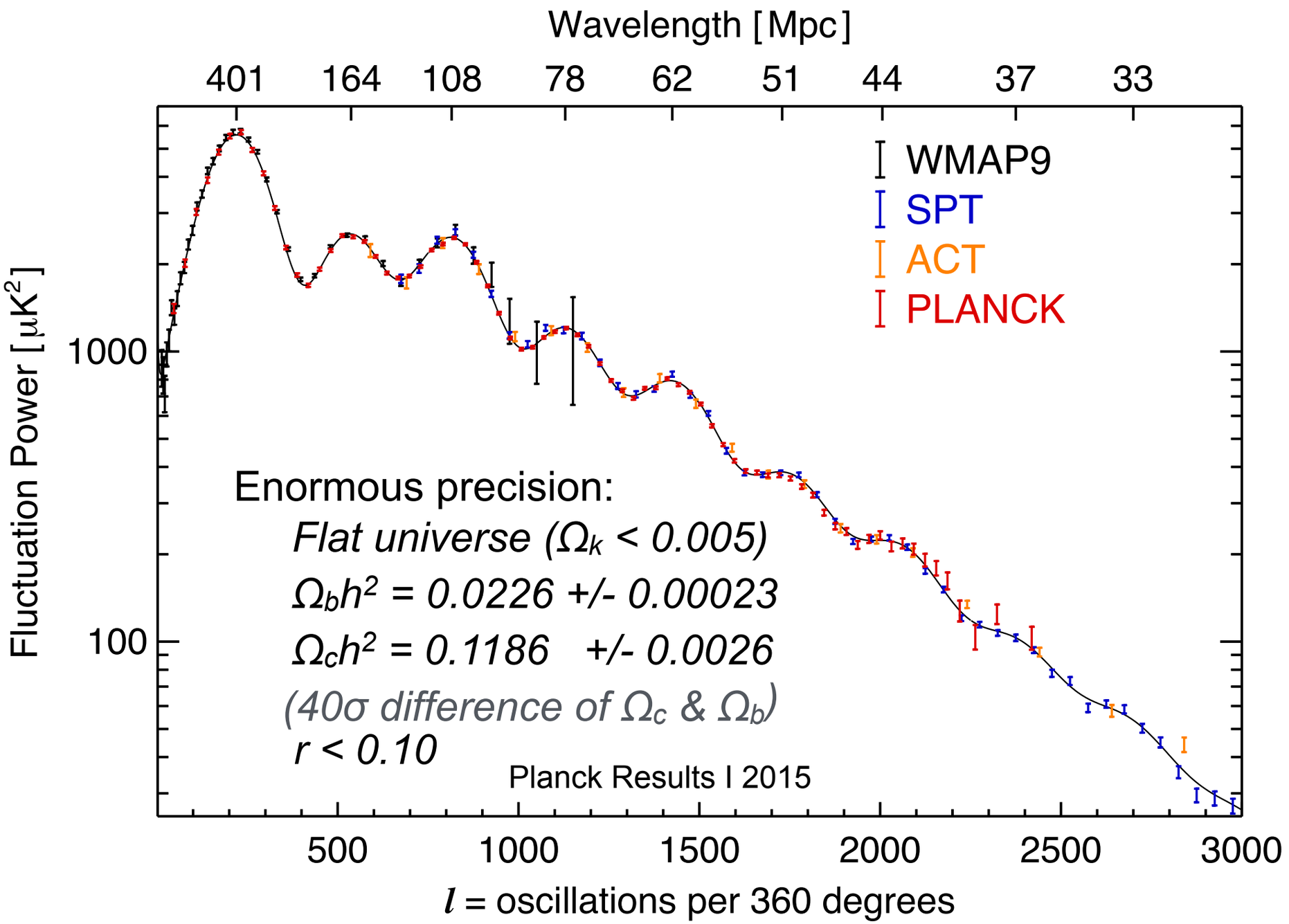
Next Generation Ground-based CMB Program: CMB-S4

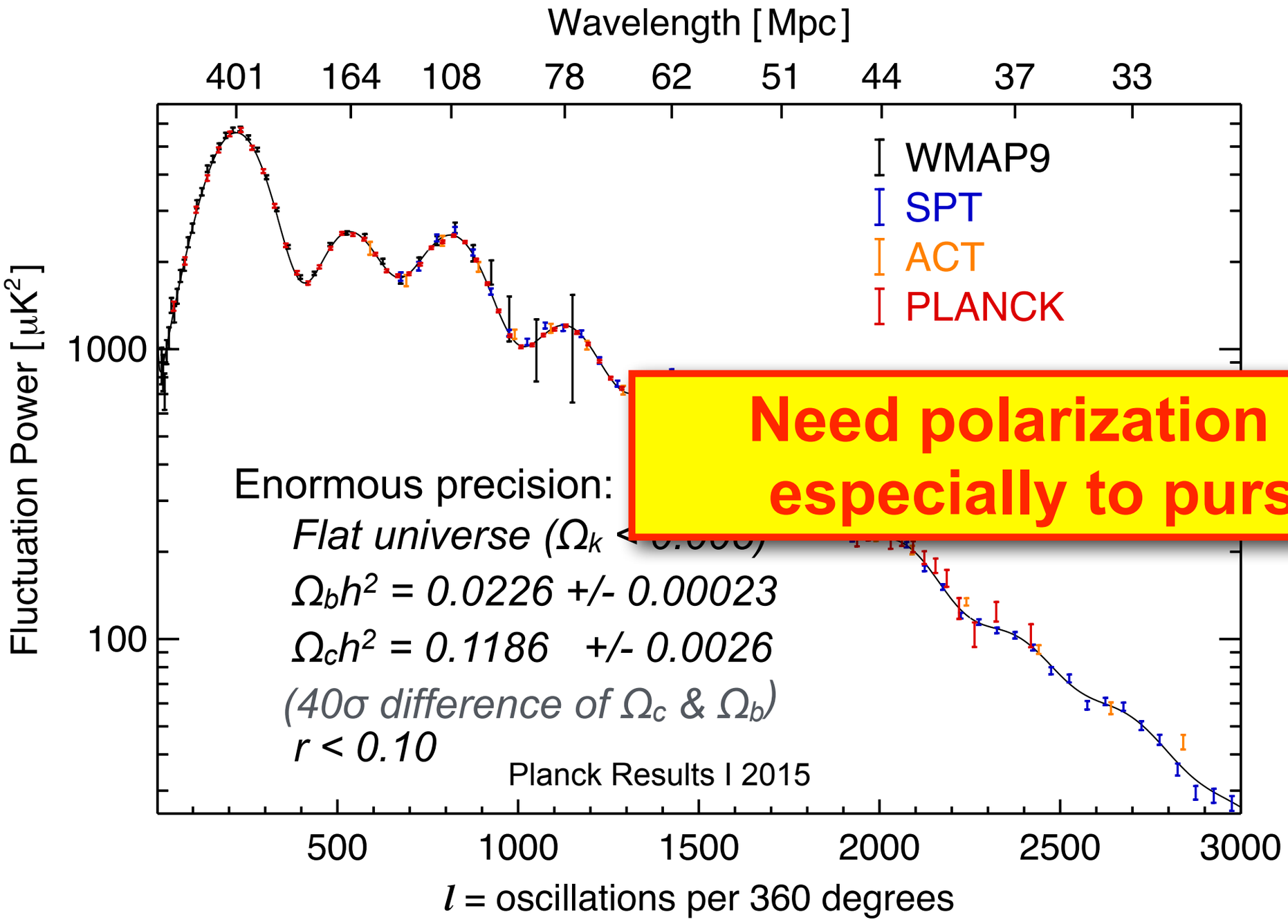
John Carlstrom
for CMB-S4ers

Primary CMB TT anisotropy done?



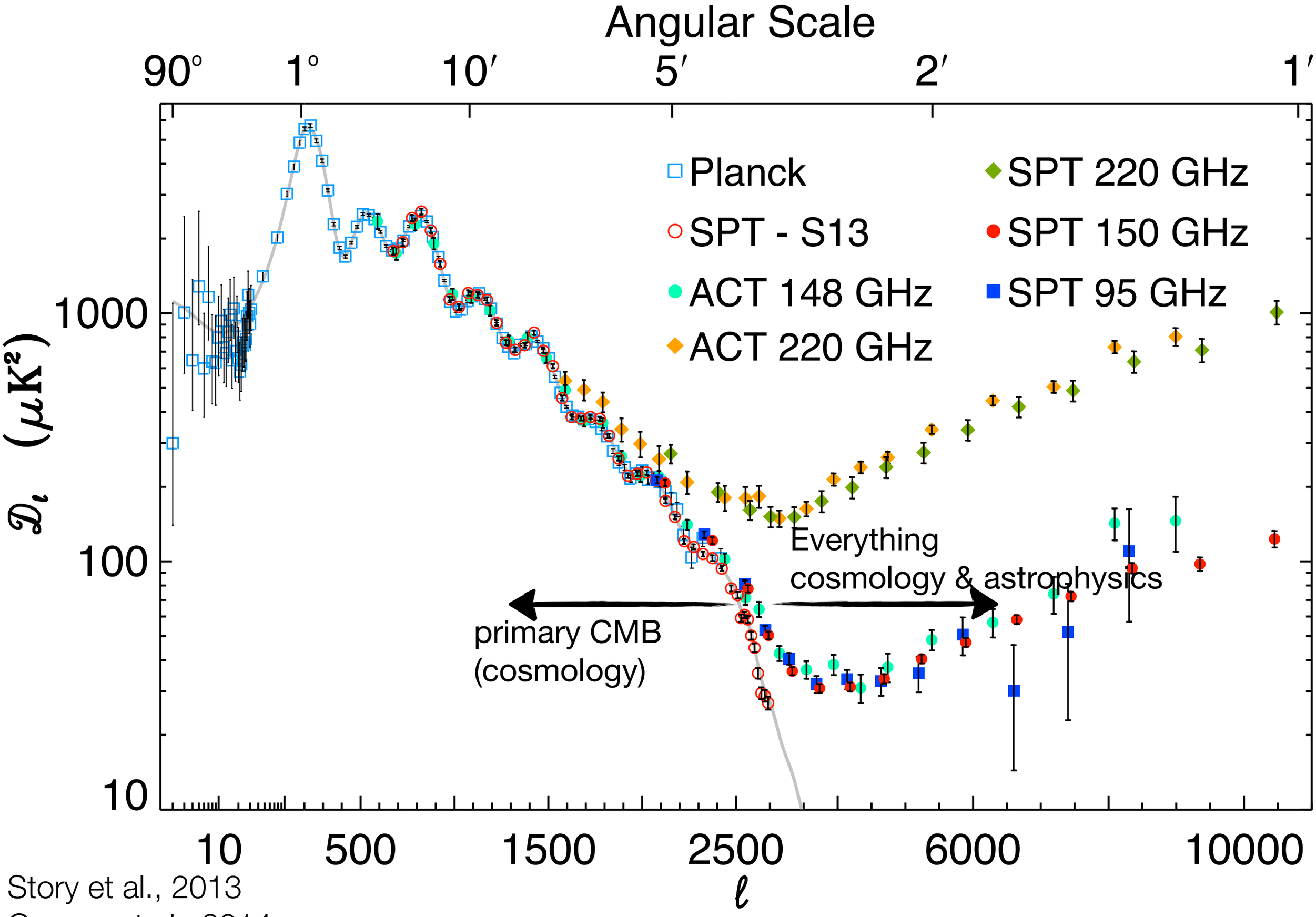
Fit by vanilla ΛCDM - just six parameters: $\Omega_b h^2$ $\Omega_c h^2$ Ω_Λ Δ^2_R n_s τ

Primary CMB TT anisotropy done?

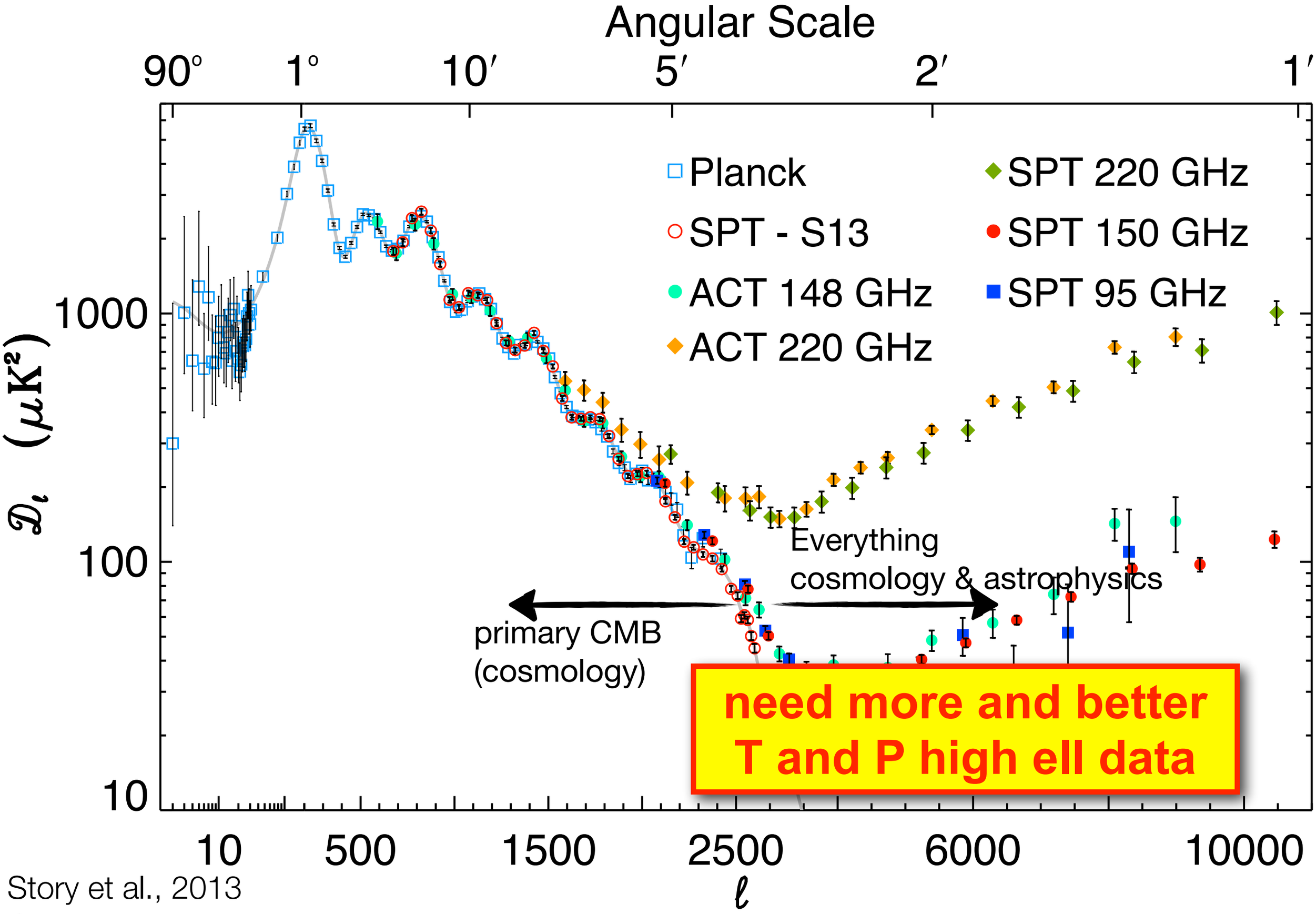


Need polarization data, especially to pursue *r*

Fit by vanilla ΛCDM - just six parameters: $\Omega_b h^2$ $\Omega_c h^2$ Ω_Λ Δ^2_R n_s τ



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



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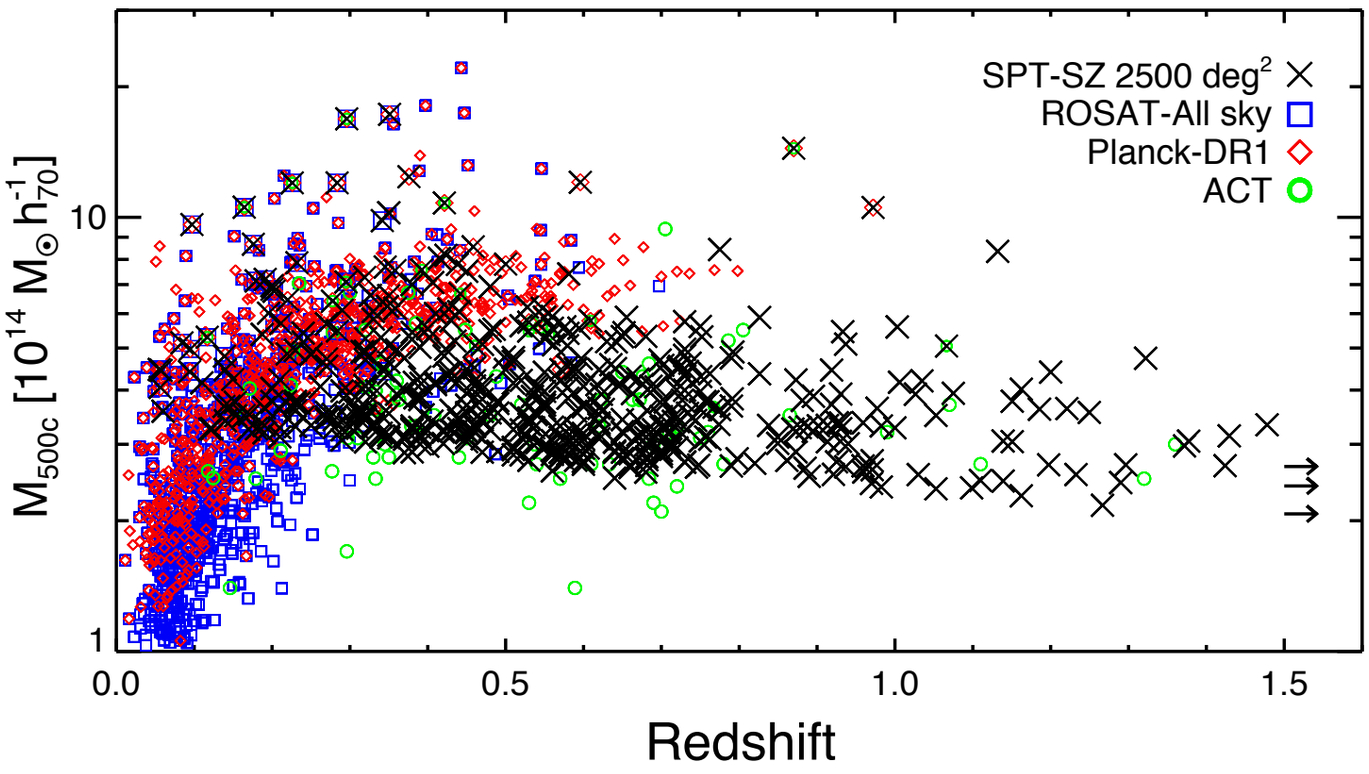
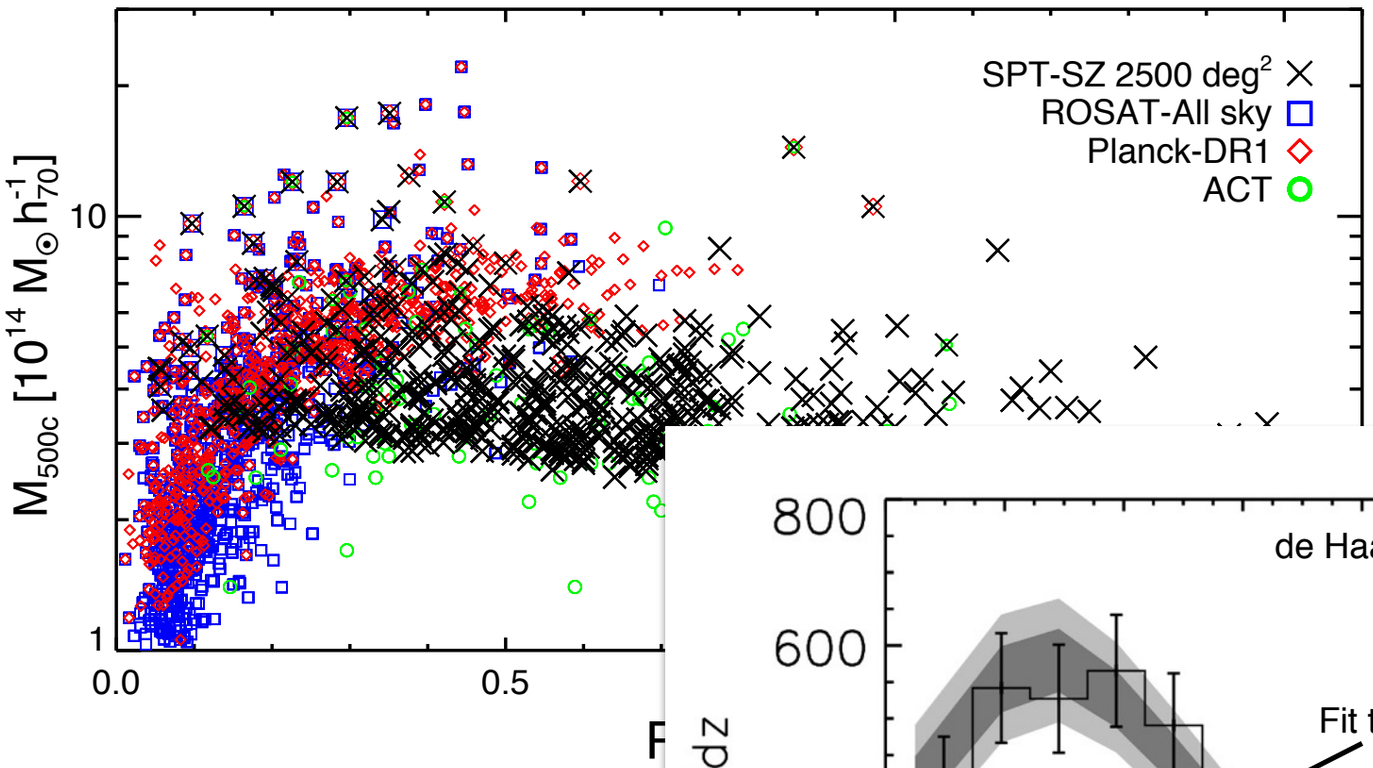
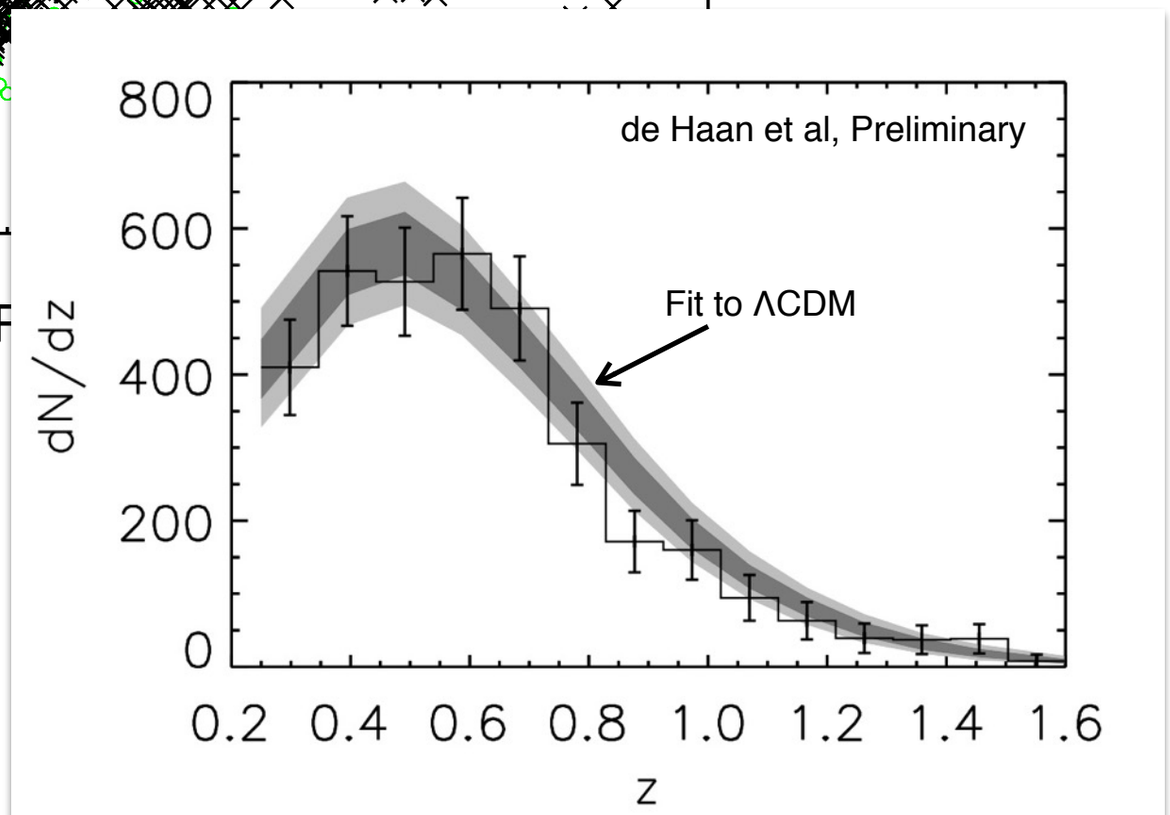


e.g., cosmology with SZ clusters

- Tracing the growth of structure with massive galaxy clusters. **Incredible progress - still a long way to go.**
- Some tension between Planck predictions and measured clusters. **Mass calibration or hint of new physics…**

e.g., cosmology with SZ clusters





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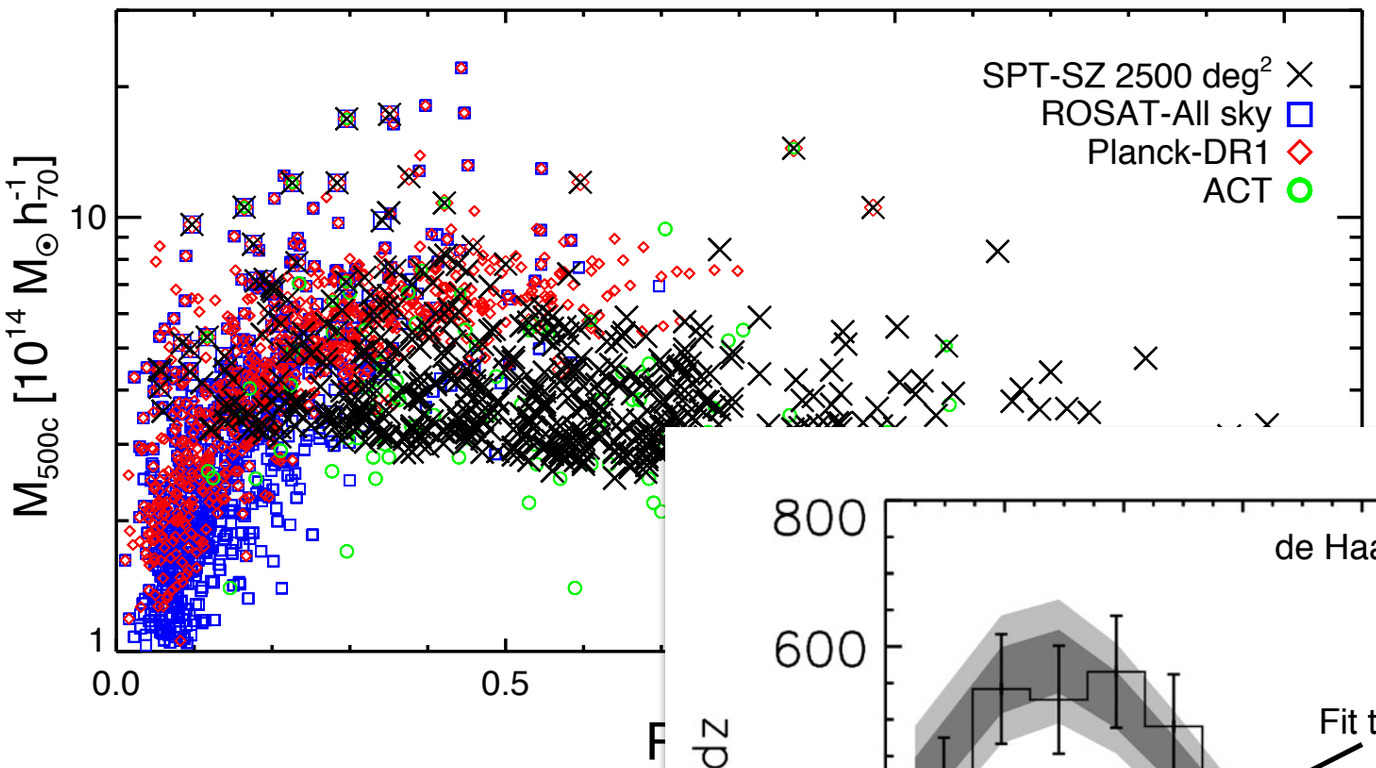
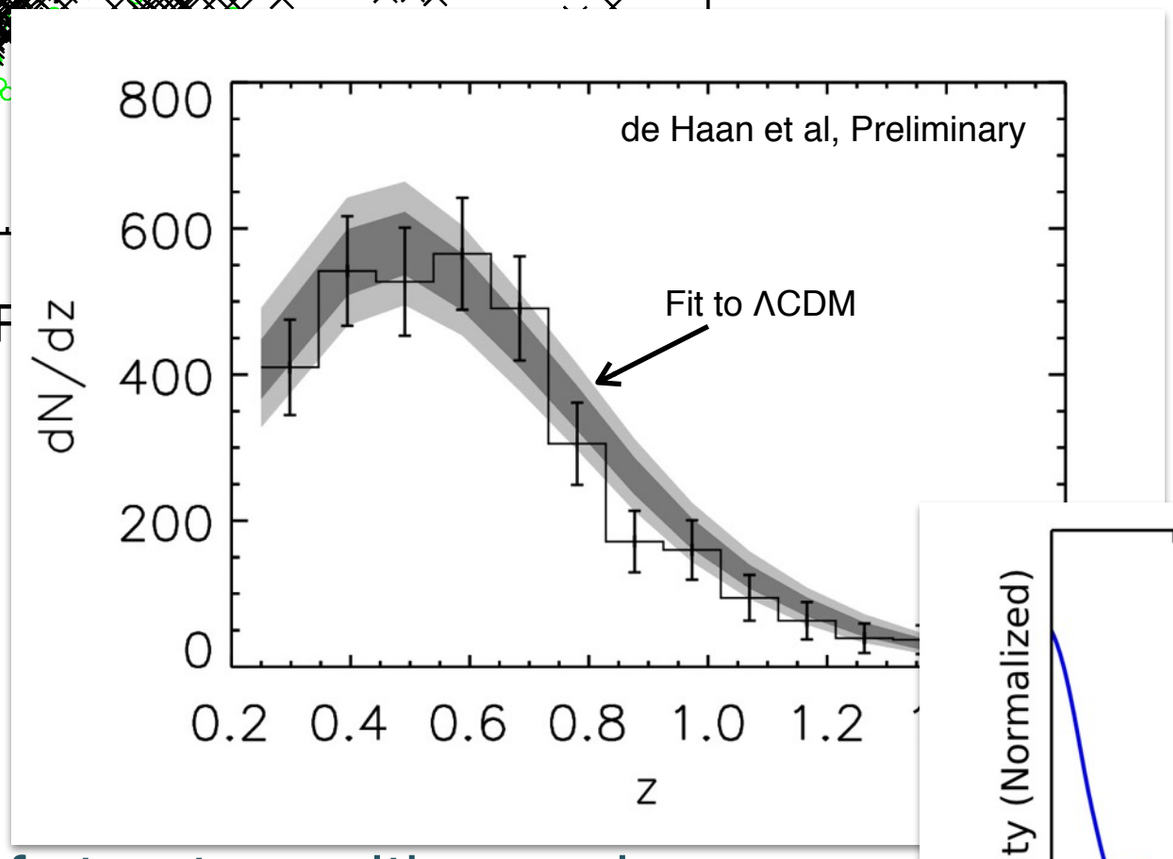
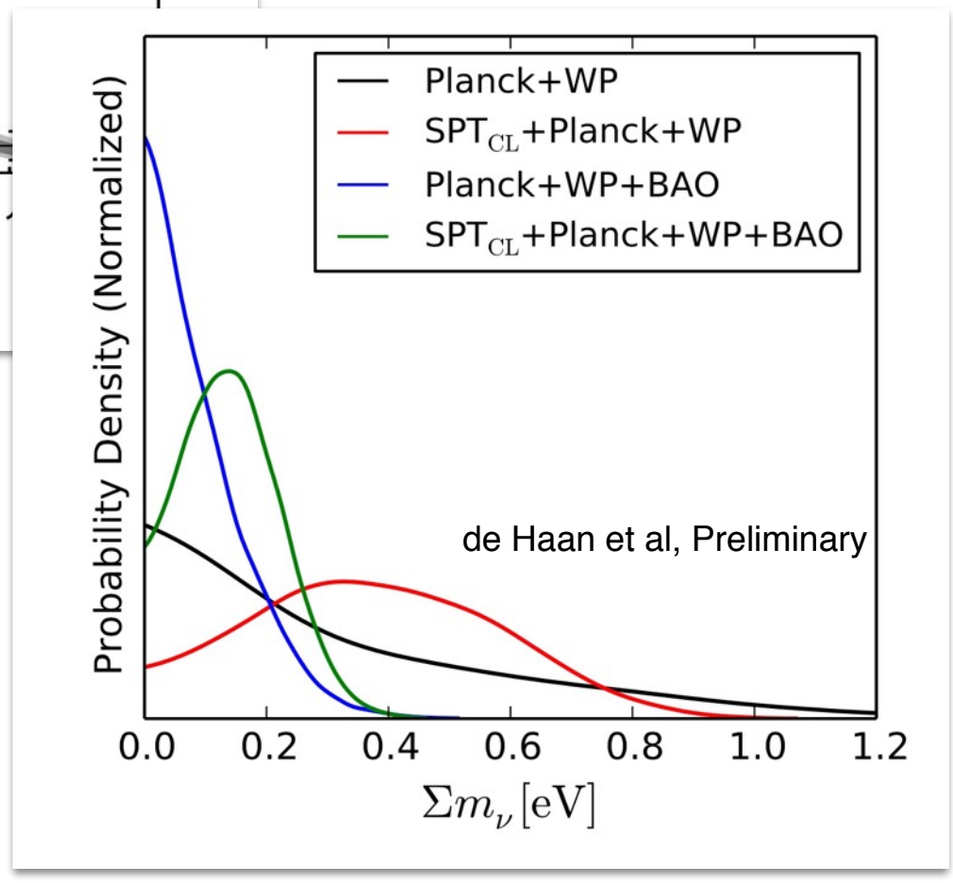
e.g., cosmology with SZ clusters







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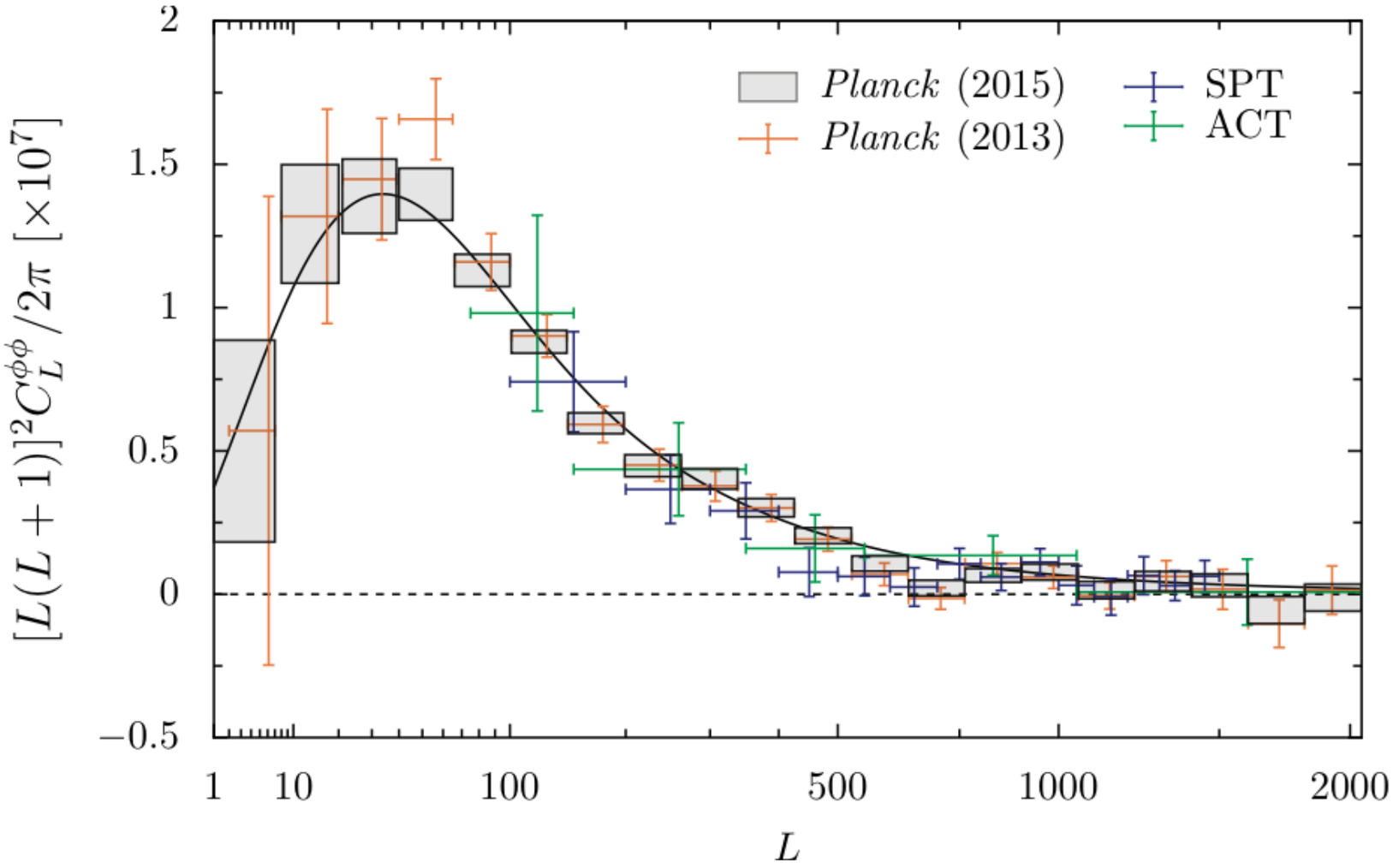
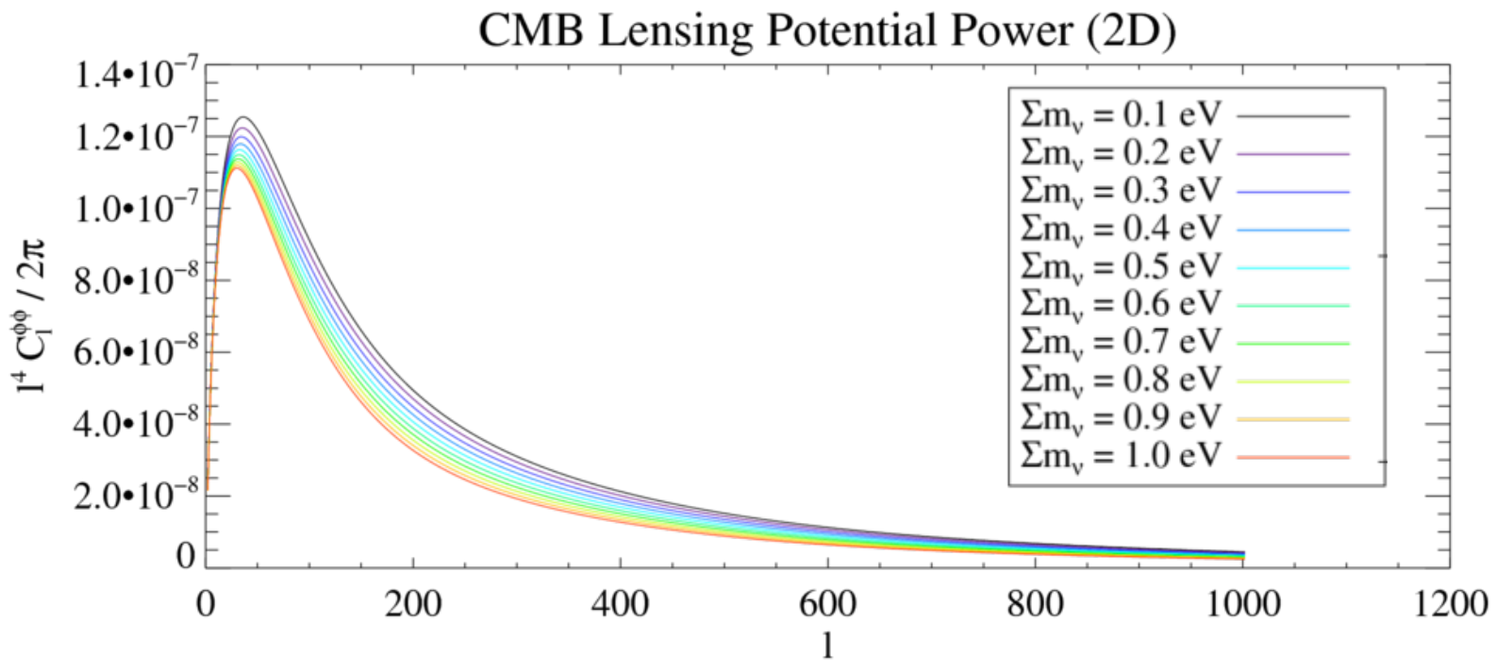
CMB lensing power spectrum

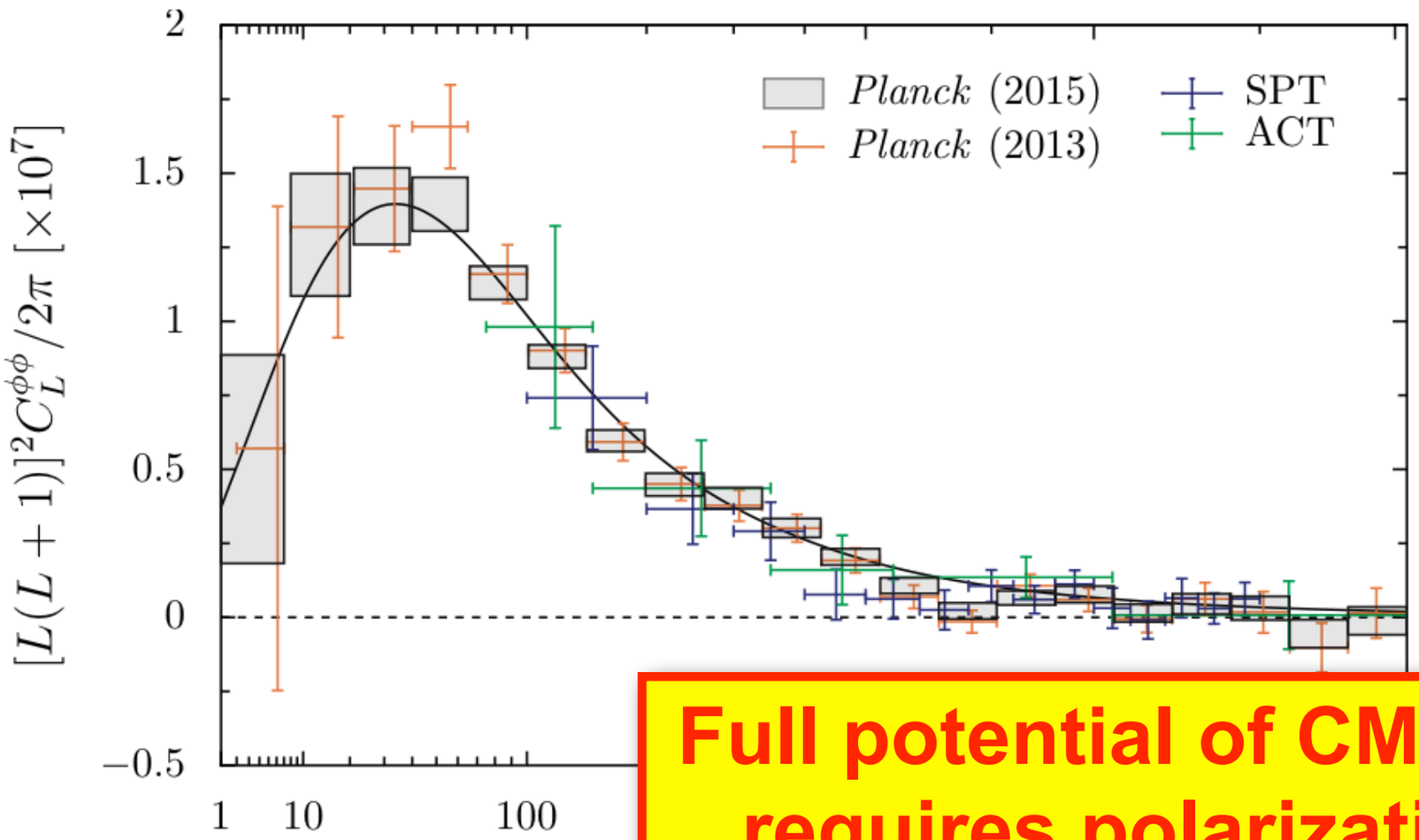


Sensitive to neutrino masses

CMB Polarization provides additional lensing sensitivity and is cleaner probe.



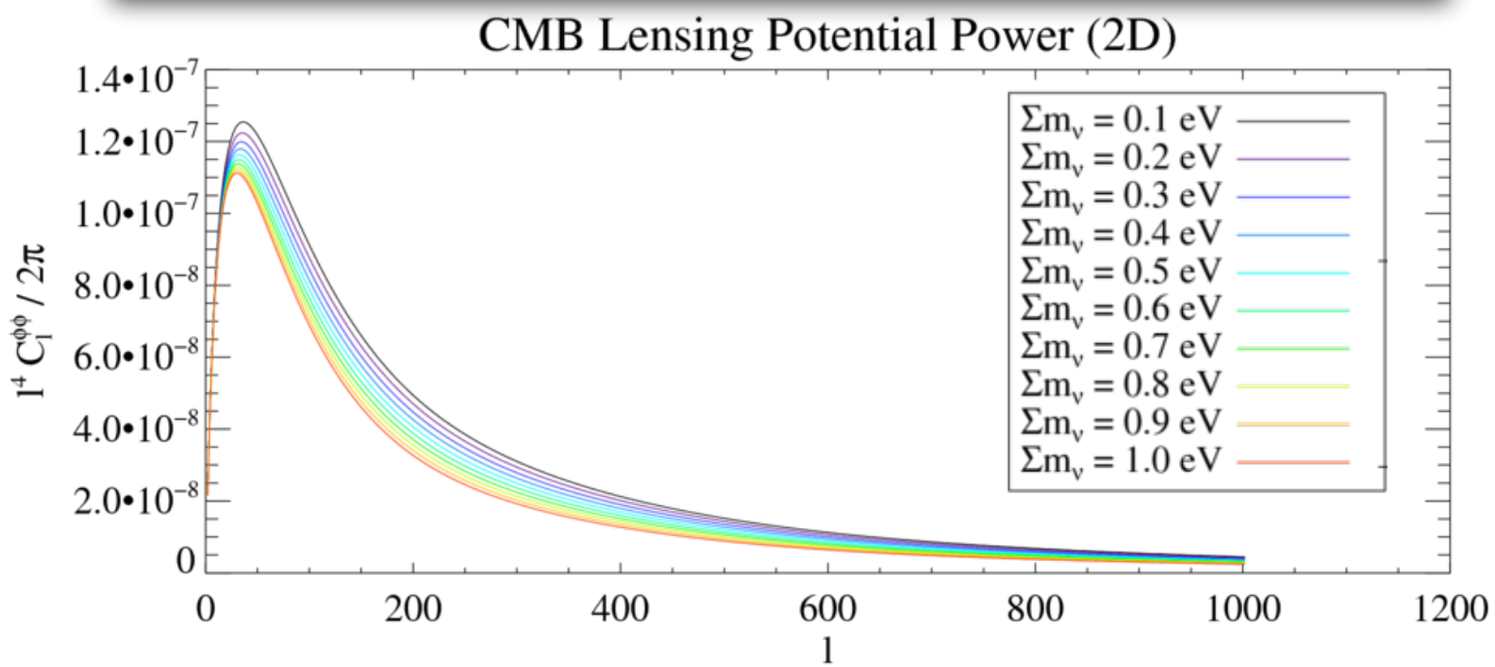
CMB lensing power spectrum



Full potential of CMB lensing requires polarization data

Sensitive to neutrino masses

CMB Polarization provides additional lensing sensitivity and is cleaner probe.

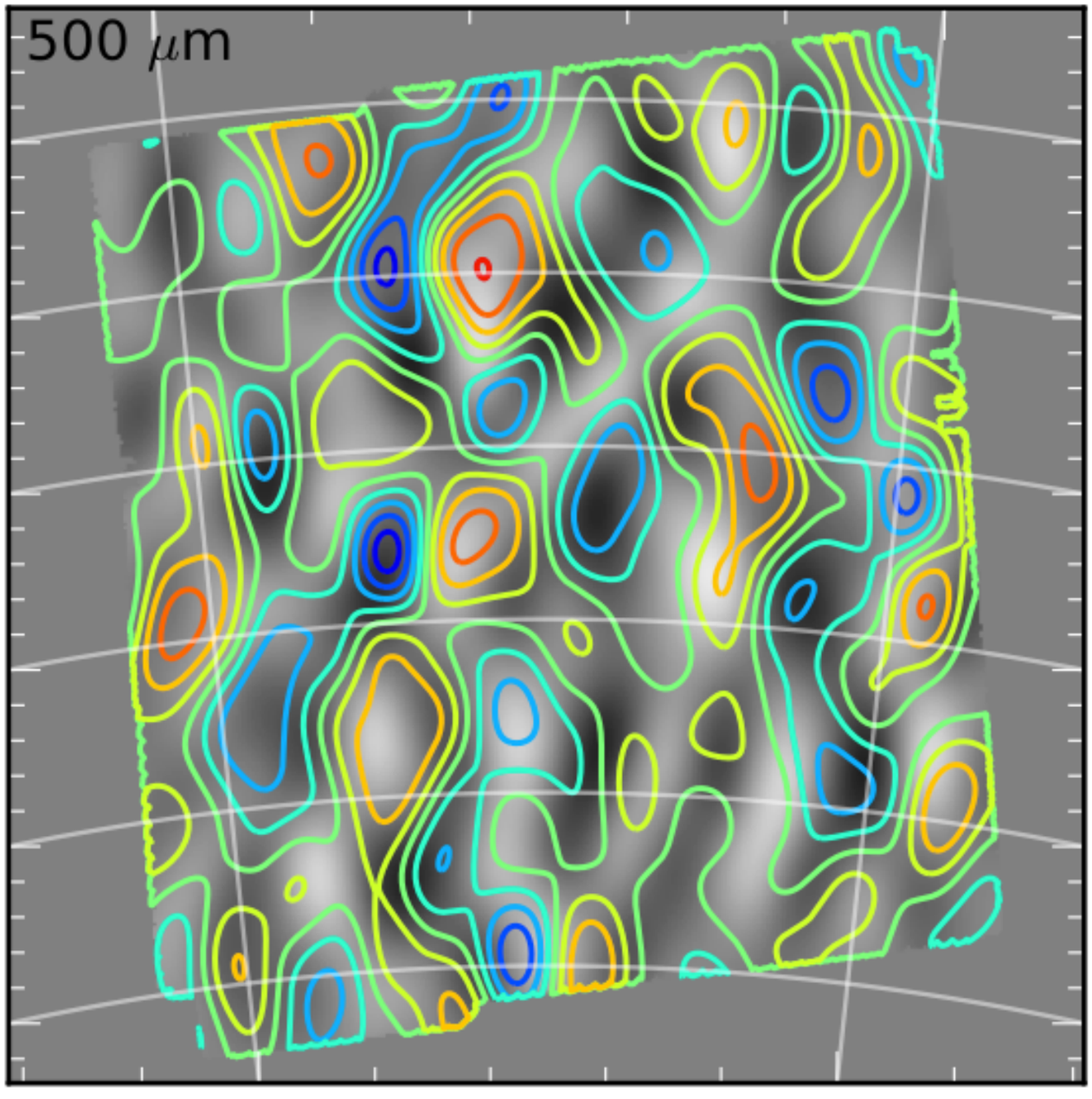


CMB lensing and optical surveys

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

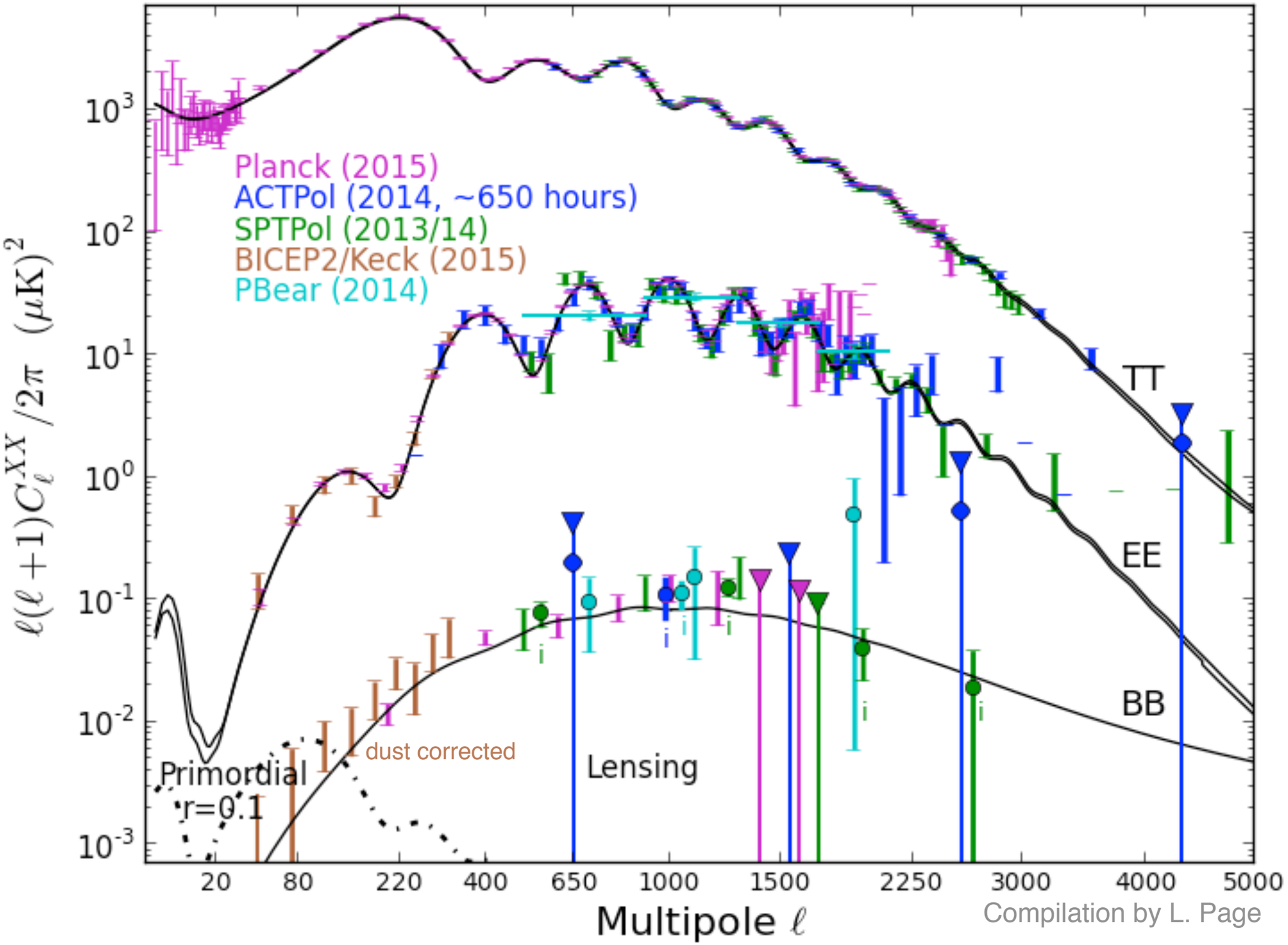
The combination leads to better shear-bias calibration and more robust constraints on Dark Energy and the properties of neutrinos.

Holder et al. arXiv:1303.5048



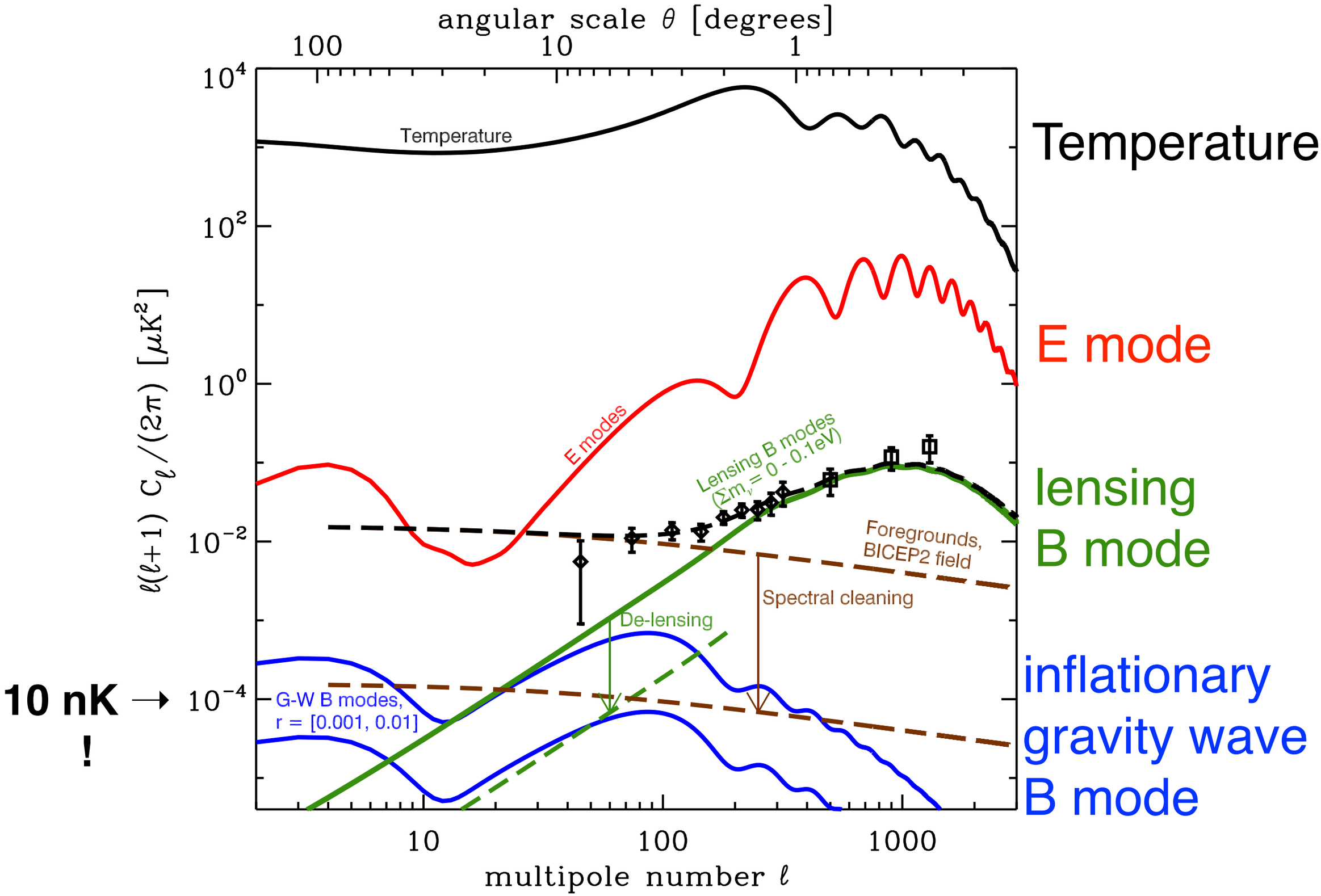
Correlation of matter traced by SPT CMB lensing (contours) and distribution of high z galaxies (grayscale; Herschel 500 um)

CMB polarization measurements



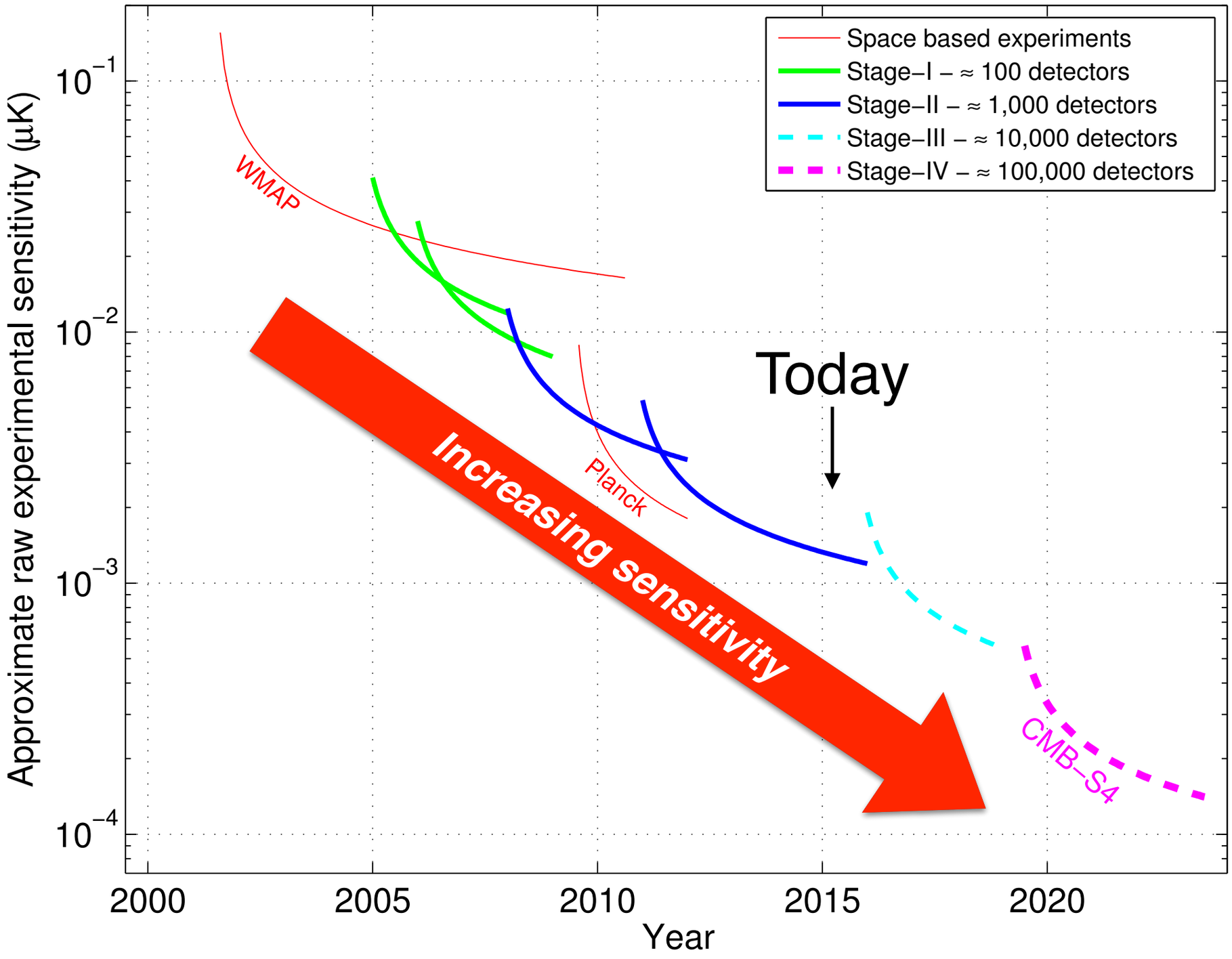
Rapid progress! All in last ~2 years.

CMB polarization measurements



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

The next great step forward - Stage IV



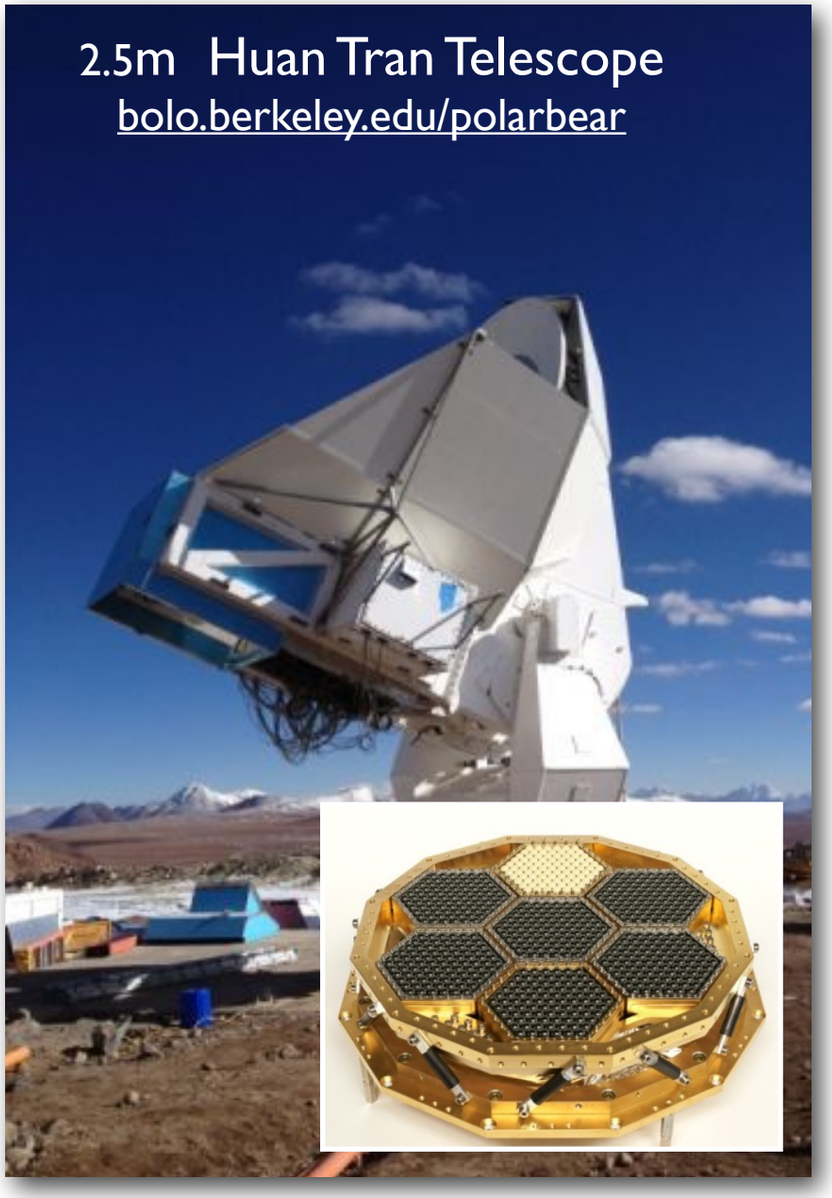
future Satellite?

A Moore's Law of CMB sensitivity

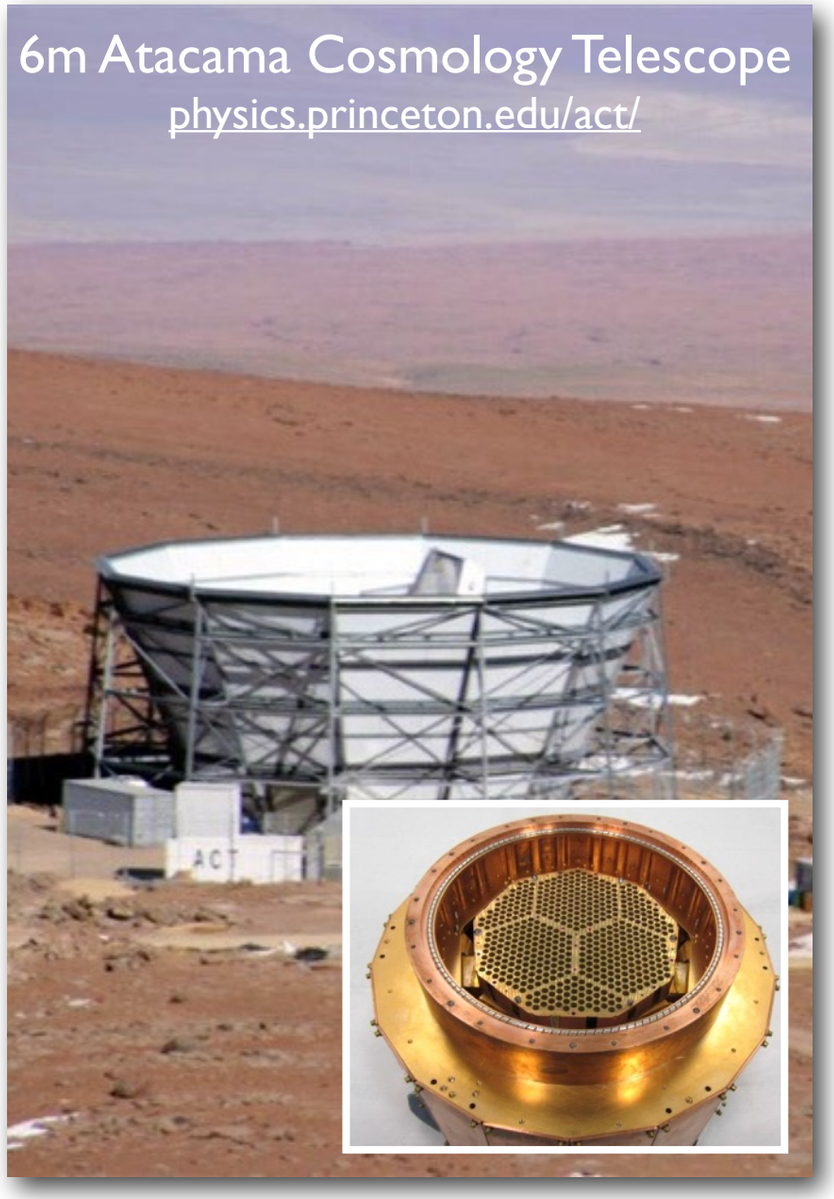
Snowmass CF5 Neutrinos Document arxiv:1309.5383; figure by Clem Pryke

Current generation of large aperture CMB telescopes

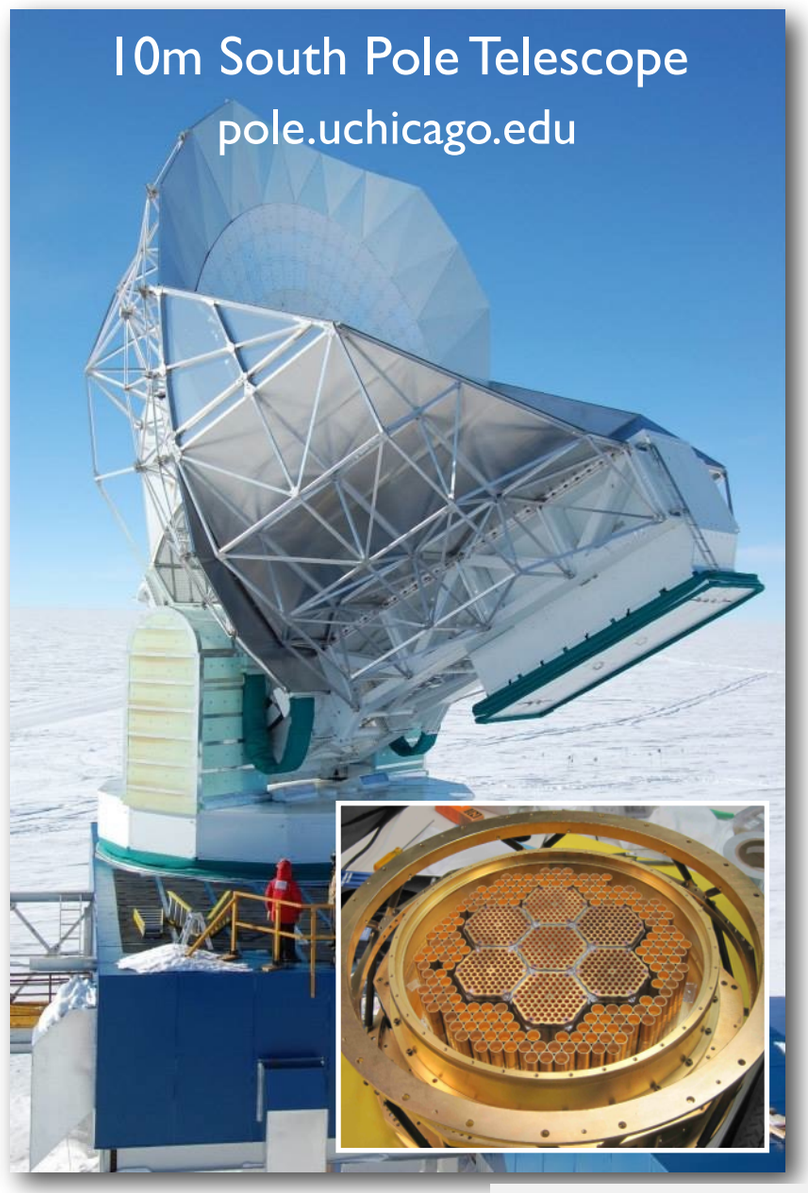
2.5m Huan Tran Telescope
bolo.berkeley.edu/polarbear



6m Atacama Cosmology Telescope
physics.princeton.edu/act/

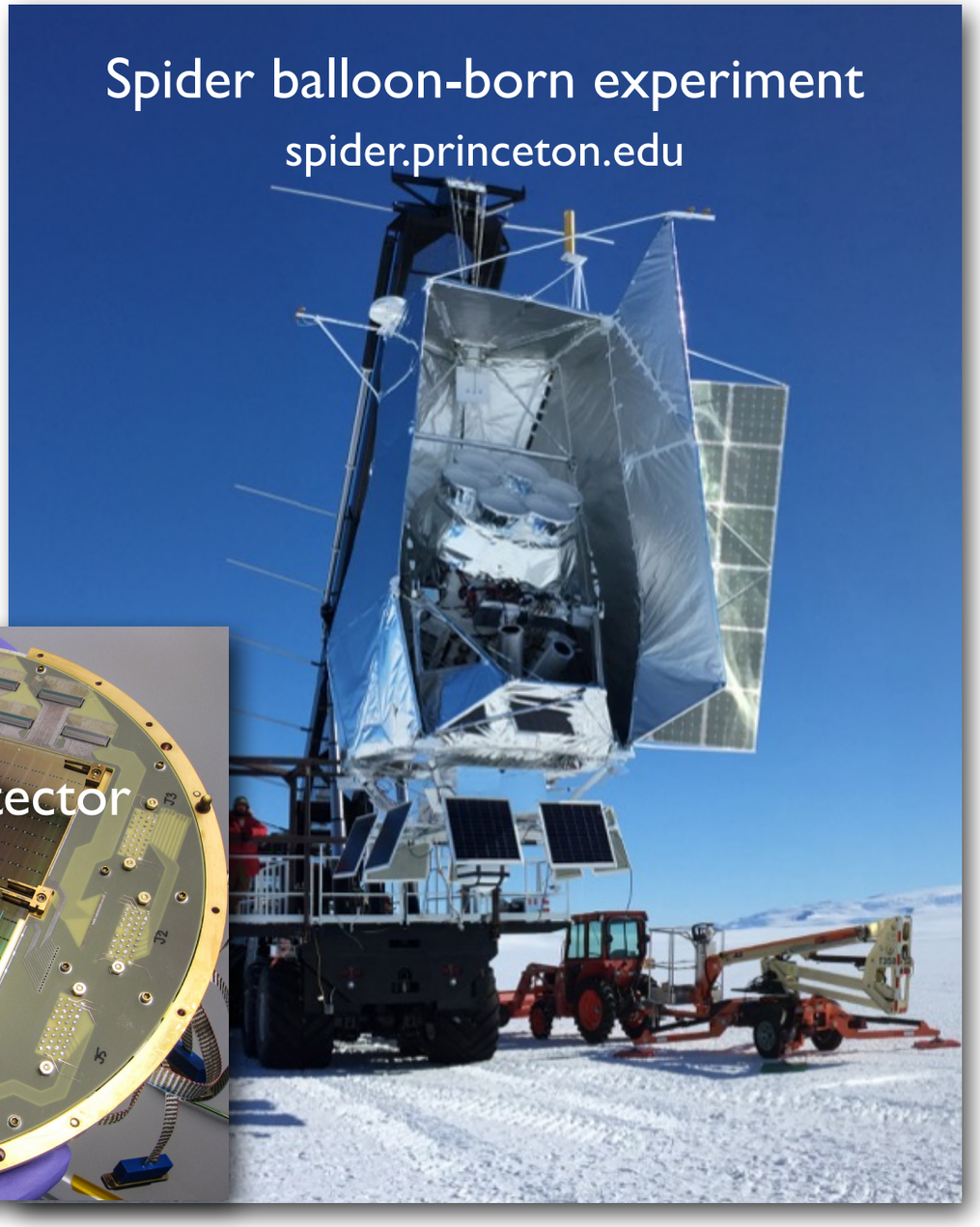


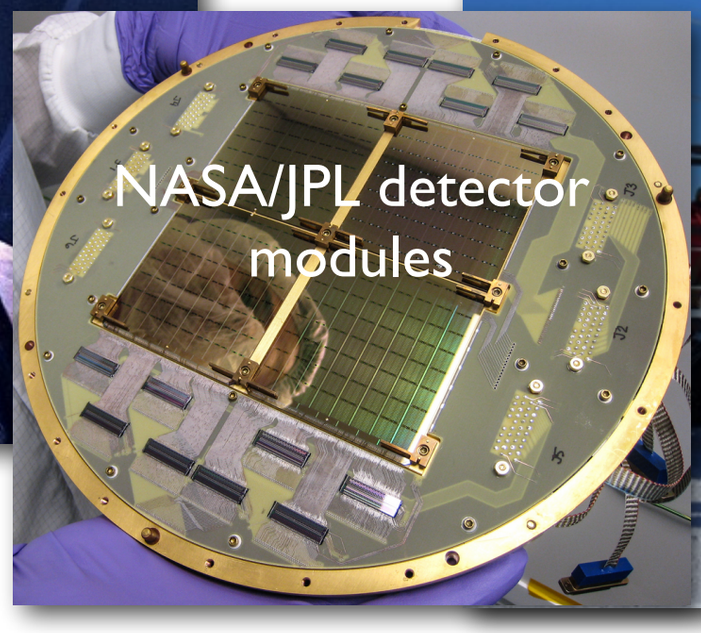
10m South Pole Telescope
pole.uchicago.edu



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

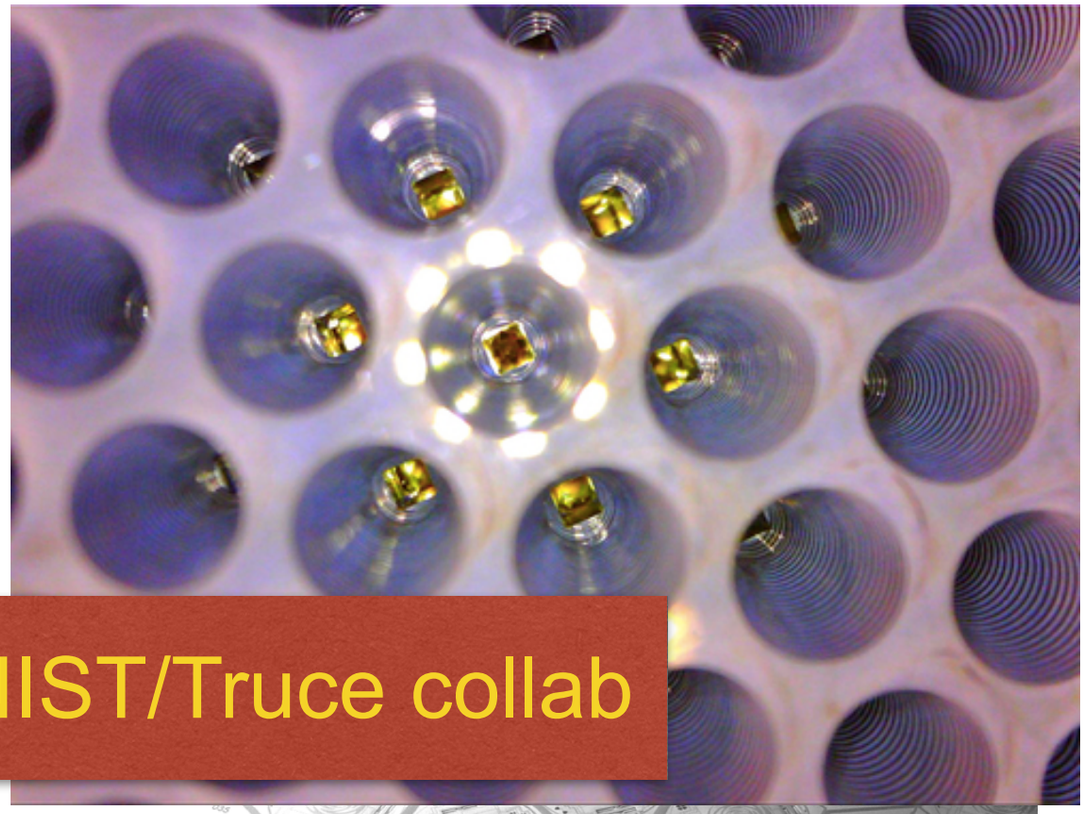
And current small aperture CMB telescopes





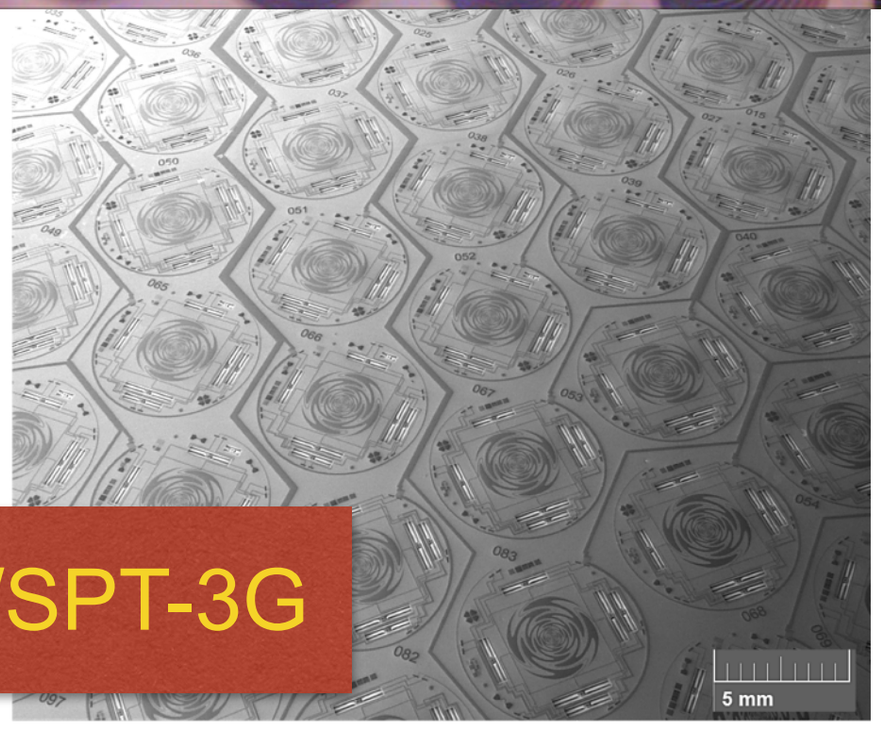
Also
Ground: ABS, CLASS,QUBIC, QUIJOTE, GroundBird
Balloon: EBEX, PIPER, LSPE
Satellite proposals: LiteBird, PIXIE

Detector design and fabrication

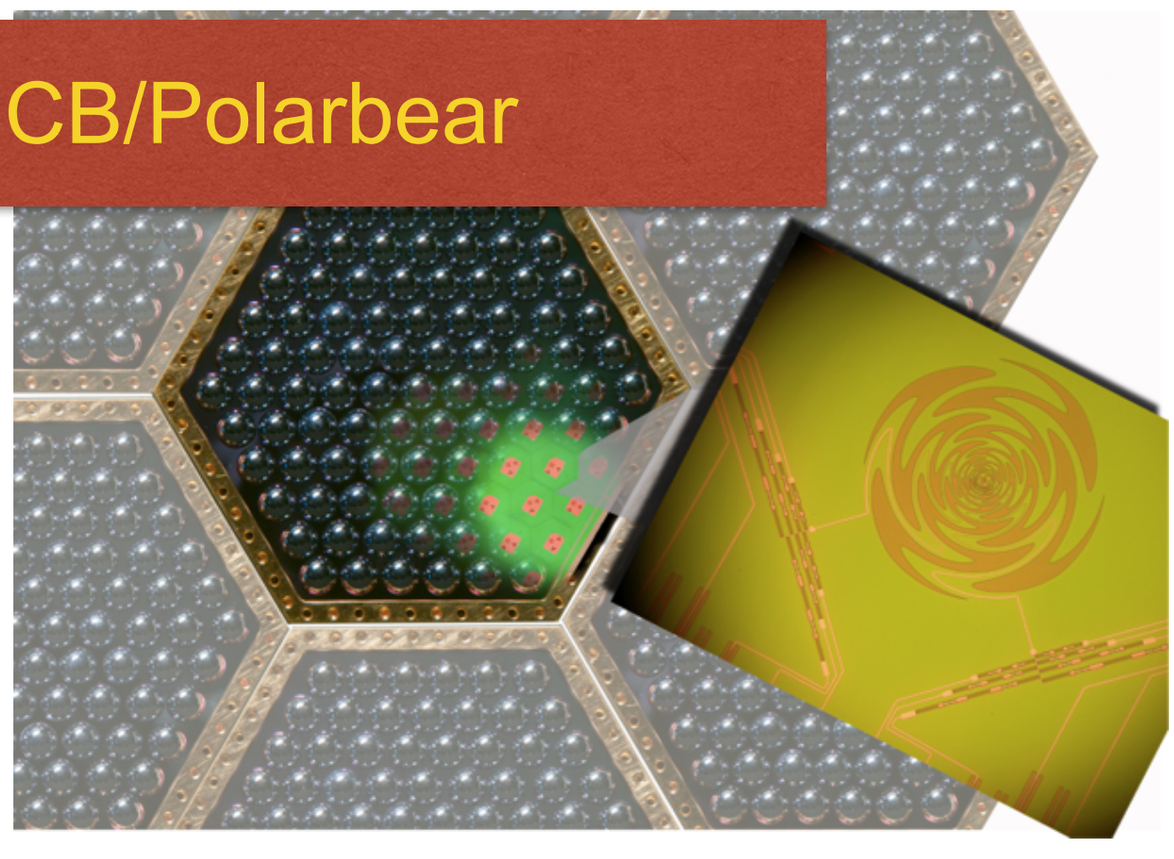


NIST/Truce collab

Caltech/JPL



ANL/SPT-3G

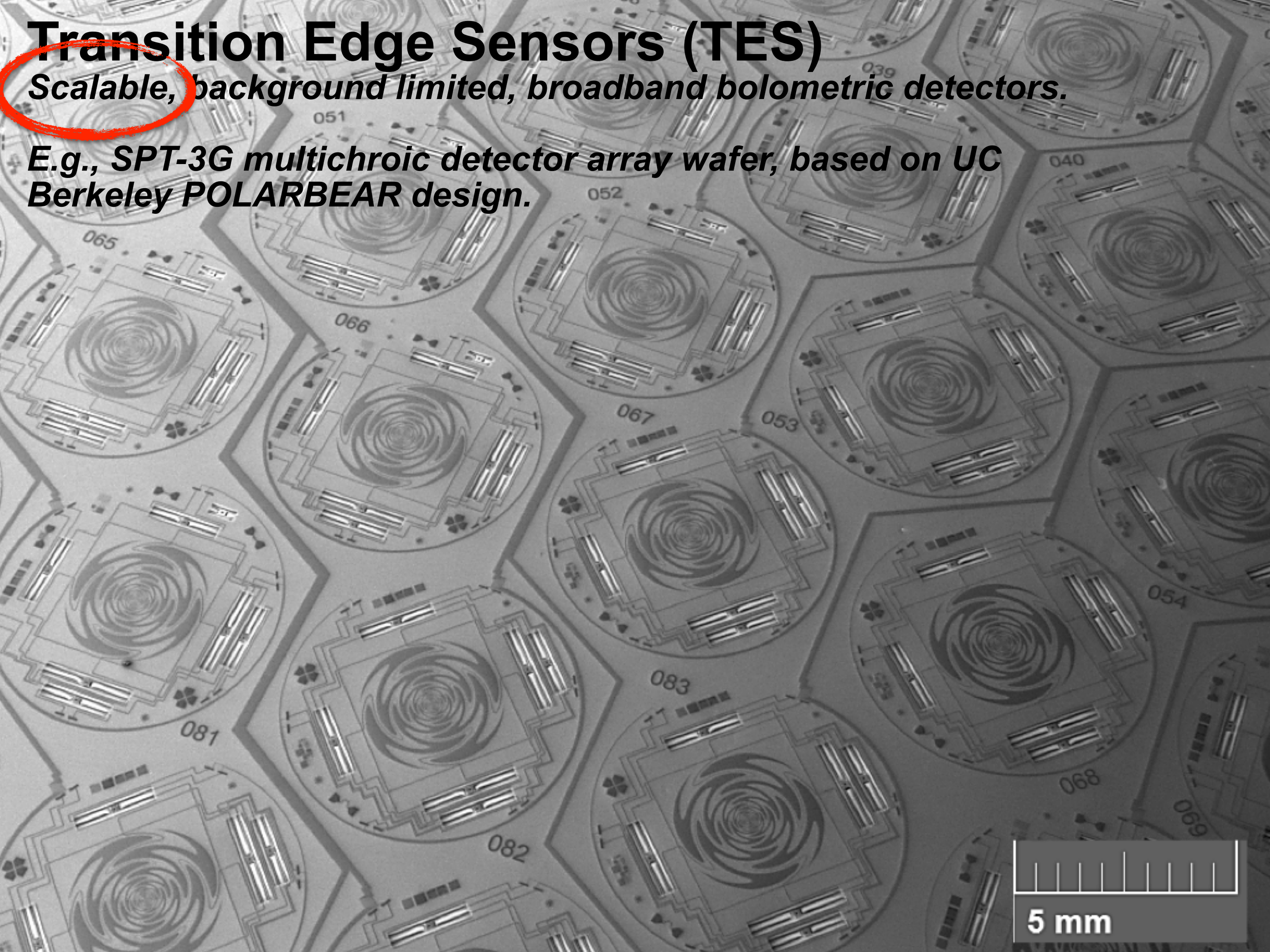


UCB/Polarbear

Transition Edge Sensors (TES)

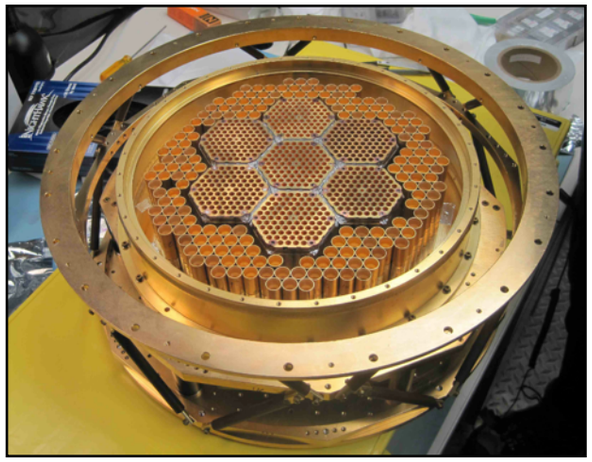
Scalable, background limited, broadband bolometric detectors.

E.g., SPT-3G multichroic detector array wafer, based on UC Berkeley POLARBEAR design.

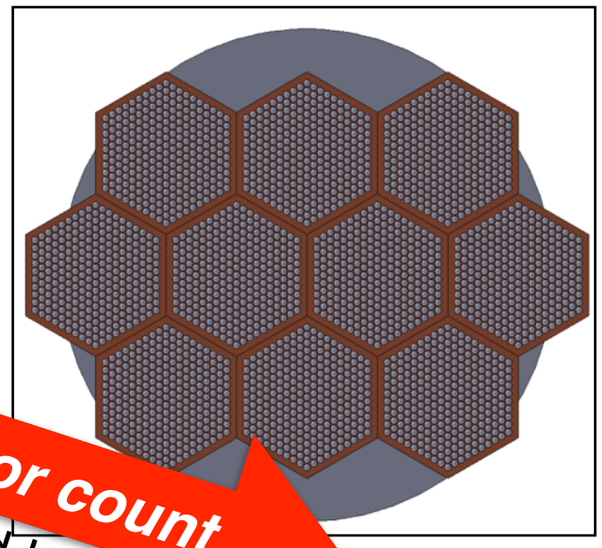


Maintaining Moore's Law: focal planes are saturated so must use parallel processing and multiple telescopes.

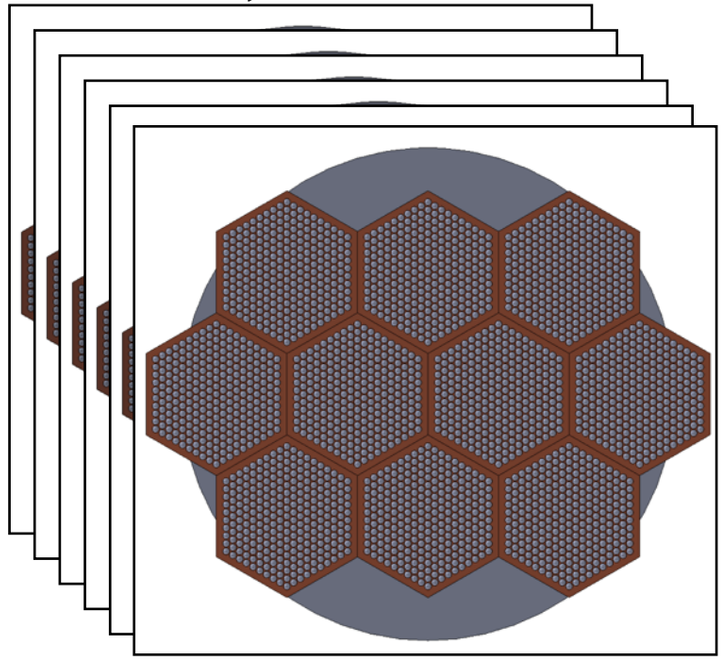
Stage II
Now
~1000 detectors



Stage III
ramping up
~10,000 detectors



Stage IV
~2020 - CMB-S4
~500,000 detectors



increasing detector count
(the trend being followed by all CMB projects, not just SPT)

CMB-S4: A coordinated community wide program to put order 500,000 detectors spanning 30 - 300 GHz using multiple telescopes and sites to map ≳70% of sky.

Stage IV experiment: CMB-S4

CMB-S4: a <u>ground-based program</u> working with, and building on, CMB stage II & III projects.

Participation includes, ***<u>but is not limited to</u>:***

- the ACT, BICEP/KECK, CLASS, POLARBEAR, SPT, … CMB Stage II & III teams and their international partners.
- Argonne, FNAL, LBNL, SLAC, NIST U.S. national labs and the high energy physics community.

International partnerships encouraged.

Strive to be complementary with balloon and space-based instruments.

Nominal CMB-S4 specifications

- **Survey:**

  - Inflation, Neutrino, and Dark Energy science requires an optimized survey which includes a range of resolution and sky coverage from deep to wide

- **Sensitivity:**

  - 1 uK-arcm over ≳70% of the sky

- **Configuration:**

  - O(500,000) detectors on multiple telescopes (small and large aperture)
  - spanning 30 - 300 GHz for foreground removal (split atmospheric bands?)
  - ≲ **3 arcmin resolution** required for CMB lensing & neutrino science
  - ***higher resolution leads to amazing and complementary dark energy constraints, gravity tests on large scales via the SZ effects, and mapping the universe in momentum.***

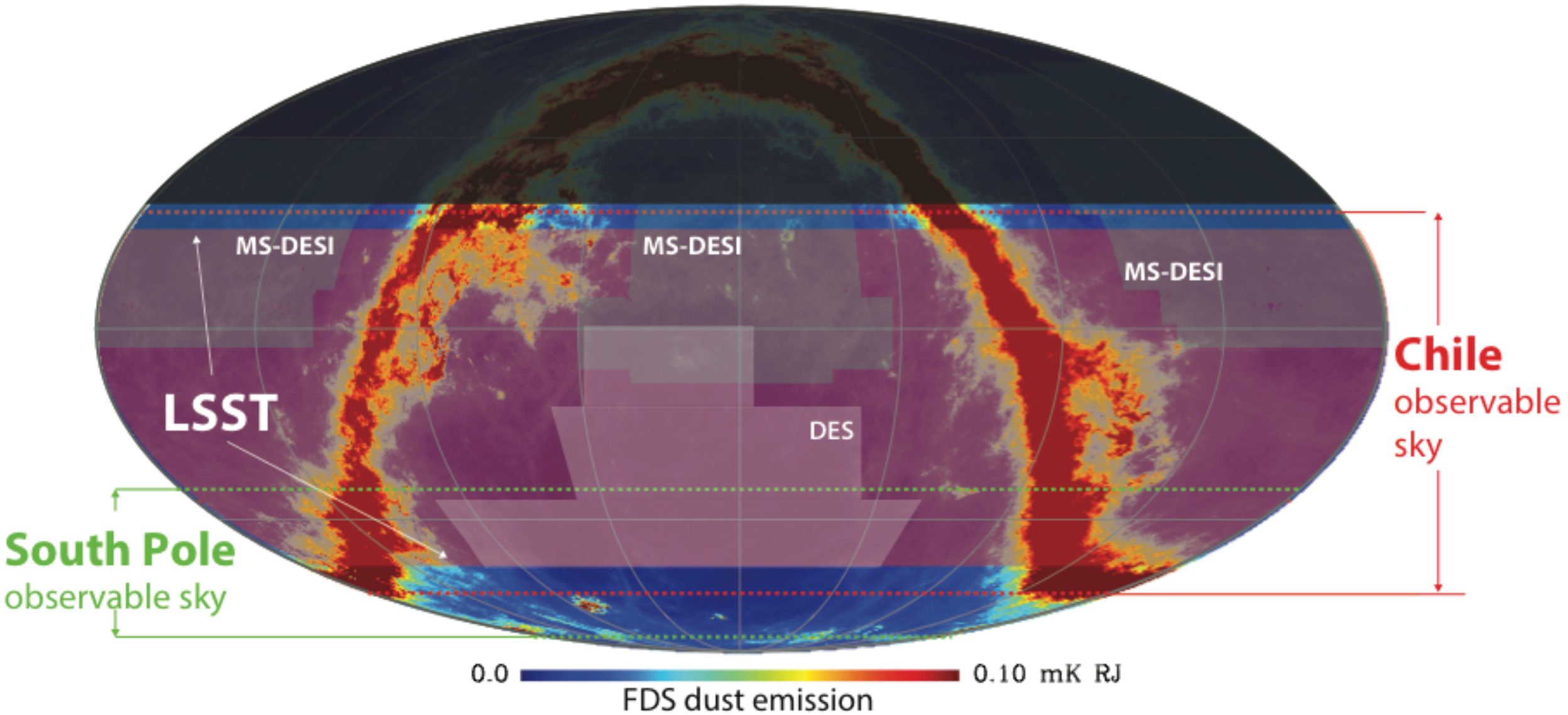
What's needed — scaling up!

- *Scaling up detectors, focal planes* ← ***this is the biggest technical challenge.***
- *Scaling up sky area and frequency coverage*
- *Scaling up number of telescopes; new designs*
- *Improved understanding and control of systematics, including foreground mitigation.*
- *Scaling up of data analysis, simulations, computation*
- *Increased precision of theory / phenomenology for analysis*
- *Scaling up project management*
- *… and more*

Combining the expertise and resources at the national labs and the deep CMB experience of the University groups.

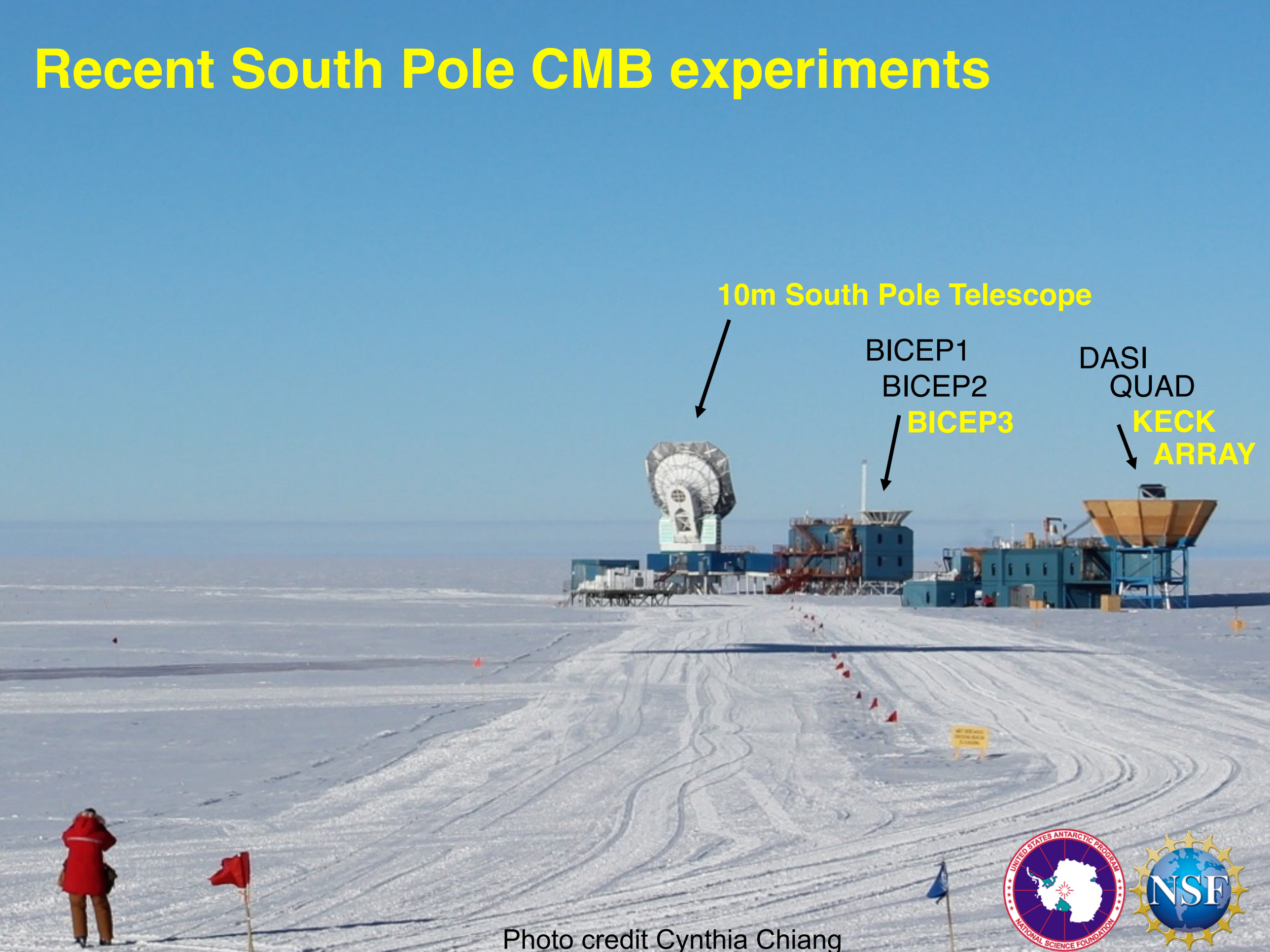
Multiple platforms exploiting superb, established sites at Chile and South Pole and possibly add Northern site(s)

Critical to overlap with LSST, MS-DESI, etc.

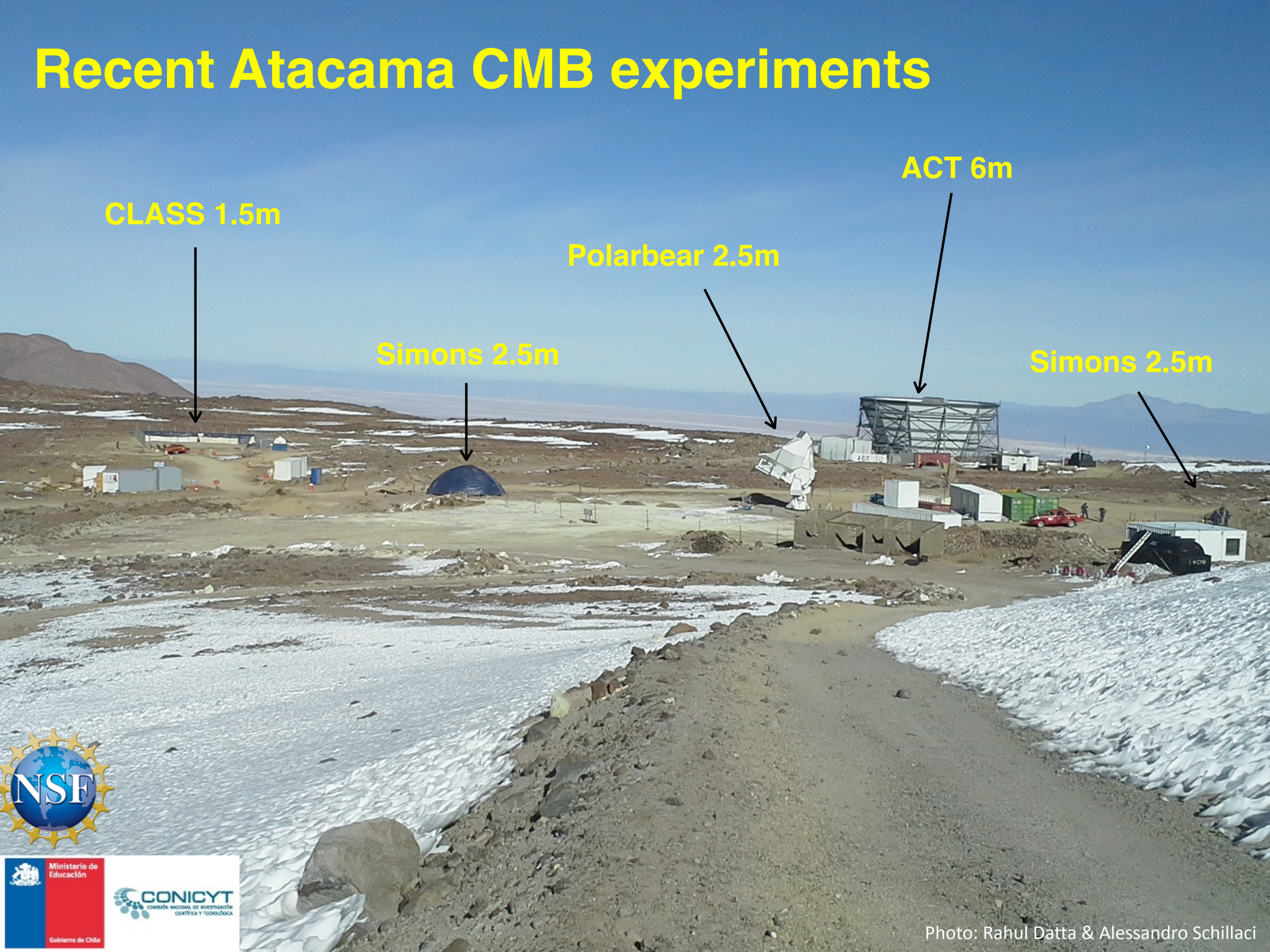


Slide from Jeff McMahon

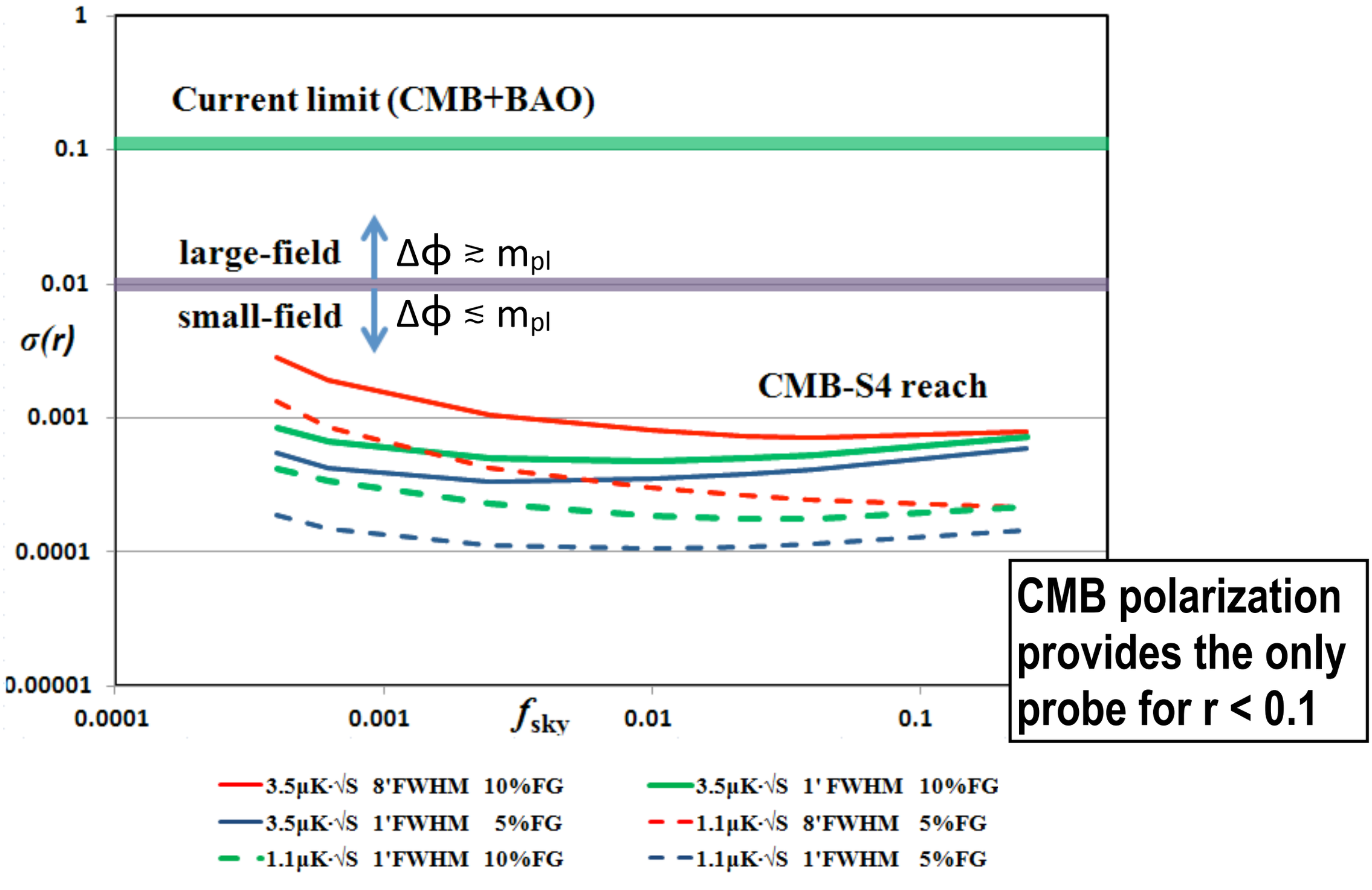
Recent South Pole CMB experiments



Recent Atacama CMB experiments

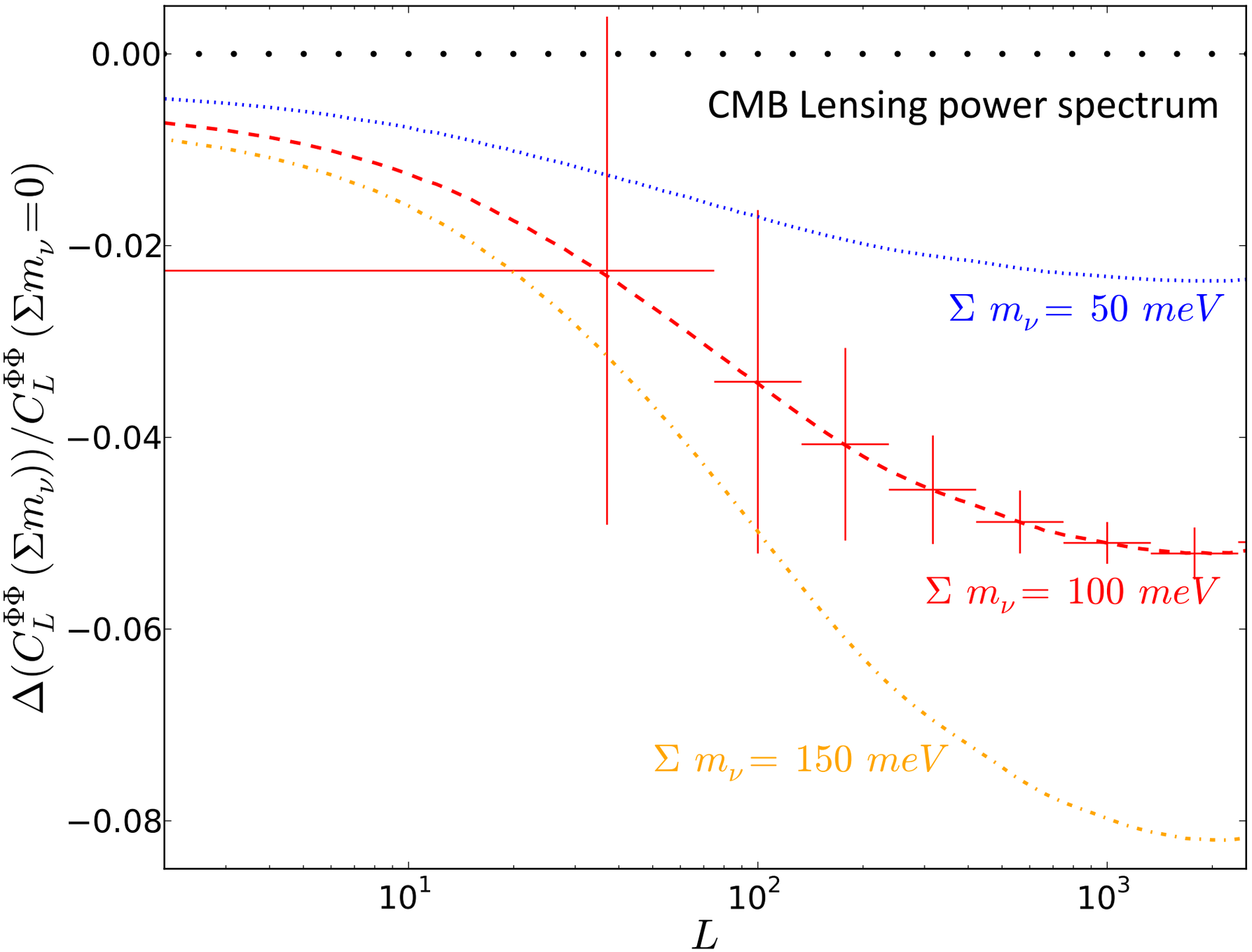


Inflation projection for CMB-S4



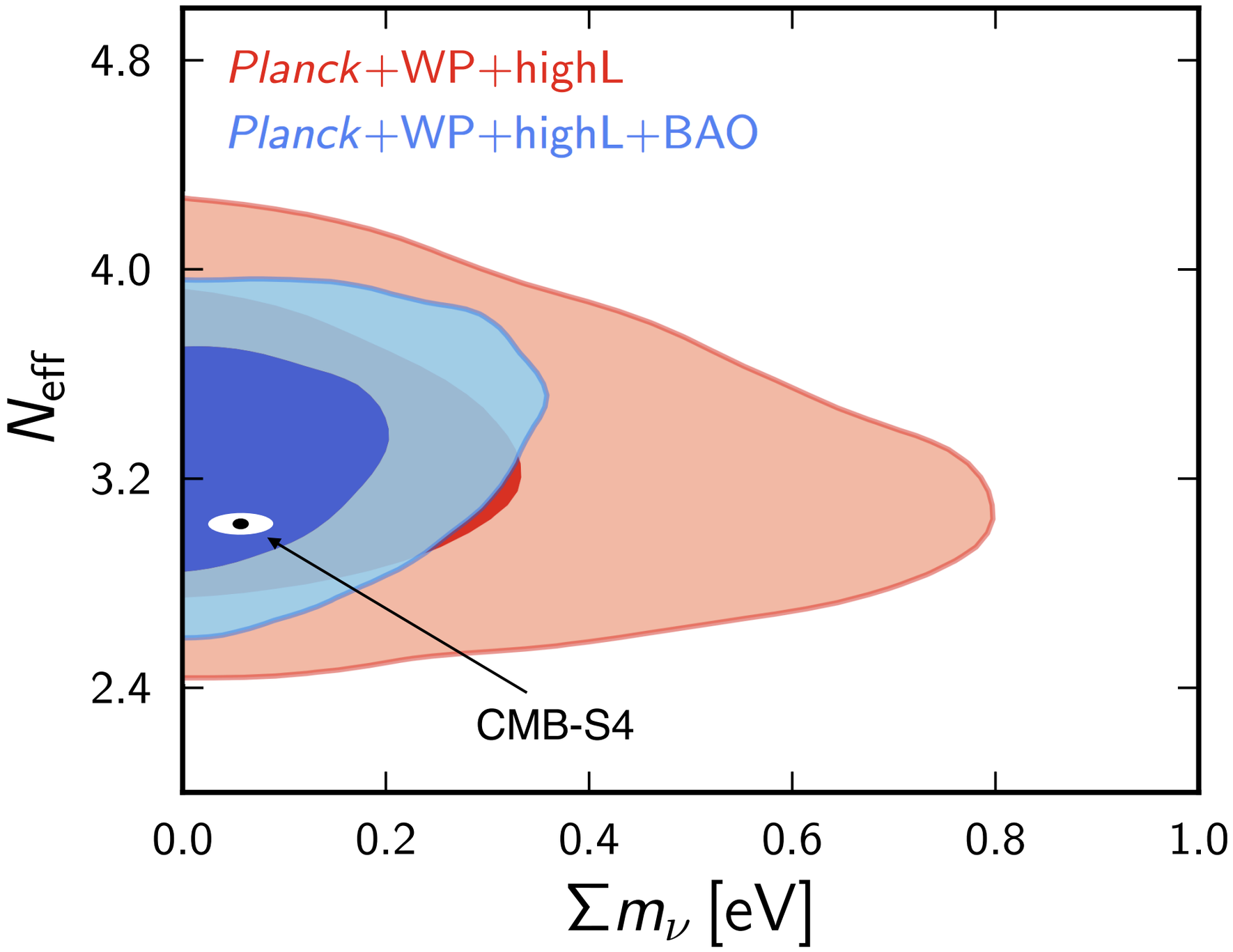
CMB polarization provides the only probe for r < 0.1

CMB-S4 lensing sensitivity to Σm_ν



Forecasters: J. Errard, P. McDonald, A. Slosar K. Wu, O. Zahn

CMB-S4 N_{eff} - Σm_ν constraints



σ(Σm_ν) = 16 meV (with DESI BAO)

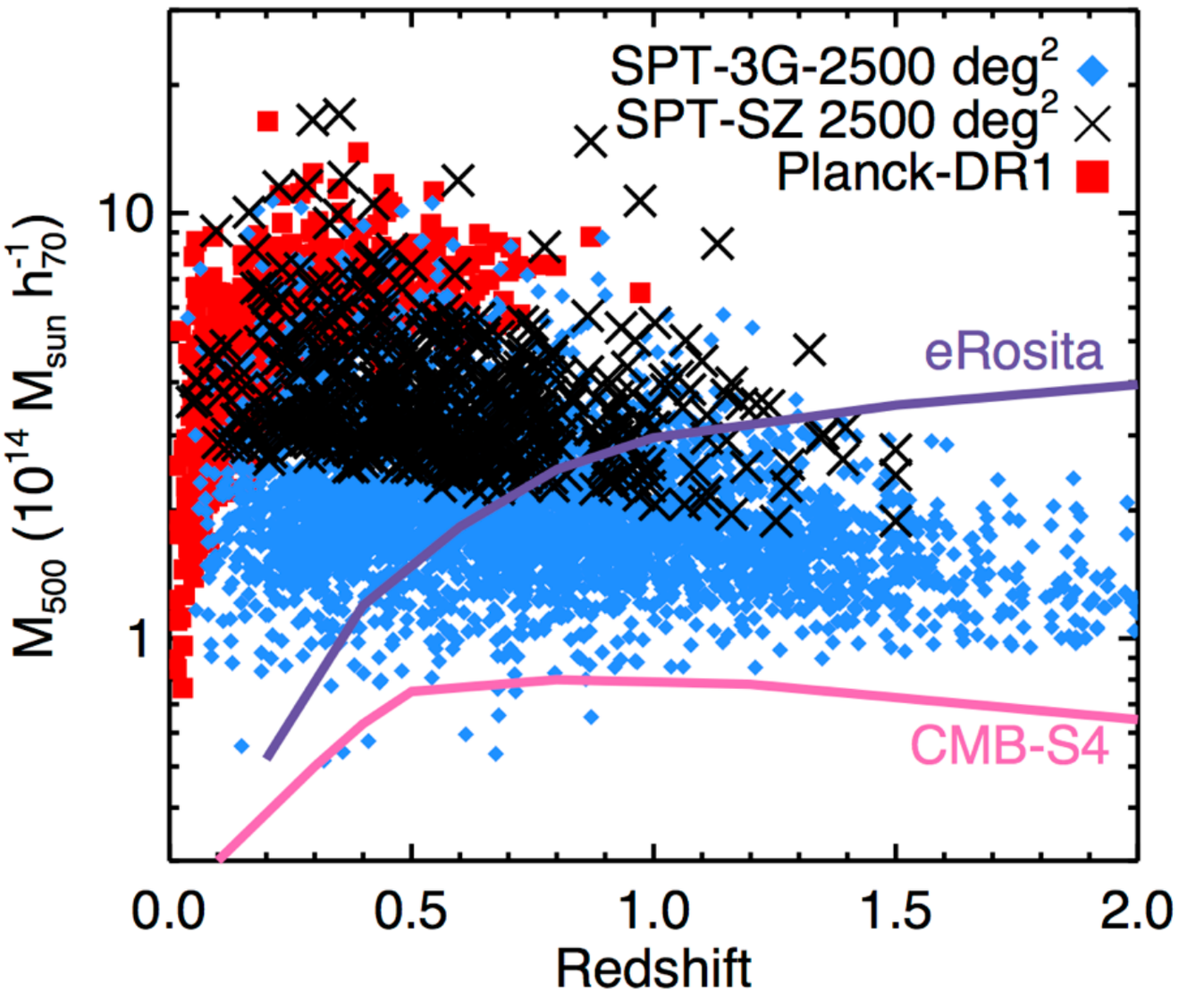
σ(N_{eff}) = 0.020

CMB uniquely probes N_{eff}

Forecasters: J. Errard, P. McDonald, A. Slosar K. Wu, O. Zahn

CMB Sunyaev-Zel'dovich Cluster Surveys

Cluster Mass vs Redshift for CMB/SZ Experiments



ACT+SPT: $N_{\rm clust}$ **~ 1,000**

Stage III: $N_{\rm clust}$ **~ 10,000**

CMB-S4: $N_{\rm clust}$ **~ 100,000**

CMB lensing can directly calibrate cluster mass SZ scaling:

Stage III: $\sigma(M) \sim 3\%$

CMB-S4: $\sigma(M) \sim 0.1\%$

making SZ cluster cosmology an extremely powerful probe of structure formation and dark energy.

CMB polarization timeline

- 2013: Stage II experiments detect lensing B-modes (SPTpol)
- now: $r \lesssim 0.12$ from B-modes (BICEP2/KECK with *Planck)*
- 2013-2016: Stage II experiments

  $\sigma(r)\sim0.03$, $\sigma(N_{eff})\sim0.1$, $\sigma(\Sigma m_\nu)\sim0.1$eV
- 2016-2020: Stage III experiments

  $\sigma(r)\sim0.01$, $\sigma(N_{eff})\sim0.06$, $\sigma(\Sigma m_\nu)\sim0.06$eV*

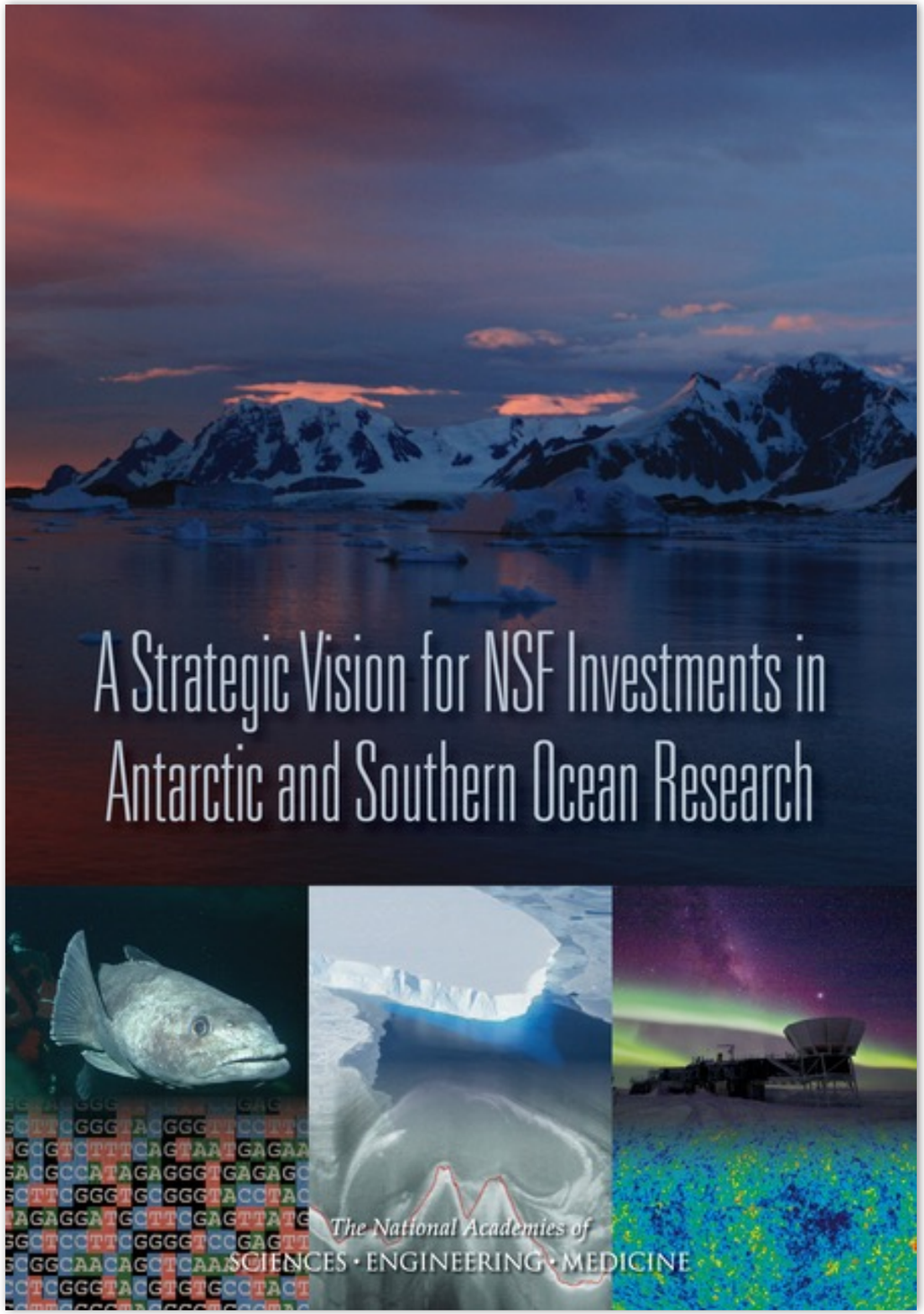
- 2020-2025: Stage IV experiment, **CMB-S4**

  $\sigma(r) \lesssim 0.001$, $\sigma(N_{eff}) = 0.020$, $\sigma(\Sigma m_\nu) = 16$ meV*

  each crosses a critical threshold

* includes BOSS prior
* includes DESI prior

recommended to U.S. agencies



P5 timeline

CMB-S4 ramps up as LSST ramps down

CMB-S4 recent efforts

After Snowmass[1] planning and P5:

- Continued funding (*phew!*) and development of Stage II & III projects.
- Increased involvement of U.S. national labs in CMB Stage III projects and in CMB-S4 planning.
- Developing DOE science, technical and programmatic planning documents, i.e., “roadmaps”
- A series of community workshops to define science reach, instrumentation specs and design.
  - UMN CMB Conference 1/16/15
  - U. Michigan CMB-S4 workshop 9/21/15 ***(v. soon!)***

[1]see arXiv:1309.5383 and arXiv:1309.538

Cosmology with CMB-S4

WORKSHOPS & CONFERENCES

Circumstellar Disks and Planet Formation Conference
Local Group Astrostatistics
Solar-Stellar Connection Workshop
Cosmology with CMB-S4

MICHIGAN INSTITUTE FOR RESEARCH IN ASTROPHYSICS UNIVERSITY OF MICHIGAN

MICHIGAN CENTER FOR THEORETICAL PHYSICS UNIVERSITY OF MICHIGAN

Kavli Institute for Cosmological Physics at The University of Chicago

Cosmology with CMB-S4 Workshop
September 21-22, 2015

University of Michigan Alumni Center
200 Fletcher, Ann Arbor, MI

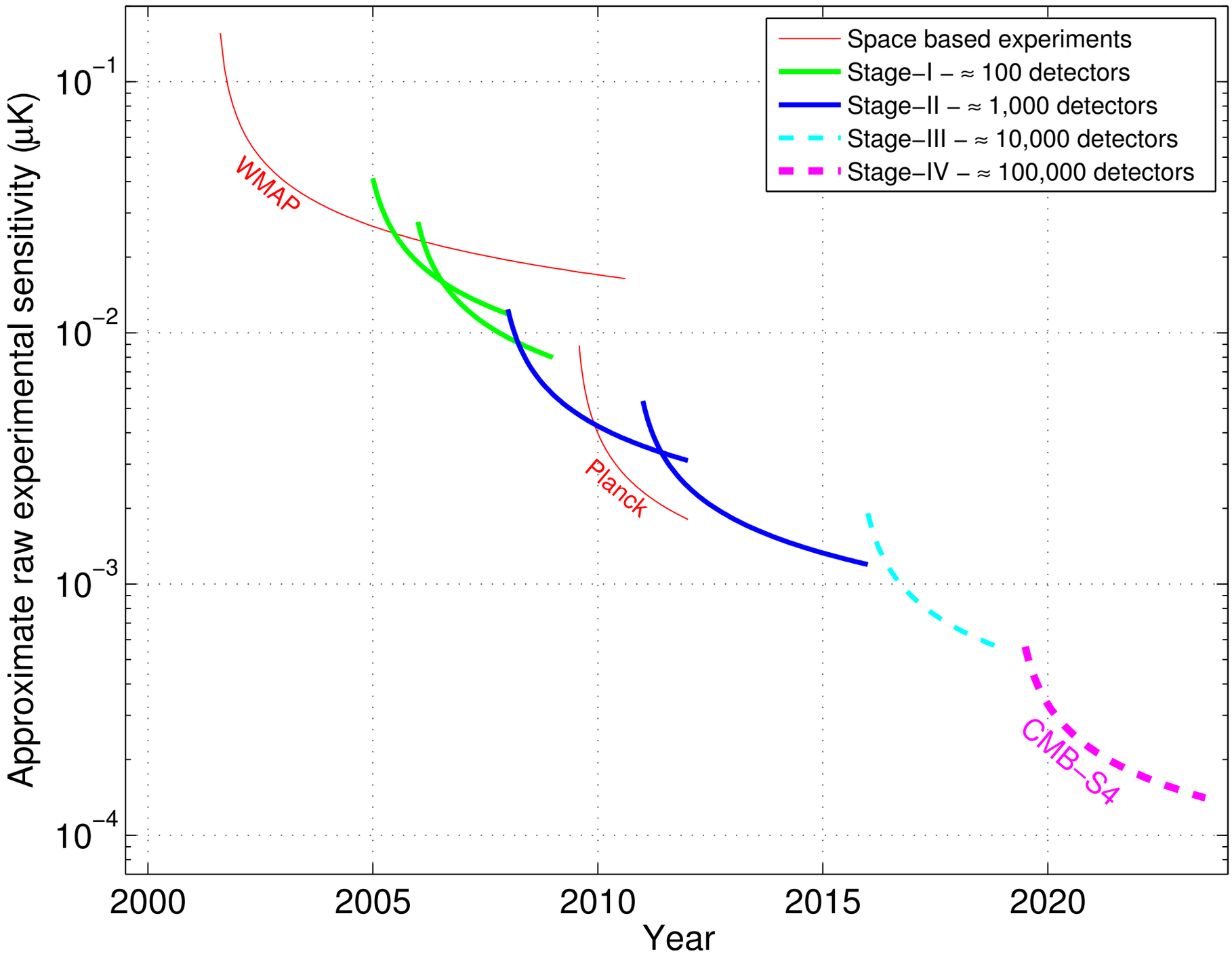
Workshop Planning Committee

Jeff McMahon (University of Michigan) I John Carlstrom (University of Chicago)

Workshop Overview:

This workshop aims to further develop the science goals, including the requisite measurements to achieve them, for the next generation ground-based Cosmic Microwave Background program, CMB-S4. The output of the workshop will be a working draft of the CMB-S4 "Science Book." This is the first in a series of potentially biannual workshops focused on developing the CMB-S4 project.

Detectors are a big challenge,



but it will take much more to achieve our goals.

condensed from technical road map

Science Def'n & Candidate Technology (CD0)

- *Science metrics and high level instrument specifications, (e.g., telescopes, bands, resolution, sensitivity)*
- *Broad Computing requirements*
- *Candidate technologies (telescopes, optics & detectors)*
- *Candidate sites*

Prototype to Preliminary Design informed by Stage II & III (CD1)

- *Simulations with realistic instrument errors → Scan & Survey strategy*
- *Analysis Pipeline*
- *Detector and readout*
- *Telescopes and Ground shielding*
- *Optics & Polarization modulation*
- *Control & monitor systems*
- *Site Selection*

Final design (CD2-CD3)

- *Analysis Pipeline detailed design*
- *Instrument detailed design*
- *Site Infrastructure detailed design*

2015 2016 2017 2018 2019 2020

Lots of enthusiasm and momentum

- CMB-S4 is the next great leap for CMB measurements. We plan to go for it and not sell ourselves short.
- The CMB is the gift that keeps on giving. We will be searching for inflationary gravitational waves, determining the neutrino masses, mapping the universe in momentum, investigating dark energy, testing general relativity and more. There will no doubt be new developments and surprising discoveries.

CMB-S4 Session at UMN CMB Conference 1/16/15

thanks