CMB Experiment

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Autumn Block Course 2014

Three parts

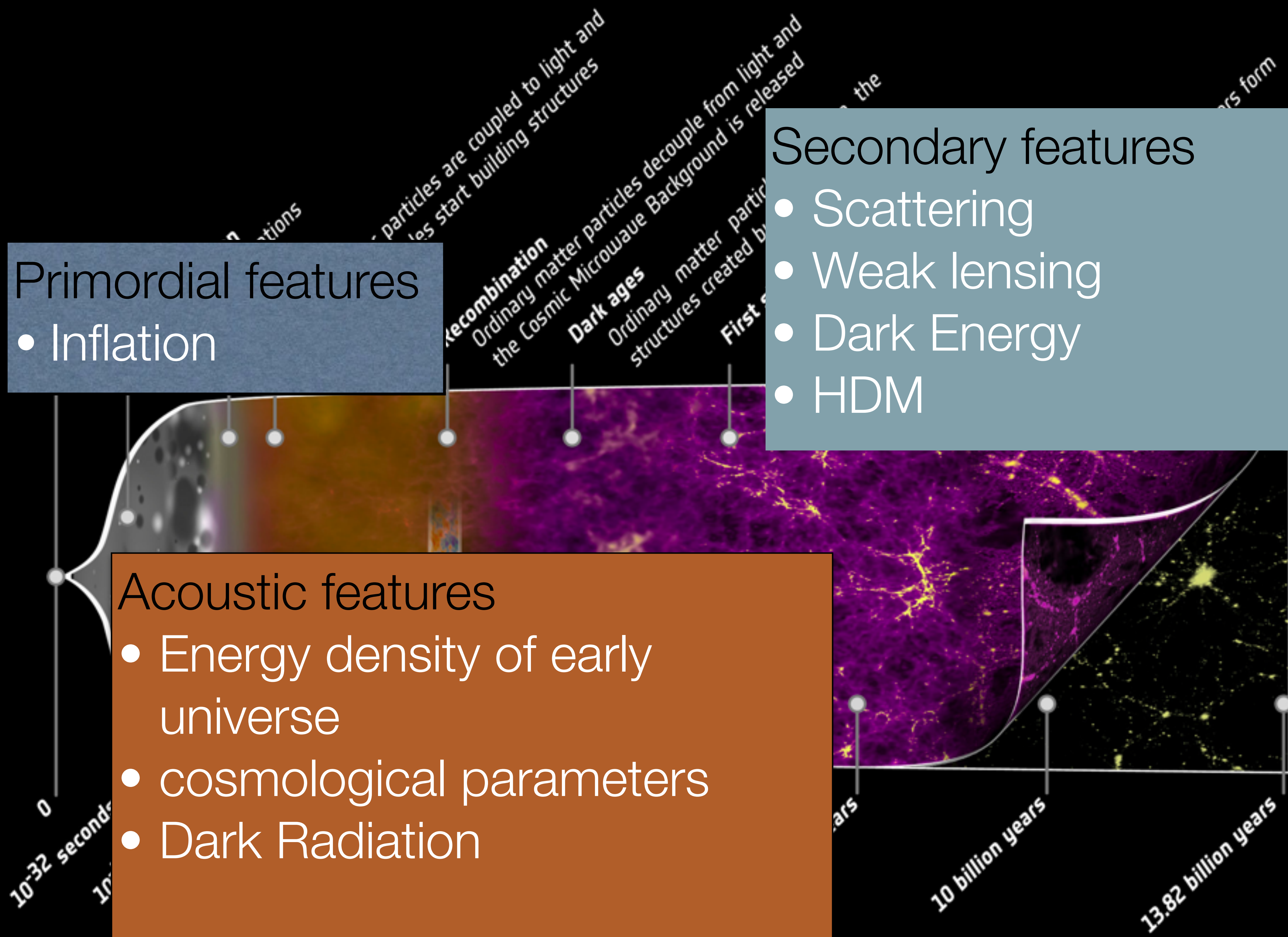
- Part 1: “History” & Motivation - CMB past
- Part 2: Technology & Detectors - CMB present
- Part 3: Recent & anticipated results - CMB future

CMB future

Some goals

- Cosmic acceleration
- Physics of inflation
- Neutrino cosmology

Roen Kelly/DISCOVER



Primordial features

- Inflation

Secondary features

- Scattering
- Weak lensing
- Dark Energy
- HDM

Acoustic features

- Energy density of early universe
- cosmological parameters
- Dark Radiation

Primordial features

- Inflation

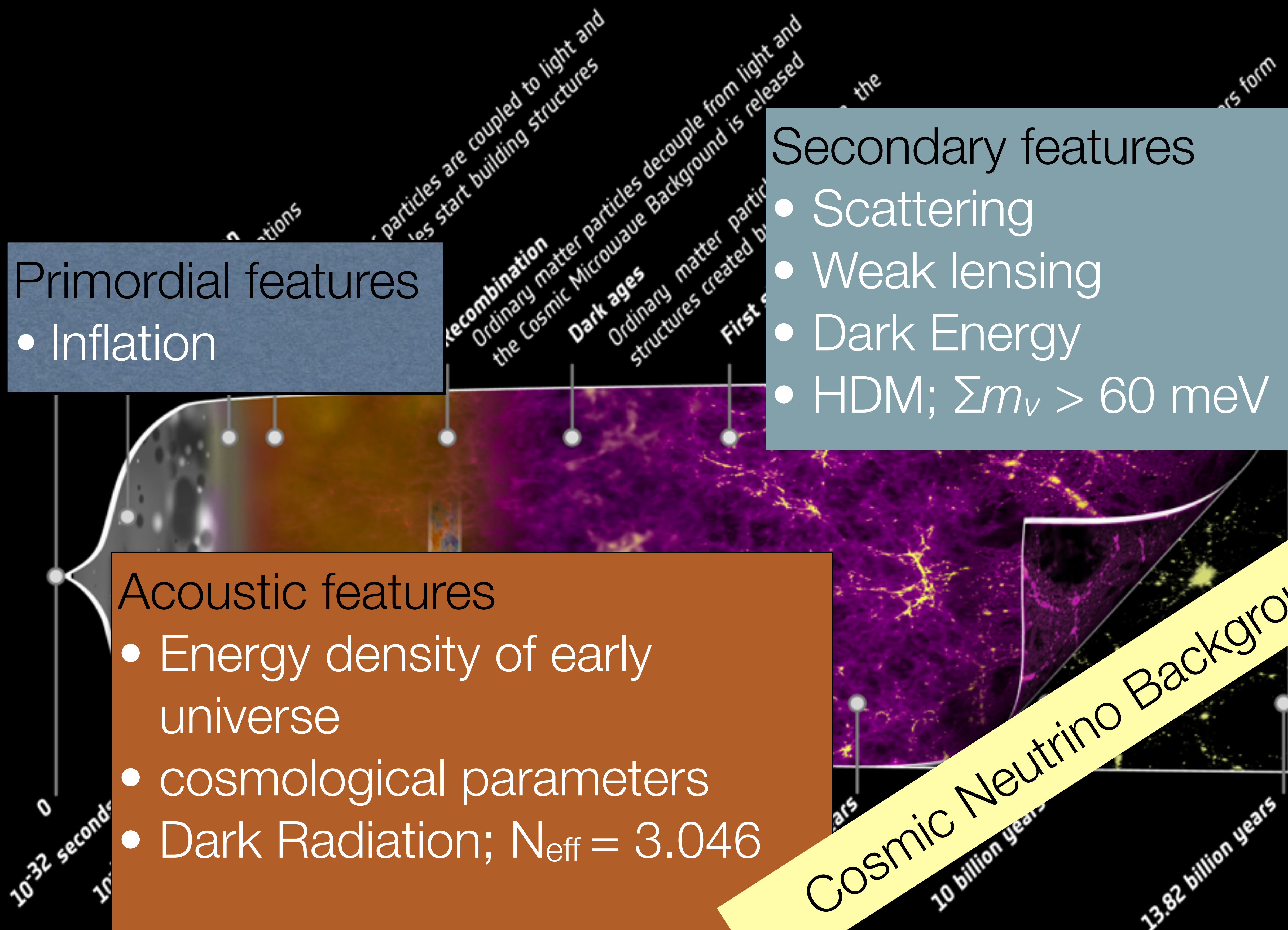
Secondary features

- Scattering
- Weak lensing
- Dark Energy
- HDM; $\Sigma m_\nu > 60$ meV

Acoustic features

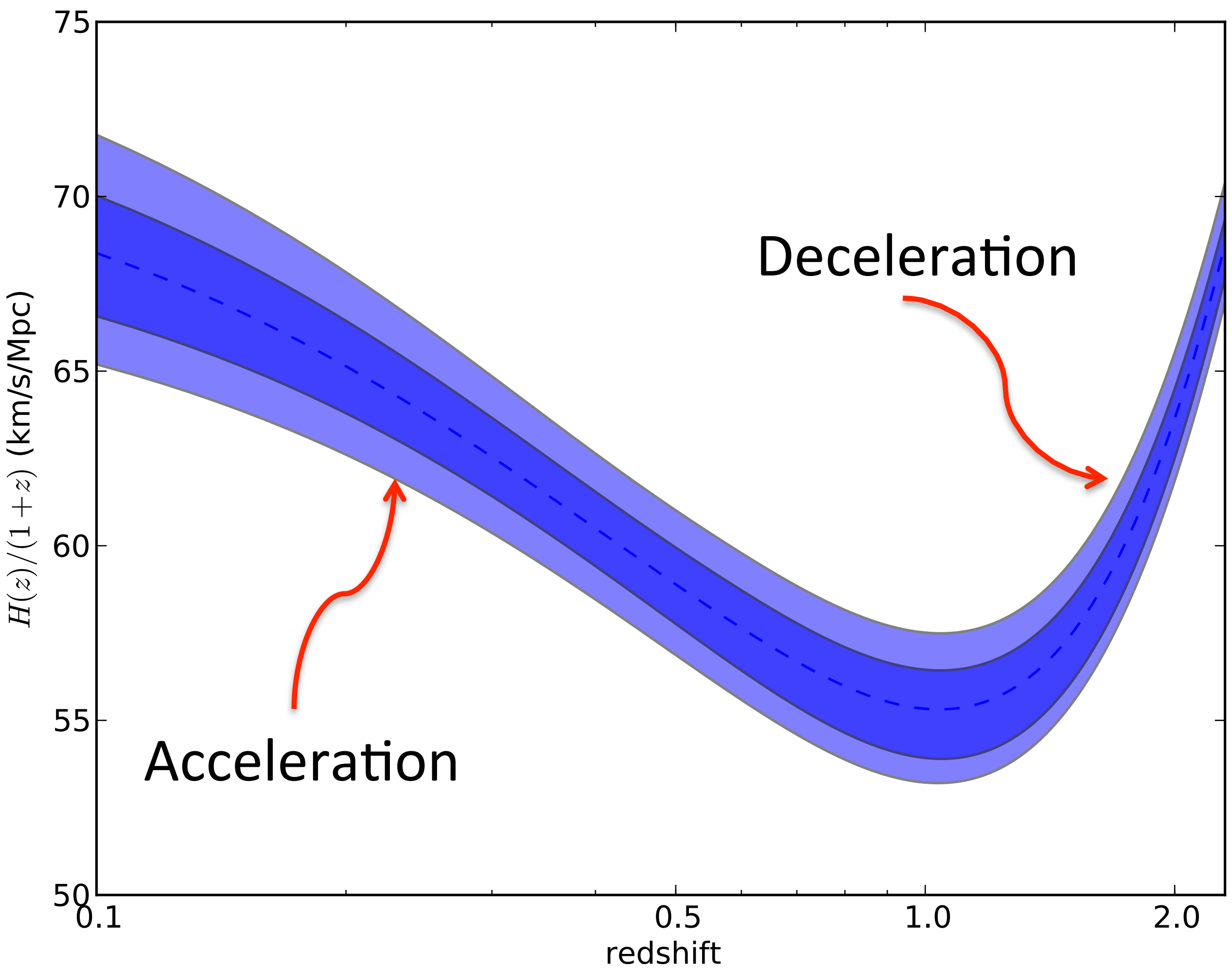
- Energy density of early universe
- cosmological parameters
- Dark Radiation; $N_{eff} = 3.046$

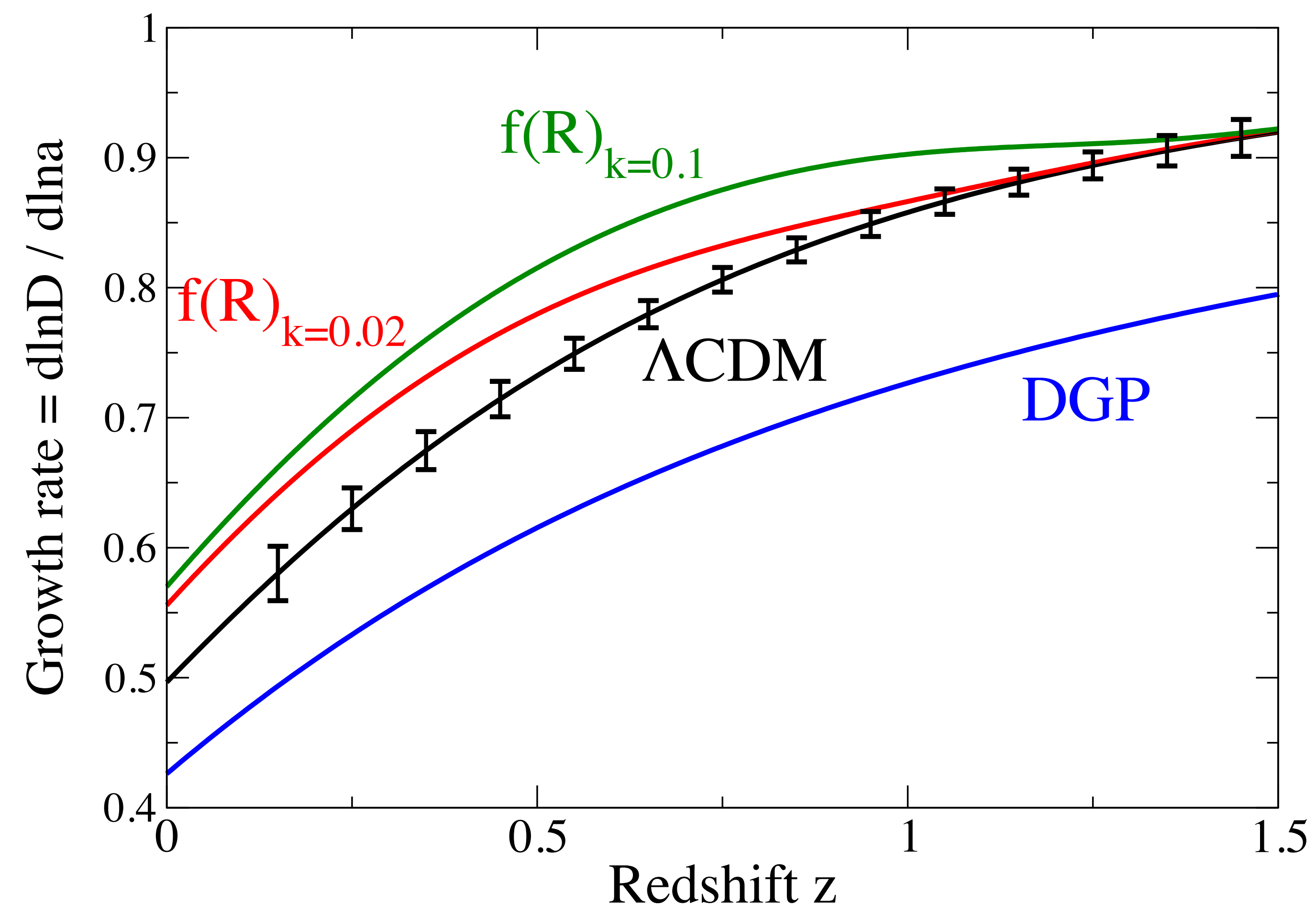
Cosmic Neutrino Background



Cosmic Acceleration: modified gravity/Dark Energy

- BAO and SNe: geometric measures of cosmic acceleration
- Discriminate between explanations by measuring something with different dependence on gravity (growth of structure)





arXiv:1309.5386

Cosmic Neutrino Background

- Initially, entire Universe was a hot dense state
- Weak interactions keep neutrinos in thermal equilibrium with rest of primordial plasma
- Neutrino decoupling
  - at $t \sim 1$ sec ($k_B T \sim 1$ MeV) Weak interaction rate too slow to keep up with expansion
  - ~ 113 cm^{-3} per neutrino specie
  - $T_{C\nu B} \sim 1.9$ K

CνB and the Early Universe

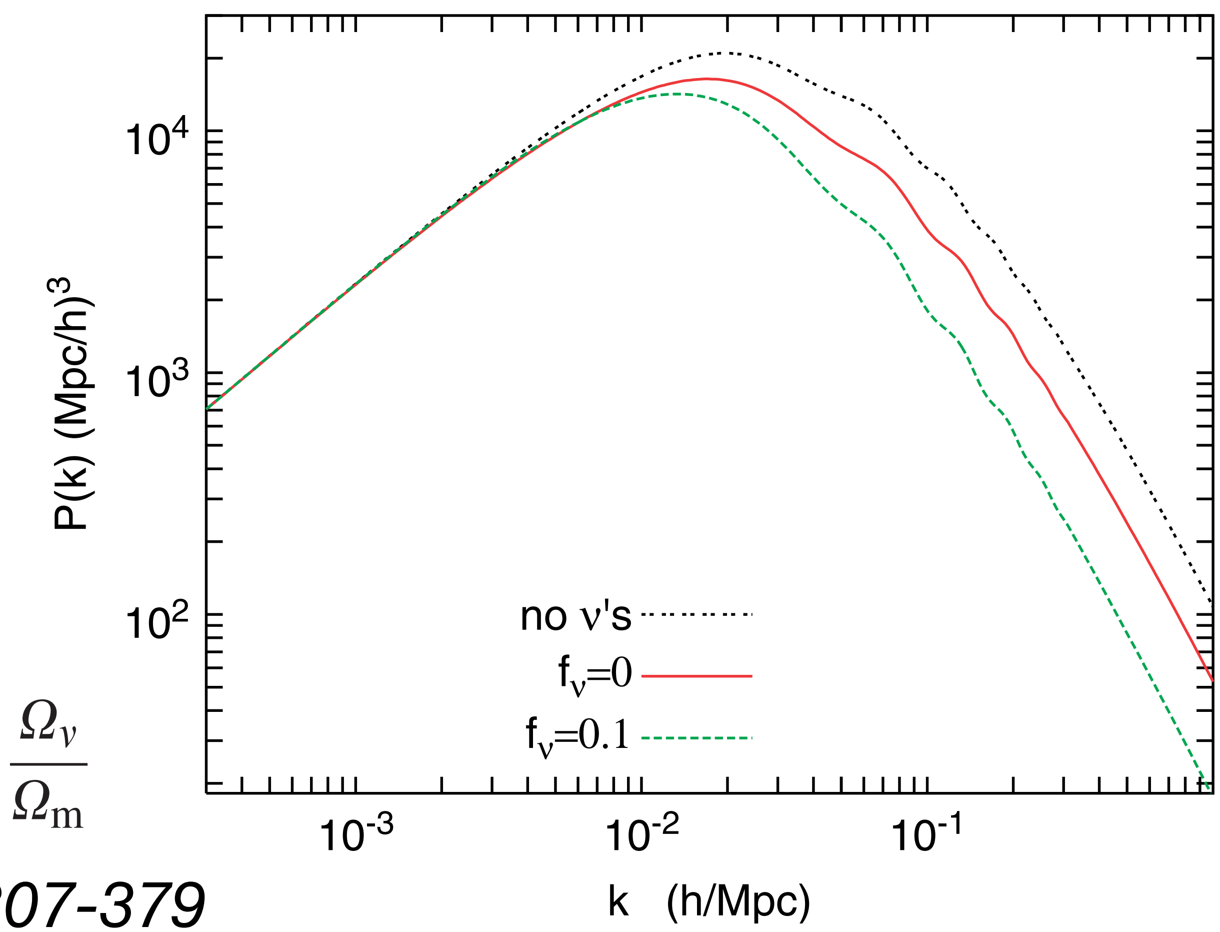
- m_ν < a few eV; relativistic energy in the early Universe

$$\rho_{\mathrm{R}} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right]\rho_\gamma$$

- Measurable via impact on the expansion rate
- BBN: $N_{\mathrm{eff}} = 3.71 \pm 0.46$ *Steigman, Adv. in HEP Vol 2012 (2012), 268321*
- CMB: Diffusion (Silk) damping

CvB and the Late Universe

- Oscillations: at least two of the neutrino species are massive
- non-relativistic in the late Universe, energy density set by n_ν and m_ν
- Free streaming smooths out small scale clumps
- Slows down the growth of structure



$$f_\nu \equiv \frac{\rho_\nu}{(\rho_{\rm cdm} + \rho_{\rm b} + \rho_\nu)} = \frac{\Omega_\nu}{\Omega_{\rm m}}$$

Lesgourgues & Pastor, Phys.Rept. 429 (2006) 307-379

Inflation

- Original motivation? Dilutes monopoles and other exotica
- *Predicts:* Flat, Homogeneous, isotropic universe
- *Predicts:* Super-horizon adiabatic fluctuations
- *Predicts:* Perturbations with nearly scale invariant ("almost white") spectrum

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

- *Predicts:* Tensor (gravity) perturbations

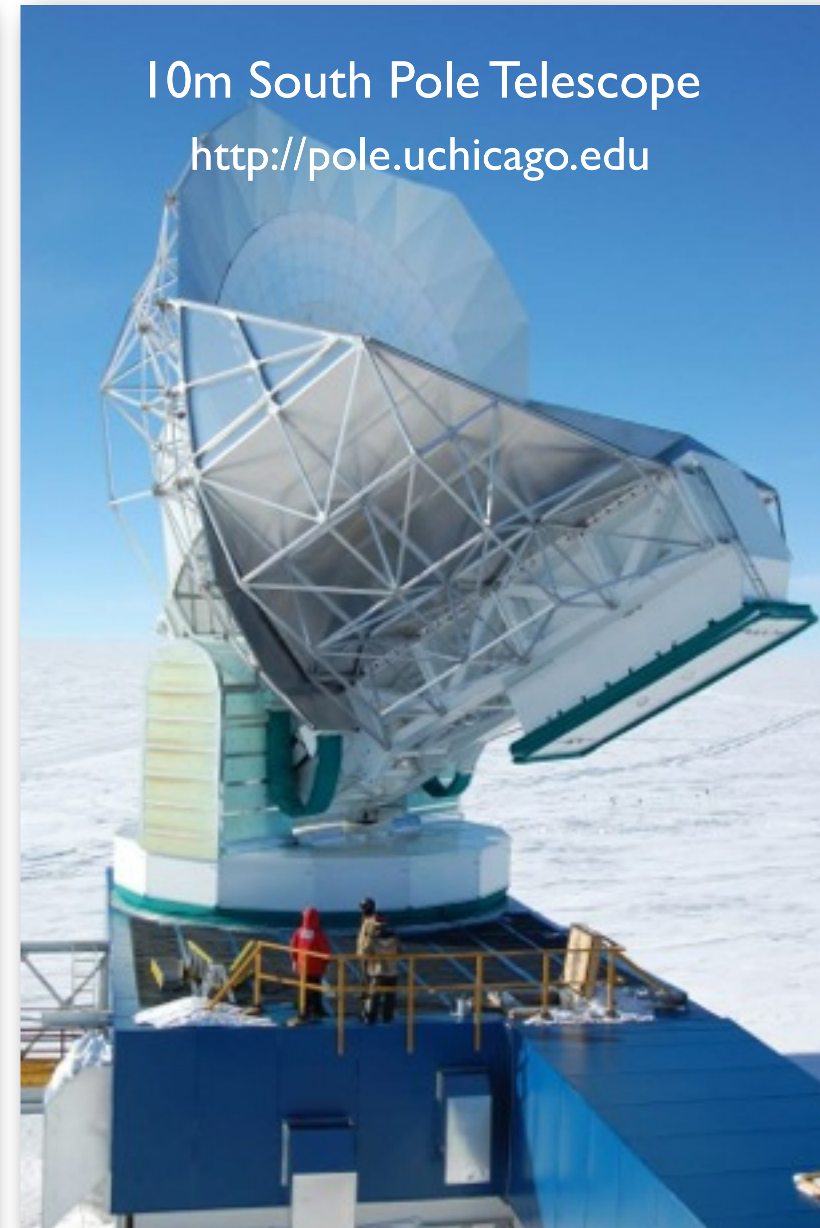
$$r \equiv \frac{\Delta_h^2}{\Delta_R^2}$$

$$V^{1/4} = 1.06 \times 10^{16}\ \mathrm{GeV}\ \left(\frac{r}{.01}\right)^{1/4}$$

$r>0.01$; $\Delta\varphi \gtrsim m_{pl}$

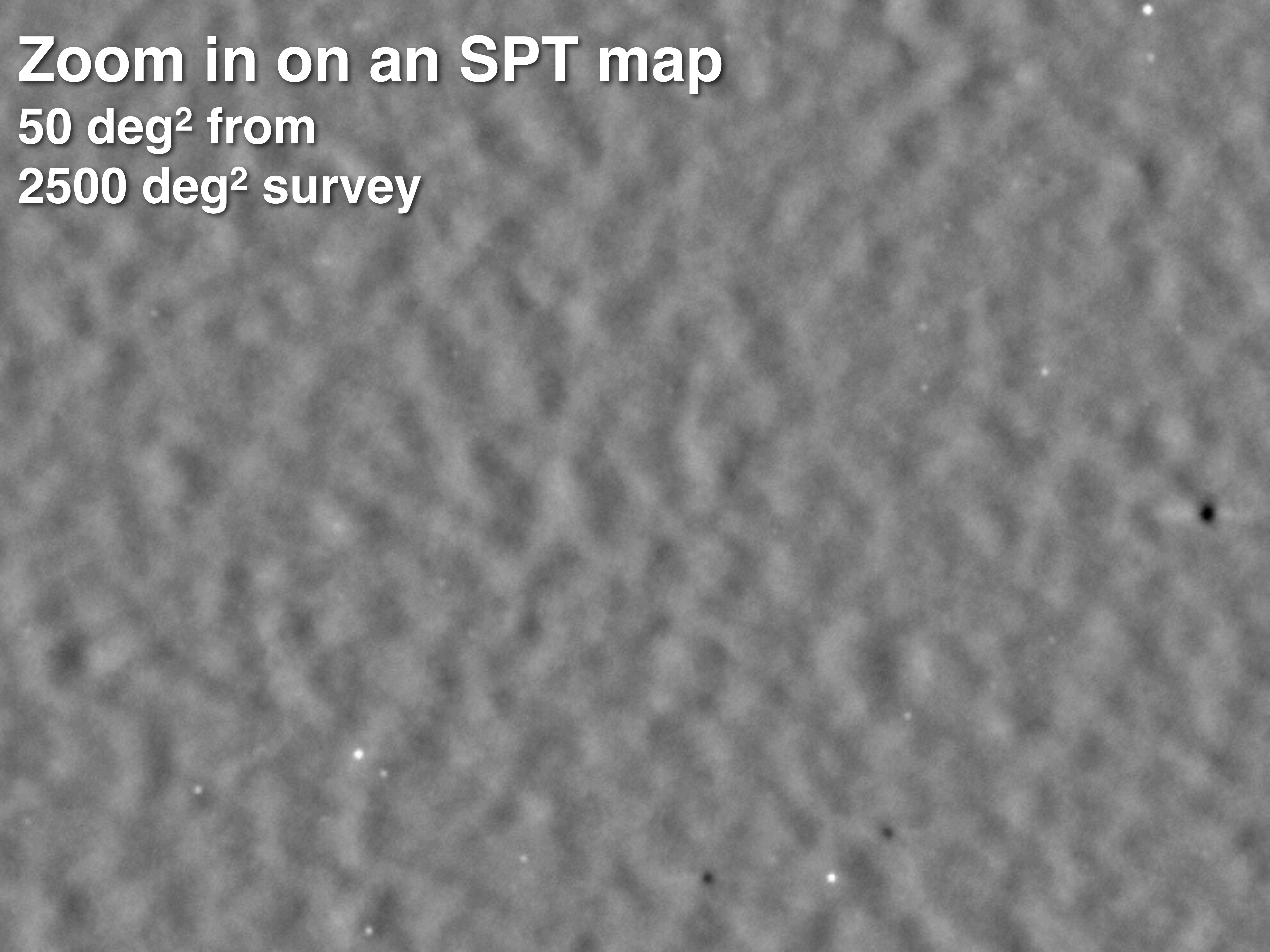
$r<0.01$; $\Delta\varphi \lesssim m_{pl}$

Dedicated Telescopes for fine angular scale CMB measurements

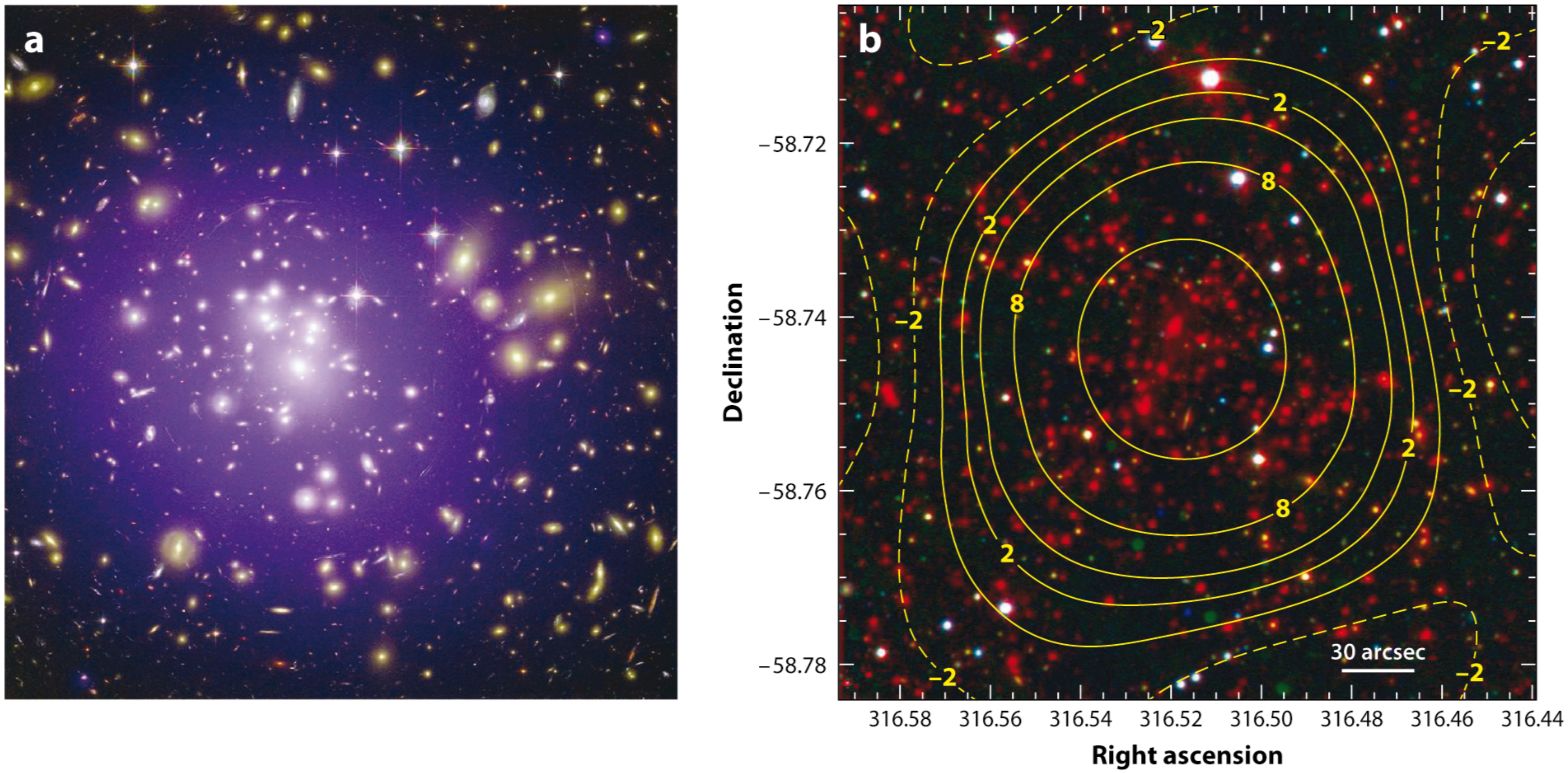


- Exceptional high and dry sites for dedicated CMB observations.
- Exploiting ongoing revolution in low-noise bolometer cameras
- Also, BICEP3, not exist yet, but will be at Pole this year.

Clusters and the Sunyaev-Zeldovich effect

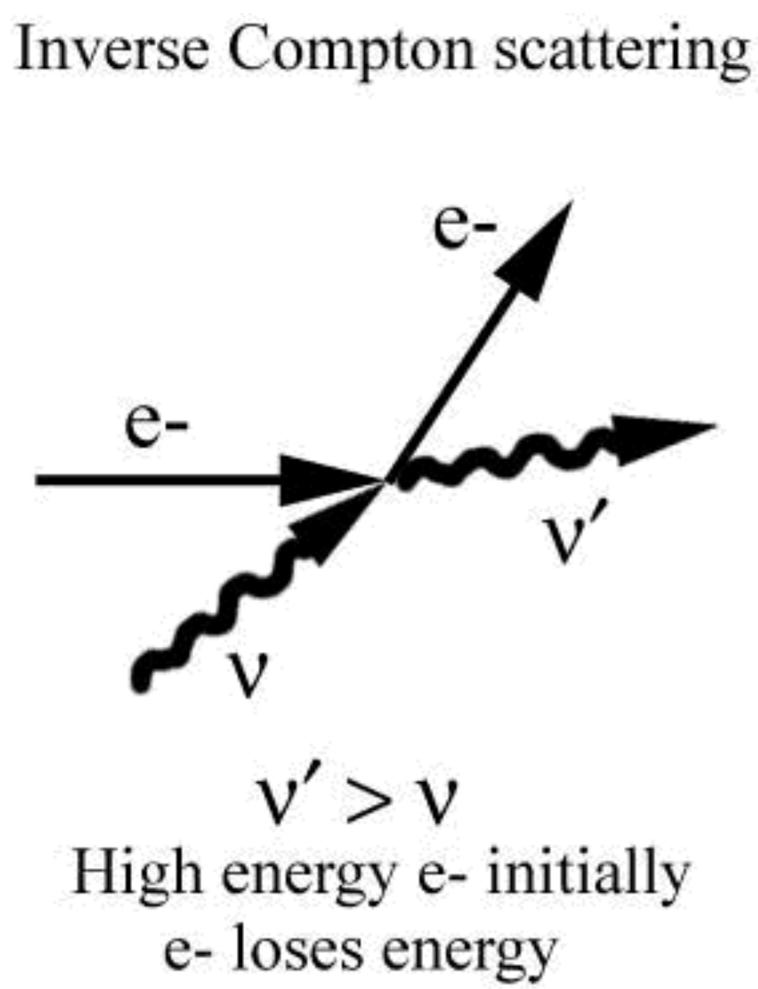

Zoom in on an SPT map
50 deg² from
2500 deg² survey

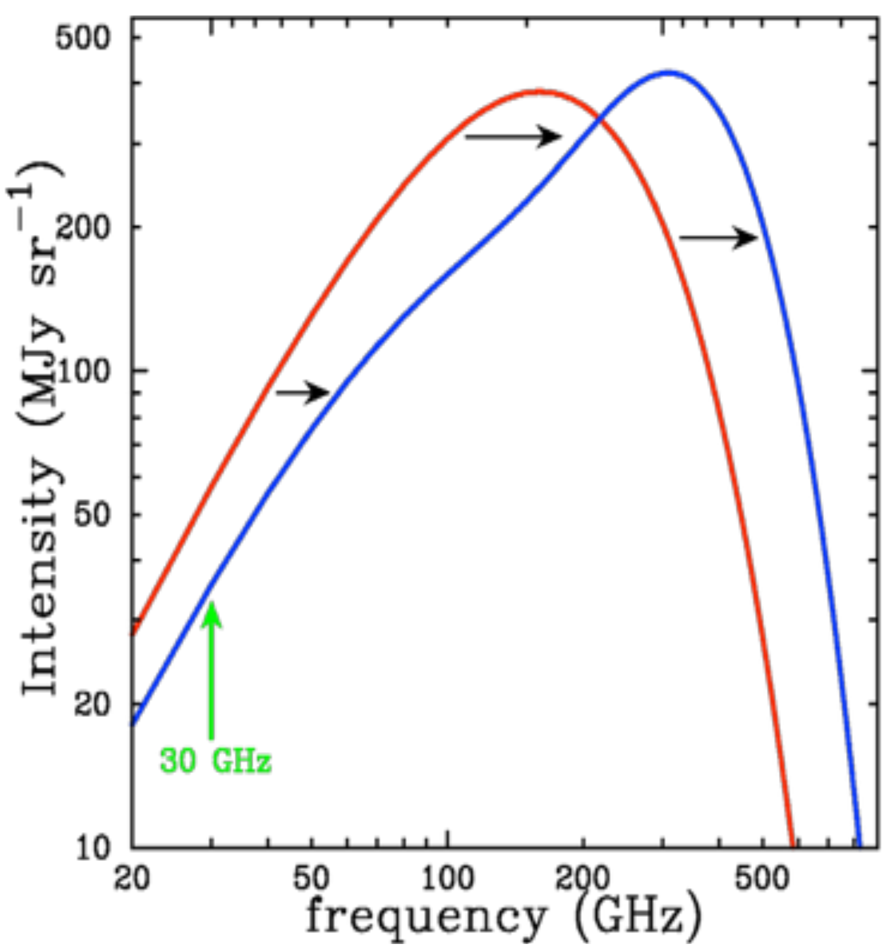
Probing structure growth: Galaxy clusters



Kravtsov AV, Borgani S. 2012.
Annu. Rev. Astron. Astrophys. 50:353–409

Sunyaev-Zeldovich effect



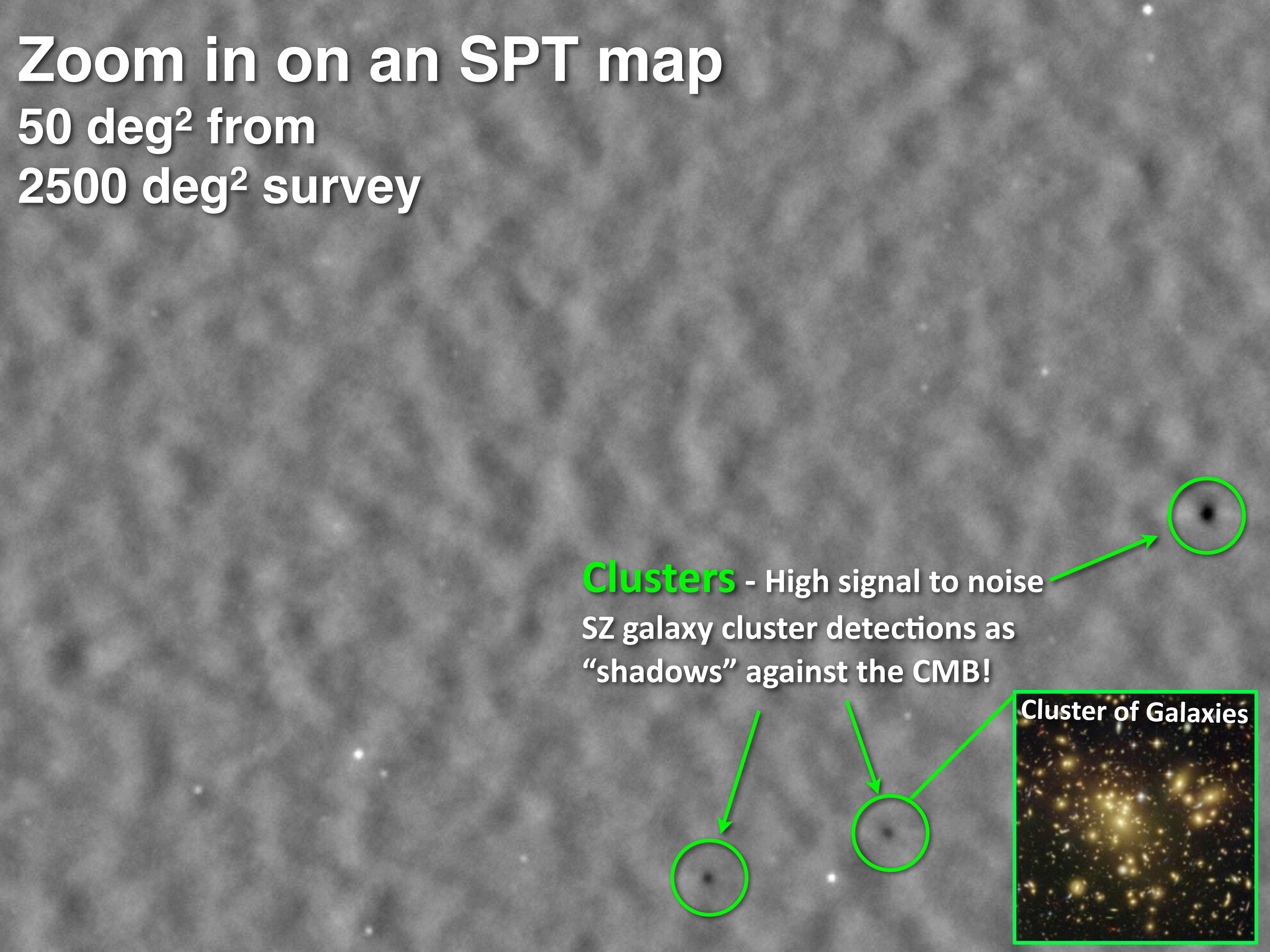


Decrement in CMB for ν <220 GHz

Depends on gas density (cluster mass)
Does not depend on redshift

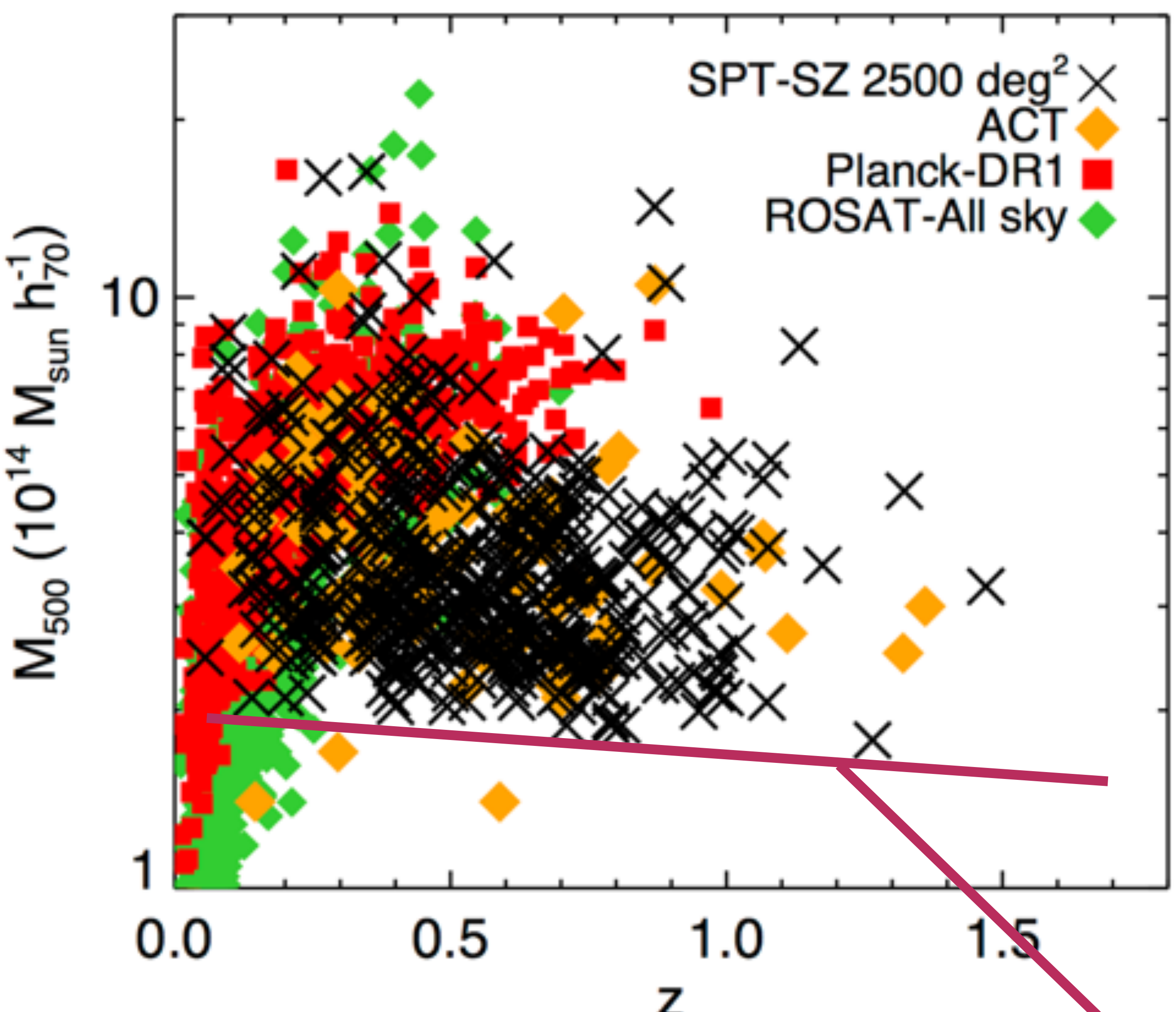
Zoom in on an SPT map

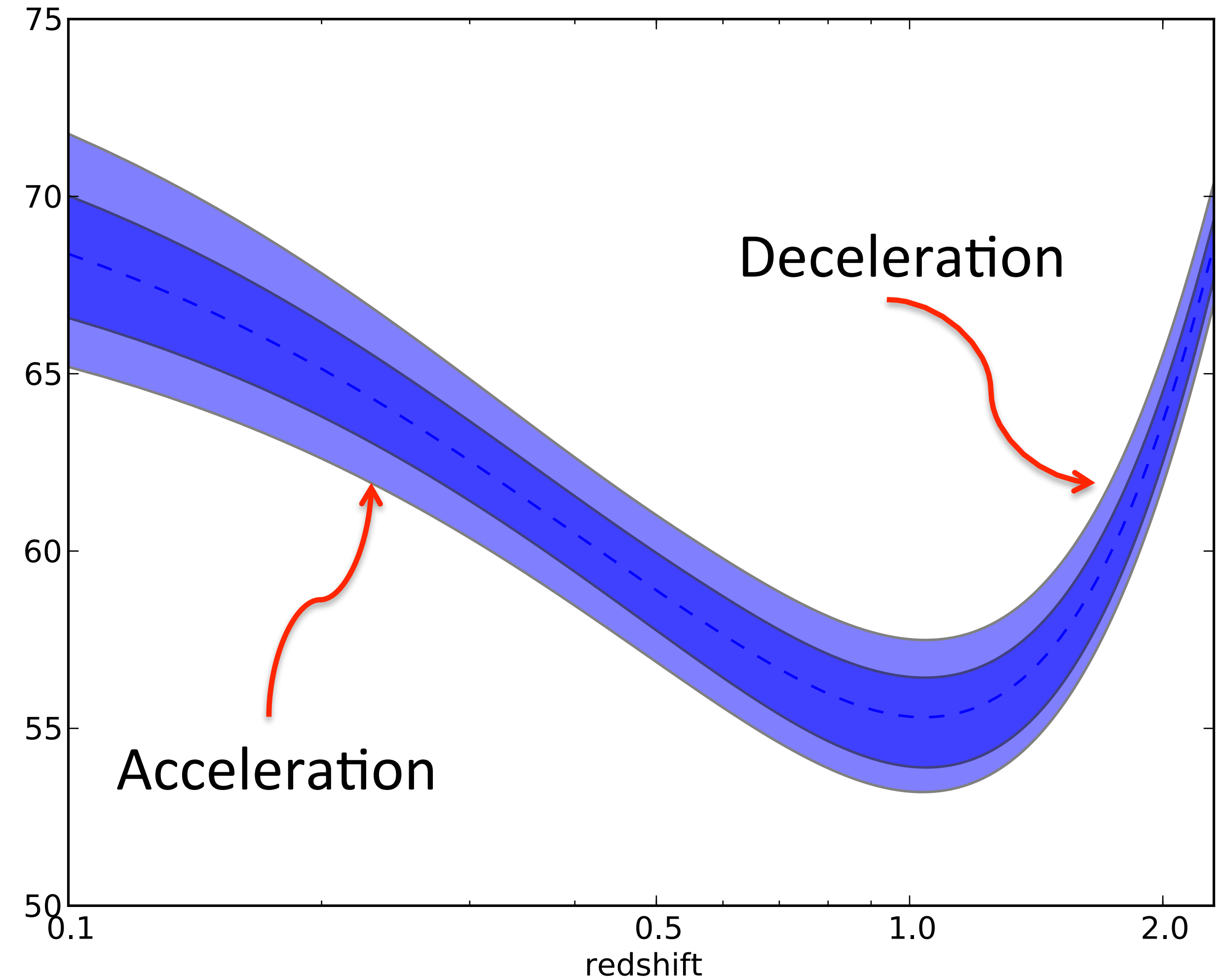
50 deg² from 2500 deg² survey



Growth of structure

SZ cluster survey

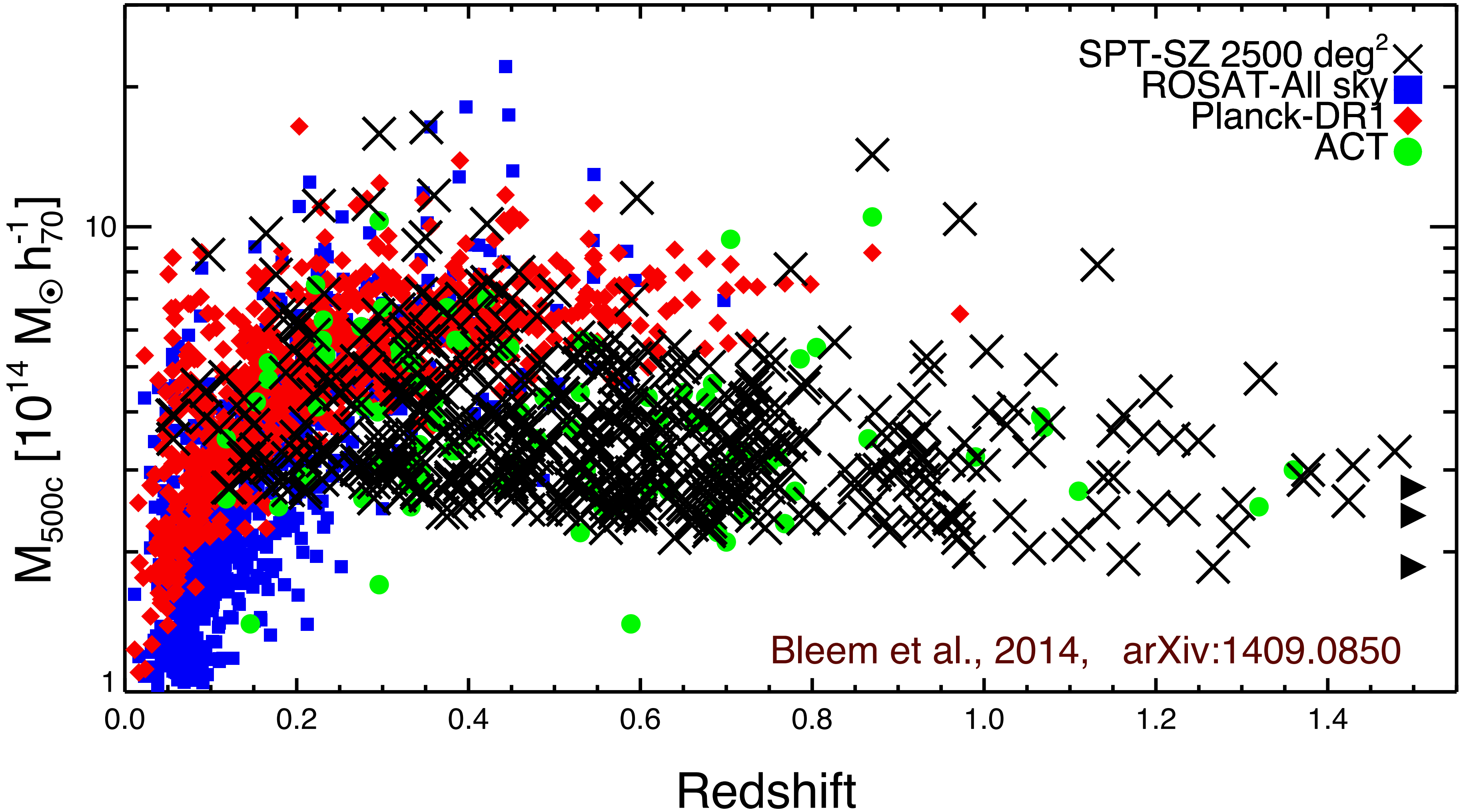




Depends on gas density (cluster mass)
Does not depend on redshift

Reichardt et al., ApJ 763 (2013) 127
Benson et al., ApJ 763 (2013) 147

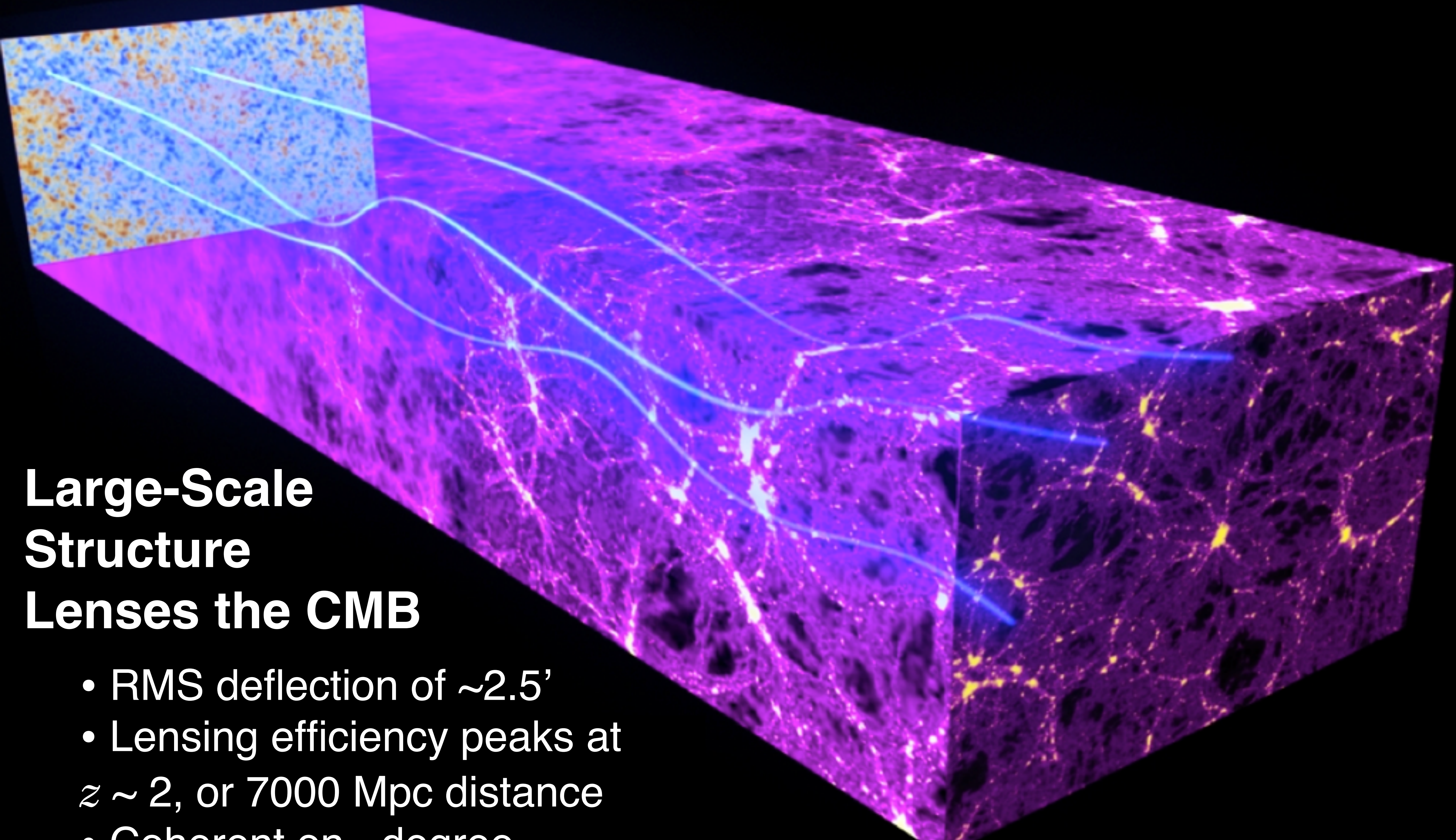
SPT-SZ cluster cosmology



	Area (deg	**Depth** (uK-arcmin)	**N**
Planck	All-sky	45	861
SPT	2500	17	522
ACT	950	23-40	91

- SPT-SZ cluster catalog reveals the growth of structure.
- SPT has more than doubled the number of $z > 0.5$ massive clusters
- Ongoing mass calibration for dark energy and neutrino mass constraints from growth of structure.

Lensing

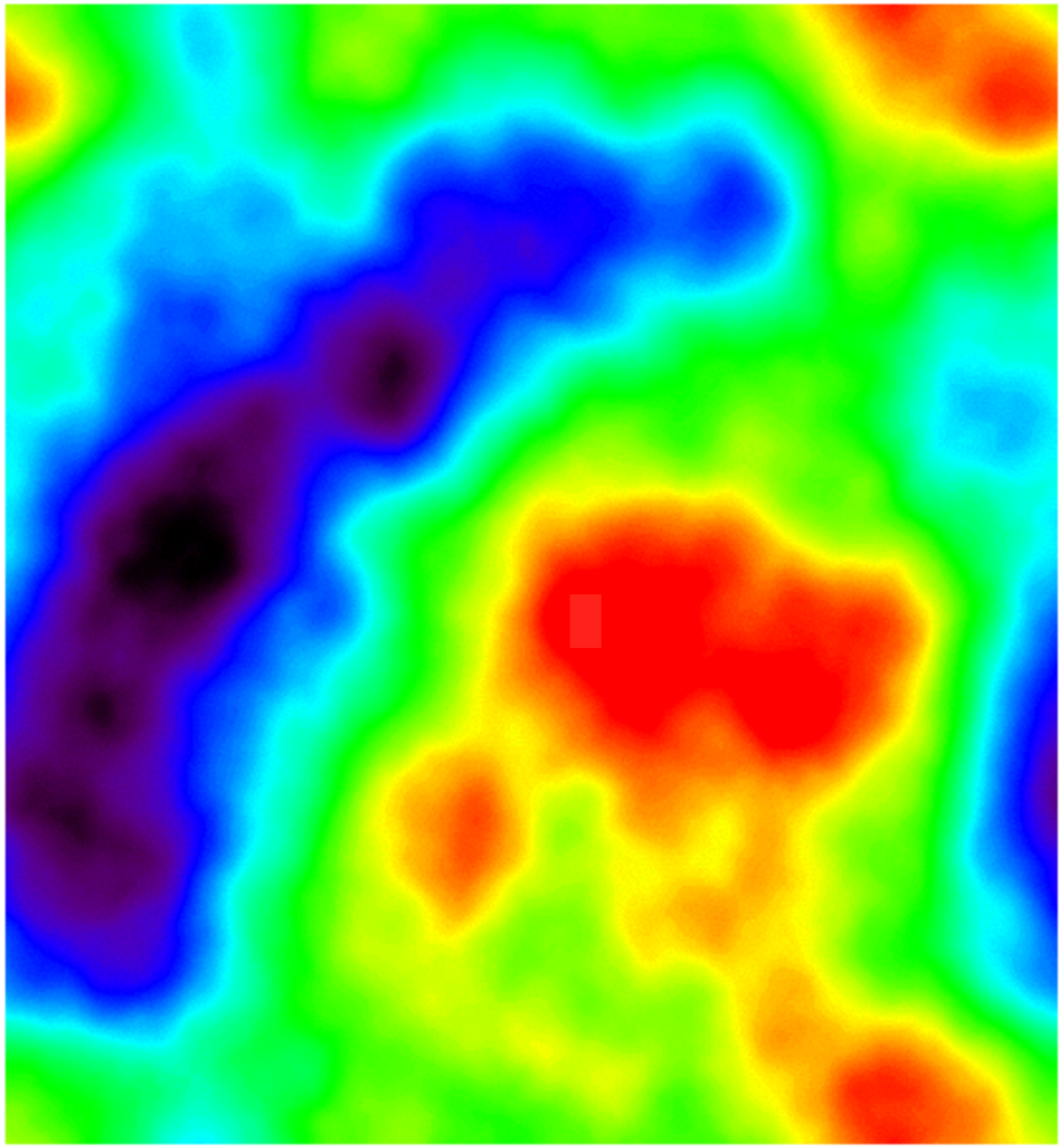


Large-Scale Structure Lenses the CMB

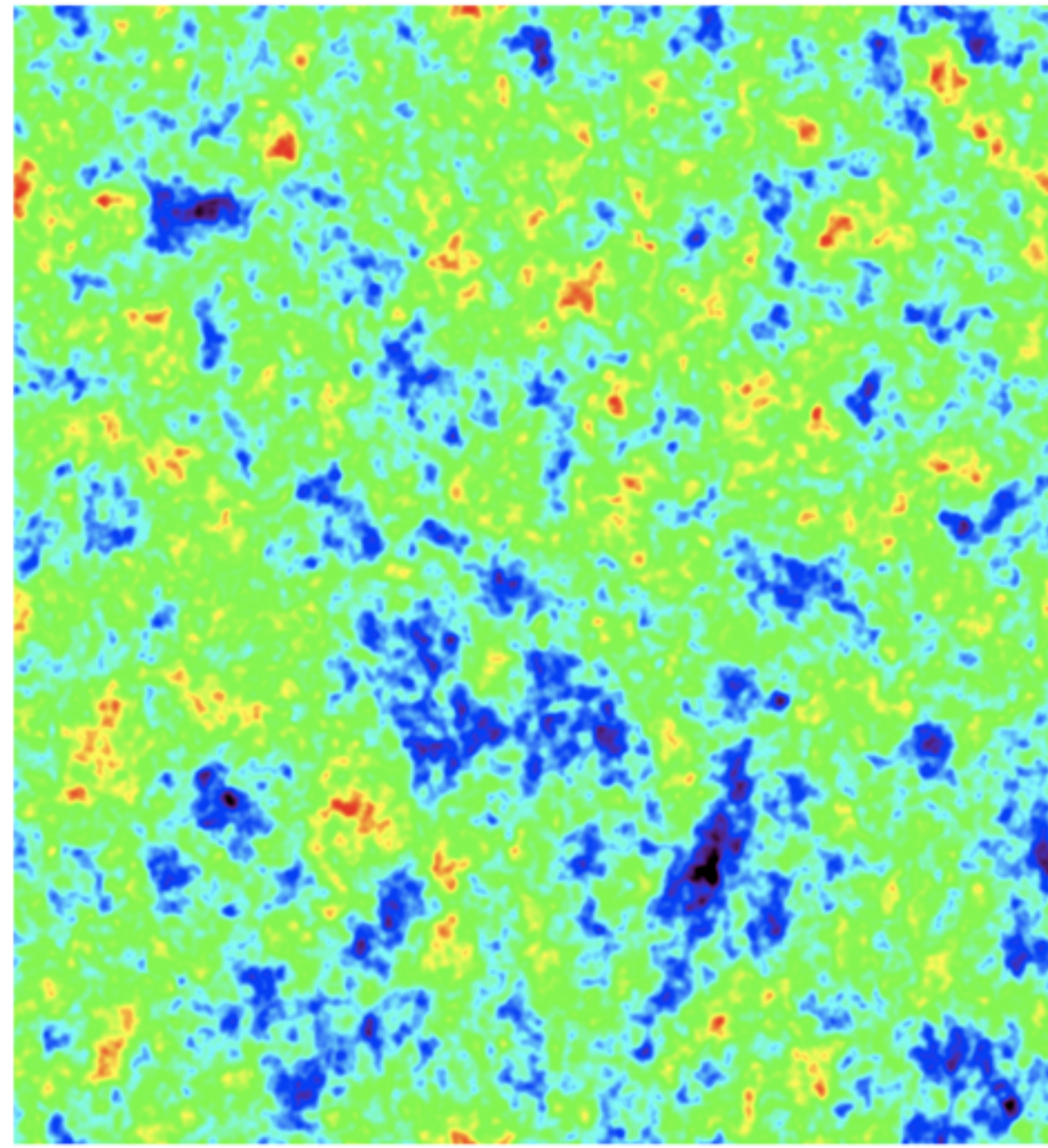
- RMS deflection of ~2.5’
- Lensing efficiency peaks at $z \sim 2$, or 7000 Mpc distance
- Coherent on ~degree (~300 Mpc) scales

Lensing of the CMB

17°x17°



lensing potential

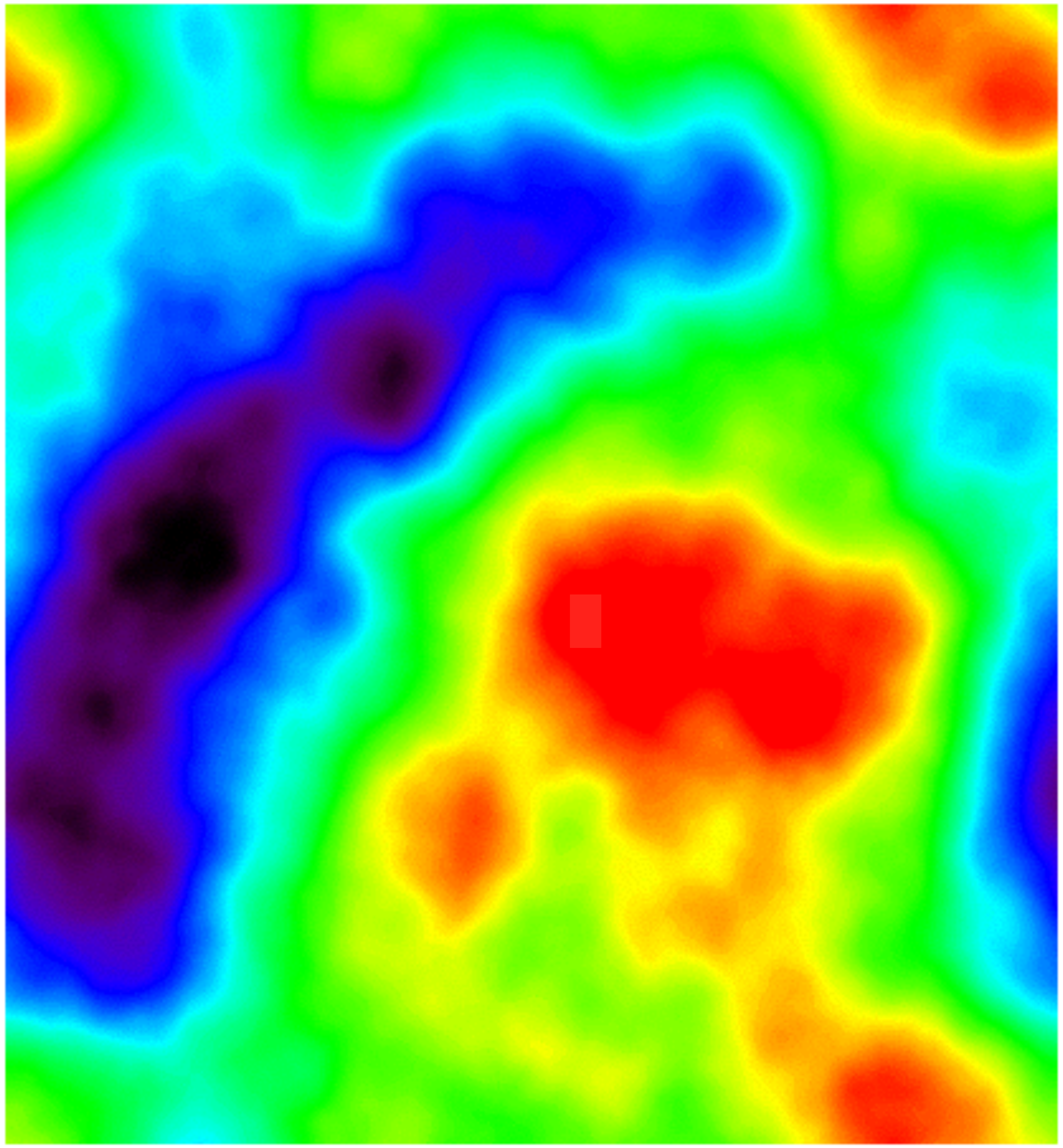


unlensed cmb

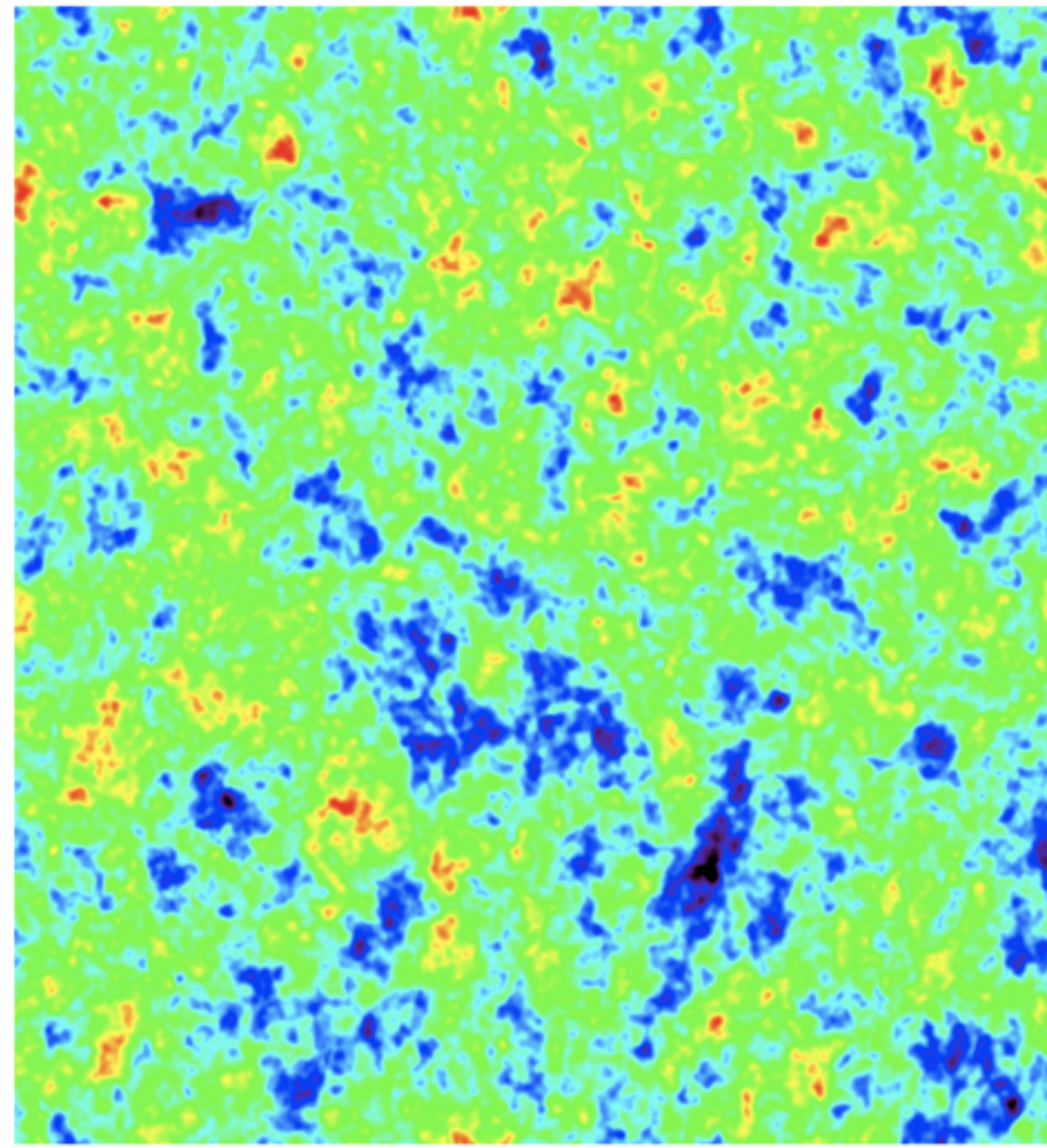
from Alex van Engelen

Lensing of the CMB

17°x17°



lensing potential

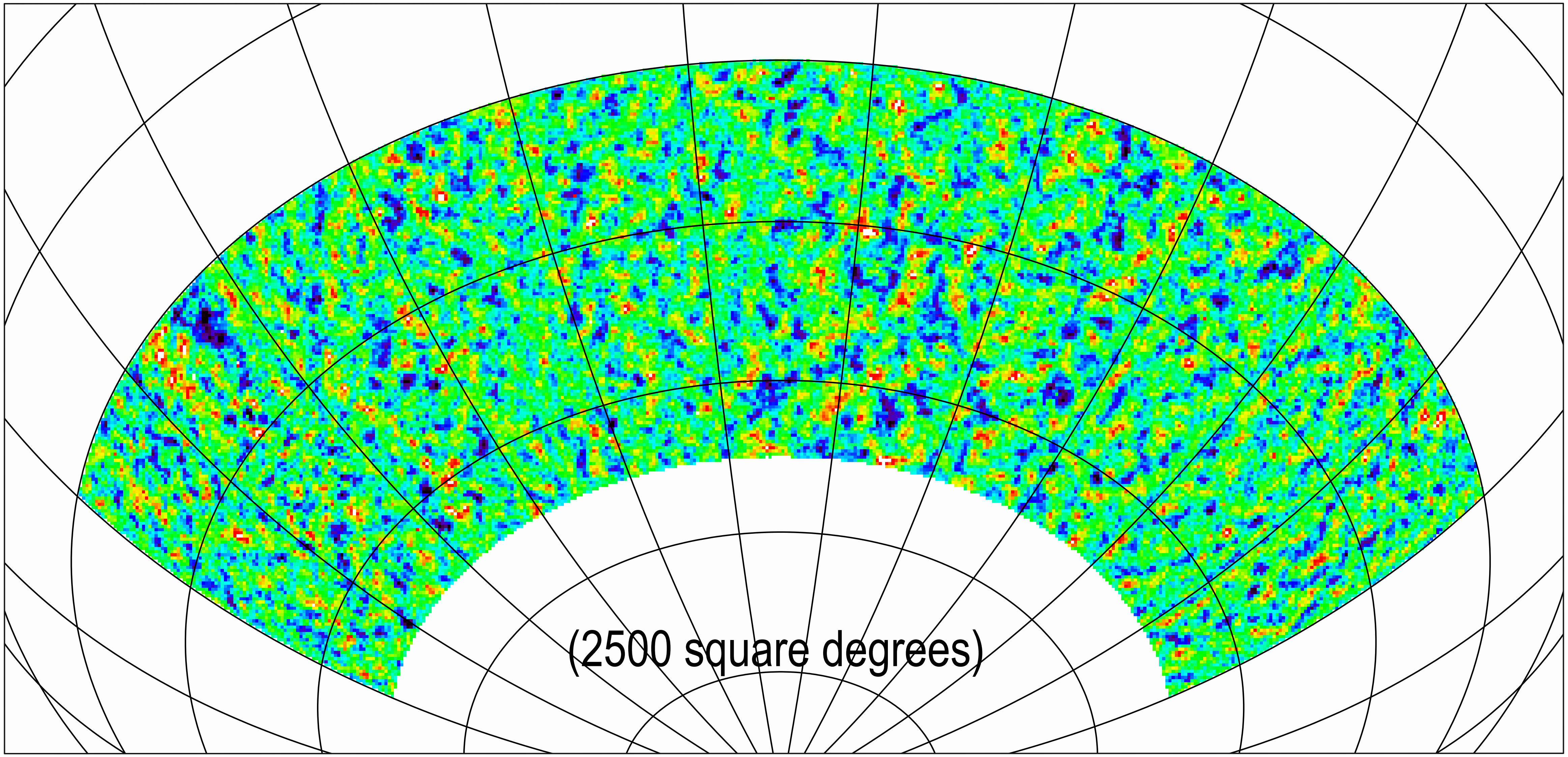


lensed cmb

from Alex van Engelen

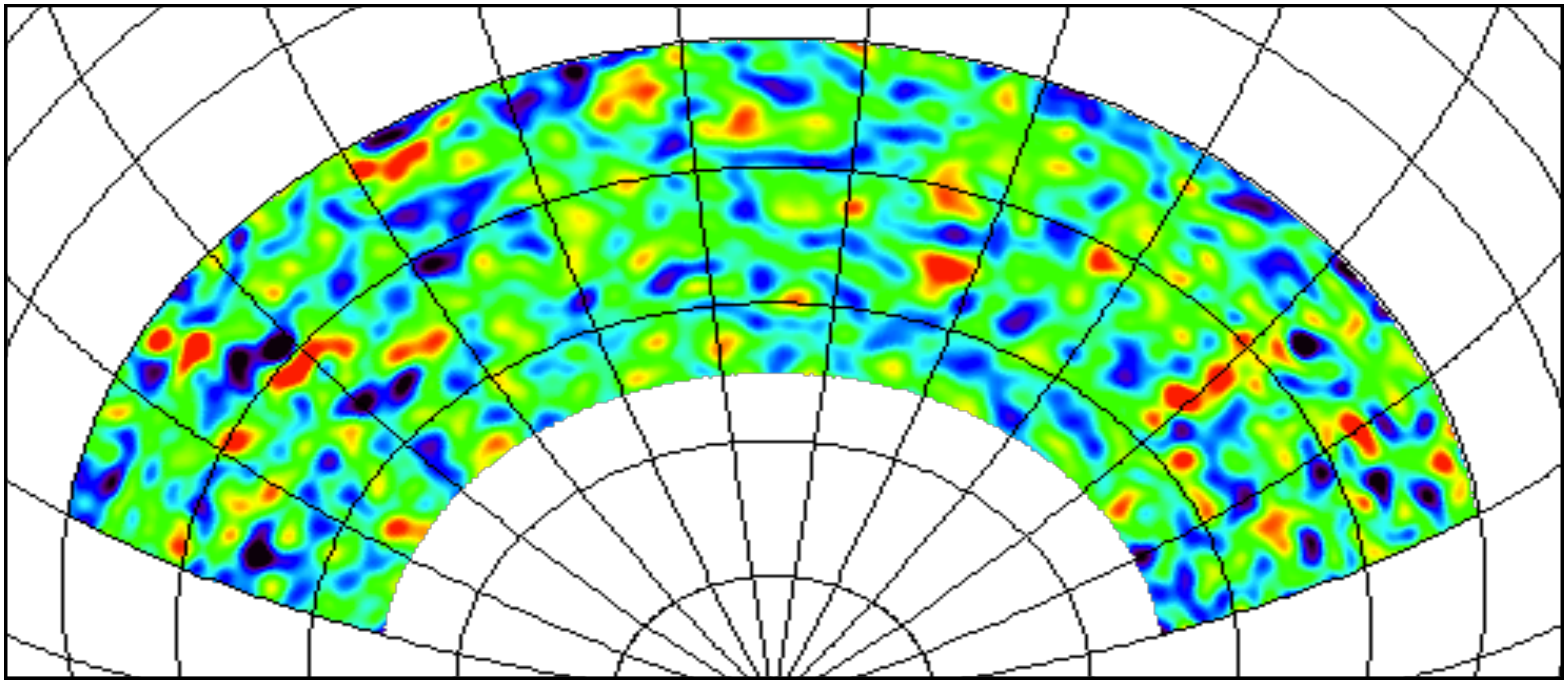
high resolution and sensitivity map of the CMB from SPT

covering 1/16 of the sky

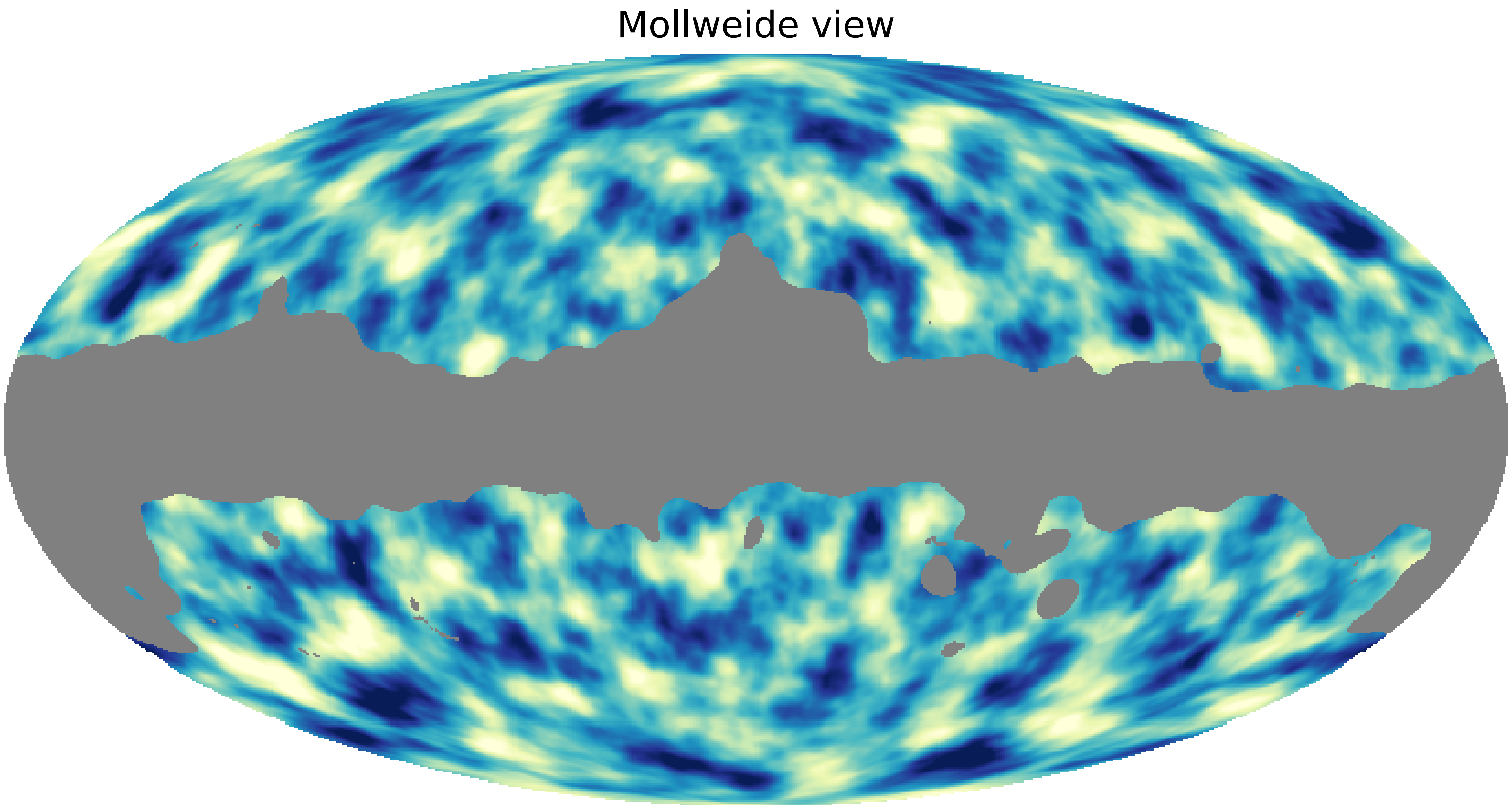


CMB Lensing Map

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

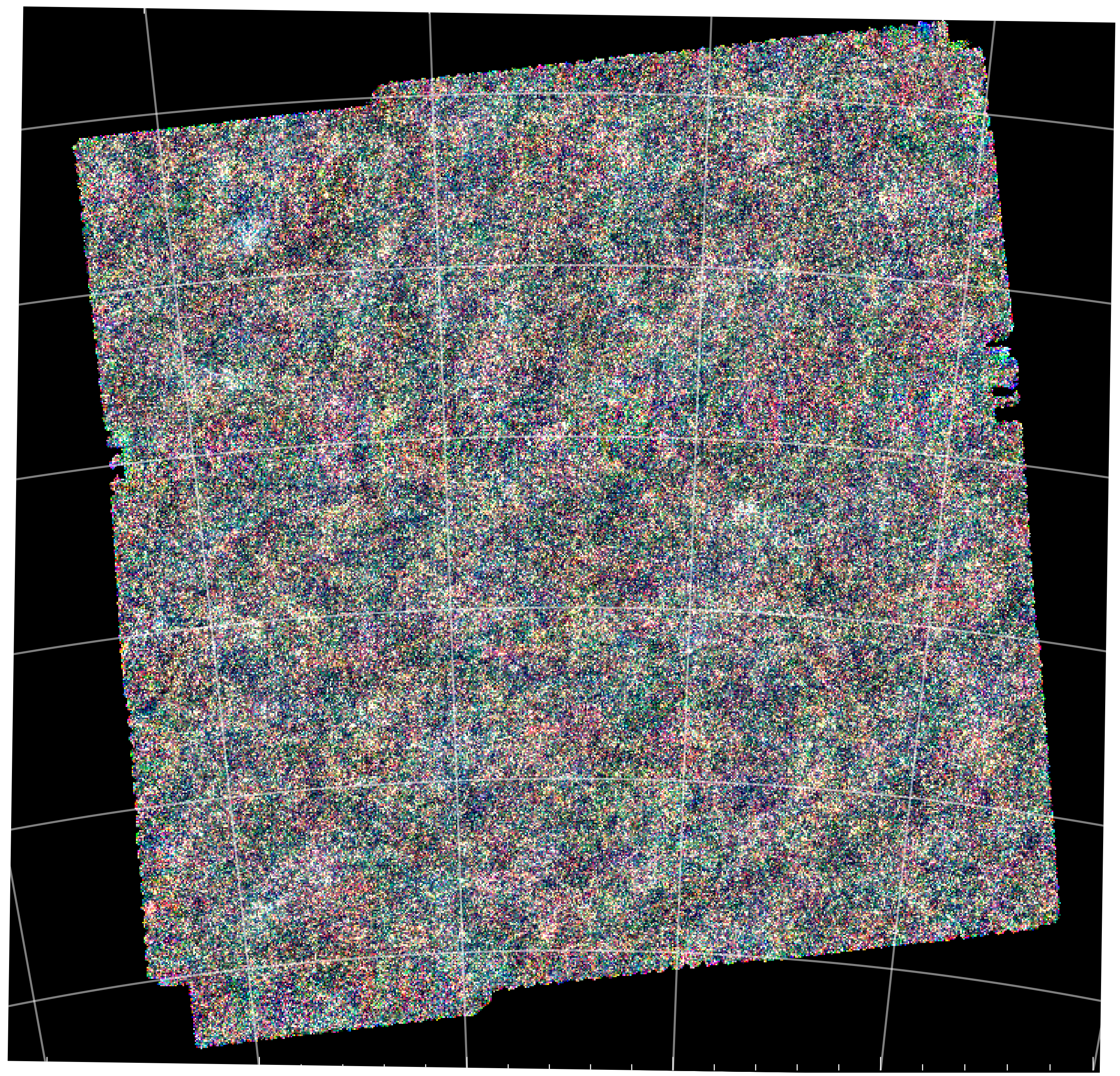


"Mass Map" from Planck, ~70% of sky

Complementary to SPT's map: noisier but all-sky.

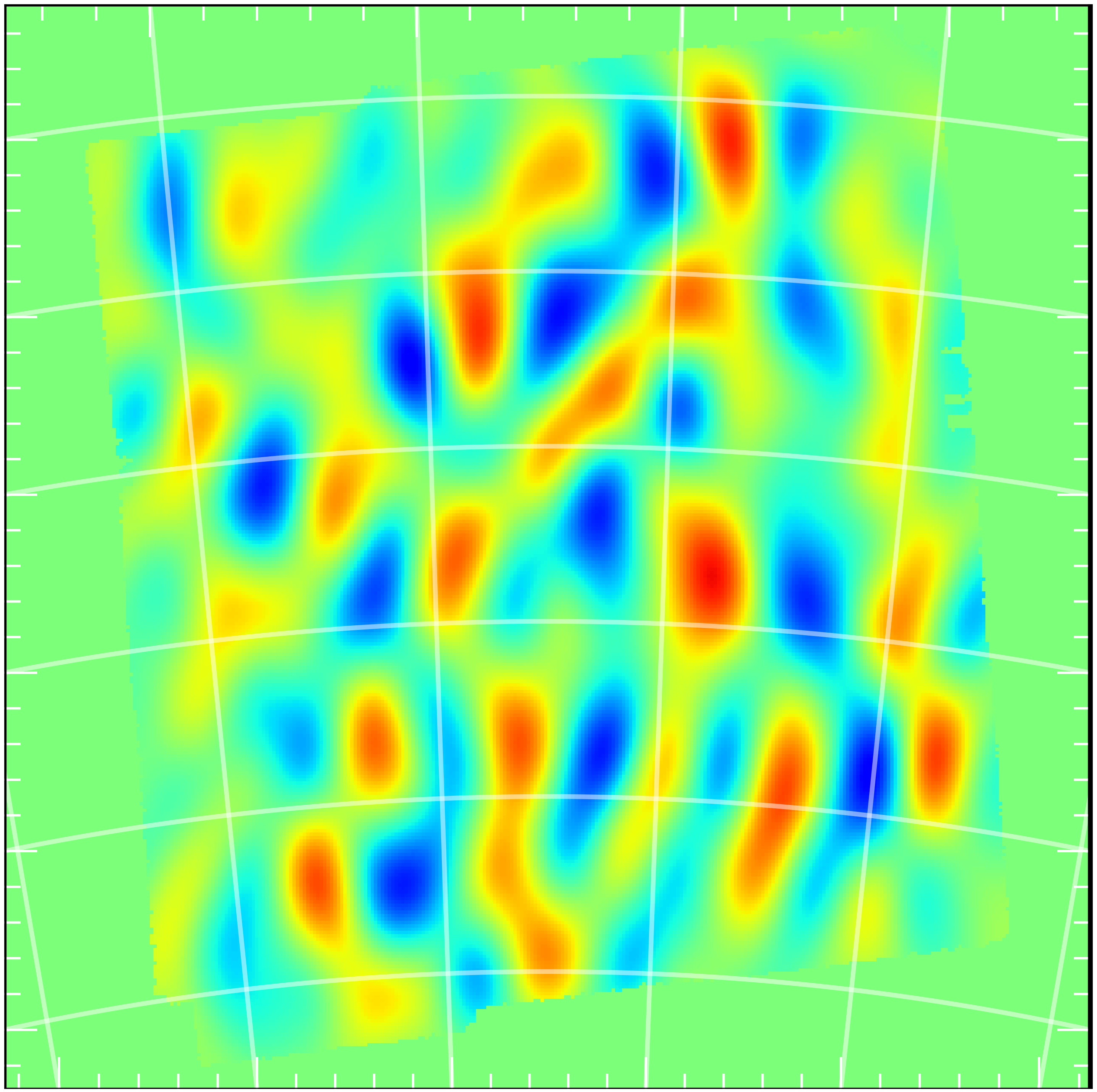
It’s really the Dark Matter:

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



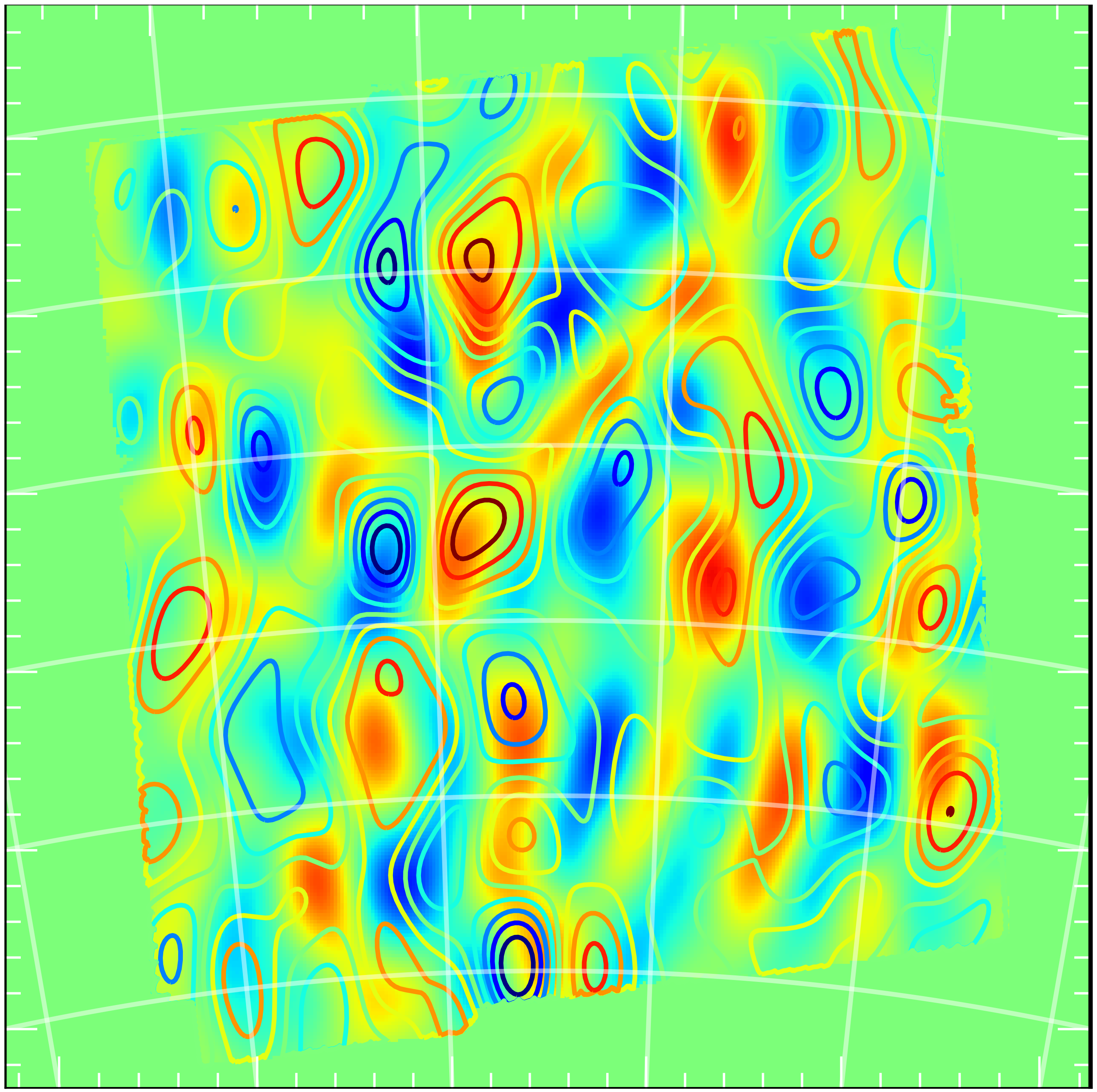
RGB = 500,350,250 um

It’s really the Dark Matter:



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

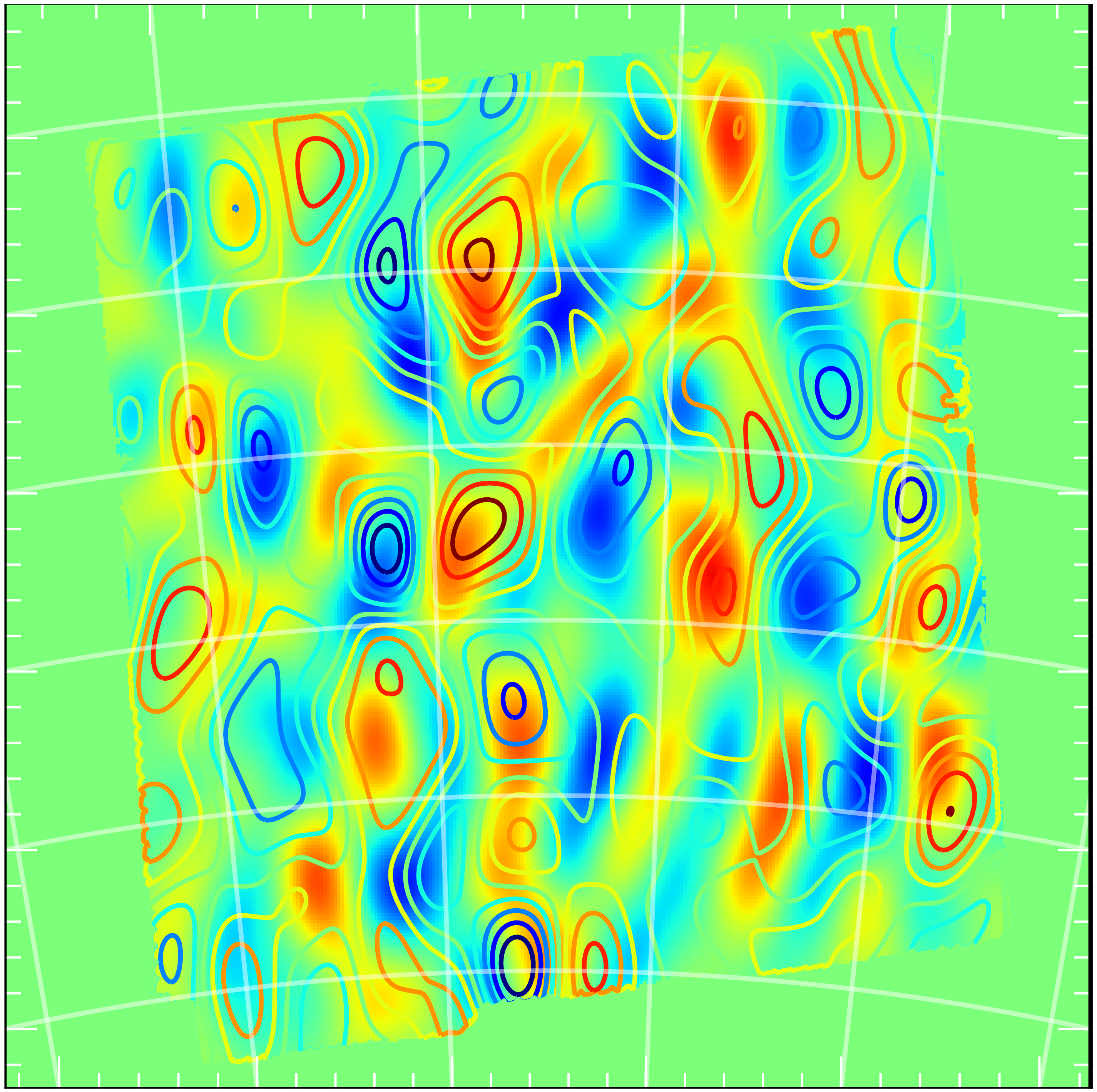
It’s really the Dark Matter:



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

Add mass contours from SPT CMB lensing.

It’s really the Dark Matter:



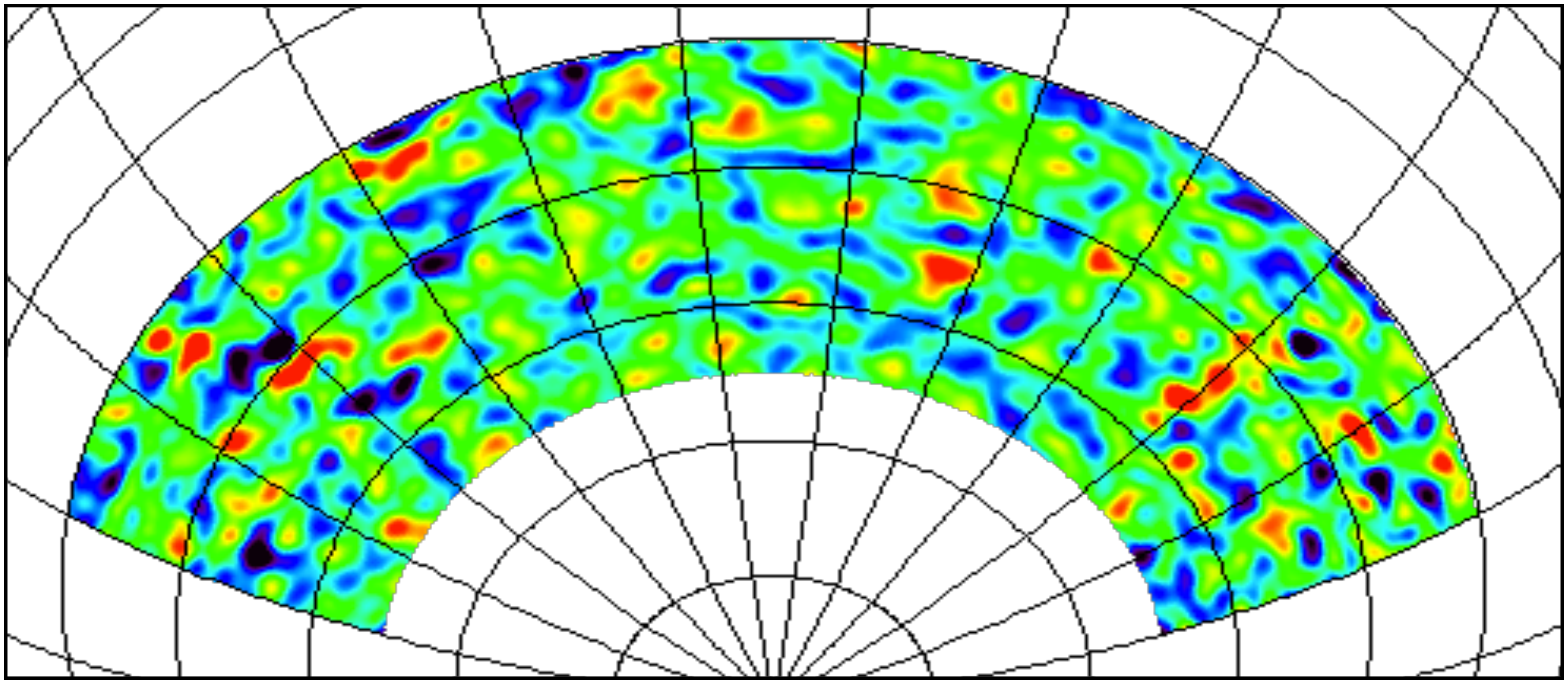
Smooth 500um map to ~1 degree scales (~100 com. Mpc).

Add mass contours from SPT CMB lensing.

~10σ correlation signal
Holder et al. 2013

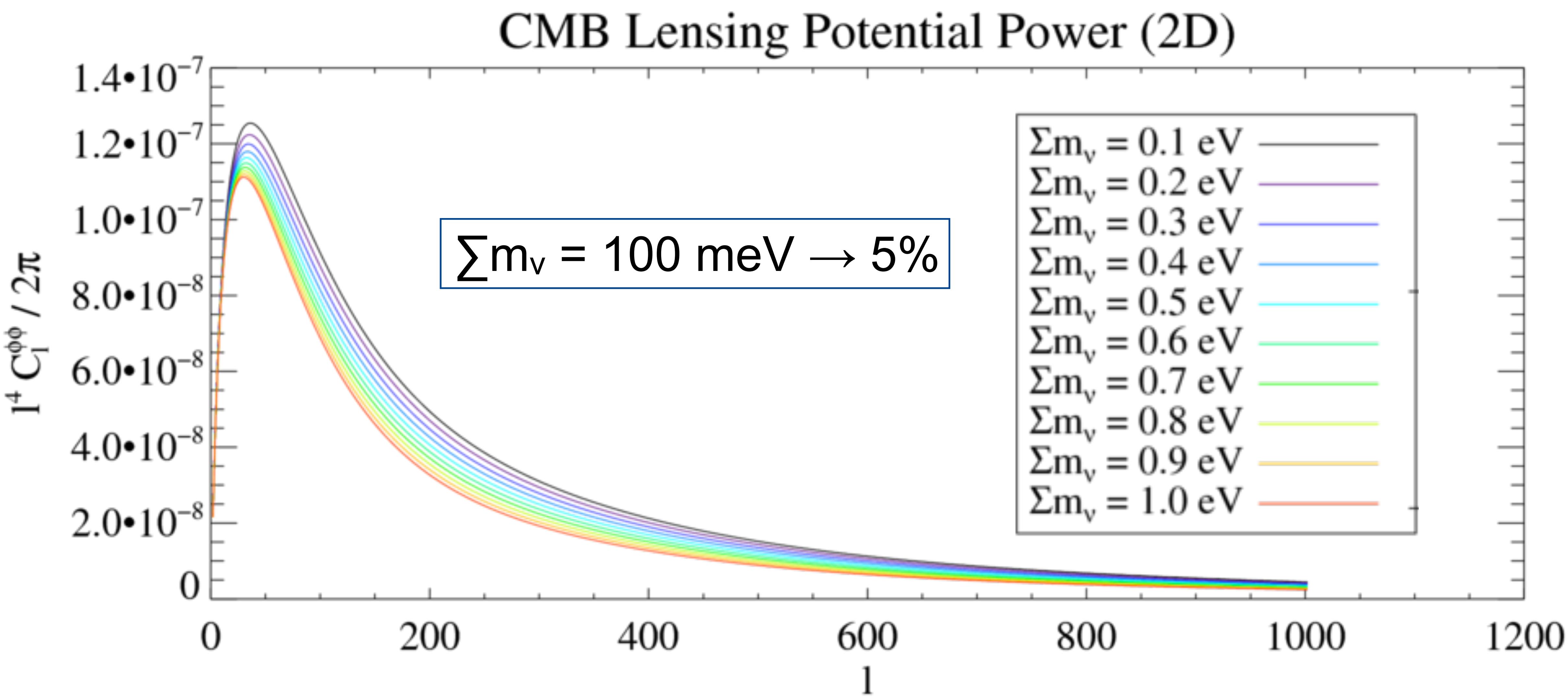
CMB Lensing Map

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



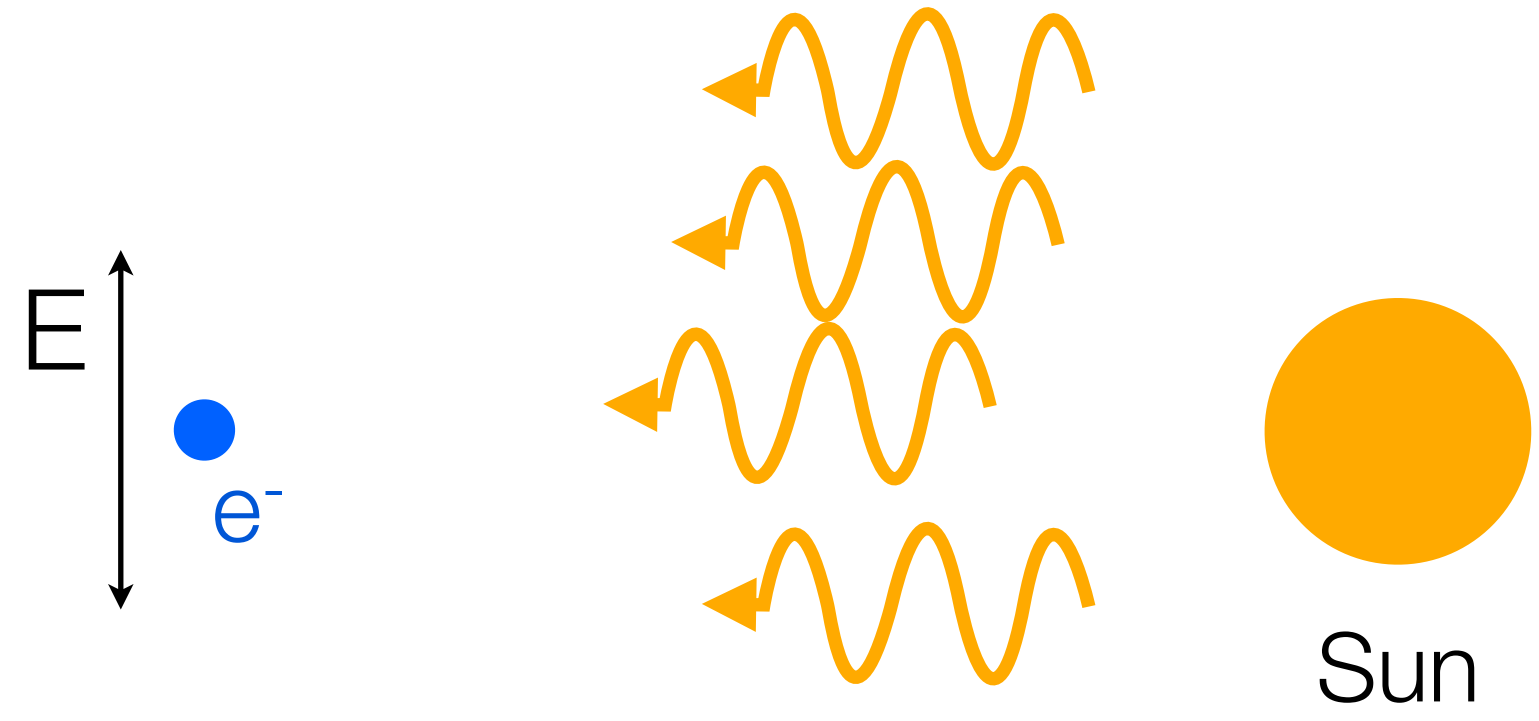
Lensing convergence map smoothed to 1 deg resolution from CMB lensing analysis of SPT 2500 deg^2 survey

Neutrino mass



CMB polarimetry

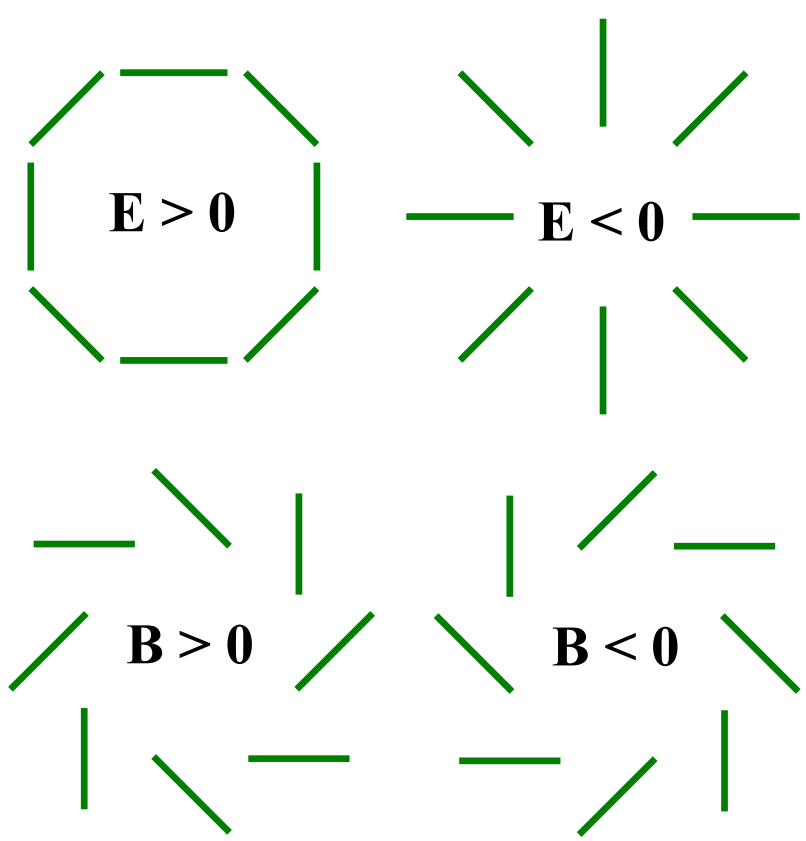
- CMB polarized via Thomson scattering and local anisotropy (e.g. Sun scattering in atmosphere)

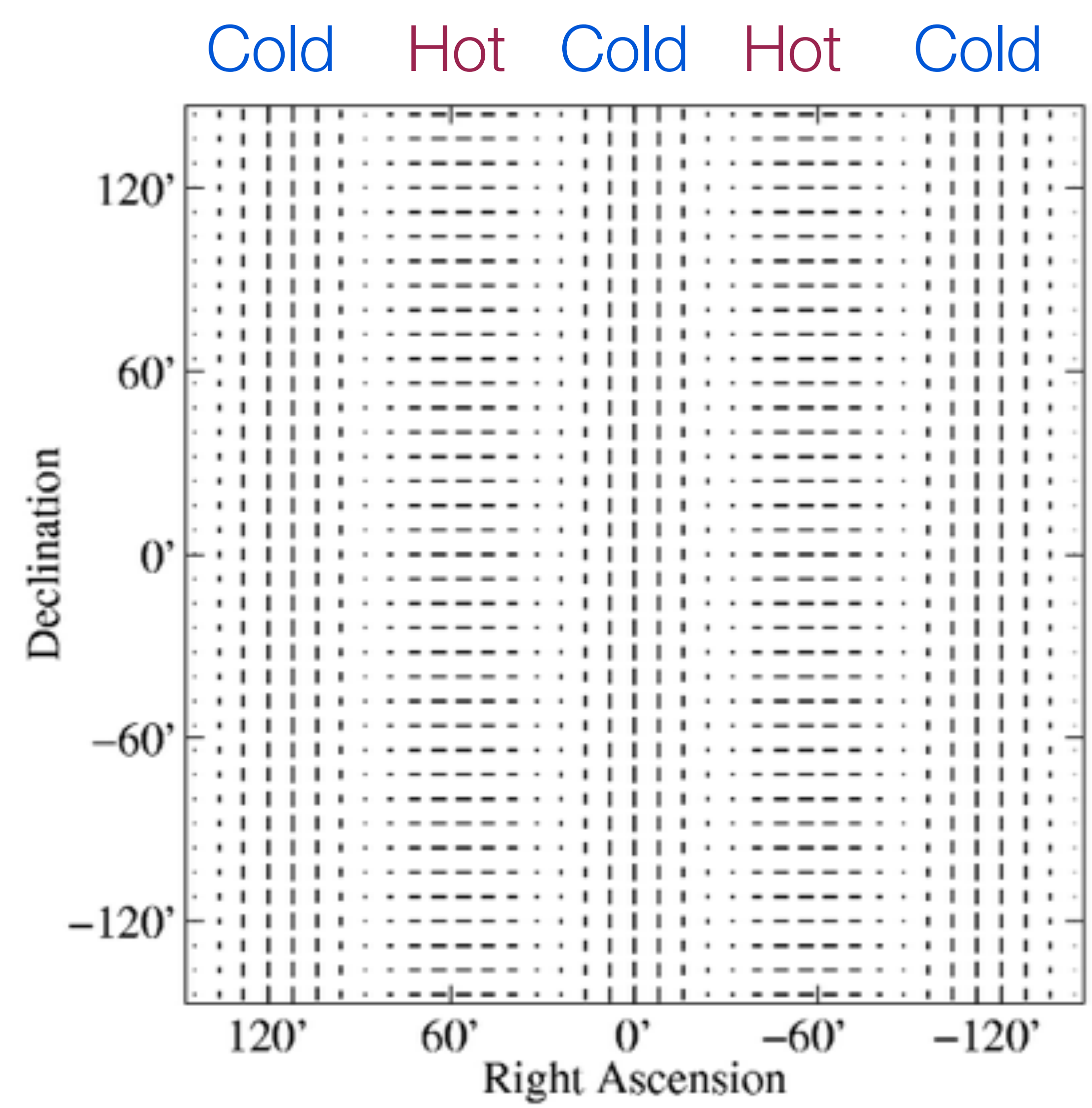


CMB polarimetry: E-modes

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

- Density/Temperature anisotropy generates intrinsic CMB polarization
  - Symmetric under “parity”
    $k \longrightarrow -k$
  - **“E-mode” only**



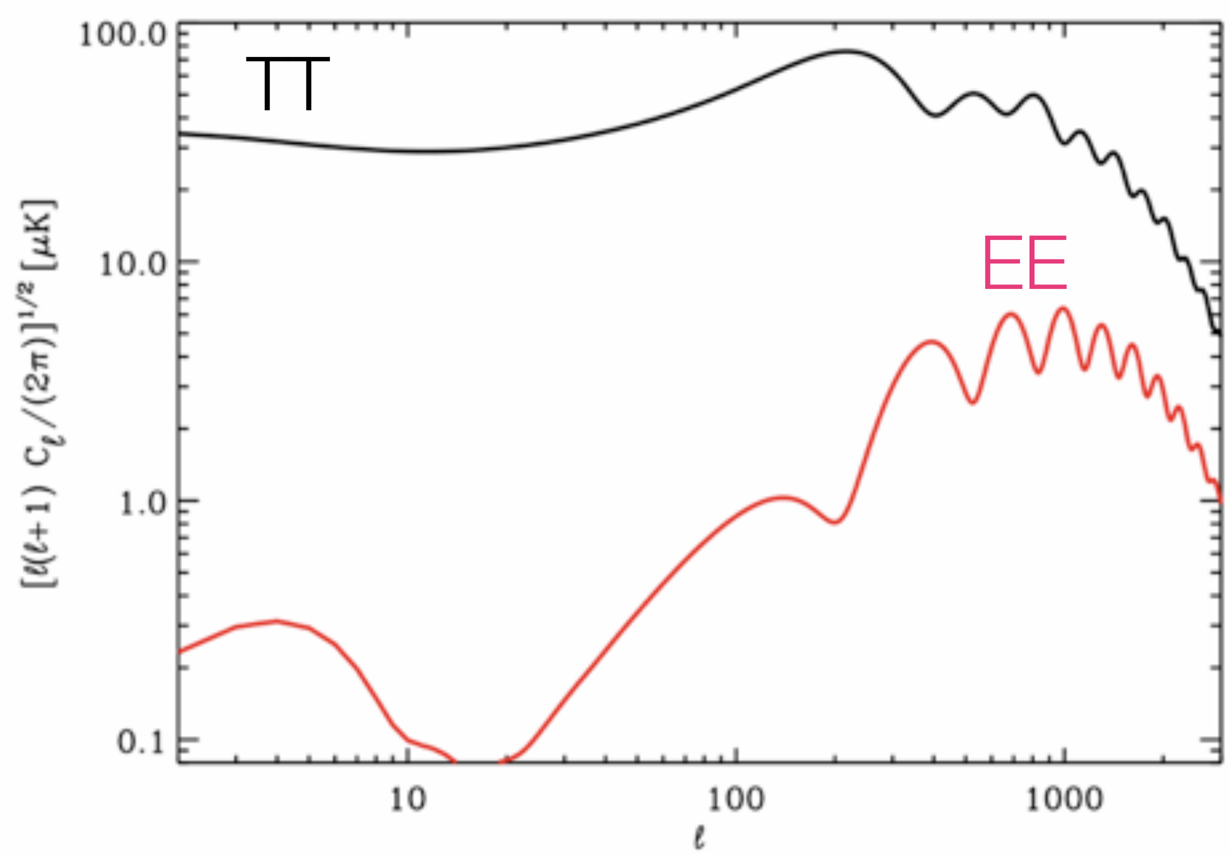


CMB polarimetry: E-modes

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

- Density/Temperature anisotropy generates intrinsic CMB polarization

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

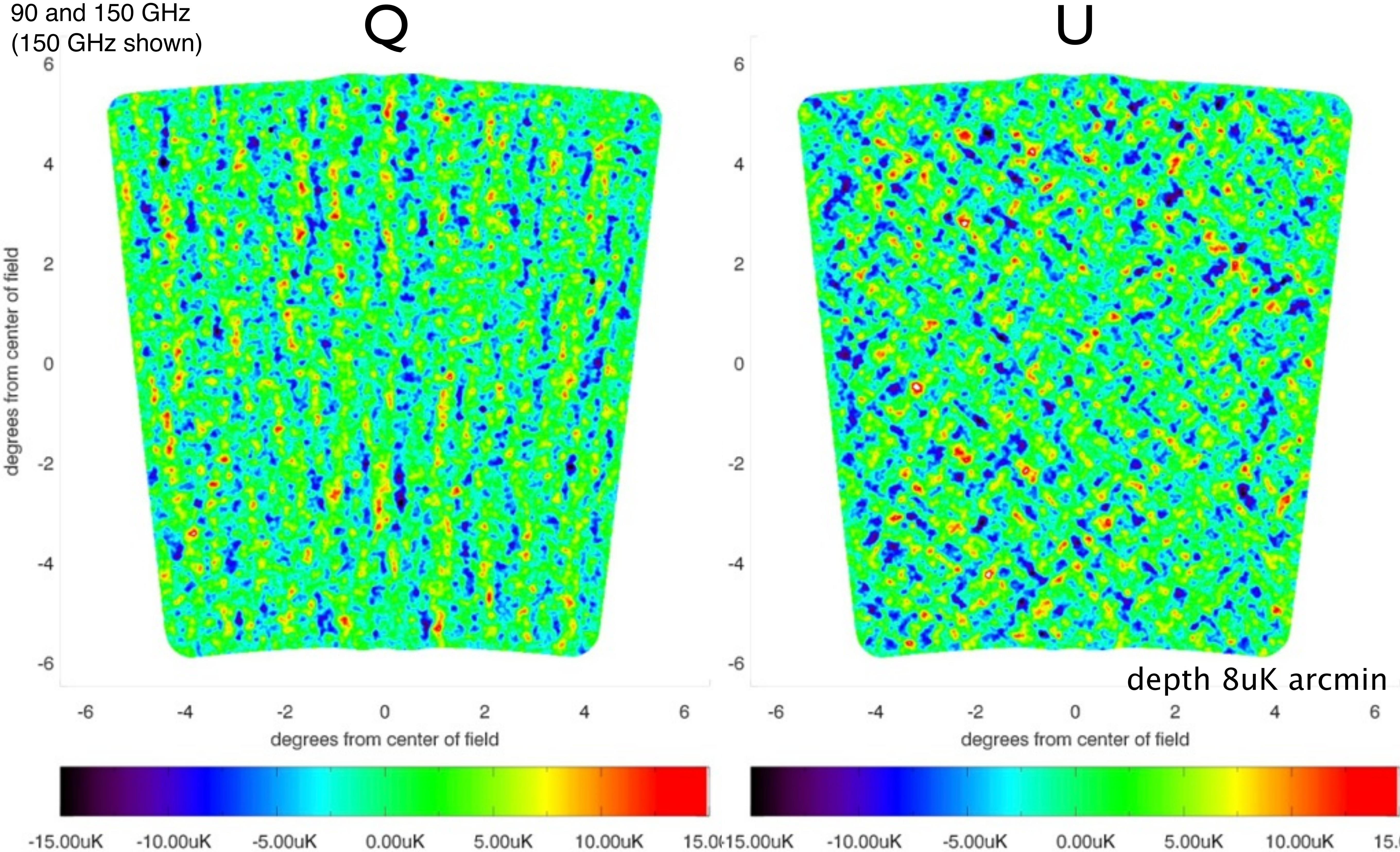


Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

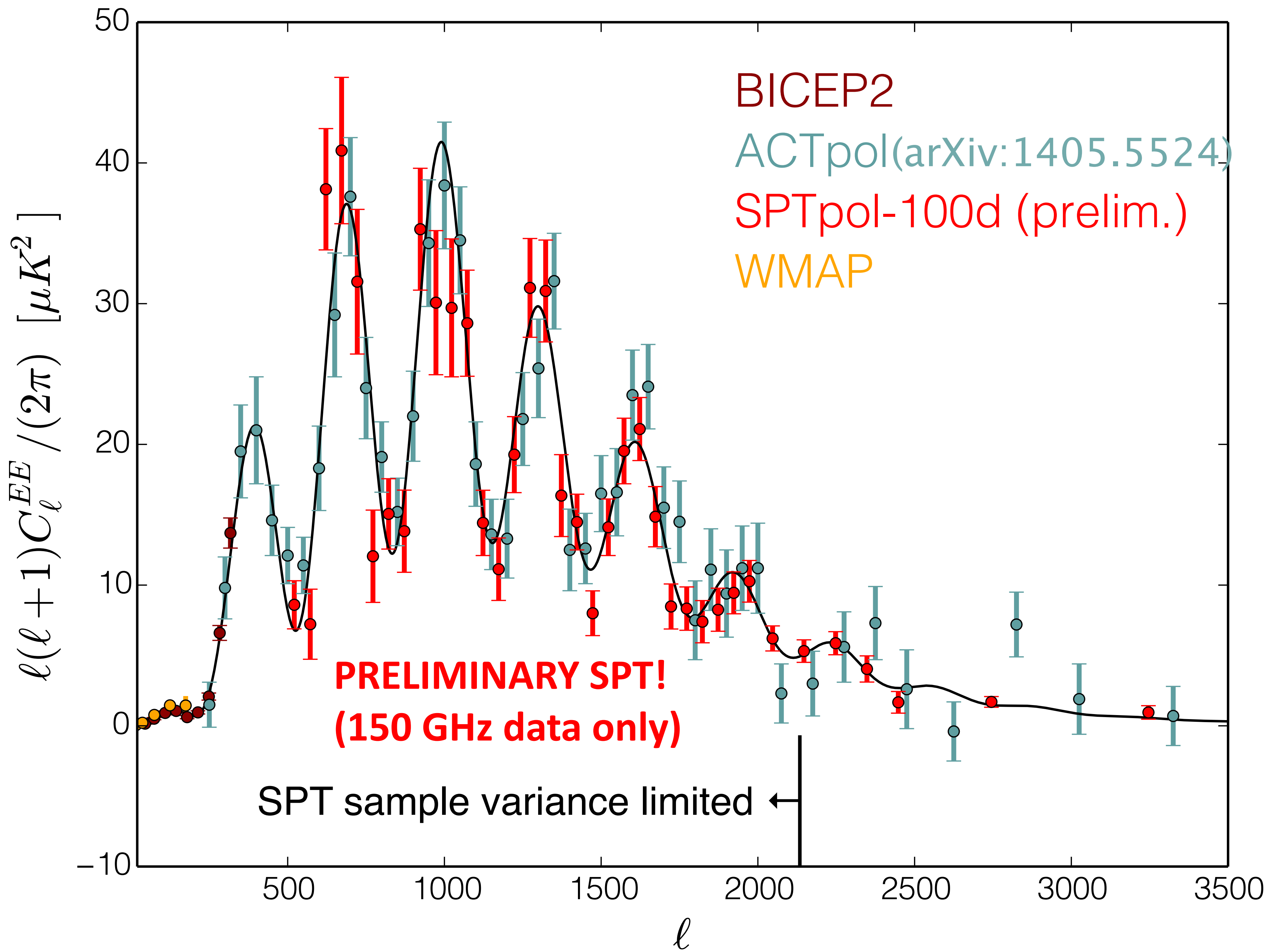
2012 SPTpol 100 deg^2 deep field polarization

E-mode polarization visible by eye in 150 GHz Stokes Q & U

Central 100 deg^2 of BICEP2 field;
90 and 150 GHz
(150 GHz shown)



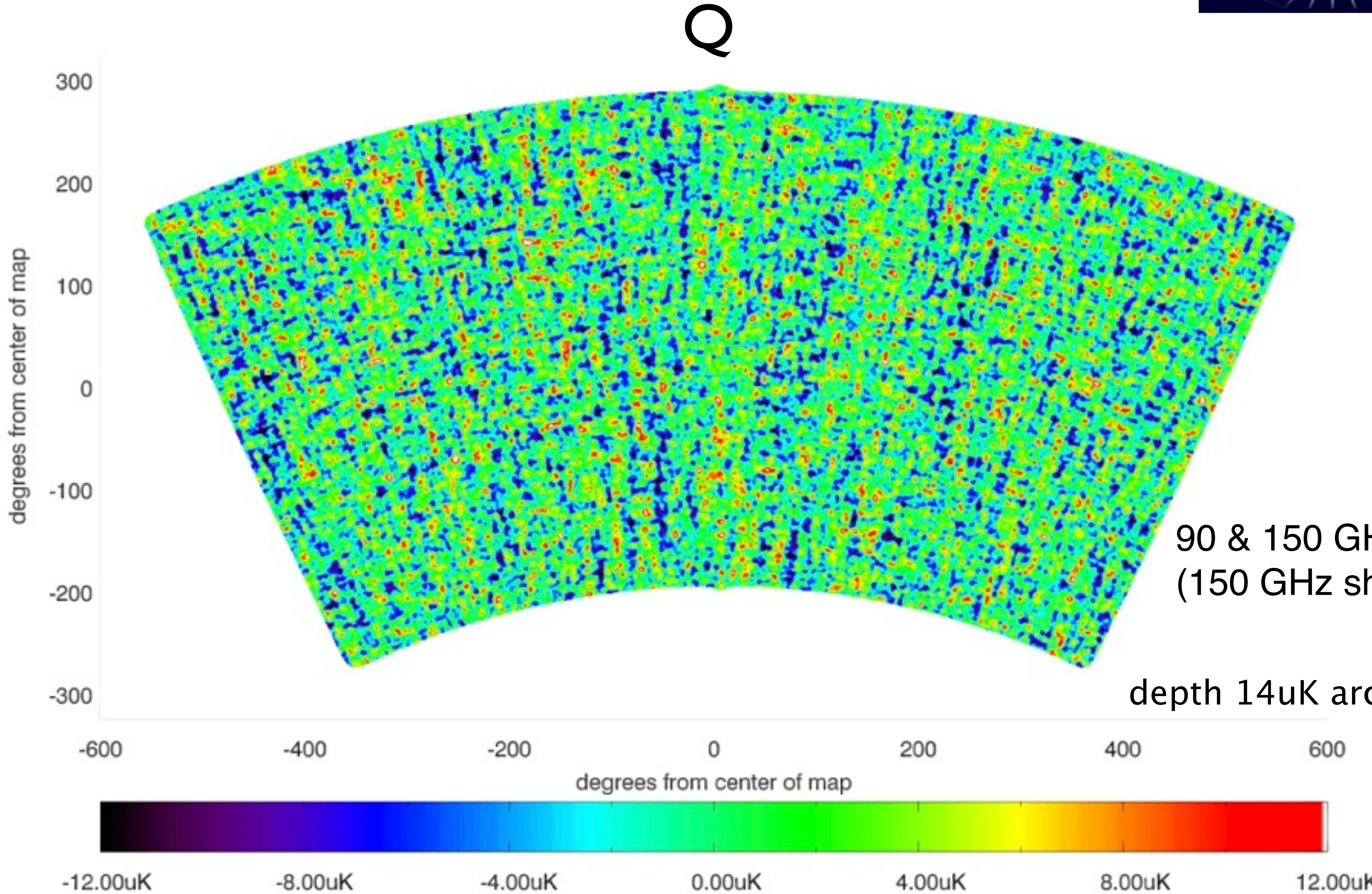
2012 SPTpol 100 deg^2 deep field EE



Abby Crites et al., in prep

2013 SPTpol 500 deg^2 field

(covers BICEP2 region)

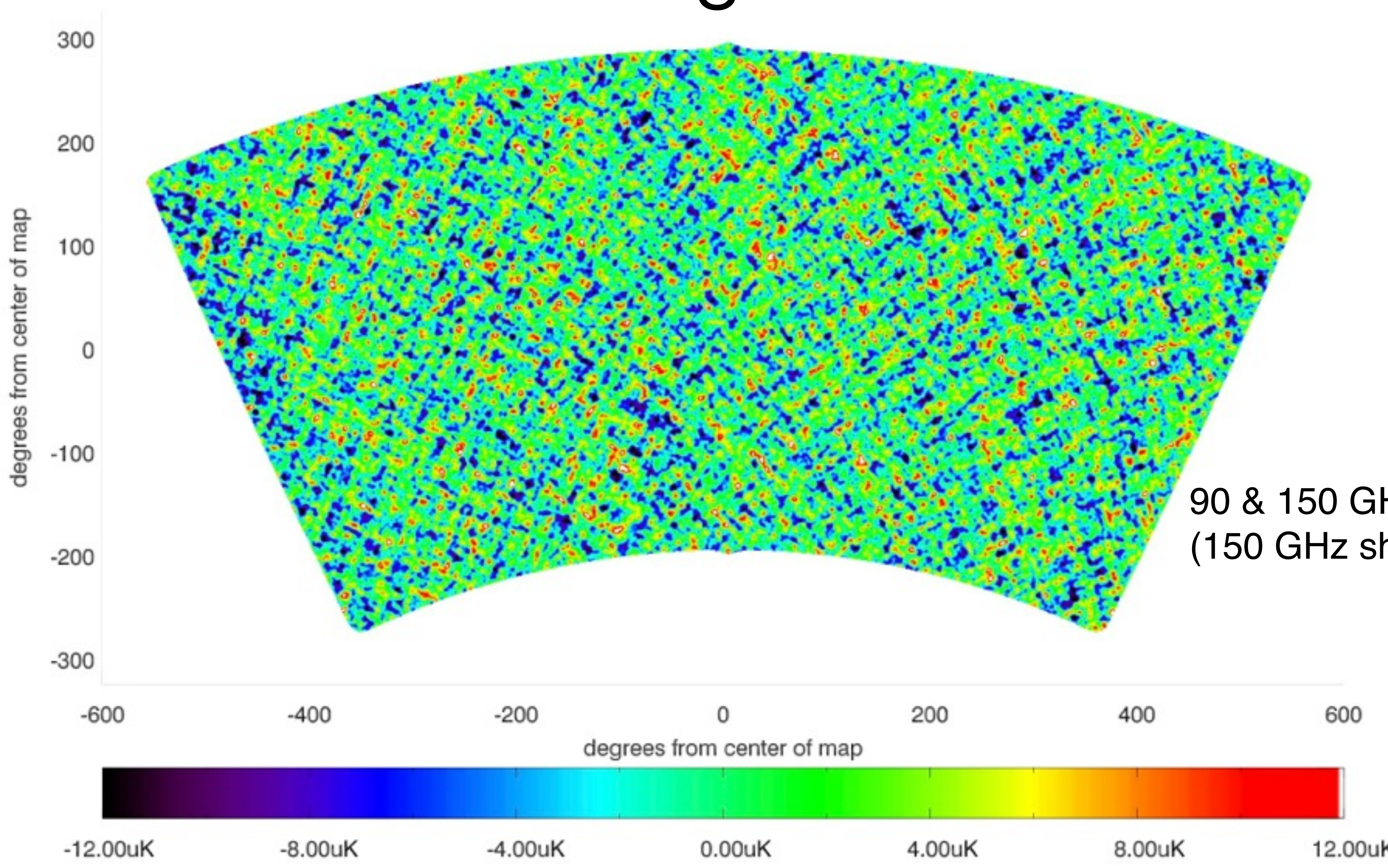


90 & 150 GHz
(150 GHz shown)

depth 14uK arcmin

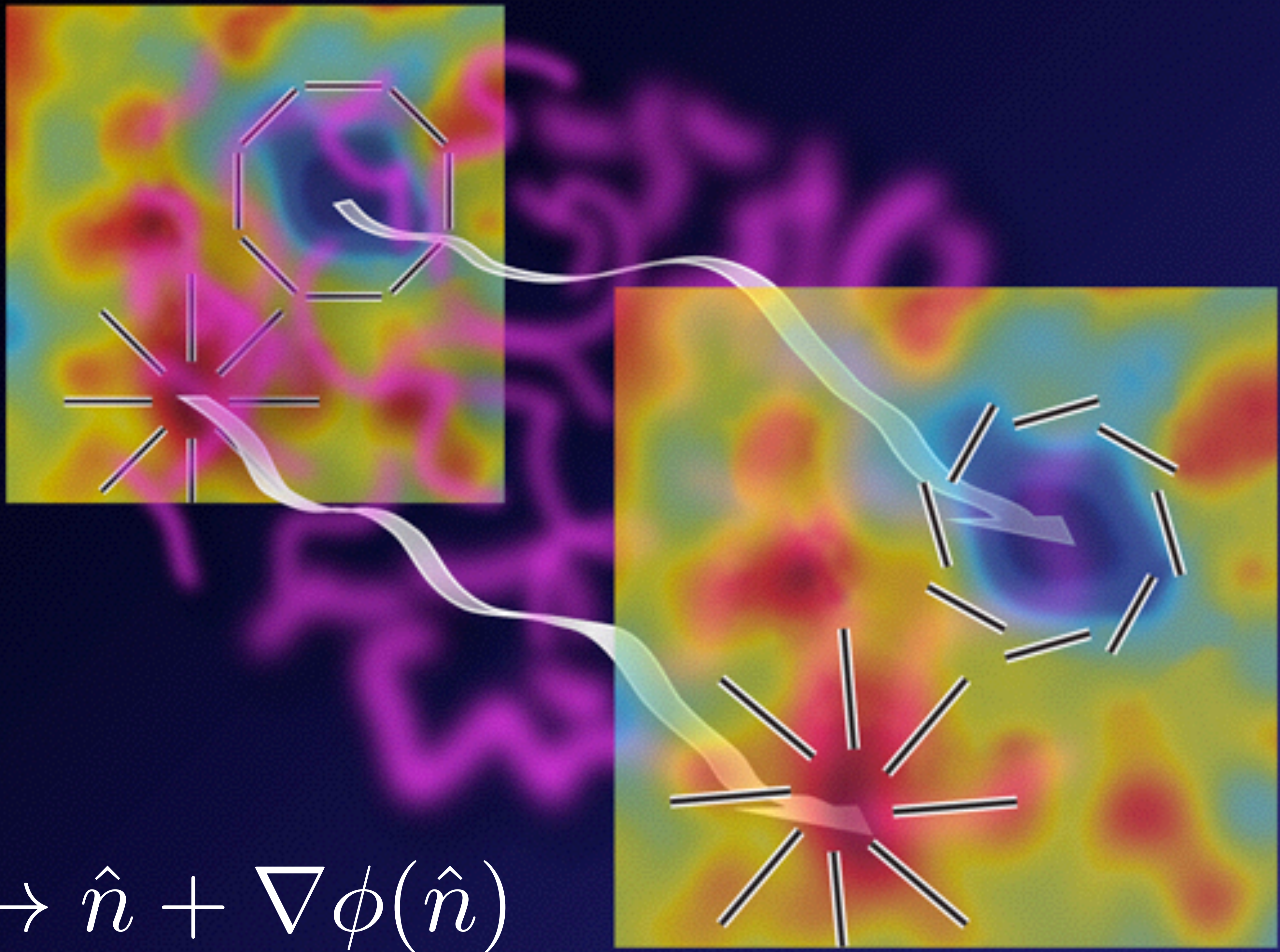
2013 SPTpol 500 deg² field
(covers BICEP2 region)

U



90 & 150 GHz
(150 GHz shown)

CMB Lensing via CMB polarization

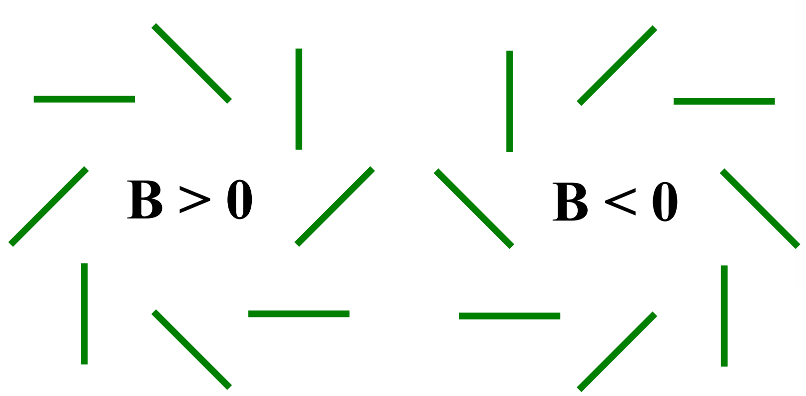


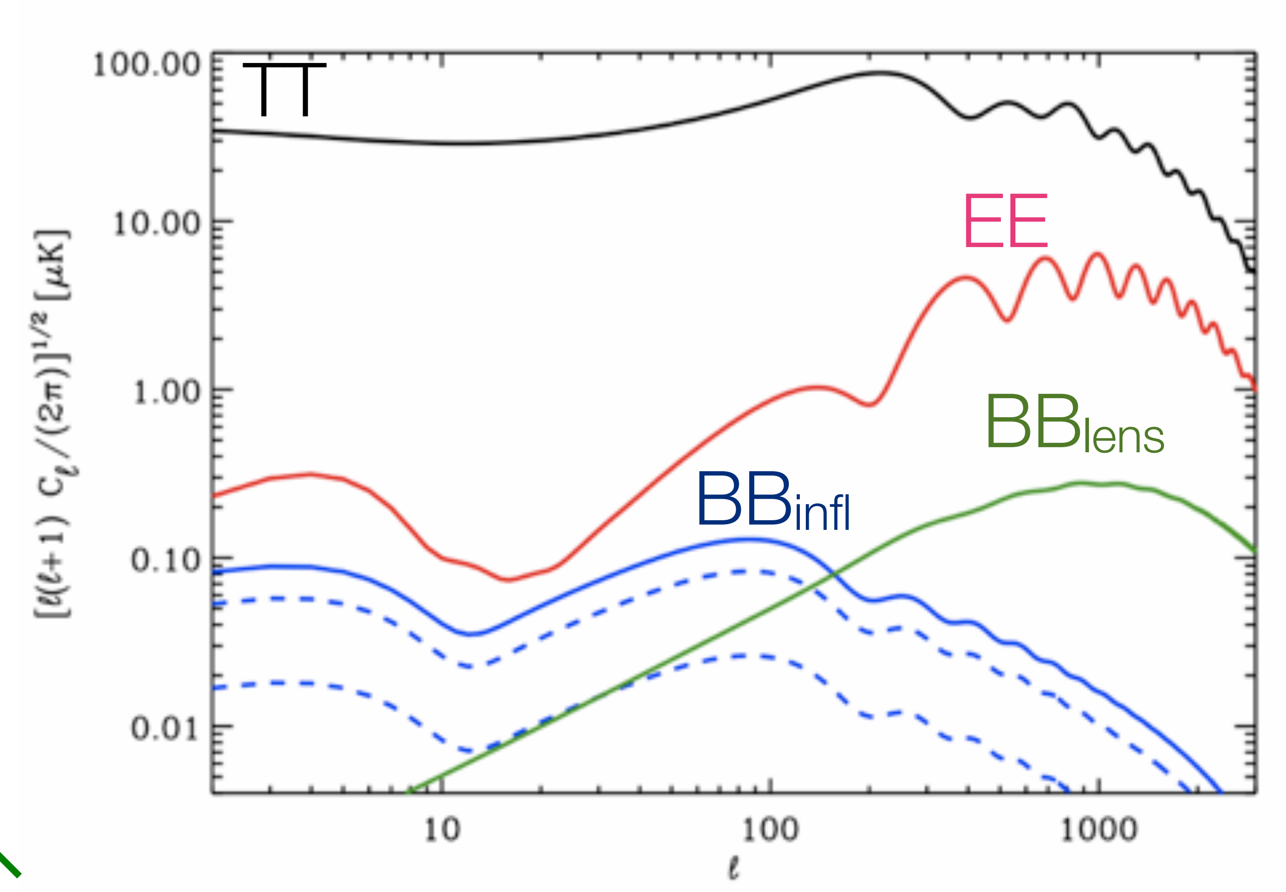
$$\hat{n} \to \hat{n} + \nabla\phi(\hat{n})$$

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

CMB polarimetry: E-modes & B-modes

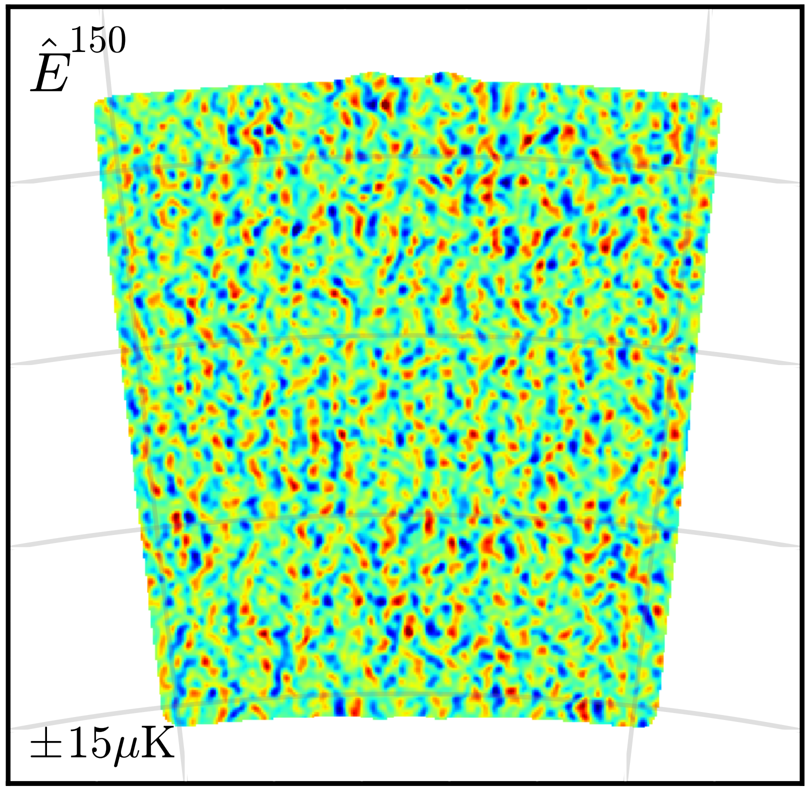
- CMB polarized via Thompson scattering and local anisotropy (e.g. Sun scattering in atmosphere)
- Density/Temperature anisotropy generates intrinsic CMB polarization
  - parity odd patterns, "B-modes"
  - Gravitational lensing of "E-modes" (shearing)
  - Gravitational waves from inflation





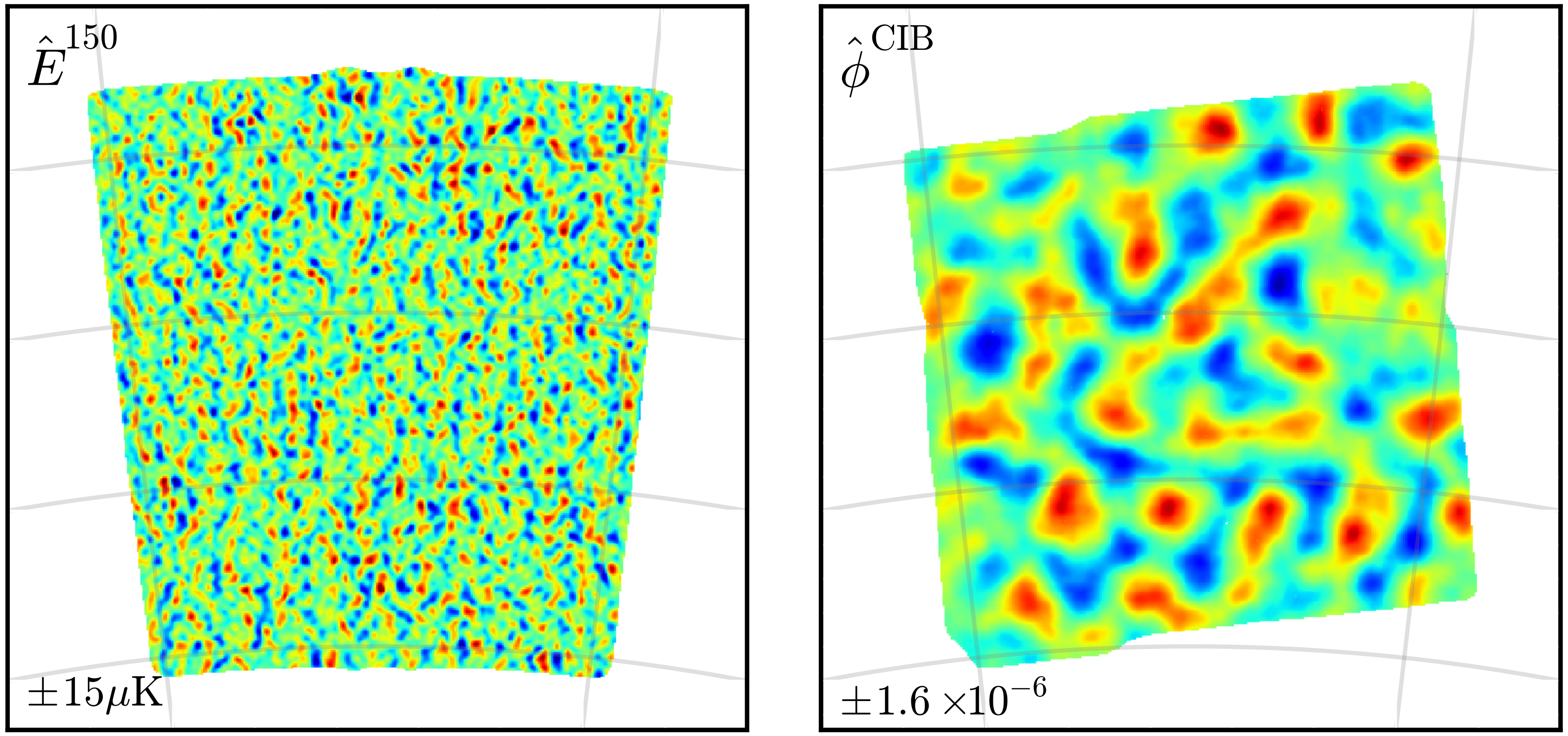
Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

Measuring CMB lensing B-modes



E

SPTpol



E

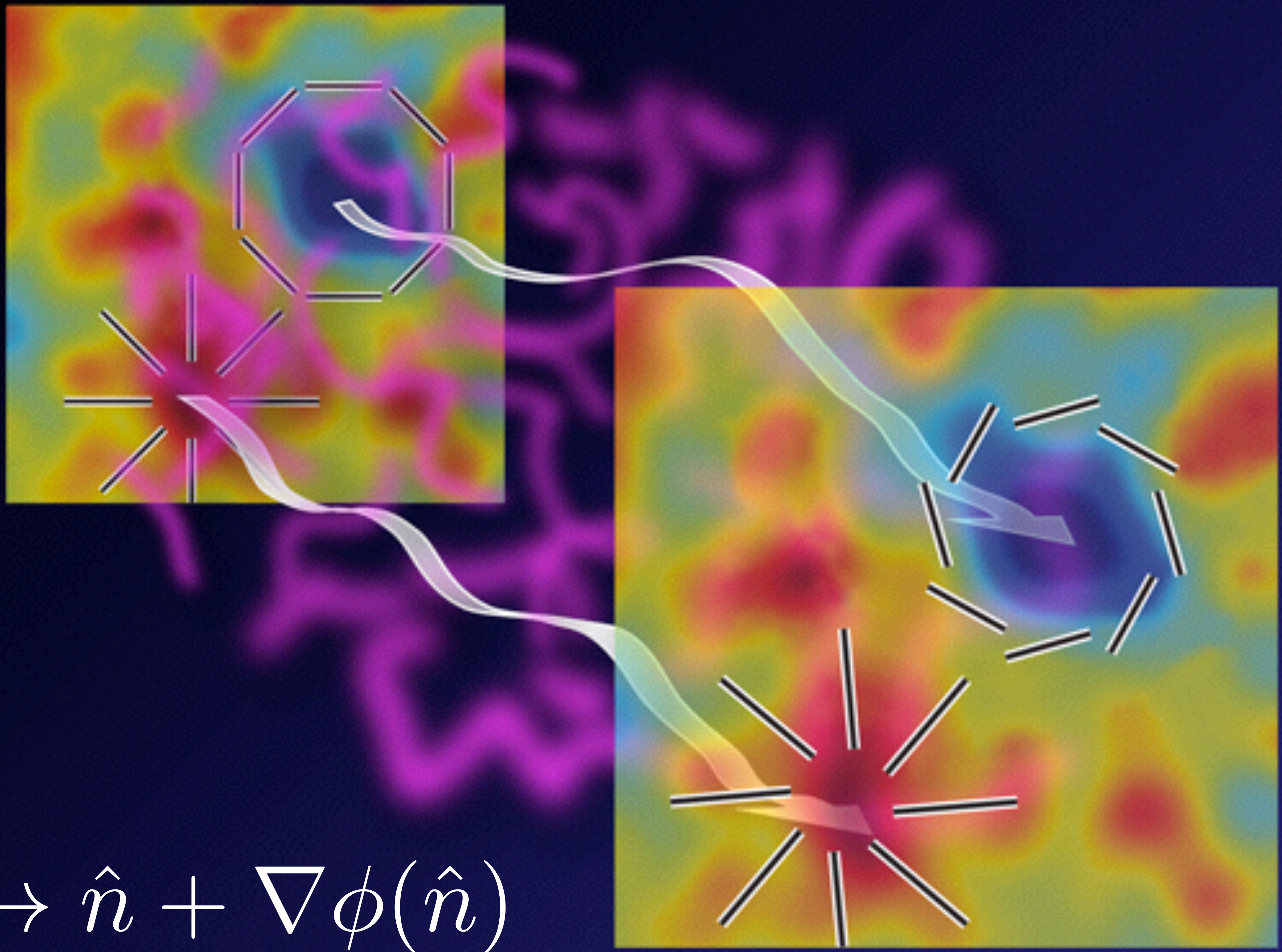
SPTpol

+

Φ

CIB (Herschel)

Traces DM/lensing potential



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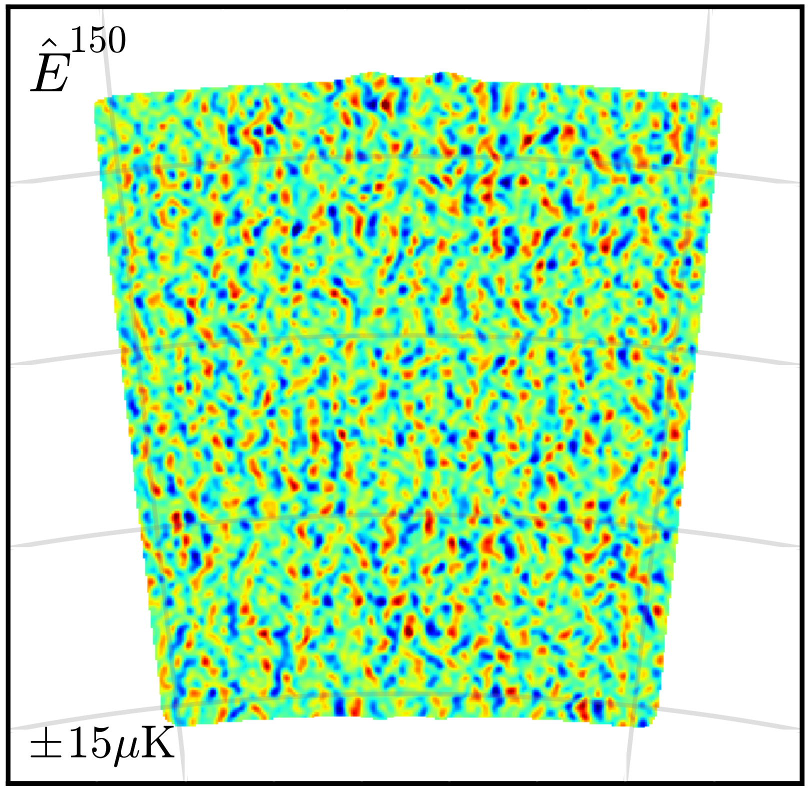
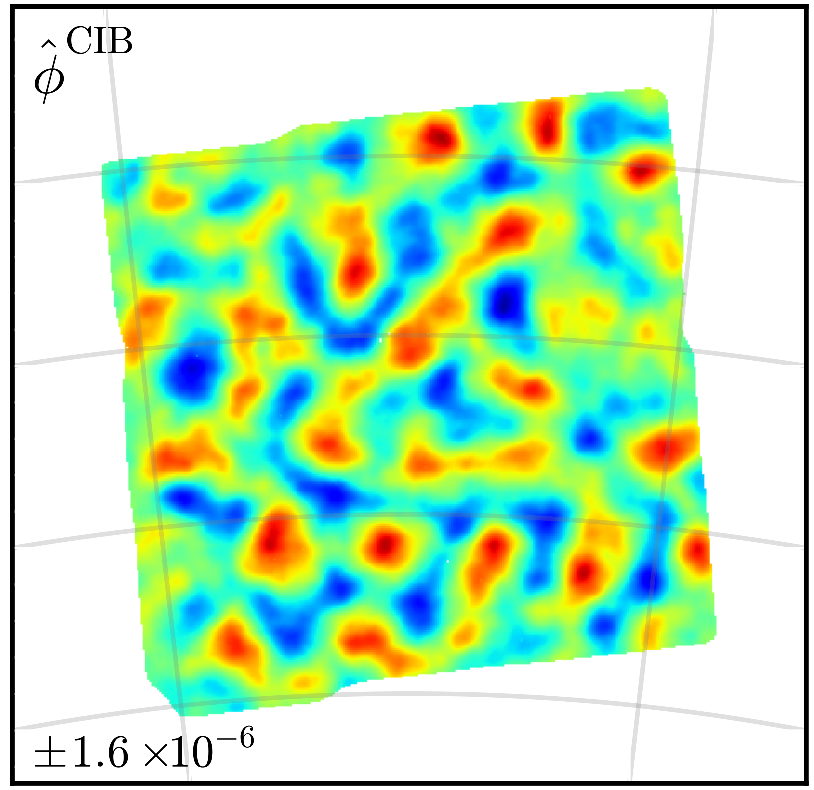
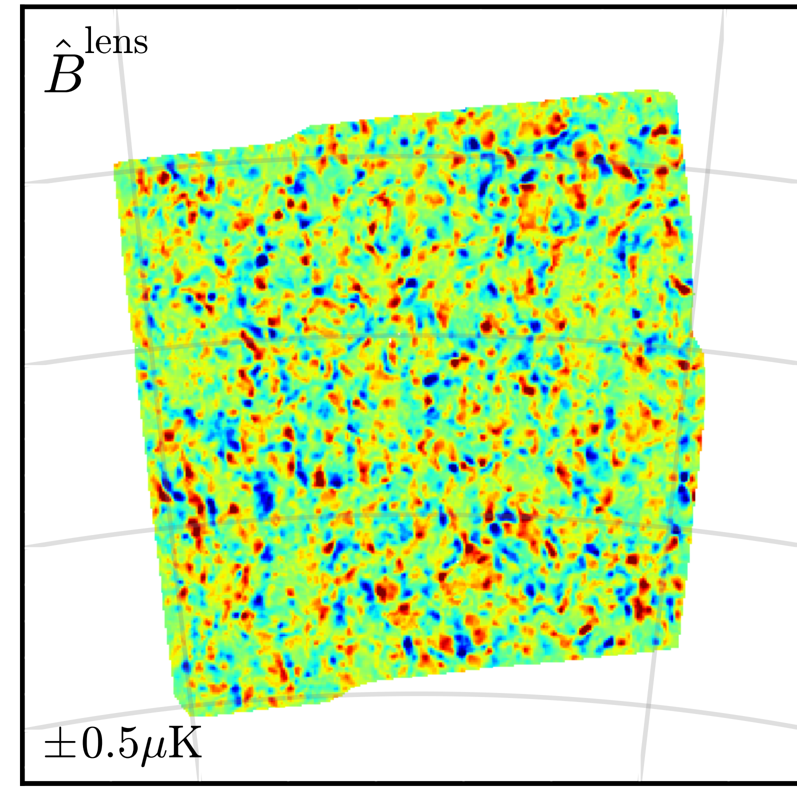


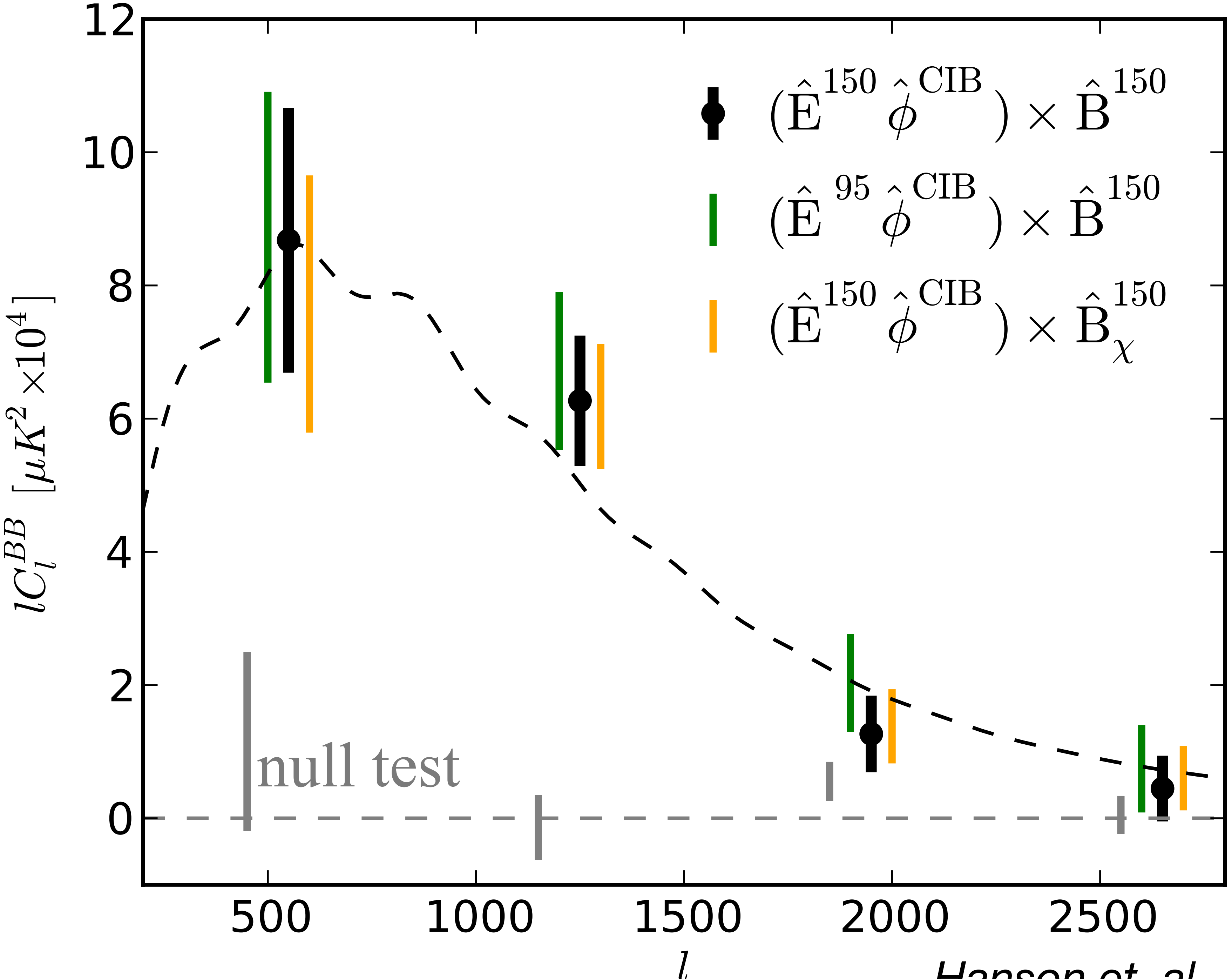




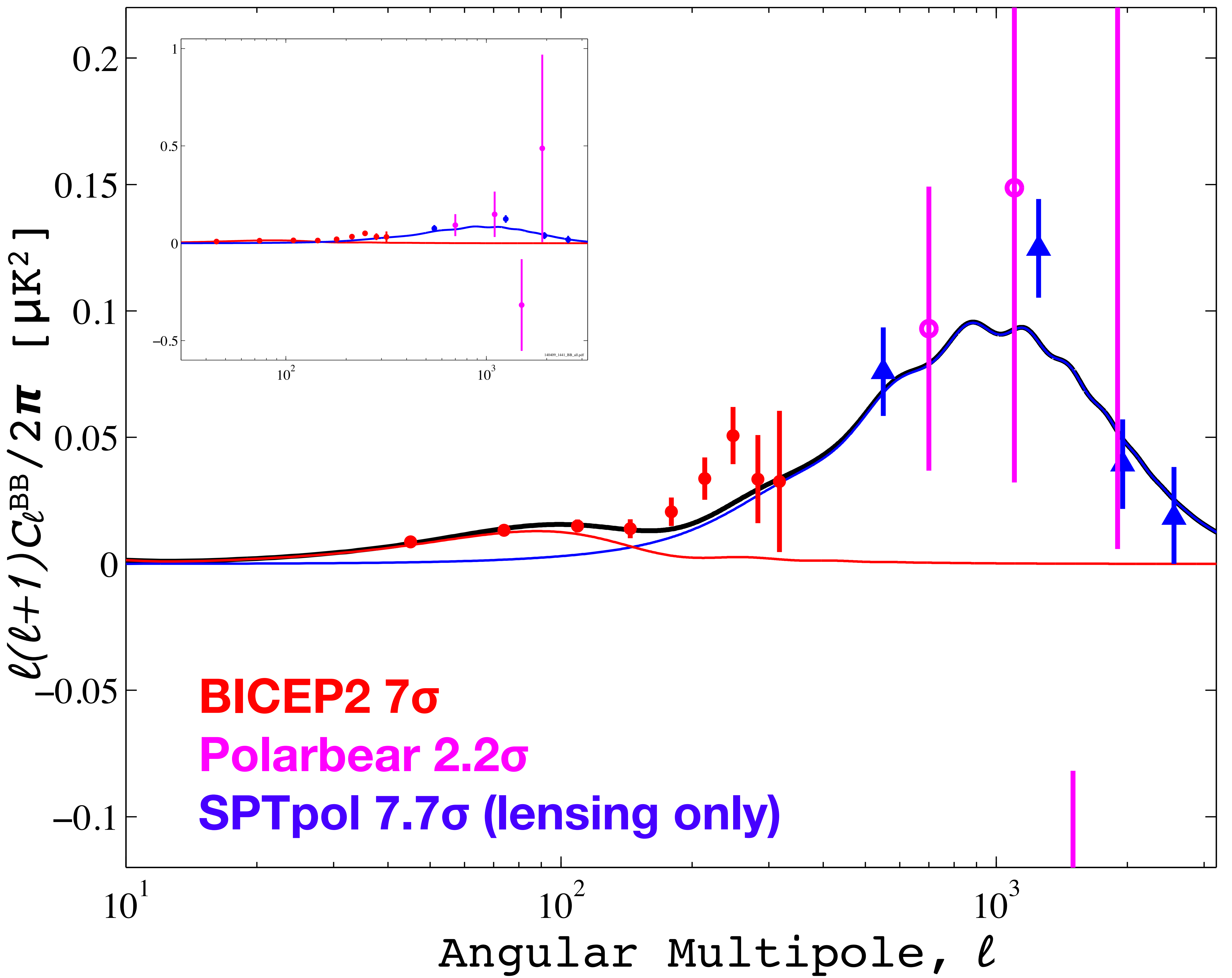
E SPTpol + Φ CIB (Herschel) → Synthesized lensing B

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

7.7σ detection of CMB lensing B-modes



Hanson et. al., PRL, 111 (2013)



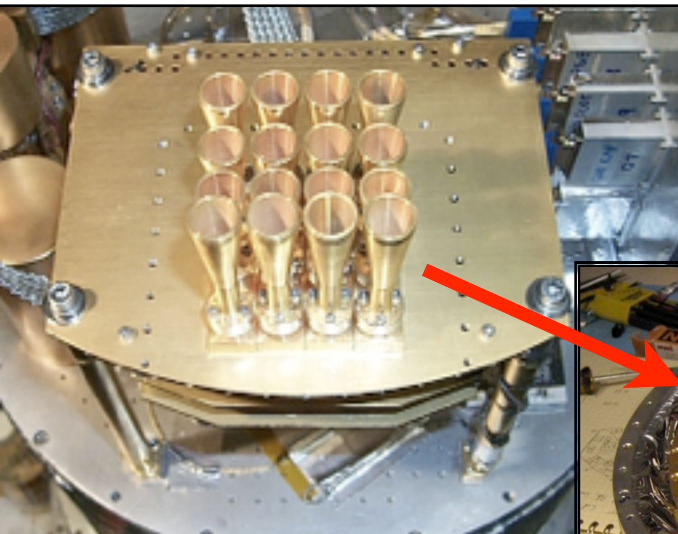
BICEP2 7σ
Polarbear 2.2σ
SPTpol 7.7σ (lensing only)
Angular Multipole, ℓ
ℓ(ℓ+1)C_ℓ^BB/2π [μK²]
0.2
0.15
0.1
0.05
0
−0.05
−0.1
10^1
10^2
10^3
1
0.5
0
−0.5
140409_1441_BB_all.pdf

B-modes: From detection to precision

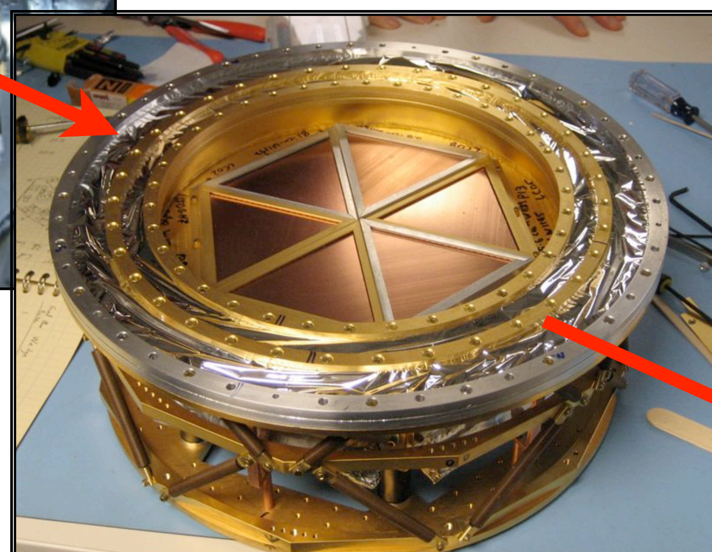
Increase sensitivity with more detectors

- Larger focal plane (bigger arrays and more of them)
- Increase detector “density” (measure more optical modes per optical element)
- SPT-3G timeline. Similar for PB-II/Simons Array, BICEP3/T-REX, and extended ACTpol

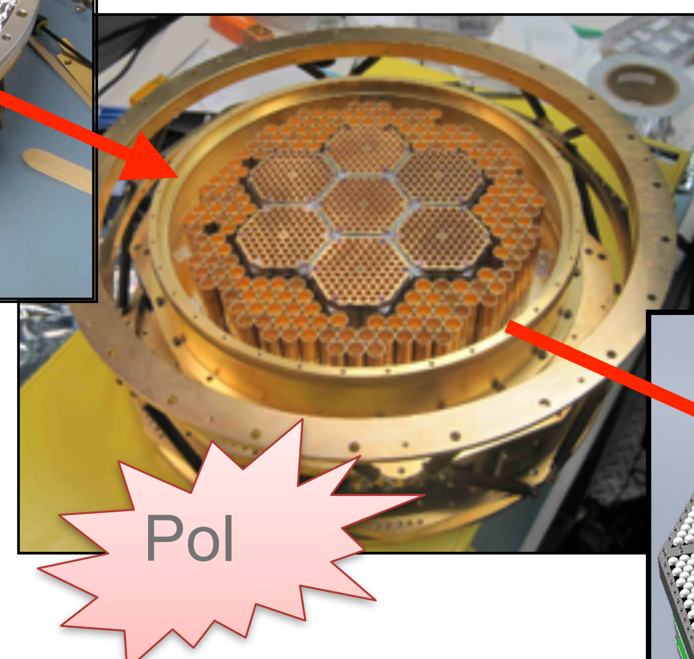
2001: ACBAR
16 detectors



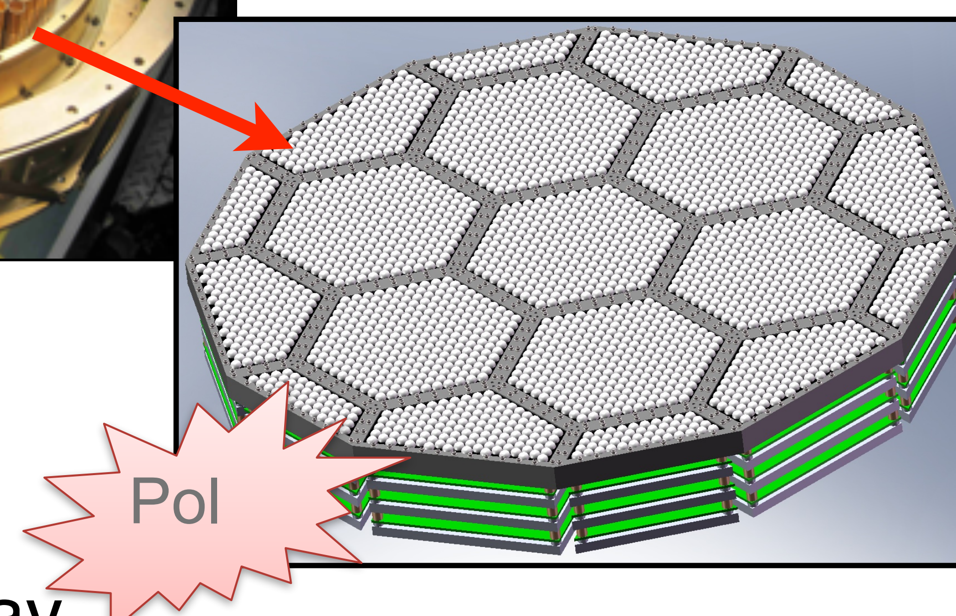
2007: SPT
960 detectors



2012: SPTpol
~1600 detectors

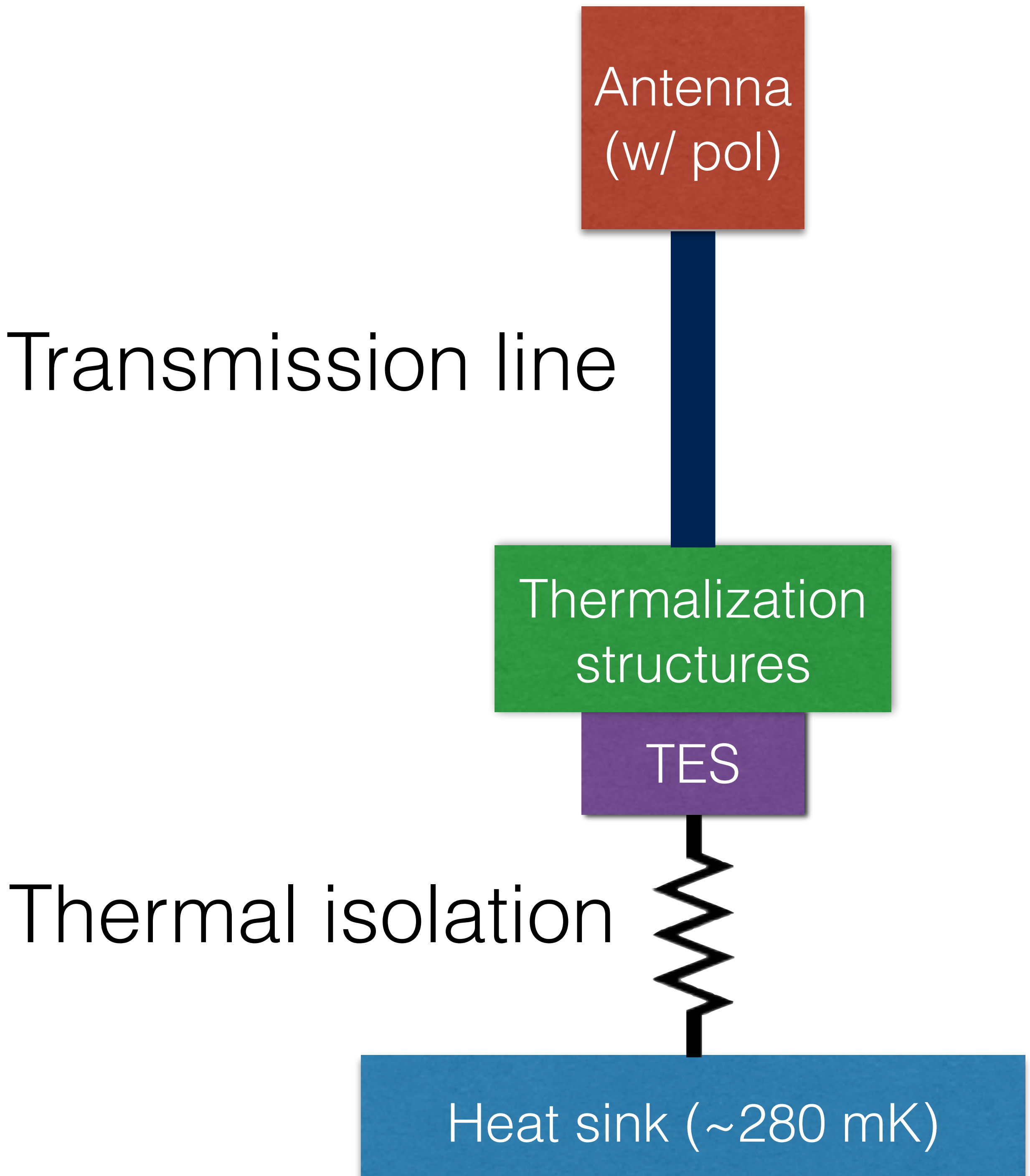


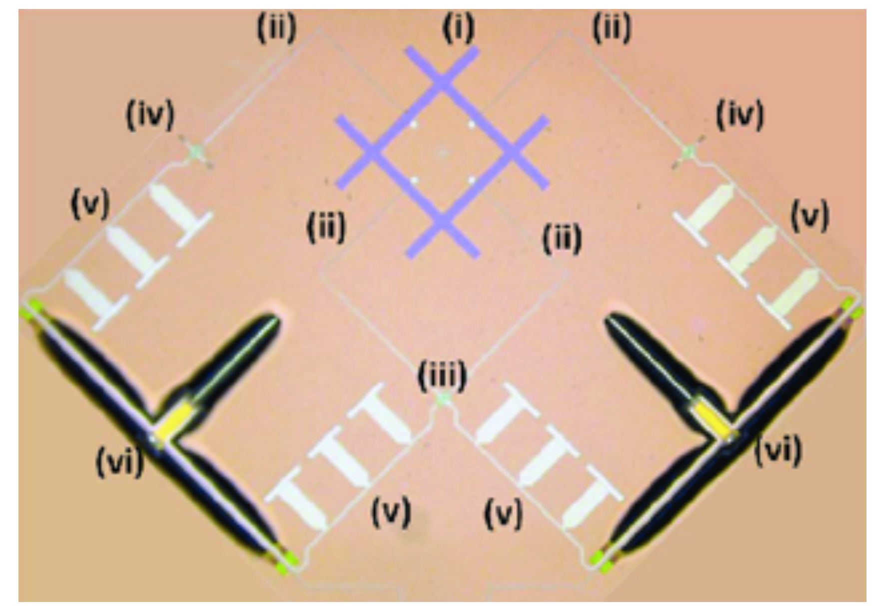
2016: SPT-3G
~15,200 detectors



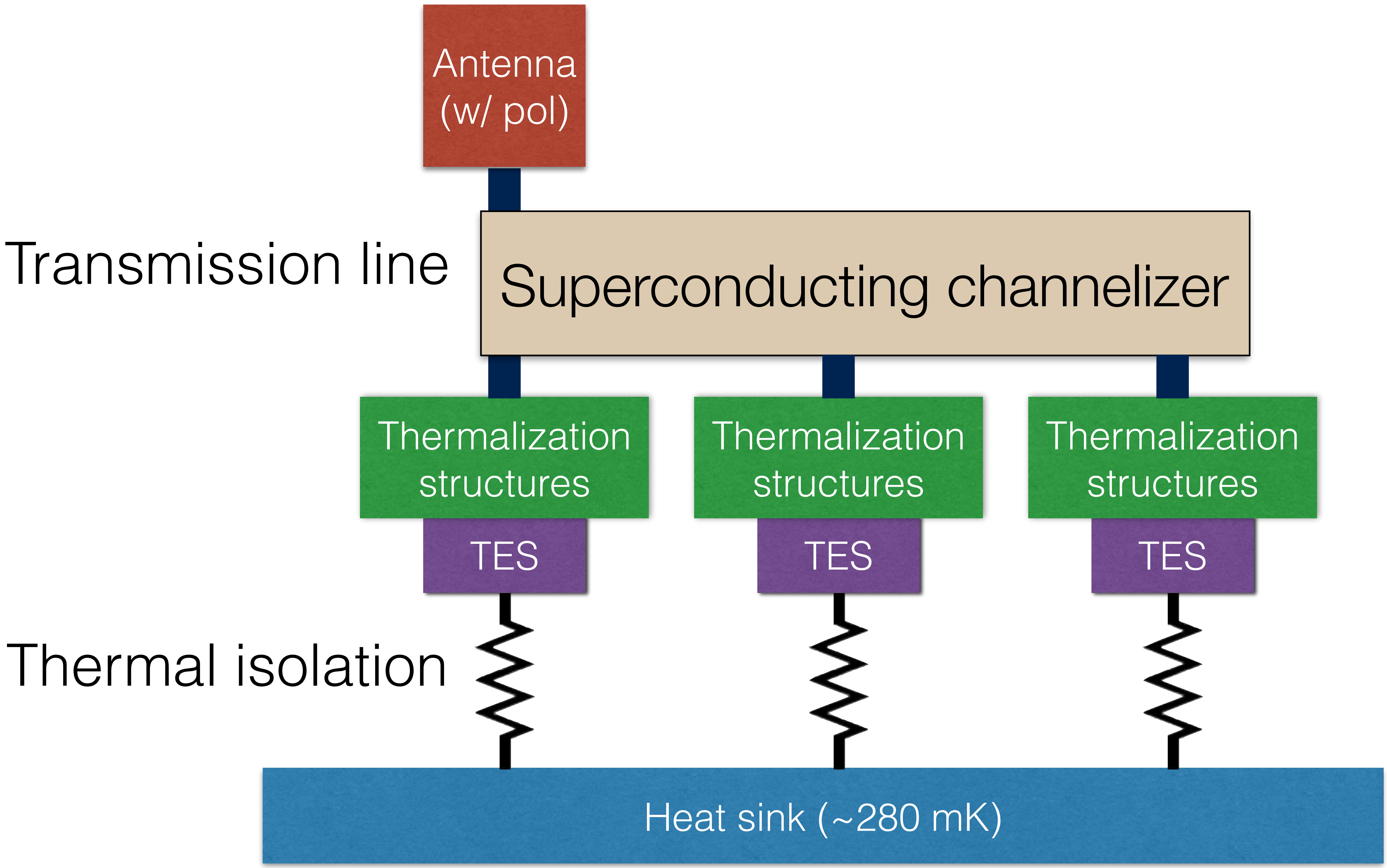
ACBAR was the first experiment to make a “background limited” detector. Since then, only way to increase sensitivity is to have more detectors

Increasing detector density: the basic idea



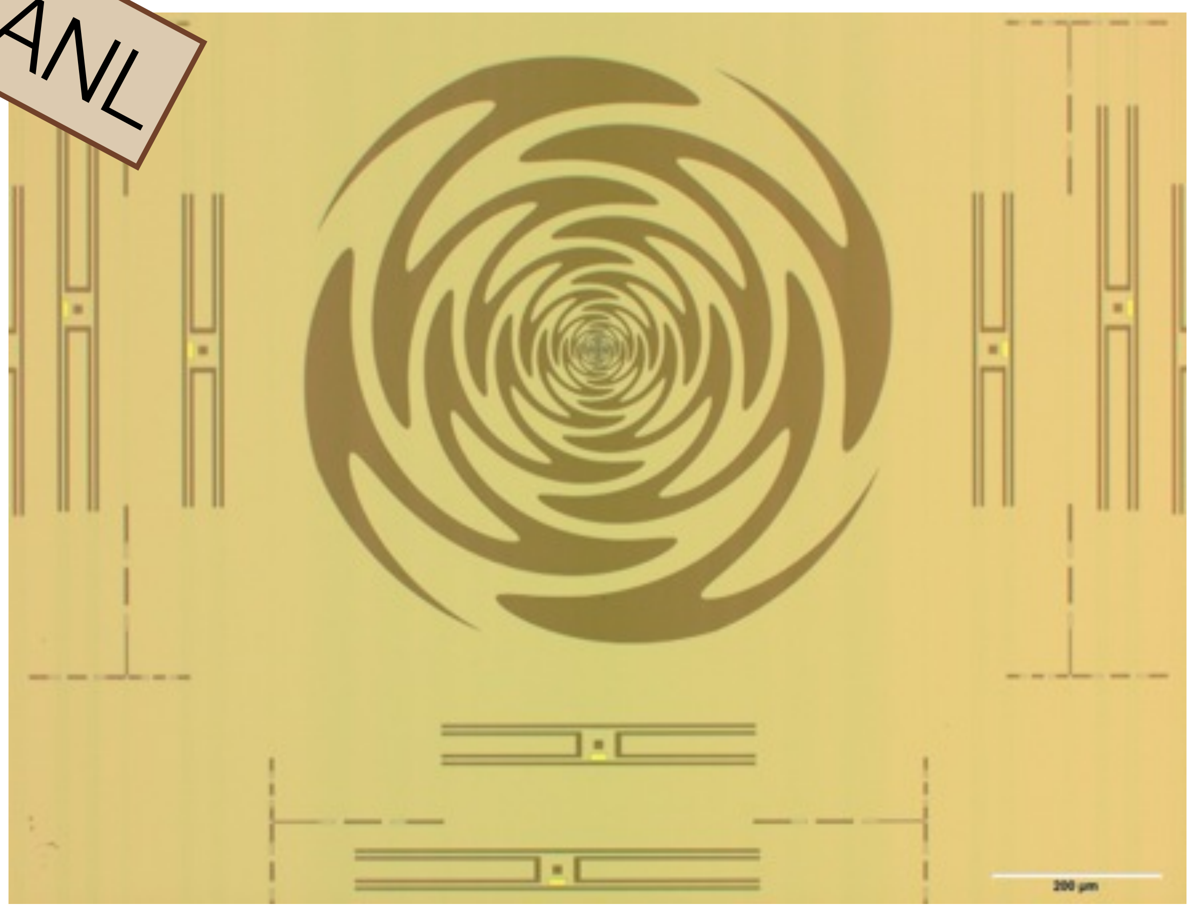


Increasing detector density: the basic idea

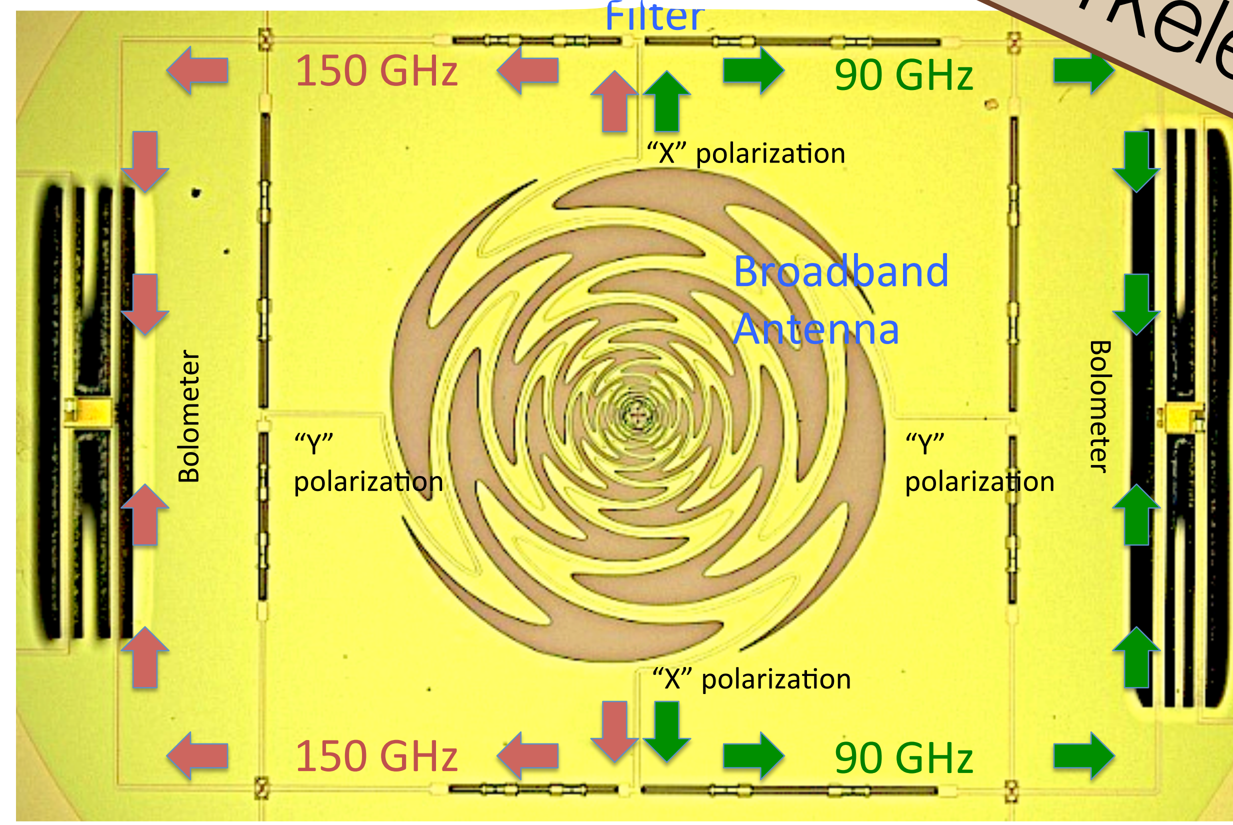


Large arrays of Multi-chroic pixels

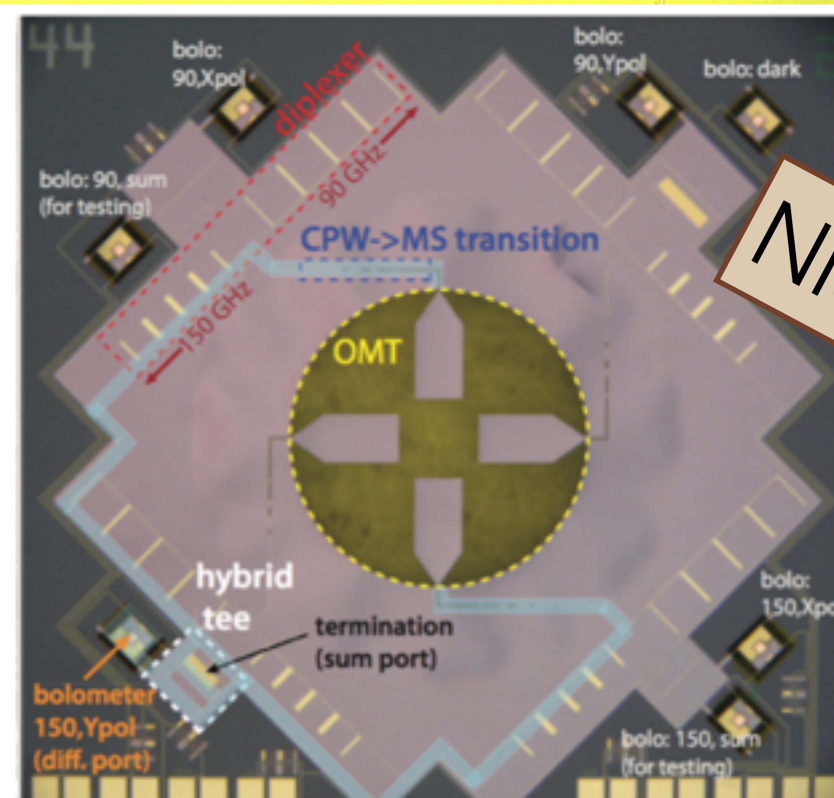
ANL



Berkeley



NIST



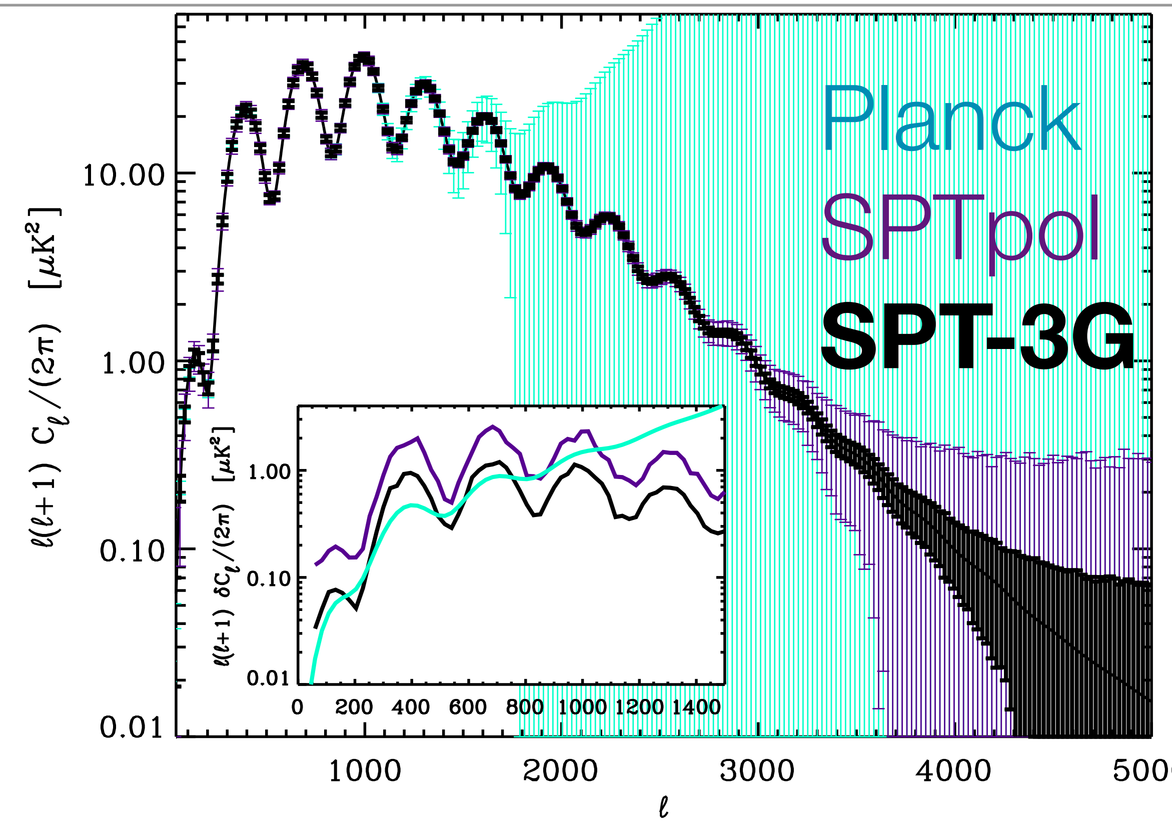
- Multi-chroic pixels observe multiple frequency bands in a single pixel
- Increases the detector density for fixed area.

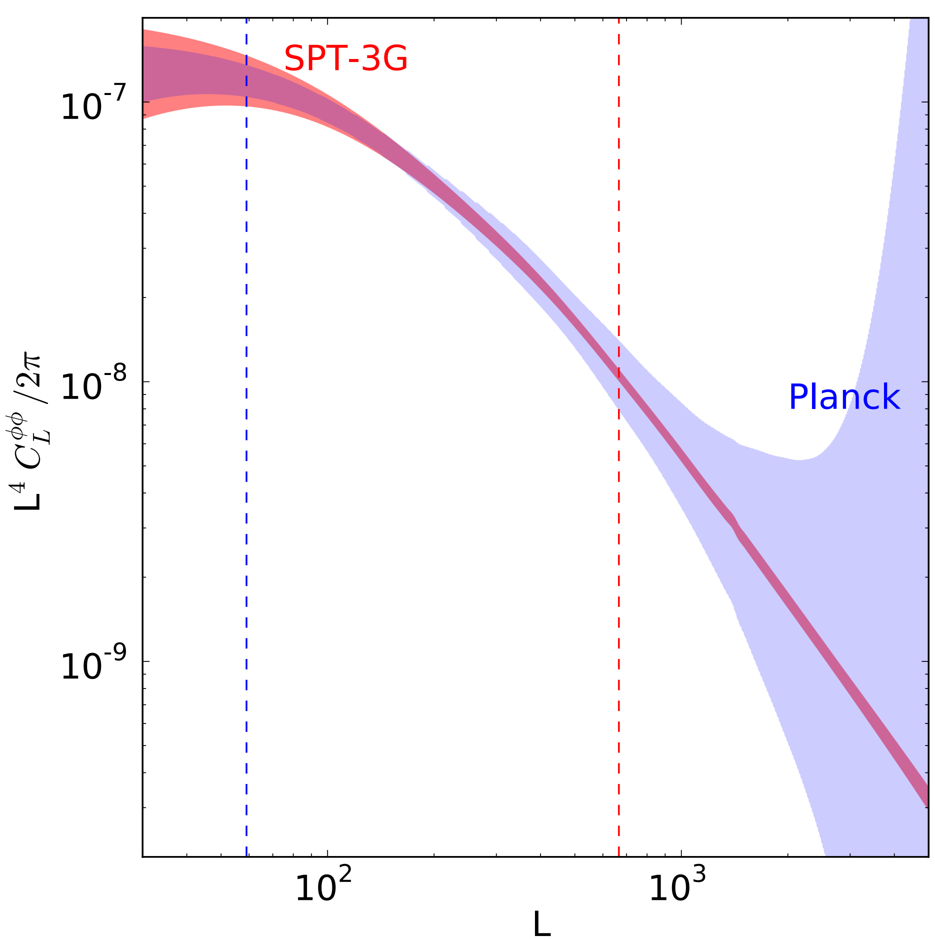
Suzuki et al., Proc. SPIE 8452, Mm, Sub-mm, and Far-IR Detectors and Instr. for Astro. VI, 84523H (October 5, 2012)

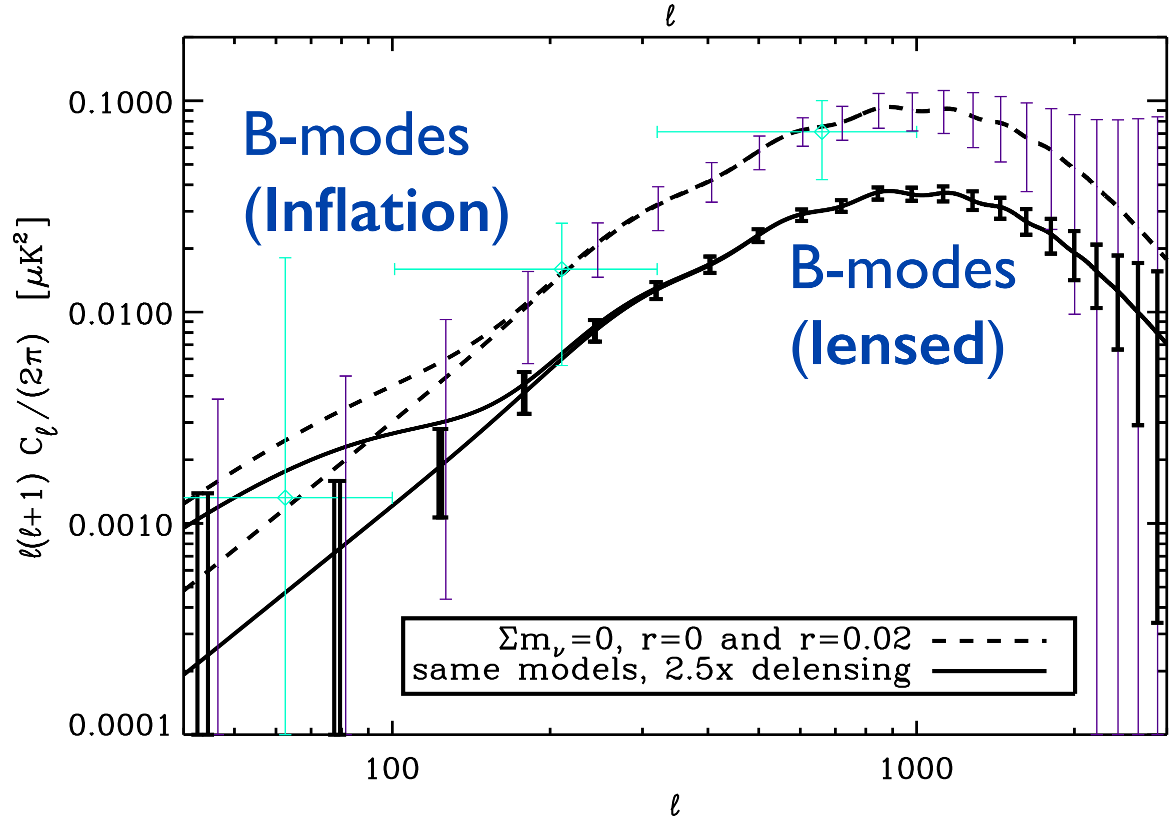
Datta et al.,Journal of Low Temperature Physics September 2014, Volume 176, Issue 5-6, pp 670-676

SPT-3G goals (first light early 2016)

- Target 10x mapping speed of SPTpol
  - 16,000 bolometer array
  - Reduce optical load
  - Double FOV
- Target 2500 deg^2 to 3 uK depth

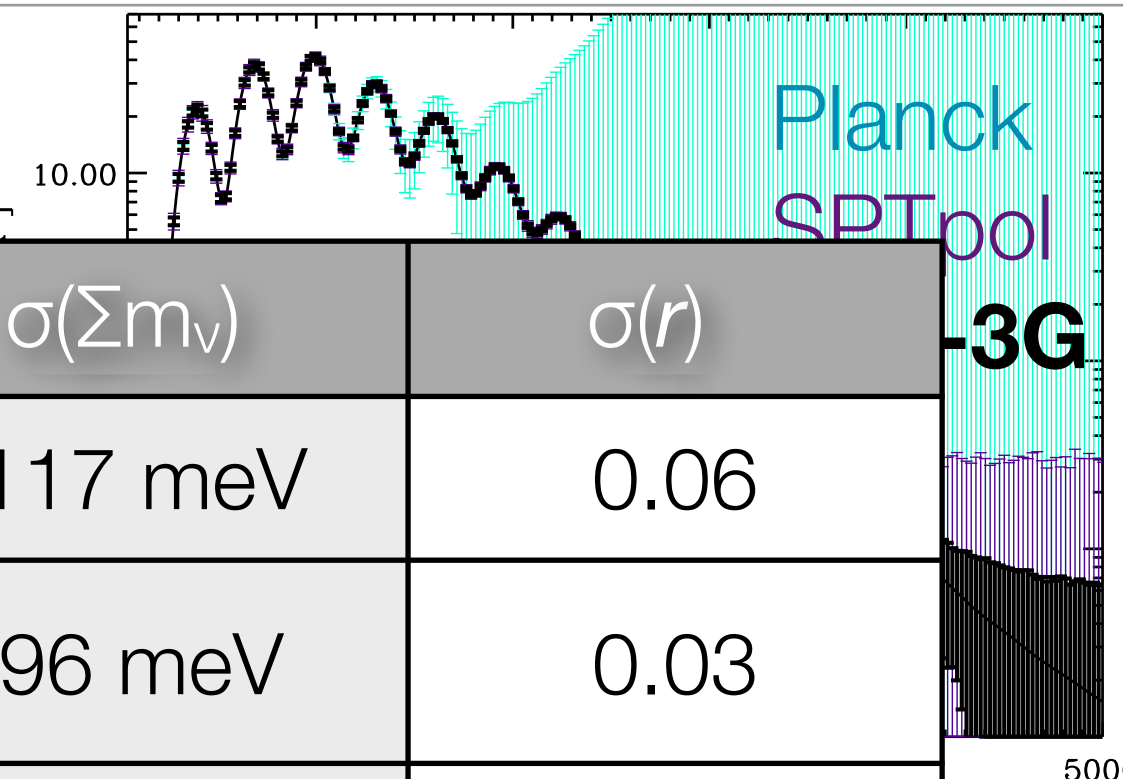




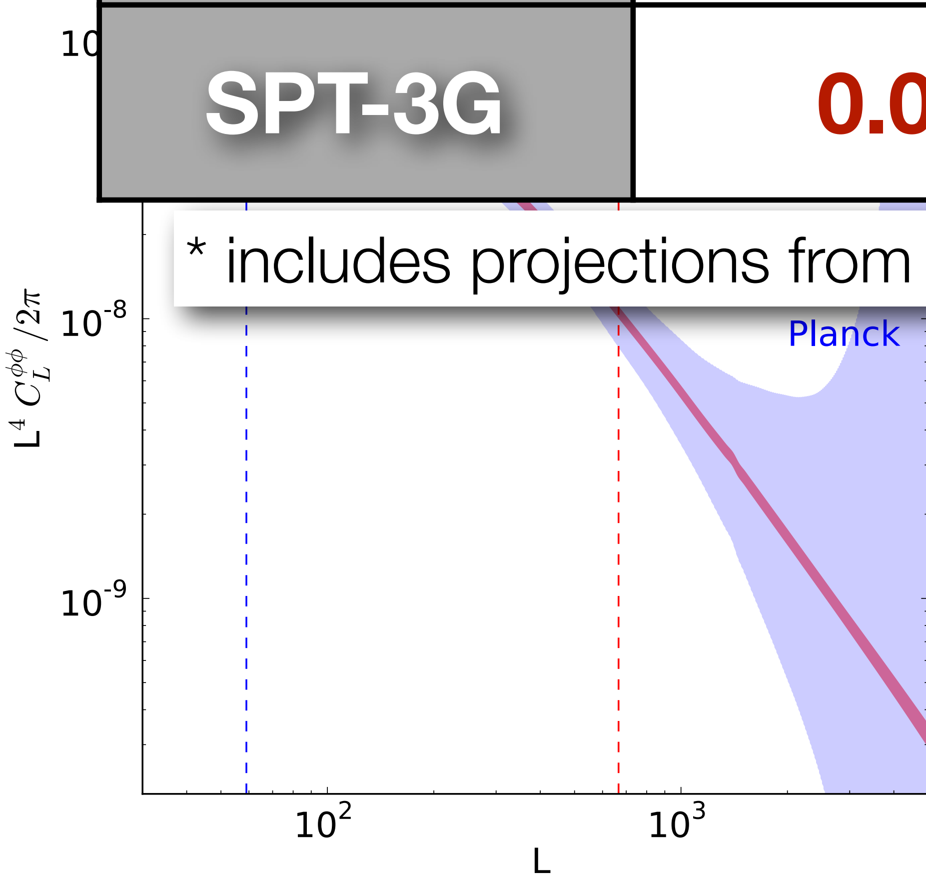


SPT-3G goals (first light early 2016)

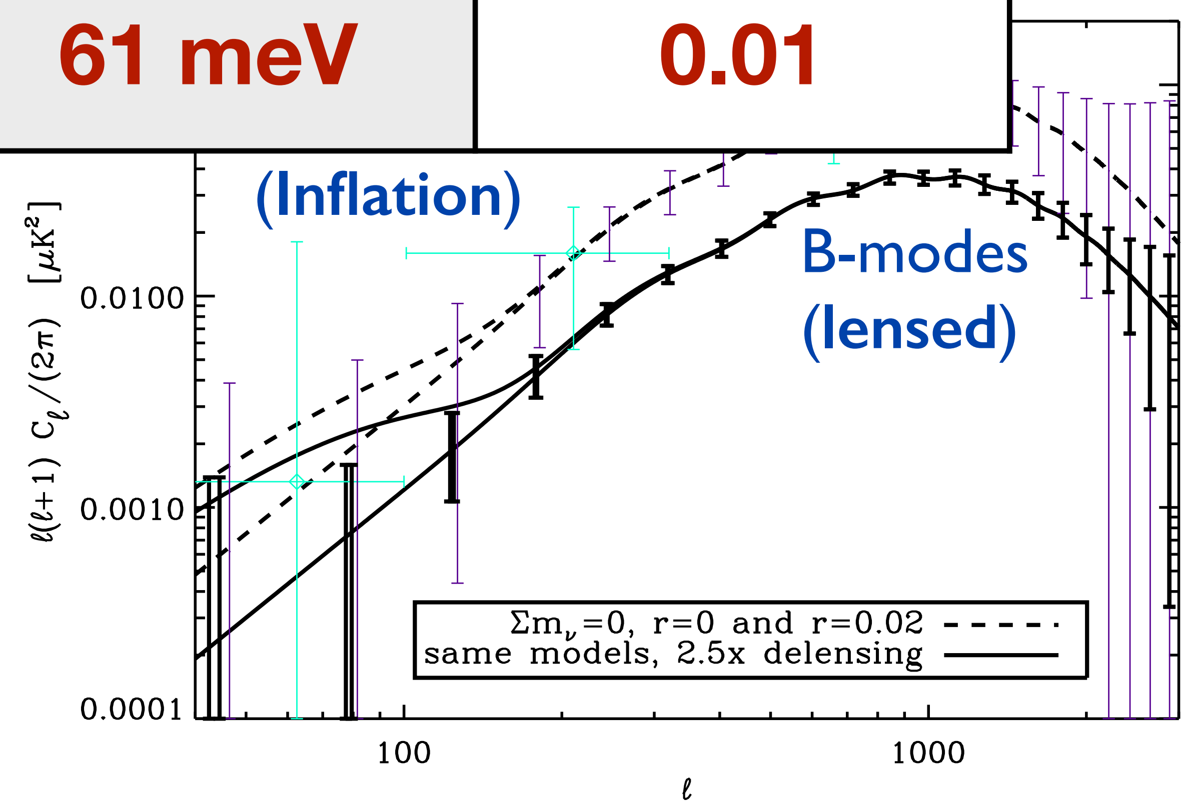
- Target 10x mapping speed of SPTpol
- Ta



	σ(N_{eff})	σ(Σm_ν)	σ(r)
Planck	0.14	117 meV	0.06
SPTpol	0.12	96 meV	0.03
SPT-3G	**0.06**	**61 meV**	**0.01**

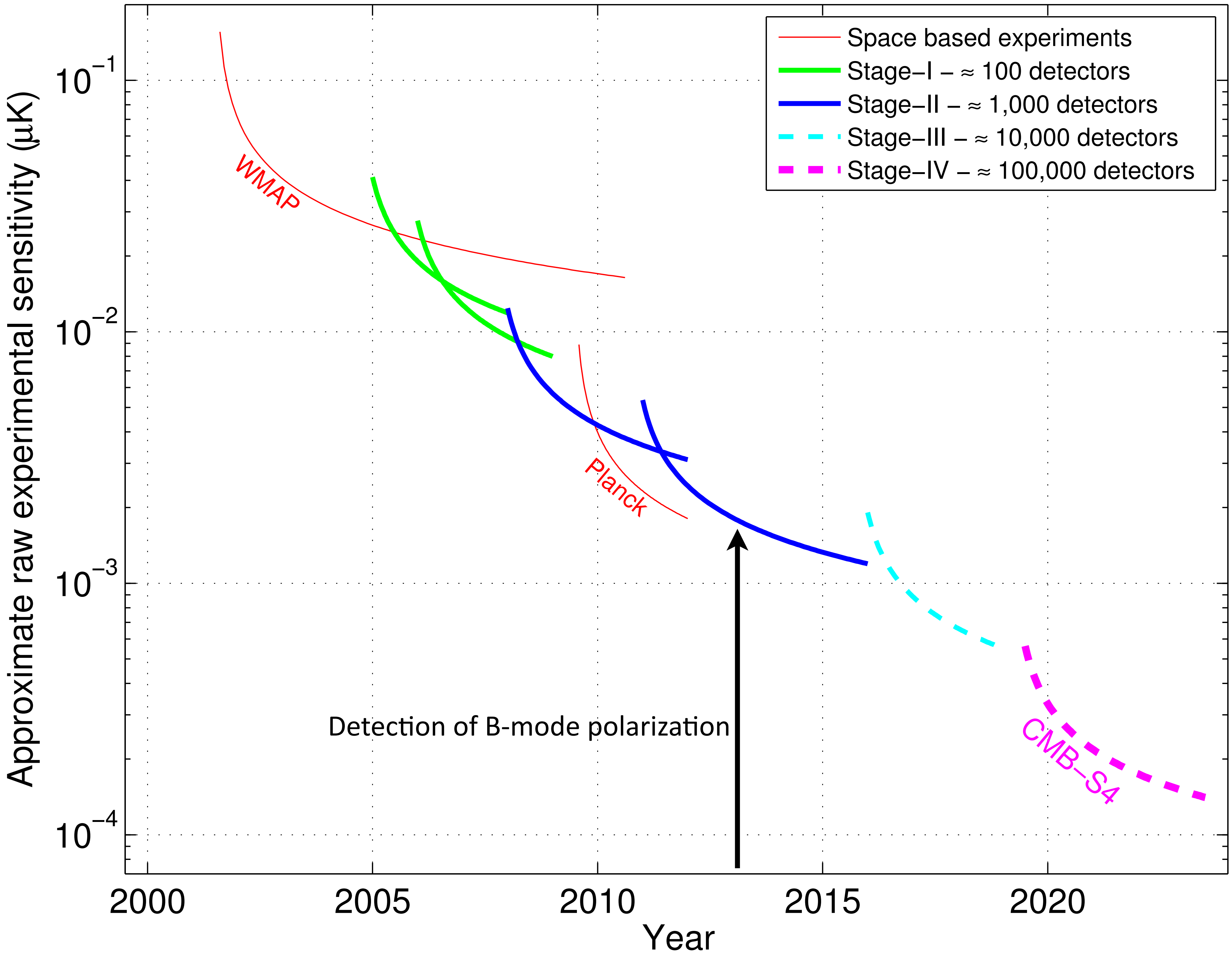


* includes projections from BOSS



Future science with B-modes: CMB-S4

Experimental Evolution



Evolution of CMB Focal Planes

CMB Stage-4 Experiment
Described in Snowmass CF5:
Neutrinos: arxiv:1309.5383
Inflation: arxiv:1309.5381

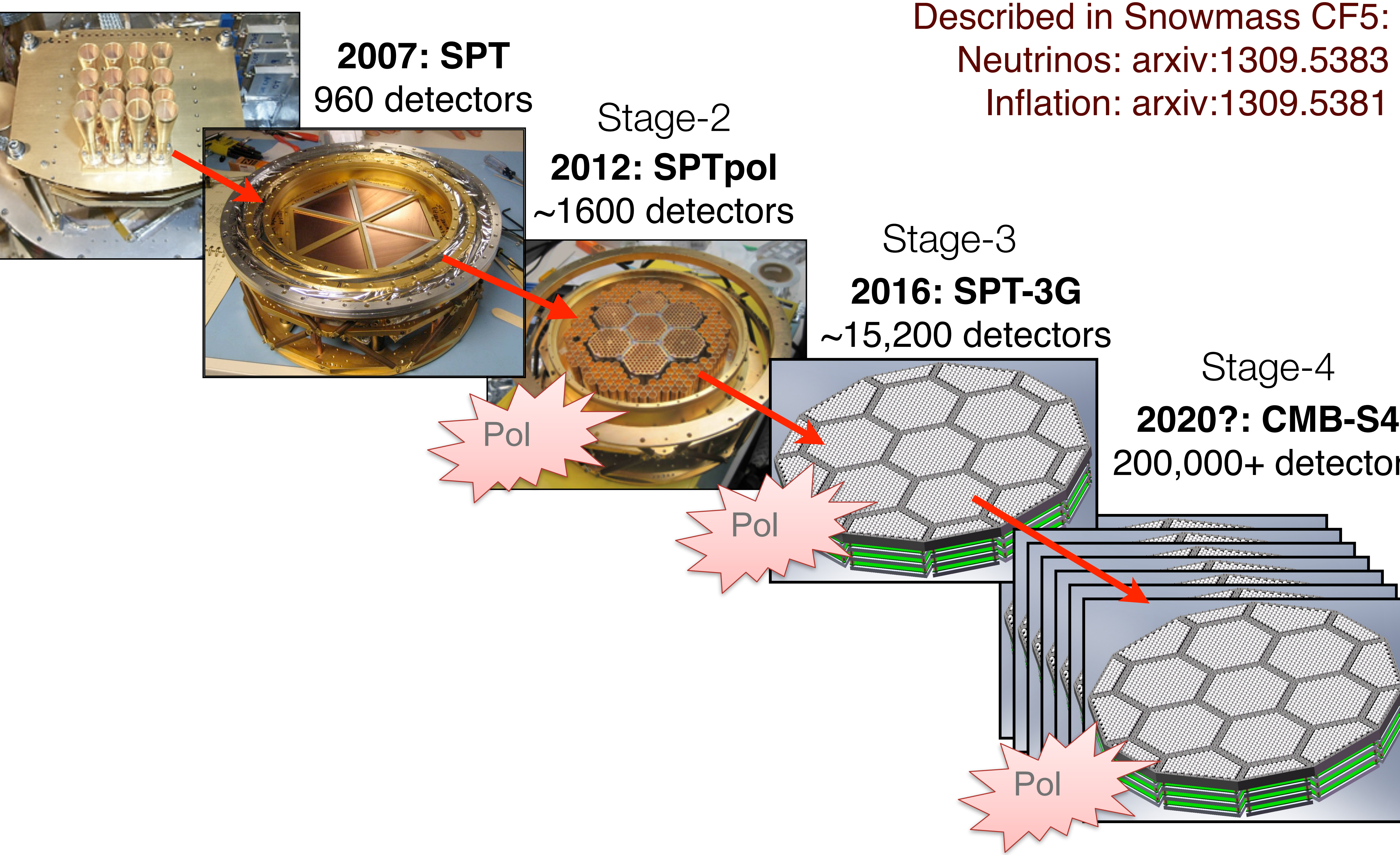
2001: ACBAR
16 detectors

2007: SPT
960 detectors

Stage-2
2012: SPTpol
~1600 detectors

Stage-3
2016: SPT-3G
~15,200 detectors

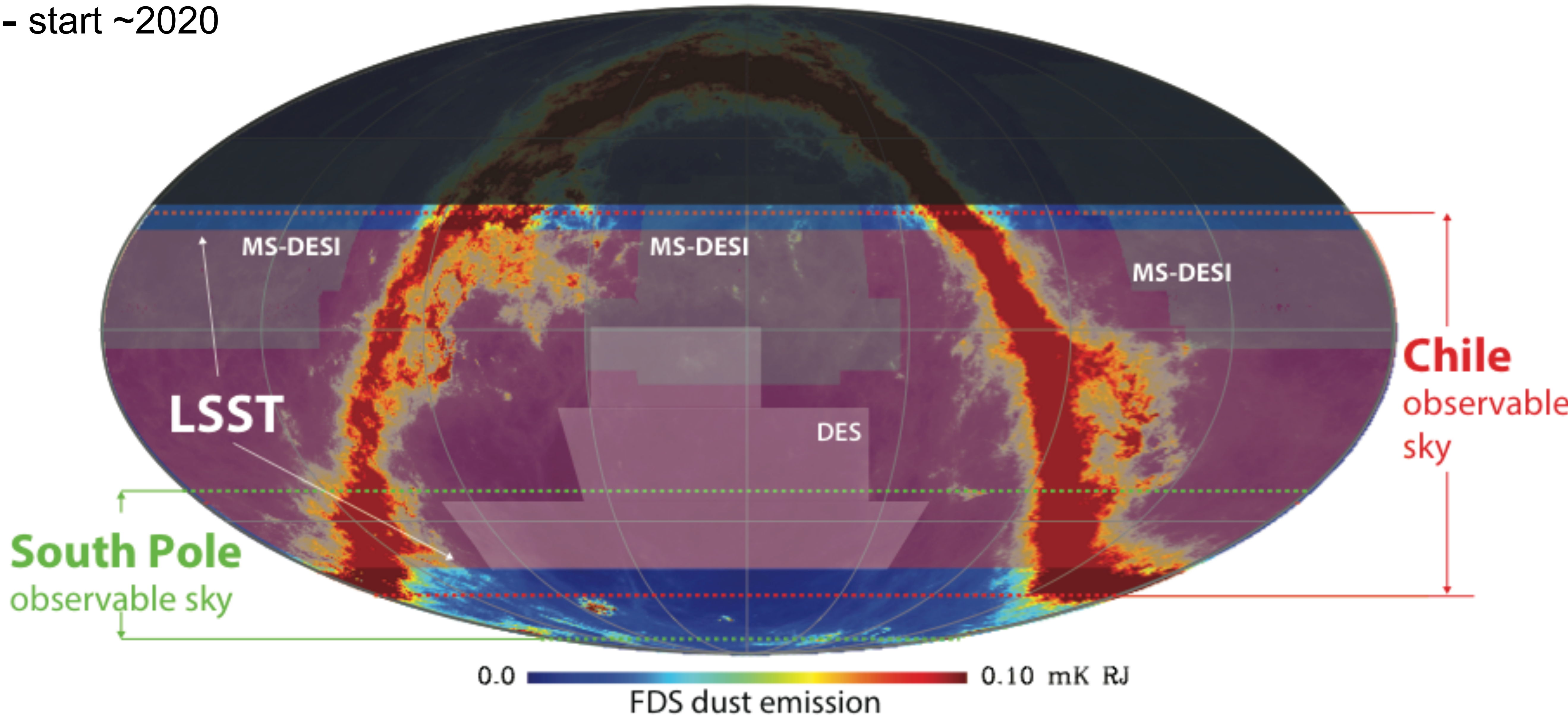
Stage-4
2020?: CMB-S4
200,000+ detectors



'CMB-S4' Stage 4 CMB experiment

(footprint overlap with DES, LSST, DESI, etc)

- 200,000 - 500,000 detectors on multiple platforms
- span 40 - 240 GHz for foreground removal
- target noise of ~1 uK-arcmin depth over half the sky
- start ~2020



Primary technical challenge will be the scaling of the detector arrays

Projected CMB Constraints

	$\sigma(r)$	$\sigma(N_{\mathrm{eff}})$	$\sigma(\Sigma m_\nu)$
Current CMB	**0.1**	**0.34**	**117 meV**
2016 Stage 2: SPTpol	0.03	0.12	96 meV
2020 Stage 3: SPT-3G	0.01	0.06	61[a] meV
2024 Stage 4: CMB-S4	**0.001**	**0.02**	**16[b] meV**

[a] Includes BOSS prior
[b] Includes DESI prior

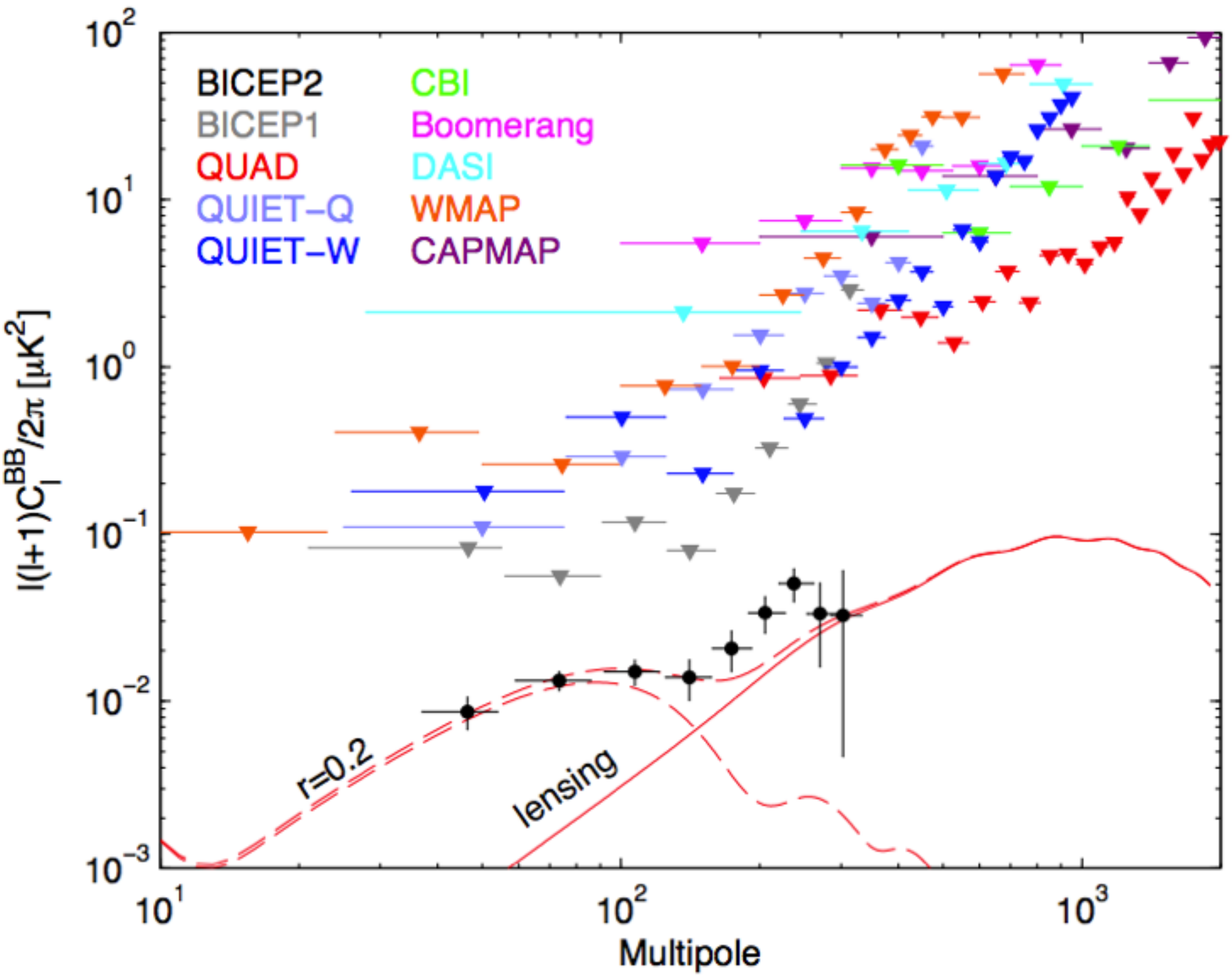
The CMB measurements will achieve important benchmarks:

- Energy scale of inflation? Test large vs small field inflation
- Dark Radiation? New physics in neutrino or dark sector?
- Cosmological detection of neutrino mass, Σm_ν.

Snowmass: CF5 Neutrinos + Inflation documents arXiv:1309.5383, 1309.5381, see also Wu et al., arXiv:1402.4108

BICEP2

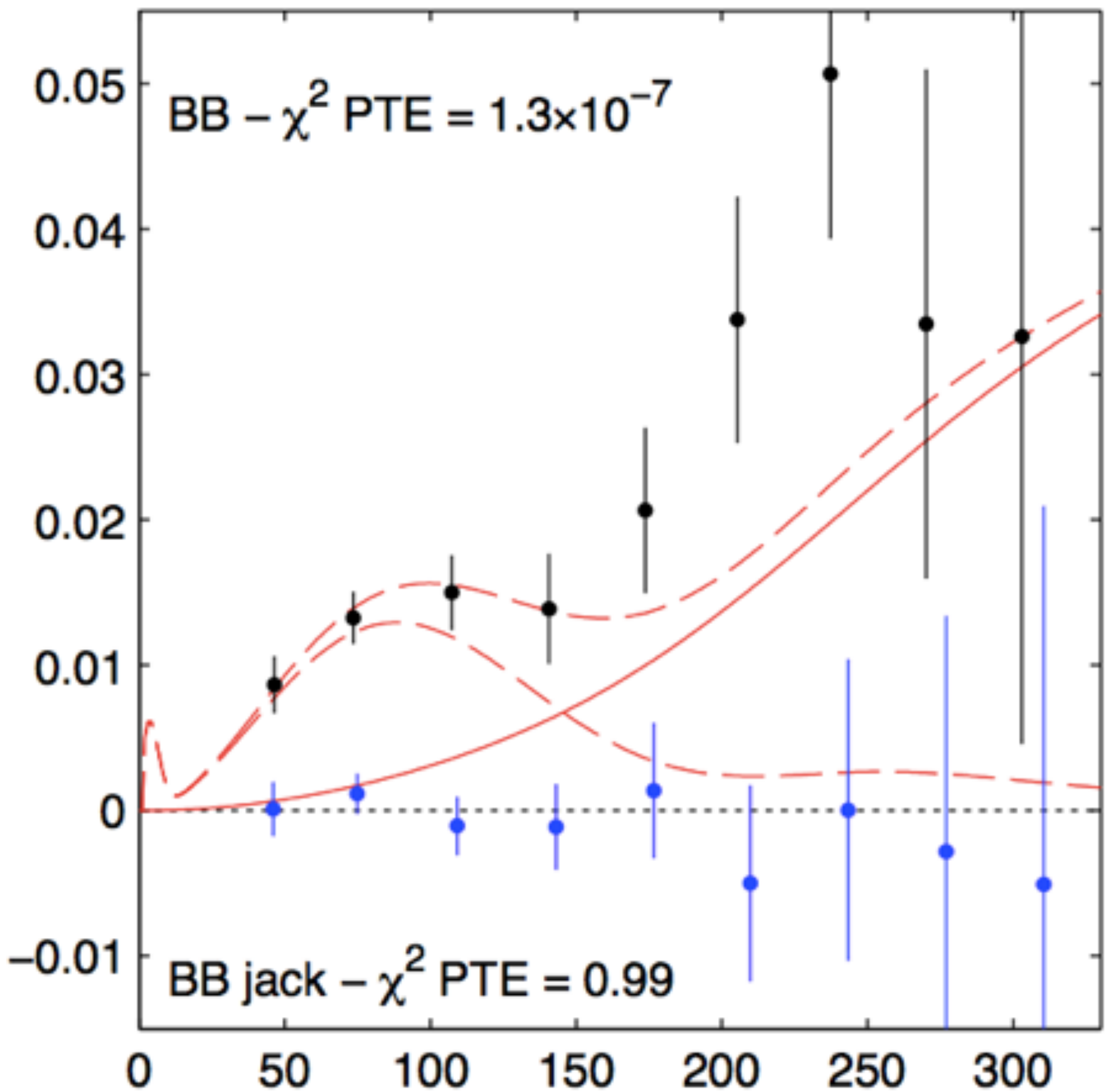
The money plot

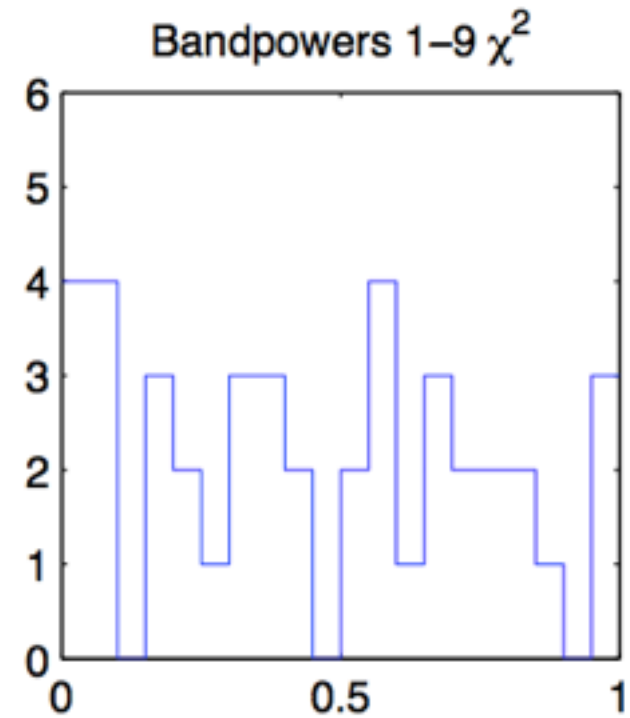


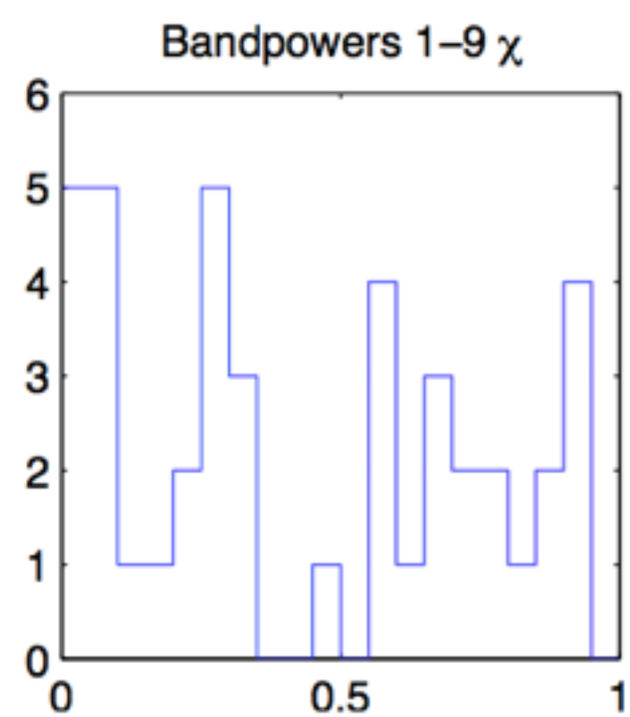
Systematics - I

- Jackknife:
  - Split maps along some criteria.
  - Subtract maps from each other. Common sky signal cancels.
  - Systematic effects may not difference away.
  - Vary split criteria to investigate spectrum of systematics.

Systematics - I



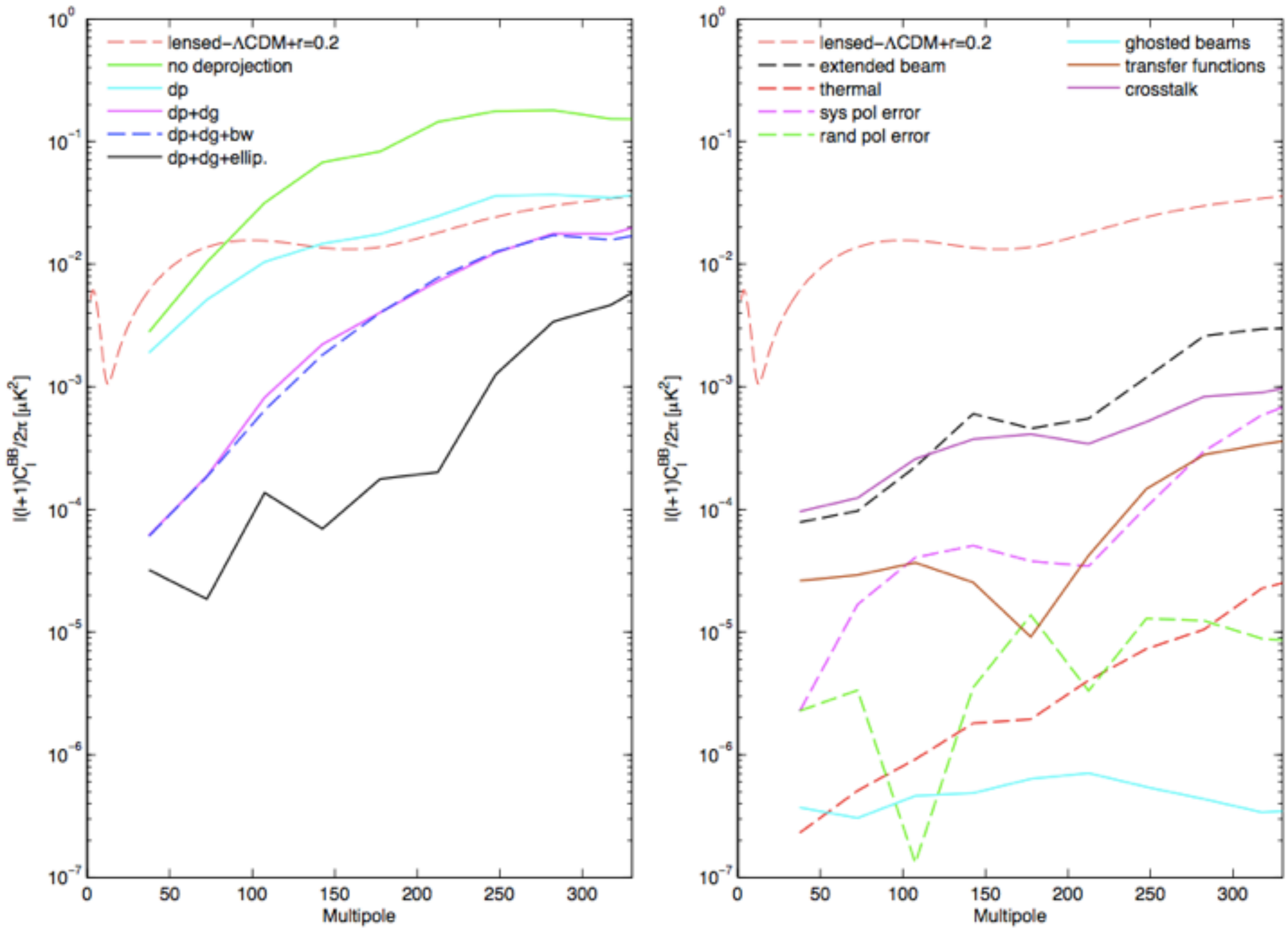




Systematics - II

- All systematics can be referred to “the sky” as an effective “beam”
- Leakage: Errors in polarization signal reconstruction can create false B-mode signal. Most dangerous is leakage from CMB T/E signals as those are the brightest.
- Map beam response to a source and simulate impact on data.

Systematics - II

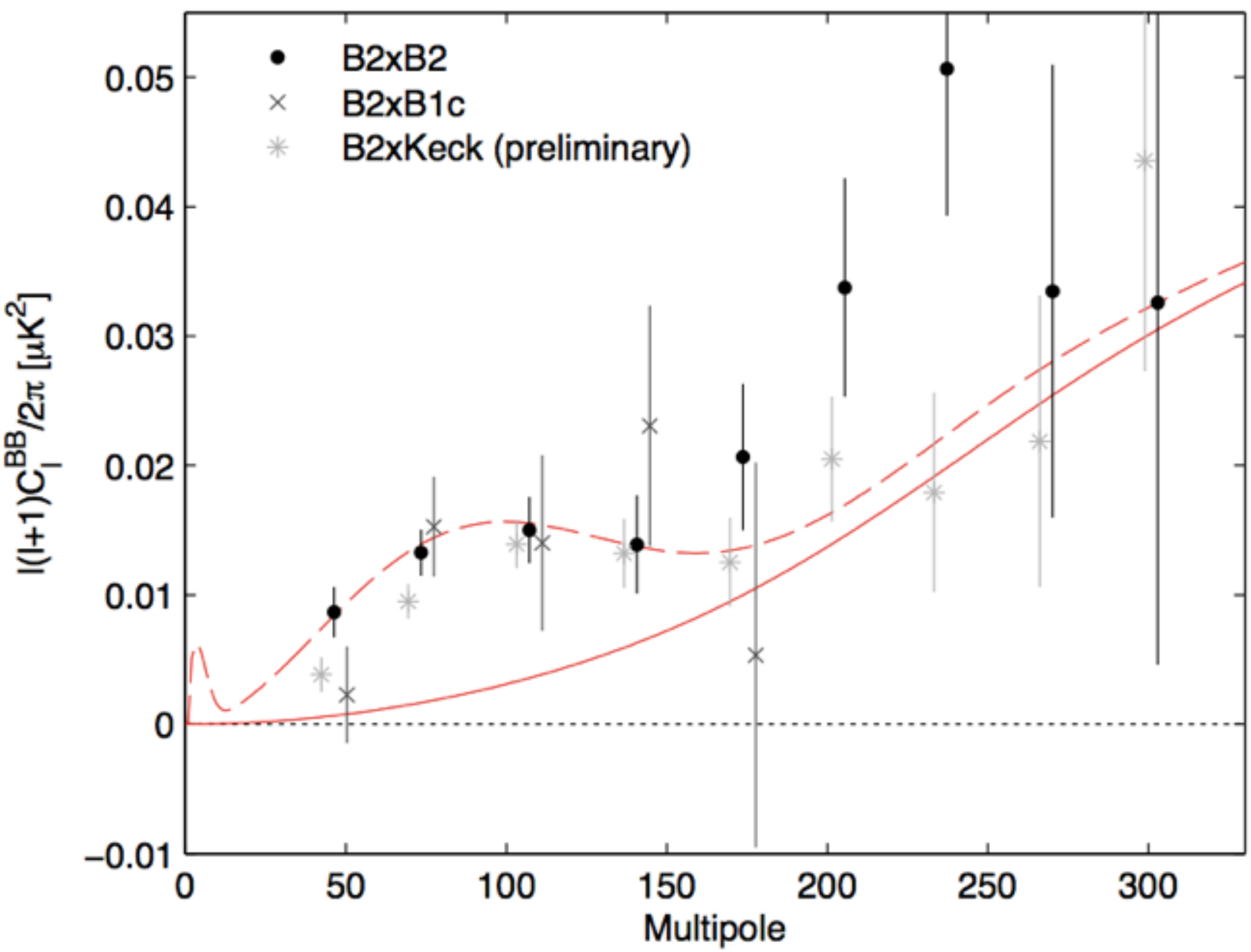


Systematics - III

- Cross-correlation of signal with other measurements is powerful as only sky signal and systematics in common between the experiments remains.

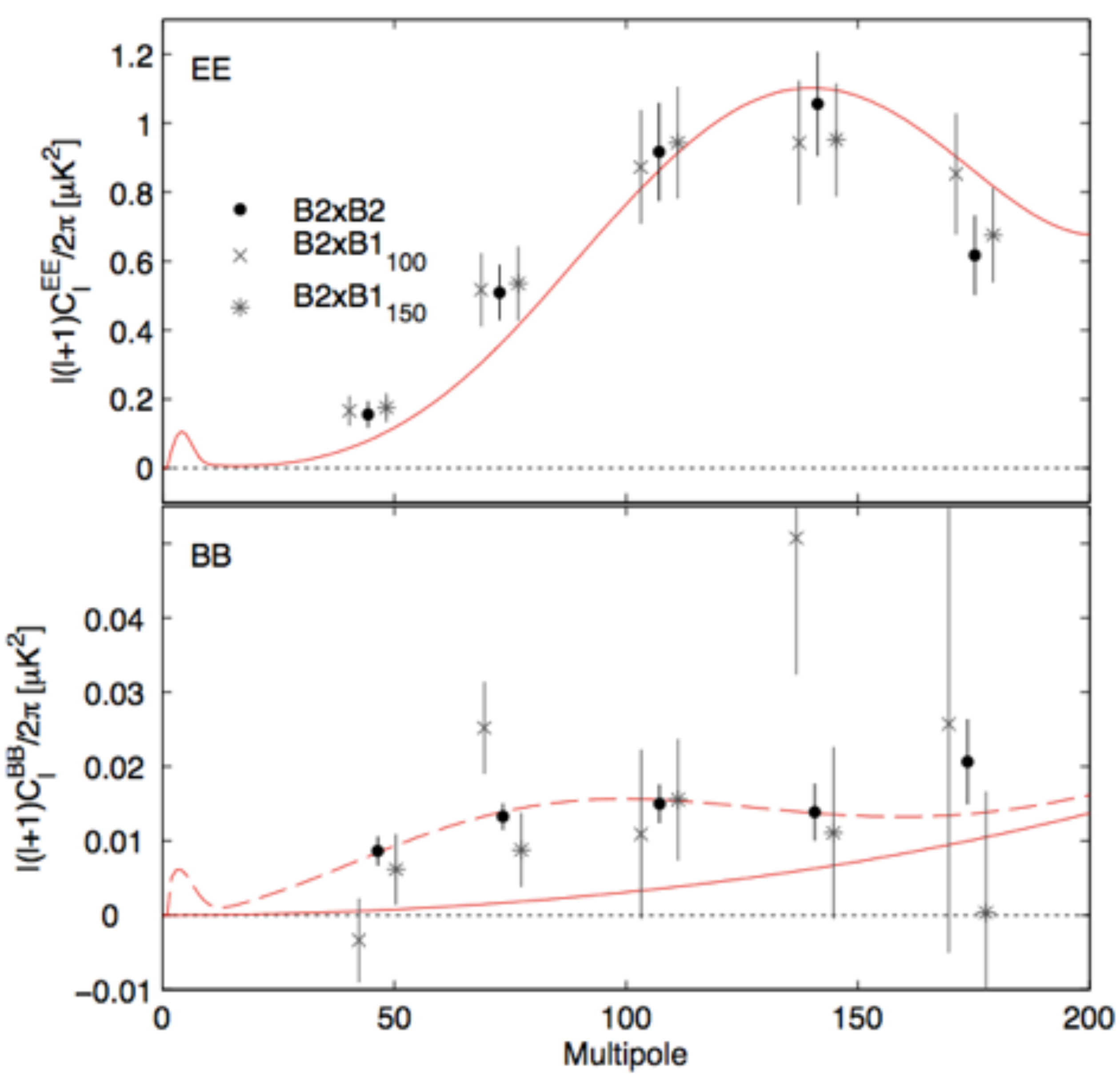
- Cross-correlate B2 with full B1 data (different focal plane, less sensitivity) and KECK array (different platform)

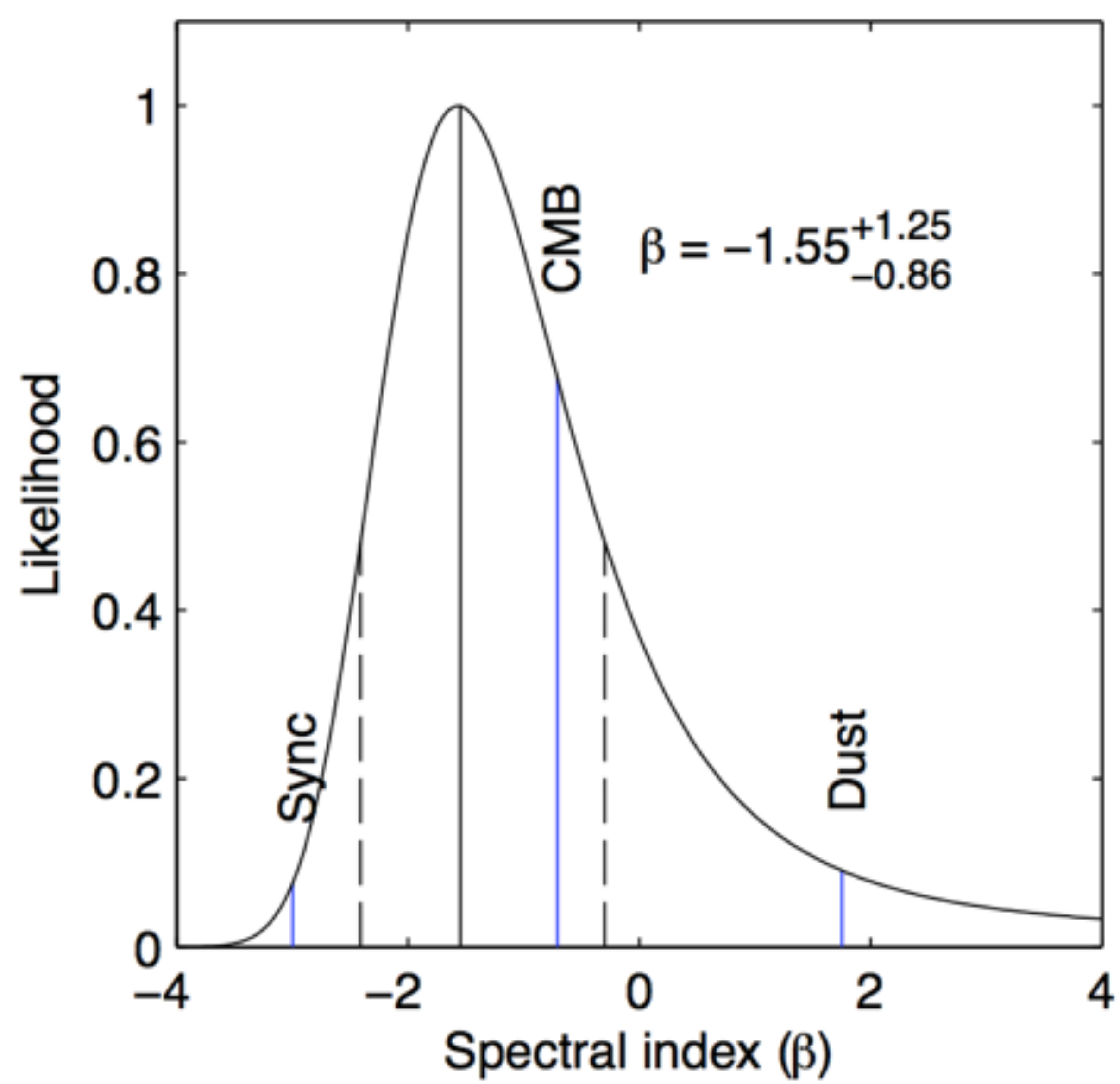
Systematics - III



Foregrounds

- Spectral information is best discriminator of foregrounds vs CMB. Cross-spectrum with B1 100 GHz.





Foregrounds

- most pernicious foreground at 150 GHz will be polarized galactic dust emission
- Consider several dust models and compare shape of angular spectrum and cross-correlation