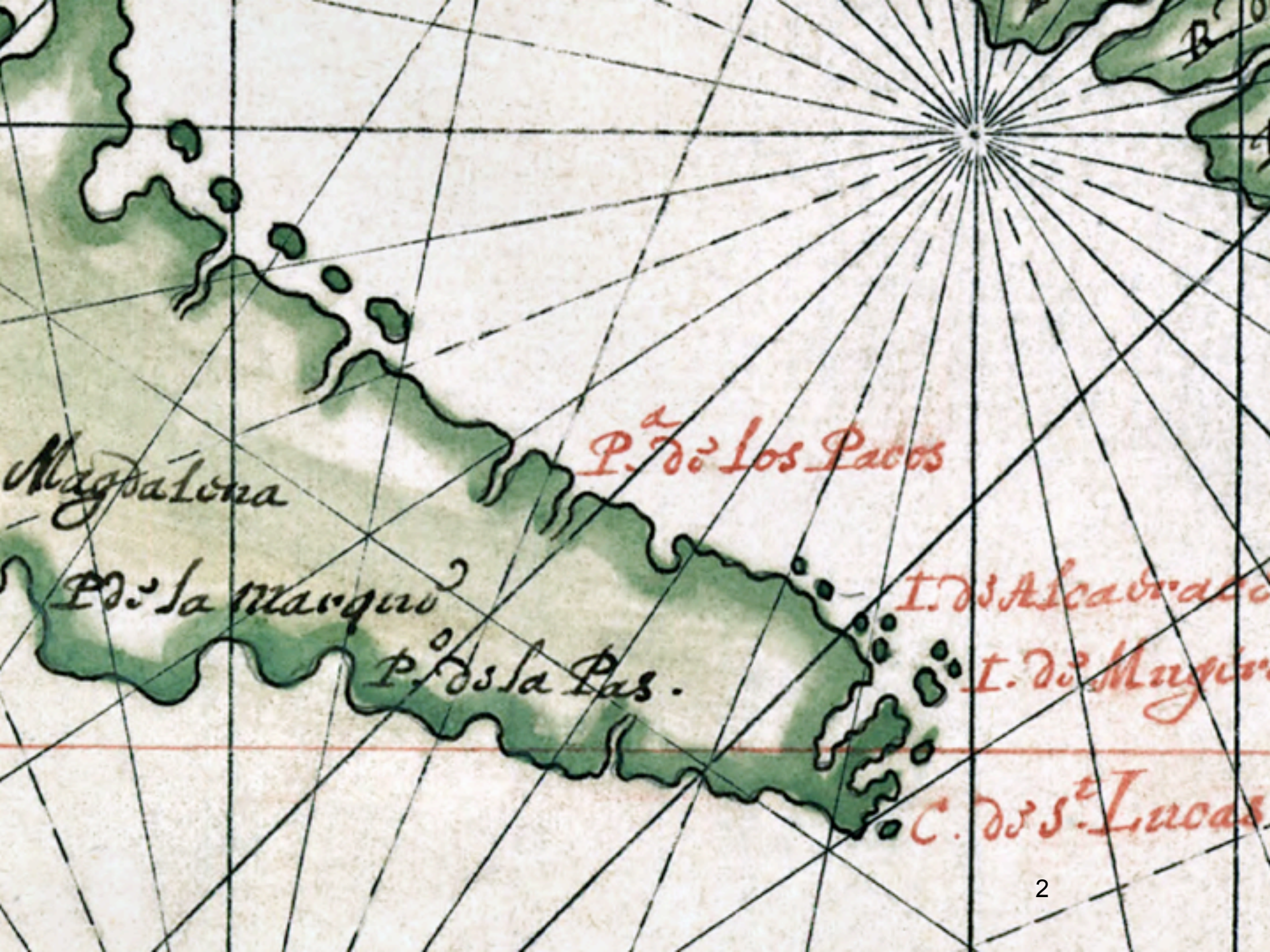
Cosmic Microwave Background Polarization

Gil Holder

McGill

CIFAR
CANADIAN INSTITUTE for ADVANCED RESEARCH


Magdalena
P.a de los Pacos
P. de la Marqué
P.o de la Pas.
I. de Alcaraco
I. de Mugér
C. de S.t Lucas

CALIFORNIA

Outline

- 1: Overview of Primary CMB Anisotropies and Polarization
  - the cmb and angular power spectra
  - review of EM polarization
  - E/B modes
- 2: Primary, Secondary Anisotropies and Foregrounds
- 3: CMB Polarization Measurements

Outline

- 1: Overview of Primary CMB Anisotropies and Polarization
- 2: Primary, Secondary Anisotropies and Foregrounds
    - gravitational lensing
    - reionization
    - our Galaxy
    - other galaxies
    - clusters of galaxies
- 3: CMB Polarization Measurements

Outline

- 1: Overview of Primary CMB Anisotropies and Polarization
- 2: CMB Polarization, Secondary Anisotropies and Foregrounds
- 3: CMB Polarization Measurements
  - how to detect photons
  - mapmaking, filtering, etc.
  - experimental landscape past, present and future
  - prospects for neutrino masses and gravitational waves

Outline

- 1: Overview of Primary CMB Anisotropies and Polarization
  - the cmb
  - review of EM polarization
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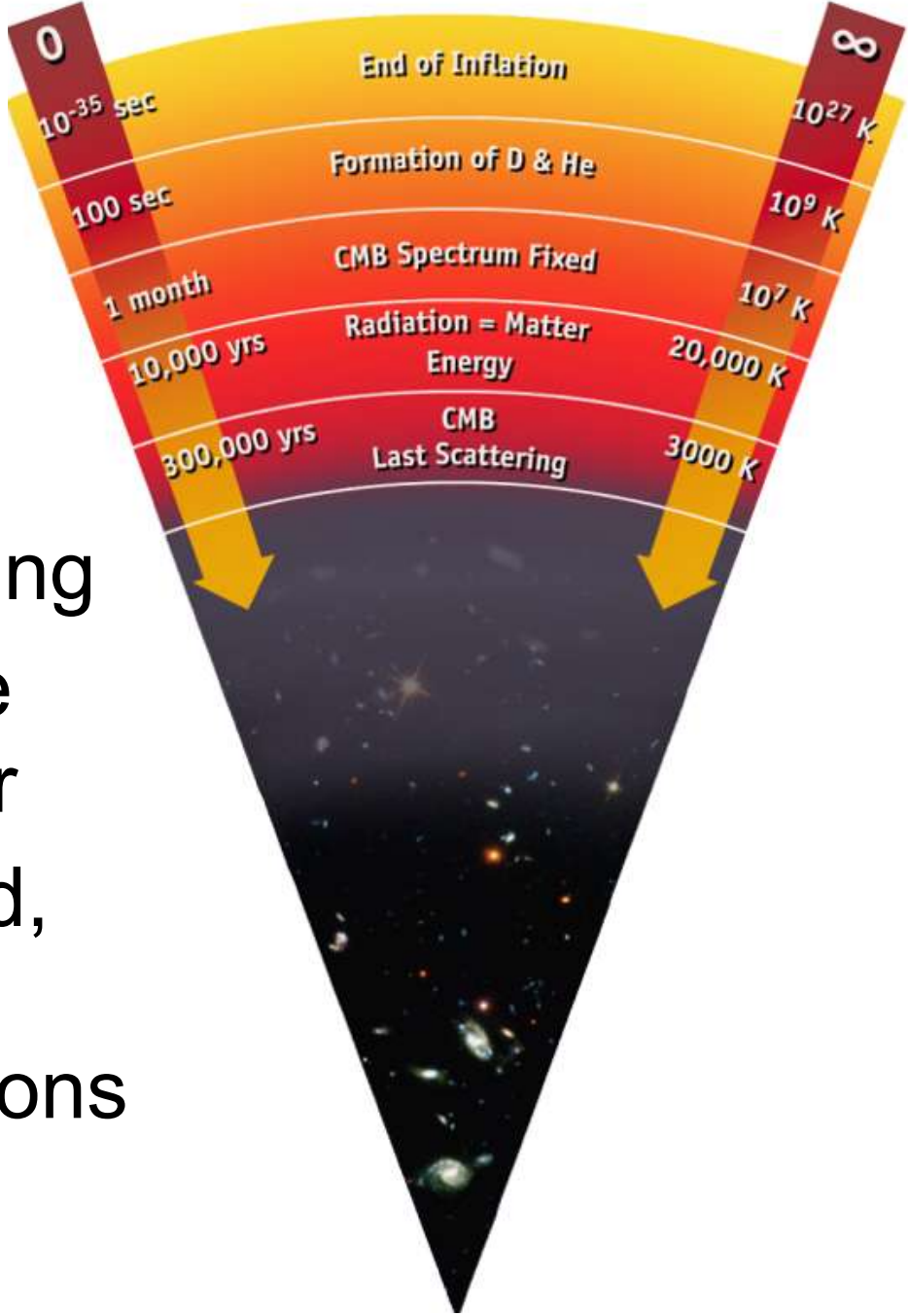
- 2: Secondary Anisotropies and Foregrounds
- 3: CMB Polarization Measurements

Excellent Reviews

- Wayne Hu tutorials:
  - http://background.uchicago.edu/index.html
- Kosowsky:
  - http://ned.ipac.caltech.edu/level5/Kosowsky/Kosowsky_contents.html
  - http://arxiv.org/abs/astro-ph/9904102
- Zaldarriaga
  - http://arxiv.org/abs/astro-ph/0305272
- Weiss report:
  - http://arxiv.org/abs/astro-ph/0604101
- CMBPol white papers:
  - http://arxiv.org/abs/0811.3919
  - http://arxiv.org/abs/0811.3916

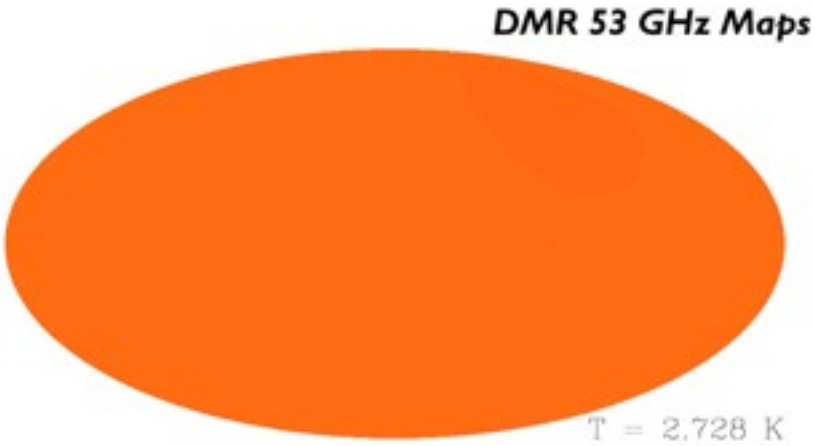
Hot Big Bang

- Expanding => cooling
- At earlier times, the universe was hotter
- when atoms formed, universe became transparent to photons
  - ***special <u>timescale</u> 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)

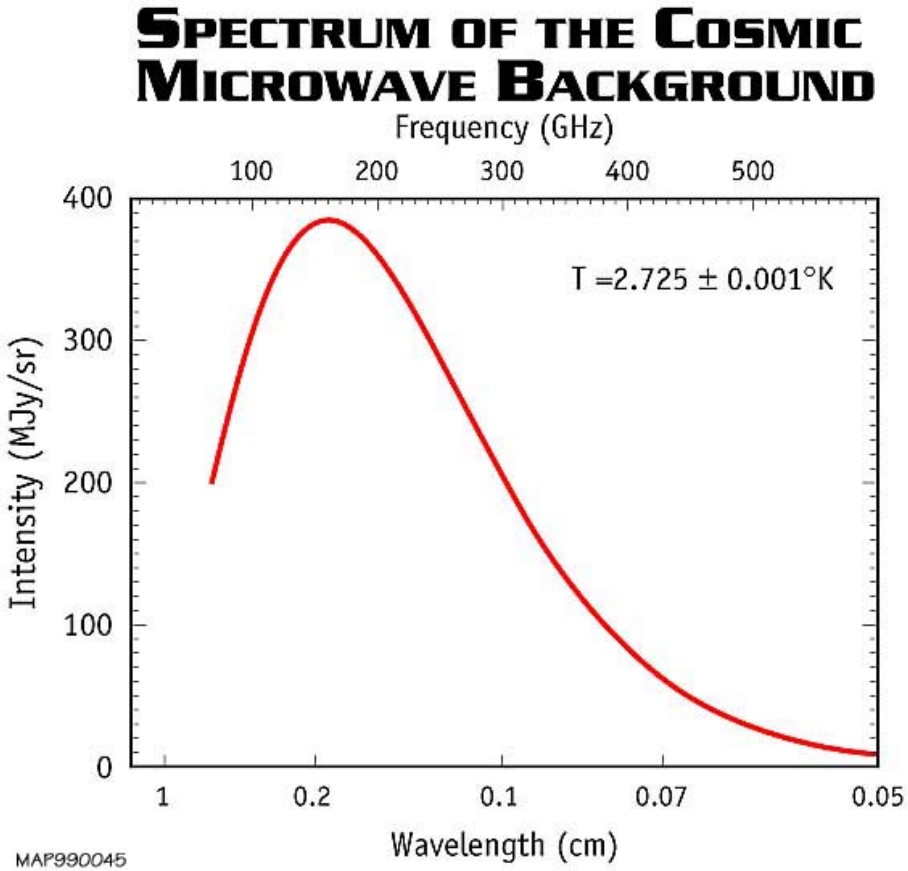
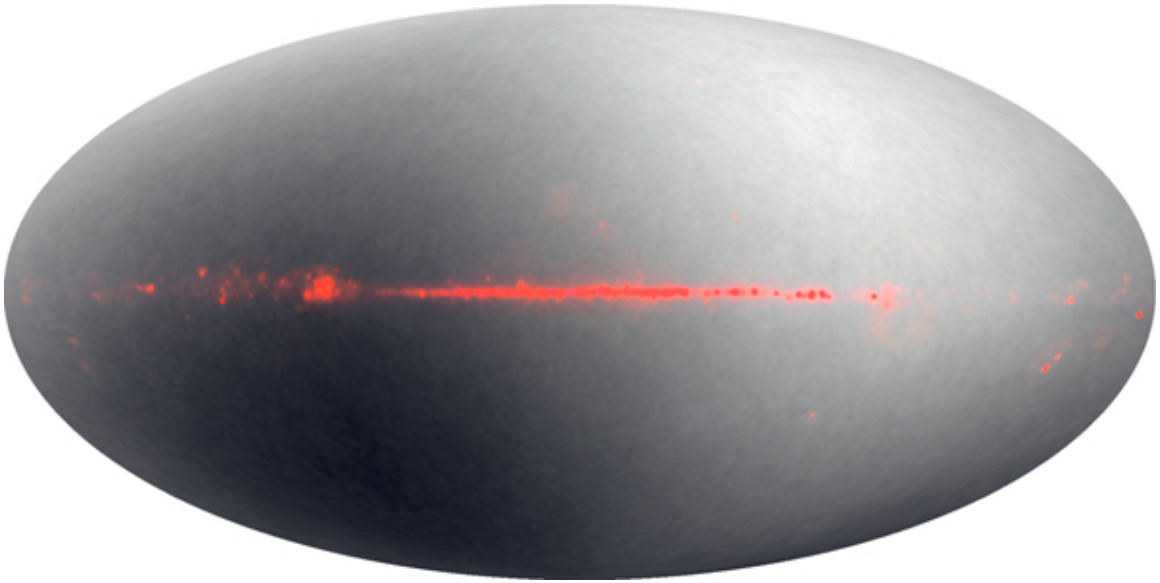


Image from COBE science team: http://lambda.gsfc.nasa.gov/product/cobe/

Isotropy

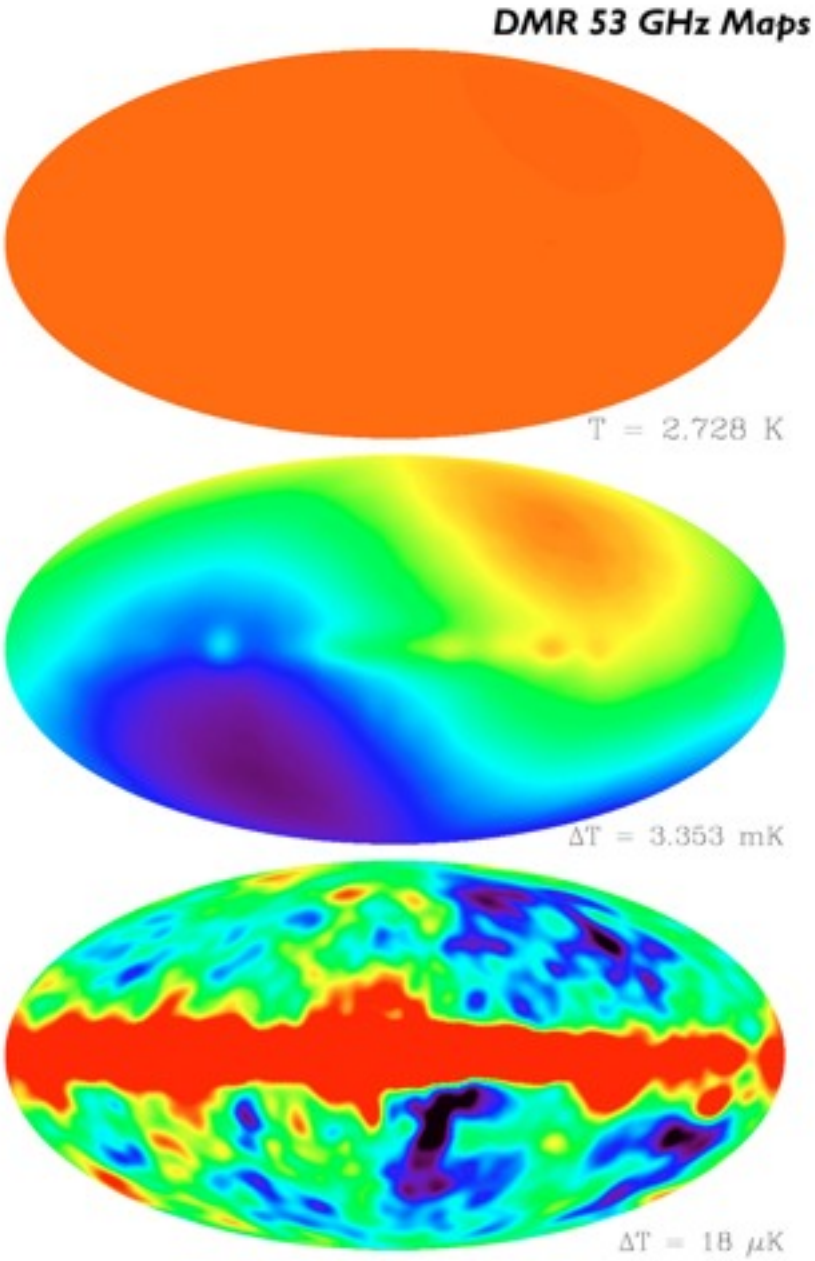
- Cosmic microwave background is remarkably isotropic
- Unnaturally isotropic!

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

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

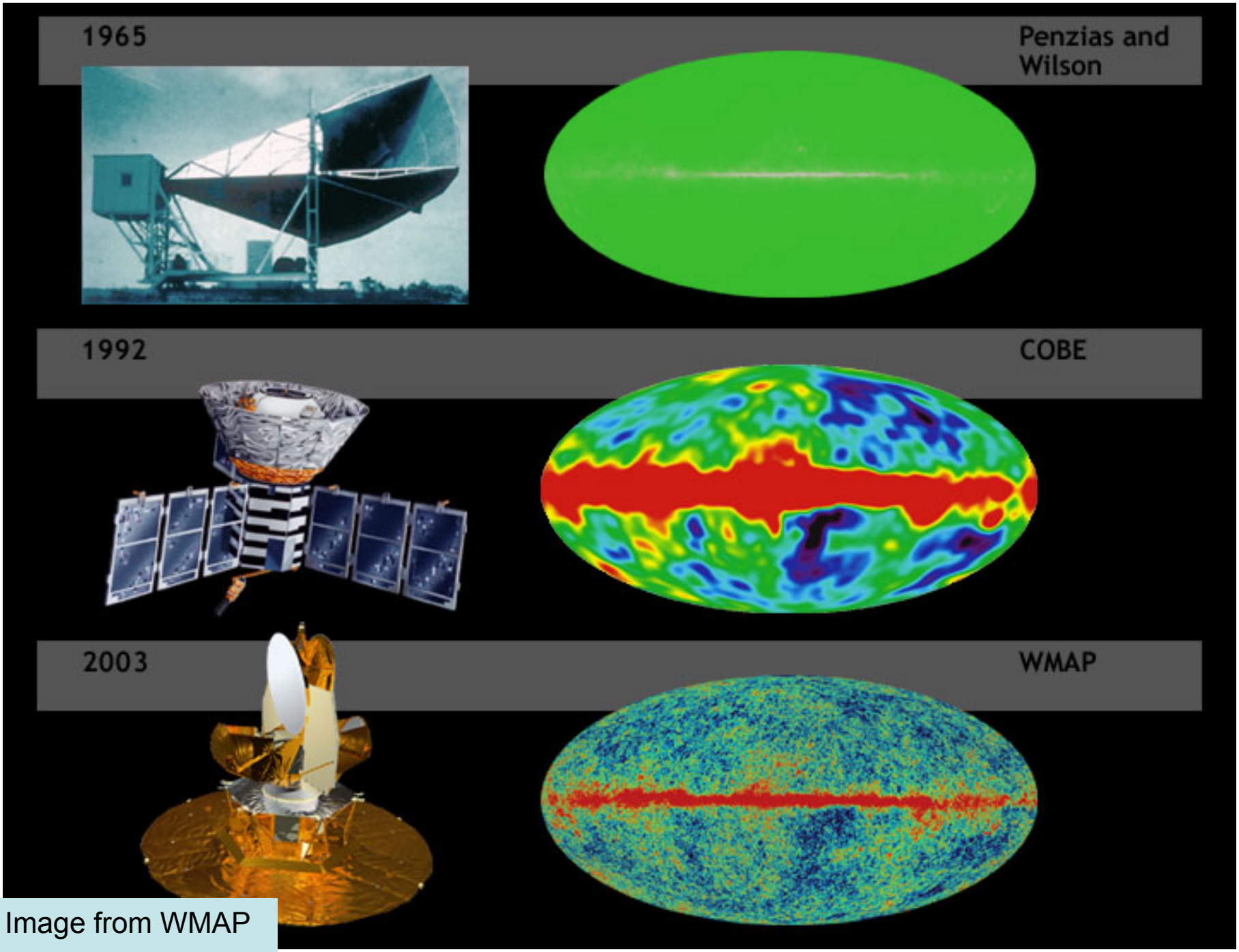
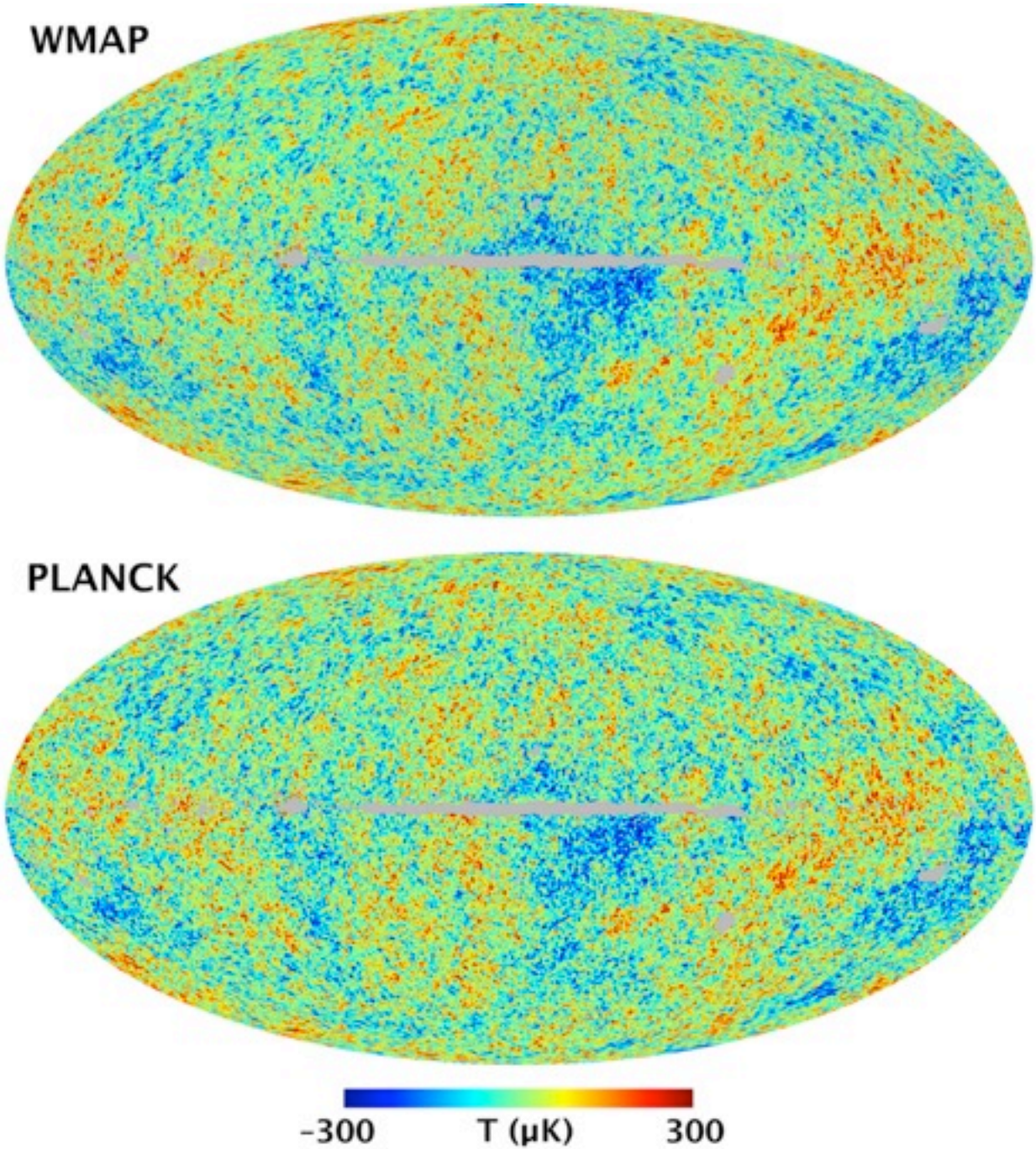
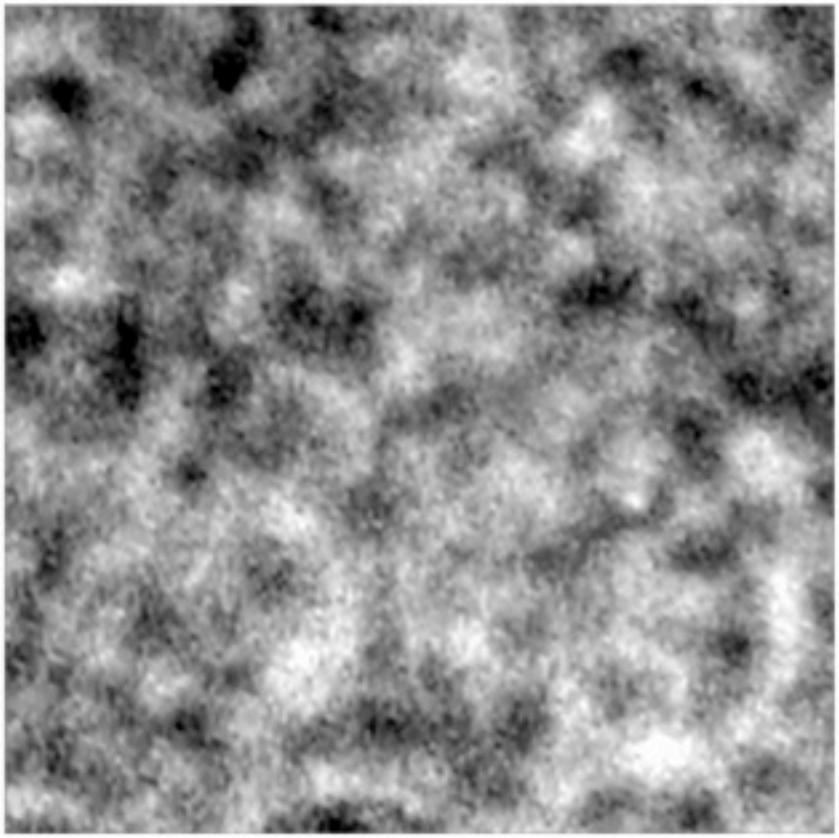


Image from WMAP

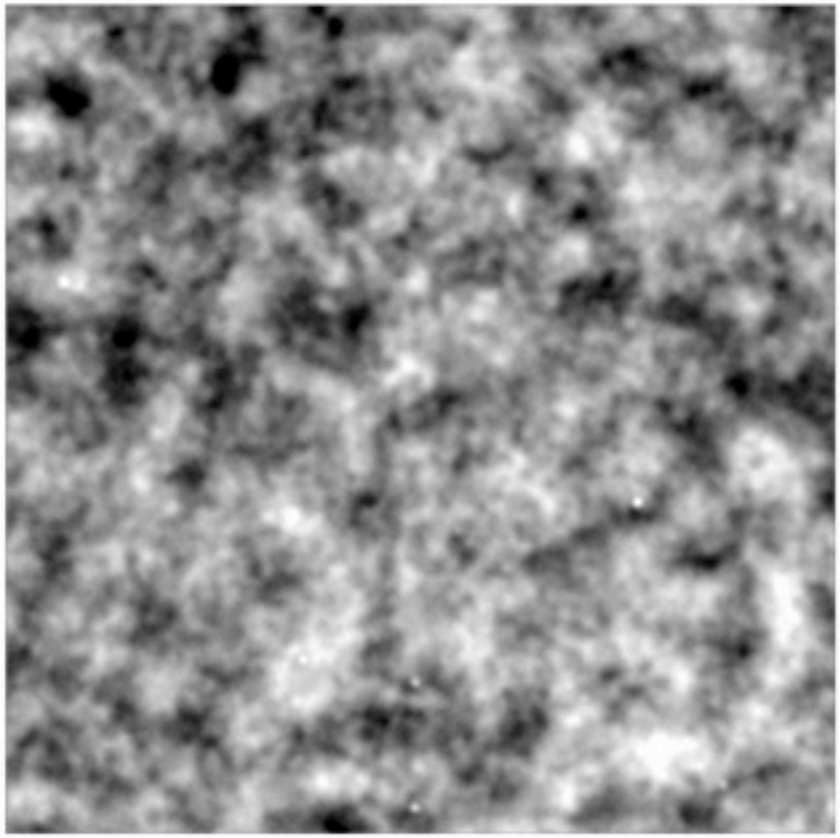

WMAP
PLANCK
-300
T (μK)
300

Planck has higher resolution than WMAP

WMAP 60 GHz



Planck 143 GHz

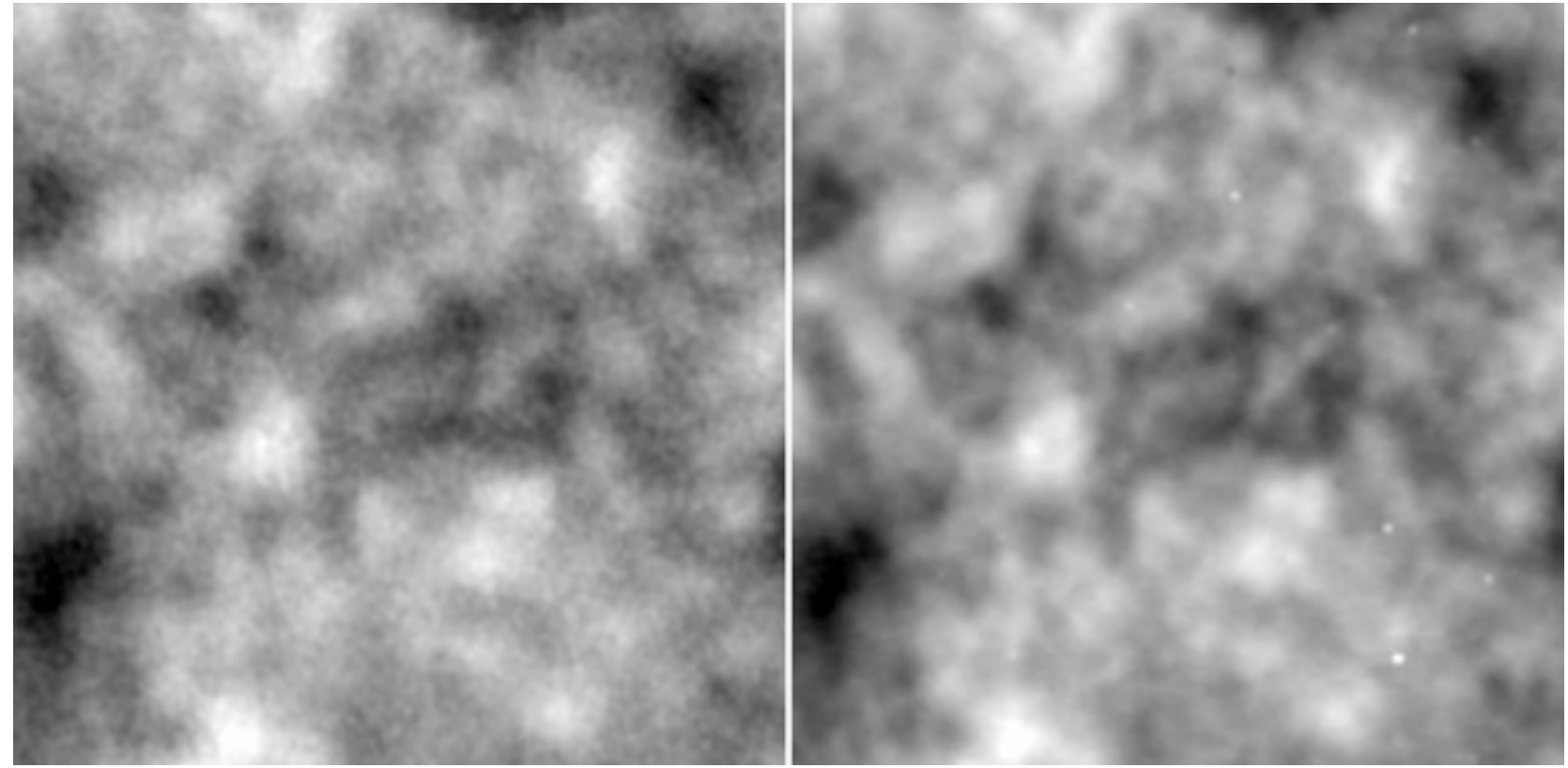


16°

SPT has higher resolution than Planck

Planck 143 GHz

Planck+SPT

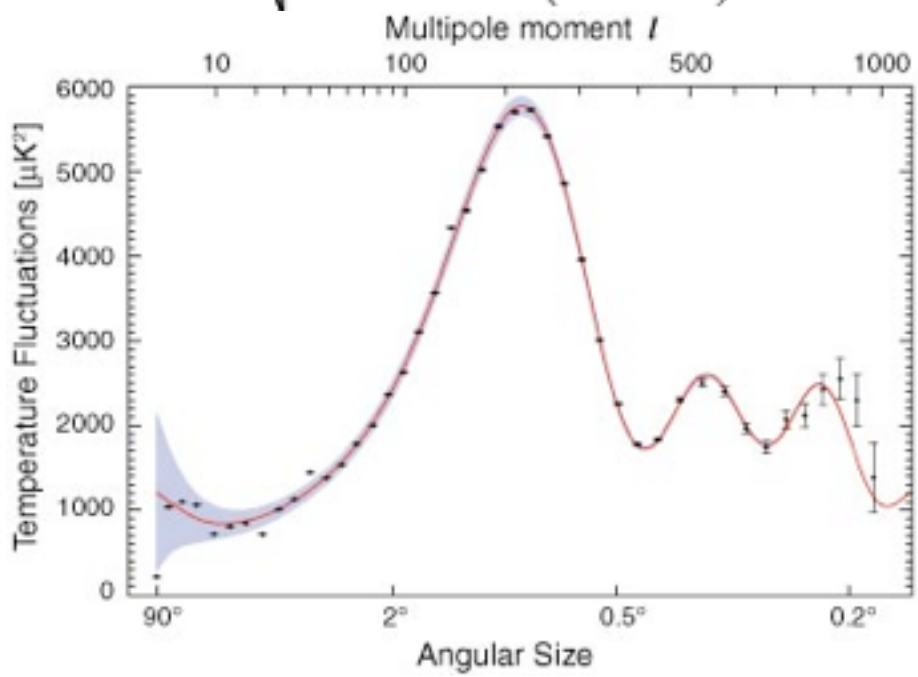


4°

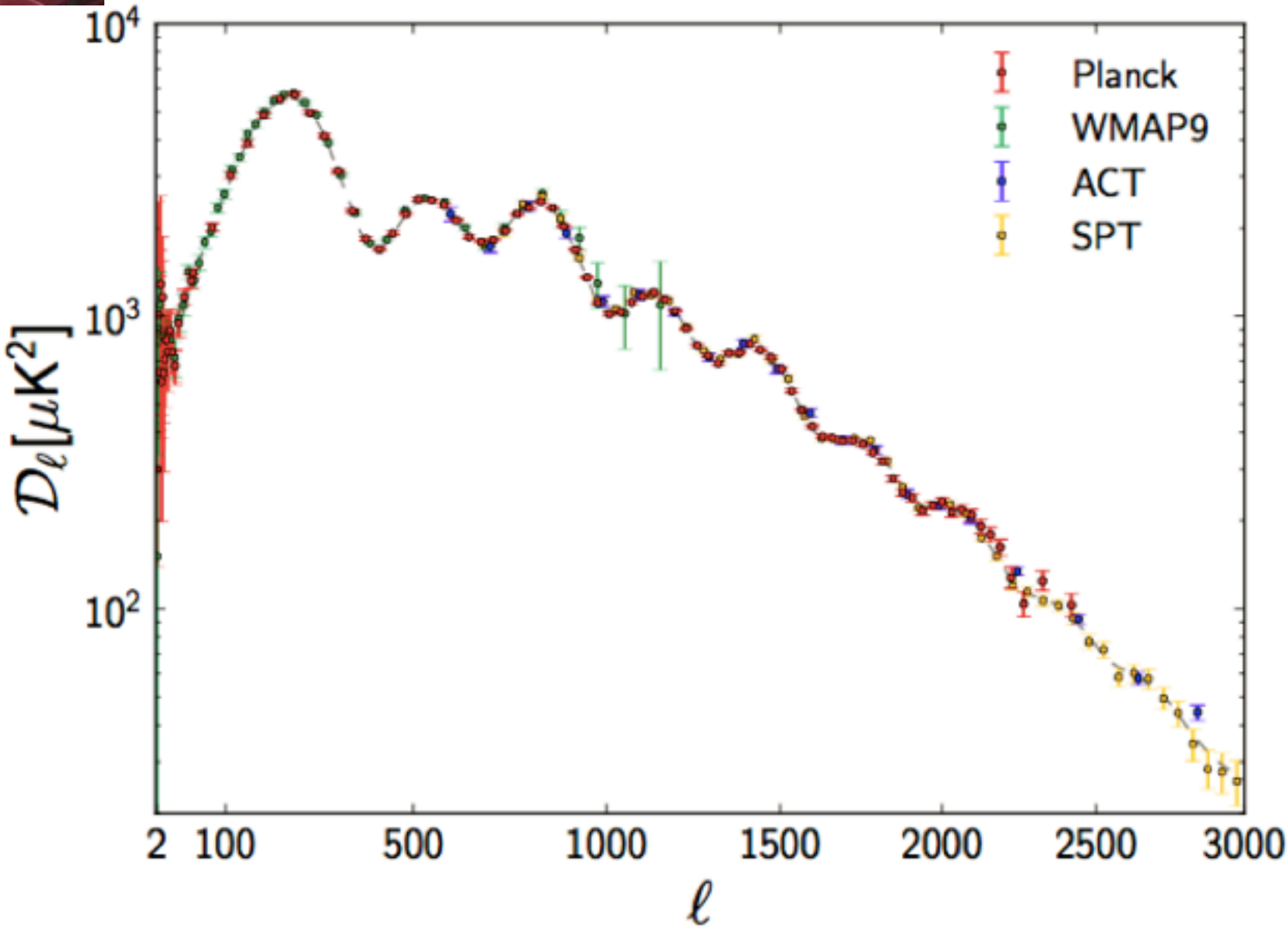
Spherical Harmonics

$$T(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi).$$

$$Y_\ell^m(\theta, \varphi) = \sqrt{\frac{(2\ell+1)}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}}\, P_\ell^m(\cos\theta)\, e^{im\varphi}$$



CMB Angular Power Spectrum



Fourier Transforms

$$s(t) = \int_{-\infty}^{\infty} S(f)\, e^{i2\pi ft}\, df$$

Does one have to choose between Fourier coefficients and spherical harmonics?
(no)

From a_{lm} to $a_{k_x k_y}$

Equation satisfied by $P_{lm}(x)$:

$$(1-x^2)\,y'' - 2xy' + \left(\ell[\ell+1] - \frac{m^2}{1-x^2}\right) y = 0,$$

For x~0:

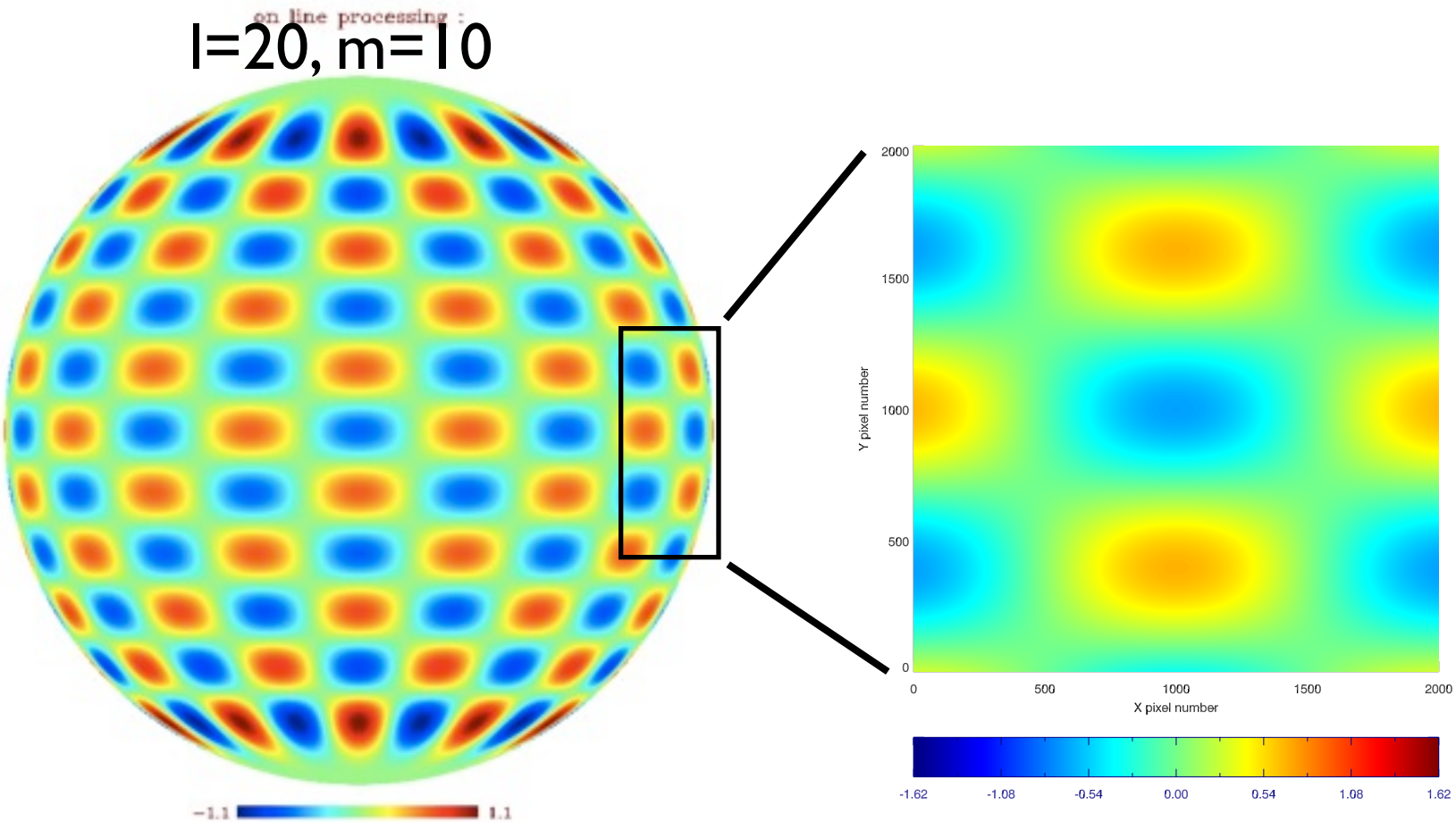
$$(1-\cancel{x^2})\,y'' - 2\cancel{x}y' + \left(\ell[\ell+1] - \frac{m^2}{1-\cancel{x^2}}\right) y = 0,$$

Harmonic Oscillator with ***k=l(l+1)-m²***

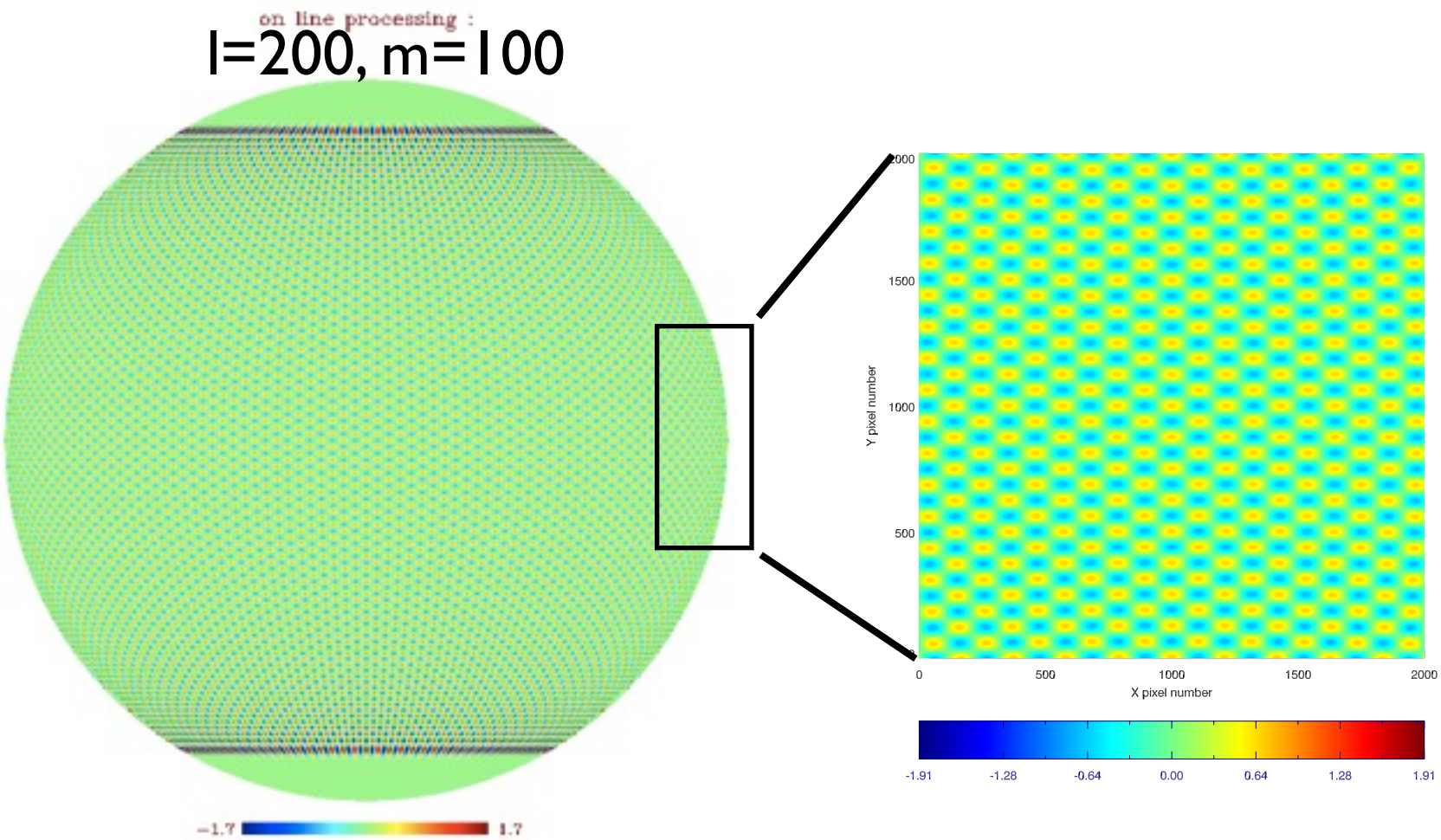
(Fourier modes!)

Projecting a_{lm}

l=20, m=10

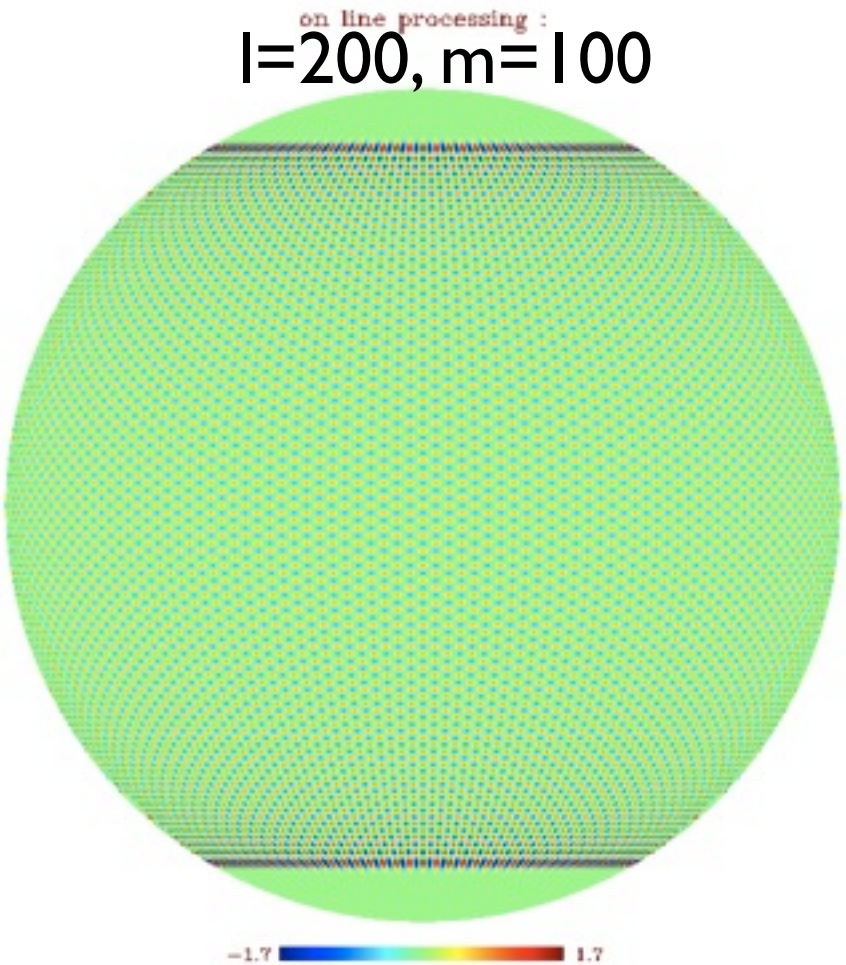


Projecting a_{lm}

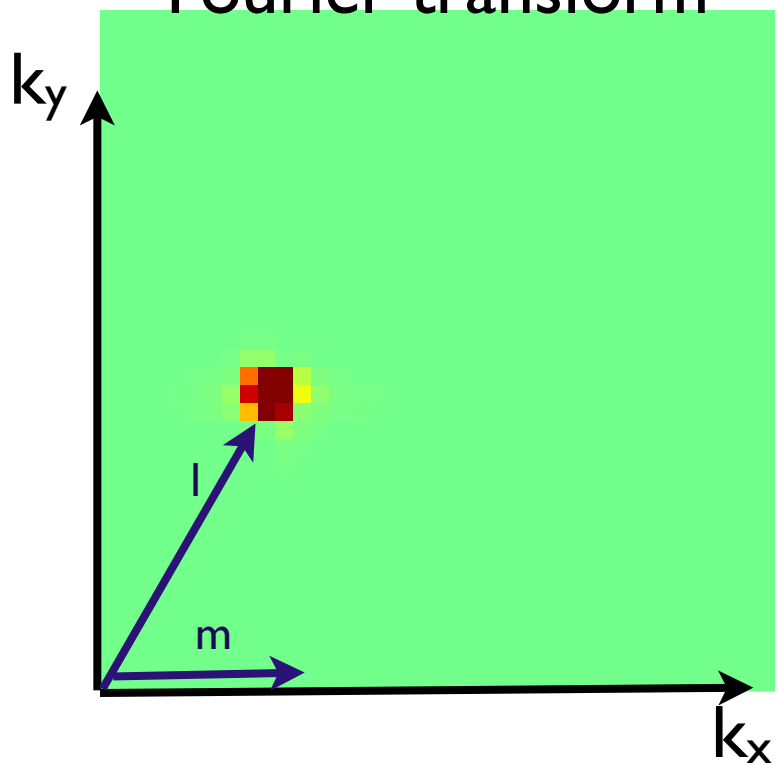


Projecting a_{lm}

l=200, m=100

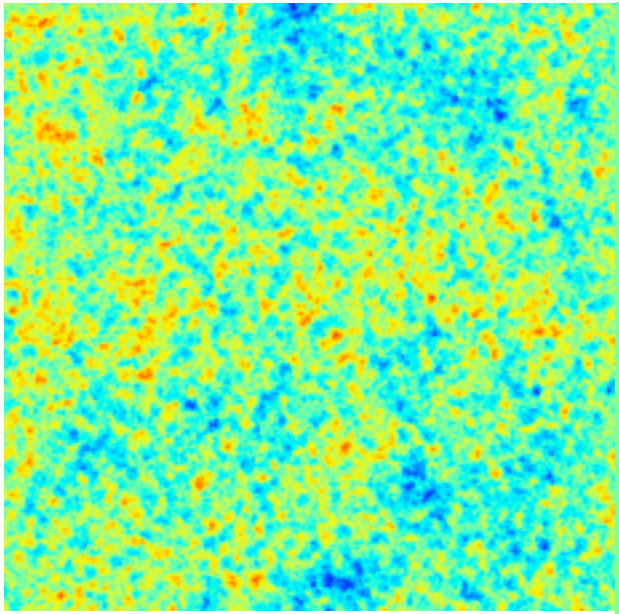


Fourier transform

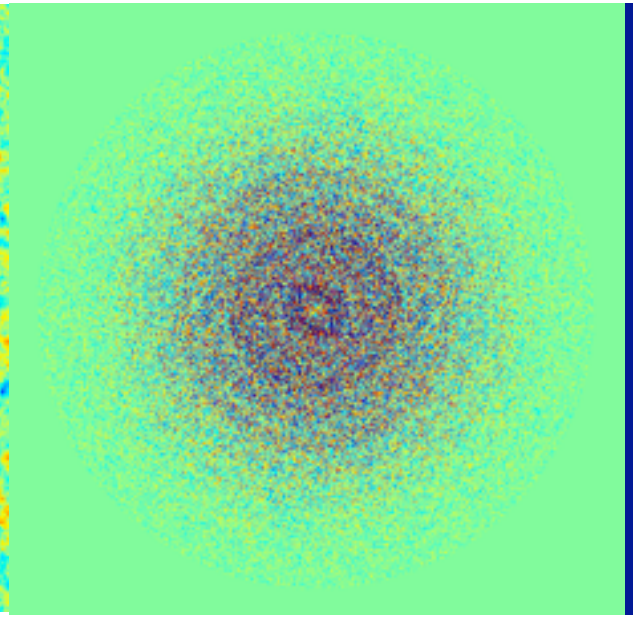


Simulated CMB

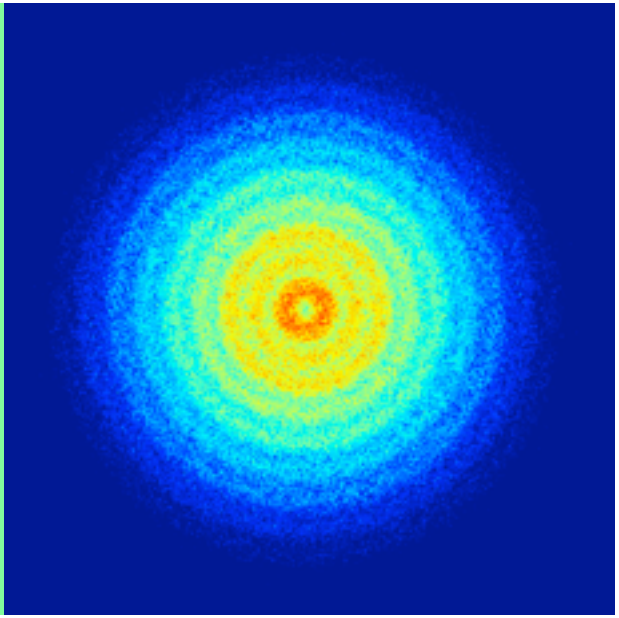
Map



Real part of FFT



$\log_{10}(|FFT|^2)$



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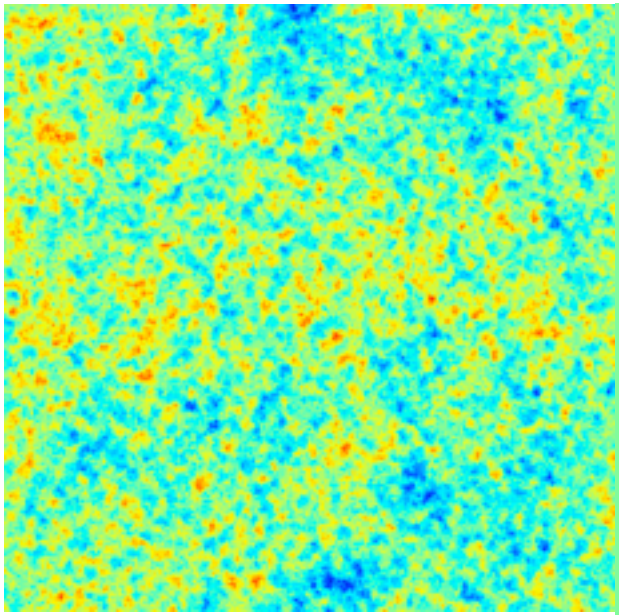
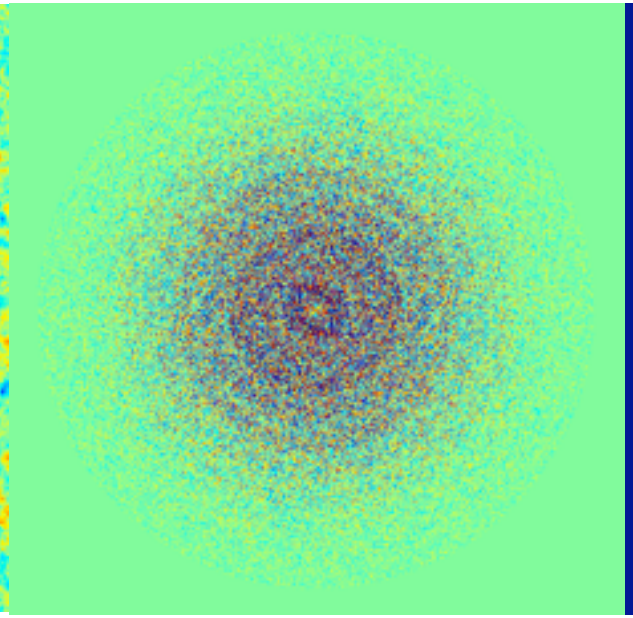


Real part of FFT



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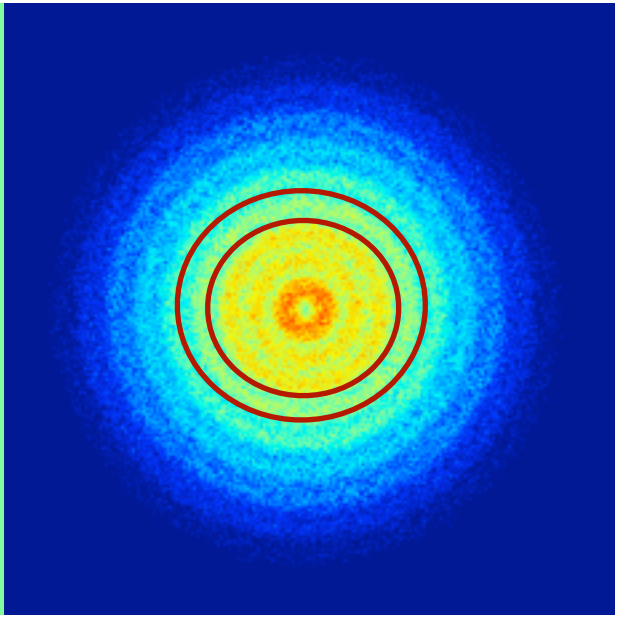


# of independent samples set by map size

Power spectrum Uncertainties

- fundamentally limited by number of independent measurements, noise
- $C_{l;meas}=C_{l;true}+C_{l;noise}$ *in any single map you can't tell the difference*
- $Var(C_l)\sim(2/n_{meas})C_l^2$ ***"sample variance"***
- more modes means better measurement of $C_{l;true}+C_{l;noise}$
- lower noise gives better measure of $C_{l;true}$

Cross Spectra

(all quantities are Fourier space!)

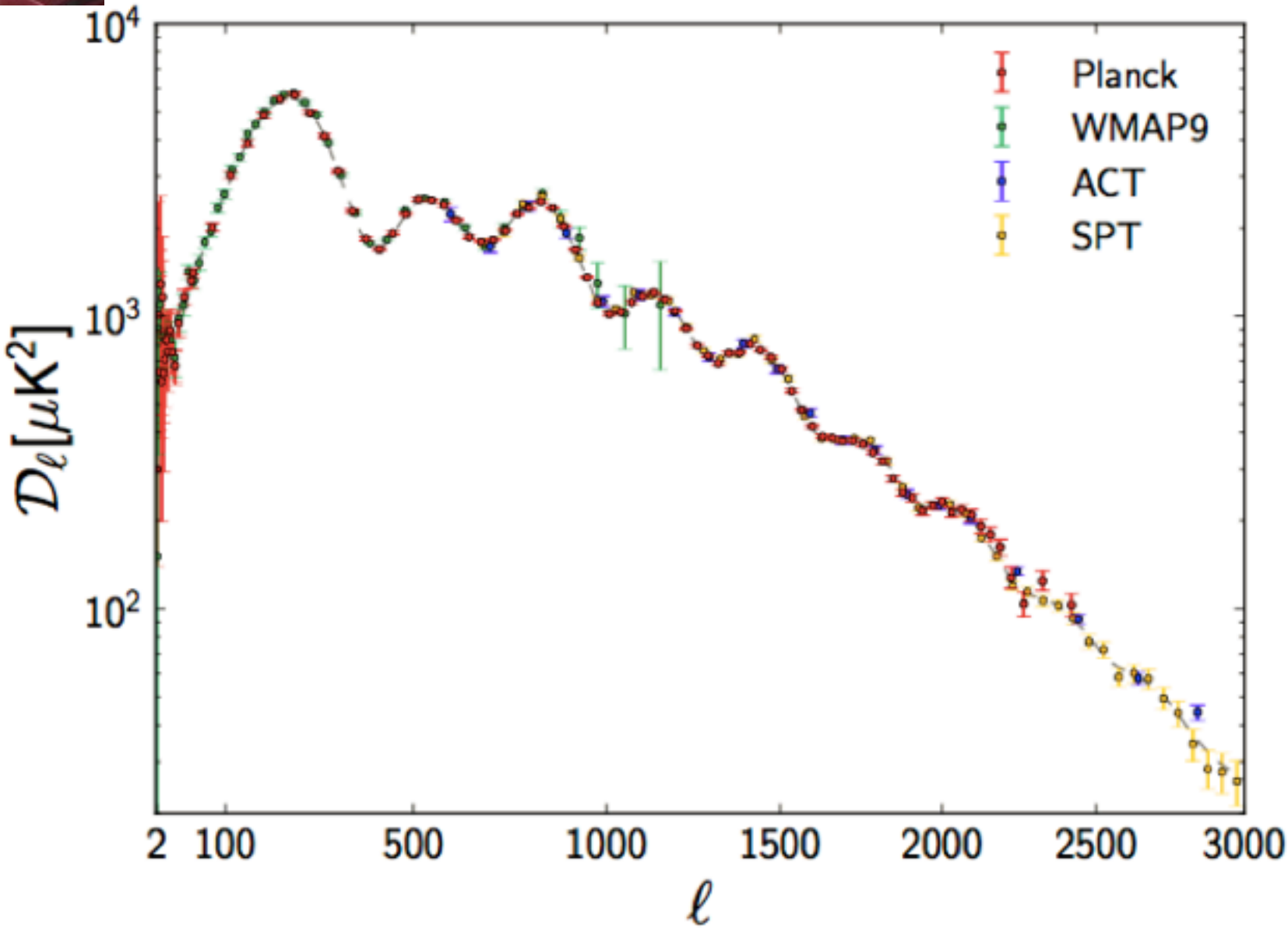
- $T_m = T + n$
- $\langle T_{1;m} T_{2;m} \rangle = \langle T_1 T_2 \rangle + \langle n_1 n_2 \rangle + \cancel{\langle T_1 n_2 + T_2 n_1 \rangle}$
- for $1=2$ (map auto power spectrum), $\langle n_1 n_2 \rangle = \sigma^2$
- if $1 \neq 2$, $\langle n_1 n_2 \rangle = 0$, so no bias
- quirks in your noise model don't affect cross spectrum!

Cross-Spectra in Action

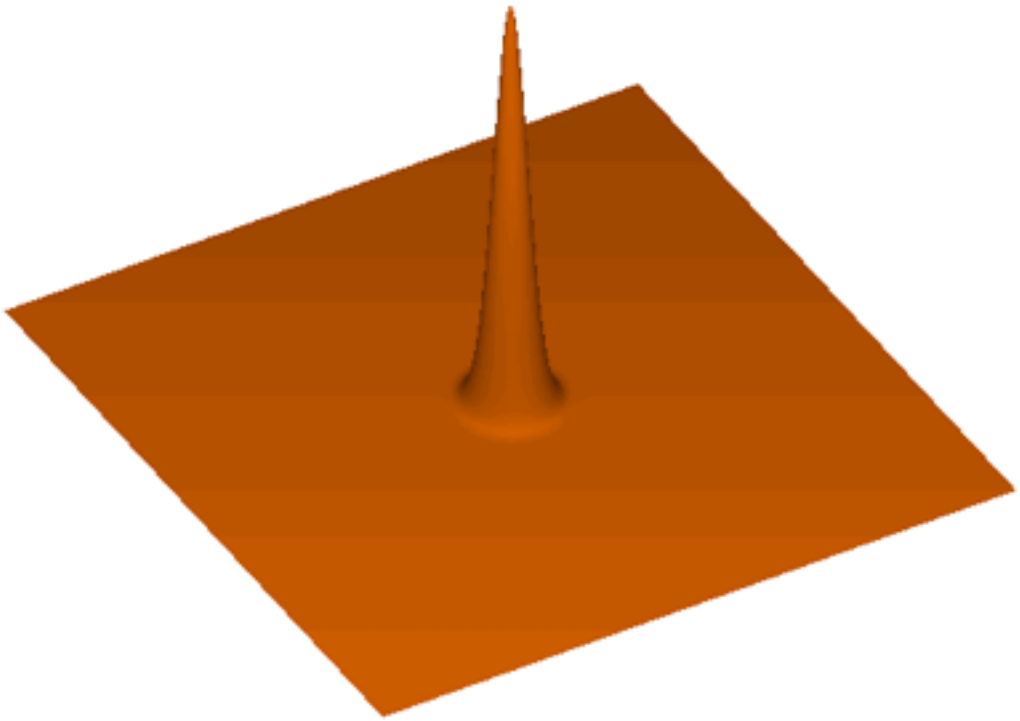
- if you have mapped a field 2 times, you can combine them: $T=(T_1+T_2T_3)$
- $C_l \sim T_1T_1+T_2T_2+T_3T_3+2(T_1T_2+T_1T_3+T_2T_3)$
- T_1T_1, T_2T_2, T_3T_3 have noise bias, so with a hit in sensitivity you can ignore these
- in the limit of large number of maps, hit in sensitivity goes to 0 while robust against problems of not knowing your detector noise

e.g., cross different days, different detectors

CMB Angular Power Spectrum

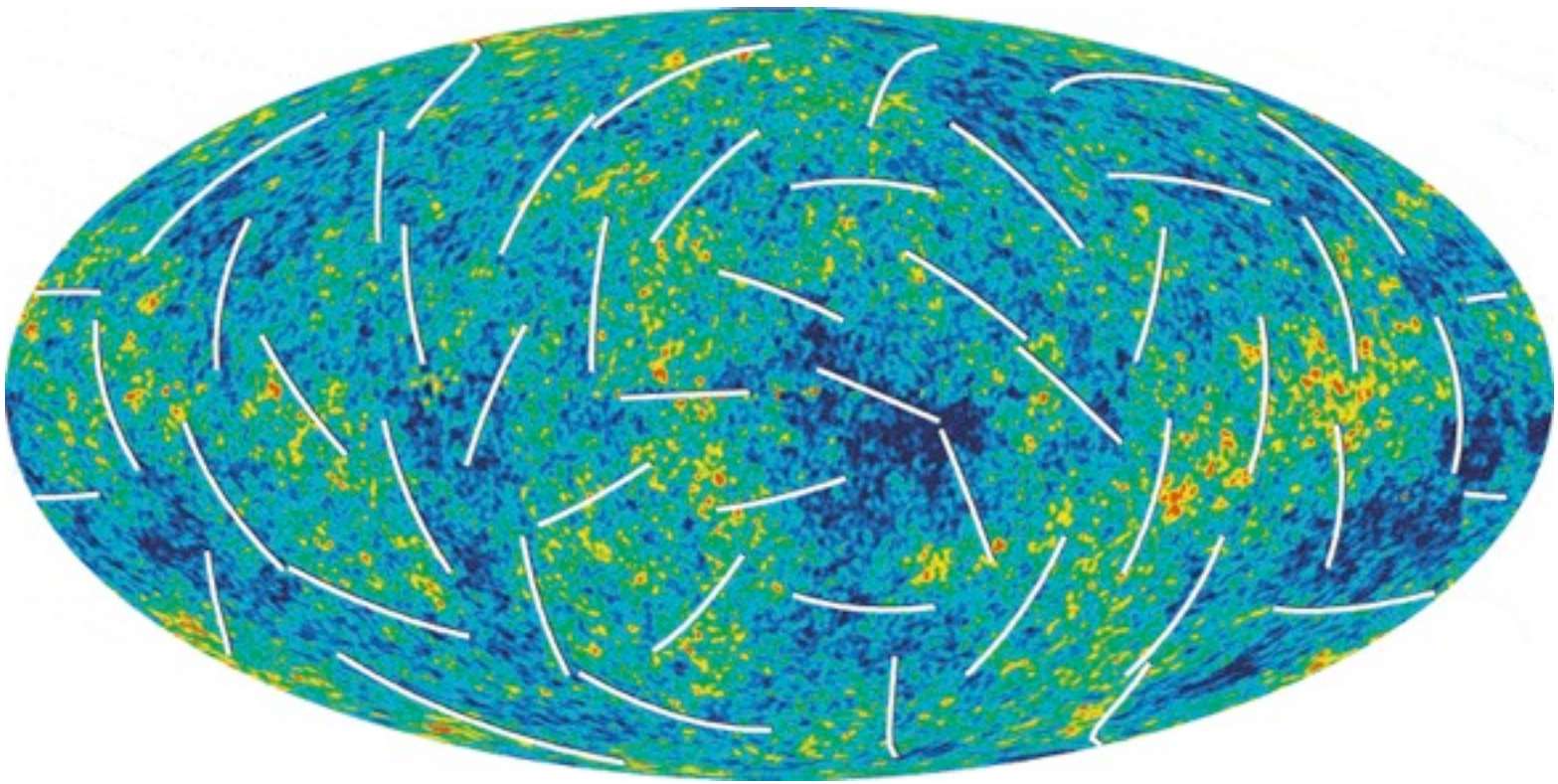


Acoustic Waves



- cmb anisotropy measures sound waves, gravitational redshifts, intrinsic photon overdensities, diffusion

CMB Polarization



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

How to make polarized light

- an accelerating charge naturally emits polarized radiation
  - http://phet.colorado.edu/sims/radiating-charge/radiating-charge_en.html
  - unpolarized radiation comes from random orientations of accelerated charges
- scattering of unpolarized light with preferred intensity orientation can generate polarization

Scattering causes Polarization

- Bouncing light picks out one polarization
- Polarized sunglasses reduce glare by blocking horizontal polarization (more likely to be scattered!)

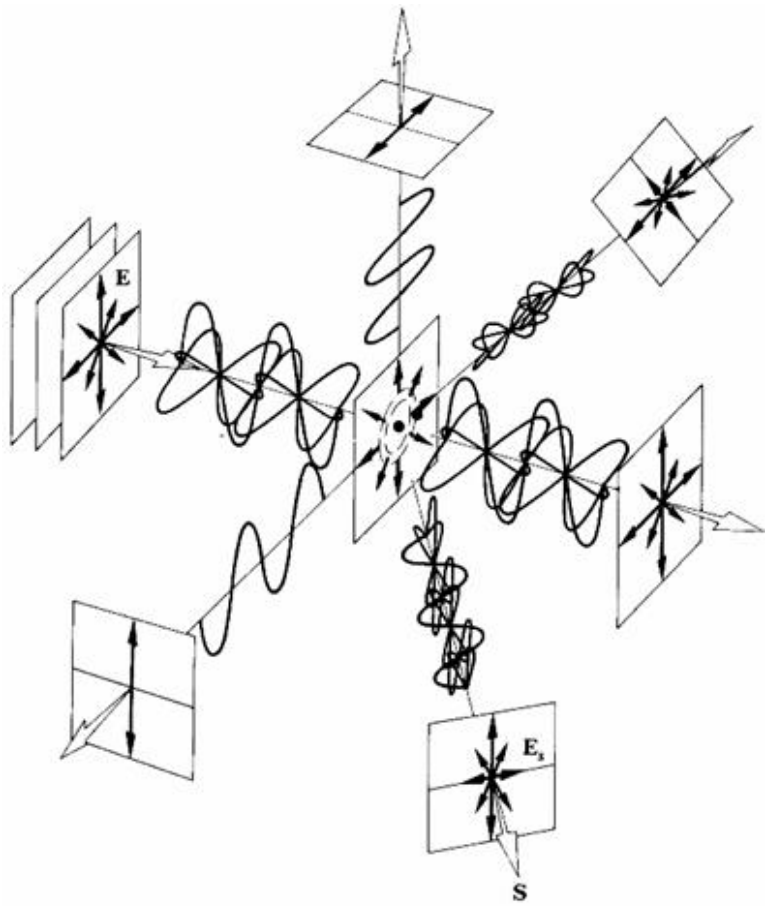
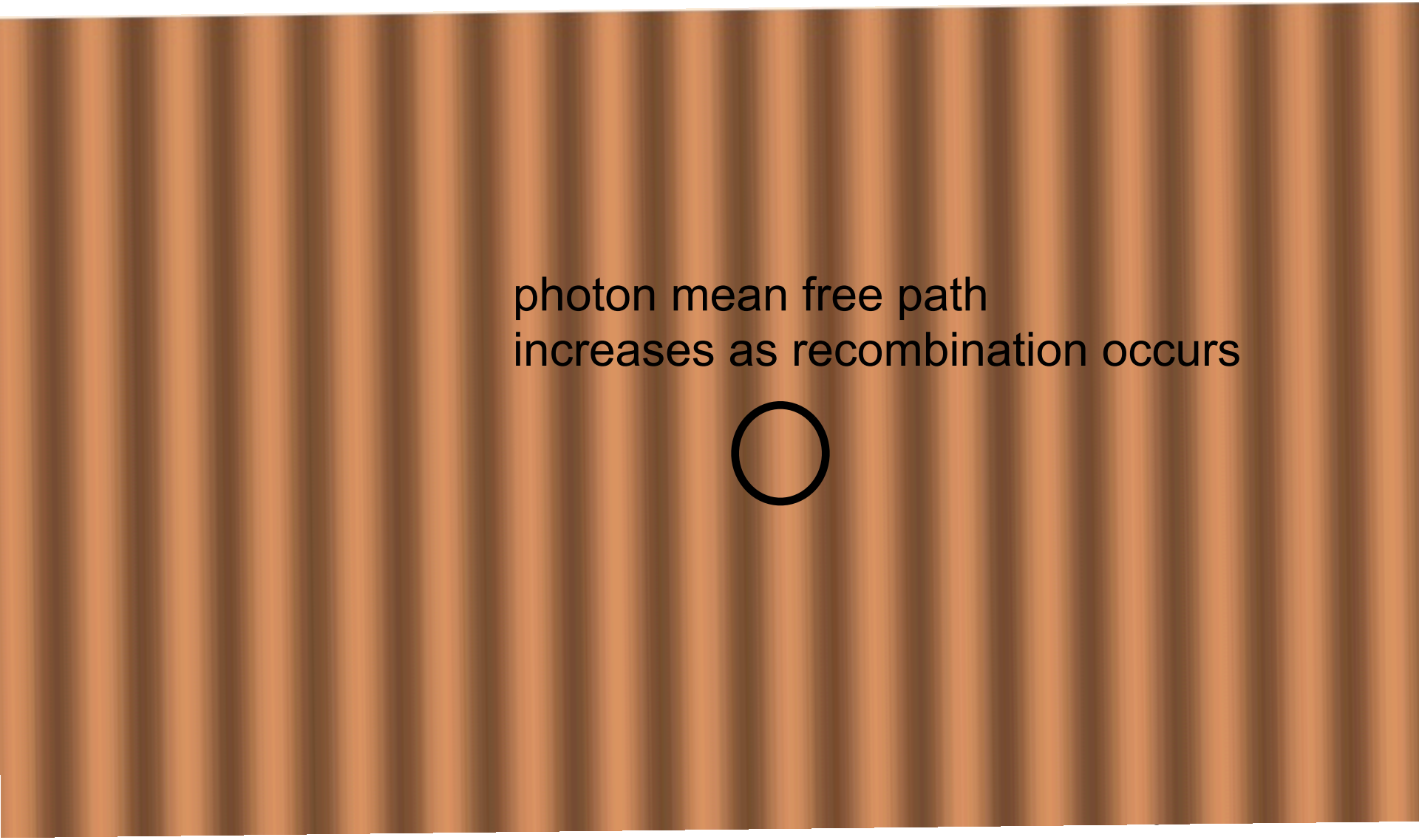


FIGURE 8.36 Scattering of unpolarized light by a molecule.

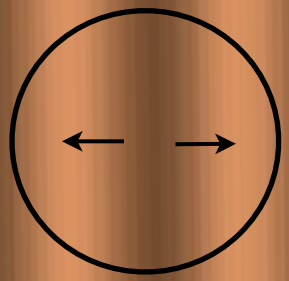
From Hecht, Optics

Polarization from Anisotropy

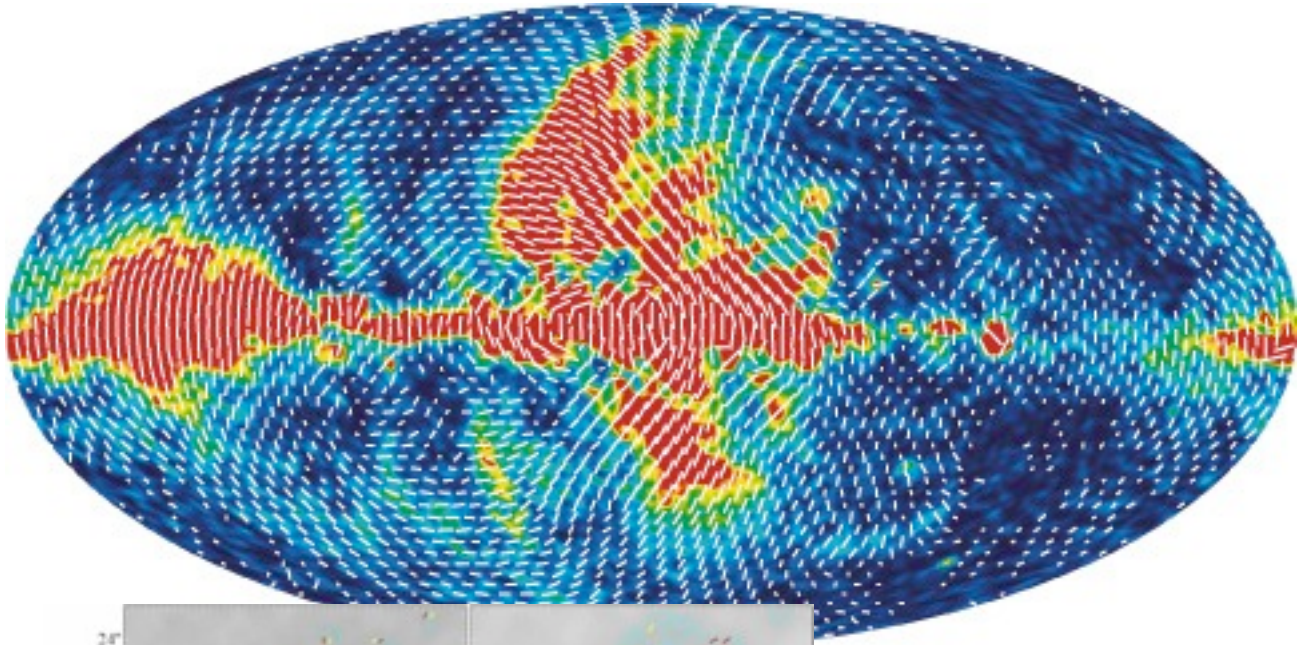


Two reasons for local photon quadrupole anisotropy

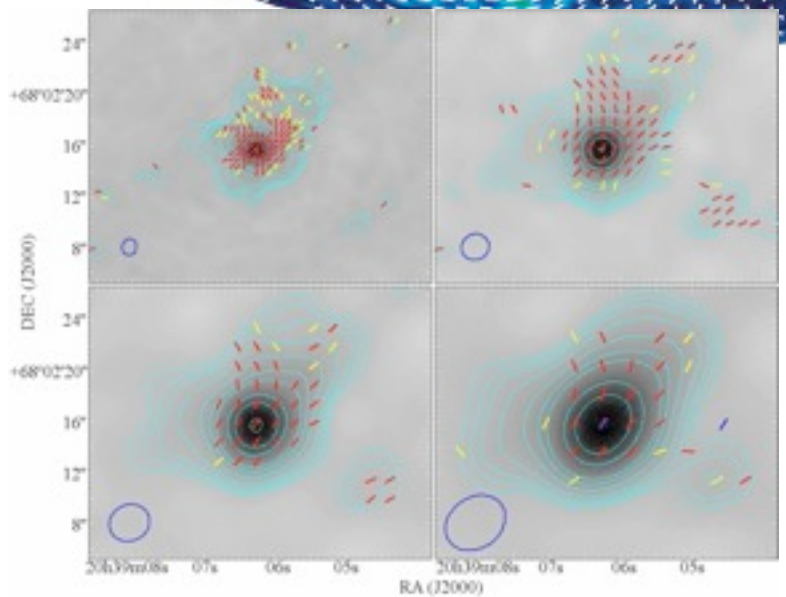
1. quadrupole in local Temperature
2. shear in Doppler shift from velocities



Polarized Maps



WMAP K-band



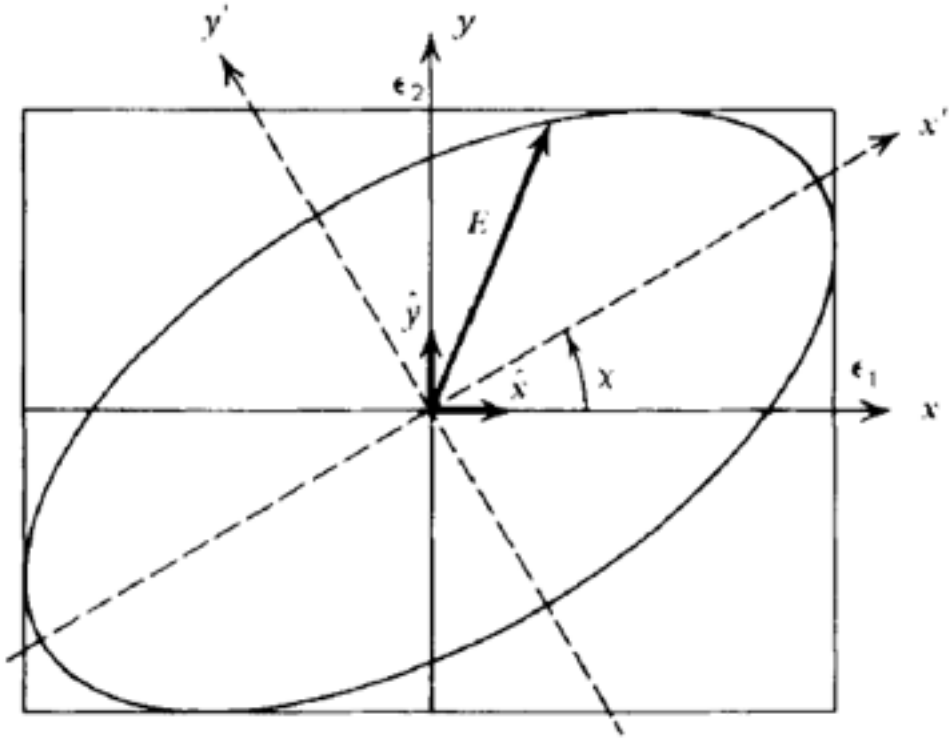
CARMA observations of a protostar (Stephens et al 2013)

POLARIZATION AND STOKES PARAMETERS (from Rybicki & Lightman Ch 2)

Monochromatic Waves

complex! take real part of "E" to get physical E field

$$\mathbf{E} = (\hat{\mathbf{x}} E_1 + \hat{\mathbf{y}} E_2) e^{-i\omega t} \equiv \mathbf{E}_0 e^{-i\omega t}. \qquad (2.35)$$



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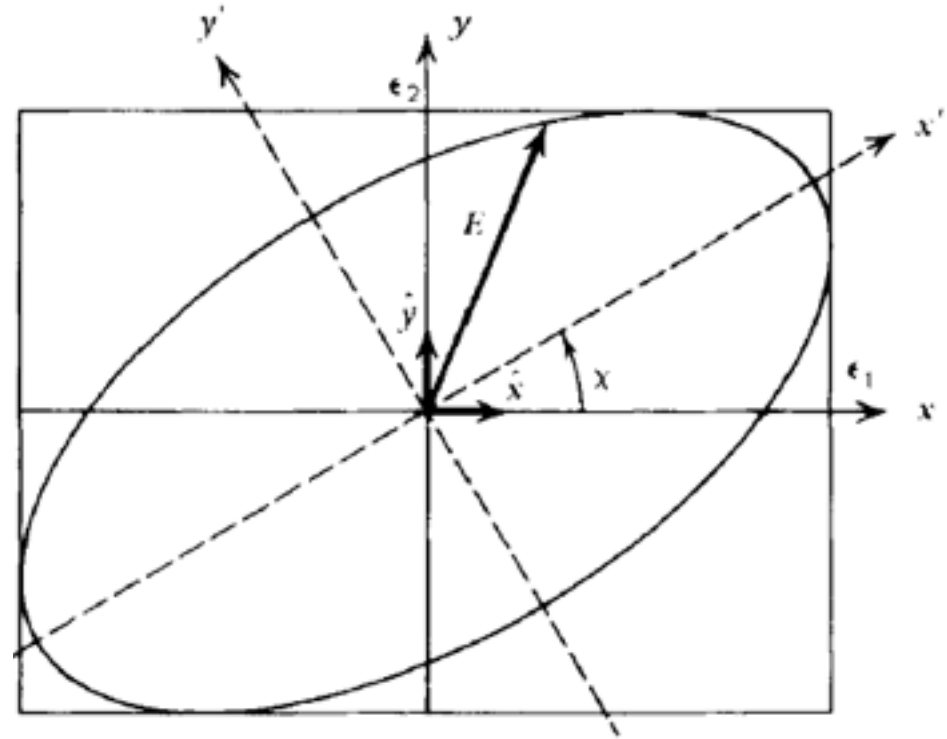
$$E_1 = \mathcal{E}_1 e^{i\phi_1}, \qquad E_2 = \mathcal{E}_2 e^{i\phi_2}. \tag{2.36}$$

Taking the real part of $\mathbf{E}$, we find the physical components of the electric field along $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ to be

$$E_x = \mathcal{E}_1 \cos(\omega t - \phi_1), \qquad E_y = \mathcal{E}_2 \cos(\omega t - \phi_2). \tag{2.37}$$

POLARIZATION AND STOKES PARAMETERS (from Rybicki & Lightman Ch 2)

Monochromatic Waves



Stokes Parameters

$$I \equiv \mathcal{E}_1^2 + \mathcal{E}_2^2 = \mathcal{E}_0^2$$

$$Q \equiv \mathcal{E}_1^2 - \mathcal{E}_2^2 = \mathcal{E}_0^2 \cos 2\beta \cos 2\chi$$

$$U \equiv 2\mathcal{E}_1 \mathcal{E}_2 \cos(\phi_1 - \phi_2) = \mathcal{E}_0^2 \cos 2\beta \sin 2\chi$$

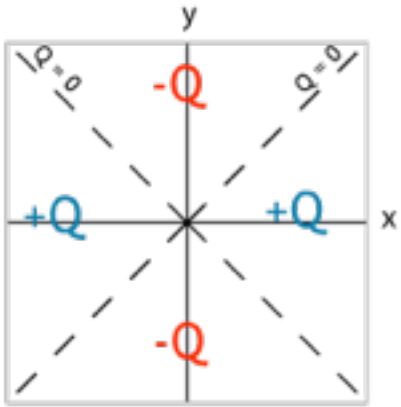
$$V \equiv 2\mathcal{E}_1 \mathcal{E}_2 \sin(\phi_1 - \phi_2) = \mathcal{E}_0^2 \sin 2\beta.$$

$$I^2 = Q^2 + U^2 + V^2$$

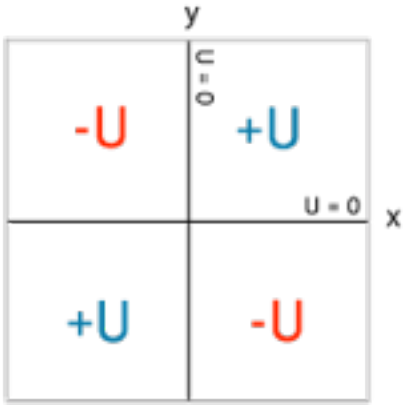
Stokes Parameters

(via wikipedia)

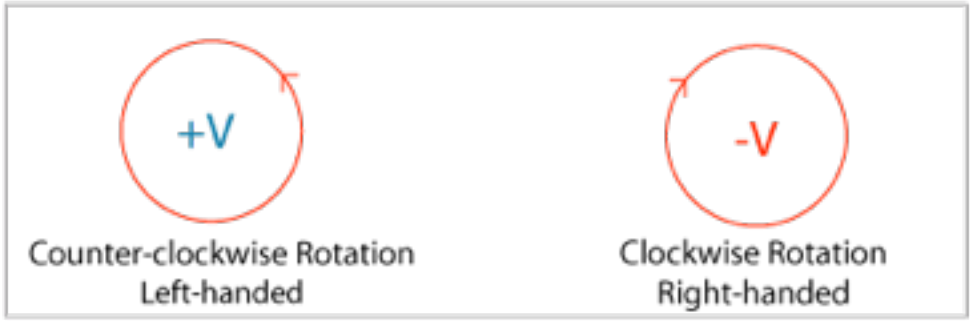
$$
\begin{aligned}
I &\equiv \langle E_x^2 \rangle + \langle E_y^2 \rangle \\
&= \langle E_a^2 \rangle + \langle E_b^2 \rangle \\
&= \langle E_l^2 \rangle + \langle E_r^2 \rangle, \\
Q &\equiv \langle E_x^2 \rangle - \langle E_y^2 \rangle, \\
U &\equiv \langle E_a^2 \rangle - \langle E_b^2 \rangle, \\
V &\equiv \langle E_l^2 \rangle - \langle E_r^2 \rangle.
\end{aligned}
$$



Sign of Q
(a)

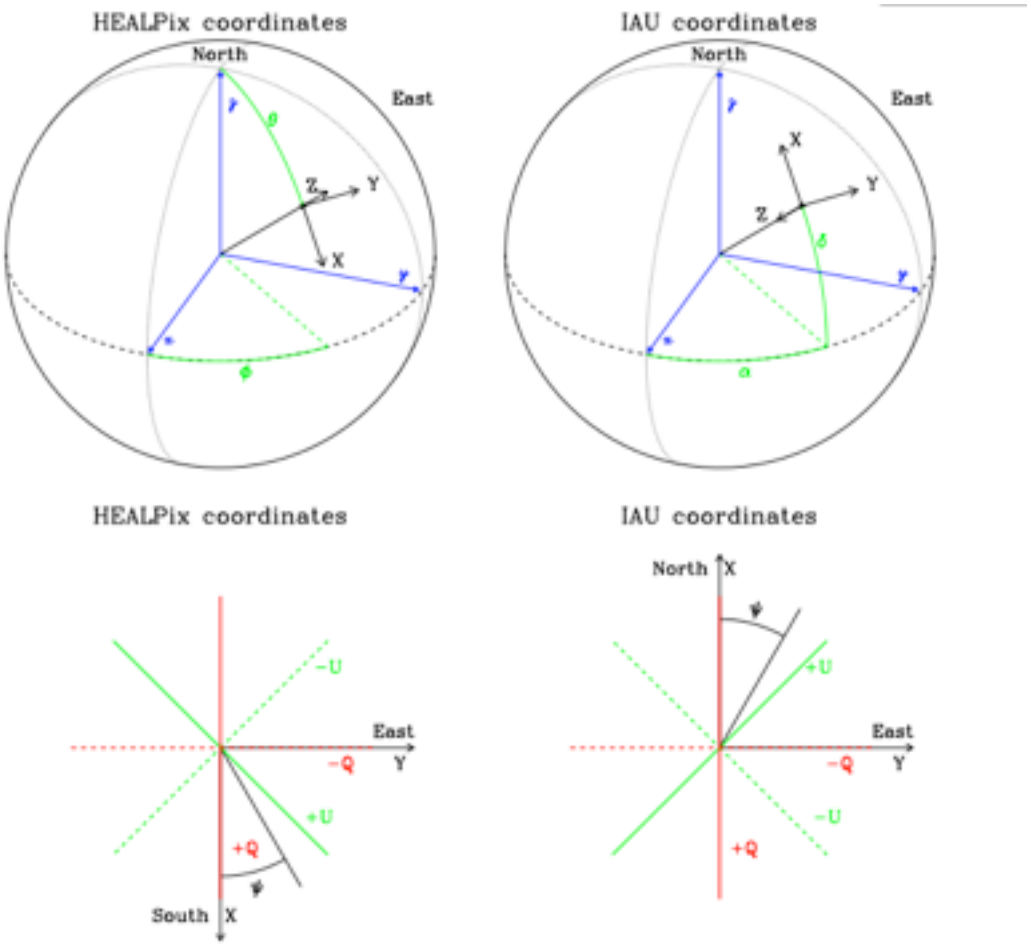


Sign of U
(b)



Sign of V
(c)

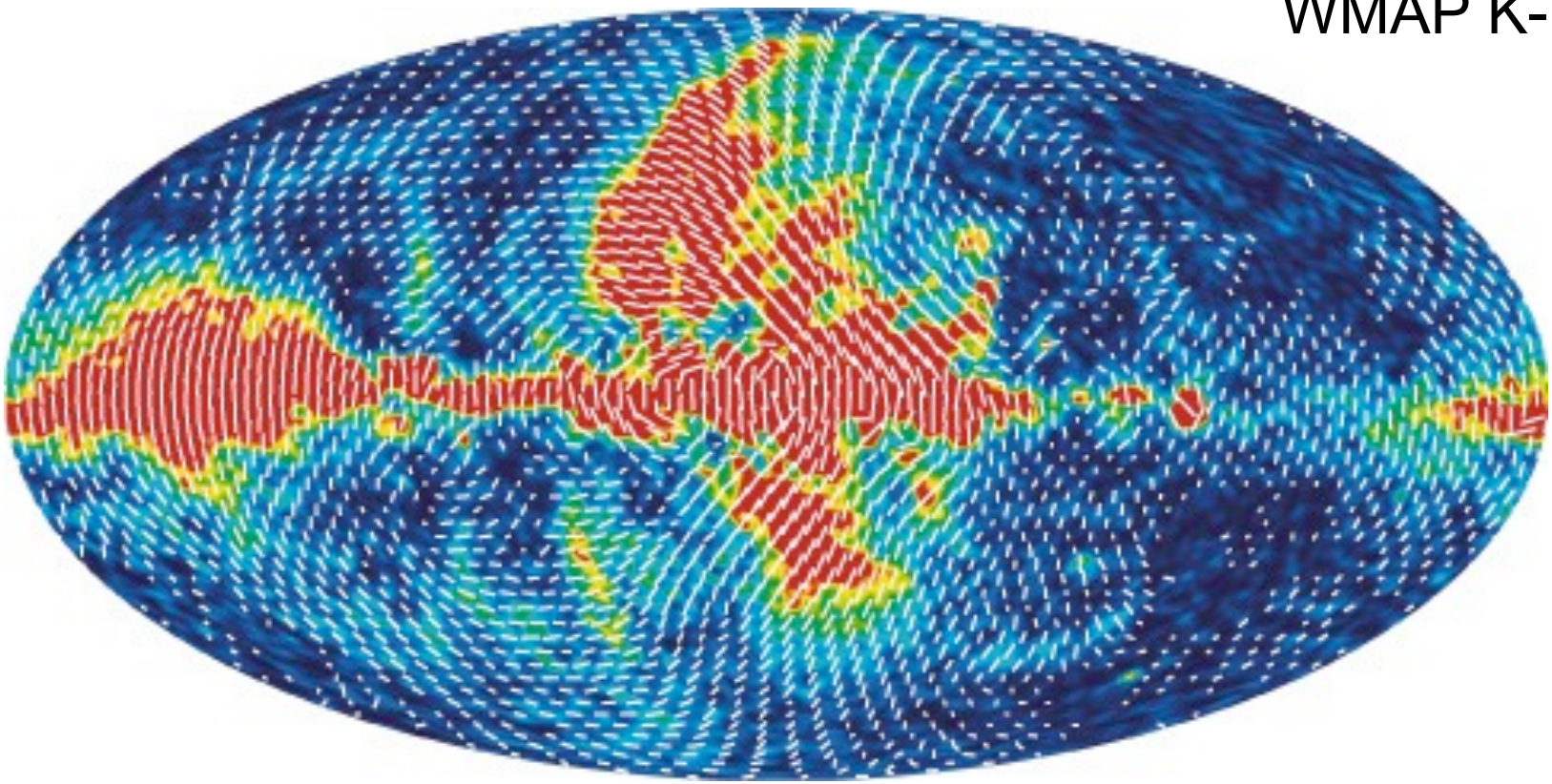
WARNING! Different conventions



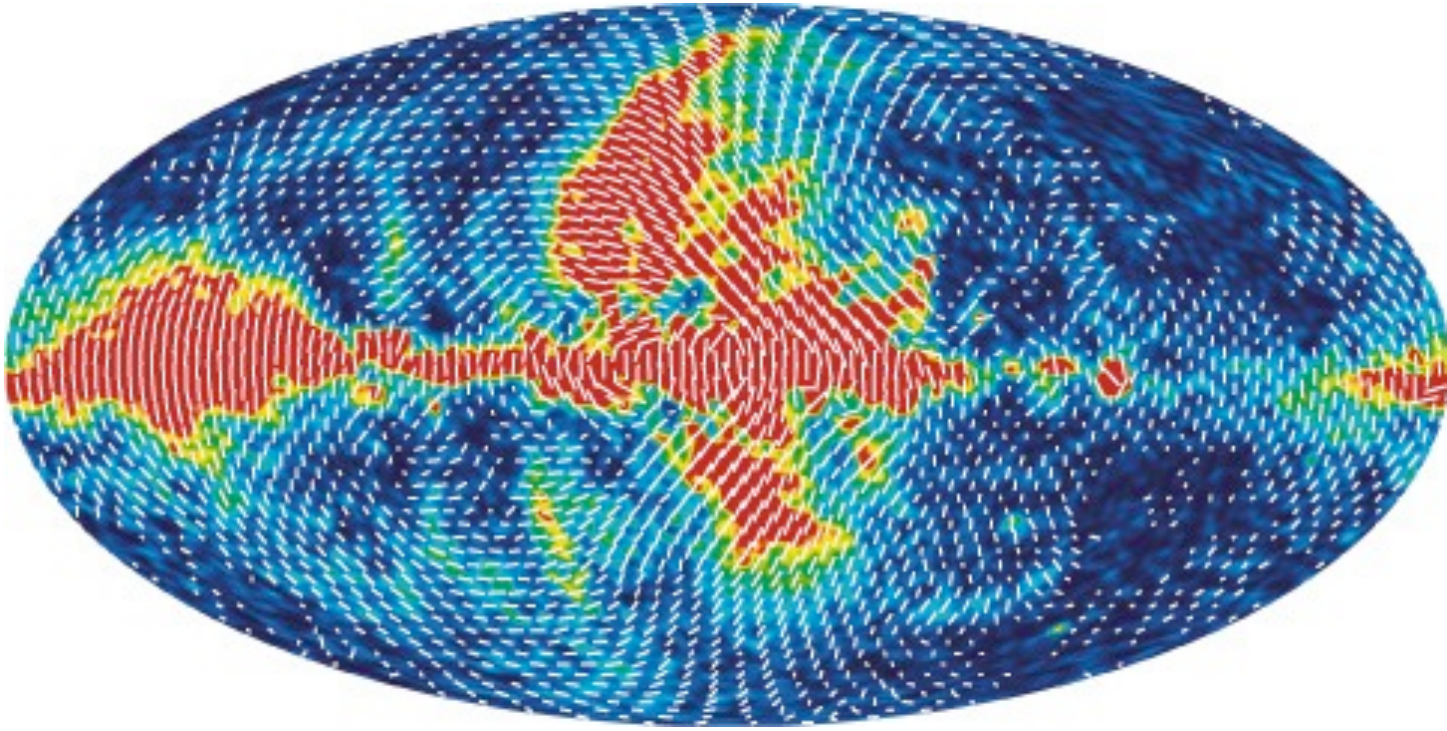
- from Healpix primer

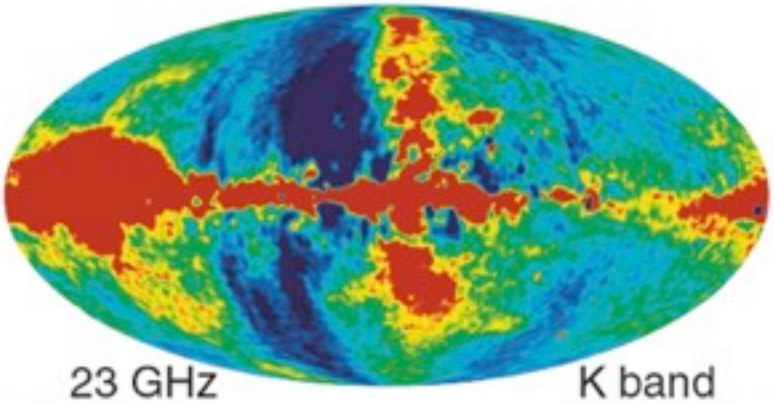
Polarized Maps

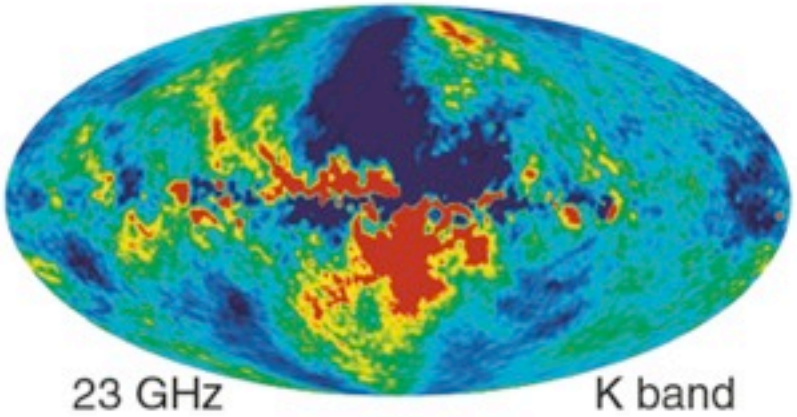
WMAP K-band



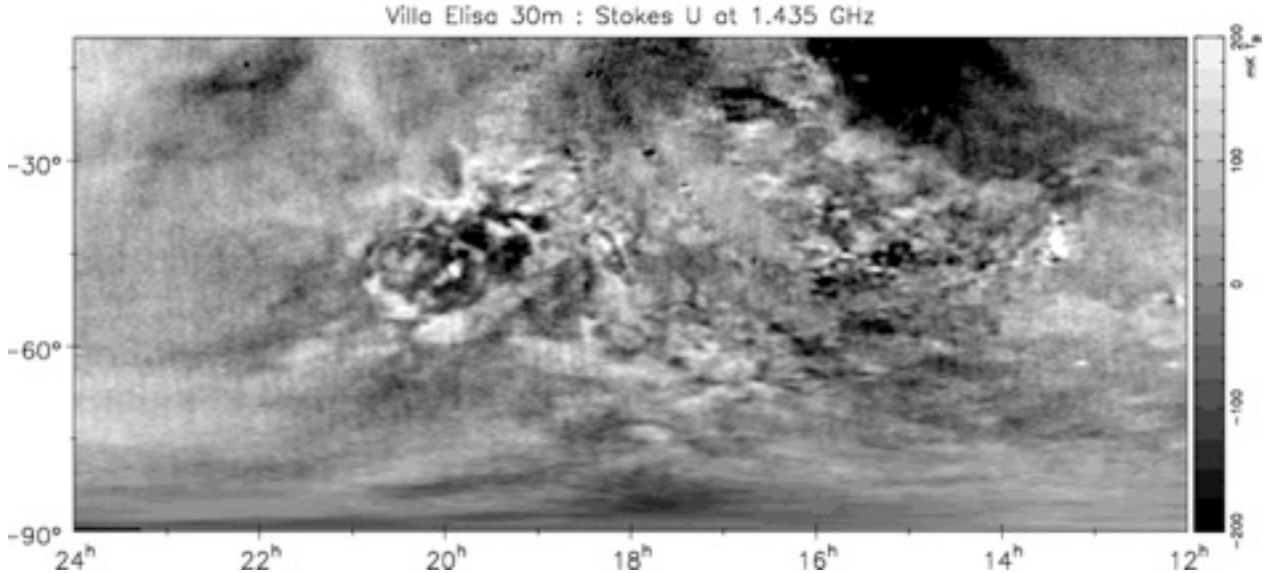
Stokes Maps

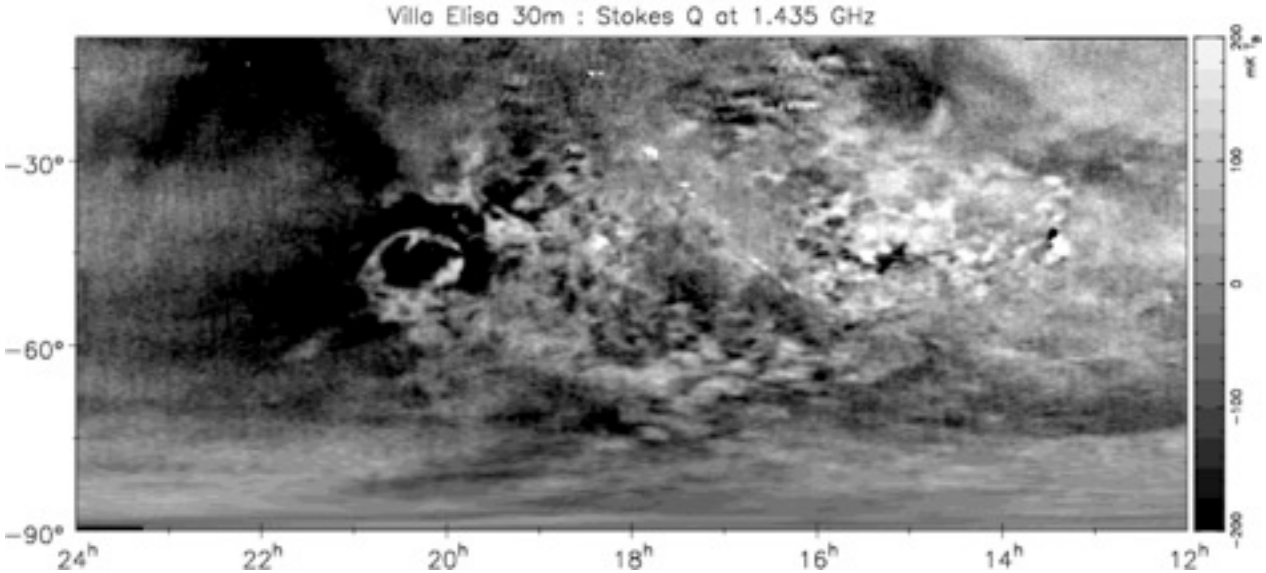






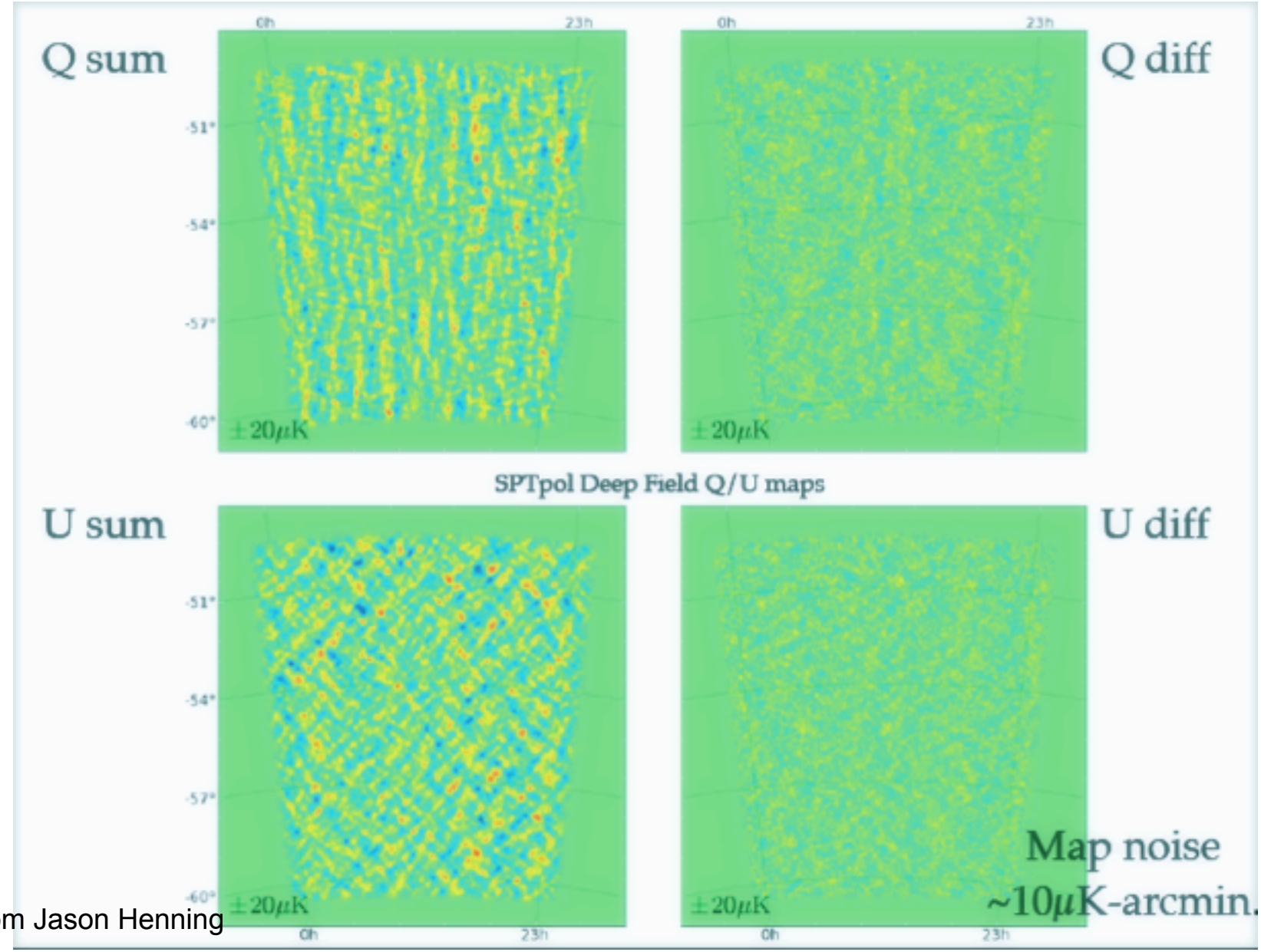
Radio Stokes Maps





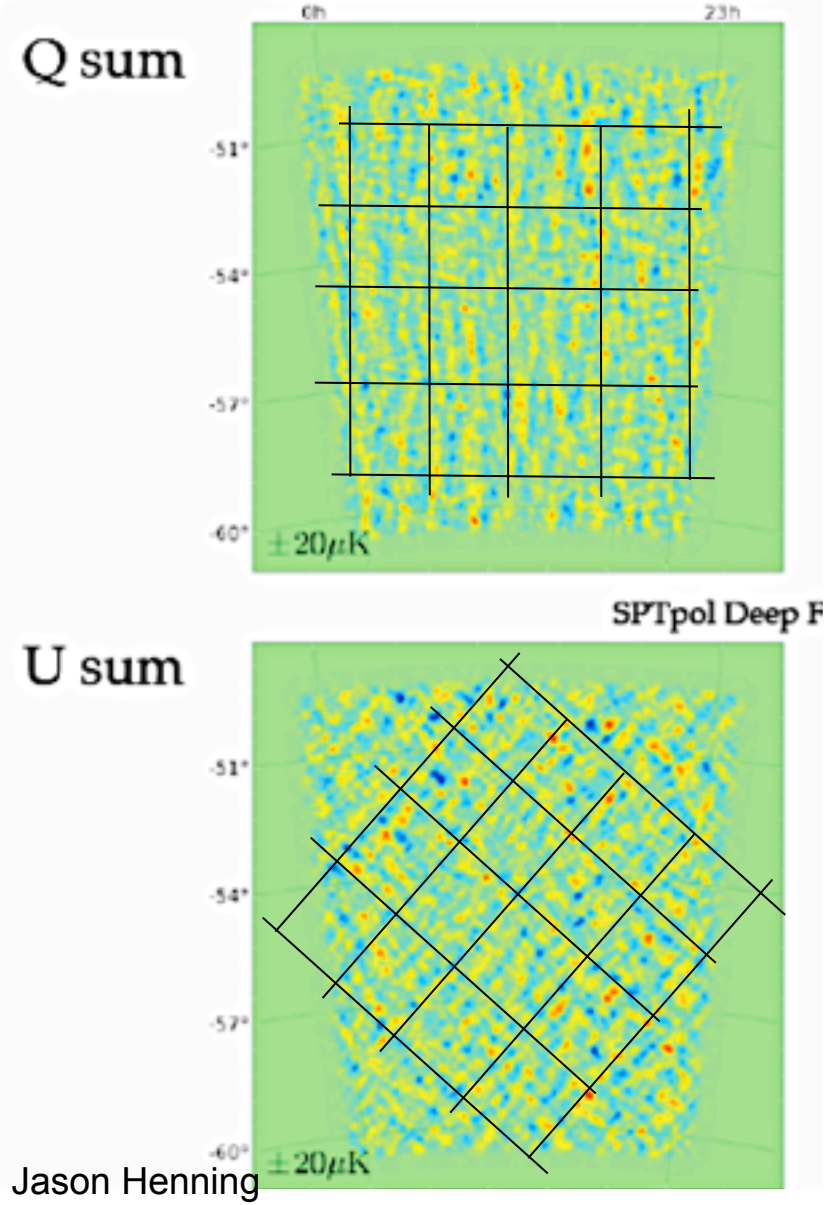
Testori et al 2008

CMB Polarization Maps



slide from Jason Henning

CMB Polarization Maps are Boxy



slide from Jason Henning

Stokes Q/U Rotated

- Stokes Q/U are tied to coordinate system
- rotate coordinates, Q/U are changed
- polarization is spin-2

$$Q' = Q\cos 2\psi + U\sin 2\psi$$
$$U' = -Q\sin 2\psi + U\cos 2\psi$$

$$(Q \pm iU)'(\hat{n}) = e^{\mp 2i\psi}(Q \pm iU)(\hat{n}),$$

The nature of the E-B decomposition of CMB polarization

Matias Zaldarriaga
Physics Department, New York University, 4 Washington Place, New York, NY 10003
(May 10 2001. Submitted to Phys. Rev. D.)

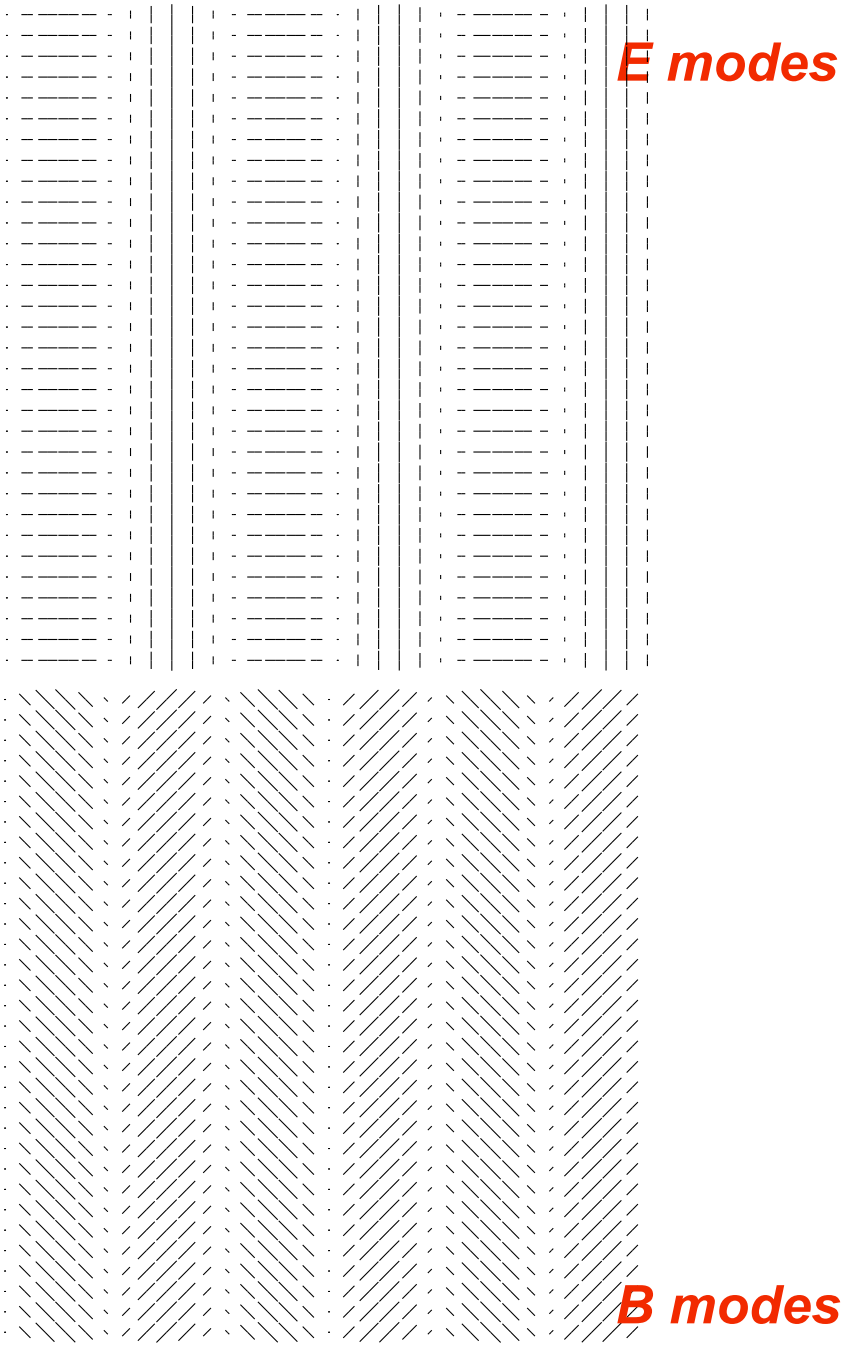
E-modes and B-modes

$$Q(\boldsymbol{l}) = [E(\boldsymbol{l})\cos(2\phi_l) - B(\boldsymbol{l})\sin(2\phi_l)]$$
$$U(\boldsymbol{l}) = [E(\boldsymbol{l})\sin(2\phi_l) + B(\boldsymbol{l})\cos(2\phi_l)].$$

- E/B is a different way to express polarization field
- easy to understand in flat-sky limit (i.e. Fourier modes)

E-modes/B-modes

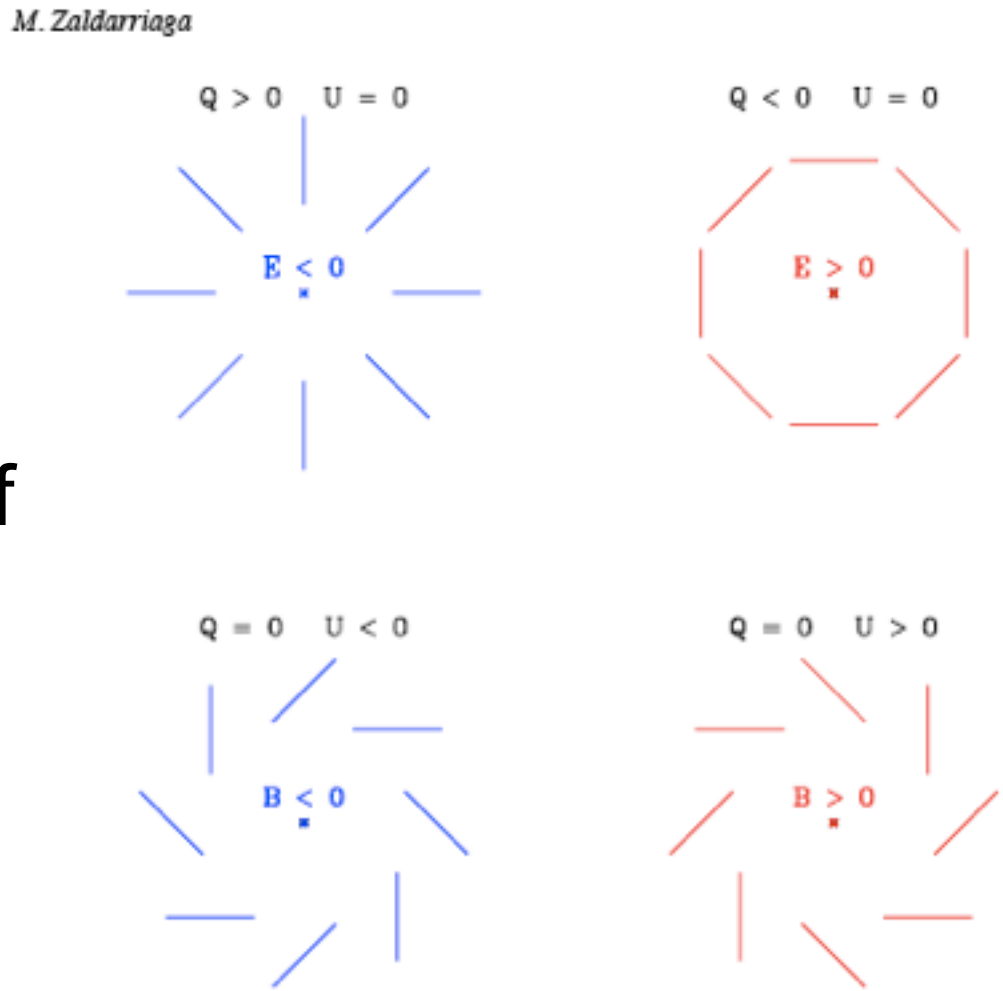
- E-modes vary spatially parallel or perpedicular to polarization direction
- B-modes vary spatially at 45 degrees
- CMB
    - scalar perturbations only generate *only* E



Bunn

Another View of E/B

- E/B can be thought of as divergence/ curl modes of polarization (but spin-2, not spin-1)



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!***

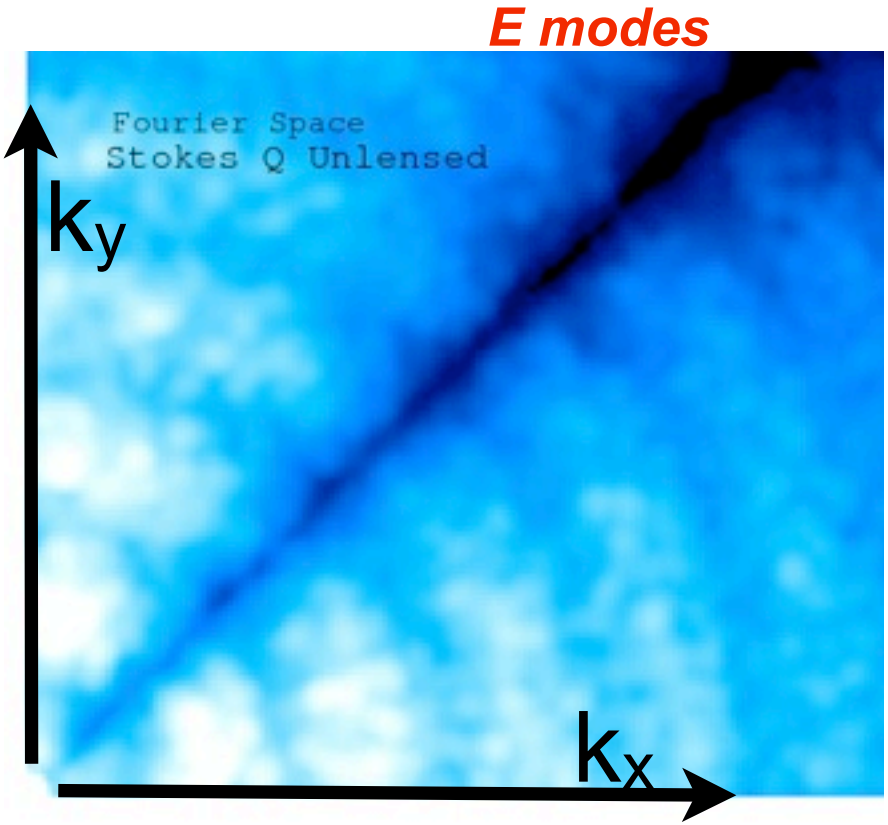
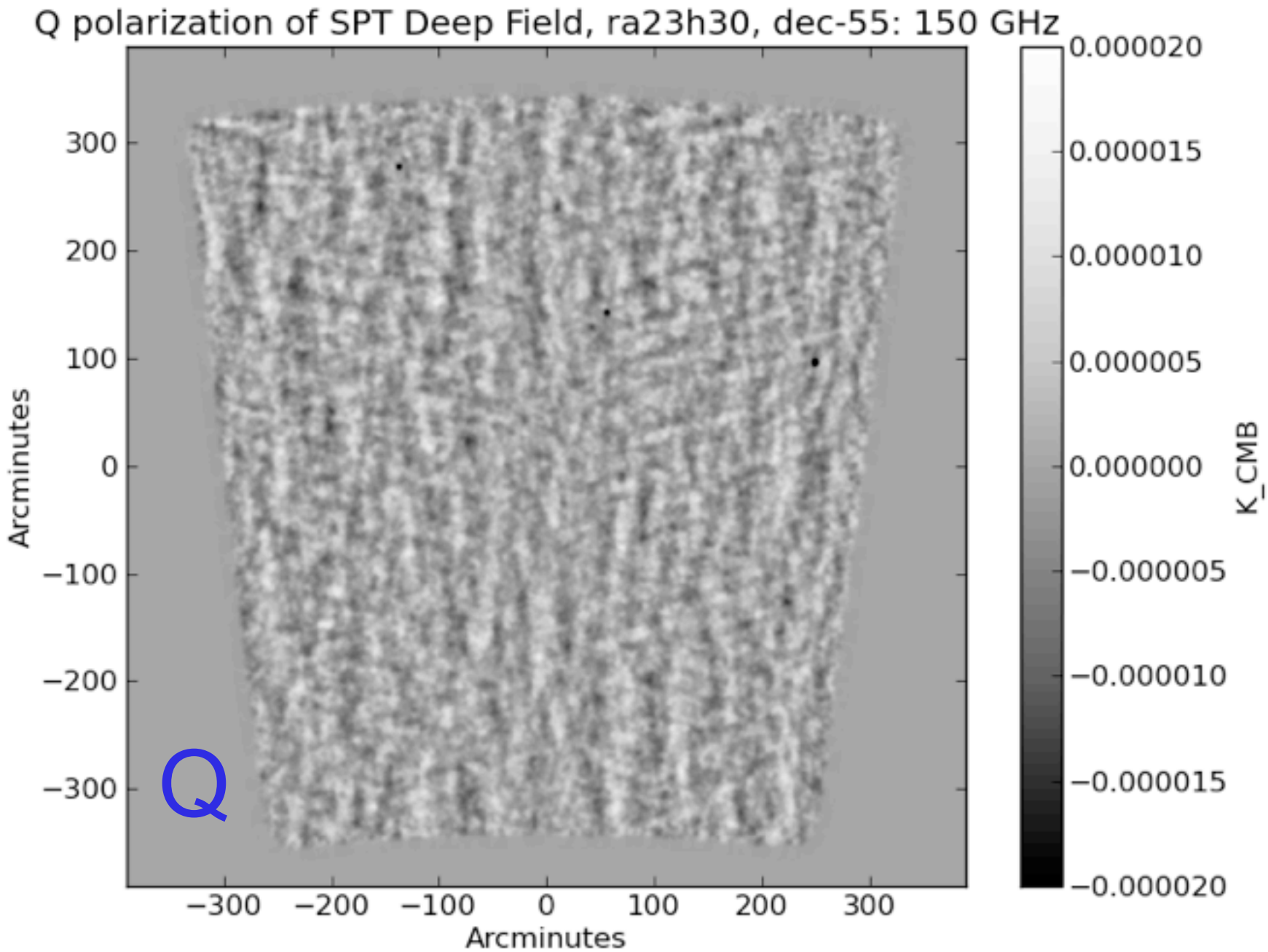
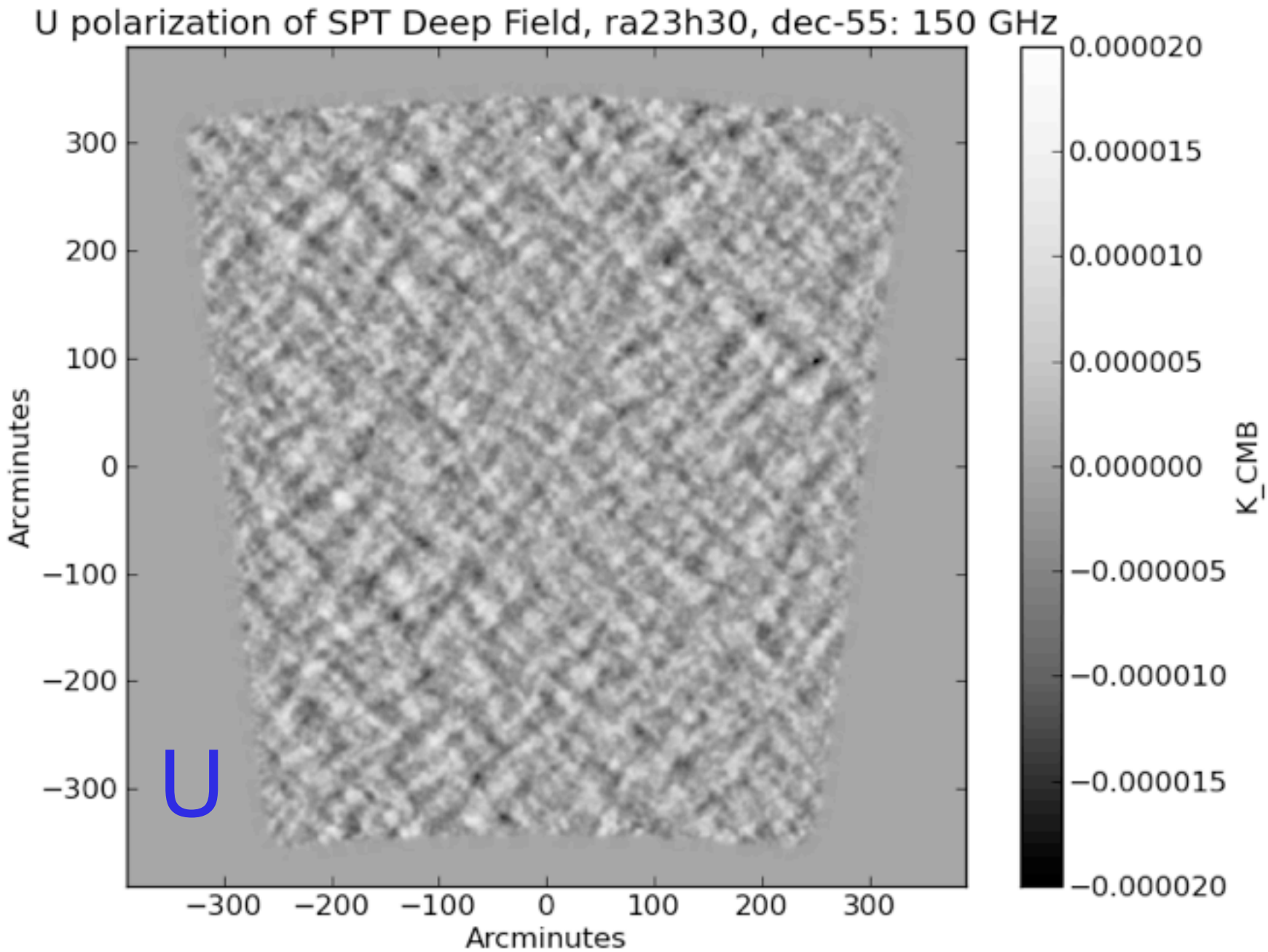
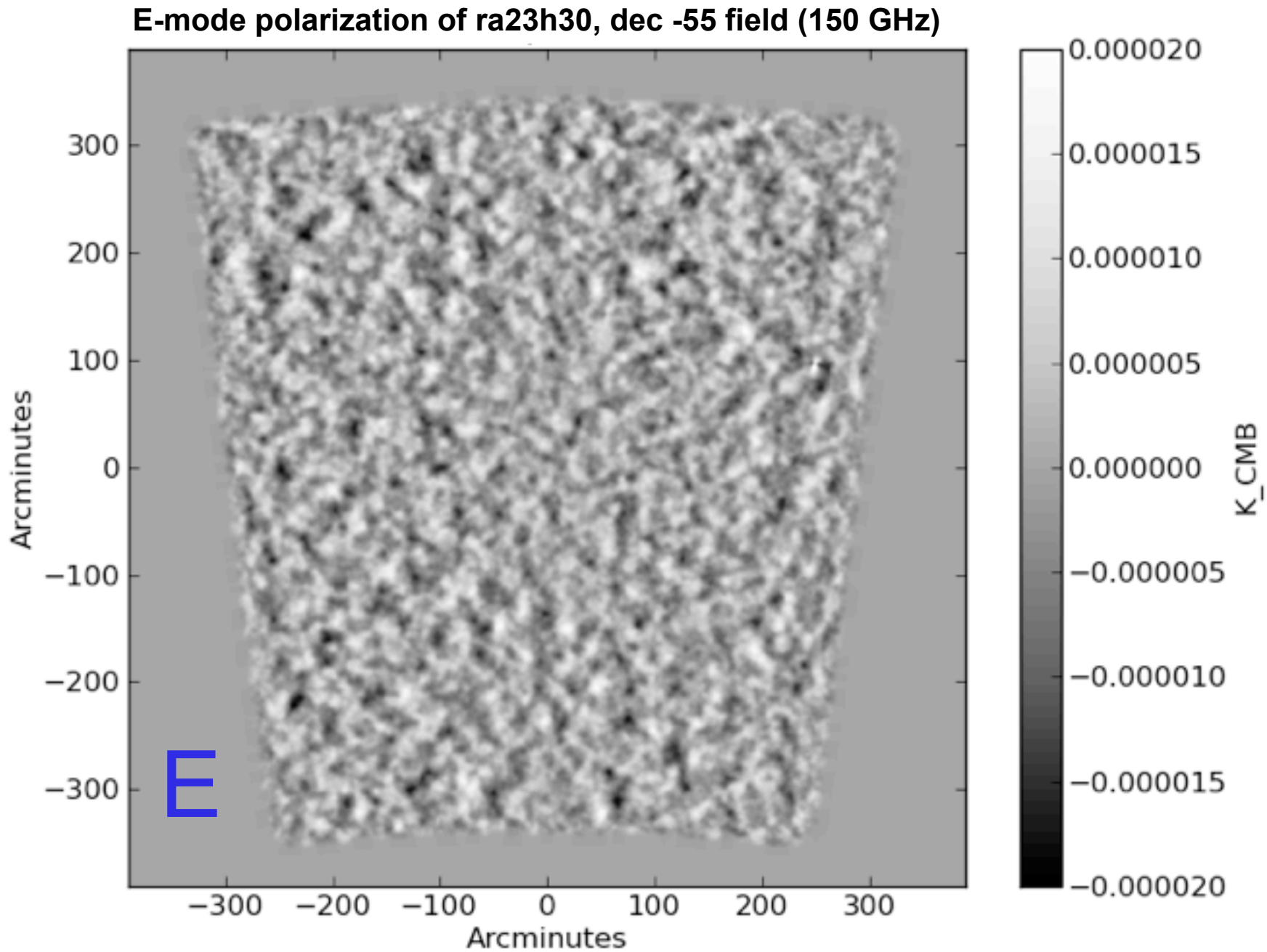


Image of positive kx/positive ky Fourier transform of a 10x10 deg chunk of Stokes Q CMB map [simulated; nothing clever done to it]


Q polarization of SPT Deep Field, ra23h30, dec-55: 150 GHz
Arcminutes
Arcminutes
K_CMB
Q
300
200
100
0
−100
−200
−300
0.000020
0.000015
0.000010
0.000005
0.000000
−0.000005
−0.000010
−0.000015
−0.000020


U polarization of SPT Deep Field, ra23h30, dec-55: 150 GHz
Arcminutes
Arcminutes
K_CMB
U
300
200
100
0
−100
−200
−300
0.000020
0.000015
0.000010
0.000005
0.000000
−0.000005
−0.000010
−0.000015
−0.000020


E-mode polarization of ra23h30, dec -55 field (150 GHz)
Arcminutes
300
200
100
0
−100
−200
−300
−300
−200
−100
0
100
200
300
Arcminutes
E
0.000020
0.000015
0.000010
0.000005
0.000000
−0.000005
−0.000010
−0.000015
−0.000020
K_CMB

Full-Sky E/B: Spin-2 Spherical Harmonics

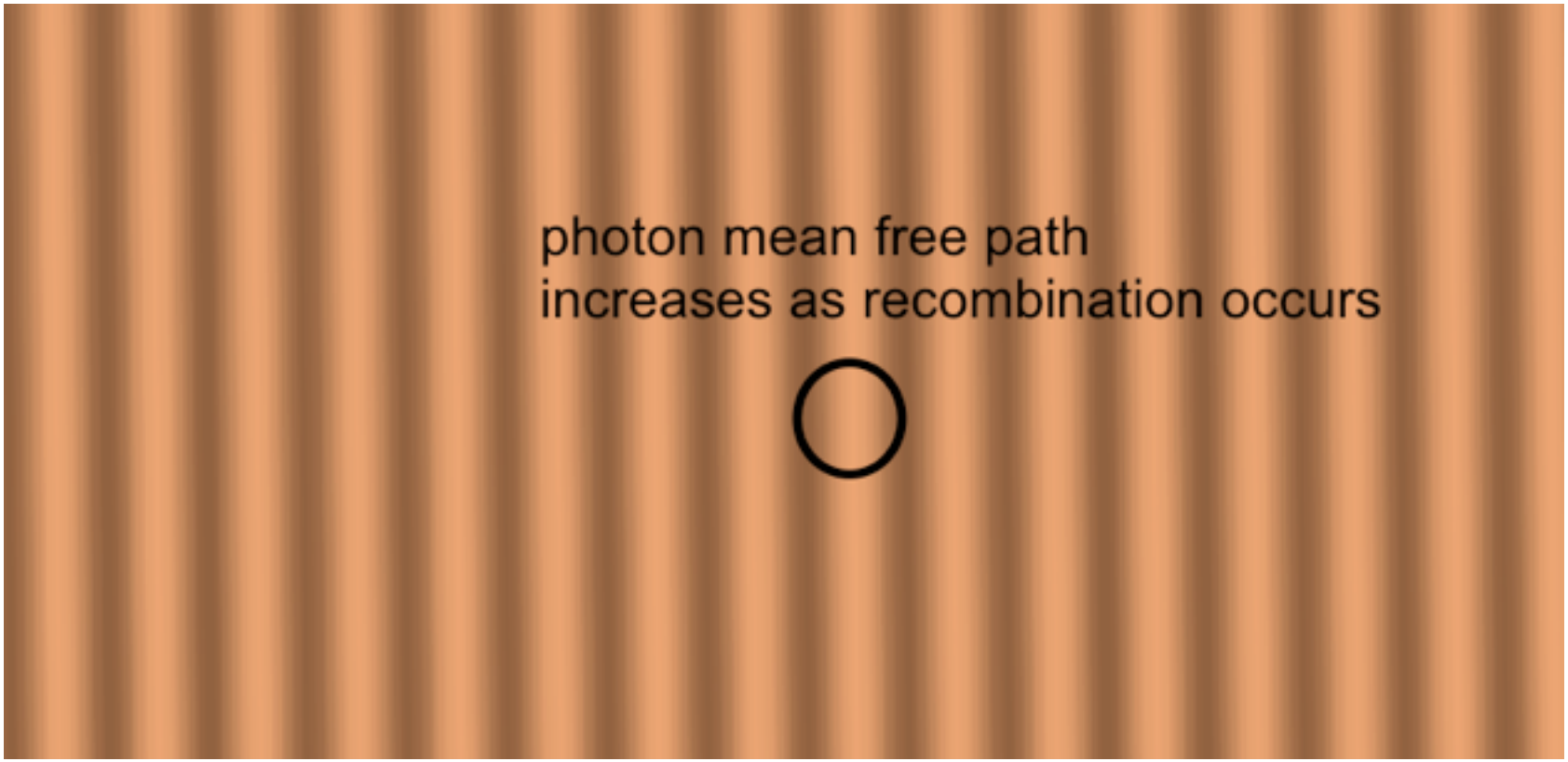
$$(Q \pm iU)(\hat{n}) = \sum_{lm} a_{\pm 2,lm}\, {}_{\pm 2}Y_{lm}(\hat{n}).$$

$$a^E_{lm} = -(a_{2,lm} + a_{-2,lm})/2$$

$$a^B_{lm} = i(a_{2,lm} - a_{-2,lm})/2.$$

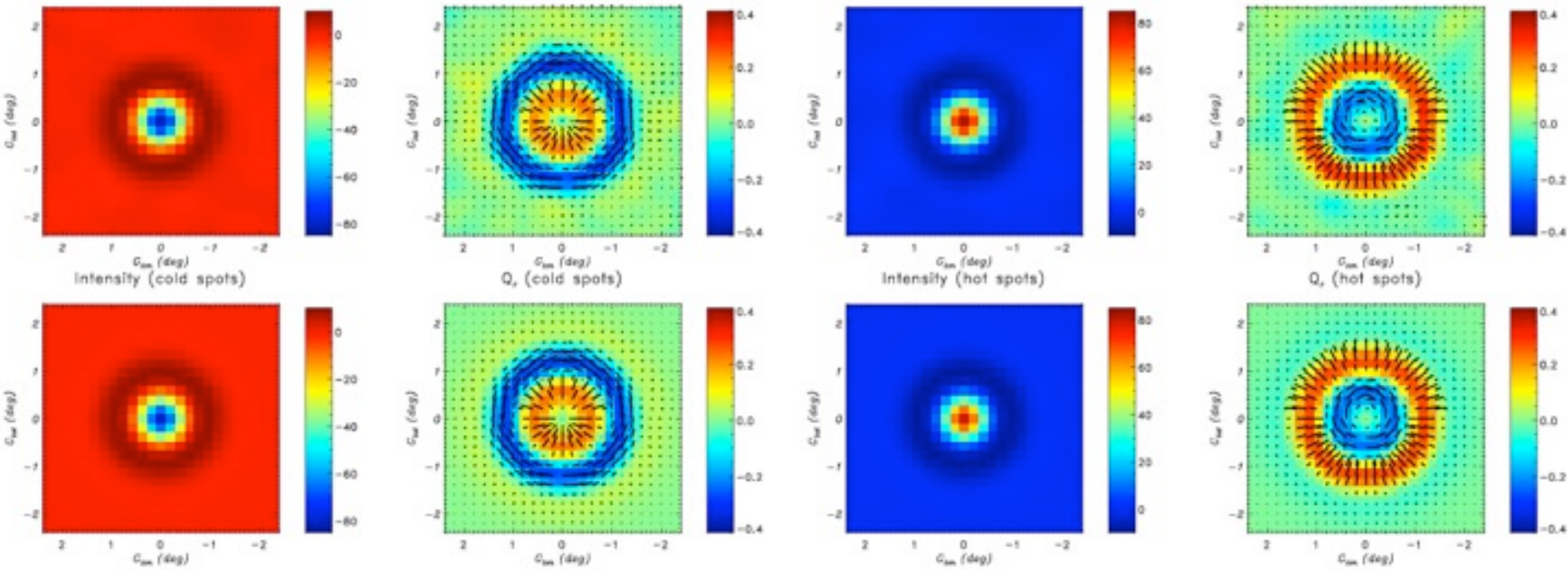
- spin-2 S.H. easily derived from regular old S.H. through derivatives
  - recall flat-sky mapping from Q/U to E/B had terms $\cos(2\phi_l)$, $\sin(2\phi_l)$
    - » $[(l_x^2-l_y^2)/l^2,\ 2l_xl_y/l^2$

Density fluctuations generate pure E mode



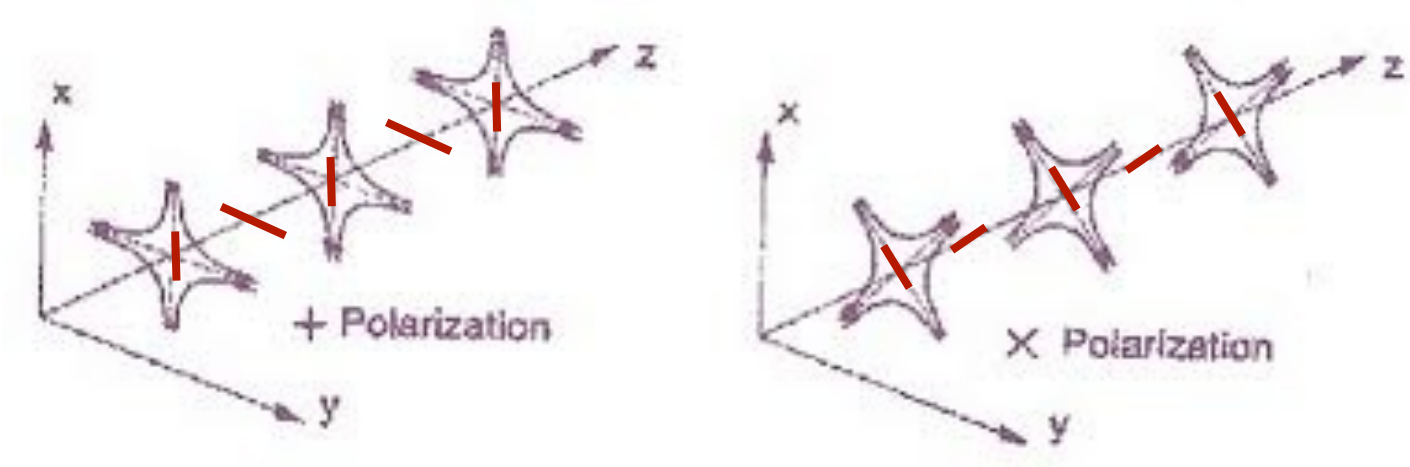
- E-modes <=> polarization
- lensing convergence <=> shear

Temperature/Polarization Correlation



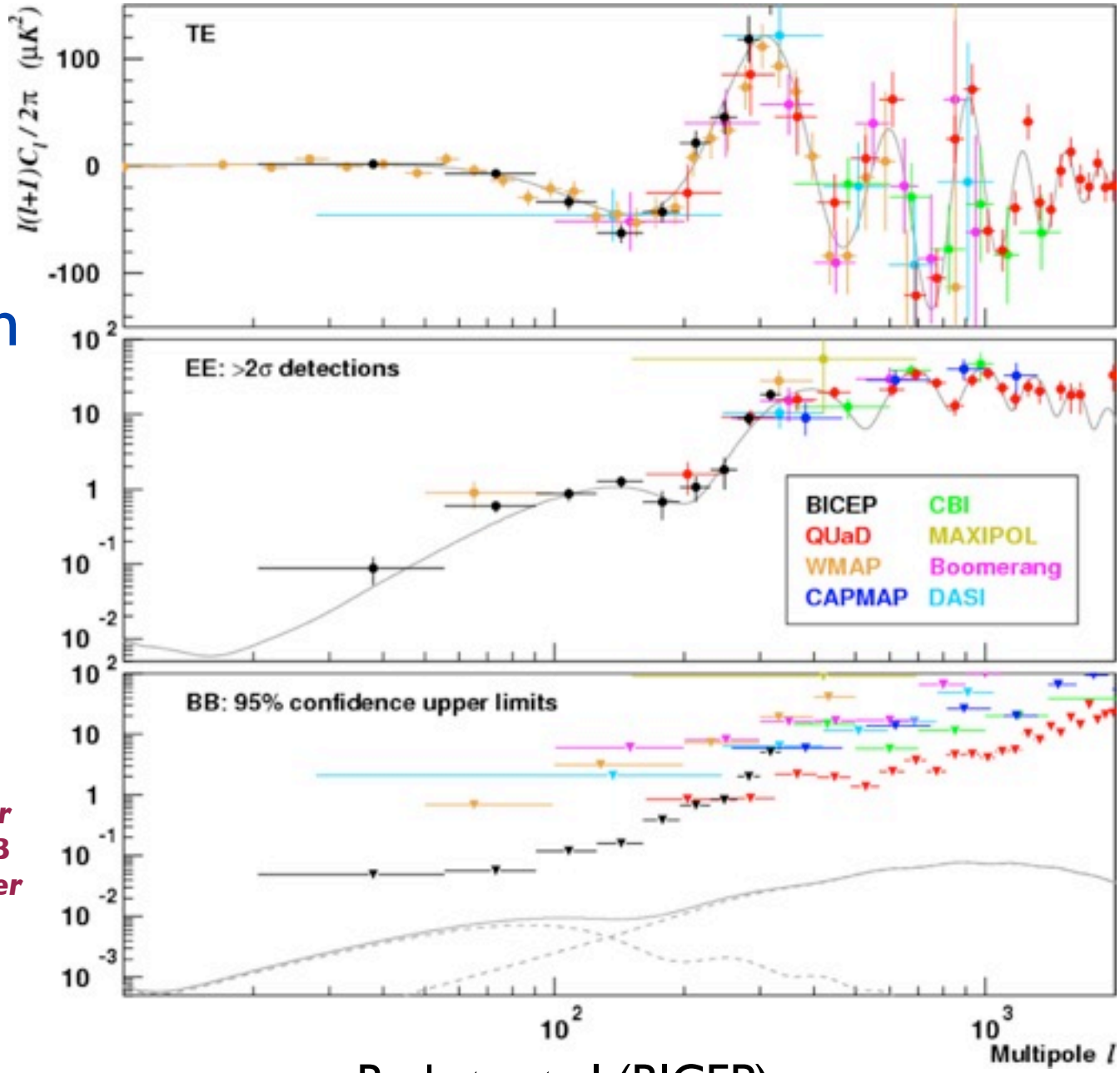
- Stack in Planck (first shown by WMAP)
- top: data, bottom: sim

Gravitational Waves Generate E and B



B modes are a great probe of gravitational radiation in the early universe!!

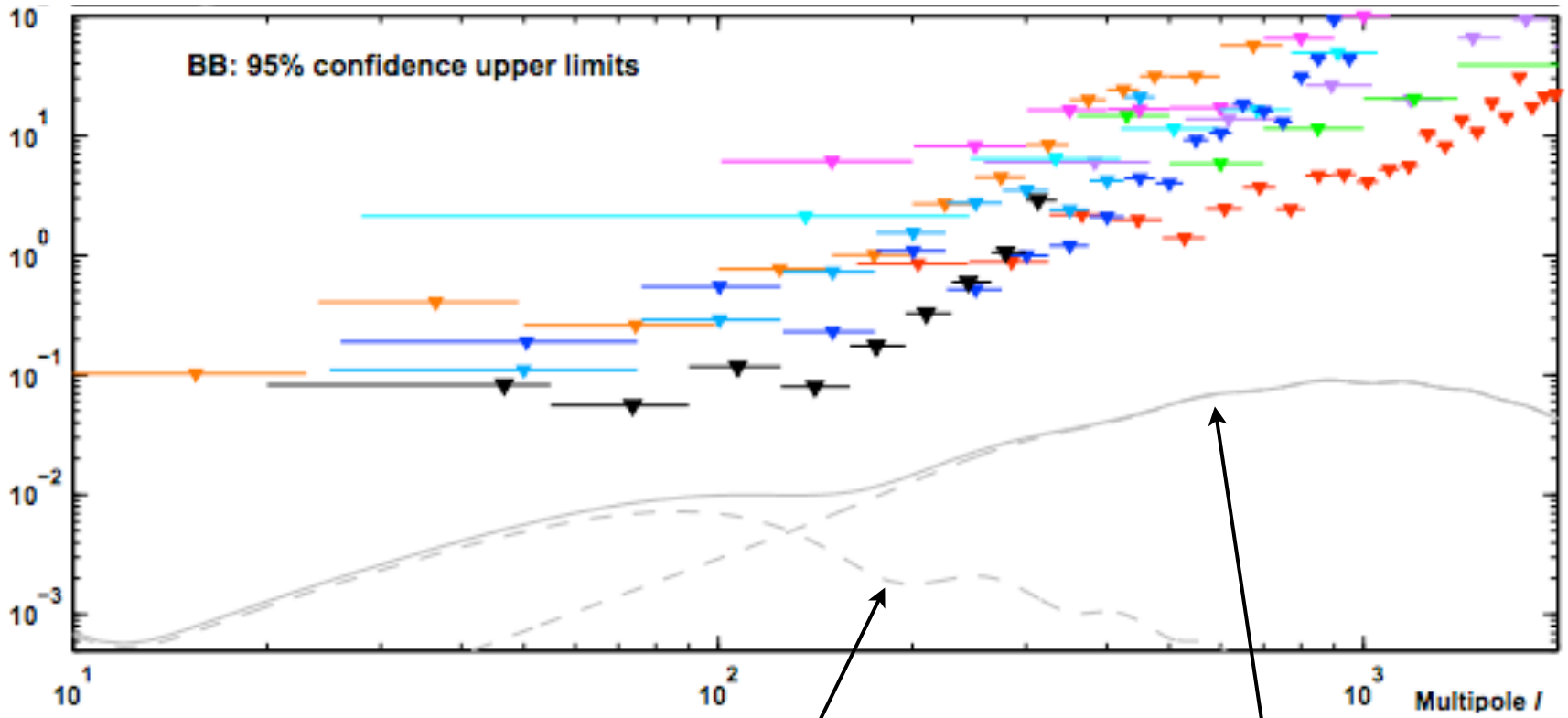
CMB Polarization Angular Power Spectra



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 (come back on Thursday!!)

Summary

- the cosmic microwave background is polarized
- CMB polarization looks very strange, compared to generic polarization patterns
- physics of polarization allows new probes of nature of perturbations: scalar vs tensor (density vs gravity waves)

Excellent Reviews

- Wayne Hu tutorials:
  - http://background.uchicago.edu/index.html
- Kosowsky:
  - http://ned.ipac.caltech.edu/level5/Kosowsky/Kosowsky_contents.html
  - http://arxiv.org/abs/astro-ph/9904102
- Zaldarriaga
  - http://arxiv.org/abs/astro-ph/0305272
- Weiss report:
  - http://arxiv.org/abs/astro-ph/0604101
- CMBPol white papers:
  - http://arxiv.org/abs/0811.3919
  - http://arxiv.org/abs/0811.3916