Neutrinos and CMB experiment

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HEP Division
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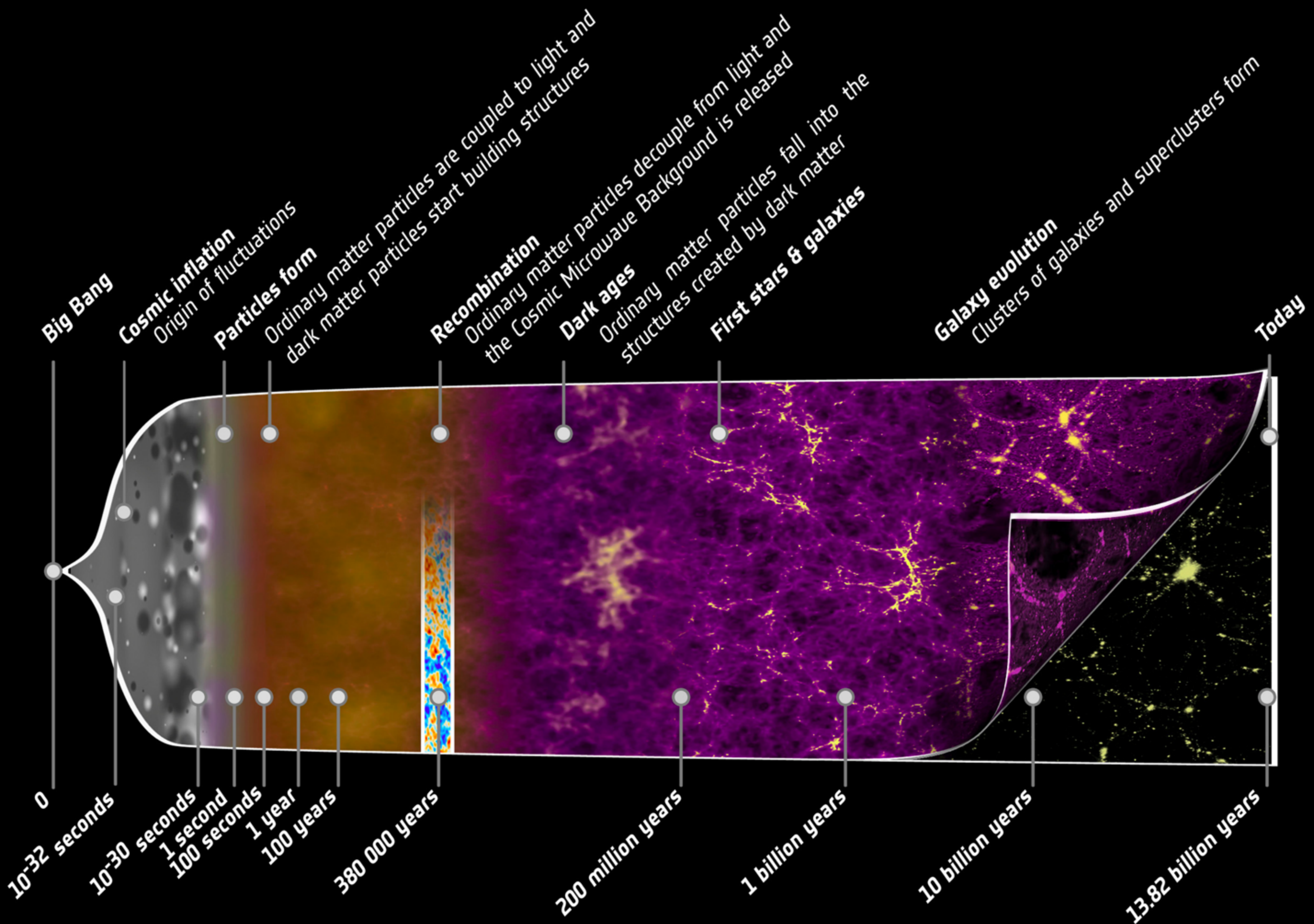
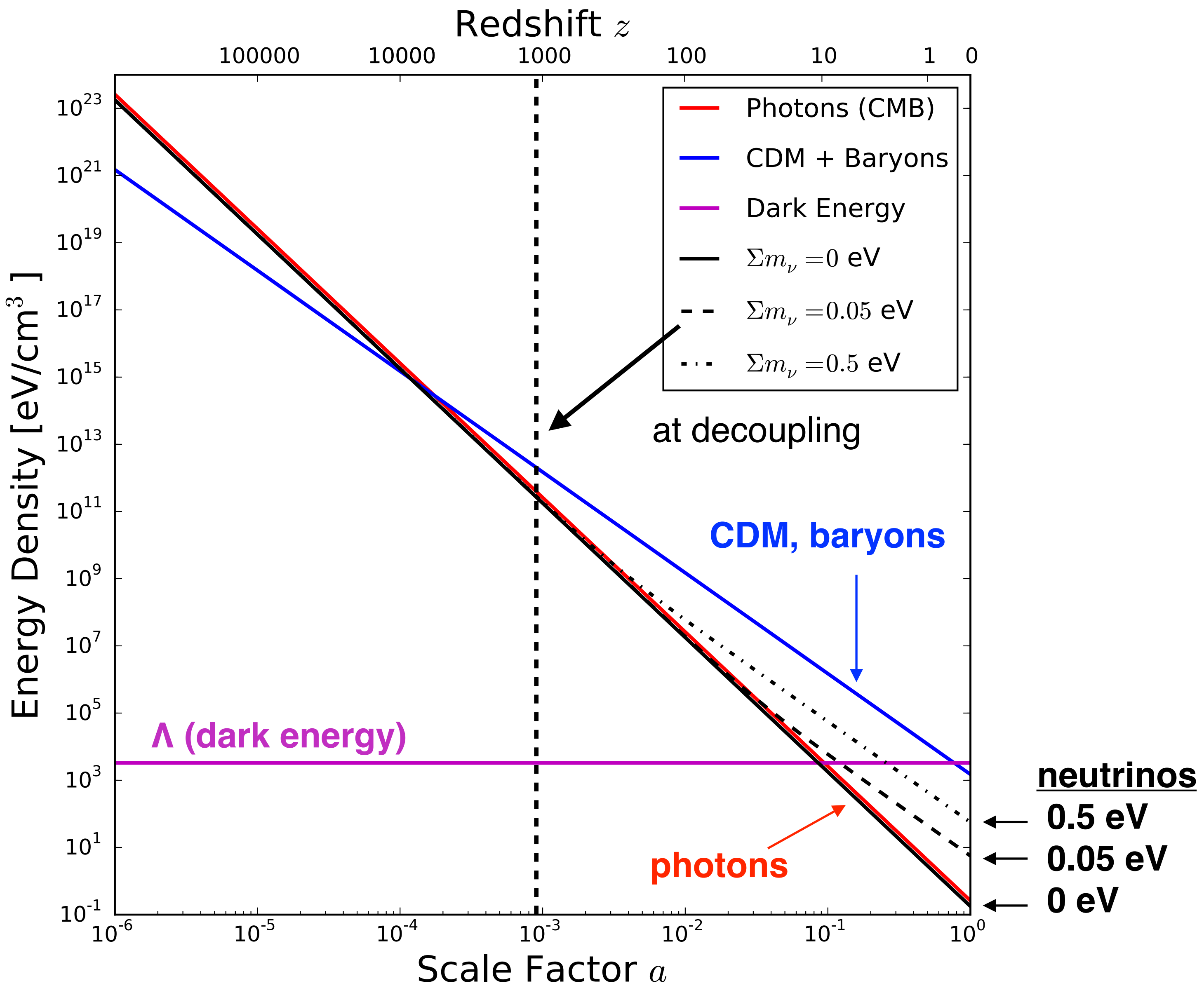
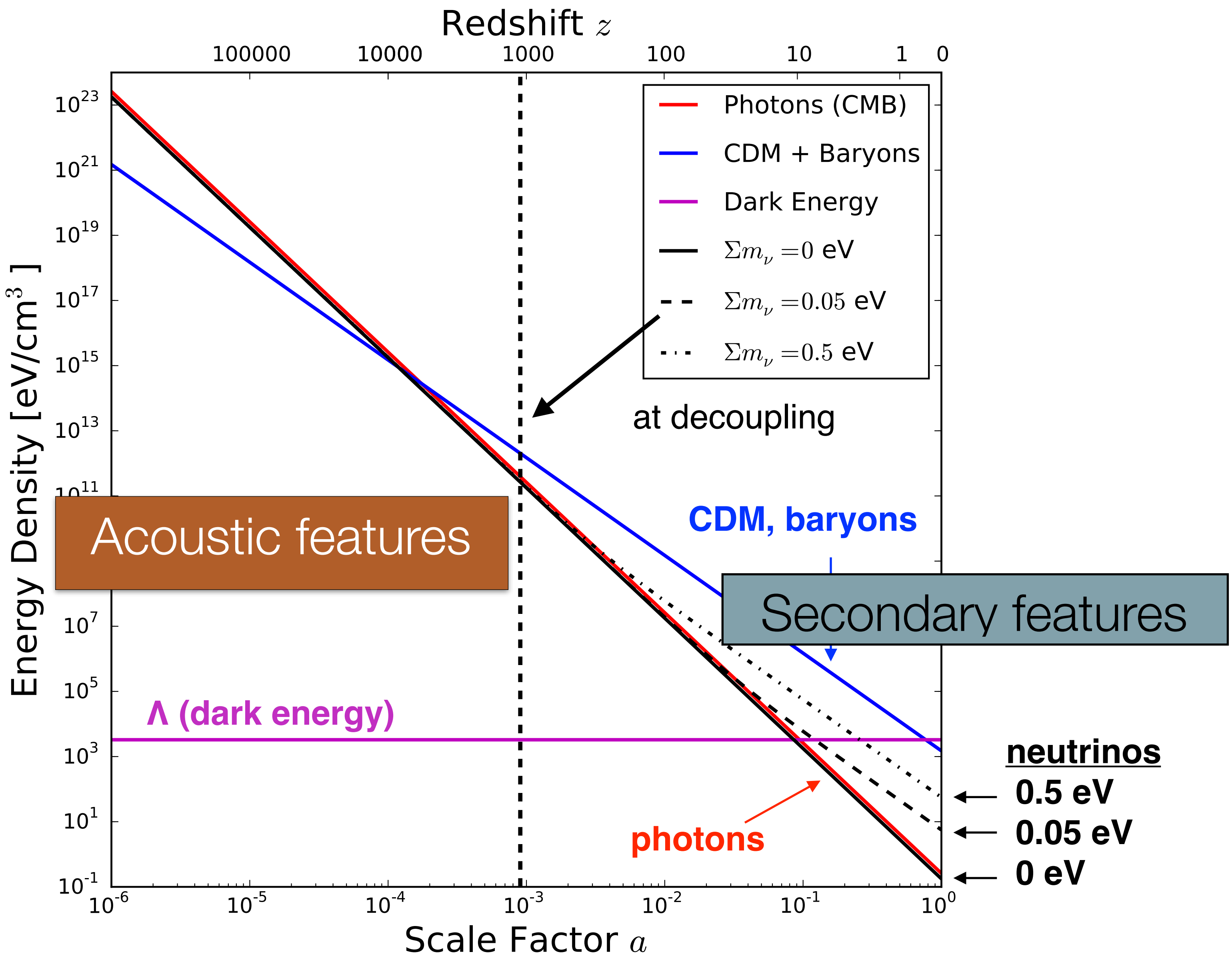
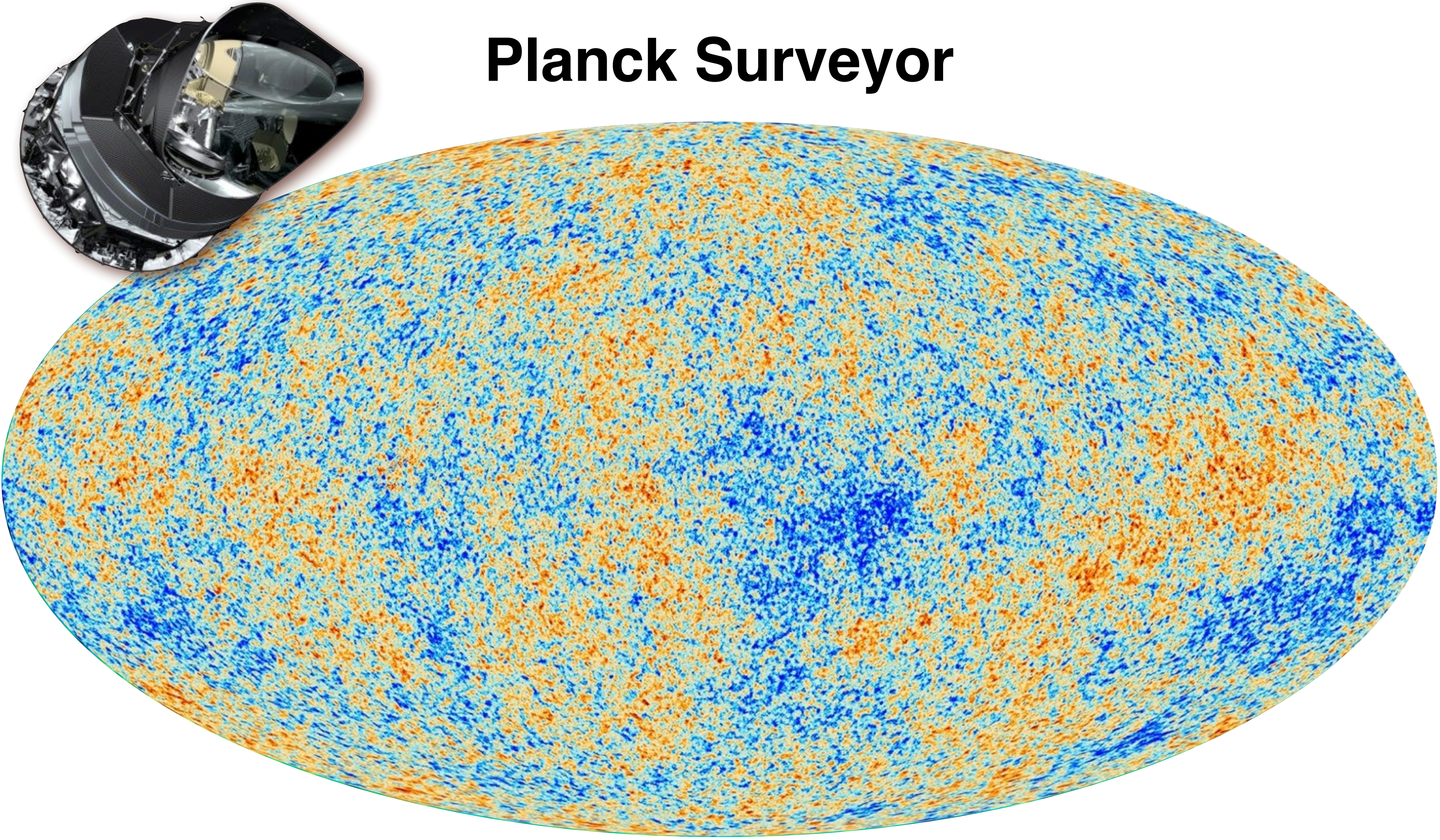

Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years



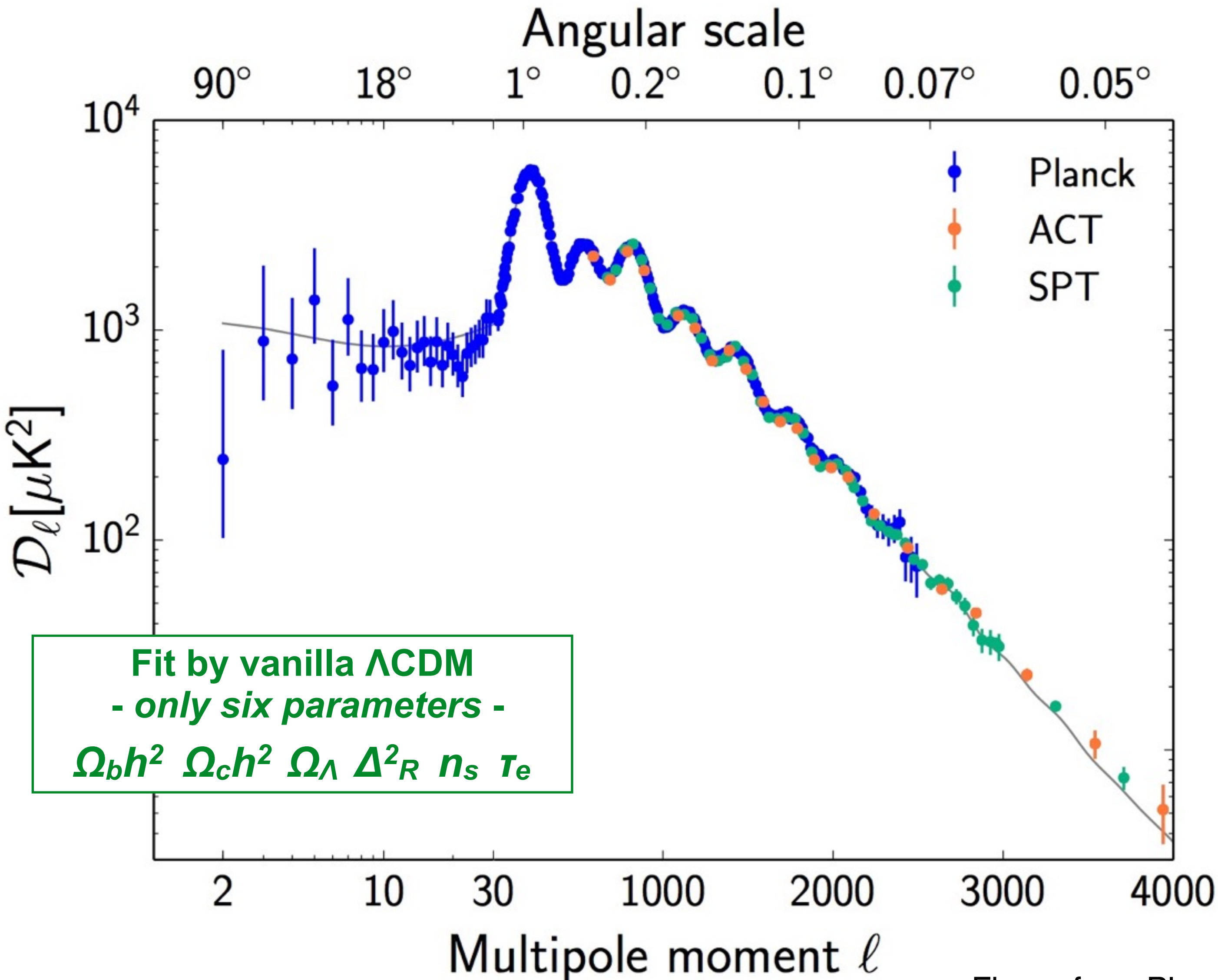
Neutrino Mass: From the Terrestrial Laboratory to the Cosmos, ACFI (2015)


Redshift z
100000
10000
1000
100
10
1
0
Energy Density [eV/cm³]
Scale Factor a
Photons (CMB)
CDM + Baryons
Dark Energy
Σm_ν =0 eV
Σm_ν =0.05 eV
Σm_ν =0.5 eV
at decoupling
Acoustic features
CDM, baryons
Secondary features
Λ (dark energy)
photons
neutrinos
0.5 eV
0.05 eV
0 eV

Planck Surveyor



Angular Power Spectrum



Fit by vanilla ΛCDM
- only six parameters -
$\Omega_b h^2$ $\Omega_c h^2$ Ω_Λ Δ^2_R n_s τ_e

Figure from Planck 2015 Results XI

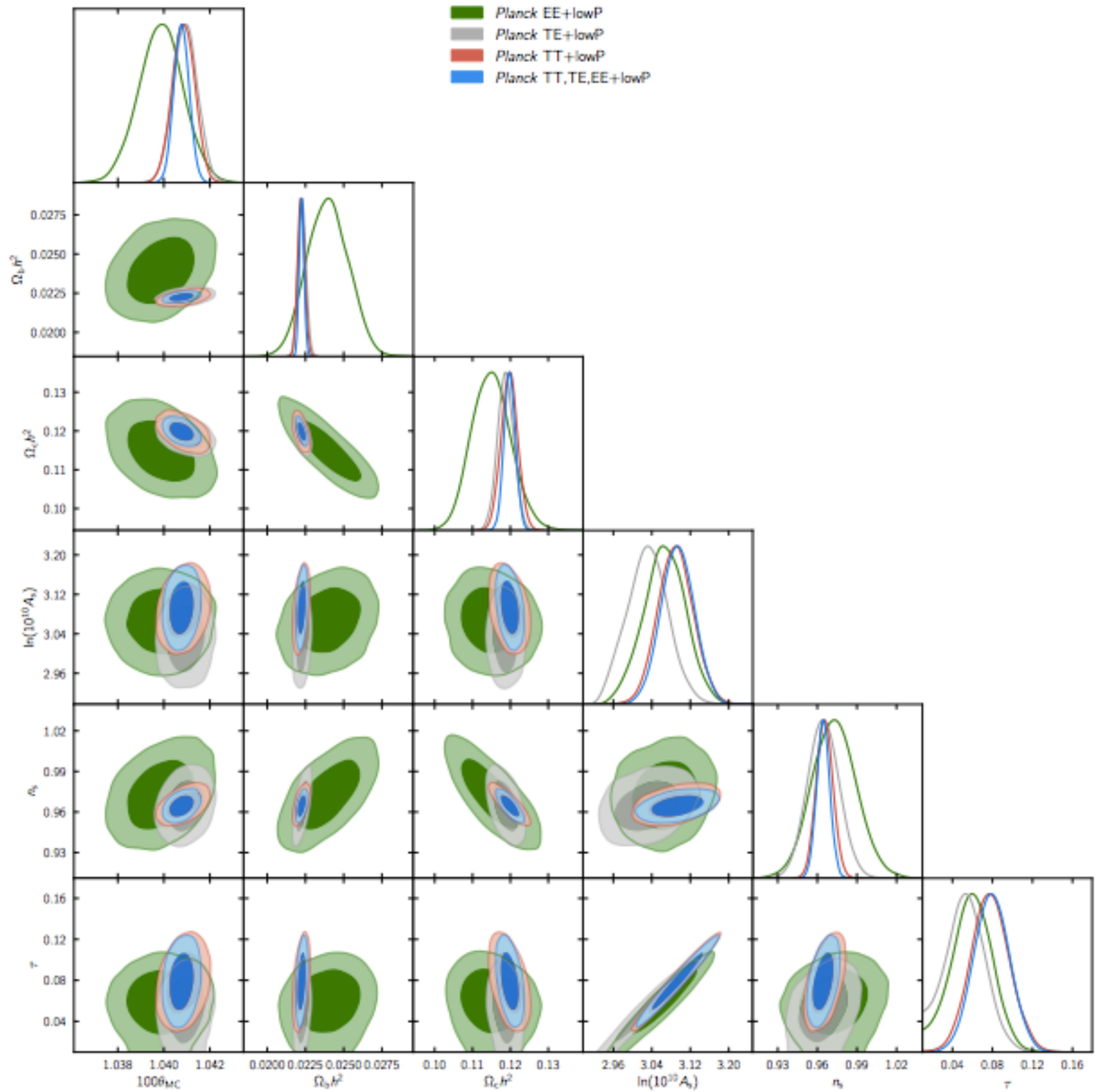


Fig. 6. Comparison of the base ΛCDM model parameter constraints from *Planck* temperature and polarization data.

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Angular Power Spectrum

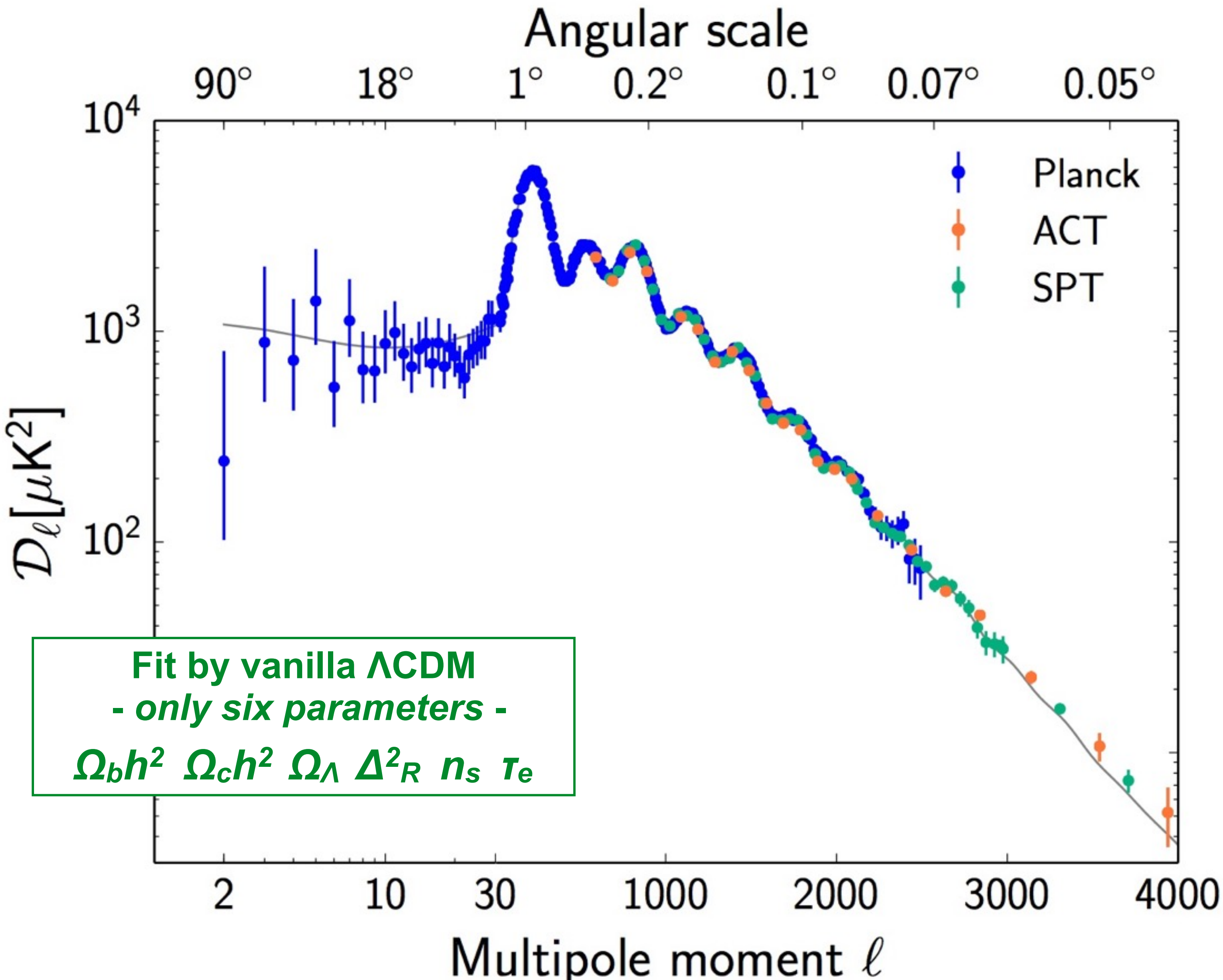

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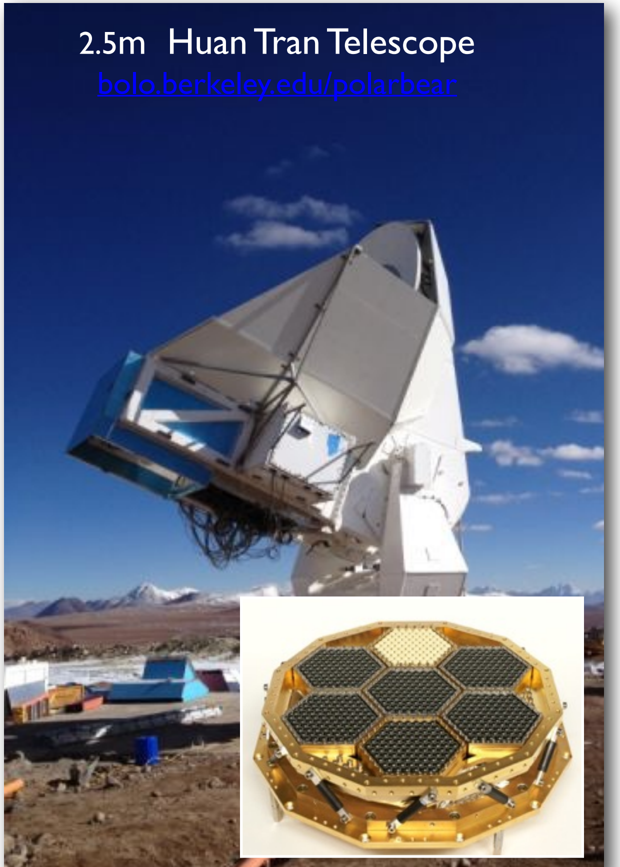
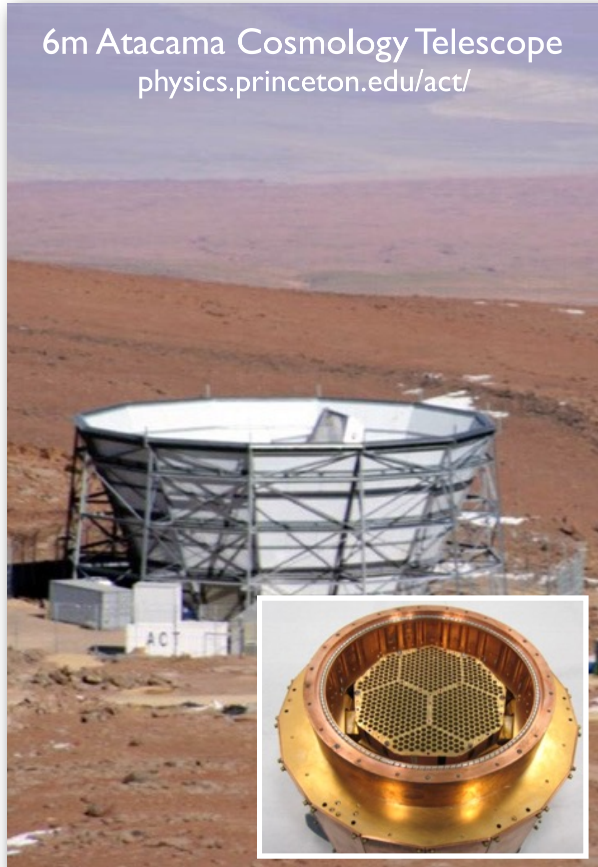
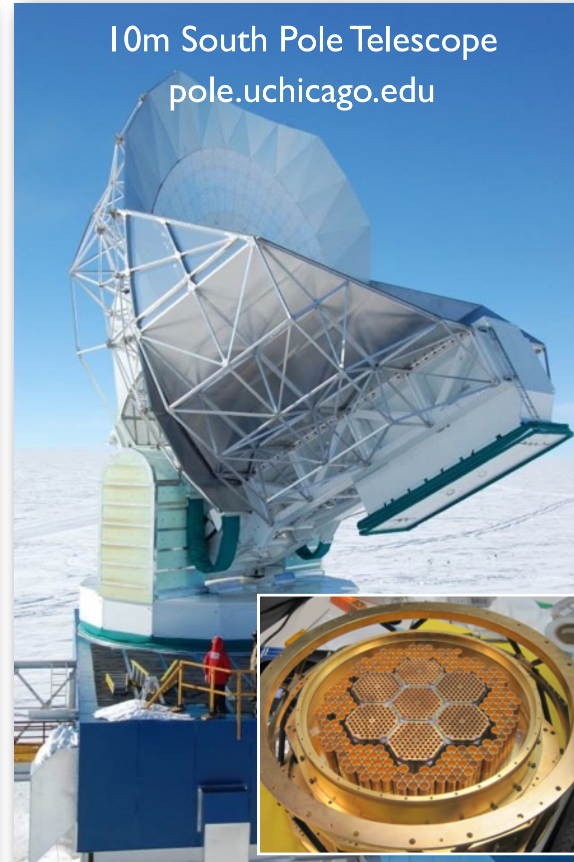
Figure from Planck 2015 Results XI

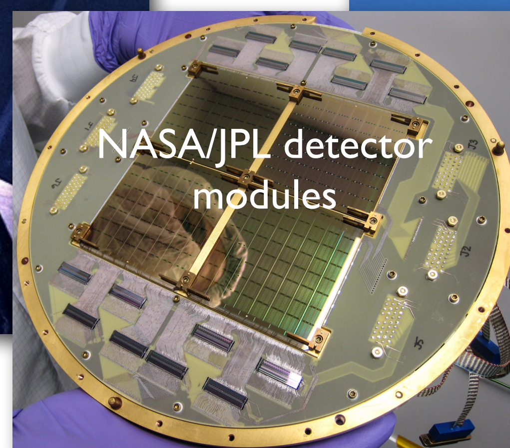
Large aperture CMB telescopes

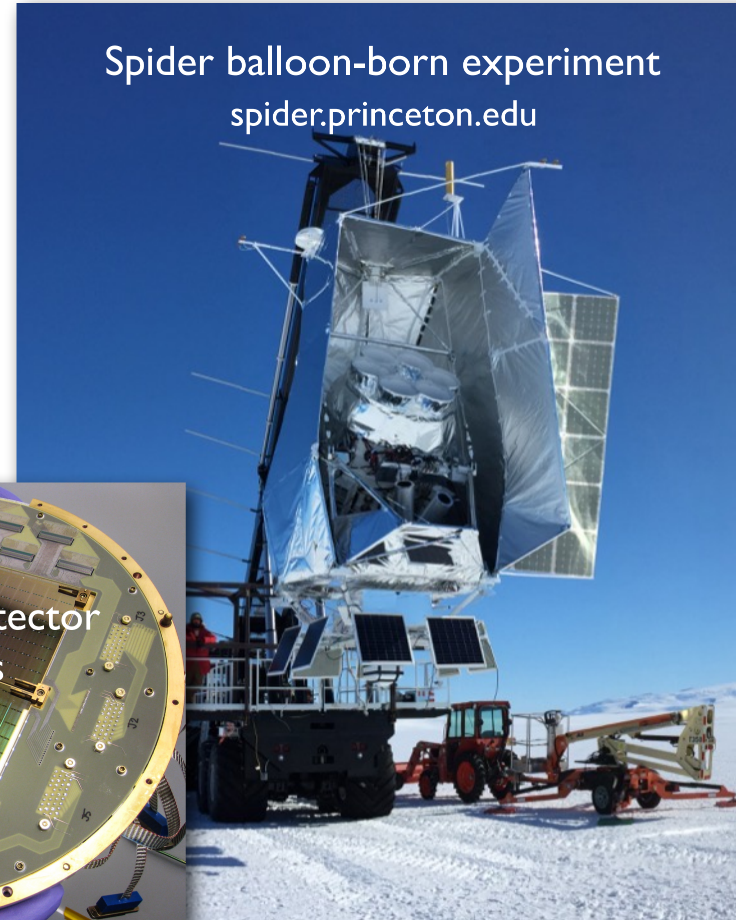






Also small aperture CMB telescopes



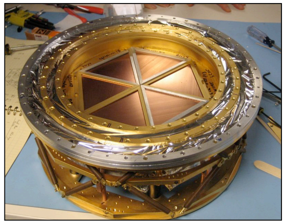


Also
Ground: ABS, CLASS,QUBIC, QUIJOTE, GroundBird
Balloon: EBEX, PIPER, LSPE
Satellite proposals: LiteBird, PIXIE

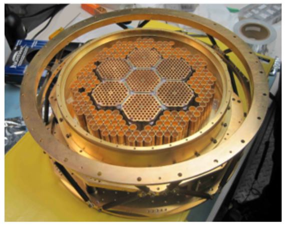
The South Pole Telescope (SPT)

A very high-tech 10-meter submm wave telescope

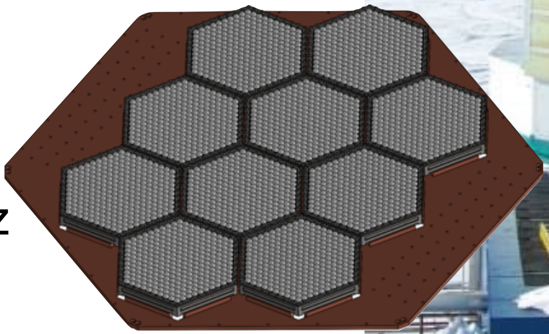
100 150 220 GHz and
1.6 1.2 1.0 arcmin resolution



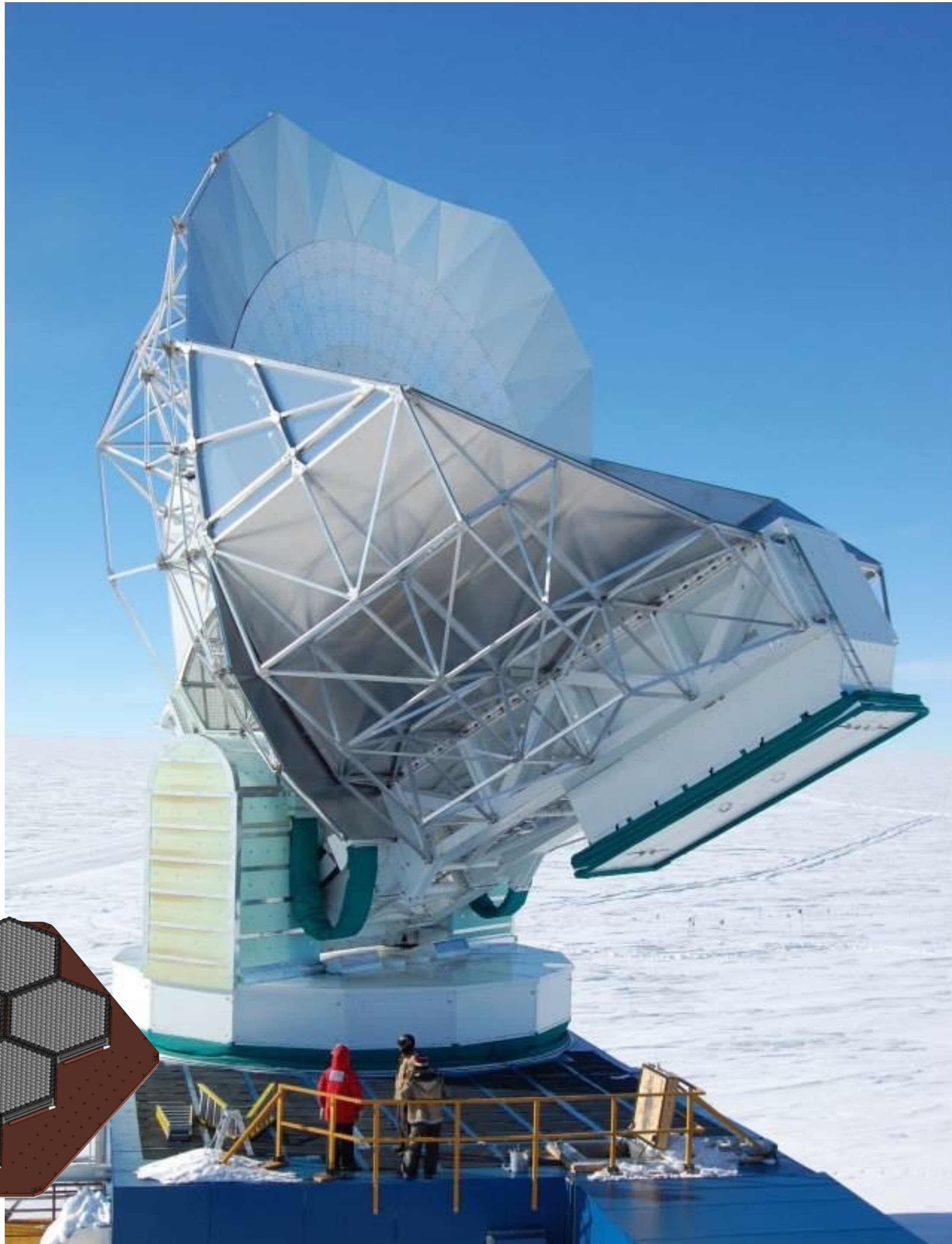
2007: SPT-SZ
960 detectors (UCB)
100,150,220 GHz



2012: SPTpol
1600 detectors
100,150 GHz
+Polarization



2016: SPT-3G
16,400 detectors
100,150, 220 GHz
+Polarization

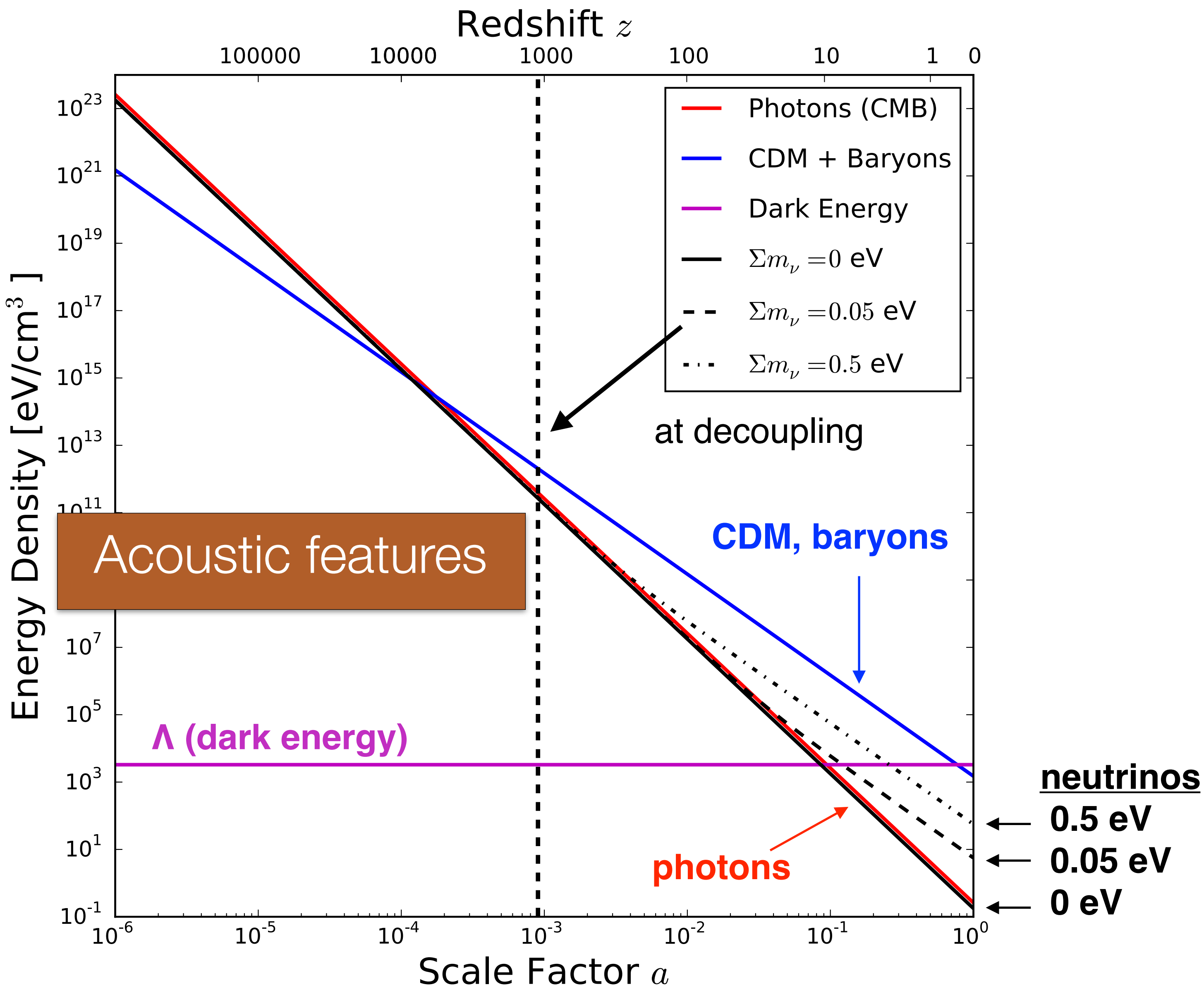


The South Pole Telescope Collaboration

Argonne National Laboratory | Berkeley Lab | Cardiff University Prifysgol Caerdydd | NIST | MIT | SLAC | KICP Kavli Institute for Cosmological Physics at the University of Chicago | Berkeley University of California | Case Western Reserve University | McGill | Colorado University of Colorado at Boulder | Stanford University | The University of Chicago | LMU Ludwig-Maximilians-Universität München | Harvard-Smithsonian Center for Astrophysics | UC Davis University of California | Fermilab | M

Funded By:

U.S. Department of Energy | Kavli | NSF | Gordon and Betty Moore Foundation



Neutrino Mass: From the Terrestrial Laboratory to the Cosmos, ACFI (2015)

Acoustic features and neutrinos

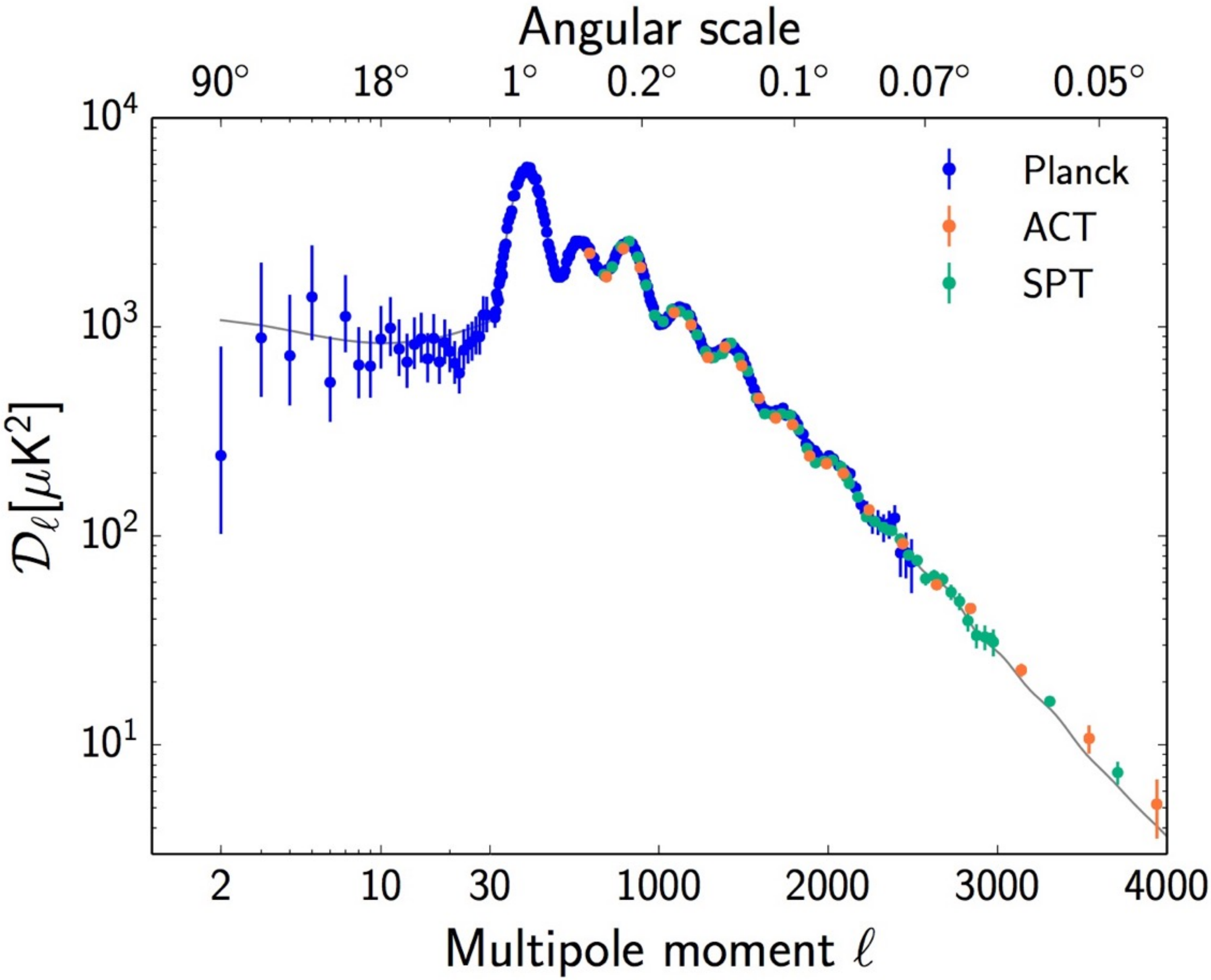
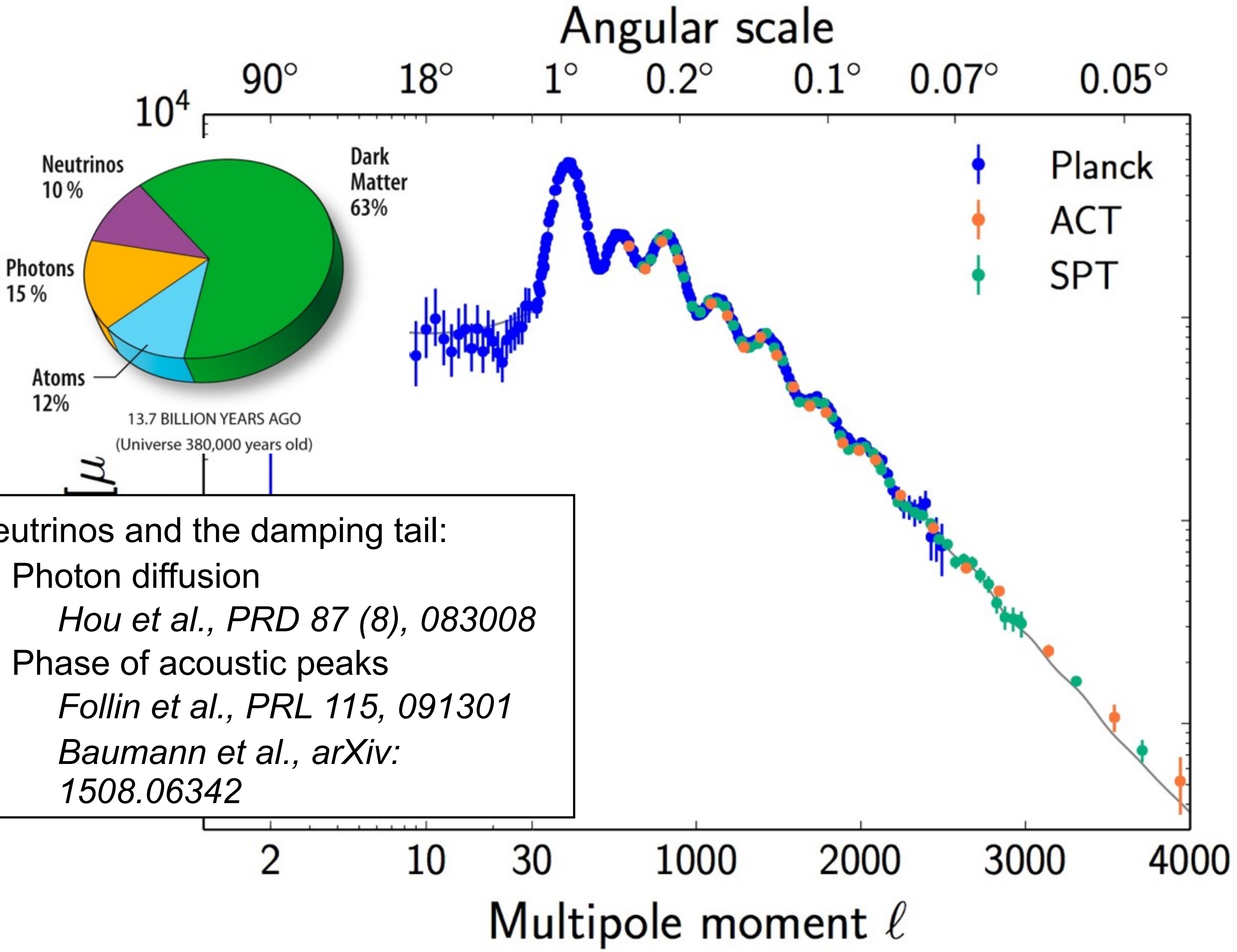


Figure from Planck 2015 Results XI

Acoustic features and neutrinos



Neutrinos and the damping tail:

Photon diffusion

Hou et al., PRD 87 (8), 083008

Phase of acoustic peaks

Follin et al., PRL 115, 091301

Baumann et al., arXiv: 1508.06342

Figure from Planck 2015 Results XI

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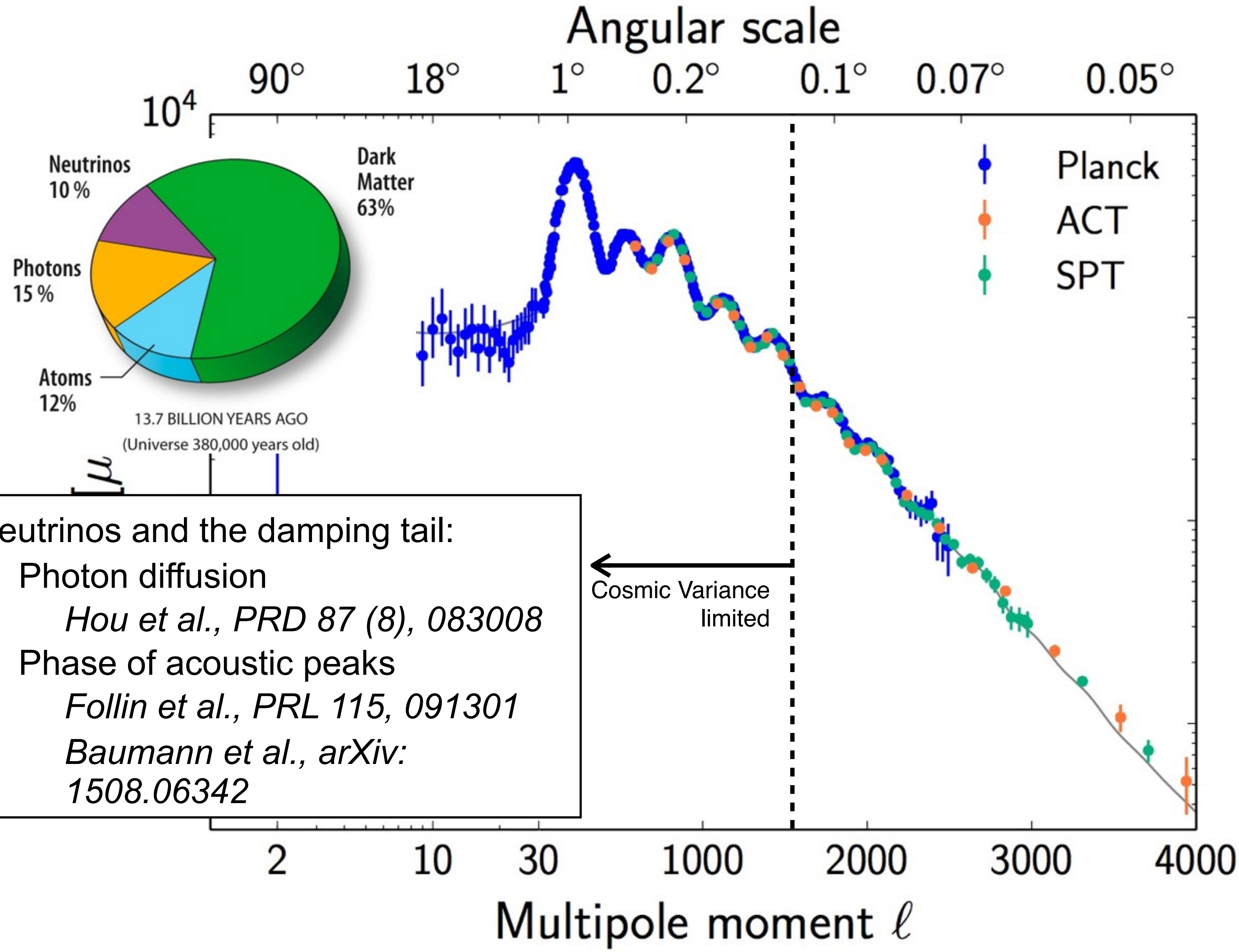

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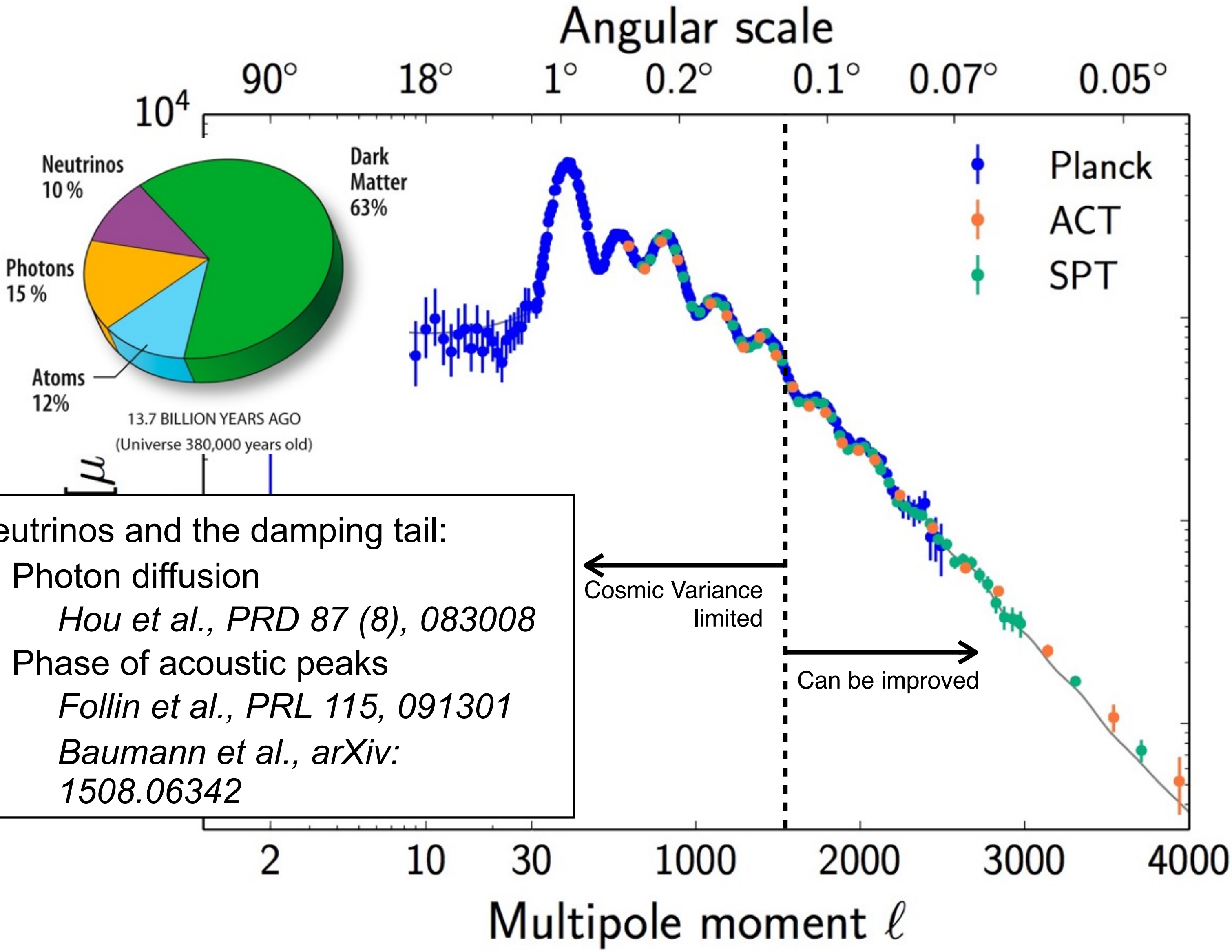

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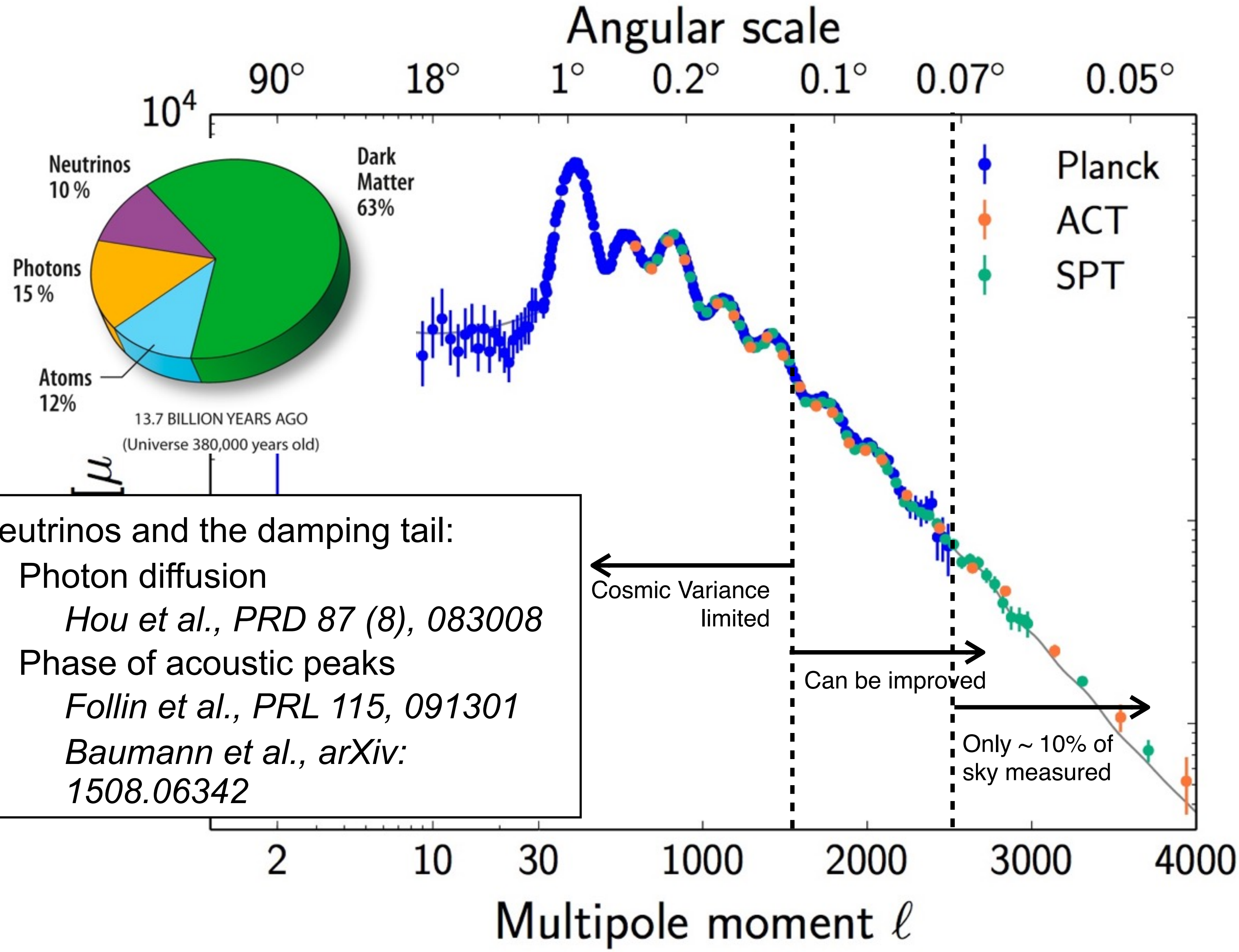

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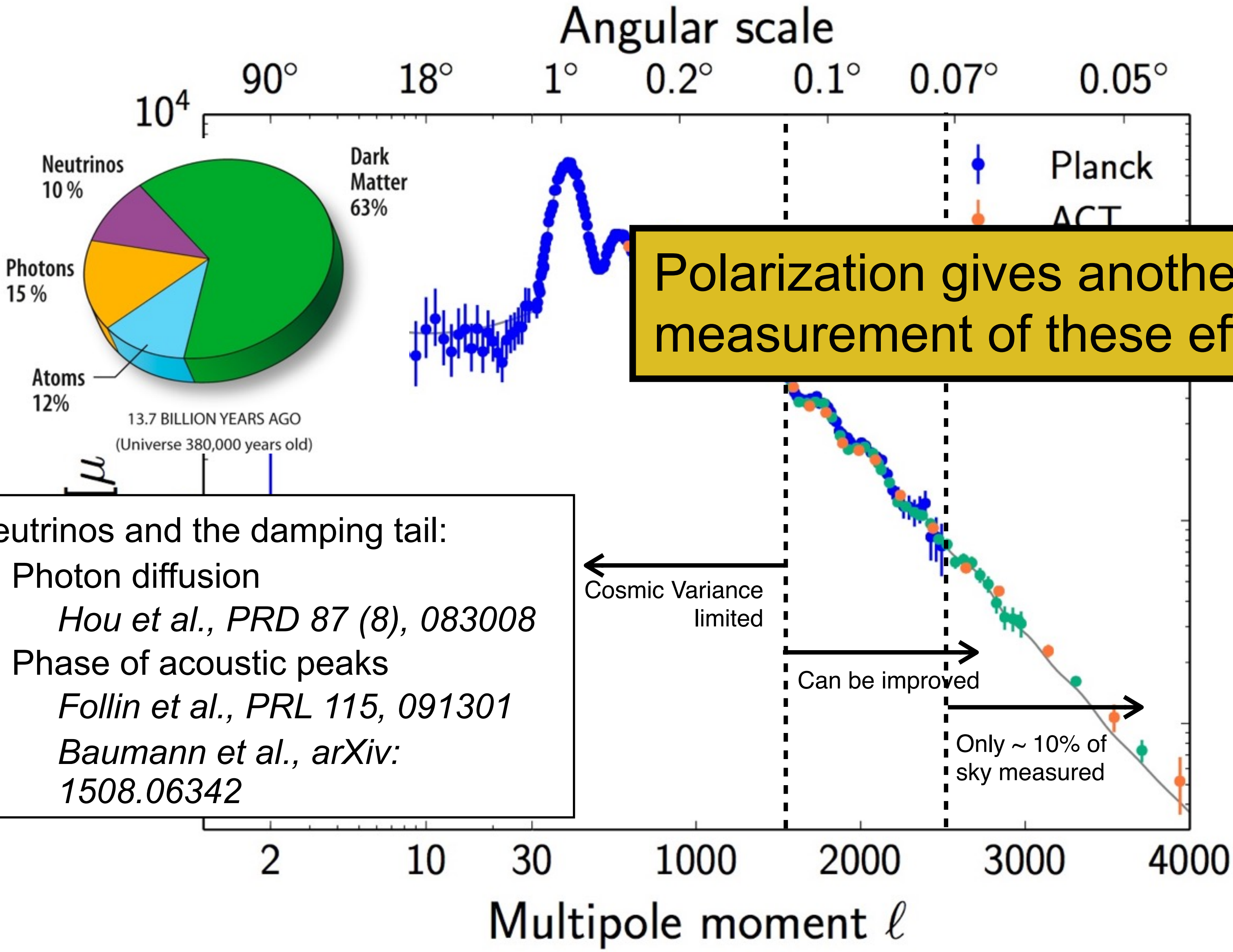
Figure from Planck 2015 Results XI

Acoustic features and neutrinos



Polarization gives another measurement of these effects

Neutrinos and the damping tail:
- Photon diffusion
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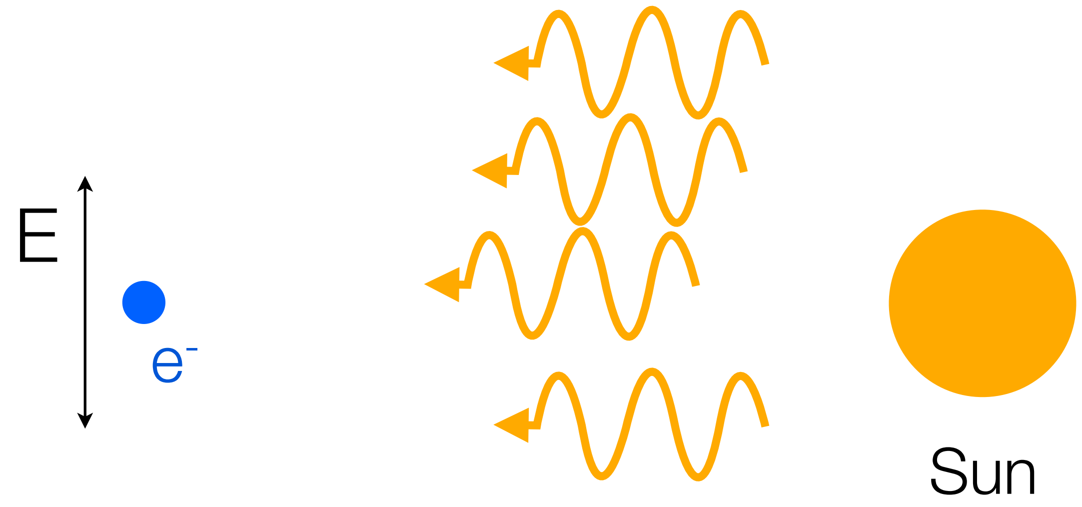
Figure from Planck 2015 Results XI

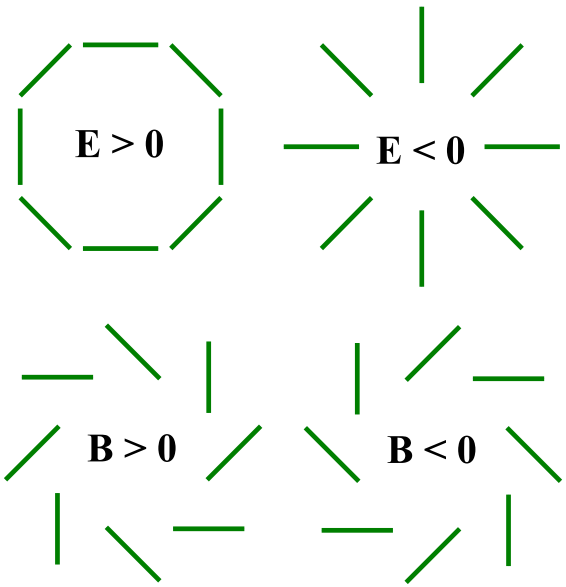
CMB polarimetry

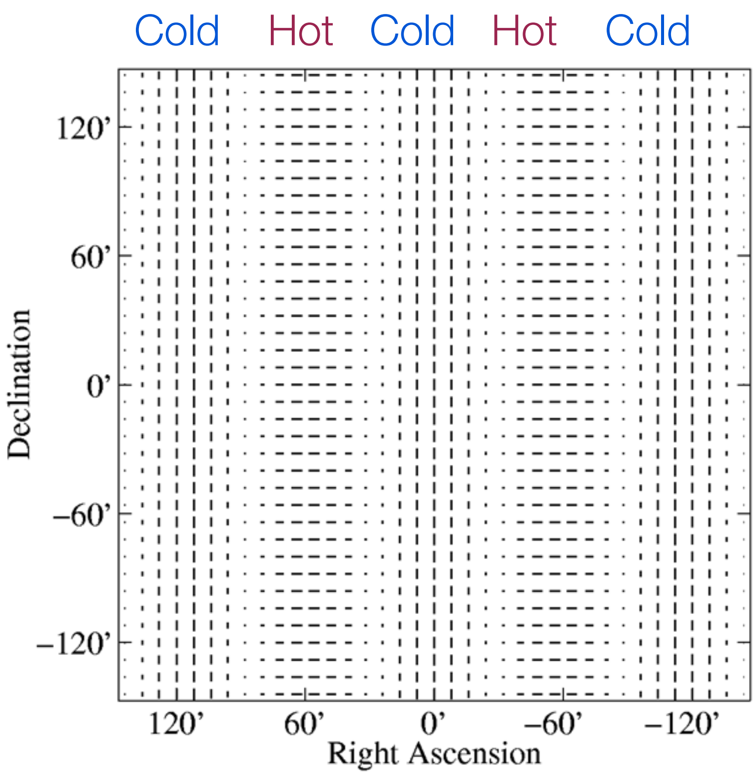
- CMB polarized via Thomson scattering and local anisotropy (e.g. Sun scattering in atmosphere)



CMB polarimetry: E-modes

- CMB polarized via Thomson scattering and local anisotropy (e.g. Sun scattering in atmosphere)
- Density/Temperature anisotropy generates intrinsic CMB polarization
  - Symmetric under “parity”
    k ⟶ -k
  - **“E-mode” only**





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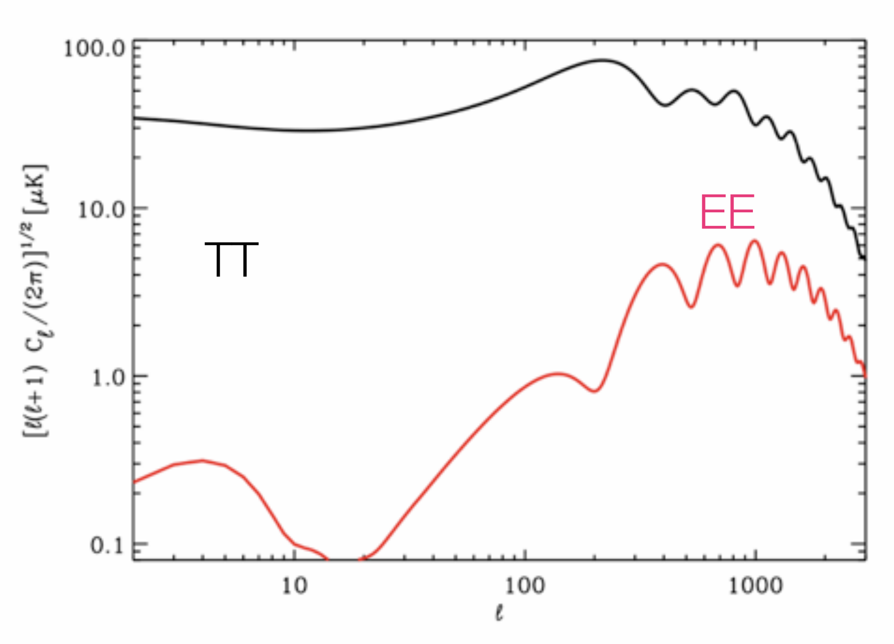


- EE power spectrum is a different probe of same physics producing TT spectrum

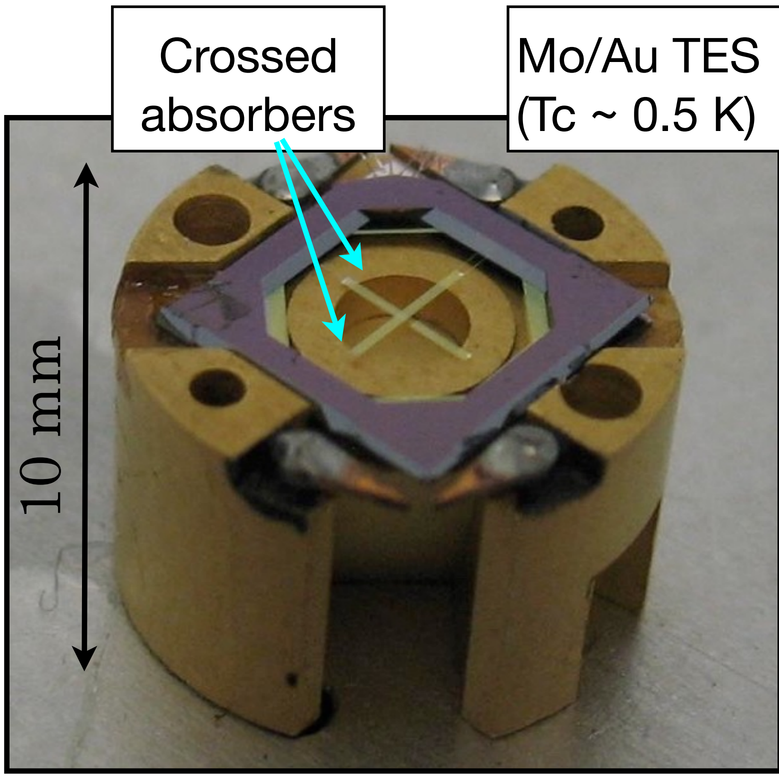
Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

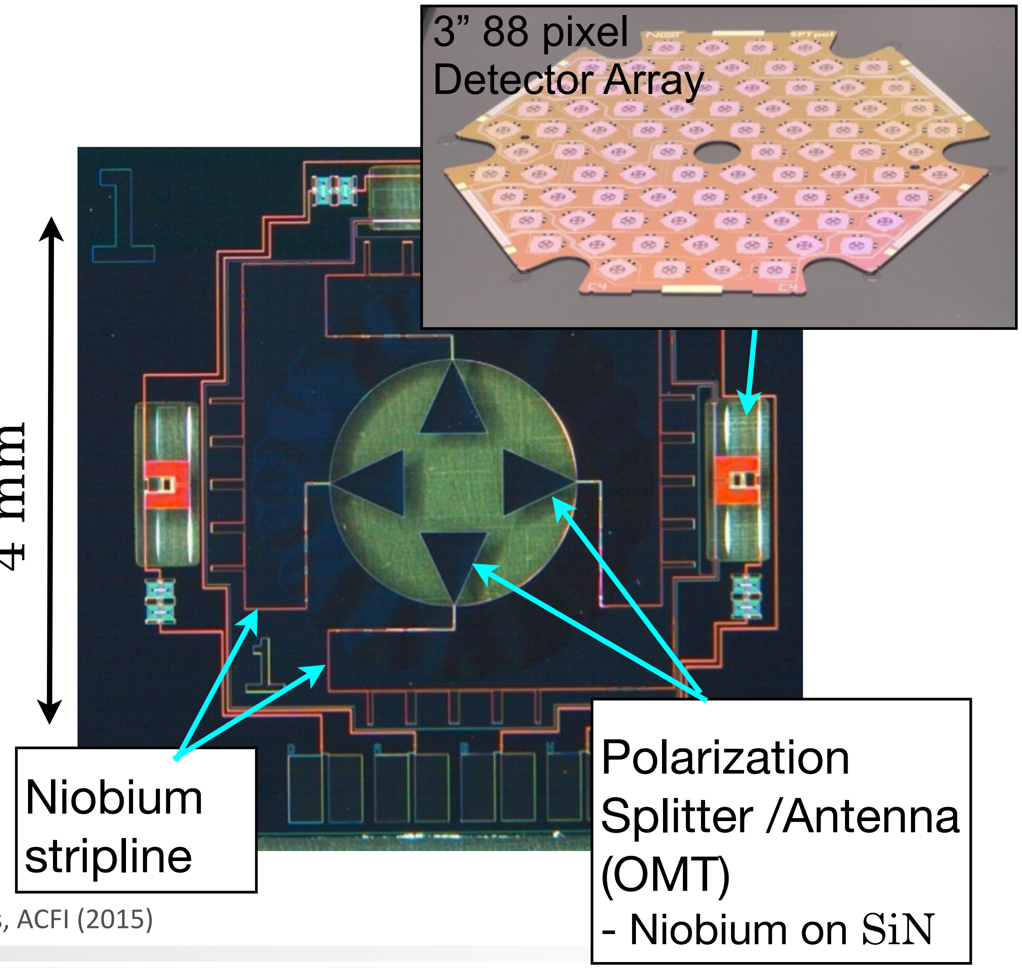
Measuring CMB polarization with SPTpol

SPTpol: Detectors

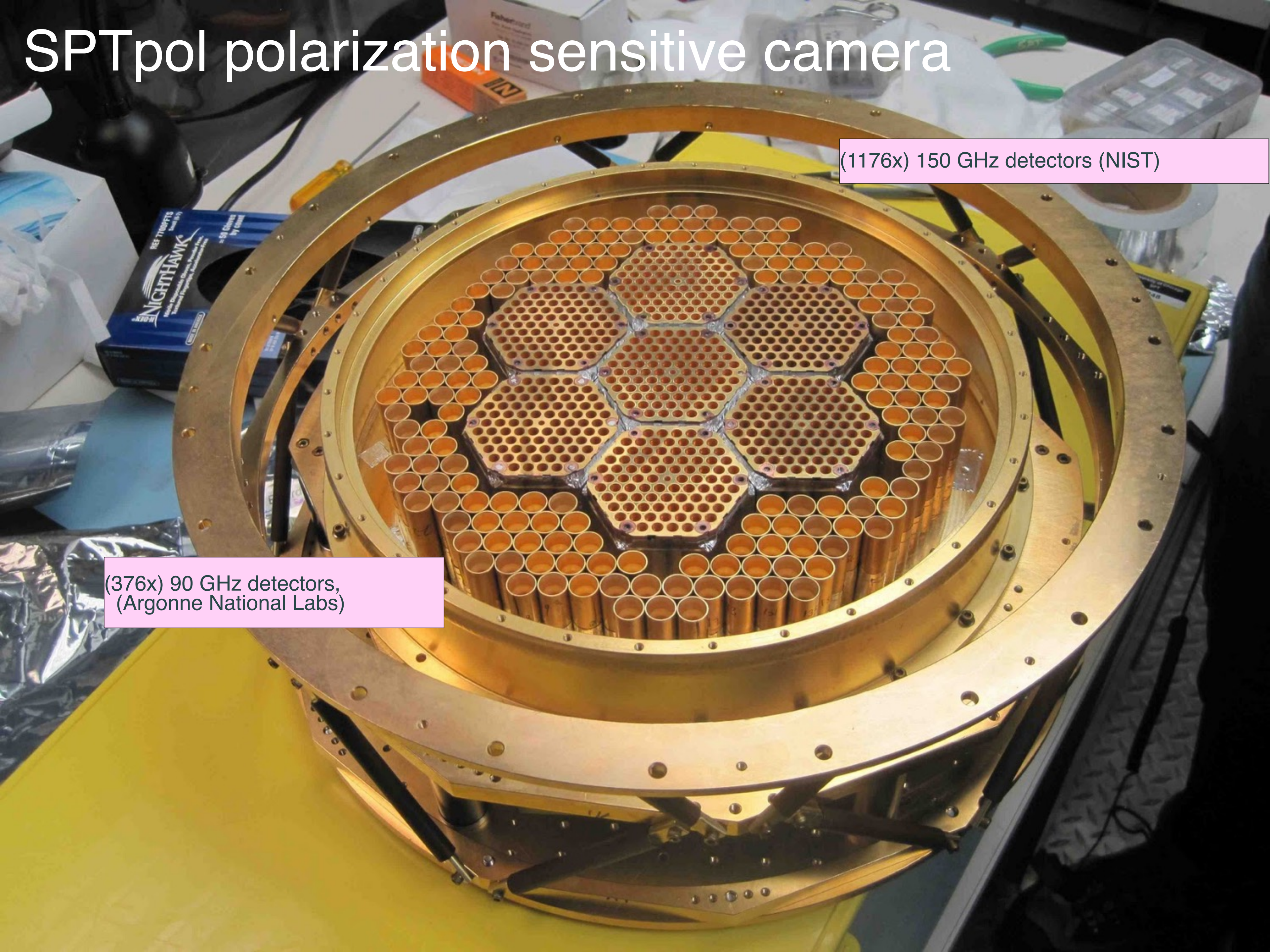
SPTpol used two different detectors technologies

- At 90 GHz, individual pixels, crossed absorbers with TES made at Argonne
- At 150 GHz, array of antenna-coupled TES made at NIST (Boulder)

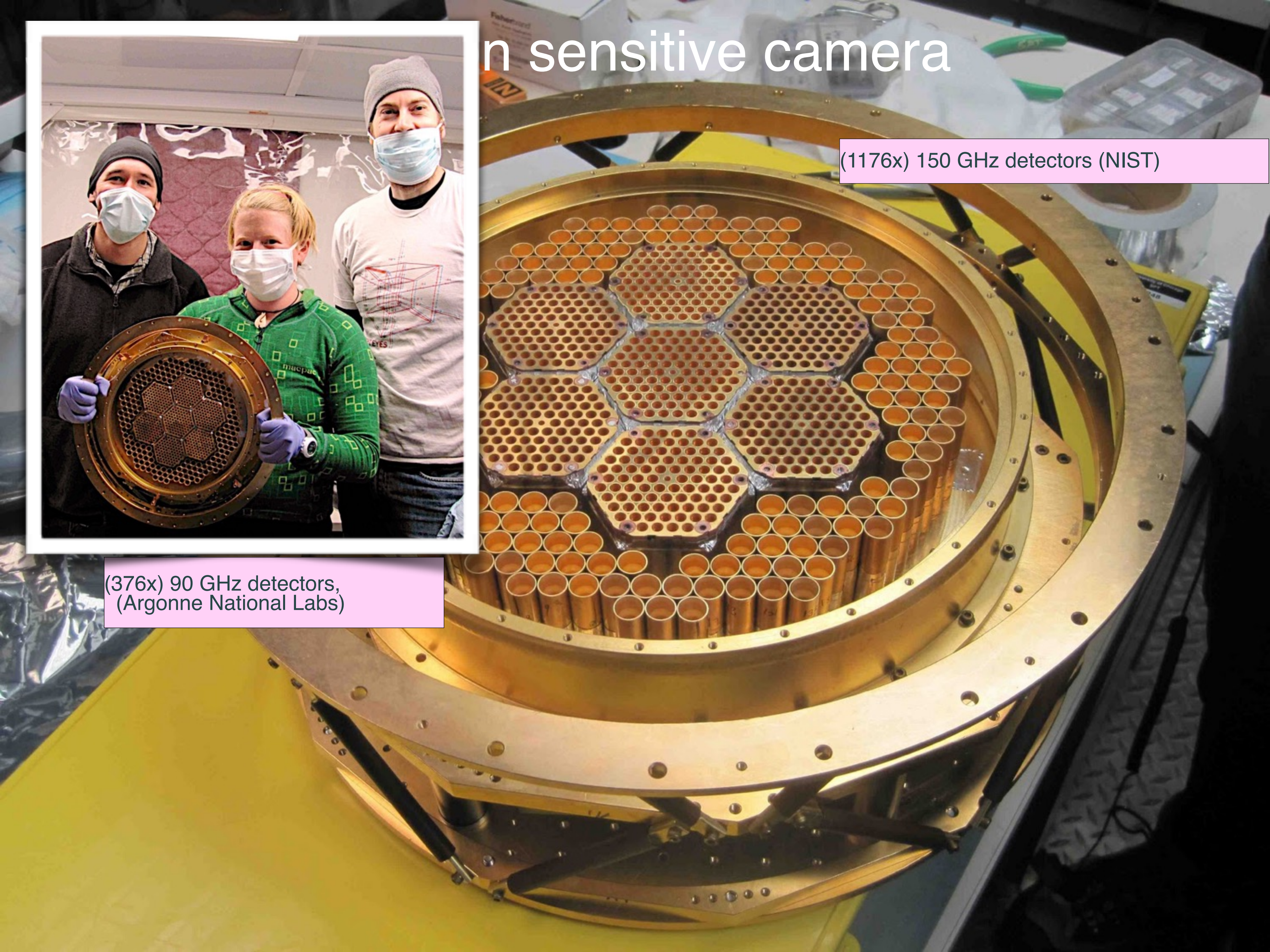




SPTpol polarization sensitive camera



n sensitive camera



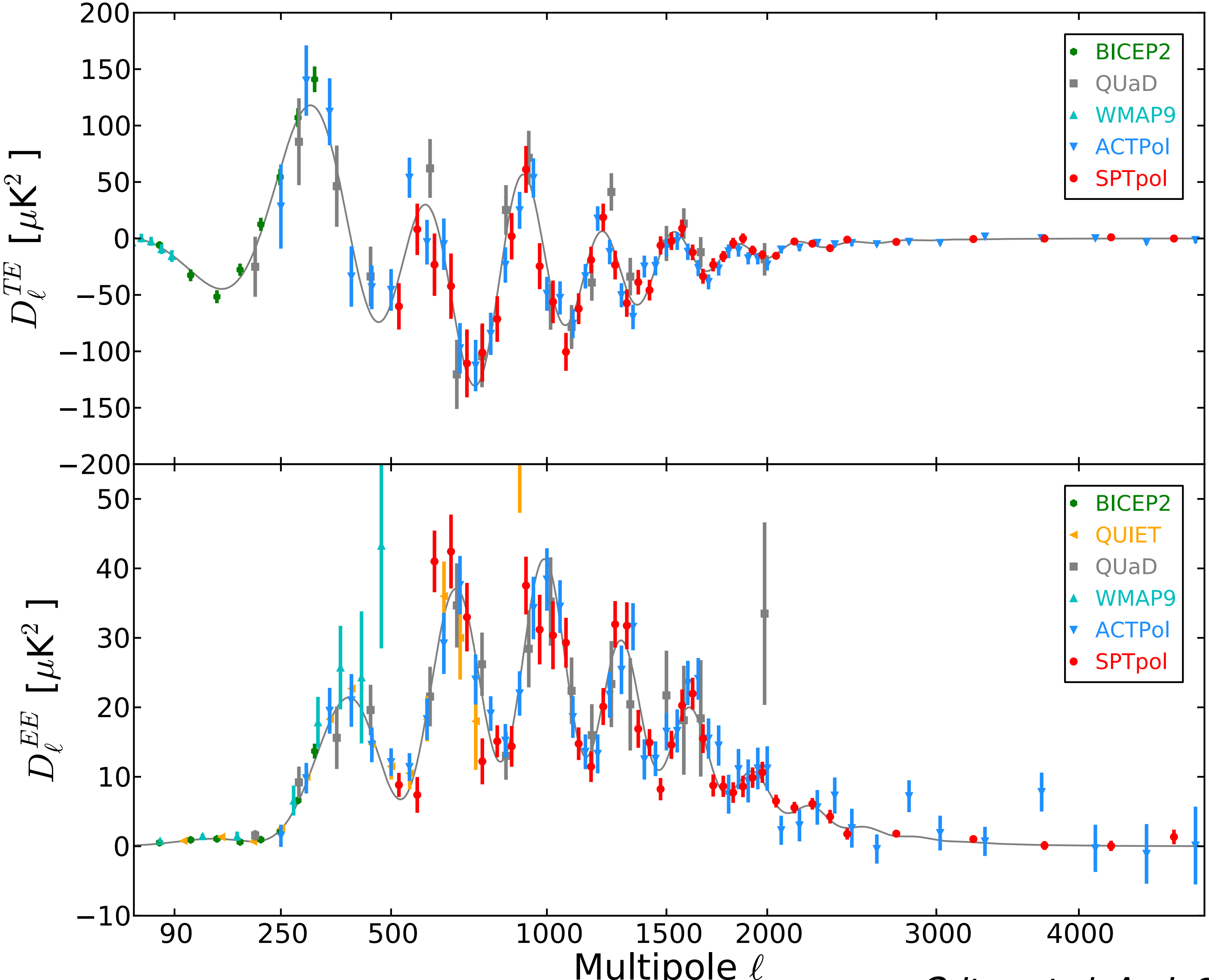
n sensitive camera

(1176x) 150 GHz detectors (NIST)

(376x) 90 GHz detectors,
(Argonne National Labs)

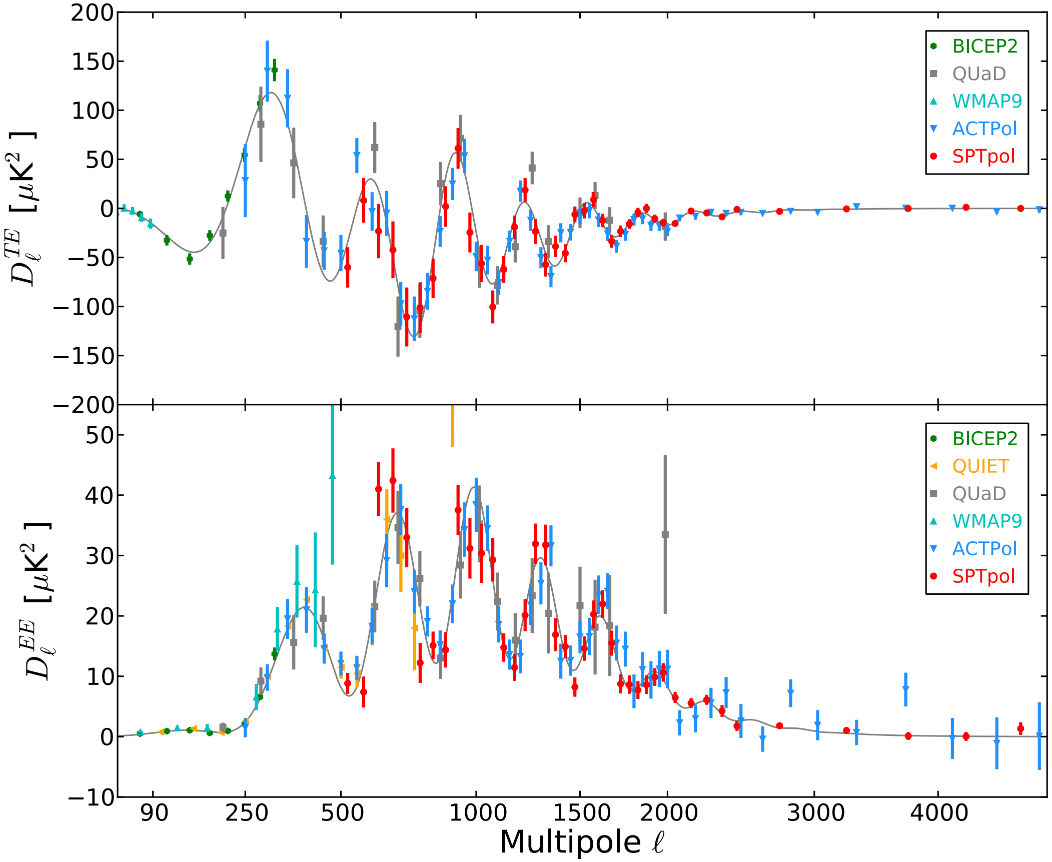
SPTpol 1st light January 2012

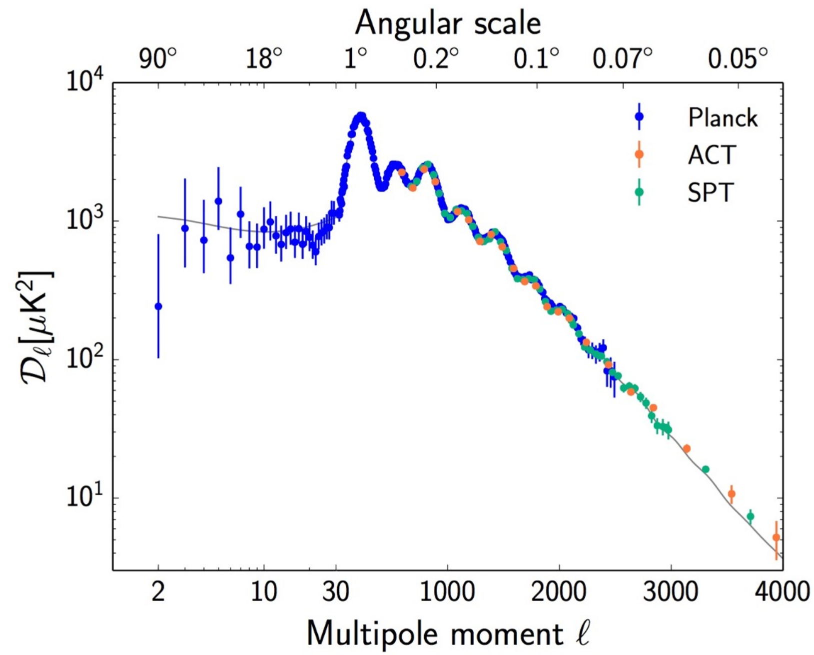
TE, EE Compilation Power Spectrum

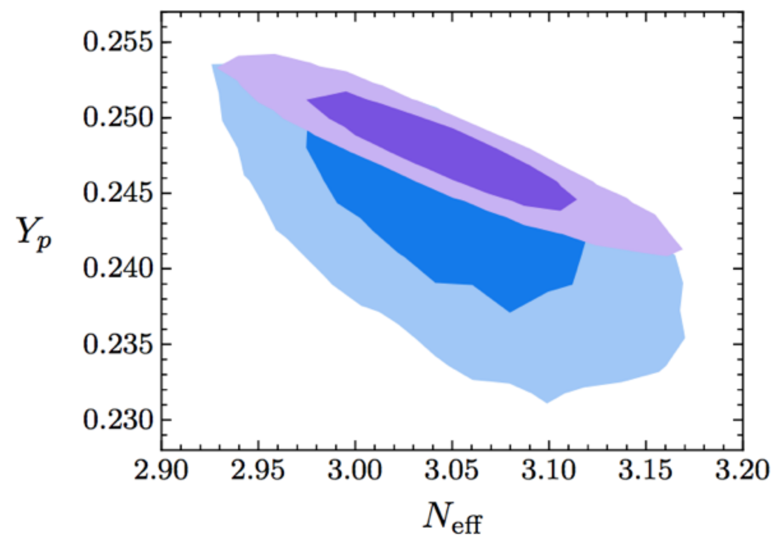


Crites et al. ApJ, 805 (2015)

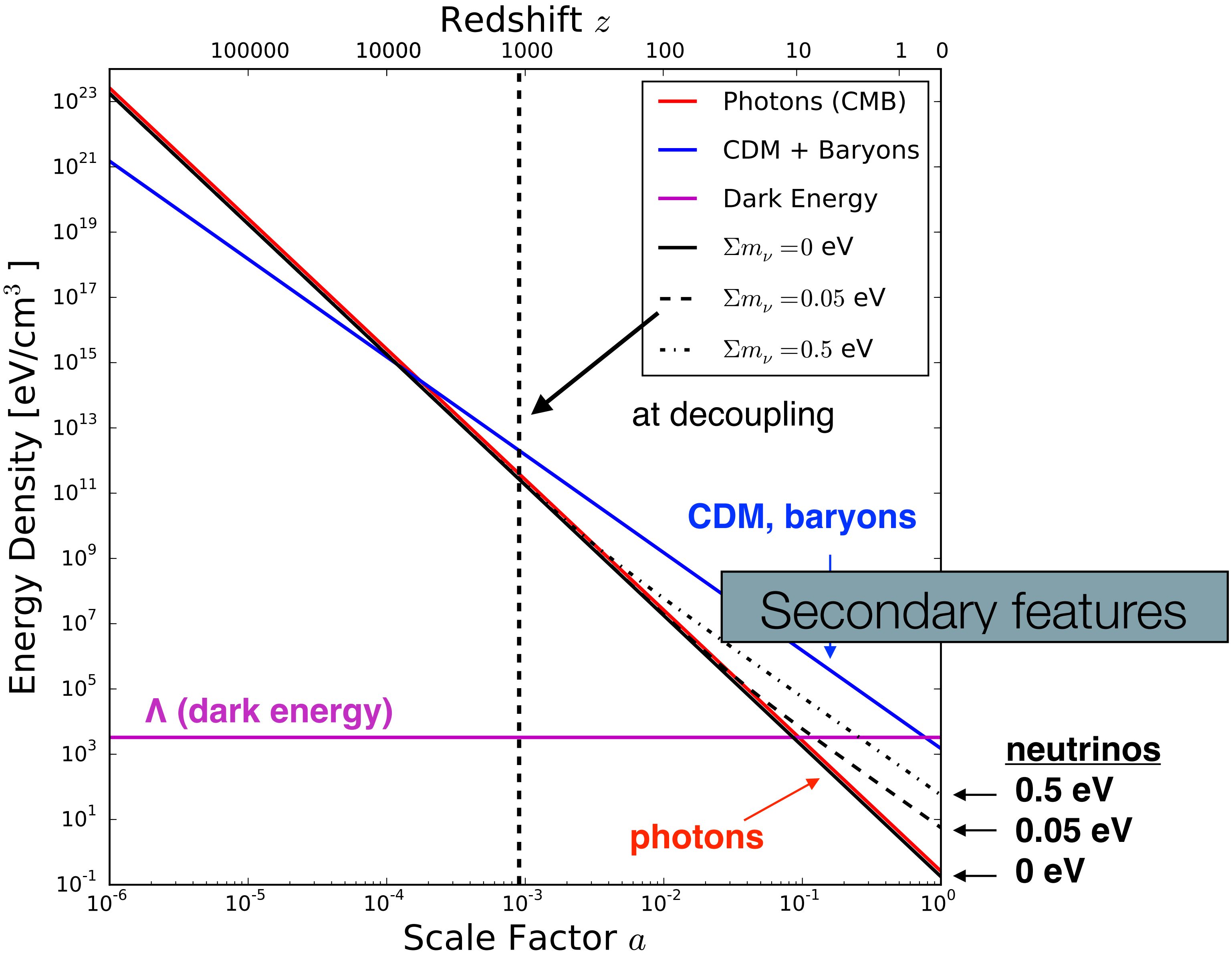
N_{eff} and Y_P from CMB acoustic features







Baumann et al., arXiv:1508.06342



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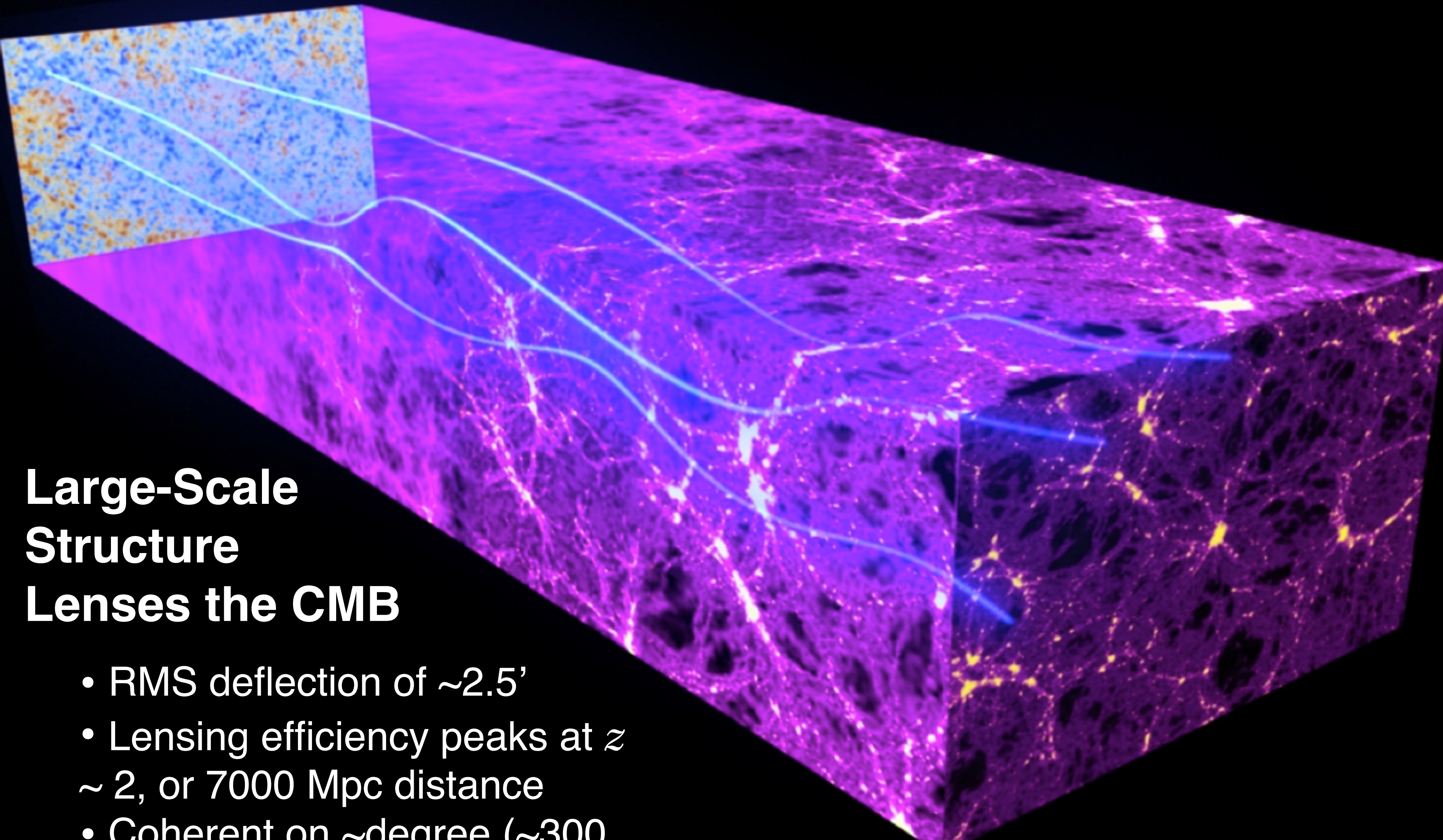
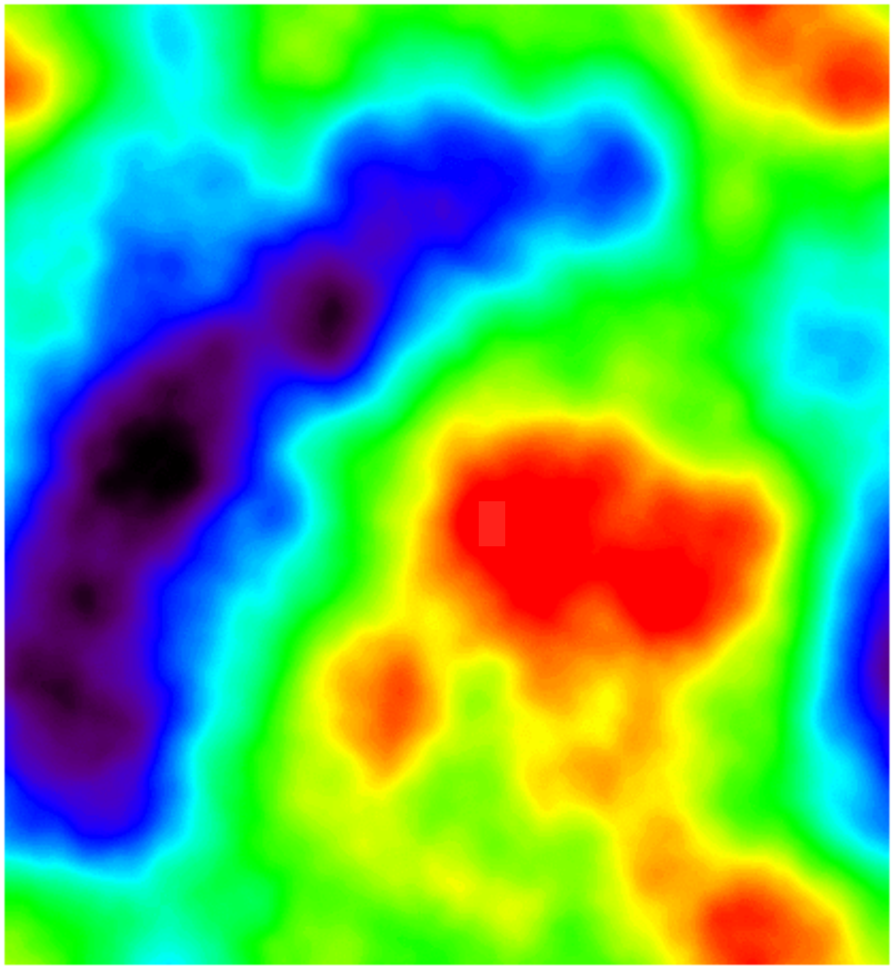


Large-Scale Structure Lenses the CMB

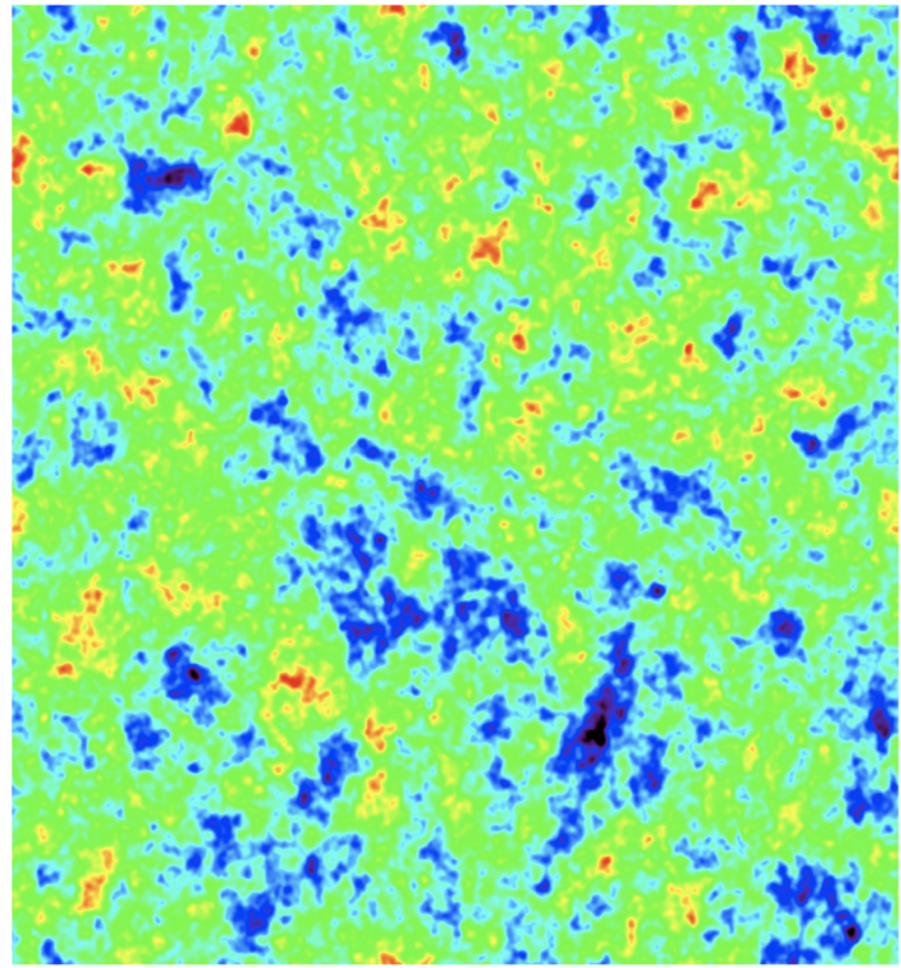
- RMS deflection of ~2.5'
- Lensing efficiency peaks at $z \sim 2$, or 7000 Mpc distance
- Coherent on ~degree (~300 Mpc) scales

Lensing of the CMB

17°x17°



lensing potential

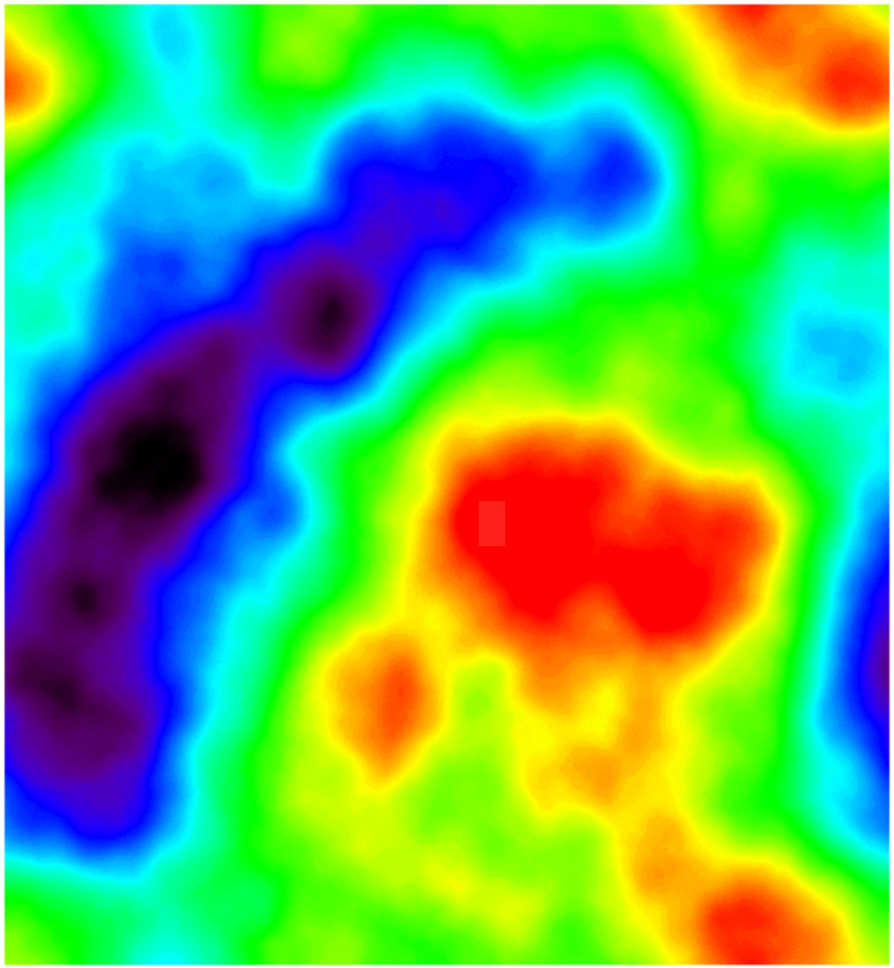


unlensed cmb

from Alex van Engelen

Lensing of the CMB

17°x17°



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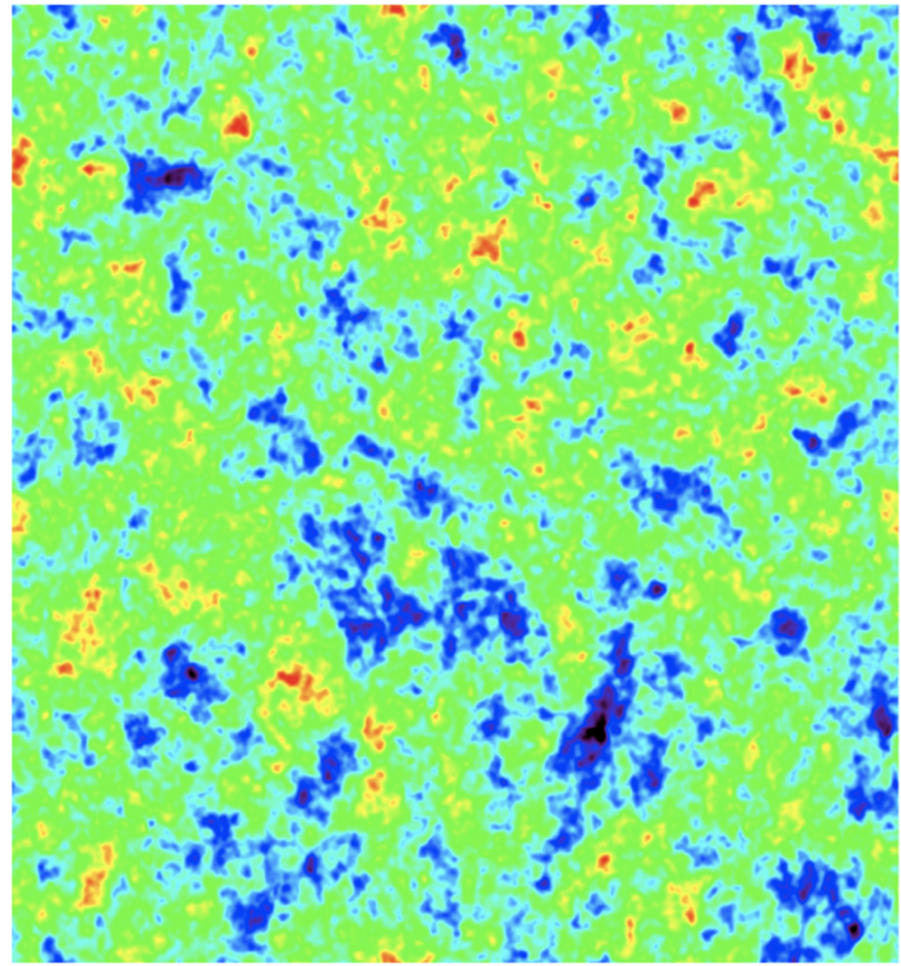
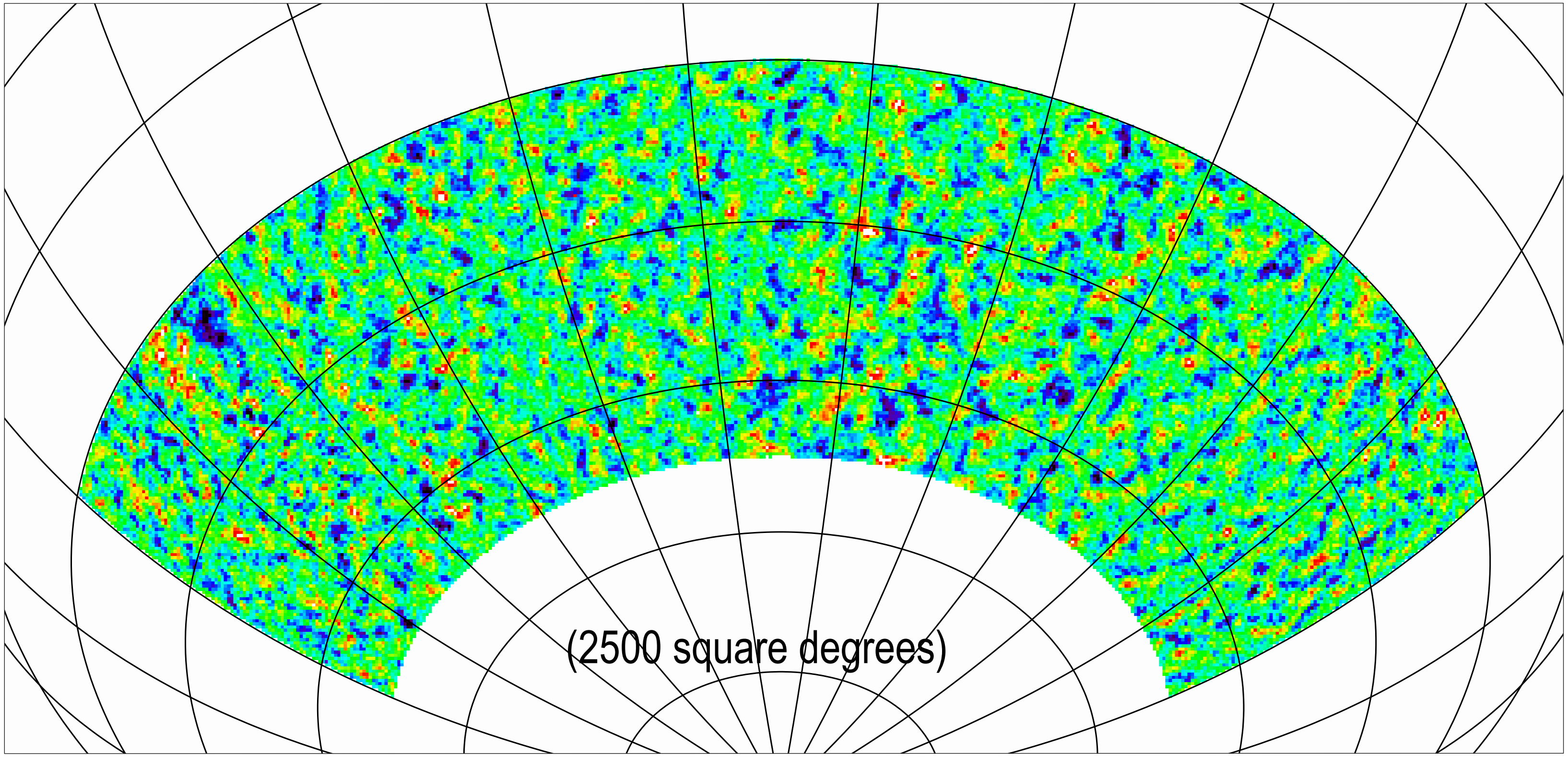


lensed cmb

from Alex van Engelen

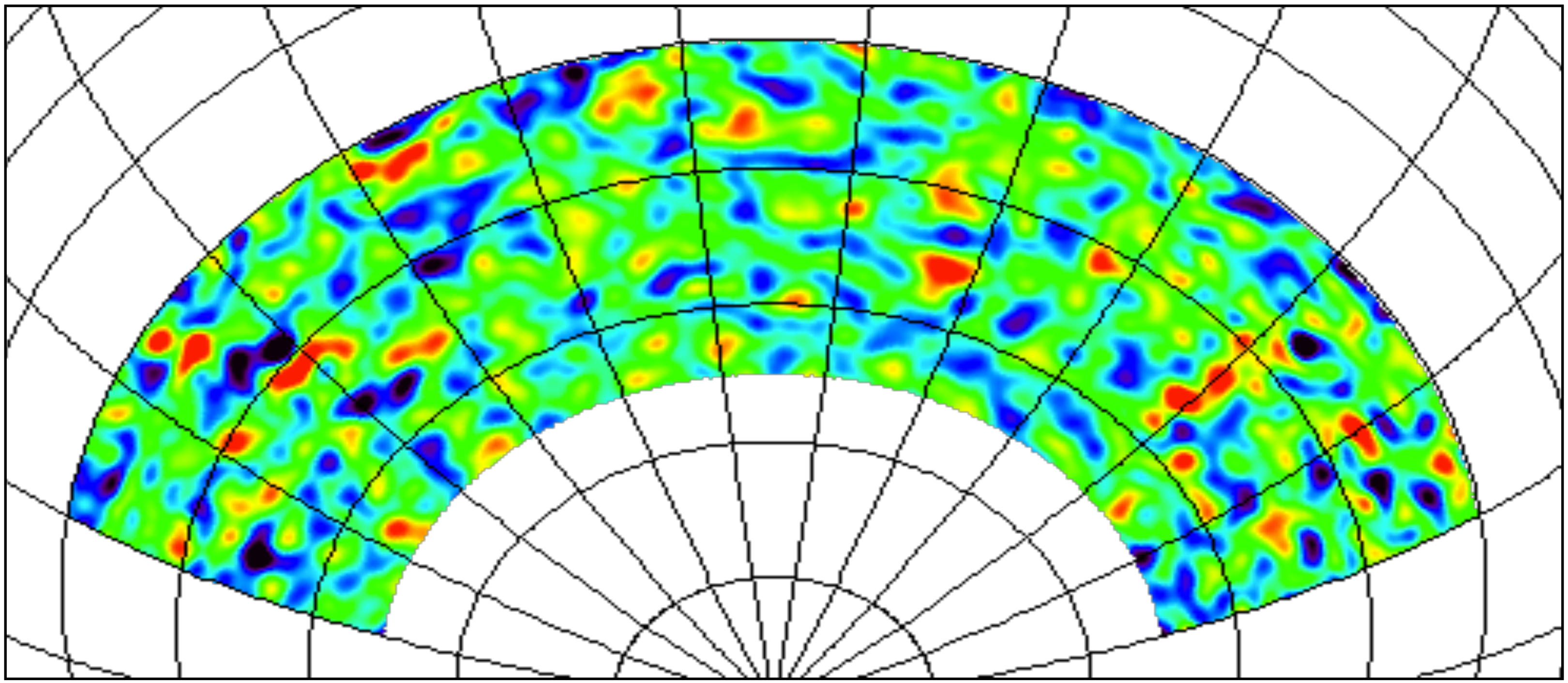
high resolution and sensitivity map of the CMB from SPT

covering 1/16 of the sky



CMB Lensing Map

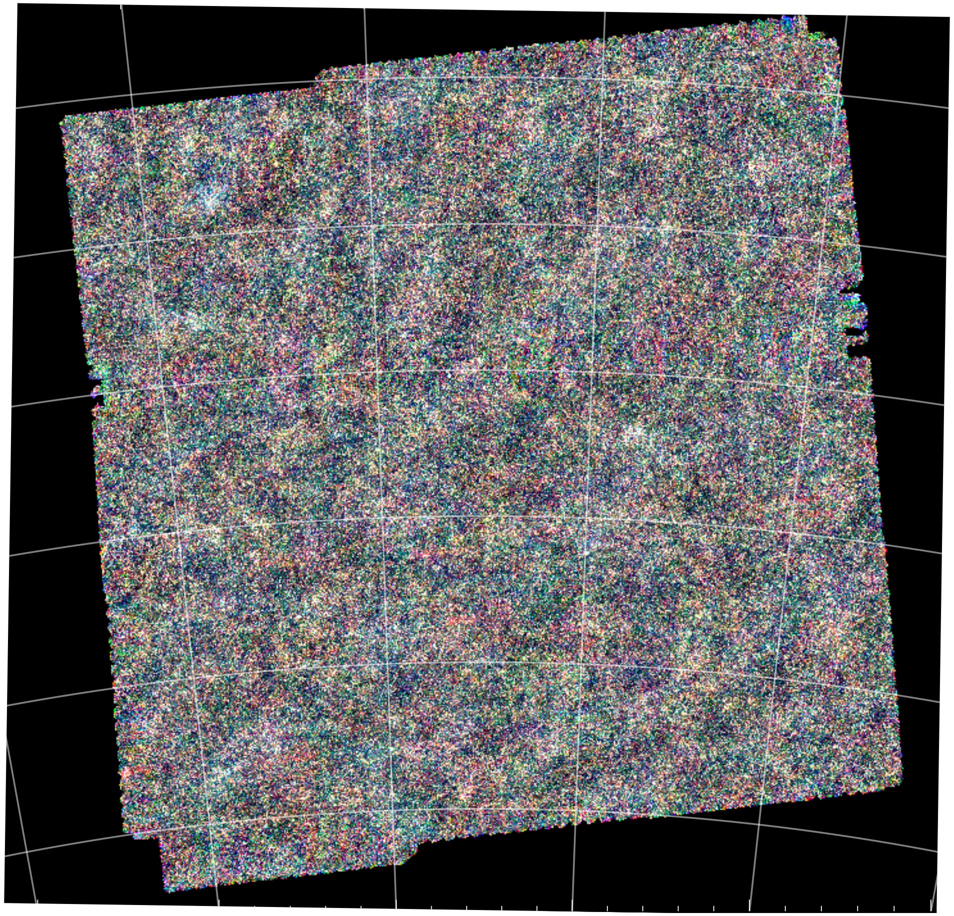
reconstruction of mass projected along the line of sight to the CMB



Lensing convergence map smoothed to 1 deg resolution
from CMB lensing analysis of SPT 2500 deg^2 survey

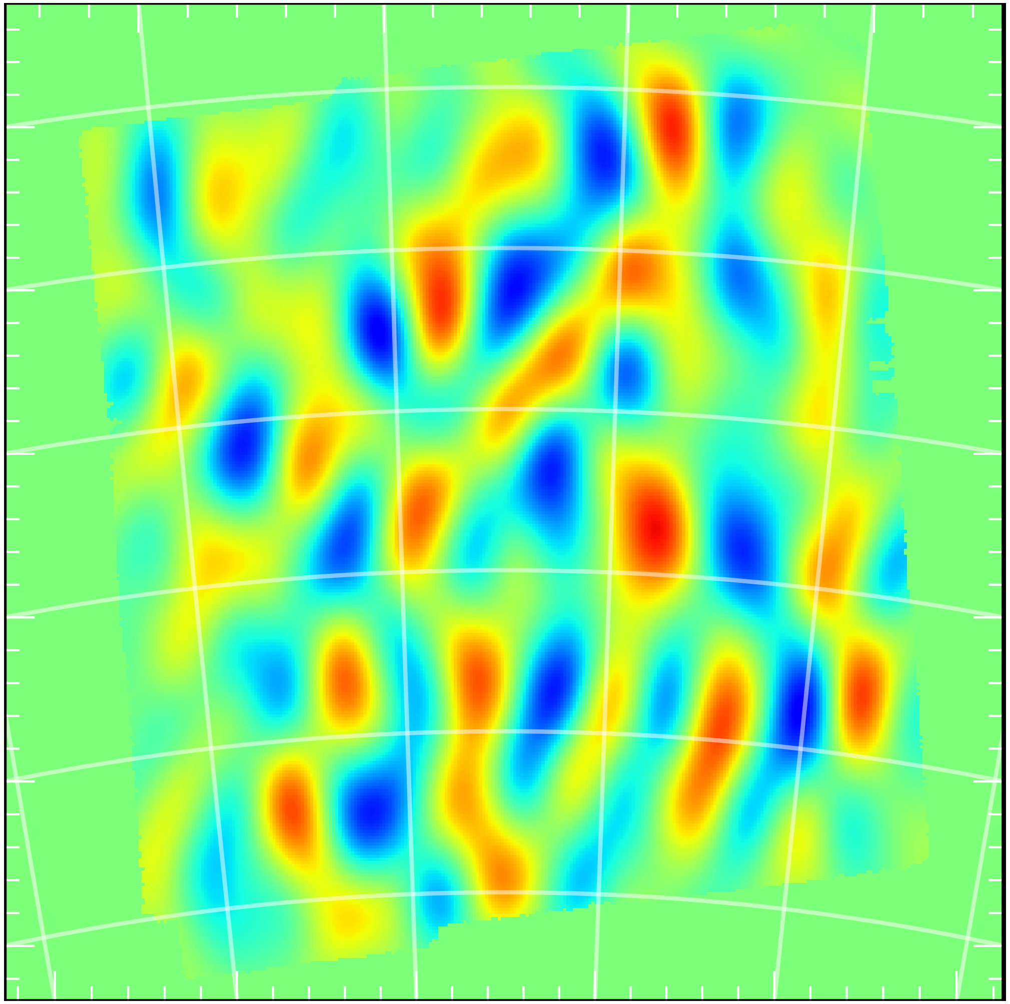
It’s really the Dark Matter:

100 sq. deg. of *Herschel* SPIRE data on “SPT deep field”



RGB = 500,350,250 um

It's really the Dark Matter:



Smooth 500um map to
~1 degree scales
(~100 com. Mpc).

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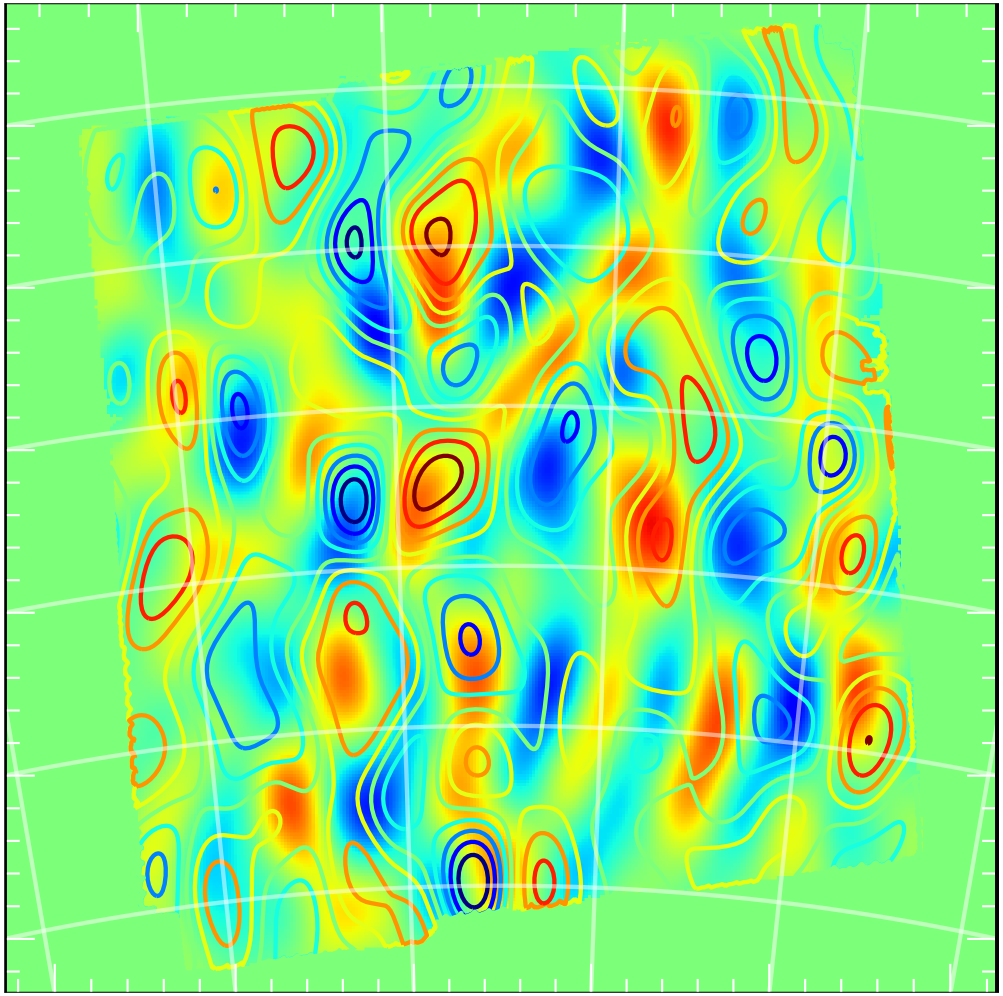

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Add mass contours from SPT CMB lensing.

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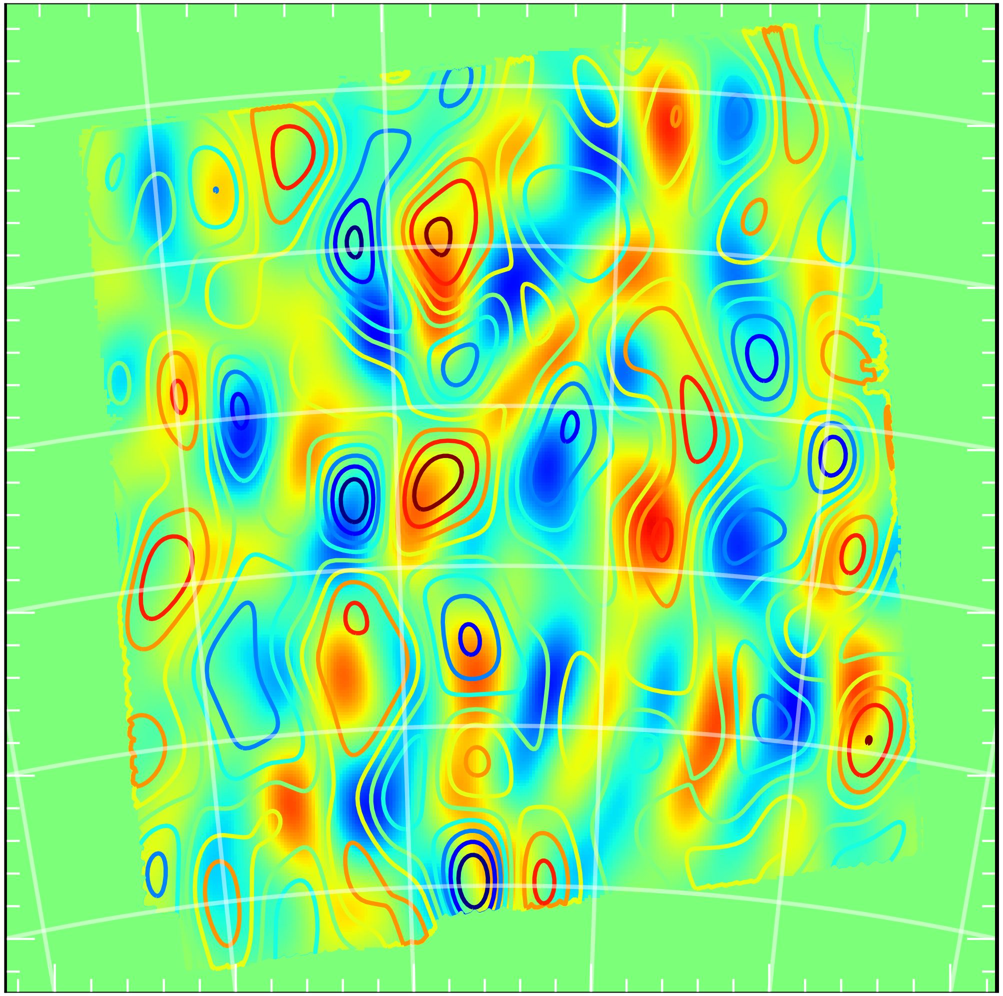

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~10σ correlation signal

Holder et al., ApJL, 771 (2013) 16
van Engelen et al., ApJ 808, 7 (2015)

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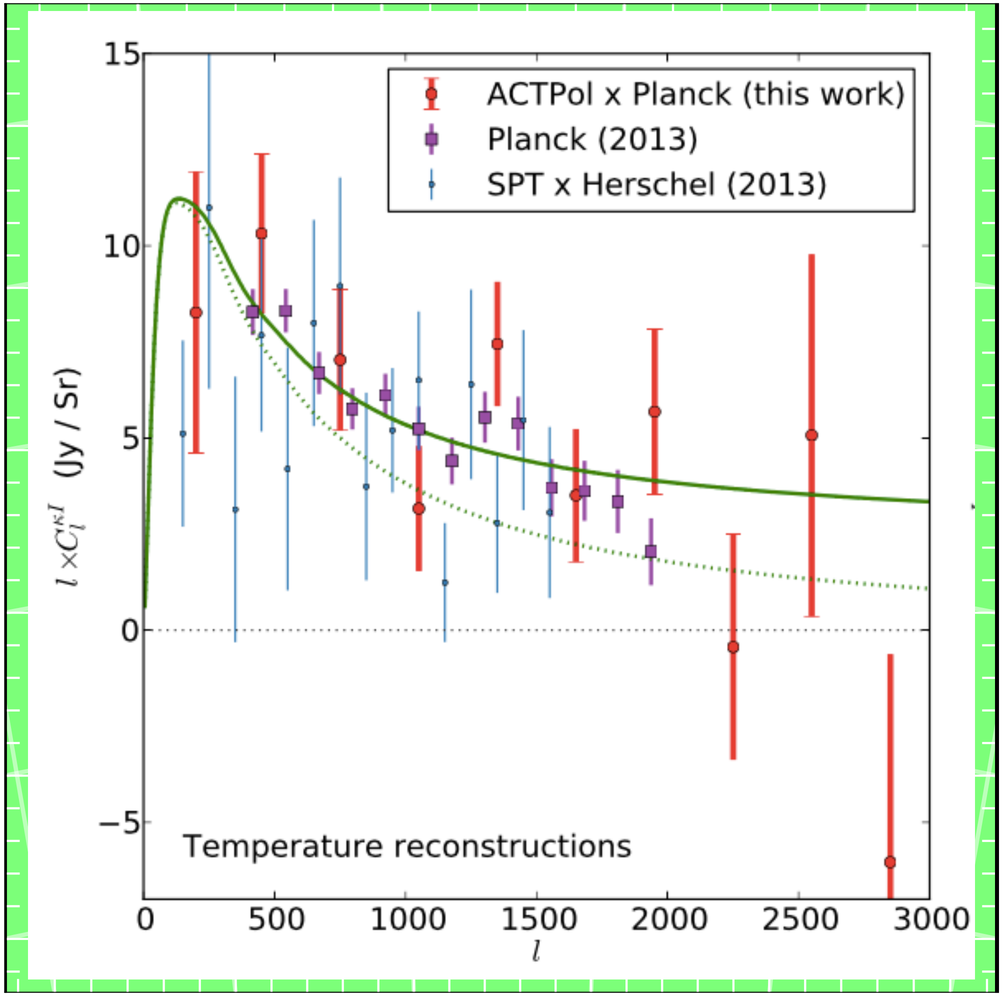

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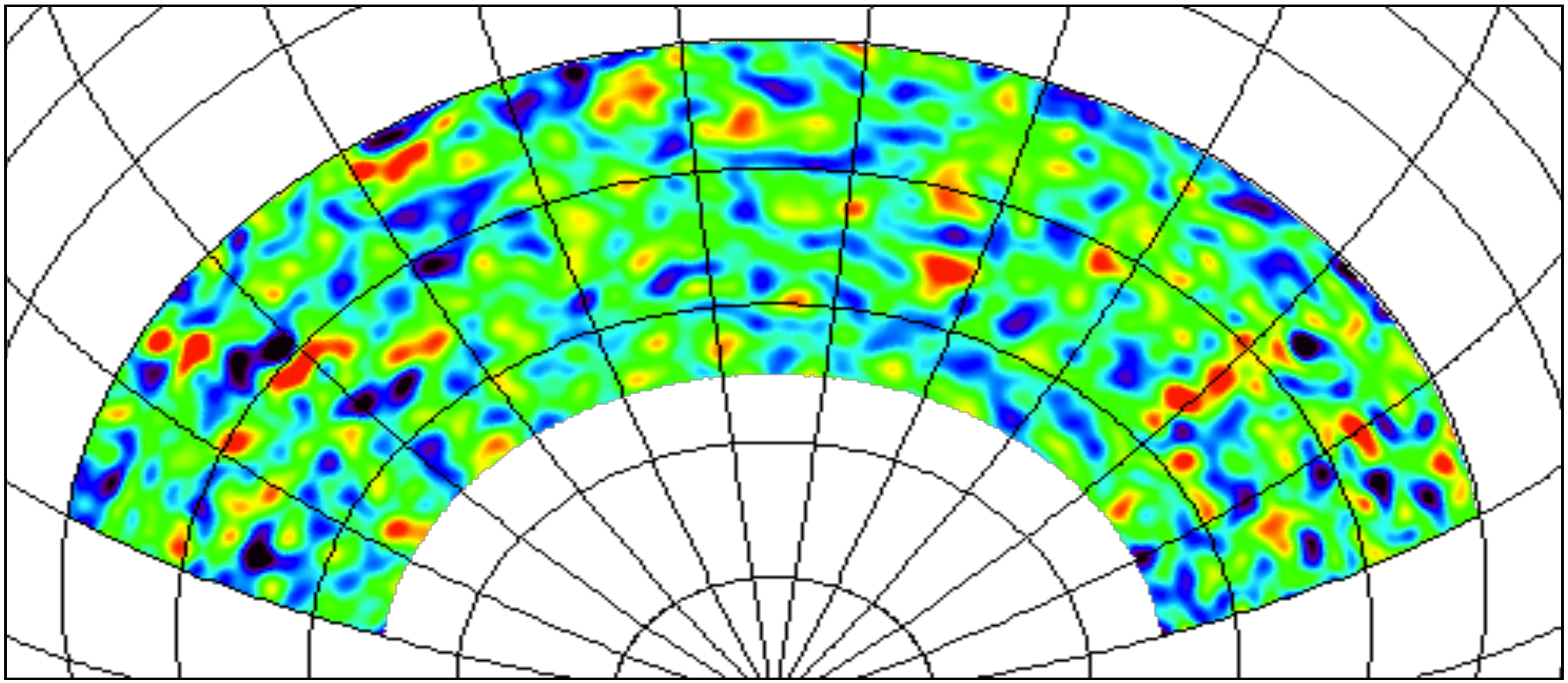

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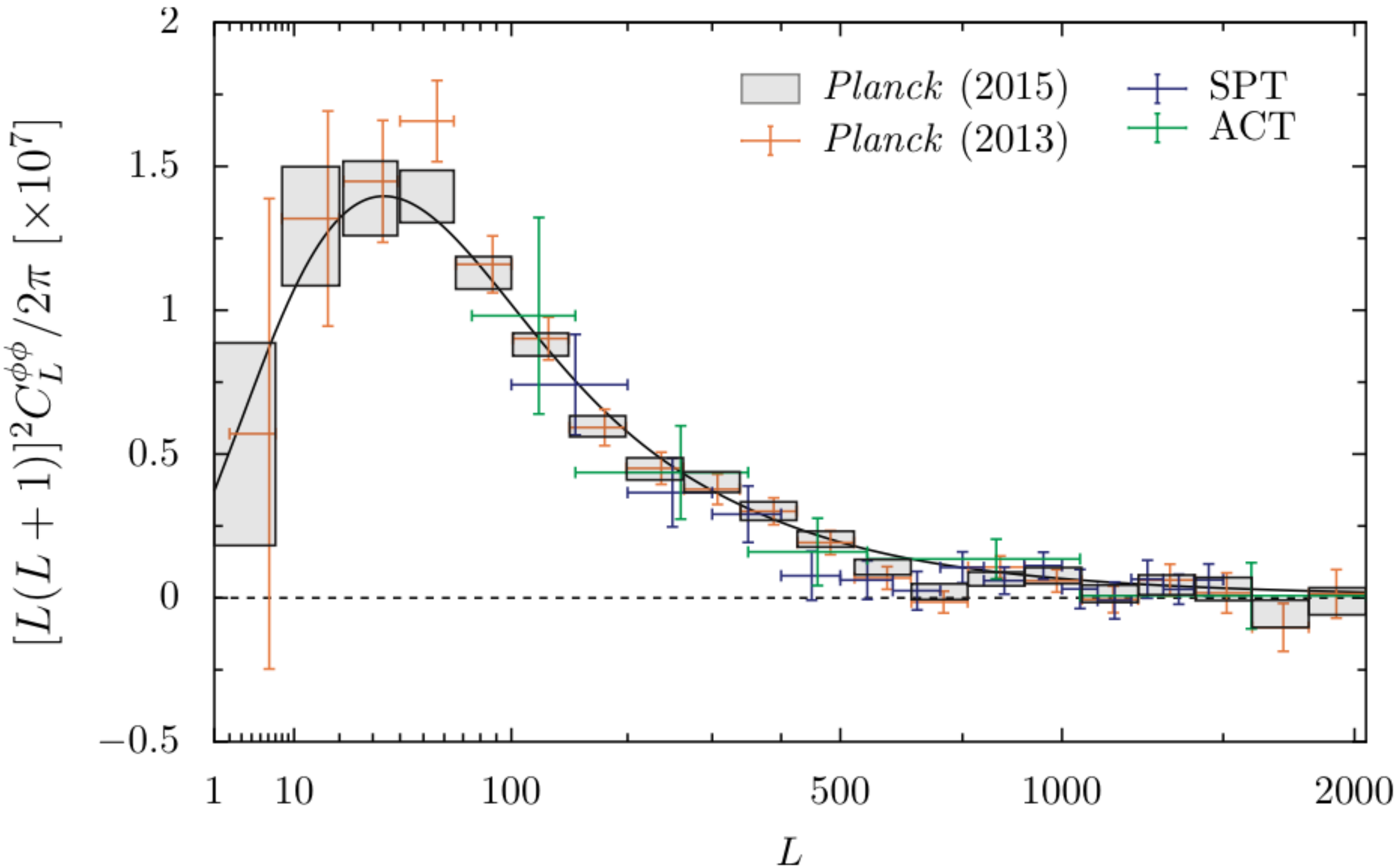
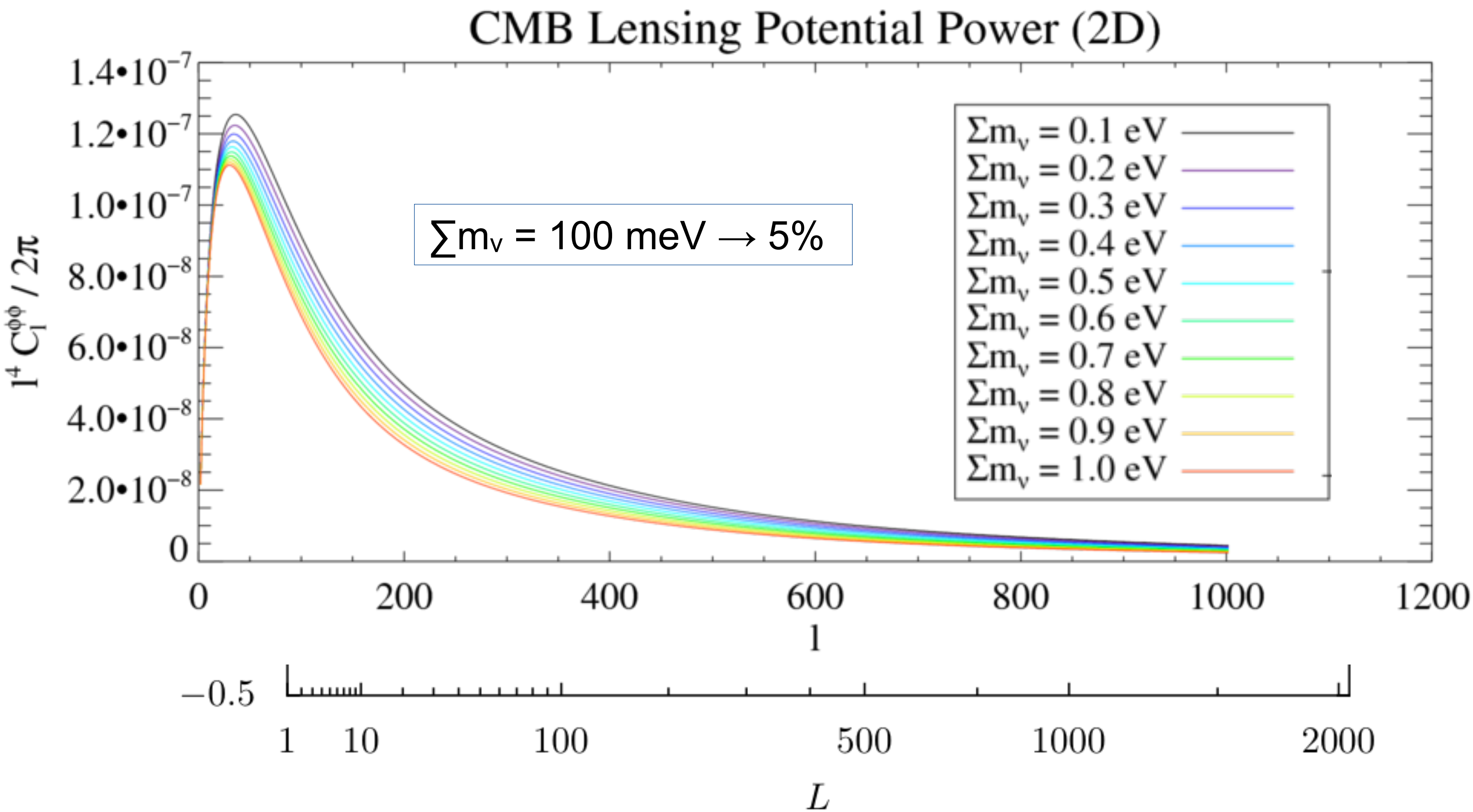


Das et al., PRL 107, 021301 (2011)
van Engelen et al., ApJ 756 (2012)



Das et al., PRL 107, 021301 (2011)
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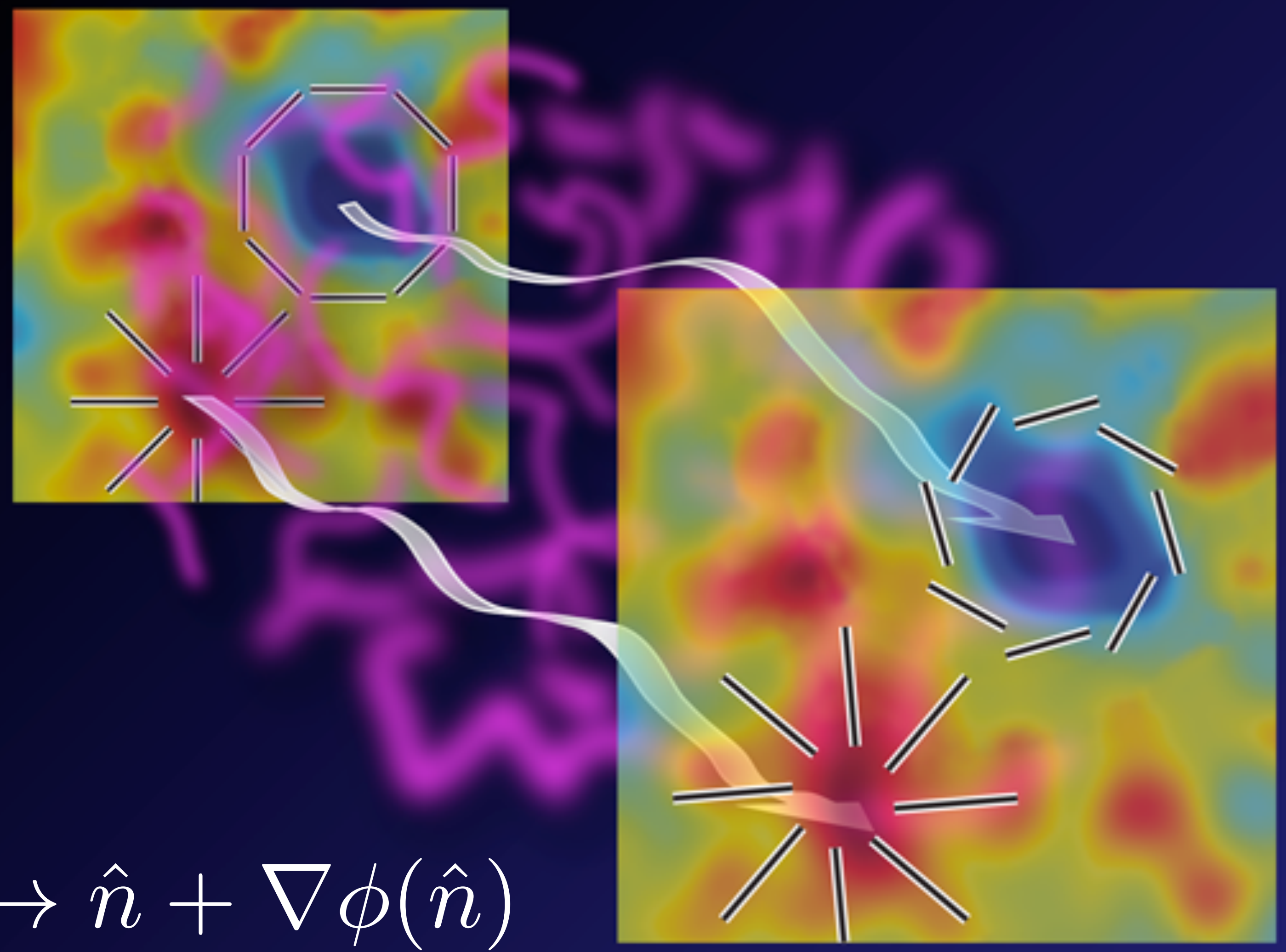
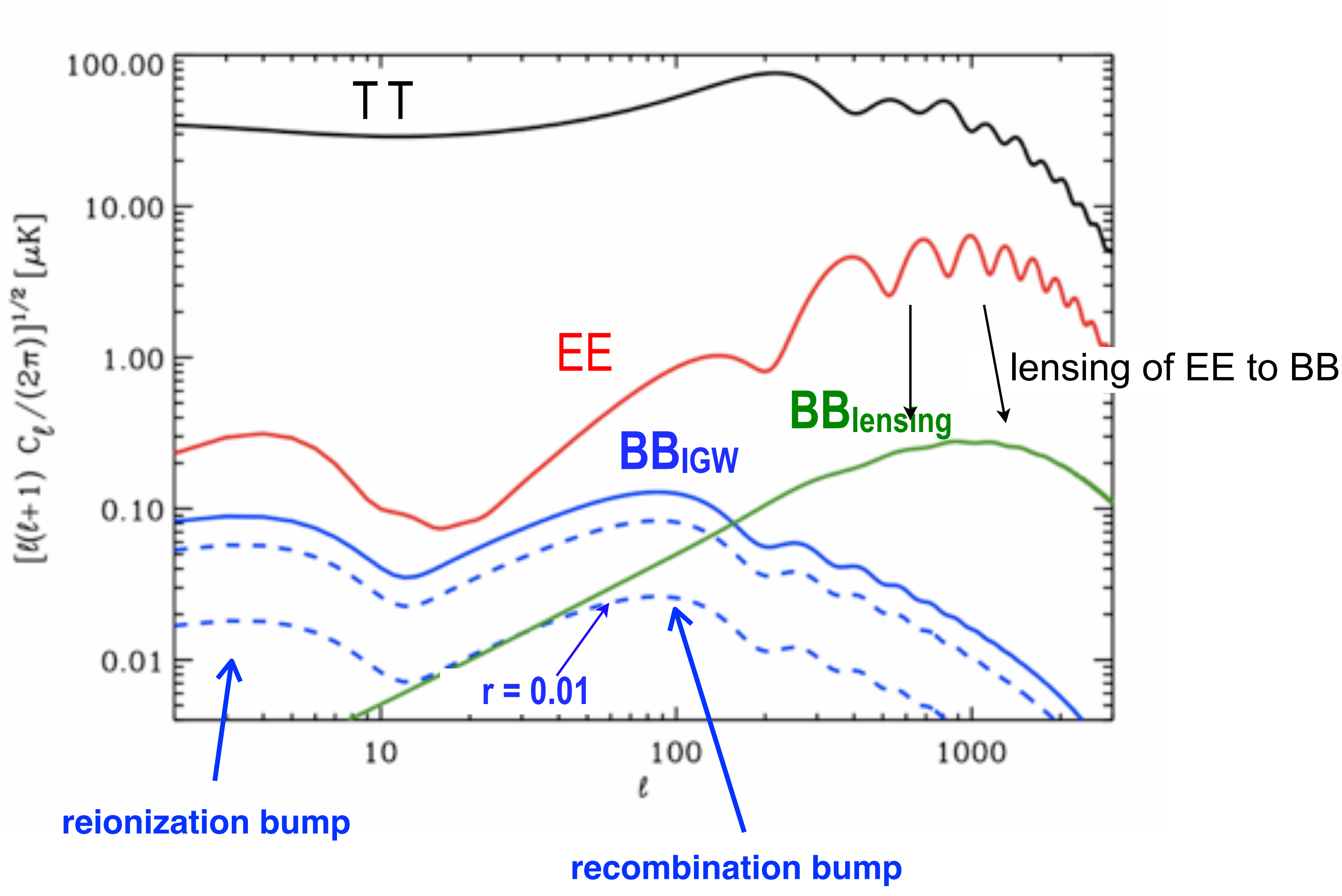
CMB Lensing via CMB polarization

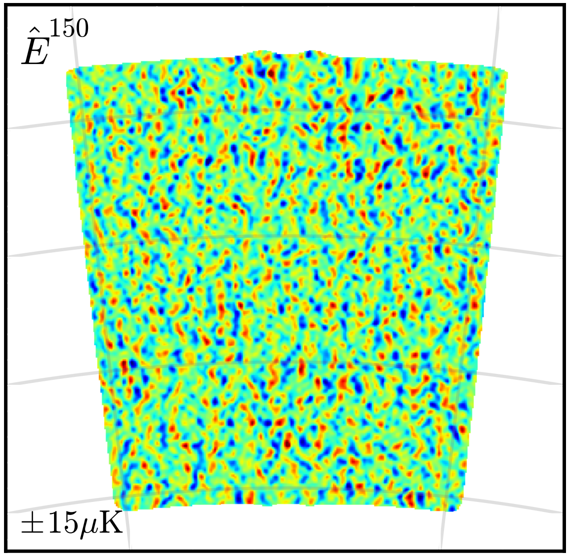


$$\hat{n} \rightarrow \hat{n} + \nabla\phi(\hat{n})$$

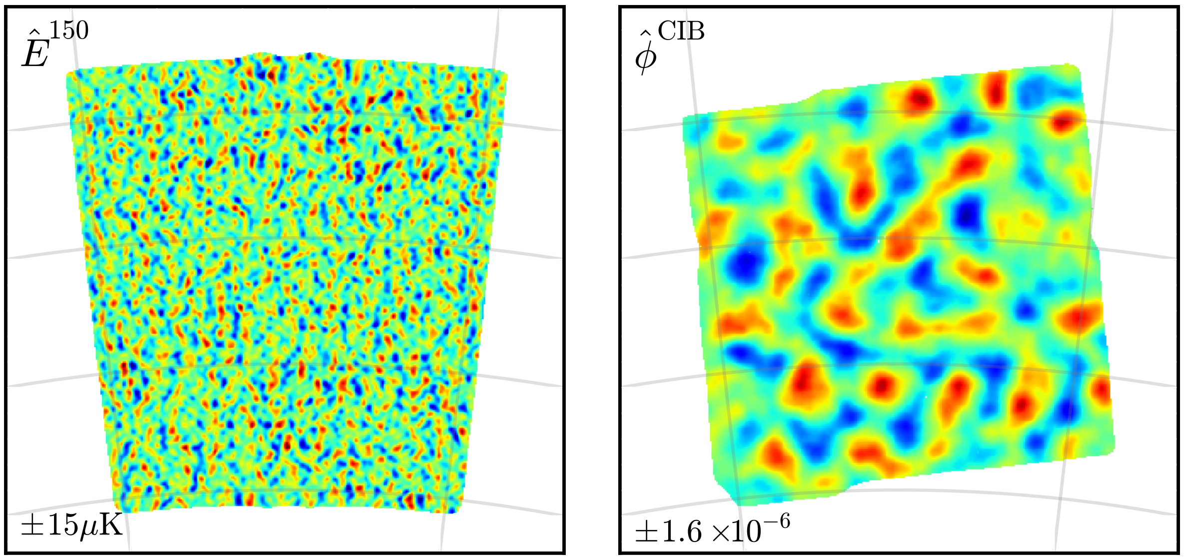
$$\phi(\hat{n}) = -2\int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{n}; \eta_0 - \chi)$$

Lensing mixes E into B

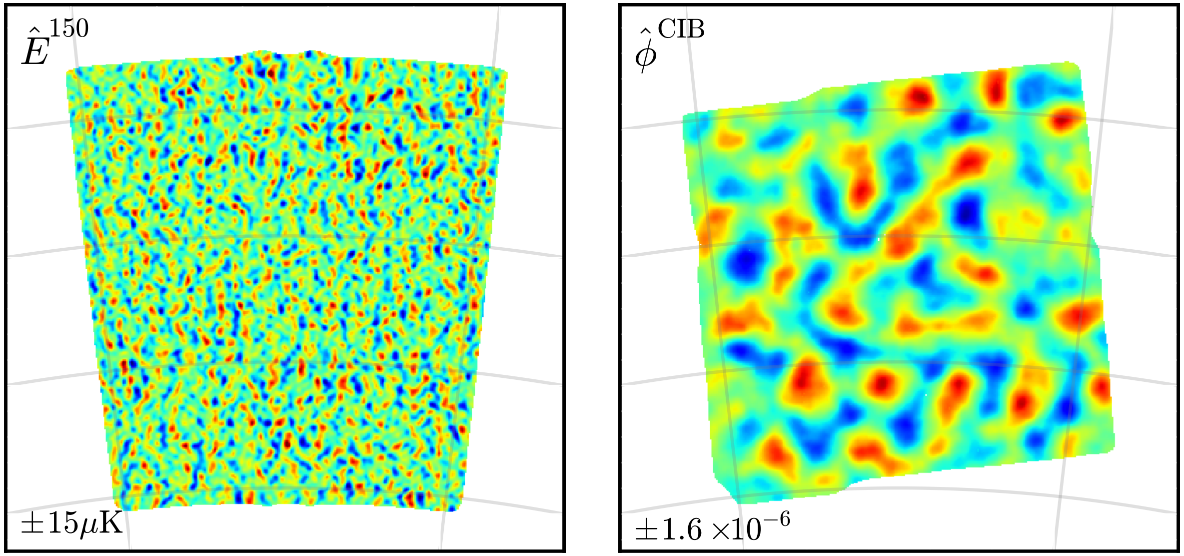




E-modes from
SPTpol

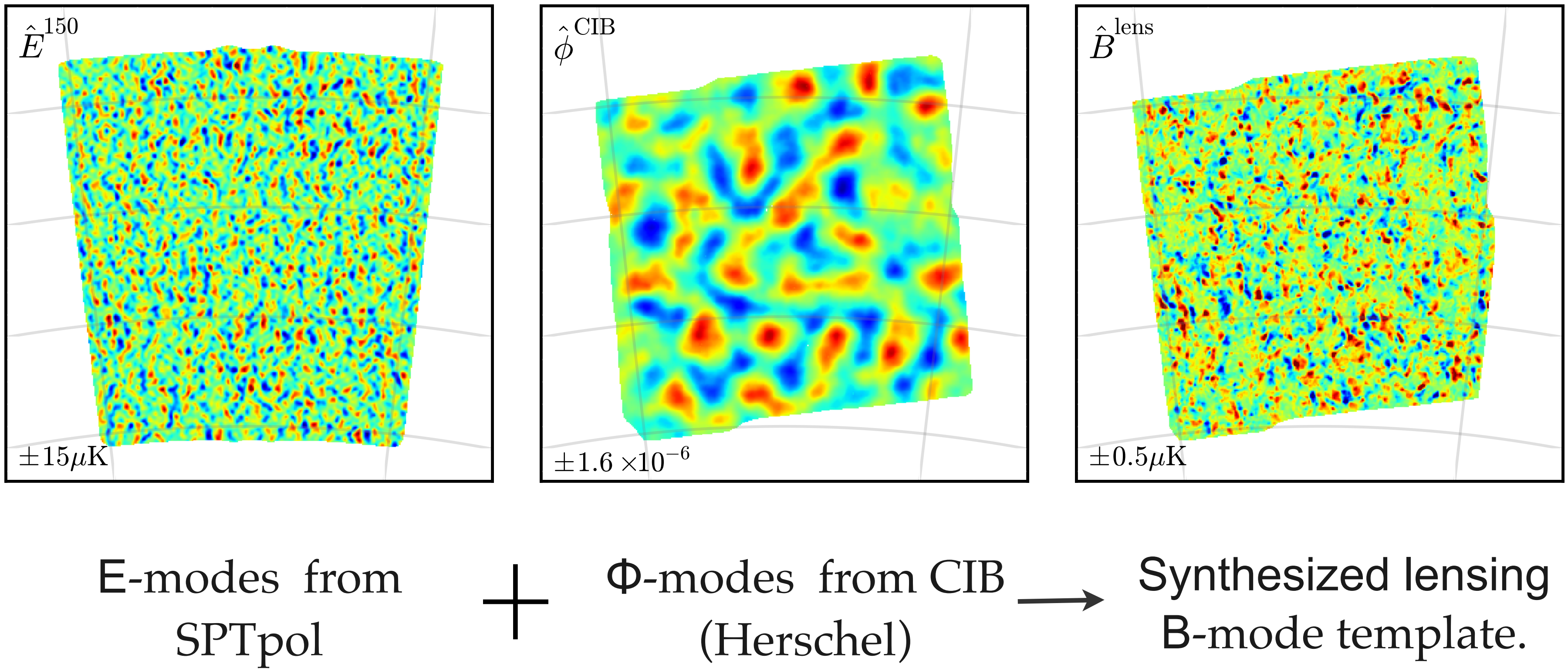


E-modes from SPTpol + Φ-modes from CIB (Herschel)

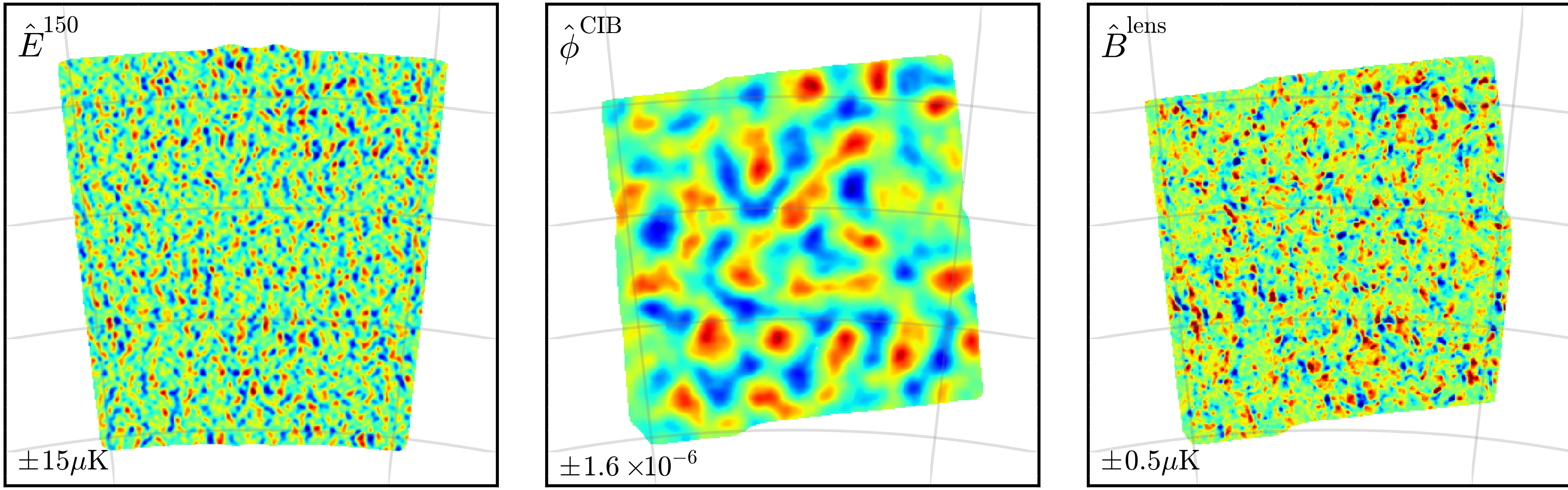


E-modes from SPTpol + Φ-modes from CIB (Herschel)

Traces DM/lensing potential



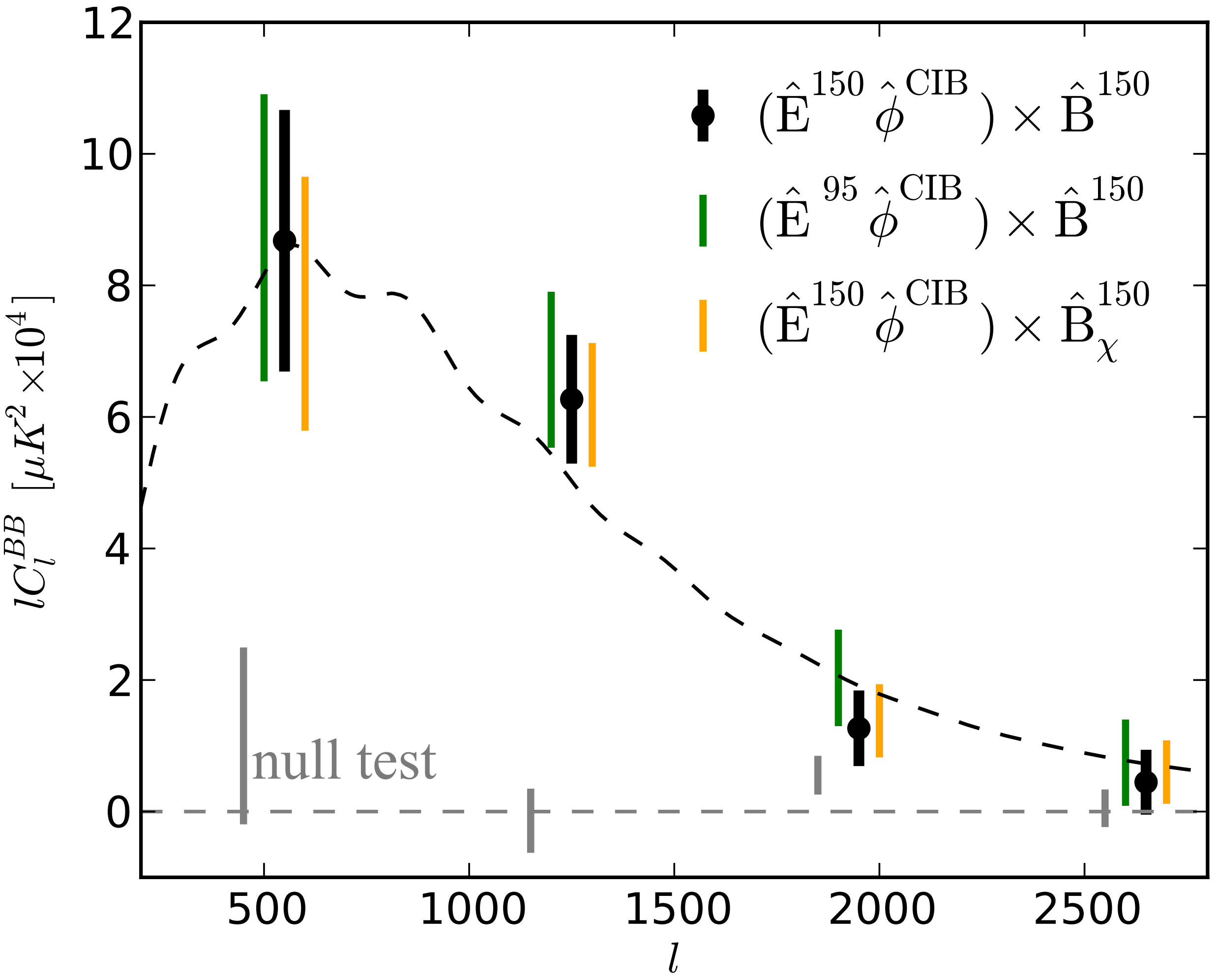
$\hat{E}^{150}$
$\pm 15\mu$K
$\hat{\phi}^{\rm CIB}$
$\pm 1.6 \times 10^{-6}$
$\hat{B}^{\rm lens}$
$\pm 0.5\mu$K
E-modes from SPTpol
+
Φ-modes from CIB (Herschel)
→
Synthesized lensing B-mode template.



E-modes from SPTpol + Φ-modes from CIB (Herschel) → Synthesized lensing B-mode template.

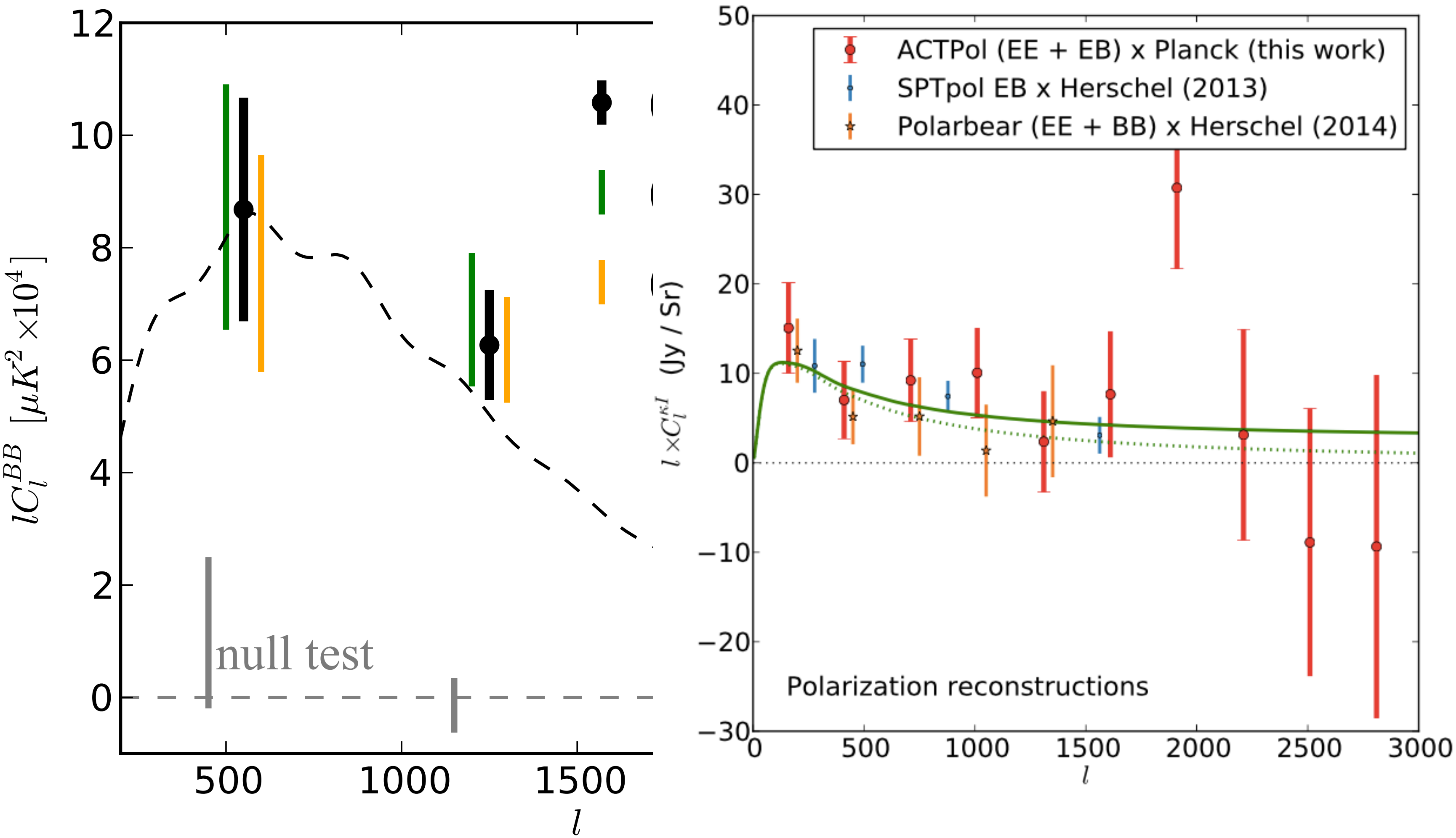
Cross template w/ B-mode map and look for signal

7.7σ detection of CMB lensing B-modes



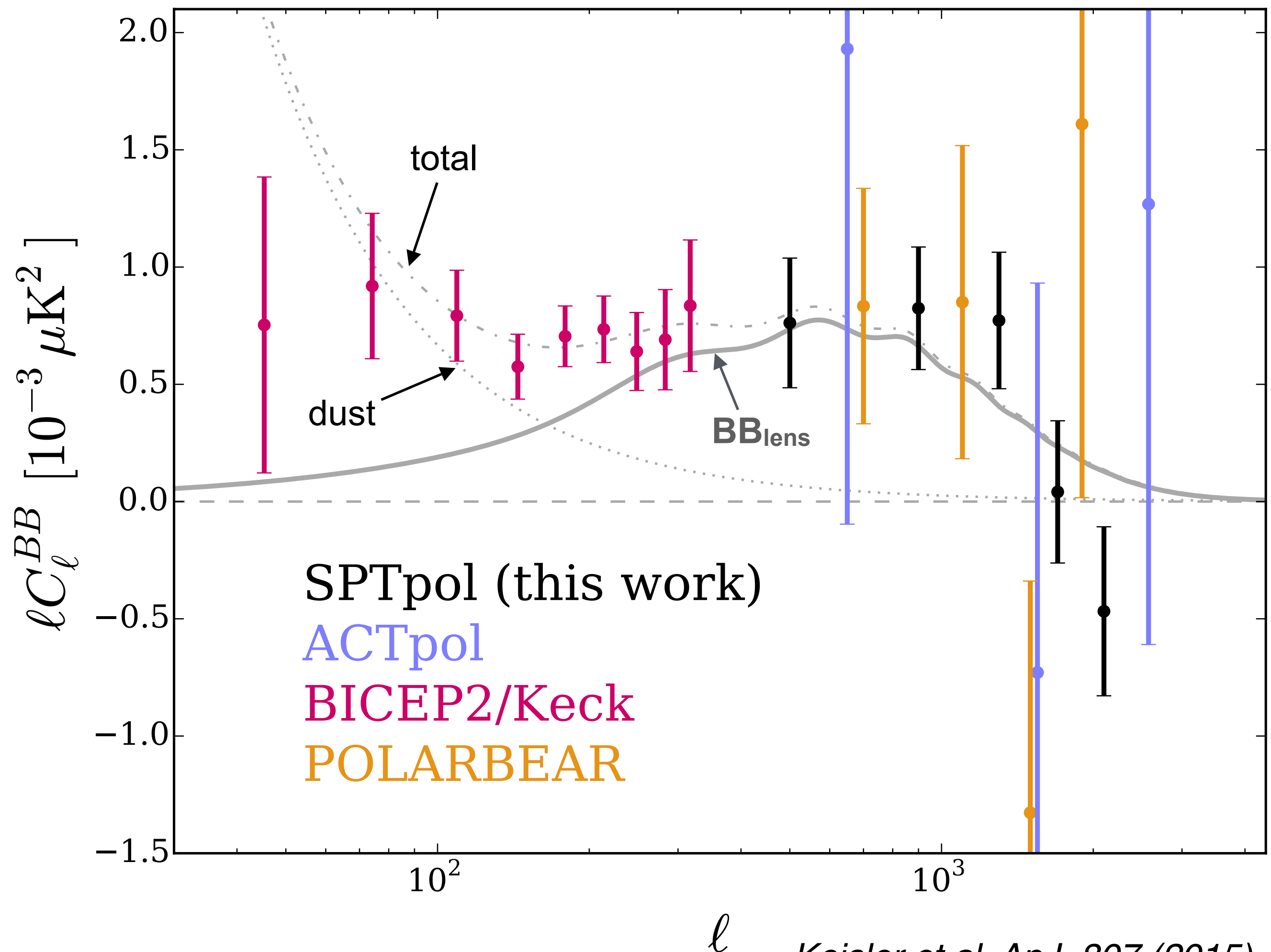
Hanson et al., PRL, 111 (2013)
van Engelen et al., ApJ 808, 7 (2015)

7.7σ detection of CMB lensing B-modes



Hanson et al., PRL, 111 (2013)
van Engelen et al., ApJ 808, 7 (2015)

BB Compilations



Keisler et al, ApJ, 807 (2015)
Naess et al., JCAP 10, 007 (2014)
BICEP2 Collab., Phys. Rev. Lett. 112, 241101
Polarbear Collab., ApJ, 794 (2014)

Full lensing

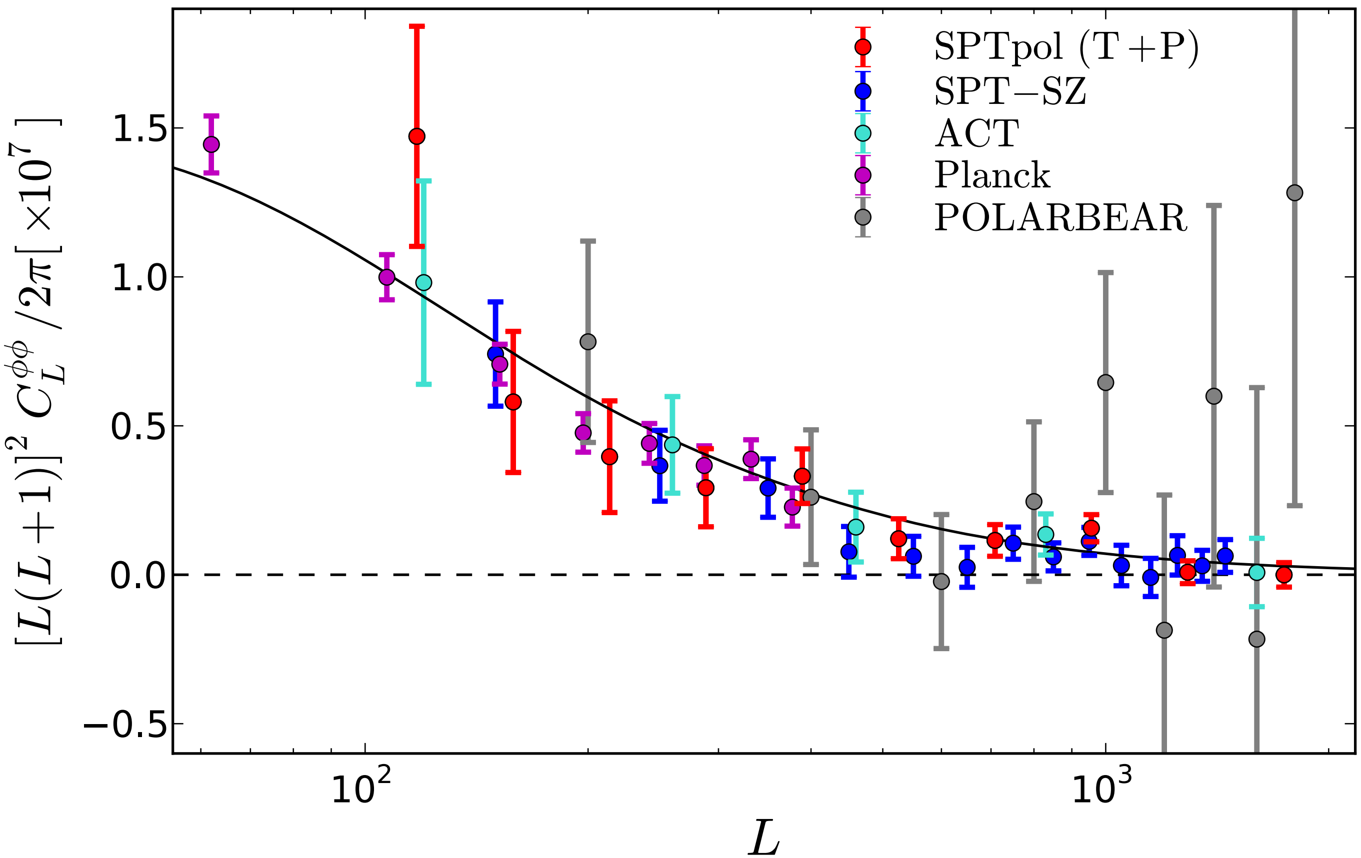
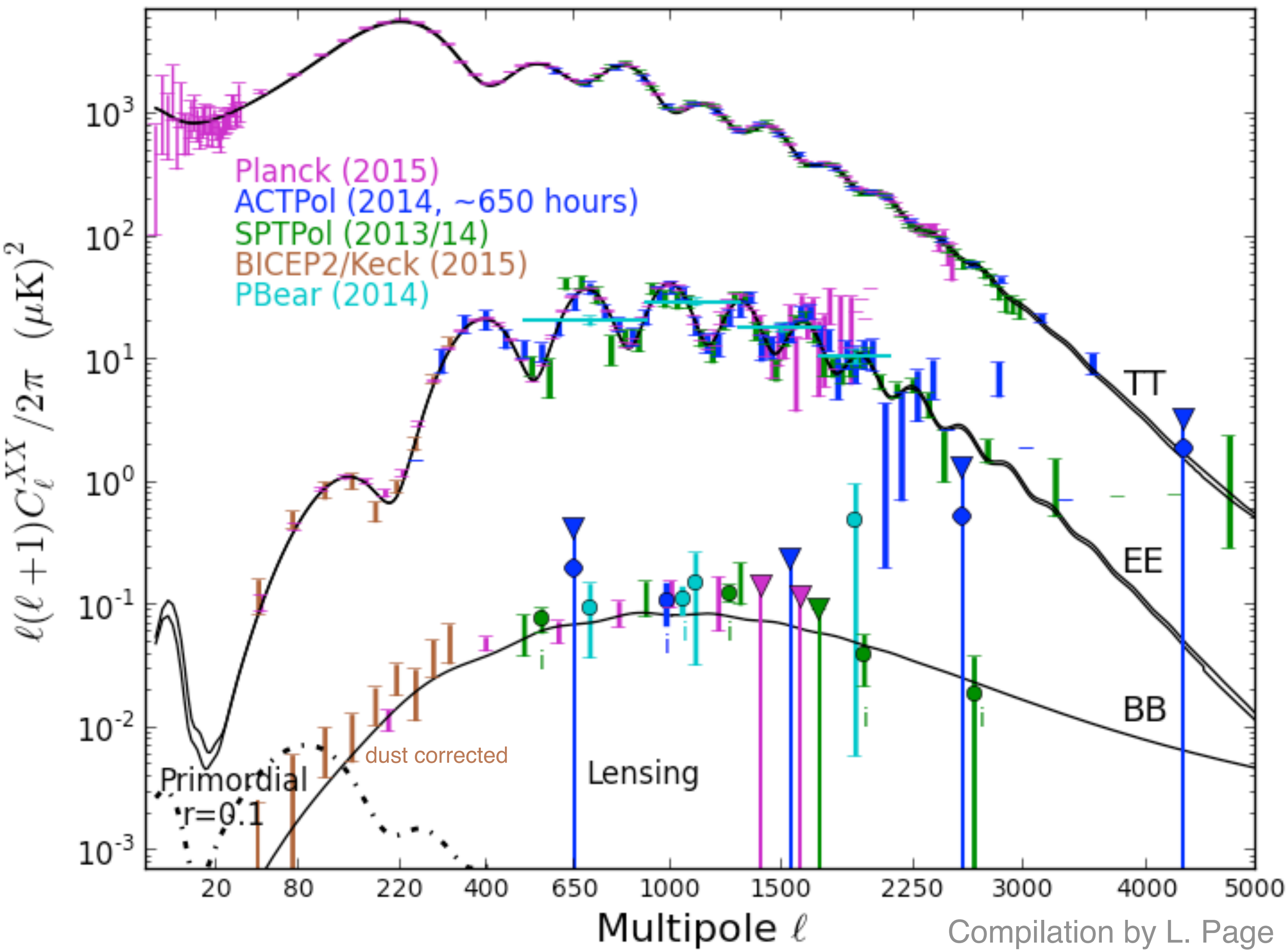


FIG. 6.— Lensing potential power spectrum bandpowers estimated from SPTpol, as well as those previously reported for temperature by SPT-SZ (van Engelen et al. 2012), ACT (Das et al. 2014), *Planck* (Planck Collaboration XVII 2013), and for polarization by POLARBEAR (POLARBEAR Collaboration). The black solid line shows the PLANCK+LENS+WP+HIGHL best-fit ΛCDM model.

Story et al., ApJ, 810 (2015)

CMB polarization measurements



Compilation by L. Page

Rapid progress! All in last ~2 years.

Moving forward

Fundamental limits of CMB measurement

- Uncertainty on measured photon power in time, τ

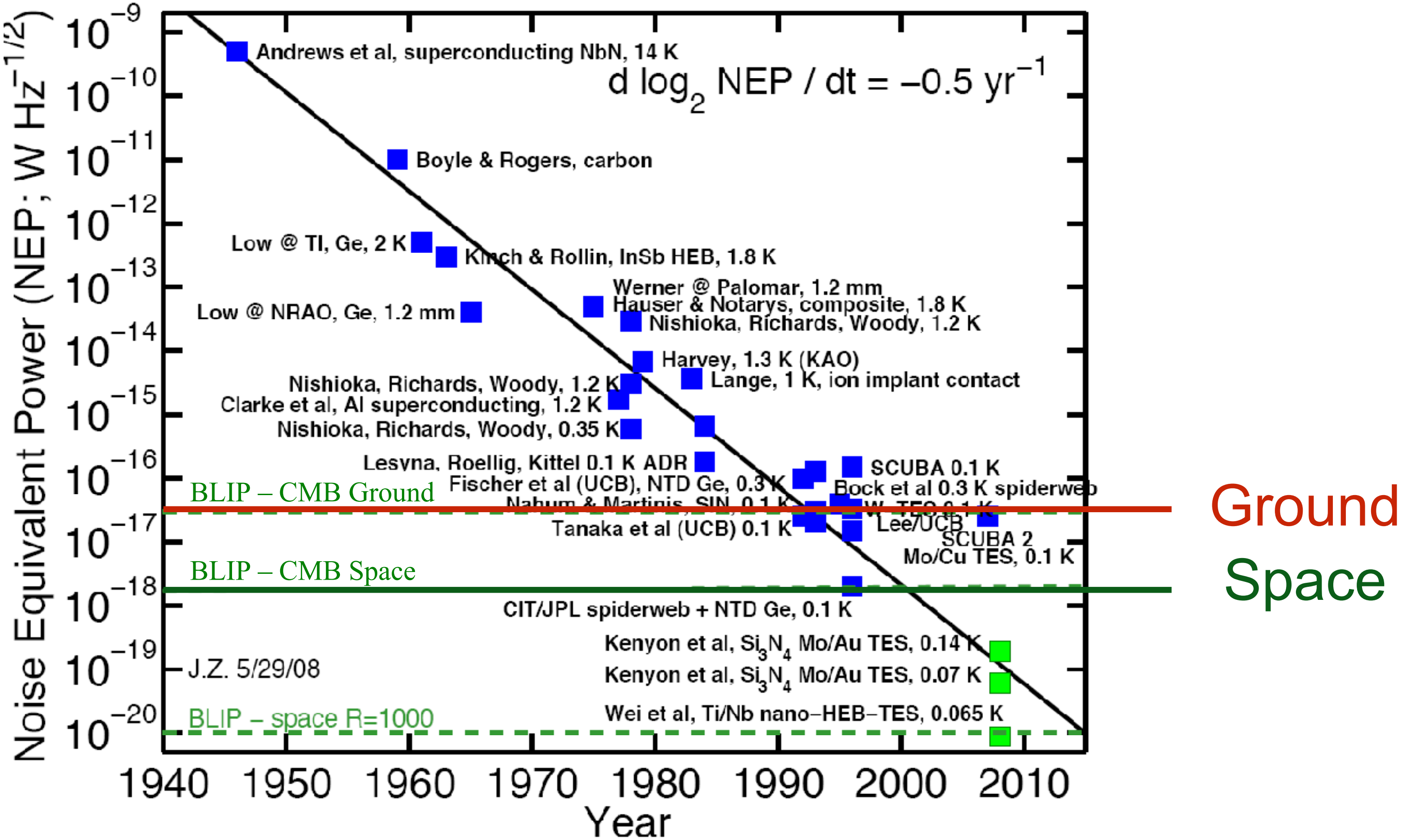
$$\sigma_P = \frac{h\nu\sigma}{\eta} = \frac{h\nu}{\sqrt{\Delta\nu\tau}}\sqrt{\frac{n_0(1+\eta n_0)}{\eta}}\,\Delta\nu$$

- Have to measure lots of photons

Jonas Zmuidzinas
Applied Optics, Vol. 42, Issue 25, pp. 4989-5008 (2003)

Background limited detectors

- Detectors are now photon noise limited

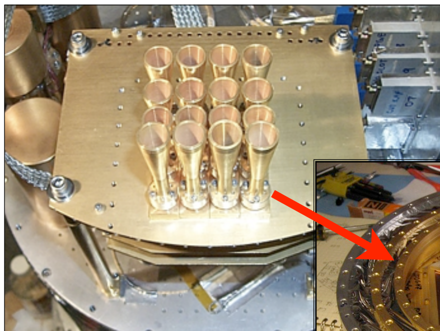


Plot from Jonas Zmuidzinas

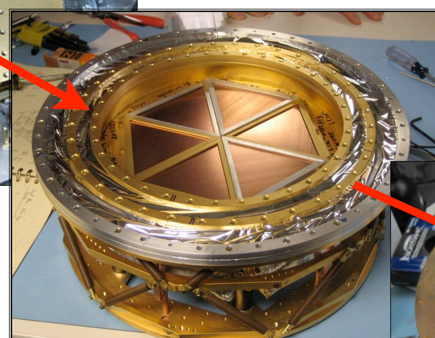
SPT experimental trajectory

Further improvements are made only by making ***more detectors!***

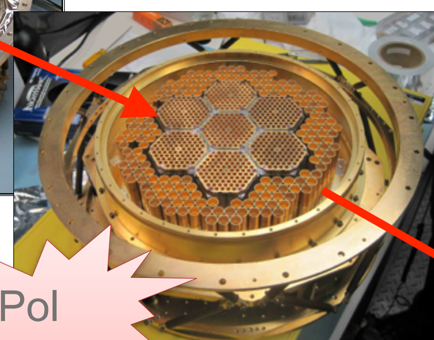
2001: ACBAR
16 detectors



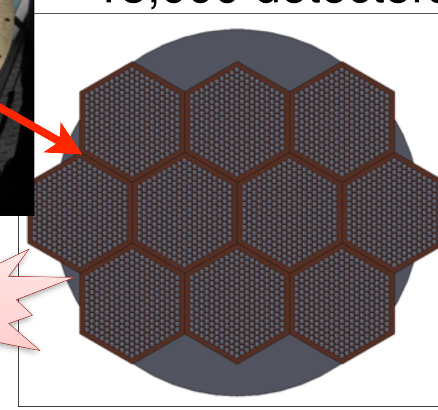
2007: SPT
960 detectors

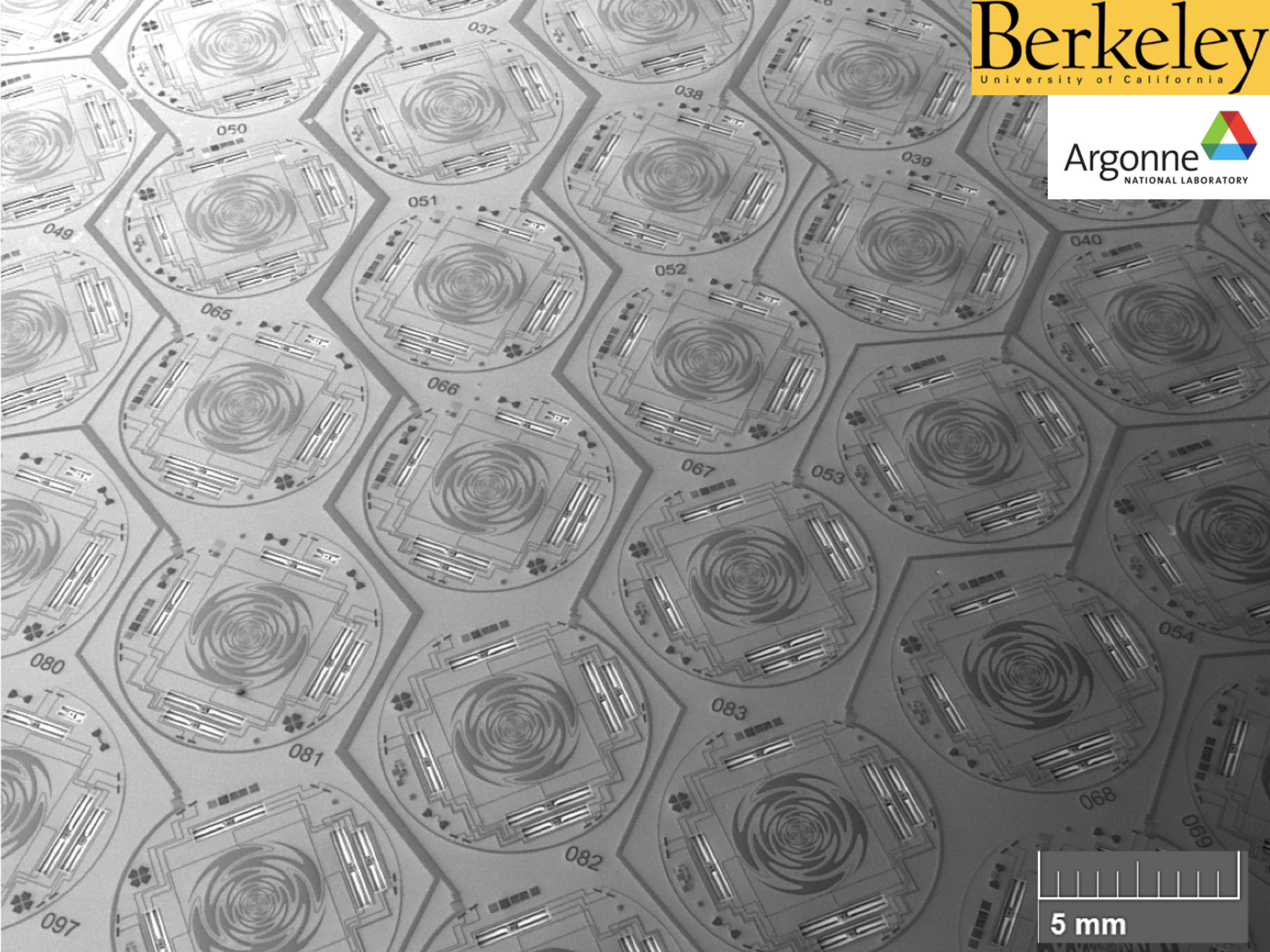


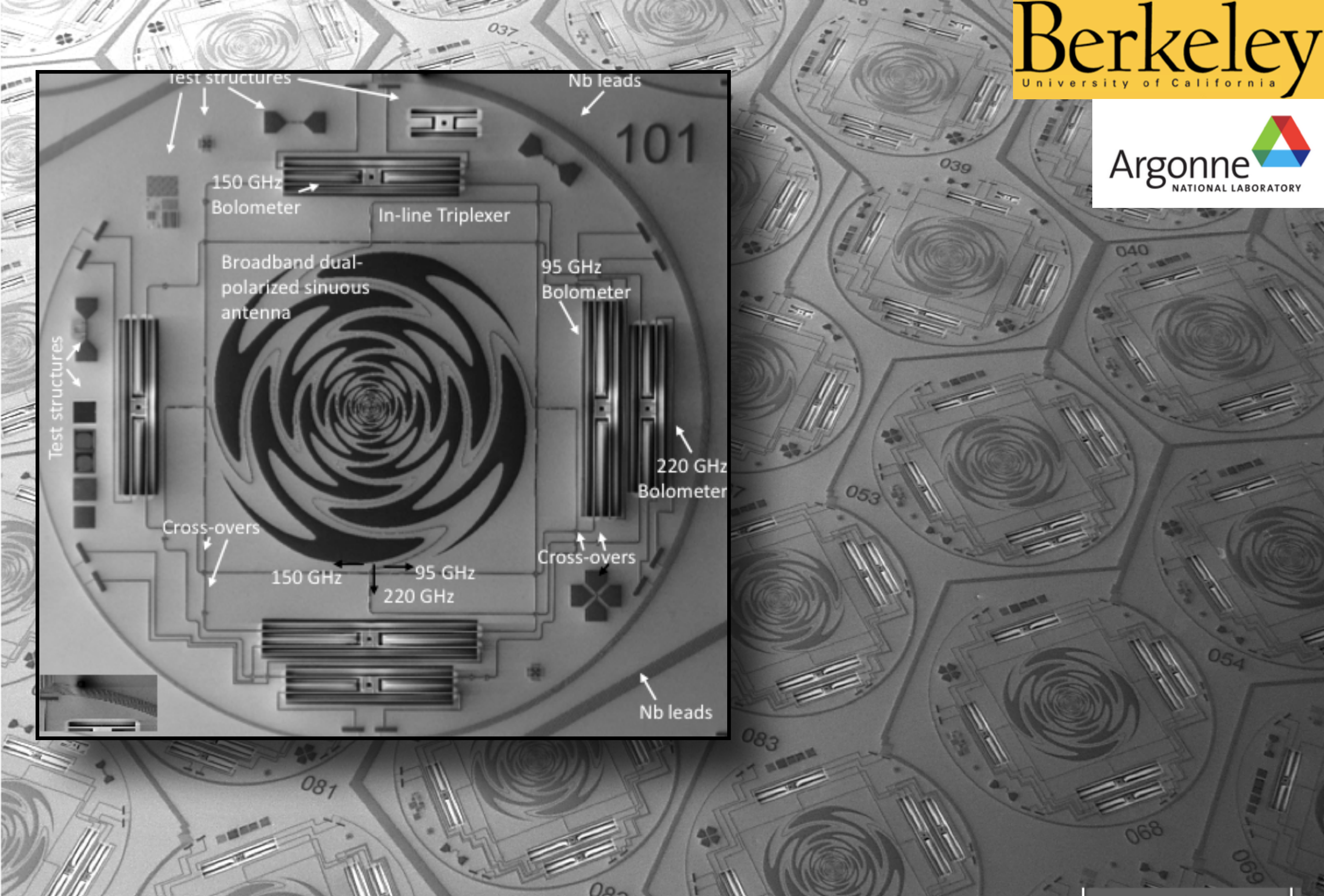
Stage-2
2012: SPTpol
~1600 detectors



Stage-3
2016: SPT-3G
~15,000 detectors

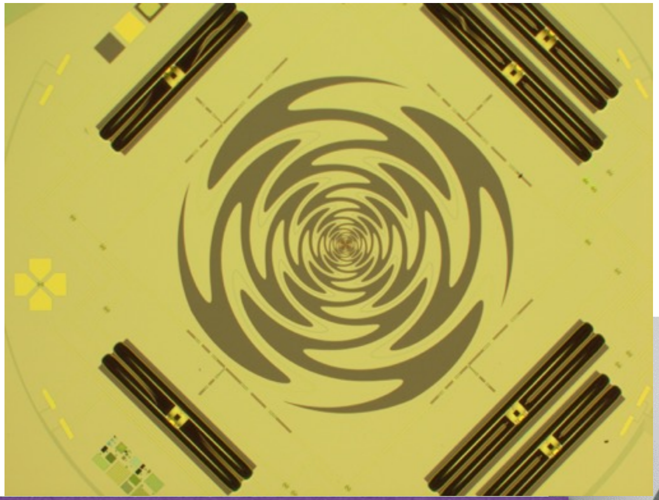



Berkeley
University of California
Argonne
NATIONAL LABORATORY
5 mm



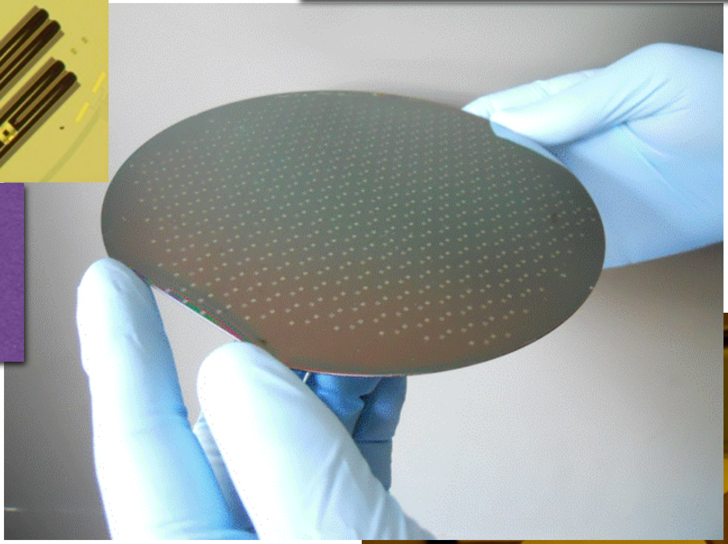
Suzuki et al., Proc. SPIE 8452, Mm, Sub-mm, and Far-IR Detectors and Instr. for Astro. VI, 84523H (October 5, 2012)
Posada et al., (2015)

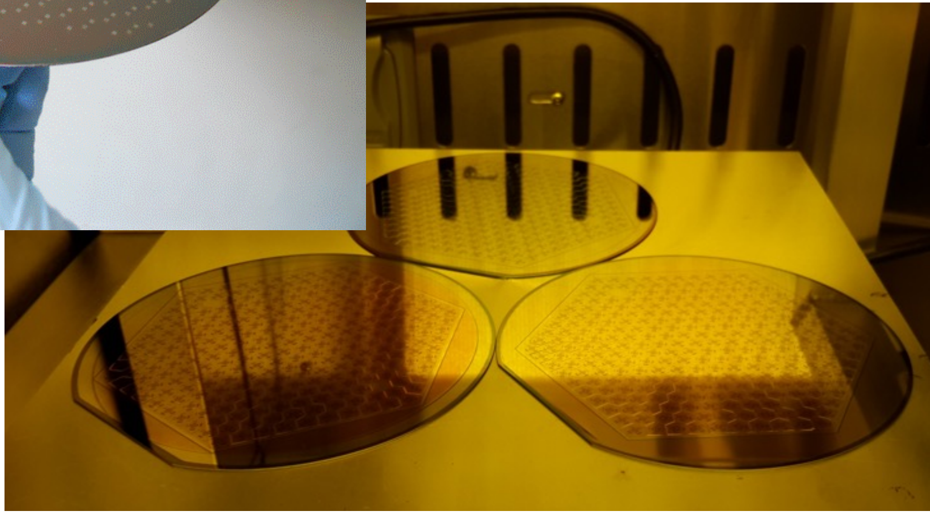
More detectors!



Multichroic for more detectors per pixel

Large wafers for more pixels per wafer

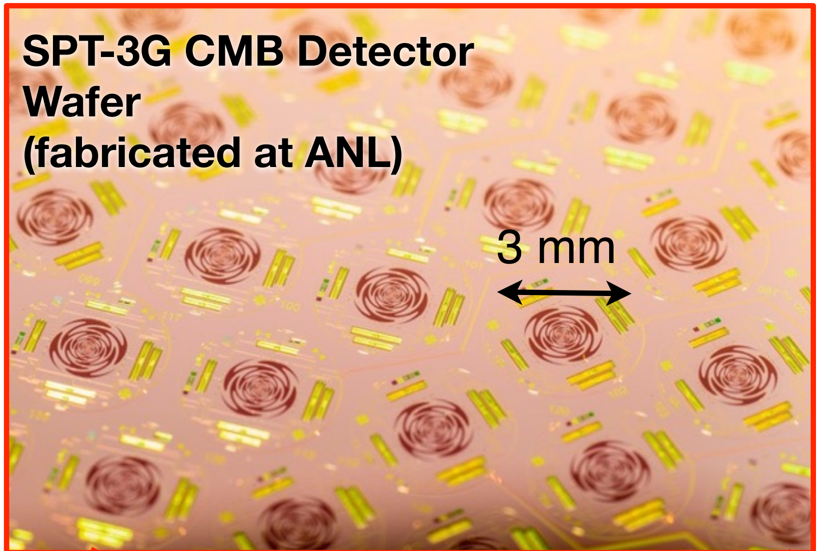


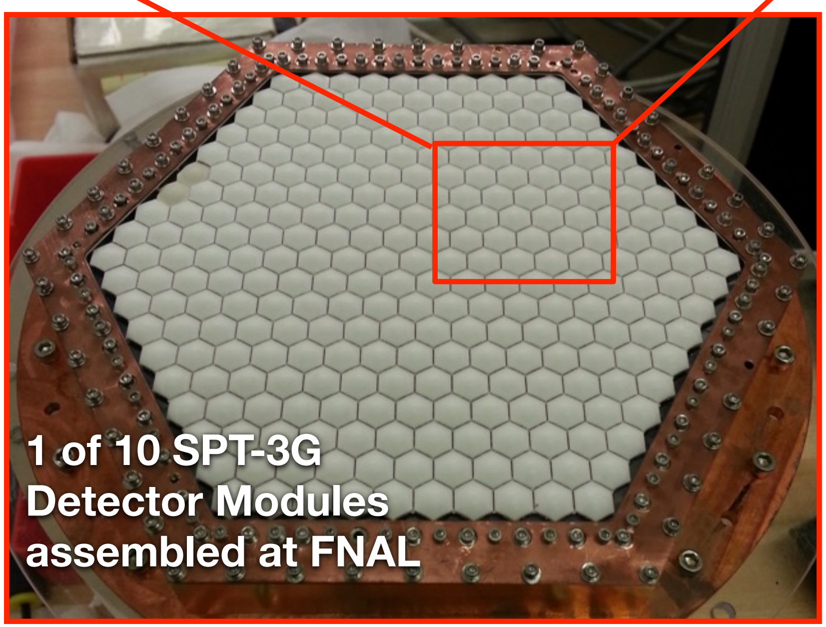


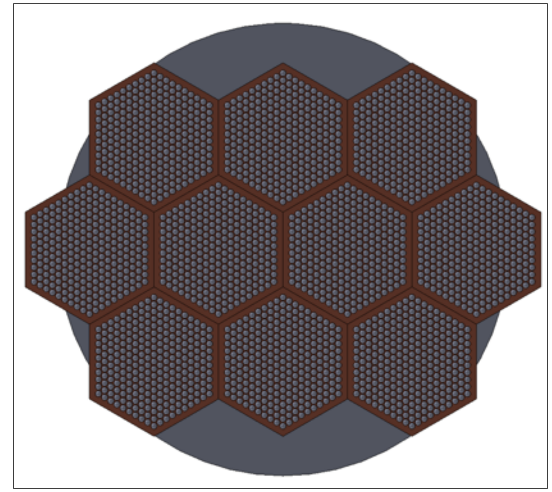
High throughput fab for more wafers per focal plane

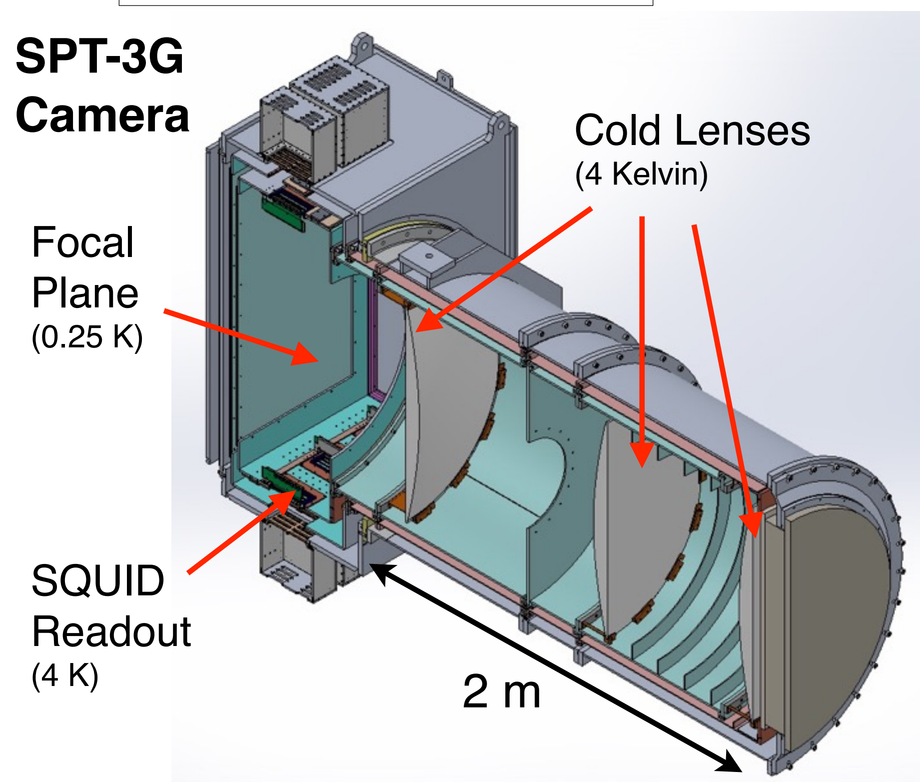
Neutrino Mass: From the Terrestrial Laboratory to the Cosmos, ACFI (2015)

Next for SPT → SPT-3G *~15K detectors!*

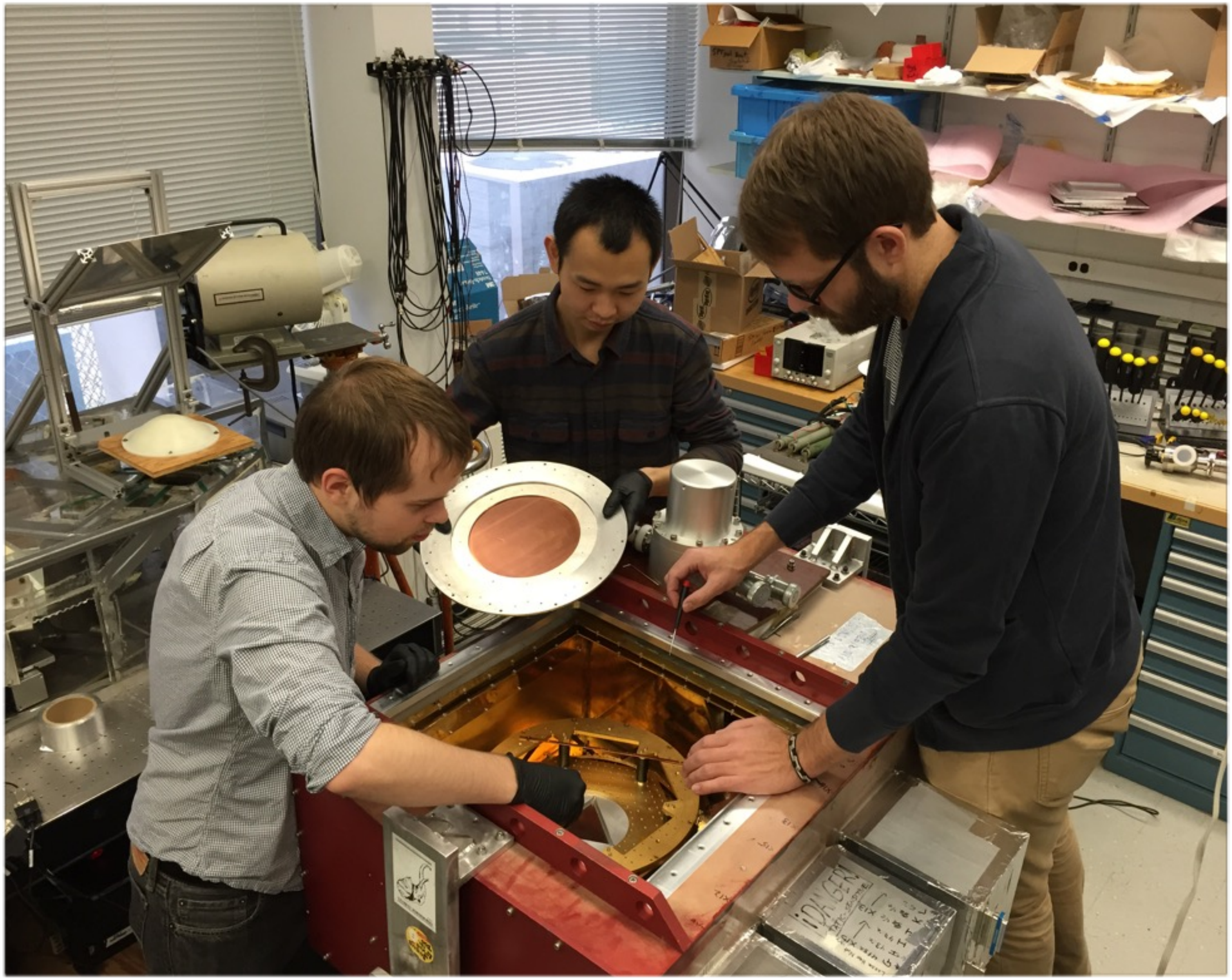




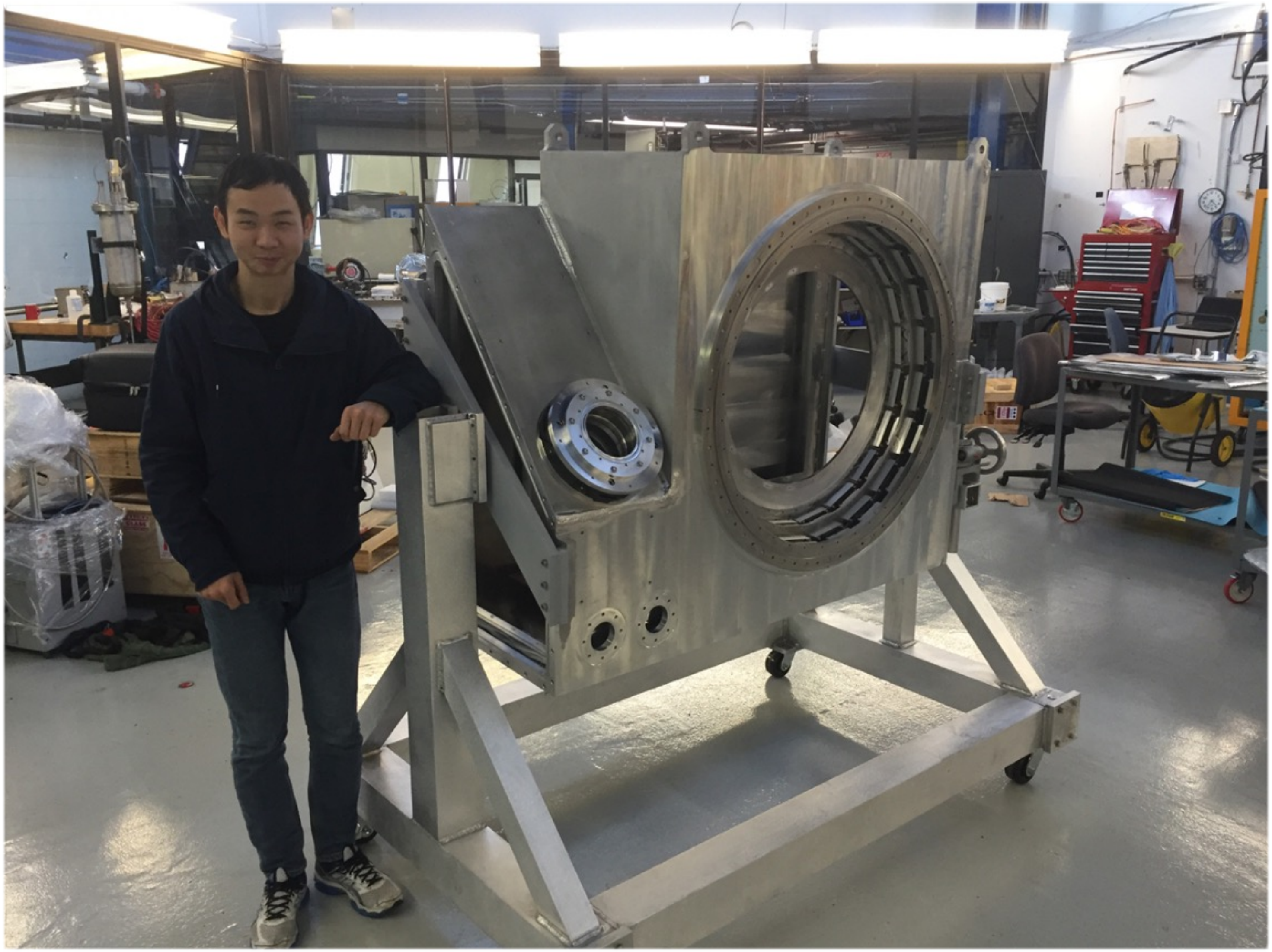




Bigger cryostats



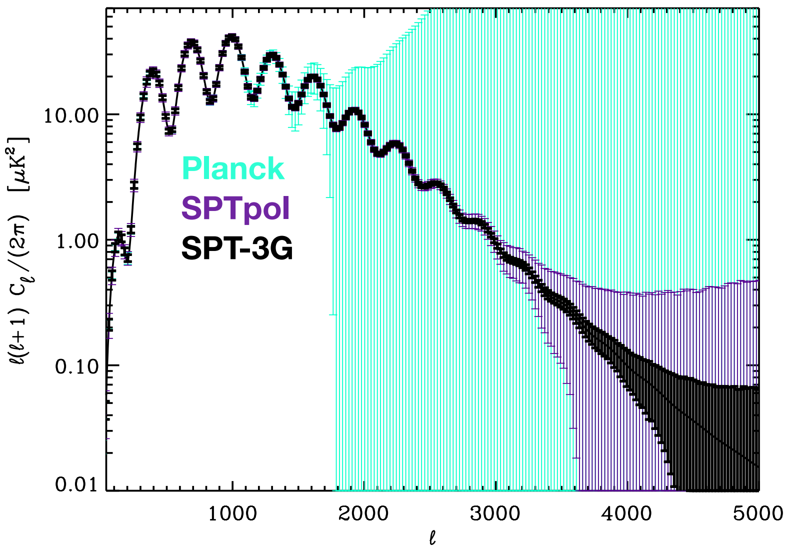
Bigger cryostats



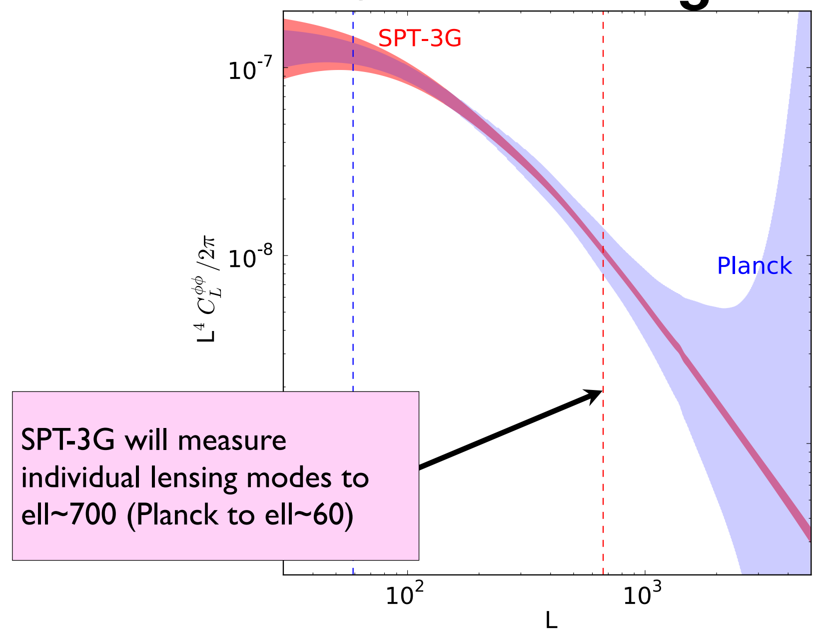
Neutrino Mass: From the Terrestrial Laboratory to the Cosmos, ACFI (2015)

SPTpol and SPT-3G projections

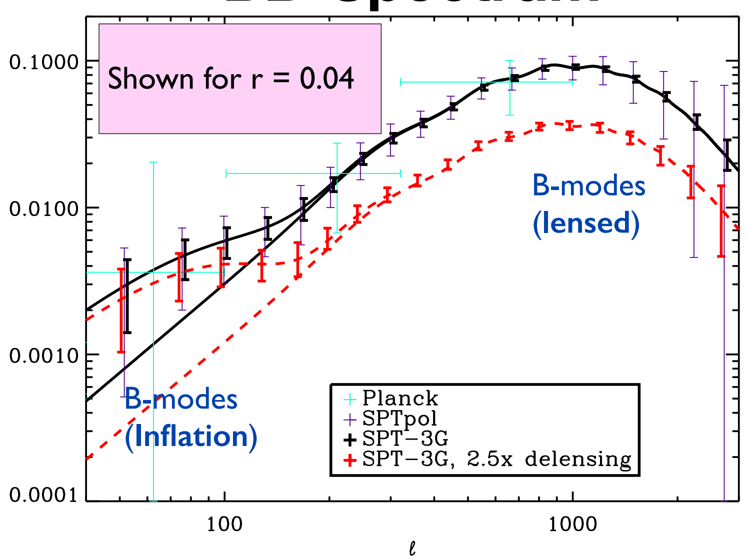
EE-Spectrum



CMB Lensing



BB-Spectrum

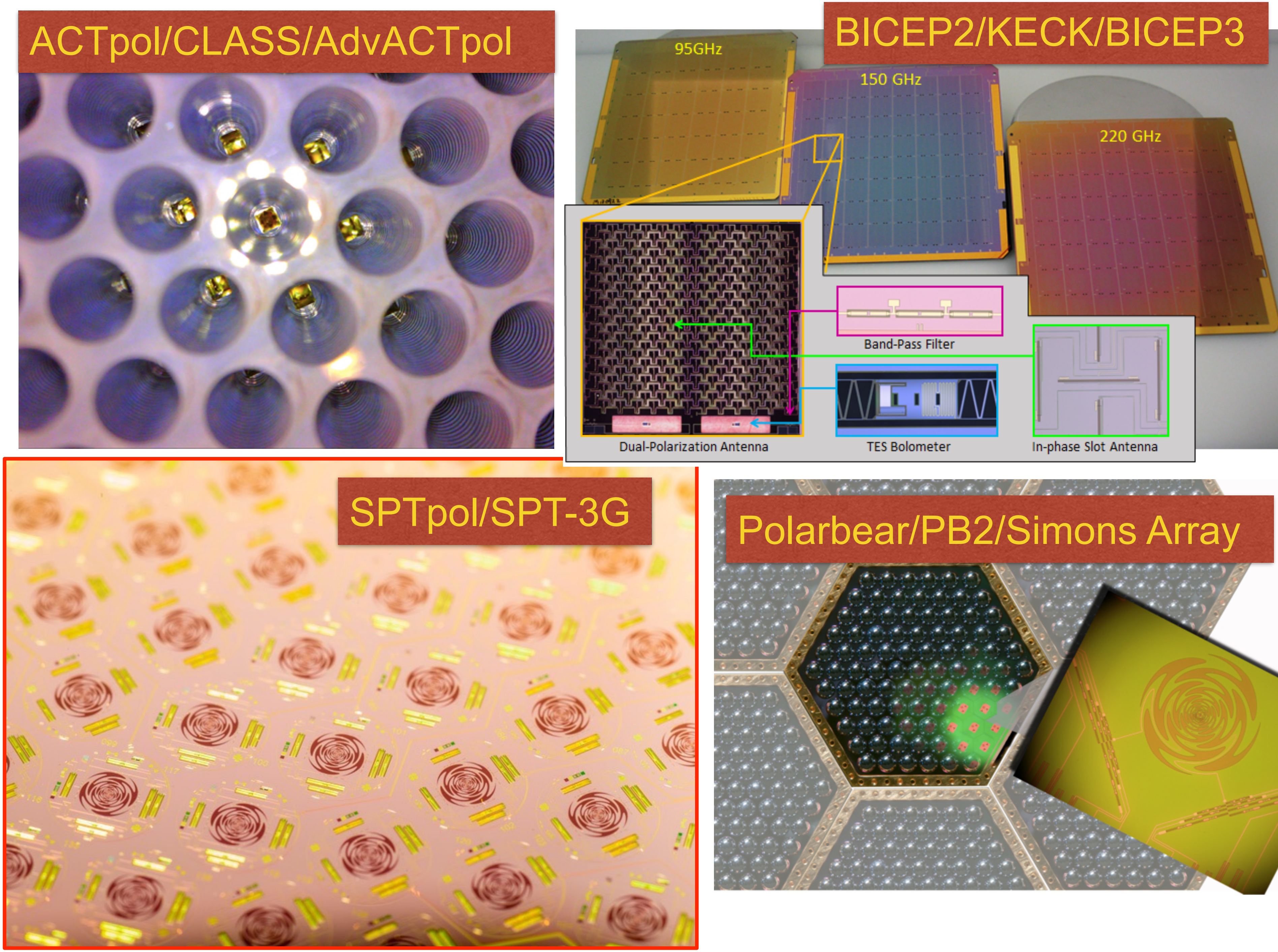


Projections

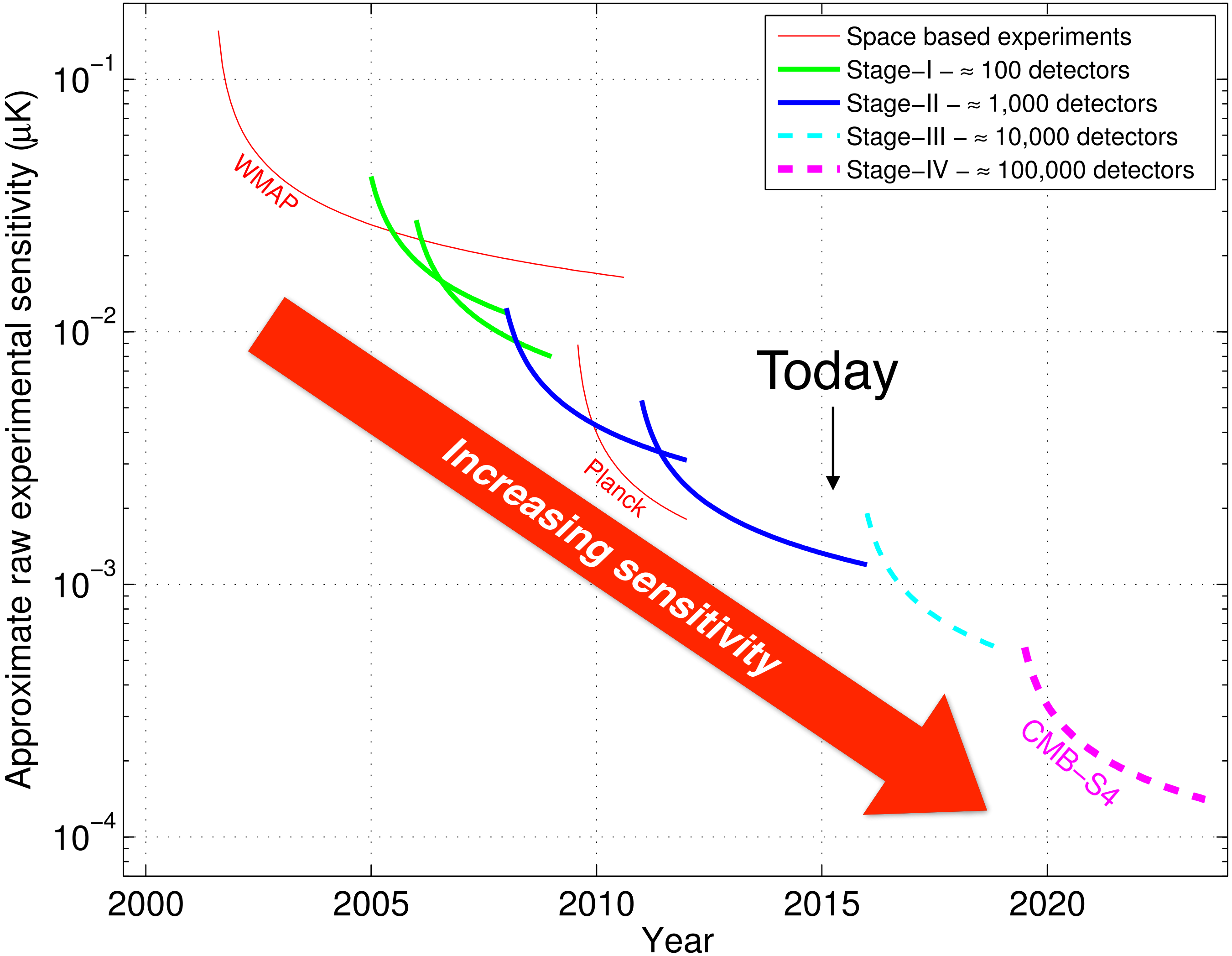
(w/Planck priors)

	SPTpol (2015)	SPT-3G (2019)
σ(r)	0.028	0.011
$\sigma(N_{eff})$	0.117	0.058
$\sigma(\Sigma m_\nu)$	0.096 eV	0.061 eV*

* includes BOSS prior


ACTpol/CLASS/AdvACTpol
BICEP2/KECK/BICEP3
95GHz
150 GHz
220 GHz
Band-Pass Filter
Dual-Polarization Antenna
TES Bolometer
In-phase Slot Antenna
SPTpol/SPT-3G
Polarbear/PB2/Simons Array

The next big step

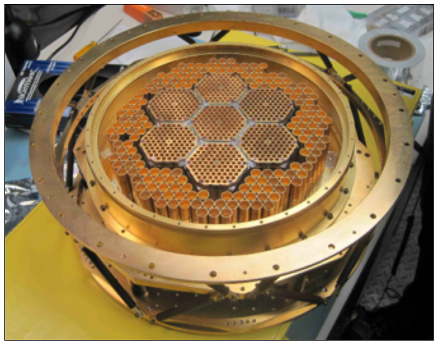


A Moore's Law of CMB sensitivity

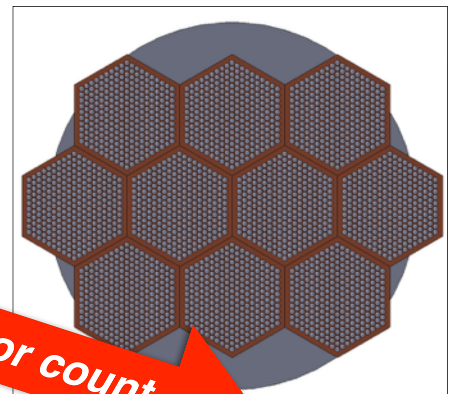
Snowmass CF5 Neutrinos Document arxiv:1309.5383; figure by Clem Pryke

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

Stage II
Now
~1000 detectors

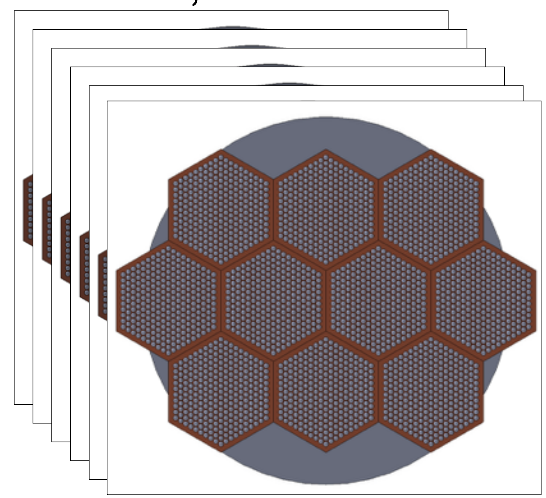


Stage III
ramping up
~10,000 detectors



CMB Stage-4 Experiment
Described in Snowmass CF5:
Abazajian et al., Astropart.Phys. 63 (2015)
Abazajian et al., arxiv:1309.5381

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 program to put *O*(500,000) detectors spanning 30 - 300 GHz using multiple telescopes and sites to map ≳70% of sky.

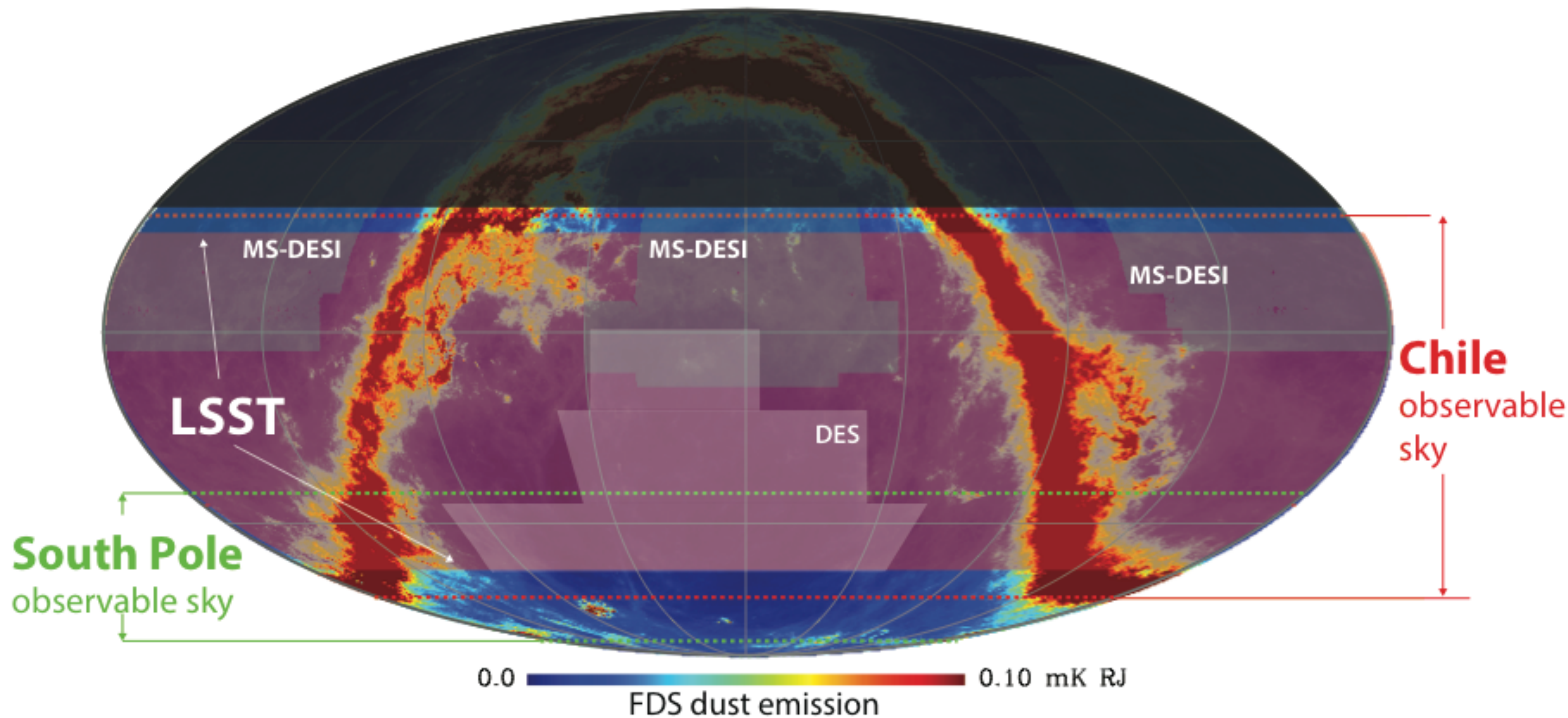
Strawman CMB-S4 specifications

- **Survey(s):**
  - Inflation, Neutrino, and Dark Energy science requires an optimized survey(s) using a range of resolution and sky coverage from deep to wide.
- **Sensitivity:**
  - polarization sensitivity of ~1 uK-arcm over ≳70% of the sky
- **Resolution:**
  - exquisite low-ℓ coverage for inflationary B modes (degree)
  - ℓ_{max} ~ 5000 for CMB lensing & neutrino science (arc-minute)
  - higher-ℓ improves dark energy constraints, gravity tests on large scales via the SZ effects, and more…
- **Configuration:**
  - *O*(500,000) detectors on multiple telescopes (small and large aperture)
  - spanning ~ 30 - 300 GHz for foreground mitigation

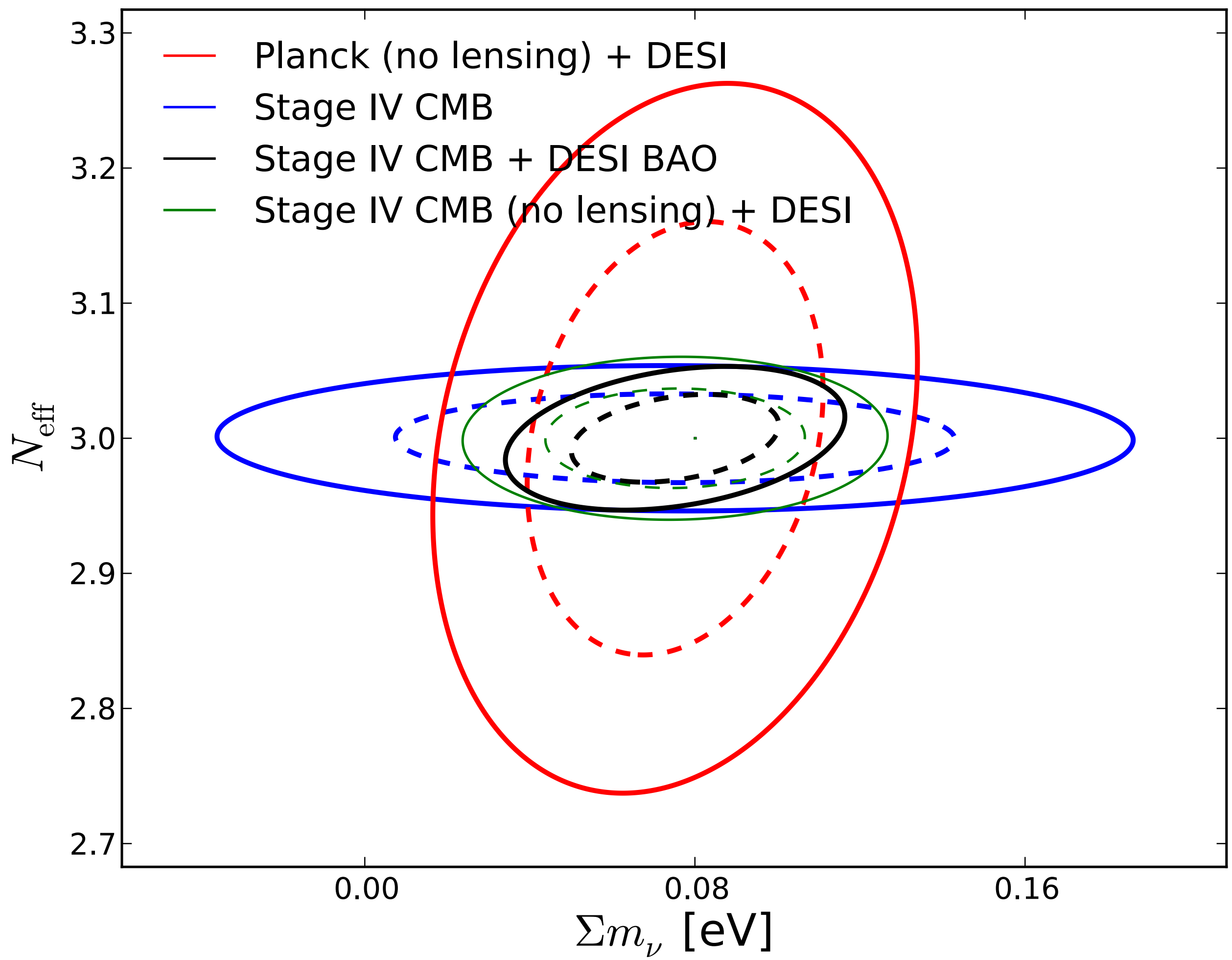
Coverage from Chile and South Pole

70% of the sky, overlapping the large optical surveys

Overlapping sky with DES, DESI and LSST



Snowmass joint projections N_{eff} - Σm_ν



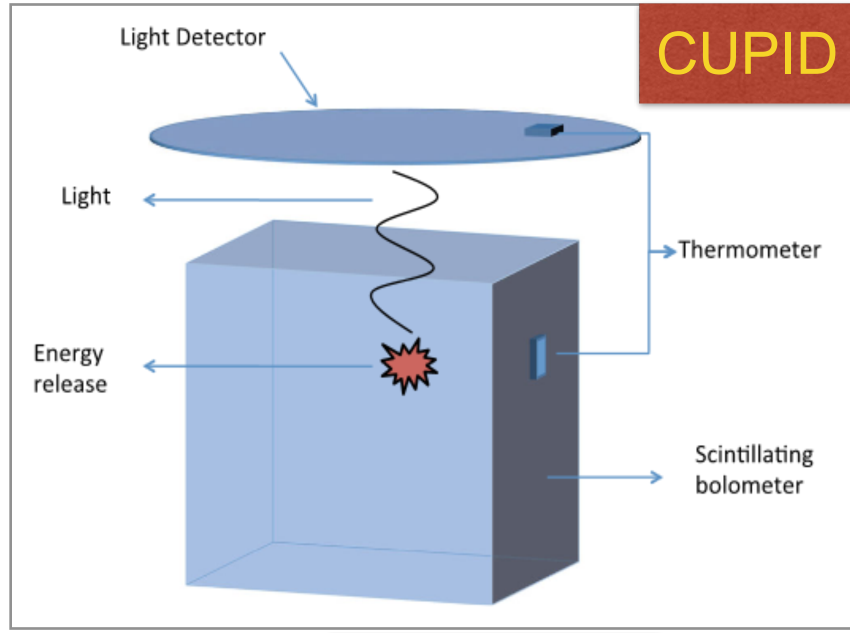
σ(N_{eff}) = 0.020

CMB uniquely probes N_{eff}

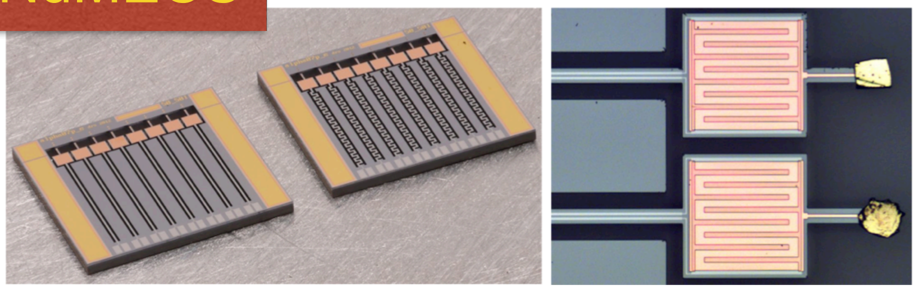
σ(Σm_ν) = 16 meV (with DESI BAO)

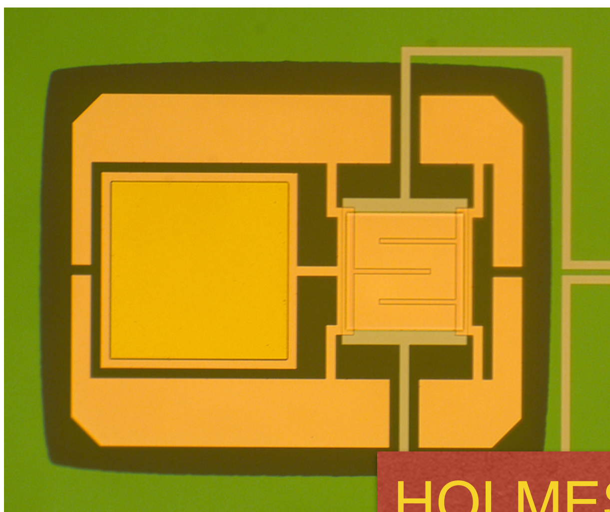
Technical connections?

CUPID



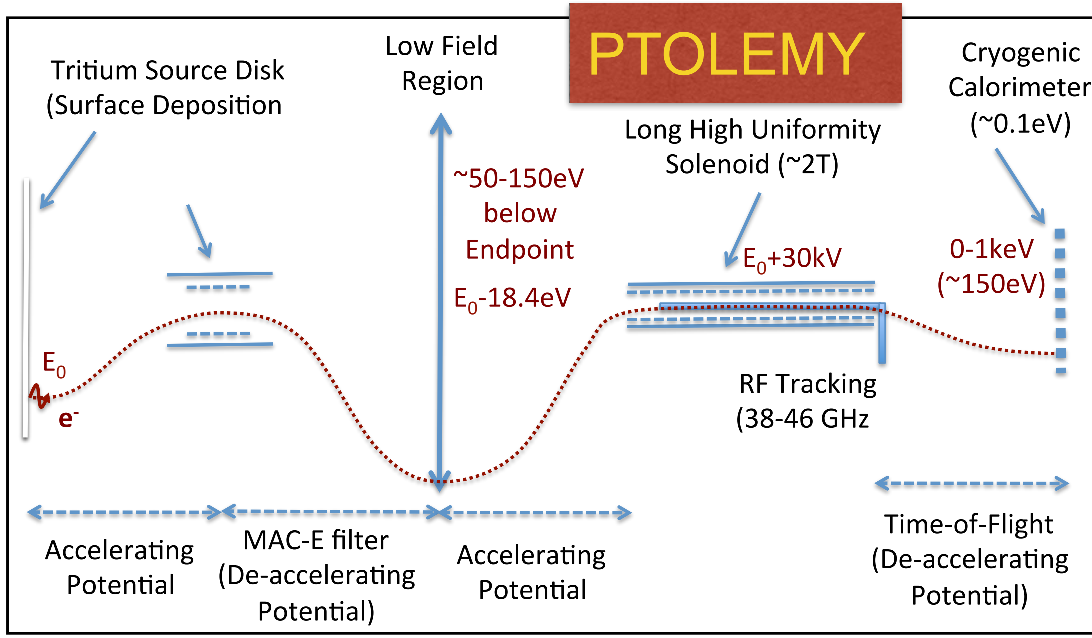
NuMECS





HOLMES

PTOLEMY



Summary

- CMB experiments will study the Cosmic Neutrino Background
  - Acoustic features measure neutrinos in the early univers
  - Lensing measures neutrino mass
  - Need CMB polarization measurements to capture all the information (also only way to measure Inflationary Gravitational Waves)
- Staged trajectory for the field of CMB polarization
  - Stage II: O(1000) detectors (SPTpol)
  - Stage III: O(10,000) detectors (SPT-3G)
  - Stage IV: O(100,000) detectors (CMB-S4)
- Technical challenge is scaling up detector arrays. TES is technology of choice
- Strong connections with both science & technology