Cosmic Microwave Background

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Plan of the lectures

Lecture 1
Physics of the CMB: Thermal history & recombination
Acoustic Oscillations
Boltzmann equation
Harmonic expansion

Lecture 2
CMB Spectra
Polarization and CMB lensing
Status of observations

References:
Cosmological perturbations: Kodama & Sasaki 1984
CMB physics and anisotropies: Hu & Dodelson 2002
Normal modes and Boltzmann equation: Hu & White 1997
Other notes: http://arxiv.org/abs/1302.4640 by J. Lesgourges.
Experiments: lambda.gfsc.nasa.gov

What we learned so far

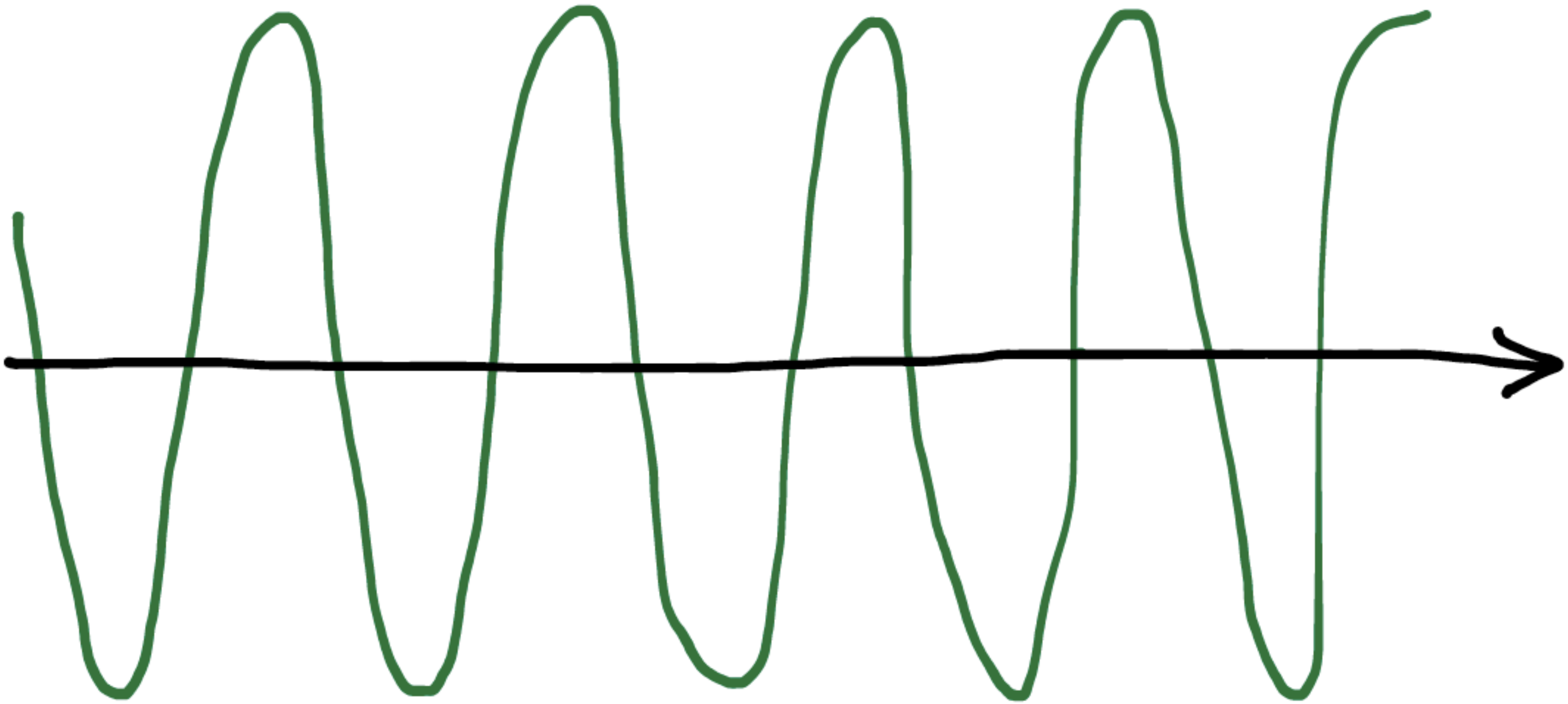
- Tight fluid photons-baryons
- (Perturbed) Boltzmann equation: the story of the distribution function
- Spectra as 2 point correlation function of the coefficients of the expansion in spherical harmonics

$$< a_{lm} a^{*}_{l'm'} >= \delta_{ll'} \delta_{mm'} C_l$$

$$\frac{\delta T}{T}(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

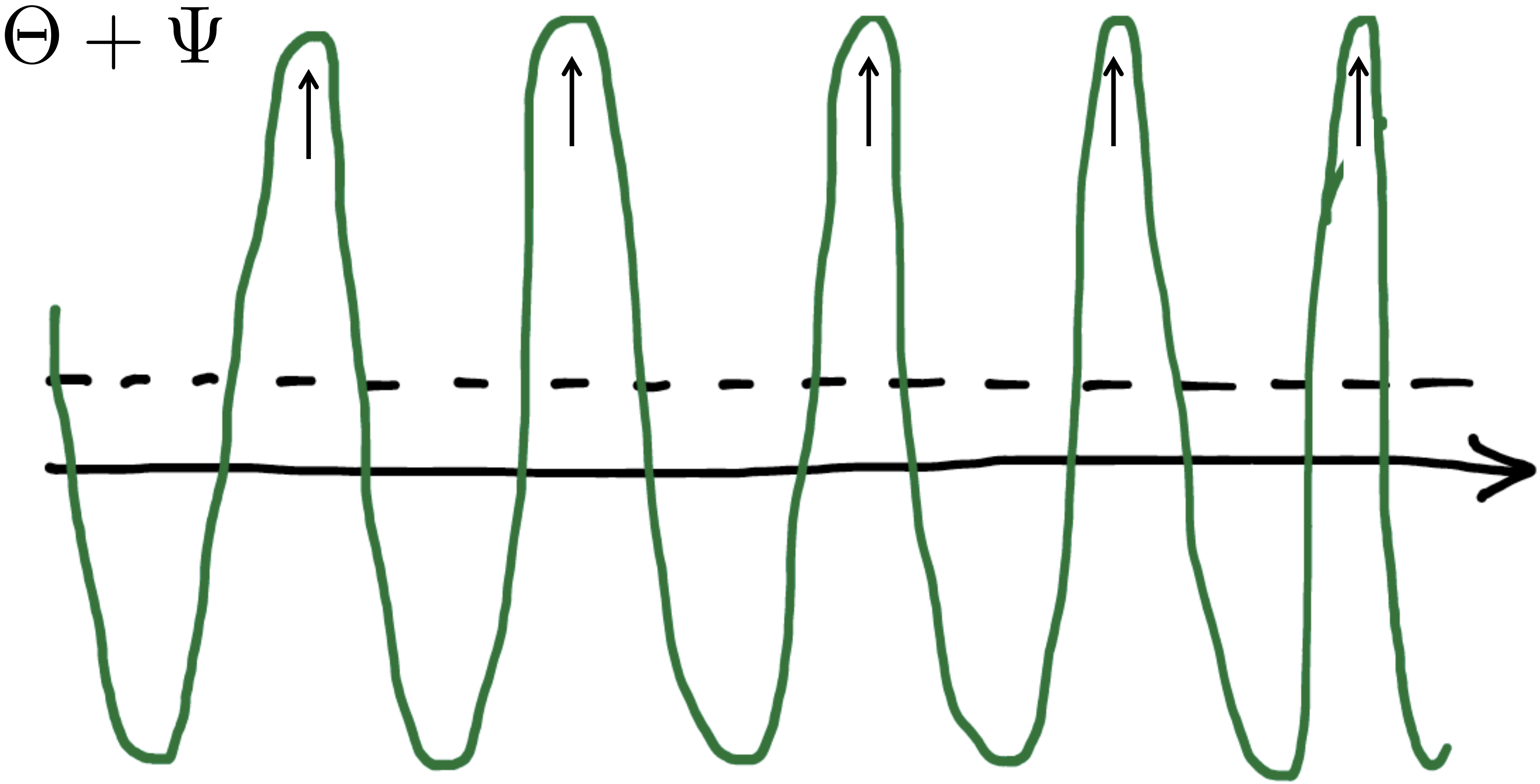
Oscillations of a tight fluid, equal amplitude

$\Theta + \Psi$



Baryon dragging

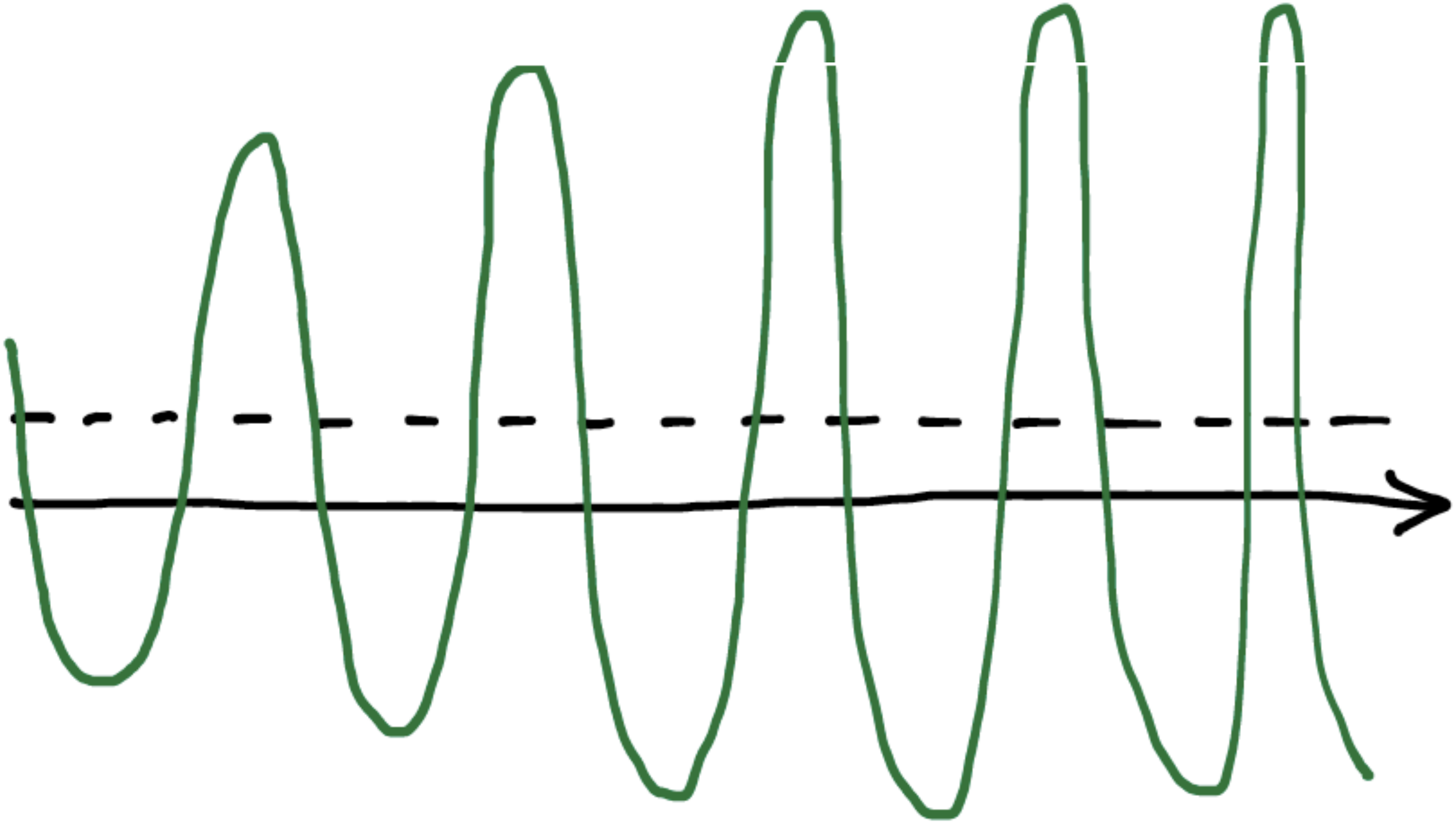
enhances compressions, shifts equilibrium point



Gravitational driving

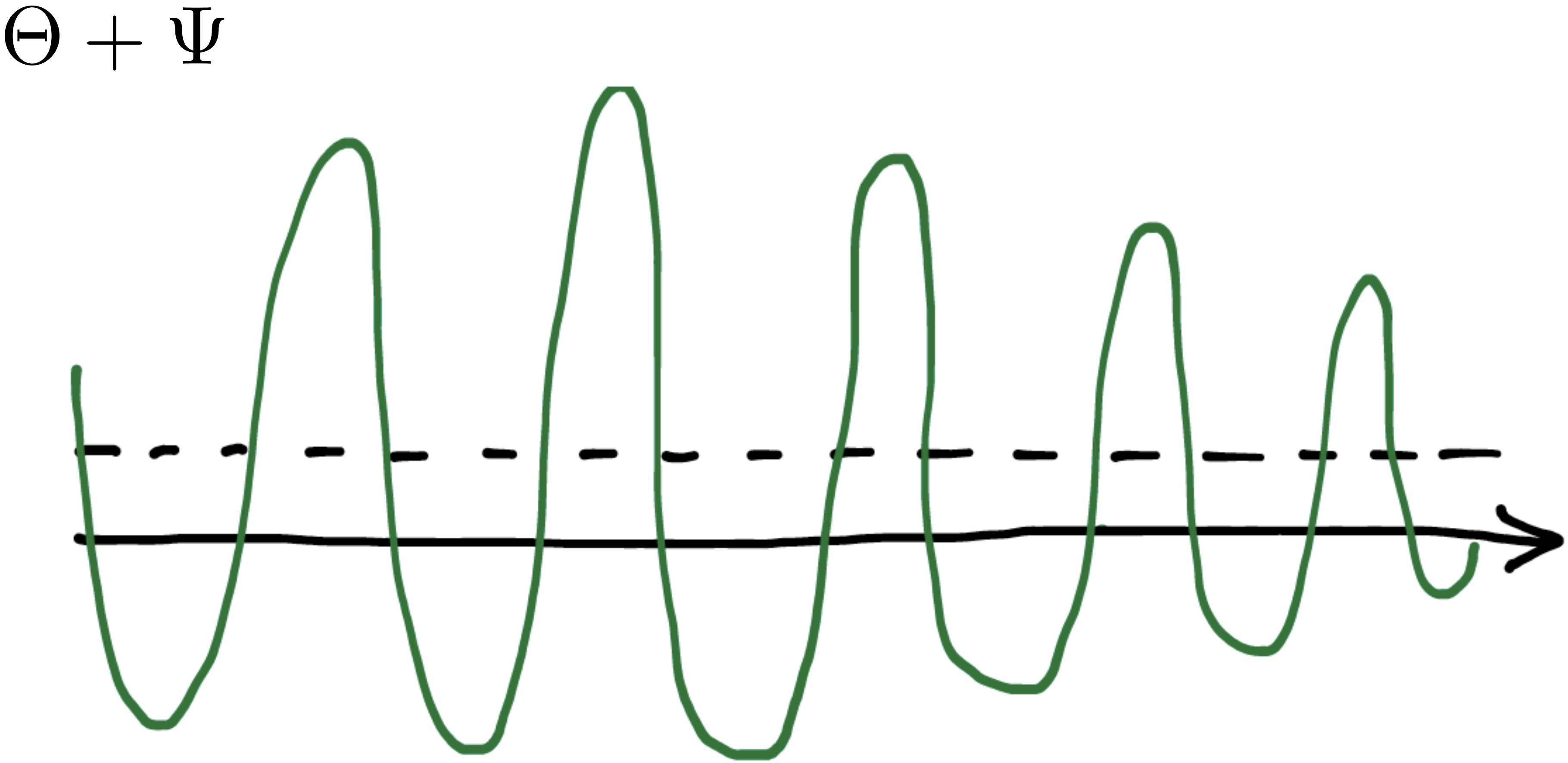
Enhances small scales with respect to large ones

$\Theta + \Psi$



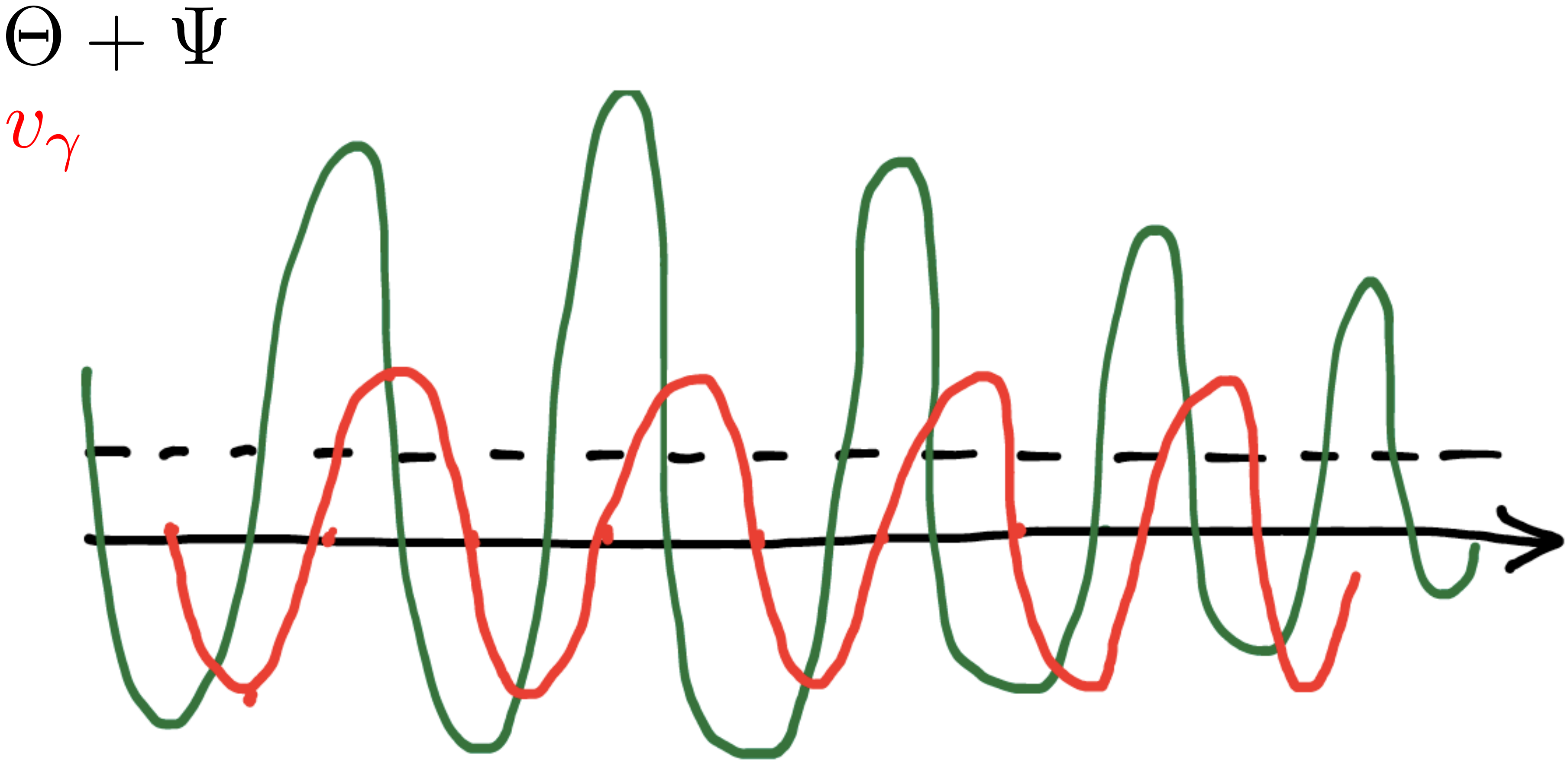
Diffusion damping

Suppresses small scales

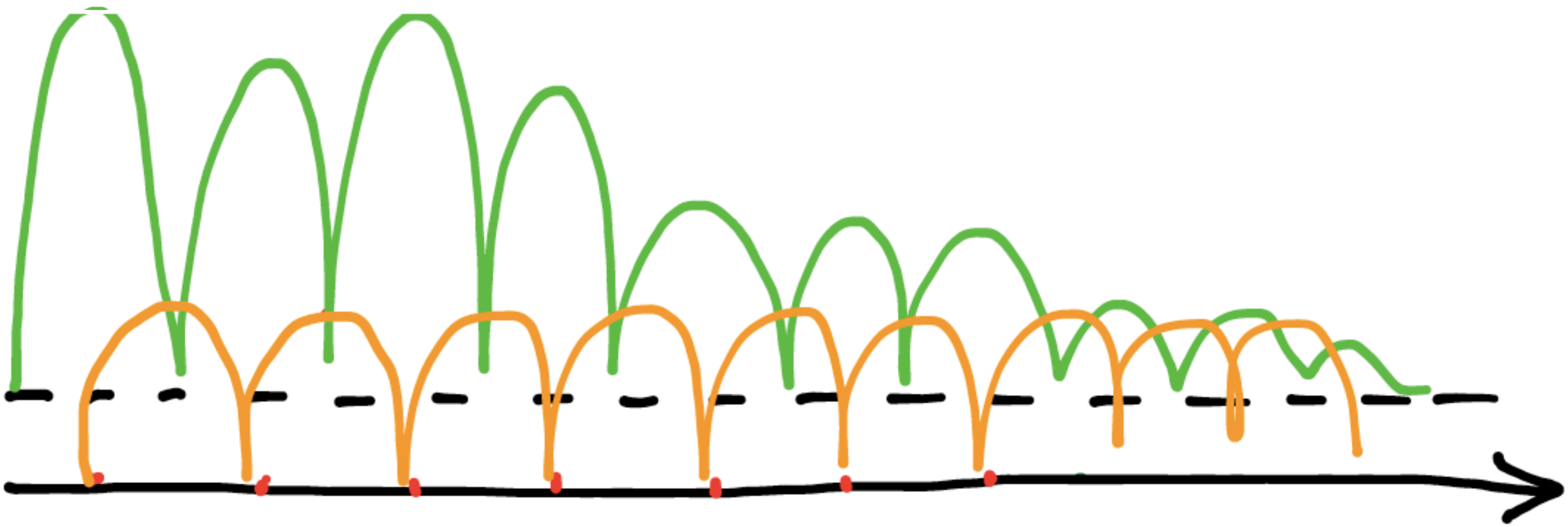


Doppler effect

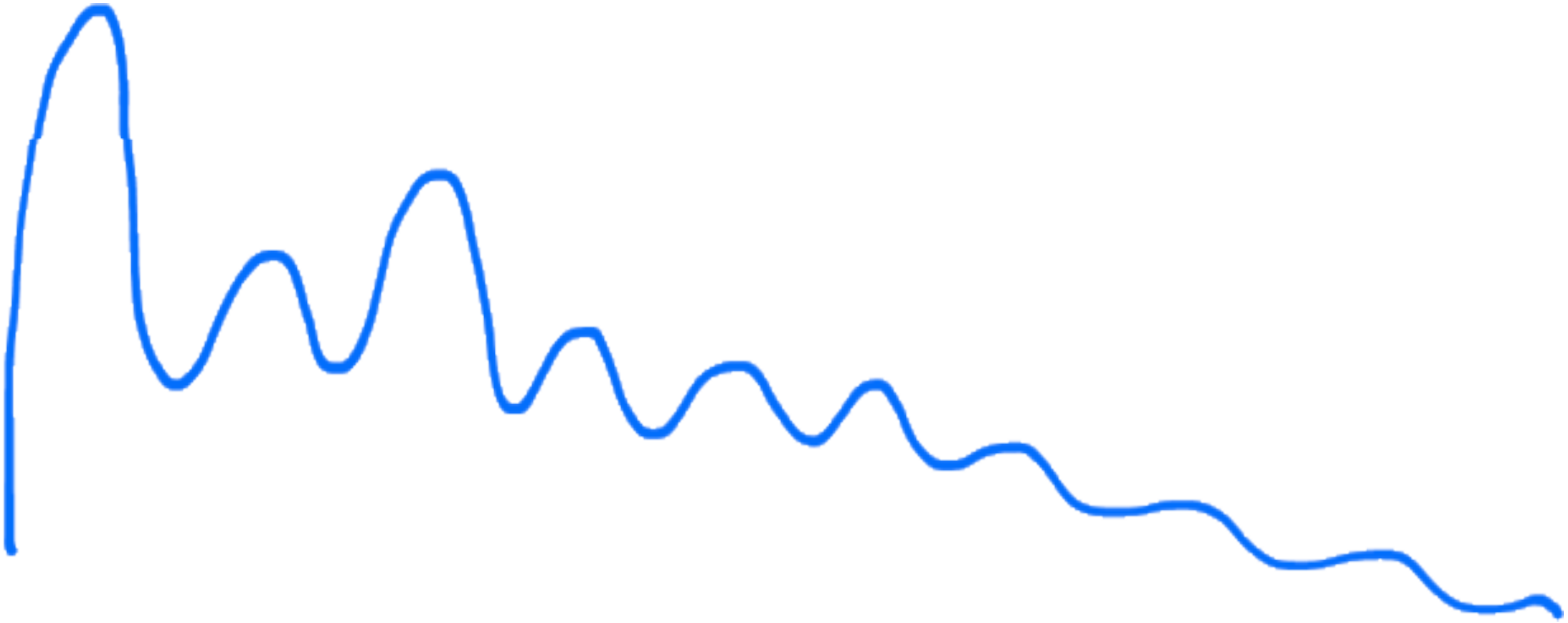
Out of phase of 90 degrees, equal amplitude



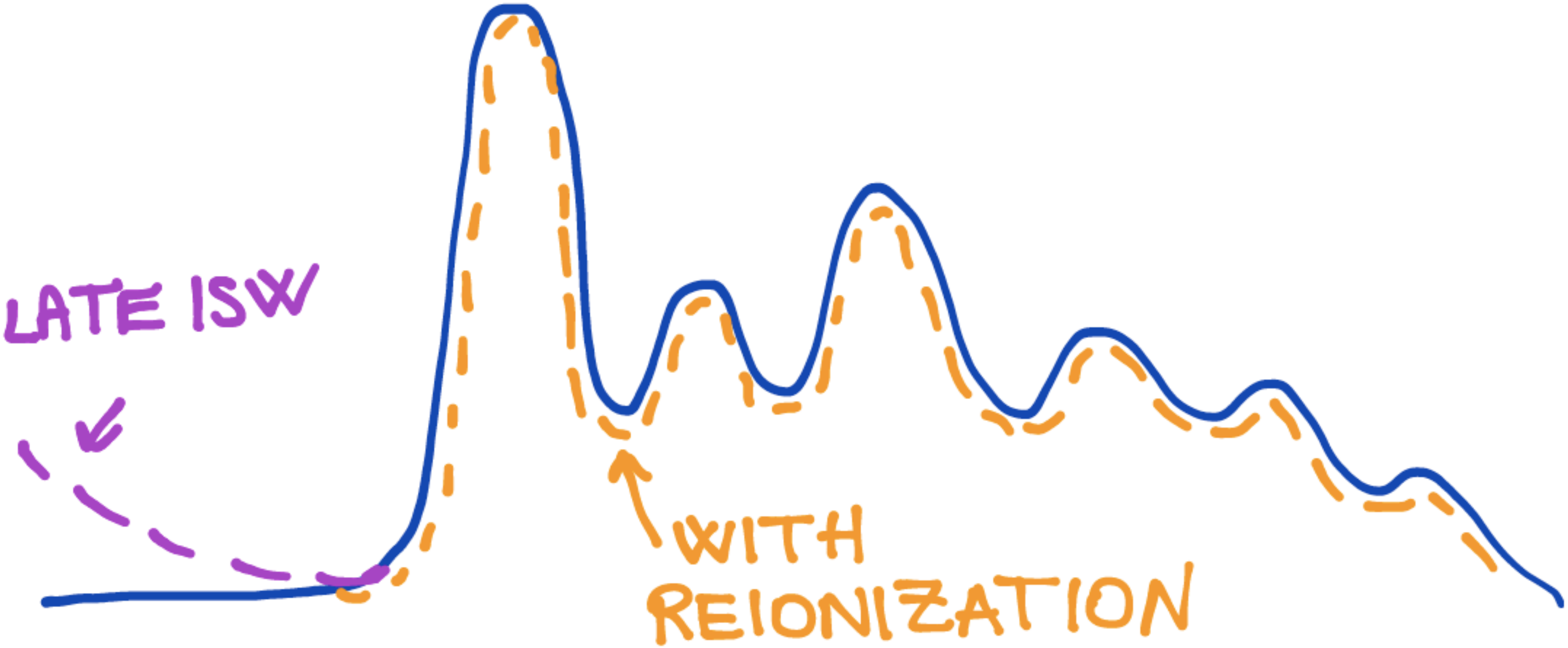
Square both



Sum



Modified along the line of sight



Start from monopole (l = 0, the 3K) and dipole (l = 1) when here is tight coupling and then populate smaller scales during free streaming.

Polarization

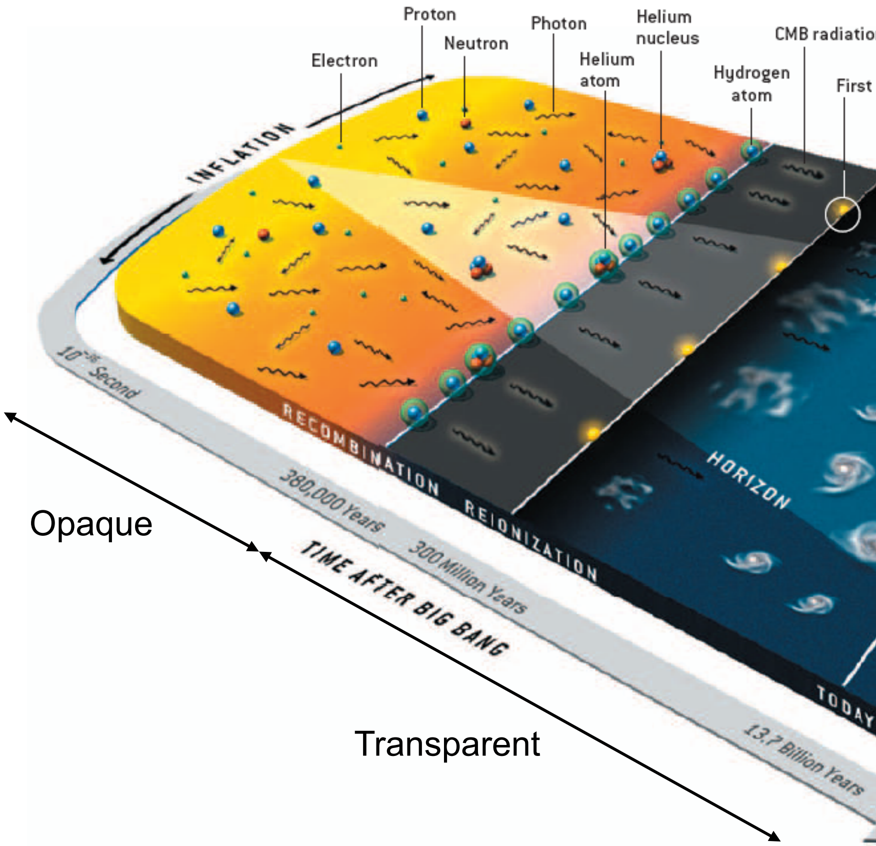
Before recombination

The photon temperature is isotropic and photons are well thermalized because of efficient interactions.

Before decoupling photons are, on average, un-polarized.

No net polarization can come from isotropy.

Evolution of the universe

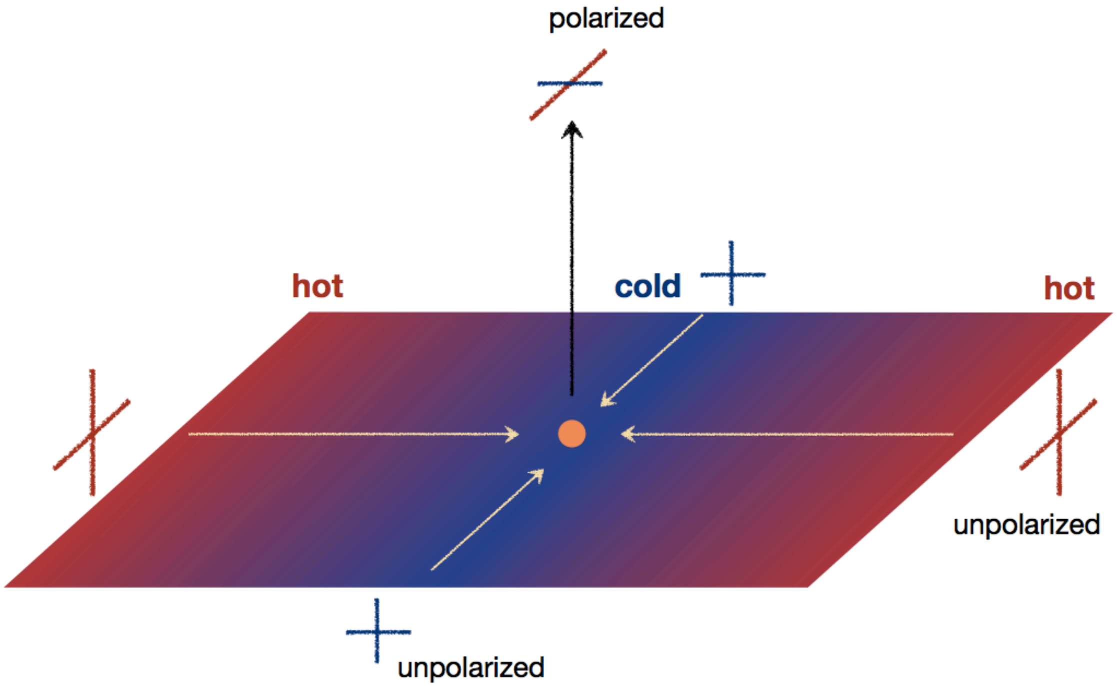


Hu & White, Sci. Am., 290 44 (2004)

Last scattering and quadrupole anisotropy

When Thomson scattering becomes inefficient, the photon temperature is no longer isotropic.

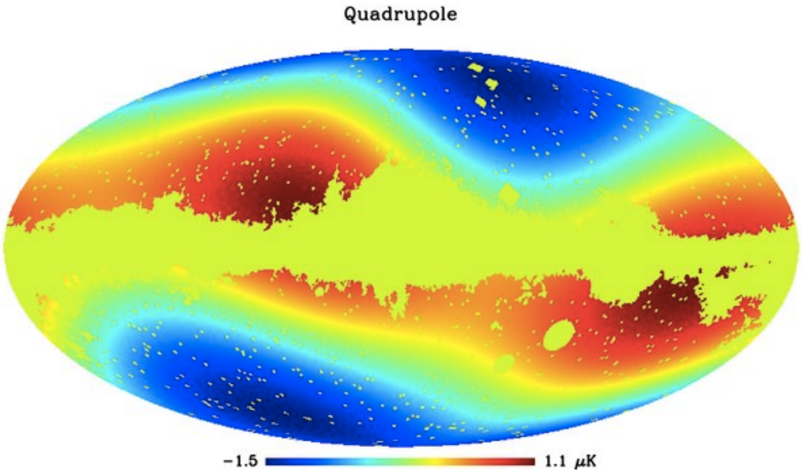
A given electron will scatter simultaneously some hotter photons coming from one direction and some colder photons coming from another direction.



CMB photons are linearly polarized: have a different polarization amplitude and orientation depending on the direction in the sky.

How much polarized?

The quadrupole is zero at early times and then grows while approaching decoupling.



Any source of quadrupole anisotropy leaves its imprint in the polarization.

The fraction depends on the duration of last scattering. It is 10% on a characteristic scale of degree scale. Since temperature anisotropies are at the 10^{-5} level, the polarized signal is at (or below) 10^{-6} level representing a significant experimental challenge.

Intensity tensor

$$I_{ab} = \frac{1}{2}\underset{\substack{\uparrow \\ \text{Total Intensity}}}{I\sigma_0} + \underset{\substack{\nwarrow \\ \text{Polarization tensor}}}{P_{ab}}$$

$$P_{ab} = \frac{1}{2}\left(Q\sigma_3 + U\sigma_1 - V\sigma_2\right)$$

$$\boldsymbol{\sigma}_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \boldsymbol{\sigma}_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \boldsymbol{\sigma}_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \boldsymbol{\sigma}_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Q, U, V Stokes parameters

Q: linear polarization; U linear polarization rotated of 45°

V circular polarization

Not convenient under rotations

(A bit) more formally

Analogously to what we did for temperature, we can expand Stokes parameter in a convenient basis, on tensor normal modes.

$$\Theta(\eta,\vec{x},\vec{n}) = \frac{\delta T}{T} = \int \frac{d^3k}{(2\pi)^3} \sum_l \sum_{m=-2}^{2} \Theta_{lm}(\eta,\vec{k}) G_{lm}(\vec{k},\vec{x},\hat{n})$$

$$(Q \pm iU)(\eta,\vec{x},\vec{n}) = \int \frac{d^3k}{(2\pi)^3} \sum_l \sum_{m=-2}^{2} (E_{lm} \pm iB_{lm})\, {}_{\pm 2}G_{lm}$$

Boltzmann equations for polarization

These coefficients satisfy the Boltzmann polarization equation:

$$\dot{E}_\ell^{(m)} = k\left[\frac{{}_2\kappa_\ell^m}{2\ell-1}E_{\ell-1}^{(m)} - \frac{2m}{\ell(\ell+1)}B_\ell^{(m)} - \frac{{}_2\kappa_{\ell+1}^m}{2\ell+3}E_{\ell+1}^{(m)}\right] - \dot{\tau}E_\ell^{(m)} + \mathcal{E}_\ell^{(m)}$$

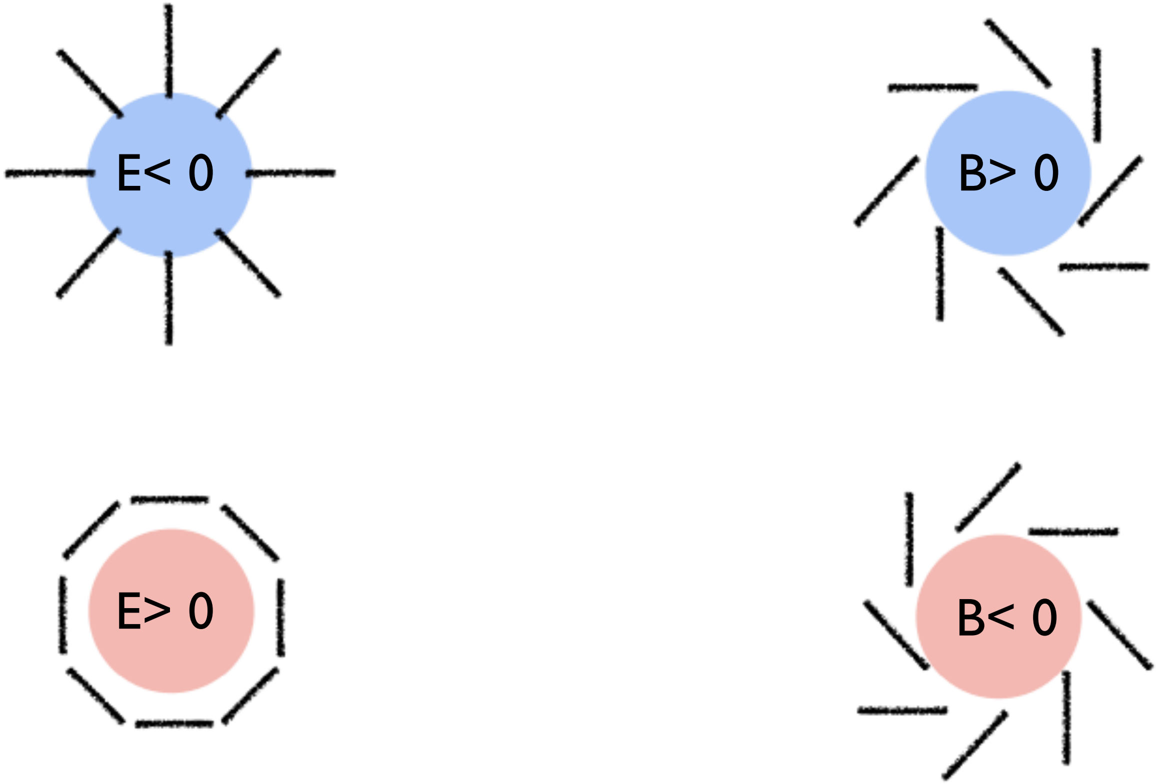
$$\dot{B}_\ell^{(m)} = k\left[\frac{{}_2\kappa_\ell^m}{2\ell-1}B_{\ell-1}^{(m)} + \frac{2m}{\ell(\ell+1)}E_\ell^{(m)} - \frac{{}_2\kappa_{\ell+1}^m}{2\ell+3}B_{\ell+1}^{(m)}\right] - \dot{\tau}B_\ell^{(m)} + \mathcal{B}_\ell^{(m)}$$

Free streaming

Thomson scattering

Sources

Summing over many waves, we get the following polarization patterns around **hot** and **cold** spots:



E-mode

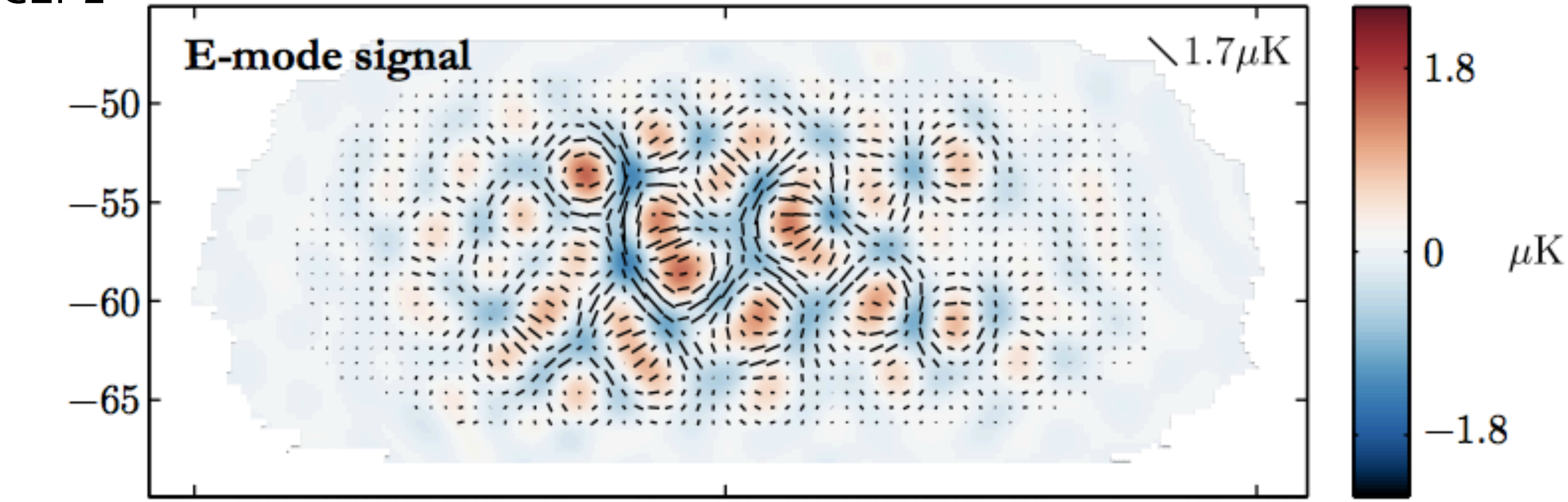
(grad)

B-mode

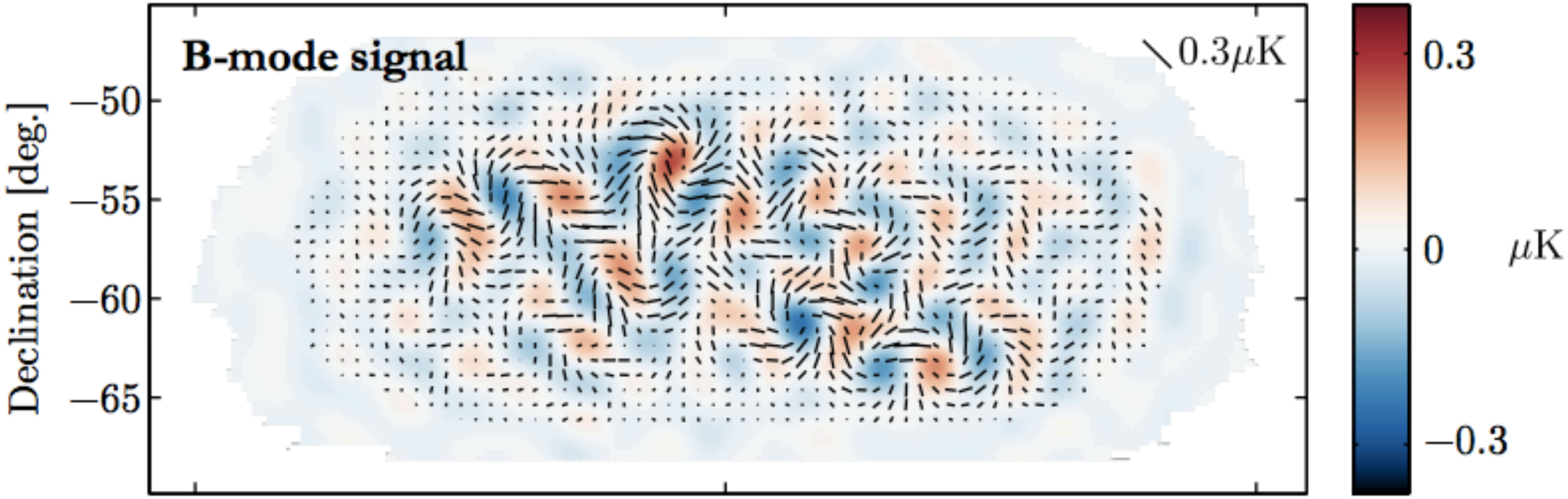
(curl)

Courtesy of
D.Baumann

BICEP2



Projection of the quadrupole anisotropy on the transverse plane (with respect to the wavevector) gives the polarization pattern.



Polarization maps are represented with sticks of different size and orientation in different points: these can be related to the magnitude and orientation of the quadrupole anisotropy on the last scattering surface.

Origin of E and B modes

Scalar perturbations → E modes → part can convert in (lensing) B modes

Vector perturbations → E and (primordial) B modes — vorticity in the plasma, decay

Tensor perturbations → E and (primordial) B modes

Hence the polarization of the CMB is a potentially useful probe of the level of gravitational waves in the early universe

Importance of polarization

If the temperature anisotropies we observe are indeed the result of primordial fluctuations, their presence at last scattering would polarize the CMB: good test that we understand the theory.

Can break some degeneracies. Ex. Amplitude/reionization; SW and Doppler terms.

Different sources of temperature anisotropies (scalar, vector and tensor) give different patterns in the polarization.

Test of inflation

Phase: T vs polarization

Polarization is sourced by quadrupole anisotropies in intensity.

The quadrupole in intensity is sourced by the dipole, so polarization is directly proportional to the dipole at recombination.

$$\boxed{\begin{aligned} \Theta + \Psi &\propto cos(ks) \\ v_\gamma &\propto sin(ks) \end{aligned}}$$

E and B modes are out of phase with T anisotropies.

Polarization spectra

The (primordial) polarization peaks at angular scales smaller than the horizon at last scattering due to causality

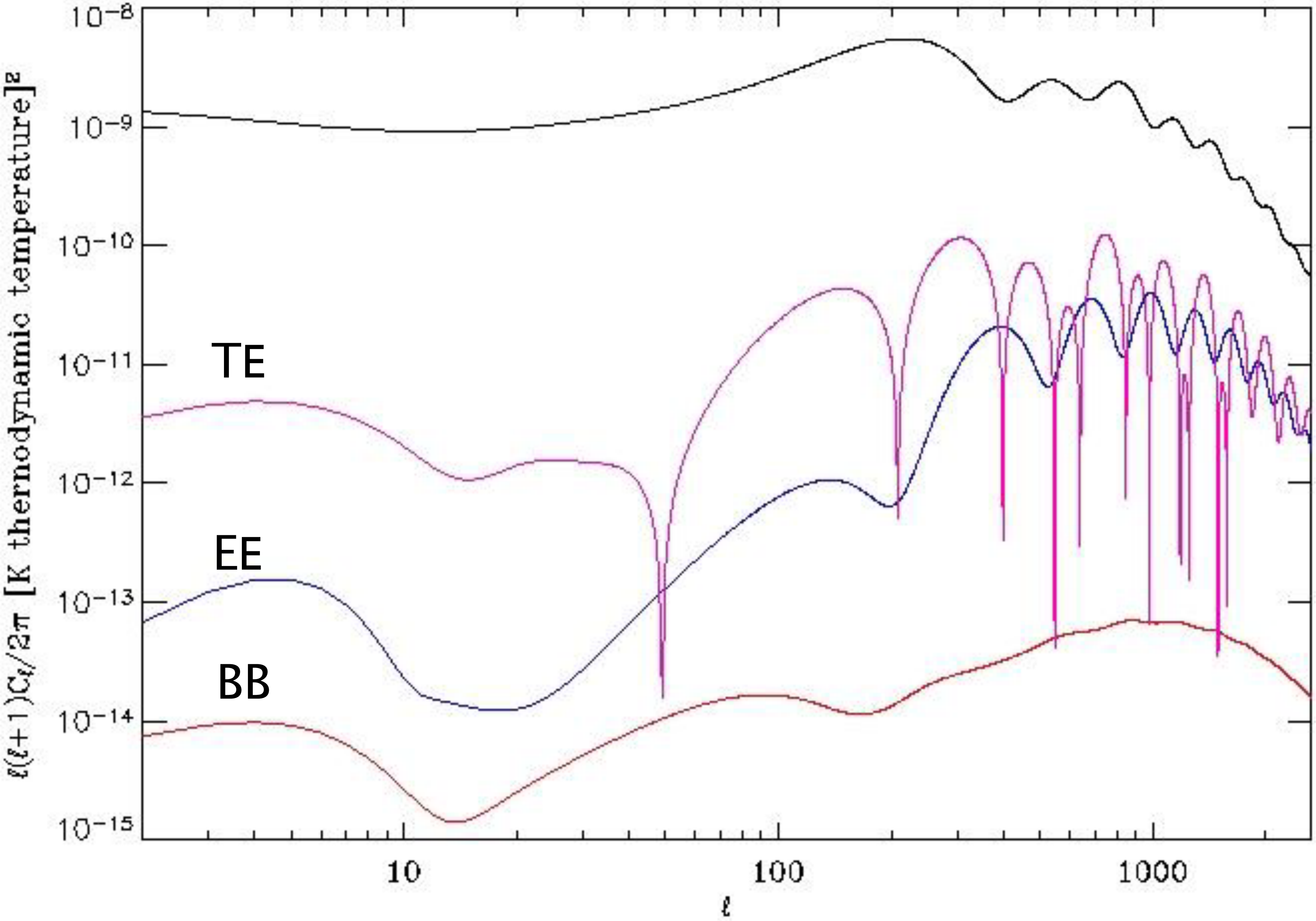
We expect also a non-zero correlation with Temperature maps.

$$C_l^{EE} = \frac{1}{2l+1}\sum_m |E_{lm}|^2 \qquad C_l^{BB} = \frac{1}{2l+1}\sum_m |B_{lm}|^2$$

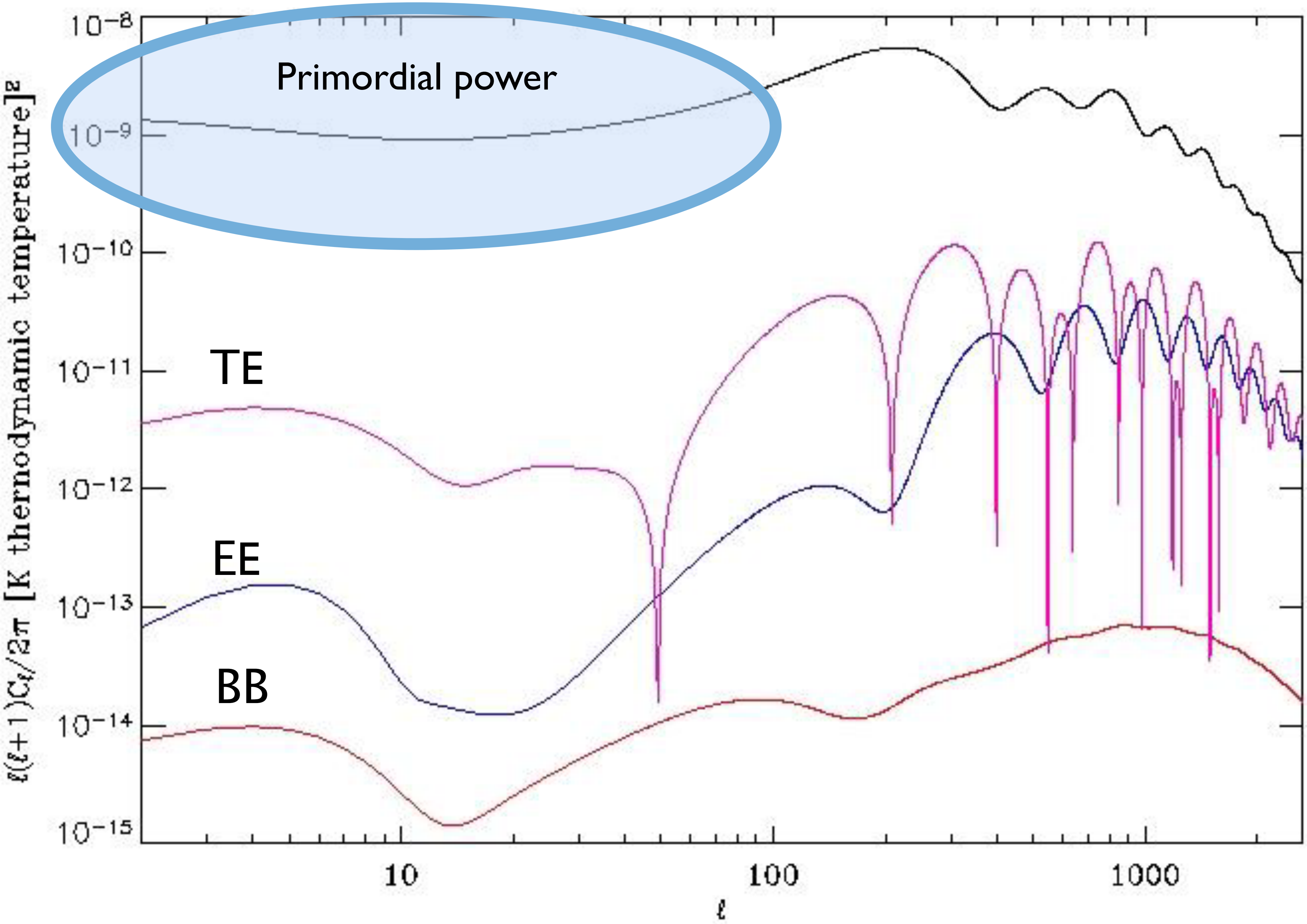
$$C_l^{TE} = \frac{1}{2l+1}\sum_m \Theta_{lm} E_{lm}$$

C_l^{TB}, C_l^{EB} are expected to be zero, they have different parity

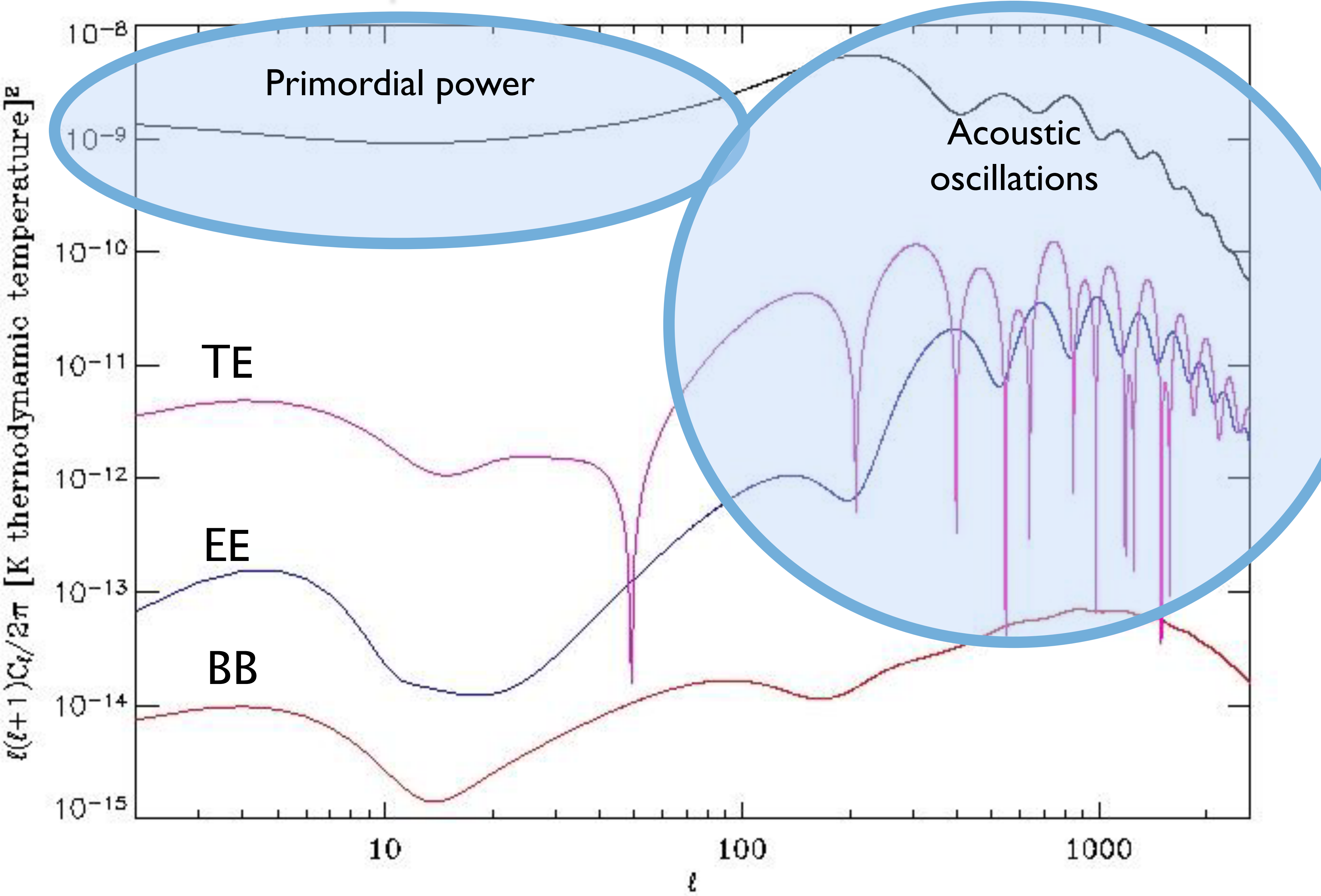
Polarization spectra



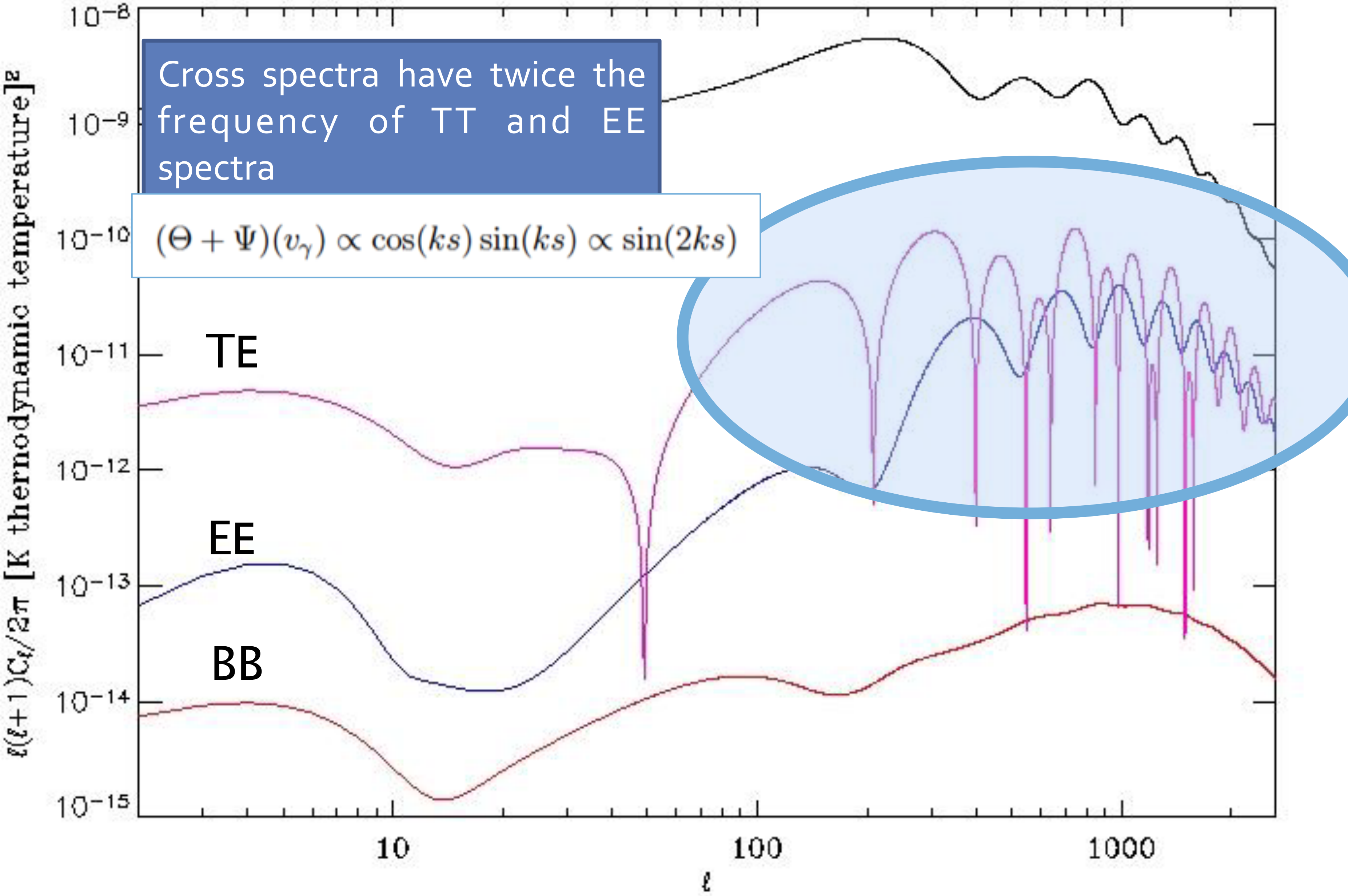
Polarization spectra



Polarization spectra



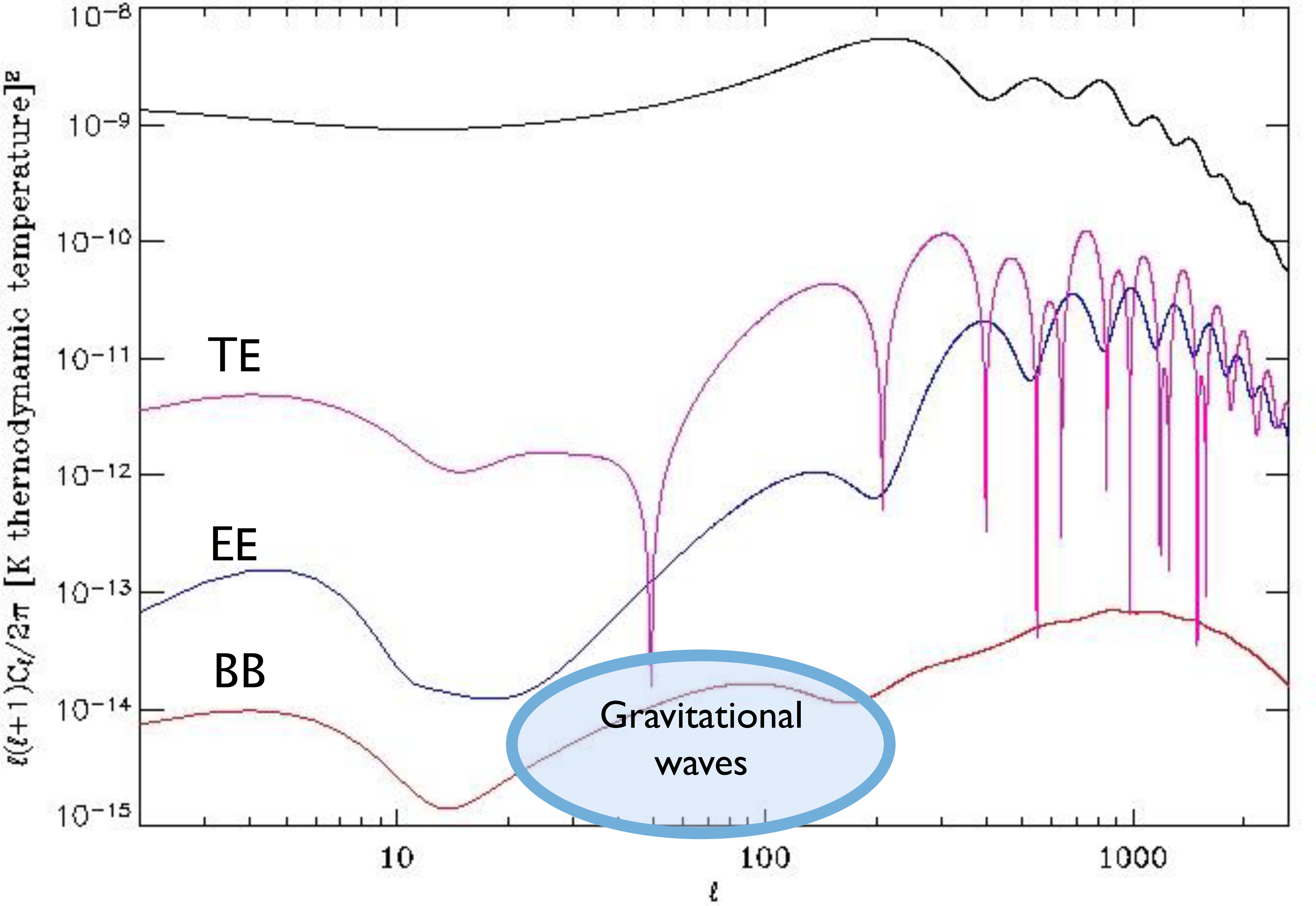
Polarization spectra



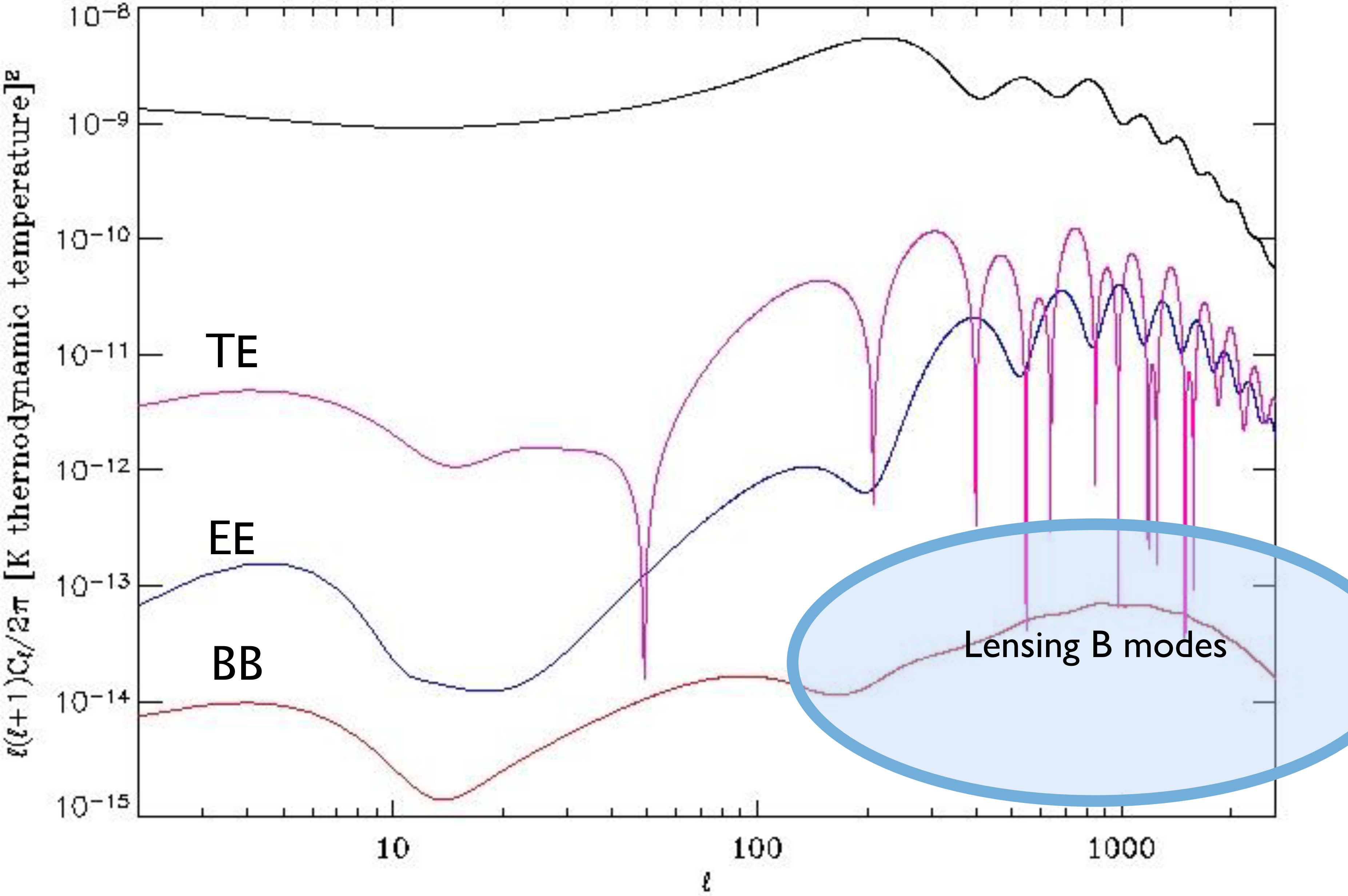
Cross spectra have twice the frequency of TT and EE spectra

$$(\Theta + \Psi)(v_\gamma) \propto \cos(ks)\sin(ks) \propto \sin(2ks)$$

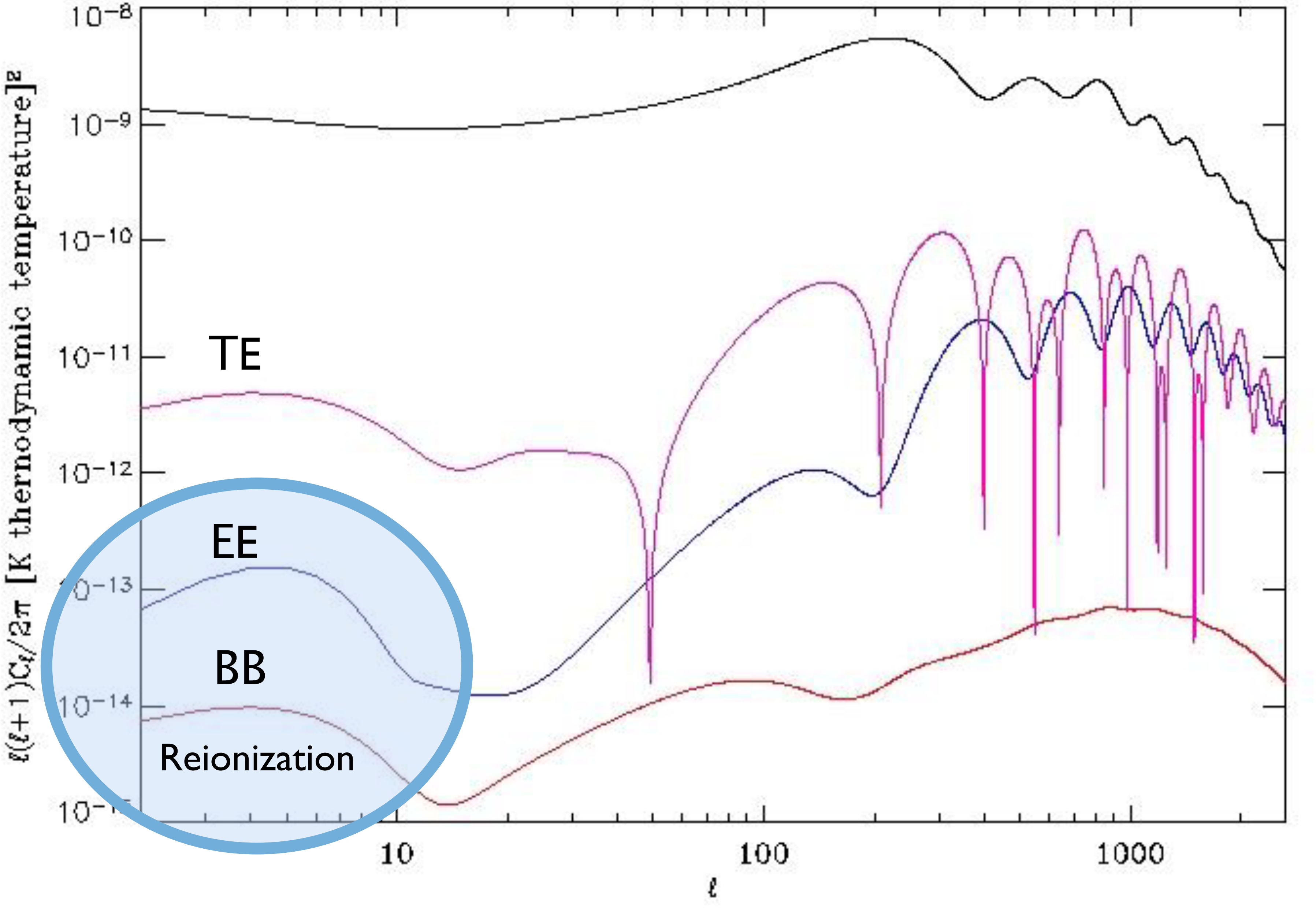
Polarization spectra



Polarization spectra



Polarization spectra



B modes and inflation

During inflation, quantum fluctuations can excite tensor perturbations

The amplitude of gravitational waves follow Einstein equation for tensor modes:

$$\ddot{H}_T^{\pm 2} + 2\mathcal{H}\dot{H}_T^{\pm 2} + k^2 H_T^{\pm 2} = 8\pi G a^2 p \pi_T^{\pm 2}$$

The power spectrum of GW amplitude is proportional to the expansion H^2 (just like for the inflaton) and therefore to the potential V(ϕ) of inflation.

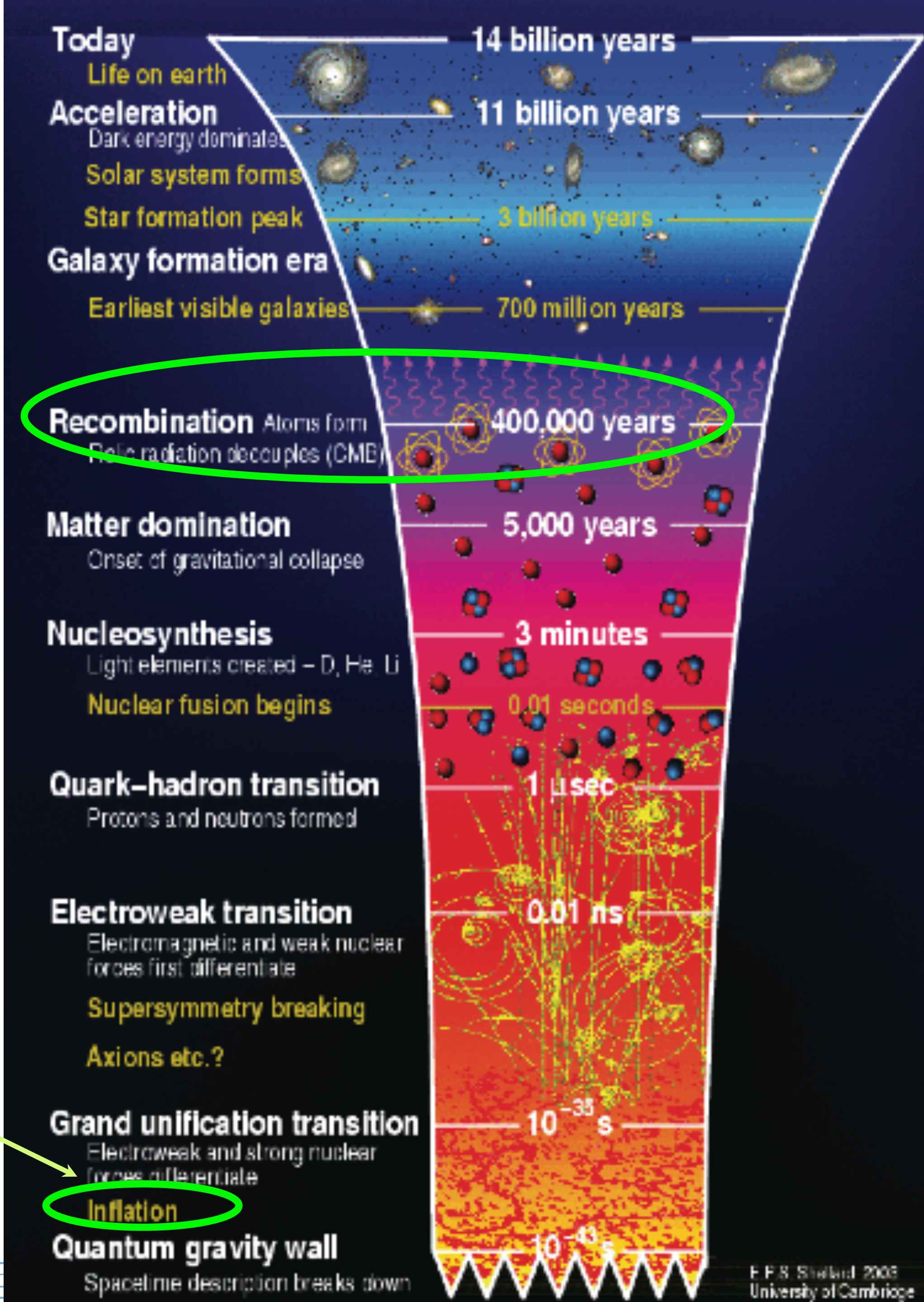
Measurement of B modes determines the energy scale of inflation $E_i = V^{1/4}$

$$B_{peak} \approx 0.024 \left(\frac{E_i}{10^{16} GeV} \right)^2 \mu K$$

Last scattering

Deriving from physics at this epoch

Lensing also generates B modes.



Tensor to scalar ratio

$$r \equiv 4\frac{P_{H_T}^2}{P_R^2} = 16\epsilon$$

In turn, the slow roll parameter depends on the inflaton

$$\epsilon = \frac{1}{2M_{Pl}^2}\left(\frac{d\phi}{d\ln a}\right)^2$$

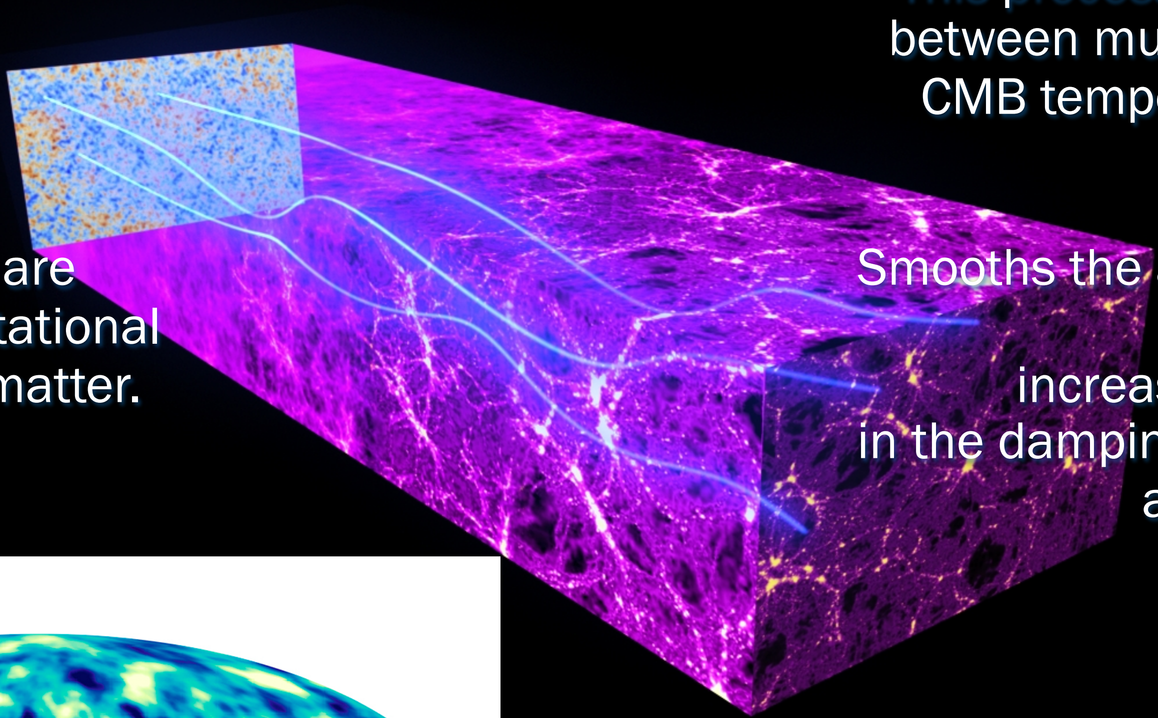
A large r implies a large slow roll parameter and a large variation of the inflaton

If the tensor amplitude is large, tensors can also feed C_l^{TT} at large scales (then decay quickly inside the horizon). A big r would distort the TT spectrum at l < 100.

CMB lensing

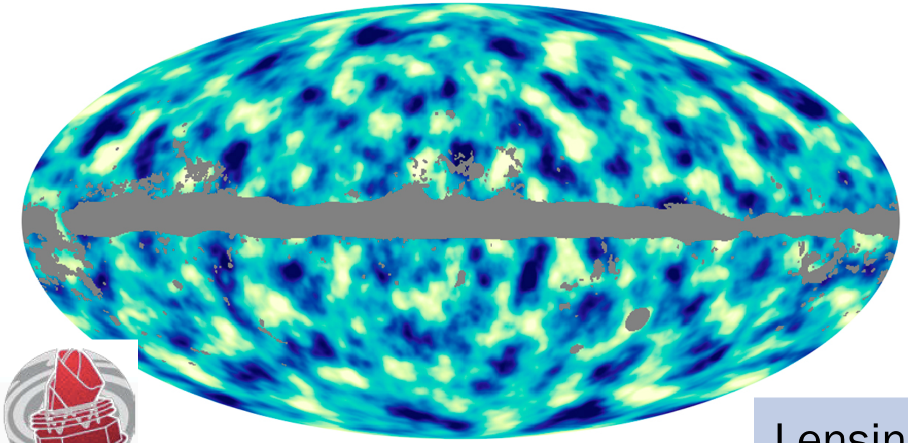
Gravitational lensing of the CMB

As CMB photons travel from the surface of last scattering to the Earth, their paths are deflected by gravitational interactions with matter.



This process mixes power between multipoles in the CMB temperature power spectrum,

Smooths the acoustic peak structure and increases the power in the damping tail at small angular scales



Distribution of matter (across history of the Universe) projected on the sky.
Darker regions are denser

Lensing encodes information from late time Universe

Deflection

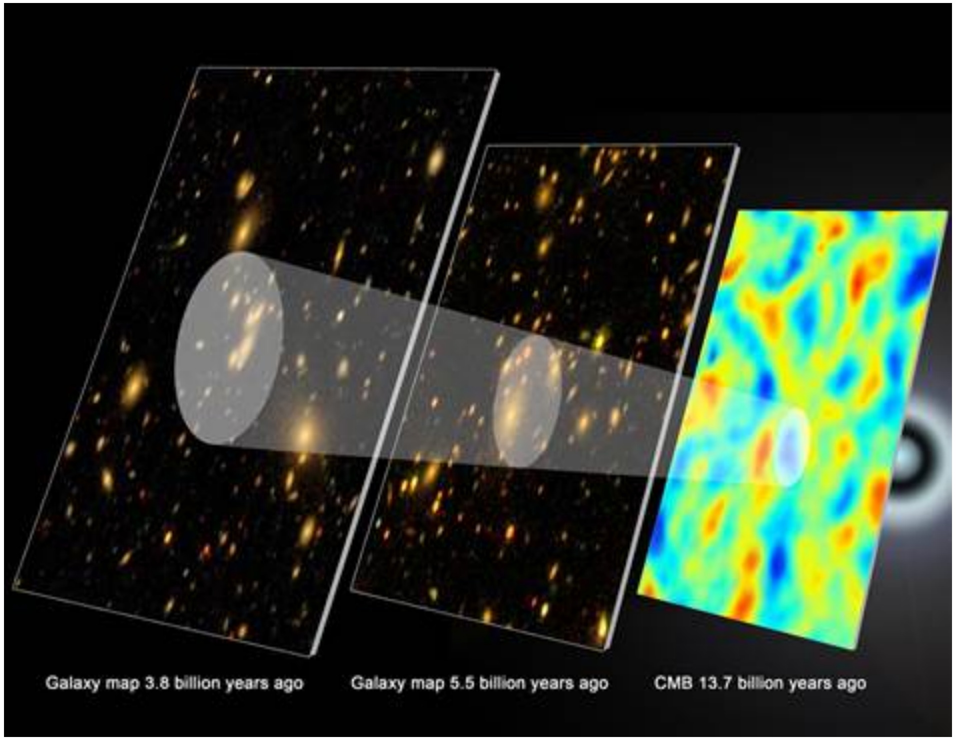
$$\tilde{\Theta}(\hat{n}) = \Theta(\hat{n} + \nabla\psi)$$

Lensed

Unlensed calculated in the deflected direction

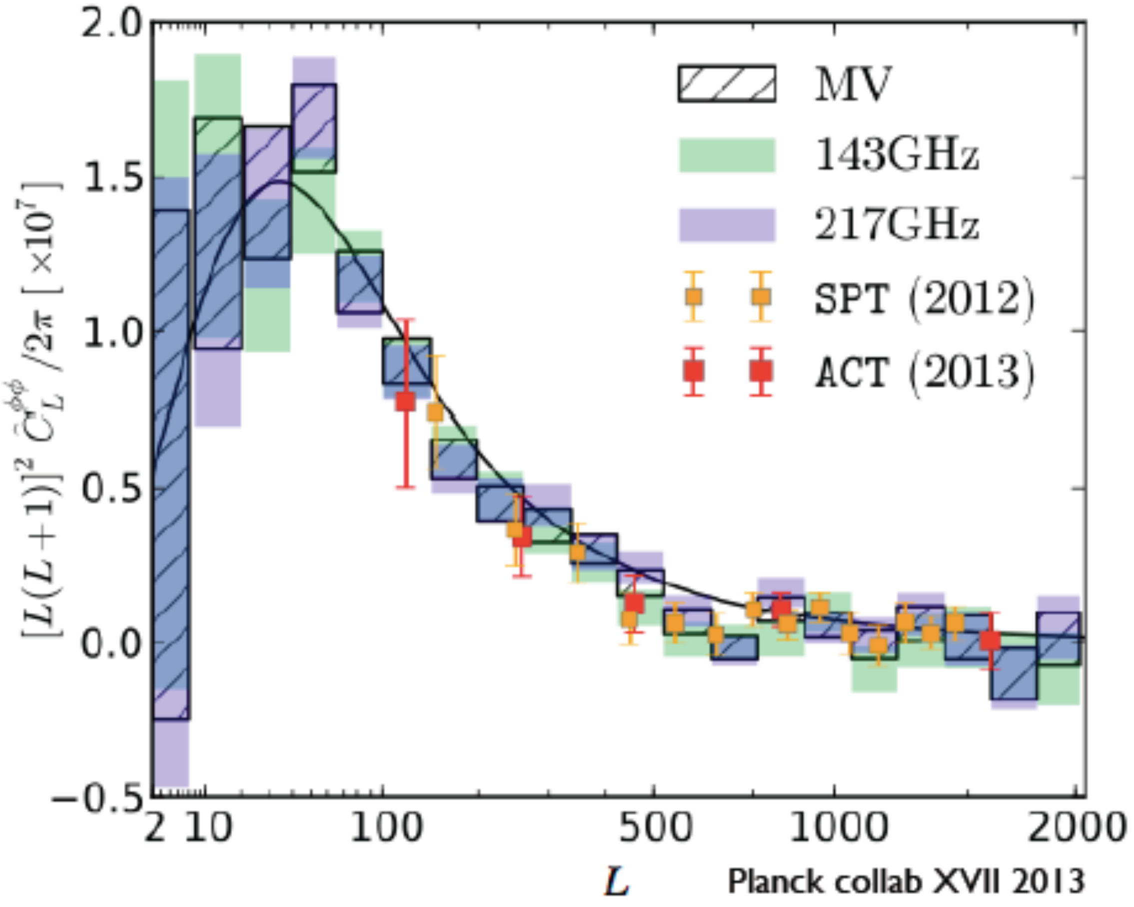
Deflection is a couple of arcminutes, but correlation among different deflection angles gives power to lensing on degree scales, where CMB peaks are.

The deflection field (the lensing potential) can be related to the matter power spectrum.



The lensing potential, convolved with the Temperature power spectrum transfers power from large to small scales

$$\tilde{C}_l^{\Theta} \approx \int dl C_{l-l'}^{\psi} C_{l'}^{\Theta}$$



Planck collab XVII 2013

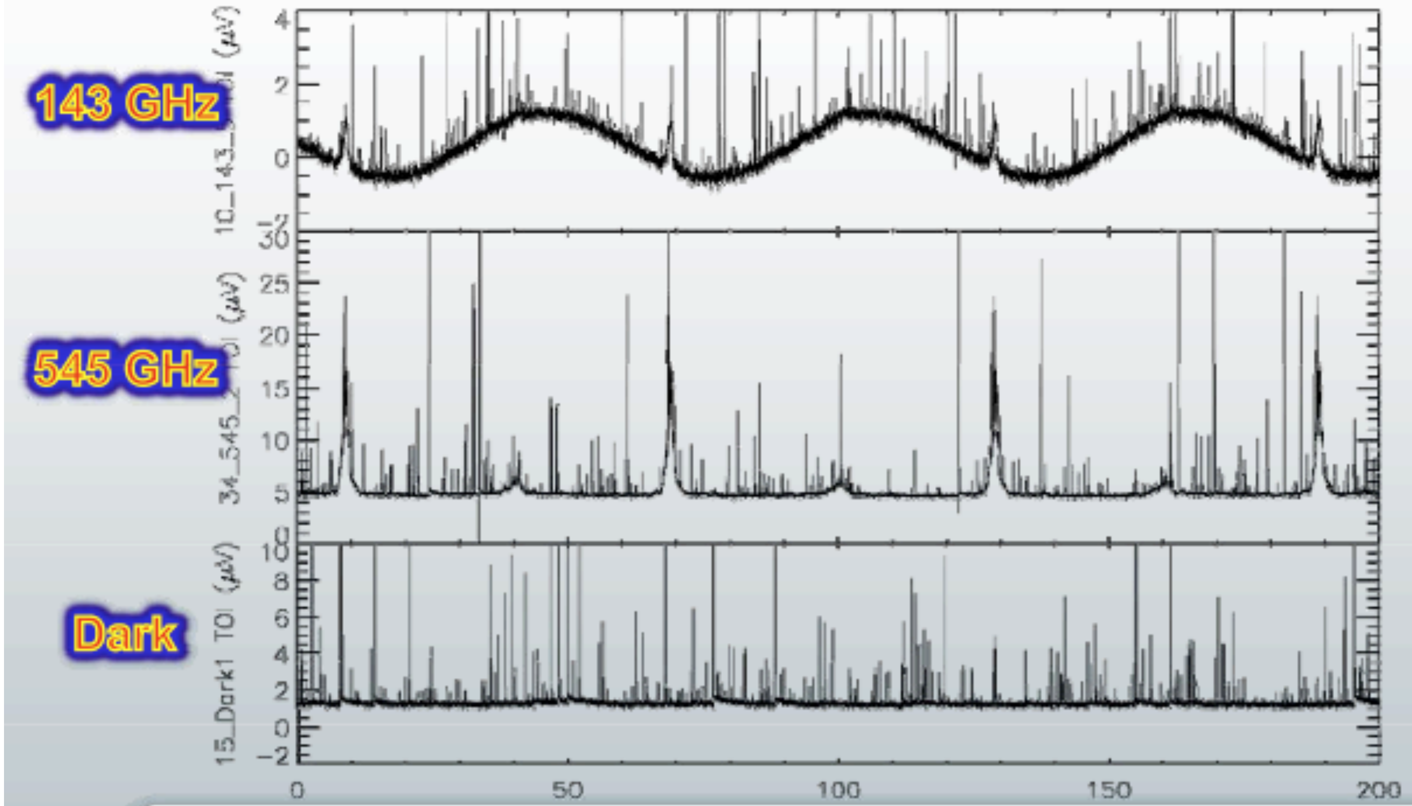
First direct measurement: ACT 2011, 4σ (Das et al, update in 2013)

Then SPT in 2012 (Van Engelen et al, 6σ)

Now Planck in 2013 (Planck Collab XVII, 25σ)

Data processing

Time ordered data



3 minutes of quasi 'raw" data (i.e. only demodulated).The Solar (cosmological) dipole is clearly visible at 145GHz with a 60 seconds period (the satellite rotates at 1 rpm), while the Galactic plane crossings (2 per rotation) are more visible at 545 GHz than at 143 GHz. The Dark bolometer sees no sky signal, but displays a similar population of glitches from cosmic rays.

From time ordered data to maps

Time ordered data stream indexed by t

$$d_t = P_{ti}\Theta_i + n_t$$

Where i denotes the pixelized position.

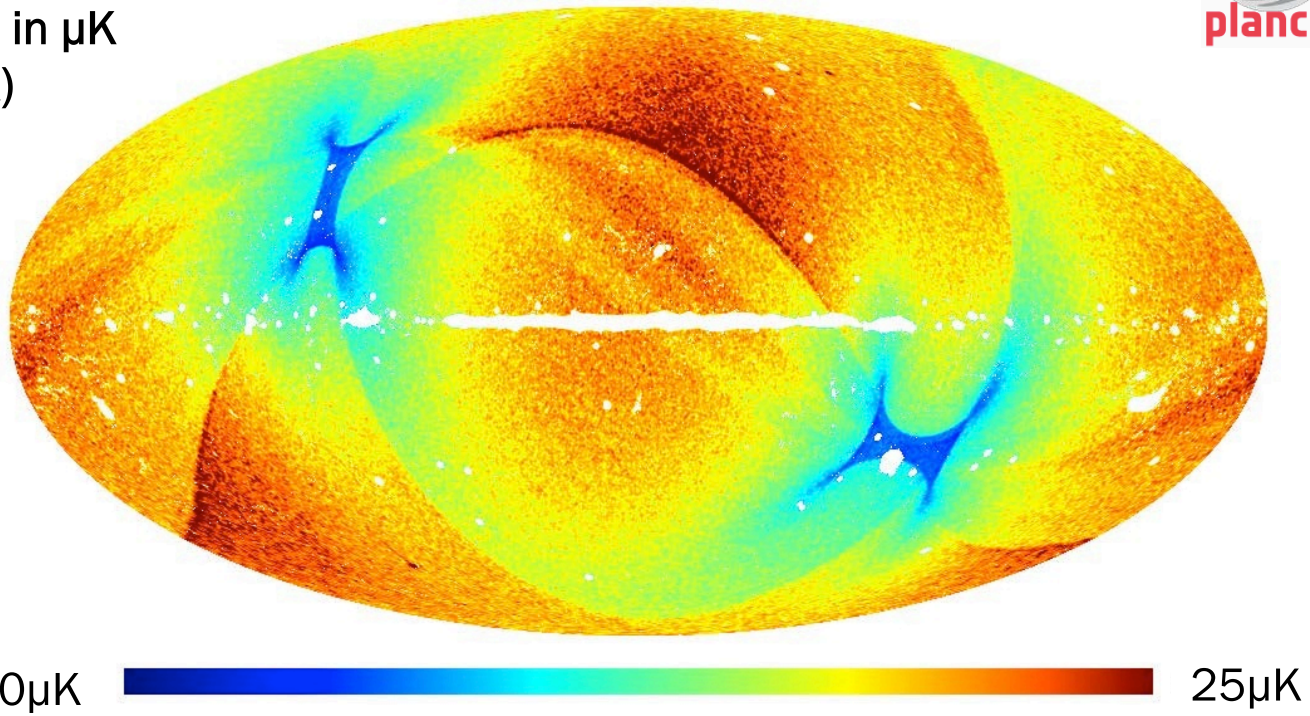
The mapping between time ordered data and pixel space needs to account for beam, rotation, unequal coverage of pixels, …

The noise n_t recovered from some distribution with known power spectrum

$$\langle n_t n_{t'} \rangle = C_{d,tt'}$$

From time ordered data to maps

Noise map:
noise per pixel for combined map
at 5’ resolution in μK
(average: 17μK)



Foregrounds

In addition, the best estimator $\hat{\Theta}_i$ for the underlying map Θ_i needs to take into account foregrounds.

$$\hat{\Theta}_i^\nu = A_i^\nu \Theta_i + n_i^\nu + f_i^\nu$$

Low frequencies:

synchrotron

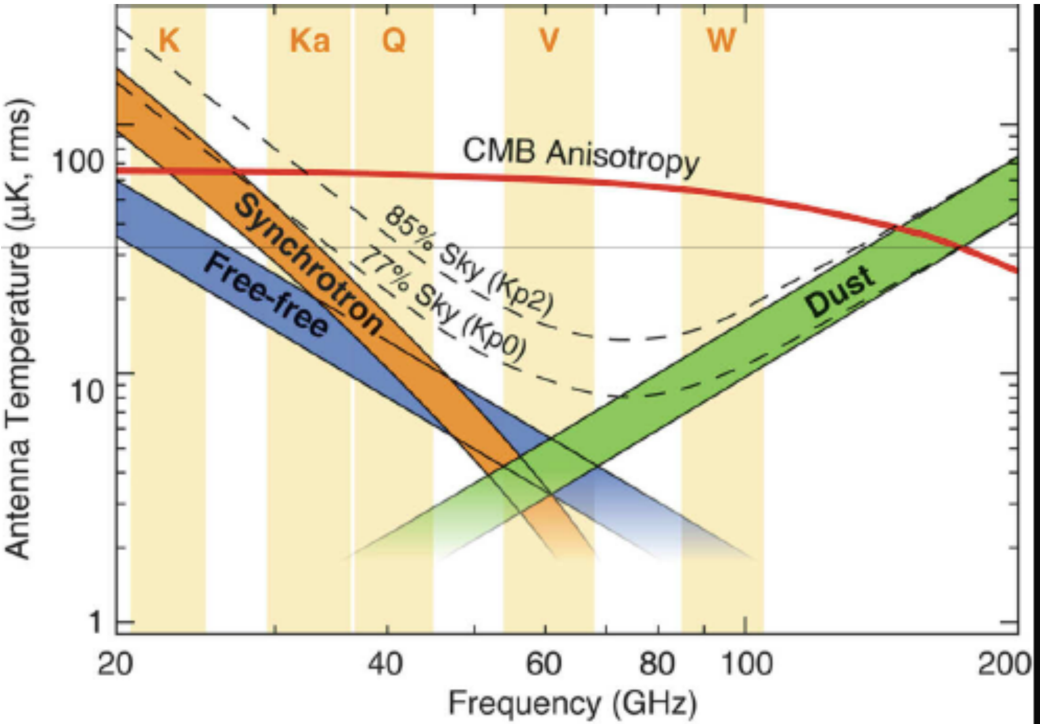
free-free (free electrons scattering off ions without being captured)

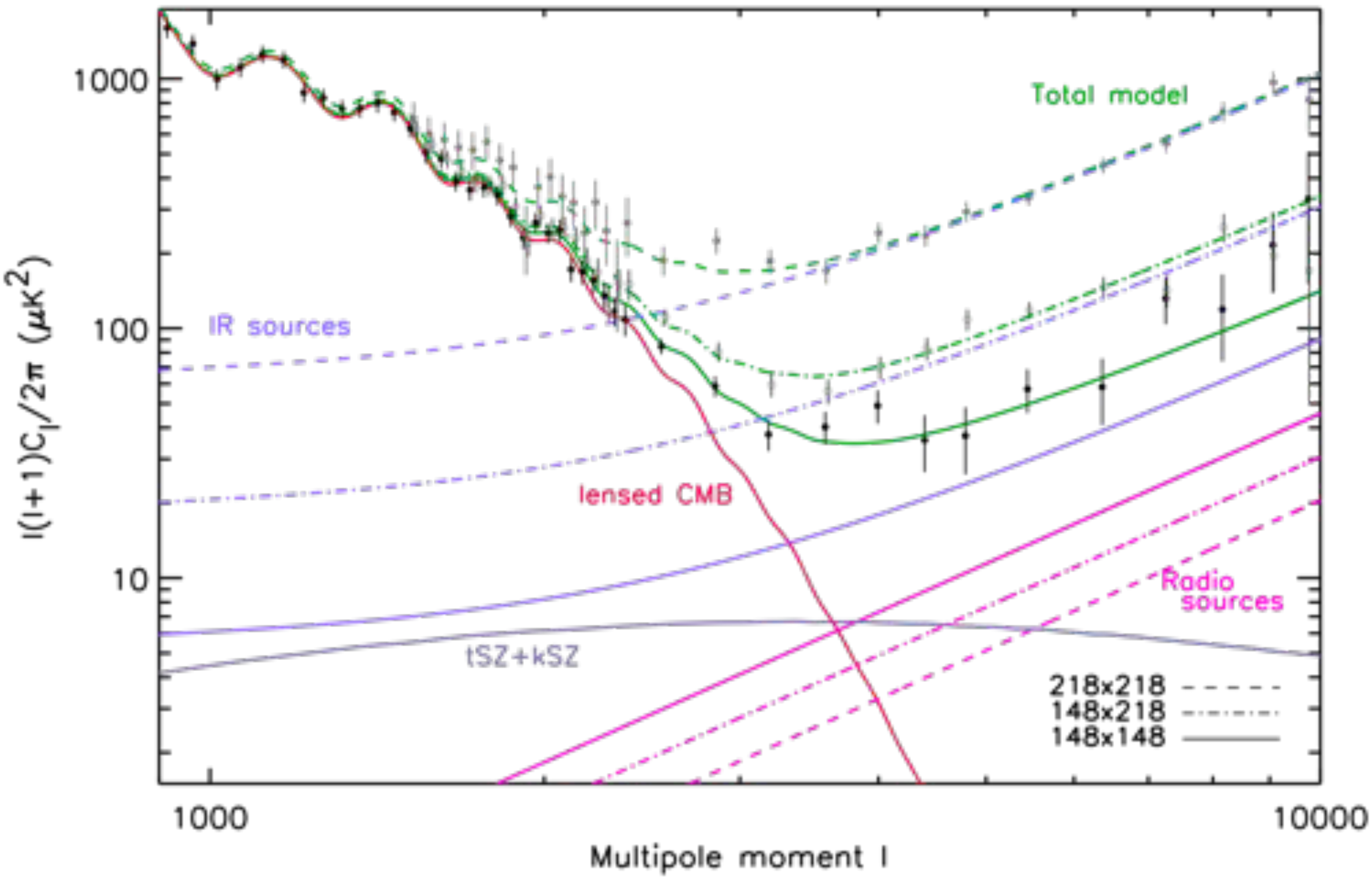
radio point sources;

High frequencies:

Dust

Cosmic Infrared Background (CIB).



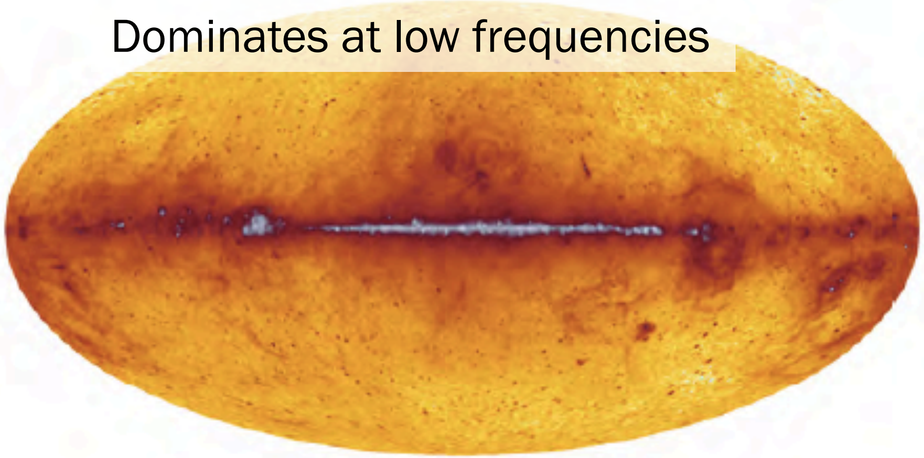


Total model
IR sources
lensed CMB
Radio sources
tSZ+kSZ
218x218
148x218
148x148
1000
100
10
1000
10000
Multipole moment l
l(l+1)C_l/2π (μK^2)

From time ordered data to maps

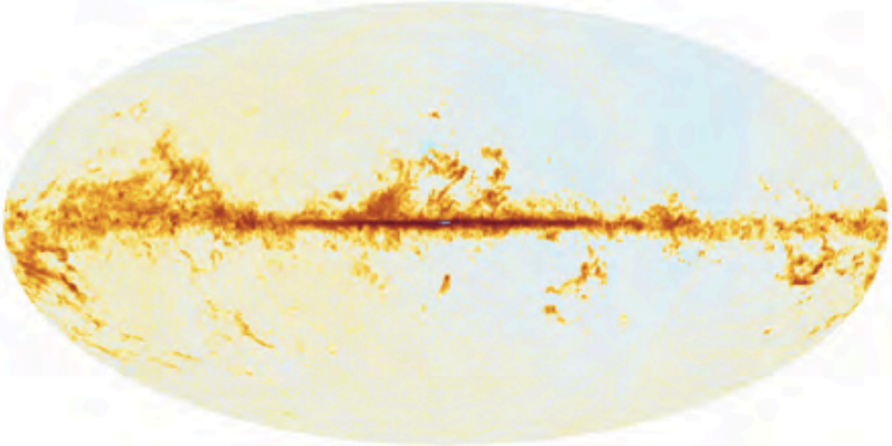
- Correct for systematics: detector noise and response, cooling instabilities and seasonal effects, cosmic rays, pointing errors, shape of the beam, …

Commander: Low–Frequency Emission Amplitude @ 30 GHz

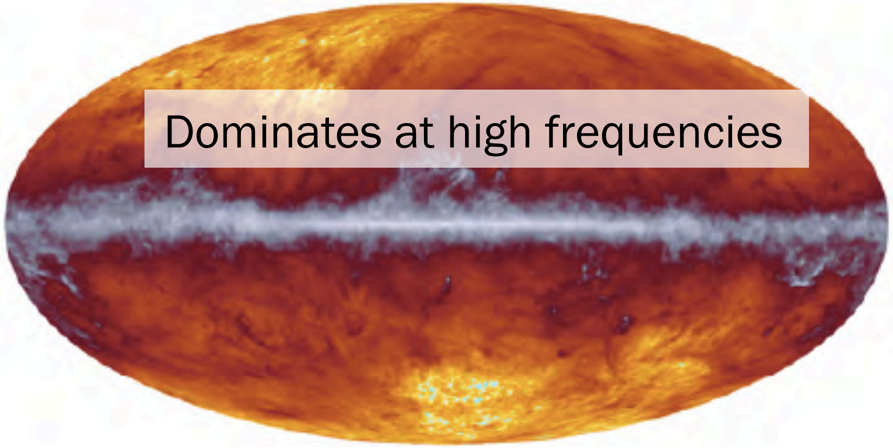


Dominates at low frequencies

Commander: "discovery" CO map @ 100 GHz



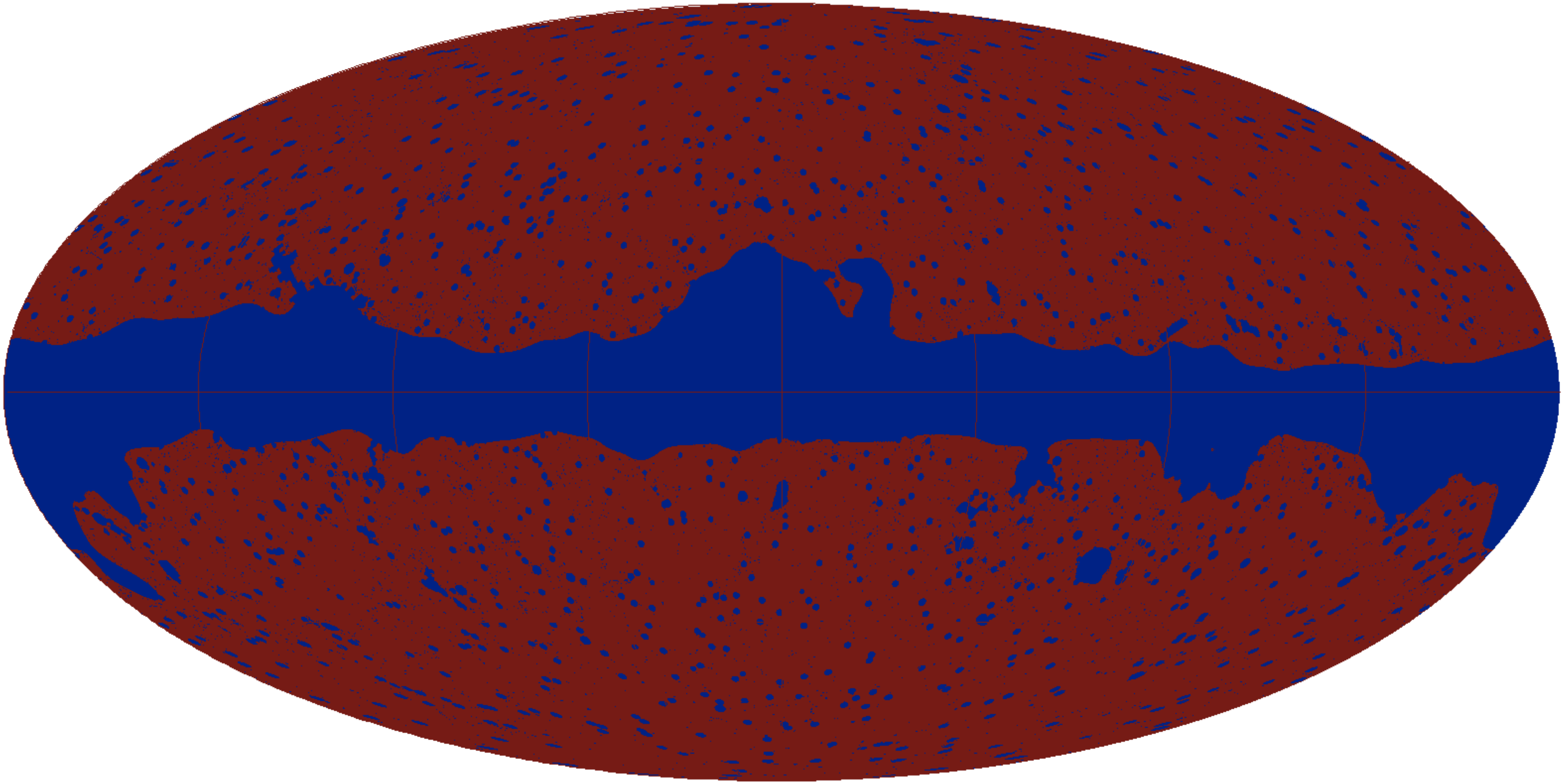
Commander: Dust Amplitude @ 353 GHz

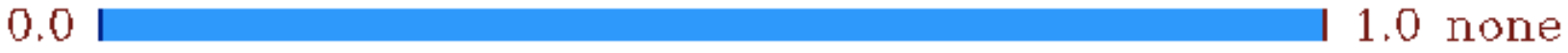


Dominates at high frequencies

COM_Mask_CMB-union_2048_R1.10   U73

2048 NESTED GALACTIC





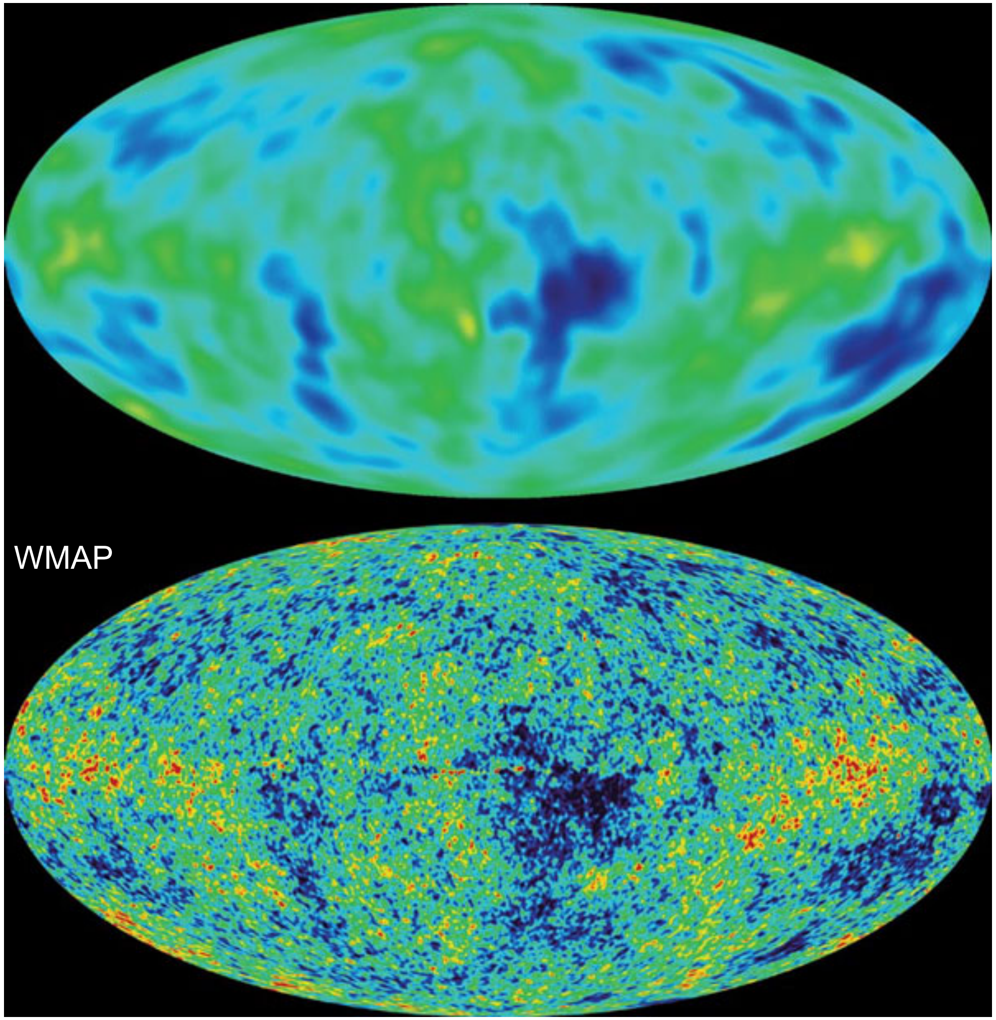
- Start with time ordered data (about 10^{10} numbers for a satellite experiment)
- Compressed to a map 10^7 numbers
- Compressed to a power spectrum (Gaussian statistics) independent of m (isotropy) 10^3 numbers
- Compressed to cosmological parameters (assuming a cosmological model) (order 10 numbers)

Reduction of 10^9!

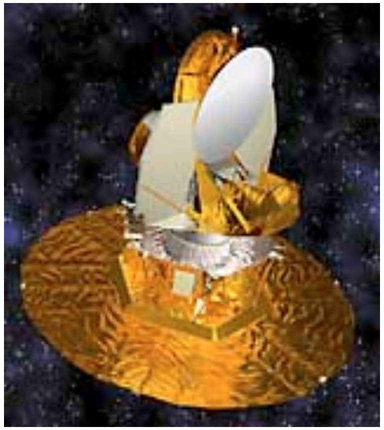
Current observations

COBE to WMAP (x35 better resolution)

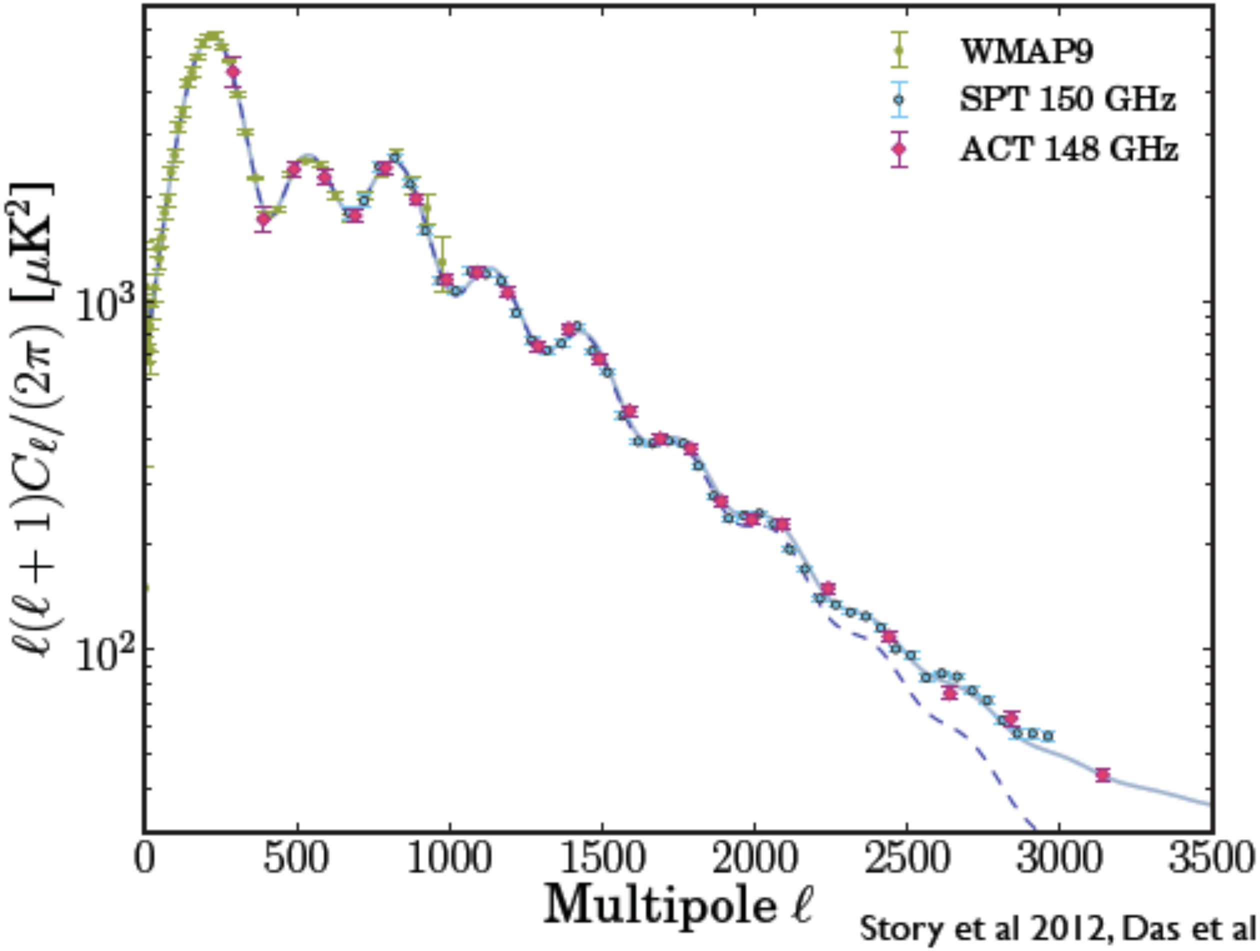
COBE
1989



WMAP
2001

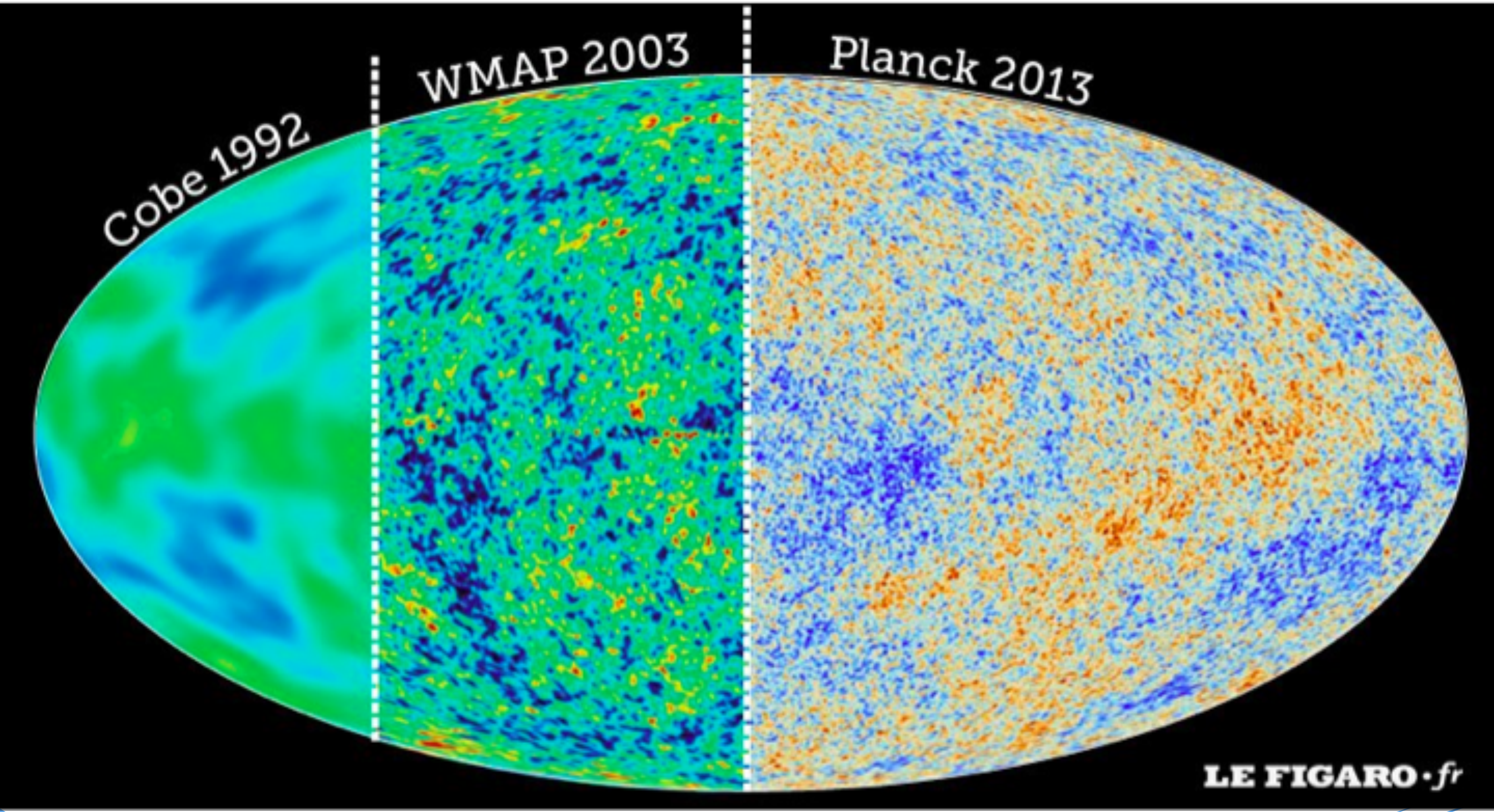


Komatsu



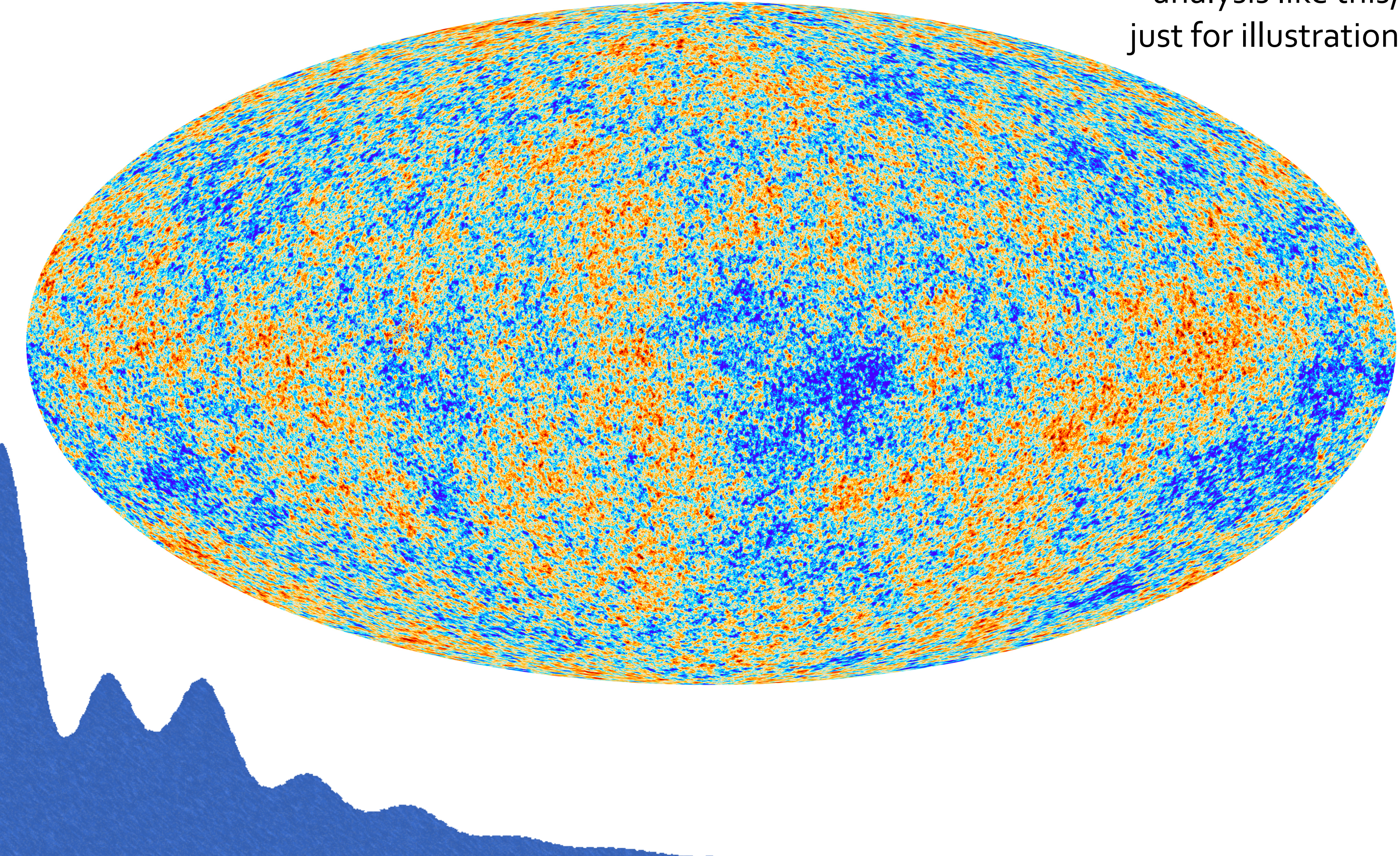
Story et al 2012, Das et al 2013

ACT is a 6 meter telescope in the Atacama Desert in the north of Chile.
SPT is a 10 meter diameter telescope operating at the NSF South Pole research station.


Cobe 1992
WMAP 2003
Planck 2013
LE FIGARO·fr

CMB anisotropies

This map is not used in the analysis like this, just for illustration



The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

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planck

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Les deux infinis

ipac

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IFCA
Instituto de Física de Cantabria

Imperial College London

UNIVERSITÀ DEGLI STUDI DI MILANO

NÉEL institut

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

ISDC
DATA CENTRE FOR ASTROPHYSICS

JPL

LAL
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

l'Observatoire de Paris
LERMA

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

The University of Manchester

MilliLab

Max-Planck-Institut für Astrophysik

NUI MAYNOOTH

INAF OSSERVATORIO ASTRONOMICO DI PADOVA

UNIVERSITY OF OXFORD

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Rutherford Appleton Laboratory

UNIVERSITÀ degli STUDI di ROMA TOR VERGATA

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UBC

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UCSB

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ESO

US
University of Sussex

HAVERFORD

esa

UNIVERSITY OF HELSINKI

UNIVERSITÉ DE GENÈVE

UNIVERSITY OF TORONTO

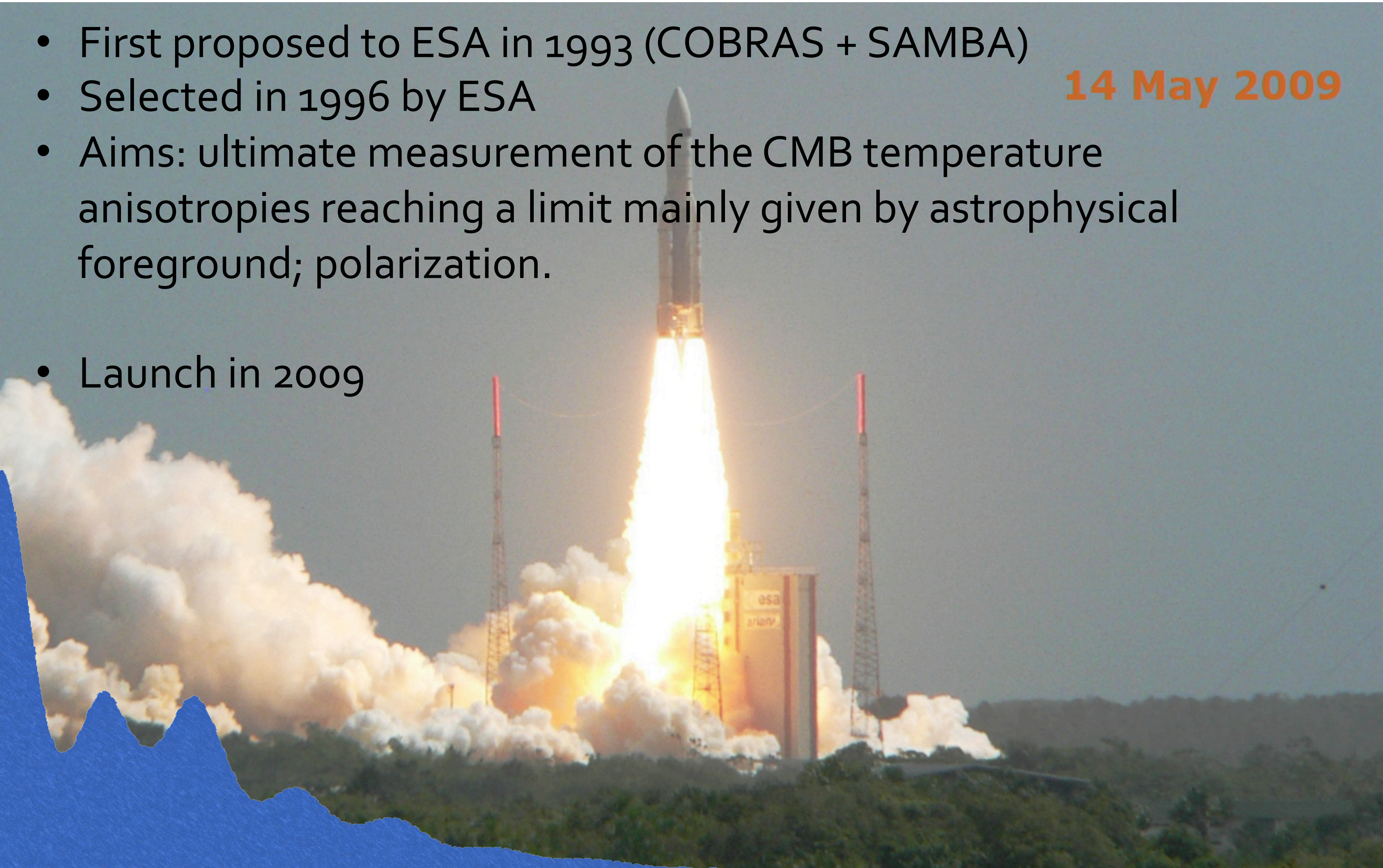
UNIVERSITÉ DE PARIS-SUD XI

asdc
ASI Science Data Center

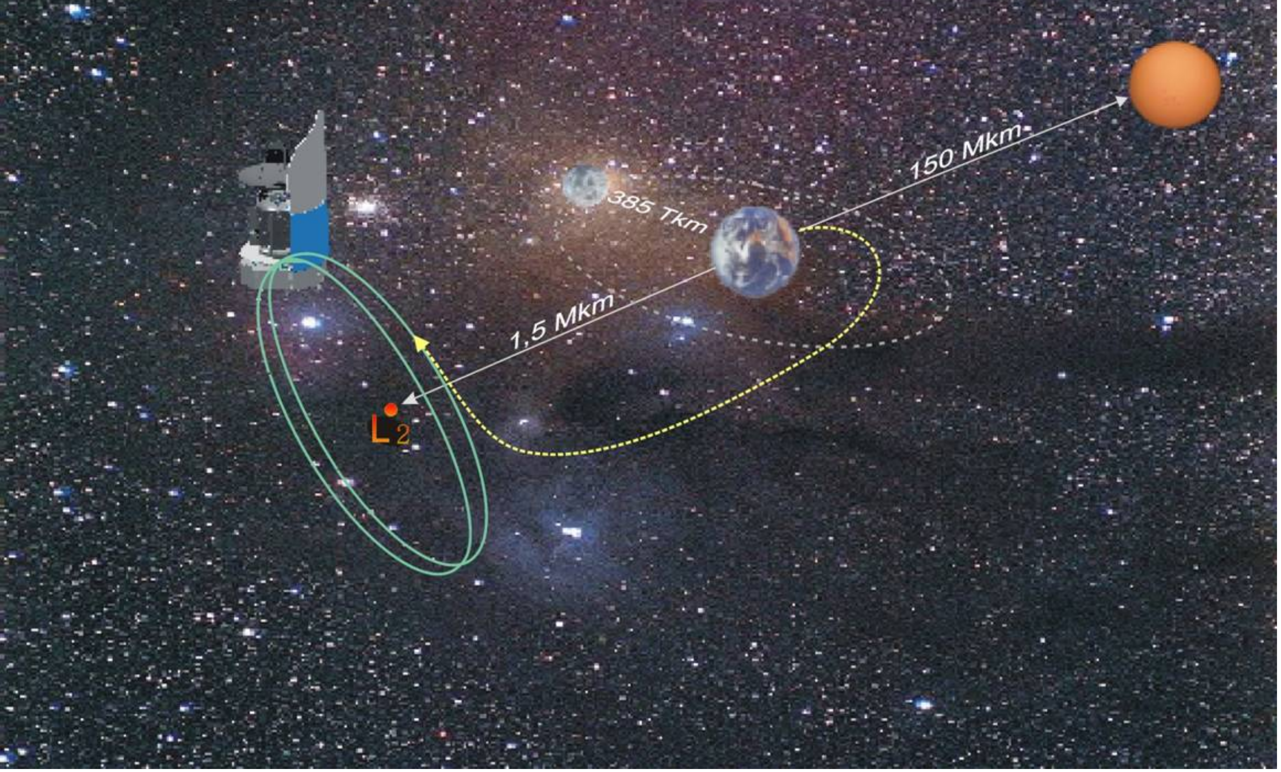
The Planck project

- First proposed to ESA in 1993 (COBRAS + SAMBA)
- Selected in 1996 by ESA
- Aims: ultimate measurement of the CMB temperature anisotropies reaching a limit mainly given by astrophysical foreground; polarization.

- Launch in 2009



14 May 2009

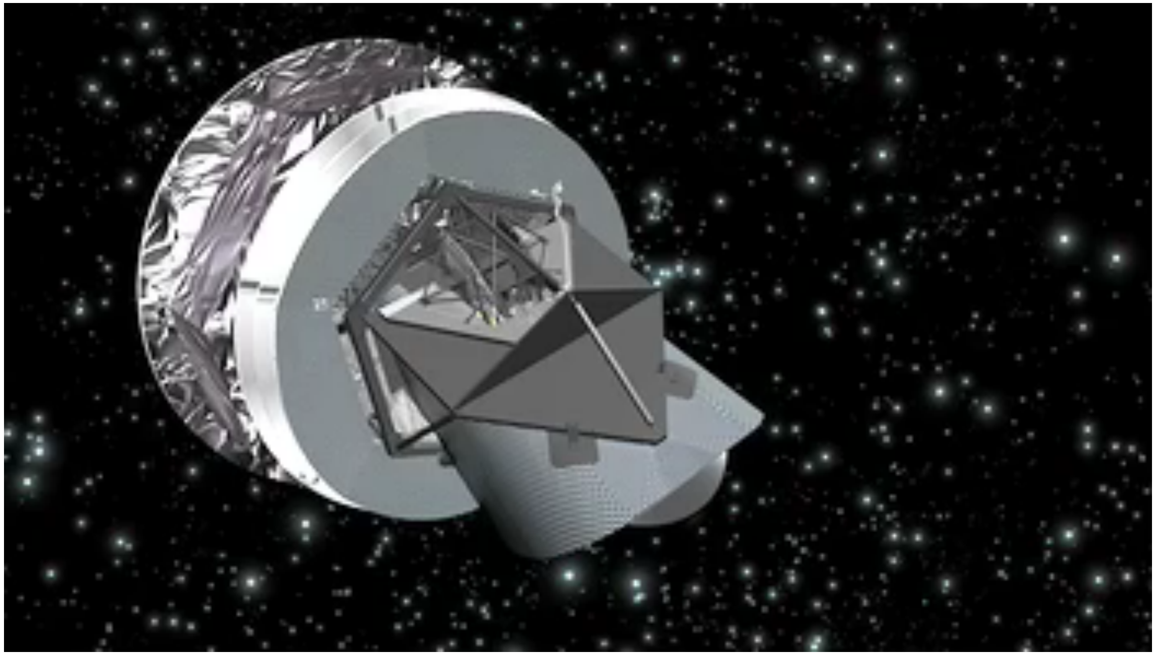


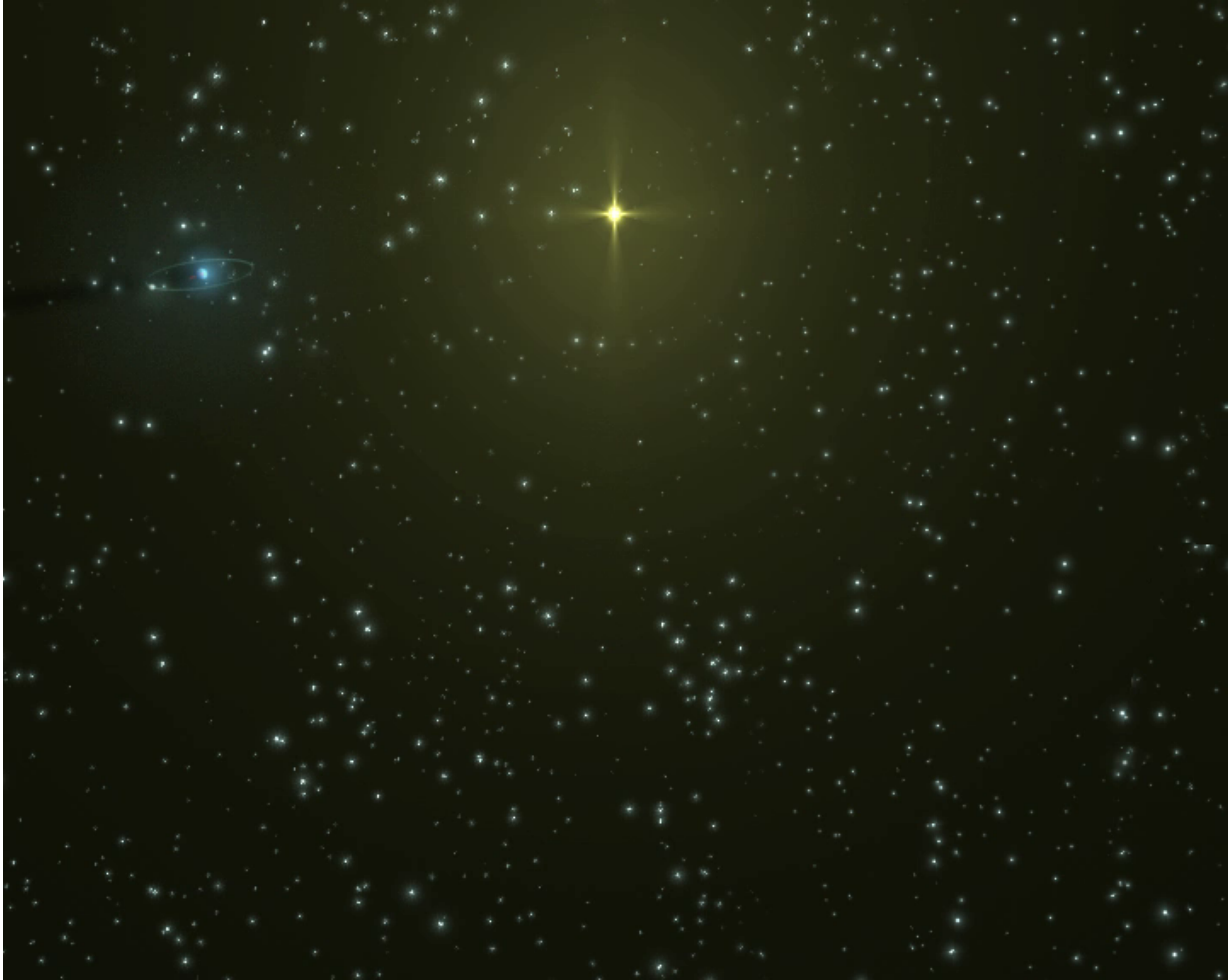
- Nominal mission completed in November 2010 (15.5 months). In practice, twice the nominal mission (full surveys: 5 HFI; 8 LFI)

(2013 data release is based on the nominal mission)

Placed in orbit around L2.
Scans the entire sky twice per year.
The spacecraft spins with 1 rotation per minute, tracing circles on the celestial sphere.

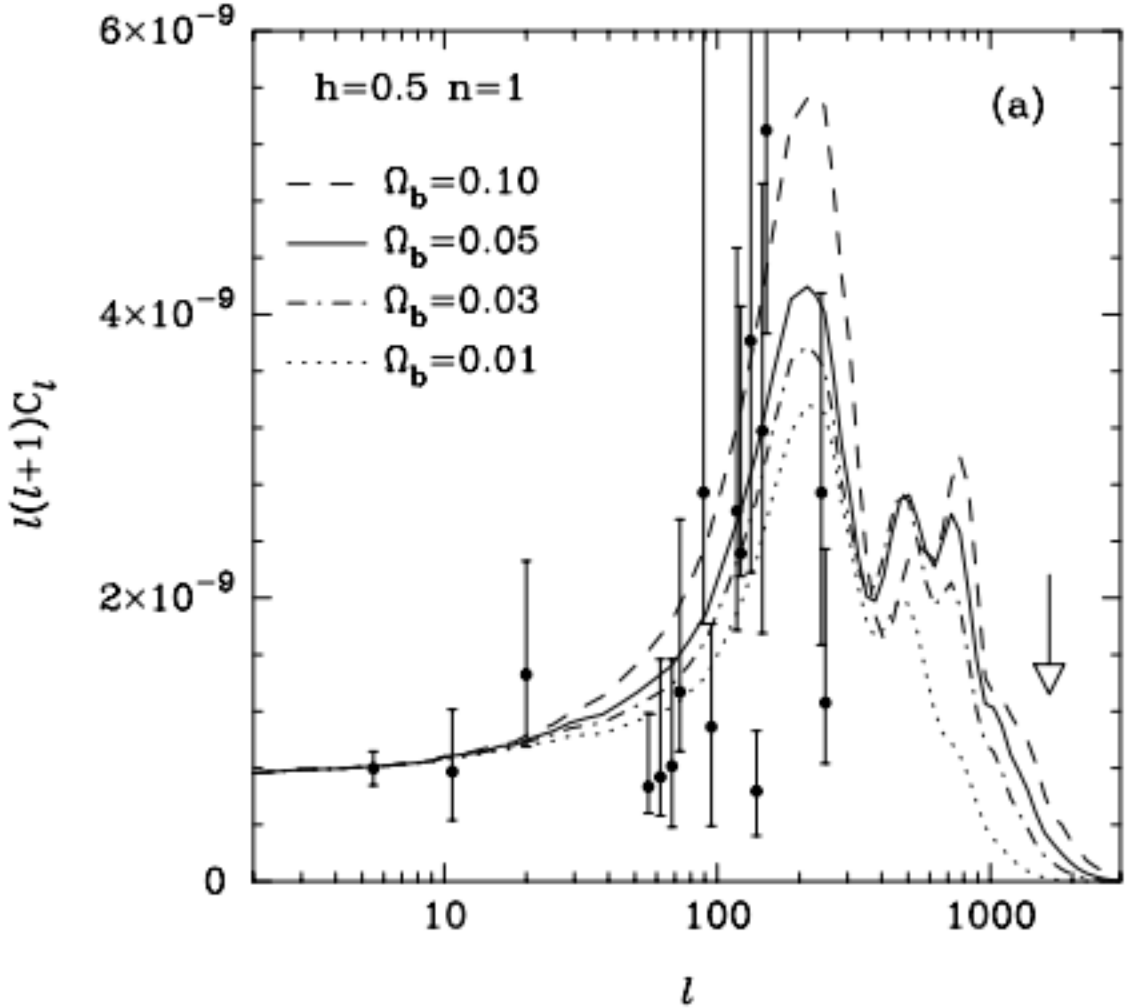
Multiple passes over same sky by each detector at each position of the axis.





State of the art in 1996

From **Planck (COBRAS/SAMBA) Redbook, 1996**
http://www.rssd.esa.int/SA/PLANCK/include/report/complete.pdf

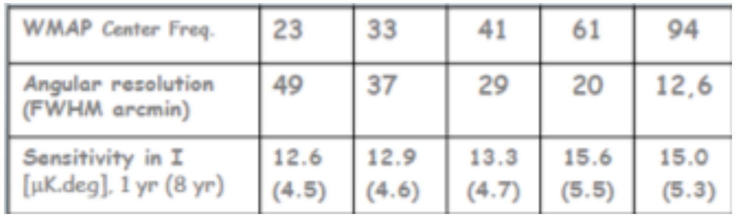


Planck detectors and technological challenge

- HFI:
  50 bolometers;
  6 frequencies: 100, 143, 217, 353, 545, 857 GHz;
  Complex cryogenic system, cooling at 0.1K
  (with He3 + He4). Ended on 14th Jan 2012.

- Three complex chains (optical, electronic and cryogenic systems) had to be integrated

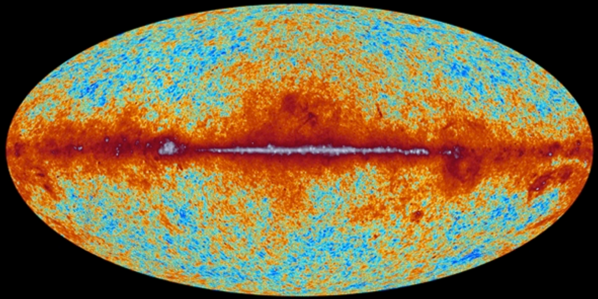
- LFI:
  22 radiometers in total (low noise HEMT amplifiers);
  3 frequencies: 20,44,70 GHz;
  cooling at 20 K with He4 only.
  Ended in autumn 2013.

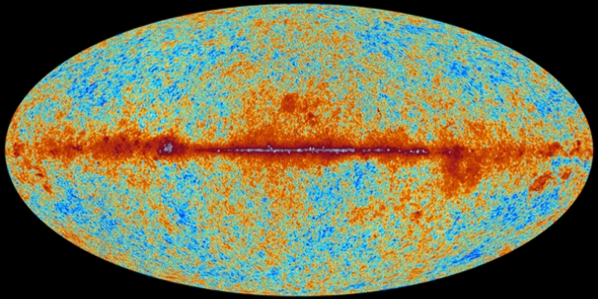


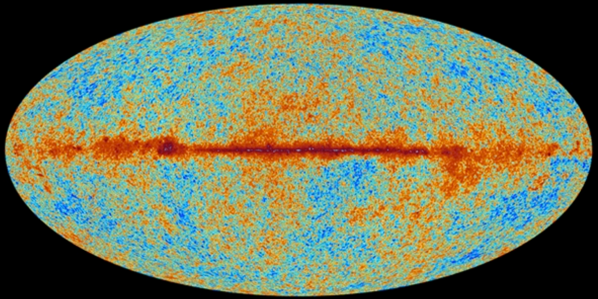
WMAP Center Freq.	23	33	41	61	94
Angular resolution (FWHM arcmin)	49	37	29	20	12,6
Sensitivity in I [μK.deg], 1 yr (8 yr)	12.6 (4.5)	12.9 (4.6)	13.3 (4.7)	15.6 (5.5)	15.0 (5.3)

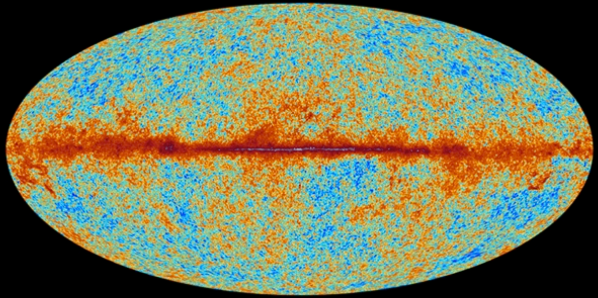
PLANCK	**LFI**			**HFI**					
Center Freq (GHz)	**30**	**44**	**70**	**100**	**143**	**217**	**353**	**545**	**857**
Angular resolution (FWHM arcmin)	**33**	**24**	**14**	**10**	**7.1**	**5.0**	**5.0**	**5**	**5**
Sensitivity in I [μK.deg] $[\sigma_{pix}\,\Omega_{pix}^{1/2}]$	**2.7**	**2.6**	**2.6**	**1.0**	**0.6**	**1.0**	**2,9**		
Sensitivity in Q or U [μK.deg] $[\sigma_{pix}\,\Omega_{pix}^{1/2}]$	**4.5**	**4.6**	**4.6**	**1.8**	**1.4**	**2.4**	**7.3**		

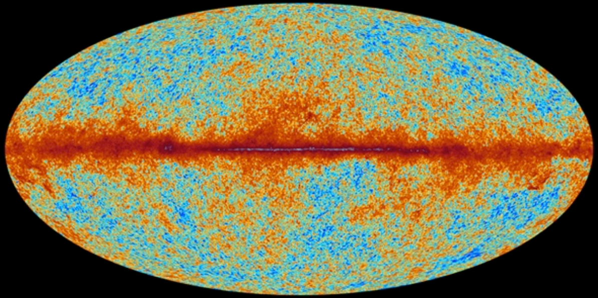
The sky seen at different frequencies

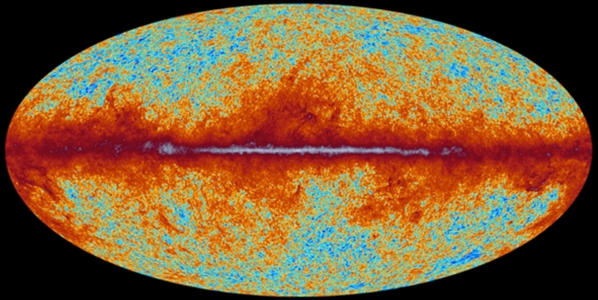

30 GHz

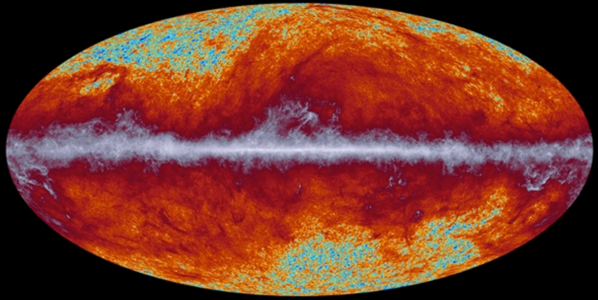

44 GHz

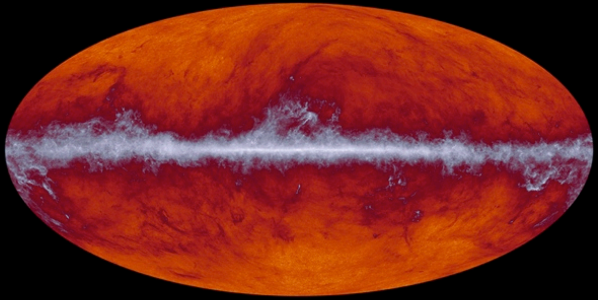

70 GHz

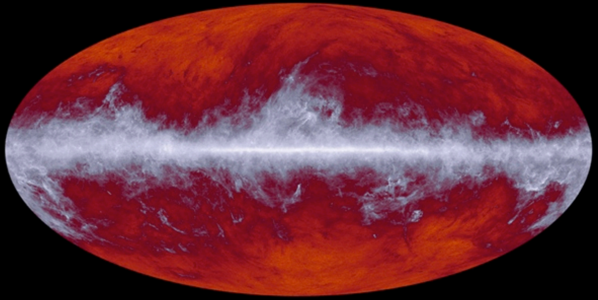

100 GHz


143 GHz

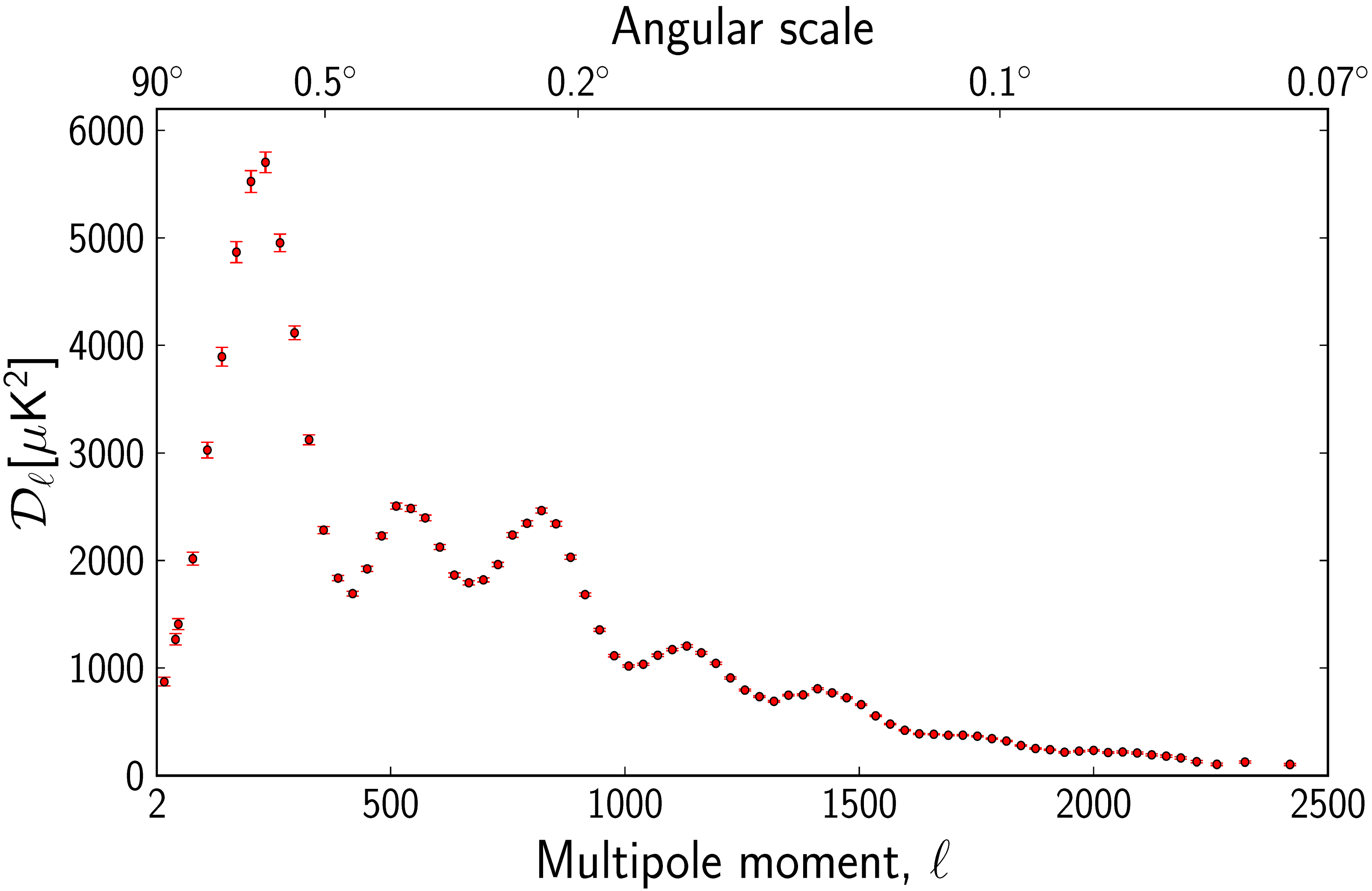

217 GHz


353 GHz

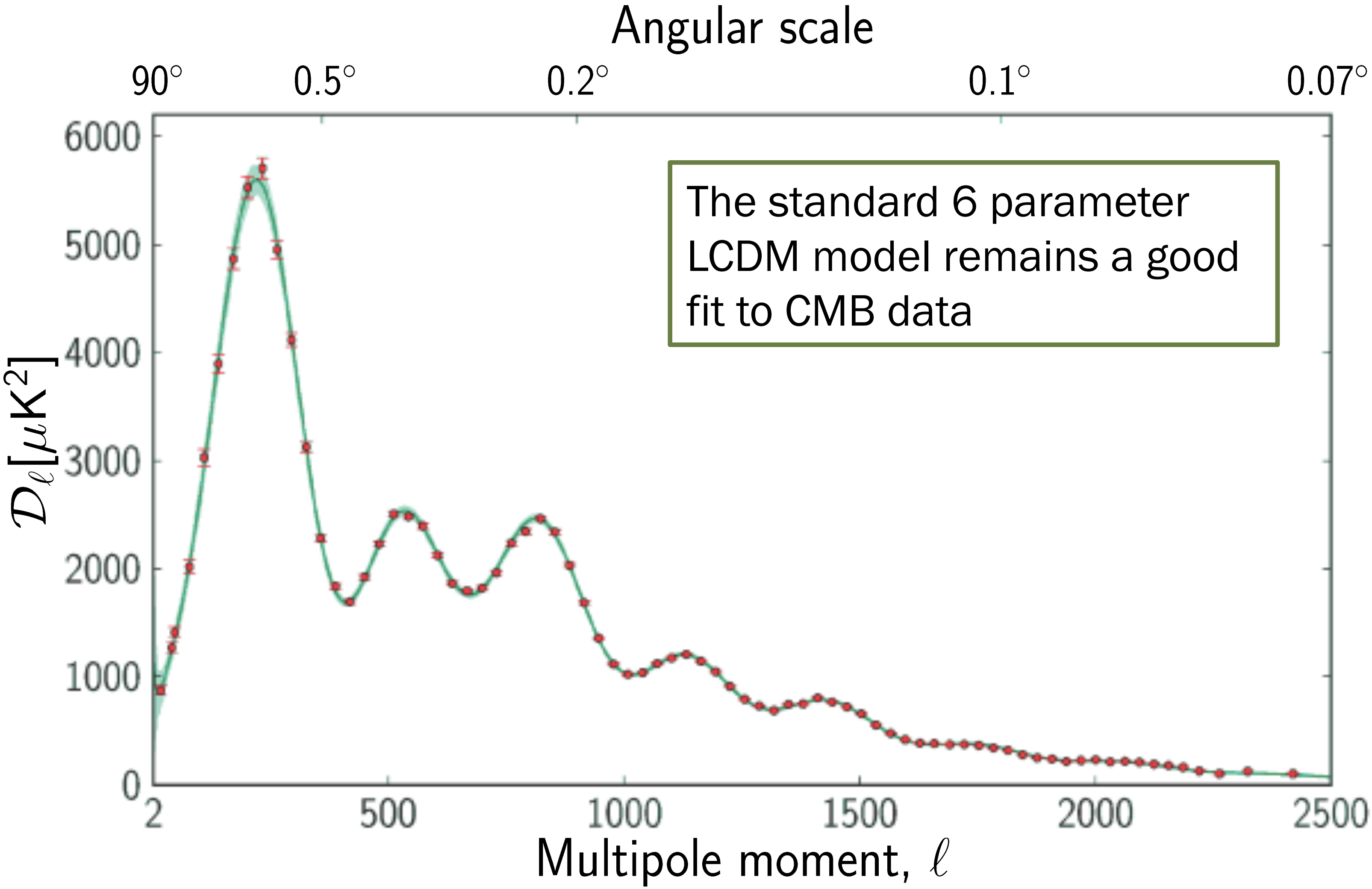

545 GHz


857 GHz

Power spectrum



ΛCDM is a very good fit

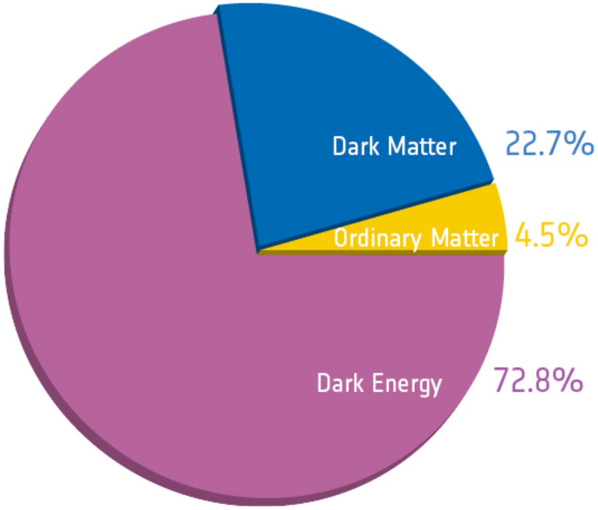


The standard 6 parameter LCDM model remains a good fit to CMB data

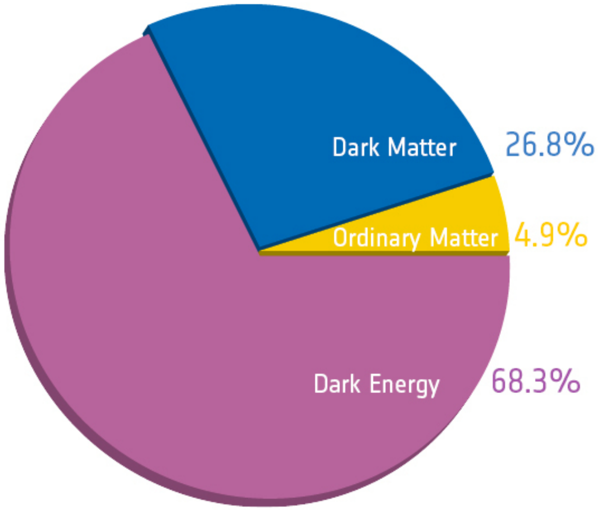
Quite impressive. From terabytes of data to 6 parameters

Content of the Universe (ΛCDM)

$$\Omega_{de} \equiv \frac{\rho_{de}}{\rho_{cr}}$$



Before Planck



After Planck

(1) Contents and expansion

Baryon density	$\Omega_b h^2$
CDM density	$\Omega_c h^2$
Peak position	θ ($\sim r_s/D_A$)

(2) Initial fluctuations

Amplitude at k=0.05/Mpc	A_s
Spectral index	n_s

(3) Impact of reionization

Reionization optical depth	τ

(1) Contents and expansion rate

Baryon fraction	Ω_b
CDM fraction	Ω_c
Cosmol constant fraction	$\Omega_\Lambda = 1 - \Omega_b - \Omega_c$
Expansion rate	H_0

(2) Late-time size of fluctuations

Amplitude on 8 Mpc/h scales	σ_8

(3) Reionization

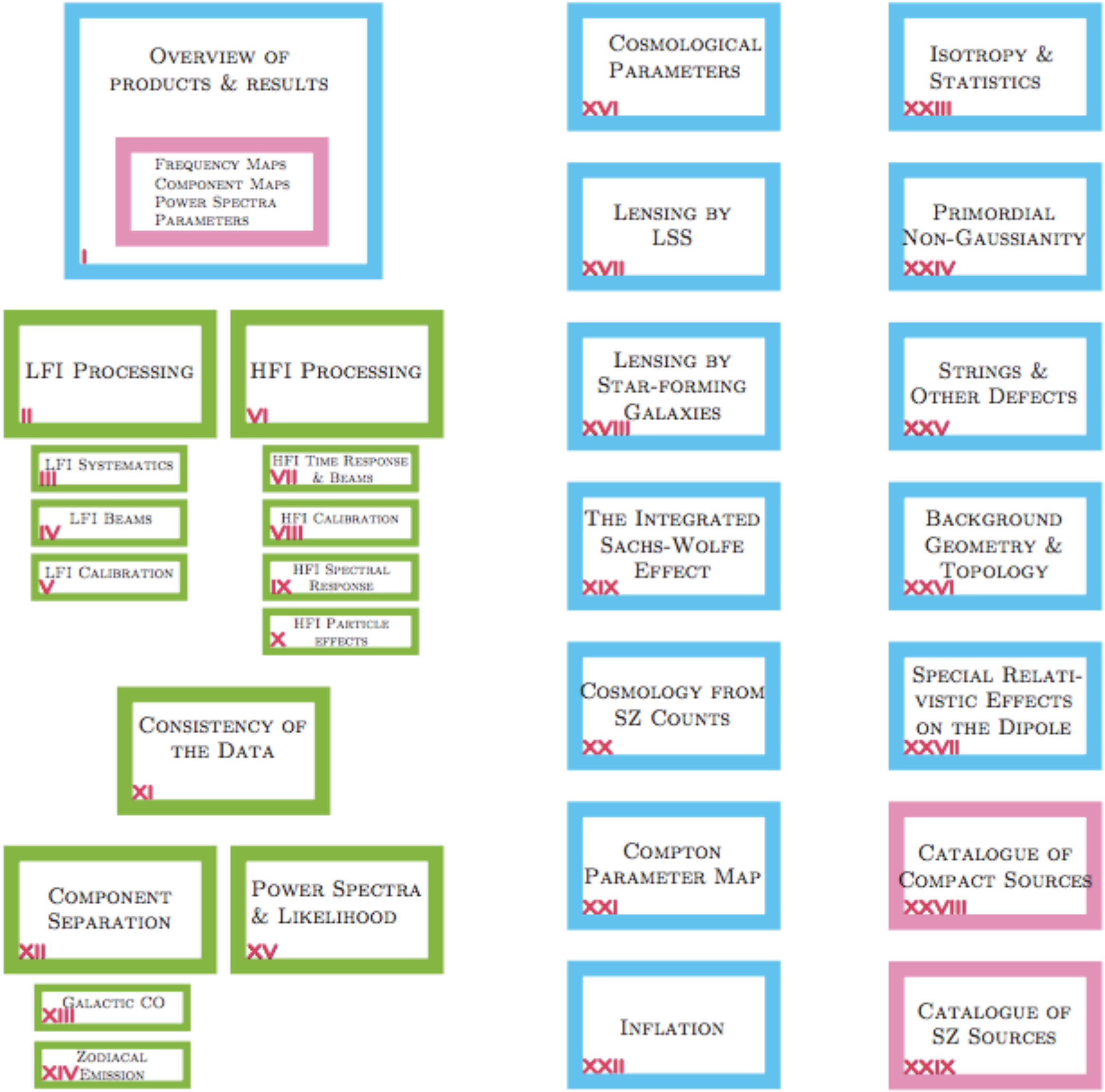
Redshift of reonization	z_{re}

J. Dunkley

Planck did a lot more than presented here

Products available on-line (PLA)

http://www.sciops.esa.int/index.php?project=planck&page=Planck_Legacy_Archive



OVERVIEW OF PRODUCTS & RESULTS
FREQUENCY MAPS
COMPONENT MAPS
POWER SPECTRA
PARAMETERS
I

LFI PROCESSING II
LFI SYSTEMATICS III
LFI BEAMS IV
LFI CALIBRATION V

HFI PROCESSING VI
HFI TIME RESPONSE & BEAMS VII
HFI CALIBRATION VIII
HFI SPECTRAL RESPONSE IX
HFI PARTICLE EFFECTS X

CONSISTENCY OF THE DATA XI

COMPONENT SEPARATION XII
GALACTIC CO XIII
ZODIACAL EMISSION XIV

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LENSING BY LSS XVII

LENSING BY STAR-FORMING GALAXIES XVIII

THE INTEGRATED SACHS-WOLFE EFFECT XIX

COSMOLOGY FROM SZ COUNTS XX

COMPTON PARAMETER MAP XXI

INFLATION XXII

ISOTROPY & STATISTICS XXIII

PRIMORDIAL NON-GAUSSIANITY XXIV

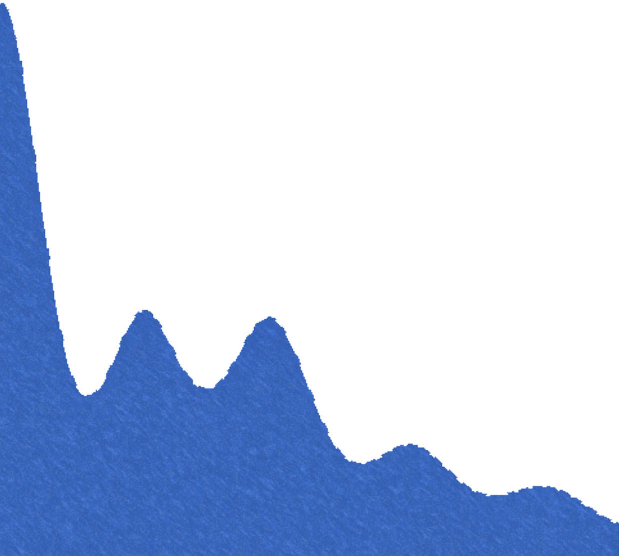
STRINGS & OTHER DEFECTS XXV

BACKGROUND GEOMETRY & TOPOLOGY XXVI

SPECIAL RELATIVISTIC EFFECTS ON THE DIPOLE XXVII

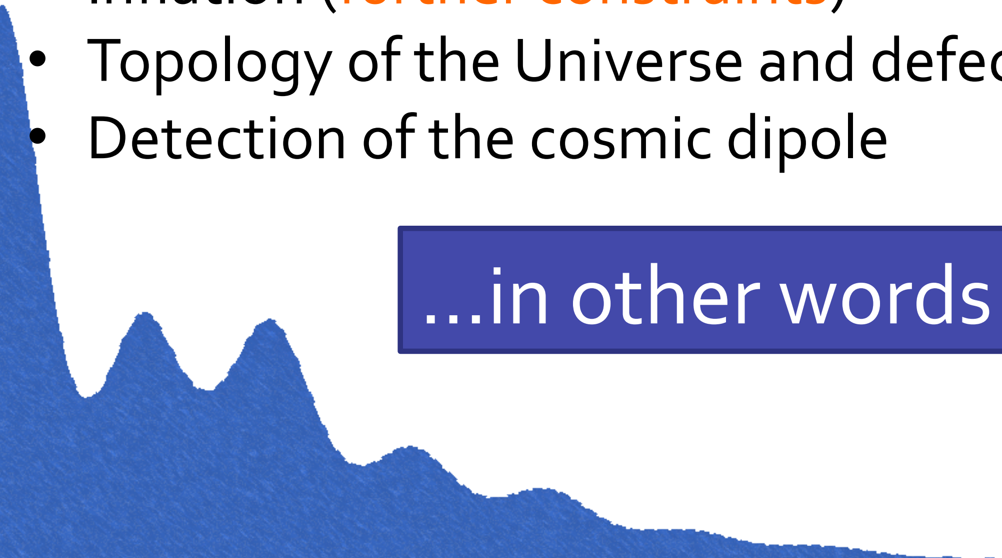
CATALOGUE OF COMPACT SOURCES XXVIII

CATALOGUE OF SZ SOURCES XXIX



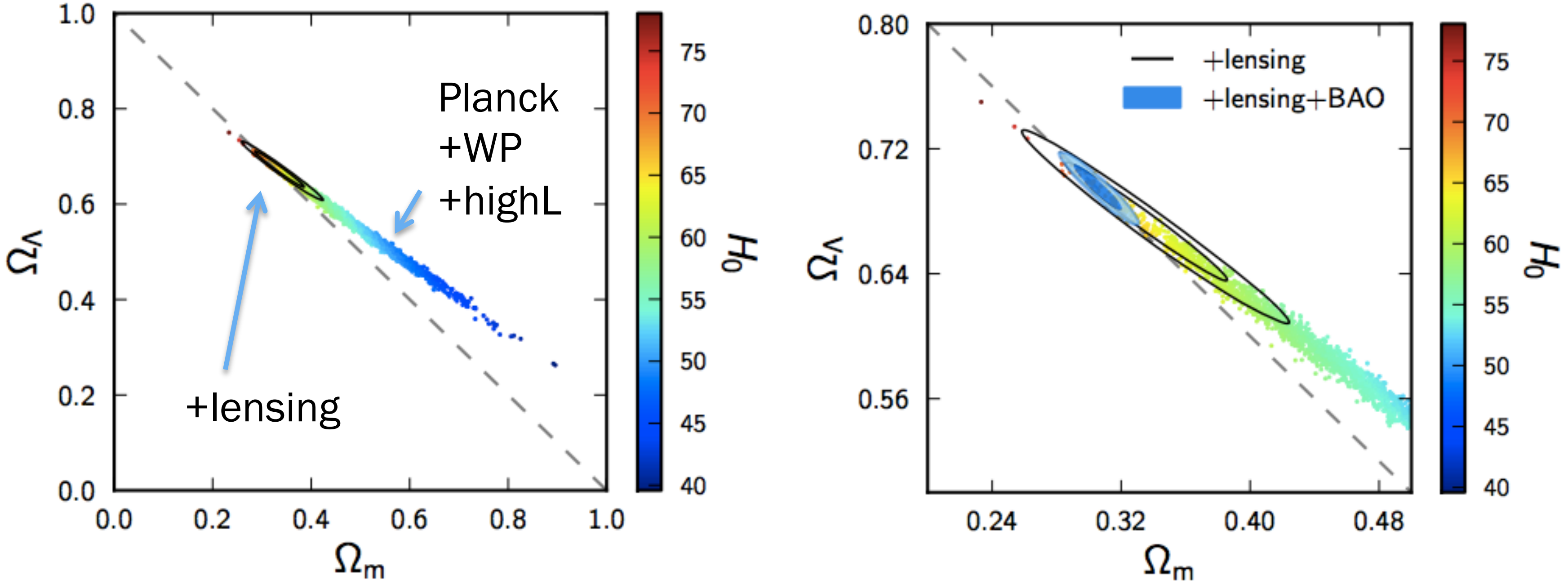
Summary list of main results

- Gravitational Lensing
- Curvature (flat geometry)
- Dark Energy (compatible with Λ)
- Neutrino masses (no detection)
- Extra relativistic particles (N_{eff} consistent with 3)
- Isotropy (consistent)
- Non-Gaussianity (strong limits)
- Spectral index (deviates from 1 at 6 sigma)
- Inflation (further constraints)
- Topology of the Universe and defects (strong limits)
- Detection of the cosmic dipole



...in other words ΛCDM is a good fit.

Curvature and flatness



Planck
+WP
+highL

+lensing

$$\Omega_K = -0.0096^{+0.010}_{-0.0082} \qquad \Omega_\Lambda = 0.67^{+0.027}_{-0.023}$$

The geometry of the Universe is consistent with spatial flatness to percent level using CMB data alone.
Need for (something like) Dark Energy from CMB alone

First done combining WMAP+SPT, Story etal 2012

Dark Energy

1. Constant w:

$$w = -1.13^{+0.24}_{-0.25} \quad (95\%; \textit{Planck}+\mathrm{WP}+\mathrm{BAO}),$$

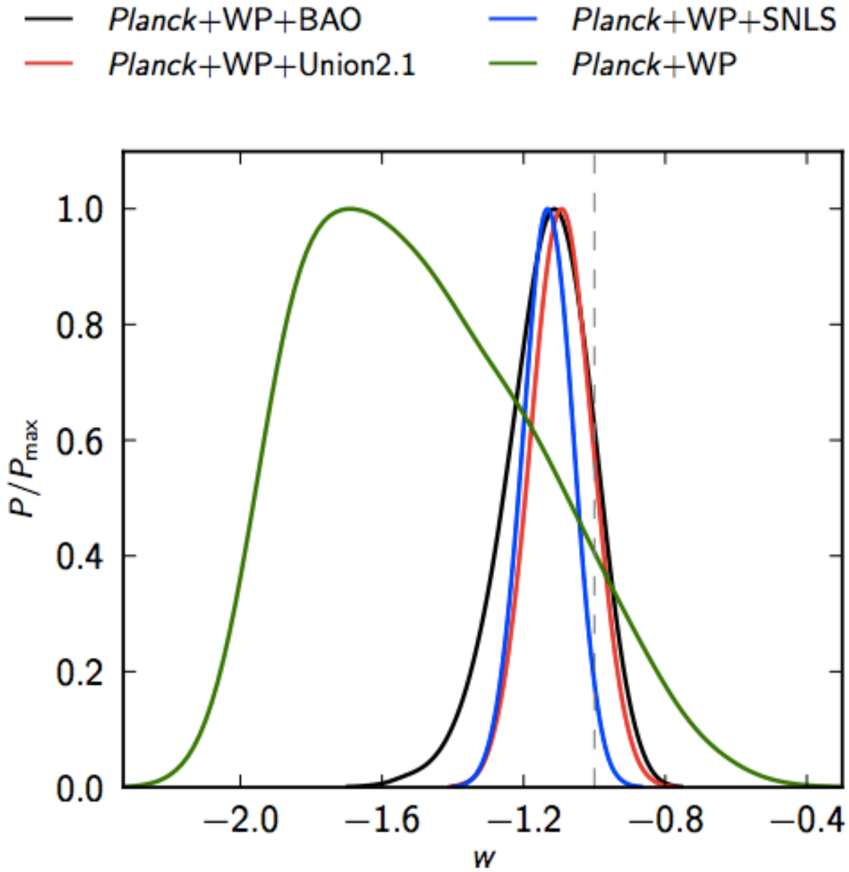
$$w = -1.24^{+0.18}_{-0.19} \quad (95\%; \textit{Planck}+\mathrm{WP}+H_0),$$

2. Varying (taylor expanded) w:

$$w(a) \equiv \frac{p}{\rho} = w_0 + (1-a)w_a$$

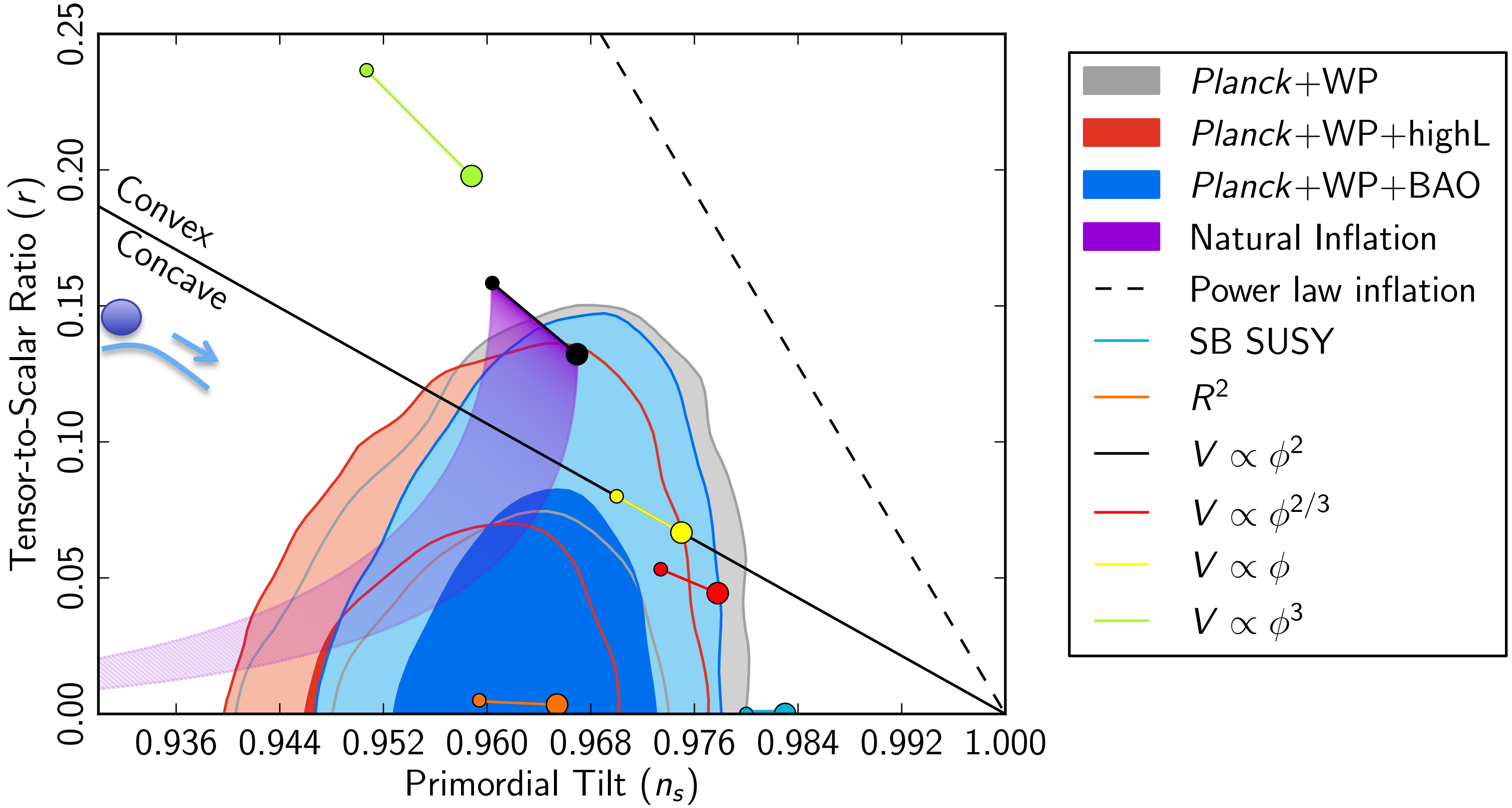
3. Early Dark Energy < 1%

Wetterich 2004
Doran & Robbers 2006
Pettorino et al 2013



Inflation

Models that fit best have a canonical kinetic term and a single field slow rolling a (preferably concave) potential.



Also the quadratic potential is now at the boundary (2sigma).

Neutrinos and N_{eff}

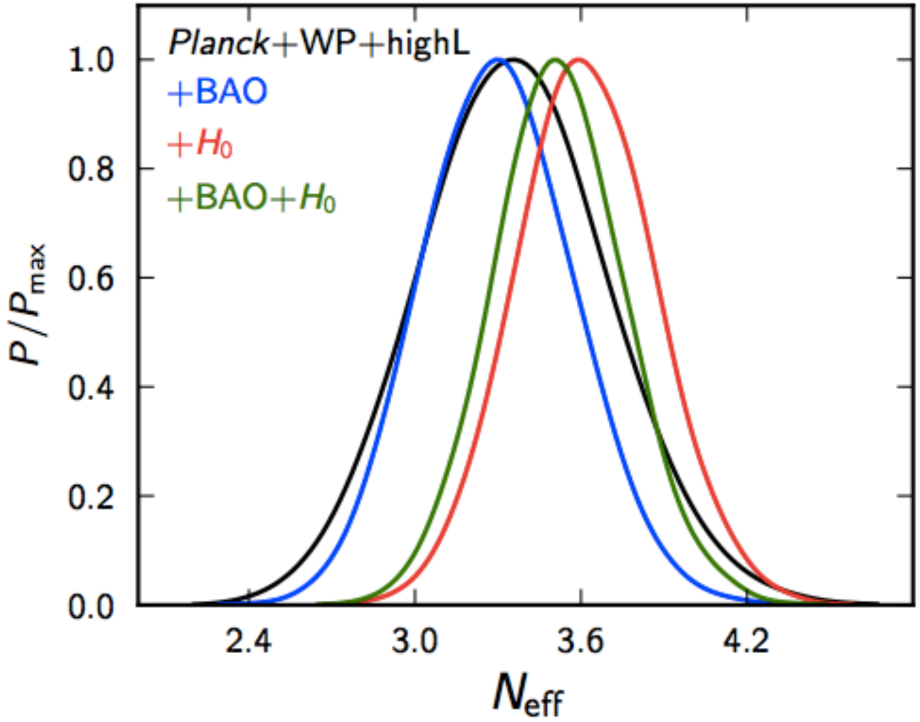
Limits on Σm_ν at 95%:		
	<0.66 eV	(Planck+WP+highL)
	<1.08 eV	(same, but marginalizing over AL)
	<0.85 eV	(Planck+lensing+WP+highL)
	<0.23 eV	(Pl+WP+highL+BAO)

$$\rho_\nu = N_{eff}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma$$

Mangano etal 2005

In the standard scenario
(with 3 neutrinos)

$$N_{eff} = 3.046$$



Compatible with 3

Geometrical degeneracy

Models with the same primordial power spectrum, matter densities and same angular diameter distance to LSS will have almost identical CMB TT spectra.

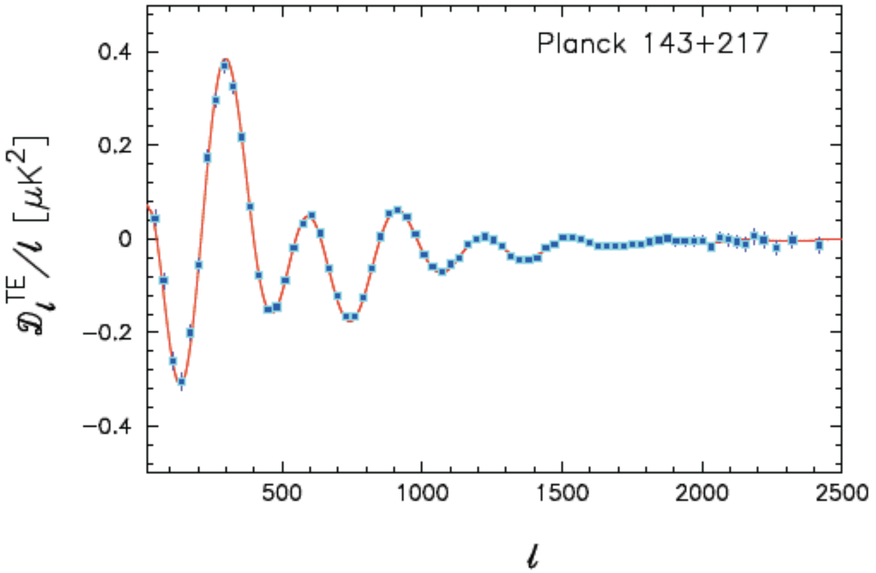
Degeneracy can be broken with:

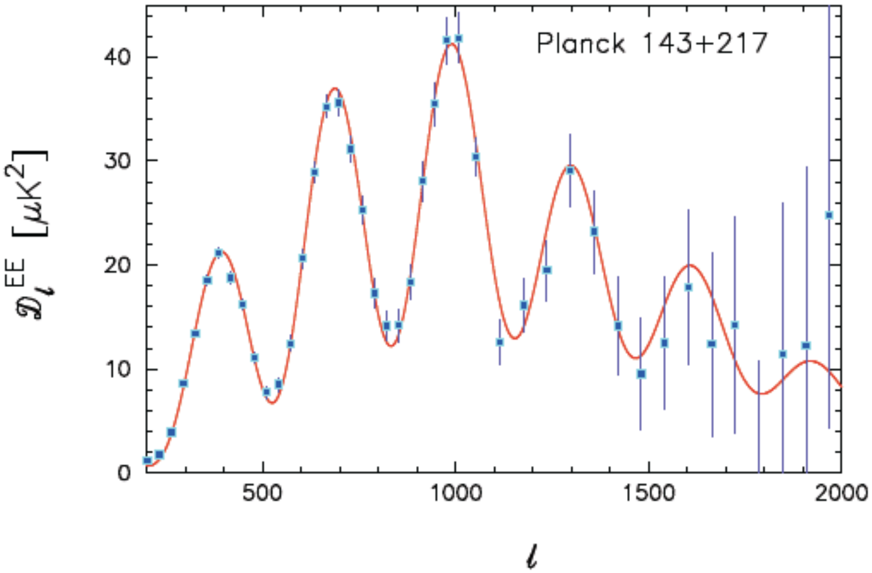
- Lensing
- Astrophysical datasets probing late time physics (BAO, SNae, HST, ...)

We need to assess whether the discrepancy with other datasets in a LCDM model with different datasets depends on poorly understood systematic effects.

Better to avoid combining many datasets together.

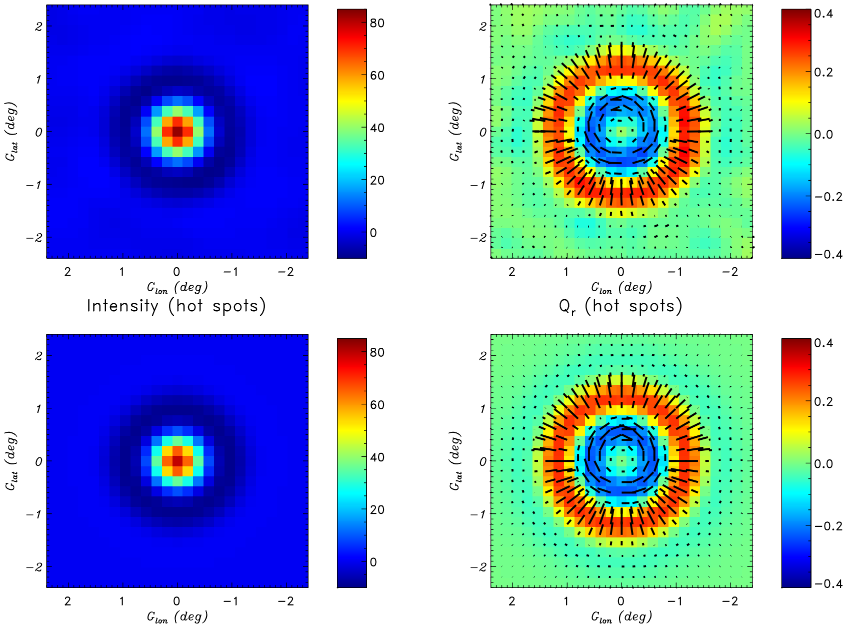
Polarization





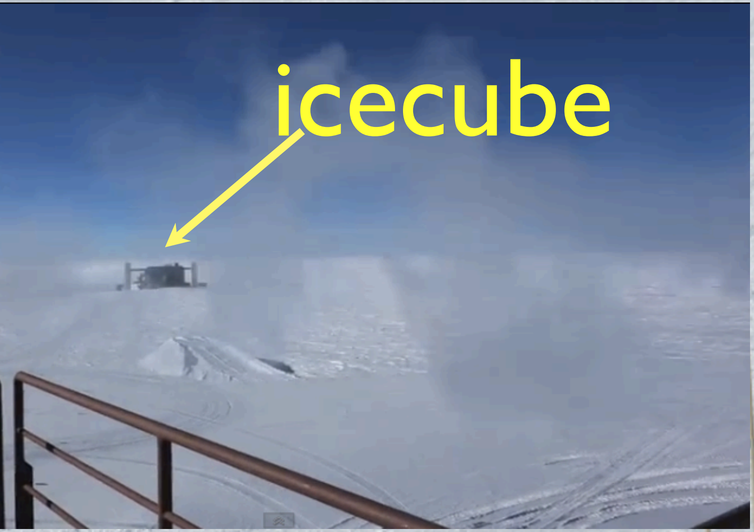
2014 release:

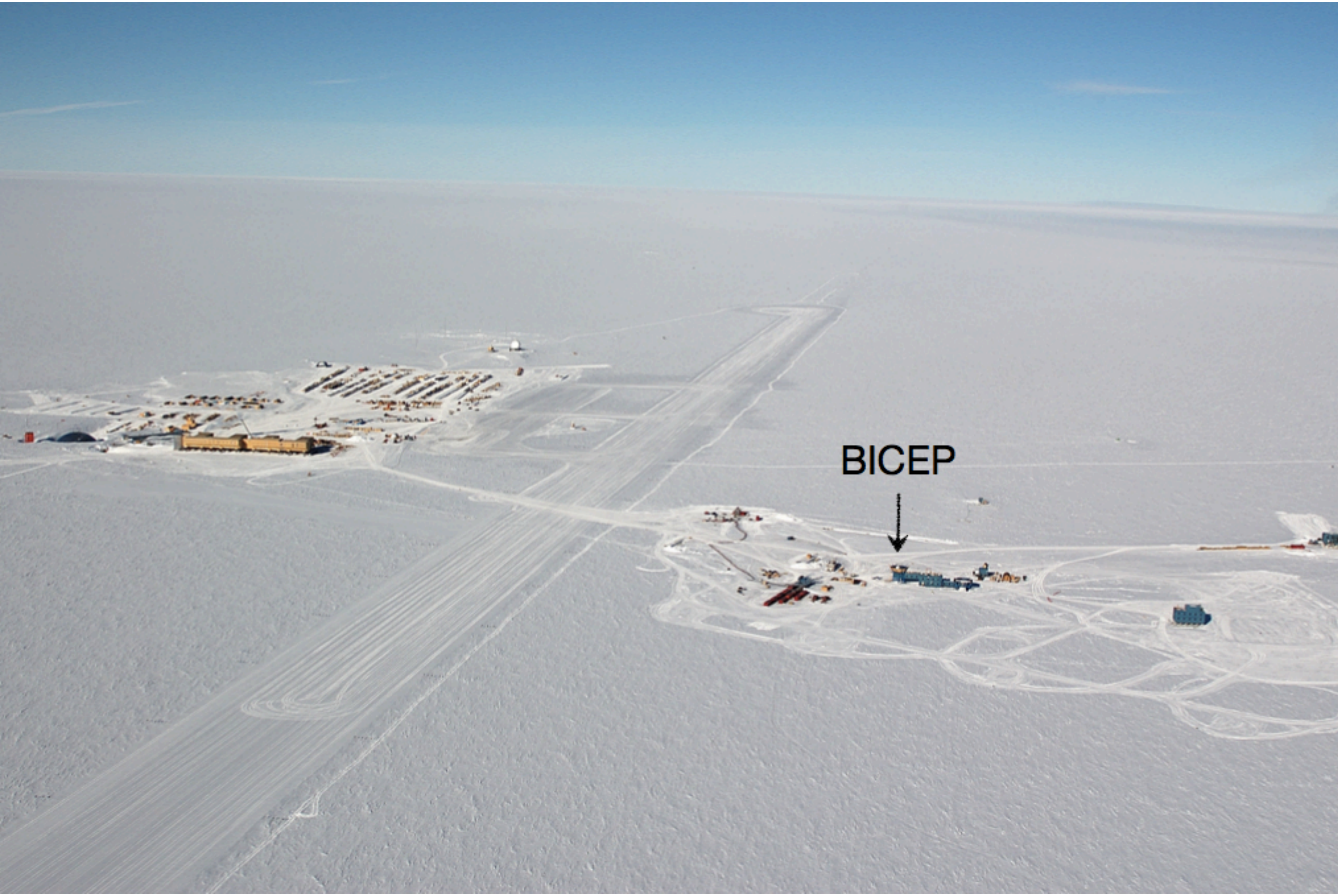
TT data (twice the present data)
Polarization



Background Imaging of Cosmic Extragalactic Polarization

The Dark Sector Lab

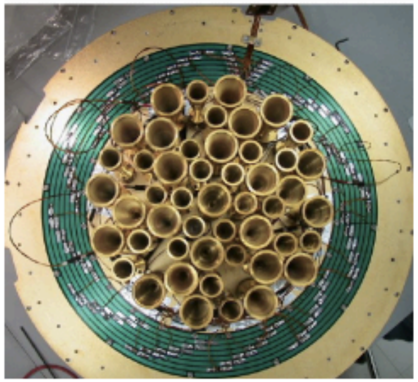


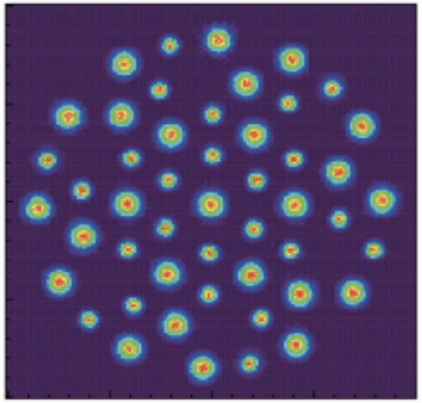

BICEP


QUIET SECTOR
DOWNWIND SECTOR
ICECUBE
SPRESO 7.5 km
Summer Camp
GEOSAT/
MARISAT Radar
SkyLab
ARO
Dome
New Station
S. Pole
CLEAN AIR
SECTOR
Skiway
PAX
terminal
SPASE 2
Viper
QUAD
BICEP
SPT
IceCube
Lab
MAPO
Dark Sector Lab
DARK SECTOR
0
300 ft
1,000 ft

BICEP1

2006-2008



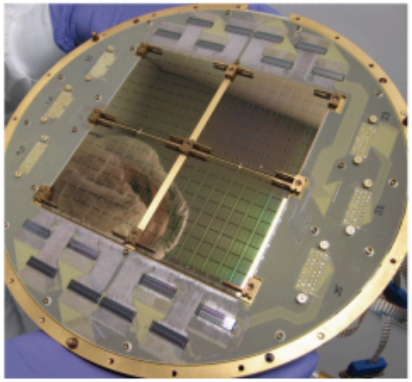


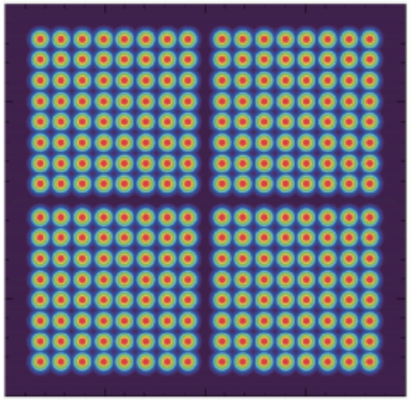
50 @ 100 GHz
48 @ 150 GHz

BICEP1 observed from 2006-2008 with 98 detectors

BICEP2

2010-2012



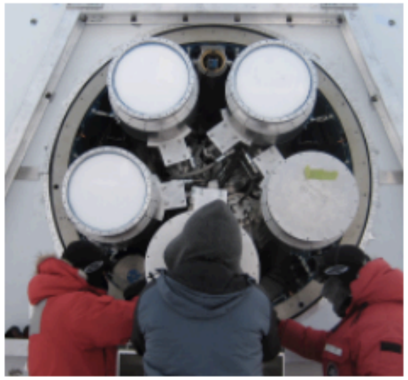


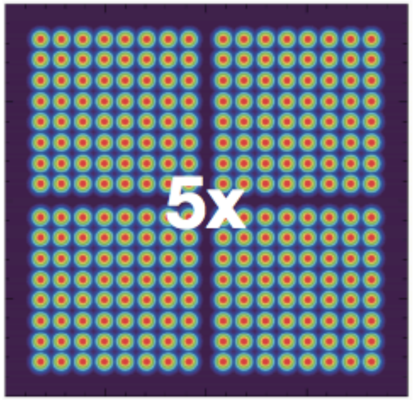
512 @ 150 GHz

BICEP2 started observing in 2010 with 512 detectors

KECK Array

2011-2016



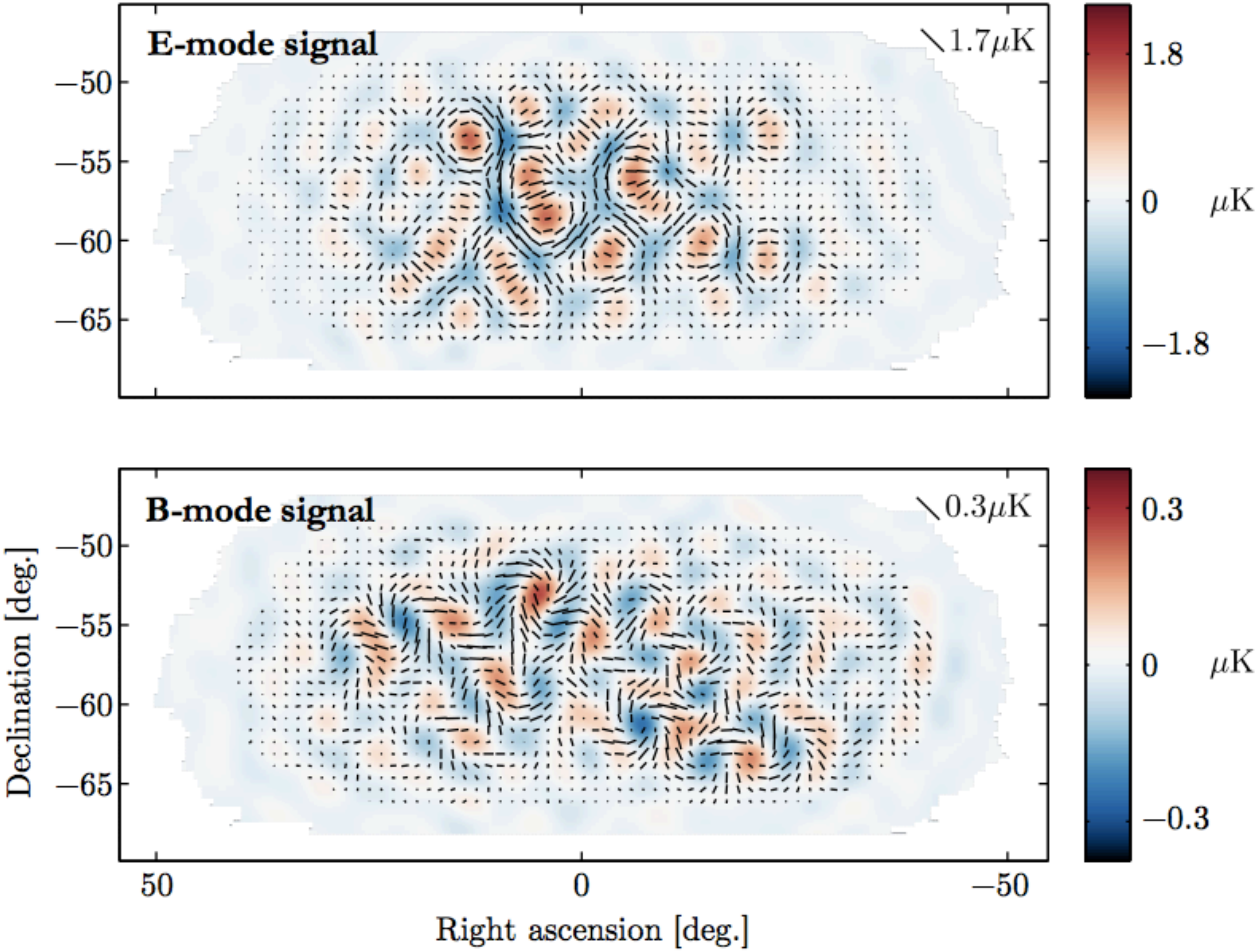


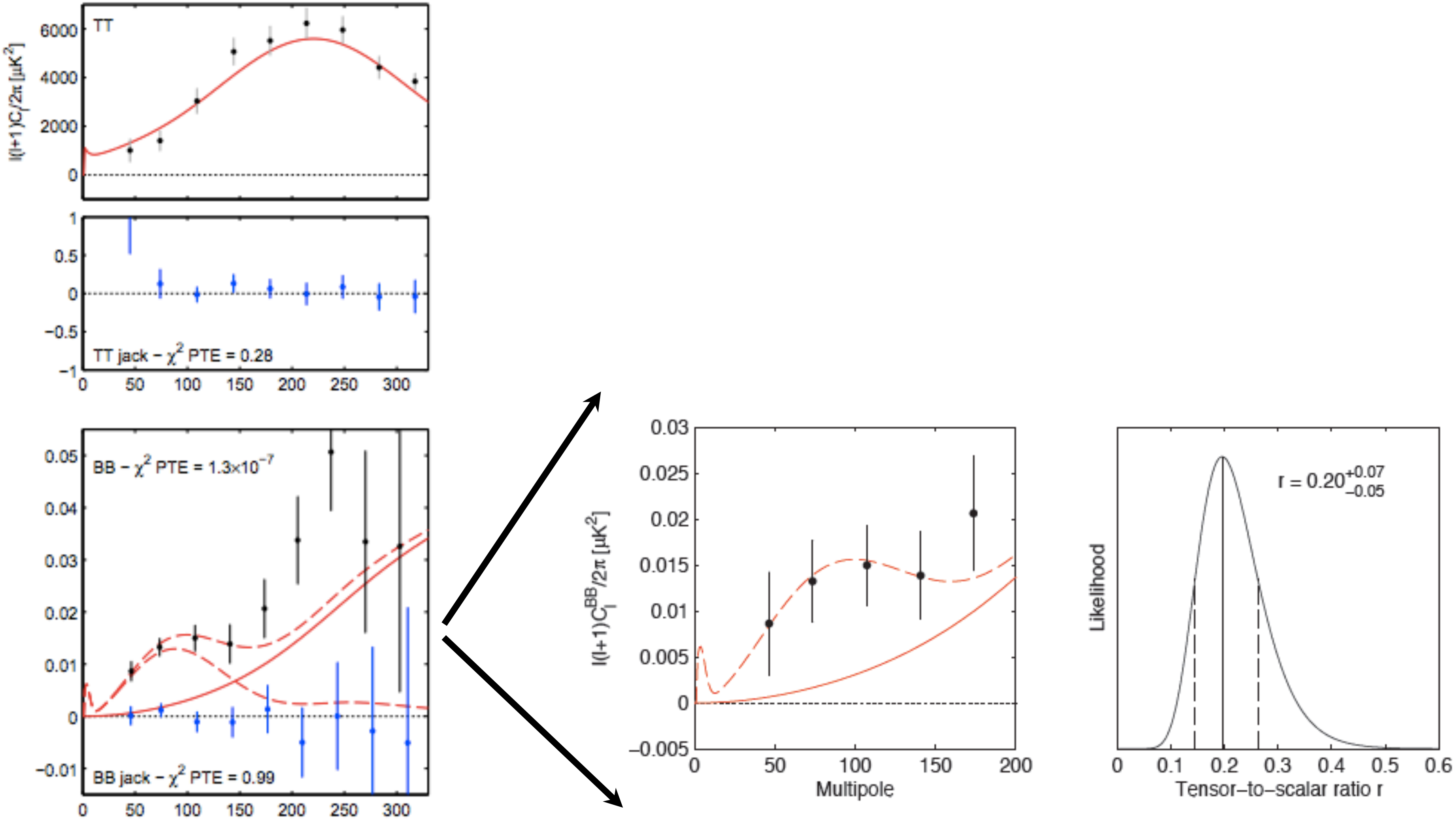
5 x 512 @ 150 GHz

The first three of five **Keck Array** telescopes started to observe in early 2011, each with 512 detectors. The other two in summer 2012. From 2011 to 2013, all receivers observed at 150 GHz. In the 2013-2014 summer season, two out of the five were converted to 100 GHz.

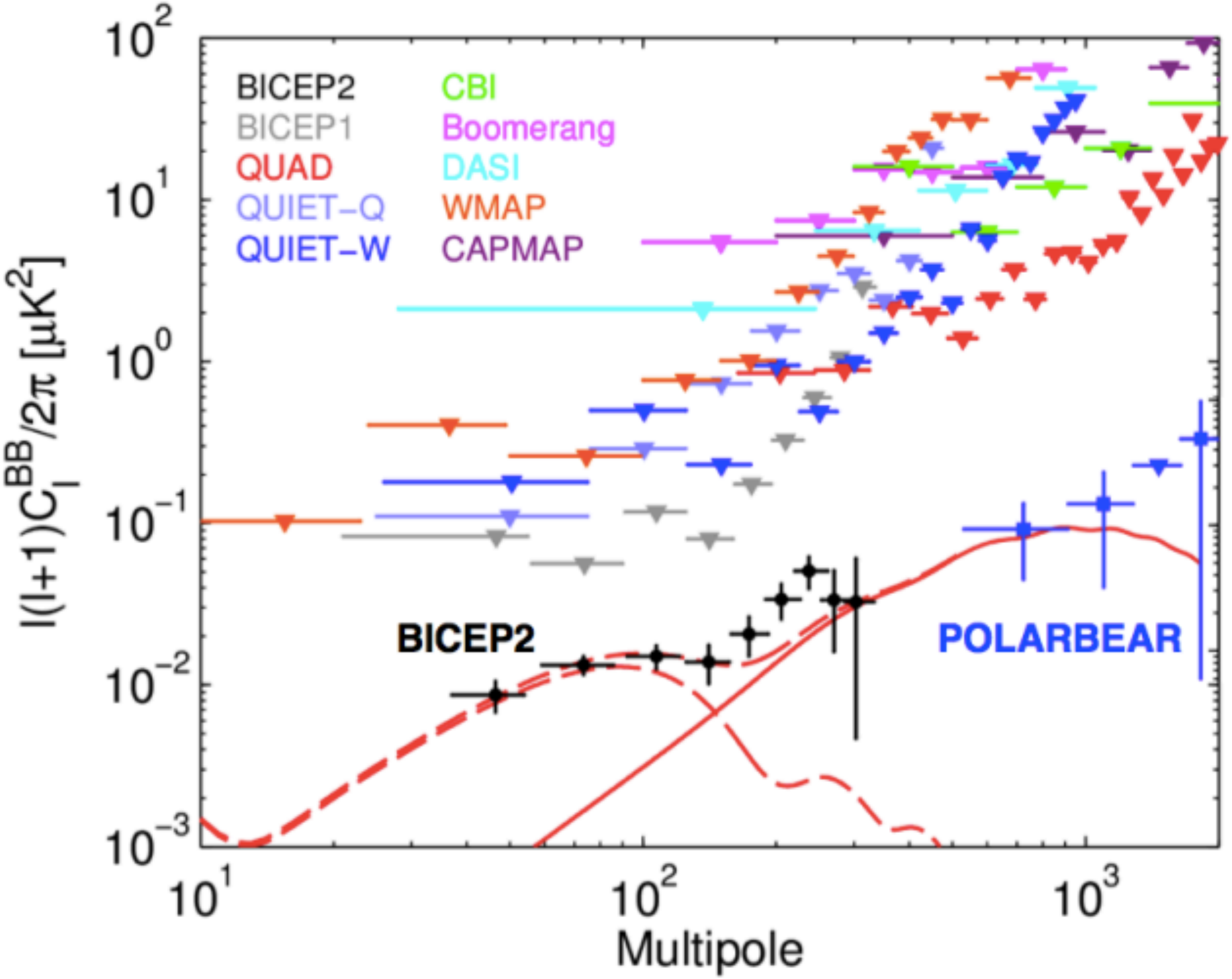
BICEP3 will begin observing in 2015 with a total of 2560 detectors, all at 100 GHz

Courtesy of D.Baumann

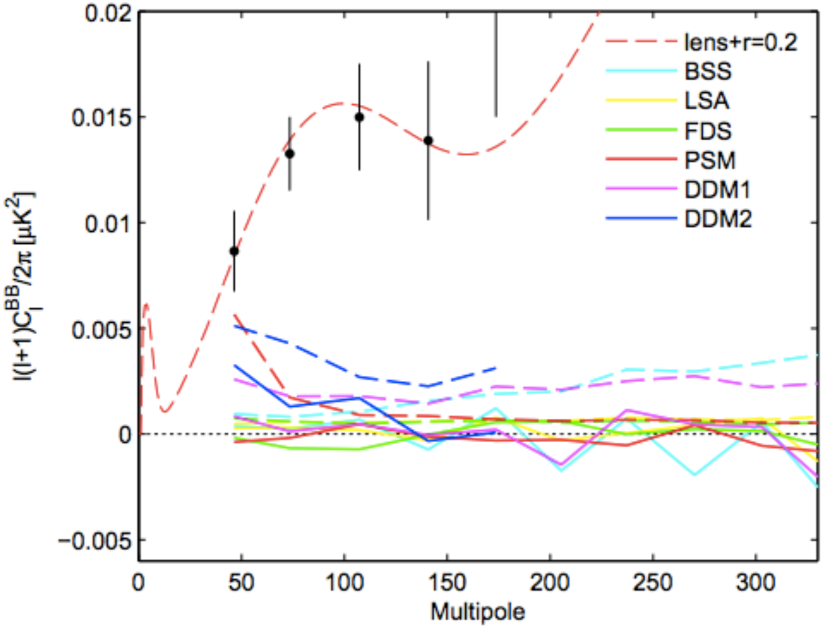

E-mode signal
1.7μK
B-mode signal
0.3μK
−50
−55
−60
−65
1.8
0
−1.8
0.3
−0.3
μK
Declination [deg.]
50
0
−50
Right ascension [deg.]

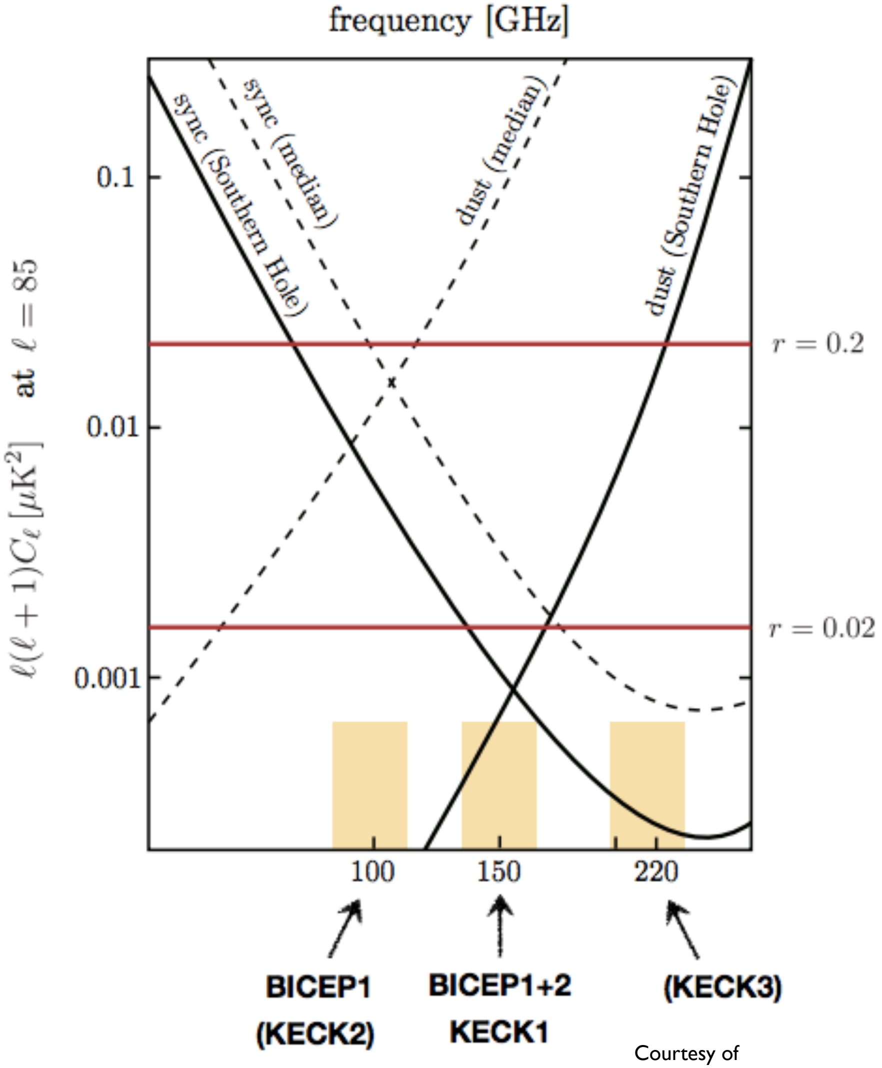


calculated on 5 bandpowers


BICEP2
BICEP1
QUAD
QUIET−Q
QUIET−W
CBI
Boomerang
DASI
WMAP
CAPMAP
BICEP2
POLARBEAR
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
$l(l+1)C_l^{BB}/2\pi\ [\mu K^2]$
10^{1}
10^{2}
10^{3}
Multipole

Foregrounds





Courtesy of
D.Baumann

See also Flauger, Hill, Spergel 2014

Future Keck Array observations at 100 GHz and Planck observations at higher frequencies will be crucial to determine whether the signal is of primordial origin

Future observations

E modes:

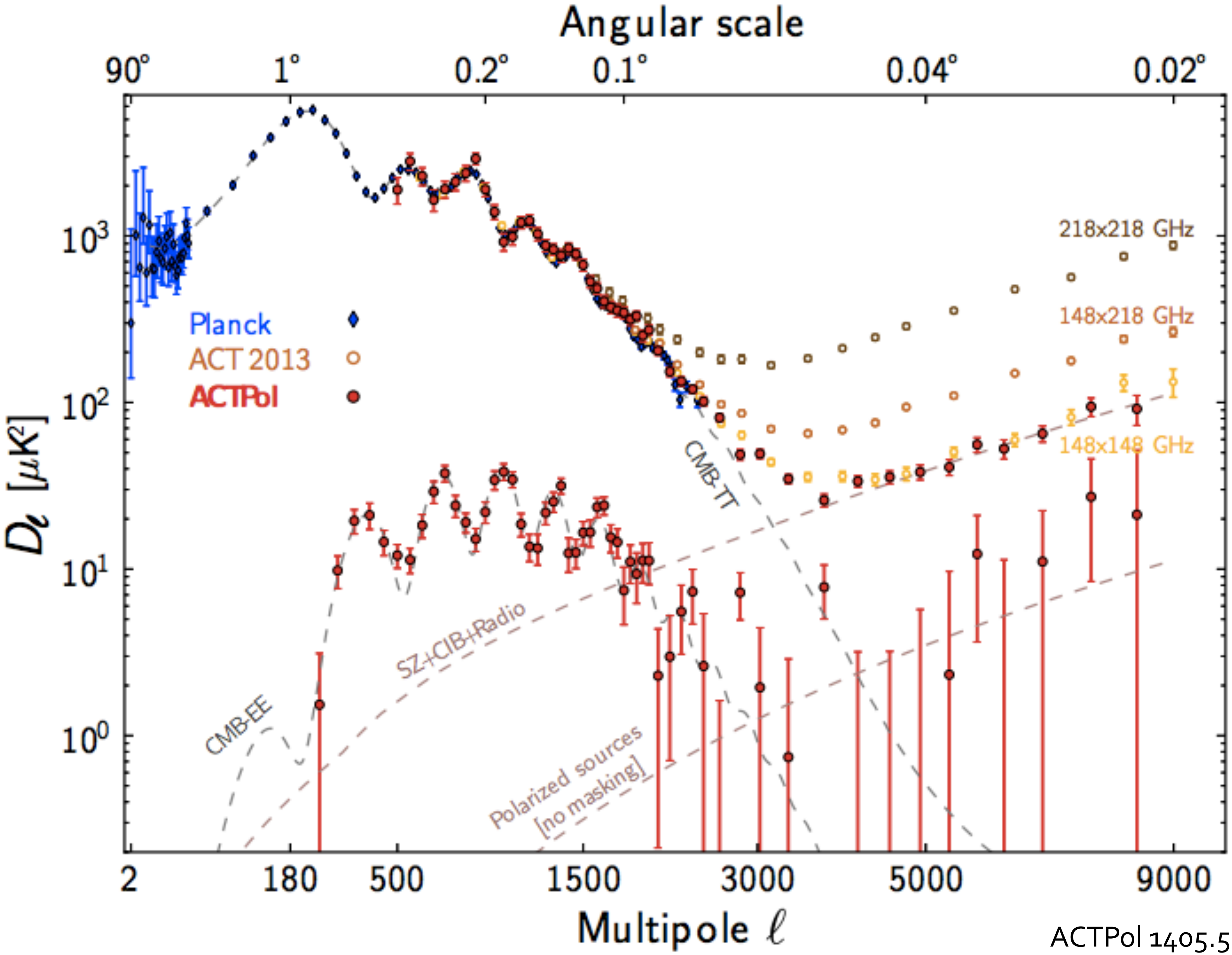
Planck, ACTPol, SPTPol

B modes (primordial range):

- Keck Array, EBEX, SPIDER, CLASS, PIPER
- Future satellites? LiteBIRD, PRISM, PIXIE

B modes (lensing range):

- SPTPol, ACTPol, POLARBEAR
- Aiming for mass limits on neutrinos of 0.05-0.1 eV
- Probe for Dark Energy at $z \approx 1\text{-}2$



ACTPol 1405.5524