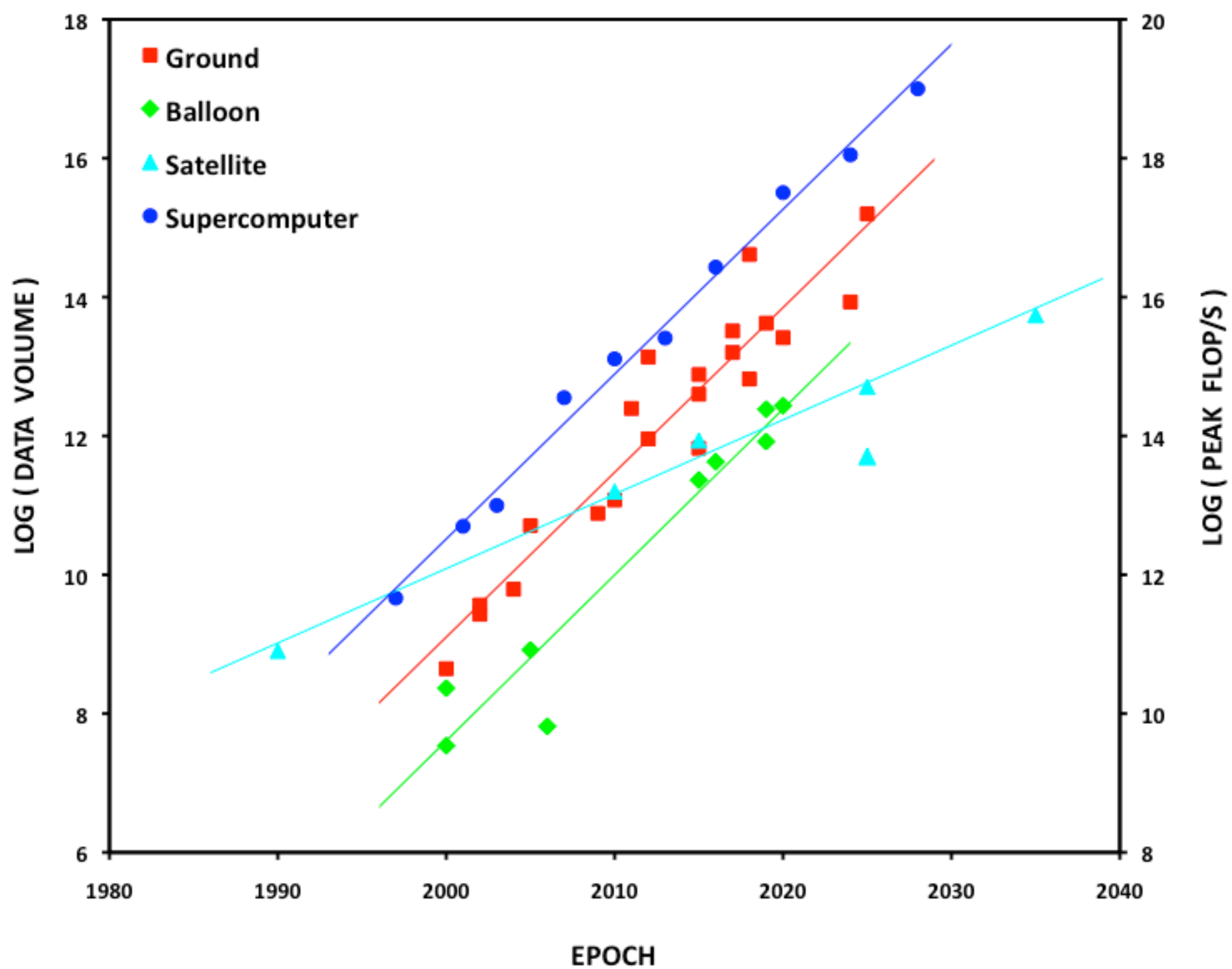
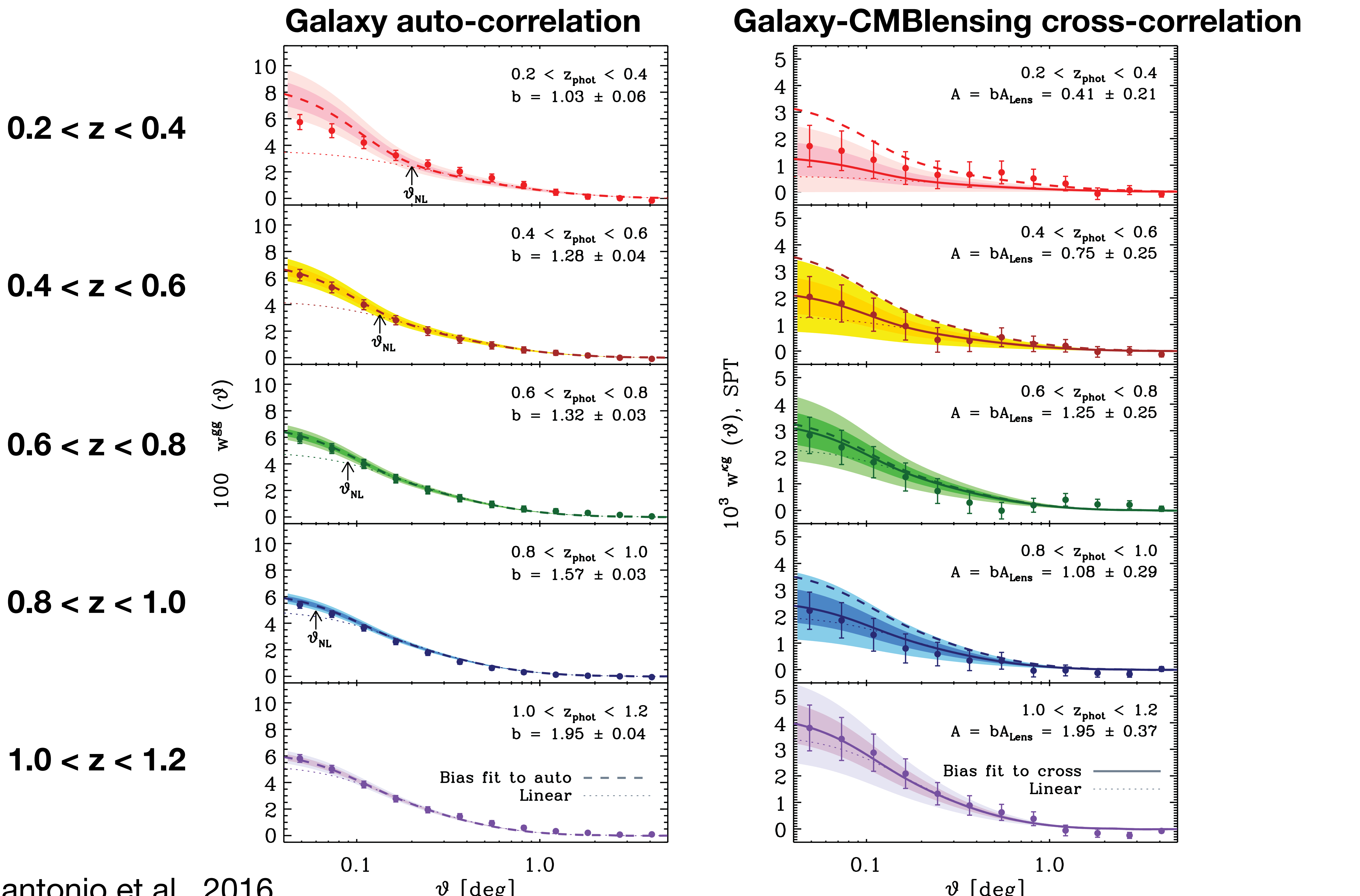
Big Data & High Performance Computing



Exponential data growth tracking Moore's Law

First start of CMB lensing tomography

3% of DES survey (science verification data)



Giannantonio et al., 2016

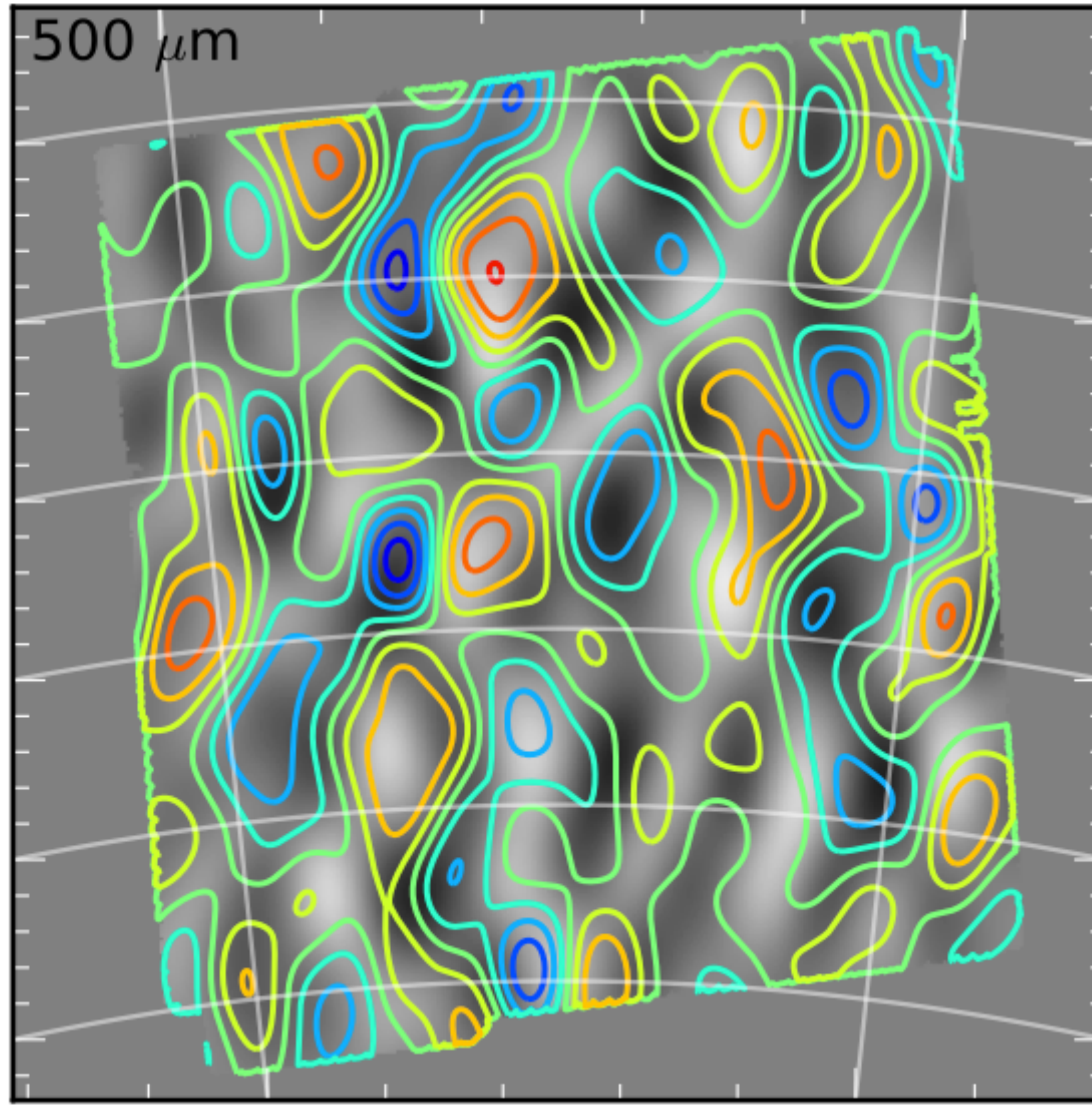
CMB lensing and optical surveys

CMB lensing reconstruction of mass maps sensitive to growth of structure, probe neutrino mass

CMB lensing will complement large optical surveys such as DES, eBOSS, LSST, DESI, 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)

Holder et al. arXiv:1303.5048



Correlation of matter traced by CMB lensing (contours) and distribution of high z galaxies (grayscale; Herschel 500 um)