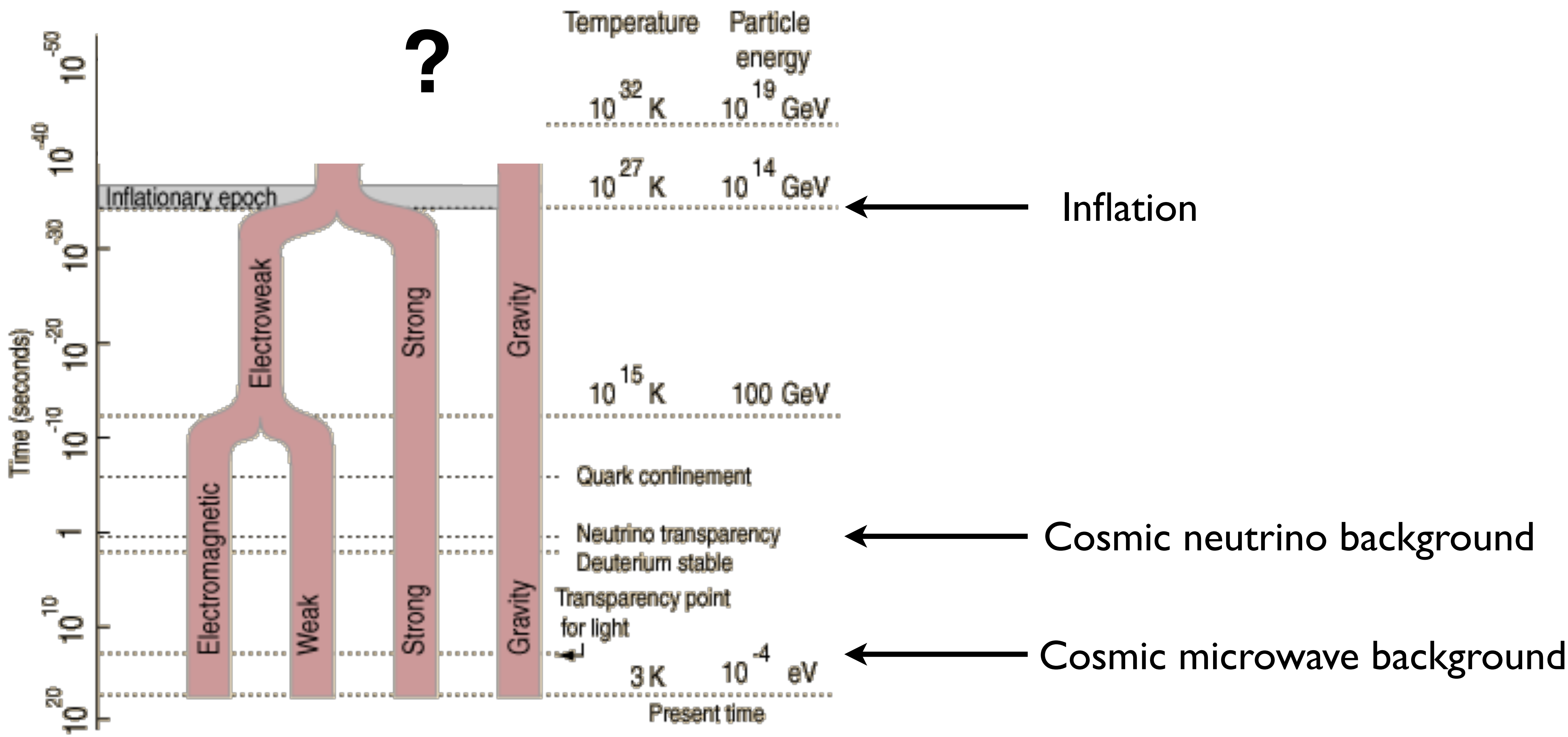
Cosmic Microwave Background
Stage 3 and Stage 4

the next big leaps…

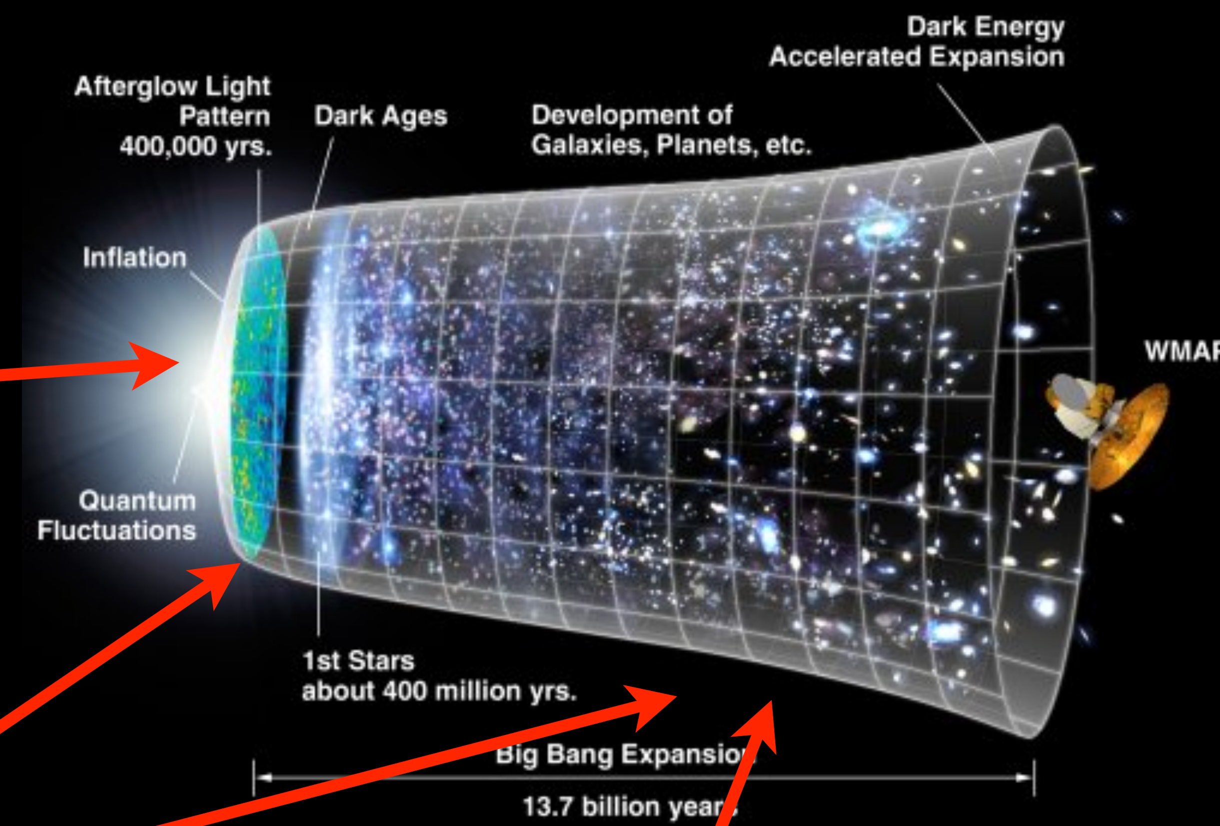
John Carlstrom

FNAL Review — February 11, 2015

Universe as a Physics Laboratory



CMB measurements probe cosmology and fundamental physics



Inflation

- Spectral index of fluctuations, n_s
- non-Gaussianity?
- constrain tensor to scalar fluctuations
- detect B modes from inflationary gravitational waves

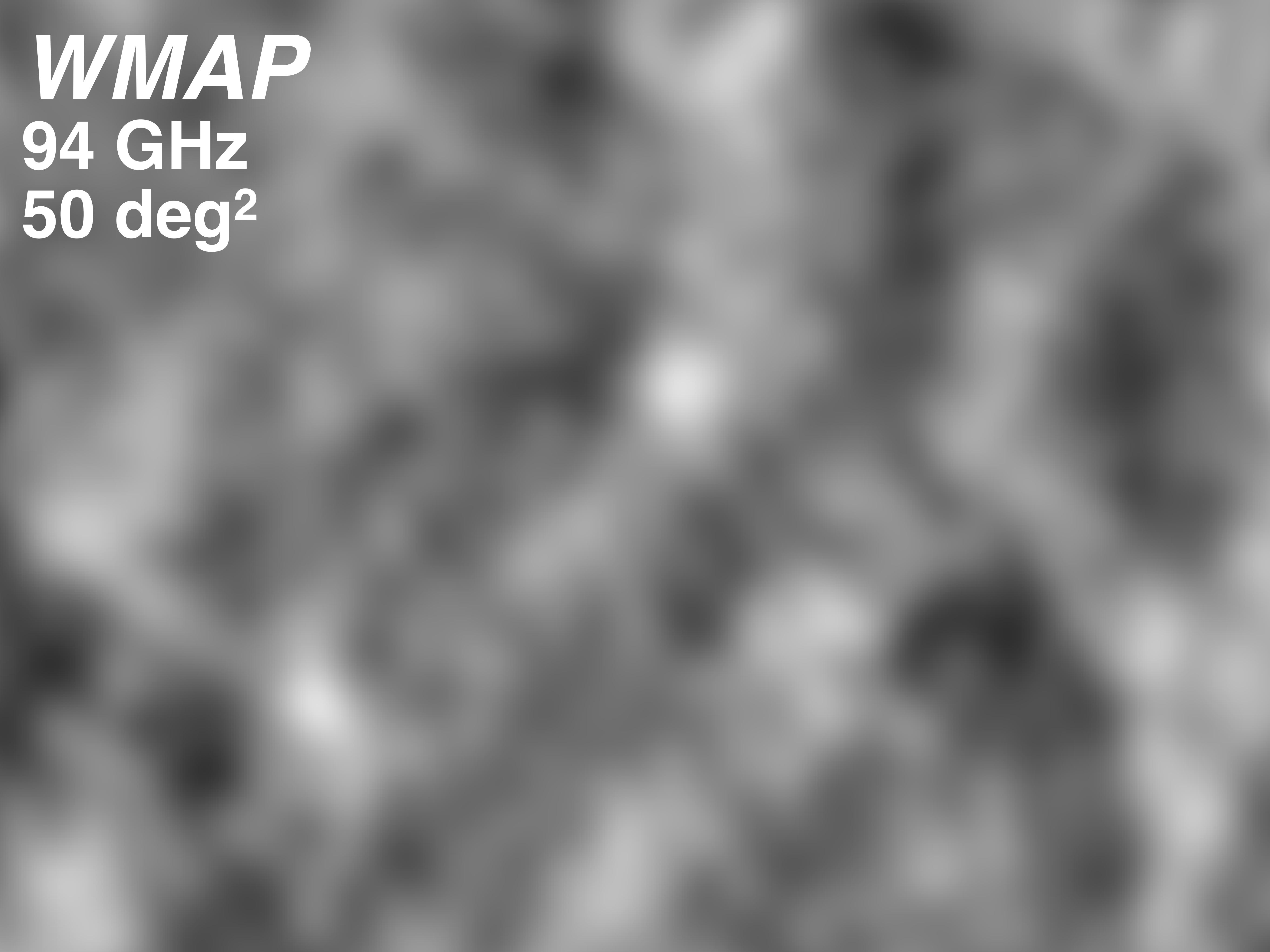
Neutrinos

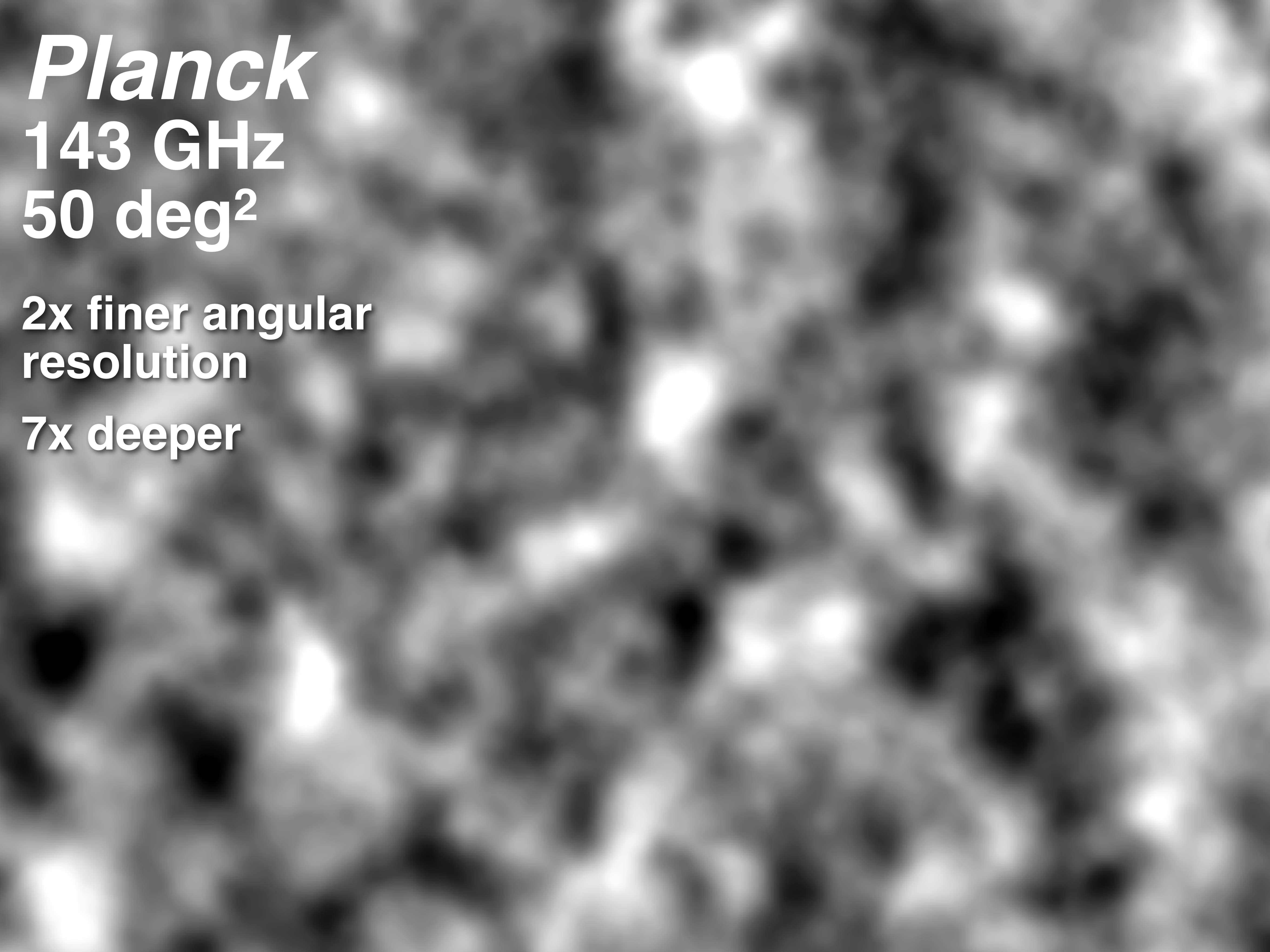
- Number of relativistic species (Neff or "dark radiation")
- Sum of the neutrino masses, ($\sum m_\nu$) through impact on growth of structure

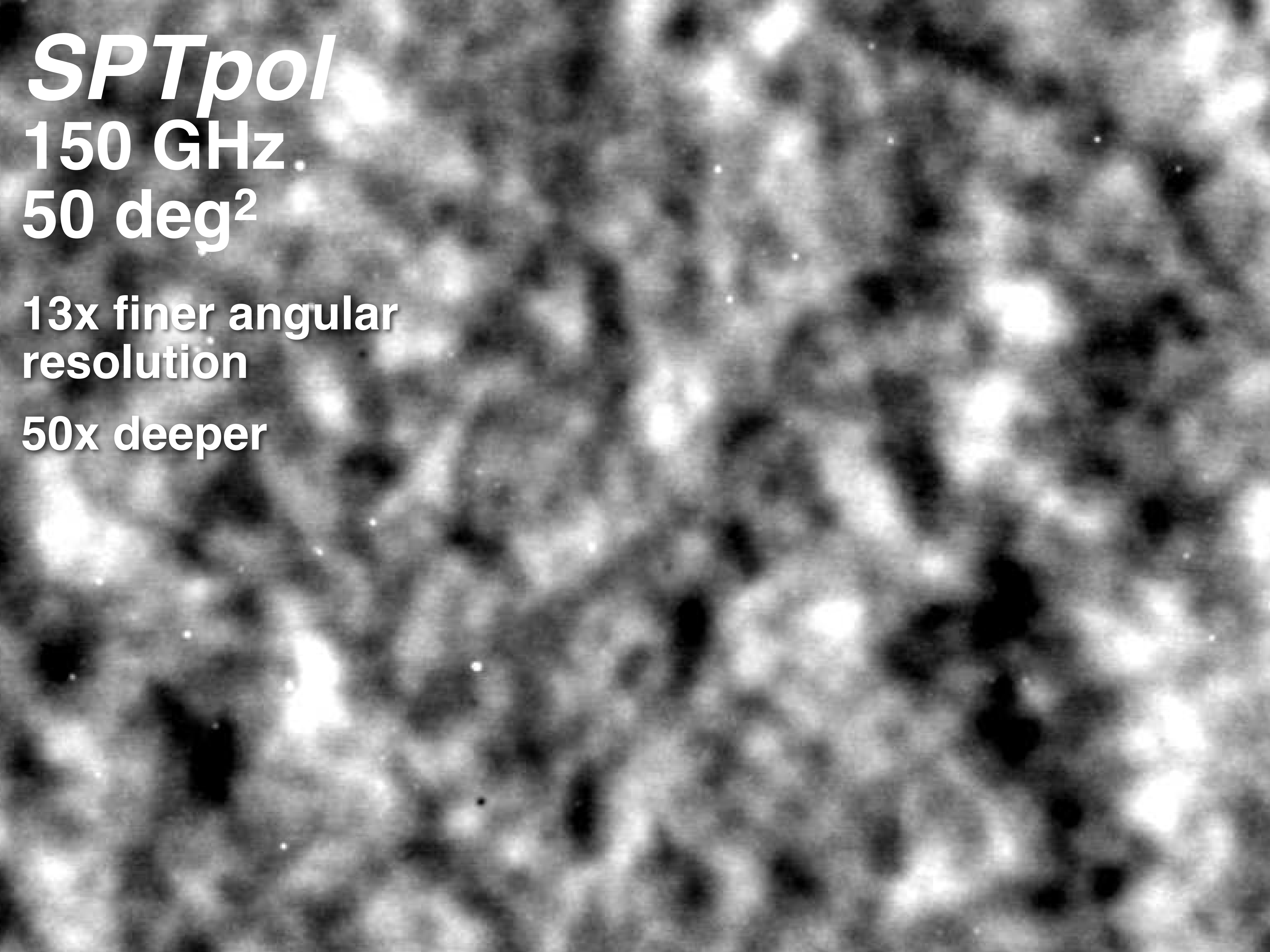
Dark Energy

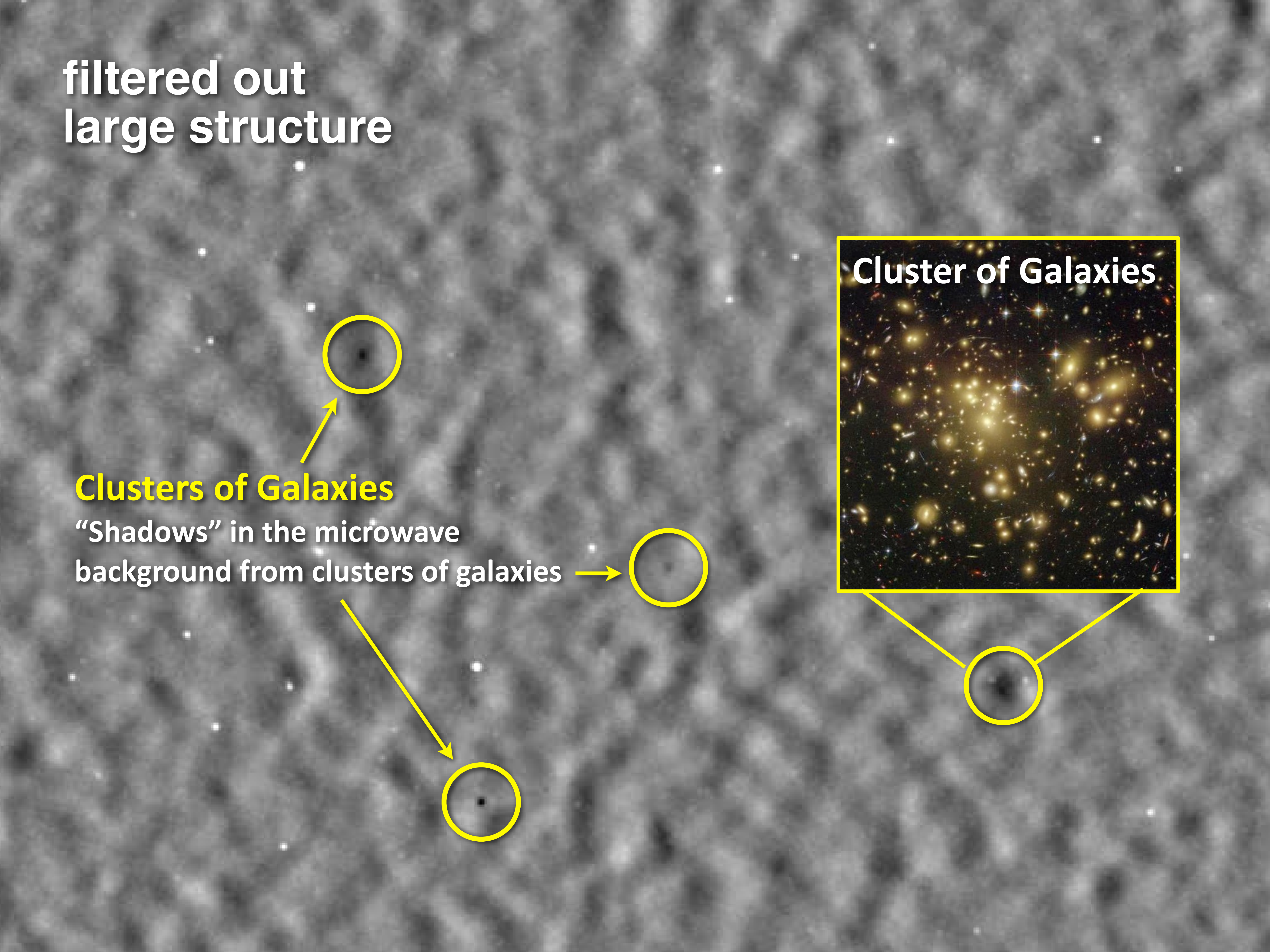
SZ clusters and CMB lensing correlation with galaxy surveys
- Is GR correct on large scales?

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

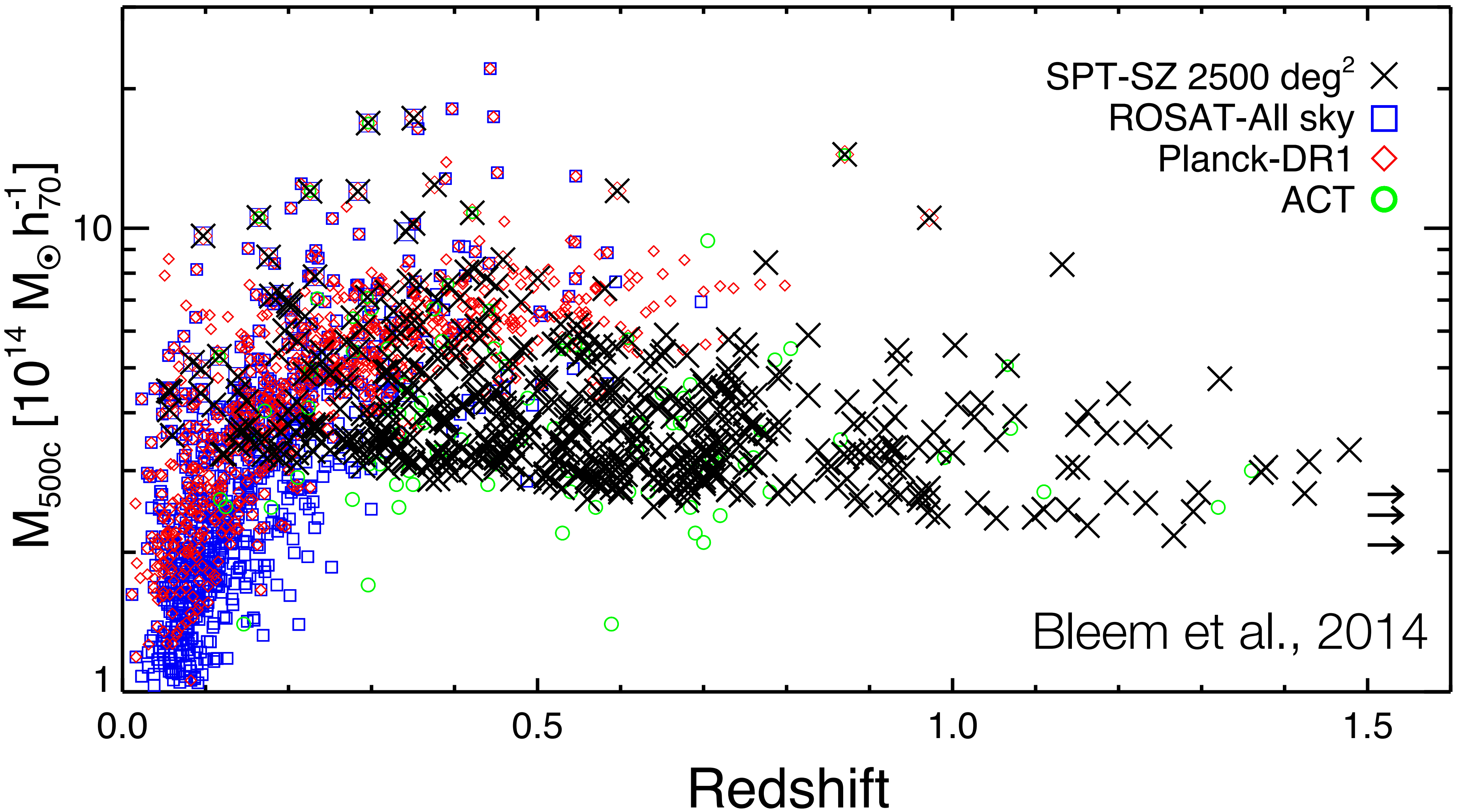

WMAP
94 GHz
50 deg²


Planck
143 GHz
50 deg^2
2x finer angular resolution
7x deeper


SPTpol
150 GHz
50 deg^2
13x finer angular resolution
50x deeper


filtered out
large structure
Clusters of Galaxies
"Shadows" in the microwave
background from clusters of galaxies
Cluster of Galaxies

Dark Energy and Sunyaev-Zel’dovich (SZ) effect discovered clusters



- Cluster evolution probes Dark Energy through growth of structure
- High angular resolution CMB experiments find clusters via SZ effect (redshift independent). SPT made 1st SZ discovery of cluster in 2008 and has more than doubled the number of $z > 0.5$ massive clusters.
- Cosmological constraints limited by cluster mass calibration.

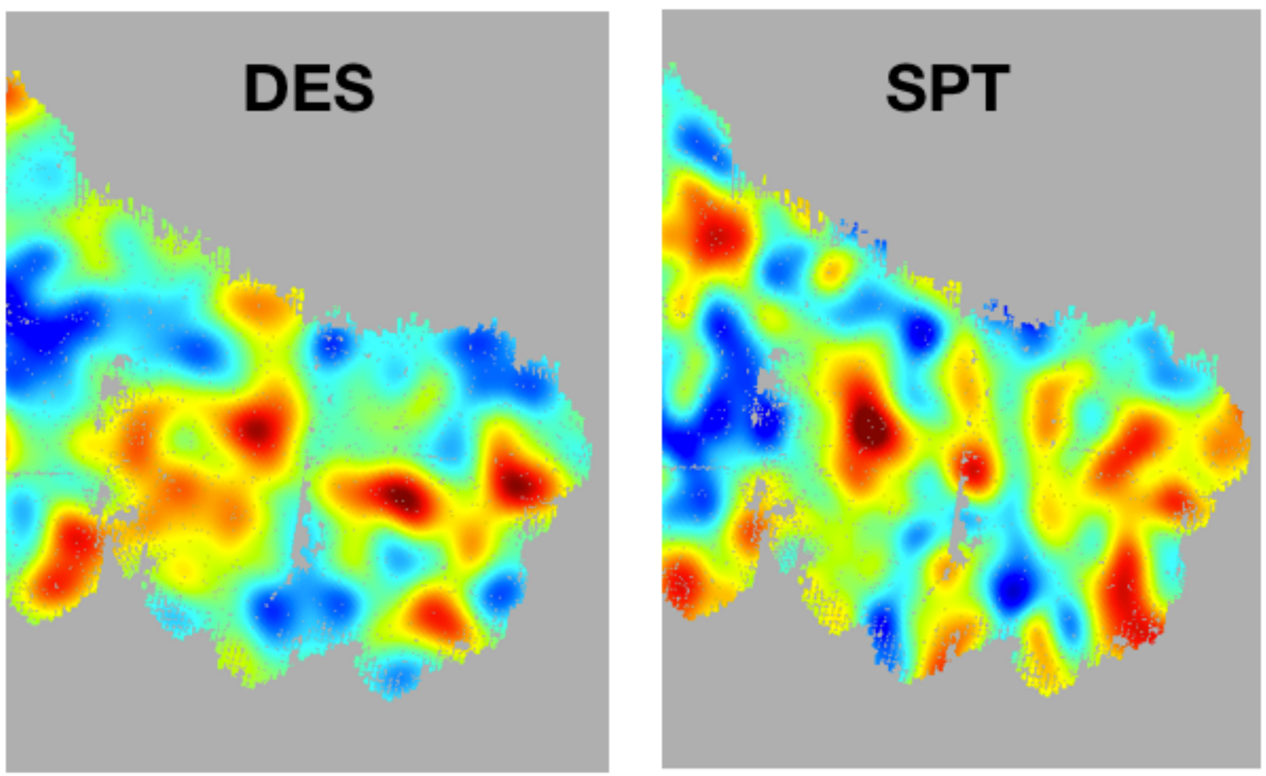
Synergy with Dark Energy Survey

Strong complementarity with SPT cluster survey and SPT CMB lensing; the combination will improve cluster constraints on dark energy by ~100x

Already a vibrant DES + SPT joint analysis effort.

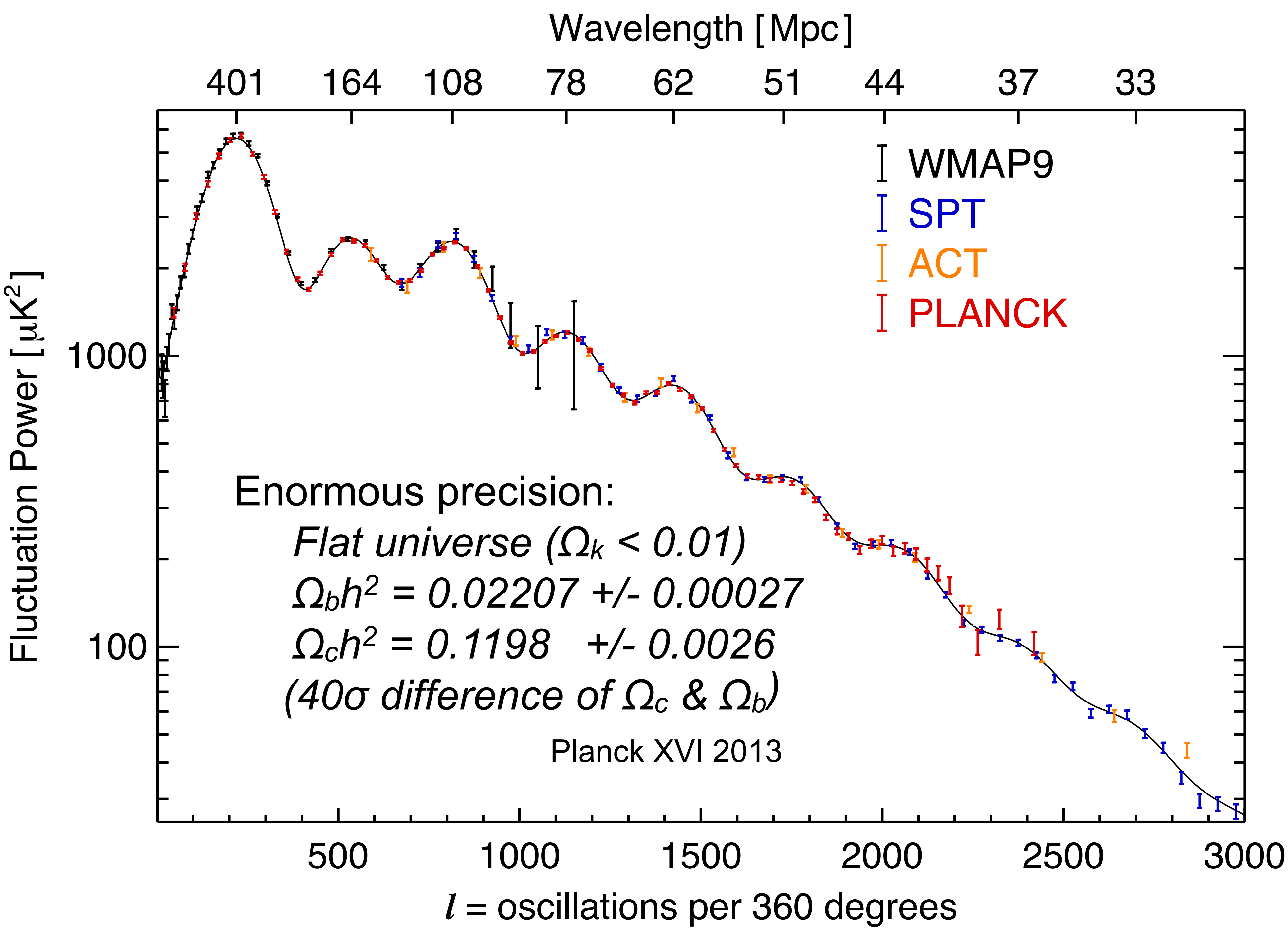
Synergy with Dark Energy Survey

DES galaxy - SPT Lensing potential Cross-Correlation



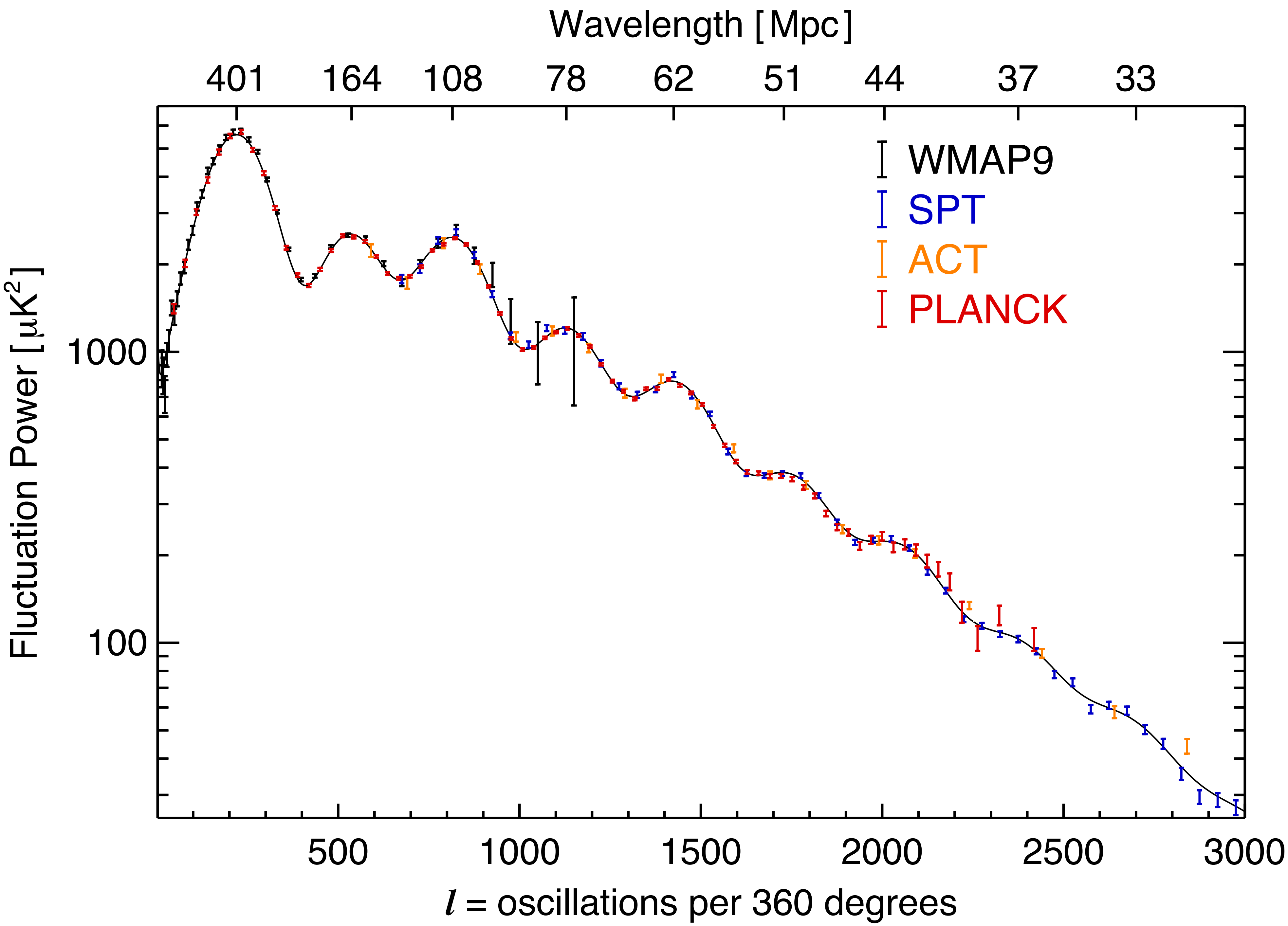
- Cosmology from LSS probes using Dark Energy Survey and the South Pole Telescope: CMB lensing cross-correlations, cluster cosmology
- **Personnel:** Dodelson (Scientist), Benson (Scientist), Soares-Santos (Scientist)

Primary CMB anisotropy - remarkable agreement



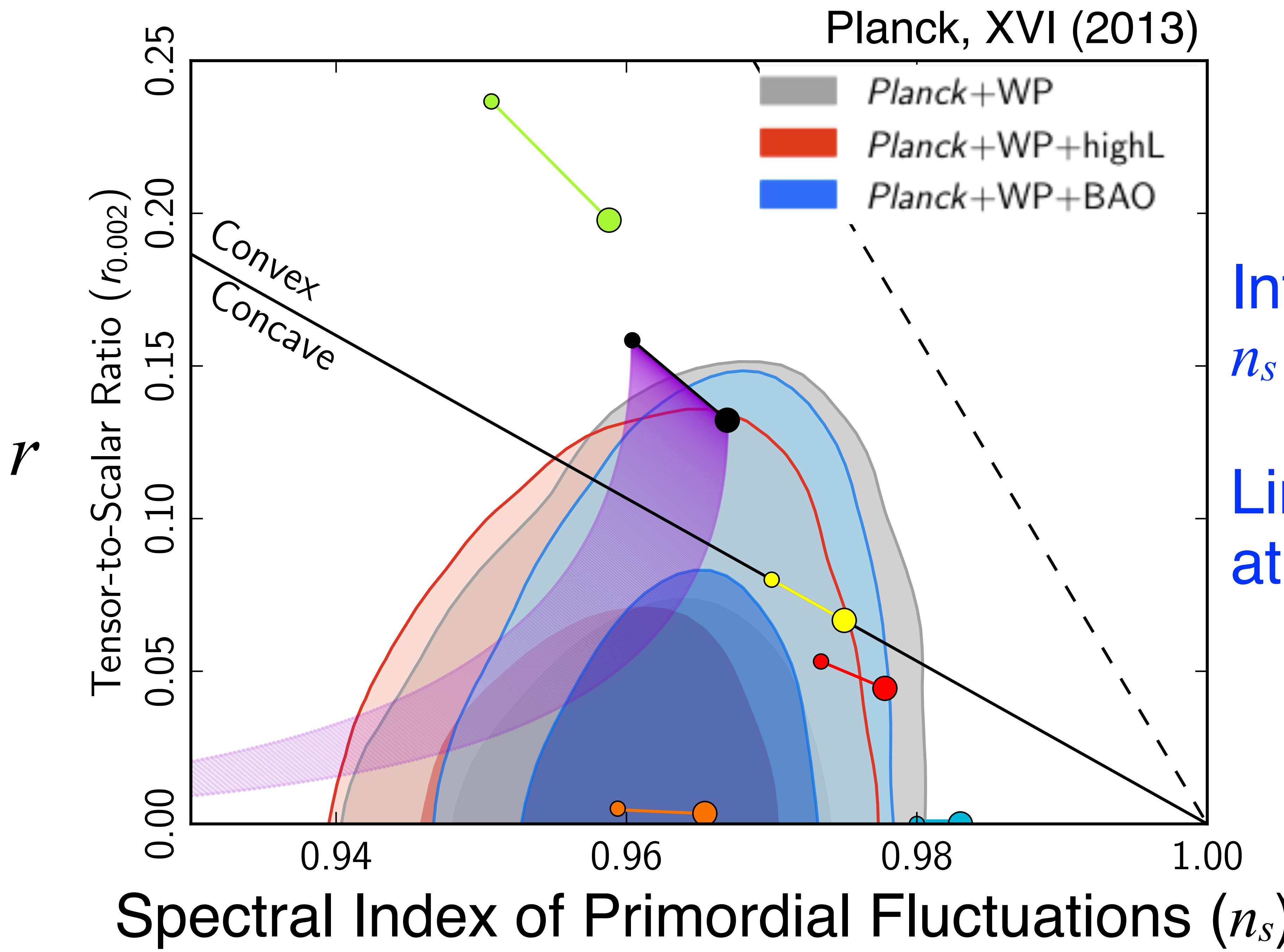
Fit by vanilla ΛCDM - just six parameters: $\Omega_b h^2$ $\Omega_c h^2$ Ω_Λ Δ^2_R n_s τ

Primary CMB anisotropy - remarkable agreement



Inflation checks: Geometrical flat universe; Superhorizon features; acoustic peaks/adiabatic fluctuations; departure from scale invariance; inflationary gravitational waves (tensors)?

TT constraints on r and n_s in ΛCDM

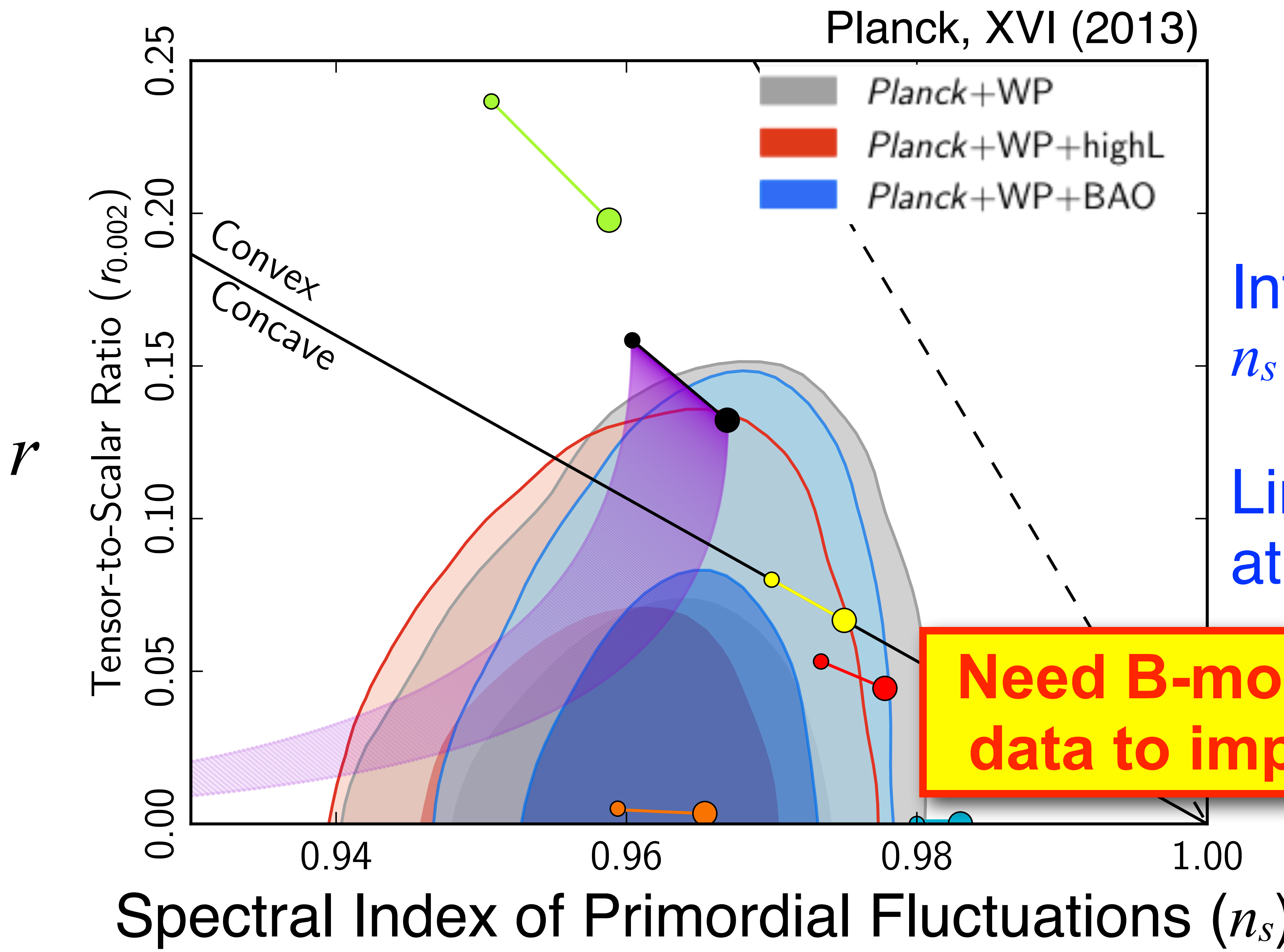


Inflation evidence:
$n_s \neq 1$ at over 5σ

Limit of $r < 0.11$
at 95% C.L.

$$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s - 1}$$

TT constraints on r and n_s in ΛCDM



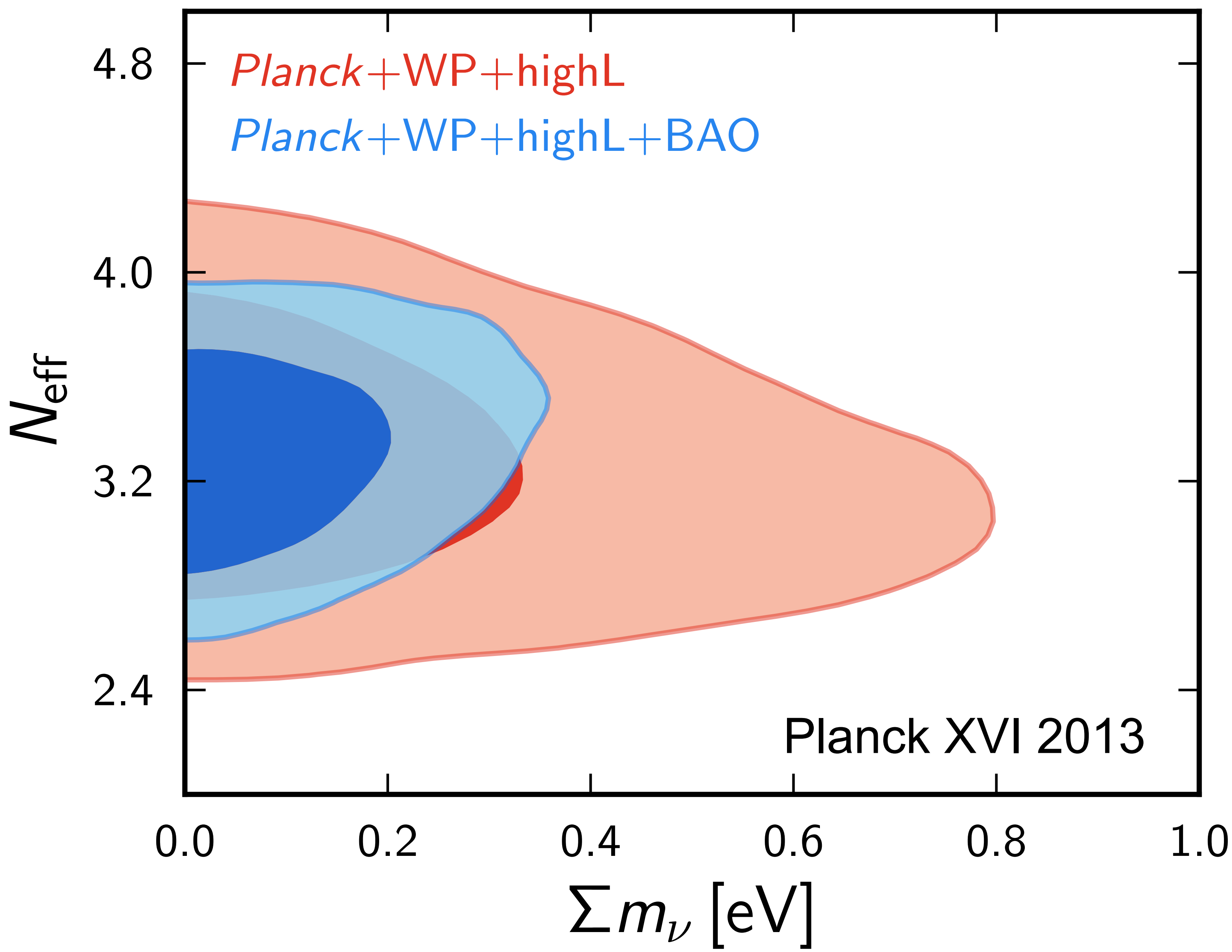
Inflation evidence:
$n_s \neq 1$ at over 5σ

Limit of $r < 0.11$
at 95% C.L.

Need B-mode polarization data to improve limit on *r*

$$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s - 1}$$

Joint Dark Radiation (N_{eff}) and Σm_ν constraints in ΛCDM



Planck 2015:

N_{eff} **= 3.15±0.23**

(>10σ detection of cosmic neutrino background)

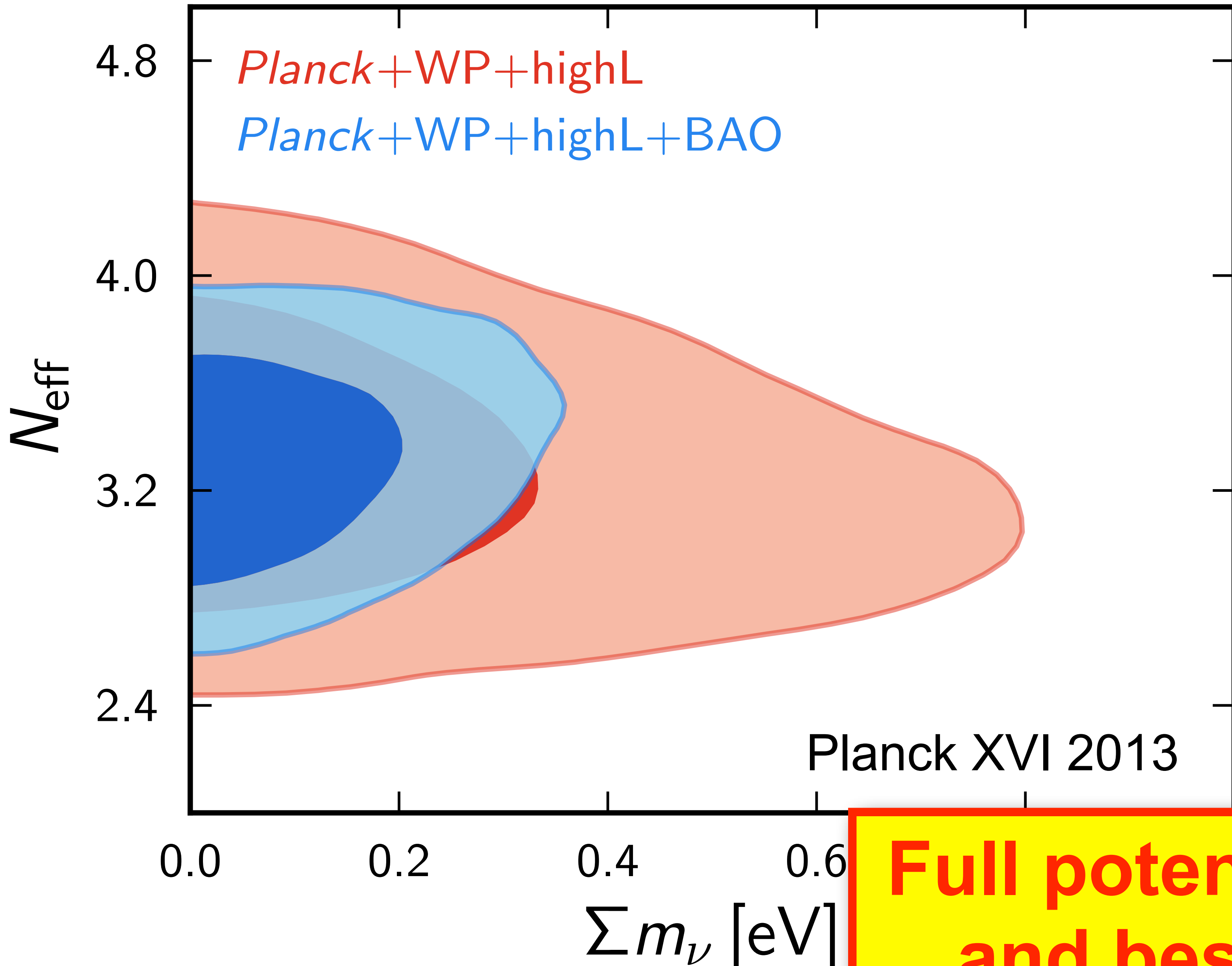
Σm_ν **< 0.23eV**

at 95% C.L.

(N_{eff} and Σm_ν constraints depend on choice of external data sets.)

N_{eff} is the effective number of relativistic species; it measures the extra relativistic energy relative to photons.
For standard 3 neutrinos N_{eff} =3.046.

Joint Dark Radiation (N_{eff}) and Σm_ν constraints in ΛCDM



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(>10σ detection of cosmic neutrino background)

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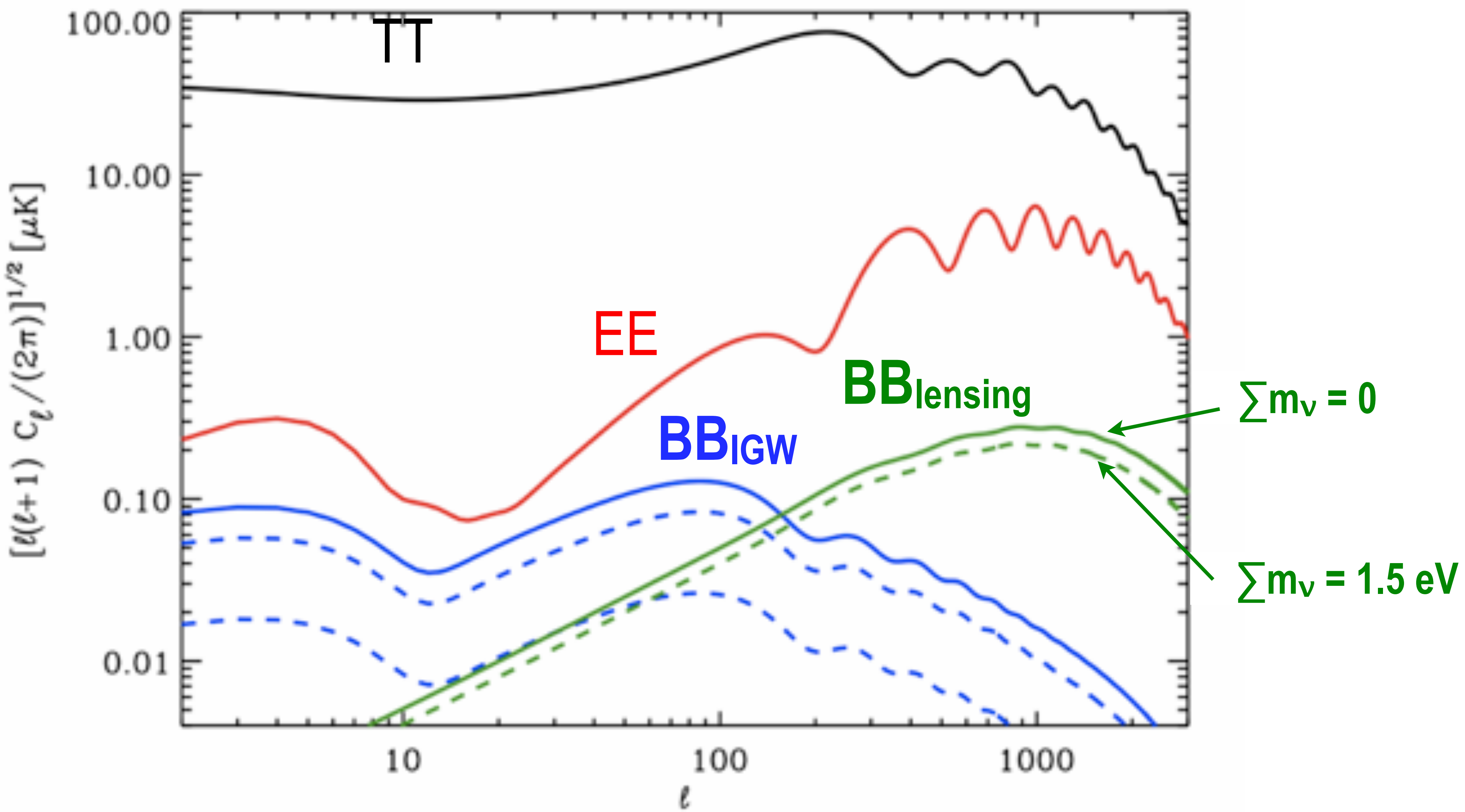
(N_{eff} and Σm_ν constraints depend on choice of external data sets.)

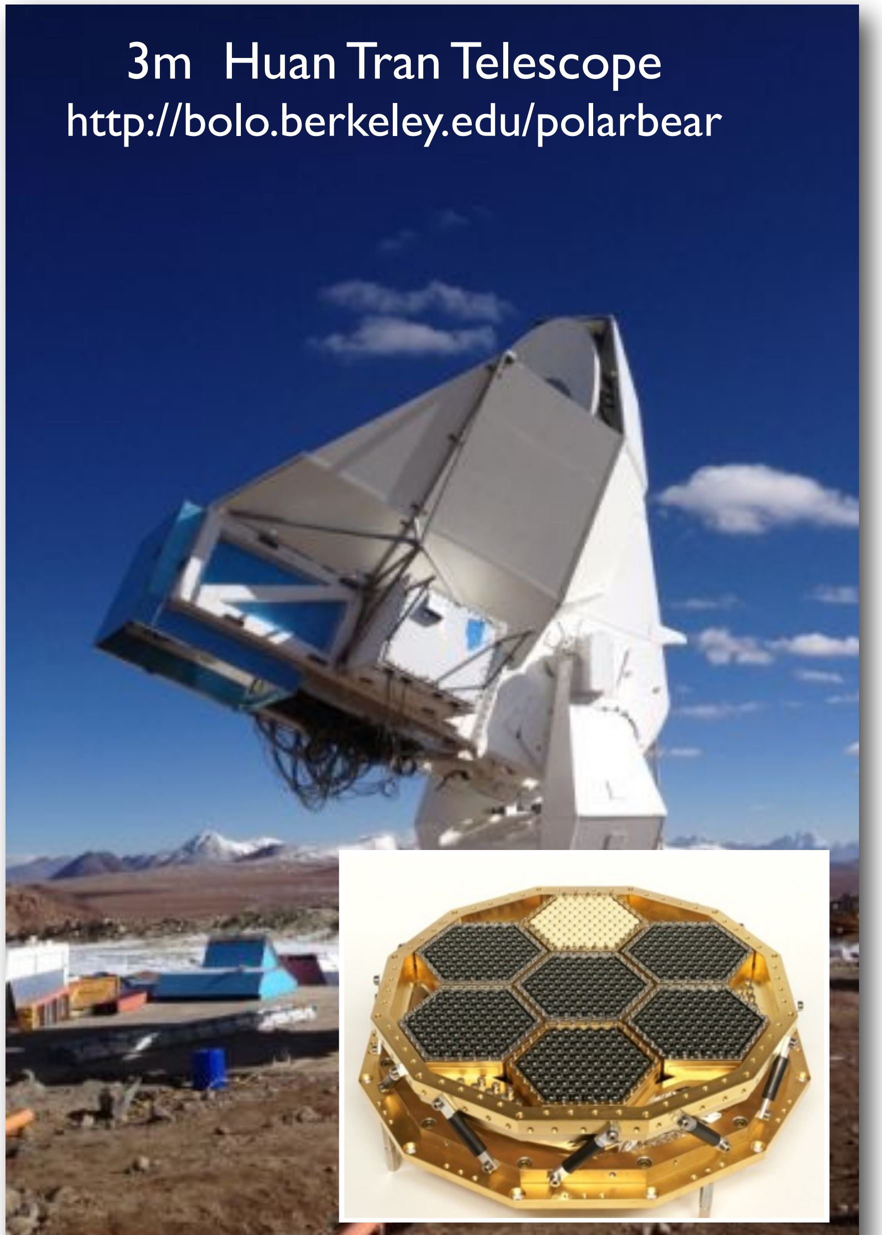
Full potential of CMB lensing and best Σm_ν constraints require polarization data

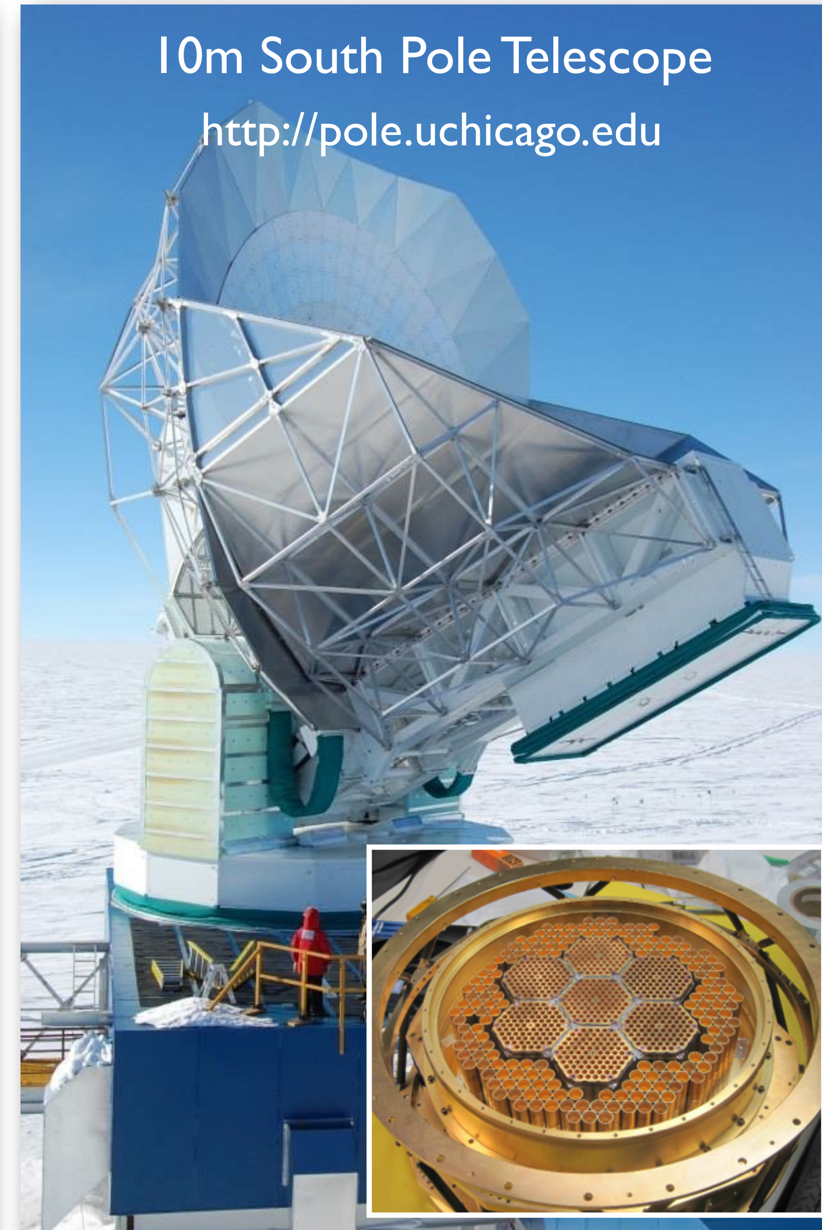
N_{eff} is the effective number of rel
extra relativistic energy relative to photons.
For standard 3 neutrinos N_{eff} =3.046.

CMB polarization:
the next frontier for lensing & inflation



Stage 2 and 3
ground-based CMB experiments

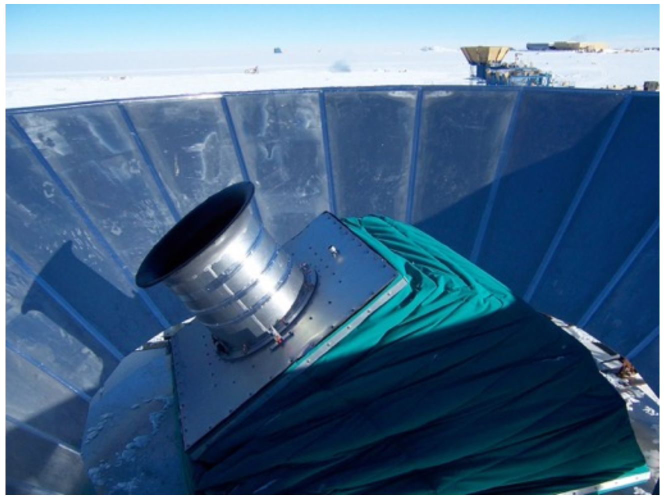


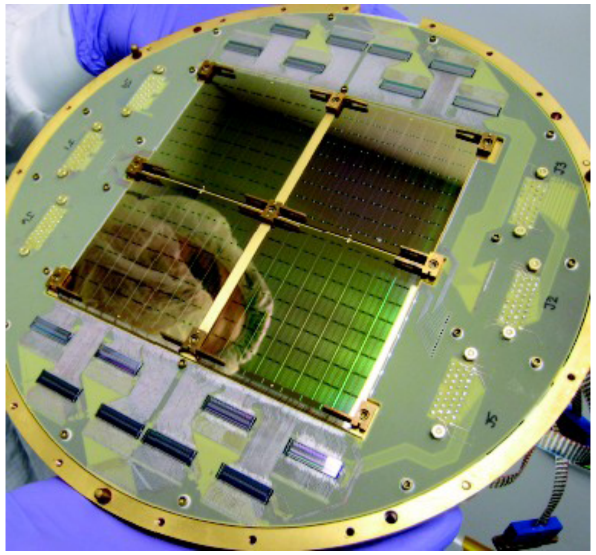


Exceptional high and dry sites for dedicated CMB observations.
Exploiting and driving ongoing revolution in low-noise bolometer cameras

Stage 2 and 3 ground-based CMB experiments

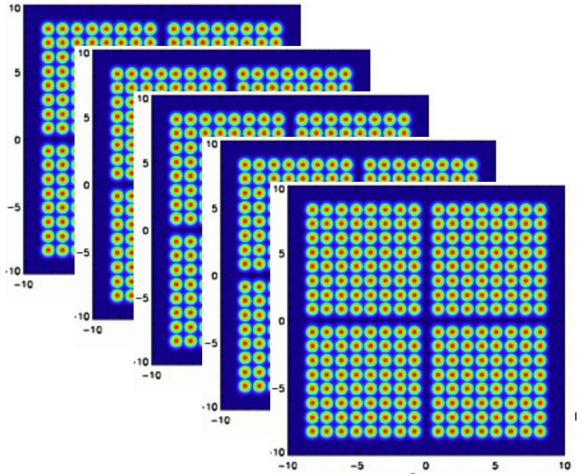
BICEP2
2010-2012





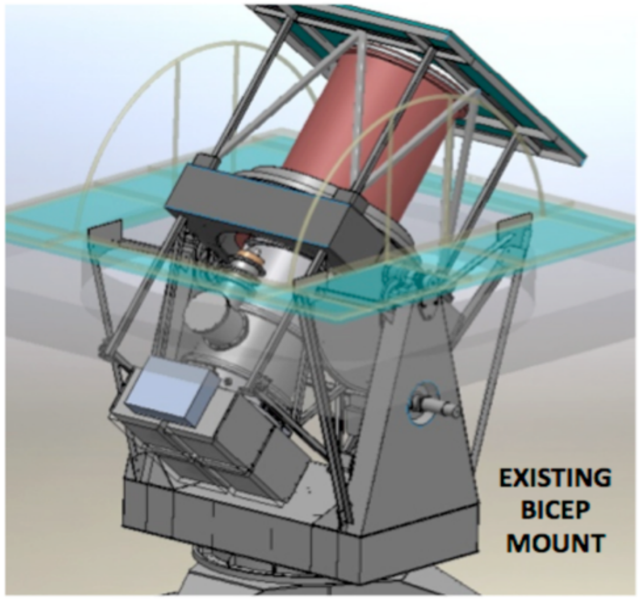
512 pixels @ 150 GHz
JPL

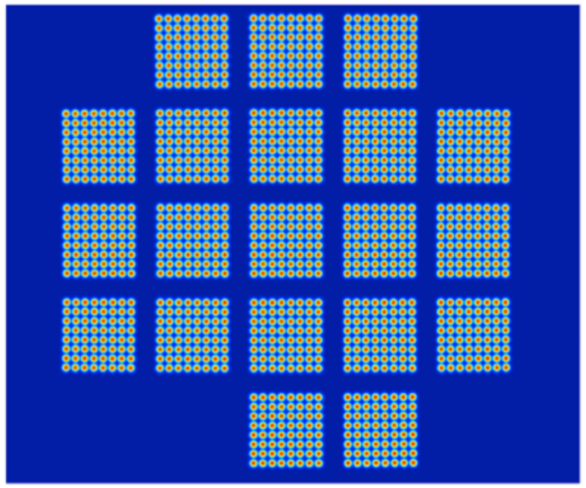
Keck Array
on DASI mount



5 x 512 @ 150 GHz

BICEP3
2015

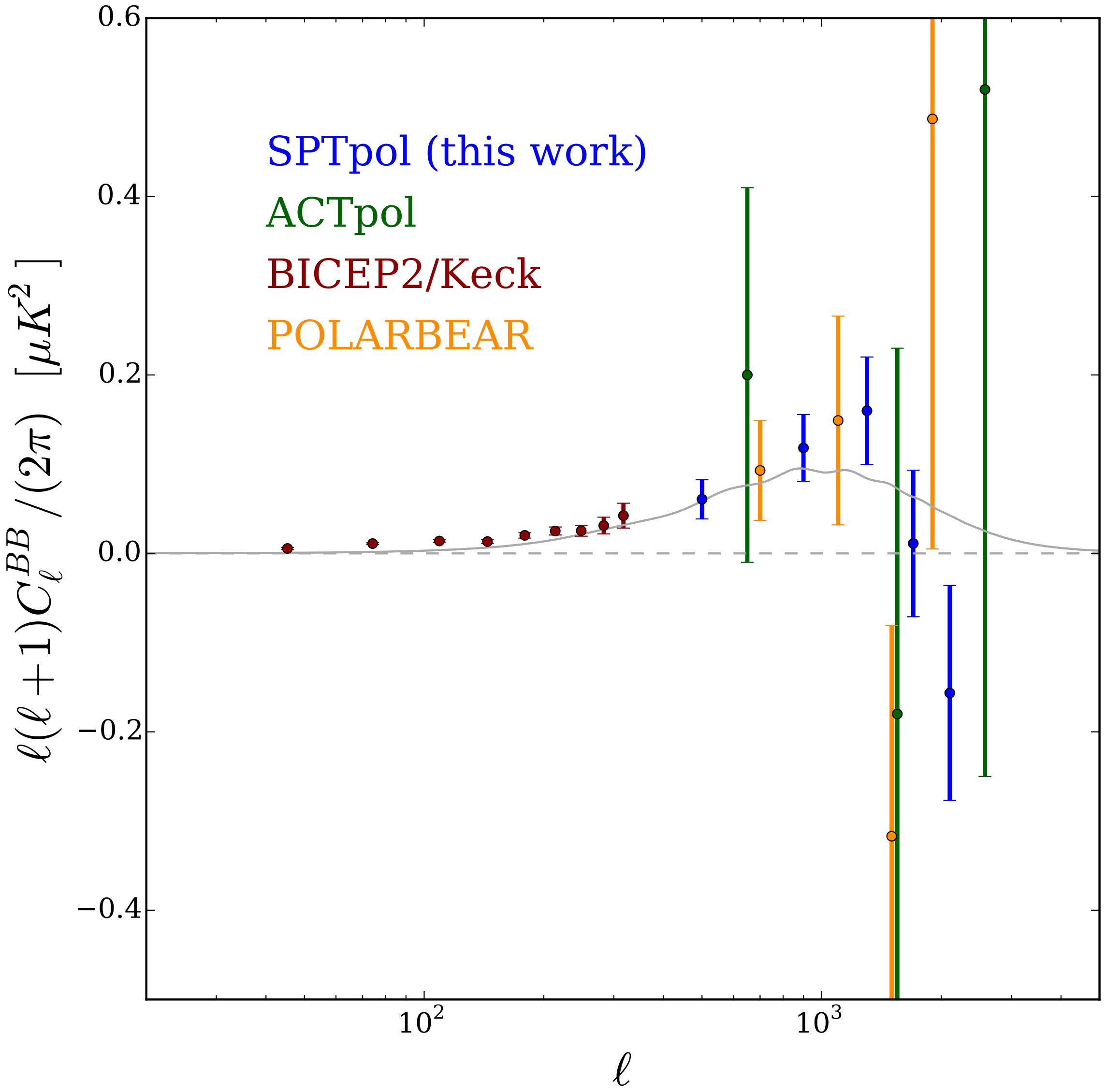




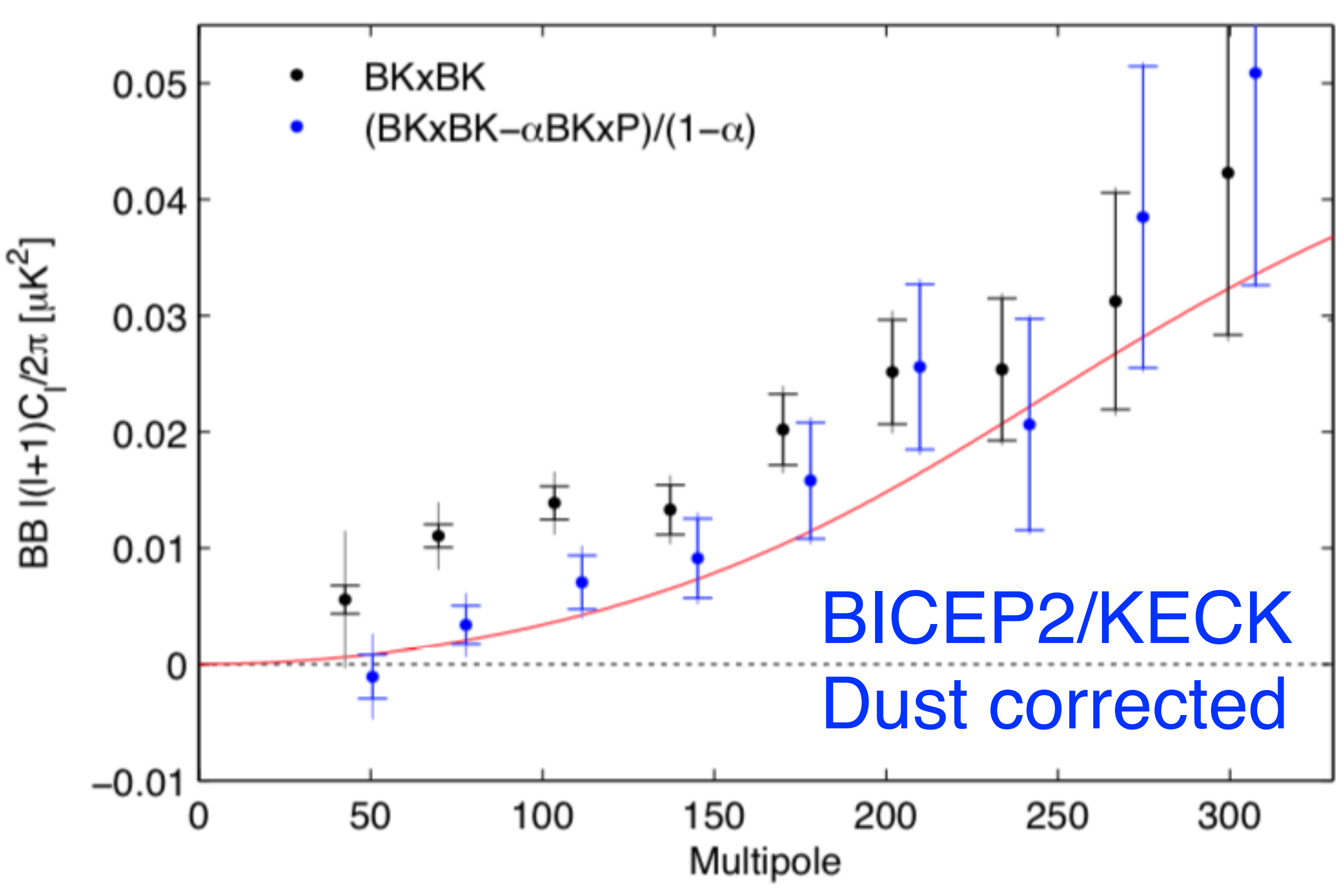
2056 @ 100 GHz

Optimized for degree scale only.
(Also CLASS starting soon)

BB Compilations

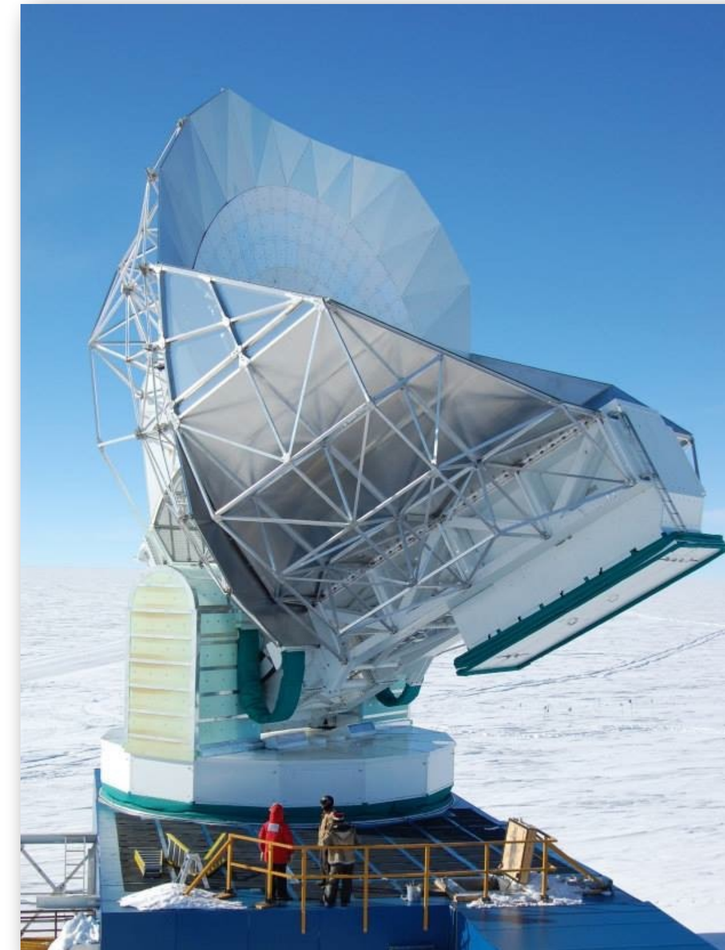


BICEP2/KECK x Planck results arXiv:1502.00612

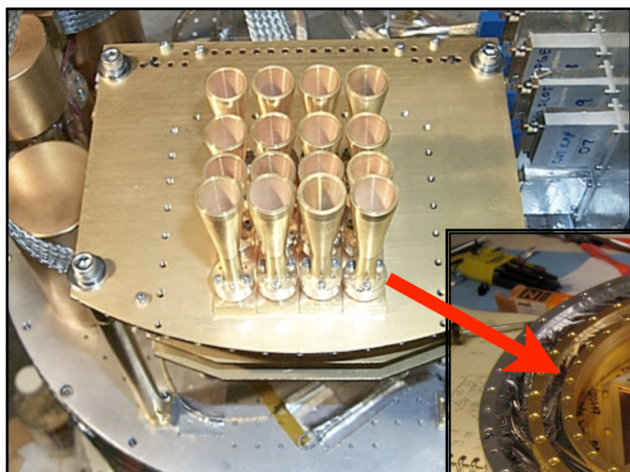


Rapid progress!
Still a long, long way to go.

SPT
Evolution of focal planes

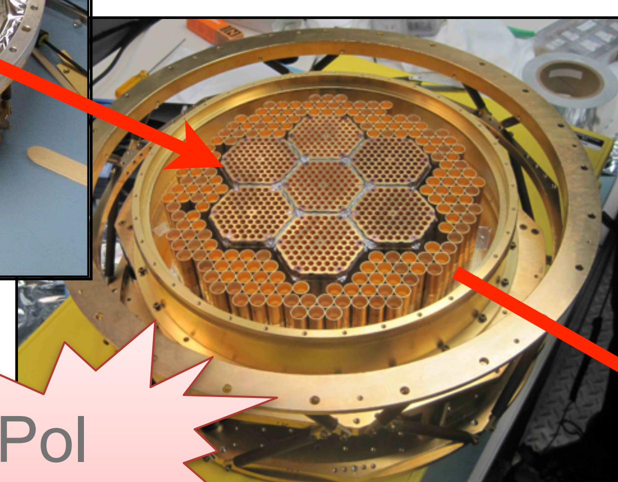


2001: ACBAR
16 detectors



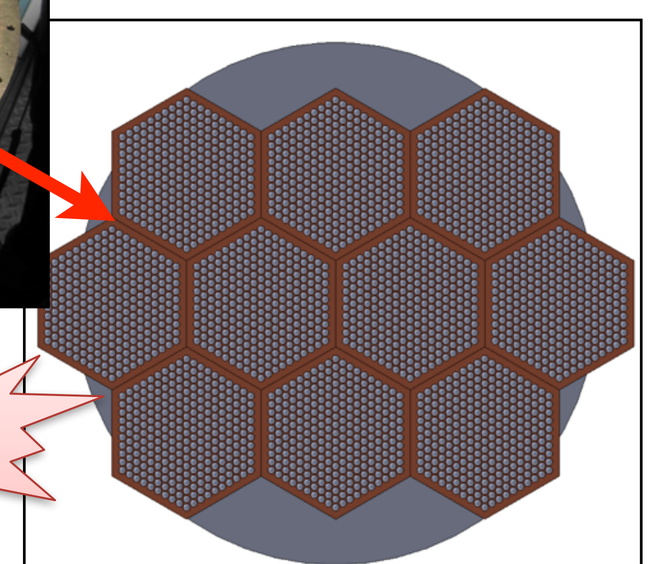
2007: SPT
960 detectors

Stage-2
2012: SPTpol
~1600 detectors



Pol

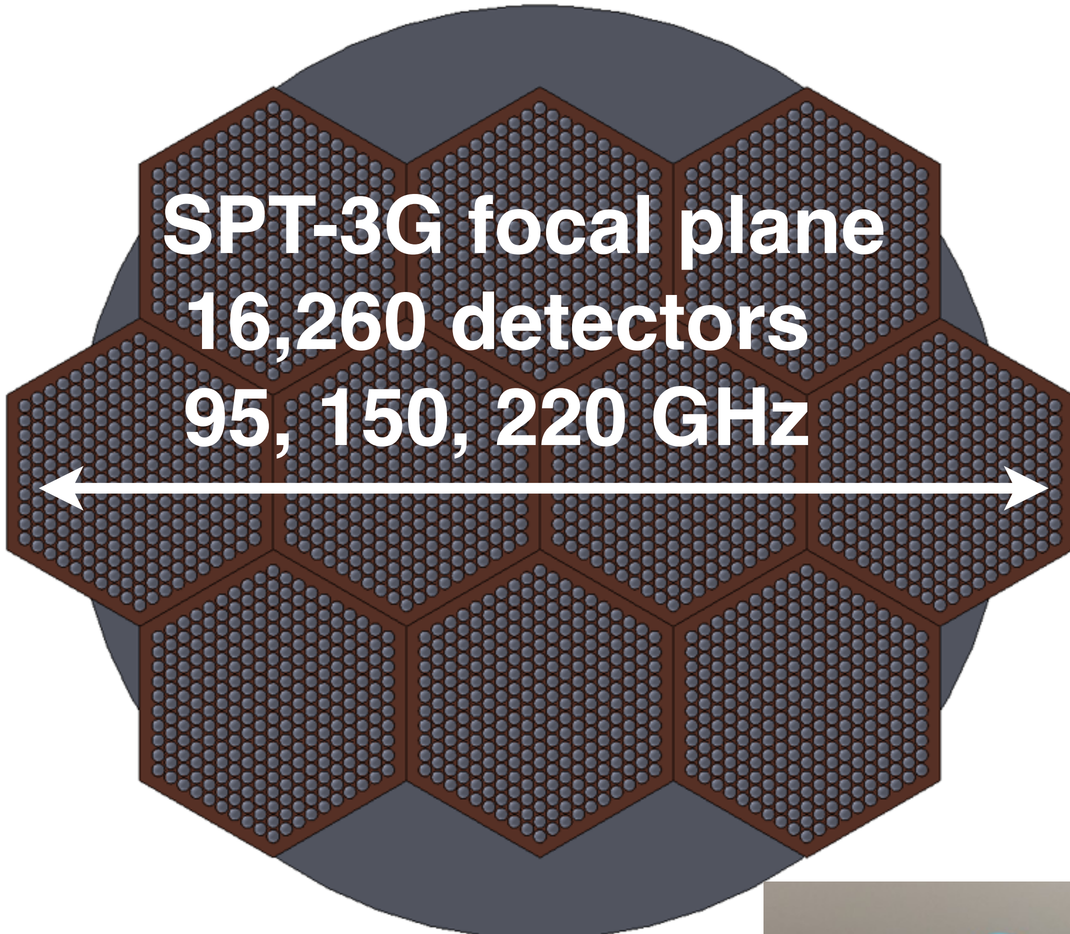
Stage-3
2016: SPT-3G
~16,000 detectors



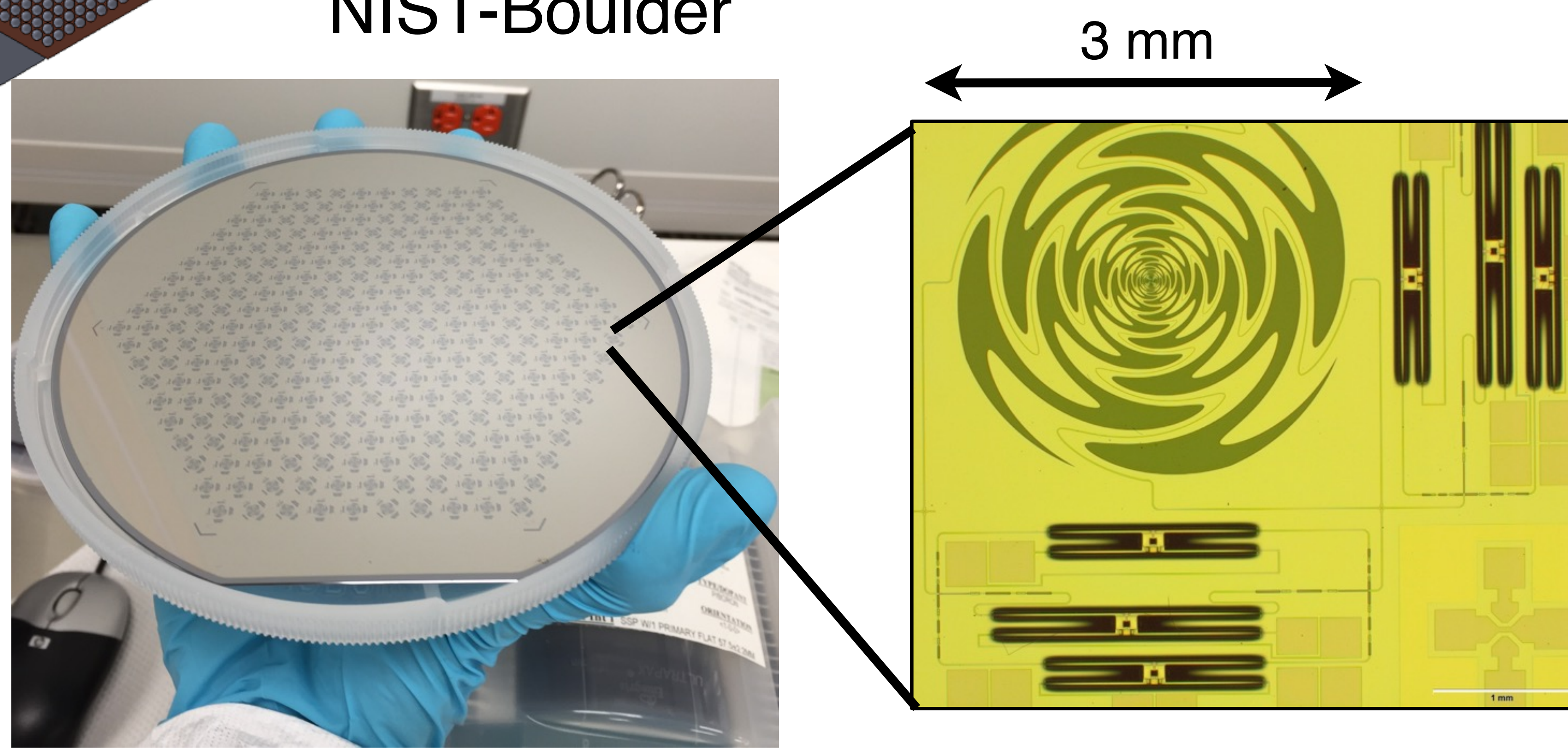
Pol

ACT and Polarbear planning similar detector upgrades

SPT-3G: 10x leap with multichroic pixels

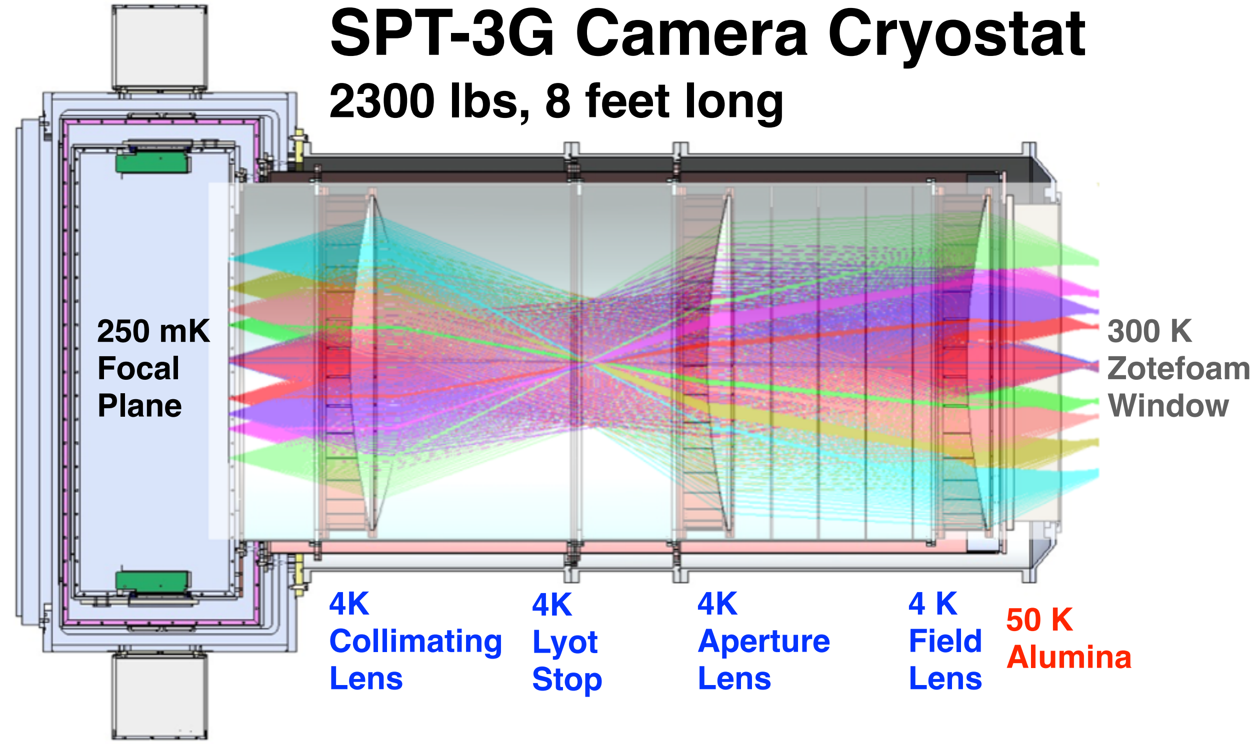


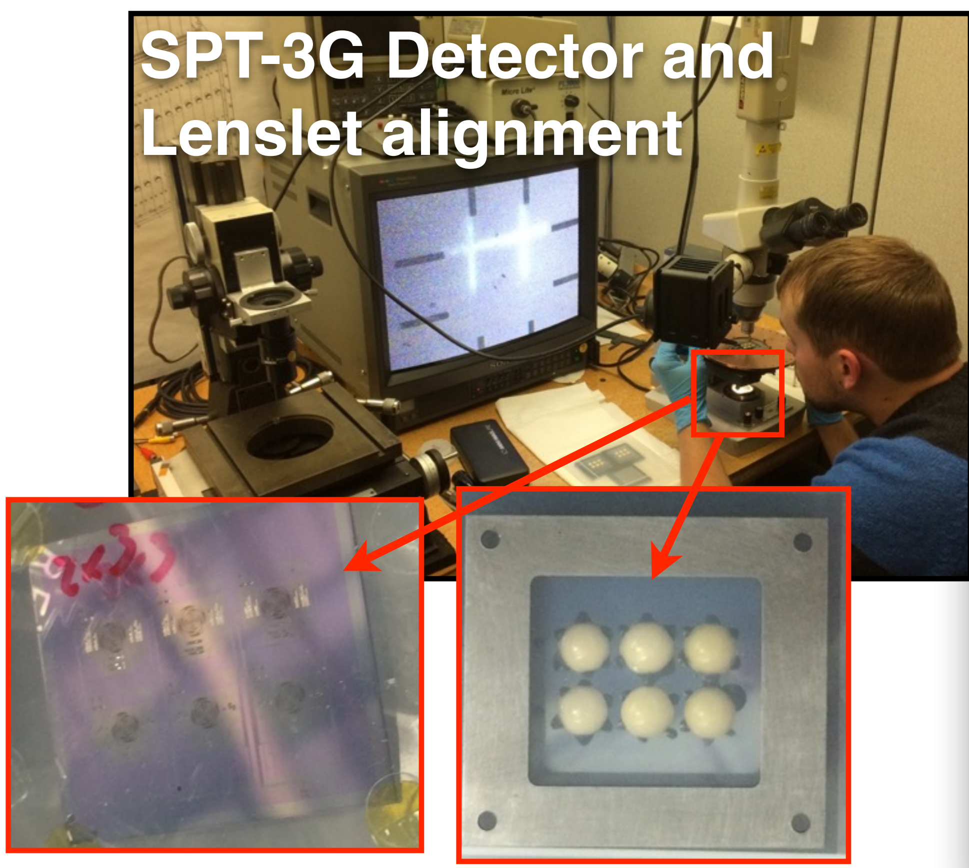
- Using lenslet coupled, 3-band sinuous antenna coupled TES detector design from UCB (Suzuki et al, 1210.8256)
- Detector fabrication at Argonne National Labs on 6” silicon wafers led by C. Chang
- 68x frequency multiplexed SQUID readout (McGill), using SQUIDs from NIST-Boulder

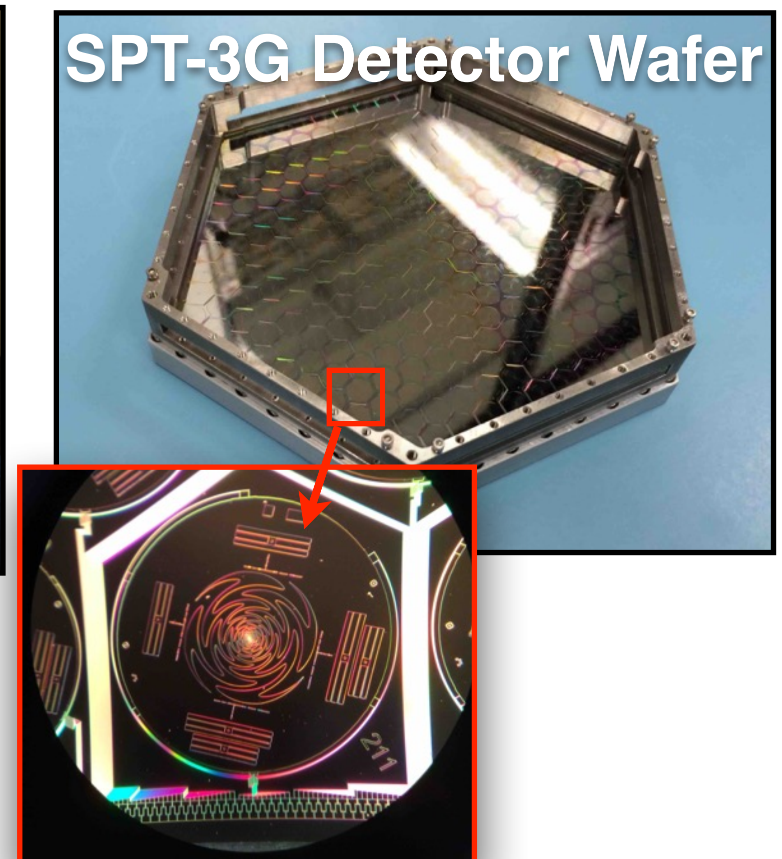


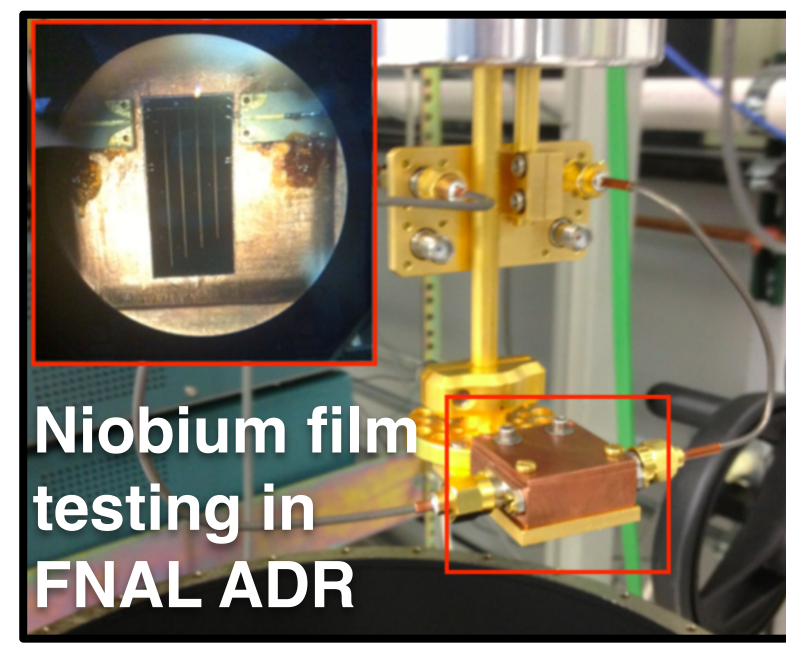
FNAL Leadership Roles for SPT-3G

- **SPT-3G Camera:** Design and fabrication of cryostat, integration with focal plane.
- **Detector Module Assembly:** Packaging detector wafers for SPT-3G (wire-bonding, wafer alignment)
- **Detector Testing:** Adiabatic de-magnetization and He3 cryostats to characterize TES detectors and superconducting films.









CMB polarization timeline

- 2013: Stage II experiments detect lensing B-modes
- now: $r \lesssim 0.12$ from Inflationary B-modes
- 2013-2016: Stage II experiments
  σ(r)~0.03, σ(N_{eff})~0.1, σ(Σm_ν)~0.1eV
- 2016-2020: Stage III experiments
  σ(r)~0.01, σ(N_{eff})~0.06, σ(Σm_ν)~0.06eV

- 2020-2025: Stage IV experiments, **CMB-S4**
  σ(r) = 0.001, σ(N_{eff}) = 0.020, σ(Σm_ν) =16 meV

CMB Experimental Stages

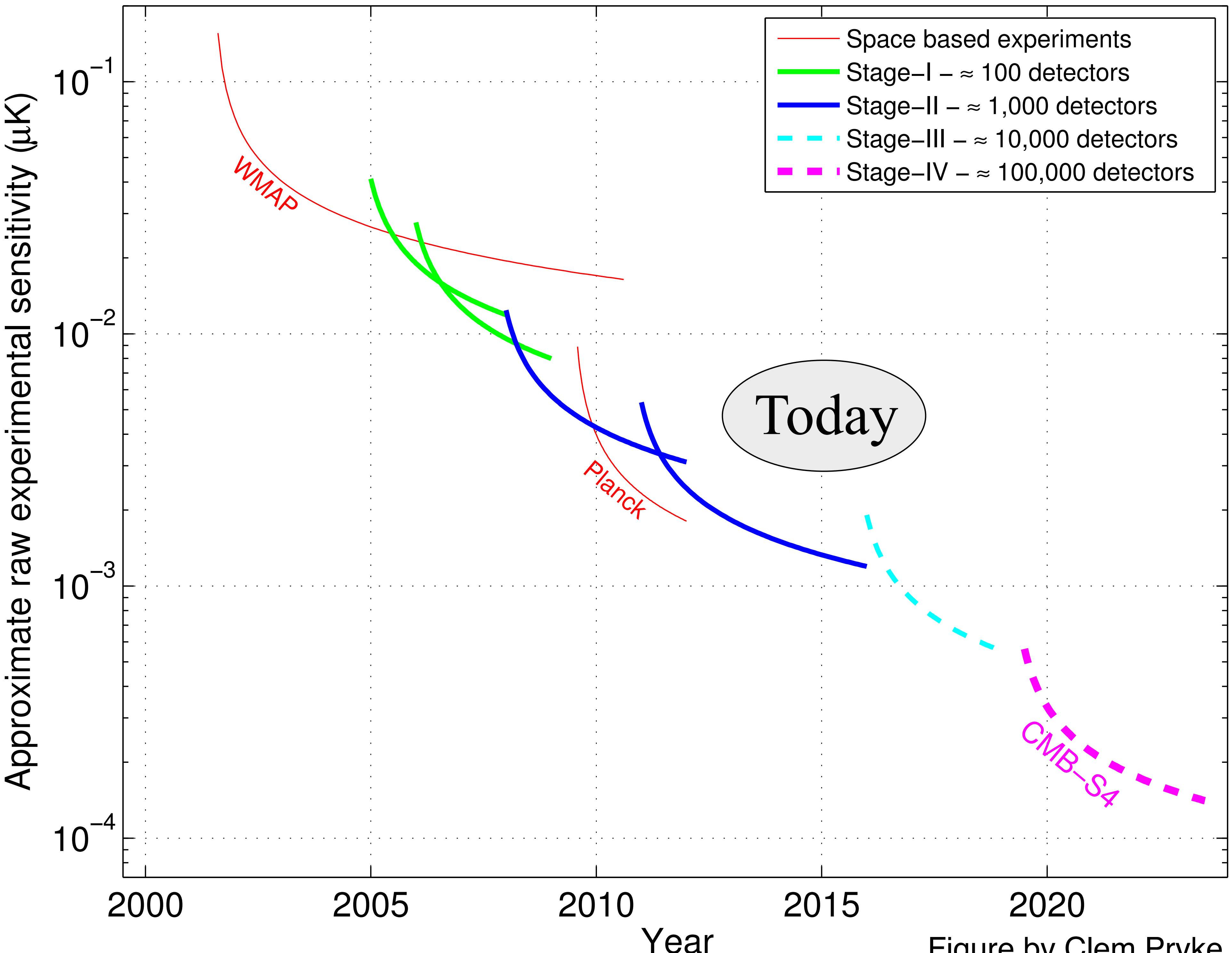


Figure by Clem Pryke

Snowmass: CF5 Neutrinos Document
arxiv:1309.5383

CMB-Stage 4 experiment

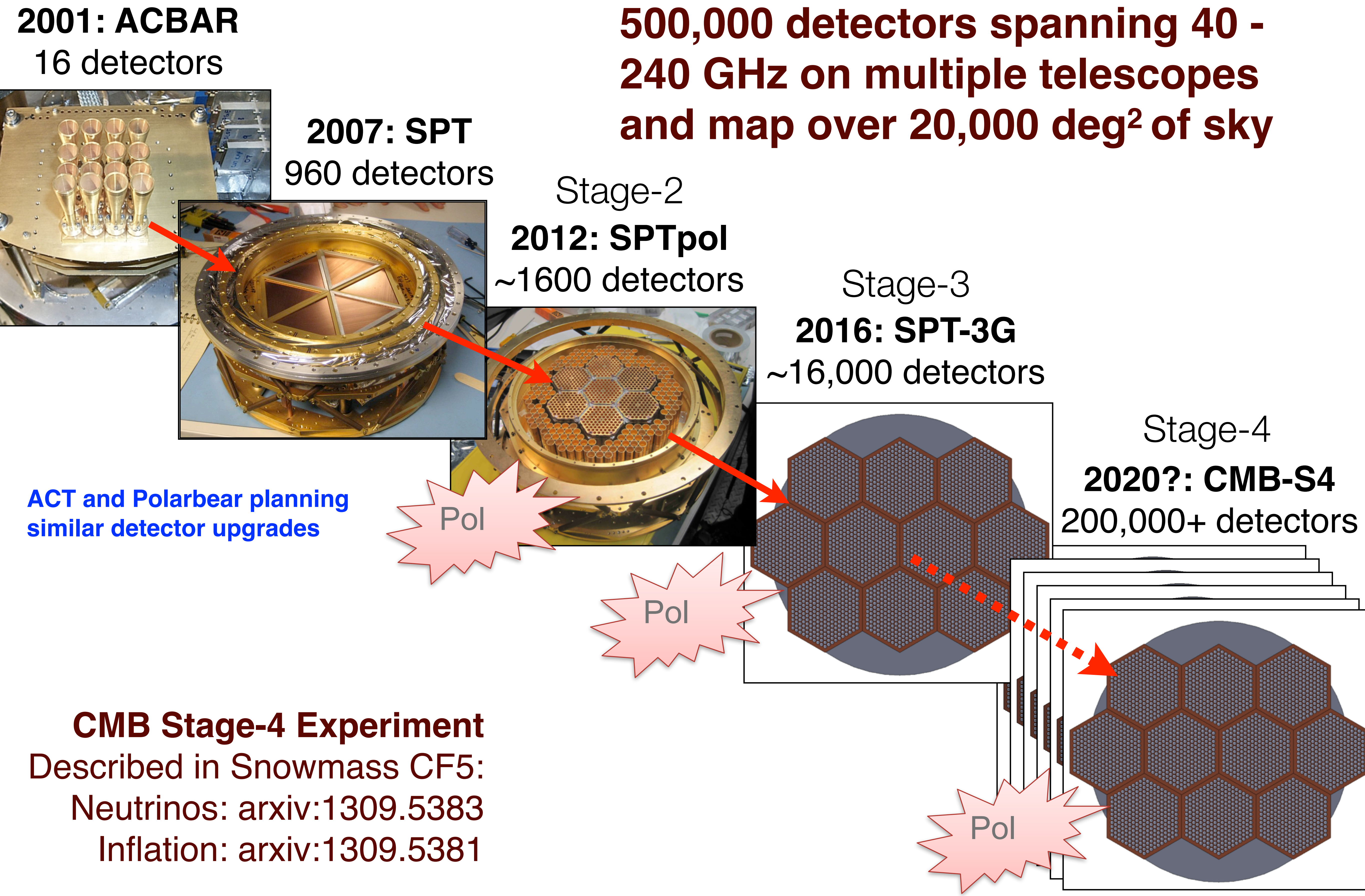
Because there is a lot more to learn from the CMB.

CMB-S4: a plan to build a coherent ground-based program working with, and building on, CMB stage II & III projects.

Participation includes, ***but is not limited to:***

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

CMB-S4: A coordinated community wide program to put 200,000 to 500,000 detectors spanning 40 - 240 GHz on multiple telescopes and map over 20,000 deg² of sky



CMB Stage-4 Experiment

Described in Snowmass CF5:

Neutrinos: arxiv:1309.5383

Inflation: arxiv:1309.5381

Argonne NATIONAL LABORATORY

- Investment in robust, large scale detector fabrication.
- Provided 90 GHz detectors for SPTpol.
- Leadership roles in SPT Stage II and Stage III, providing detectors.
- Large scale cosmological simulatio

Fermilab

- Investment in detector testing.
- SiDet facility for module assembly.
- Camera design and fabrication, testing and integration.
- Experience with QUIET detector module testing and assembly.
- Leadership roles in SPT-3G.

CMB-S4

BERKELEY LAB

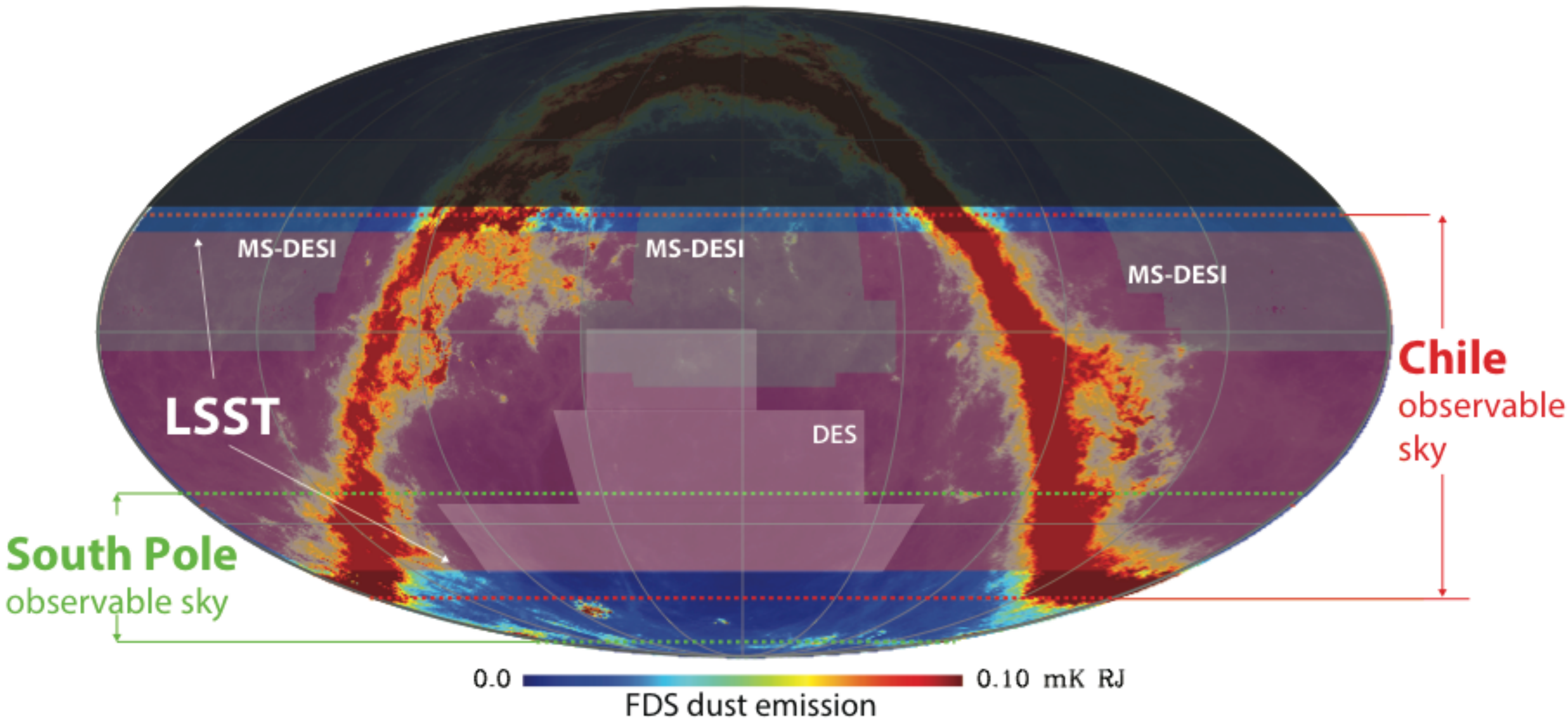
- CMB heritage and connections with UCB detector development.
- Investment in multiplexer readout.
- High performance computing/massively parallel data analysis.
- Involvement in Polarbear and SPT all stages.

SLAC NATIONAL ACCELERATOR LABORATORY

- Investment in developing large aperture cryogenic optics, providing optics for SPT-3G
- Investing in robust, large scale detector and SQUID design and fabrication, migrating from NIST.
- Leadership roles in BICEP / KECK.

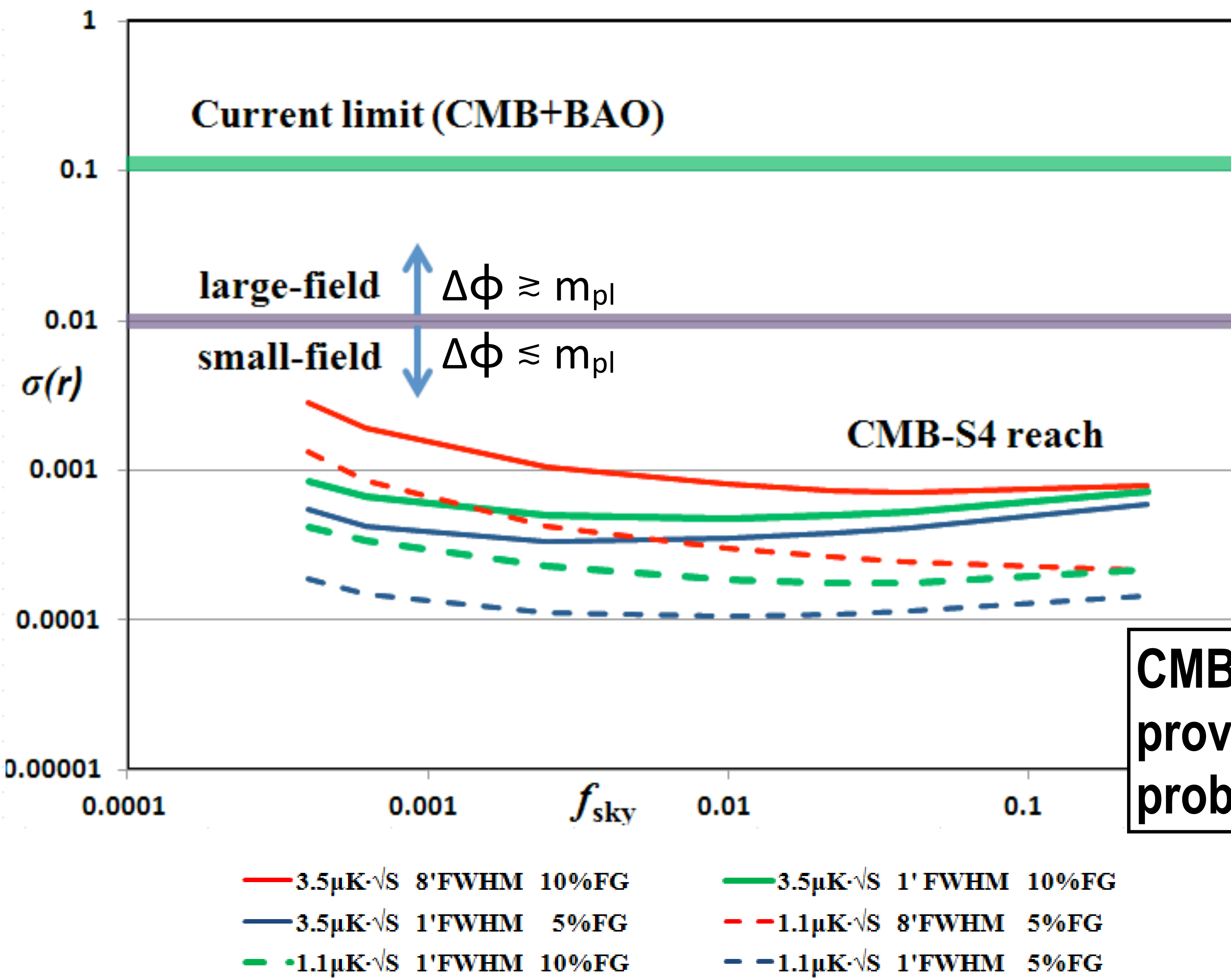
Exploit superb, established sites at Chile and South Pole and possibly add Northern site(s)

(critical to overlap with LSST, MS-DESI, etc)



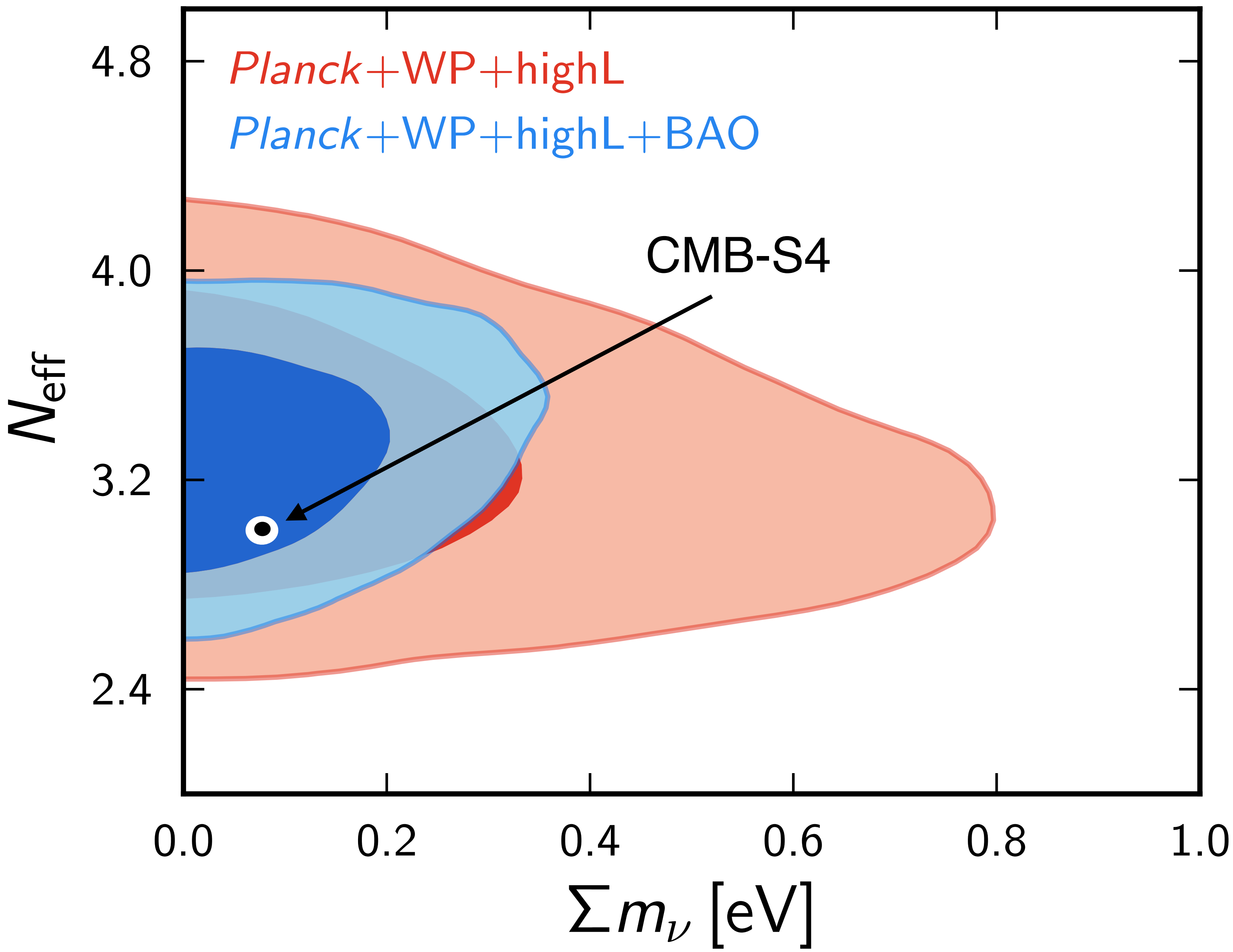
Slide from Jeff McMahon

Inflation projection for CMB-S4



CMB polarization provides the only probe for r < 0.1

N_{eff} - Σm_ν projections for CMB-S4



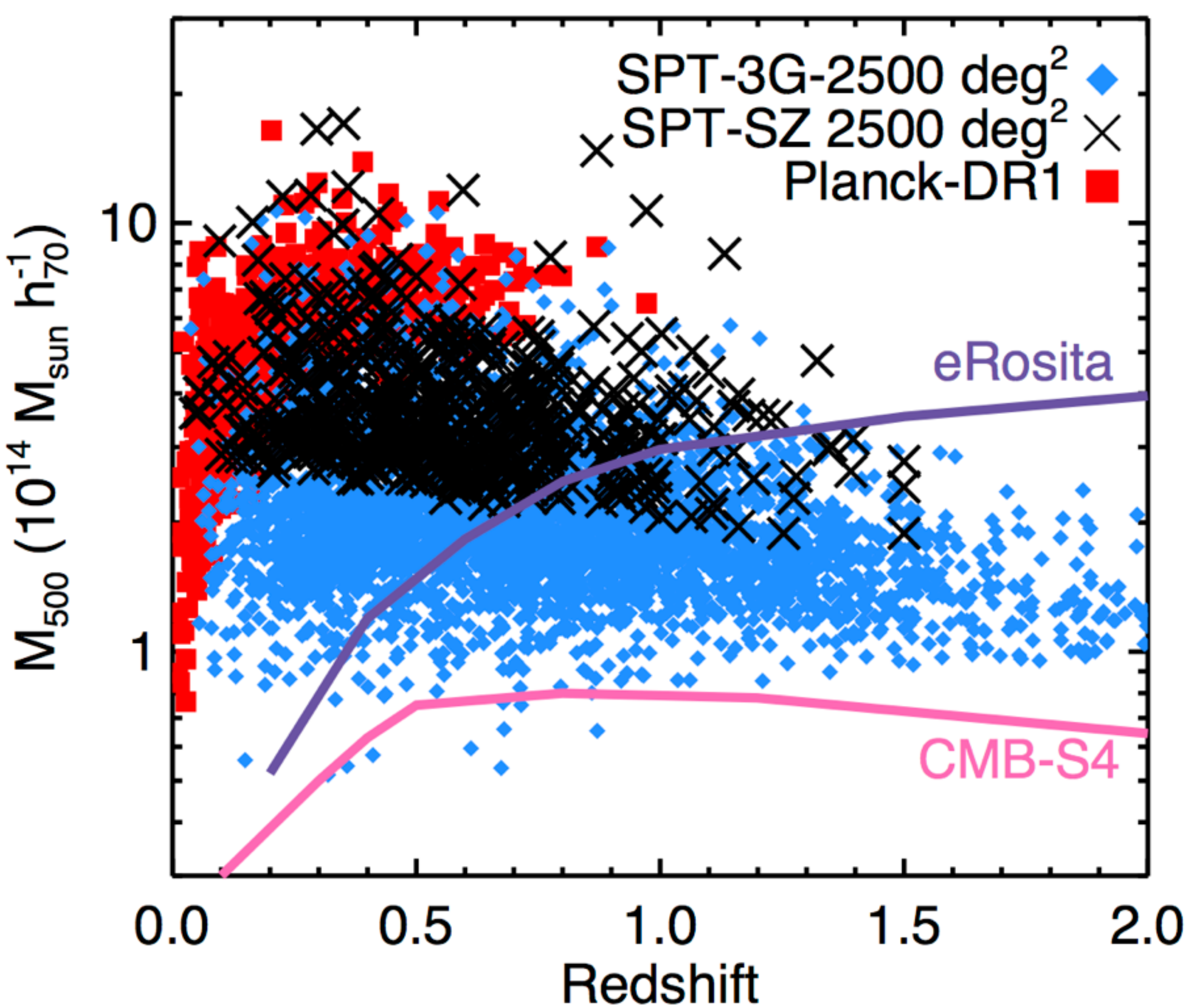
$\sigma(\Sigma m_\nu)$ = 16 meV (with DESI BAO)

$\sigma(N_{eff})$ = 0.020
CMB is the only probe of N_{eff}

Our 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



SPT-SZ/pol: N_{clust} **~ 1,000**

SPT-3G: N_{clust} **~ 10,000**

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

CMB lensing can directly calibrate cluster mass:

SPT-3G: ***σ(M) ~ 3%***

CMB-S4: ***σ(M) ~ 0.1%***

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

Efforts toward CMB-S4

CMB-S4 concept developed during Snowmass planning exercise in 2013 (see arXiv:1309.5383 and arXiv:1309.538)

CMB groups presented coherent program to Particle Physics Project Prioritization Panel (P5) (12/2013)
P5 endorsed CMB and CMB-S4 project.

Recently submitted NSF Science & Technology Center preproposal as a vehicle to bring community together and, if successful, to bring in NSF funds: Center for Microwave Background Research (CMBR).

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

CMBR participants

Directorship

Carlstrom, John	*U. Chicago*	Director
Page, Lyman	*Princeton*	Co-Director
Meyer, Stephan	*U. Chicago*	Associate Director
Basri, Gibor	*U.C. Berkeley*	Diversity Officer
TBD		Center Manager

Internal Guiding Board

Staggs, Suzanne [c]	*Princeton*	Irwin, Kent	*Stanford*	Miller, Amber	*Columbia*
Borrill, Julian	*LBL*	Knox, Lloyd	*U.C. Davis*	Padin, Steve	*Caltech*
Devlin, Mark	*U. Penn*	Kovac, John	*Harvard U.*	Ruhl, John	*Case Western*
Holzapfel, Bill	*U.C. Berkeley*	Lee, Adrian	*U.C. Berkeley*	Stassun, Keivan	*Fisk U.*

Coordinators

Stassun, Keivan	*Fisk*	Education, Diversity and Outreach (EDO)
TBD		EDO Executive Coordinator
Lloyd Knox	*U.C. Davis*	Physics & Cosmology
Padin, Steve	*Caltech*	Tehnology and Methods

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Benson, Bradford	*FNAL*	Kamionkowski, Marc	*JHU*	Pryke, Clem	*UMN*
Bock, Jamie	*Caltech*	Keating, Brian	*UCSD*	Readhead, Anthony	*Caltech*
Burger, Arnold	*Fisk U.*	Kosowsky, Arthur	*Pitt*	Schaffer, Kathryn	*SAIC*
Chang, Clarence	*ANL*	Kuo, Chao-Lin	*Stanford*	Sehgal, Neelima	*Stony Brook*
Crawford, Tom	*U. Chicago*	Kusaka, Akito	*LBL*	Seljak, Uros	*U.C. Berkeley*
Dodelson, Scott	*FNAL*	Landsberg, Randy	*U. Chicago*	Shandera, Sarah	*Penn State*
Filippini, Jeff	*UIUC*	Leitch, Erik	*U. Chicago*	Shirokoff, Erik	*U. Chicago*
Flauger, Raphael	*CMU*	LoVerde, Marilena	*Stony Brook*	Spergel, David	*Princeton*
Halverson, Nils	*CU Boulder*	Lubin, Phil	*UCSB*	Timbie, Peter	*UW Madision*
Hanany, Shaul	*UMN*	Marriage, Toby	*JHU*	Vieira, Joaquin	*UIUC*
Heitmann, Katrin	*ANL*	Mauskopf, Phil	*Arizona State*	Vieregg, Abigail	*U. Chicago*
Hirata, Chris	*OSU*	McMahon, Jeff	*U.Michigan*	White, Martin	*U.C. Berkeley*
Ho, Shirley	*CMU*	Meinhold, Peter	*UCSB*	Zaldarriaga, Matias	*IAS*

Summary

We ~~can~~ will make CMB-S4 happen.

We have a lot of work to do and decisions to make, e.g.,

- Fully define the science goals.
- Complete the pre-conceptual design.
- Set up the collaboration, with careful attention to balance of national labs, university groups, and international partners
- Coordination with possible space mission(s)?