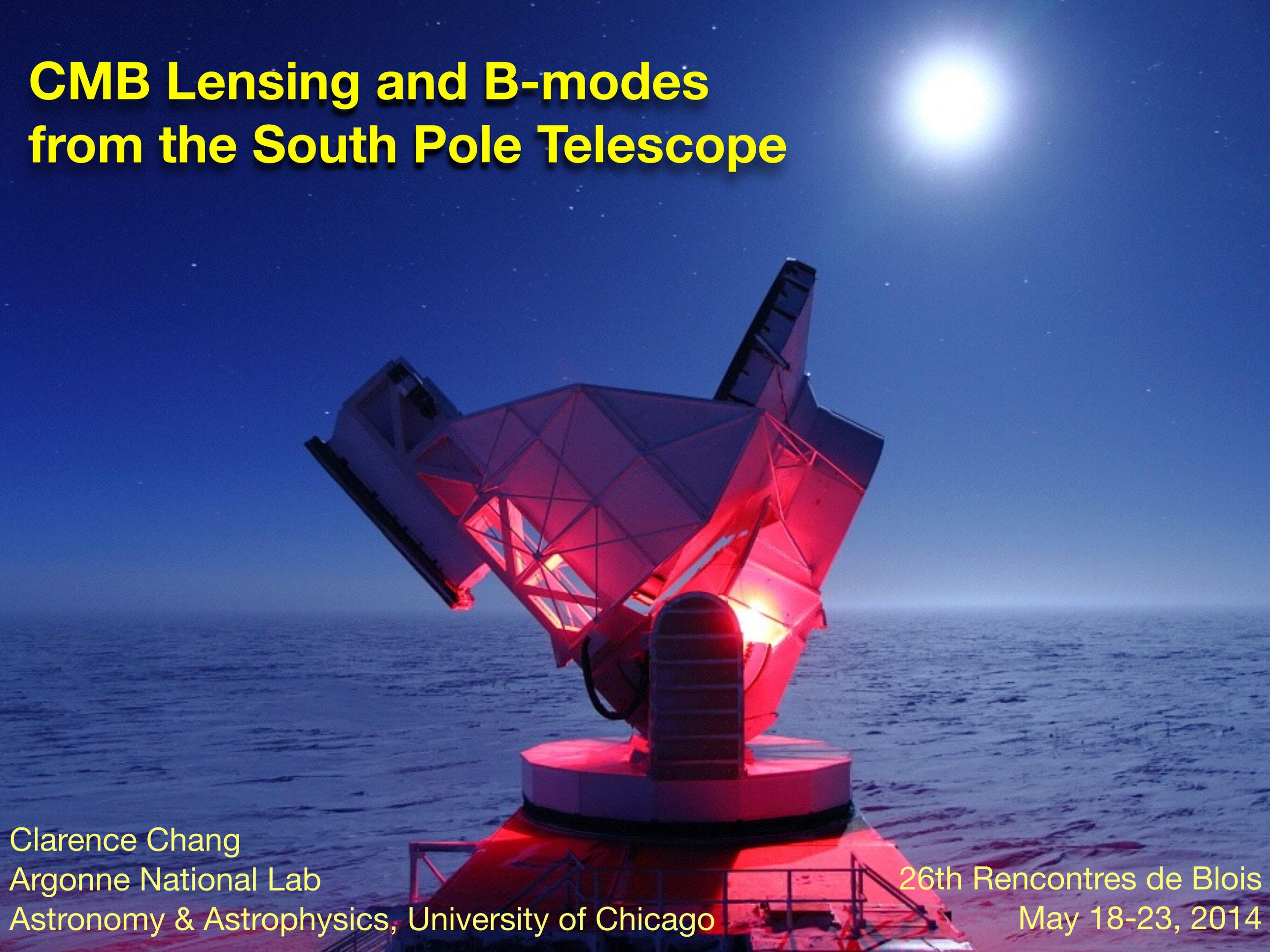
CMB Lensing and B-modes from the South Pole Telescope



Clarence Chang
Argonne National Lab
Astronomy & Astrophysics, University of Chicago

26th Rencontres de Blois
May 18-23, 2014

The South Pole Telescope Collaboration

Argonne NATIONAL LABORATORY

Berkeley Lab

NIST

Fermilab

KICP Kavli Institute for Cosmological Physics AT THE UNIVERSITY OF CHICAGO

Berkeley University of California

Case CASE WESTERN RESERVE UNIVERSITY

McGill

Colorado University of Colorado at Boulder

THE UNIVERSITY OF CHICAGO

LMU

Harvard-Smithsonian Center for Astrophysics

UC DAVIS UNIVERSITY OF CALIFORNIA

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

M

Funded By:

Funded by:

NATIONAL SCIENCE FOUNDATION

U.S. DEPARTMENT OF ENERGY

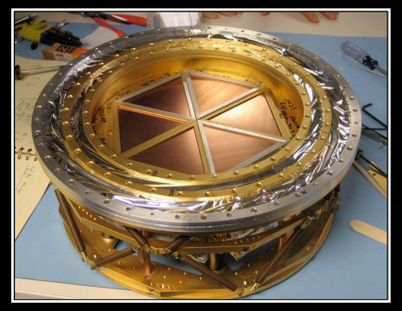
The South Pole Telescope (SPT)

10-meter sub-mm quality wavelength telescope

100, **150**, **220** GHz and
1.6, **1.2**, **1.0** arcmin resolution

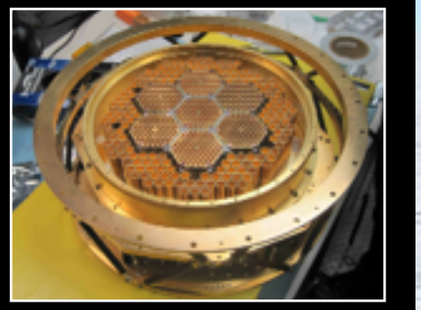
2007: SPT-SZ

960 detectors
100,150,220 GHz



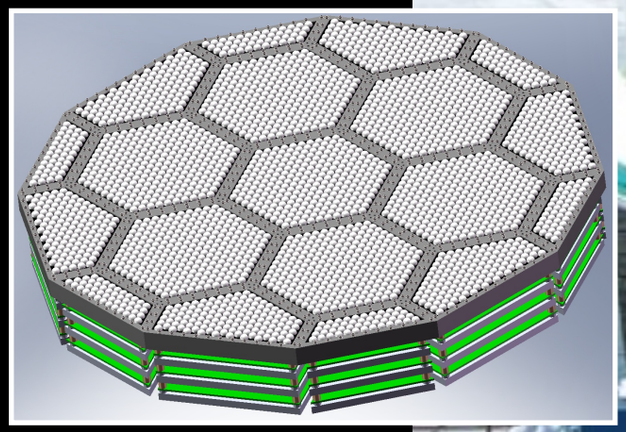
2012: SPTpol

1600 detectors
100,150 GHz
+Polarization



2016: SPT-3G

~15,200 detectors
100,150,220 GHz
+Polarization



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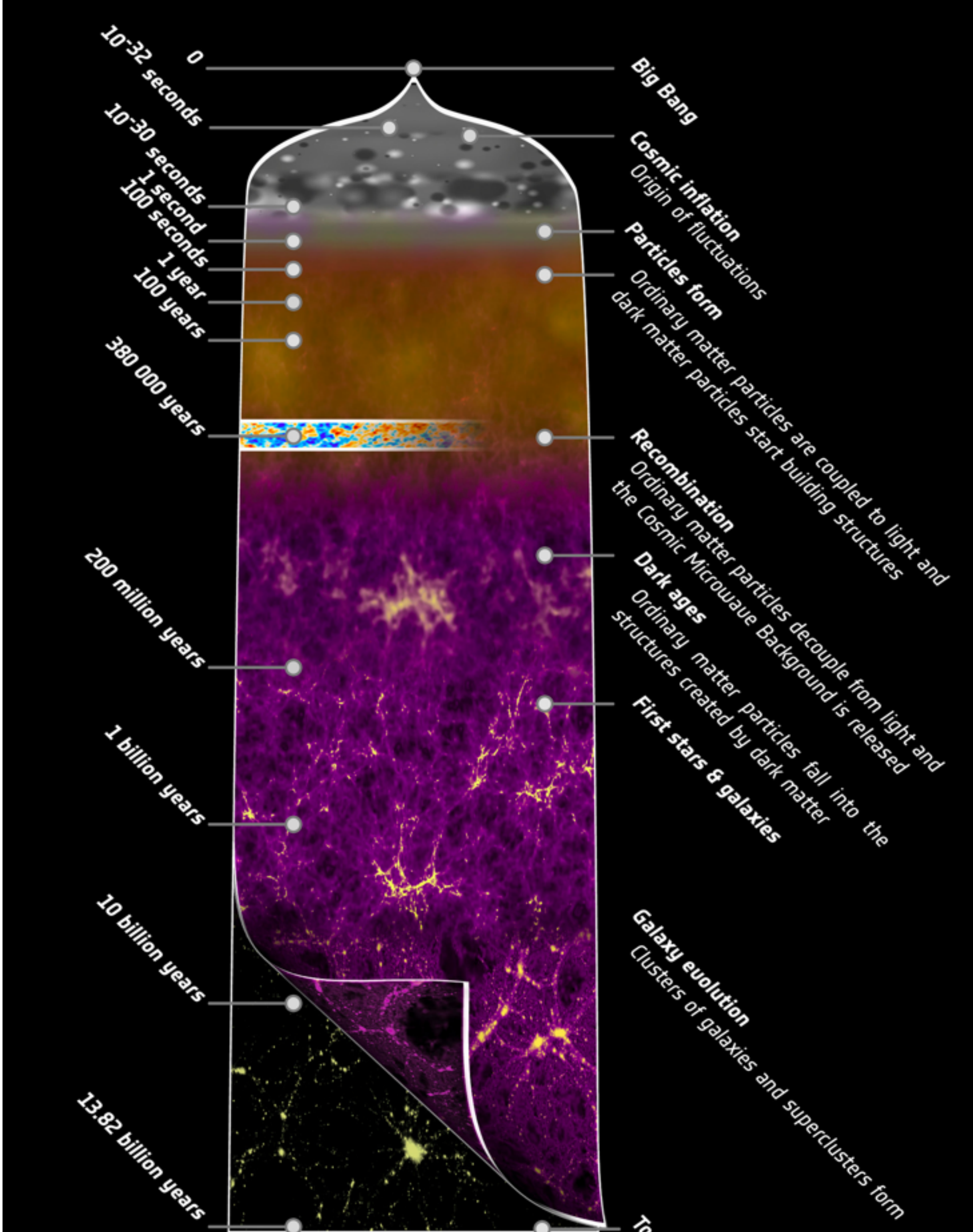
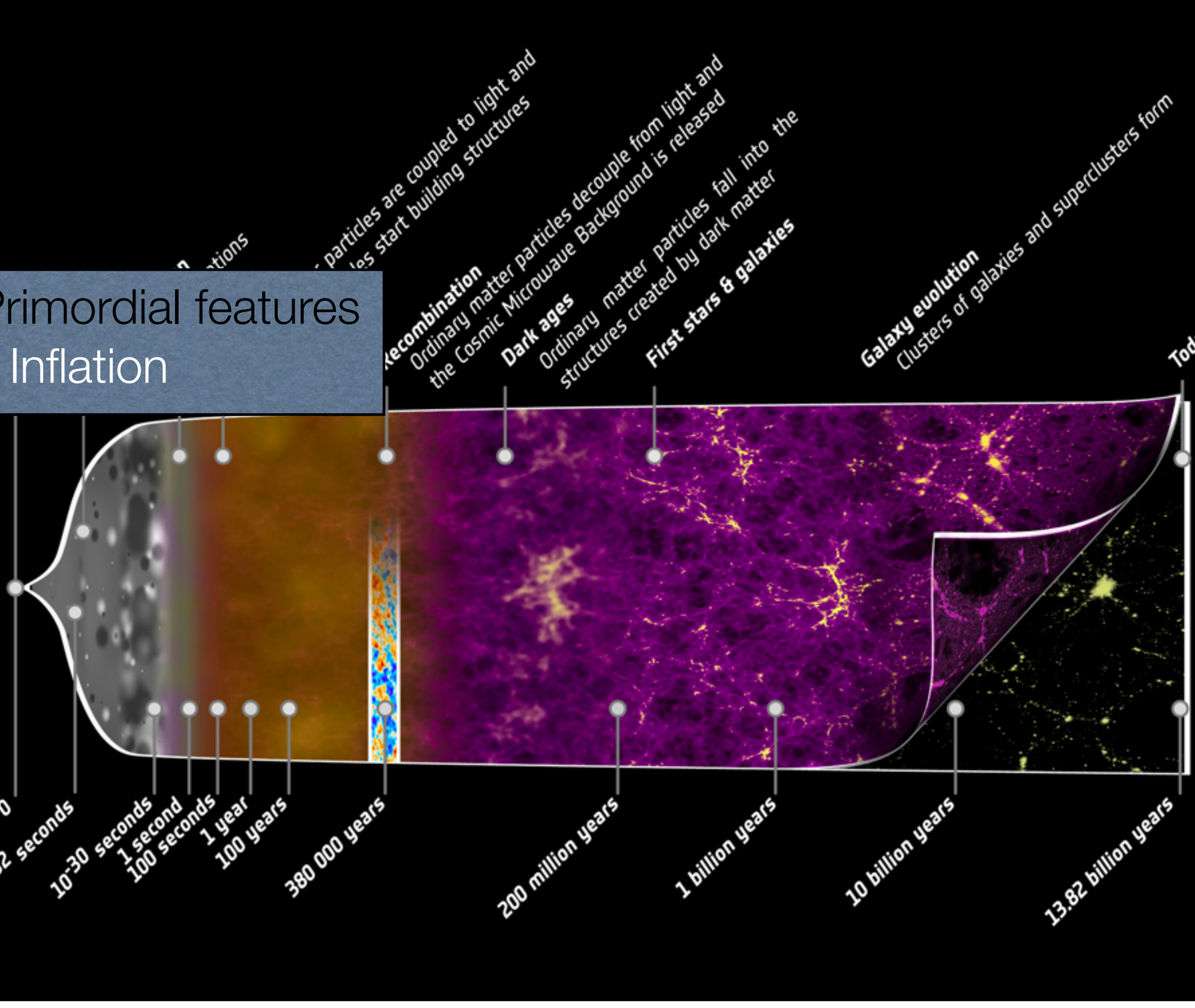

0
Big Bang
10-32 seconds
10-30 seconds
Cosmic inflation
Origin of fluctuations
1 second
100 seconds
Particles form
Ordinary matter particles are coupled to light and
dark matter particles start building structures
1 year
100 years
380 000 years
Recombination
Ordinary matter particles decouple from light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

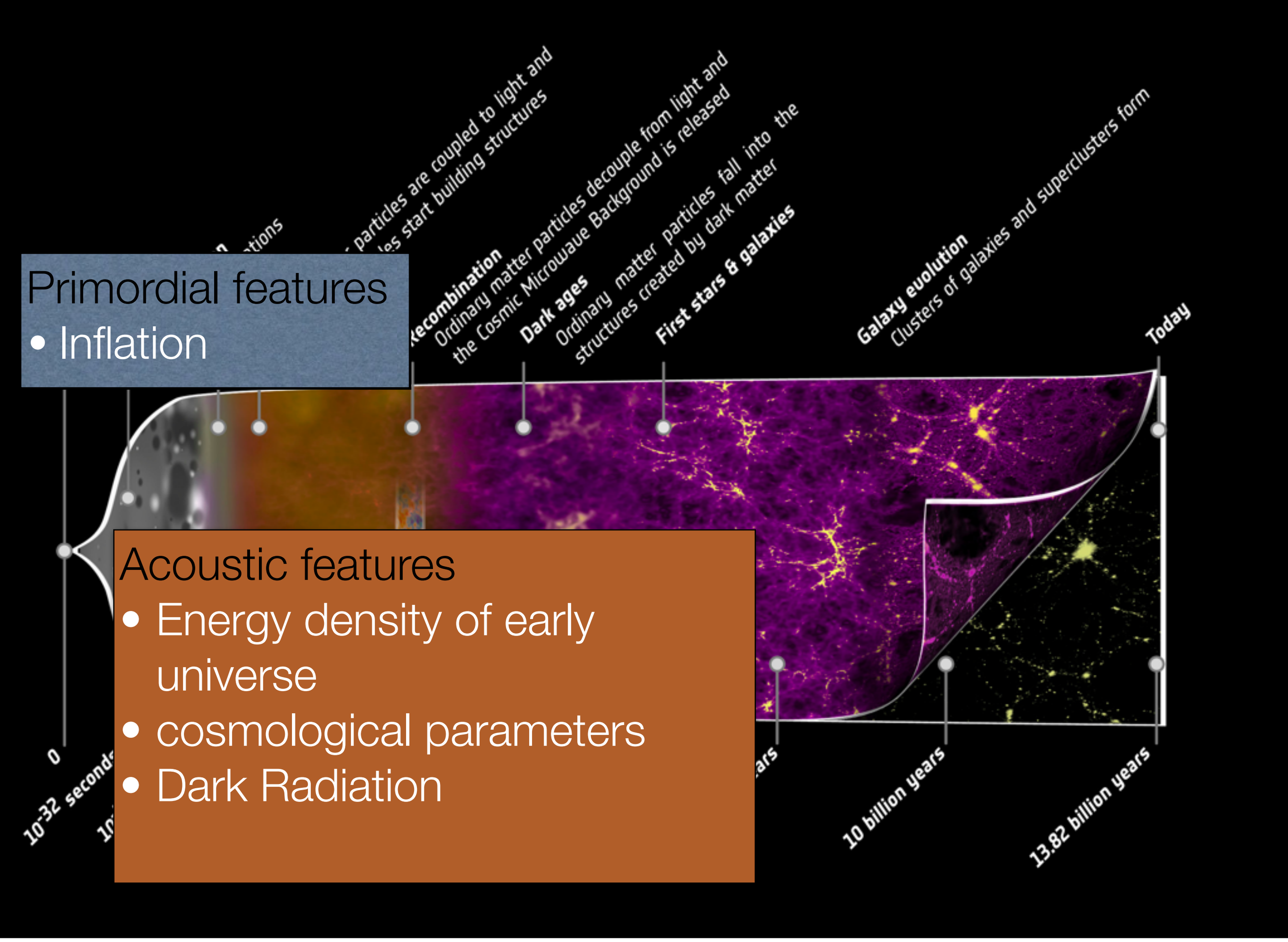
Primordial features

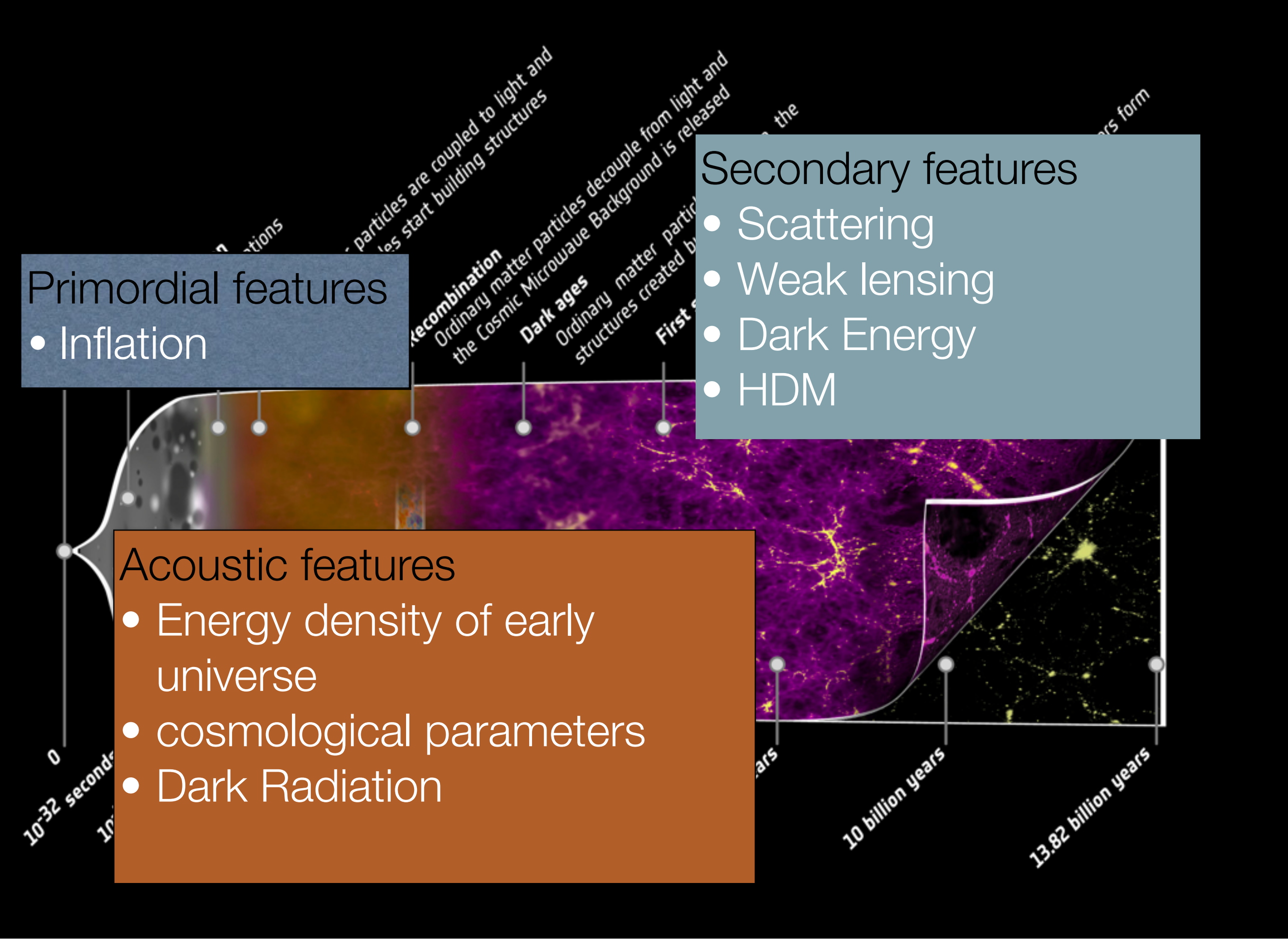
- Inflation



Primordial features
- Inflation

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




particles are coupled to light and
start building structures
Recombination
Ordinary matter particles decouple from light and
the Cosmic Microwave Background is released
Dark ages
Ordinary matter
structures created
First
the
ers form
Primordial features
• Inflation
Secondary features
• Scattering
• Weak lensing
• Dark Energy
• HDM
Acoustic features
• Energy density of early universe
• cosmological parameters
• Dark Radiation
0
10-32 seconds
10 billion years
13.82 billion years

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

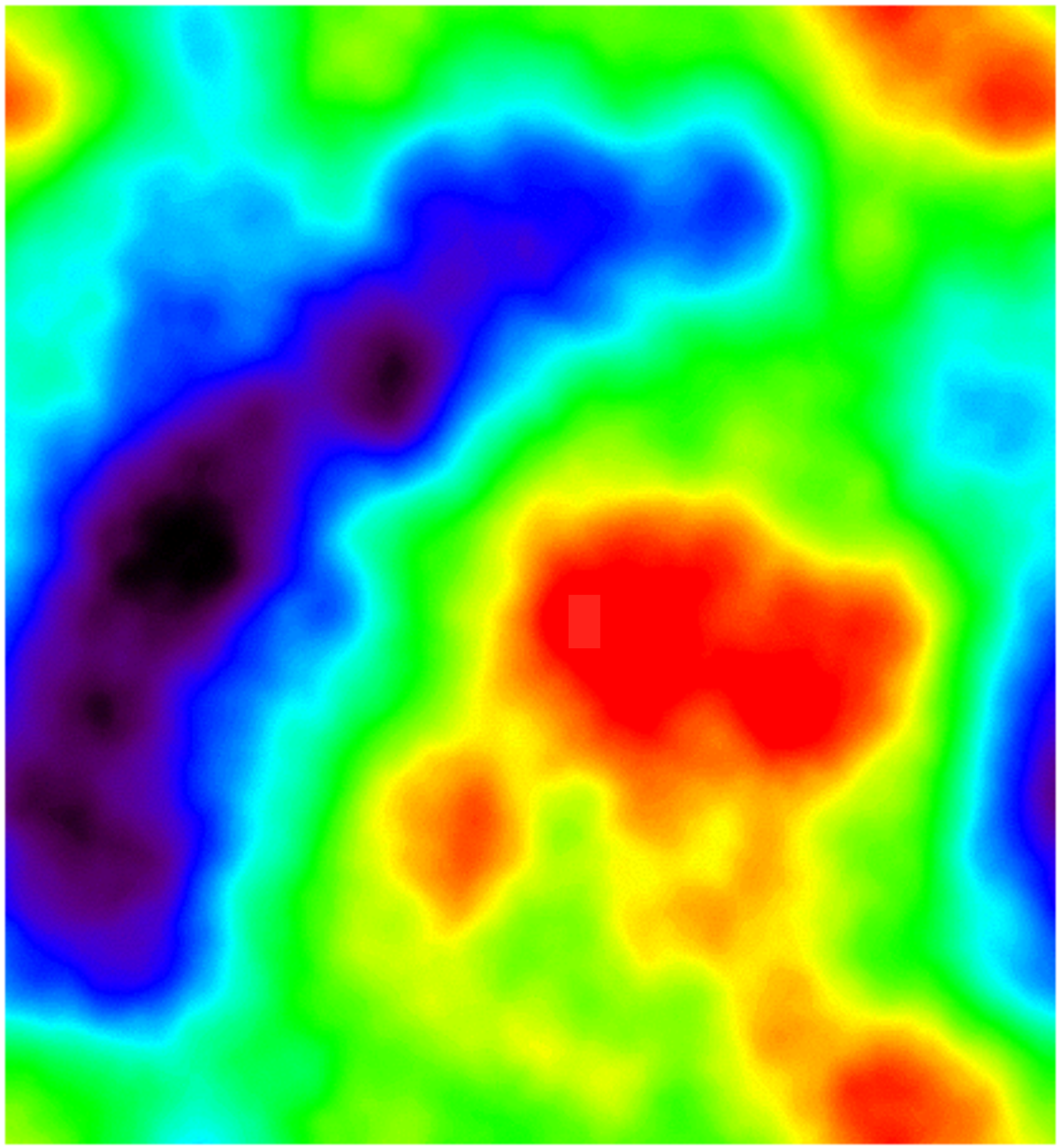
Lensing

Large-Scale Structure Lenses the CMB

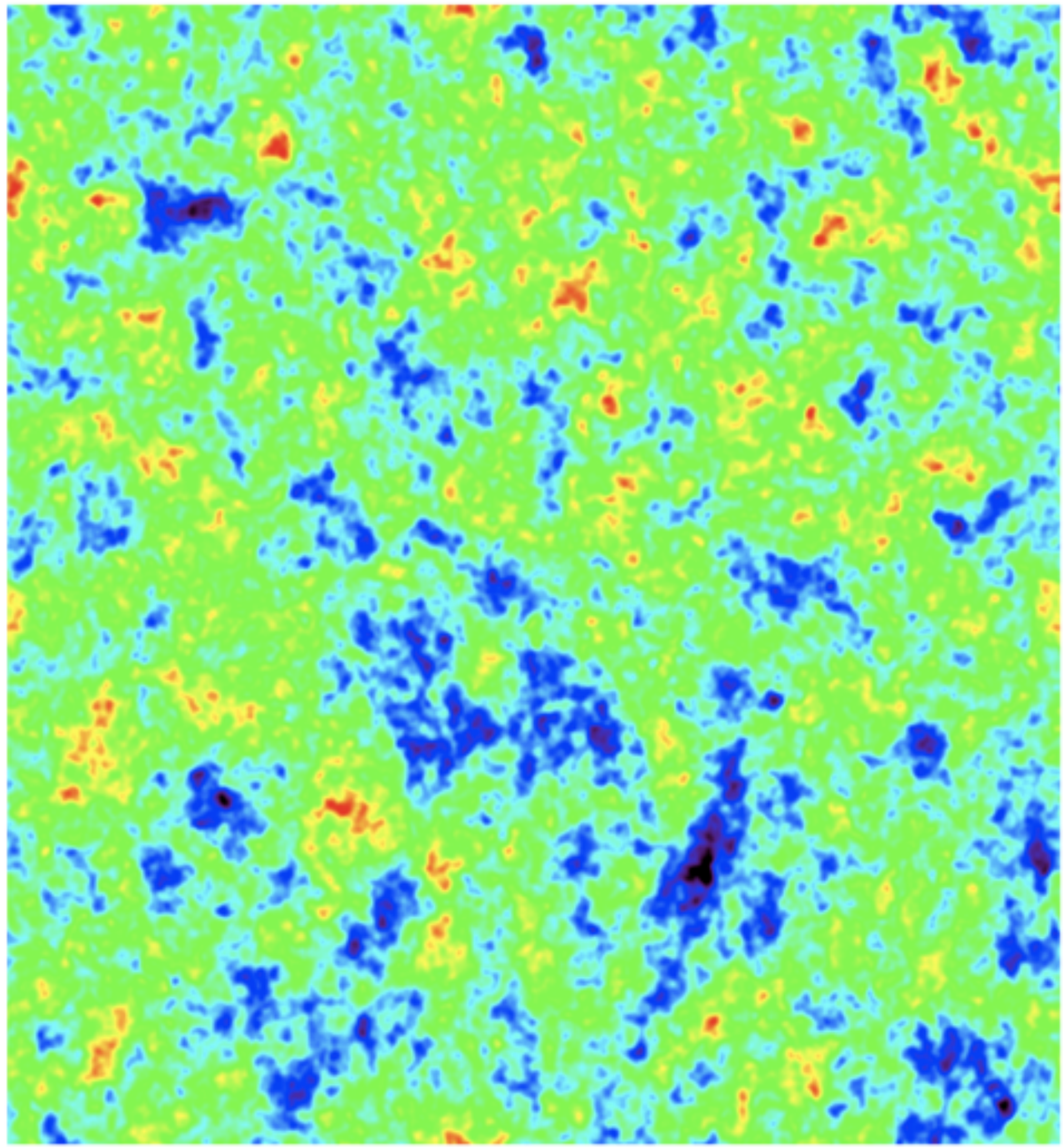
- RMS deflection of ~2.5’
- Lensing efficiency peaks at $z \sim 2$, or 7000 Mpc distance
- Coherent on ~degree (~300 Mpc) scales

Lensing of the CMB

17°x17°



lensing potential

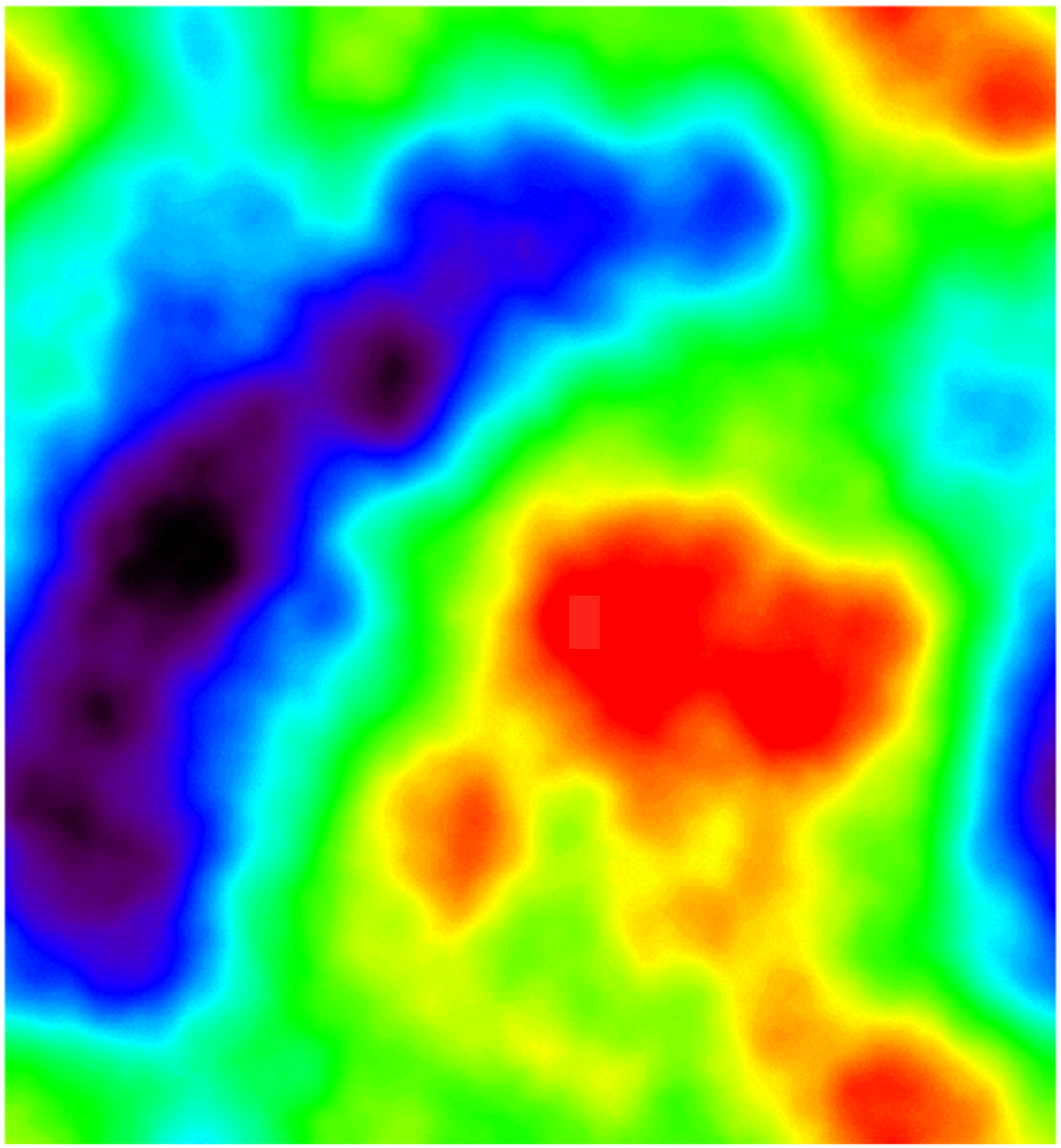


unlensed cmb

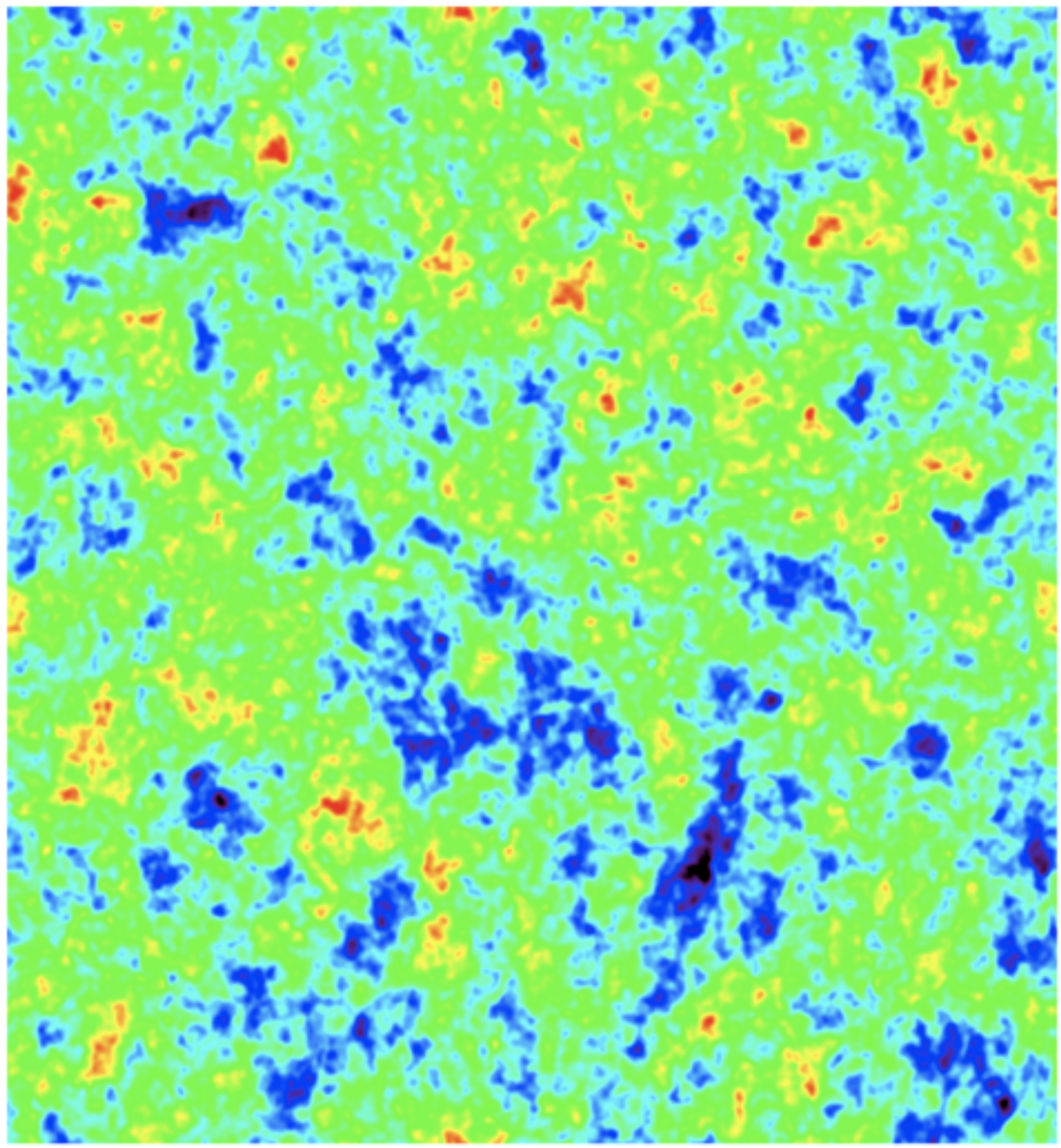
from Alex van Engelen

Lensing of the CMB

17°x17°



lensing potential

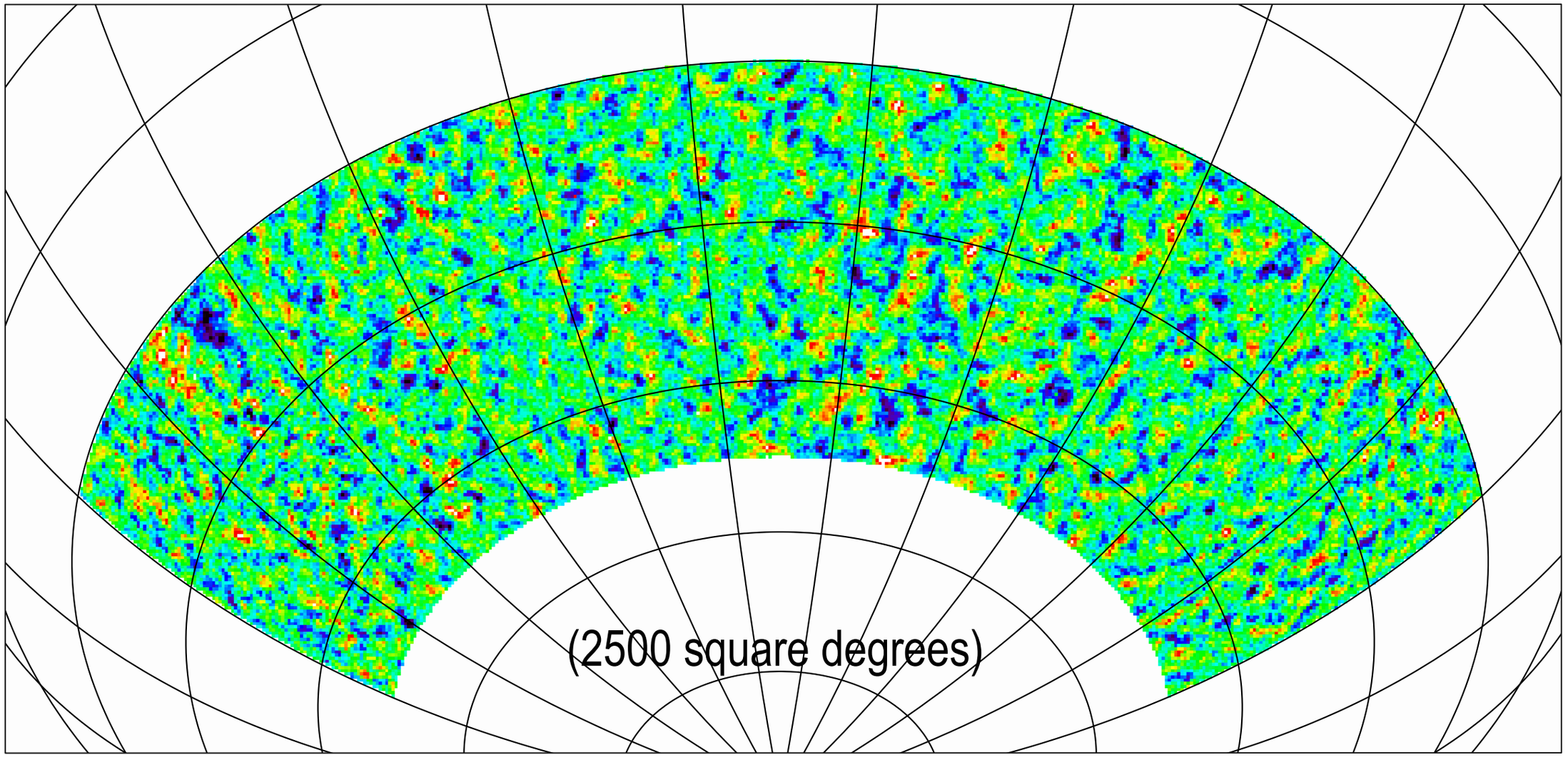


lensed cmb

from Alex van Engelen

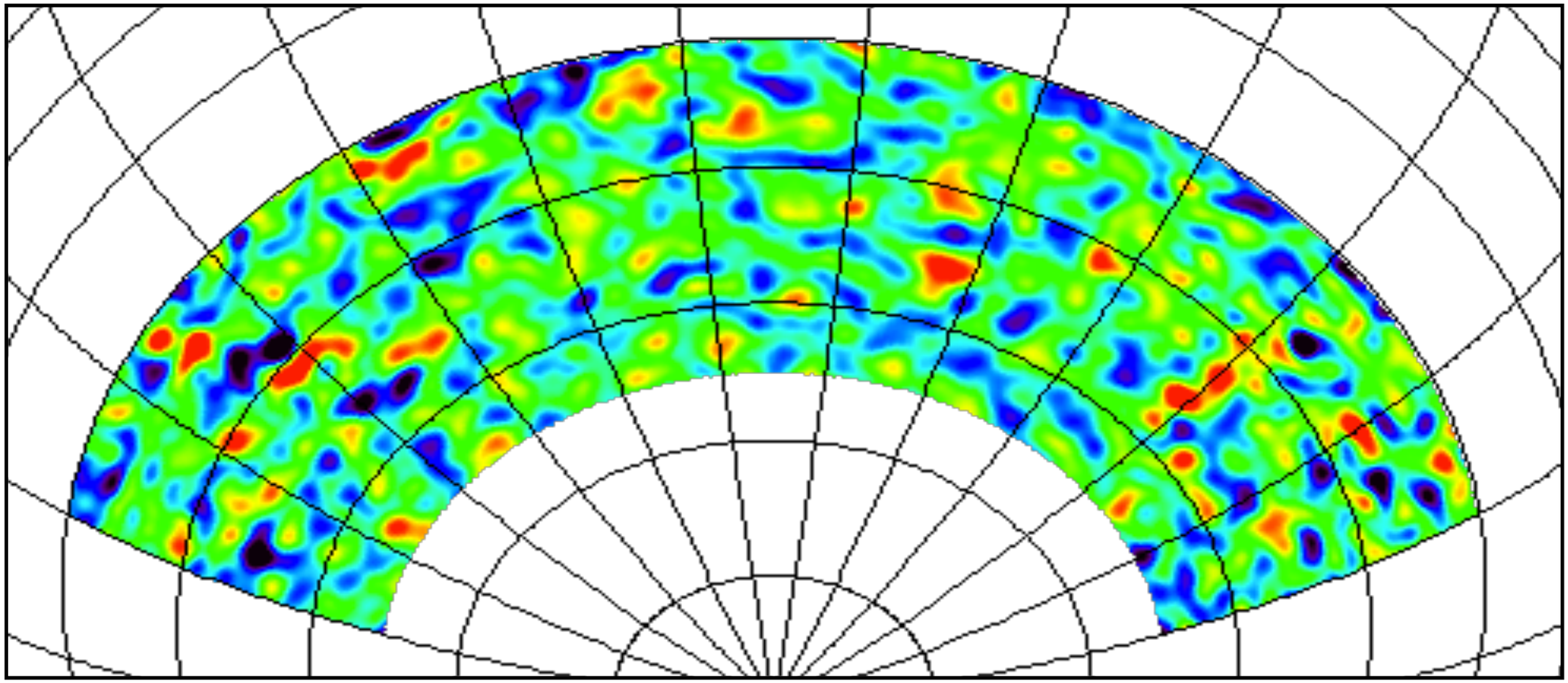
high resolution and sensitivity map of the CMB from SPT

covering 1/16 of the sky

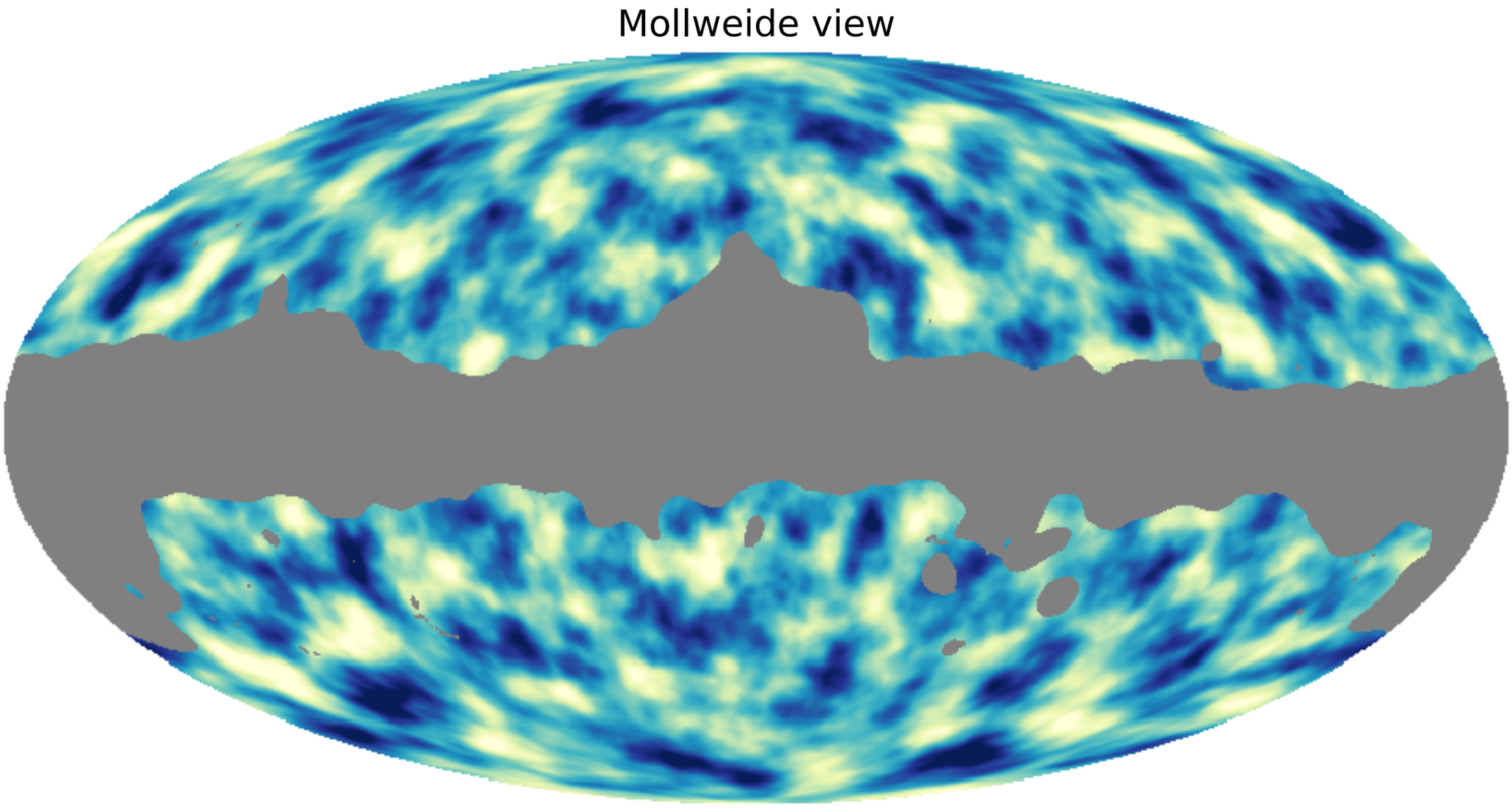


CMB Lensing Map

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

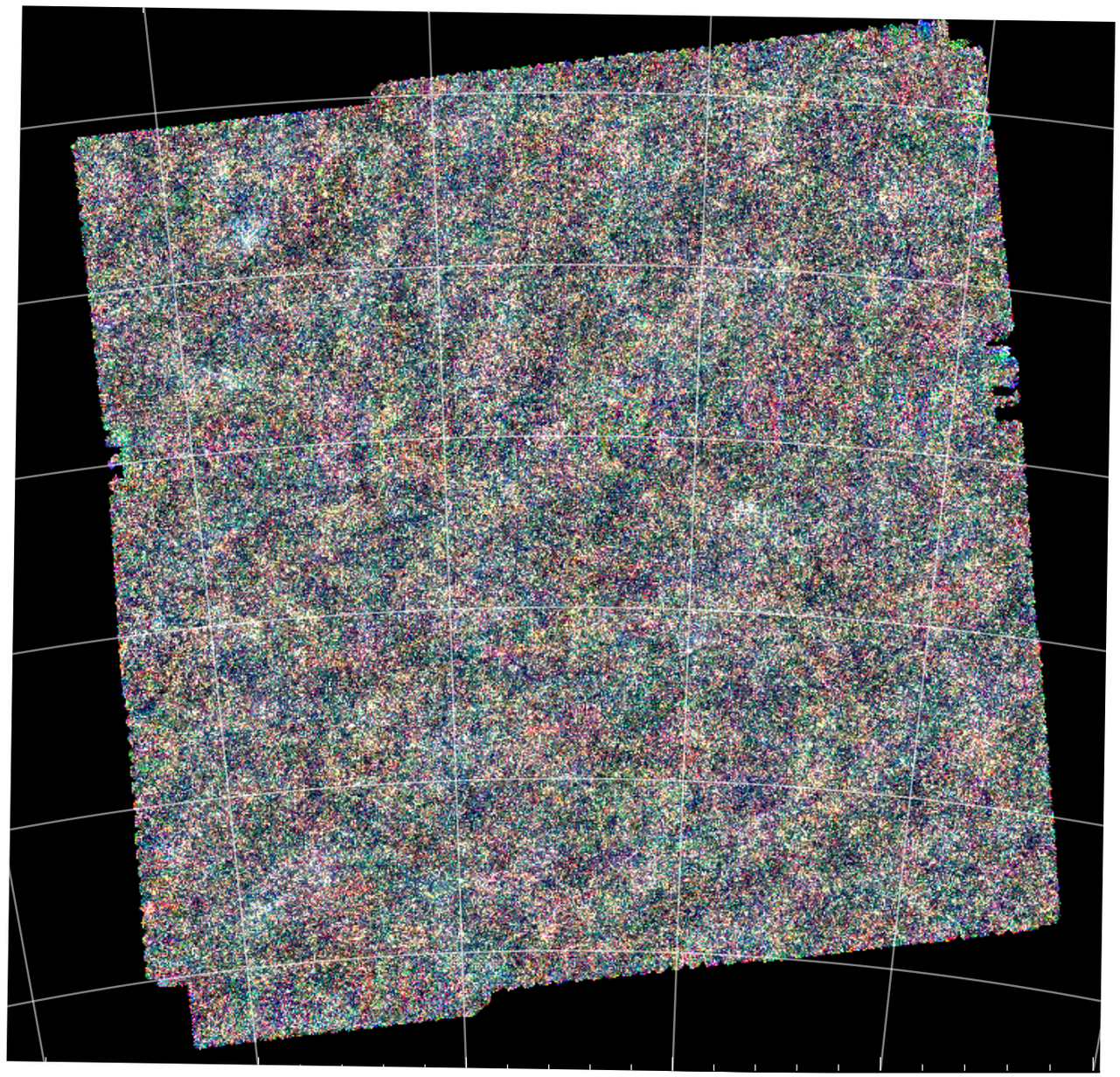


“Mass Map” from Planck, ~70% of sky

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

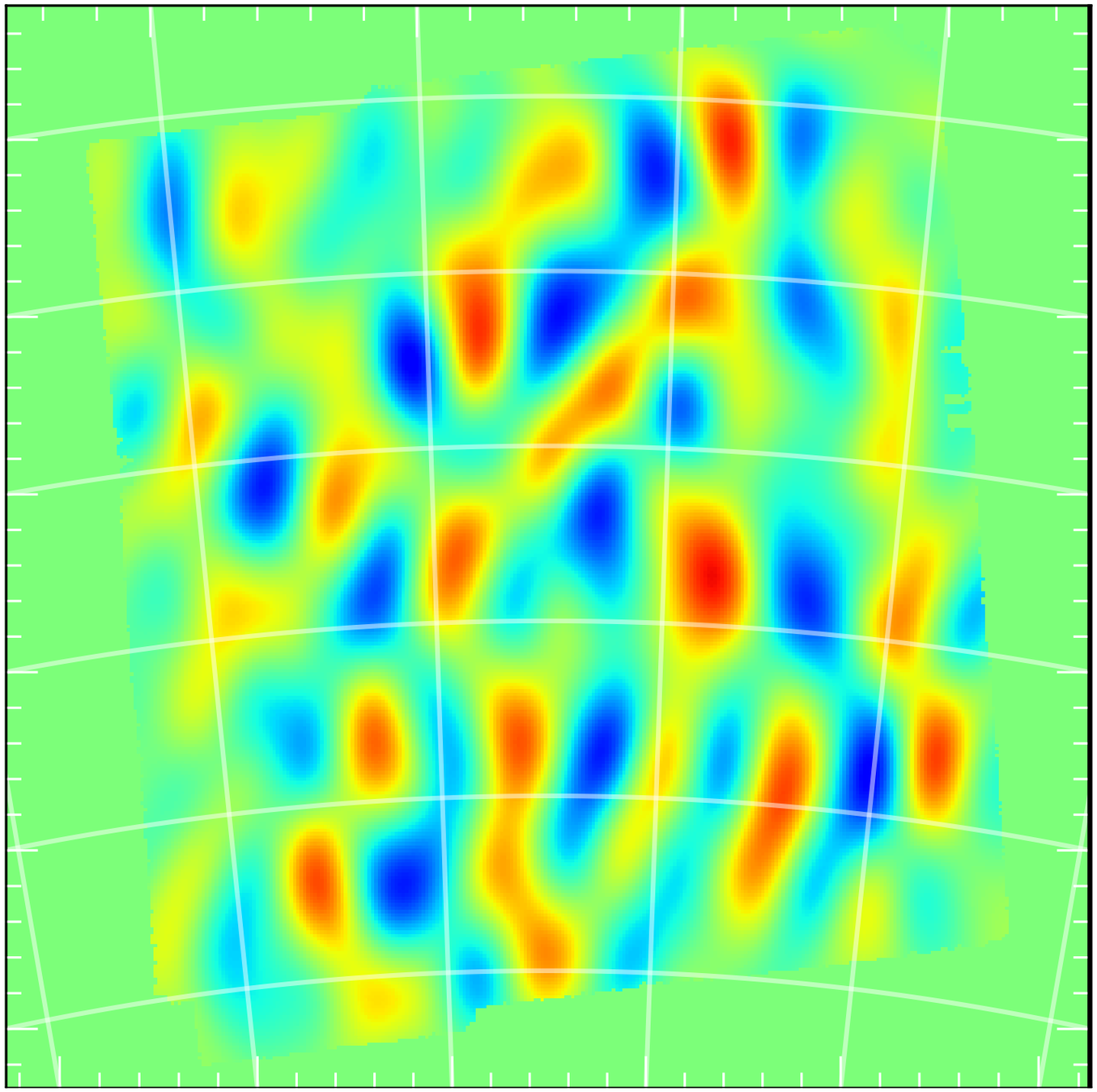
It’s really the Dark Matter:

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



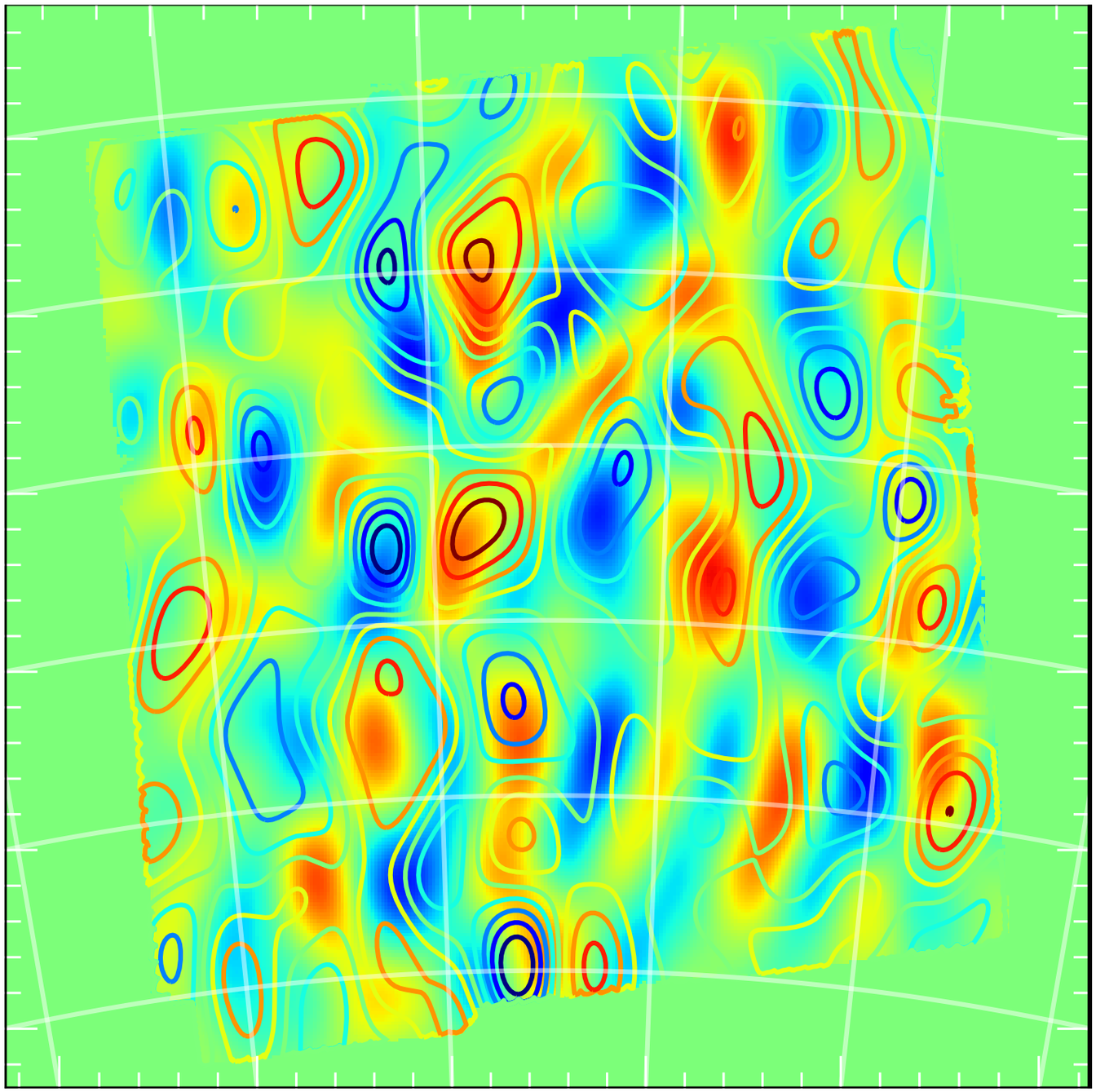
RGB = 500,350,250 um

It’s really the Dark Matter:



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

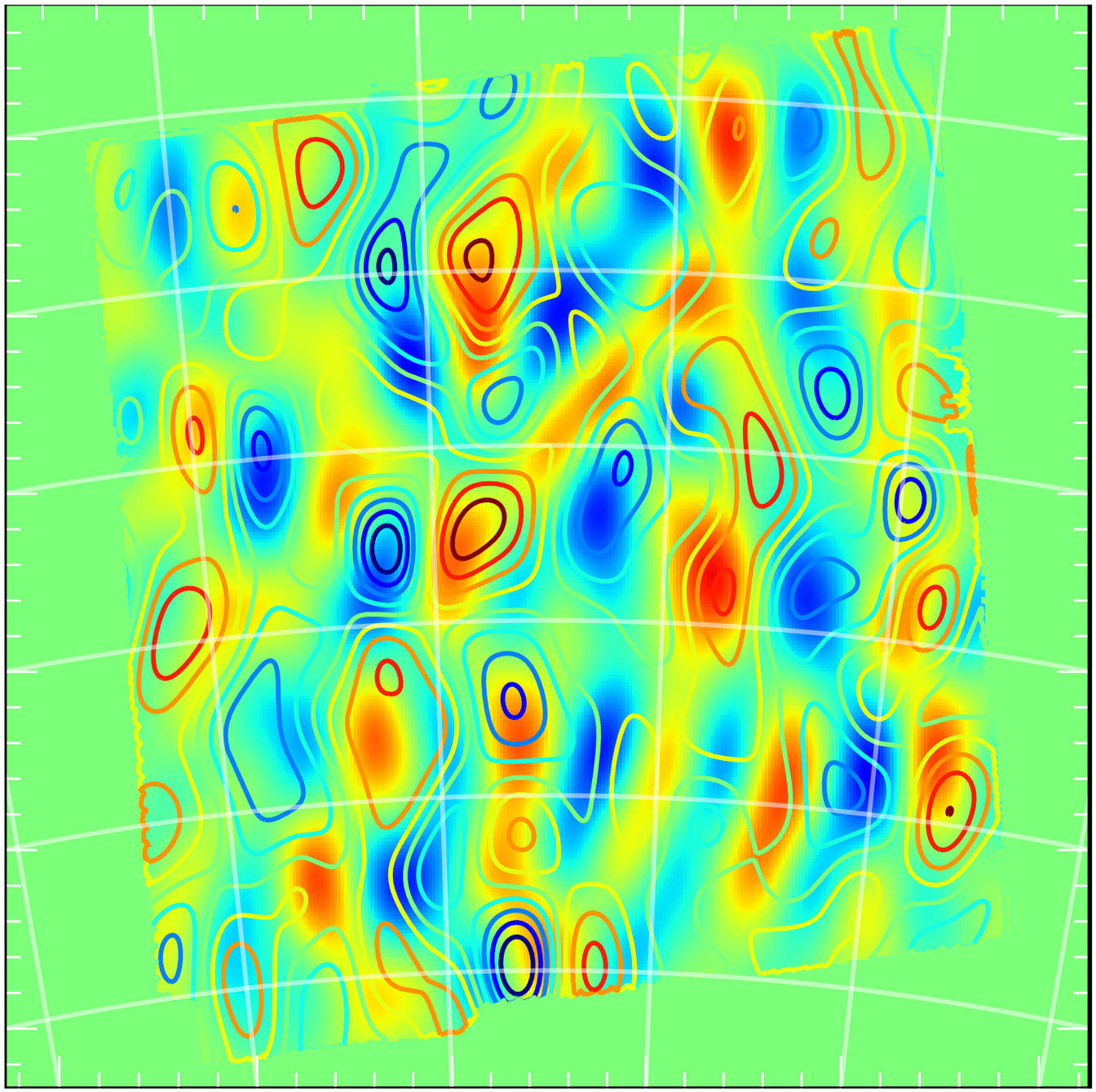
It's really the Dark Matter:



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).

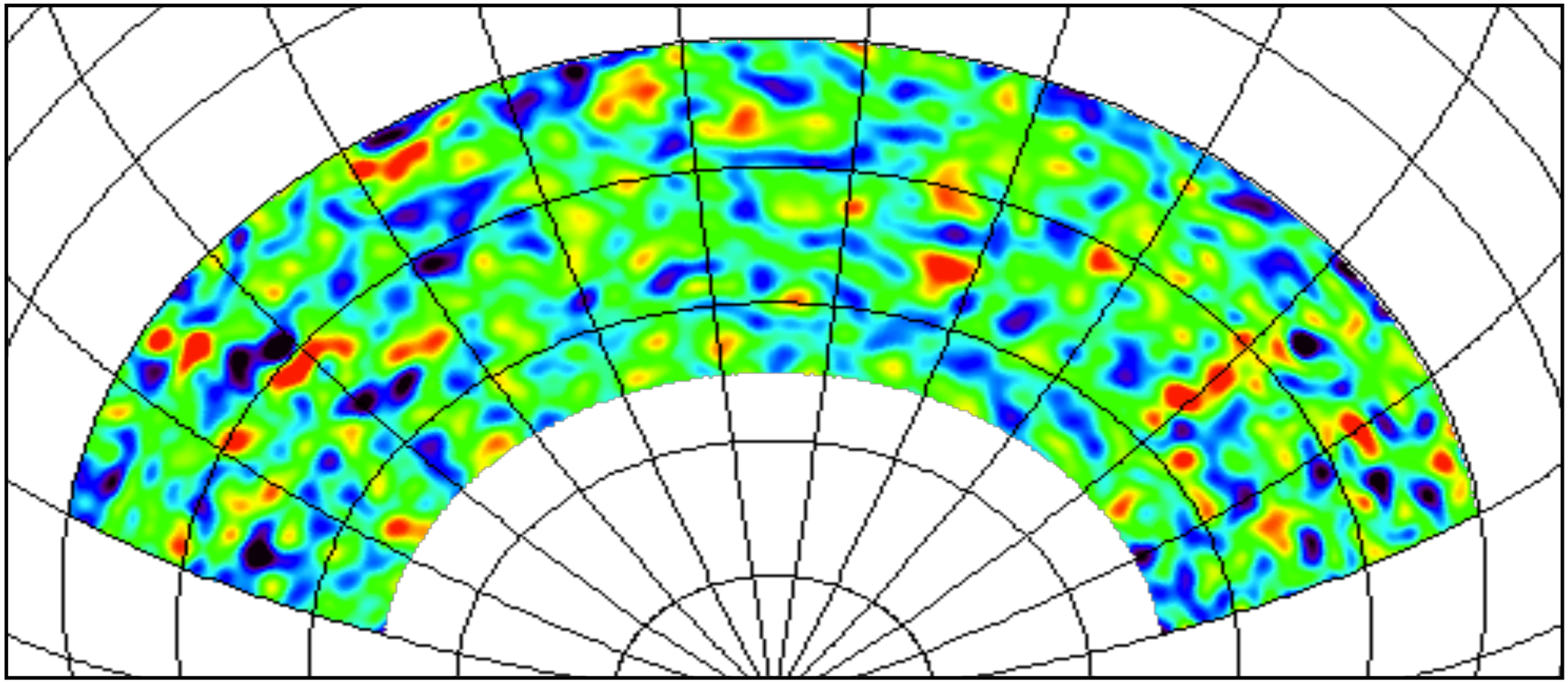
Add mass contours from SPT CMB lensing.

~10σ correlation signal

Holder et al. 2013

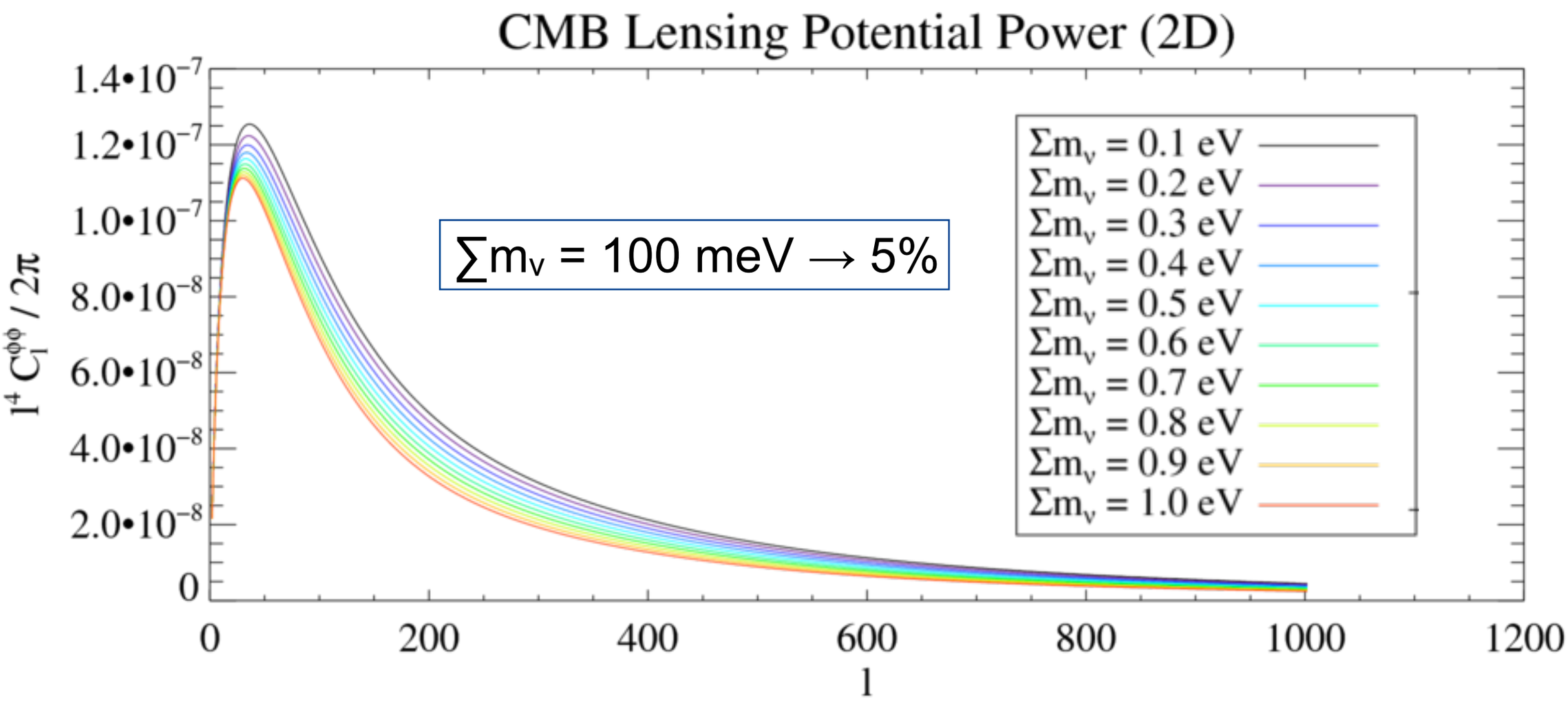
CMB Lensing Map

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



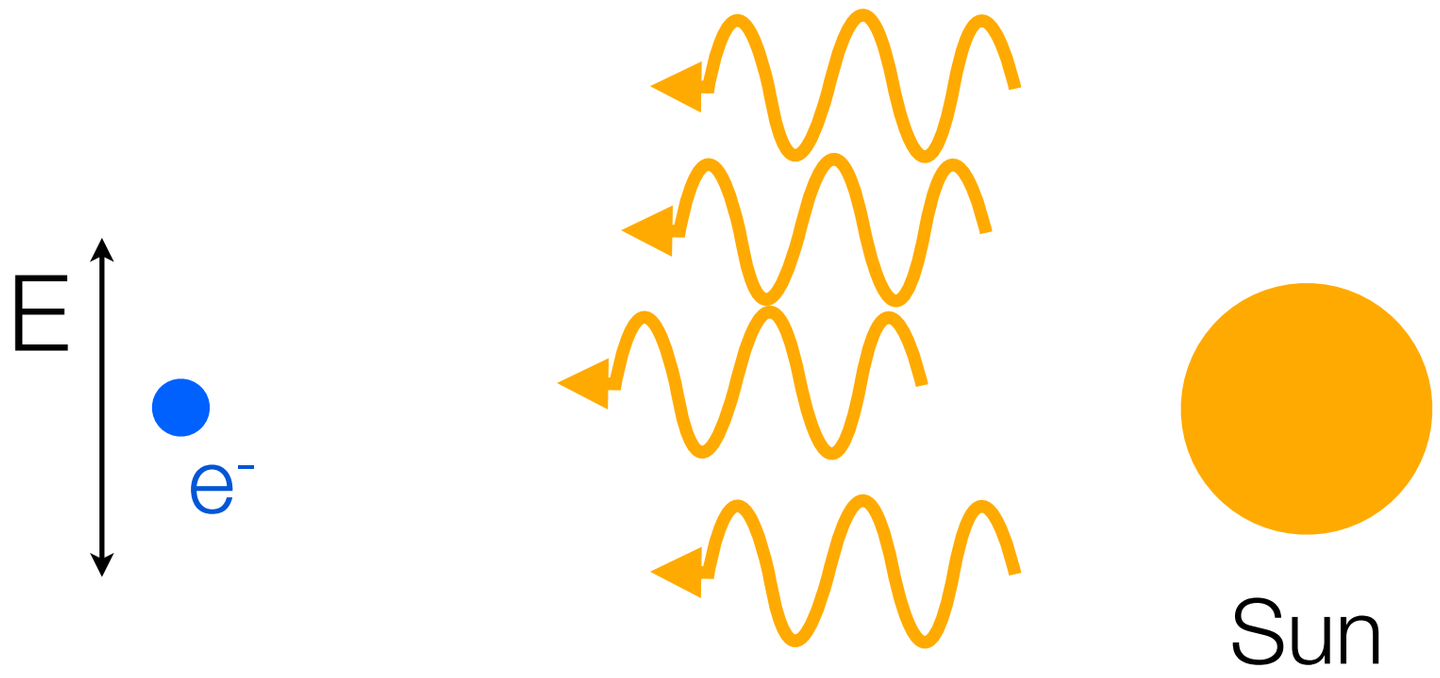
Lensing convergence map smoothed to 1 deg resolution
from CMB lensing analysis of SPT 2500 deg^2 survey

Neutrino mass



CMB polarimetry

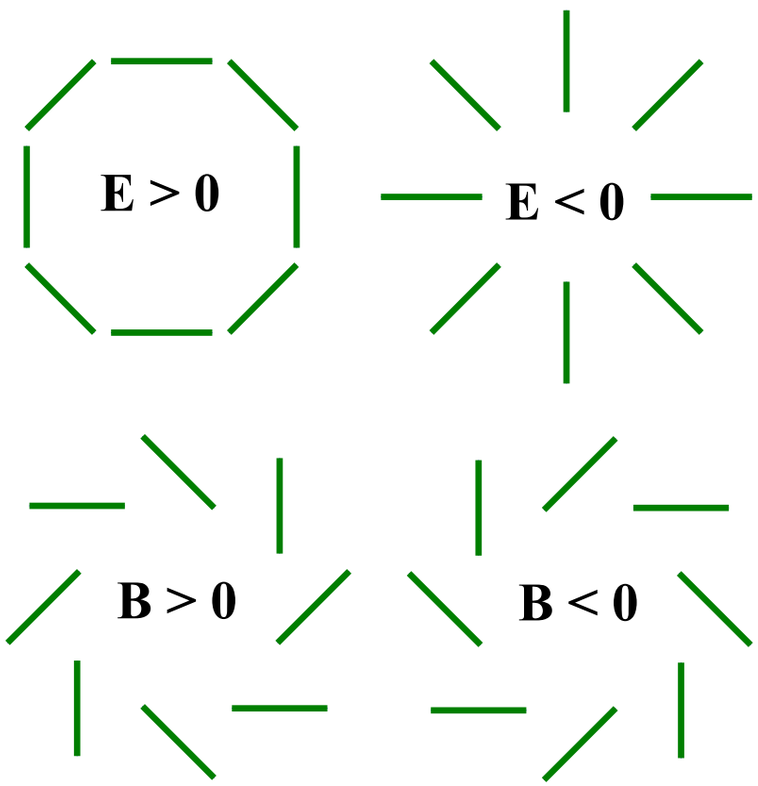
- CMB polarized via Thomson scattering and local anisotropy (e.g. Sun scattering in atmosphere)

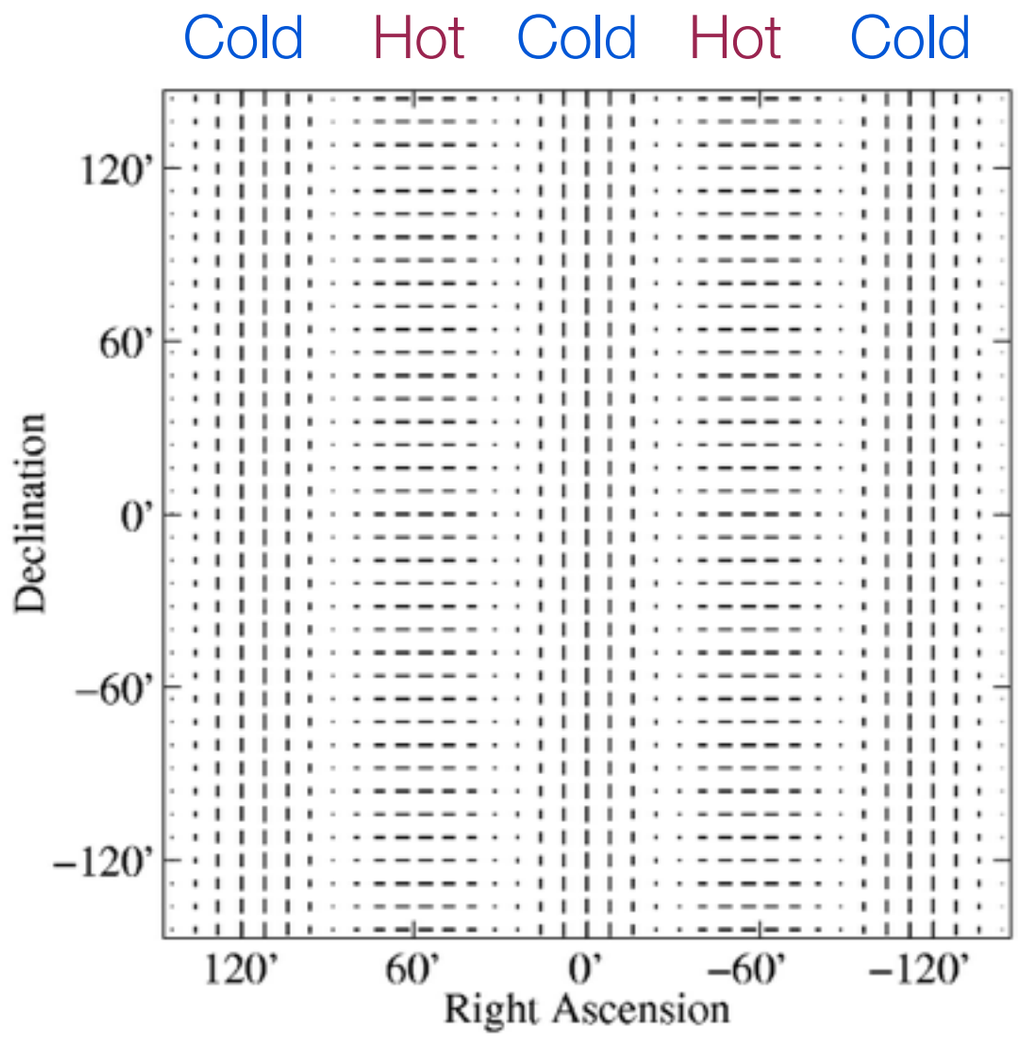


CMB polarimetry: E-modes

- 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 ⟶ -k
  - **“E-mode” only**



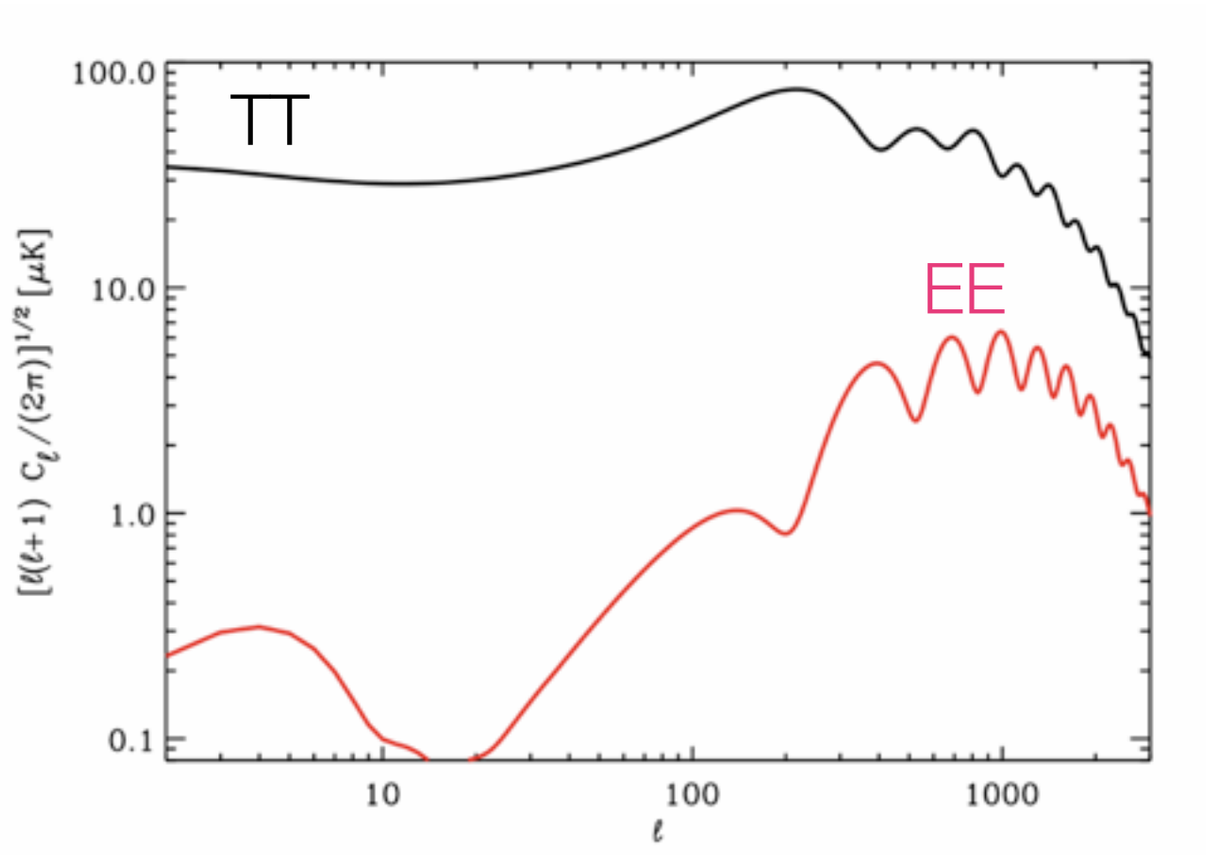


CMB polarimetry: E-modes

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

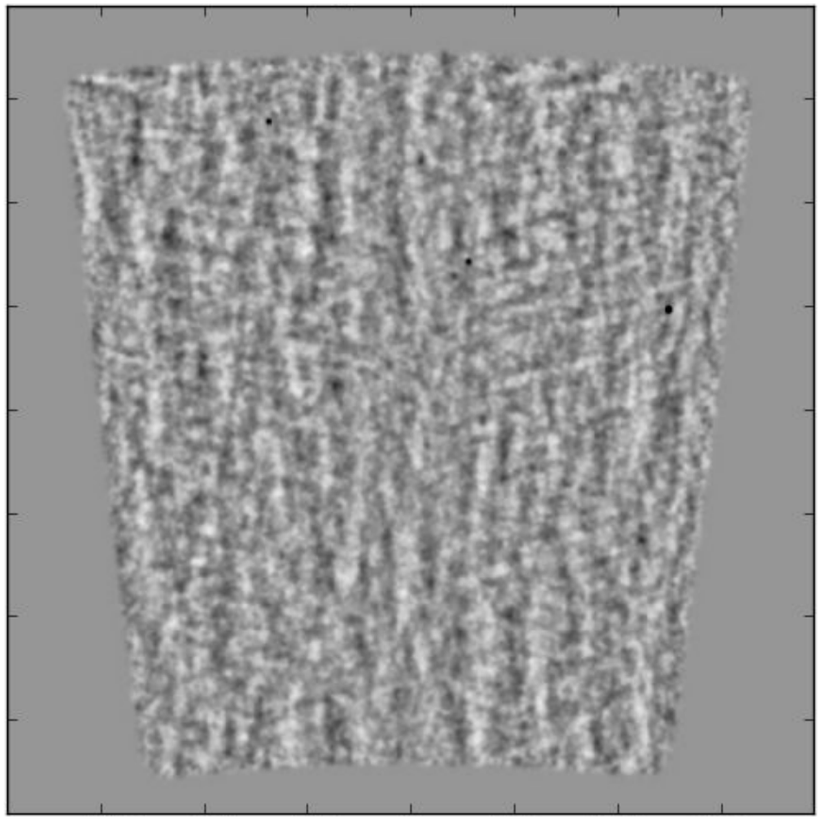
- Density/Temperature anisotropy generates intrinsic CMB polarization

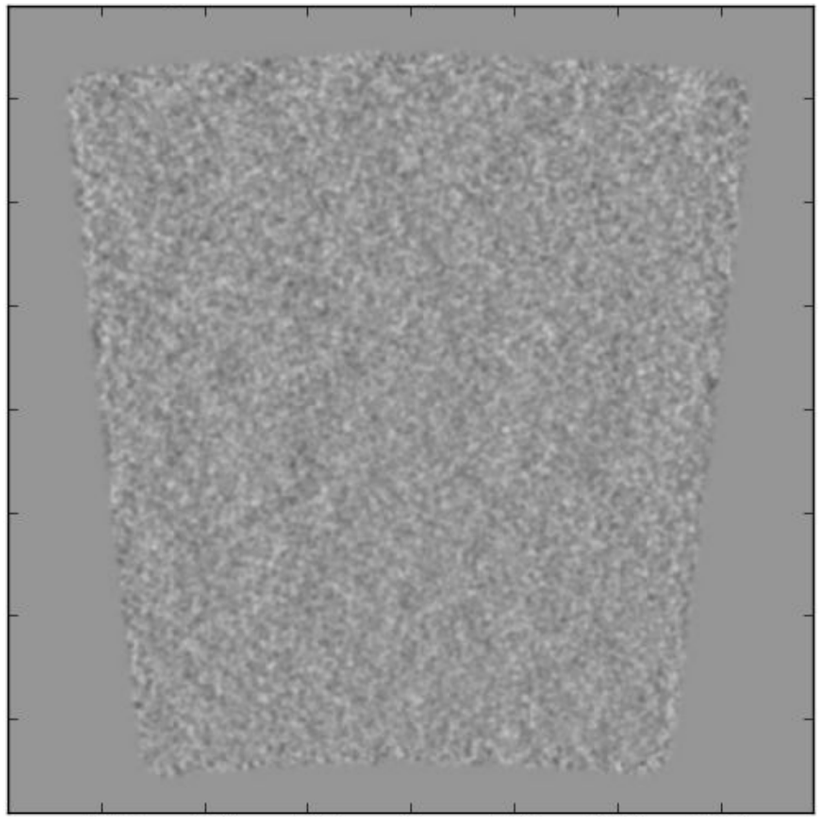
- EE power spectrum is a different probe of same physics producing TT spectrum



Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

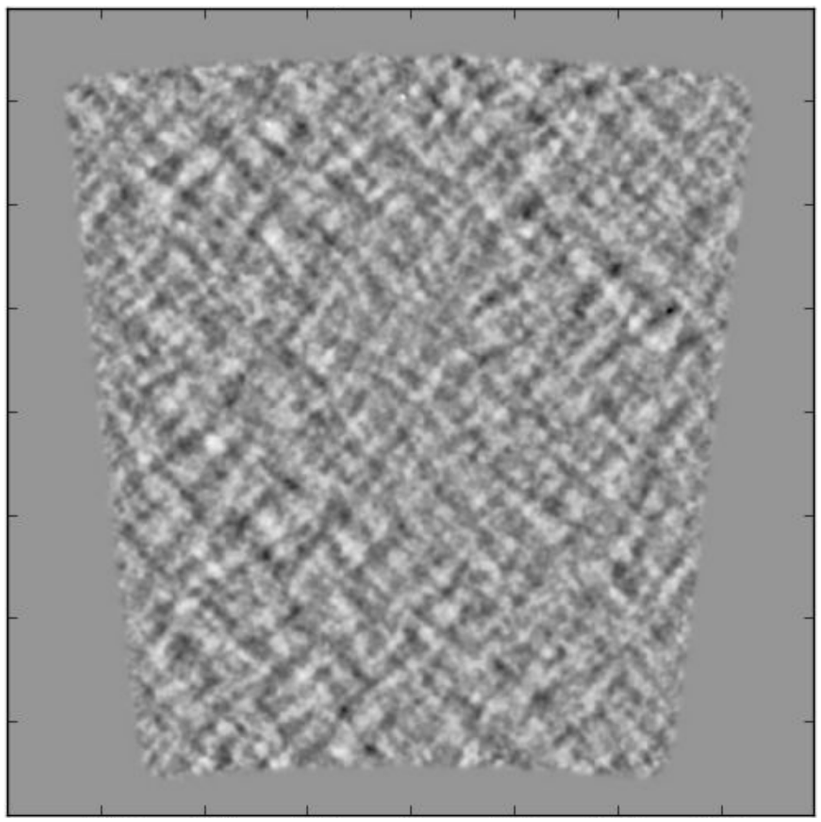
Q sum

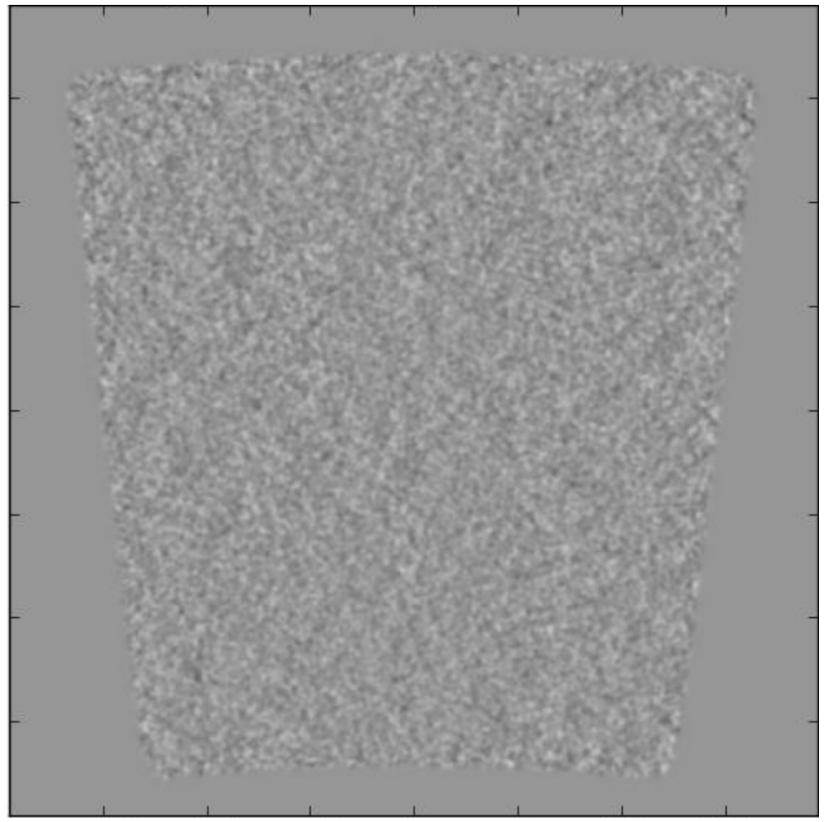




Q diff

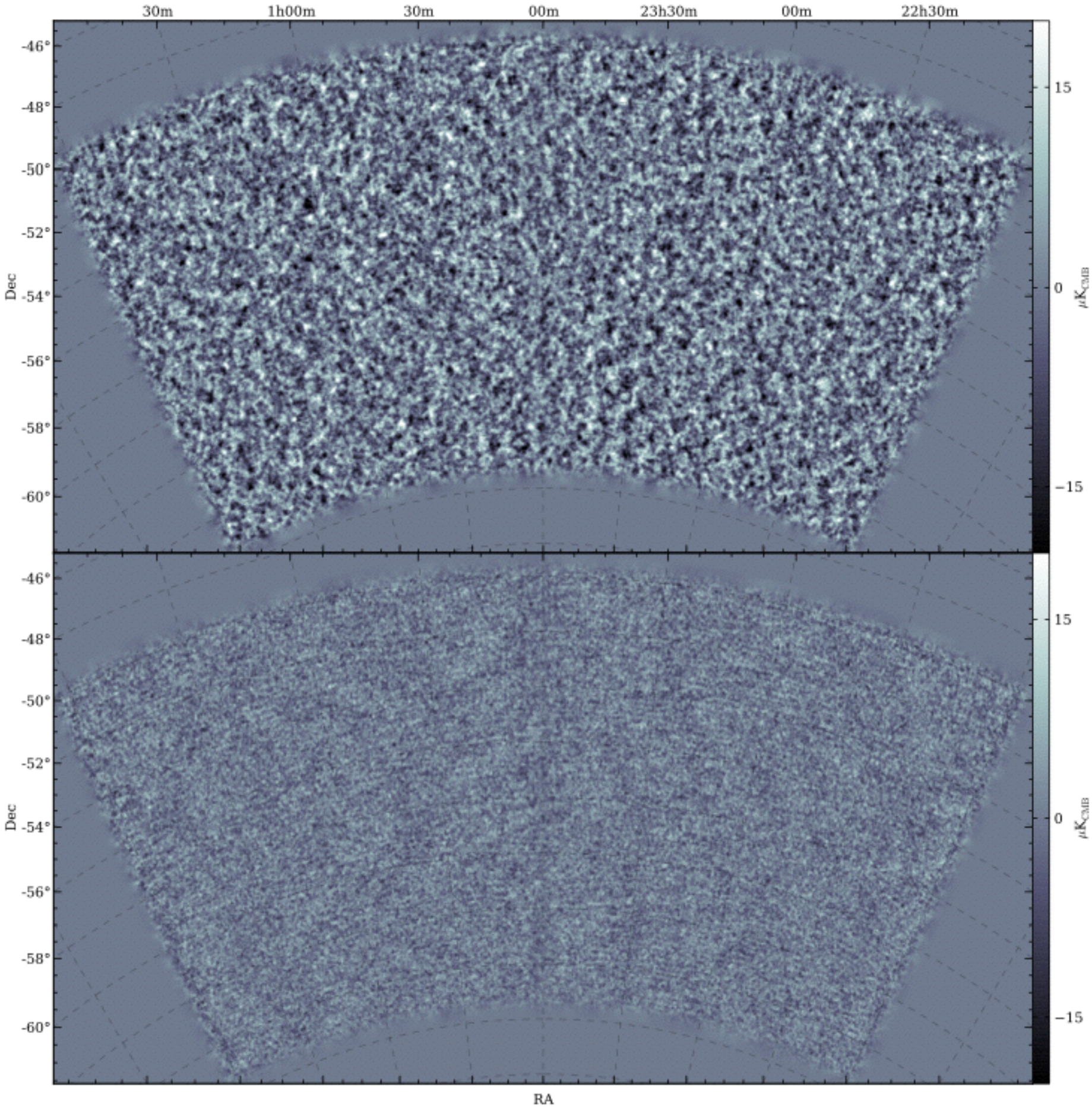
U sum





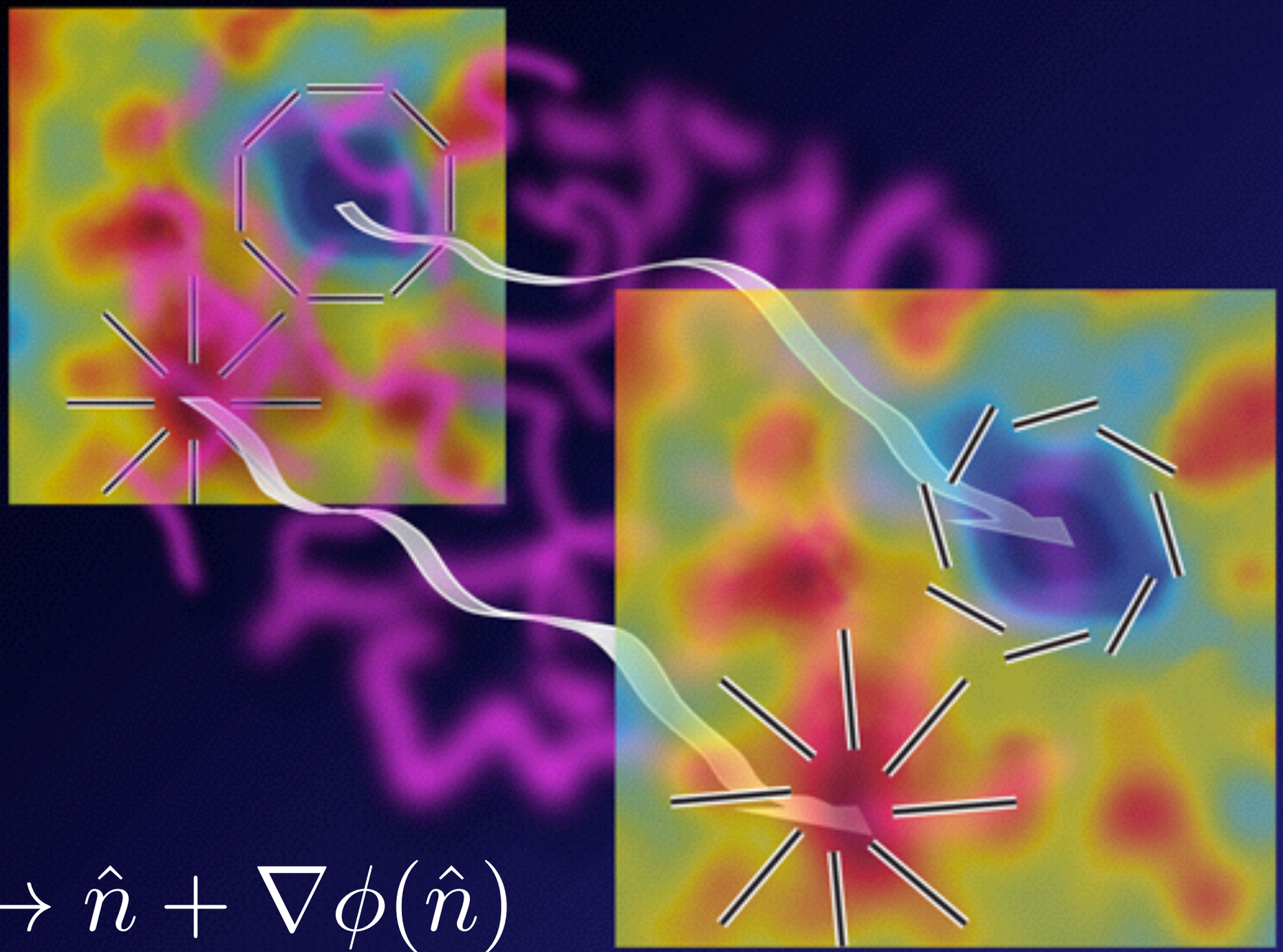
U diff

SPTpol 1st year Q/U maps (E-modes)



E-modes,
500 deg^2

CMB Lensing via CMB polarization



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

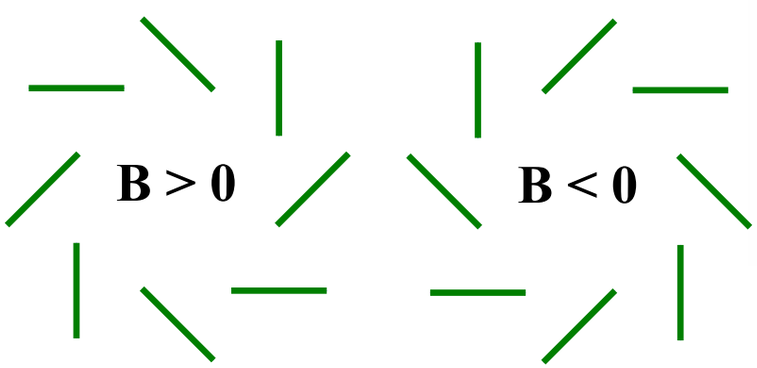
$$\phi(\hat{n}) = -2\int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{n}; \eta_0 - \chi)$$

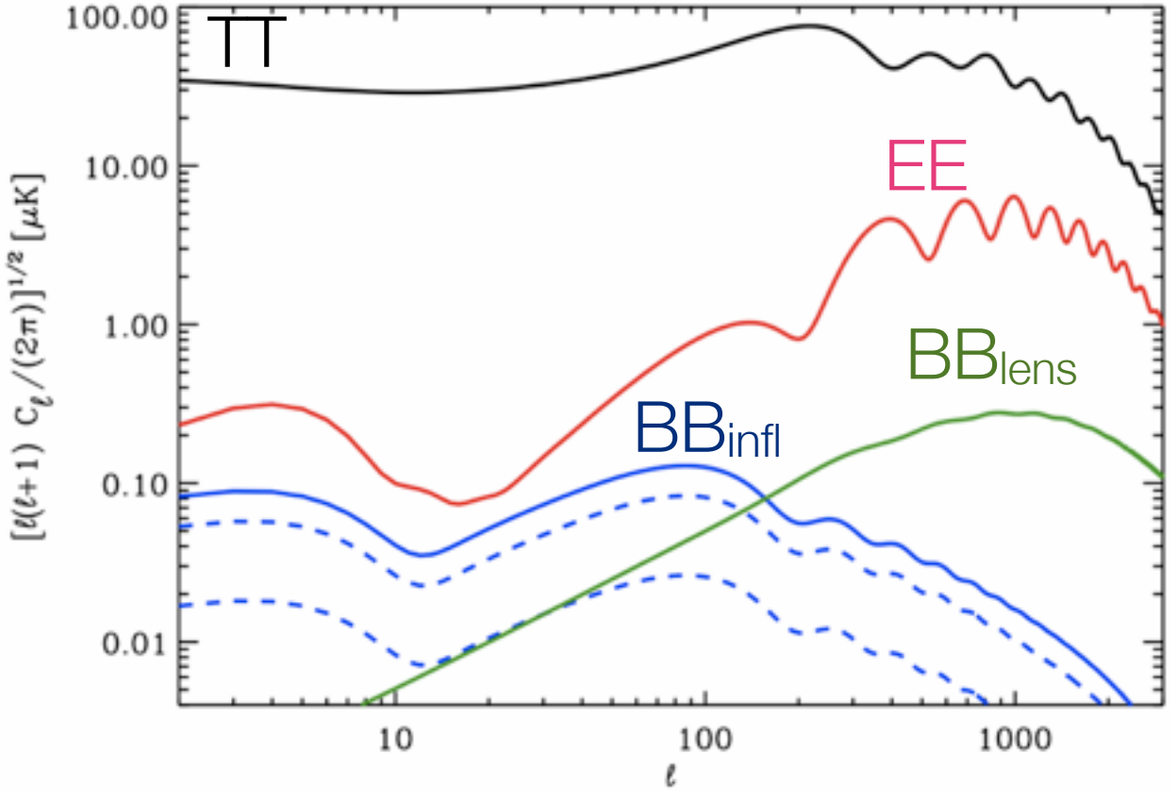
CMB polarimetry: E-modes & B-modes

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

- Density/Temperature anisotropy generates intrinsic CMB polarization

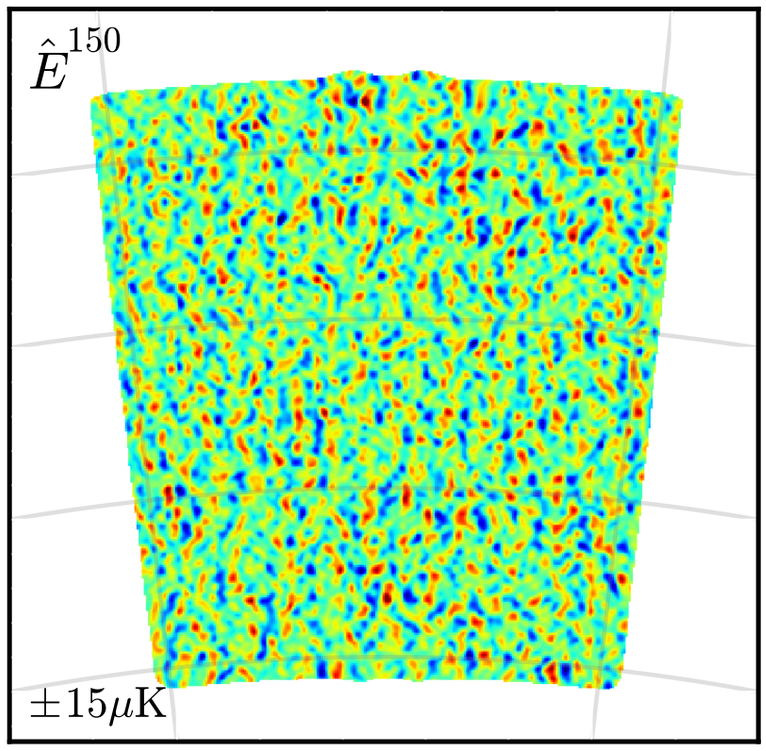
  - parity odd patterns, “B-modes”
  - Gravitational lensing of “E-modes” (shearing)
  - Gravitational waves from inflation





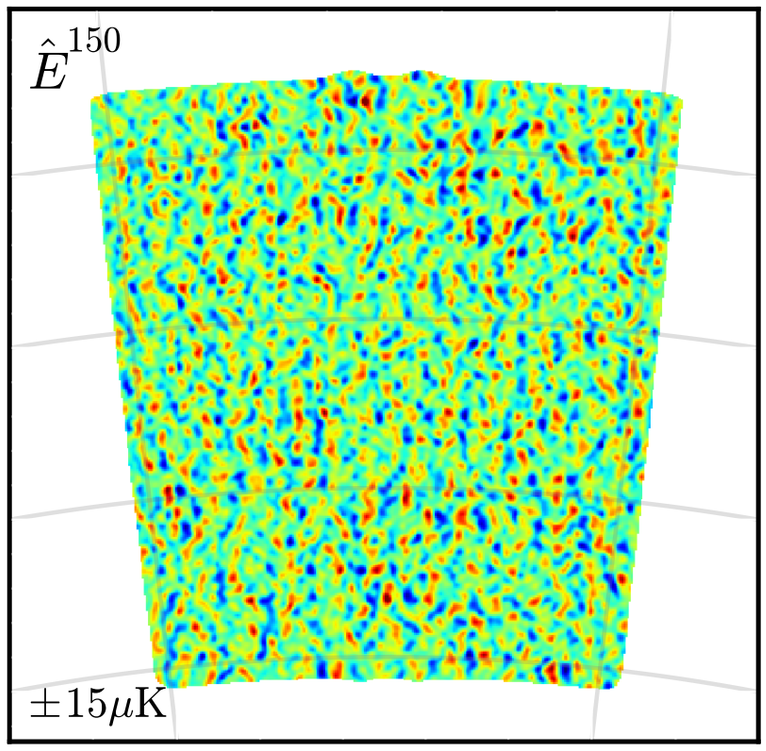
Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

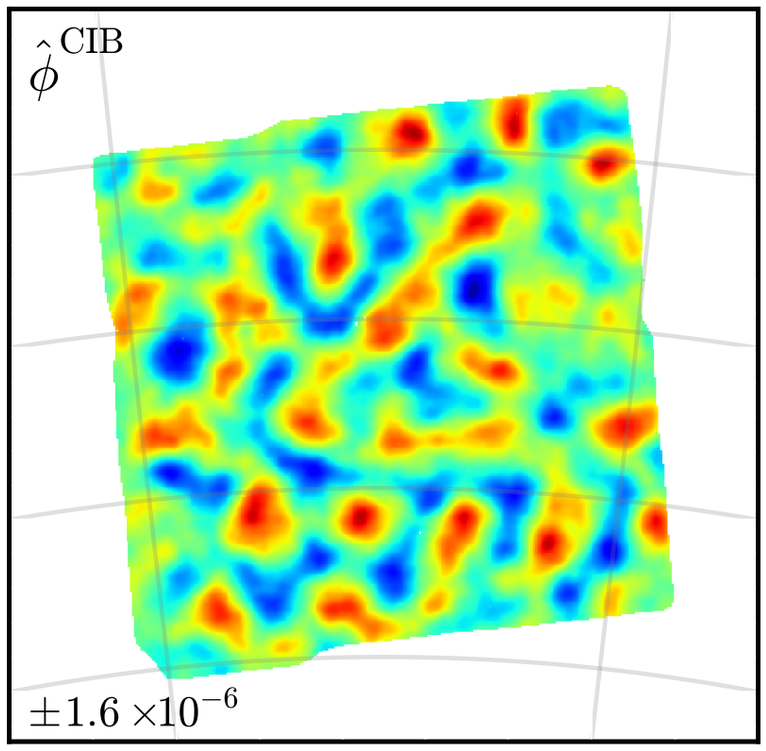
Measuring CMB lensing B-modes



E

SPTpol





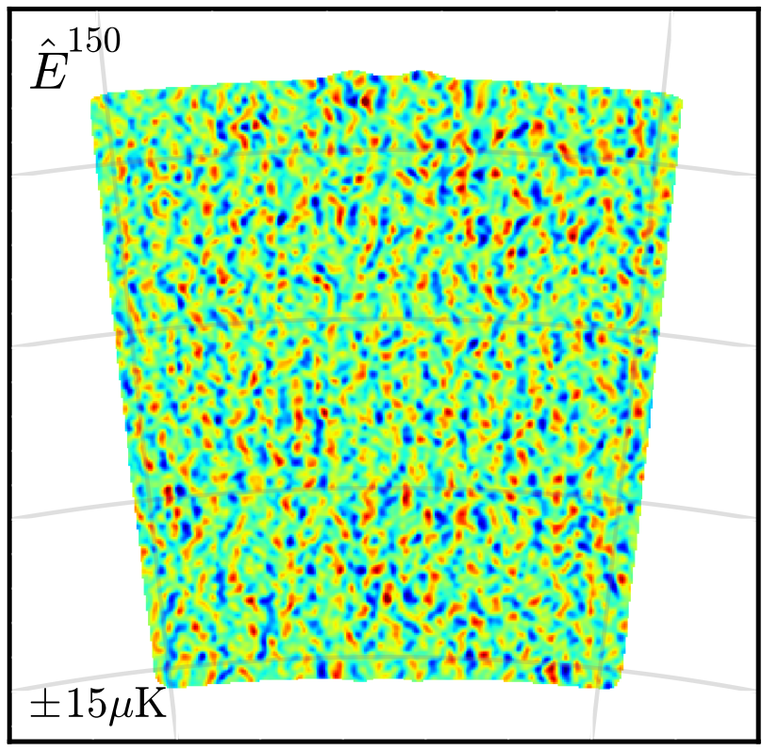
E

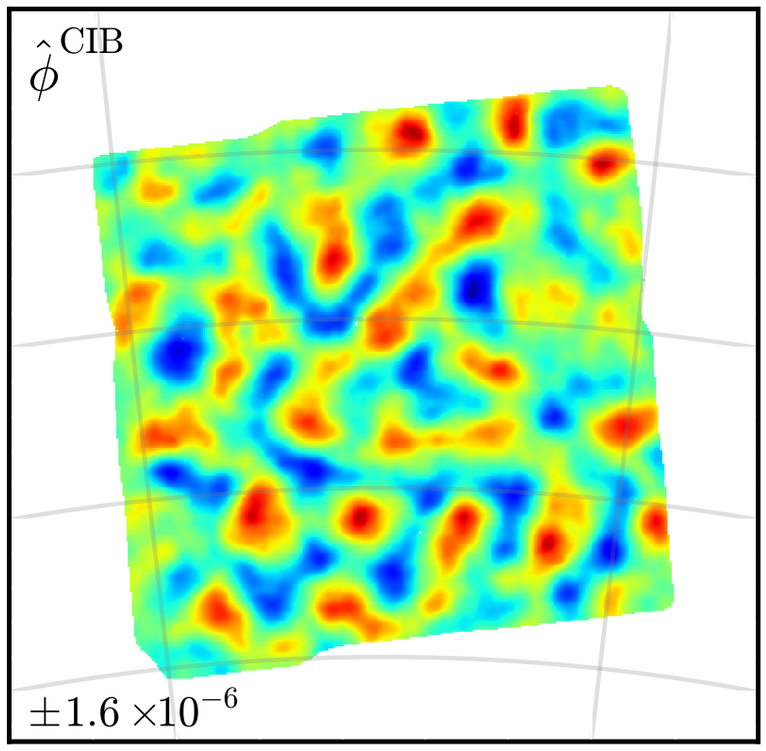
SPTpol

+

Φ

CIB (Herschel)





E

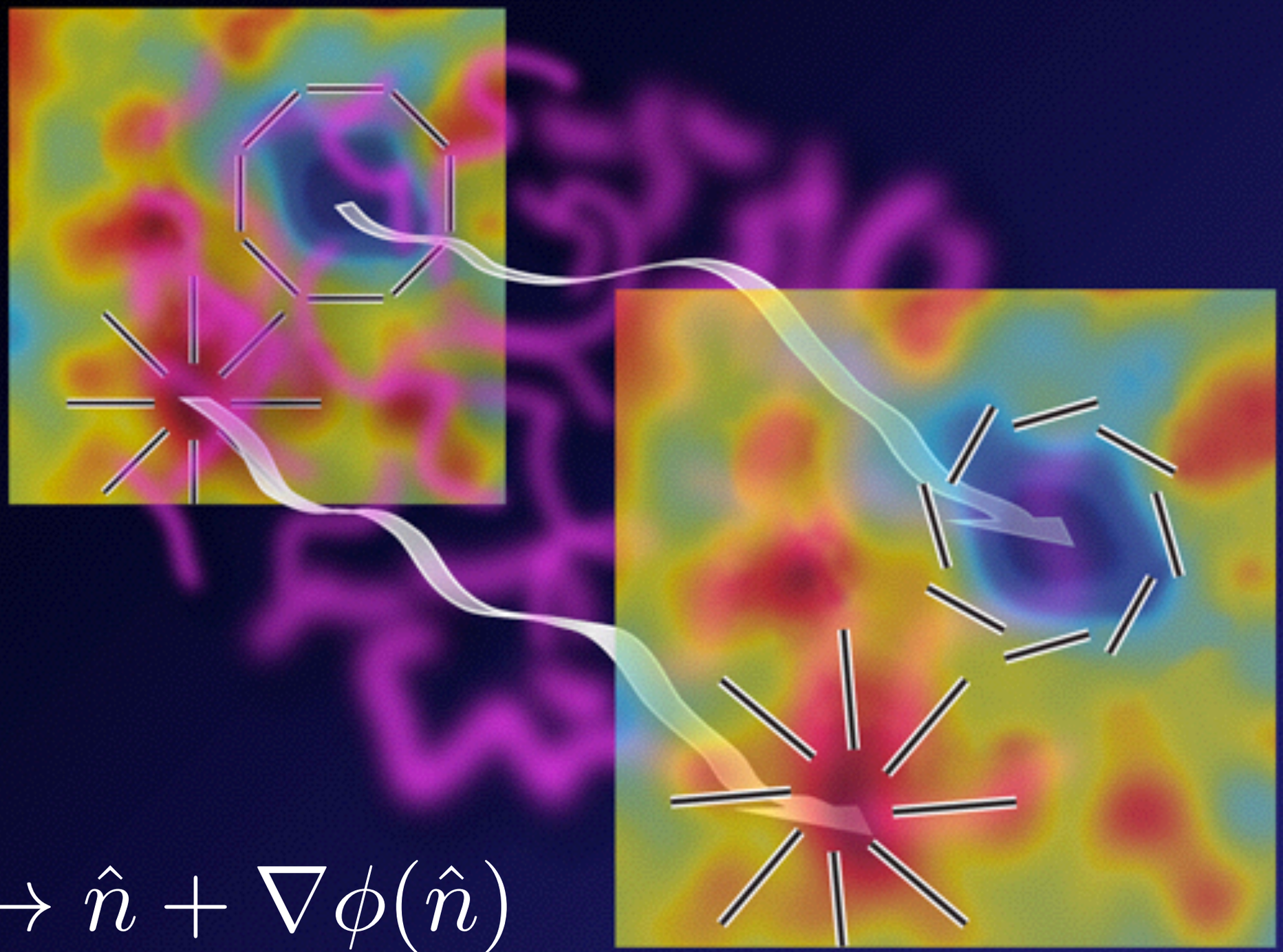
SPTpol

+

Φ

CIB (Herschel)

Traces DM/lensing potential



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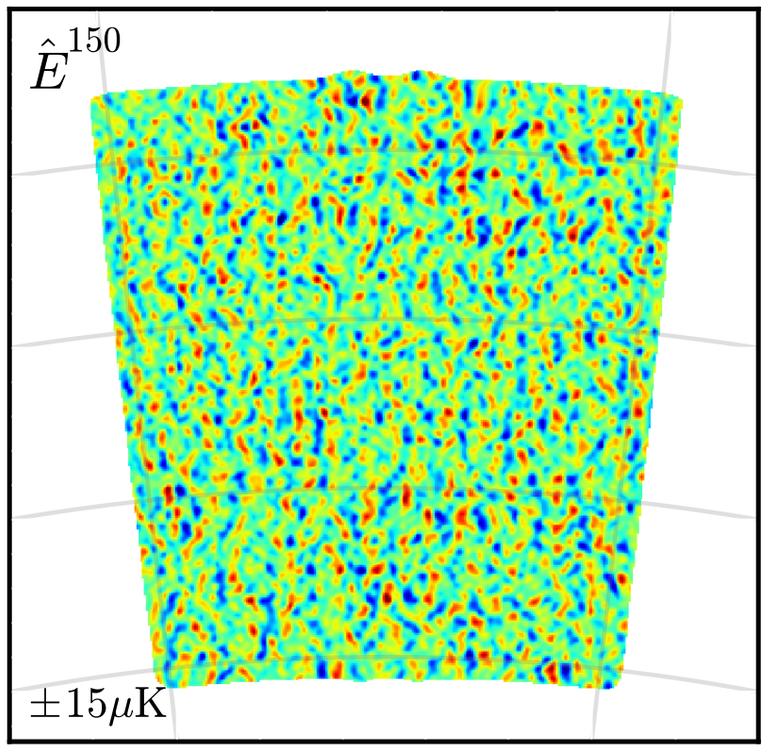
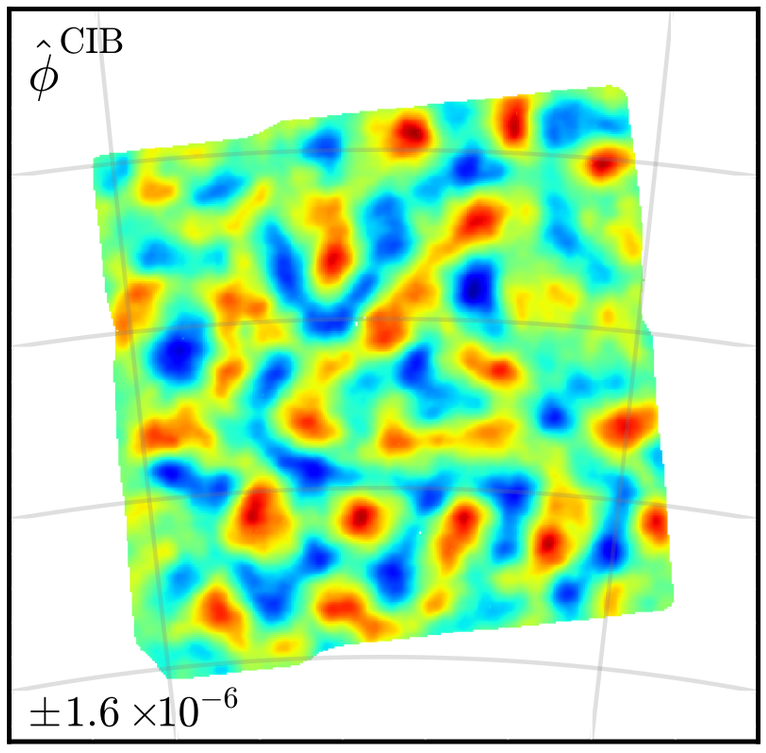
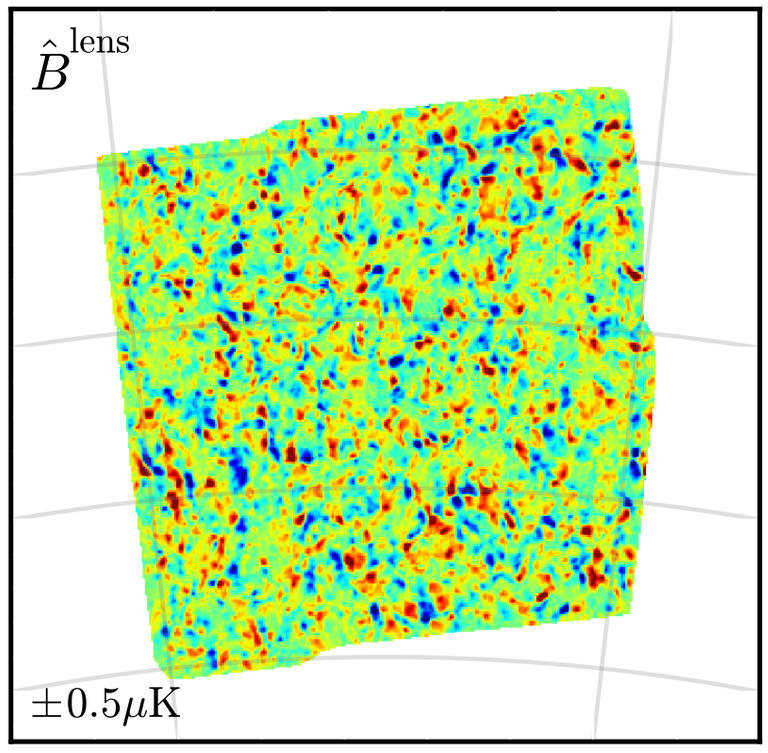






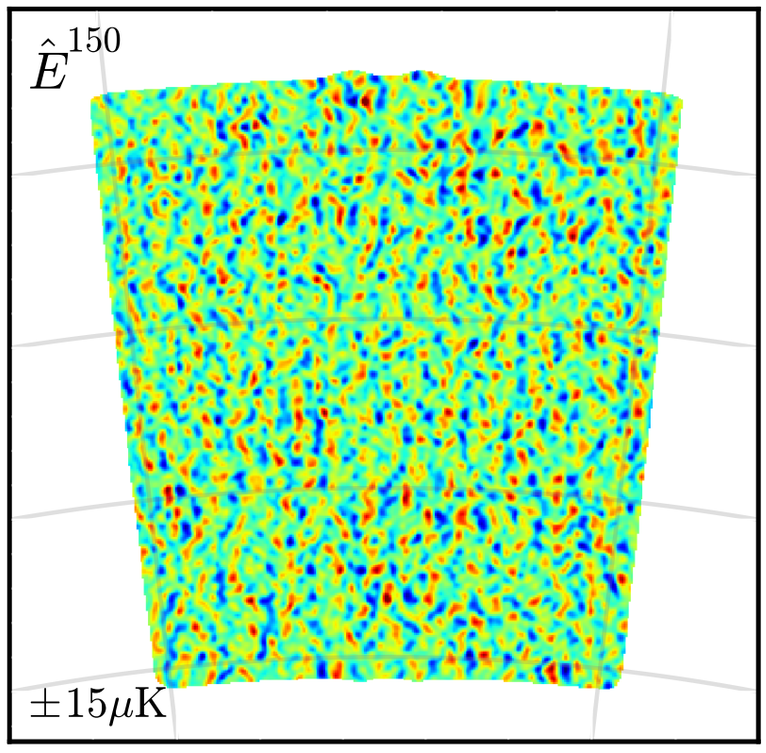
E
SPTpol

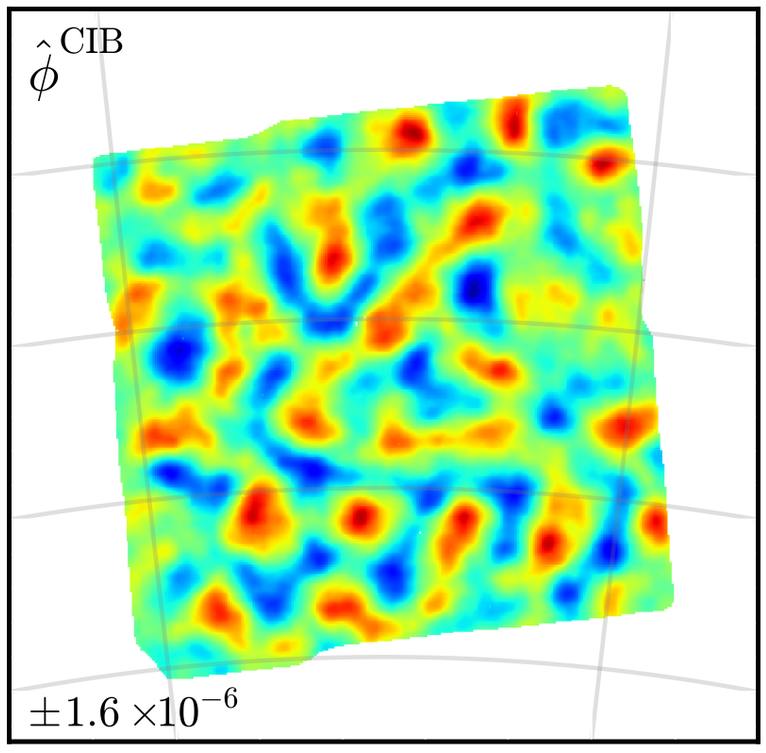
+

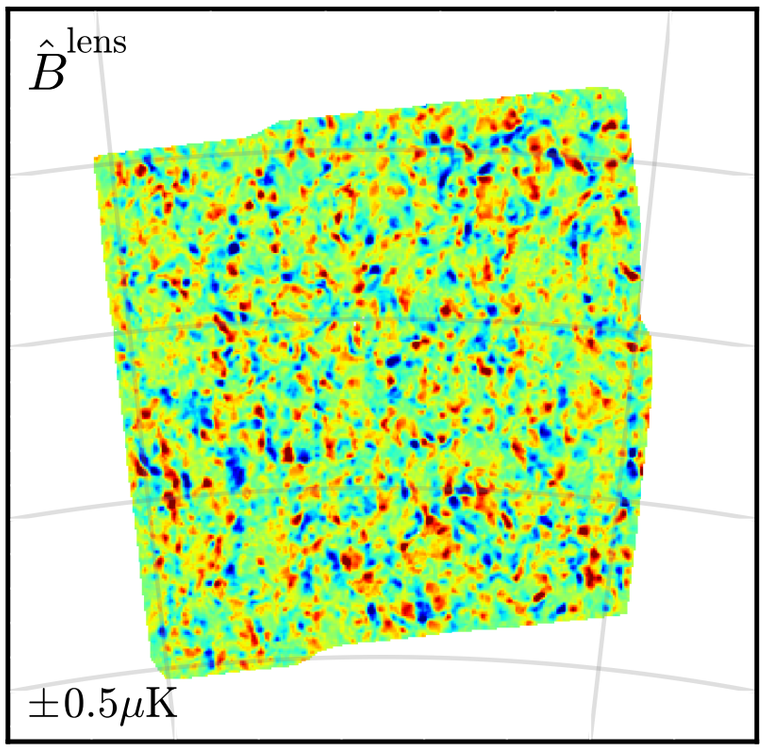
Φ
CIB (Herschel)

→

Synthesized lensing
B







E
SPTpol

+

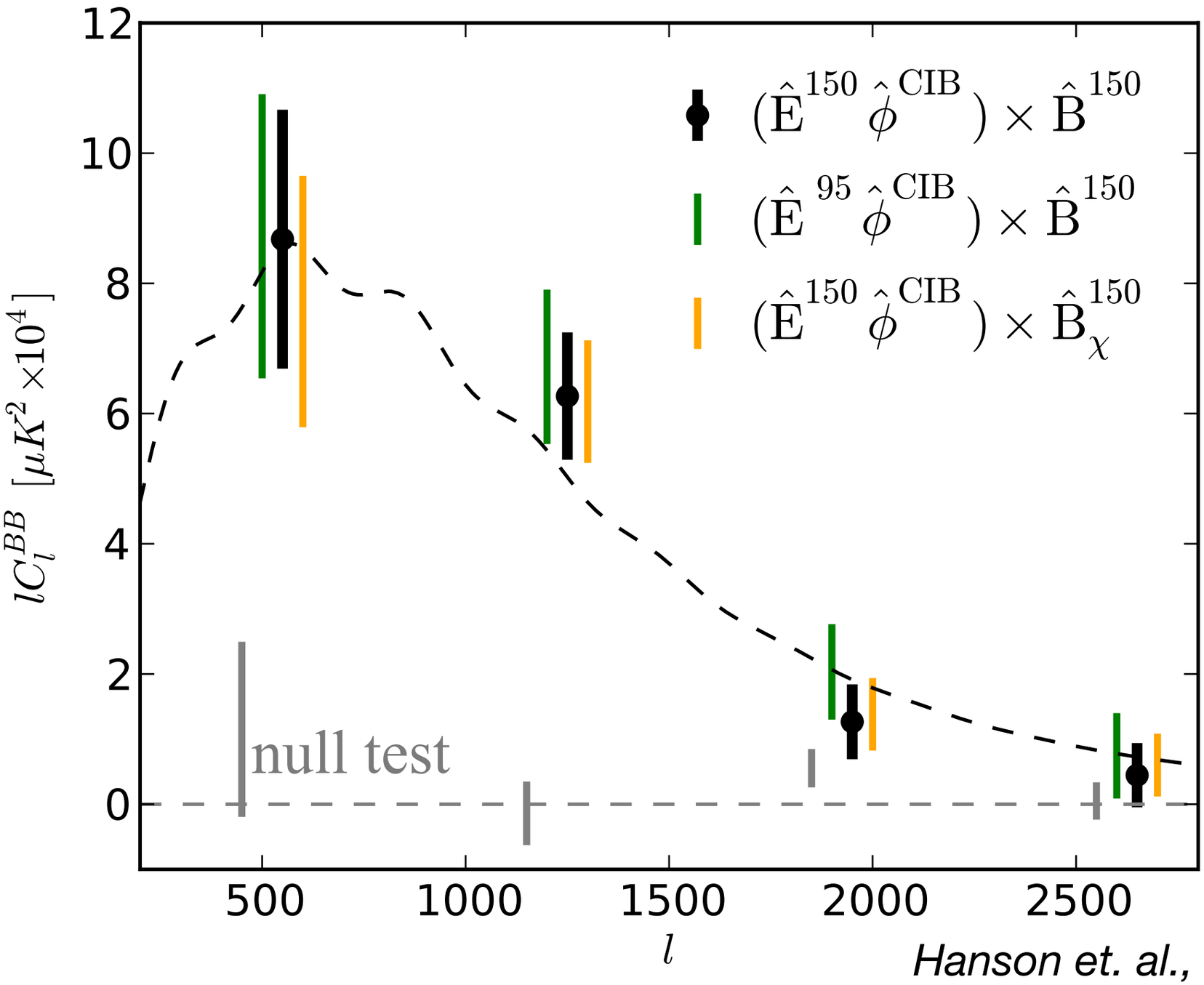
Φ
CIB (Herschel)

→

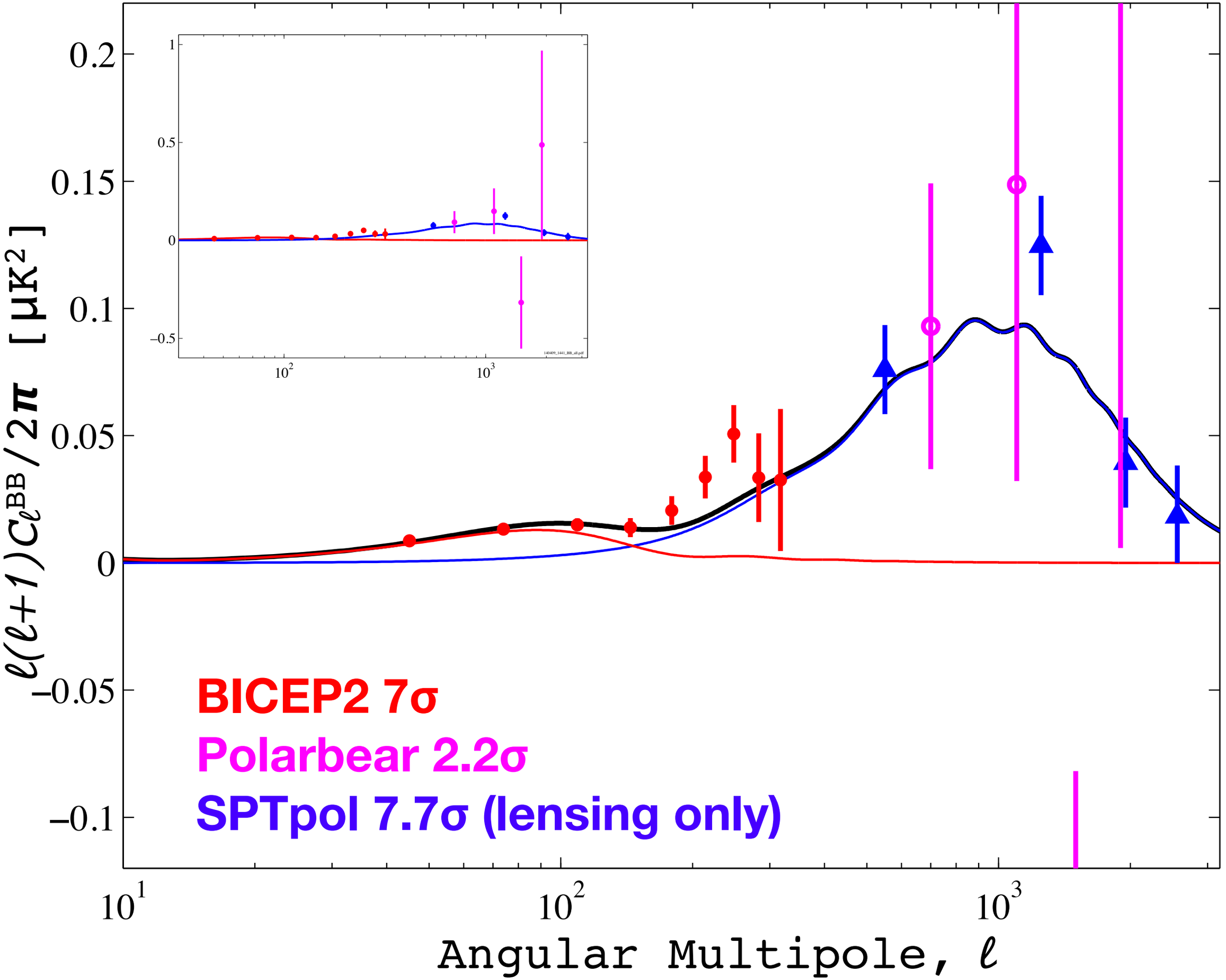
Synthesized lensing
B

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

7.7σ detection of CMB lensing B-modes

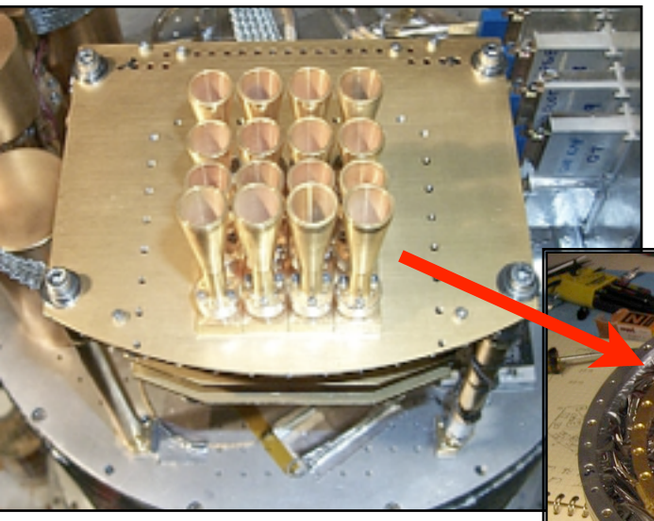


Hanson et. al., PRL, 111 (2013)

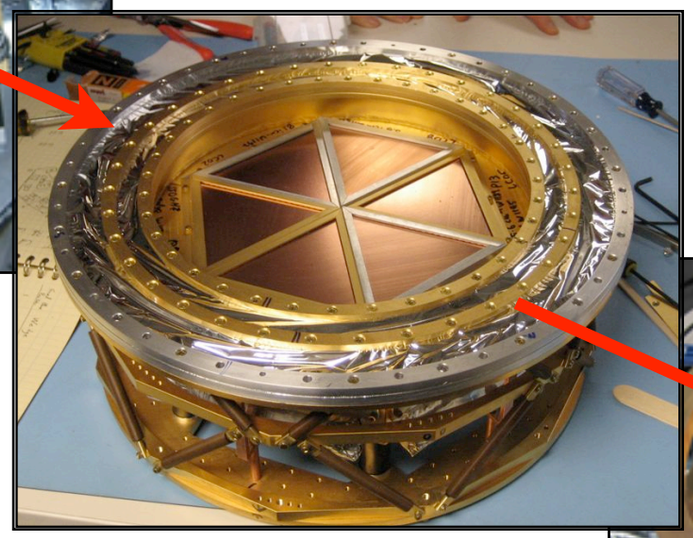

0.2
0.15
0.1
0.05
0
−0.05
−0.1
$\ell(\ell+1)C_\ell^{BB}/2\pi$ [μK²]
1
0.5
0
−0.5
10^2
10^3
BICEP2 7σ
Polarbear 2.2σ
SPTpol 7.7σ (lensing only)
10^1
10^2
10^3
Angular Multipole, ℓ

B-modes: From detection to precision

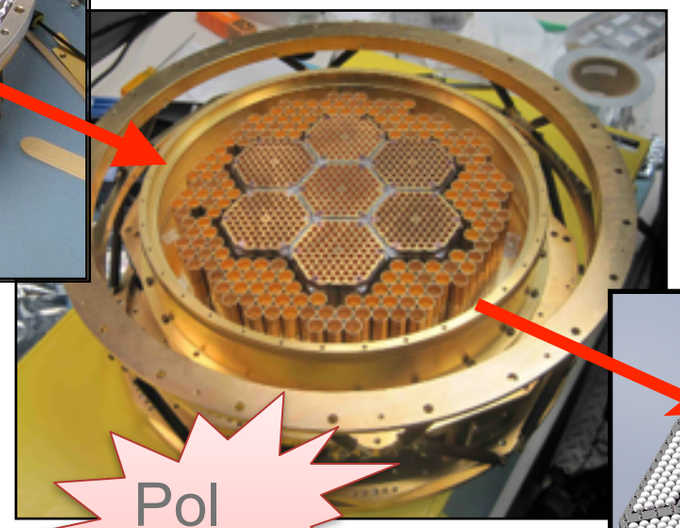
2001: ACBAR
16 detectors



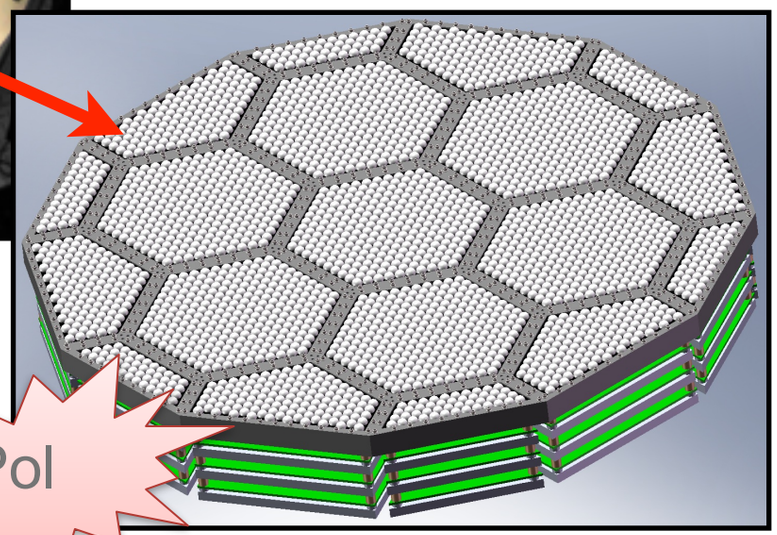
2007: SPT
960 detectors



2012: SPTpol
~1600 detectors



2016: SPT-3G
~15,200 detectors

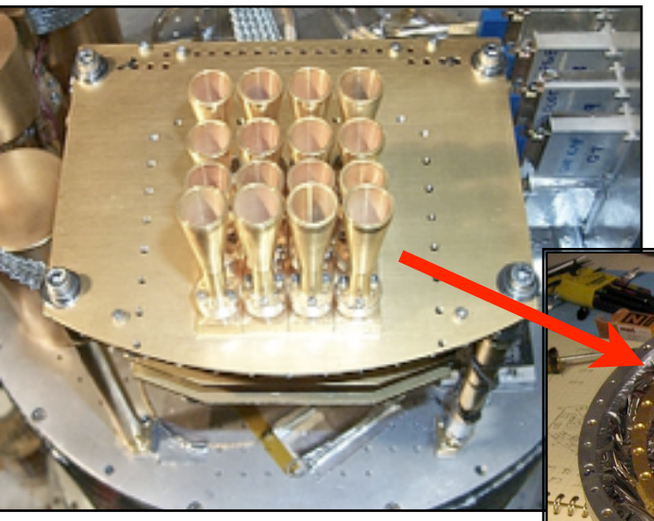


ACBAR was the first experiment to make a "background limited" detector. Since then, only way to increase sensitivity is to have more detectors

Increase sensitivity with more detectors

- Larger focal plane (bigger arrays and more of them)
- Increase detector “density” (measure more optical modes per optical element)

2001: ACBAR
16 detectors



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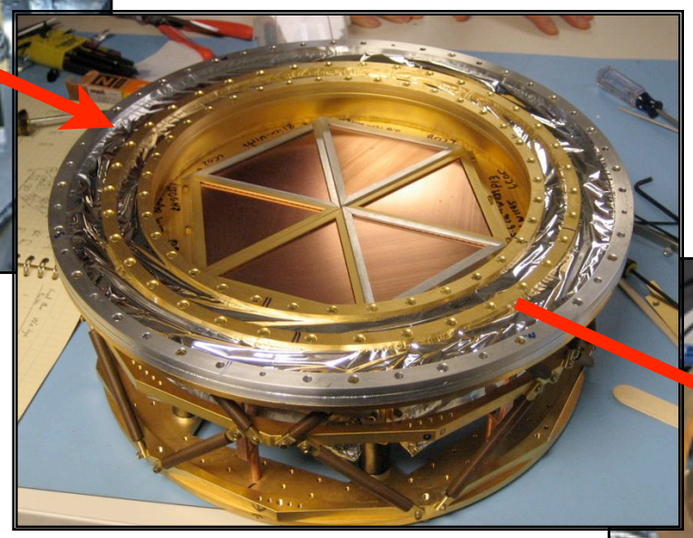
960 detectors



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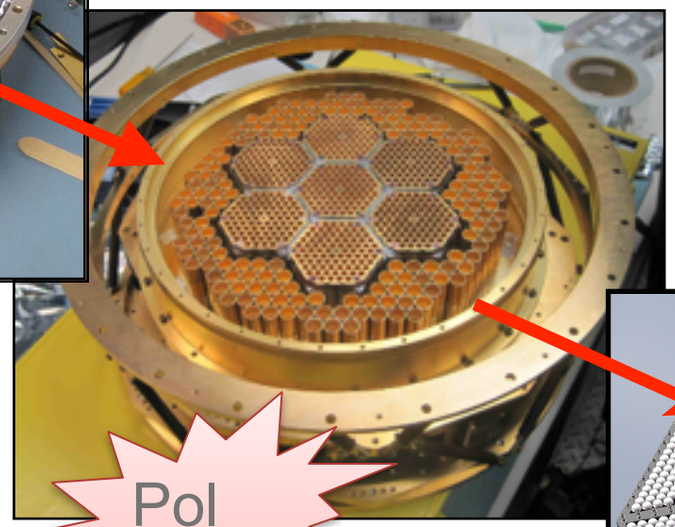

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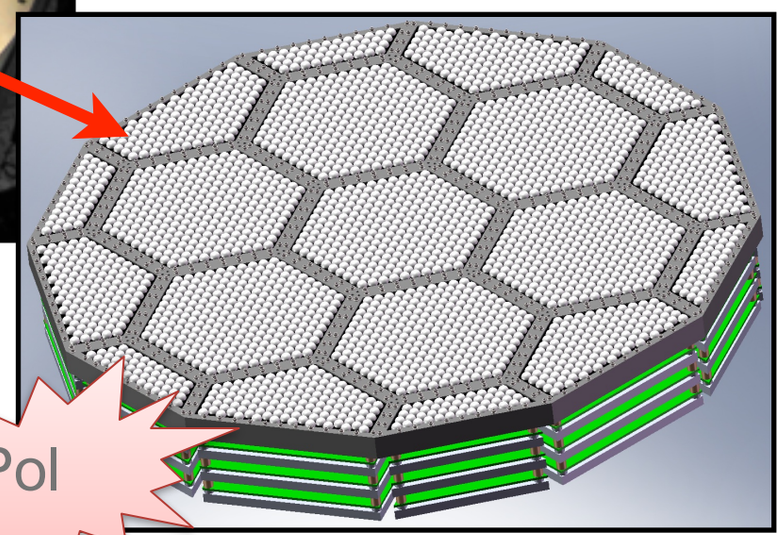
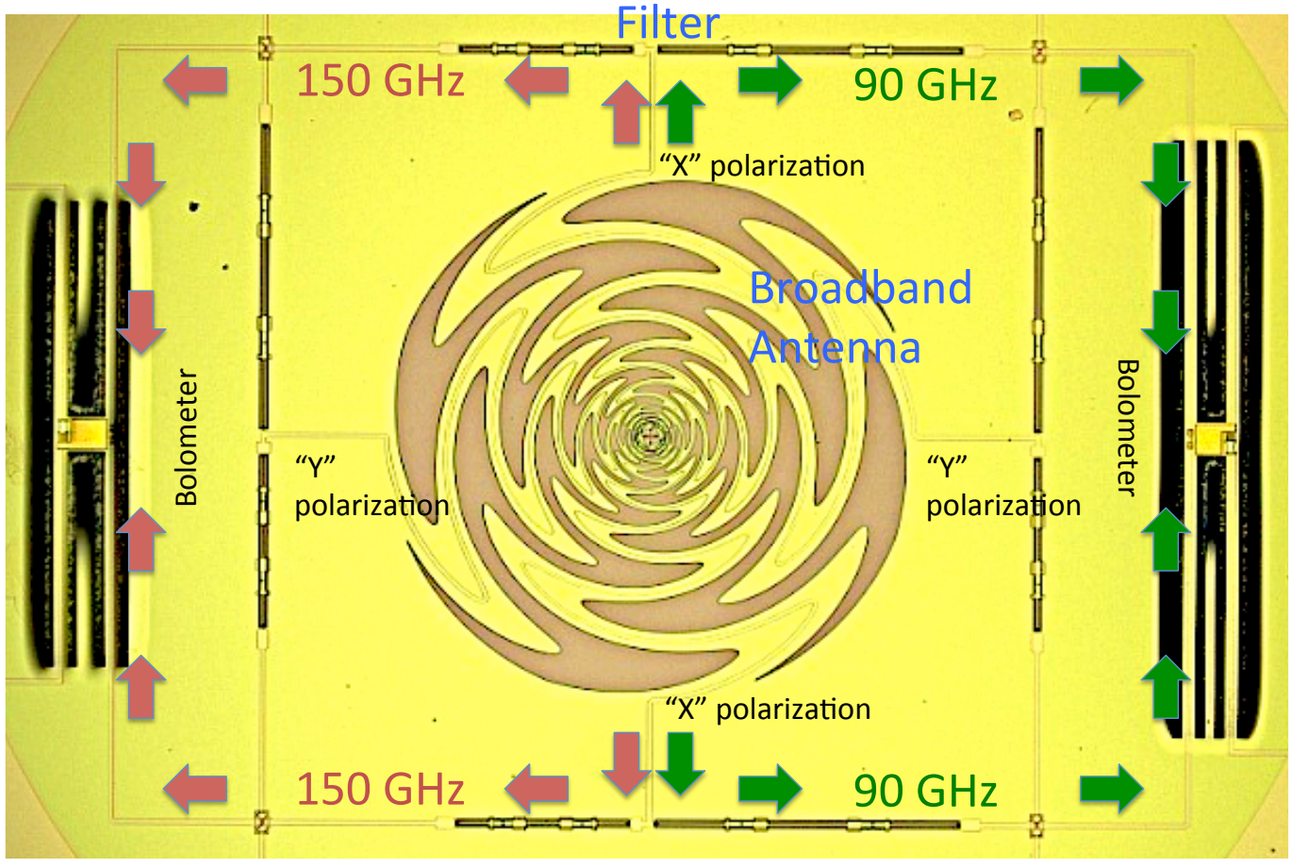
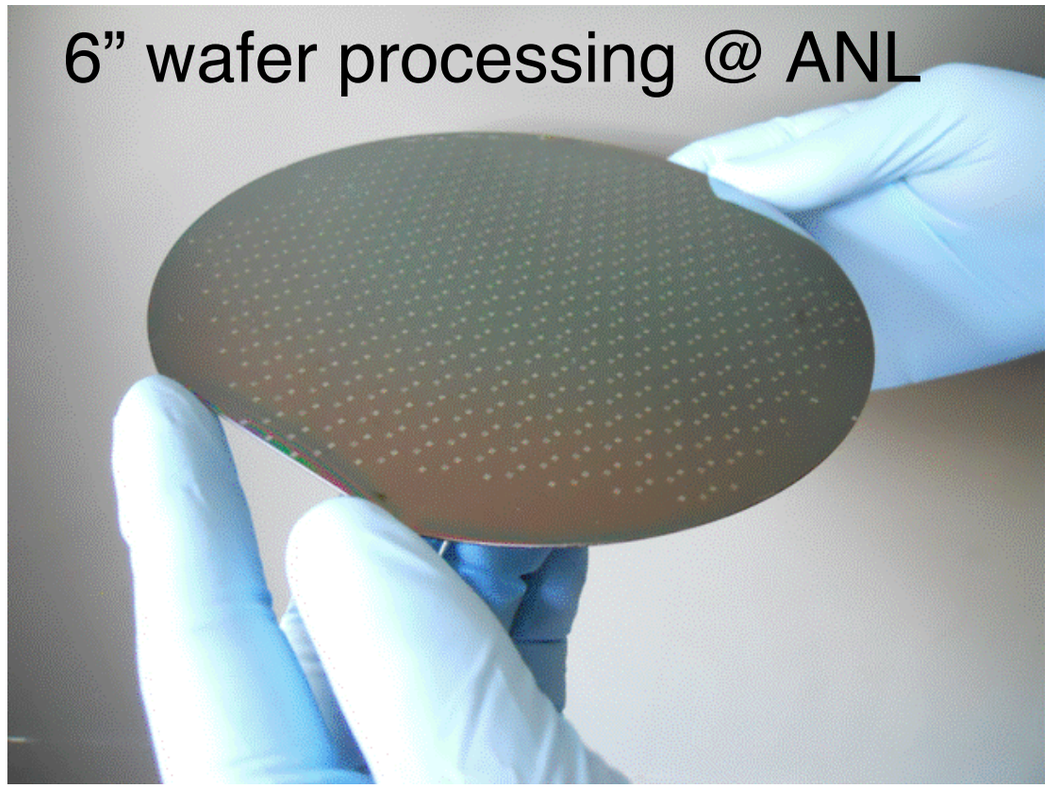
~15,200 detectors



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

Large arrays of Multi-chroic pixels





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

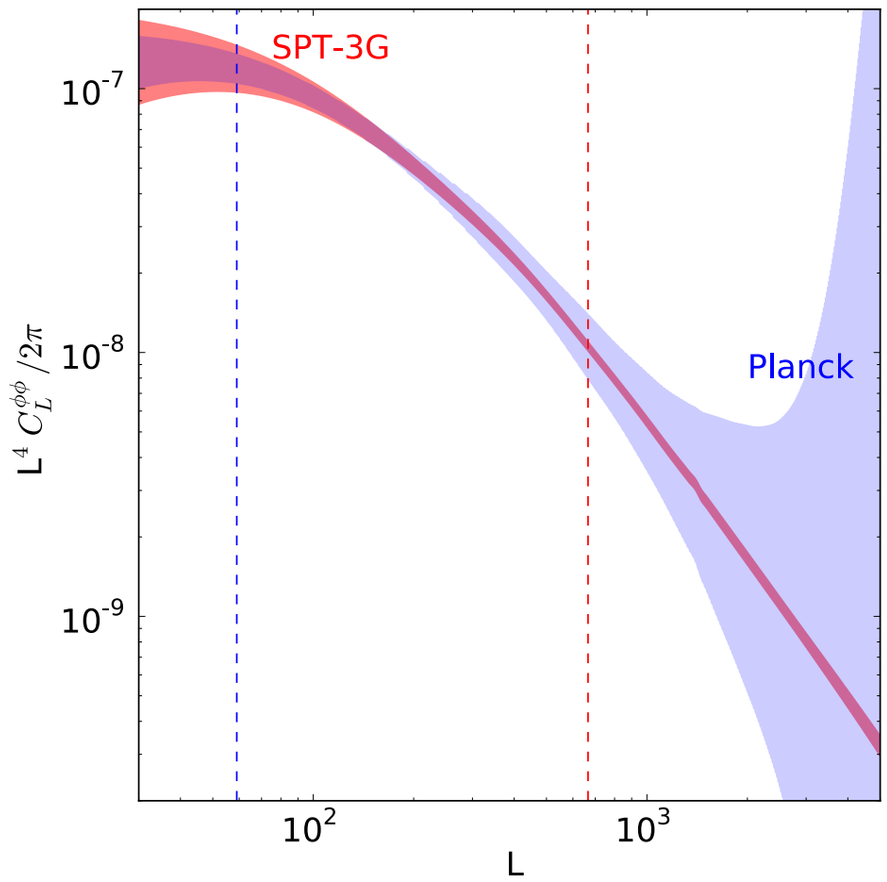
- Developing arrays of three-color pixels for SPT-3G
- Increase bolo density from 2 per pixel to 6 per pixel

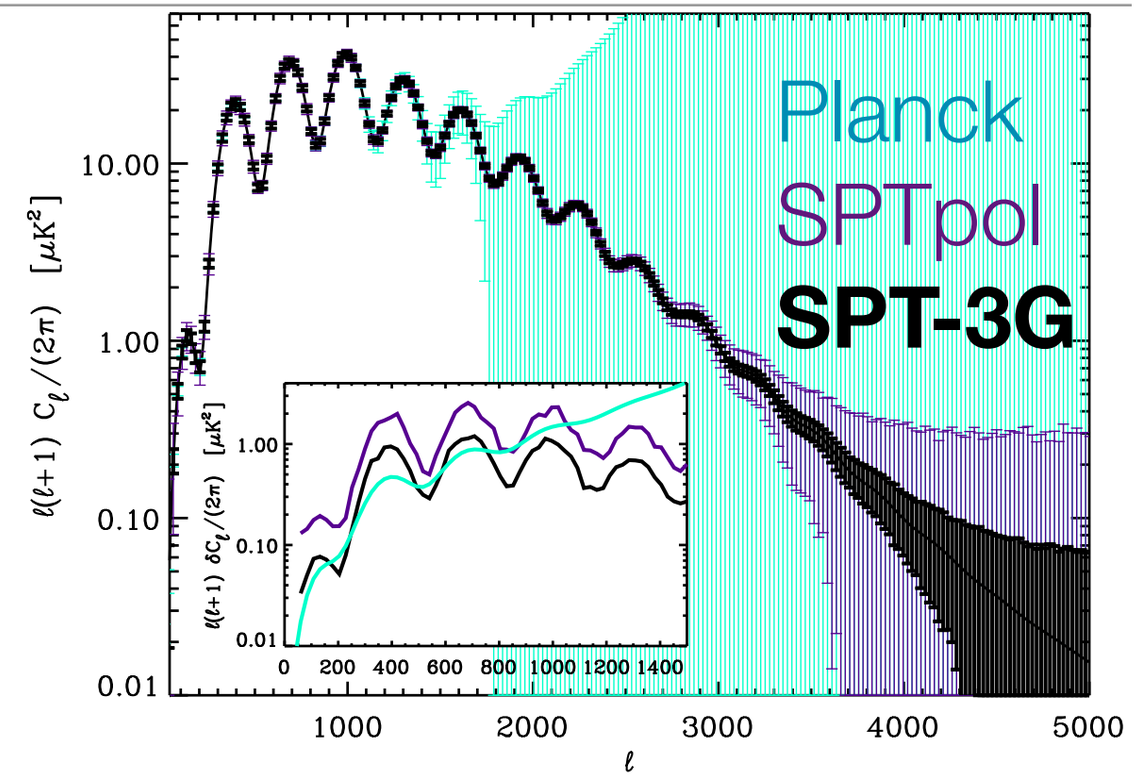
Argonne NATIONAL LABORATORY

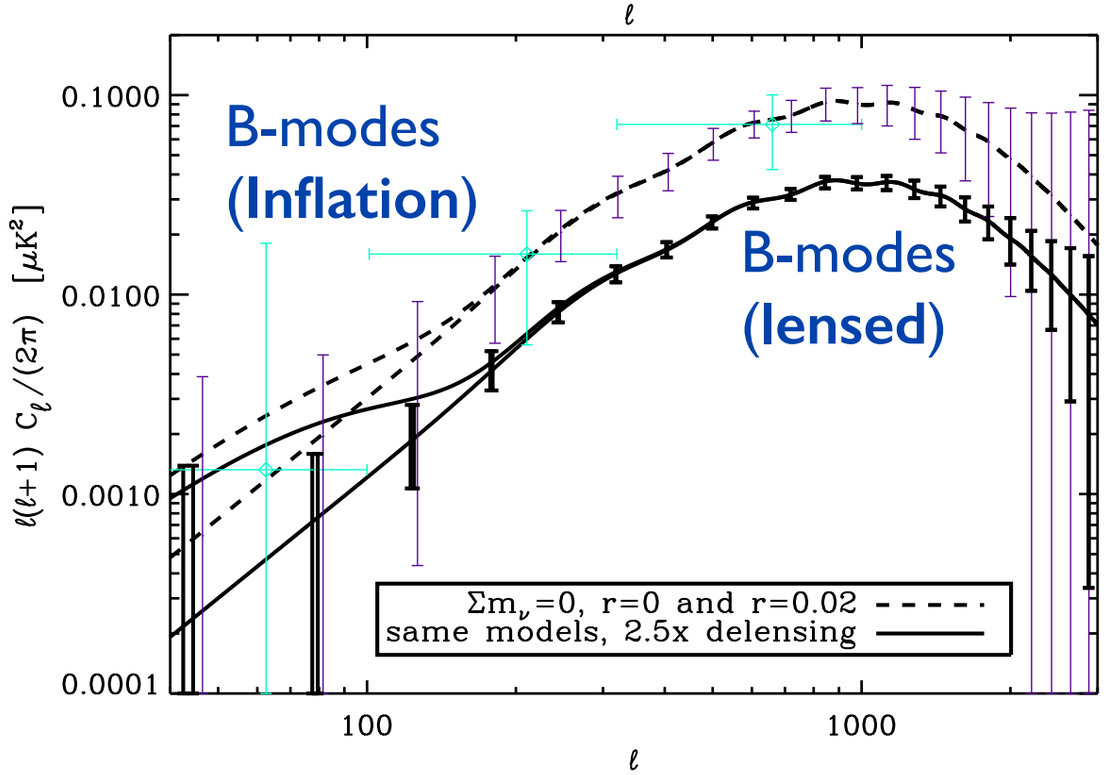
Berkeley University of California

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



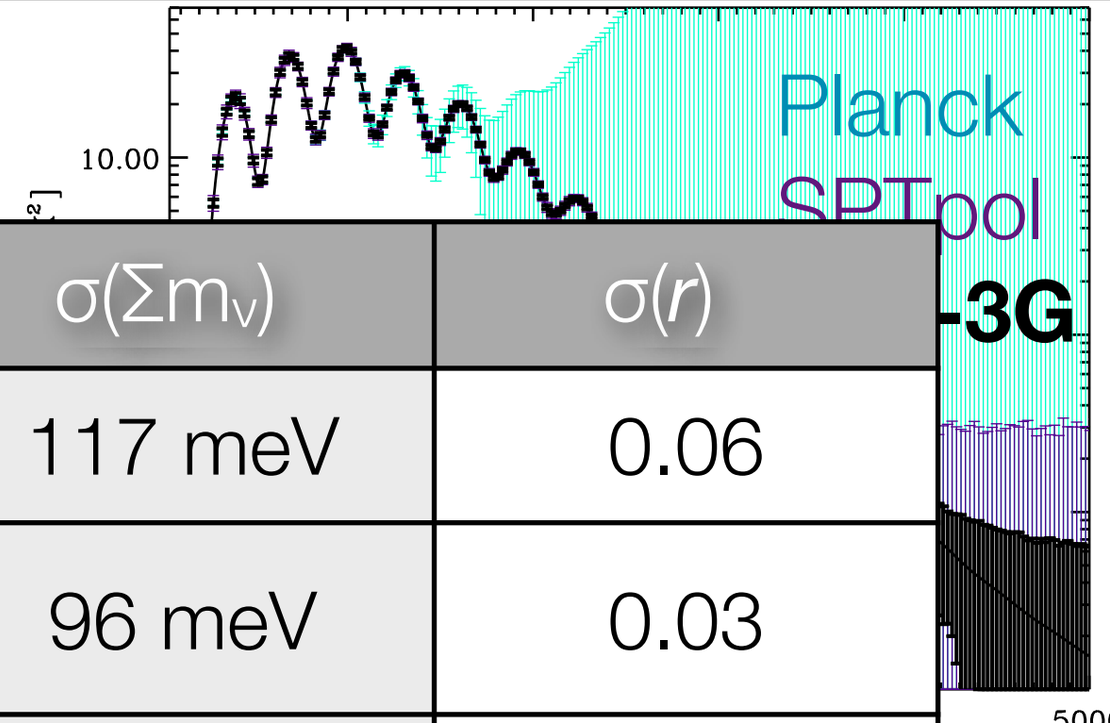


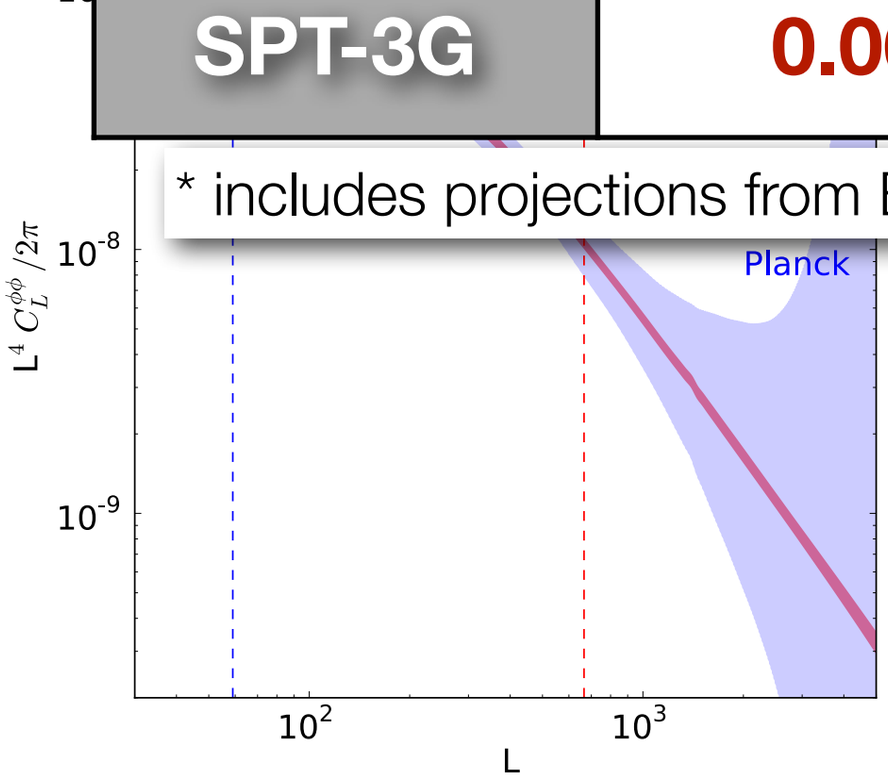


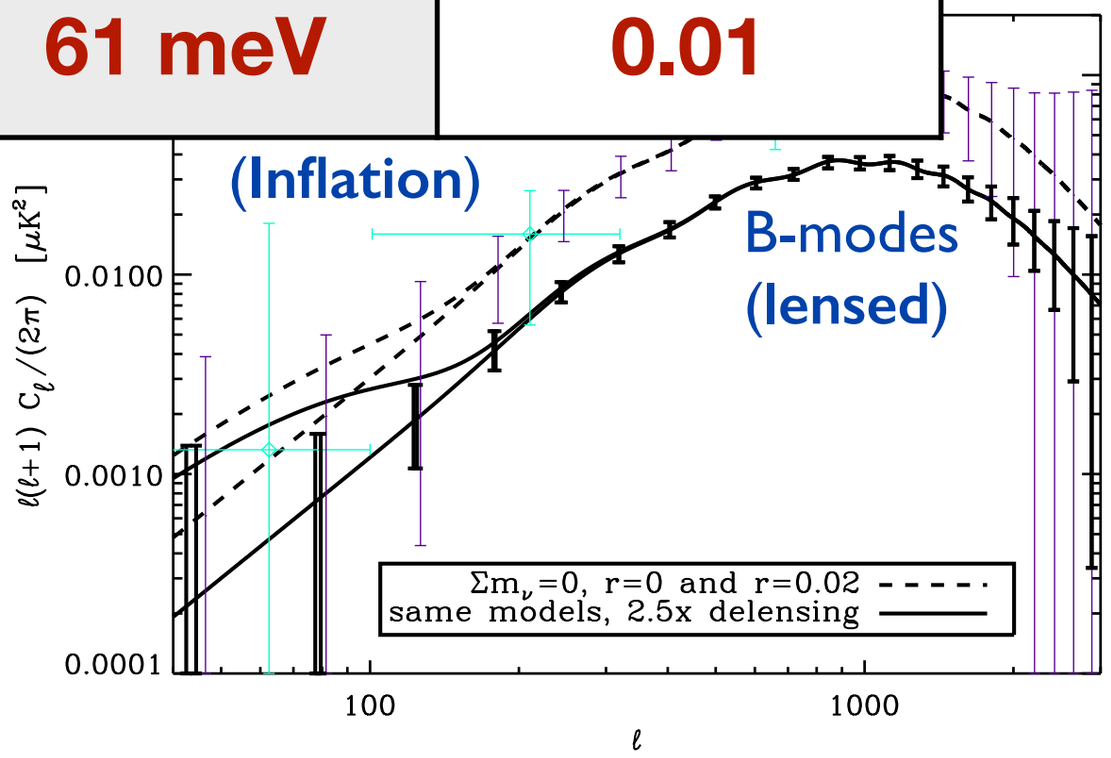
SPT-3G goals (first light early 2016)

- Target 10x mapping speed of SPTpol
  - [illegible]
  - [illegible]
  - [illegible]
- Ta[illegible]

	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	$\sigma(r)$
Planck	0.14	117 meV	0.06
SPTpol	0.12	96 meV	0.03
SPT-3G	**0.06**	**61 meV**	**0.01**

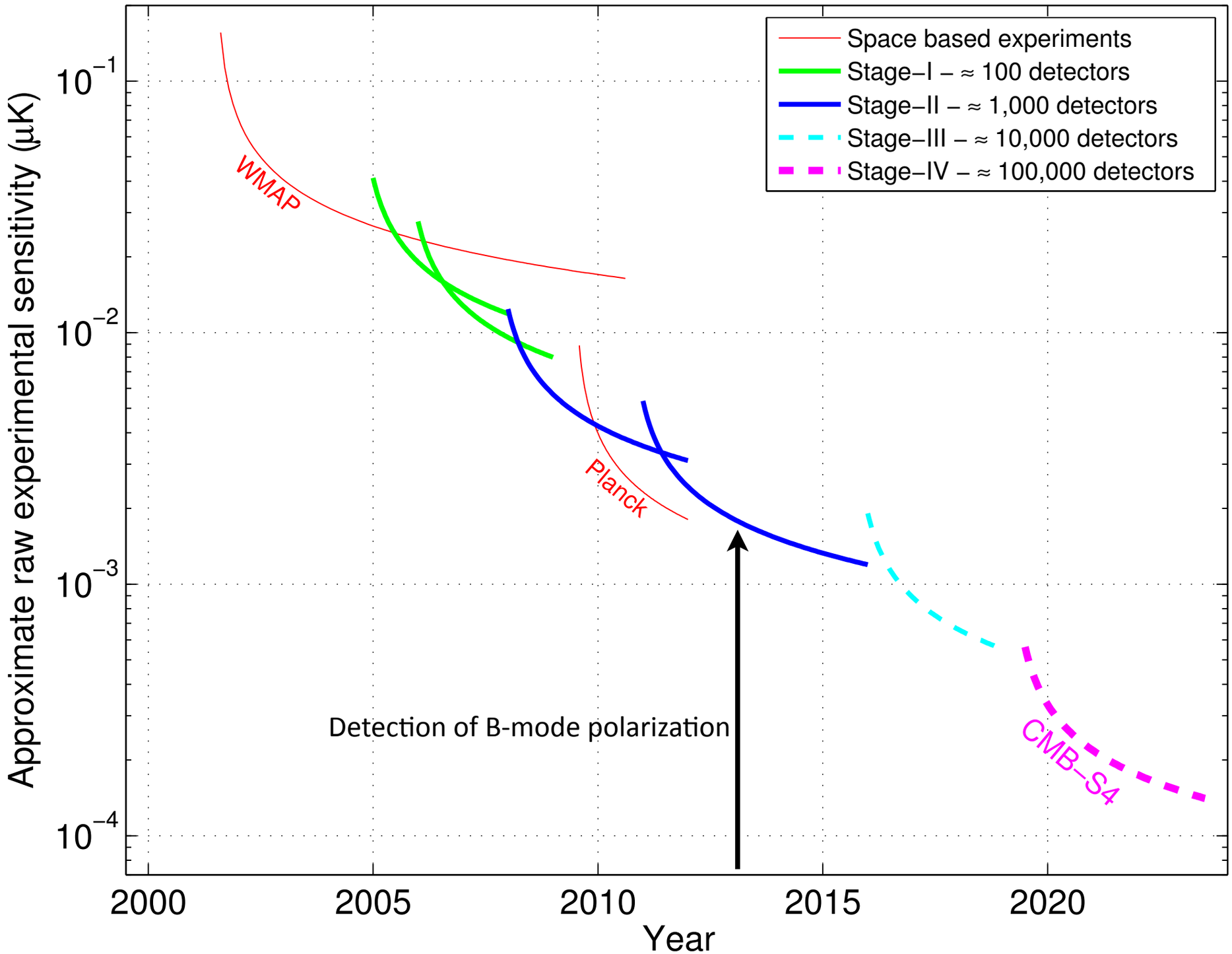






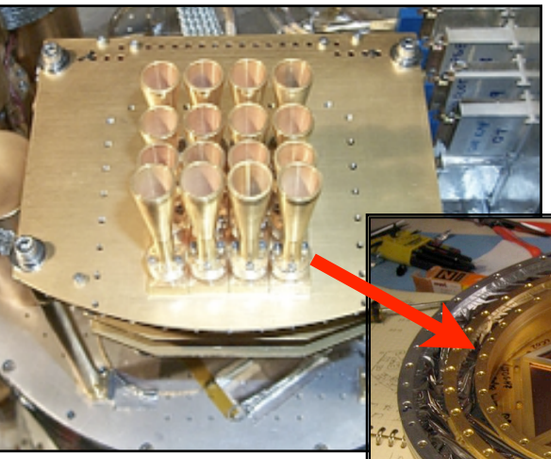
Future science with B-modes: CMB-S4

Experimental Evolution

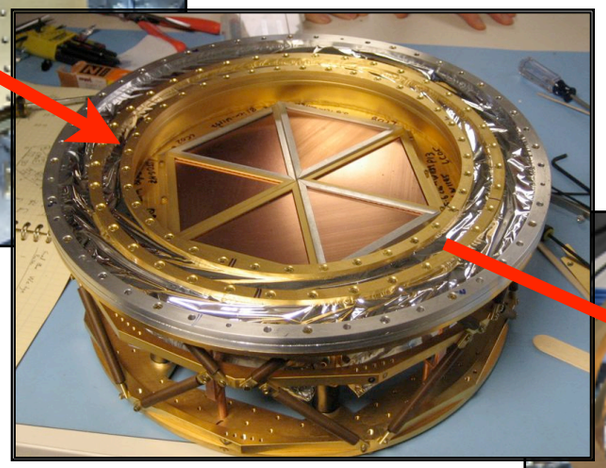


Evolution of CMB Focal Planes

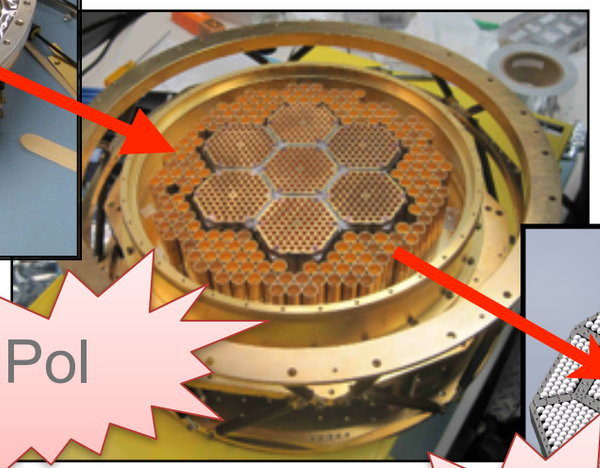
2001: ACBAR
16 detectors



2007: SPT
960 detectors

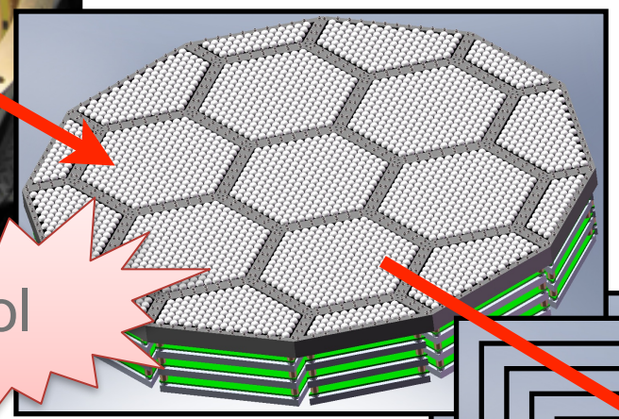


Stage-2
2012: SPTpol
~1600 detectors



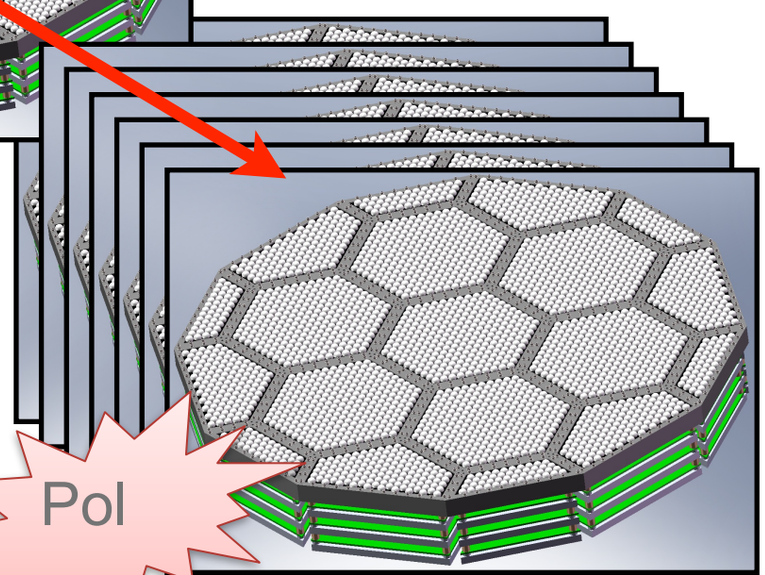
Pol

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



Pol

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



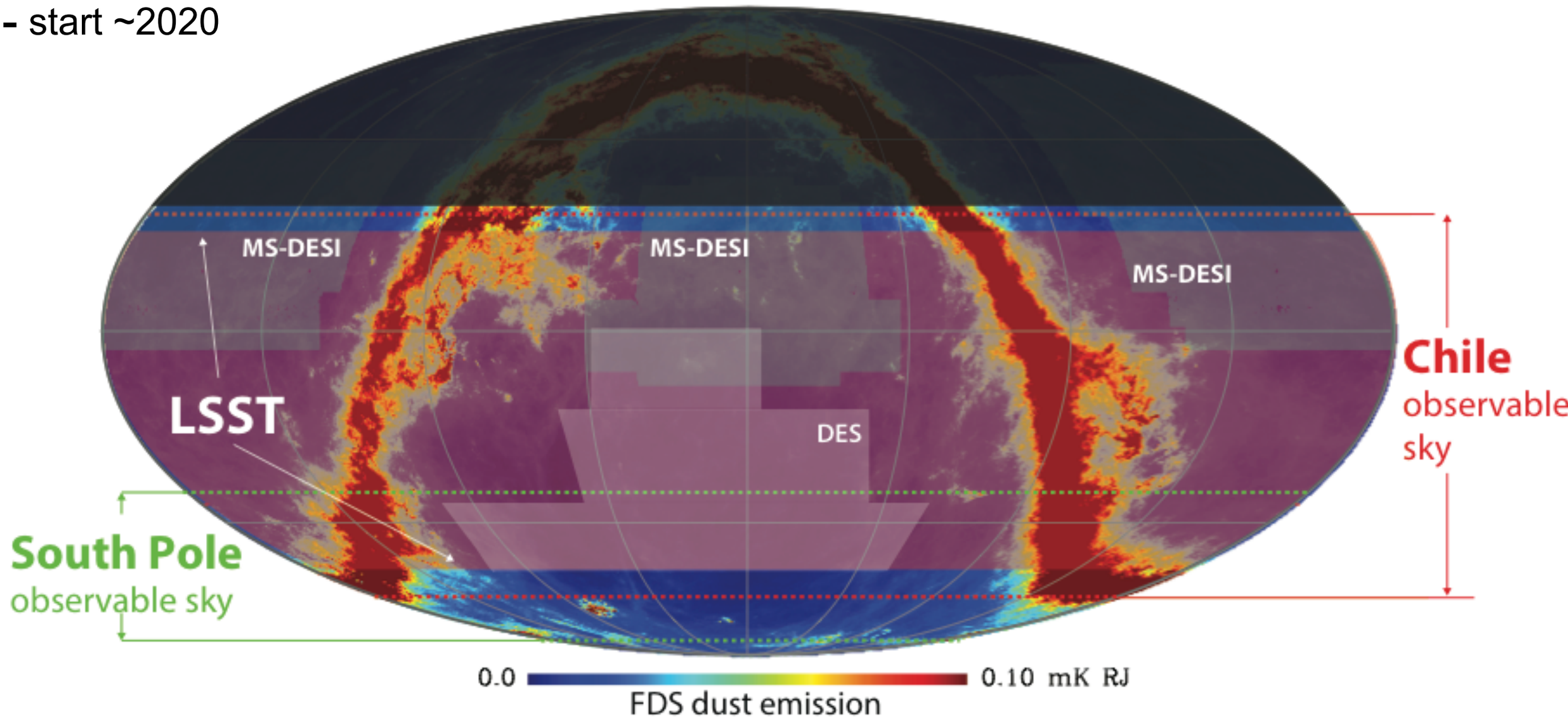
Pol

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

'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

	$\sigma(r)$	$\sigma(N_{\rm eff})$	$\sigma(\Sigma m_\nu)$
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

Summing up

- Exciting time for CMB!
- Post-Planck CMB science lies with higher resolution and polarization
- We see B-modes!
  - SPTpol measures B-modes from lensing @ 7.7σ
- Future science with B-modes: detector array technology
- Next: SPT-3G
- Follow: CMB-S4