# CMB Lensing and B-modes from the South Pole Telescope

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Argonne National Lab
Astronomy & Astrophysics, University of Chicago

# 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

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NATIONAL SCIENCE FOUNDATION

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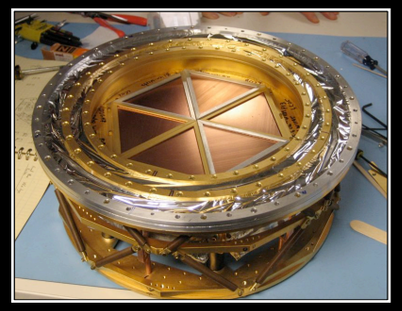
# The South Pole Telescope (SPT)

10-meter sub-mm quality wavelength telescope

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

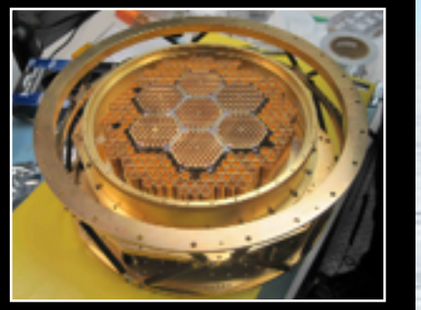
## 2007: SPT-SZ

960 detectors
100,150,220 GHz



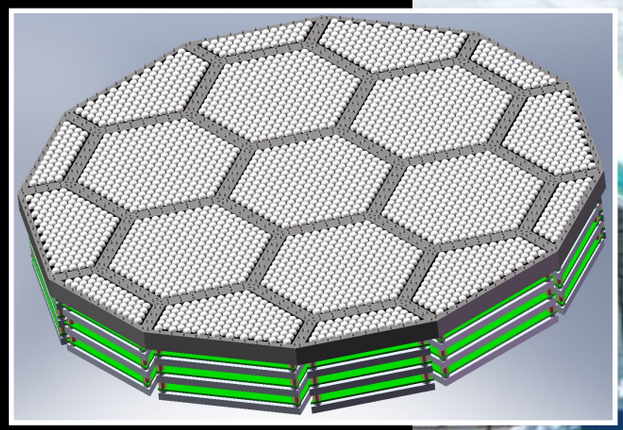
## 2012: SPTpol

1600 detectors
100,150 GHz
***+Polarization***



## 2016: SPT-3G

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



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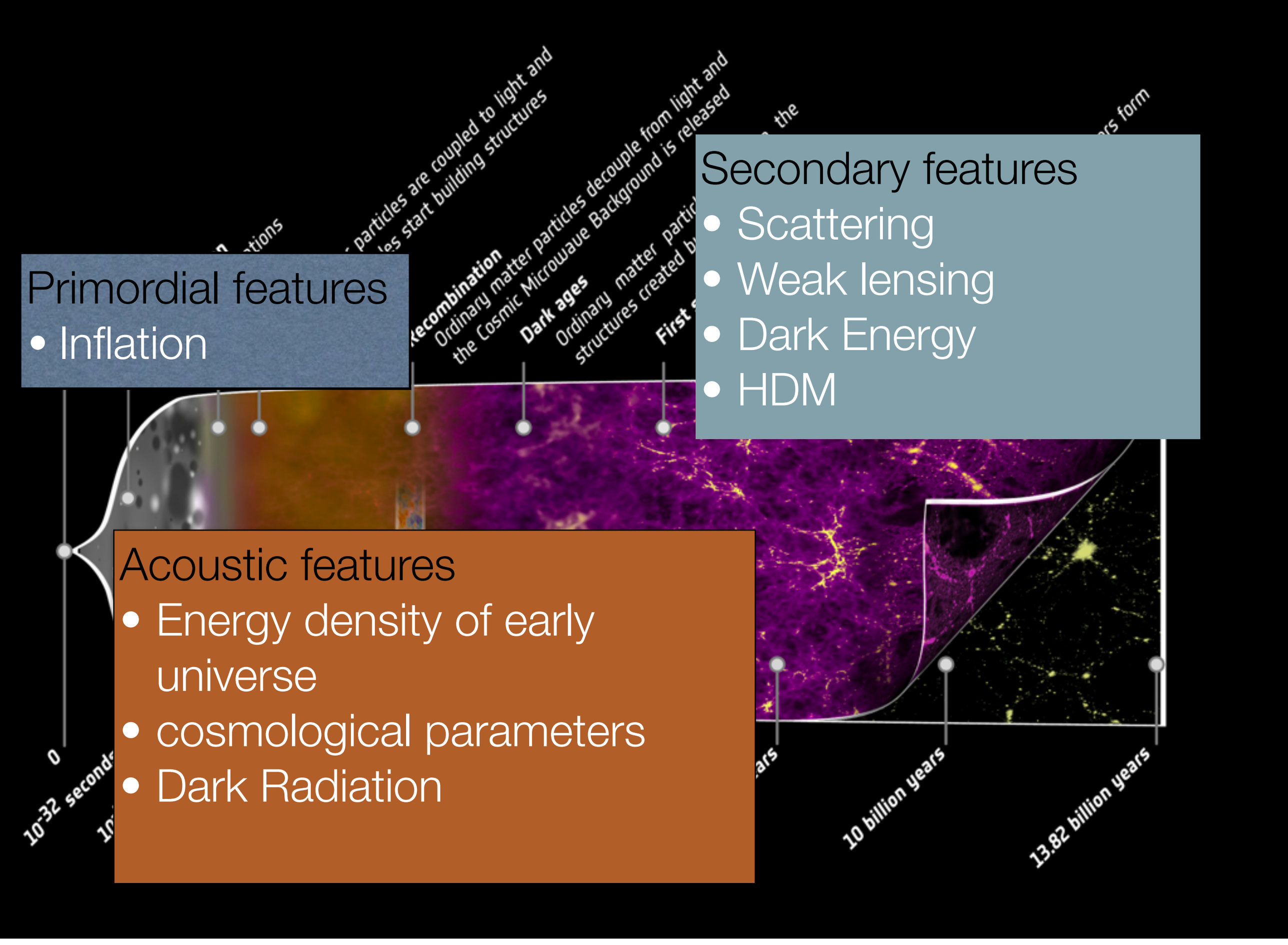

particles are coupled to light and
start building structures
Recombination
Ordinary matter particles decouple from light and
the Cosmic Microwave Background is released
Dark ages
Ordinary matter
structures created
First
the
ers form
Primordial features
• Inflation
Secondary features
• Scattering
• Weak 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

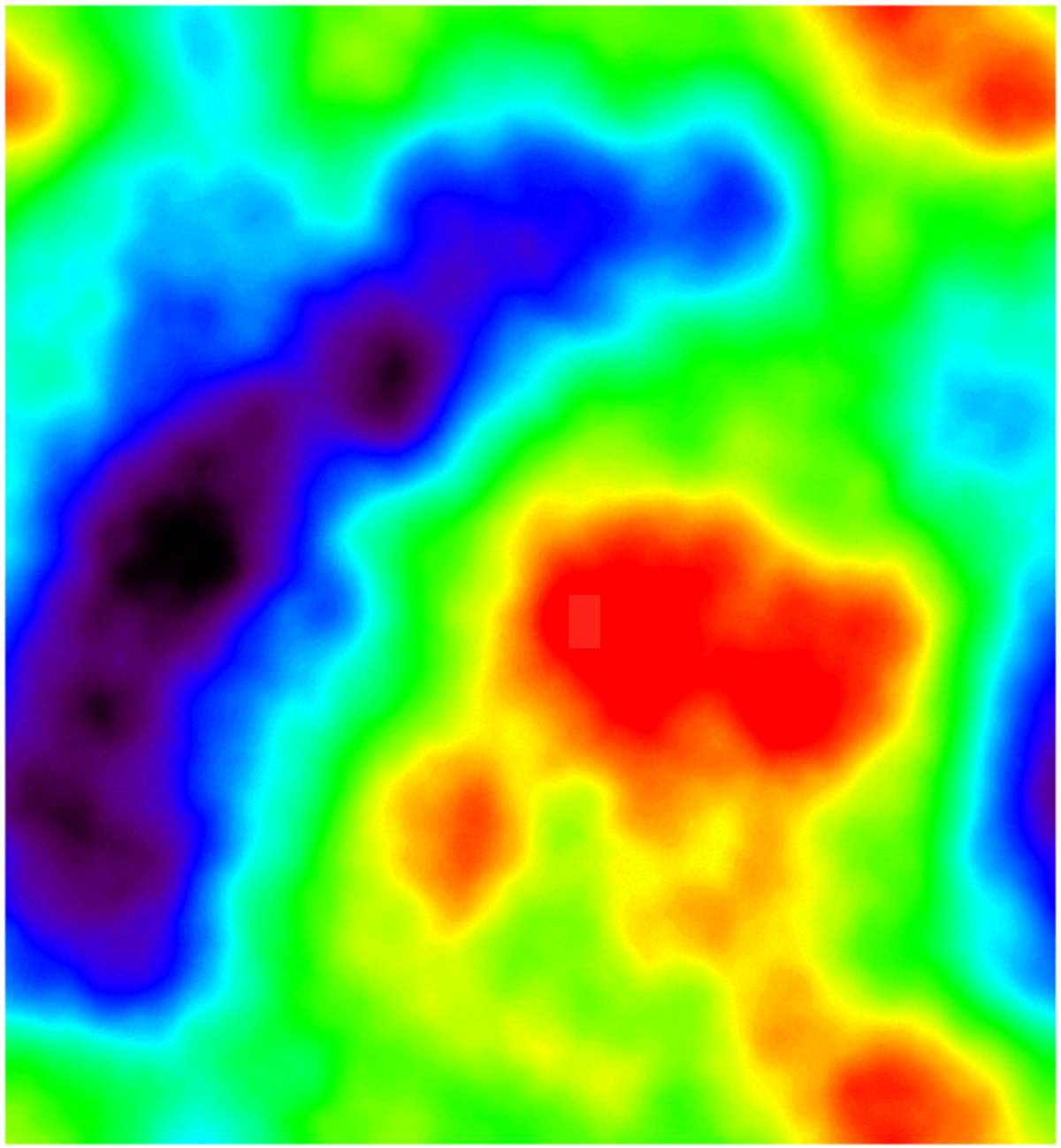
# Lensing

# Large-Scale Structure Lenses the CMB

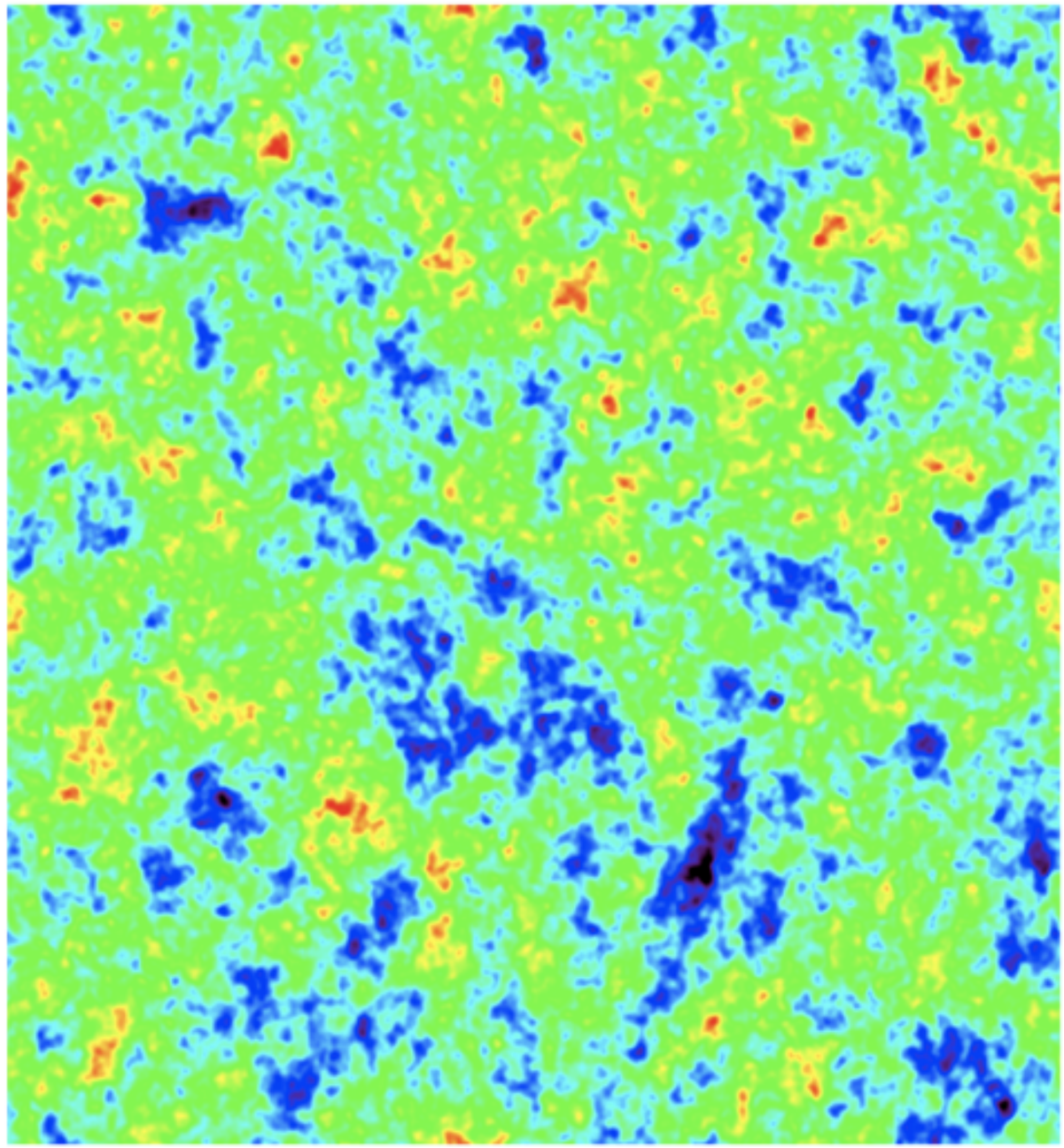
- RMS deflection of ~2.5’
- Lensing efficiency peaks at $z \sim 2$, or 7000 Mpc distance
- Coherent on ~degree (~300 Mpc) scales

# Lensing of the CMB

17°x17°



lensing potential

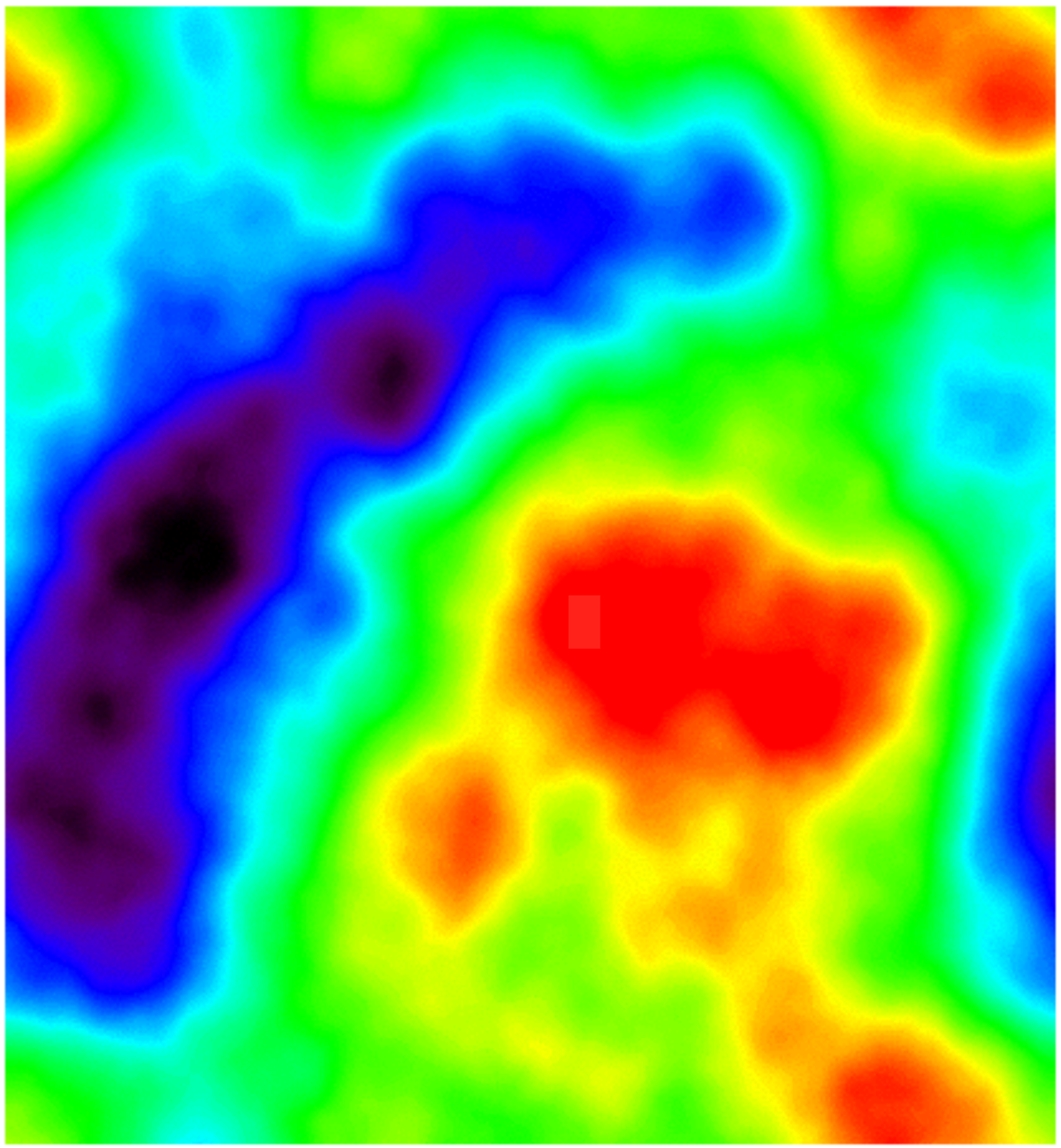


unlensed cmb

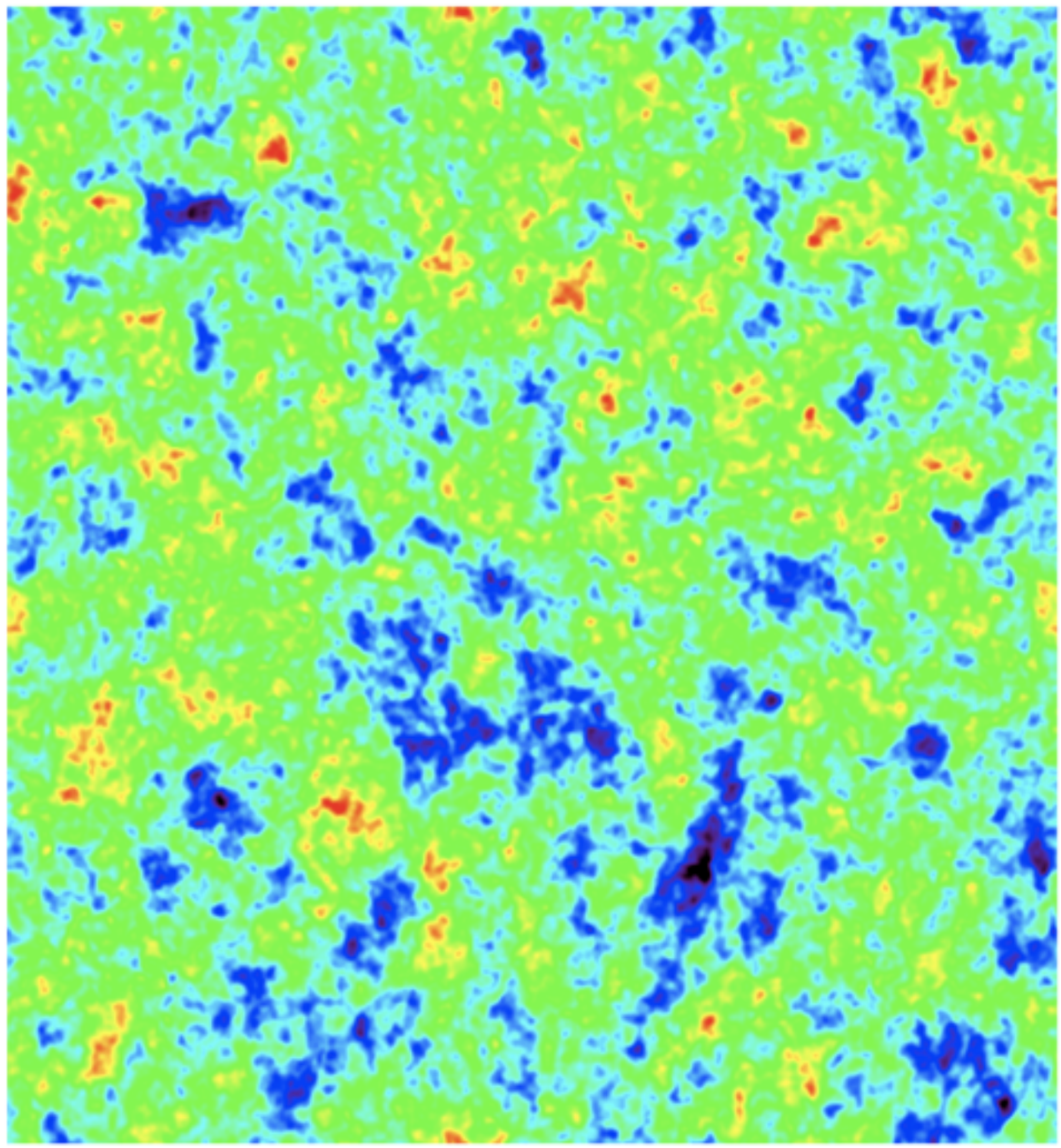
*from Alex van Engelen*

# *Lensing* of the CMB

17°x17°



lensing potential

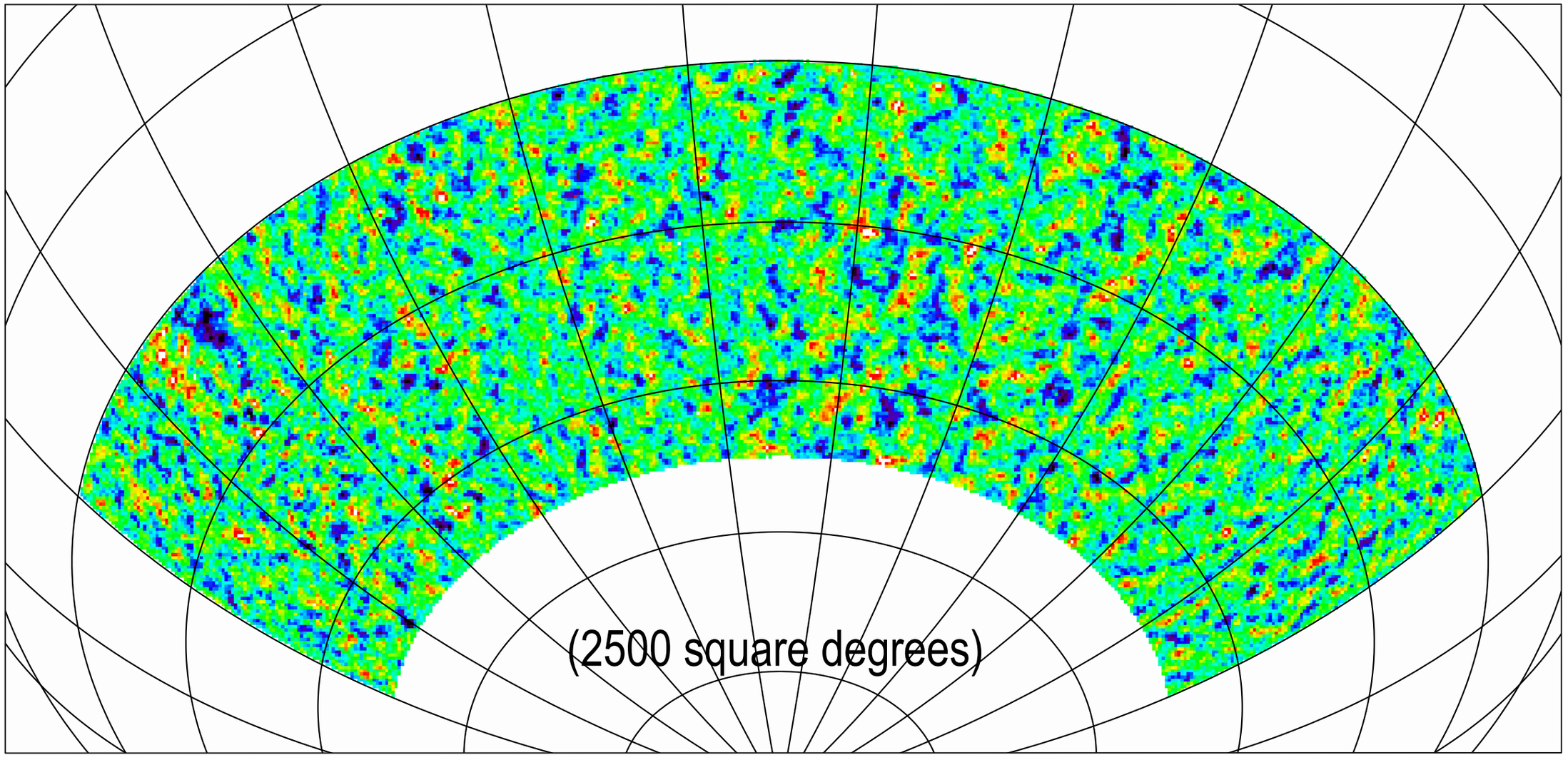


lensed cmb

*from Alex van Engelen*

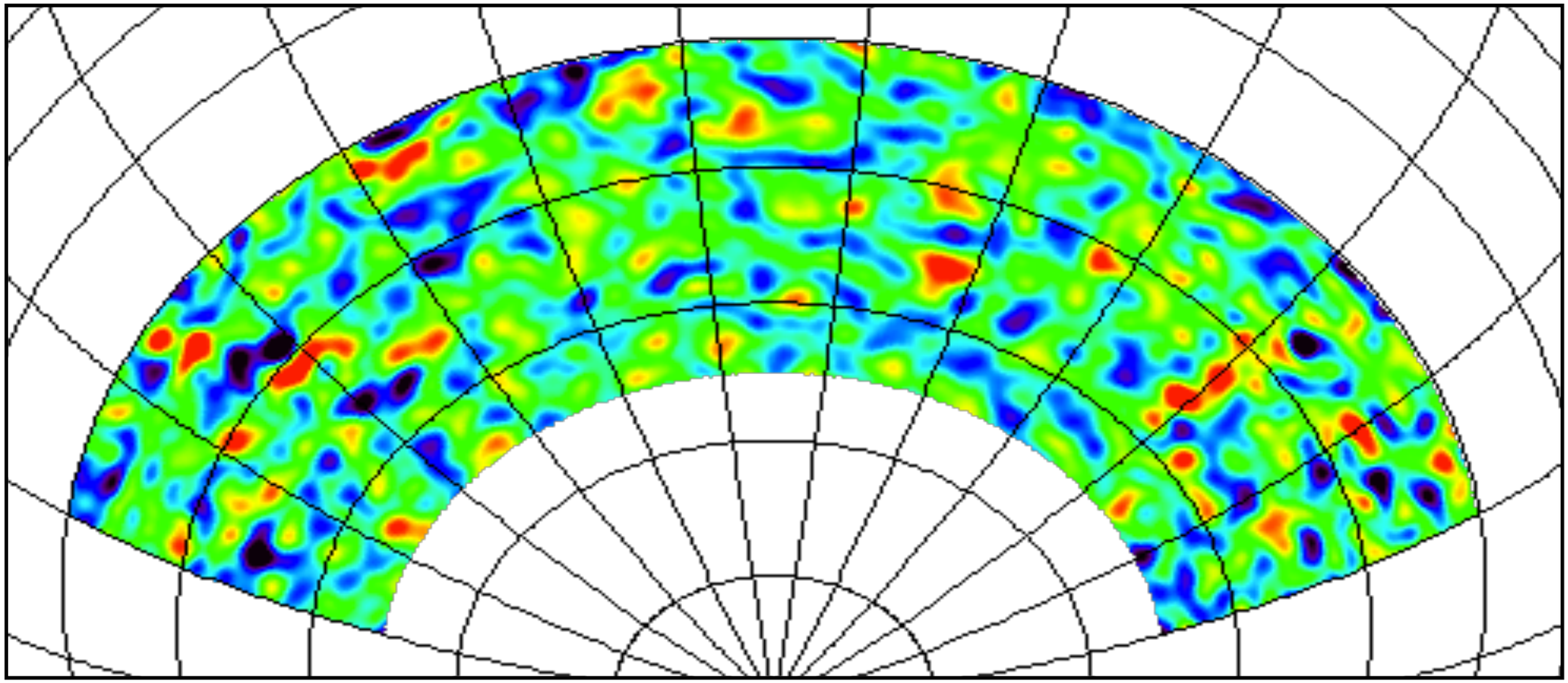
# high resolution and sensitivity map of the CMB from SPT

## covering 1/16 of the sky

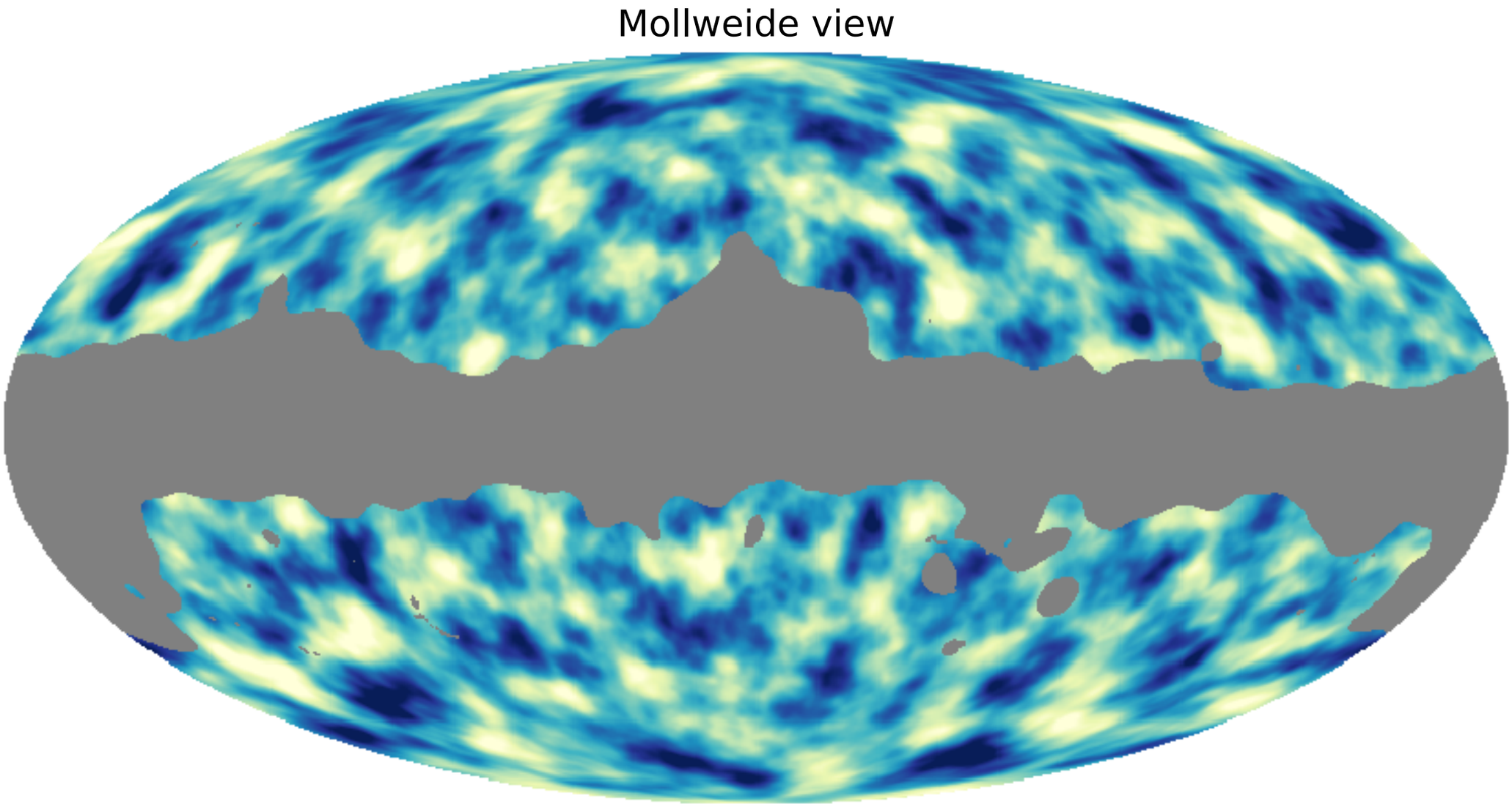


# CMB Lensing Map

## 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

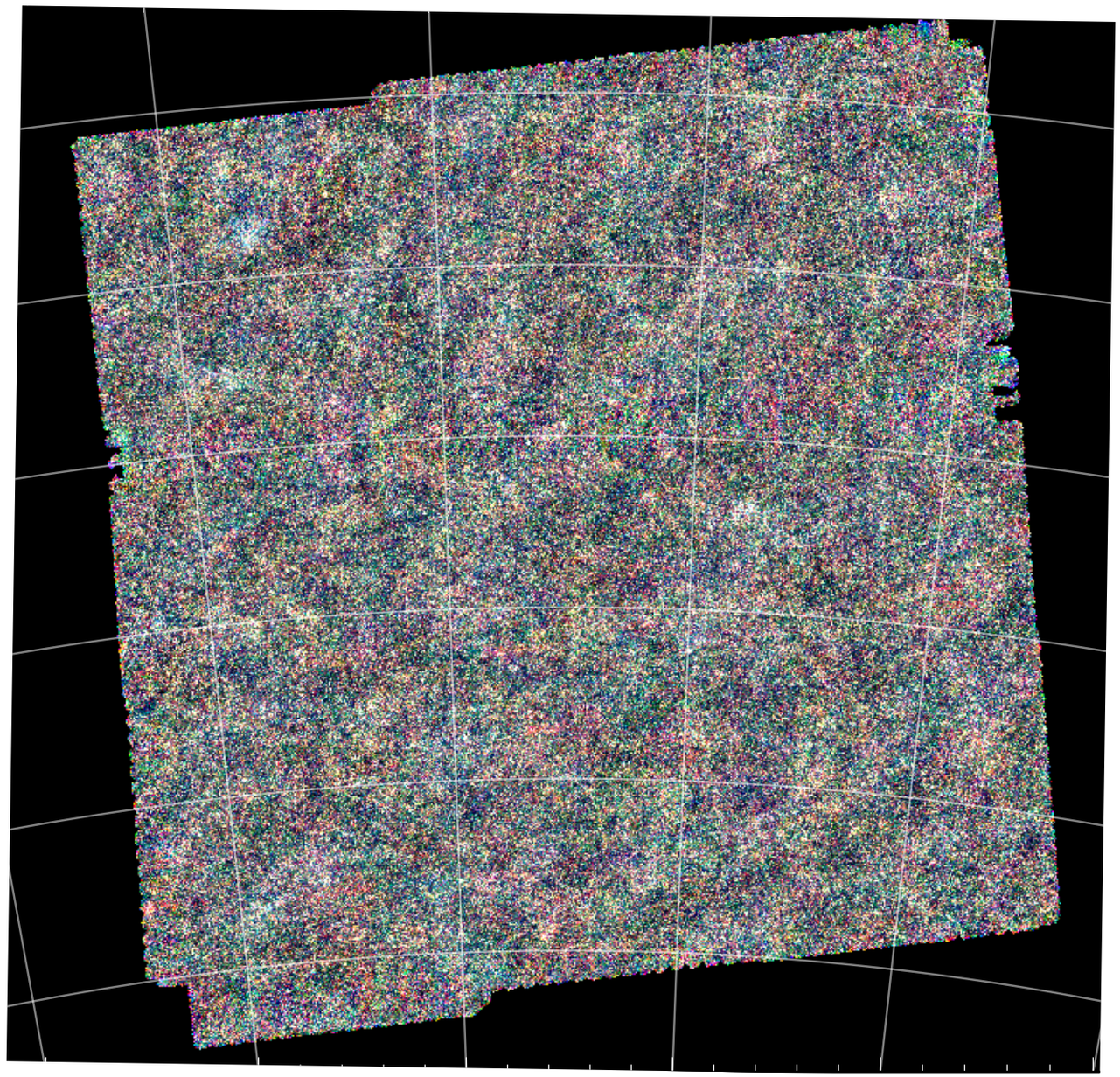



“Mass Map” from Planck, ~70% of sky

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

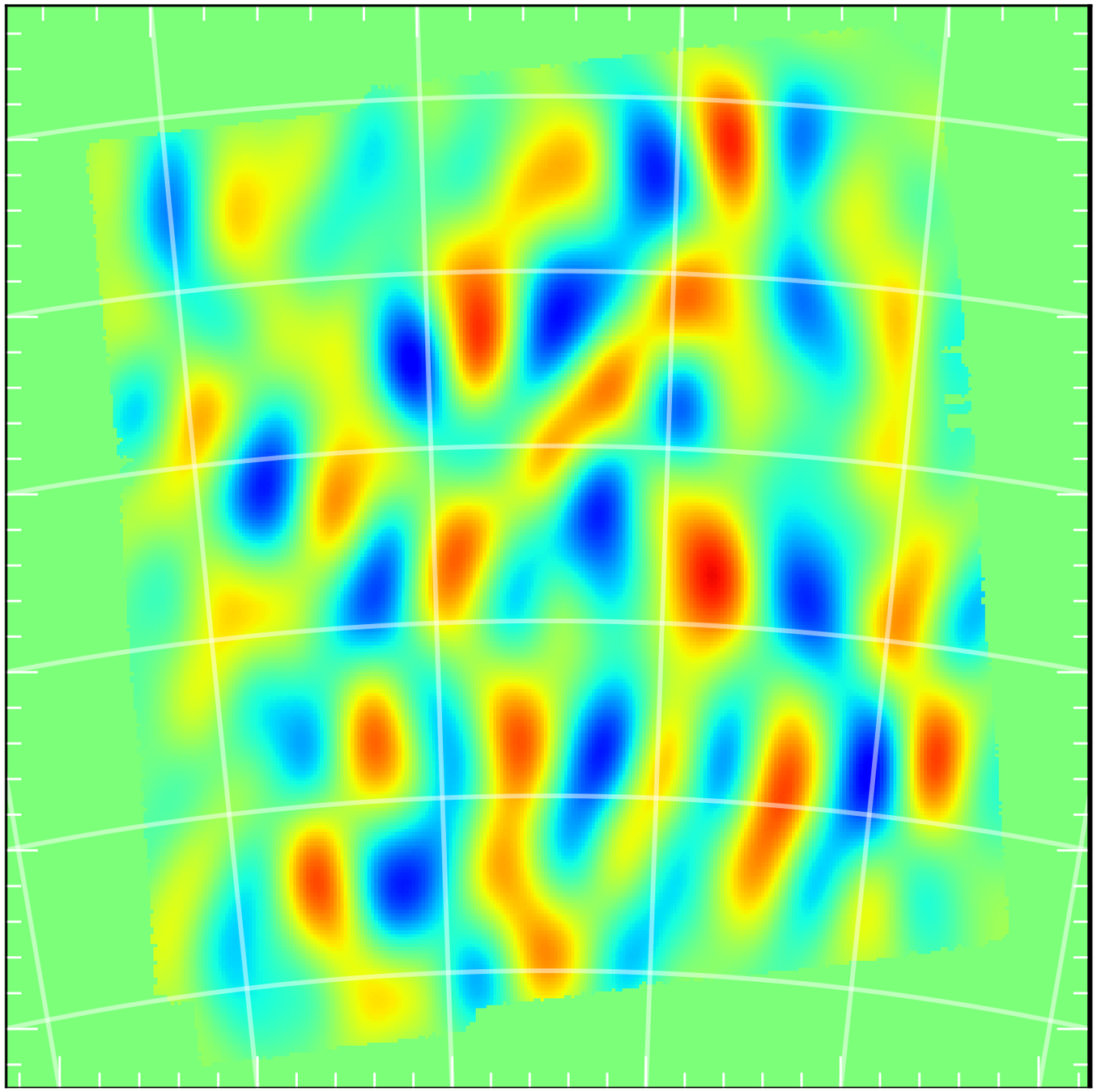
# It’s really the Dark Matter:

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



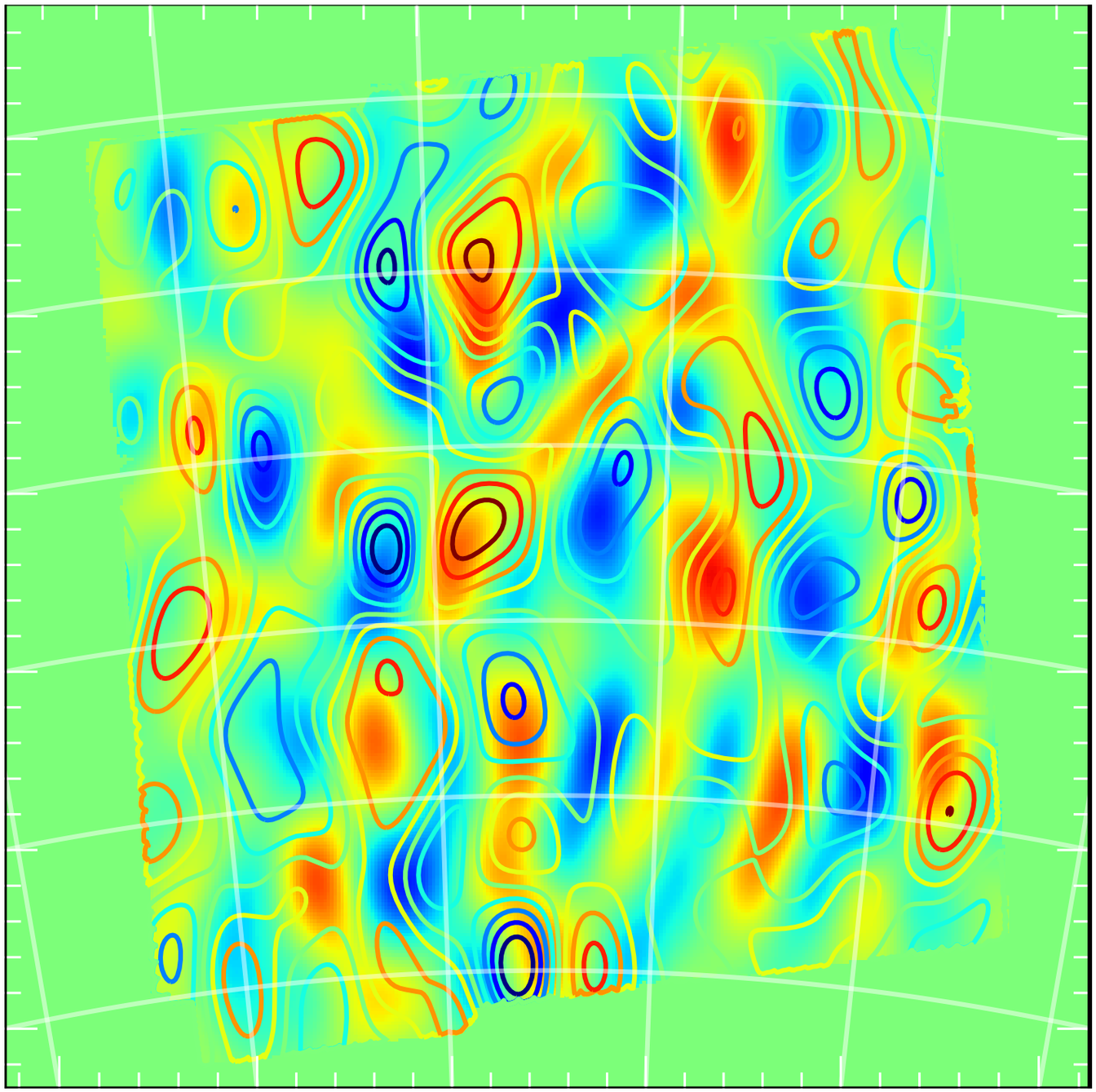
RGB = 500,350,250 um

# It’s really the Dark Matter:



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

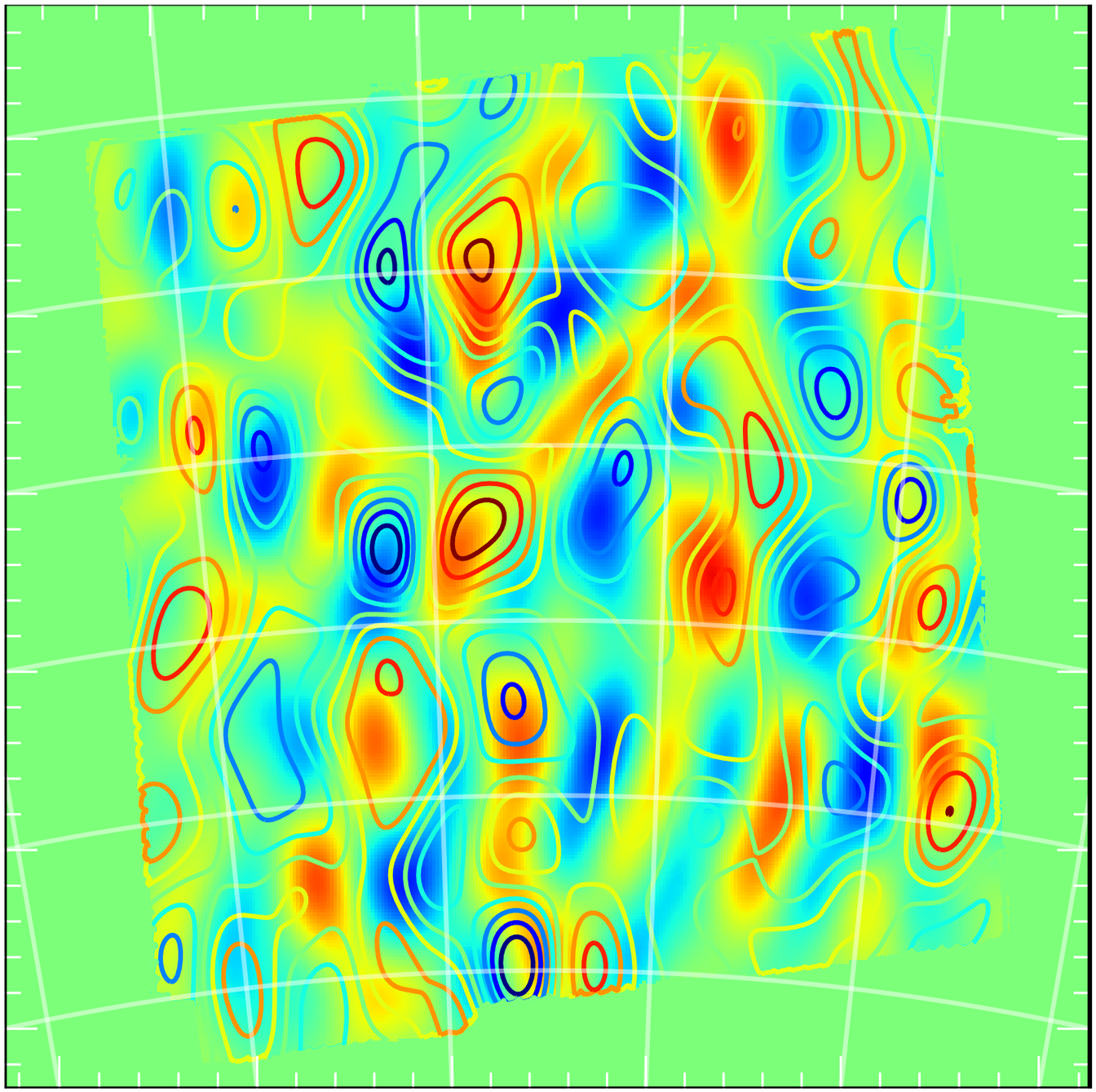
# It's really the Dark Matter:



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).

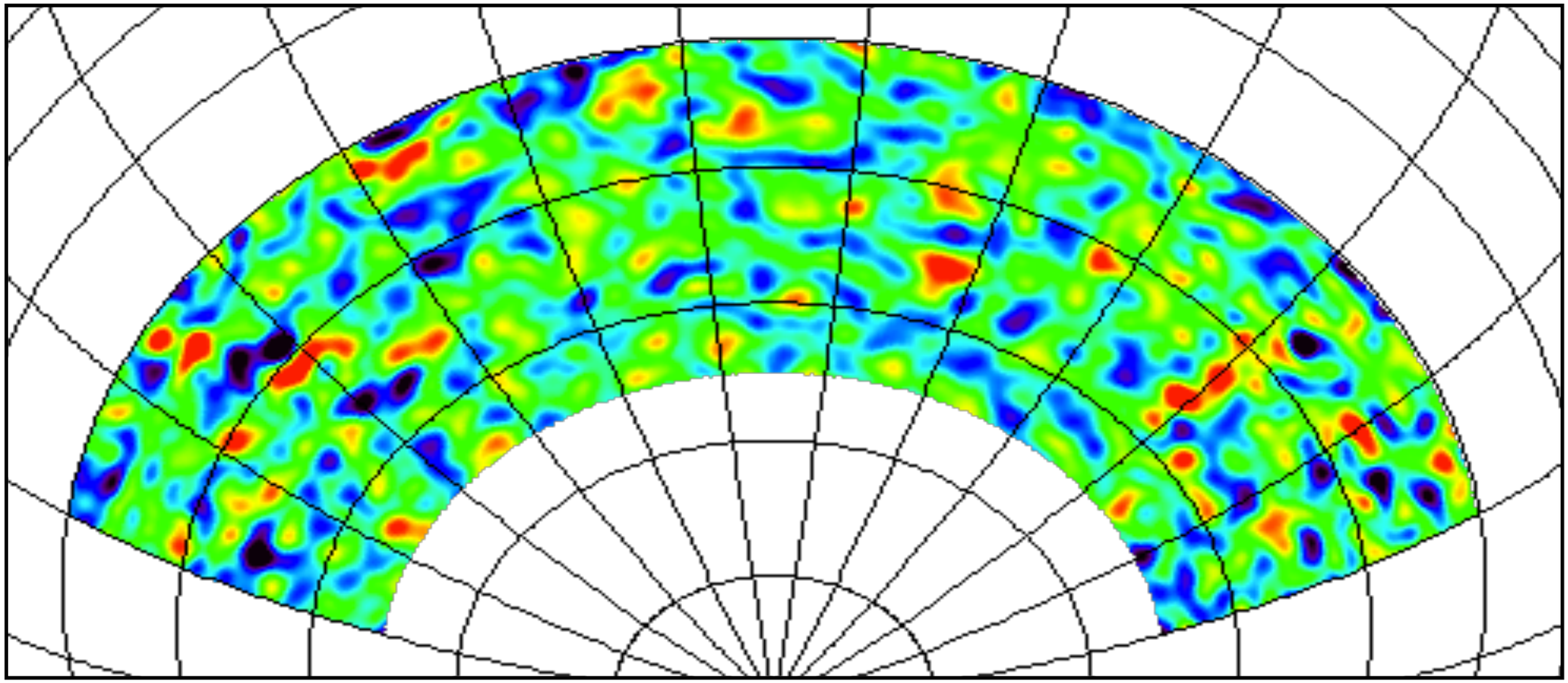
Add mass contours from SPT CMB lensing.

~10σ correlation signal

*Holder et al. 2013*

# CMB Lensing Map

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



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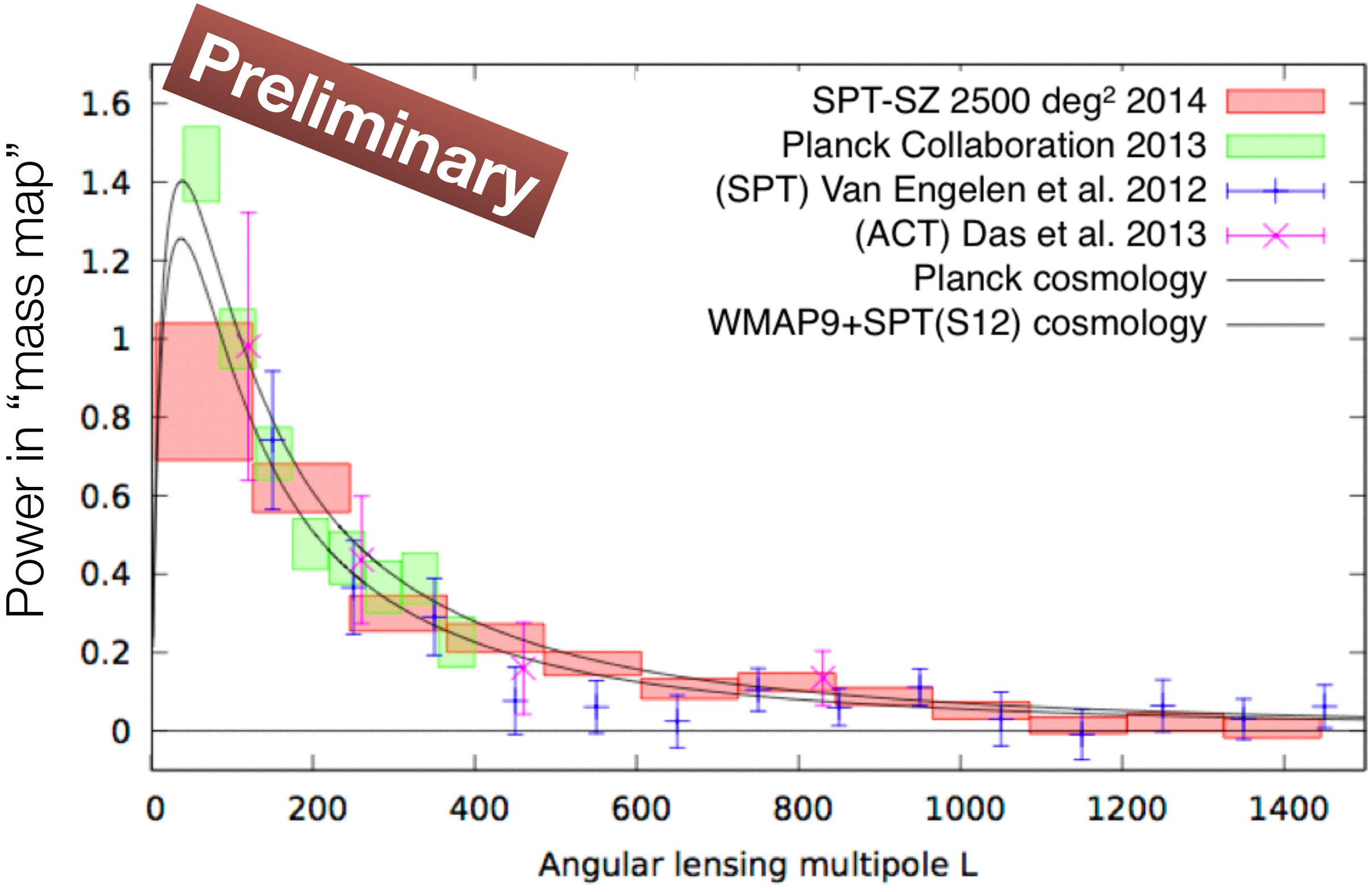
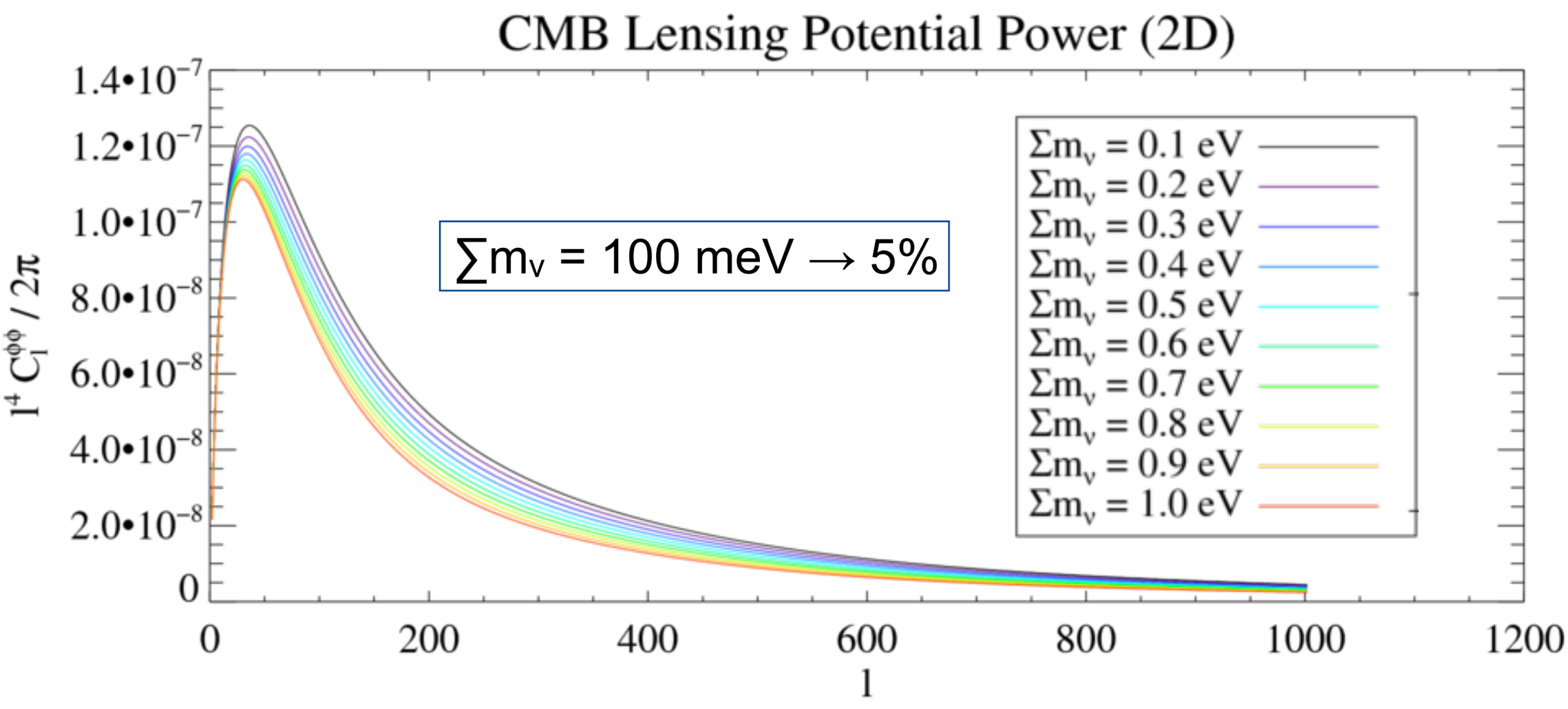
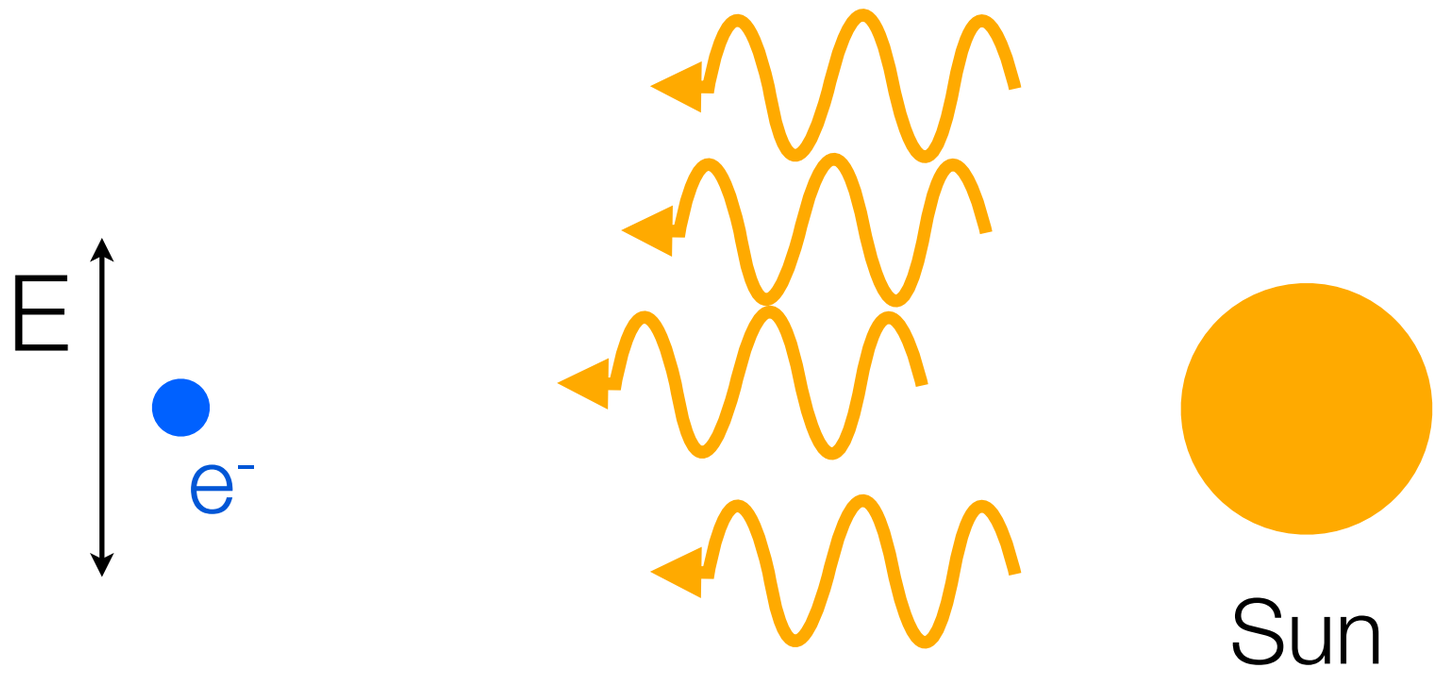

Preliminary
SPT-SZ 2500 deg² 2014
Planck Collaboration 2013
(SPT) Van Engelen et al. 2012
(ACT) Das et al. 2013
Planck cosmology
WMAP9+SPT(S12) cosmology
Power in "mass map"
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
1200
1400
Angular lensing multipole L

# Neutrino mass



# CMB polarimetry

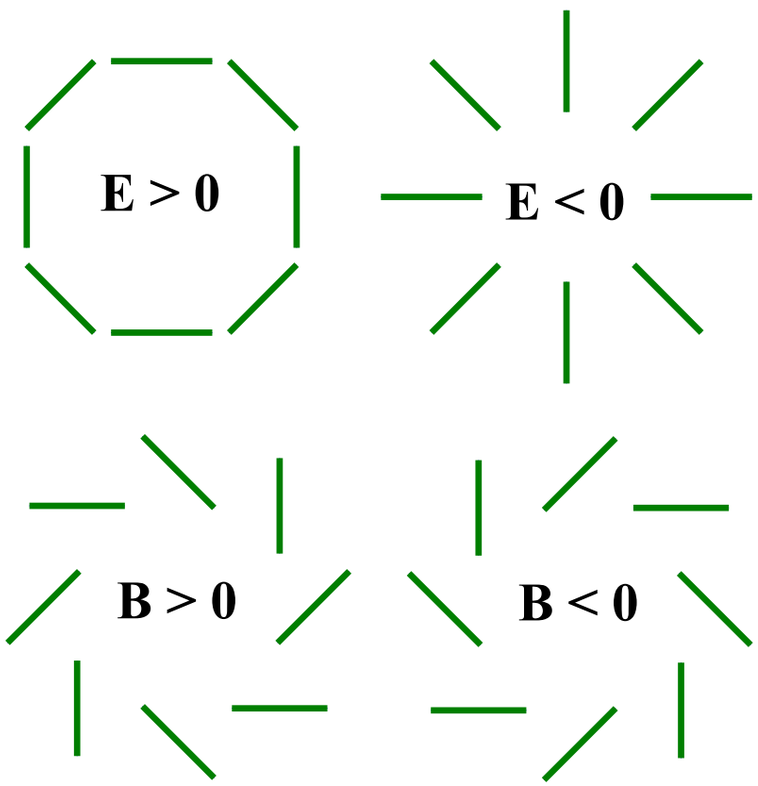
- CMB polarized via Thomson scattering and local anisotropy (e.g. Sun scattering in atmosphere)

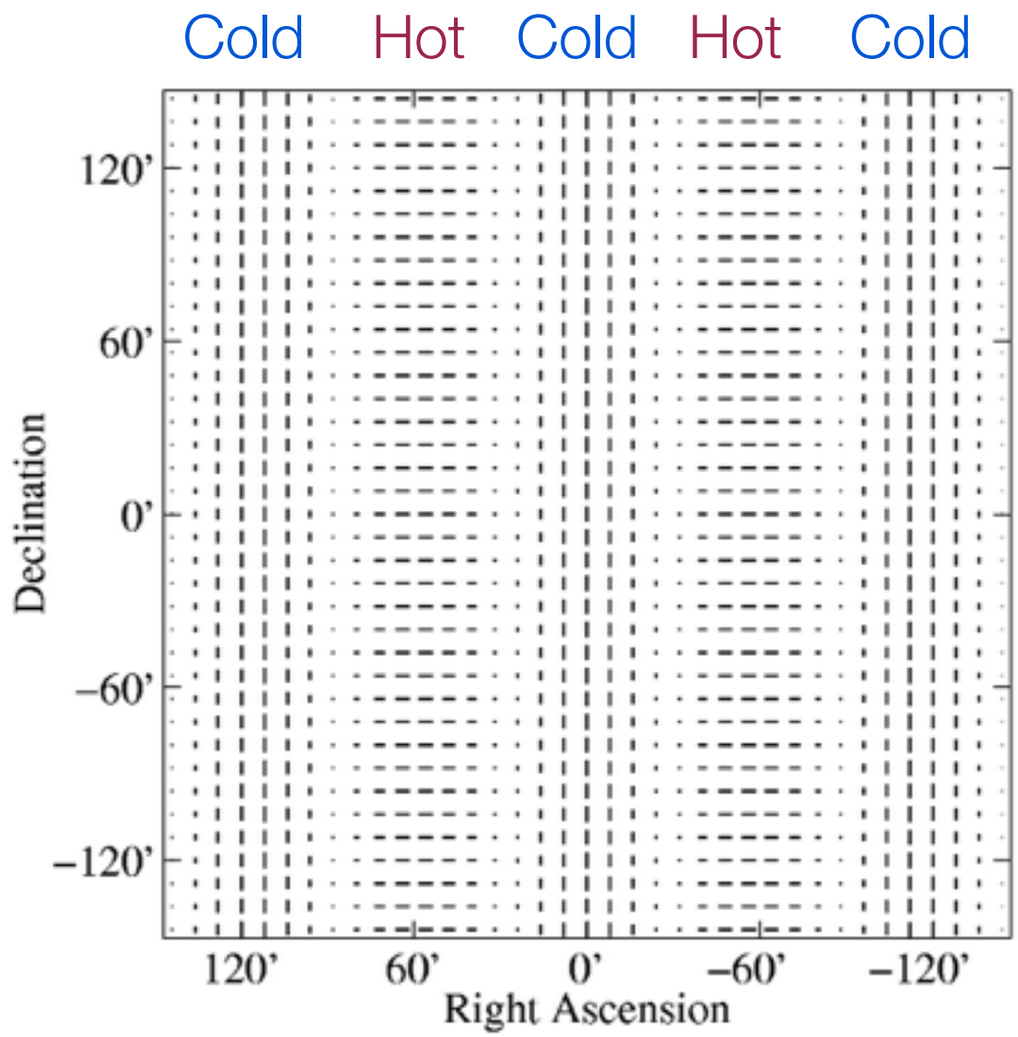


# CMB polarimetry: E-modes

- 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**



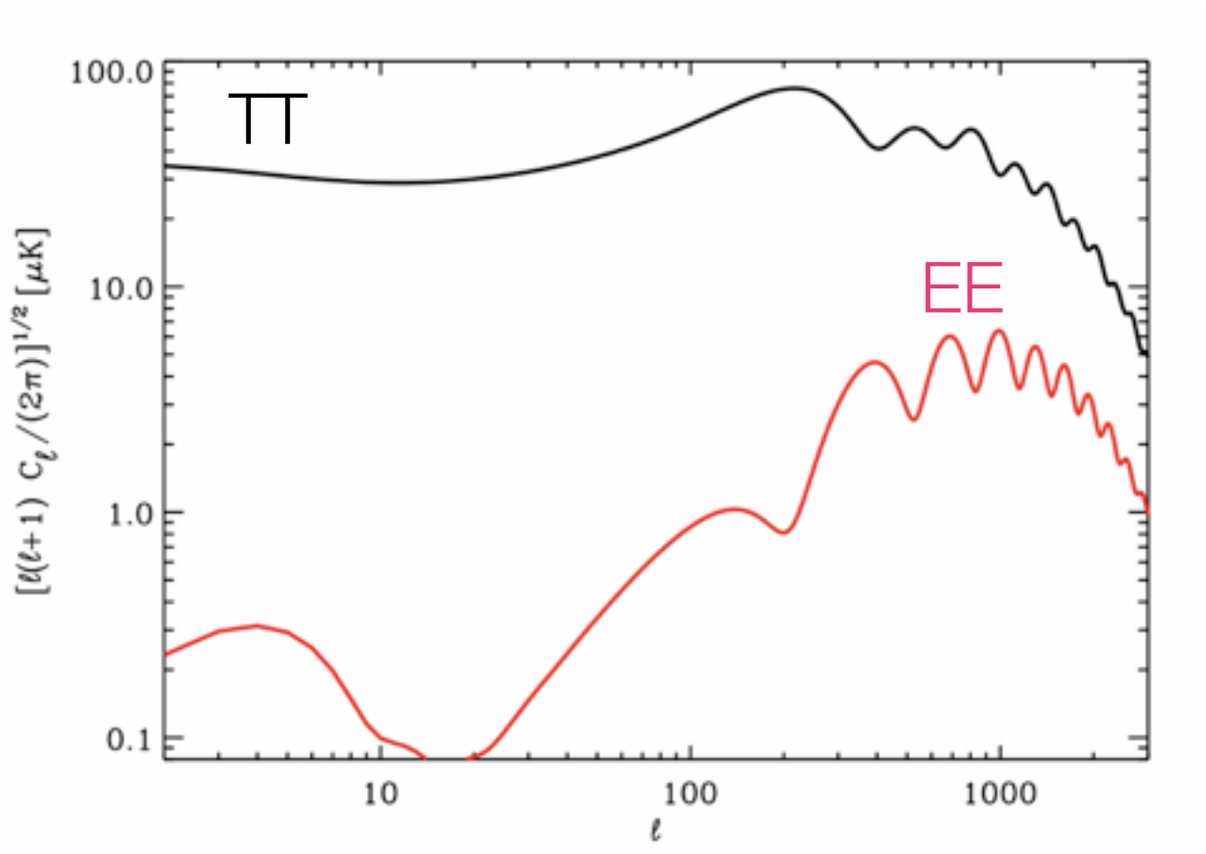



# CMB polarimetry: E-modes

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

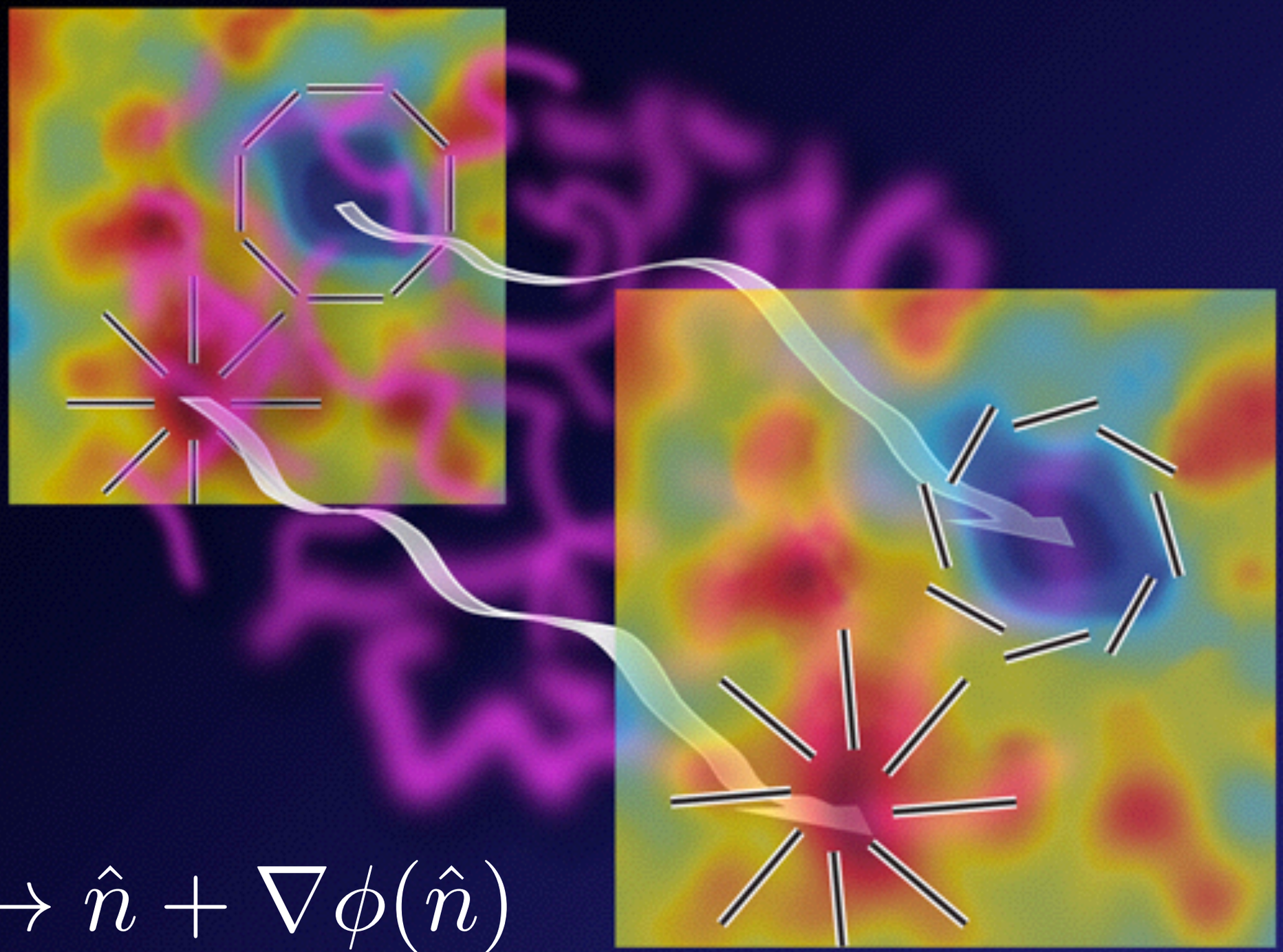
- Density/Temperature anisotropy generates intrinsic CMB polarization

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




Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

# CMB Lensing via CMB polarization



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

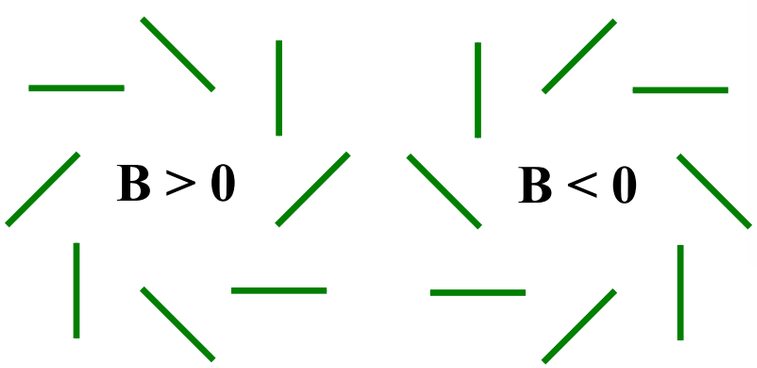
$$\phi(\hat{n}) = -2\int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{n}; \eta_0 - \chi)$$

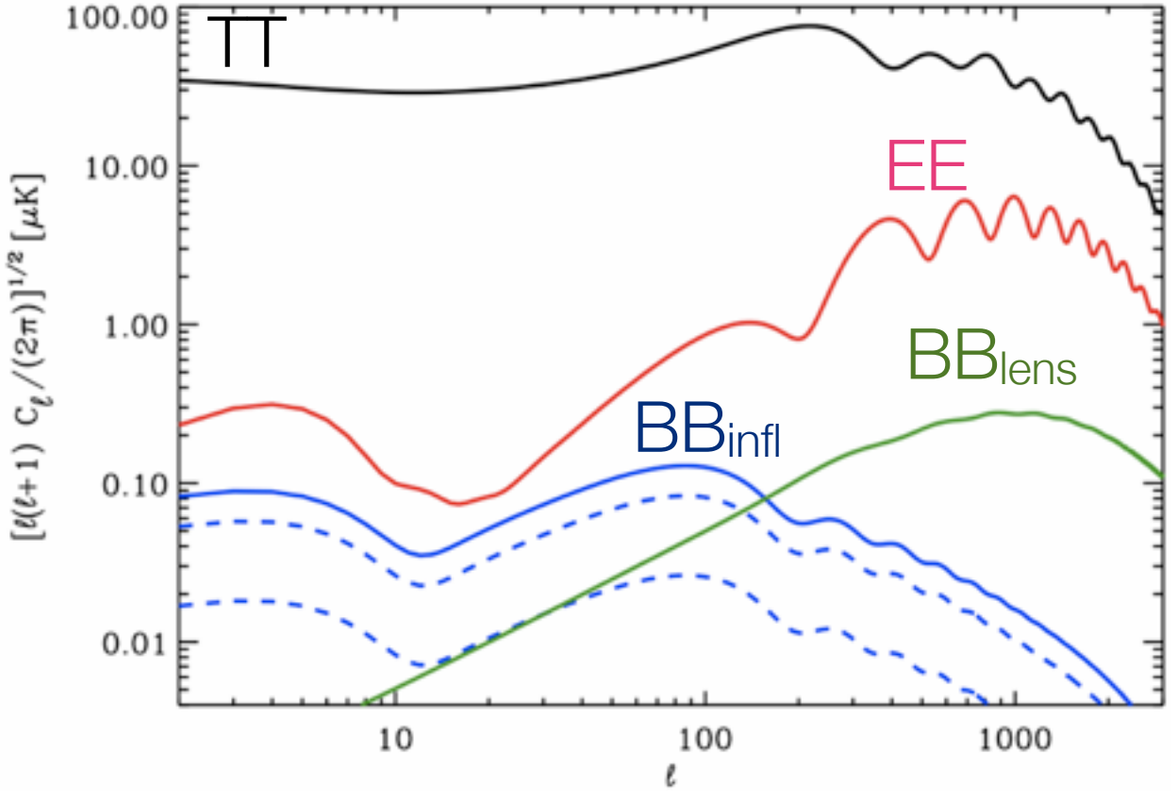
# CMB polarimetry: E-modes & B-modes

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

- Density/Temperature anisotropy generates intrinsic CMB polarization

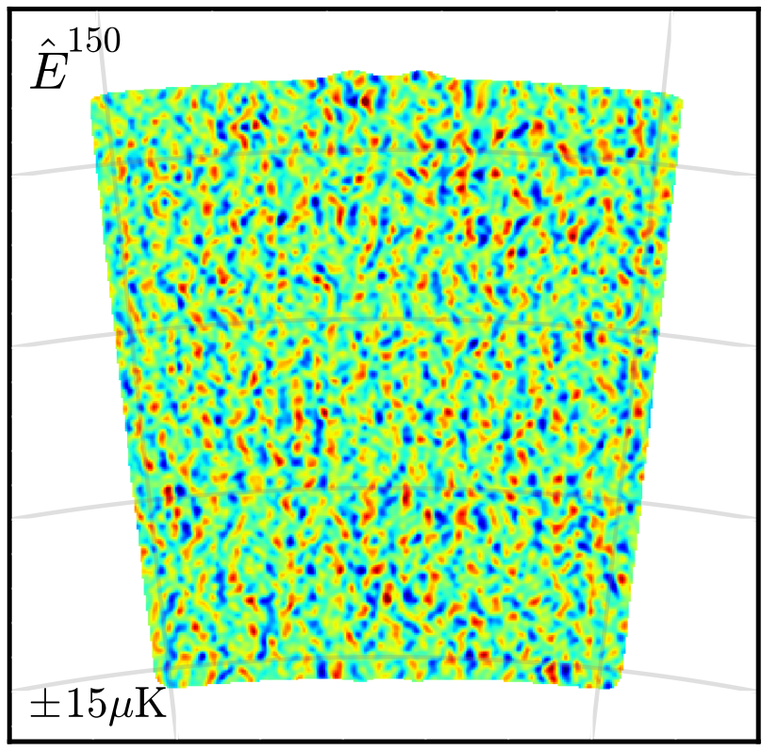
  - parity odd patterns, “B-modes”
  - Gravitational lensing of “E-modes” (shearing)
  - Gravitational waves from inflation



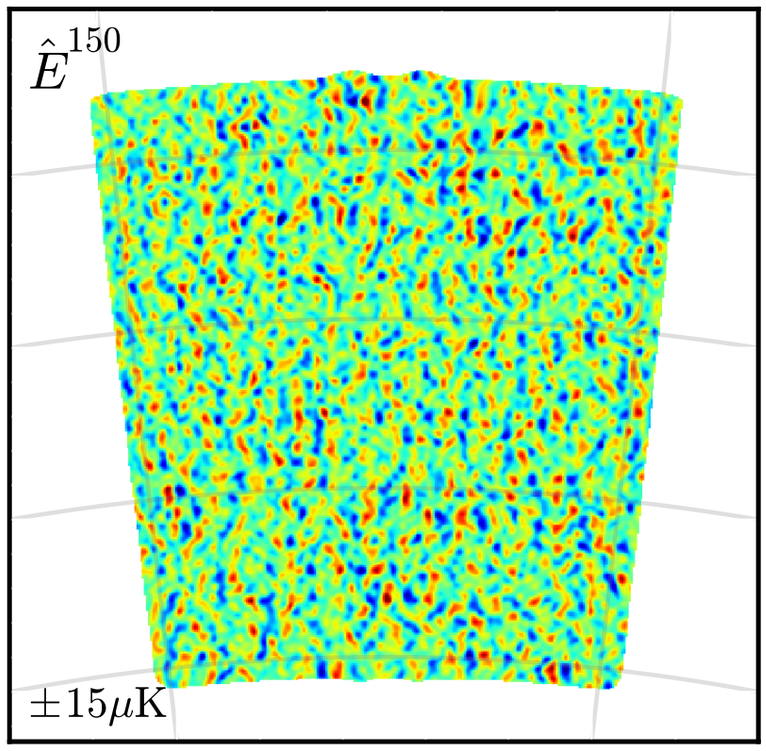

Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

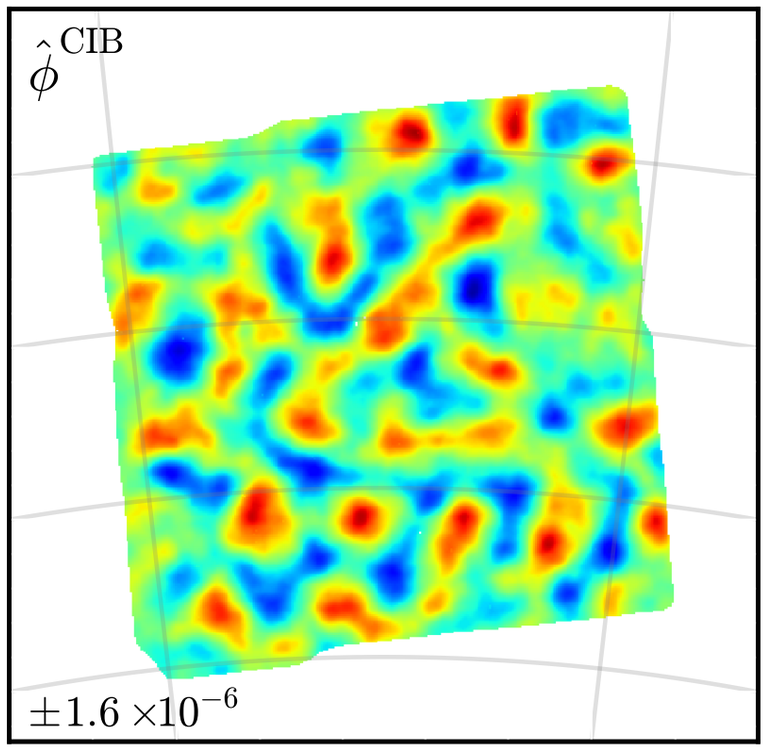
# Measuring CMB lensing B-modes




E

SPTpol




E

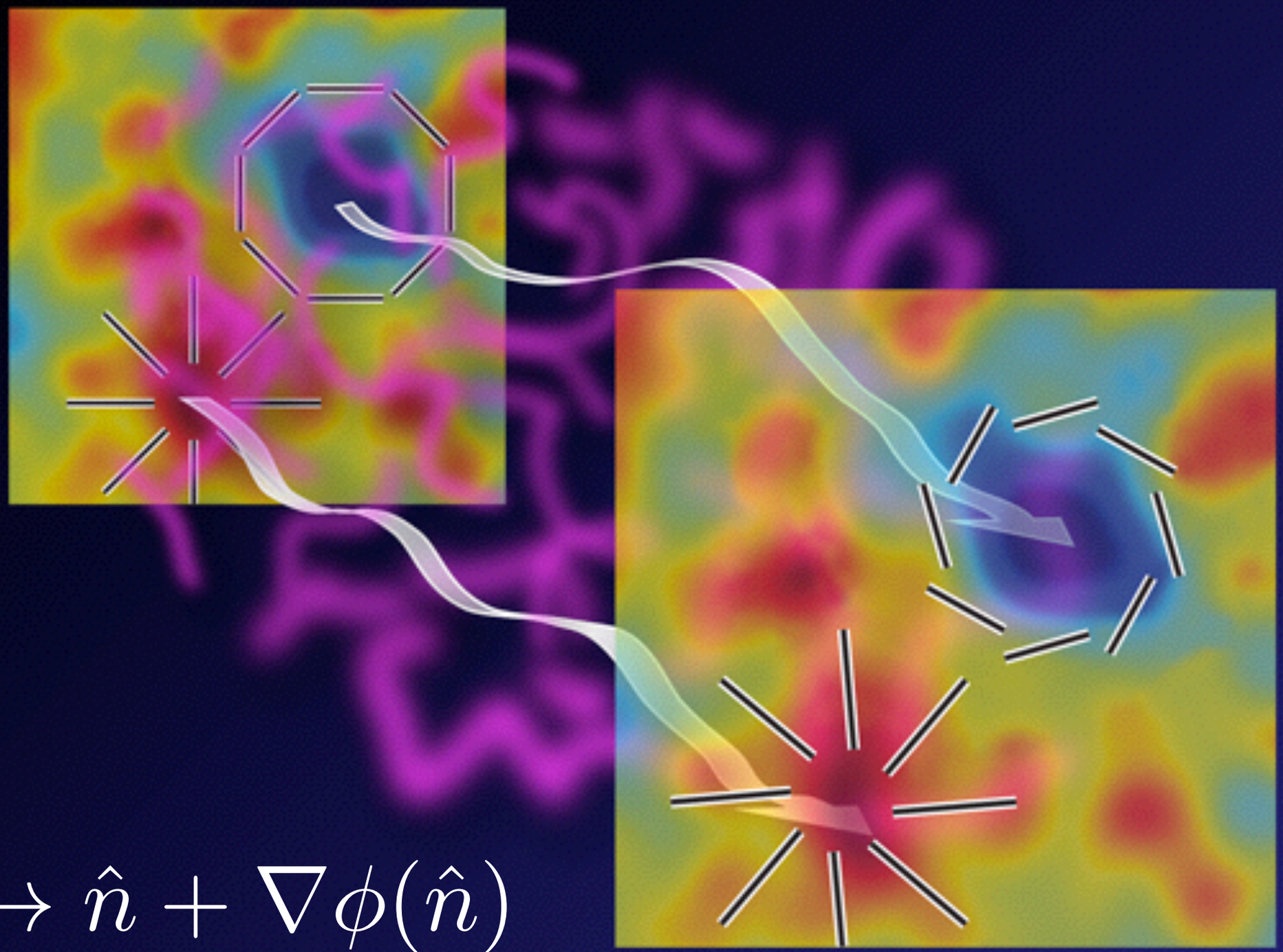
SPTpol

+

Φ

CIB (Herschel)

Traces DM/lensing potential



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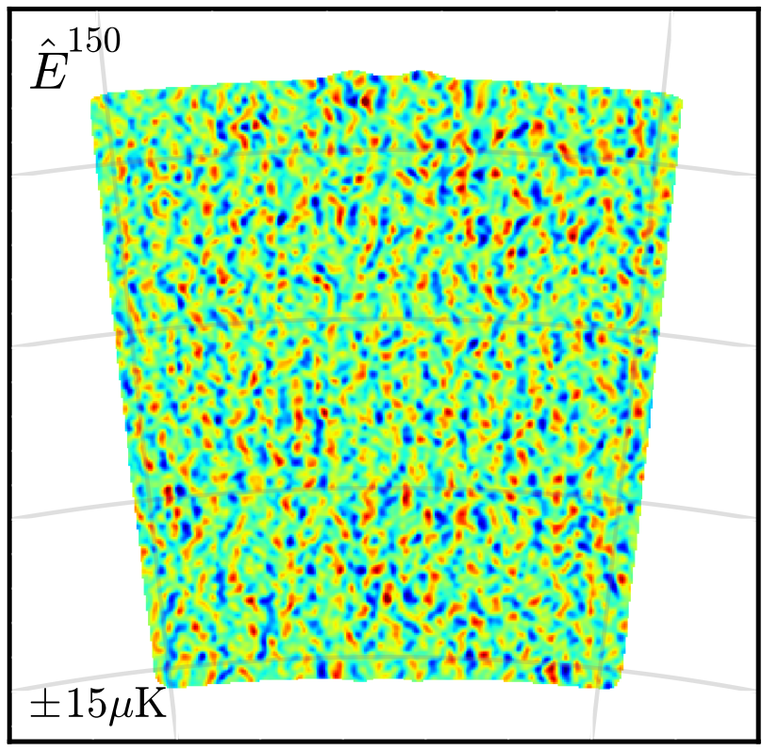
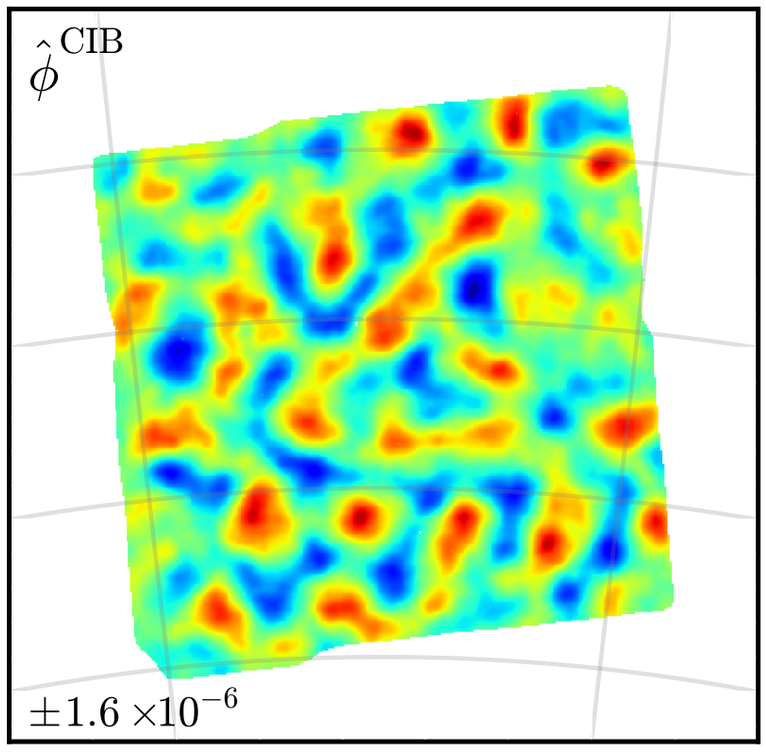
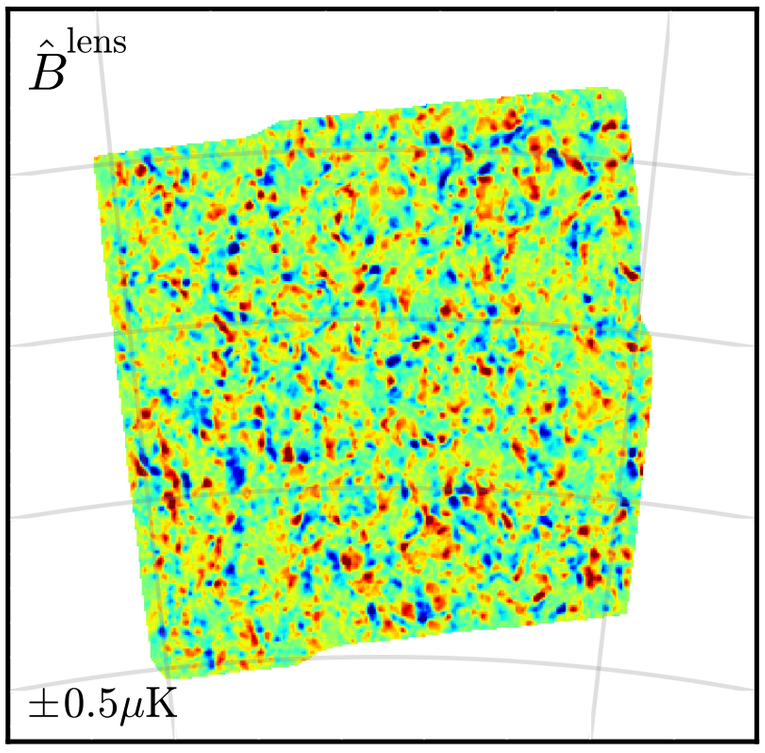
$$\phi(\hat{n}) = -2\int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{n}; \eta_0 - \chi)$$




E
SPTpol

+

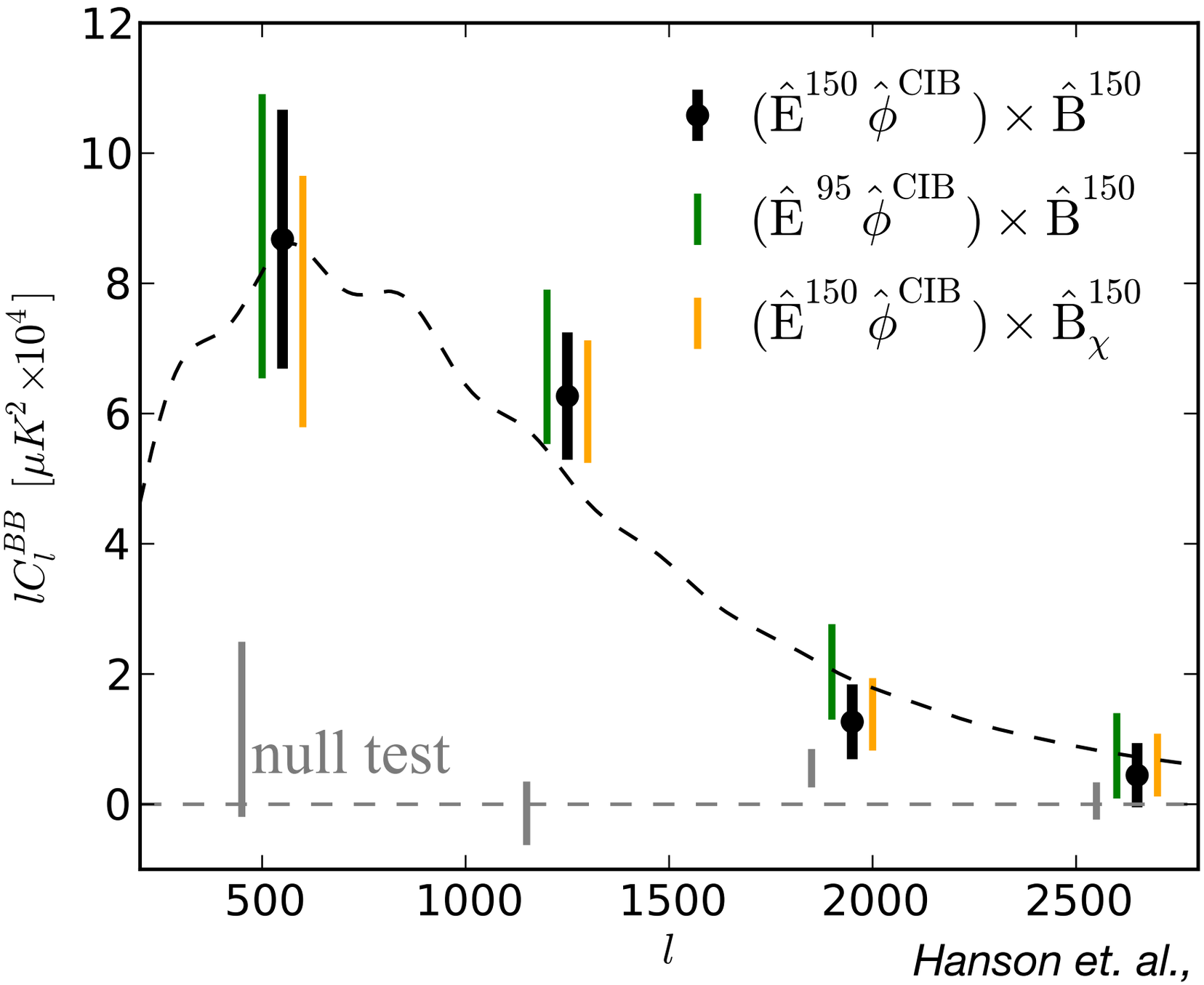
Φ
CIB (Herschel)

→

Synthesized lensing
B

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

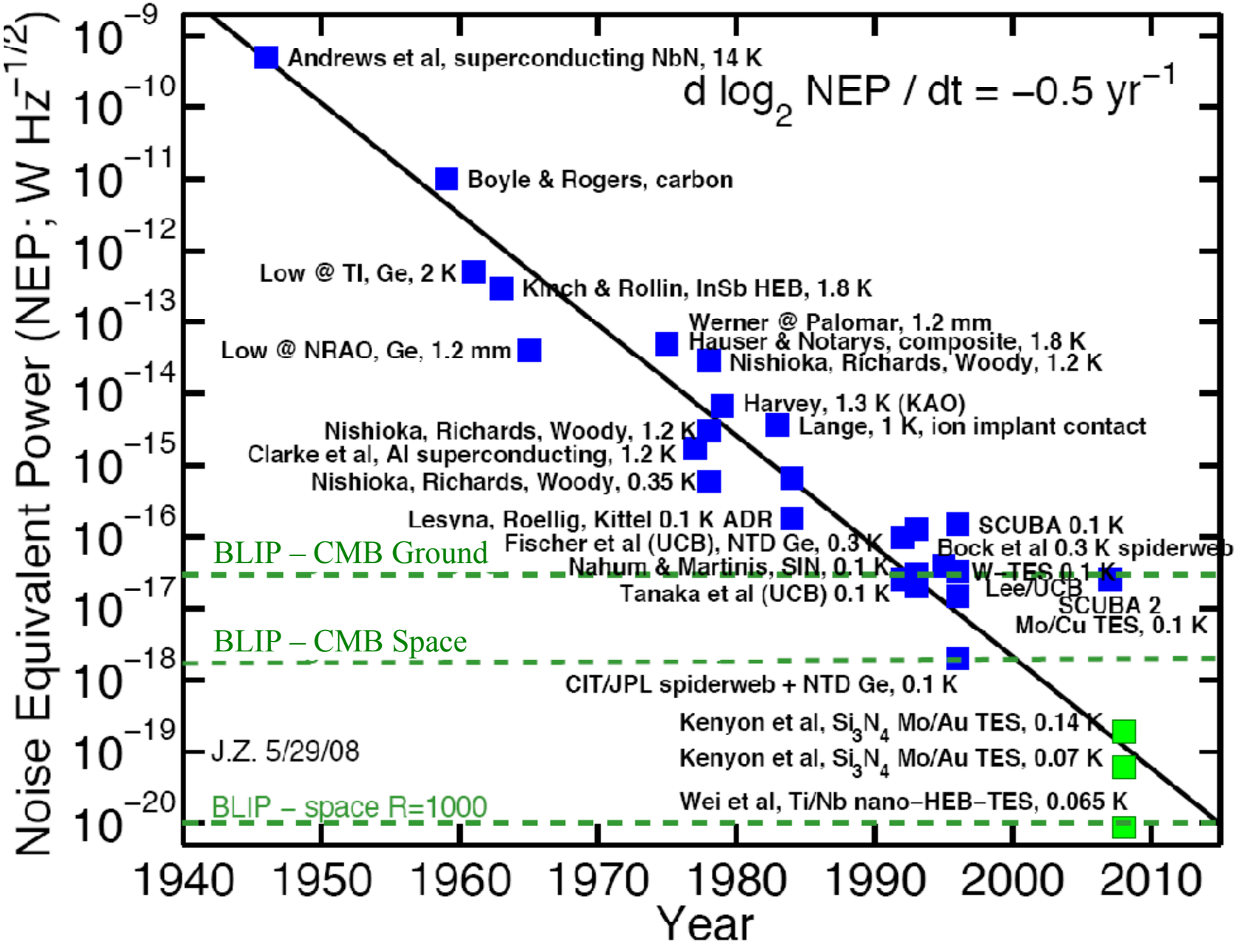
# 7.7σ detection of CMB lensing B-modes




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

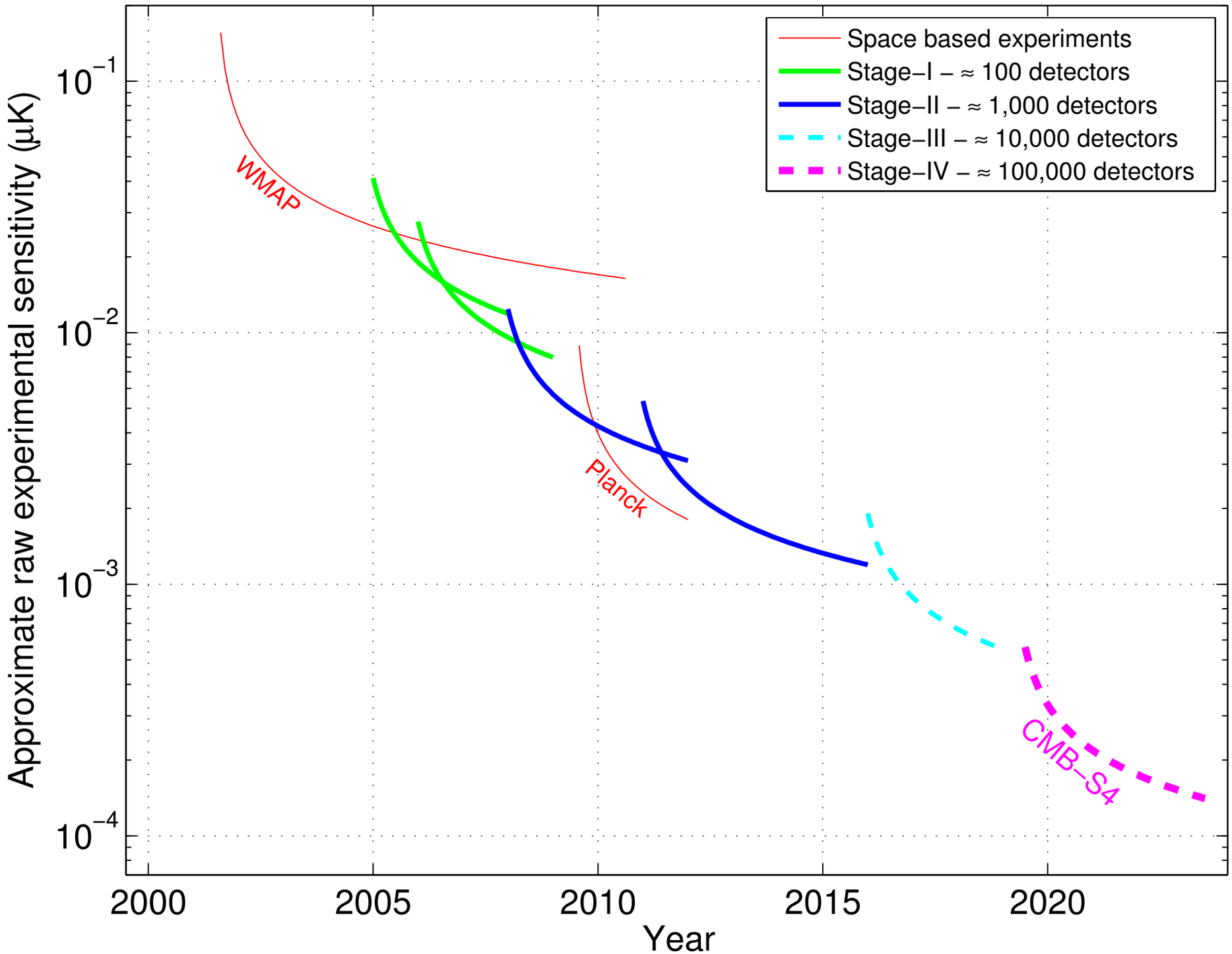
# B-modes: From detection to precision

# Fundamental limit to detector sensitivity



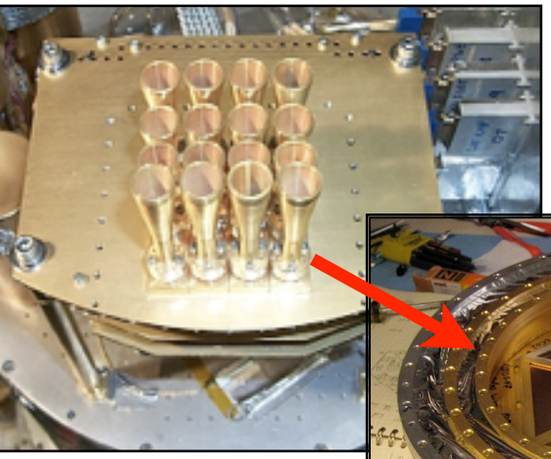

Photon noise dominated

*J. Zmuidzinas*

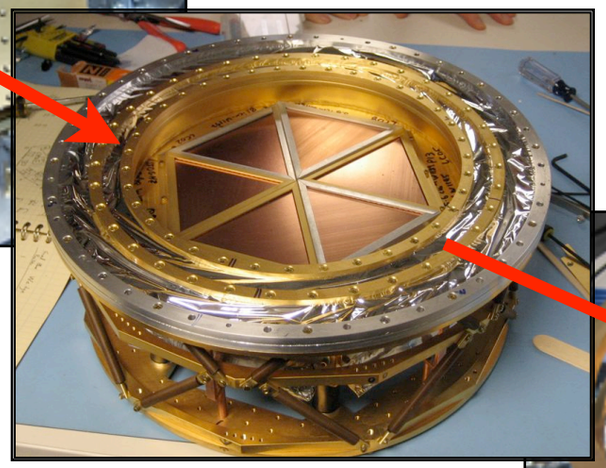

Space based experiments
Stage–I – ≈ 100 detectors
Stage–II – ≈ 1,000 detectors
Stage–III – ≈ 10,000 detectors
Stage–IV – ≈ 100,000 detectors
WMAP
Planck
CMB–S4
Approximate raw experimental sensitivity (μK)
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
2000
2005
2010
2015
2020
Year

# *Evolution of CMB Focal Planes*

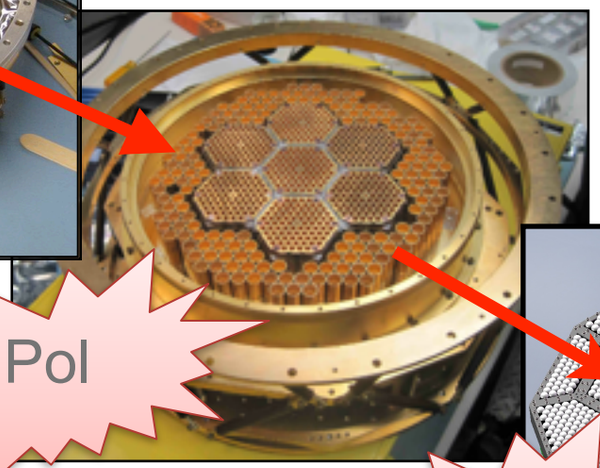
**2001: ACBAR**
16 detectors



**2007: SPT**
960 detectors

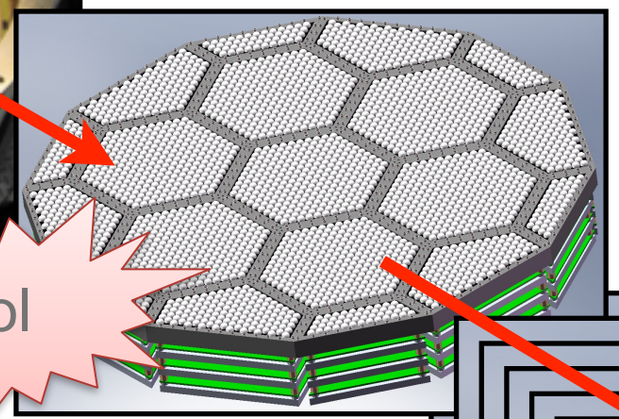


Stage-2
**2012: SPTpol**
~1600 detectors



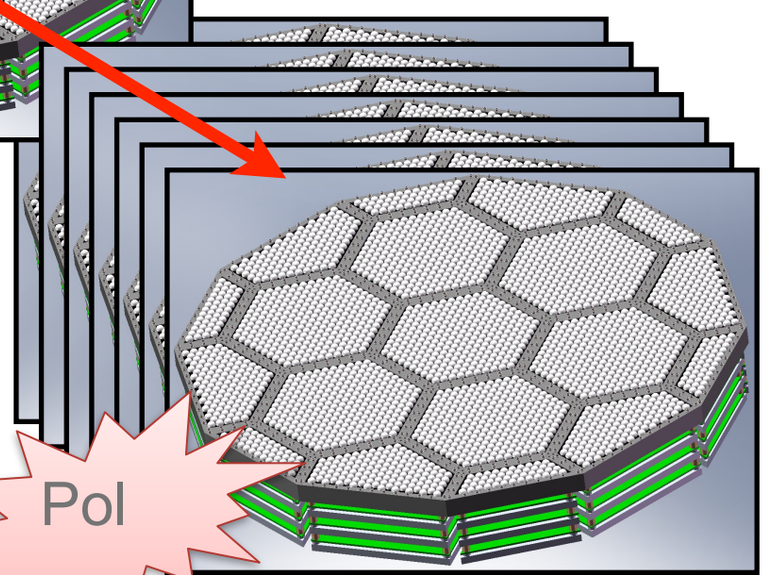
Pol

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



Pol

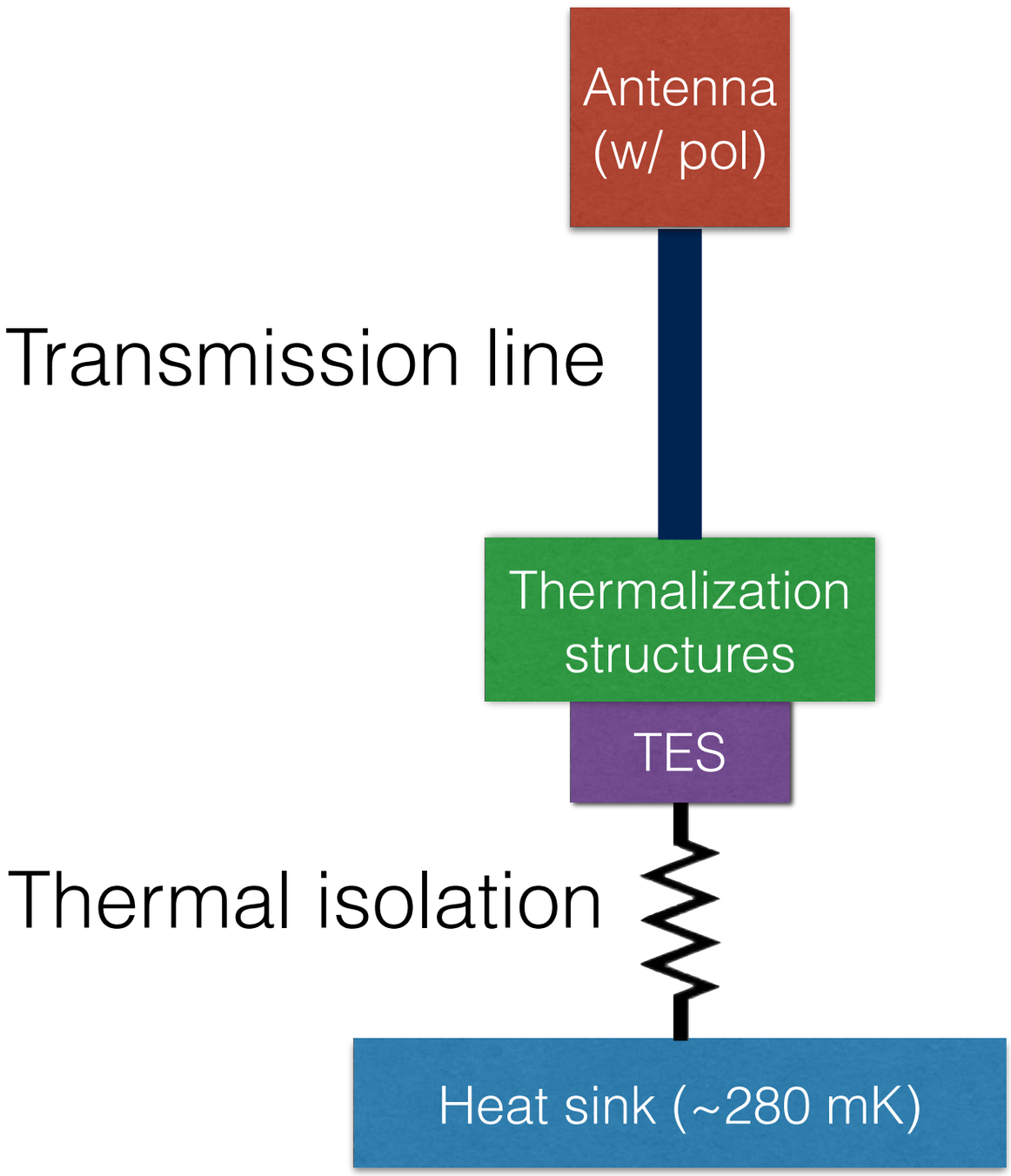
Stage-4
**2020?: CMB-S4**
200,000+ detectors



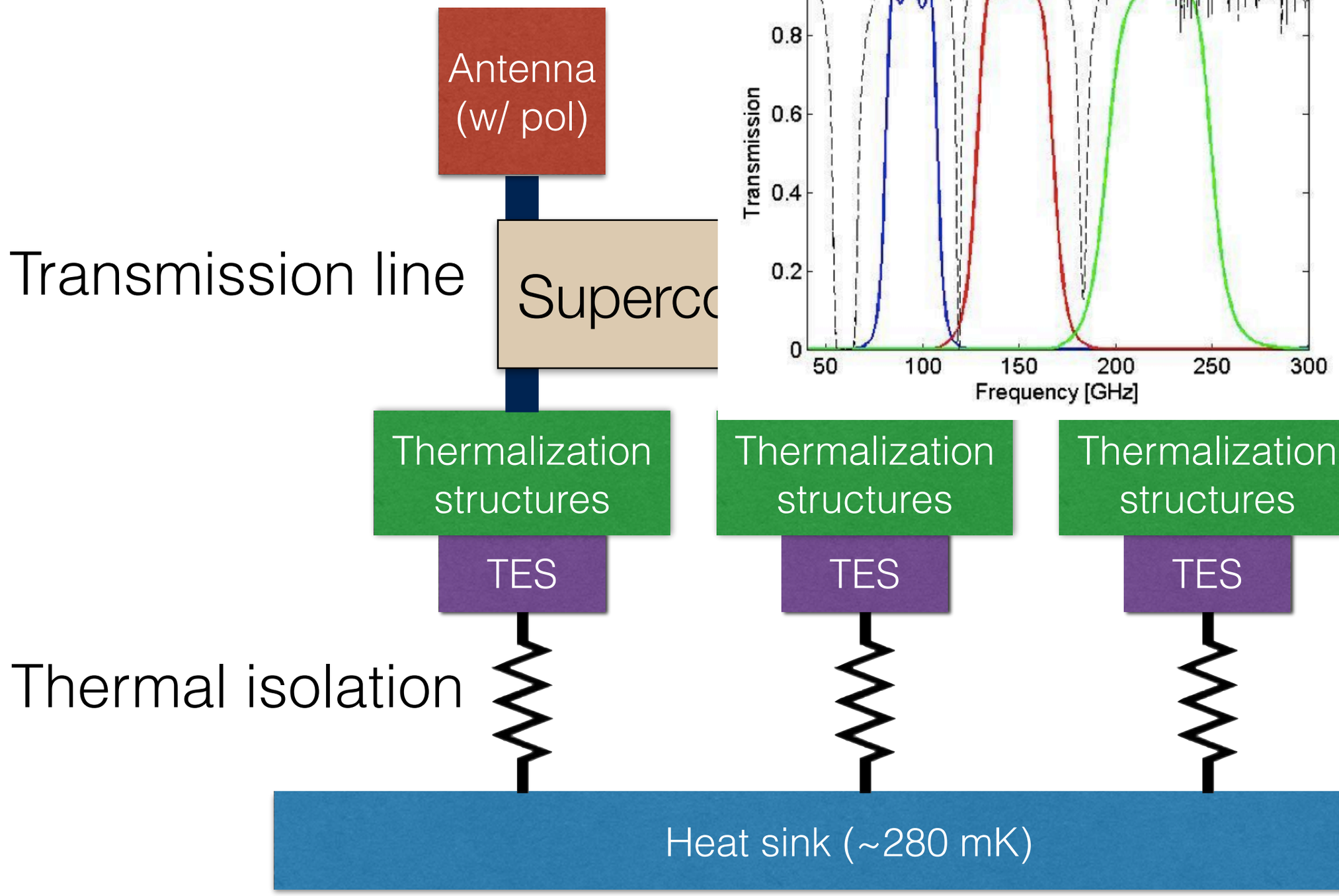
Pol

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

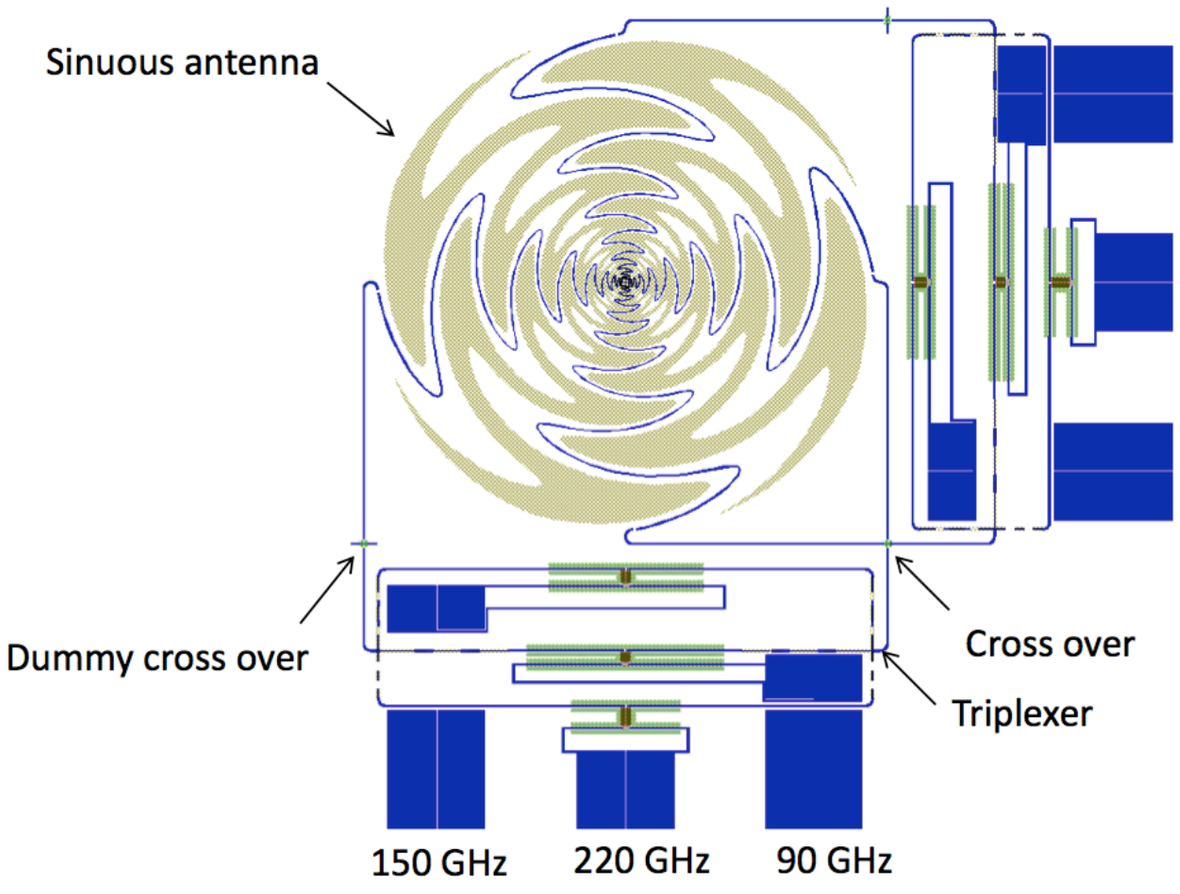
# Increasing detector density: the basic idea

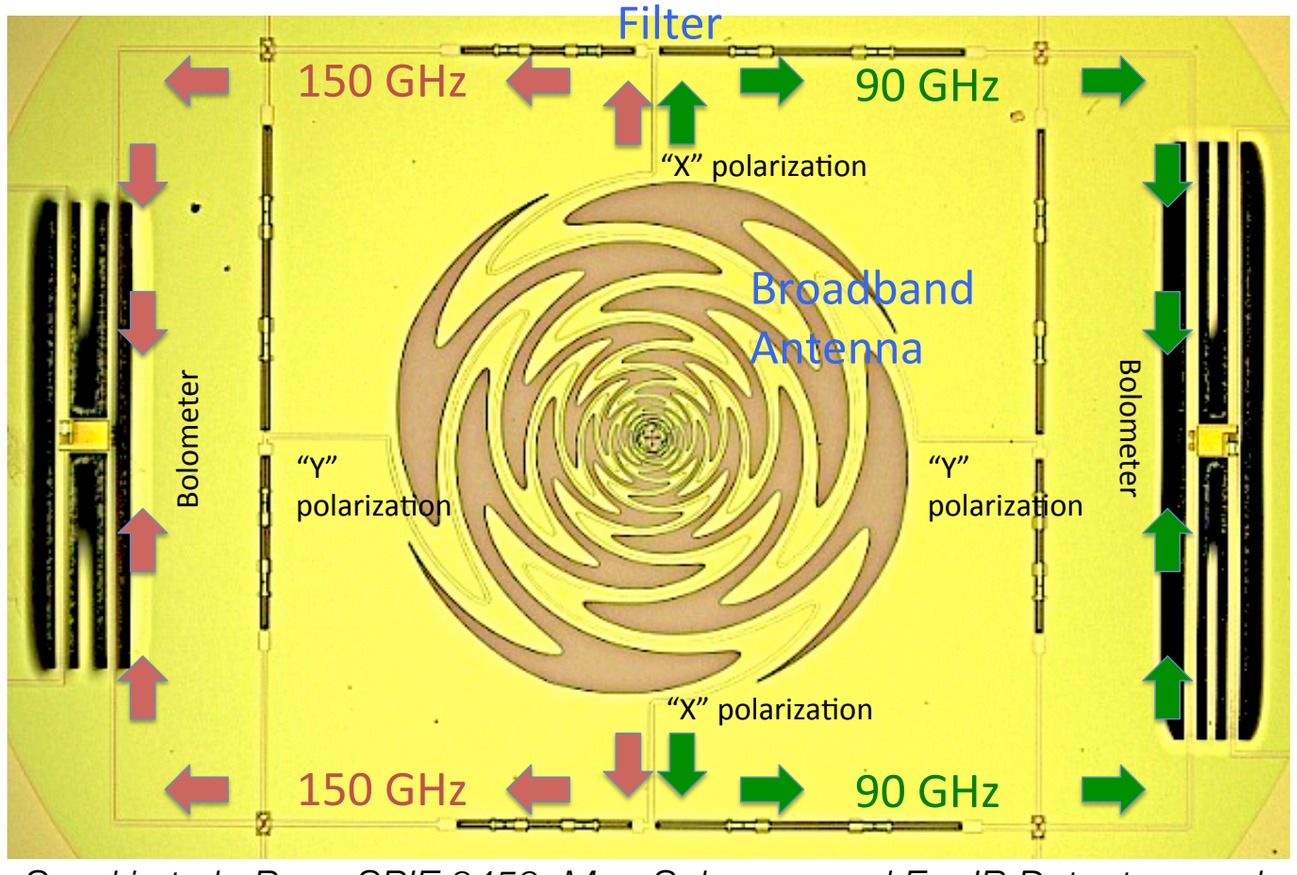


# Increasing detector density: the basic idea



# Detectors for 3G and beyond



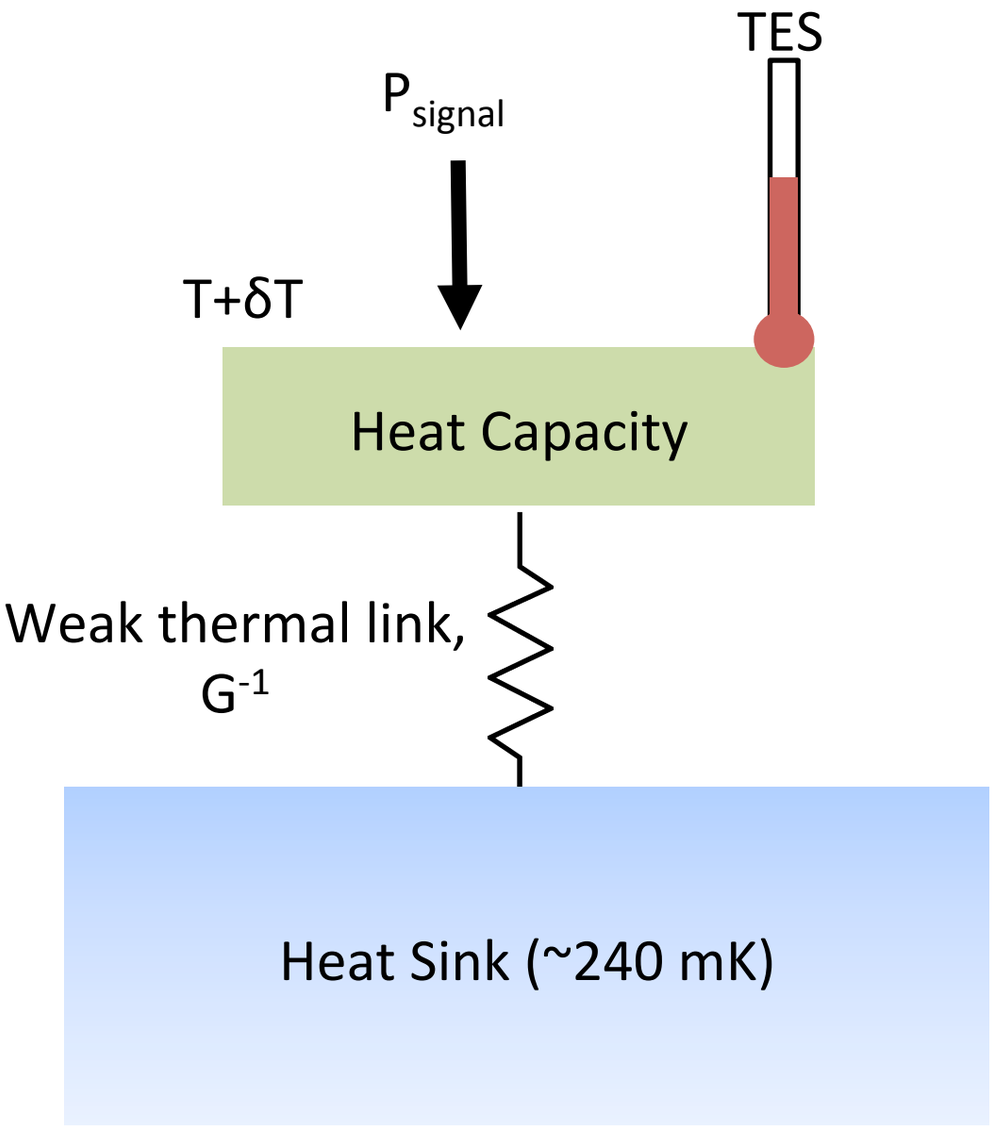



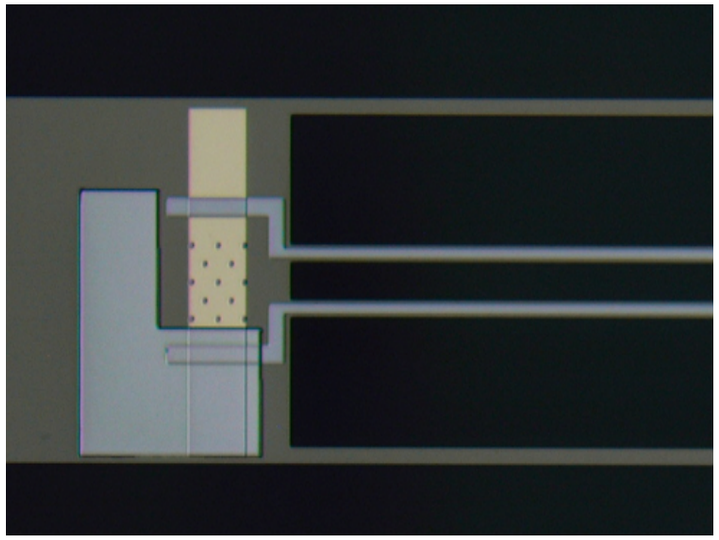

*Suzuki et al., Proc. SPIE 8452, Mm, Sub-mm, and Far-IR Detectors and Instr. for Astro. VI, 84523H (October 5, 2012)*

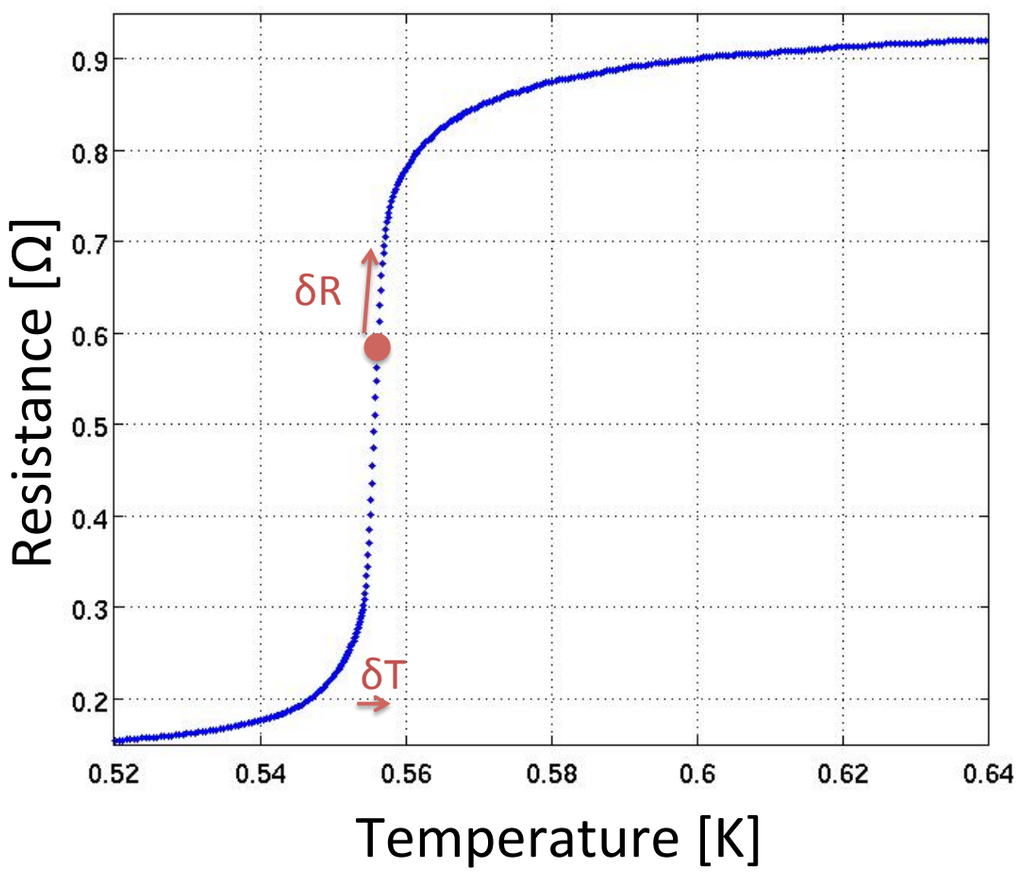
Developing 3 band dual pol pixel (based on Berkeley two-band version). Increase detector density from 2 per pixel to 6.

Berkeley
University of California

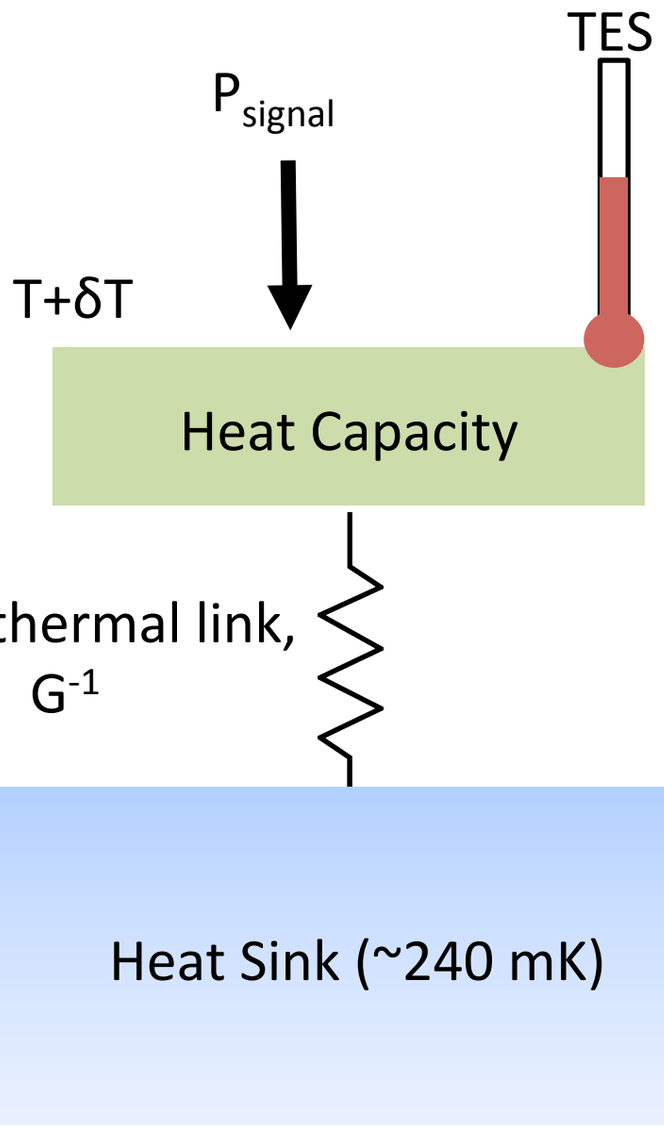
# The Modern Transition Edge Sensor



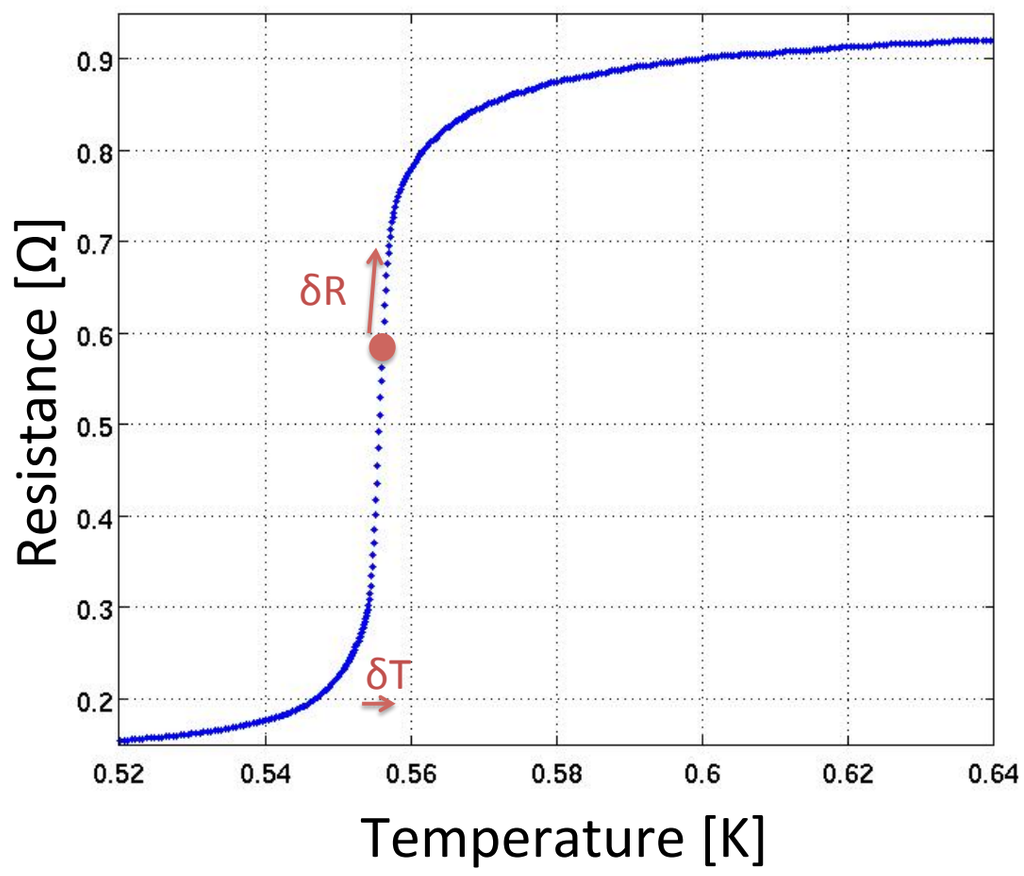





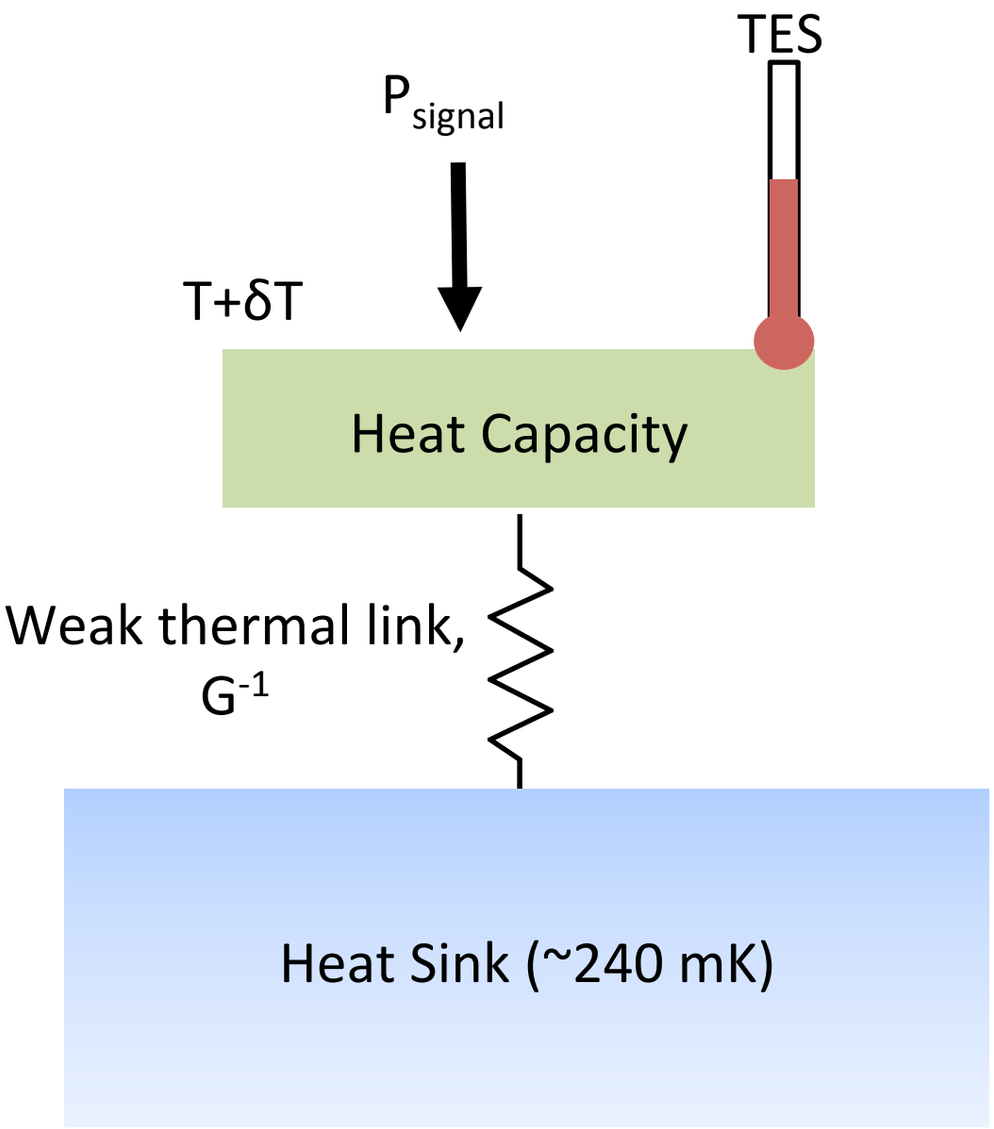
# The Modern Transition Edge Sensor



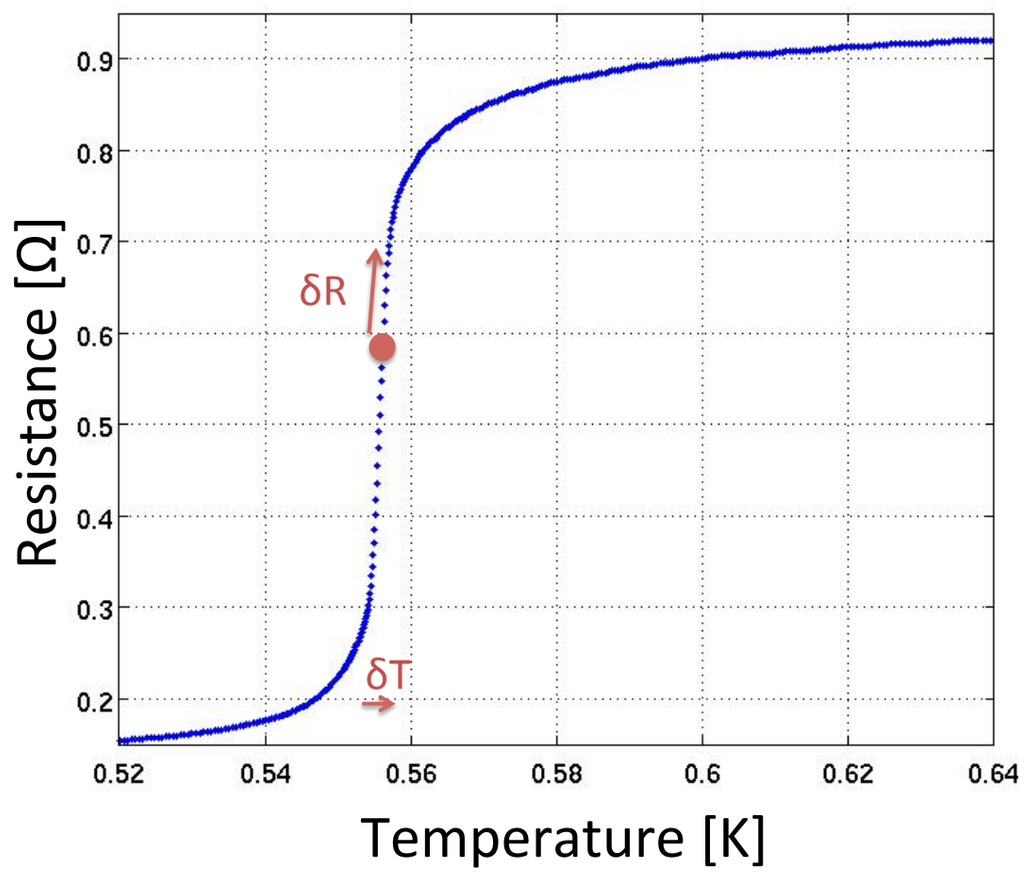

$$P_{Joule} = \frac{V_0^2}{R(T)}$$



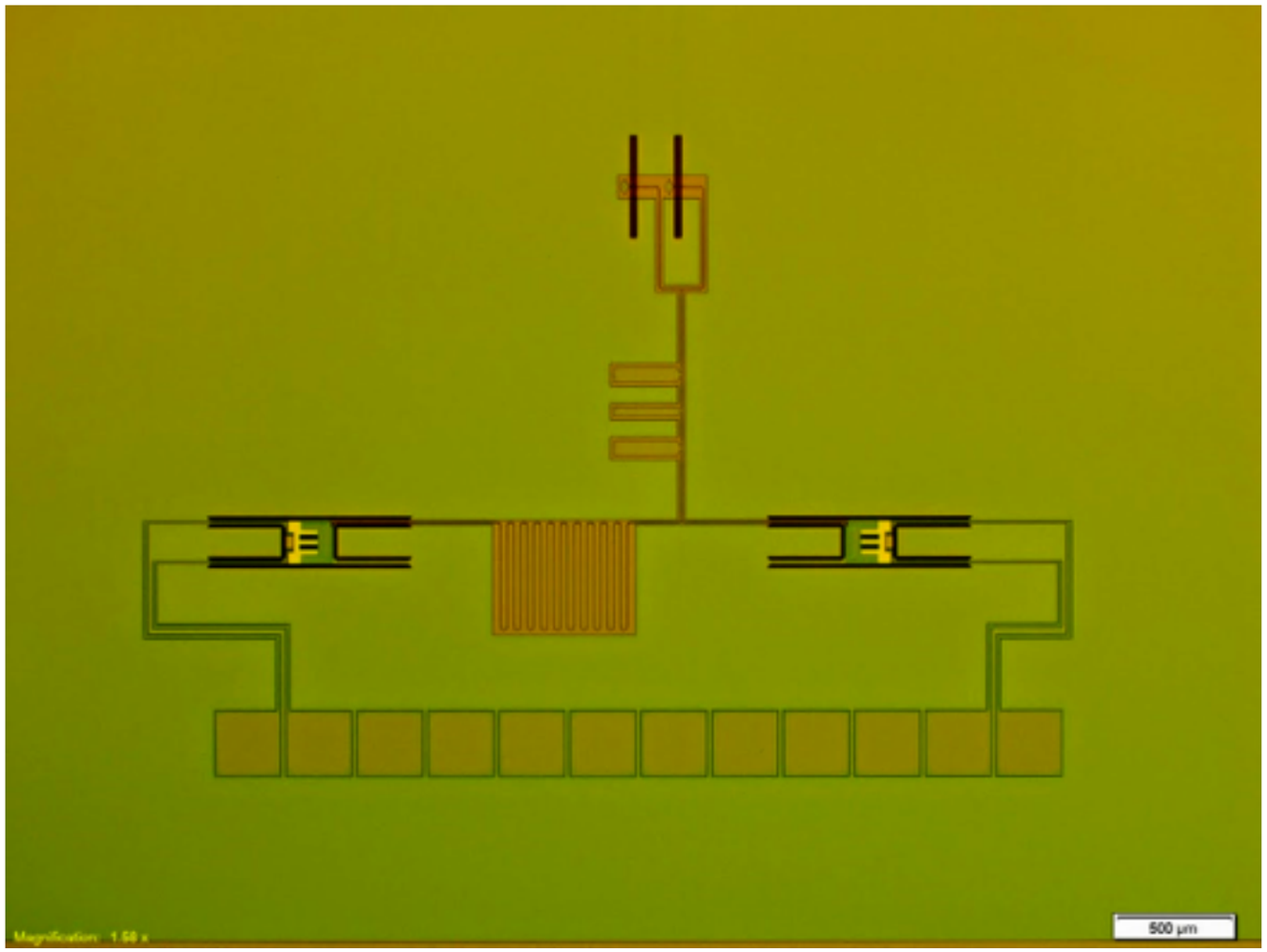
# The Modern Transition Edge Sensor

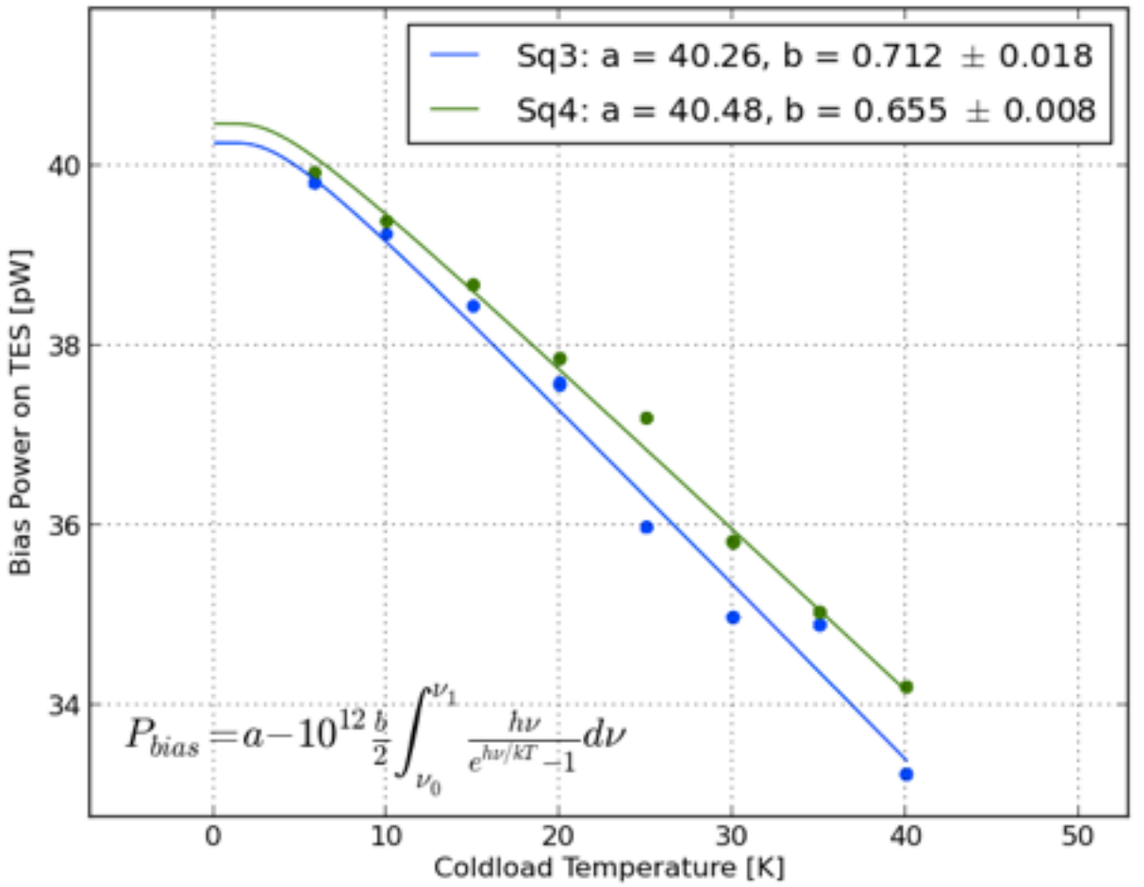



$$\delta P_{Joule} = \frac{d}{dT}\left(\frac{V_0^2}{R(T)}\right) = -\left(\frac{V_0}{R}\right)^2 \frac{dR}{dT}\delta T$$

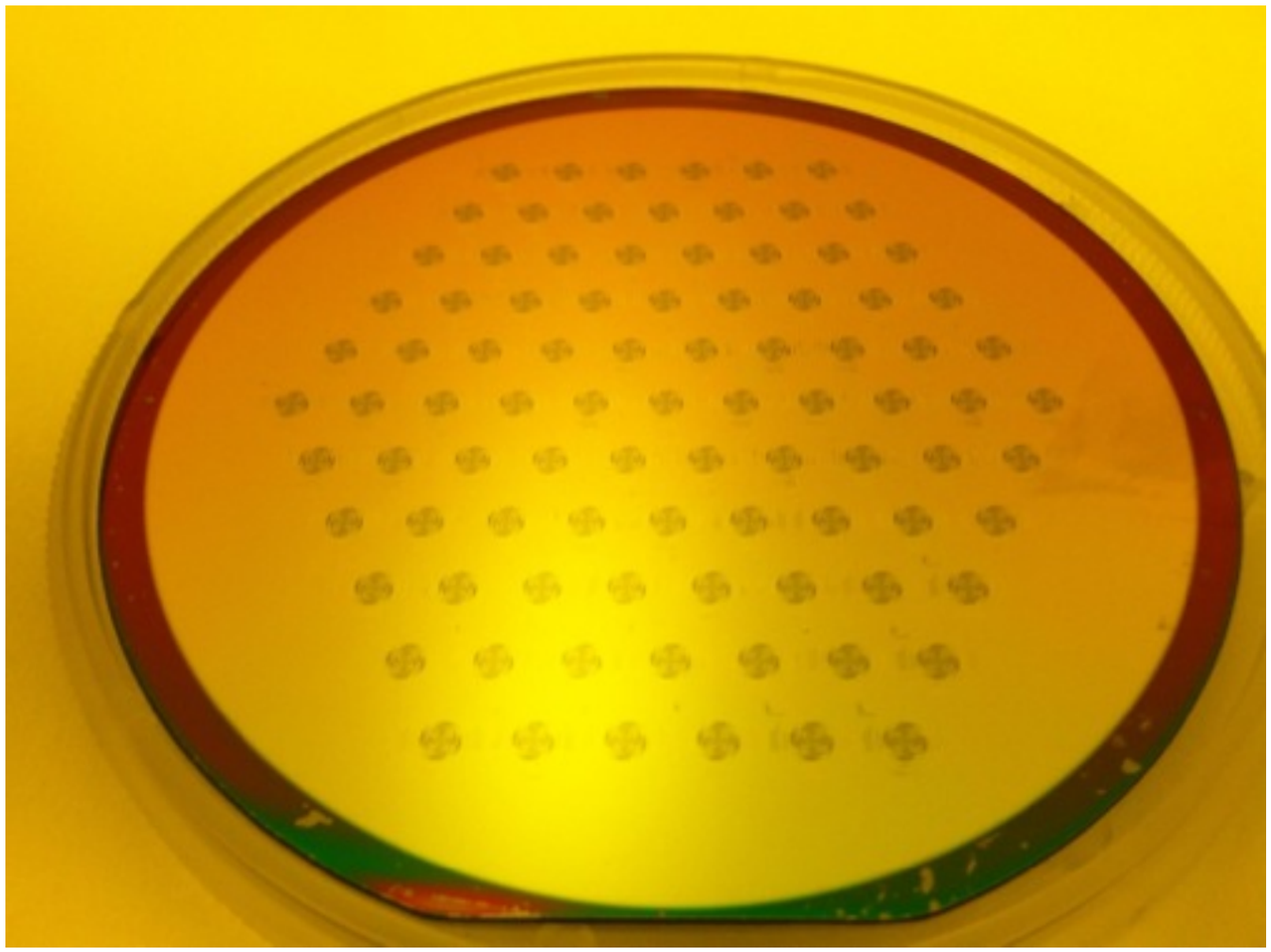


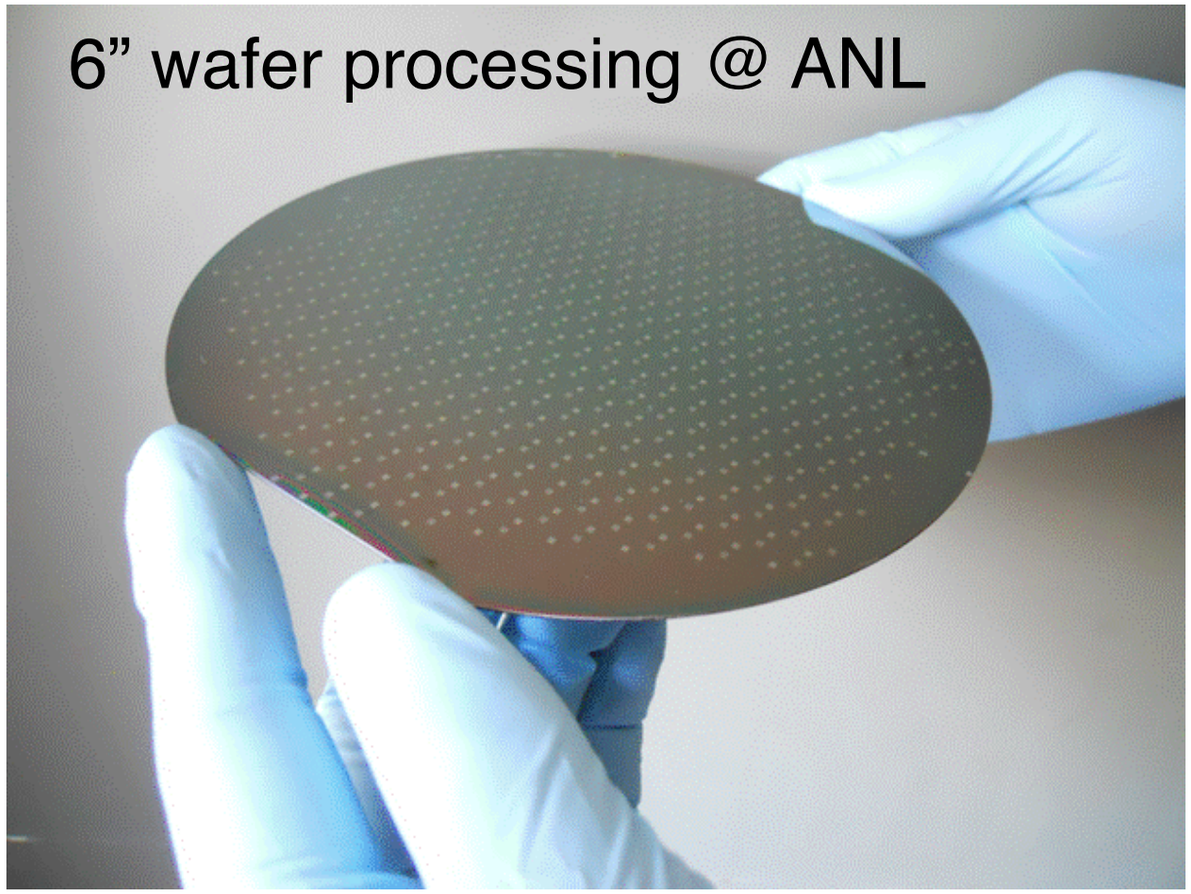
# Low loss microstrip transmission lines



# Broadband pol antenna & large arrays





# Weather in South Pole, Antarctica

## Now

-98 °F

Snow flurries. Sunny.

Feels Like: -134 °F
Forecast: -72 / -63 °F
Wind: 8 mph from Southeast

| | |
|---|---|
| Location: | Amundsen-Scott South Pole Station |
| Current Time: | Aug 1, 2014 at 7:14:02 PM |
| Latest Report: | Aug 1, 2014 at 6:00 PM |
| Visibility: | 7 mi |
| Pressure: | N/A |
| Humidity: | N/A |
| Dew point: | N/A |