The Cosmic Microwave Background in High Definition

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McGill

CIFAR
CANADIAN INSTITUTE for ADVANCED RESEARCH

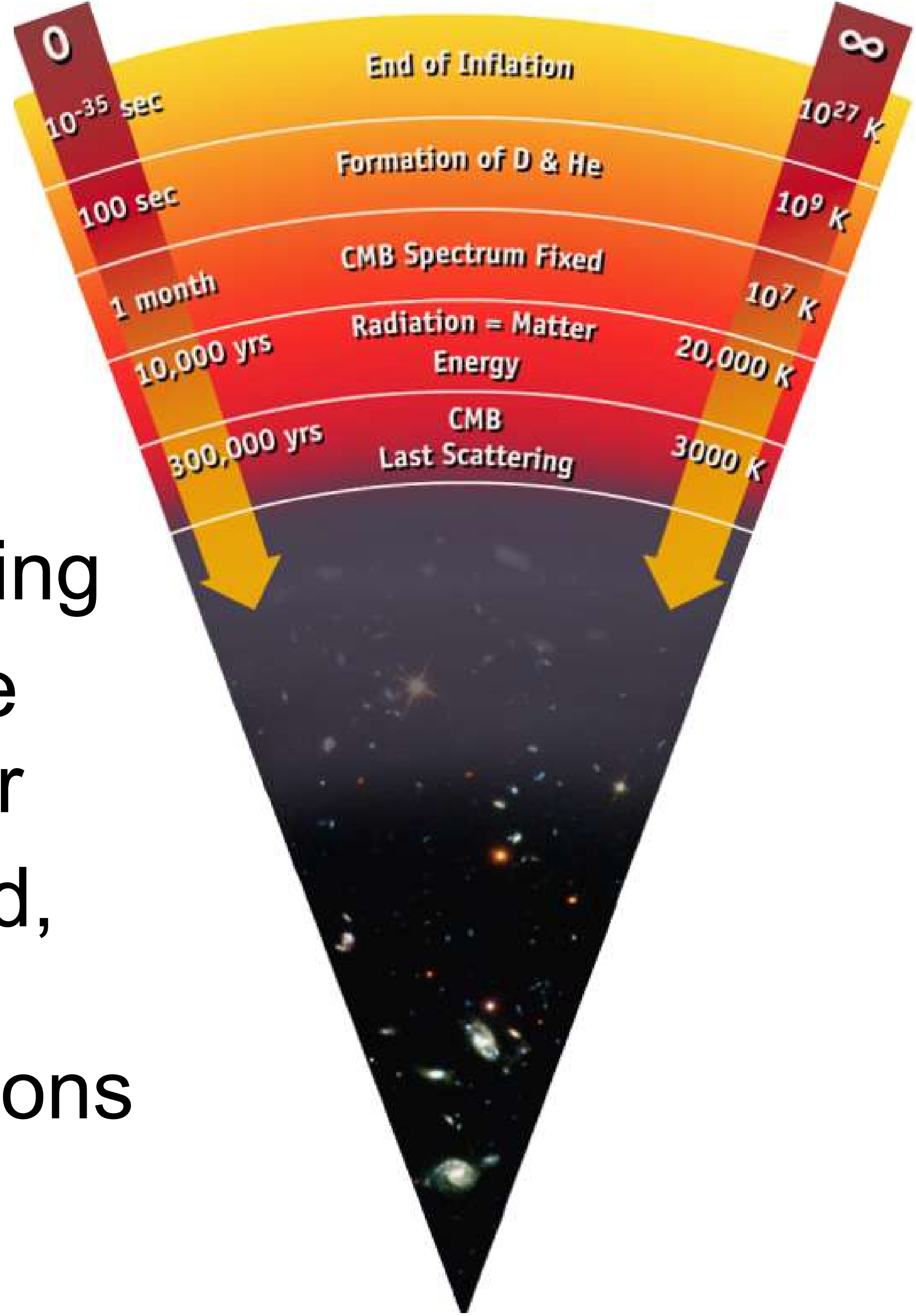
as part of:
SPT collaboration

Outline

- the cosmic microwave background (CMB)
  - temperature & polarization fluctuations
- Sunyaev-Zeldovich effect
  - galaxy clusters
- CMB gravitational lensing
  - chasing neutrino masses
- first detection of “B-modes”

Hot Big Bang

- Expanding => cooling
- At earlier times, the universe was hotter
- when atoms formed, universe became transparent to photons
  - *special __timescale__ in the universe for photons*

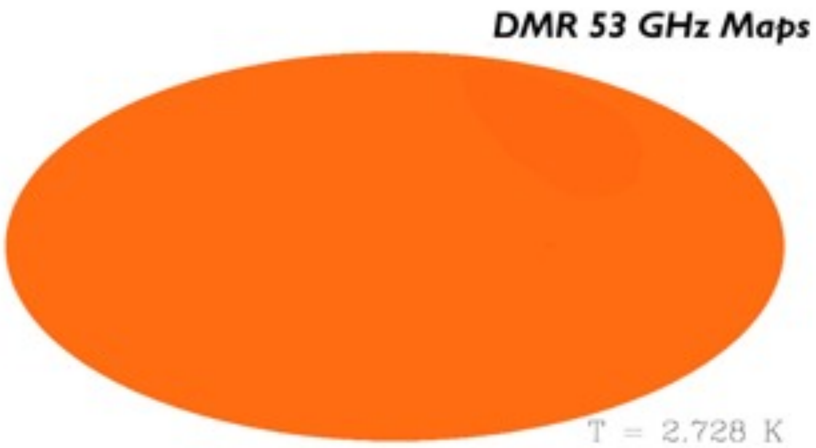


http://www.astro.ucla.edu/~wright/BBhistory.html

The Cosmic Microwave Background

CMB according to COBE

(Bennett et al 1996)



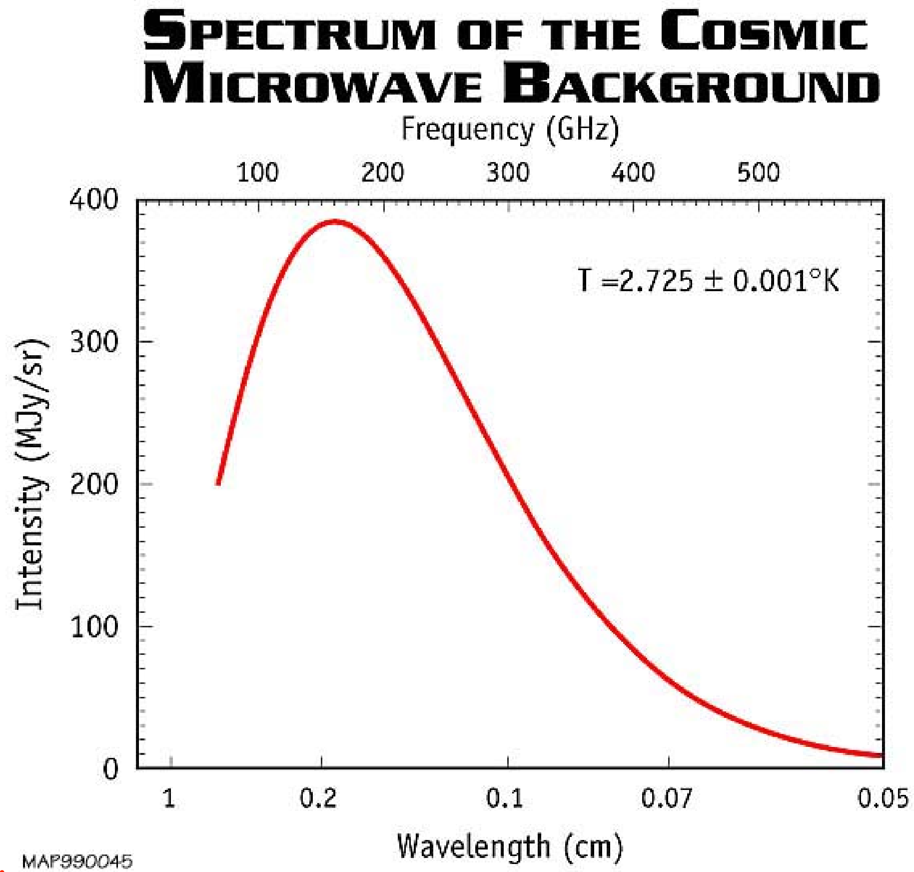
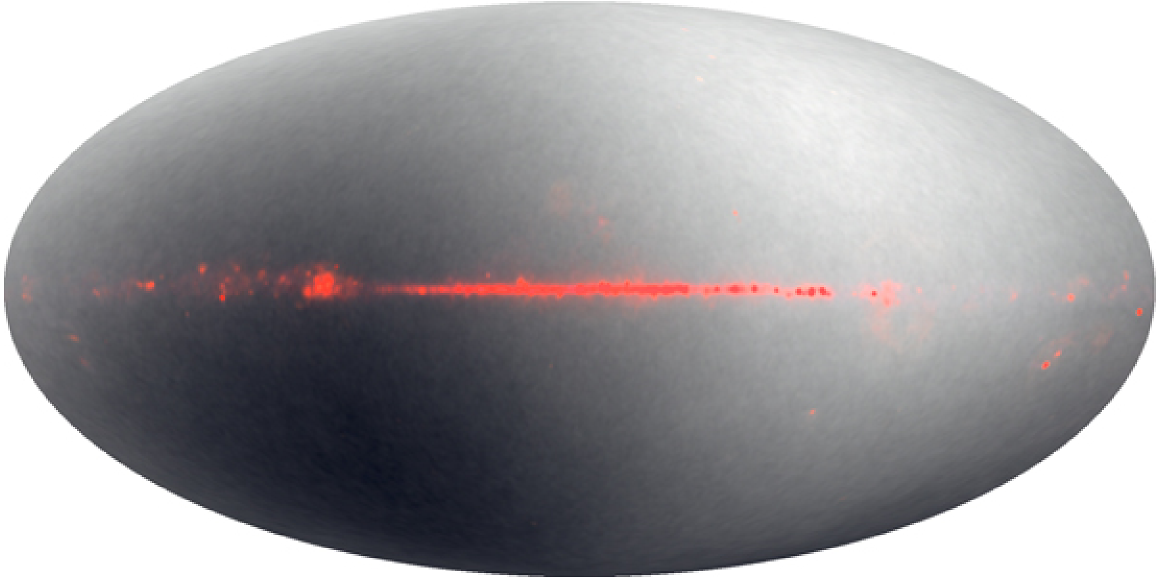


Image from COBE science team: http://lambda.gsfc.nasa.gov/product/cobe/

Isotropy

- Cosmic microwave background is remarkably isotropic
- Unnaturally isotropic!

WMAP science team



+-3.5 mK scale

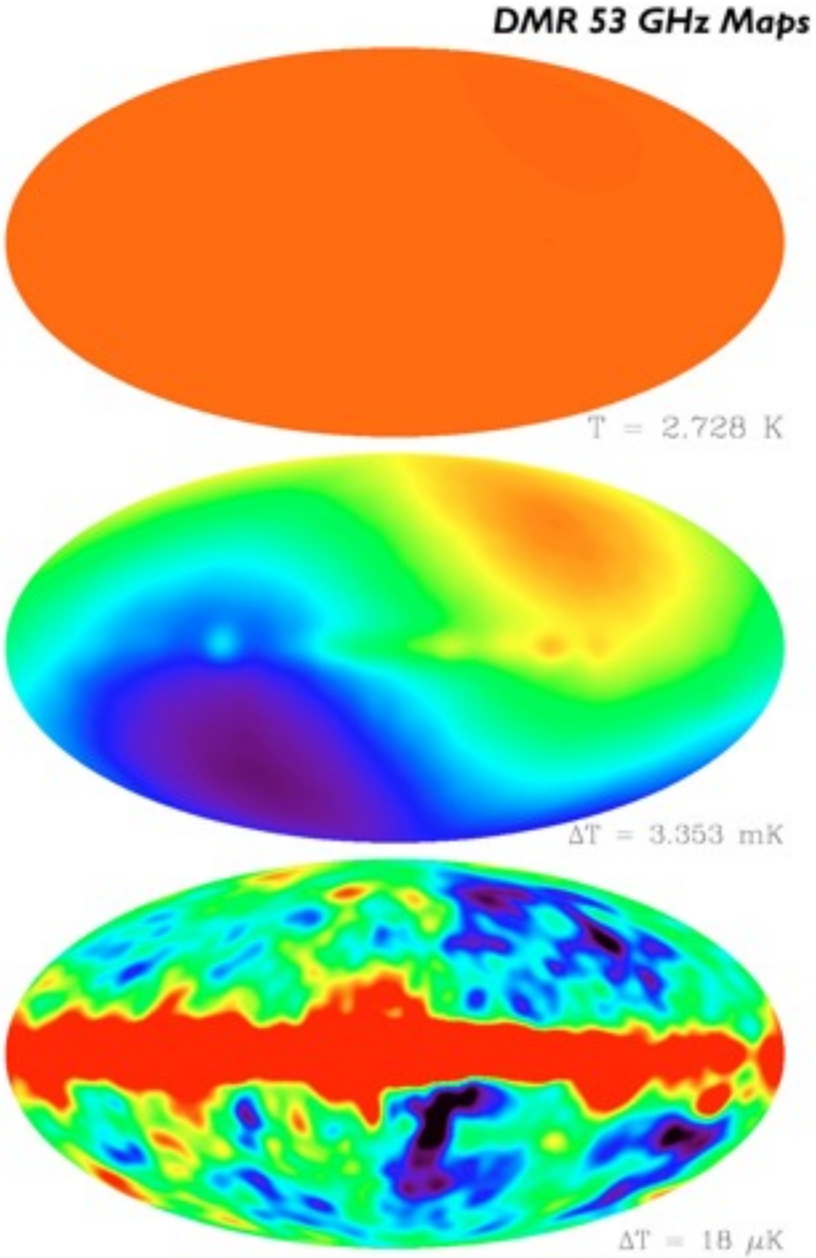
The Cosmic Microwave Background

CMB according to COBE

(Bennett et al 1996)

Nothing too strange within our "horizon":

40 billion light years



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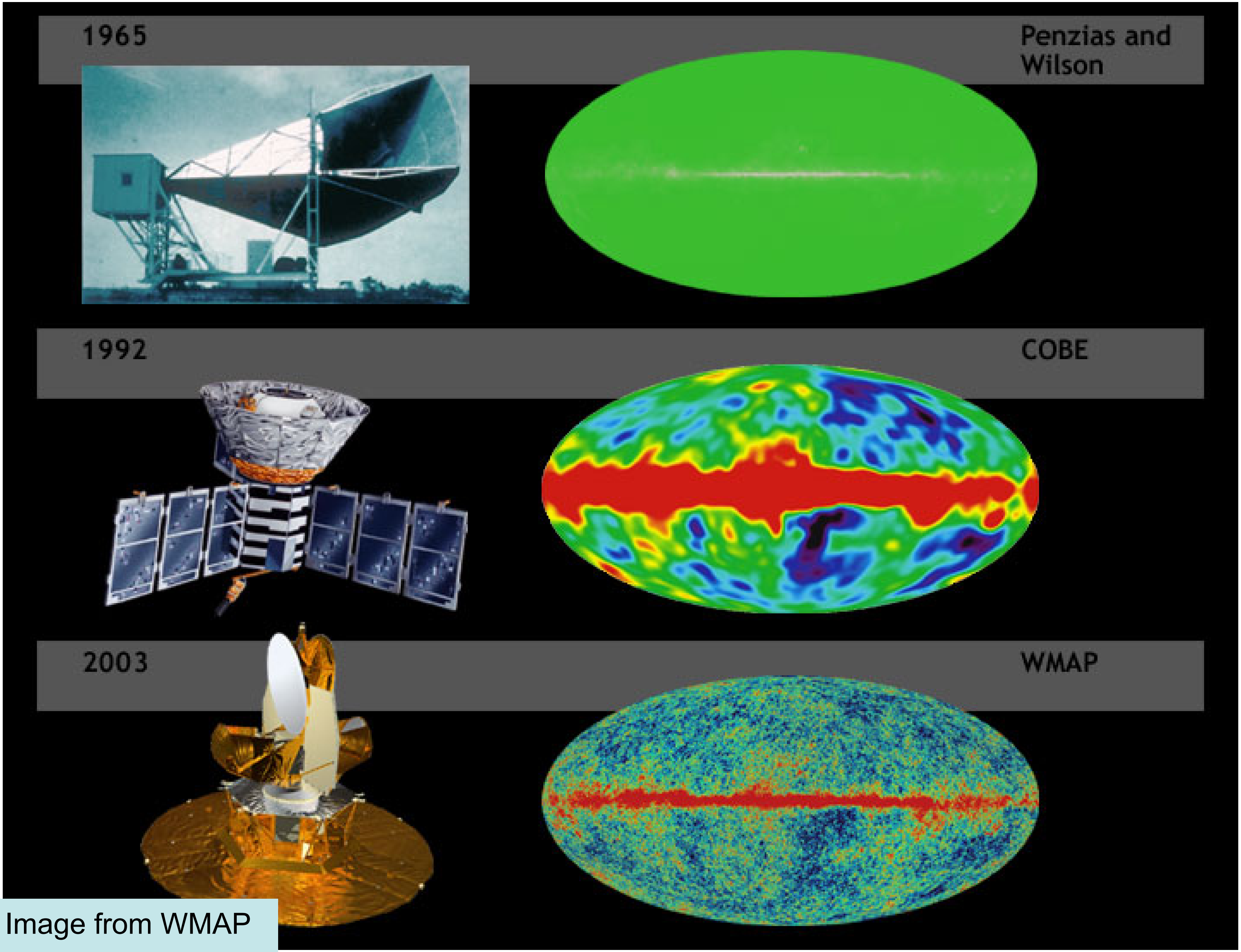
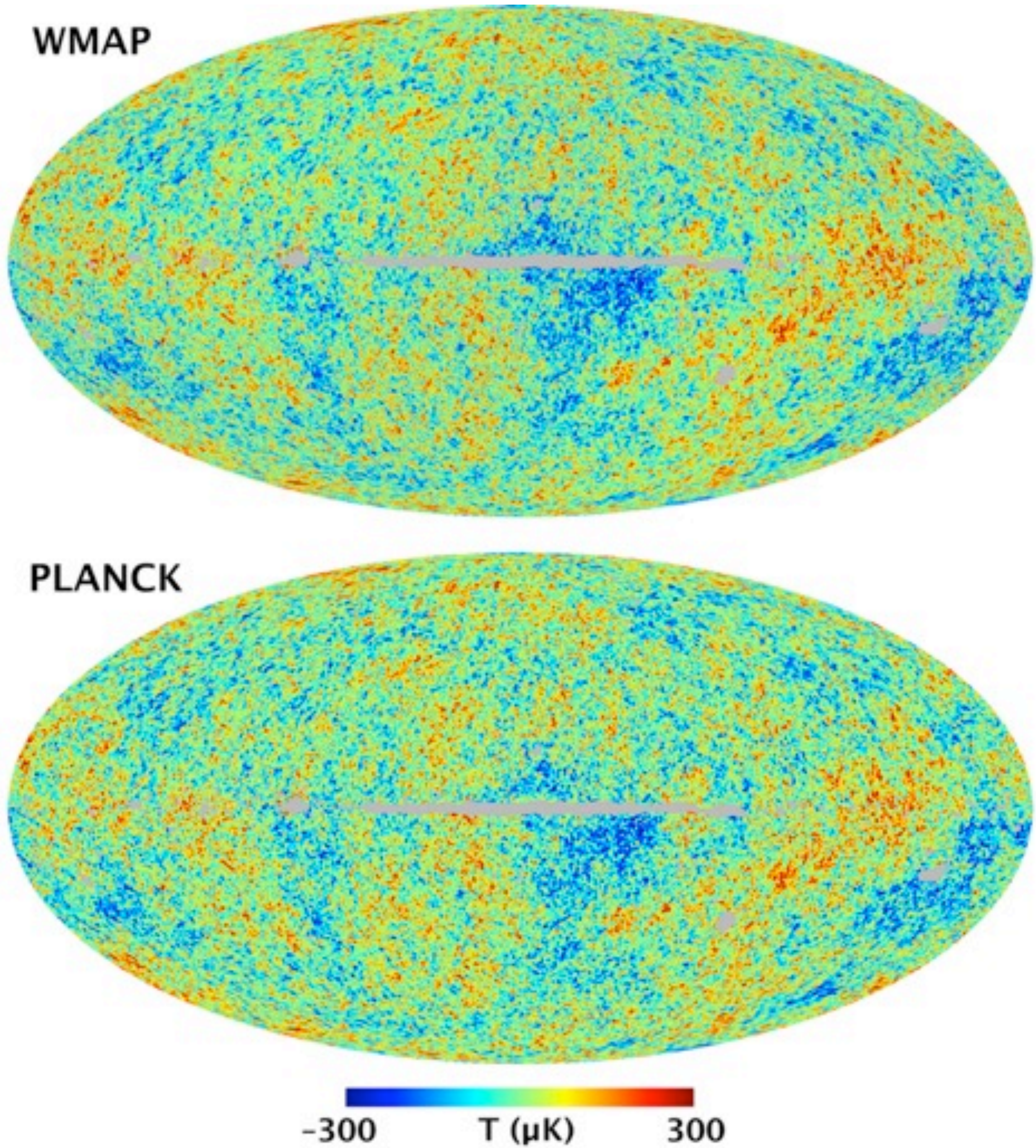
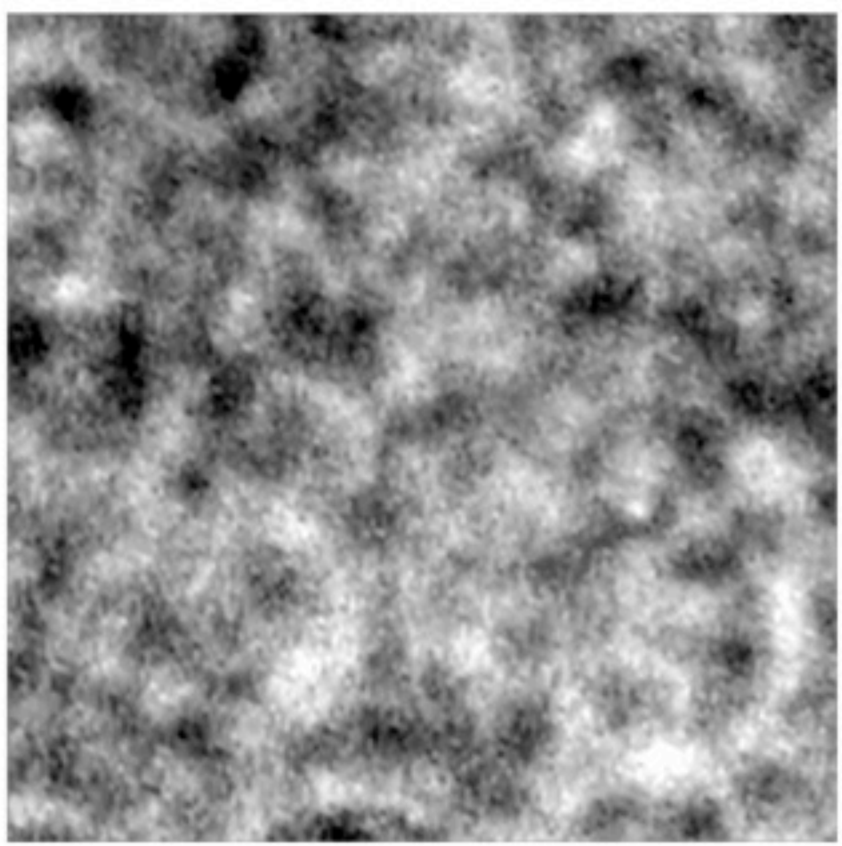


Image from WMAP

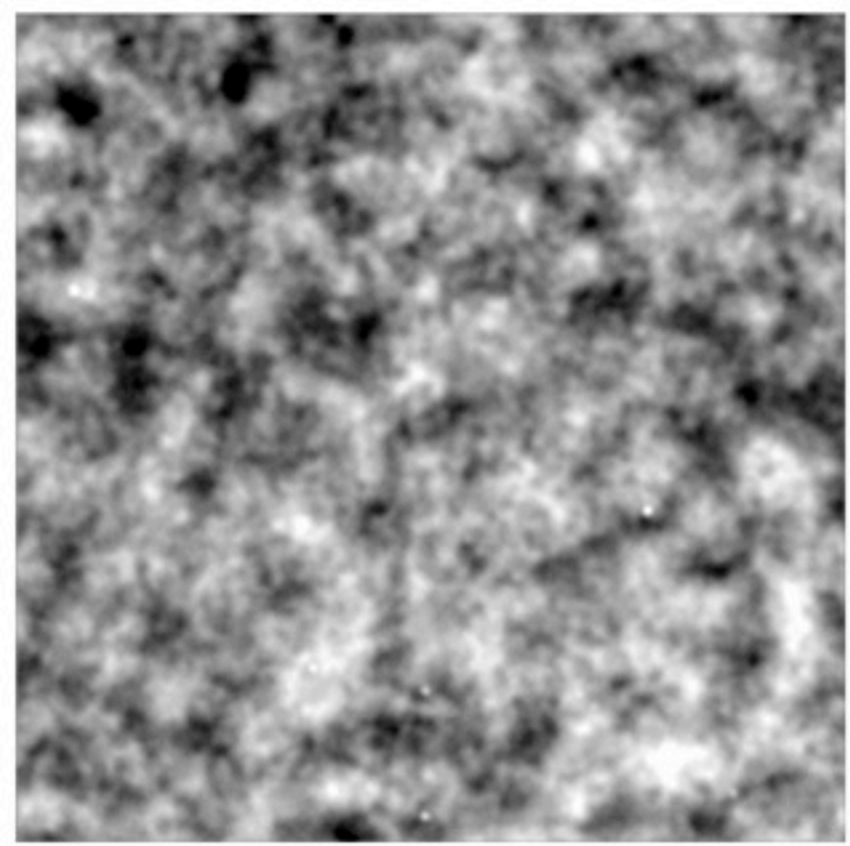

WMAP
PLANCK
-300
T (μK)
300

Planck has higher resolution than WMAP

WMAP 60 GHz

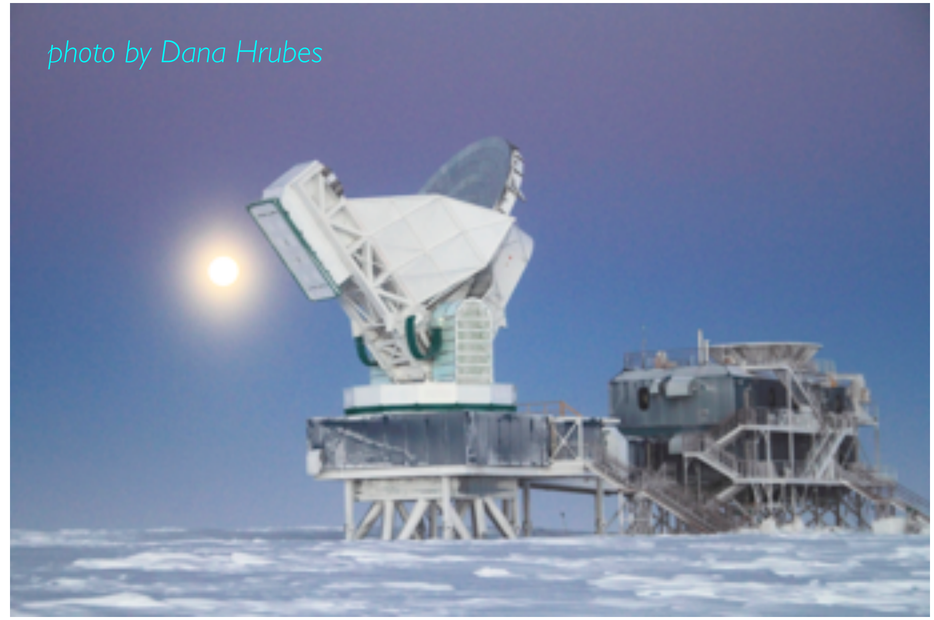


Planck 143 GHz



16^o

South Pole Telescope



10 m mm-wave (3 different wavelengths) telescope at the south pole

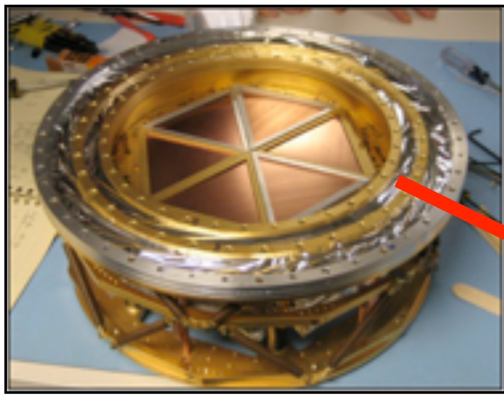
- extremely dry
- very stable
- good support

NSF

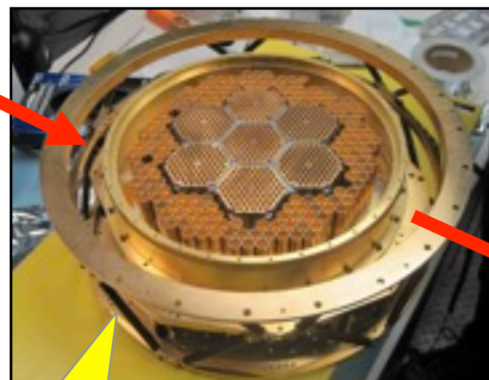
Chicago Colorado
UC Berkeley Case Western
McGill Harvard
UC Davis Munich +++

The evolution of SPT cameras

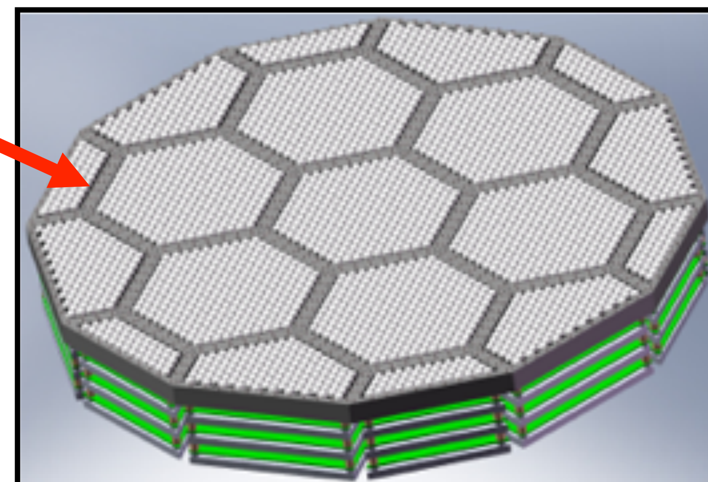
2007-2011: SPT
960 detectors



2012-2015: SPTpol
~1600 detectors



2016: SPT-3G
~15,200 detectors



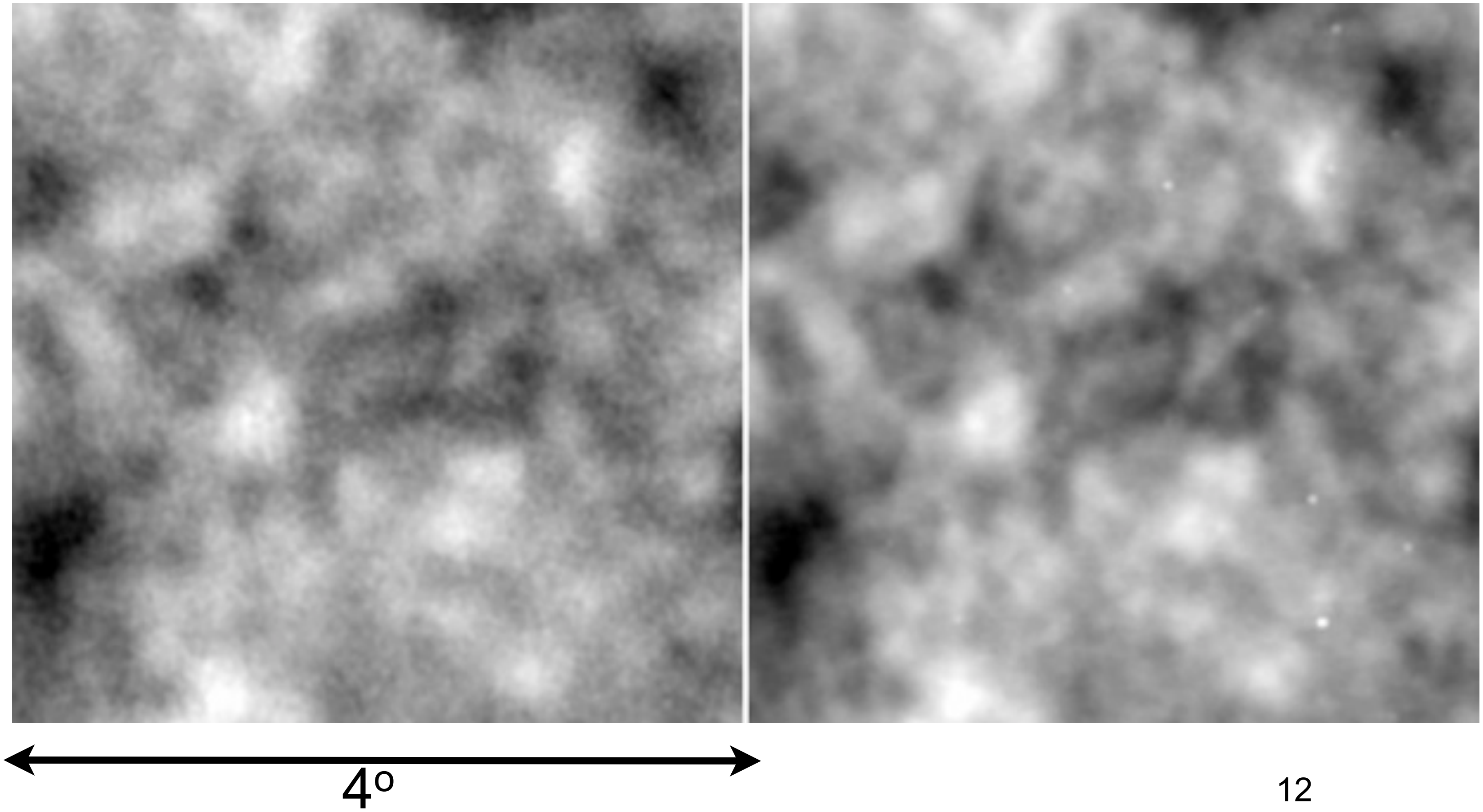
Now with polarization!

slide from S Hoover

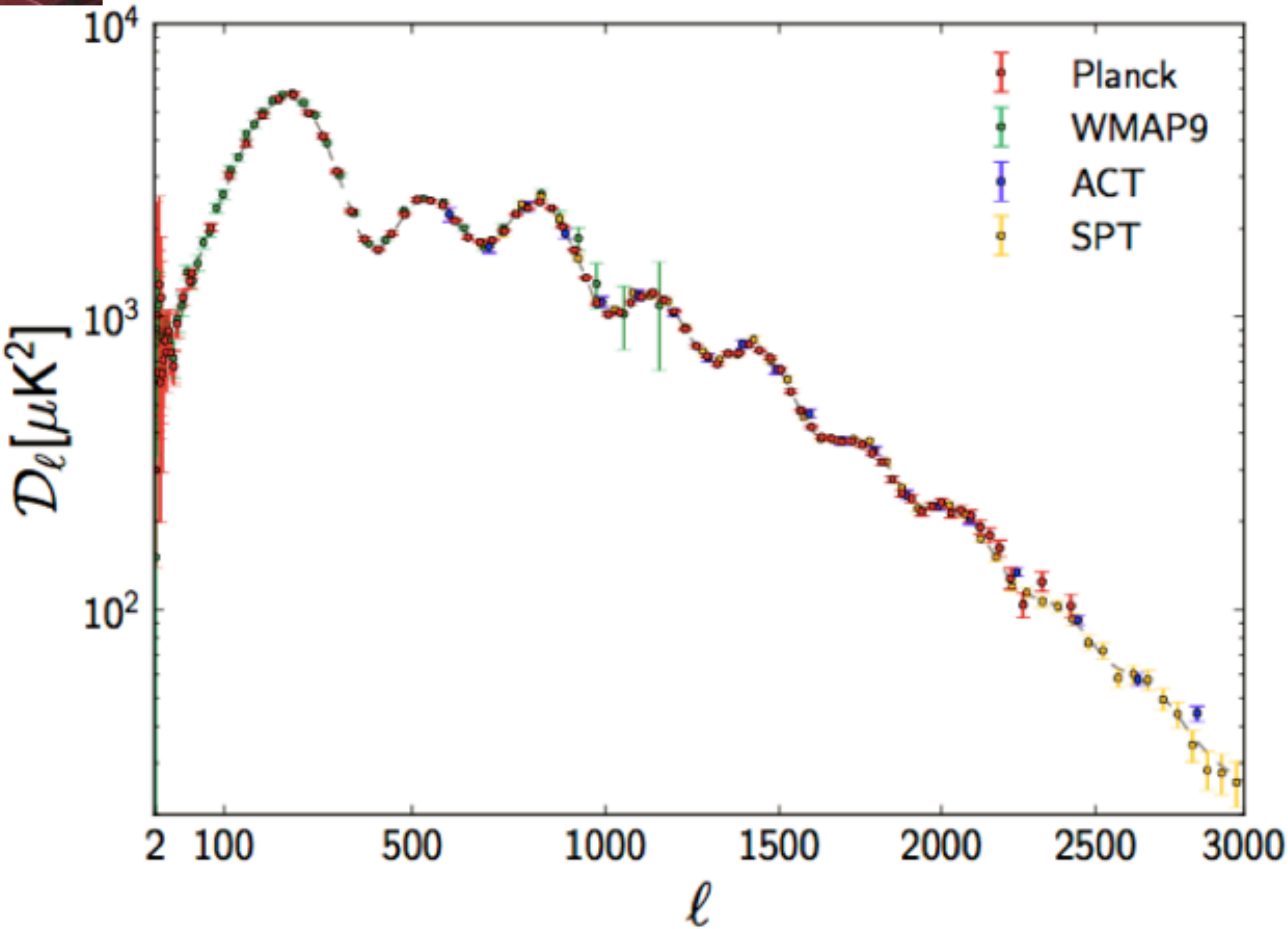
SPT has higher resolution than Planck

Planck 143 GHz

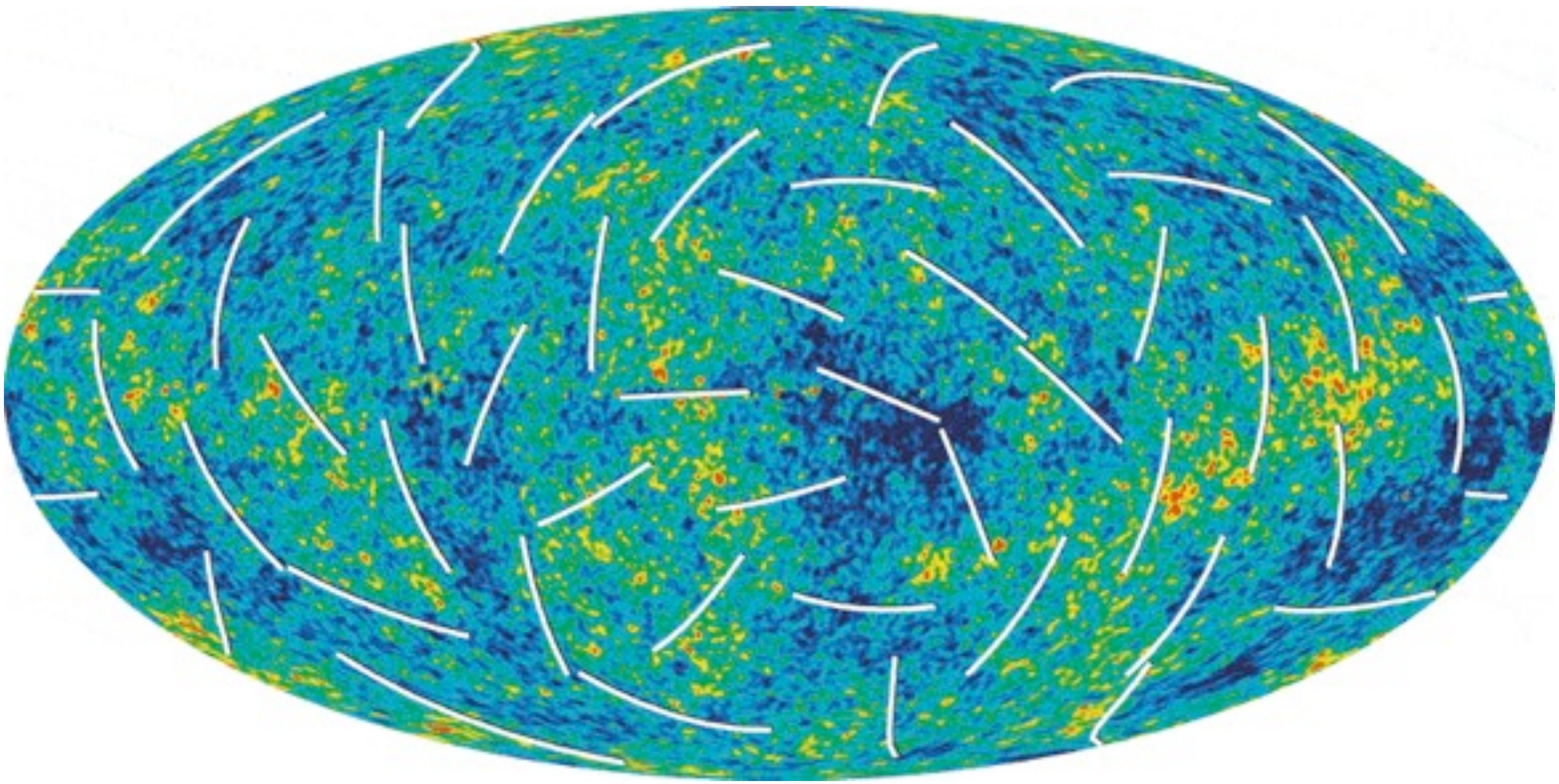
Planck+SPT



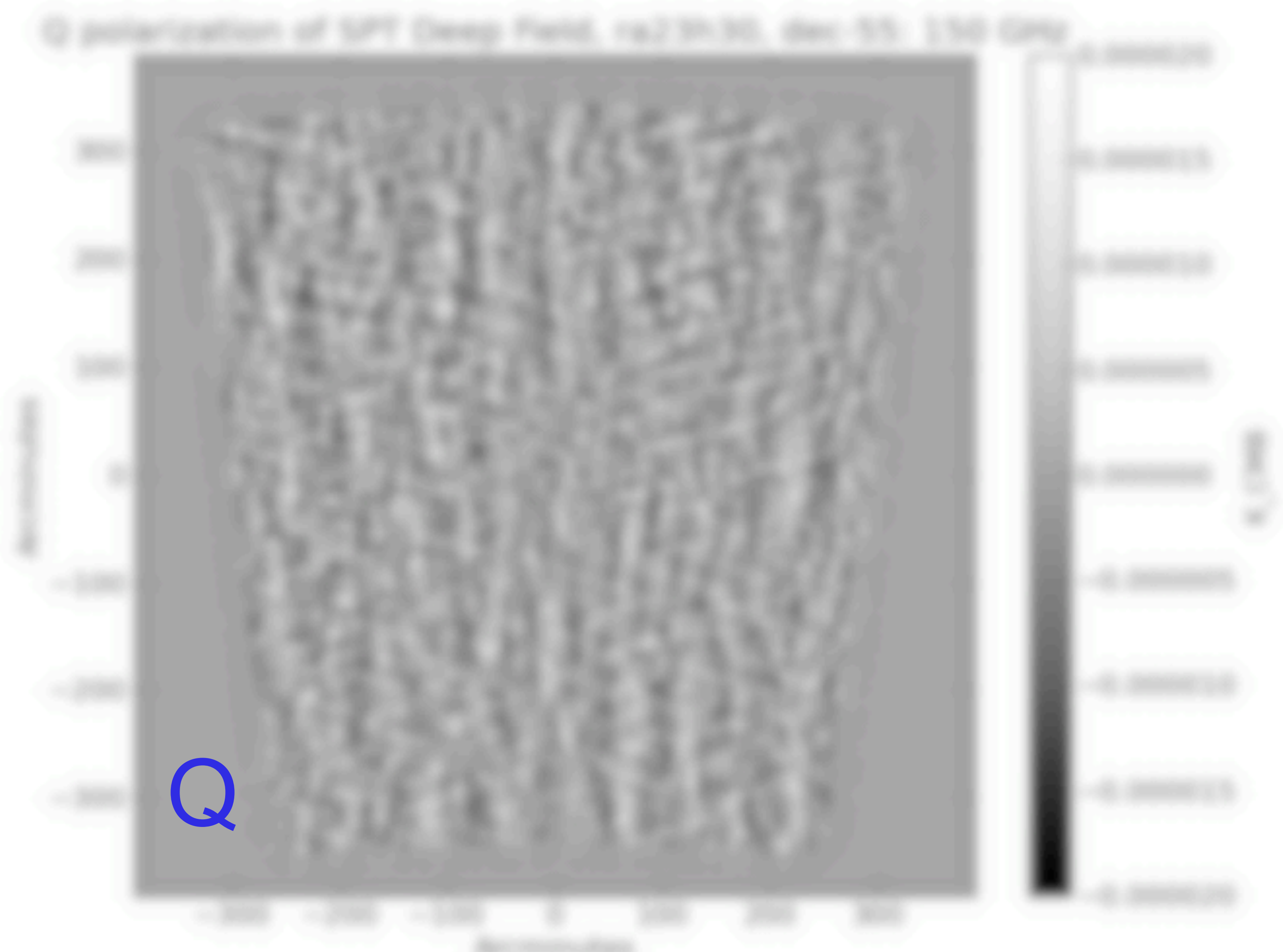
CMB Angular Power Spectrum

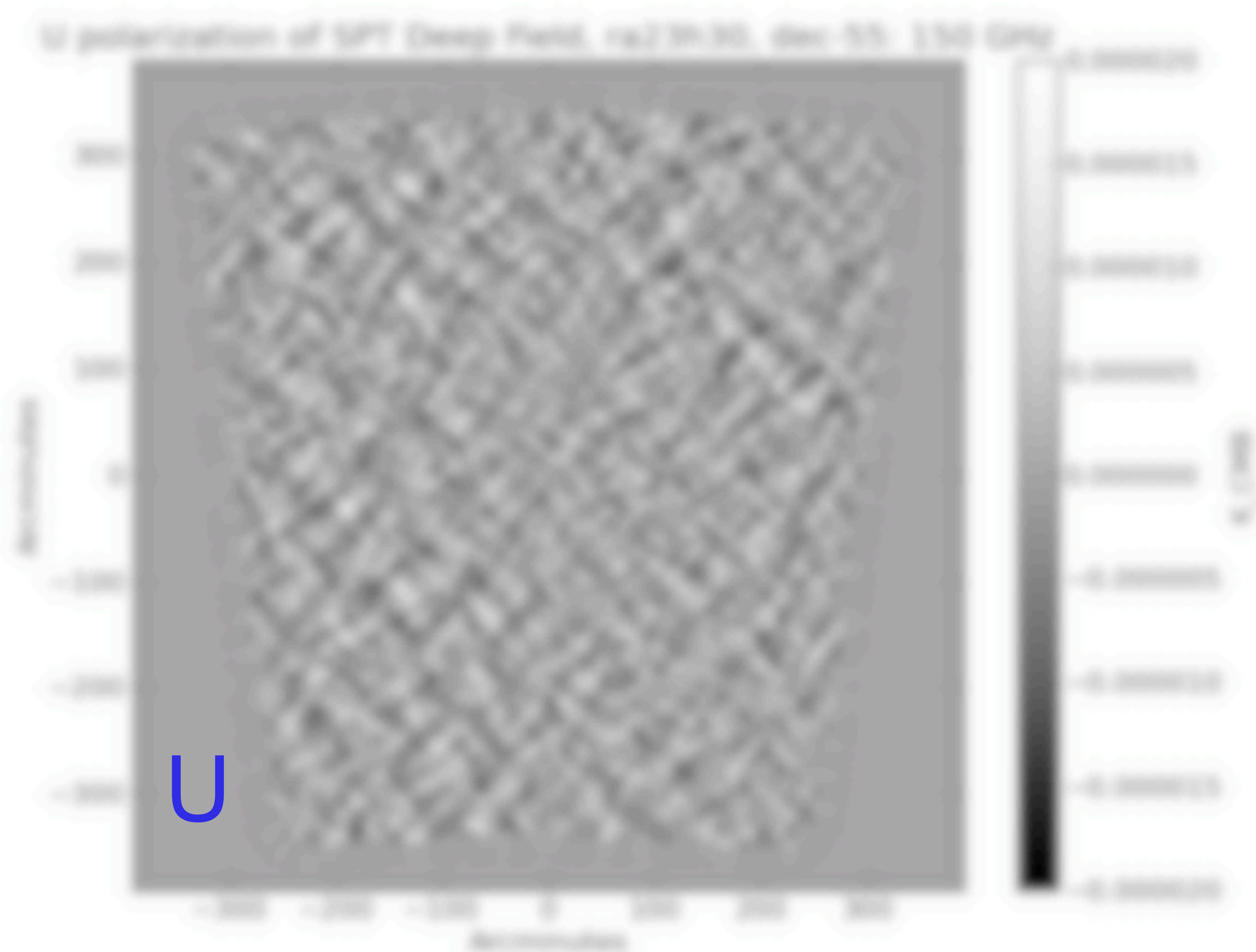


CMB Polarization



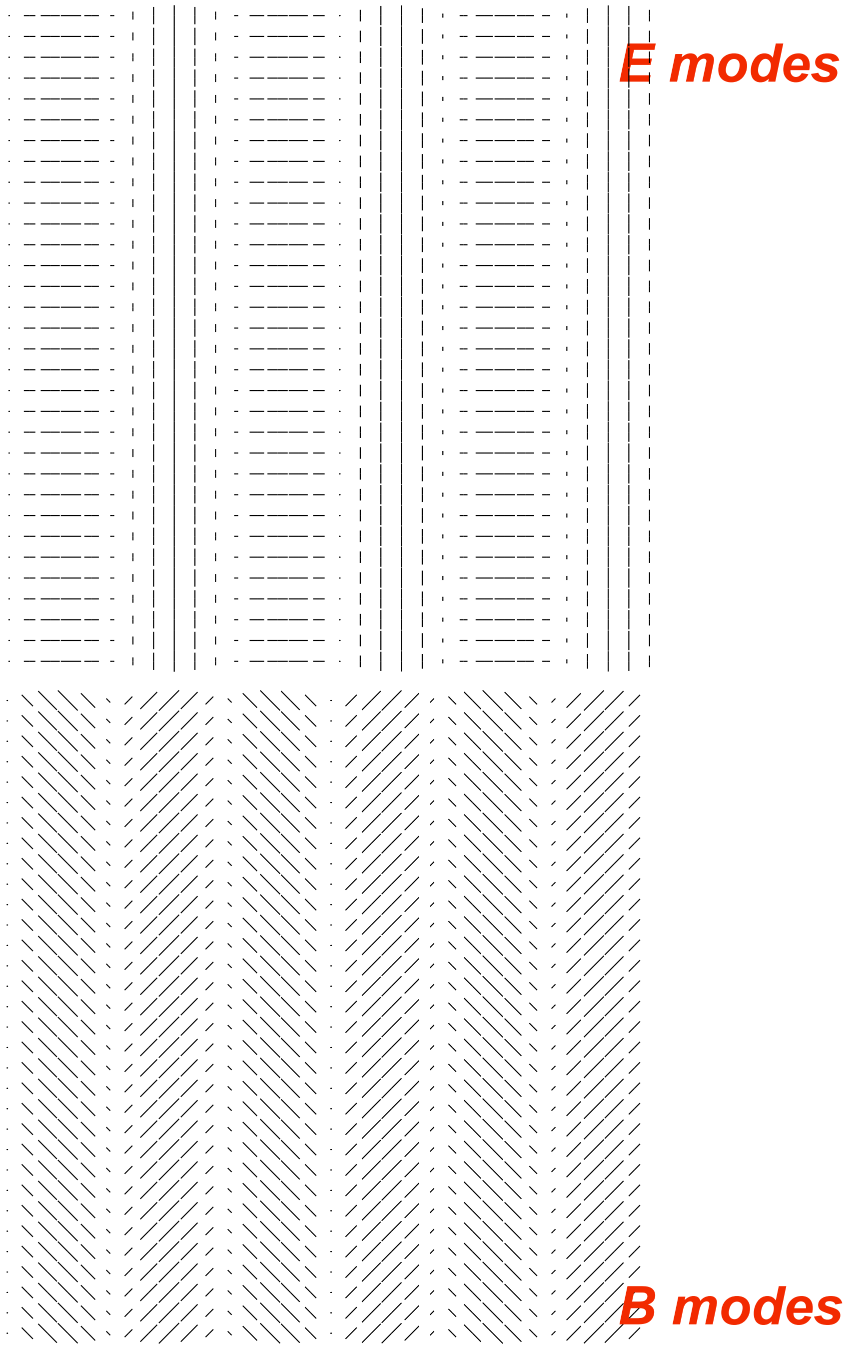
- CMB fluctuations are relatively strongly polarized (~10%)


Q


U

E-modes/B-modes

- E-modes vary spatially parallel or perpedicular to polarization direction
- B-modes vary spatially at 45 degrees
- CMB
    - scalar perturbations only generate *only* E



Bunn

E-modes/B-modes

- E-modes vary spatially parallel or perpedicular to polarization direction
- B-modes vary spatially at 45 degrees
- CMB
  - scalar perturbations only generate *only* E
- ***Lensing of CMB is much more obvious in polarization!***

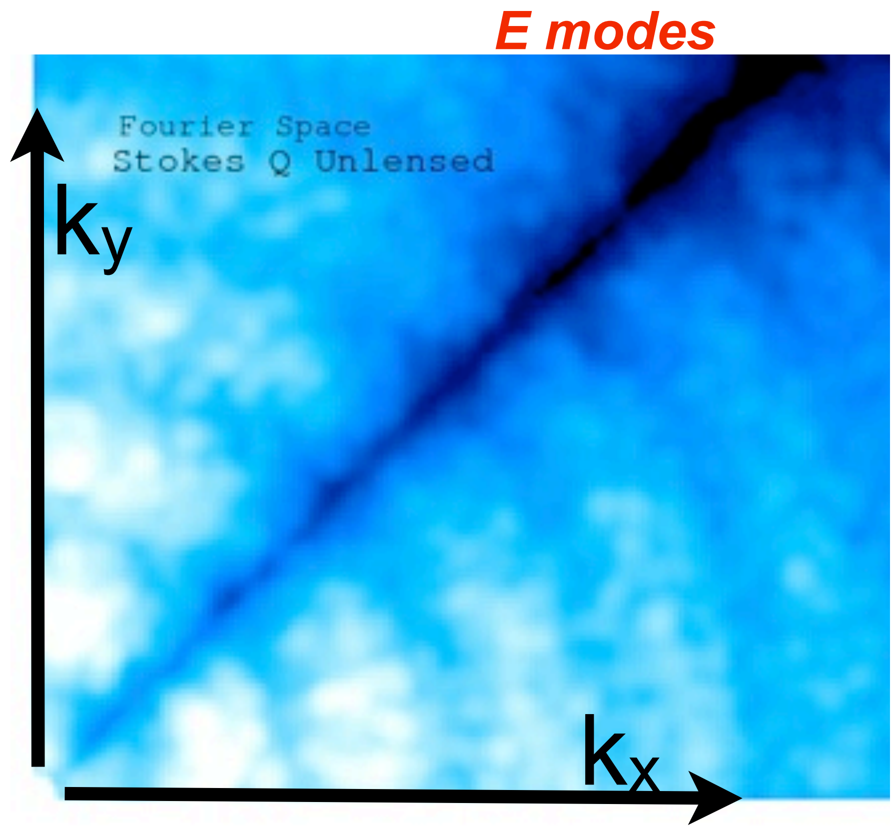
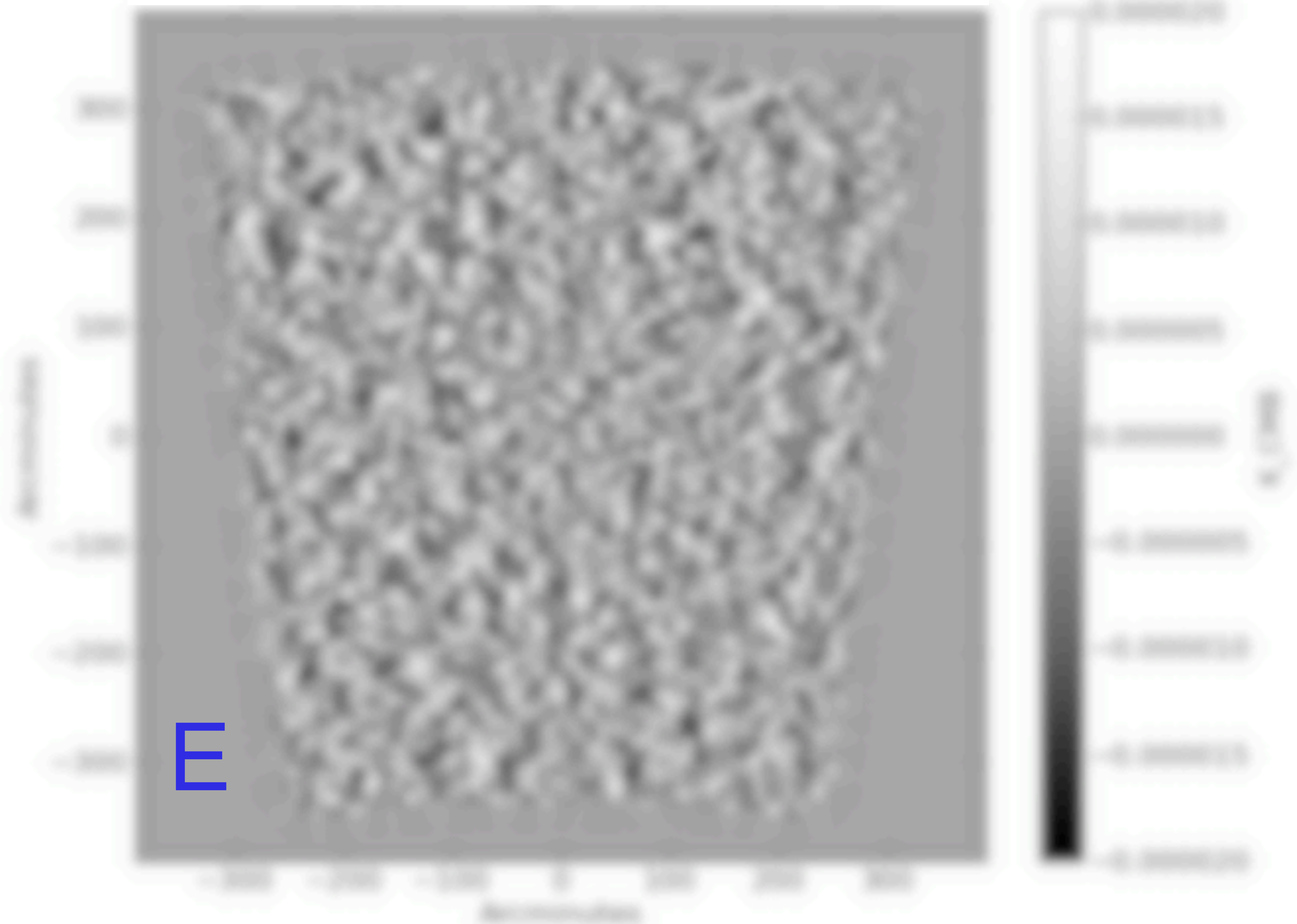
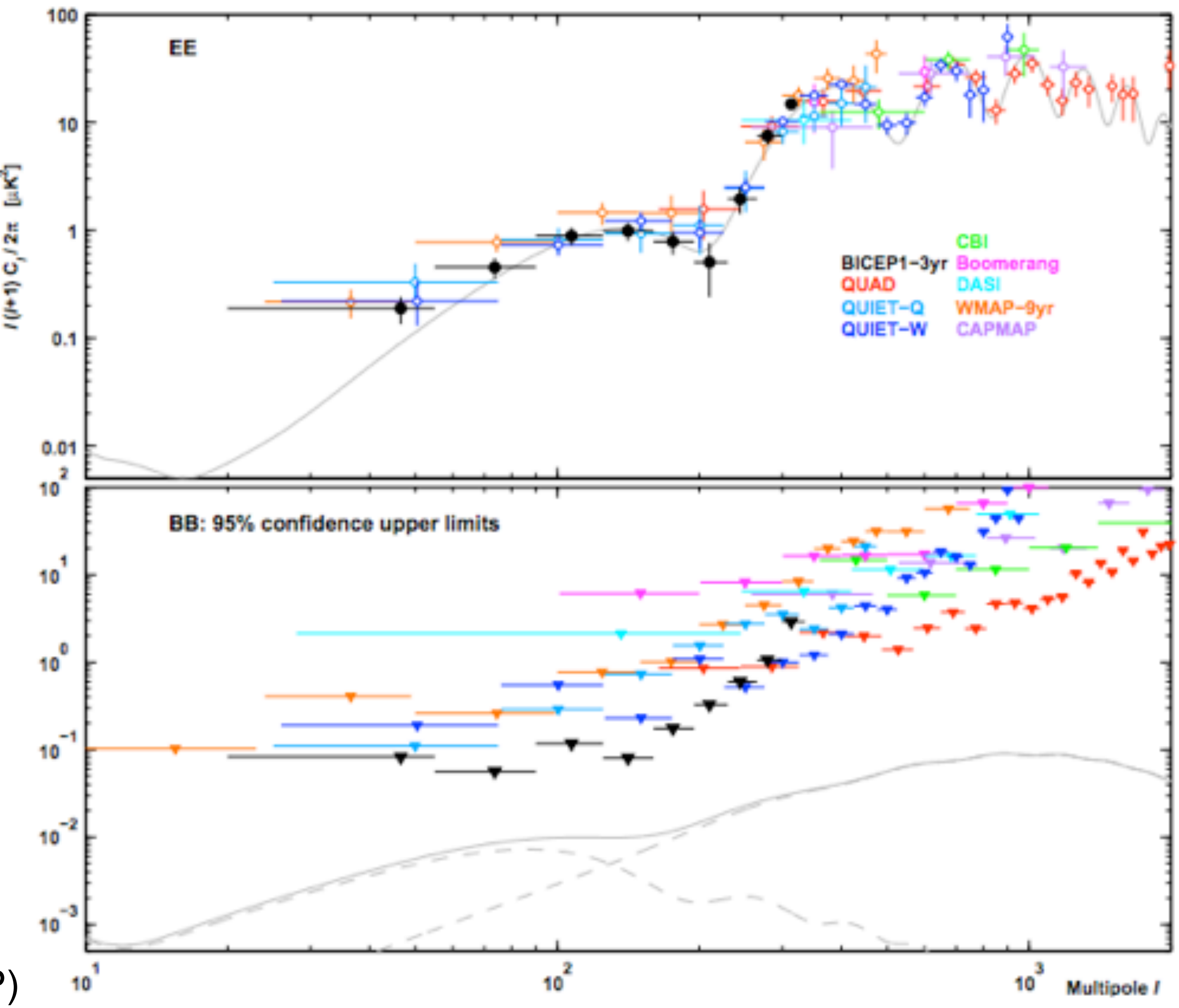


Image of positive kx/positive ky Fourier transform of a 10x10 deg chunk of Stokes Q CMB map [simulated; nothing clever done to it]

E-mode polarization of ra23h30, dec -55 field (150 GHz)



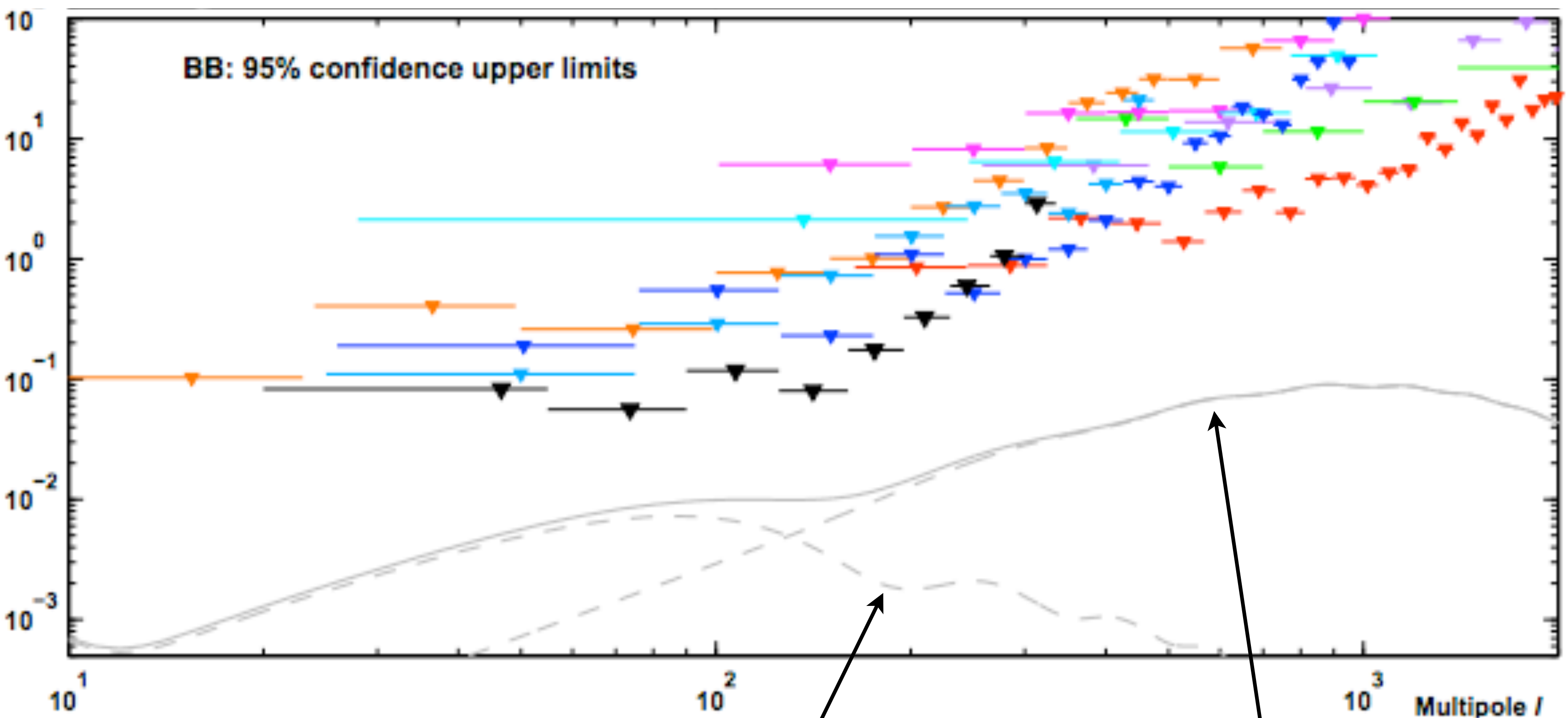
CMB Polarization Angular Power Spectrum



only upper limits on B mode power

Barkats et al (BICEP)

Two Expected Sources of B Modes



Gravitational Radiation in Early Universe
(amplitude unknown!)

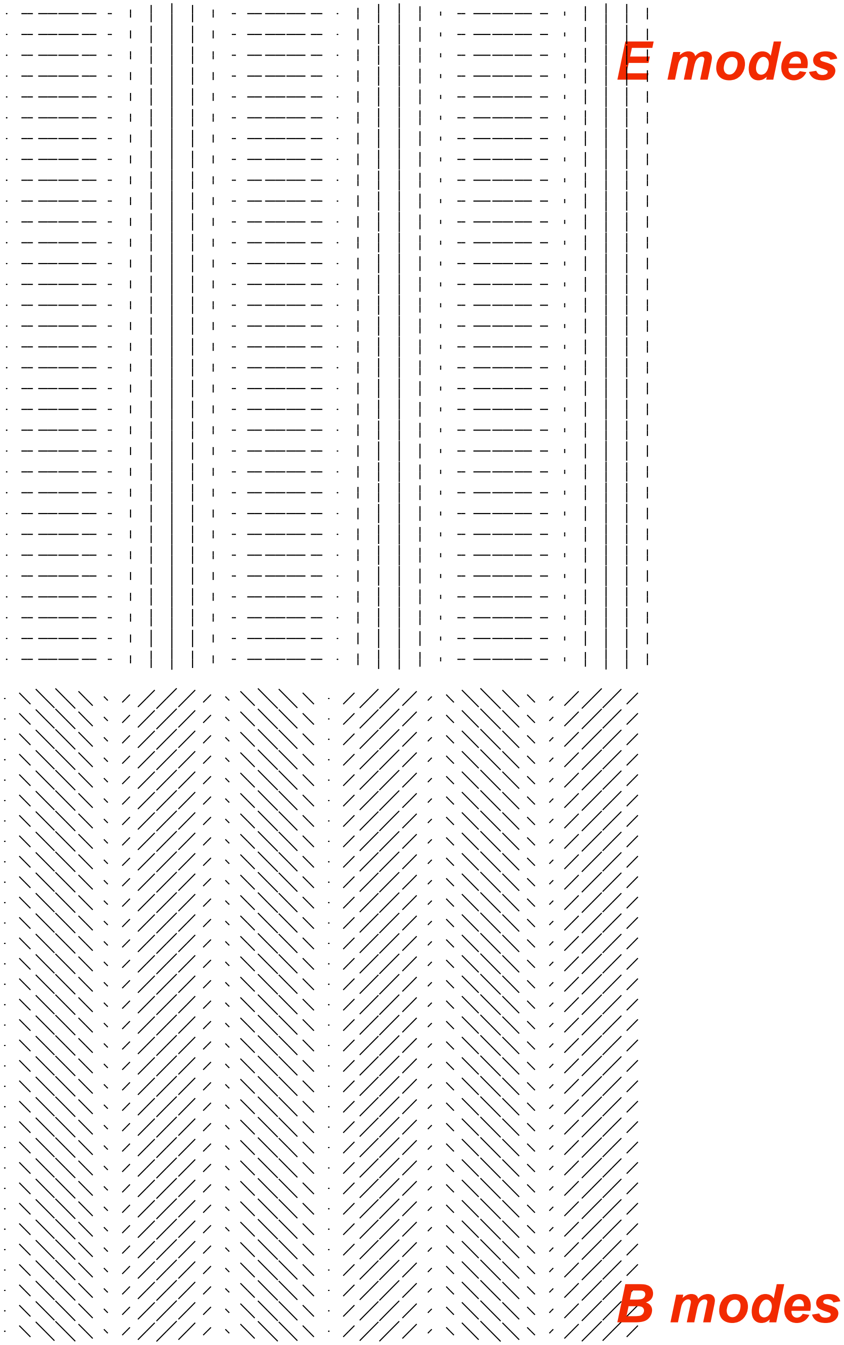
Gravitational lensing of
E modes (amplitude
well-predicted, but no
measured B modes
until later in talk)

E-modes/B-modes

• E-modes vary spatially parallel or perpedicular to polarization direction

• B-modes vary spatially at 45 degrees

• scalar perturbations only generate *only* E



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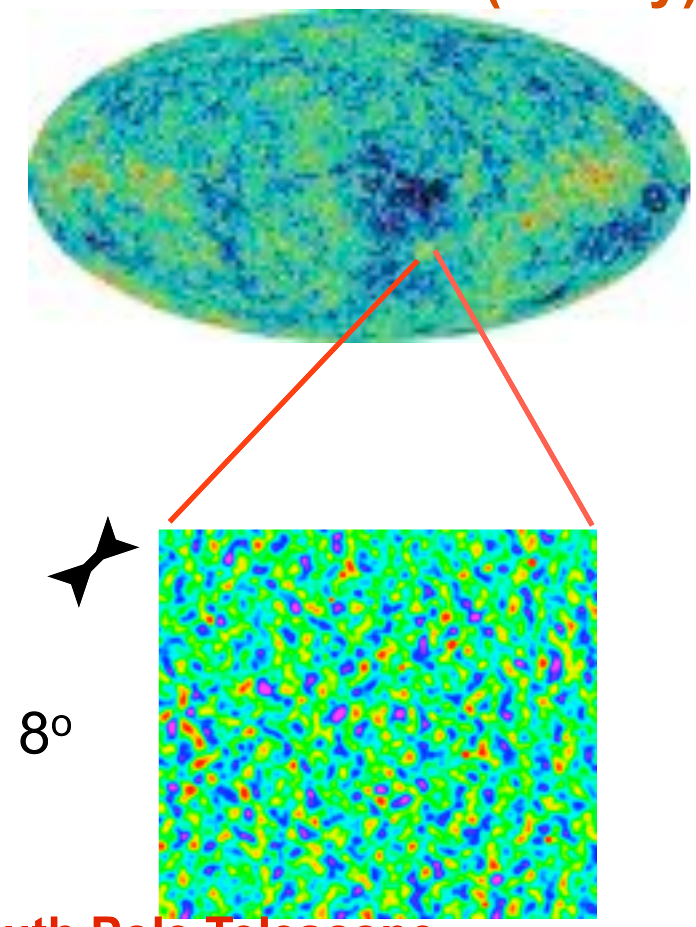
Cosmic Microwave Background

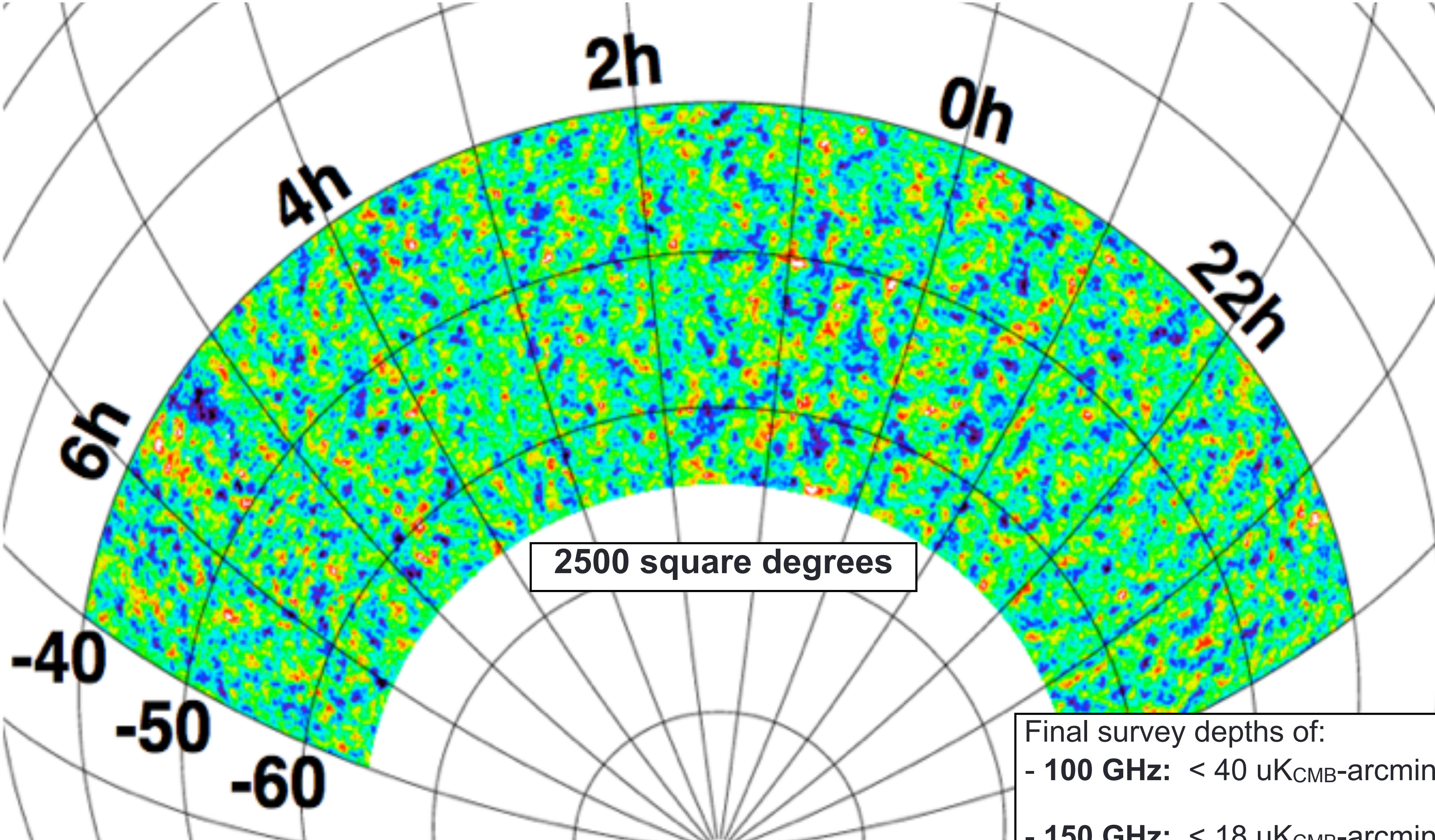
- acoustic scale (in cm) set by physics unrelated to dark energy
  - angular scale depends on expansion history
- provides normalization of fluctuation amplitude at z~1100

WMAP (all sky)



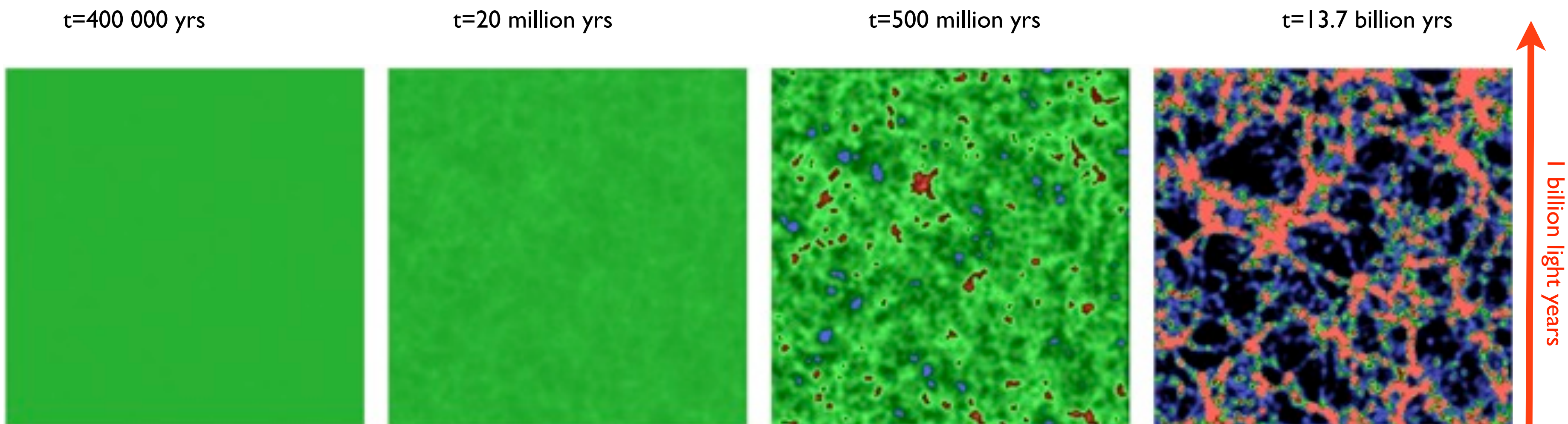
South Pole Telescope (total 2500 sq deg)

SPT-SZ Survey (completed)



Final survey depths of:
- **100 GHz:** < 40 uK_{CMB}-arcmin
- **150 GHz:** < 18 uK_{CMB}-arcmin
- **220 GHz:** < 80 uK_{CMB}-arcmin

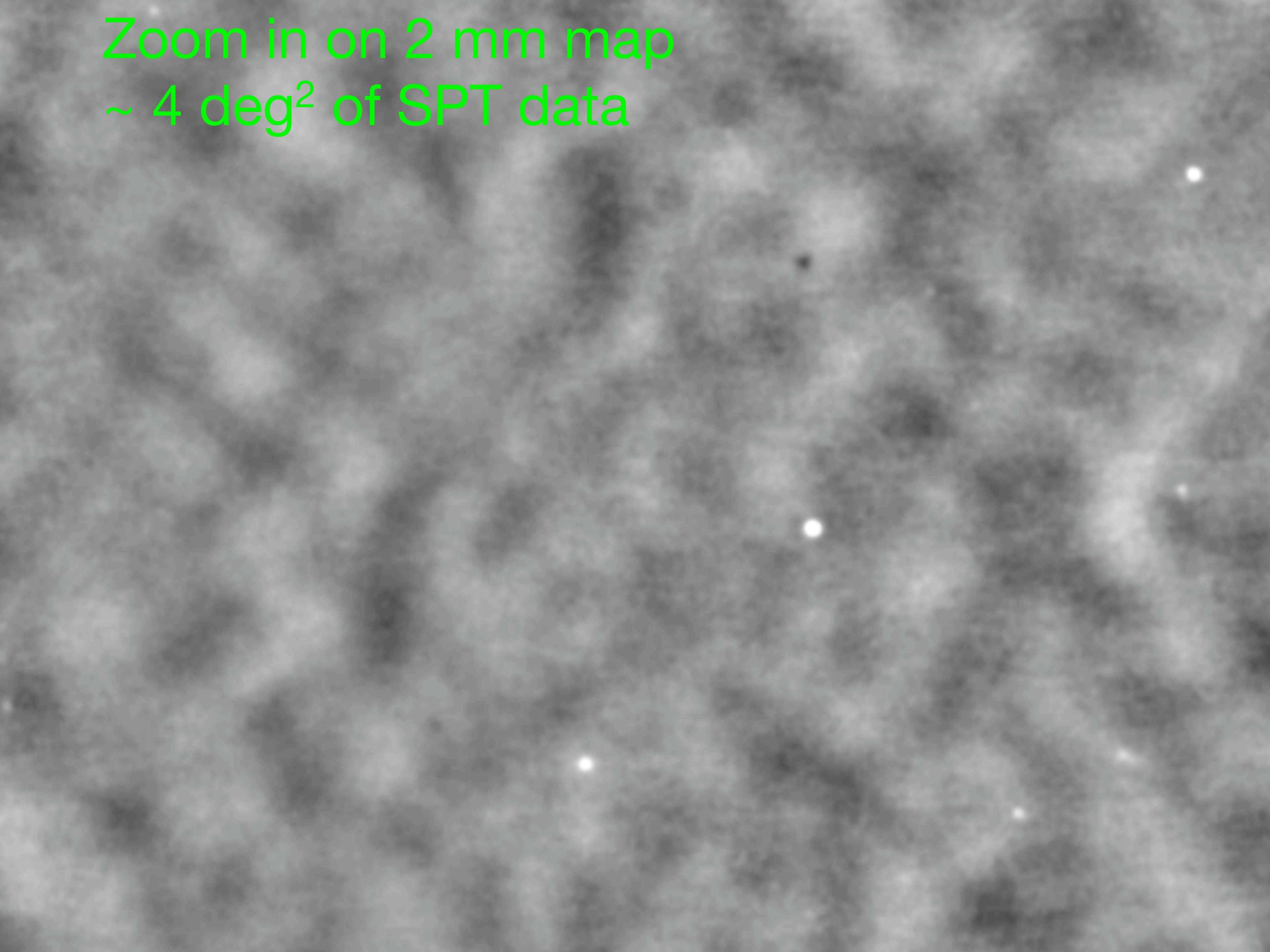
Gravity at work

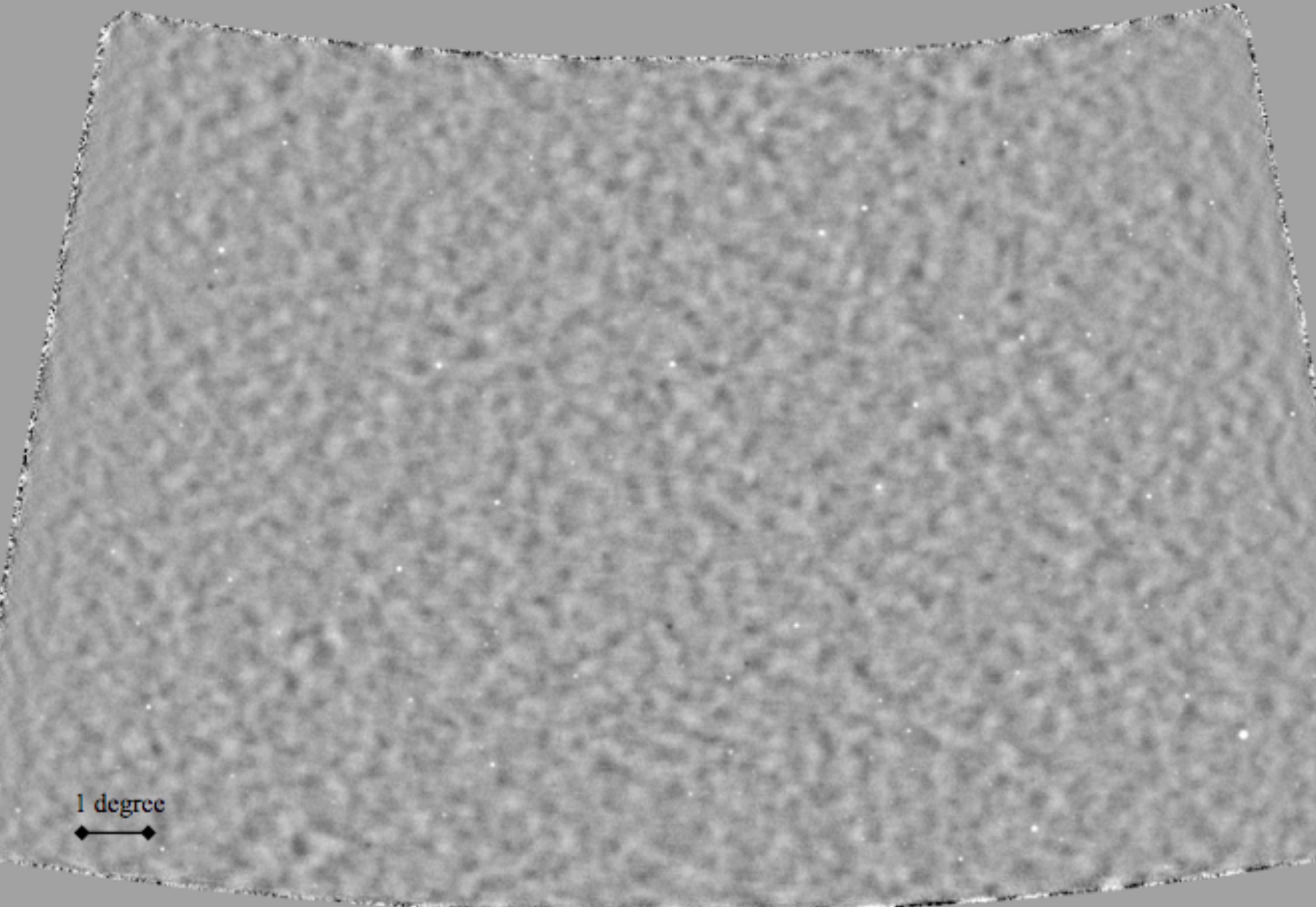


***simulated* density contrast at different times**

simulations carried out by the Virgo Supercomputing Consortium using computers based at Computing Centre of the Max-Planck Society in Garching and at the Edinburgh Parallel Computing Centre. The data are publicly available at www.mpa-garching.mpg.de/NumCos

$$\ddot{\delta} + 2H(z)\dot{\delta} = 4\pi G\rho_o\delta$$


Zoom in on 2 mm map
~ 4 deg^2 of SPT data



18 uK sensitivity at observing wavelength of 2 mm
roughly same resolution as your eye

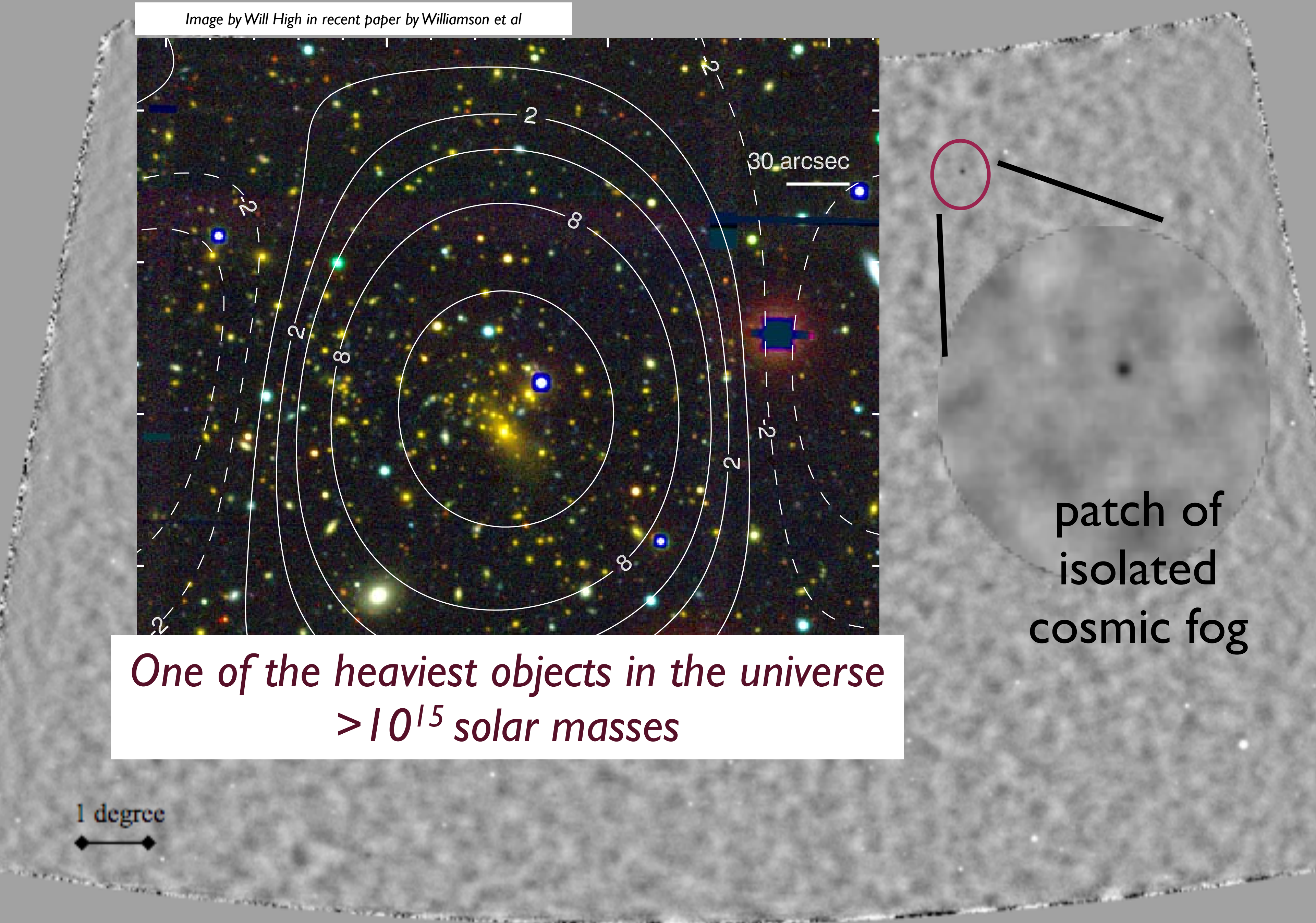
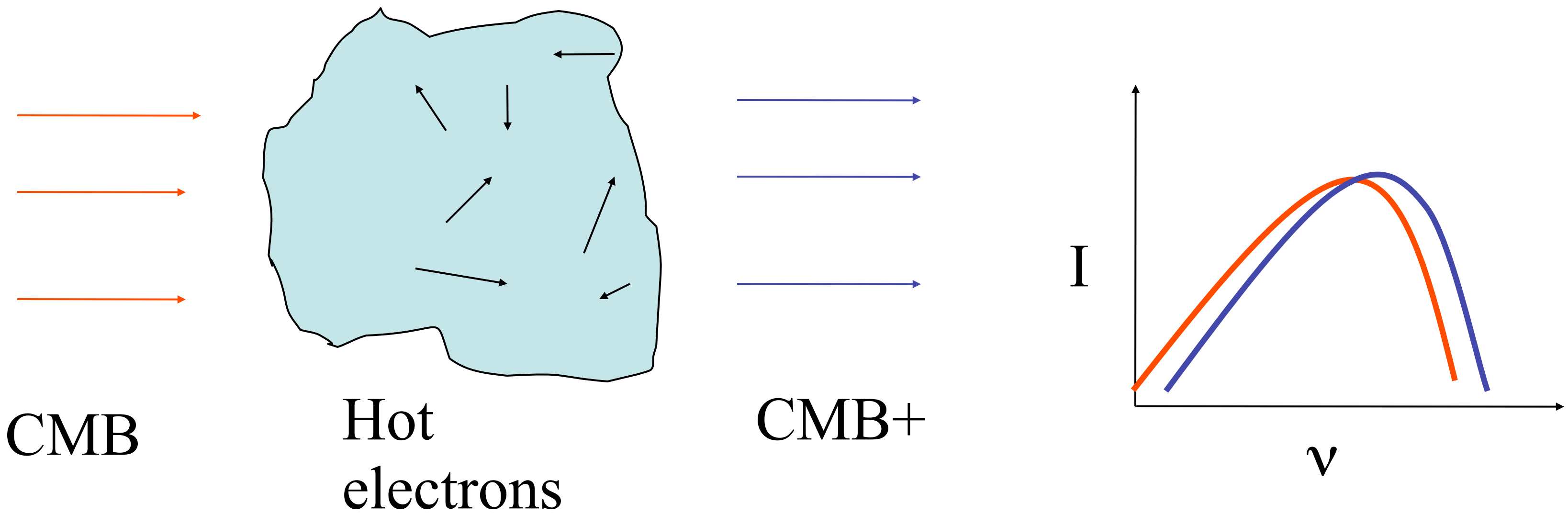


Image by Will High in recent paper by Williamson et al
30 arcsec
One of the heaviest objects in the universe
>10^{15} solar masses
patch of isolated cosmic fog
1 degree

Thermal Sunyaev-Zel'dovich Effect



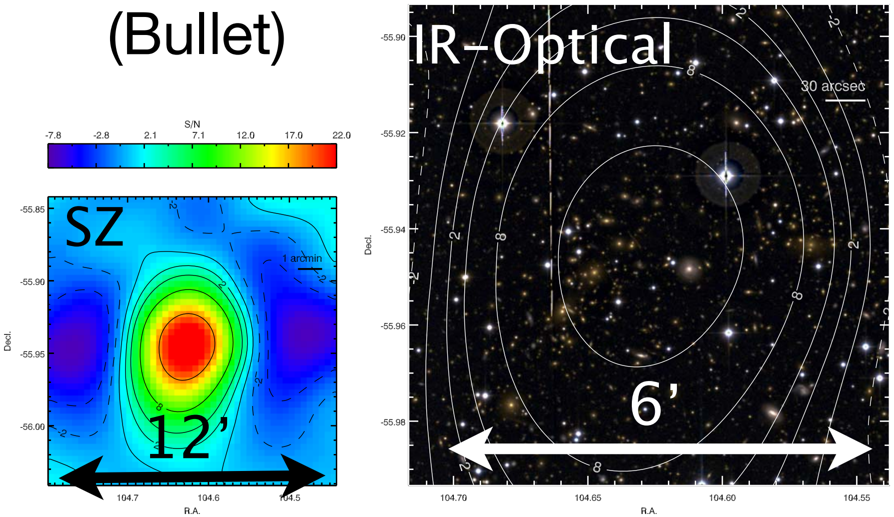
Optical depth: $\tau \sim 0.01$

Fractional energy gain per scatter: $\frac{kT}{m_e c^2} \sim 0.01$

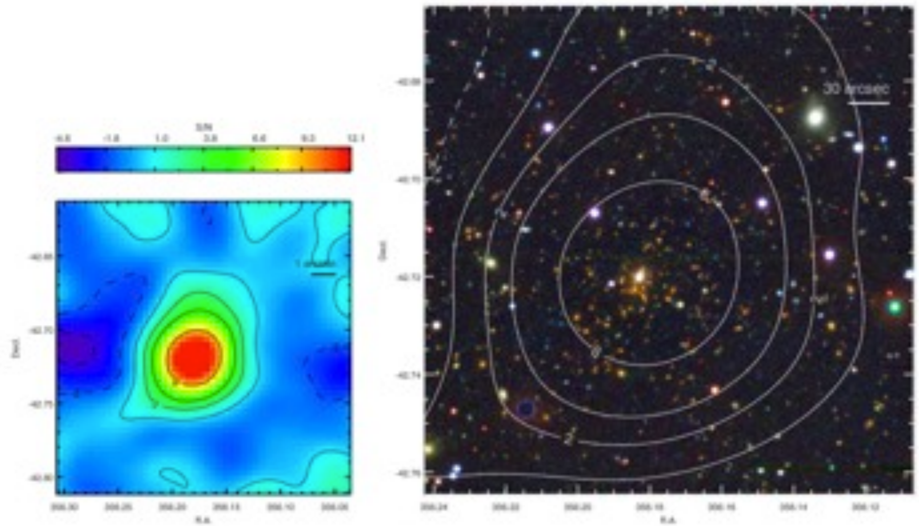
Typical cluster signal: ~500 uK

SPT Cluster Images

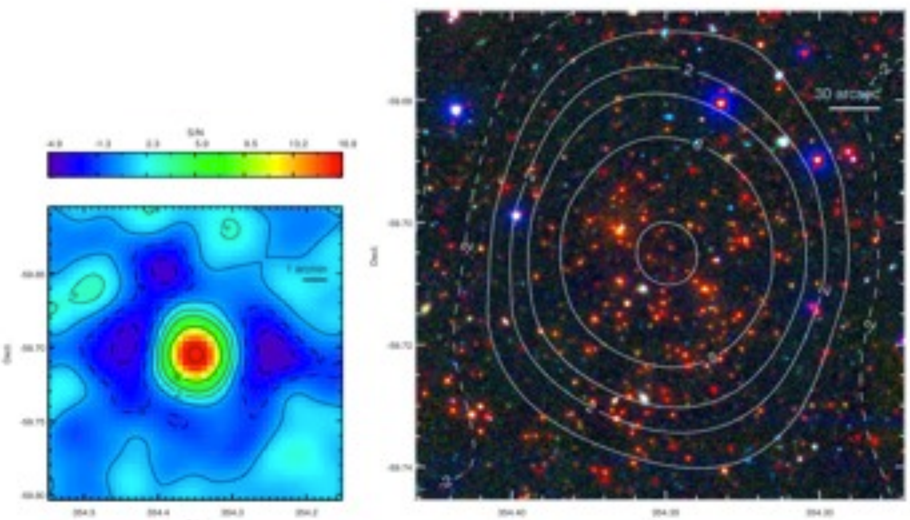
0658-5556 (z=0.30)
(Bullet)



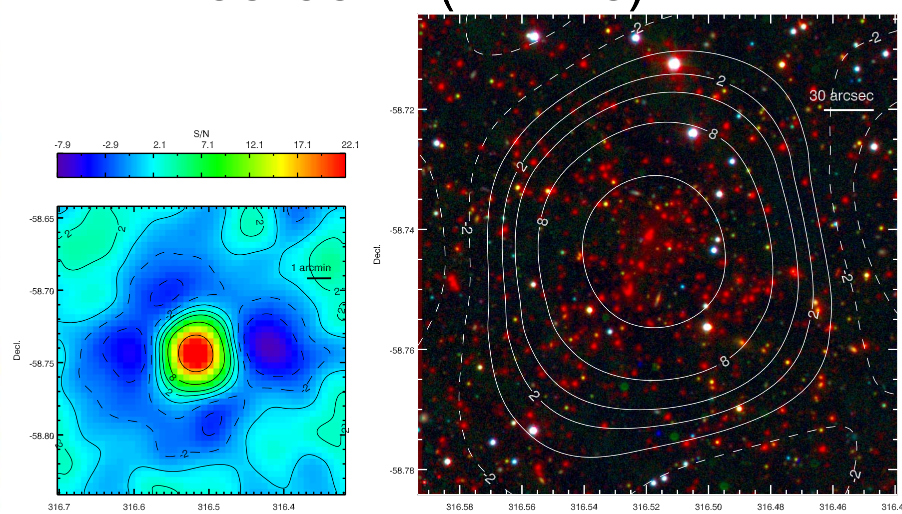
2344-4243 (z=0.62)



2337-5942 (z=0.78)



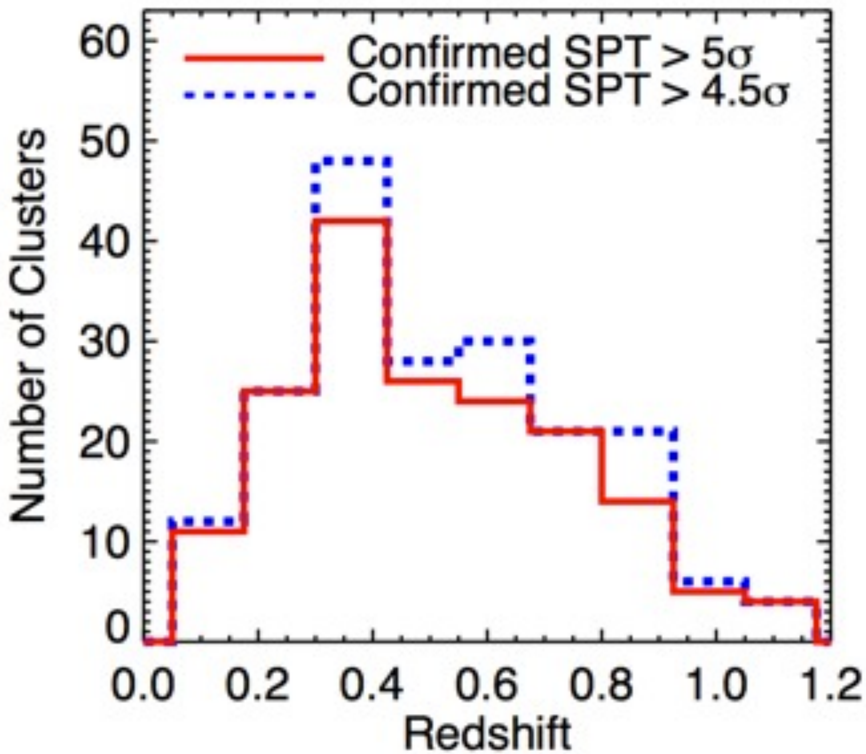
2106-5844 (z=1.13)



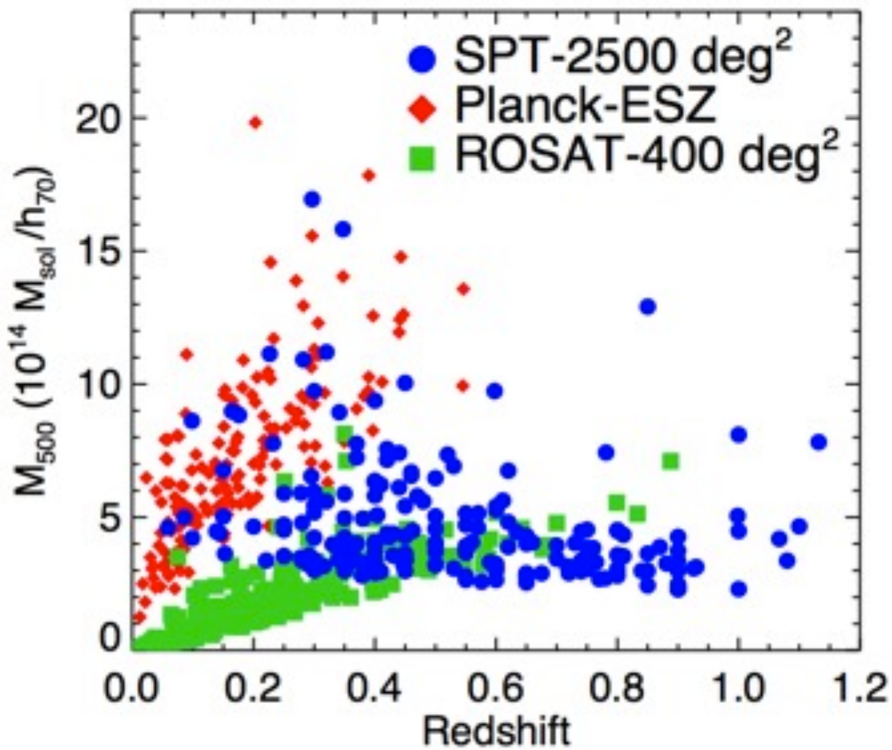
Williamson et al 2011, arXiv:1101.1290

SPT Cluster Sample Properties

Redshift Histogram

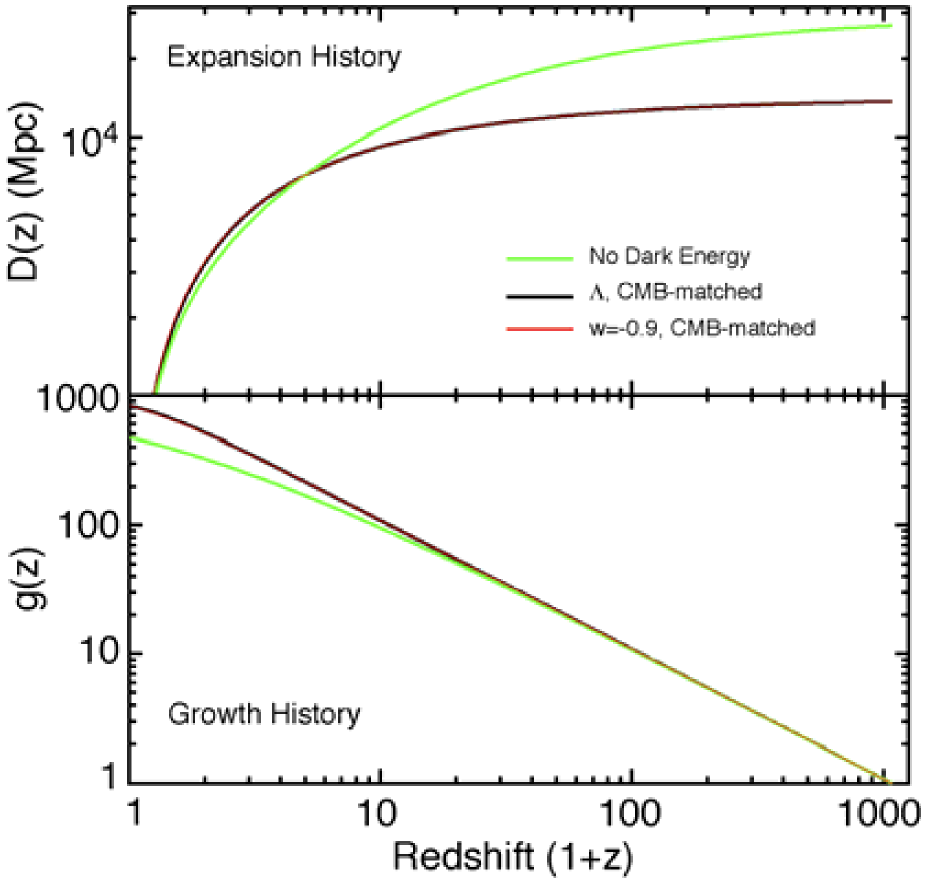


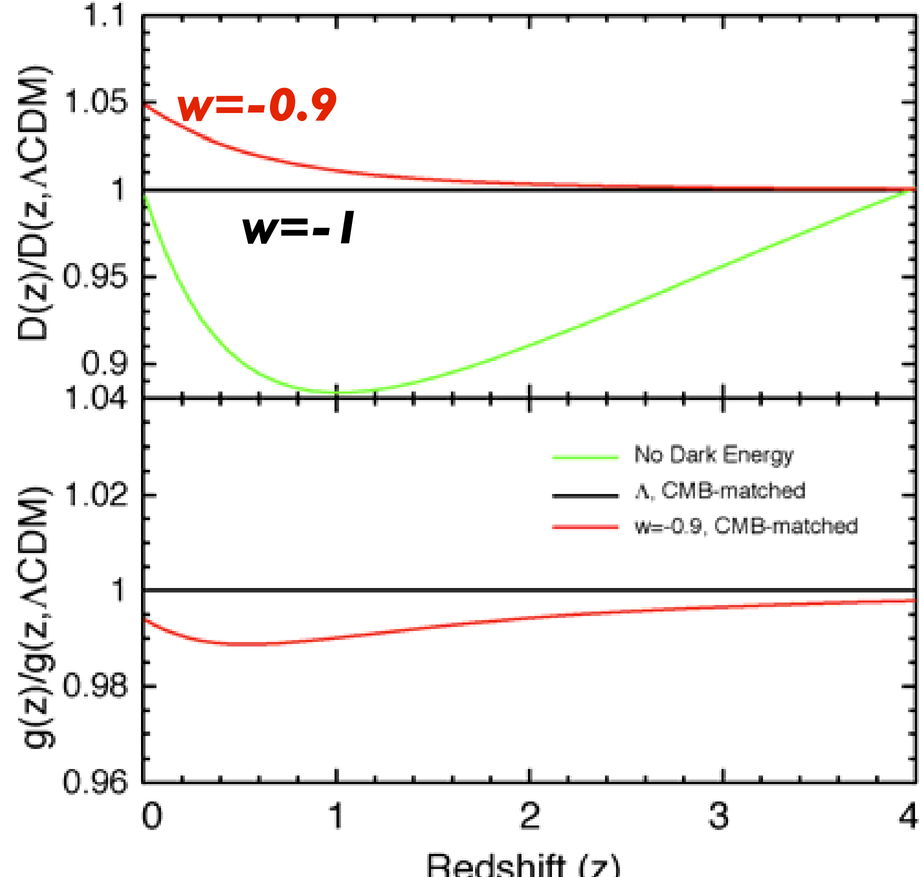
SZ Mass vs Redshift



- Optically confirmed >300 clusters, ~80% newly discovered
- High redshift: $<z>$ = 0.55 and ~20-25% of clusters at $z > 0.8$
- Optical measurements also confirm ~95% purity at S/N = 5
- Mass threshold flat/falling w/ redshift: $M_{500}(z=0.6) > \sim 3\times10^{14}\ M_{sol}/h_{70}$

Characterizing Dark Energy

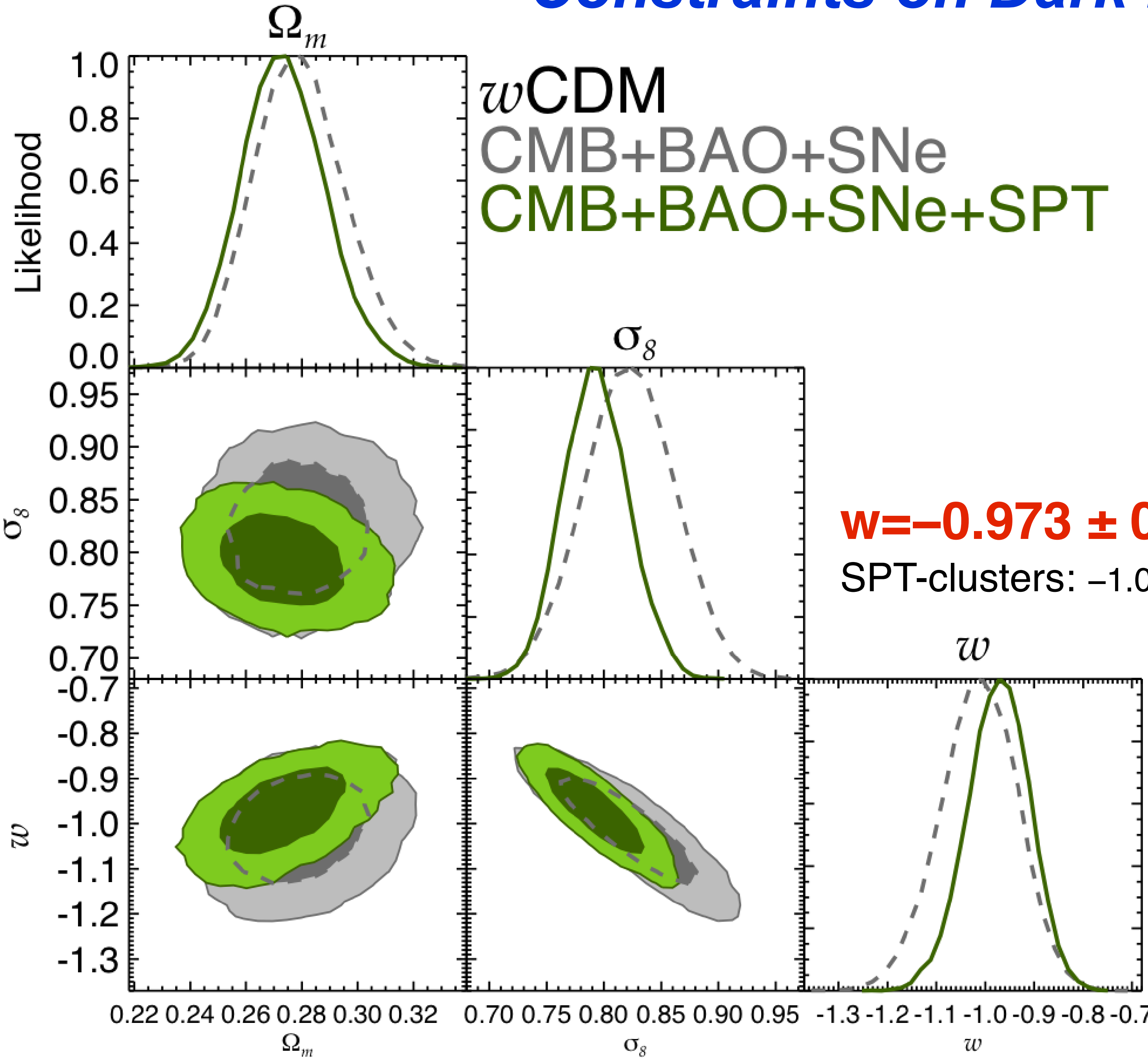




from Dark Energy Task Force report

Benson et al 2011

Constraints on Dark Energy

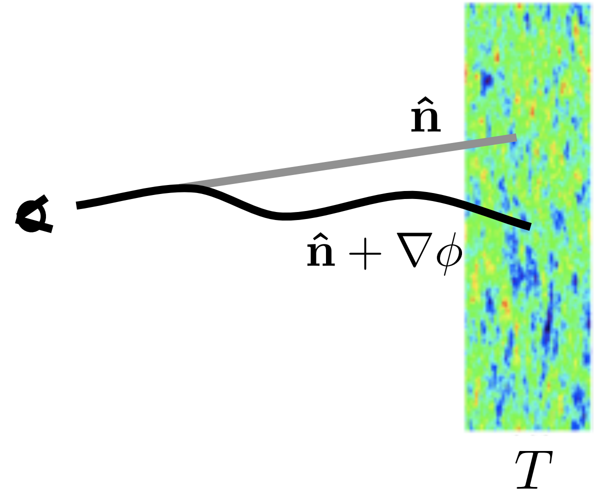


w=–0.973 ± 0.063

SPT-clusters: –1.087 ± 0.363

Gravitational deflection

CMB Lensing



Photons get shifted

$$T^L(\hat{\mathbf{n}}) = T^U(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}))$$

In WL limit, add many deflections along line of sight

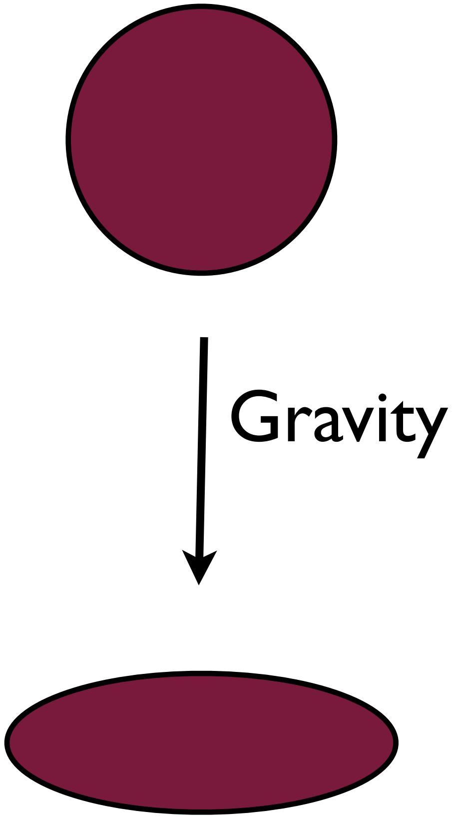
$$\nabla\phi(\hat{\mathbf{n}}) = -2\int_0^{\chi_\star} d\chi\, \frac{\chi_\star - \chi}{\chi_\star \chi} \nabla_\perp \Phi(\chi\hat{\mathbf{n}}, \chi)$$

Broad kernel, peaks at z ~ 2

- CMB is a unique source for lensing
    - Gaussian, with well-understood power spectrum (contains all info)
    - At redshift which is (a) unique, (b) known, and (c) highest

Lensing simplified

- gravitational potentials distort shapes by stretching, squeezing, shearing



Lensing simplified

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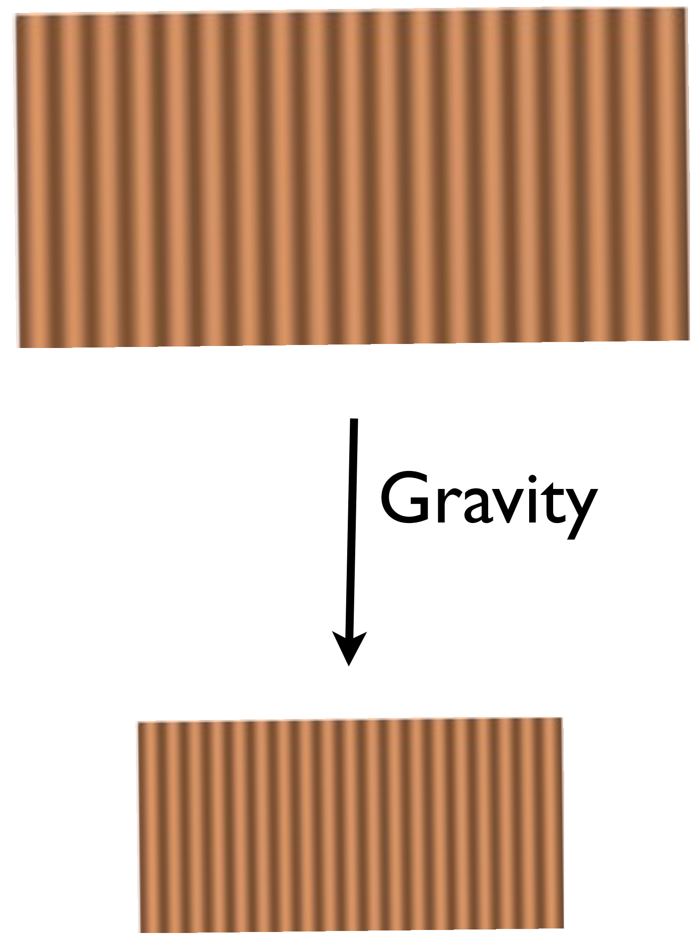
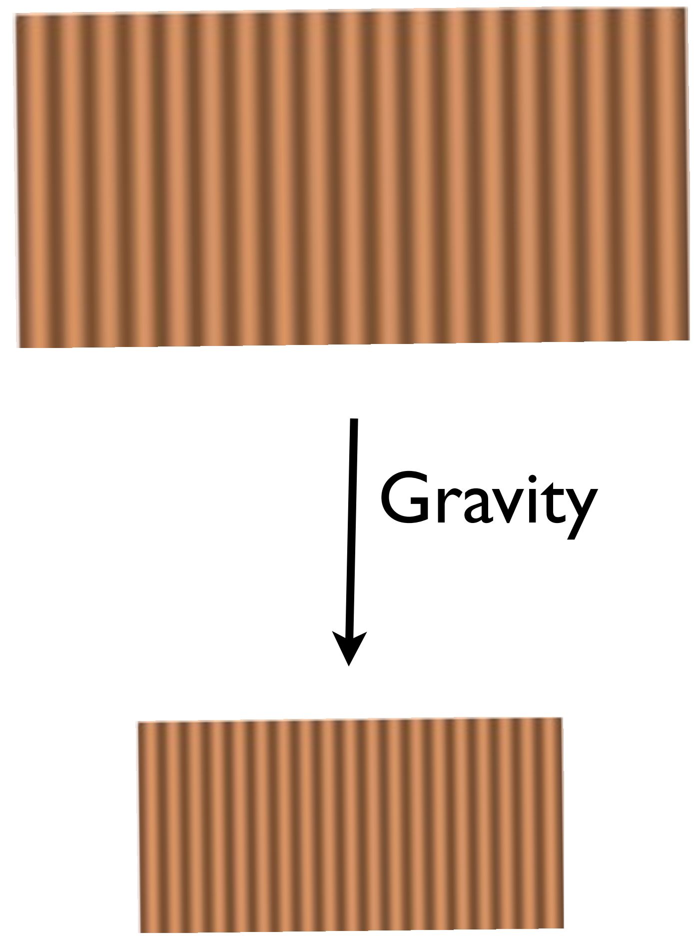


Lensing simplified

- where gravity stretches, gradients become smaller
- where gravity compresses, gradients are larger
- shear changes ***direction***



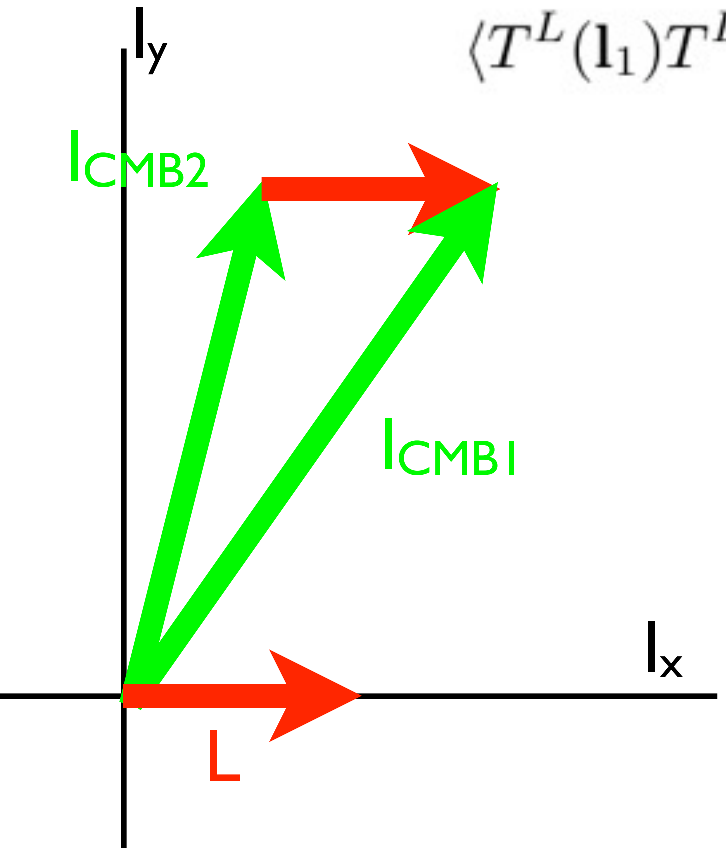
Mode Coupling from Lensing

$$T^L(\hat{\mathbf{n}}) = T^U(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})) = T^U(\hat{\mathbf{n}}) + \nabla T^U(\hat{\mathbf{n}}) \cdot \nabla\phi(\hat{\mathbf{n}}) + O(\phi^2),$$

- Non-gaussian mode coupling for $\mathbf{l_1} \neq -\mathbf{l_2}$:

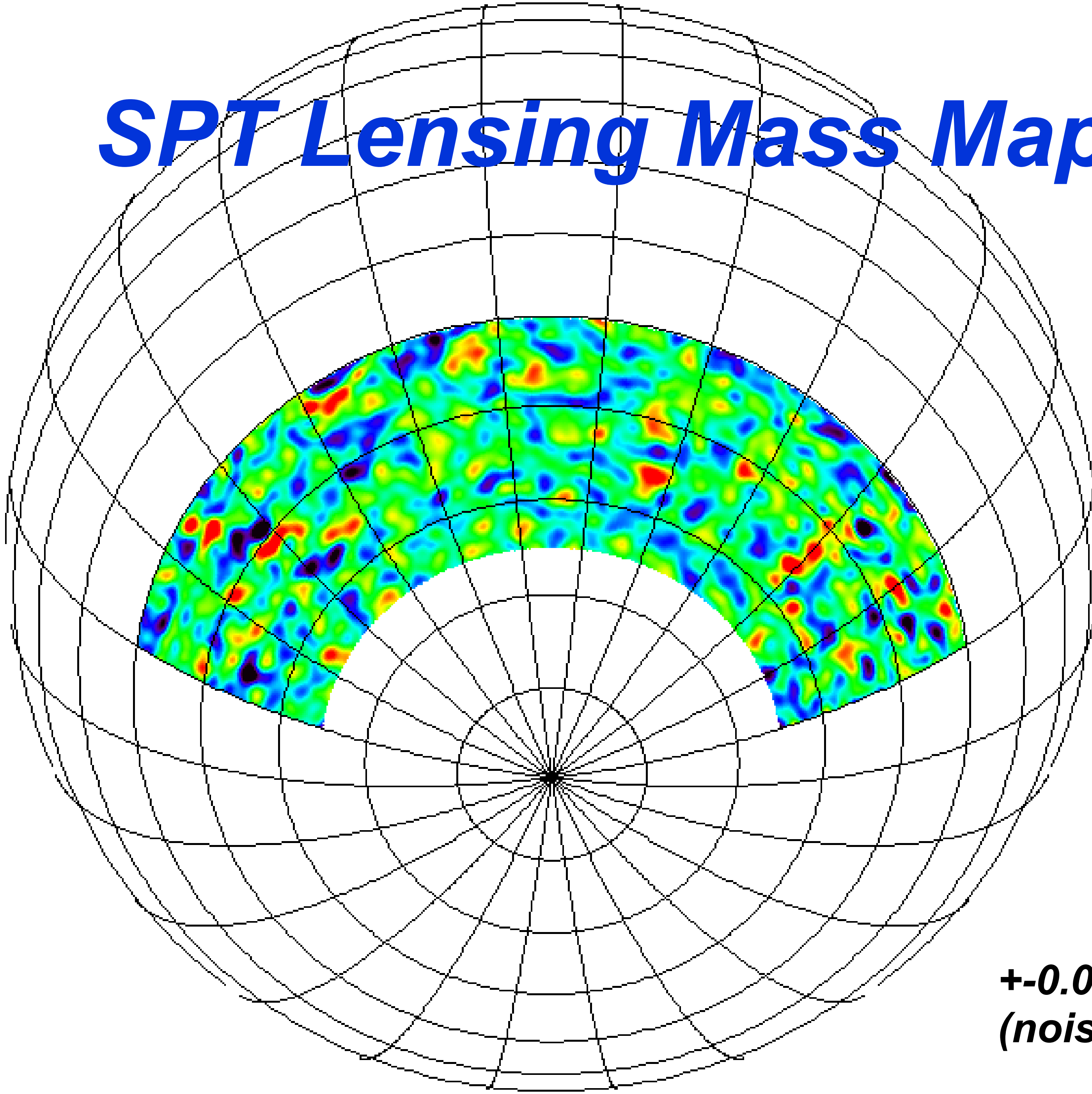
$$\langle T^L(\mathbf{l}_1) T^L(\mathbf{l}_2)\rangle = \mathbf{L} \cdot (\mathbf{l}_1 C^T_{l_1} + \mathbf{l}_2 C^T_{l_2})\phi(\mathbf{L}) + O(\phi^2)$$

$$\mathbf{L} = \mathbf{l}_1 + \mathbf{l}_2$$

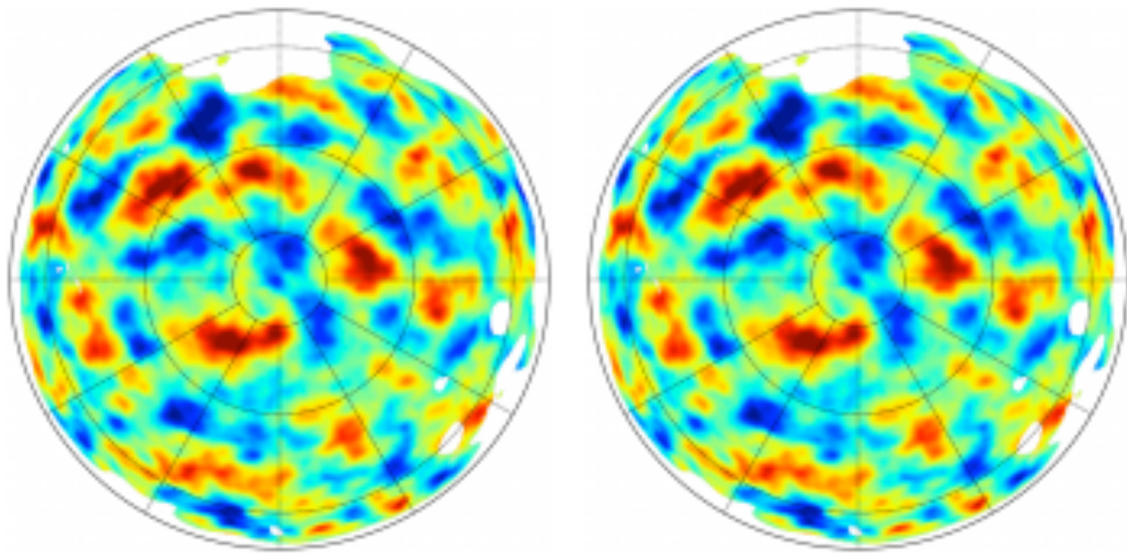


- We extract ϕ by taking a suitable average over CMB multipoles separated by a distance L
- We use the standard Hu quadratic estimator.

SPT Lensing Mass Map

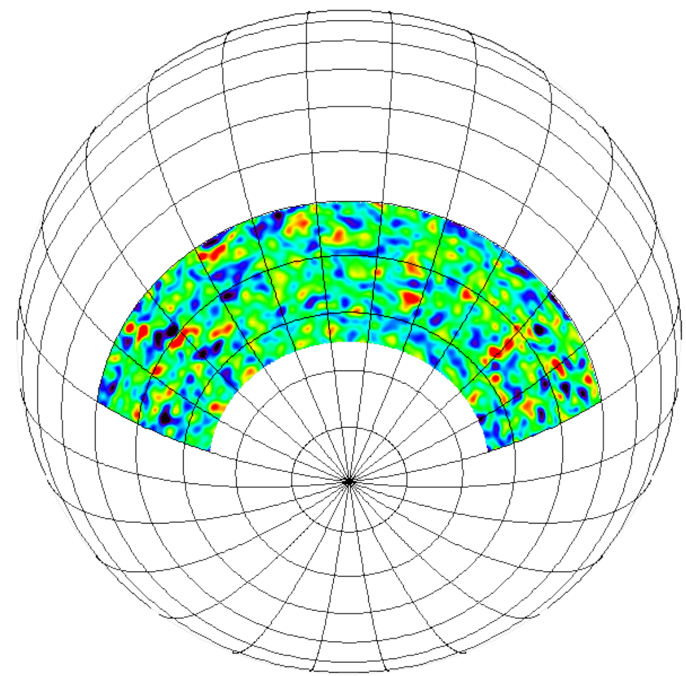


+-0.05 color bar
(noise ~0.01)



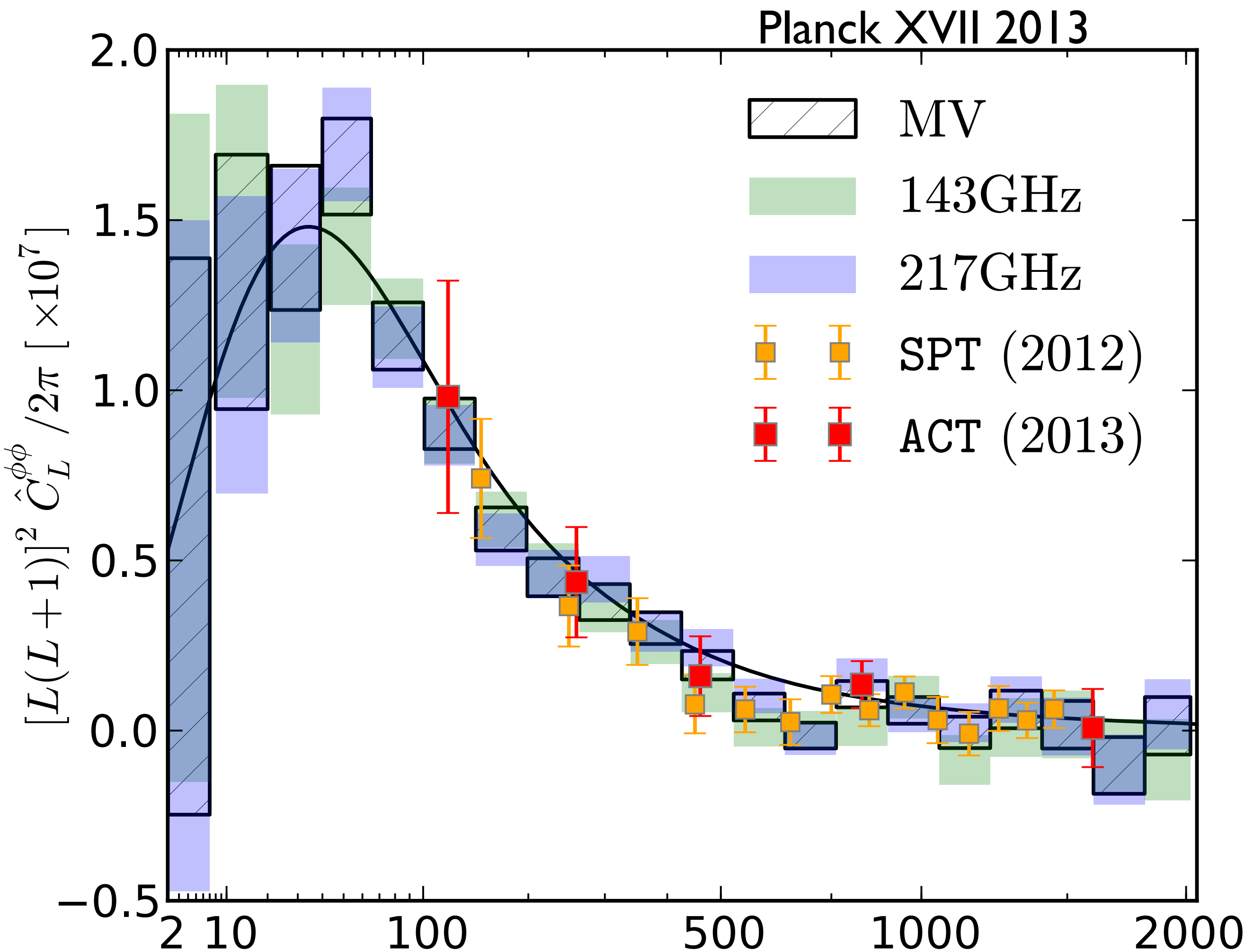
Planck
(all-sky)

SPT
(2500 sq deg)



CMB Lensing Power Spectrum

- well measured with Planck, SPT, ACT

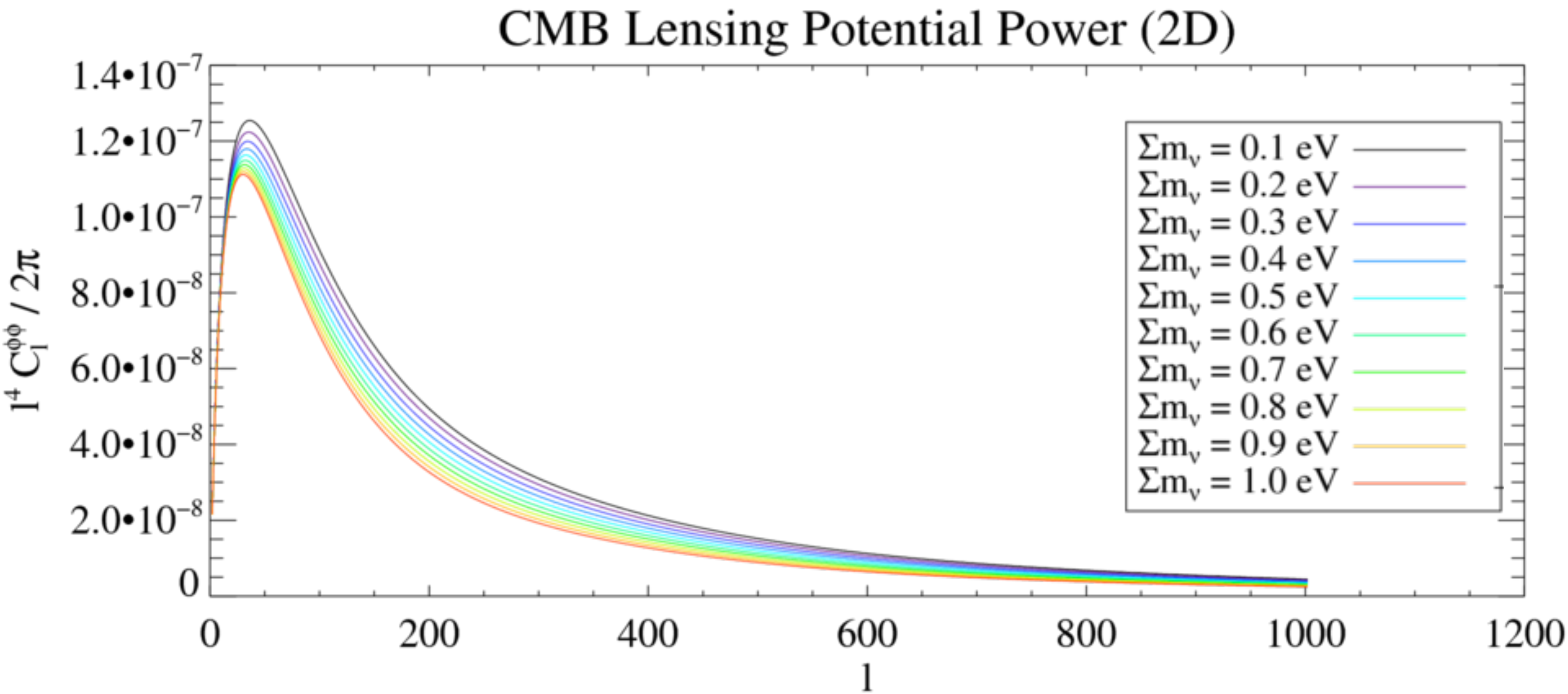


Massive Neutrinos in Cosmology

$$\Omega_\nu \approx \sum_i (m_i / 0.1\ eV) \quad 0.0022\, h_{0.7}^{-2}$$

- Below free-streaming scale, neutrinos act like **radiation**
  - *drag on growth*
- Above free-streaming scale, neutrinos act like **matter**

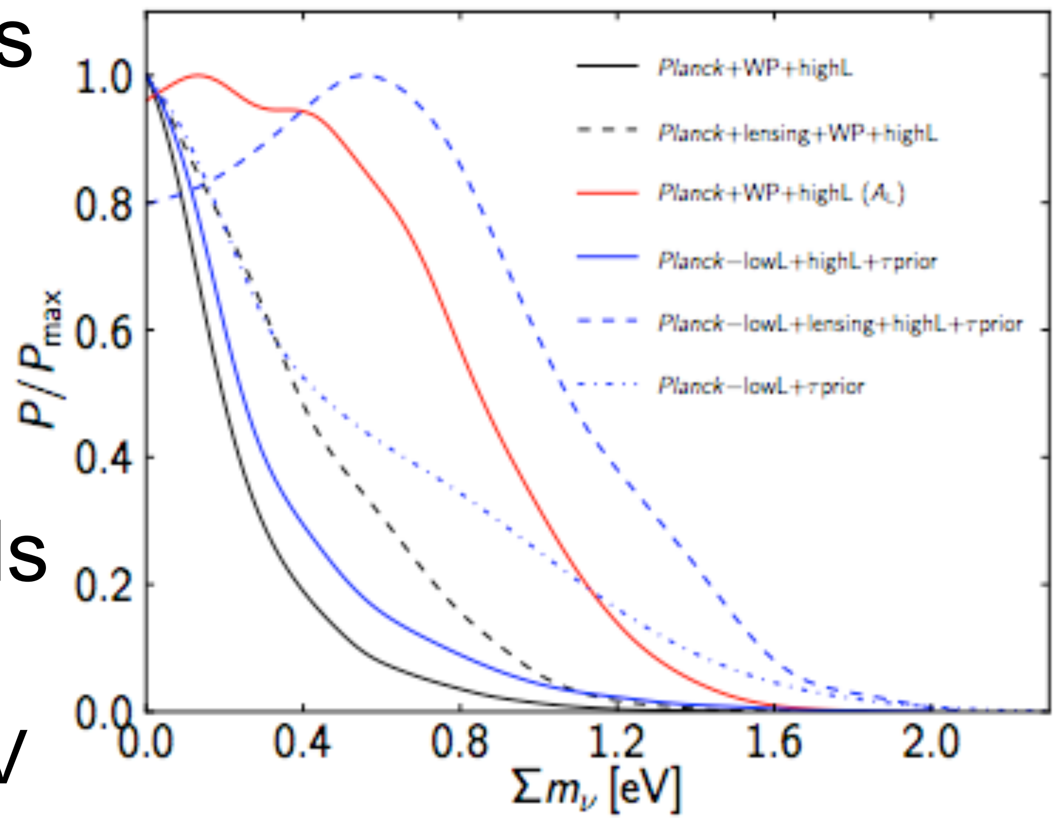
Neutrinos & CMB Lensing



- Peak at l=40 (k_{eq} =[300 Mpc]$^{-1}$ at z = 2): coherent over degree scales
- RMS deflection angle is only ~2.7'

Upper limits on neutrino masses

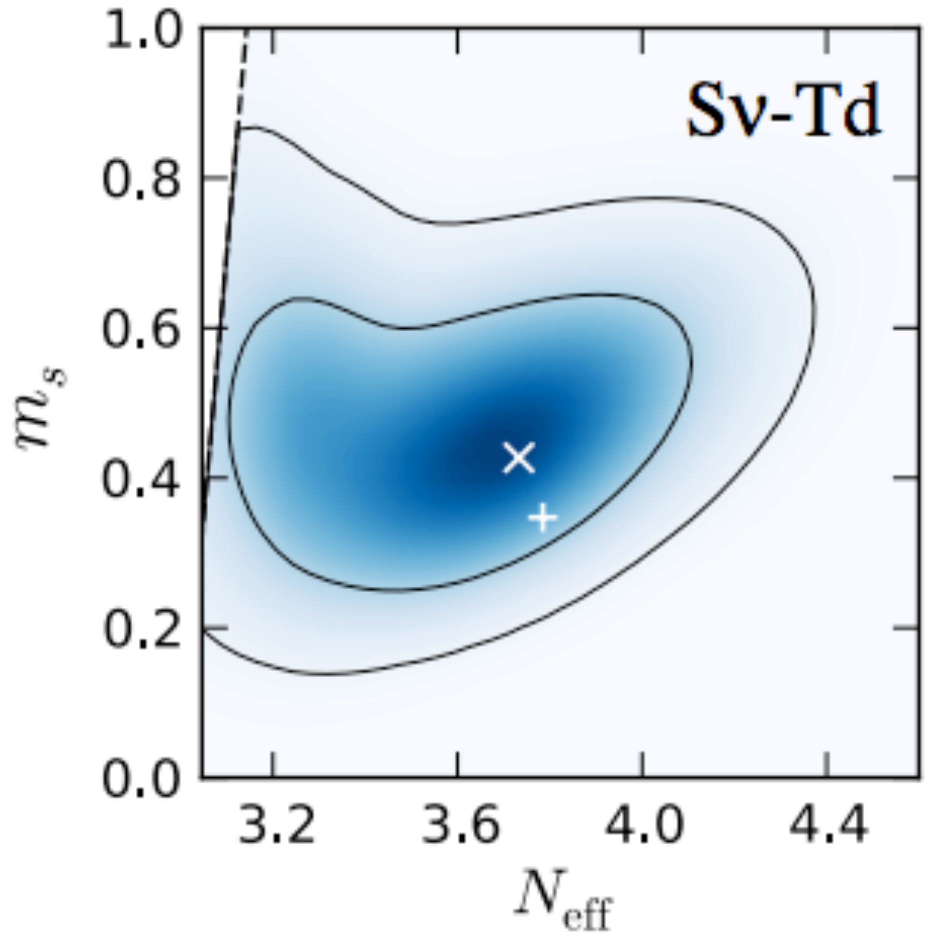
- CMB experiments closing in on interesting neutrino mass range
- CMB lensing adds new information
  - forecast ~0.05 eV sensitivity in ~4 yrs



Planck collaboration 2013

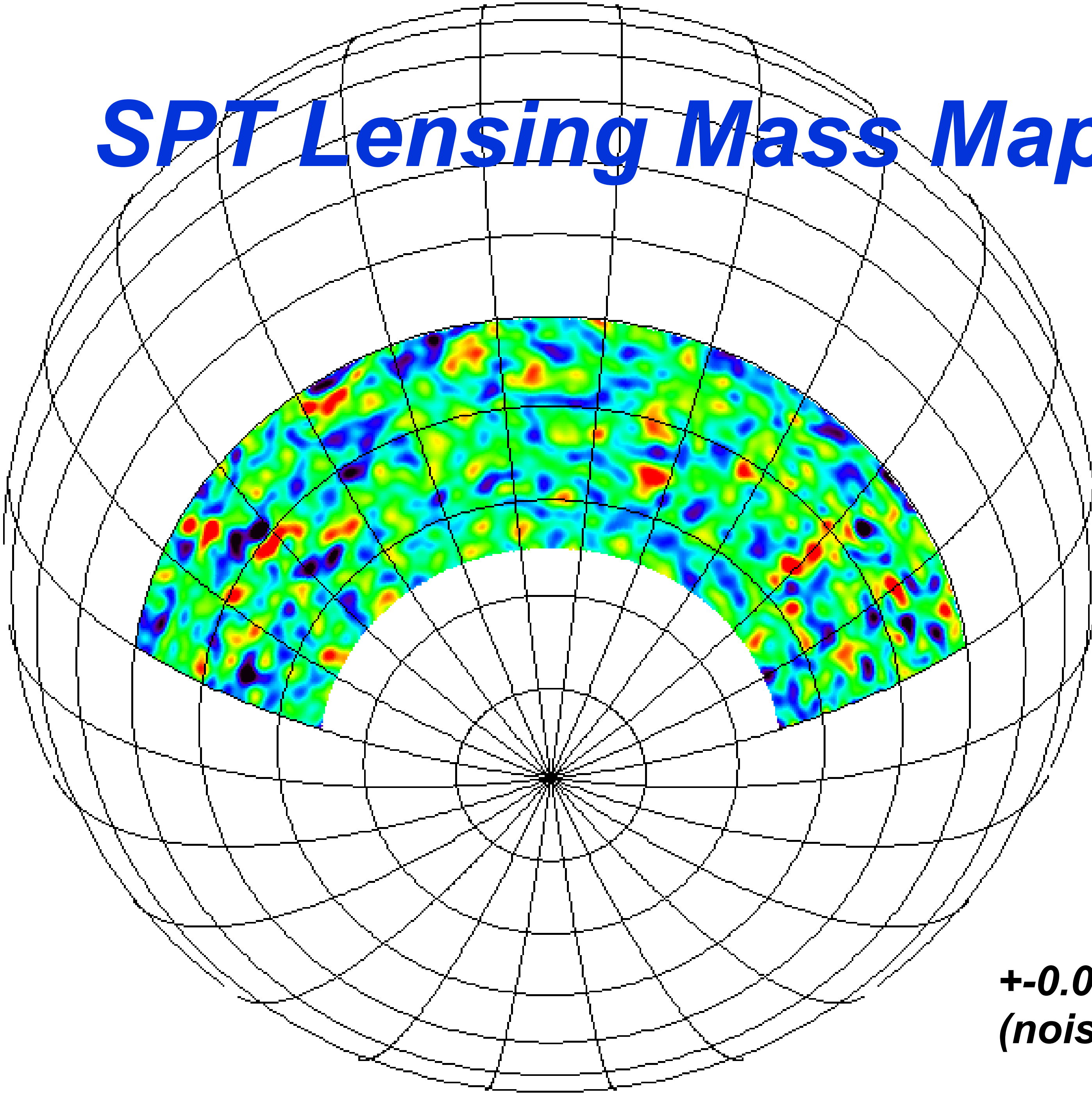
Not everything makes total sense

- combining all cosmological information leads to a preference for a high neutrino mass and some form of new light particle in the universe



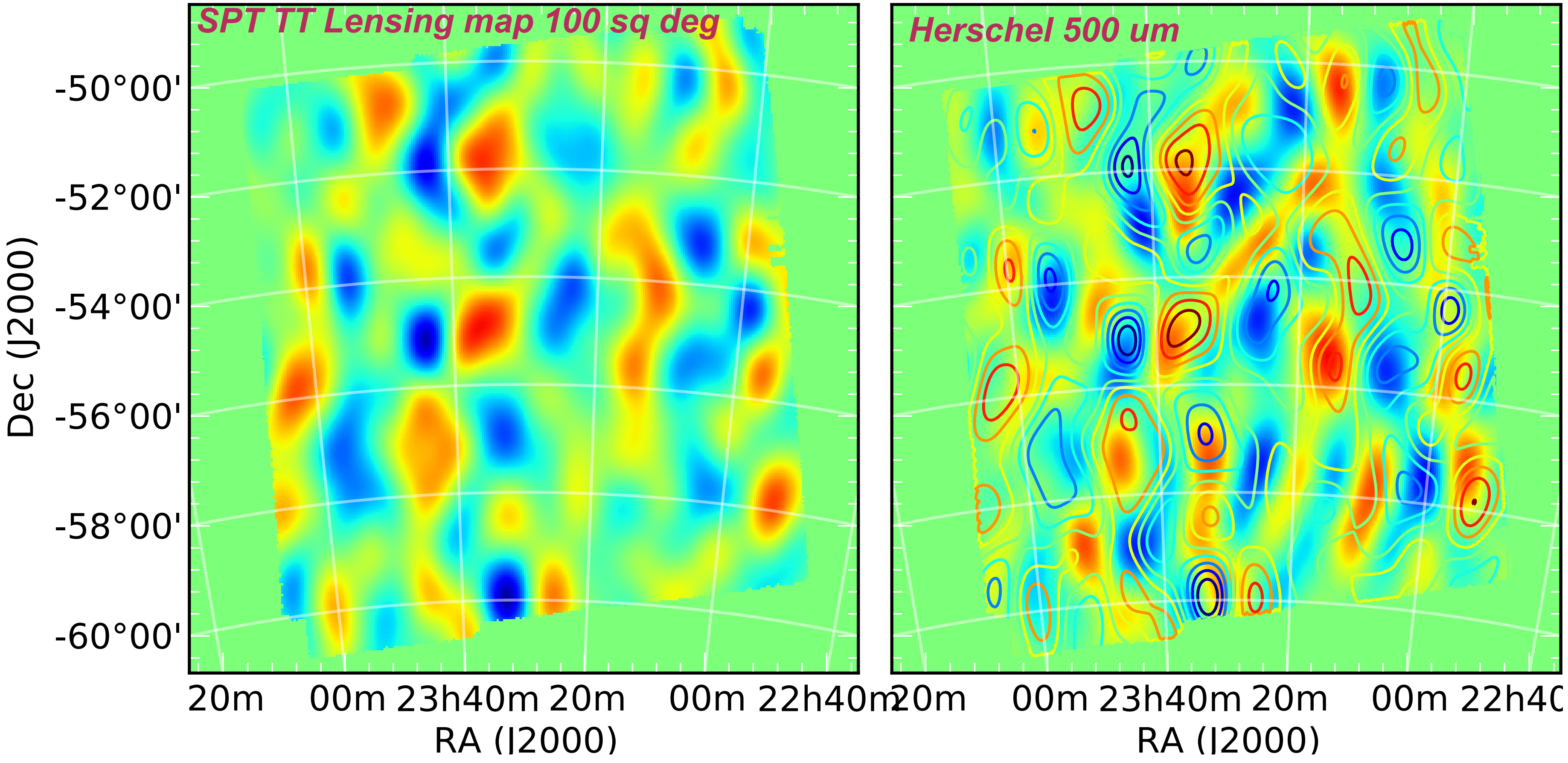
Wyman et al 2013

SPT Lensing Mass Map

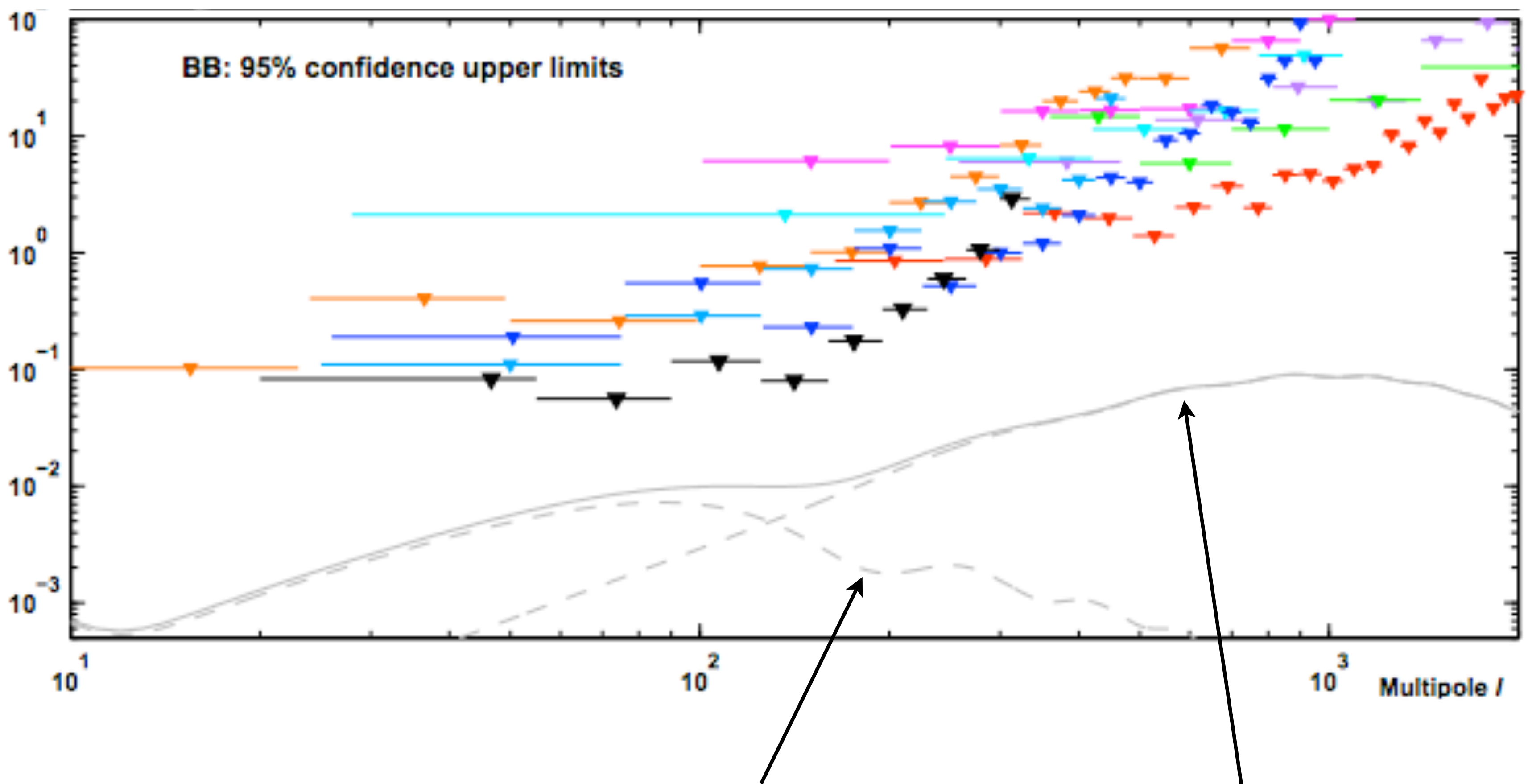


+-0.05 color bar
(noise ~0.01)

Cosmic Infrared Background Traces Mass



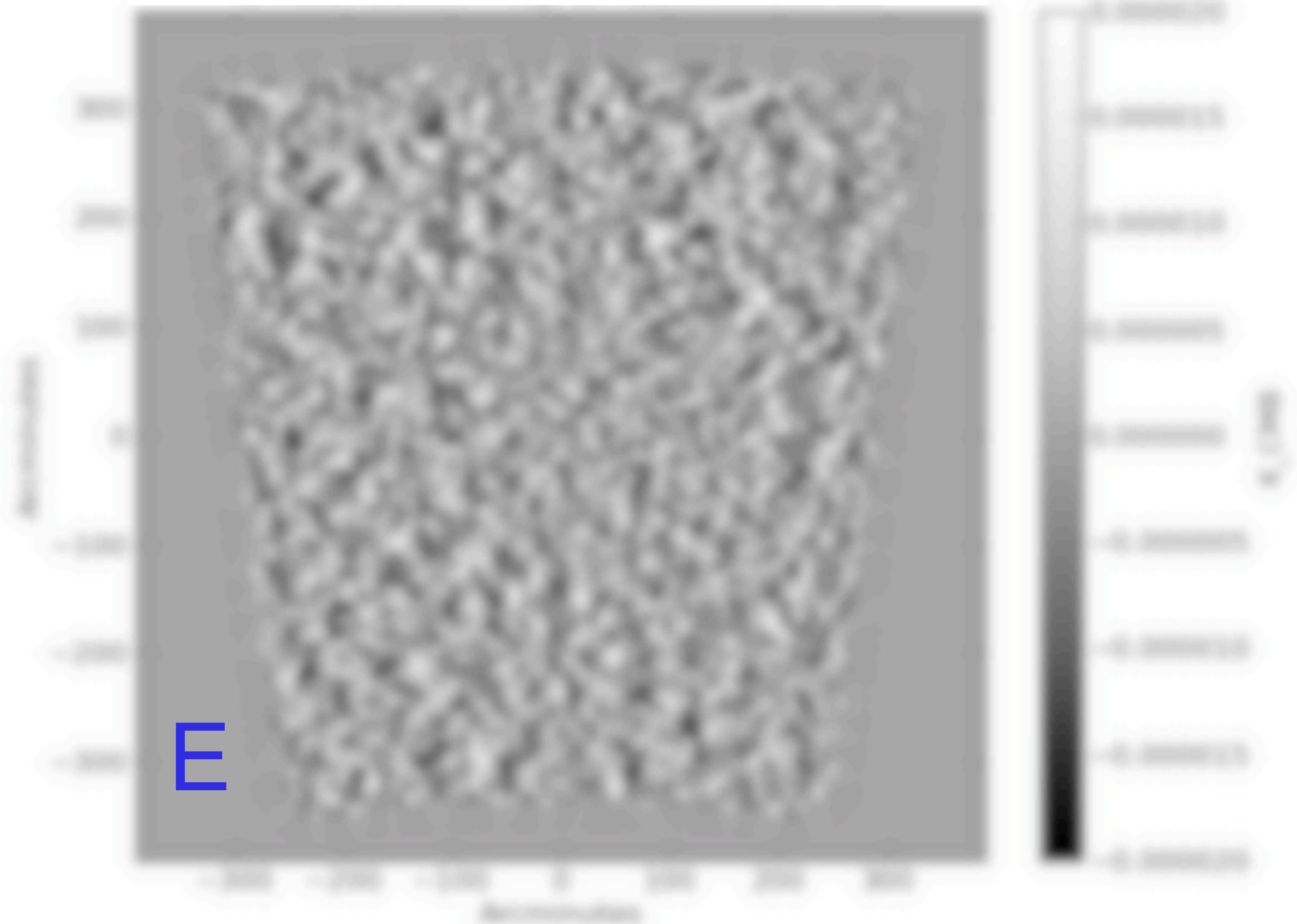
Two Expected Sources of B Modes



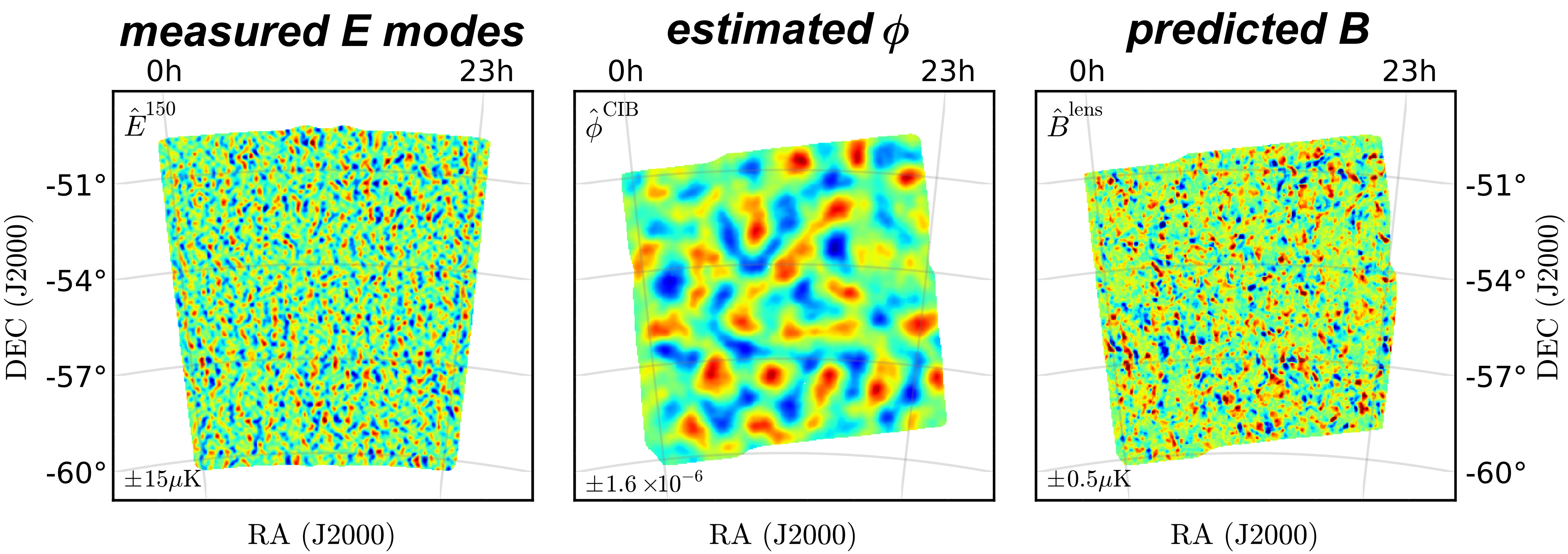
Gravitational Radiation in Early Universe
(amplitude unknown!)

Gravitational lensing of
E modes (amplitude
well-predicted, but no
measured B modes
until later in talk)

E-mode polarization of ra23h30, dec -55 field (150 GHz)

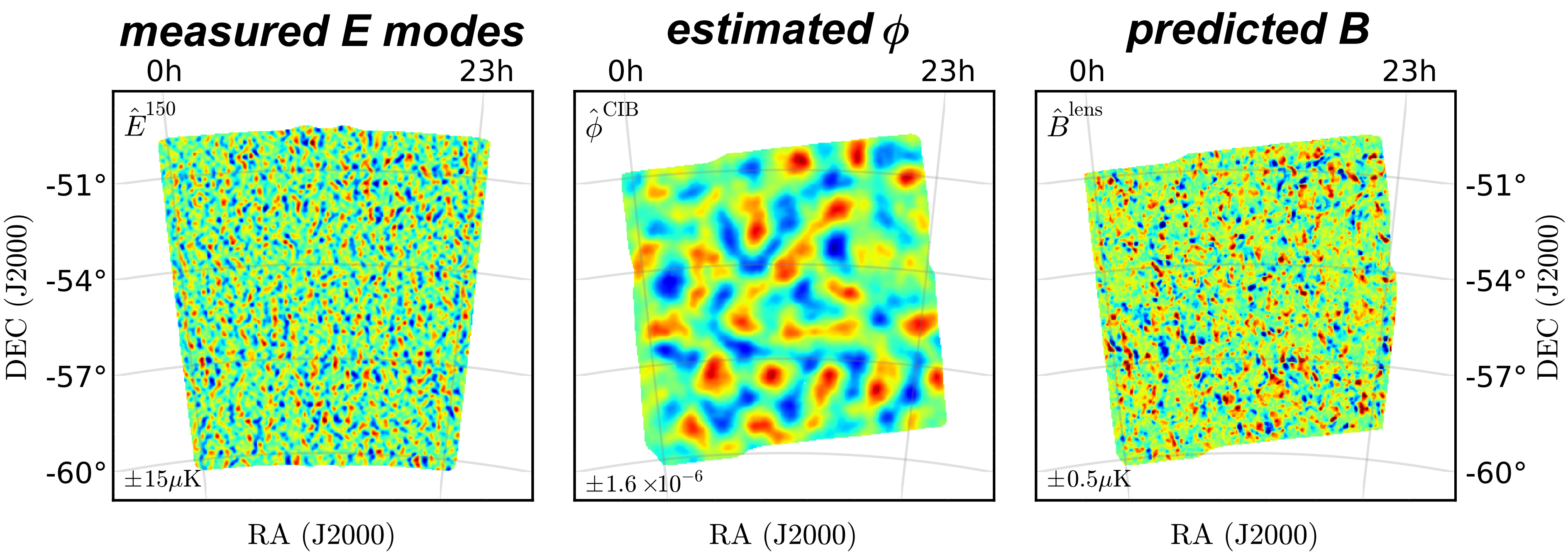


Predicting B-Modes



Hanson, Hoover, Crites et al 2013

Many Ways of Predicting B-Modes



E 150 GHz
E 90 GHz
E from Temperature

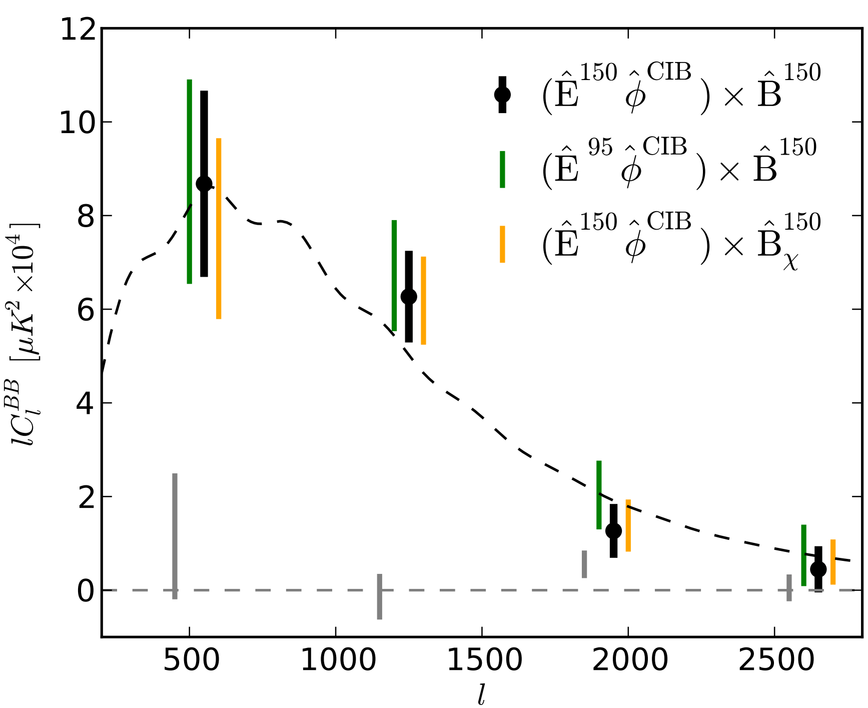
ϕ CIB
ϕ TT
ϕ EE
ϕ TE
(ϕ Spitzer cat)

X B 150 GHz
X B 90 GHz

Hanson, Hoover, Crites et al 2013

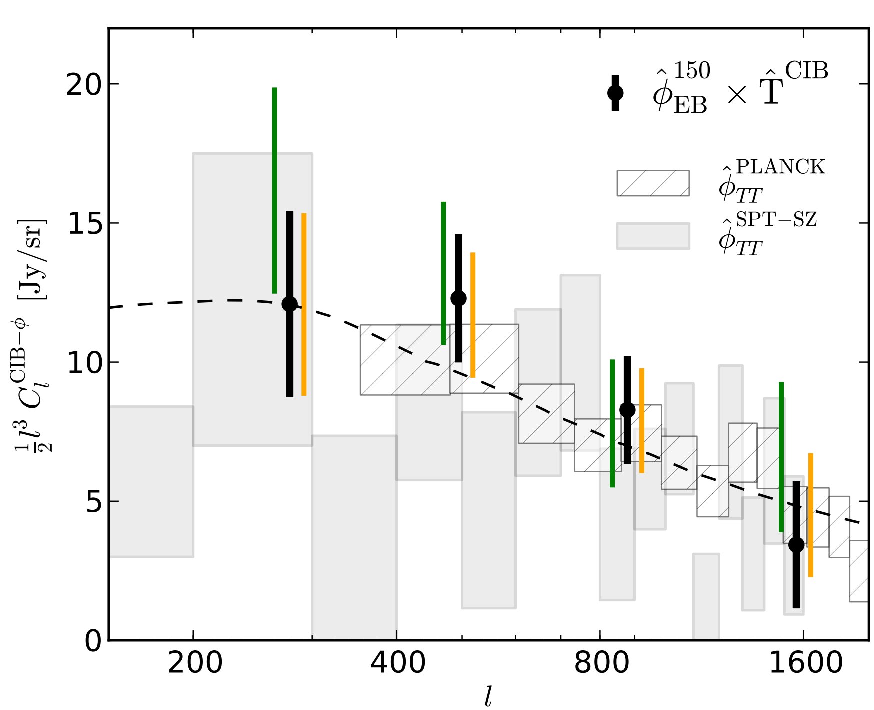
First Detection of B-Modes

(predicted B) X (measured B)



not zero at 7.7σ

ϕ^{EB} X T^{cib}



Hanson, Hoover, Crites et al 2013

Summary & Outlook

- high resolution CMB maps give new information about the universe
- gravitational lensing of the CMB a powerful new probe
  - lensing of temperature fluctuations now a mature field
  - lensing of polarization fluctuations just measured for first time
- B-mode polarization anisotropy has now been detected
  - next up: B modes from early universe!