The Cosmic Microwave Background

Jean-Paul KNEIB

Quiz

- How to identify multiple images?
- What is the simplest thermodynamical model of a mass distribution? What are the limitations of this model?
- What is the model derived by numerical simulations?
- How to describe the mass model in a galaxy cluster?
- How precise is the best lens mass model of a cluster of galaxies?
- How to probe the central mass profile of a cluster?

Introduction

- Mass estimates of objects/structures in the Universe are possible:
  - *In a direct way*: through lensing, dynamics, X-ray, SZ ...
  - *In an indirect way*: through HI absorption along the line of sight of quasars (next week)
- These mass measurements probe the content of the Universe in the $0<z<\sim 4$ range
- **The CMB probes the earlier Universe at z~1100.**
- *What can be learned by measuring the CMB light?*

Outline

- Origin of the CMB
- Anisotropies in the CMB and their Formation
- Statistical Assessment of the CMB
- Cosmological Tests with the CMB

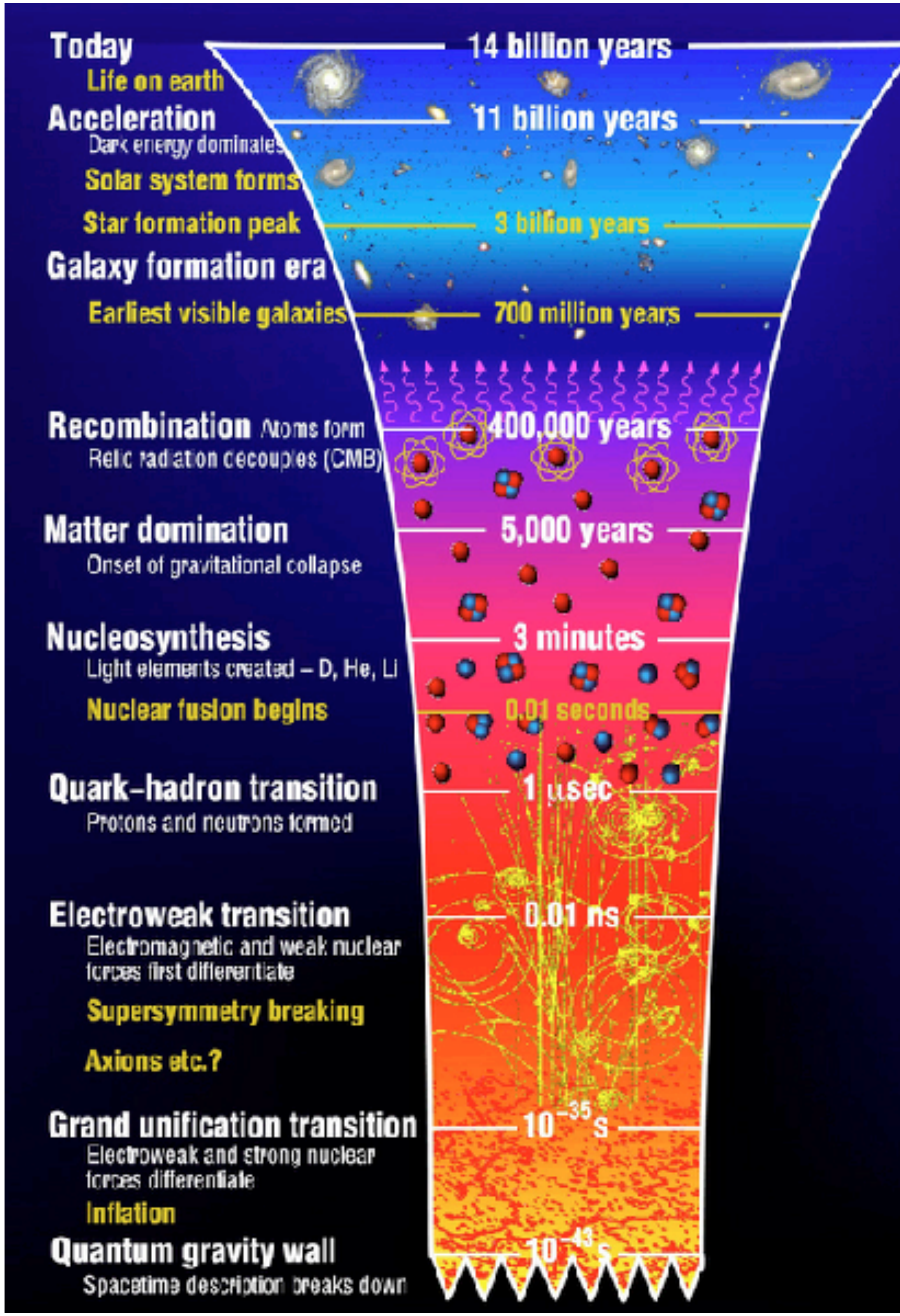
https://en.wikipedia.org/wiki/Cosmic_microwave_background

Next CMB ground experiment (US led) https://cmb-s4.org/

LiteBIRD space-mission (Japan led+ESA?) https://www.isas.jaxa.jp/en/missions/spacecraft/future/litebird.html

Quick Universe History

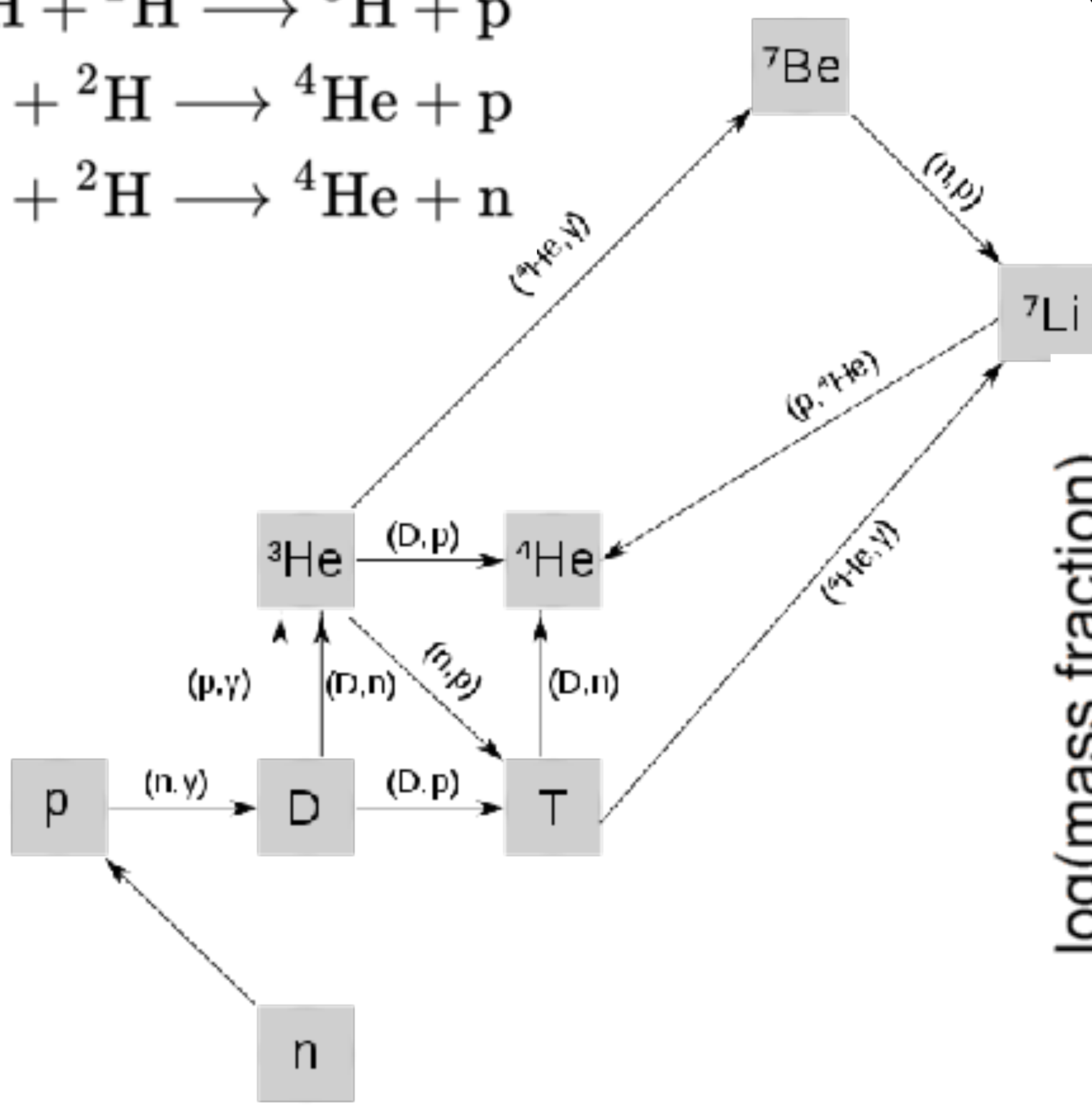
- T~10^{15} K, t~10^{-12} sec: Primordial soup of fundamental particles (quarks & gluons).
- T~10^{13} K, t~10^{-6} sec: Protons and neutrons form.
- T~10^{10} K, t~3 min: **Big-Bang Nucleosynthesis: nuclei form ~76% Hydrogen, 24% Helium**
- T~3000 K, t~300, 000 years: **Hydrogen atoms form (recombination).**
- T~10 K, t~10^9 years: Galaxies form.
- T~3 K, t~10^{10} years: Today.

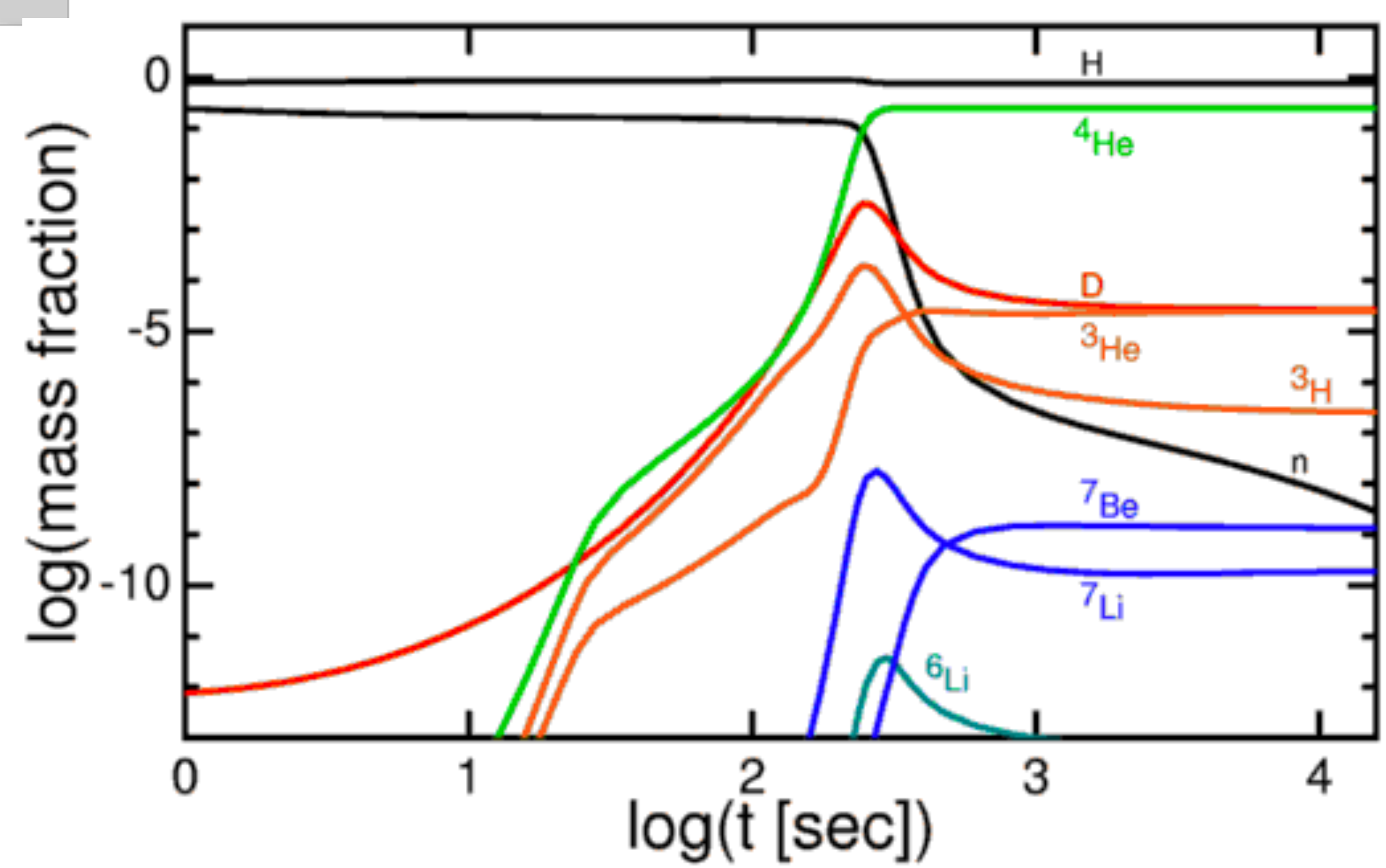


Big-Bang Nucleosynthesis

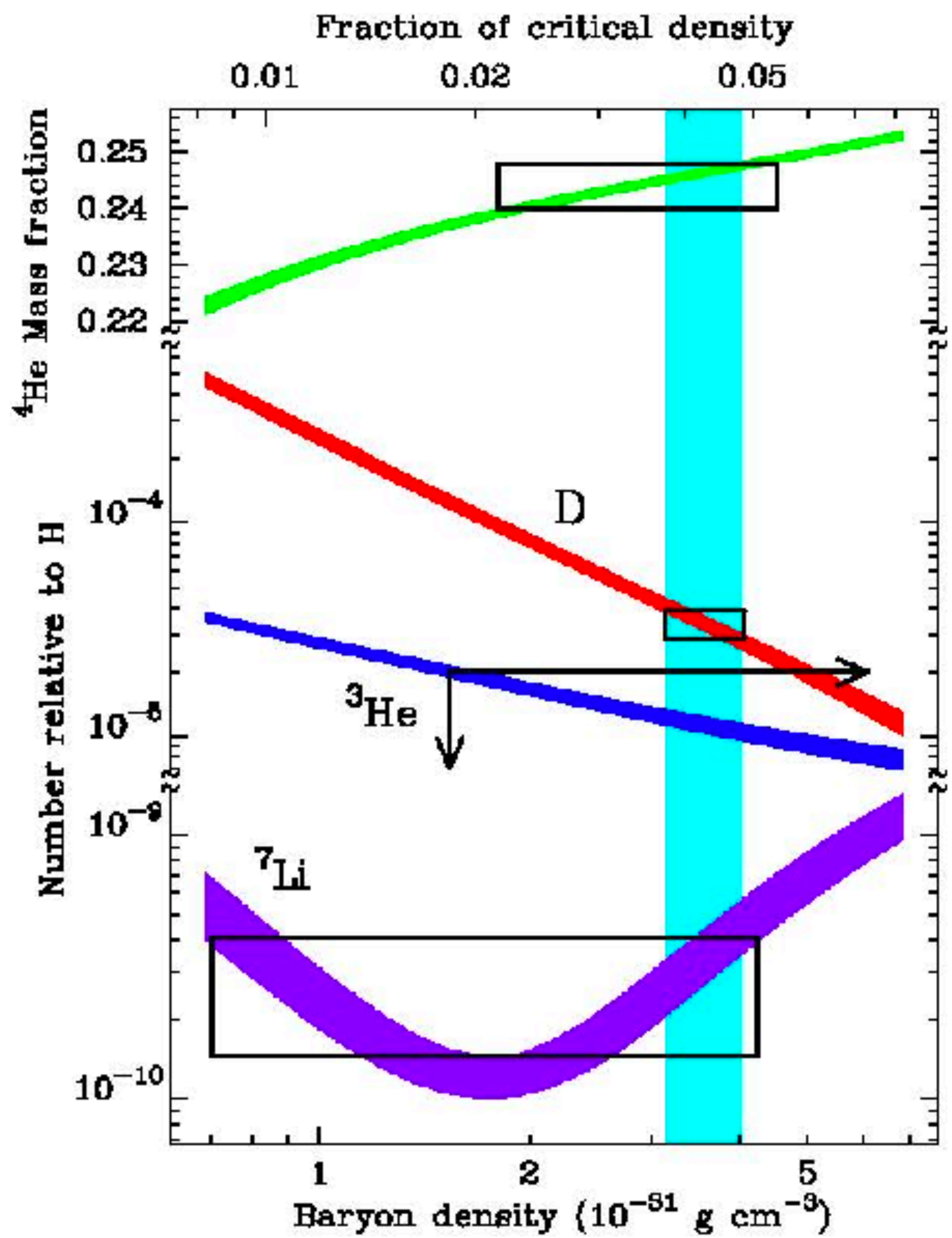
- Nuclear fusion begins ~1 sec after BigBang, 10^{10} K
- Produced mostly H and He
- With traces of D, ^{3}He, ^{7}Be, and ^{7}Li

$$\mathrm{p} + \mathrm{n} \longrightarrow {}^2\mathrm{H} + \gamma$$
$$\mathrm{p} + {}^2\mathrm{H} \longrightarrow {}^3\mathrm{He} + \gamma$$
$${}^2\mathrm{H} + {}^2\mathrm{H} \longrightarrow {}^3\mathrm{He} + \mathrm{n}$$
$${}^2\mathrm{H} + {}^2\mathrm{H} \longrightarrow {}^3\mathrm{H} + \mathrm{p}$$
$${}^3\mathrm{He} + {}^2\mathrm{H} \longrightarrow {}^4\mathrm{He} + \mathrm{p}$$
$${}^3\mathrm{H} + {}^2\mathrm{H} \longrightarrow {}^4\mathrm{He} + \mathrm{n}$$



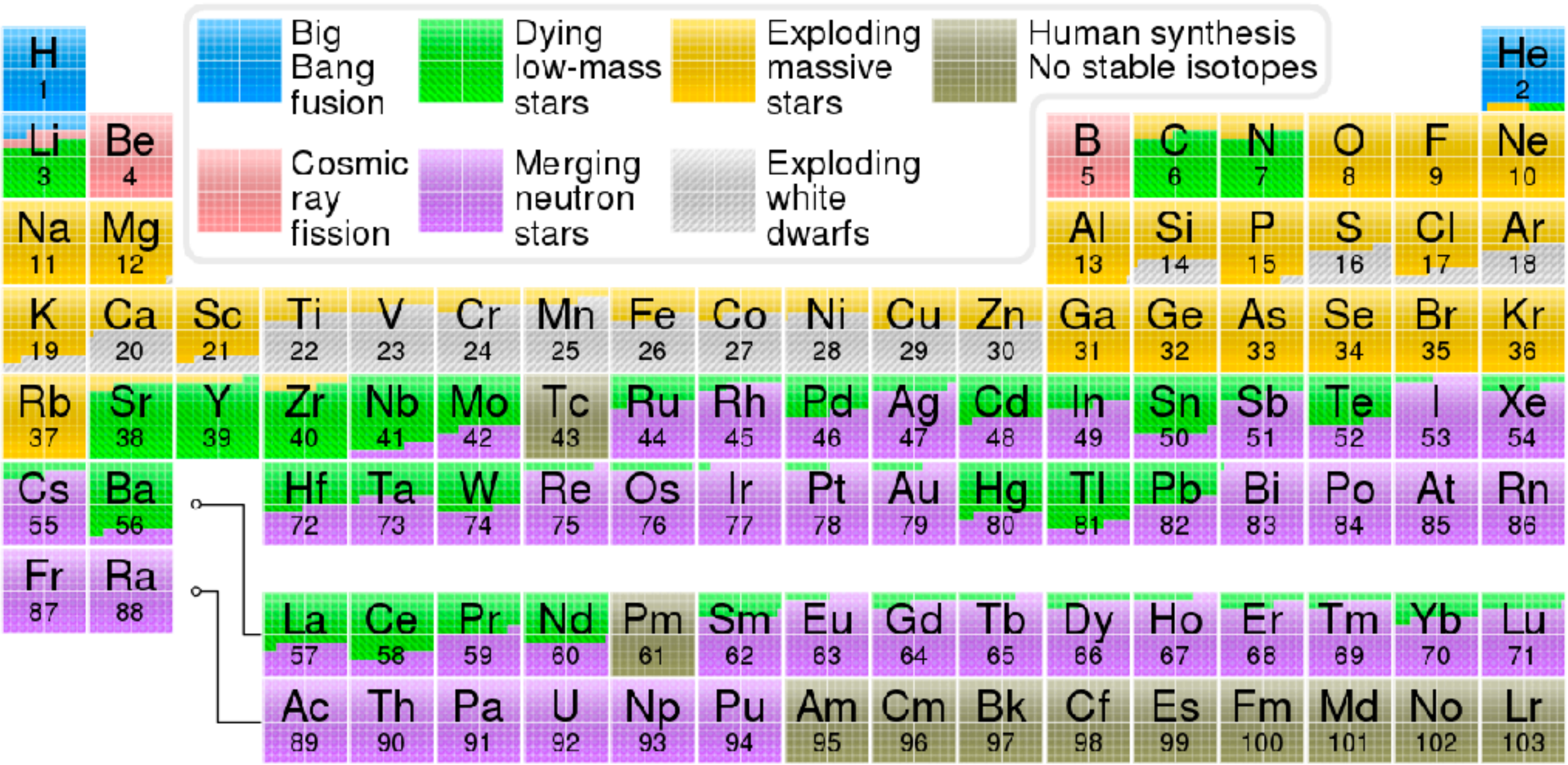


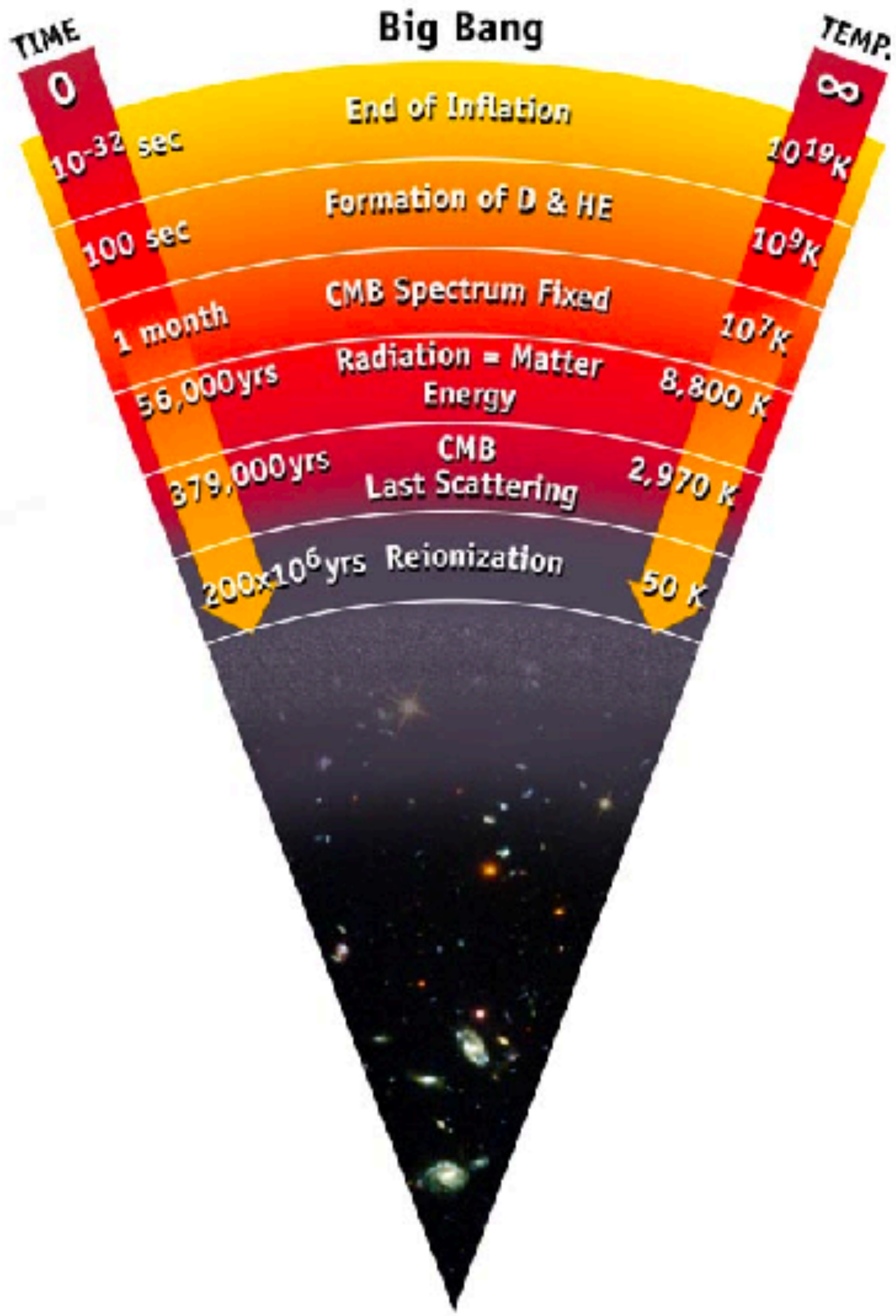
Big-Bang Nucleosynthesis



Densities relative to Hydrogen depend on the baryon density

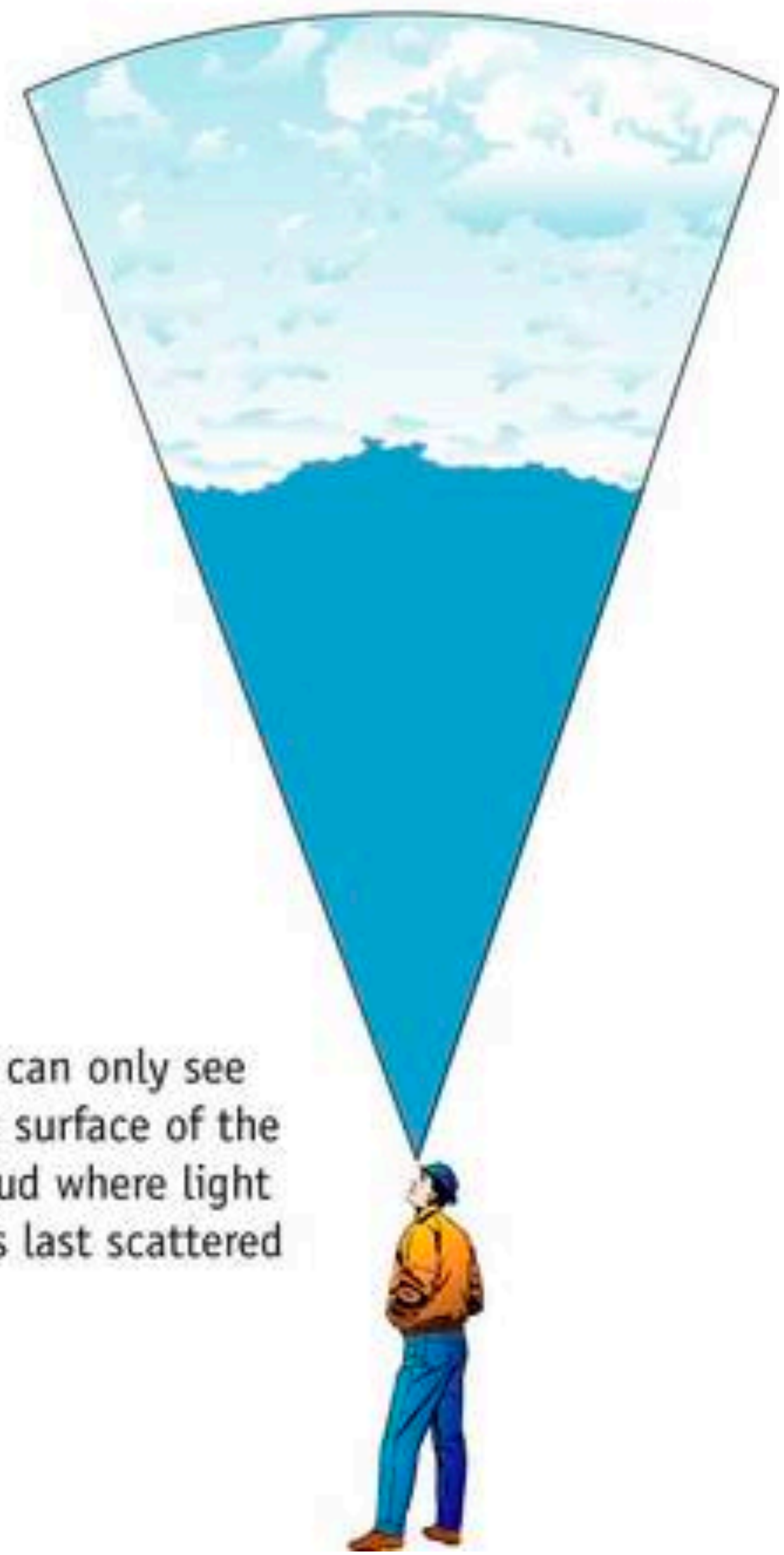
Cosmogenic origin of each element





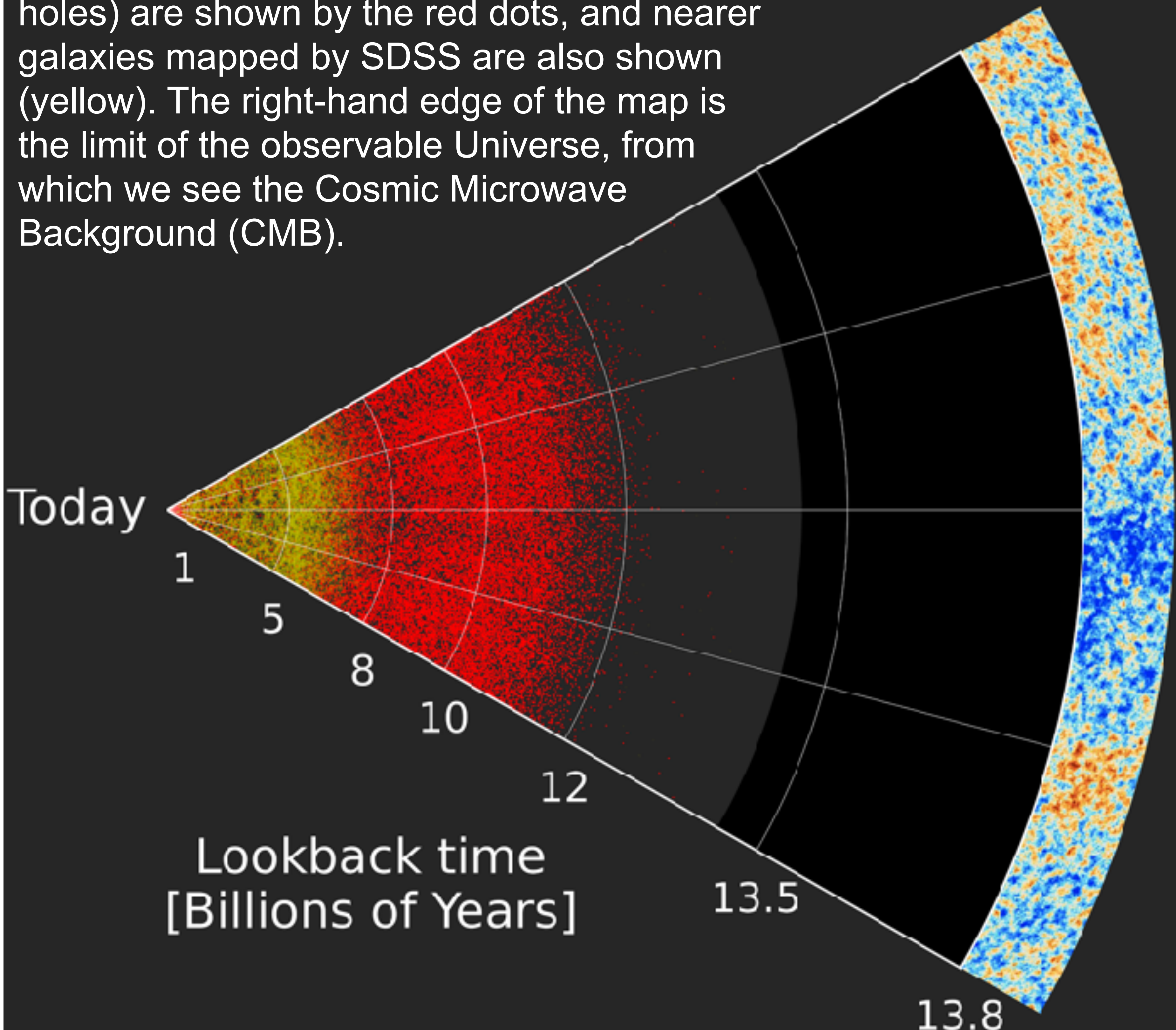
PRESENT
13.7 Billion Years
after the Big Bang

The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



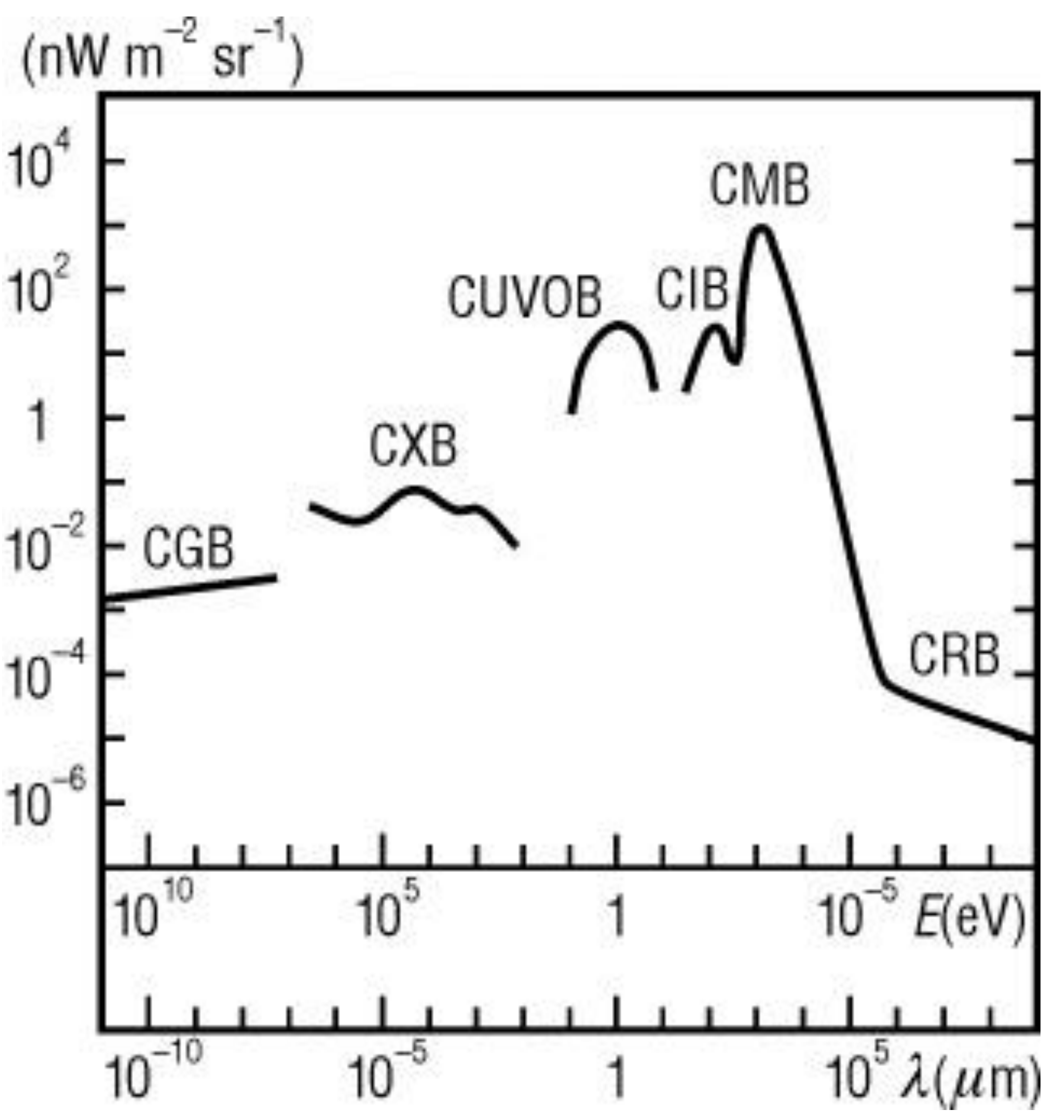
We can only see the surface of the cloud where light was last scattered

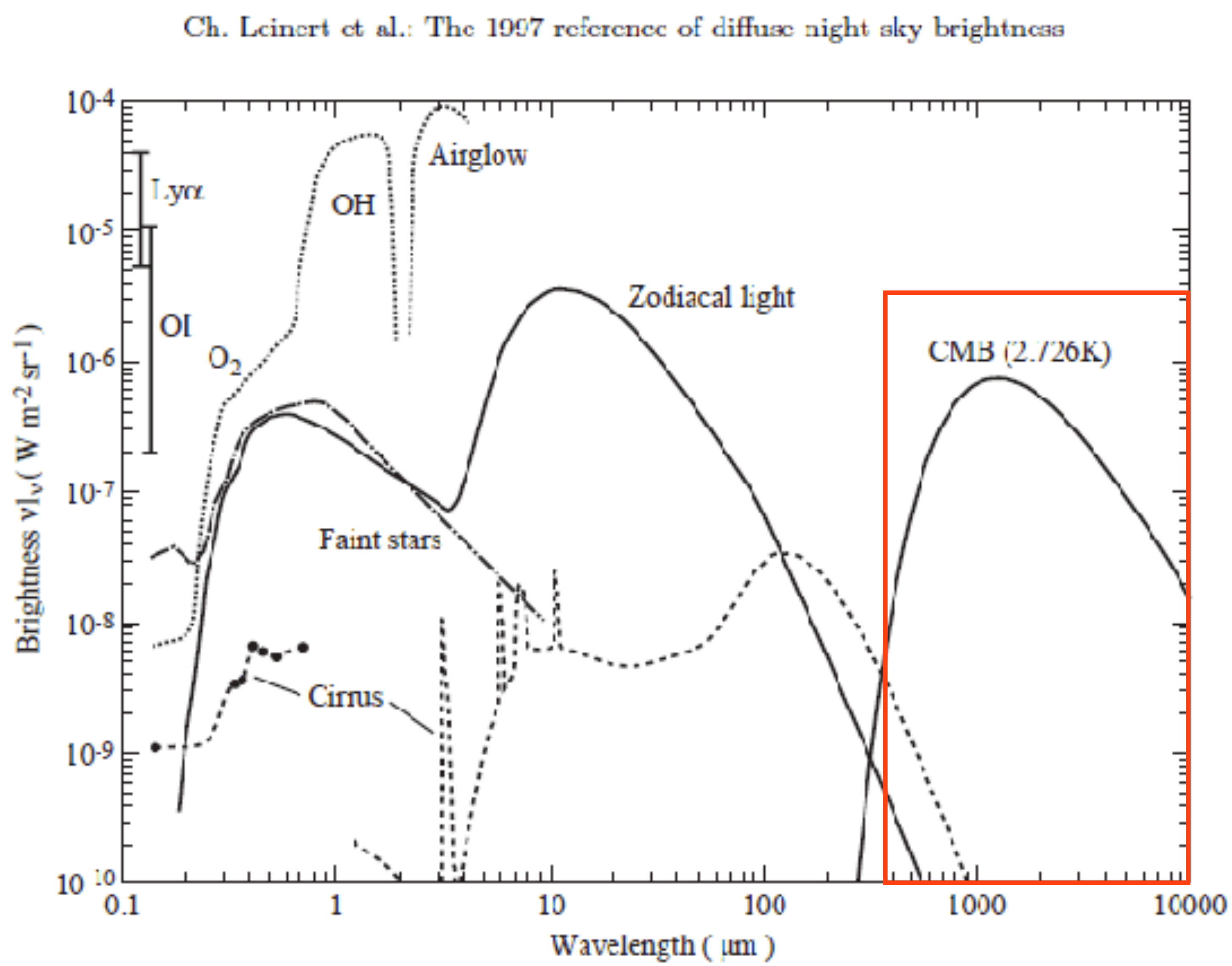
Slice through largest-ever three-dimensional map of the Universe. The locations of quasars (galaxies with supermassive black holes) are shown by the red dots, and nearer galaxies mapped by SDSS are also shown (yellow). The right-hand edge of the map is the limit of the observable Universe, from which we see the Cosmic Microwave Background (CMB).



Extragalactic Background

The cosmic microwave background completely dominates the EBG in the centimetre and millimetre wavelengths region.





Ionisation equilibrium

- Consider a plasma of Hydrogen

$$e + p \leftrightarrow H + \gamma$$

- The **ionisation equilibrium** is determined by the Saha equation that reads:

$$\frac{n_e n_p}{n_H} = \frac{(2\pi m_e kT)^{3/2}}{h^3} e^{-\frac{I_H}{kT}}$$

- with I_H=13.6 eV is the ionisation energy of hydrogen.
- Defining the degree of ionisation:

$$X \equiv \frac{n_p}{n_p + n_H}$$

Rough estimate of recombination

- Assuming neutral medium: $n_e = n_p$; the ionisation equilibrium reads:

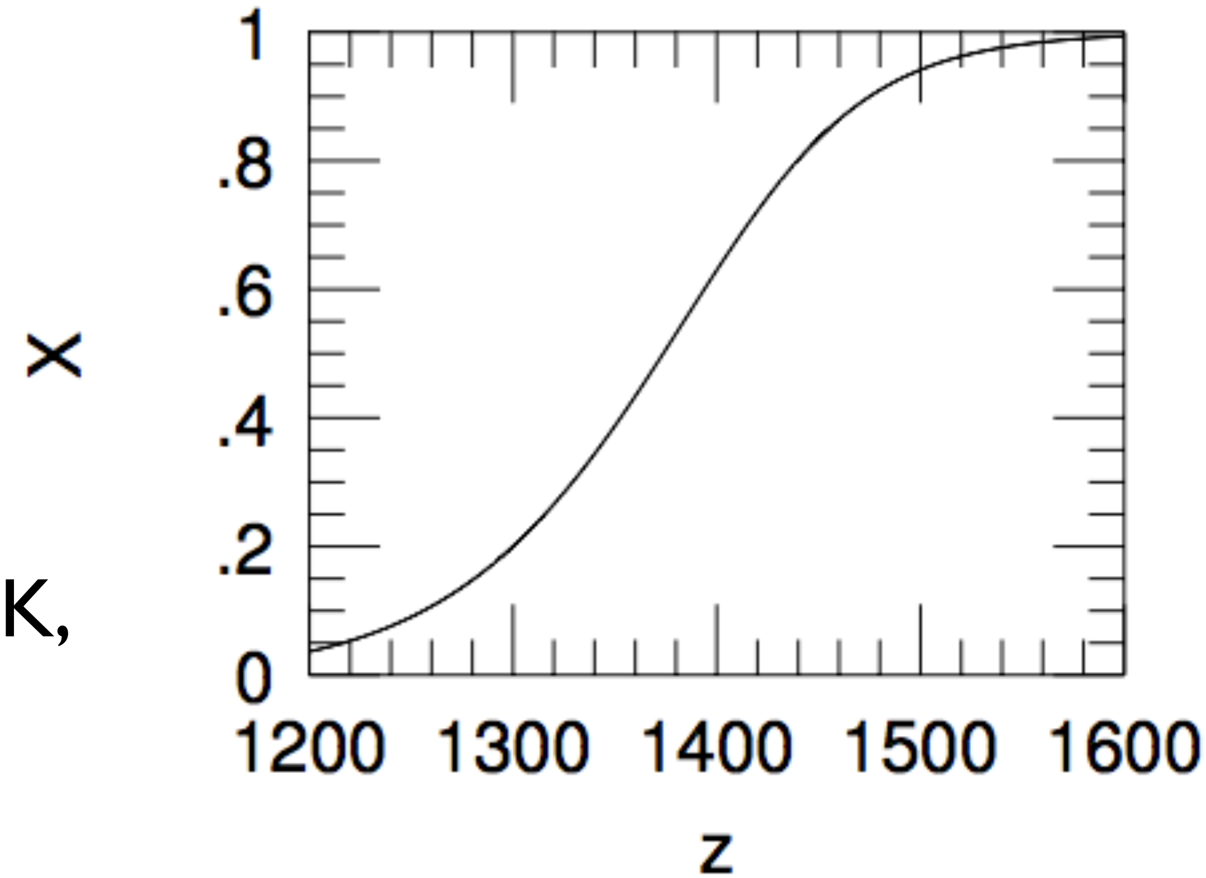
$$\frac{X^2}{1-X} = \frac{1}{n_p + n_H} \frac{(2\pi m_e kT)^{3/2}}{h^3} e^{-\frac{I_H}{kT}}$$

- Temperature and Hydrogen density are a function of redshift:

$$T = 2.728(1+z) \;\; \mathrm{K}$$

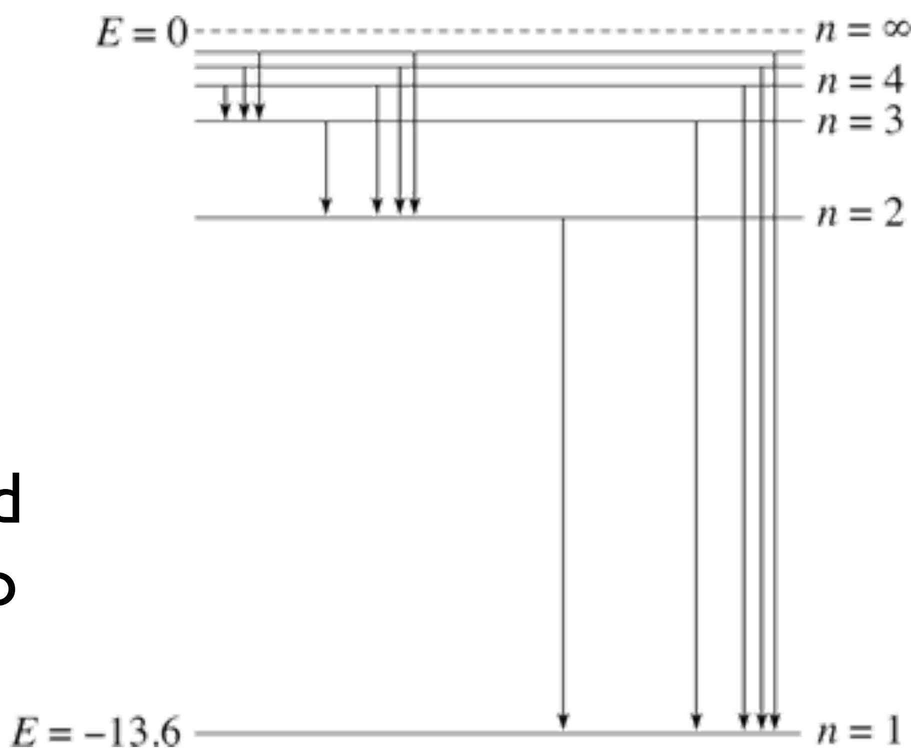
$$n_p + n_H = 1.6(1+z)^3 \;\; \mathrm{m}^{-3}$$

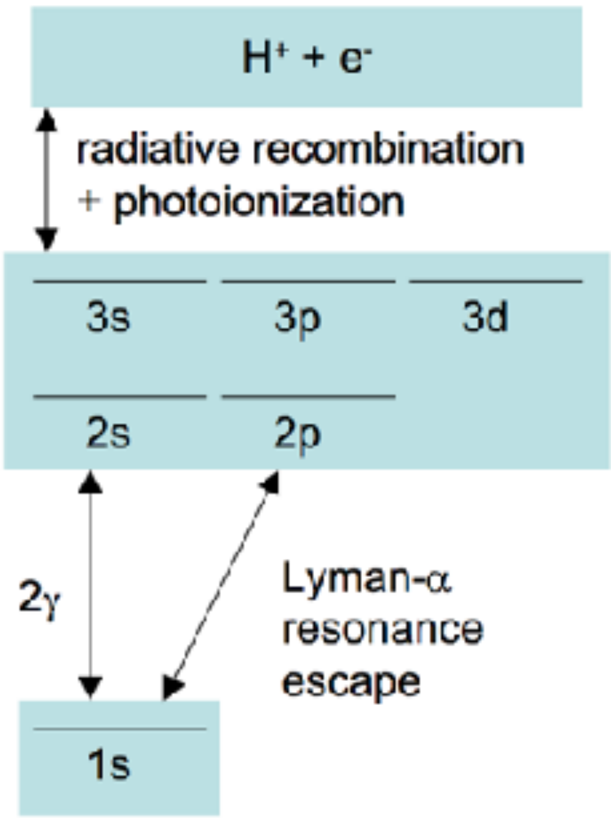
- Solving this equation for a 50% ionization fraction yields a recombination temperature of ~4000 K, corresponding to redshift z~1400.



More accurate estimate recombination

- In 1968, physicists computed the non-equilibrium recombination history of H.
  - Direct recombination to ground state (n=1) of H is very inefficient, as photons produced will re-ionise the neighbour H atom.
  - Electrons only efficiently recombine to higher excited states of H, from which they cascade quickly down to the first excited state (n=2).
  - From the first excited state (n=2), electrons can then reach the ground state (n=1)
  - Atoms in the first excited state (n=2) may also be re-ionized by the ambient CMB photons before they reach the ground state.
- This model is usually described as an **"effective three-level atom"** as it requires keeping track of hydrogen under 3 forms: ground state, first excited state, and ionized.





More accurate estimate recombination

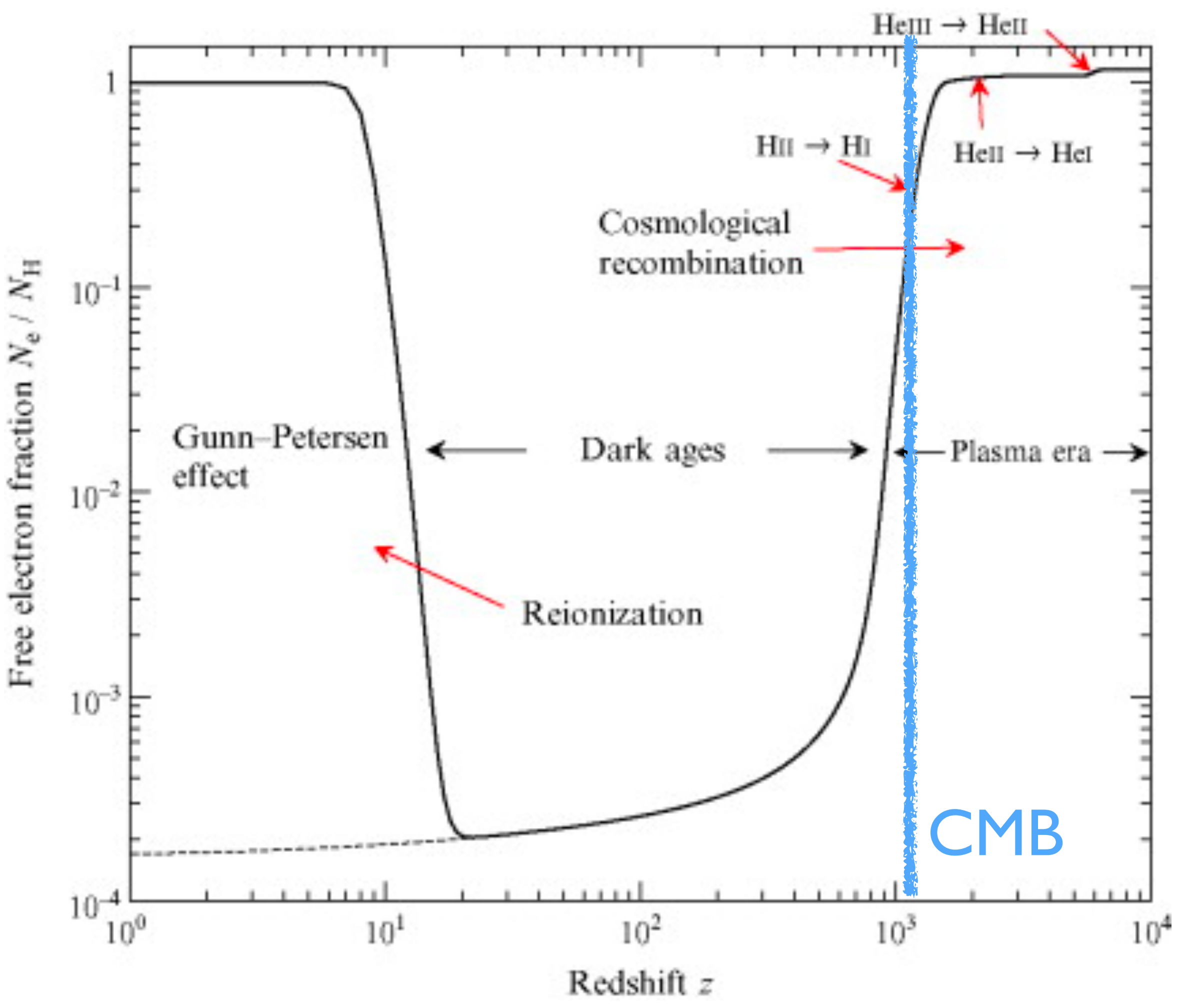
- The recombination history is then described by the differential equation:

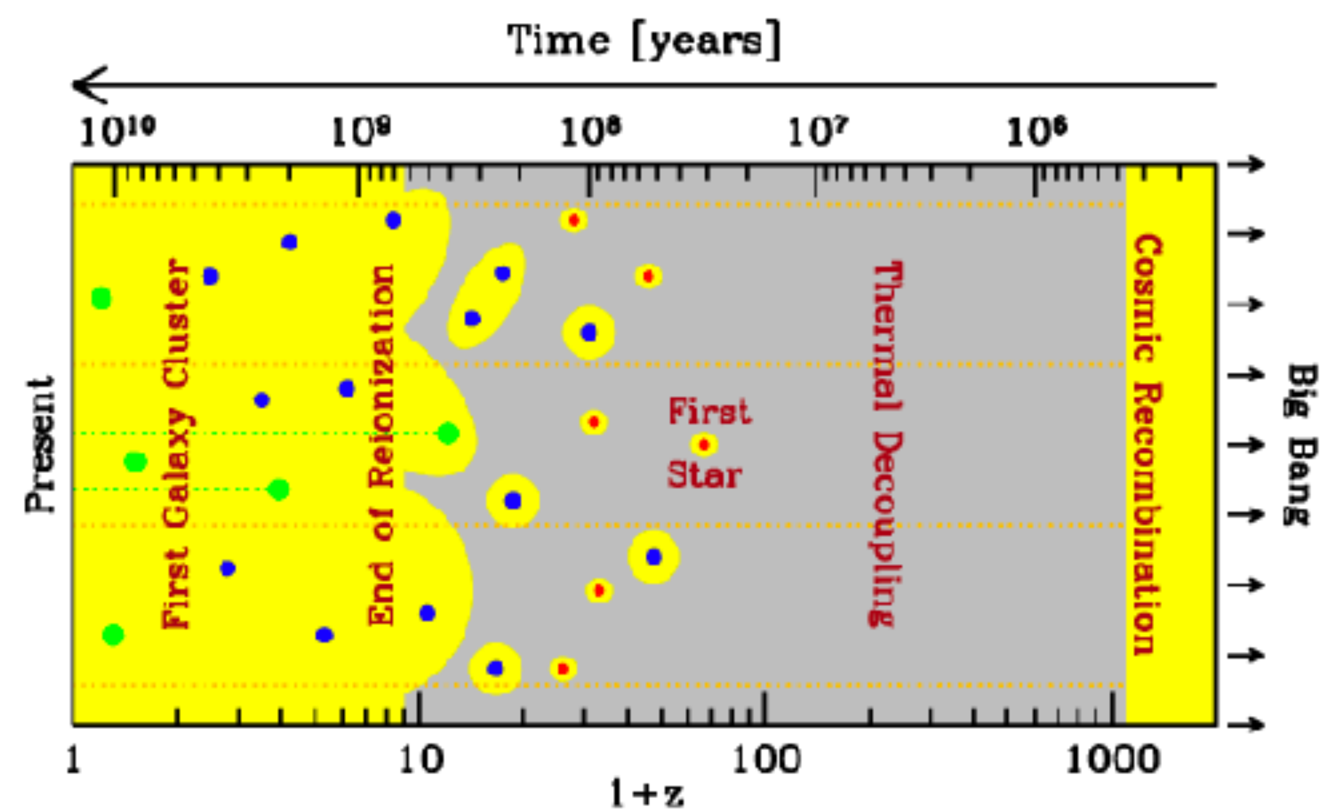
Recombination Photo-ionisation

$$\frac{dX}{dt} = -C(\alpha_B(T)n_p.X - 4\beta_B(T)e^{E_{21}/kT}.(1-X))$$

- where α_B is for "case B" recombination coefficient to the excited states of hydrogen, β_B is the photo-ionization rate, and $E_{21}=10.2$ *eV* is the energy of the first excited state.
- With modern values of cosmological parameters, the universe is **90% neutral at z ≈ 1070.**

Recombination history





Helium recombination

- Helium (He) represents 24% of the total mass of baryonic matter after the BigBang nucleosynthesis.
- Ionization energy of He is larger than H and *it recombines earlier.*
- Neutral He carries 2 e^-, its recombination is in 2 steps.
- The first recombination, follows Saha equilibrium and takes place around redshift z≈6000.

$$He^{++} + e^- \leftrightarrow He^+ + \gamma$$

- The second recombination is slower than predicted from Saha equilibrium and takes place around redshift z≈2000.

$$He^+ + e^- \leftrightarrow He + \gamma$$

- He recombination is not critical for the prediction of CMB anisotropies, since the Universe is optically thick after He has recombined.

Blackbody properties

- the energy density (energy per unit volume) in frequency interval dν about ν is:

$$\epsilon(\nu)d\nu = \frac{8\pi h}{c^3}\,\frac{\nu^3 d\nu}{e^{h\nu/kT}-1}$$

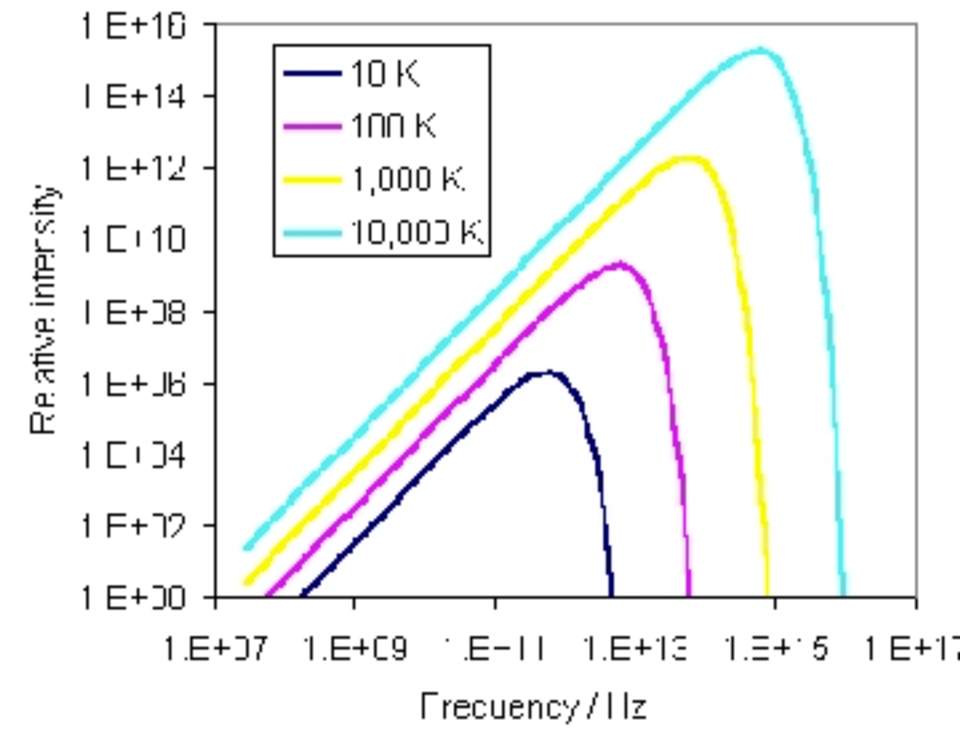
- Wien's law:

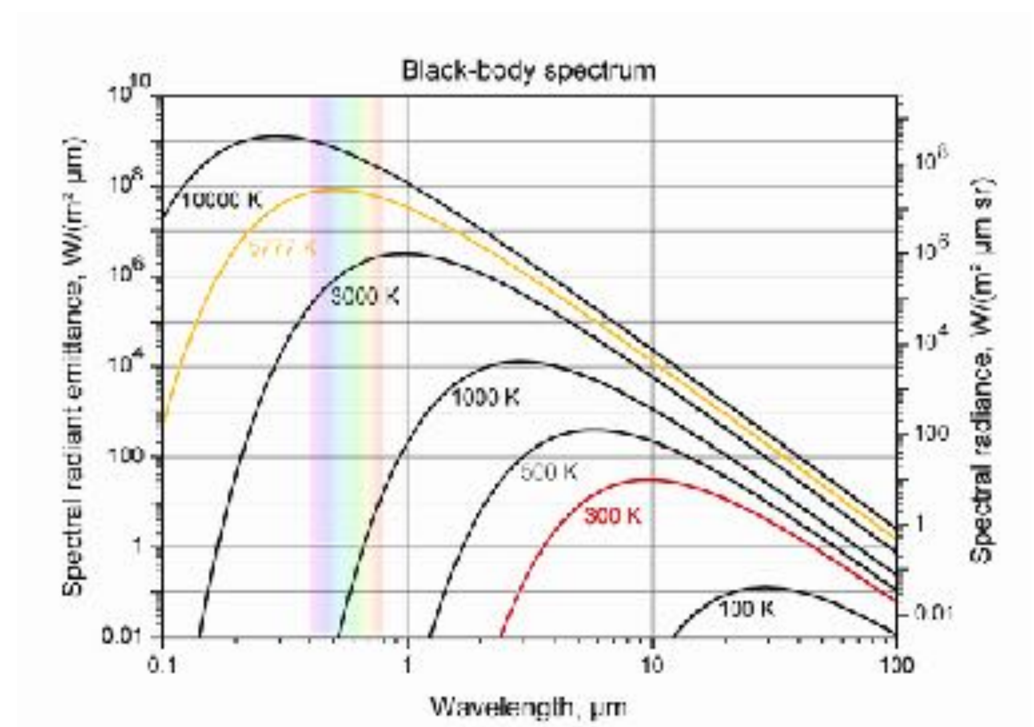
$$\lambda_{max}.T = 2897\ \mu\text{m.T}$$

- The total energy (integrating the energy density over all frequencies):

$$\epsilon_{rad} = \alpha.T^4 = \frac{4\sigma}{c^3}.T^4$$

- σ is the Stefan-Boltzman constant





Number of CMB photons

- The total energy of the CMB is:

$$\epsilon_{rad,t_0} = \alpha . T_0^4 = 0.261 \ \ \mathrm{MeVm}^{-3}$$

- The energy per CMB photon is small:

$$\mathrm{h}\nu_{\mathrm{mean}} = 6.34 \times 10^{-4} \ \ \mathrm{eV}$$

- The number density of CMB photons in the universe is large:

$$n_{\gamma,t_0} = \ 411 \ \ \mathrm{cm}^{-3}$$

Baryon to Photon ratio

- The density of baryon is measured to be:

$$\Omega_b h^2 = 0.02$$

- corresponding to a number density of (one baryon for 5 cubic meter)

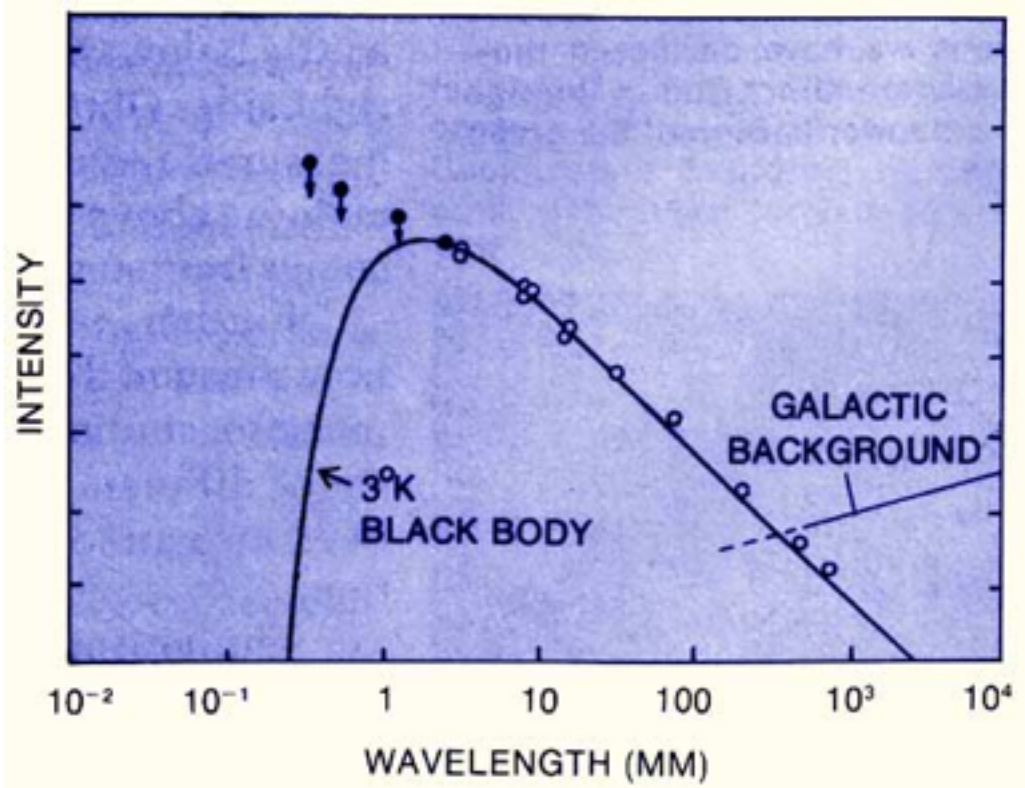
$$n_b = 0.22 \ \mathrm{m}^{-3}$$

- Thus the baryon to photon ration is:

$$\eta = \frac{n_b}{n_\gamma} \approx 5 \times 10^{-10}$$

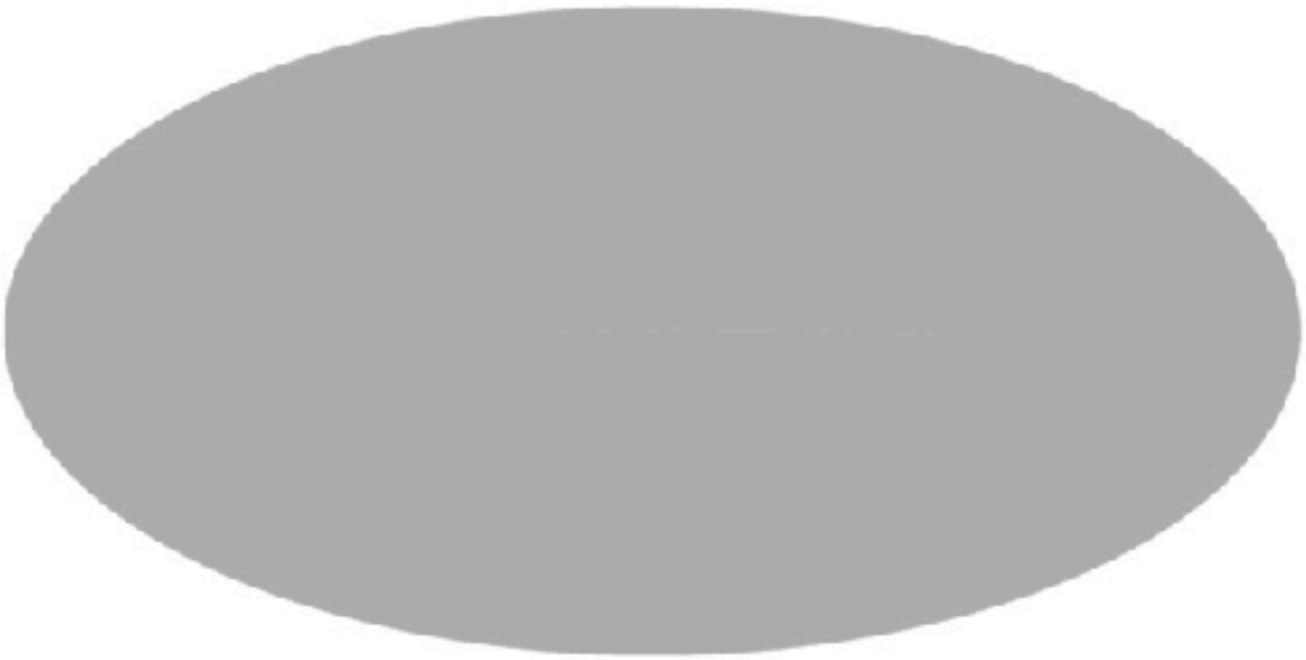
CMB Observations

- [CMB photons are as common as dust]
- In 1964-65 Arno Penzias and Robert Wilson were surprised when they serendipitously discovered the CMB light!
- As radio astronomers working at Bell Laboratories, they were using a horn-reflector radio antenna to receive microwave signals, at λ=7.35 cm, reflected from an orbiting communications satellite.
- They found a slightly stronger signal than they expected, and the noise signal was constant in any direction! (consistent with an added temperature noise of 3.5 Kelvin)

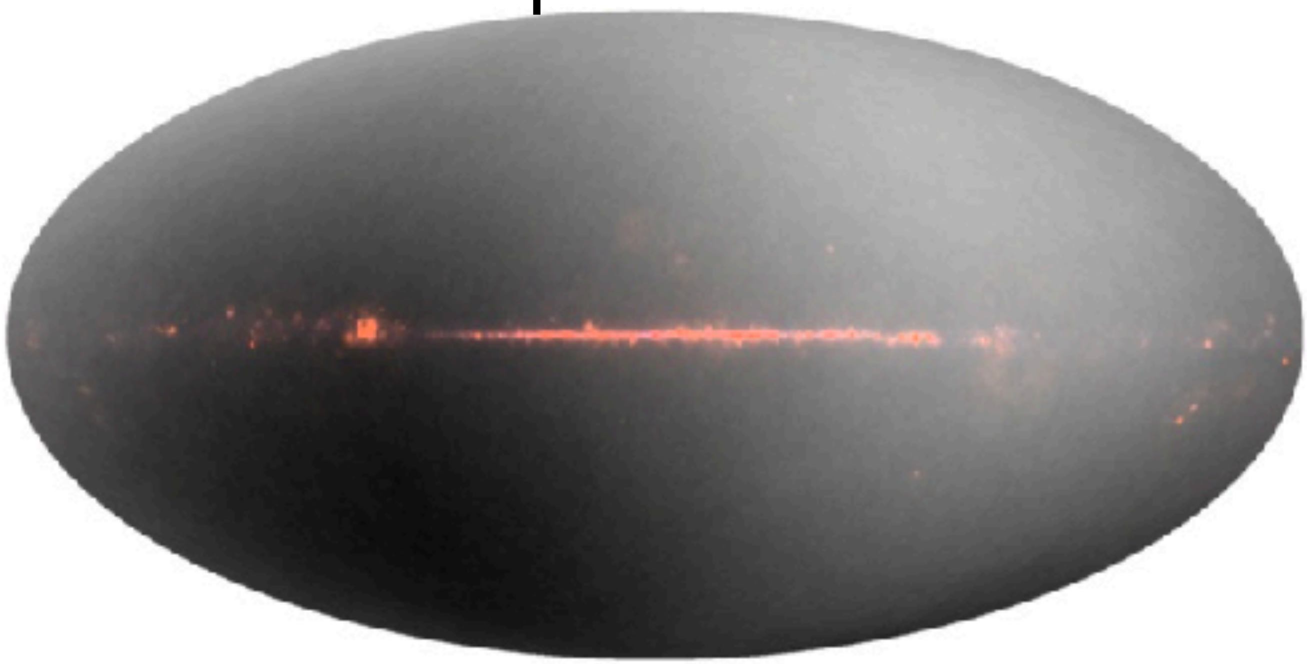


CMB observations

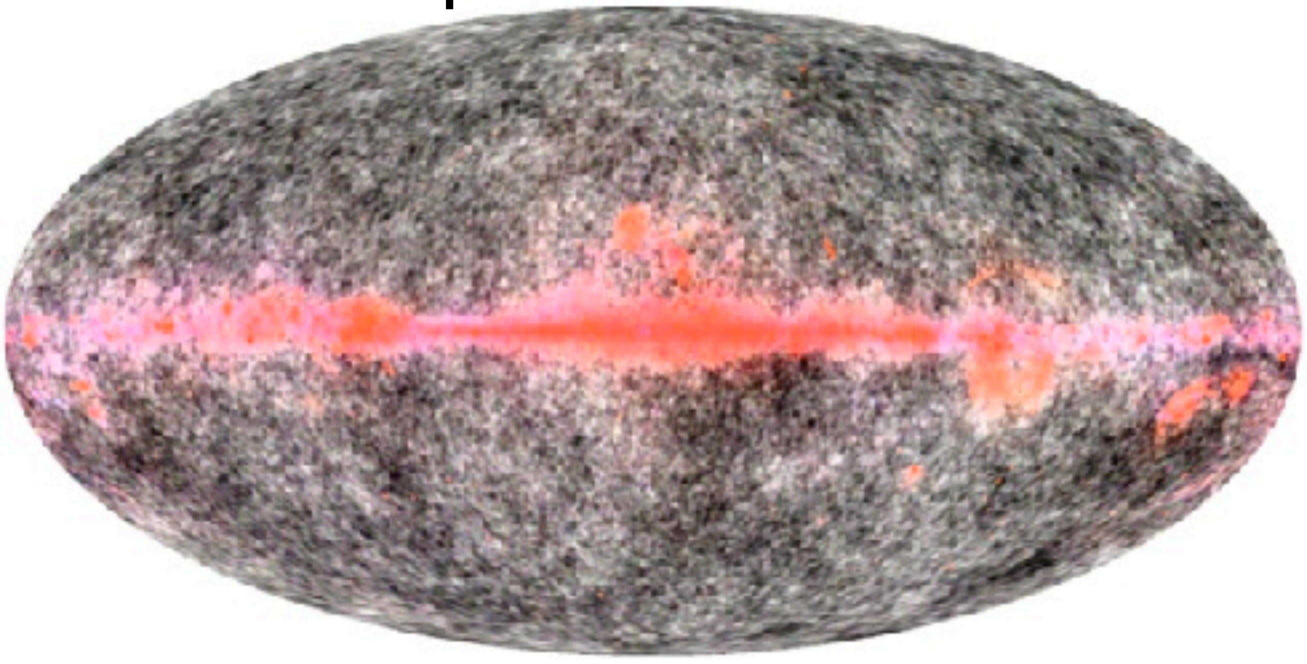
T~2.73 K



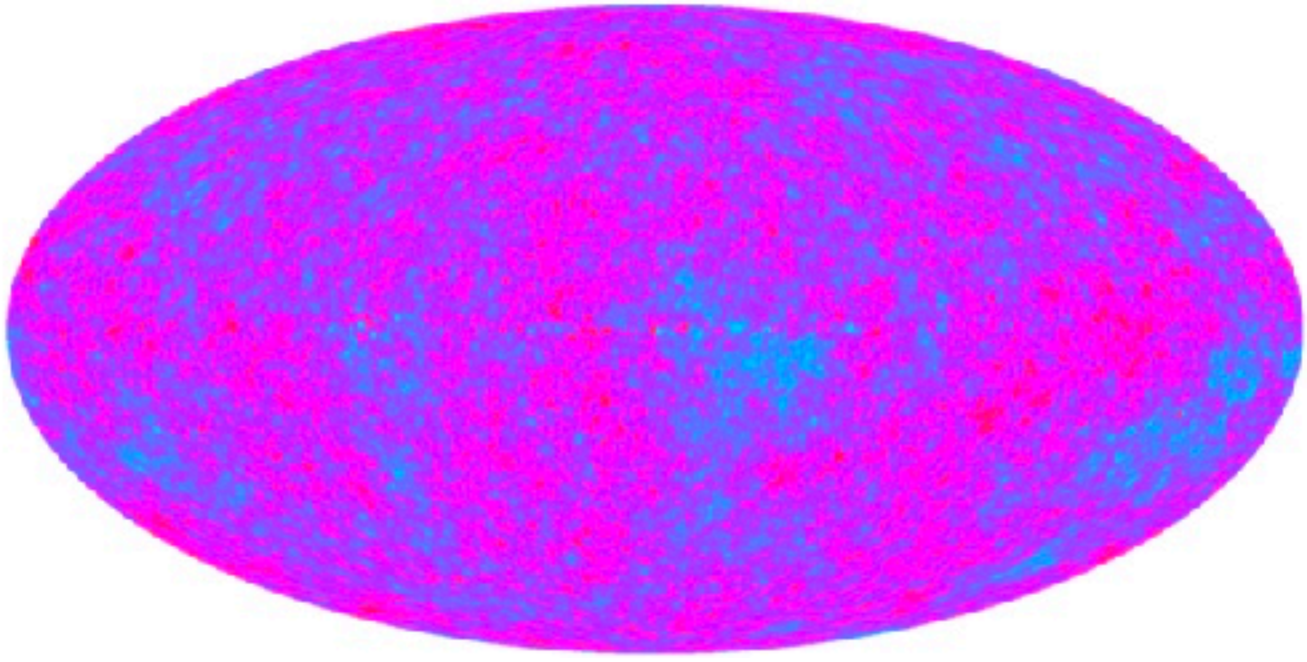
Dipole $\sim 10^{-3}$



Dipole removed



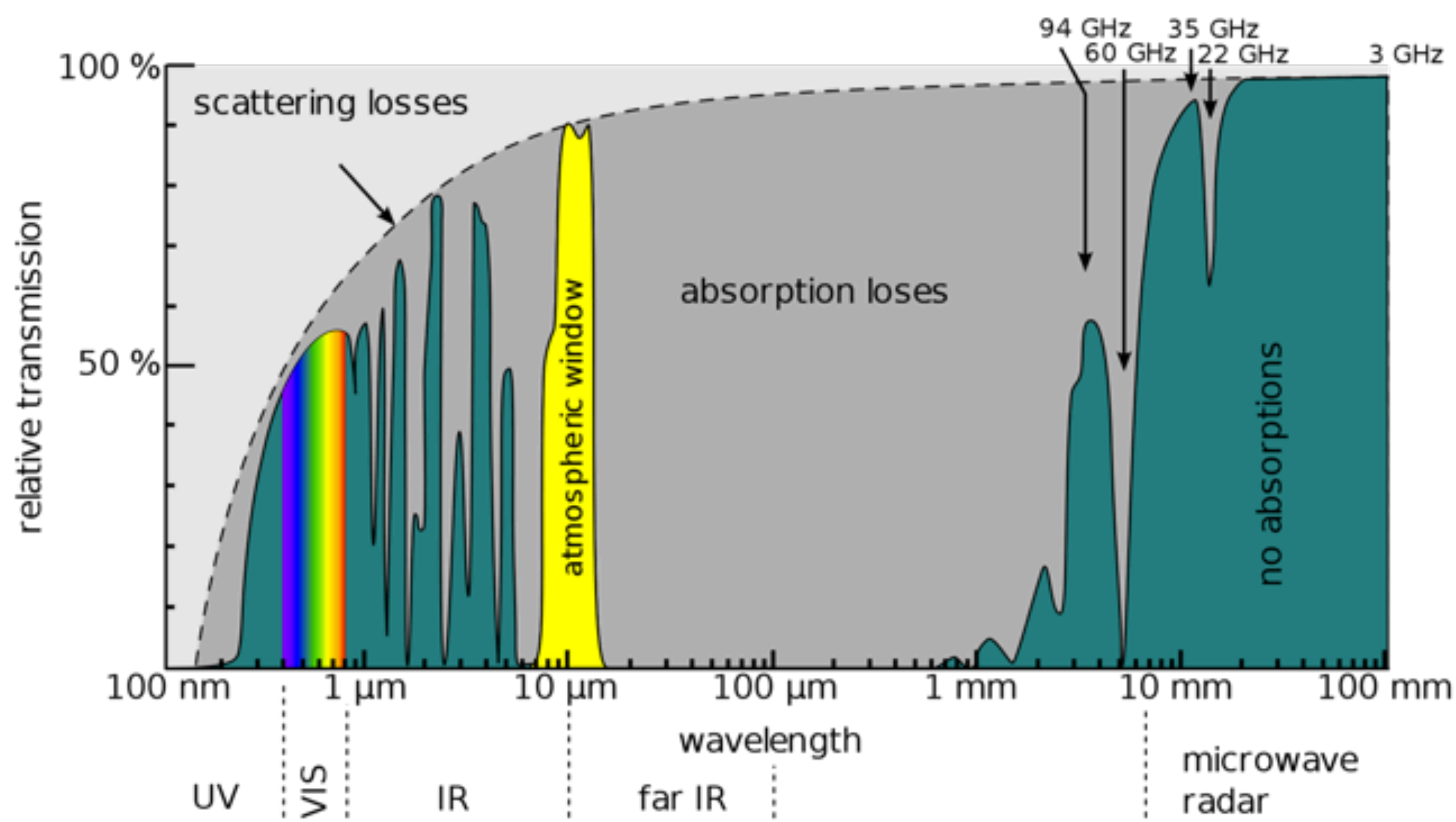
MW removed $\sim 10^{-5}$



WMAP. Credit: Ned Wright

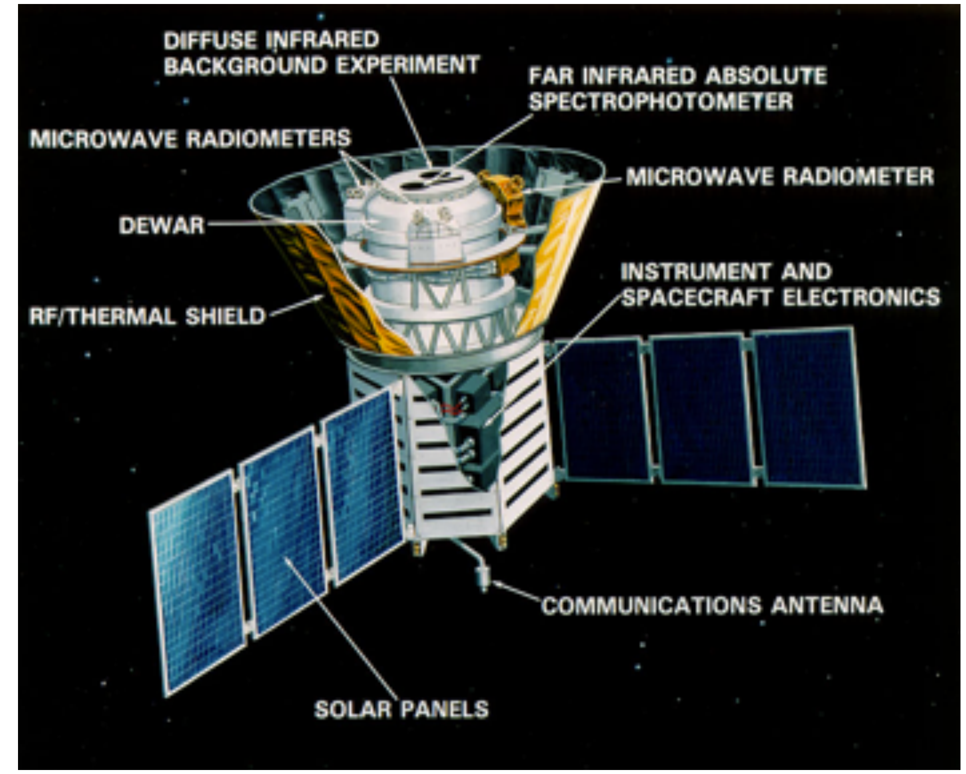
CMB observations

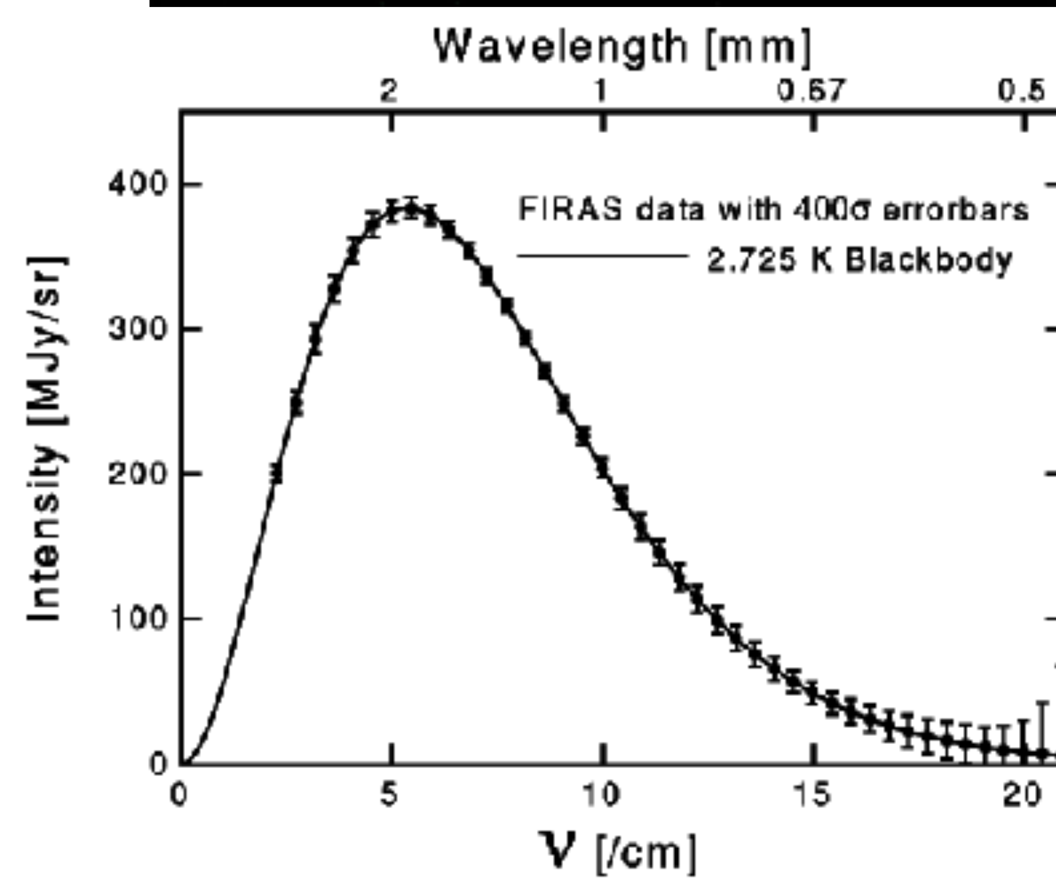
- Microwaves with wavelengths shorter than λ~3 cm are strongly absorbed by water molecules in the atmosphere.
- The CMB can be measured at wavelengths shorter than 3 cm by observing from high-altitude balloons or from the South Pole, where the combination of cold temperatures and high altitude keeps the atmospheric humidity low.



COBE observations

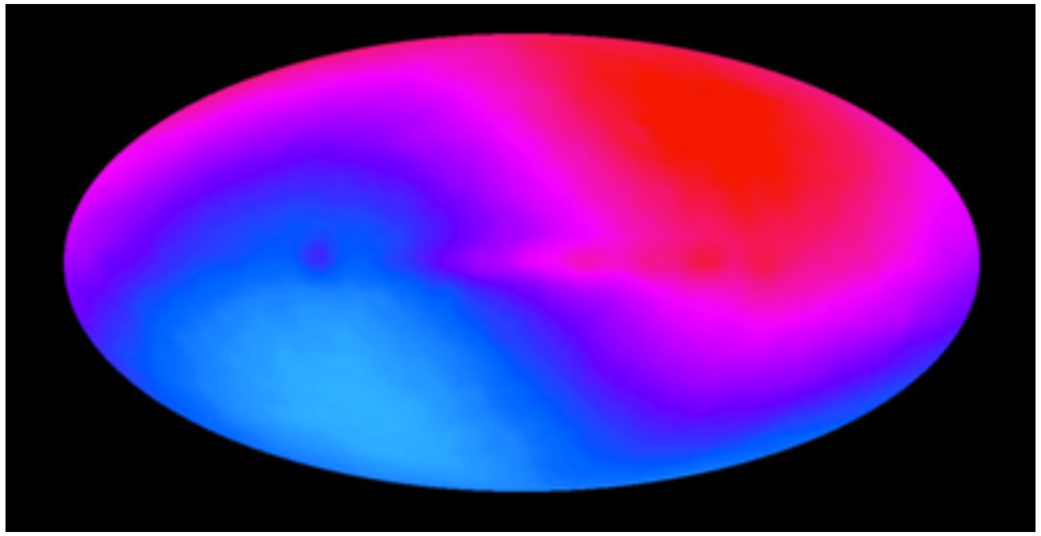
- The CMB was first measured accurately over a wide range of wavelengths by the COsmic Background Explorer (COBE) launched in 1989
- COBE actually contained 3 instruments.
  - The Diffuse InfraRed Background Experiment (DIRBE) to measure radiation at 0.001<λ<0.24mm; (primarily detecting stars and dust within our own Galaxy)
  - The Far InfraRed Absolute Spectrophotometer (FIRAS), to measure the spectrum of the CMB in the range 0.1<λ<10 mm
  - The Differential Microwave Radiometer (DMR), to make full-sky maps of the CMB at 3 wavelengths: λ=3.3, 5.7, and 9.6mm.





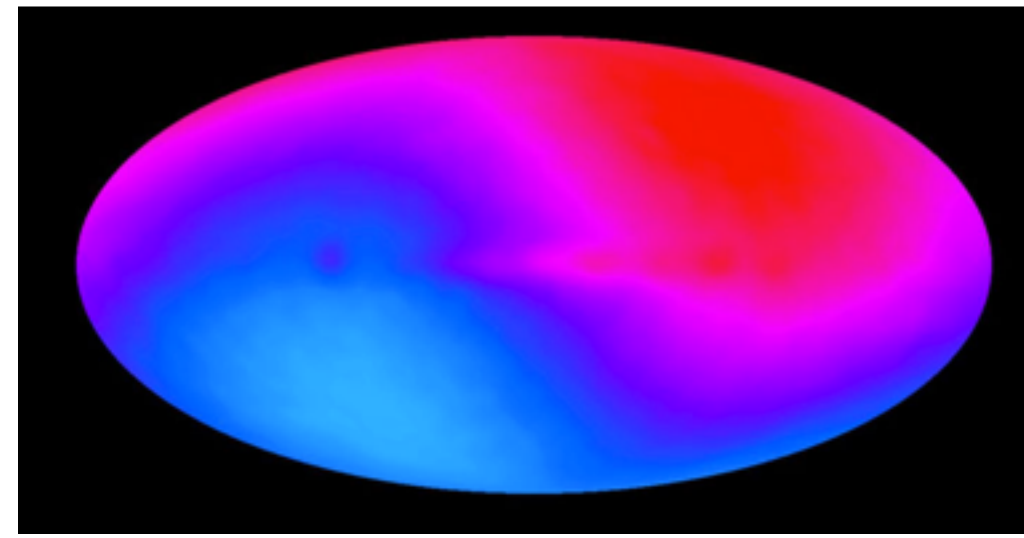
COBE DMR map

- FIRAS could have detected fluctuations in the spectrum as small as $\Delta\varepsilon/\varepsilon \approx 10^{-4}$. No deviations were found at this level.
- The CMB has the dipole distortion in temperature (fluctuation of 10^{-3} in temperature) as measured by the DMR instruments.
- Each point on the sky has a BB spectrum, half of the sky the spectrum is slightly blue-shifted to higher temperatures, and the other half the spectrum is slightly redshifted to lower temperatures.



COBE DMR map

- FIRAS could have detected fluctuations in the spectrum as small as $\Delta\varepsilon/\varepsilon \approx 10^{-4}$. No deviations were found at this level.
- The CMB has the dipole distortion in temperature (fluctuation of 10^{-3} in temperature) as measured by the DMR instruments.
- Each point on the sky has a BB spectrum, half of the sky the spectrum is slightly blue-shifted to higher temperatures, and the other half the spectrum is slightly redshifted to lower temperatures.
- This dipole distortion is a simple Doppler shift, caused by the net motion of the COBE satellite relative to a frame of reference in which the CMB is isotropic.



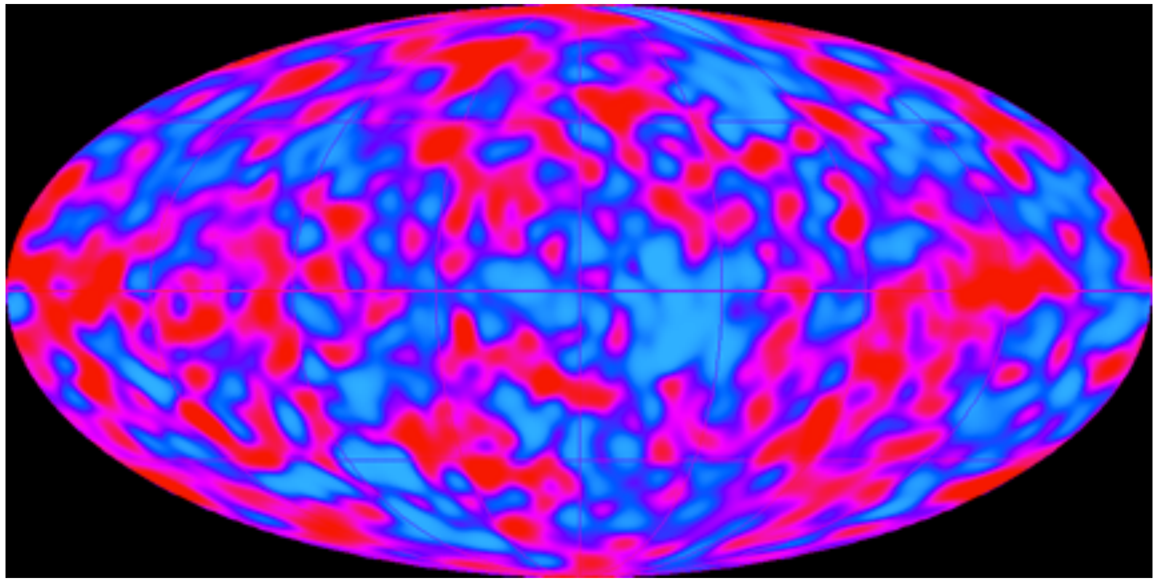
COBE around the Earth:	8 km/s
Earth around sun	30 km/s
Sun around Milky Way center	220 km/s
Local Group motion (towards Virgo)	80 km/s
Local Group towards Hydra	627 +-22 km/s

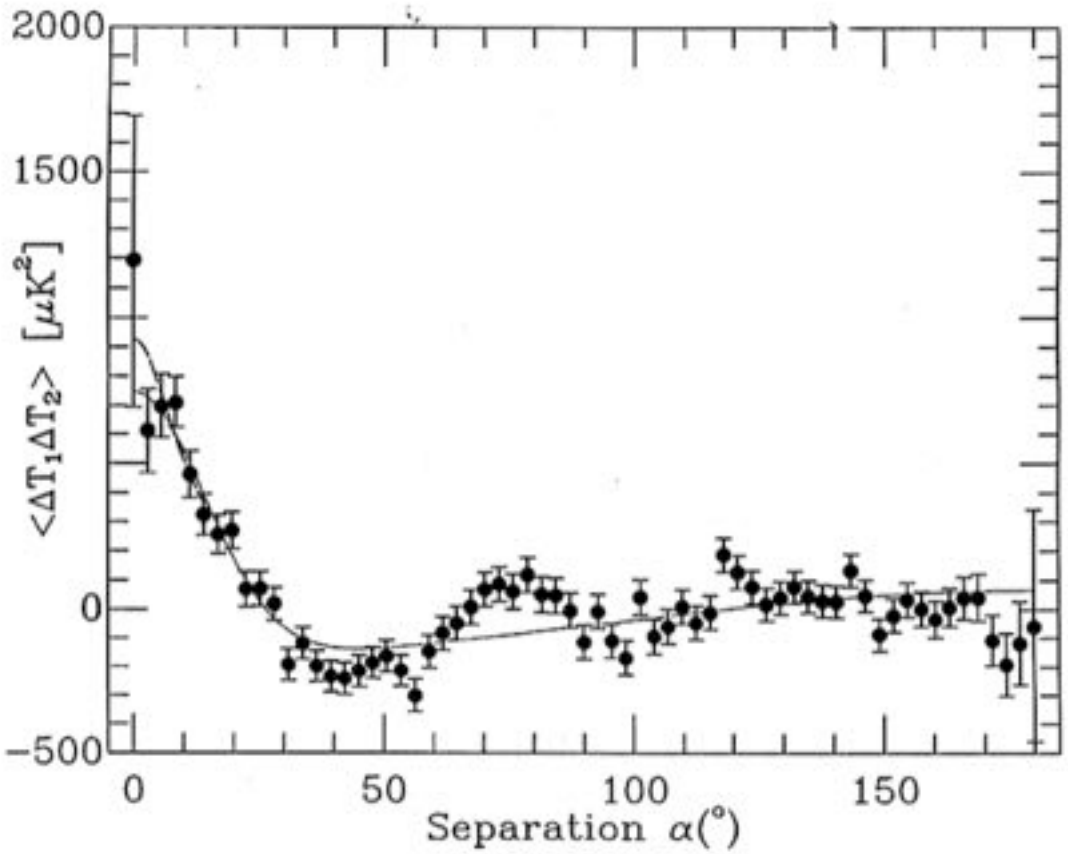
COBE DMR anisotropy map

- From the maps of the sky made by DMR, after subtraction of the Doppler dipole, the root mean square temperature fluctuation is:

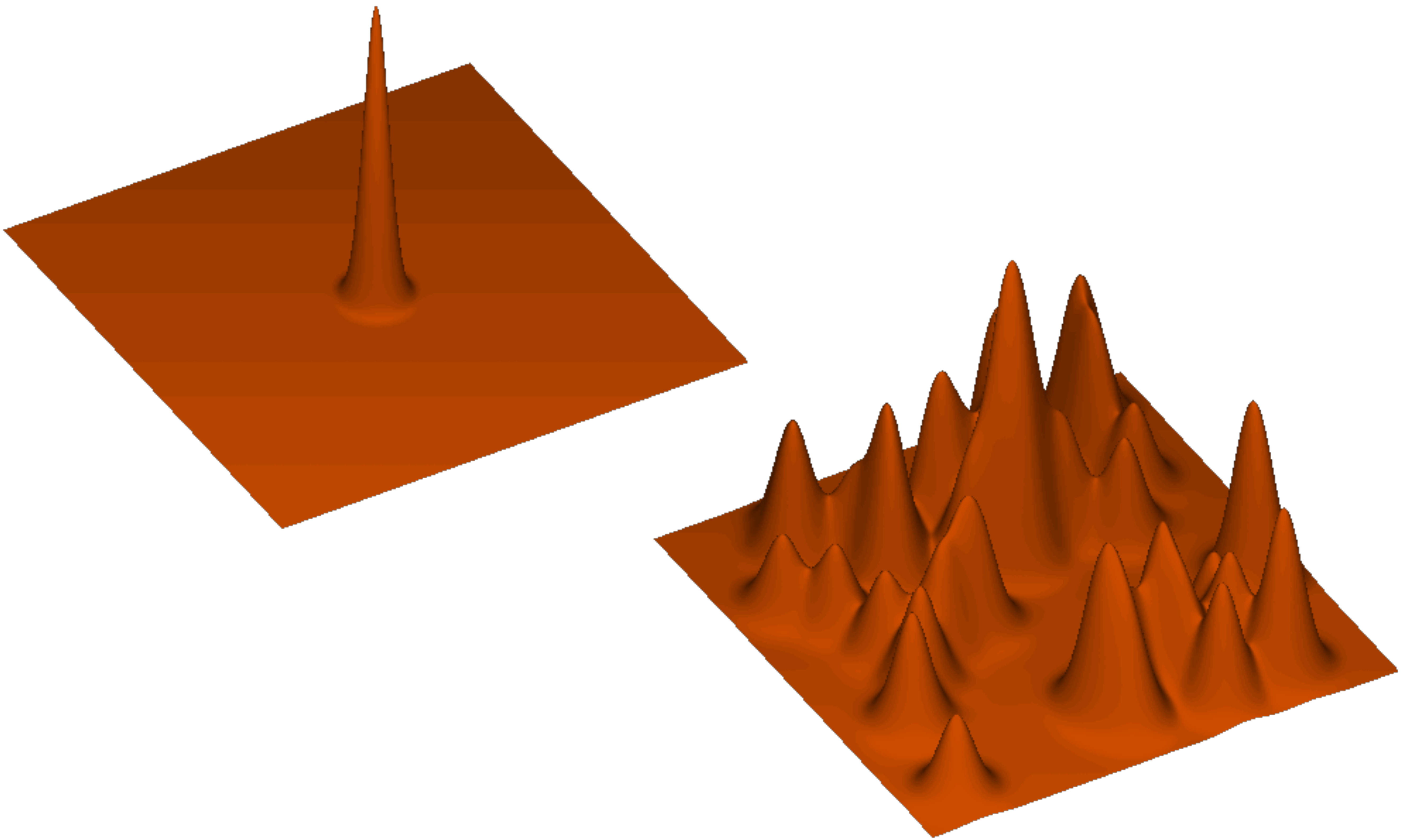
$$\left\langle \left(\frac{\delta T}{T} \right)^2 \right\rangle^{1/2} = 1.1 \times 10^{-5}$$

- The distortions on a smaller angular scale, shown, tell us that the universe was not perfectly homogeneous at the time of last scattering (z ≈ 1100).
- The angular size of the temperature fluctuations reflects in part the physical size of the density & velocity fluctuations at z≈1100.
- The COBE DMR experiment had limited angular resolution, and was only able to detect temperature fluctuations larger than δθ ≈ 7○.

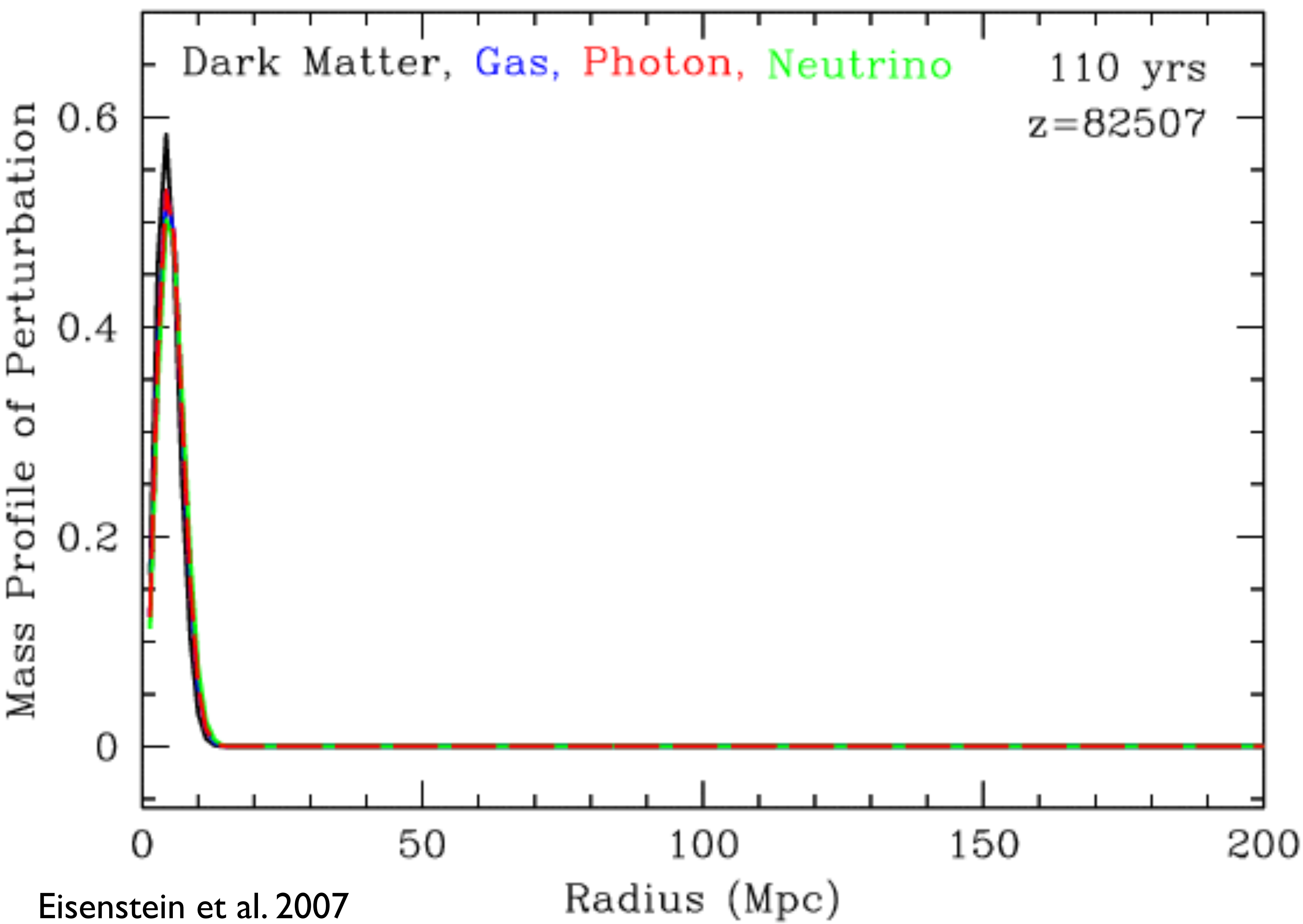




The sound horizon

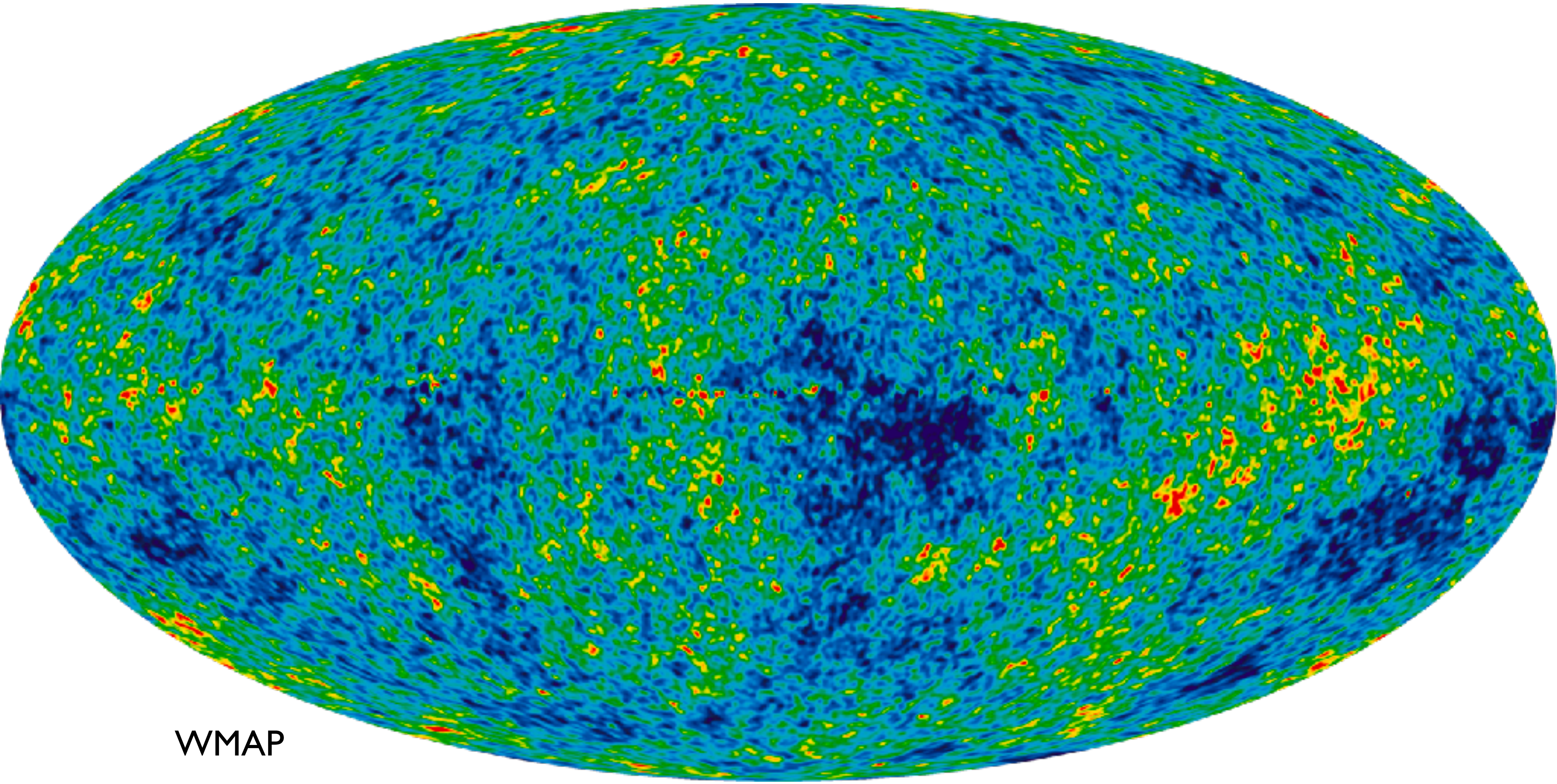


The sound horizon



Eisenstein et al. 2007

The sound horizon



WMAP

Temperature Fluctuation

- The angular size δθ of a temperature fluctuation in the CMB is related to a physical size ℓ on the last scattering surface by the relation:

$$d_A = \frac{\ell}{\delta\theta}$$

- This can be written (14'000 Mpc ~ 45 G Light-Year):

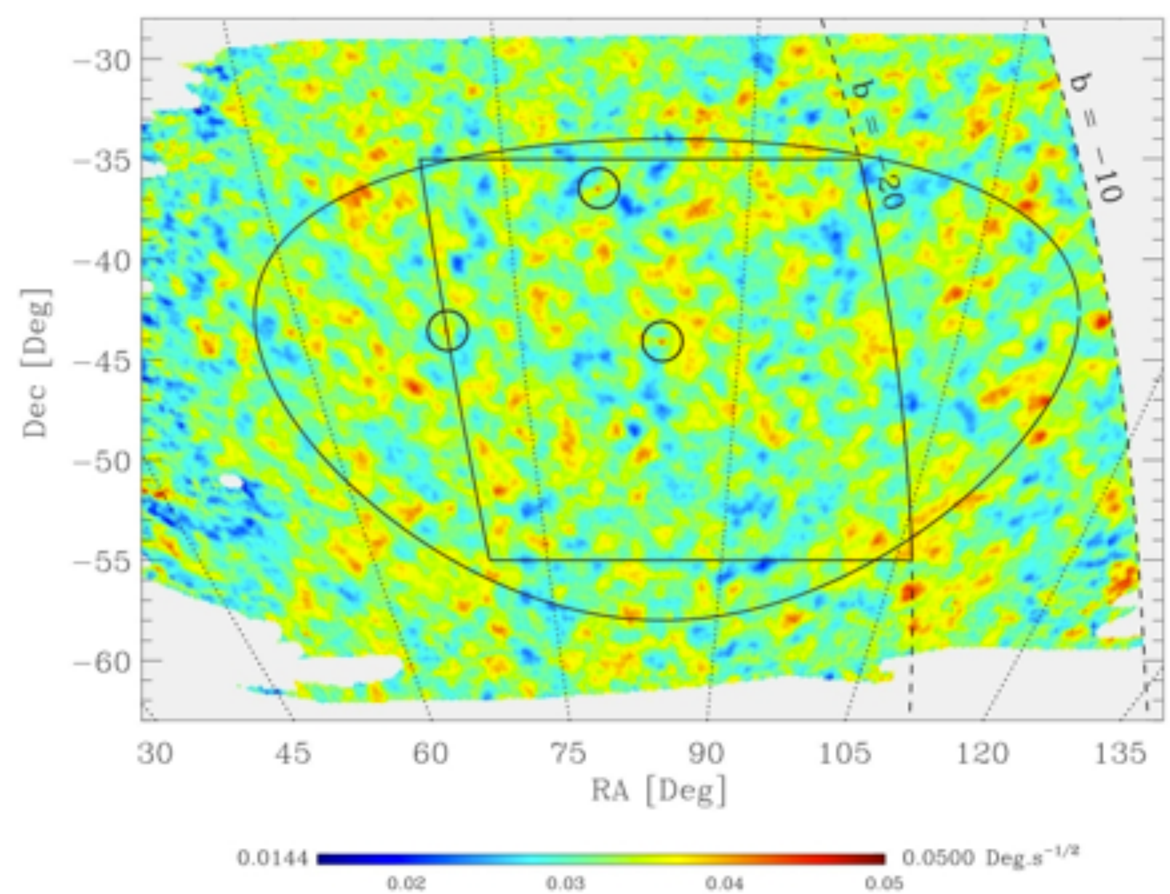
$$d_A = \frac{d_{horizon}(t_0)}{1+z_{ls}} \approx \frac{d_{horizon}(t_0)}{z_{ls}} \approx \frac{14'000\,\mathrm{Mpc}}{1100} = 13\,\mathrm{Mpc}$$

- Thus, fluctuations on the last scattering surface with an observed angular size δθ had a proper size:

$$\ell = d_A \delta\theta = 13\ \mathrm{Mpc}\left(\frac{\delta\theta}{1\ \mathrm{rad}}\right) = 0.22\ \mathrm{Mpc}\left(\frac{\delta\theta}{1\ \mathrm{deg}}\right)$$

Temperature Fluctuation

- Fluctuations seen by COBE (with δθ > 7○) had a proper size >1.6 Mpc or 1700 Mpc today.
- Higher-resolution experiments such as MAXIMA, DASI, and BOOMERANG measured fluctuations corresponding to scales as small as 0.04 Mpc at the time of last scattering, or 40 Mpc today, about the size of today's superclusters.

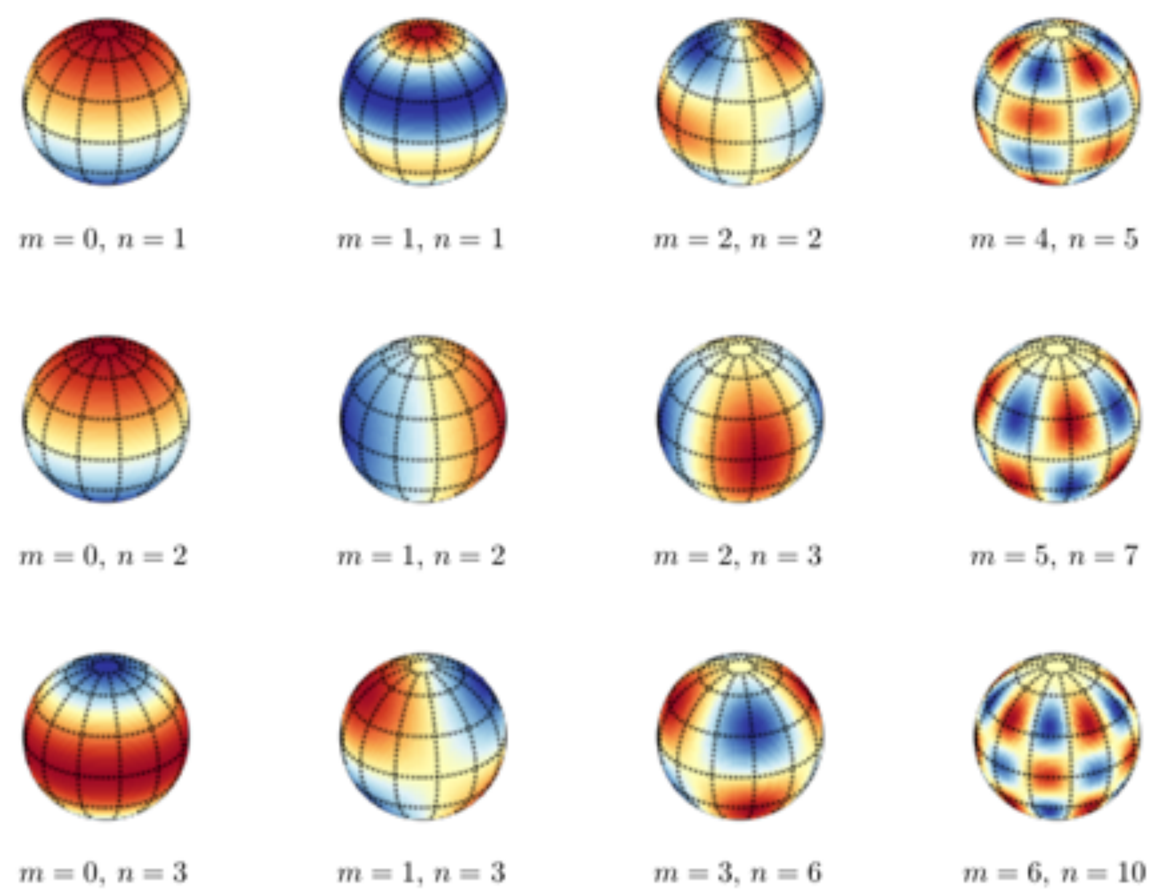


Modelling Temperature Fluctuations

- δT/T is defined on the surface of the celestial sphere – it is useful to expand it in spherical harmonics:

$$\frac{\delta T}{T}(\theta,\phi)=\sum_{l=0}^{\infty}\sum_{m=-l}^{l}a_{lm}Y_{lm}(\theta,\phi)$$

- where $Y_{lm}(\theta,\phi)$ are the usual spherical harmonic functions.
- What concerns cosmologists is not the exact pattern of hot spots and cold spots on the sky, but their statistical properties.



Modelling Temperature Fluctuations

- The most important statistical property of δT/T is the correlation function C(θ).
- To compute C(θ), we multiply together the values of δT/T at two points separated by the angle θ, then average the product over all points:

$$C(\theta) = \left\langle \frac{\delta T}{T}(n) \frac{\delta T}{T}(n') \right\rangle_{n.n' = cos(\theta)}$$

- If cosmologists knew the precise value of C(θ) for all angles, they would have a complete statistical description of the temperature fluctuations over all angular scales.
- Unfortunately, the CMB measurements which tell us about C(θ) contain information over only a limited range of angular scales (limited by the instrument resolution)

Modelling Temperature Fluctuations

- Using the expansion of δT/T in spherical harmonics, the correlation function can be written in the form:

$$C(\theta)=\frac{1}{4\pi}\sum_{l=0}^{\infty}(2l+1)C_l P_l(\cos(\theta))$$

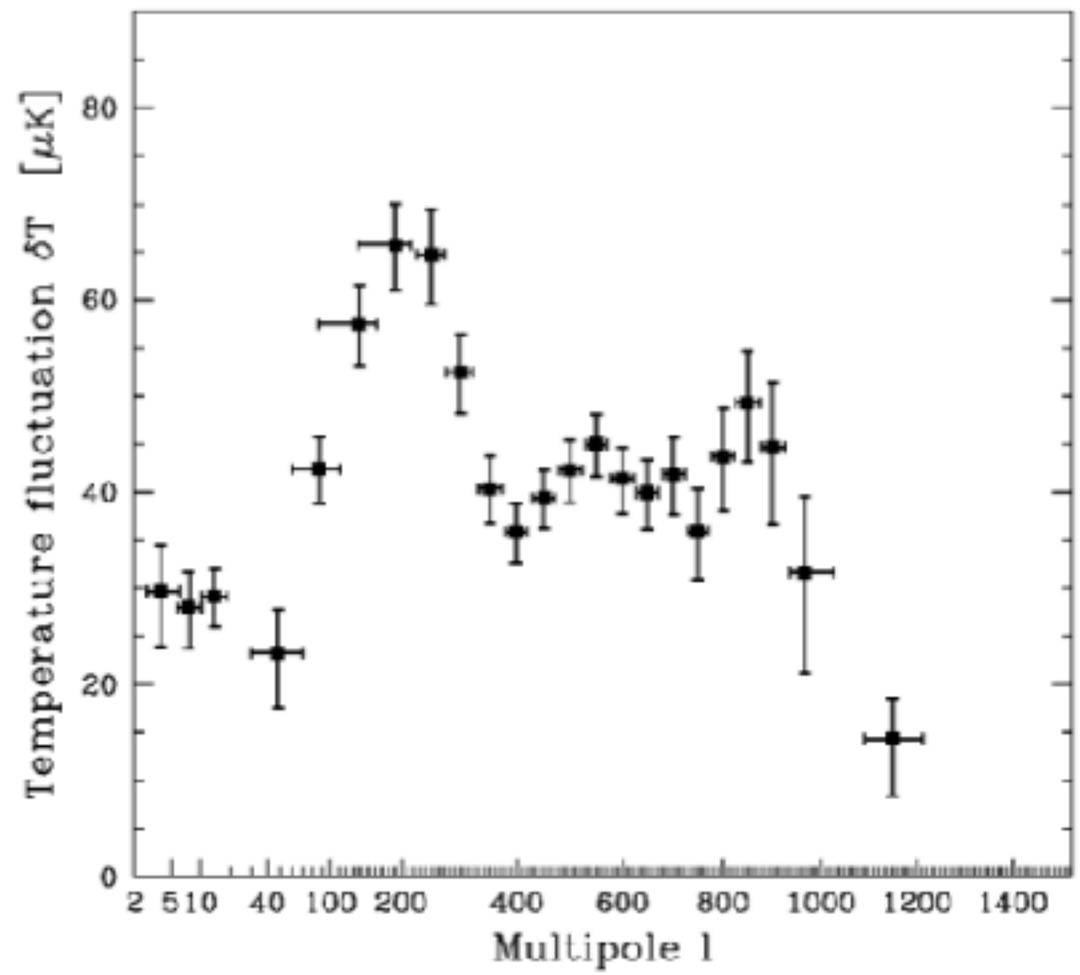
- where P_ℓ are the Legendre polynomials
- C_ℓ is a measure of temperature fluctuations on the angular scale $\theta \sim 180/\ell$
- The $\ell = 1$ (dipole) term results from the Doppler shift due to our motion through space.

Anisotropy measurements

- presenting the results of CMB observations, it is customary to plot the function:

$$\Delta_T = \left(C(\theta) = \frac{l(l+1)}{2\pi} C_l \right)^2 \langle T \rangle$$

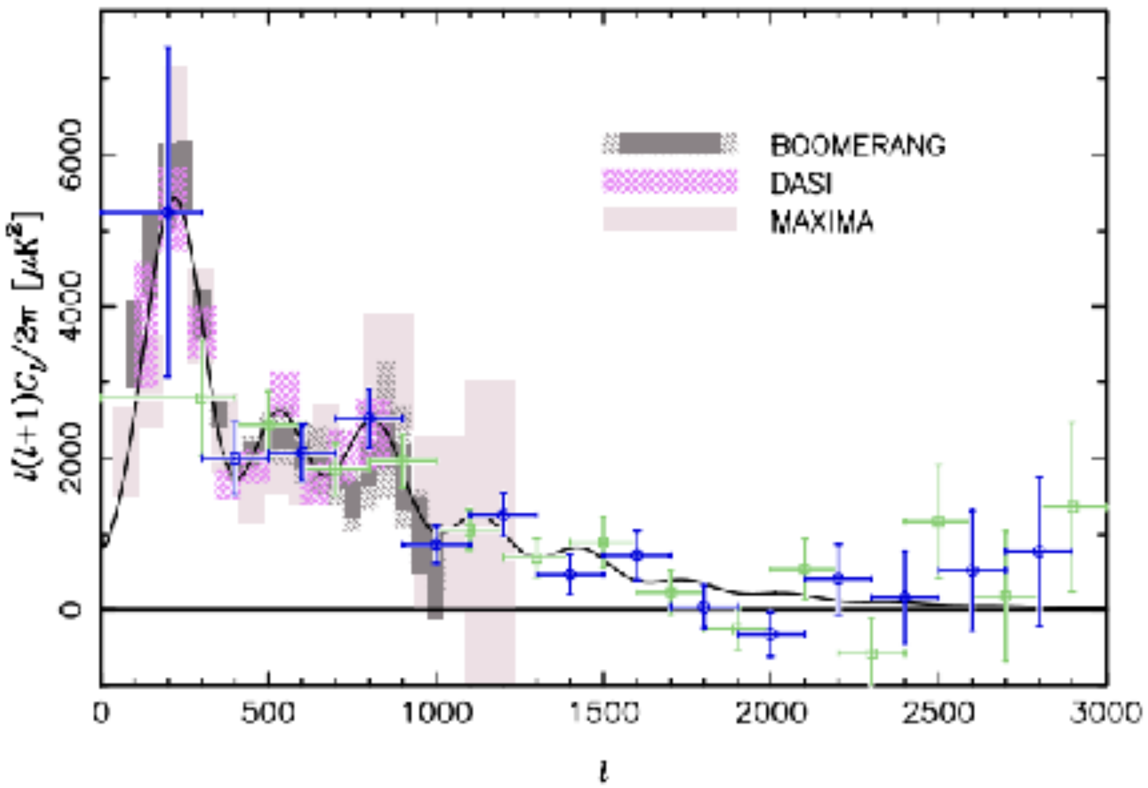
- it gives the contribution per logarithmic interval in ℓ to the total temperature fluctuation δT of the CMB.
- Note that the temperature fluctuation has a peak at $\ell \sim 200$, corresponding to an angular size of ~1 degree.



Measurement from BOOMERANG (Bernardis et al 2000)

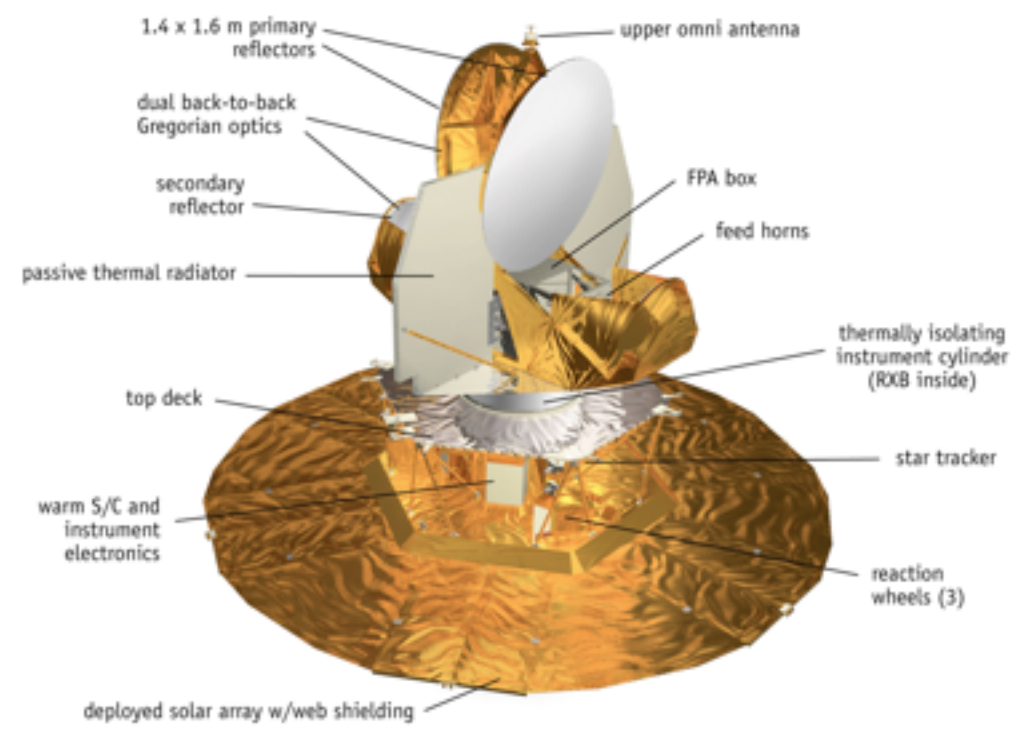
CBI measurement

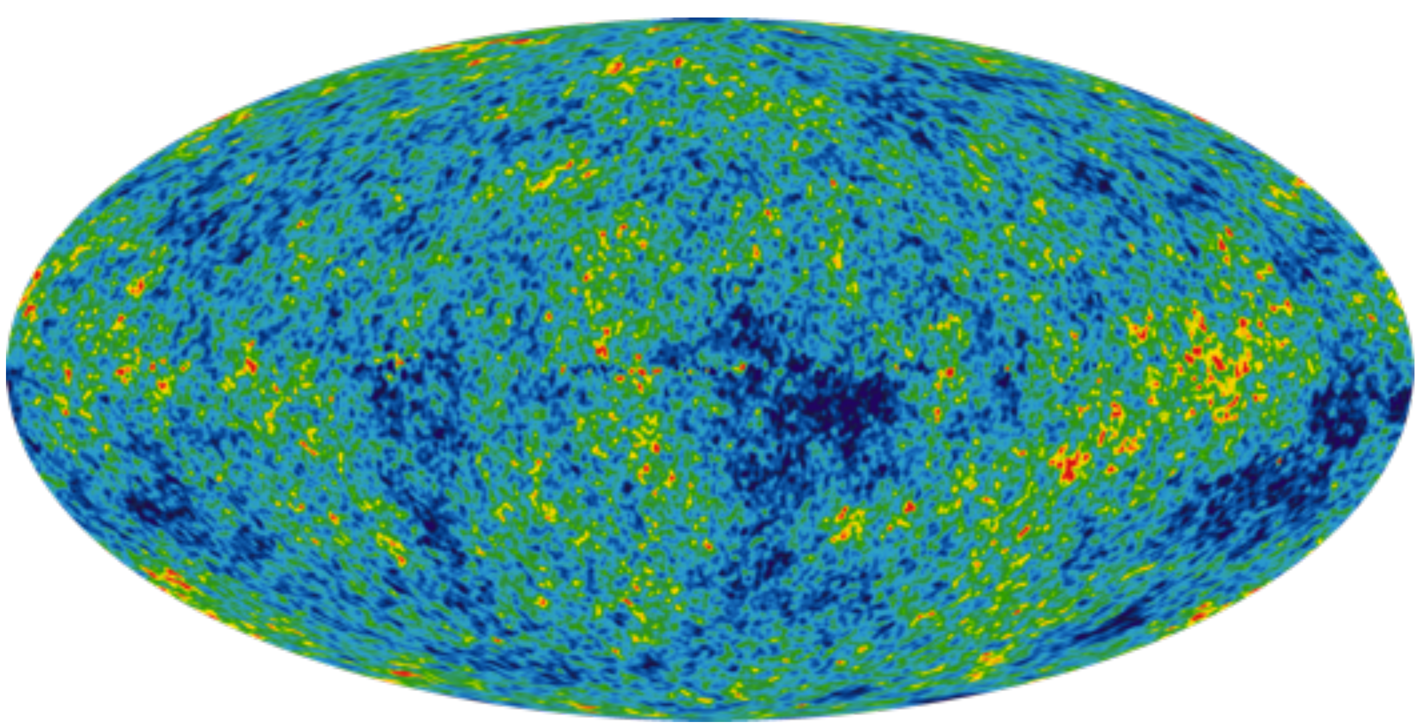
- Run by Caltech, at 5000m in the Chilean Cordillera
- Spatial resolution: ~ 5 arcmin
- From a13-element interferometer at 26–36 GHz
- Measurement completed in 2002



WMAP mission

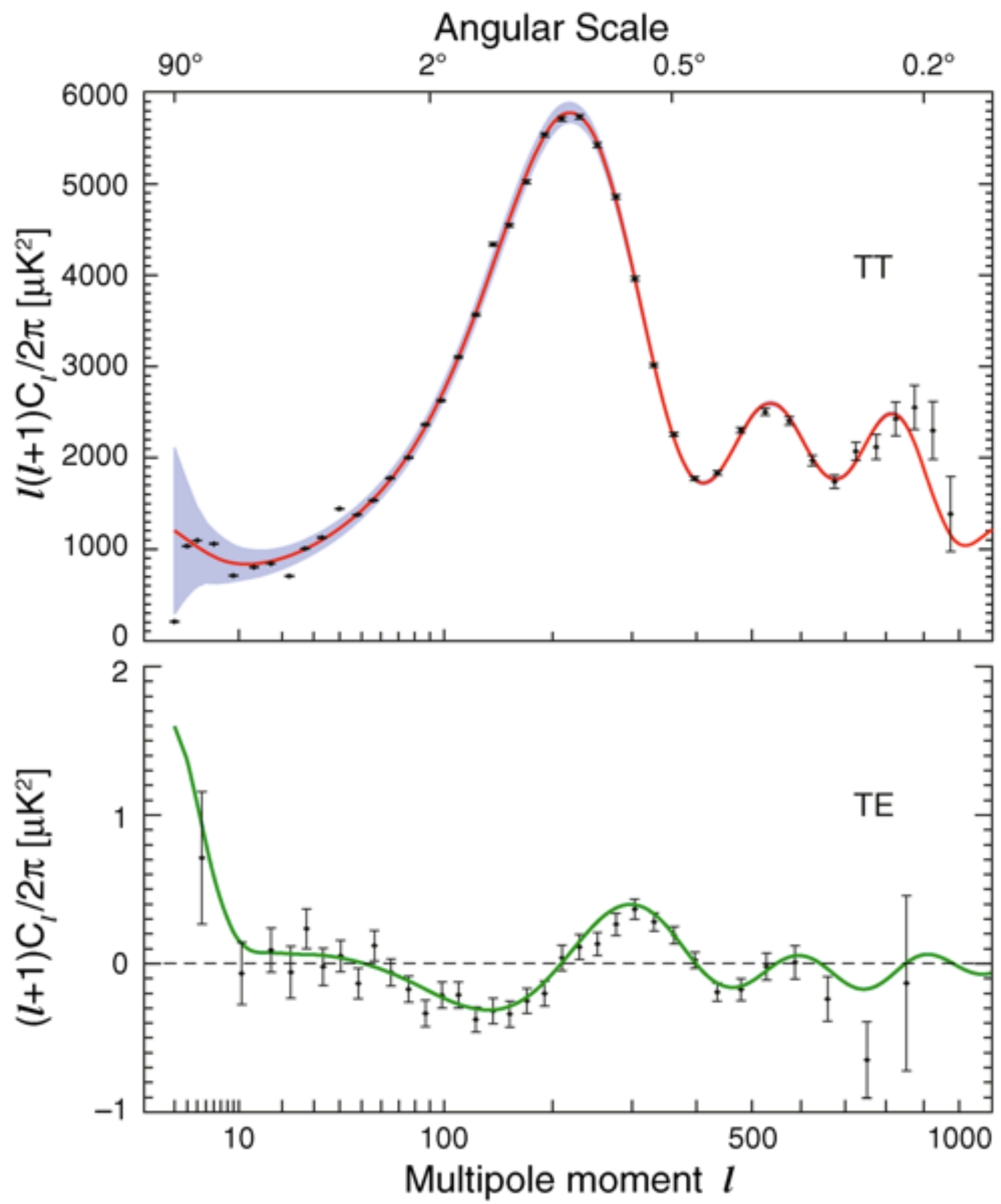
- The Wilkinson Microwave Anisotropy Probe (WMAP), operated from 2001 to 2010 to measure differences across the sky in the temperature of the cosmic microwave background (CMB)
- WMAP's measurements played a key role in establishing the current Standard Model of Cosmology: the Lambda-CDM model.





WMAP anisotropy

- The Wilkinson Microwave Anisotropy Probe (WMAP), operated from 2001 to 2010 to measure differences across the sky in the temperature of the cosmic microwave background (CMB)
- WMAP's measurements played a key role in establishing the current Standard Model of Cosmology: the Lambda-CDM model.



WMAP cosmological results

- WMAP 3 year results

Parameter	Symbol	Best fit (WMAP only)
Age of the universe (Ga)	t_0	$13.73^{+0.16}_{-0.15}$
Hubble's constant (km/Mpc·s)	H_0	$73.2^{+3.1}_{-3.2}$
Baryonic content	$\Omega_b h^2$	0.0229 ±0.000 73
Matter content	$\Omega_m h^2$	$0.1277^{+0.0080}_{-0.0079}$
Optical depth to reionization [a]	τ	0.089 ±0.030
Scalar spectral index	n_s	0.958 ±0.016
Fluctuation amplitude at $8h^{-1}$ Mpc	σ_8	$0.761^{+0.049}_{-0.048}$
Tensor-to-scalar ratio [b]	r	< 0.65

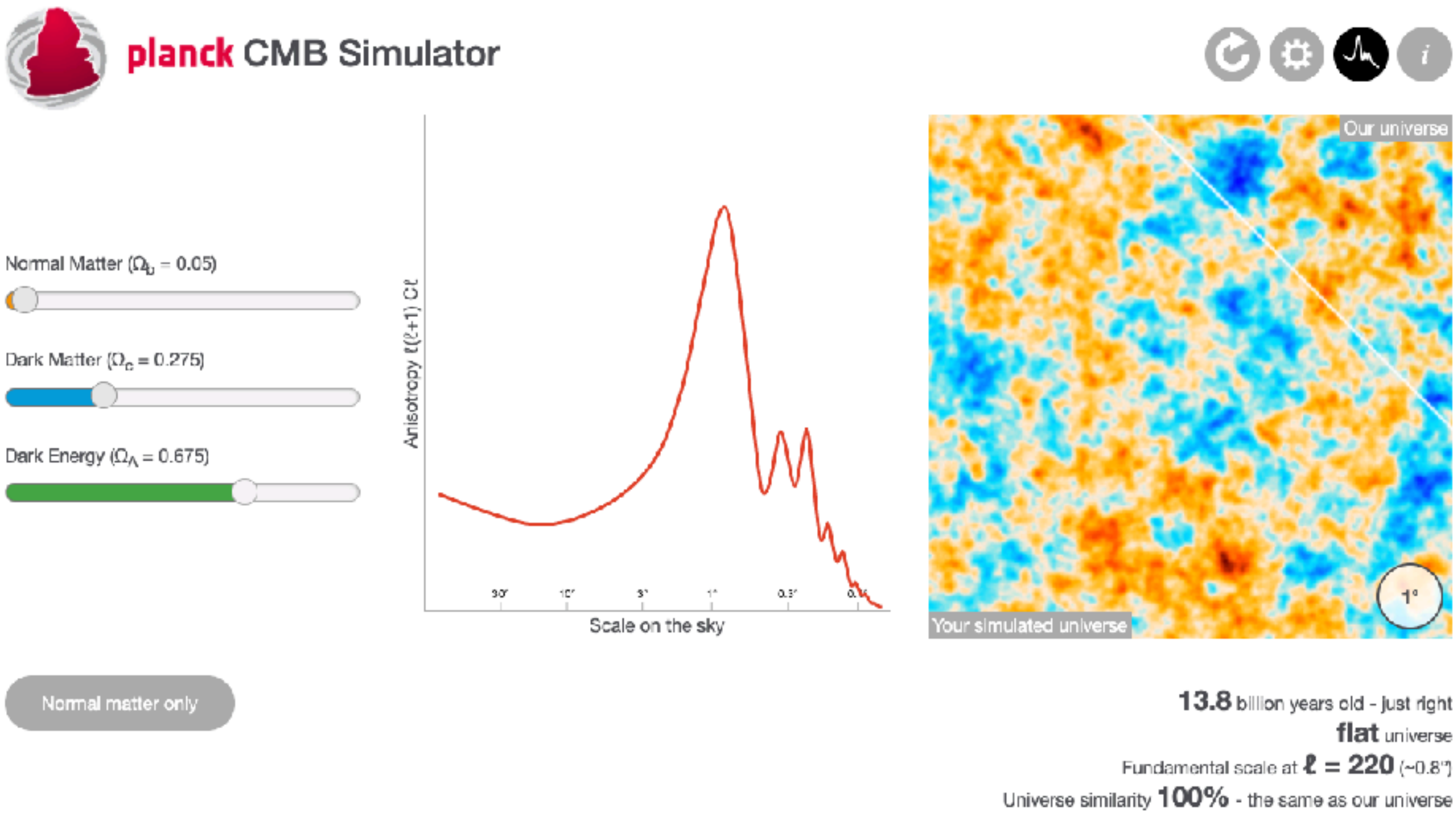
WMAP cosmological results

- WMAP 9 year results

Parameter	Symbol	Best fit (WMAP only)	Best fit (WMAP + eCMB + BAO + H_0)
Age of the universe (Ga)	t_0	13.74 ±0.11	13.772 ±0.059
Hubble's constant (km/Mpc·s)	H_0	70.0 ±2.2	69.32 ±0.80
Baryon density	Ω_b	0.0463 ±0.0024	0.046 28 ±0.000 93
Physical baryon density	$\Omega_b h^2$	0.022 64 ±0.000 50	0.022 23 ±0.000 33
Cold Dark matter density	Ω_c	0.233 ±0.023	$0.2402^{+0.0088}_{-0.0087}$
Physical cold dark matter density	$\Omega_c h^2$	0.1138 ±0.0045	0.1153 ±0.0019
Dark energy density	Ω_Λ	0.721 ±0.025	$0.7135^{+0.0095}_{-0.0096}$
Density fluctuations at $8h^{-1}$ Mpc	σ_8	0.821 ±0.023	$0.820^{+0.013}_{-0.014}$
Scalar spectral index	n_s	0.972 ±0.013	0.9608 ±0.0080
Reionization optical depth	τ	0.089 ±0.014	0.081 ±0.012
Curvature	$1-\Omega_{tot}$	$-0.037^{+0.044}_{-0.042}$	$-0.0027^{+0.0039}_{-0.0038}$
Tensor-to-scalar ratio (k_0 = 0.002 Mpc^{-1})	r	< 0.38 (95% CL)	< 0.13 (95% CL)
Running scalar spectral index	$dn_s/d\ln k$	−0.019 ±0.025	−0.023 ±0.011

Modeling the Anisotropies

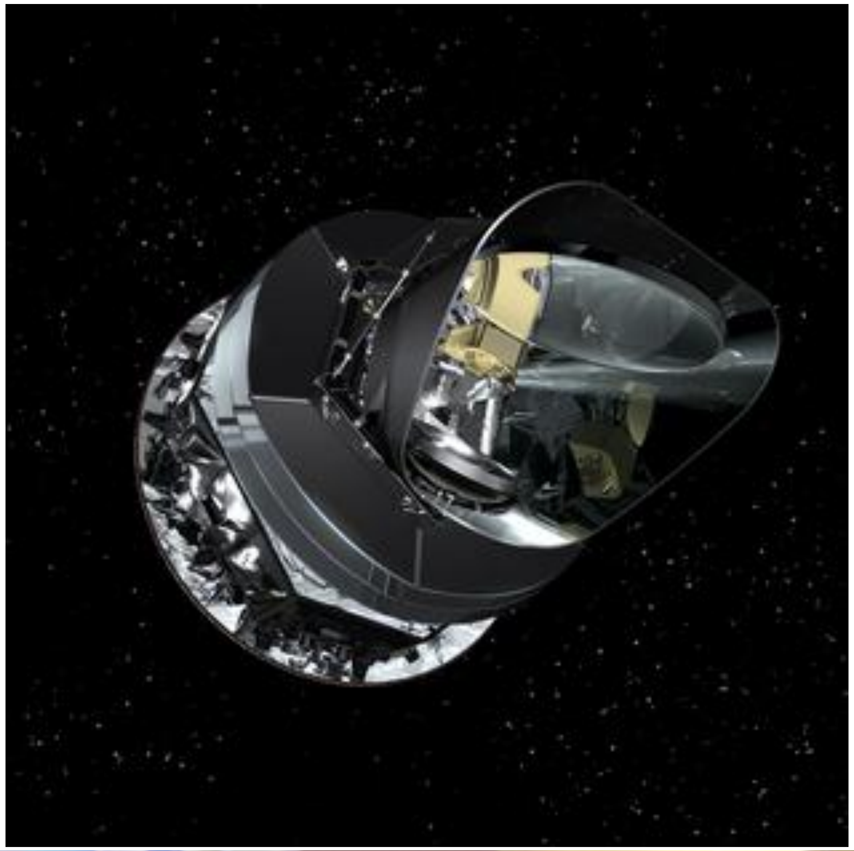
https://chrisnorth.github.io/planckapps/Simulator/

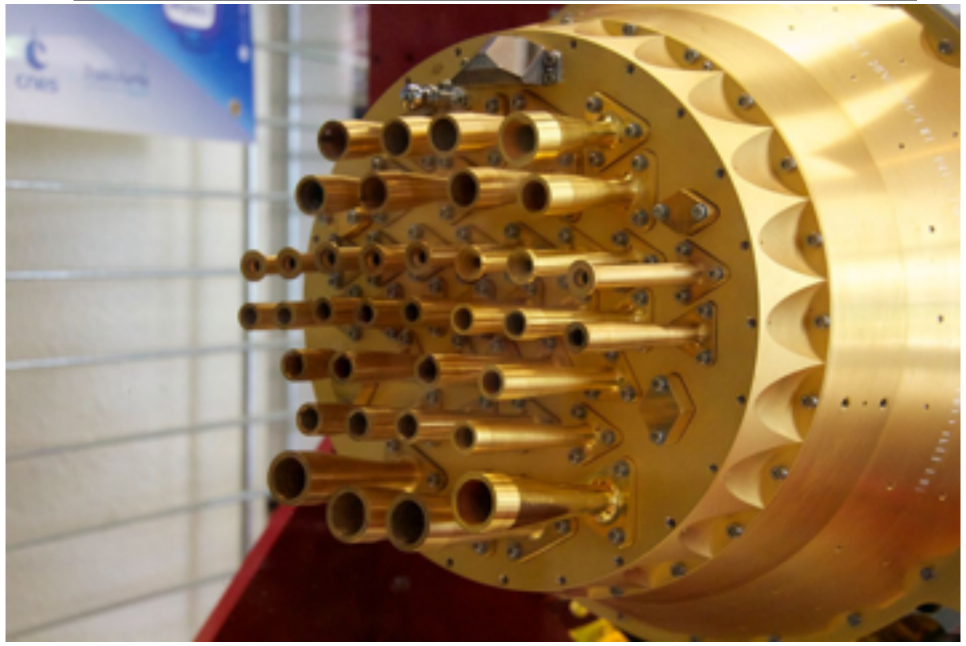


Planck Mission

http://www.esa.int/Science_Exploration/Space_Science/Planck/Planck_and_the_cosmic_microwave_background

- Planck operated by ESA from 2009 to 2013, to map the anisotropies of the CMB with high sensitivity and small angular resolution. Planck has measured:
  - total intensity and polarization of primordial CMB anisotropies,
  - a catalogue of galaxy clusters through the Sunyaev–Zel'dovich effect,
  - the gravitational lensing of the CMB, as well as the integrated Sachs–Wolfe effect,
  - bright extragalactic radio (active galactic nuclei) and infrared (dusty galaxy) sources





HFI camera

Planck cosmology results

Parameter	Symbol	TT+lowP 68% limits	TT+lowP +lensing 68% limits	TT+lowP +lensing+ext 68% limits	TT,TE,EE+lowP 68% limits	TT,TE,EE+lowP +lensing 68% limits	TT,TE,EE+lowP +lensing+ext 68% limits
Baryon density	$\Omega_b h^2$	0.022 22 ±0.000 23	0.022 26 ±0.000 23	0.022 27 ±0.000 20	0.022 25 ±0.000 16	0.022 26 ±0.000 16	0.022 30 ±0.000 14
Cold dark matter density	$\Omega_c h^2$	0.1197 ±0.0022	0.1186 ±0.0020	0.1184 ±0.0012	0.1198 ±0.0015	0.1193 ±0.0014	0.1188 ±0.0010
100x approximation to r_s / D_A (CosmoMC)	$100\theta_{MC}$	1.040 85 ±0.000 47	1.041 03 ±0.000 46	1.041 06 ±0.000 41	1.040 77 ±0.000 32	1.040 87 ±0.000 32	1.040 93 ±0.000 30
Thomson scattering optical depth due to reionization	τ	0.078 ±0.019	0.066 ±0.016	0.067 ±0.013	0.079 ±0.017	0.063 ±0.014	0.066 ±0.012
Power spectrum of curvature perturbations	$ln(10^{10}A_s)$	3.089 ±0.036	3.062 ±0.029	3.064 ±0.024	3.094 ±0.034	3.059 ±0.025	3.064 ±0.023
Scalar spectral index	n_s	0.9655 ±0.0062	0.9677 ±0.0060	0.9681 ±0.0044	0.9645 ±0.0049	0.9653 ±0.0048	0.9667 ±0.0040
Hubble's constant (km Mpc^{-1} s^{-1})	H_0	67.31 ±0.96	67.81 ±0.92	67.90 ±0.55	67.27 ±0.66	67.51 ±0.64	67.74 ±0.46
Dark energy density	Ω_Λ	0.685 ±0.013	0.692 ±0.012	0.6935 ±0.0072	0.6844 ±0.0091	0.6879 ±0.0087	0.6911 ±0.0062
Matter density	Ω_m	0.315 ±0.013	0.308 ±0.012	0.3065 ±0.0072	0.3156 ±0.0091	0.3121 ±0.0087	0.3089 ±0.0062
Density fluctuations at $8h^{-1}$ Mpc	σ_8	0.829 ±0.014	0.8149 ±0.0093	0.8154 ±0.0090	0.831 ±0.013	0.8150 ±0.0087	0.8159 ±0.0086
Redshift of reionization	z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
Age of the Universe (Gy)	t_0	13.813 ±0.038	13.799 ±0.038	13.796 ±0.029	13.813 ±0.026	13.807 ±0.026	13.799 ±0.021
Redshift at decoupling	z_*	1 090.09 ±0.42	1 089.94 ±0.42	1 089.90 ±0.30	1 090.06 ±0.30	1 090.00 ±0.29	1 089.90 ±0.23
Comoving size of the sound horizon at z = z_*	r_*	144.61 ±0.49	144.89 ±0.44	144.93 ±0.30	144.57 ±0.32	144.71 ±0.31	144.81 ±0.24
100x angular scale of sound horizon at last-scattering	$100\theta_*$	1.041 05 ±0.000 46	1.041 22 ±0.000 45	1.041 26 ±0.000 41	1.040 96 ±0.000 32	1.041 06 ±0.000 31	1.041 12 ±0.000 29
Redshift with baryon-drag optical depth = 1	z_{drag}	1 059.57 ±0.46	1 059.57 ±0.47	1 059.60 ±0.44	1 059.65 ±0.31	1 059.62 ±0.31	1 059.68 ±0.29
Comoving size of the sound horizon at z = z_{drag}	r_{drag}	147.33 ±0.49	147.60 ±0.43	147.63 ±0.32	147.27 ±0.31	147.41 ±0.30	147.50 ±0.24

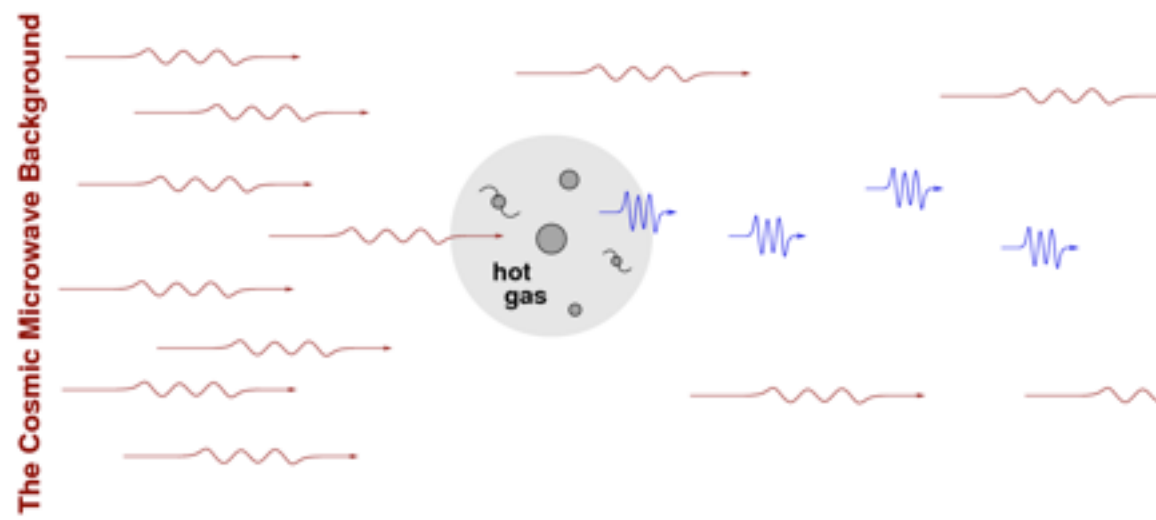
Legend

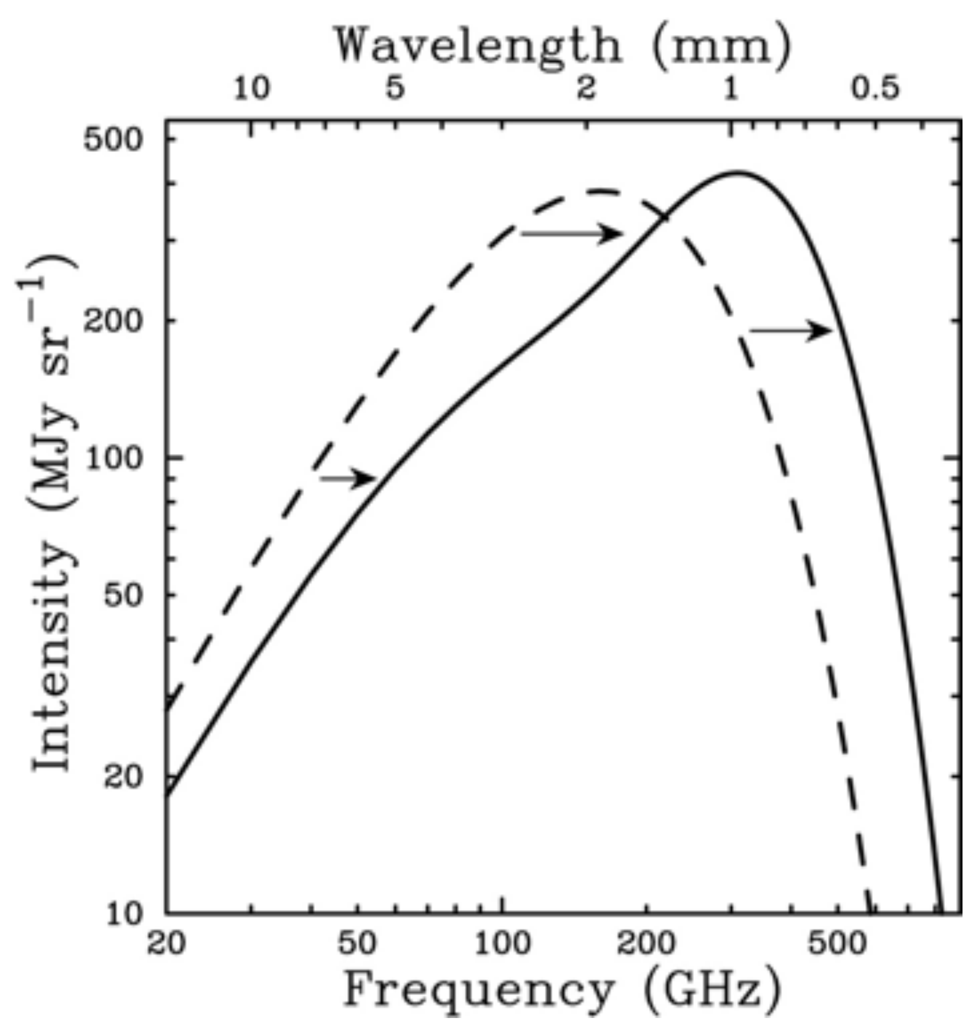
- **68% limits**: Parameter 68% confidence limits for the base ΛCDM model
- **TT, TE, EE**: Planck Cosmic microwave background (CMB) power spectra; here TT represents temperature power spectrum, TE is temperature-polarization cross spectrum, and EE is polarisation power spectrum.
- **lowP**: Planck polarization data in the low- ℓ likelihood
- **lensing**: CMB lensing reconstruction
- **ext**: External data (BAO+JLA+H0). BAO: Baryon acoustic oscillations, JLA: Joint Light-curve Analysis (of supernovae), H0: Hubble constant

Sunayev-Zeldovich effect

- The Sunyaev-Zel'dovich effect (SZE) is a small spectral distortion of CMB spectrum caused by the scattering of the photons off a distribution of high energy electrons (e.g. cluster hot plasma).
- The *inverse Compton scattering* **boosts** the energy of the CMB photon by roughly kT_e/m_ec^2 causing a small (~1 mK) distortion in the CMB spectrum.

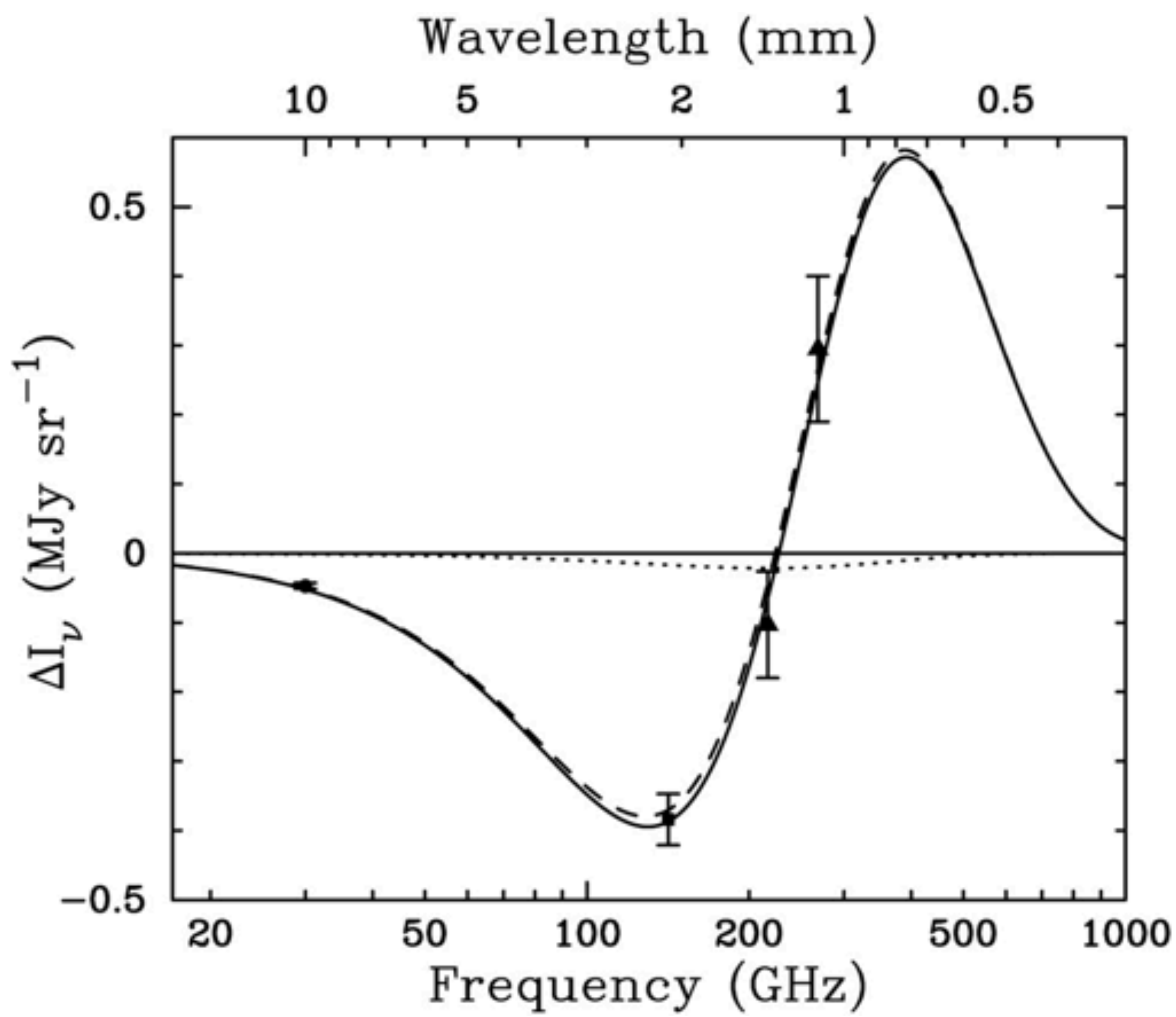
$$\frac{\Delta T_{SZE}}{T_{CMB}} \approx \int n_e \frac{kT_e}{m_e c^2} \sigma_T dl$$

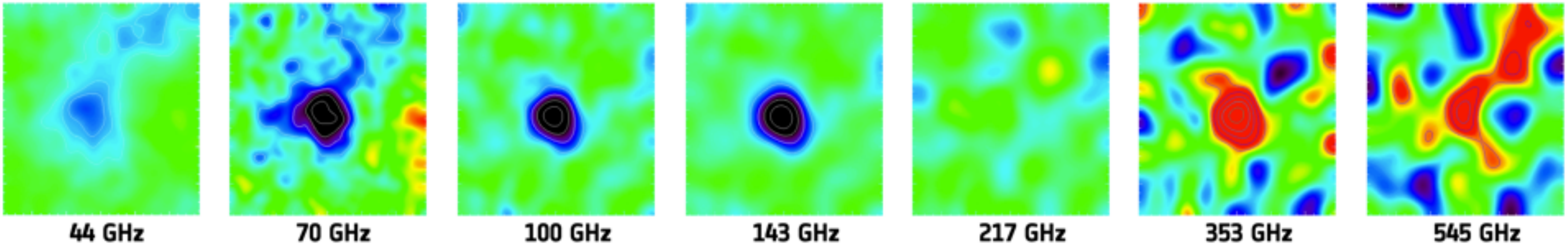




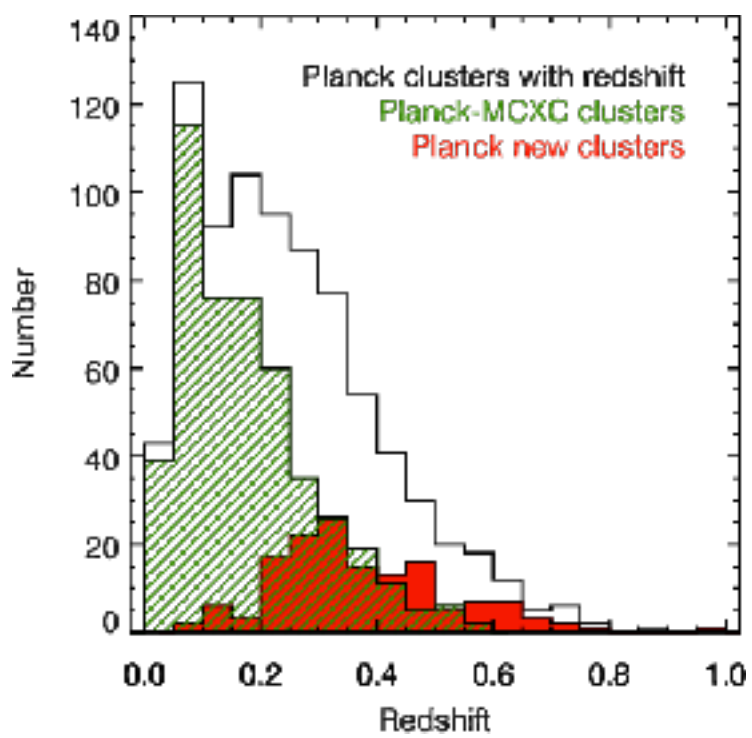
SZ detections

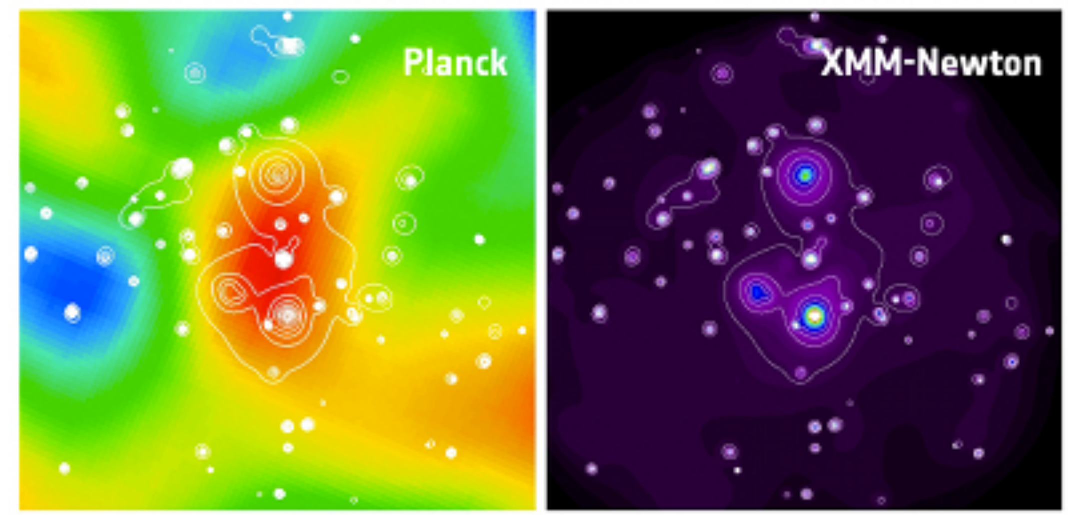
Cluster detection is seen as a positive or negative signal depending on the observation frequency

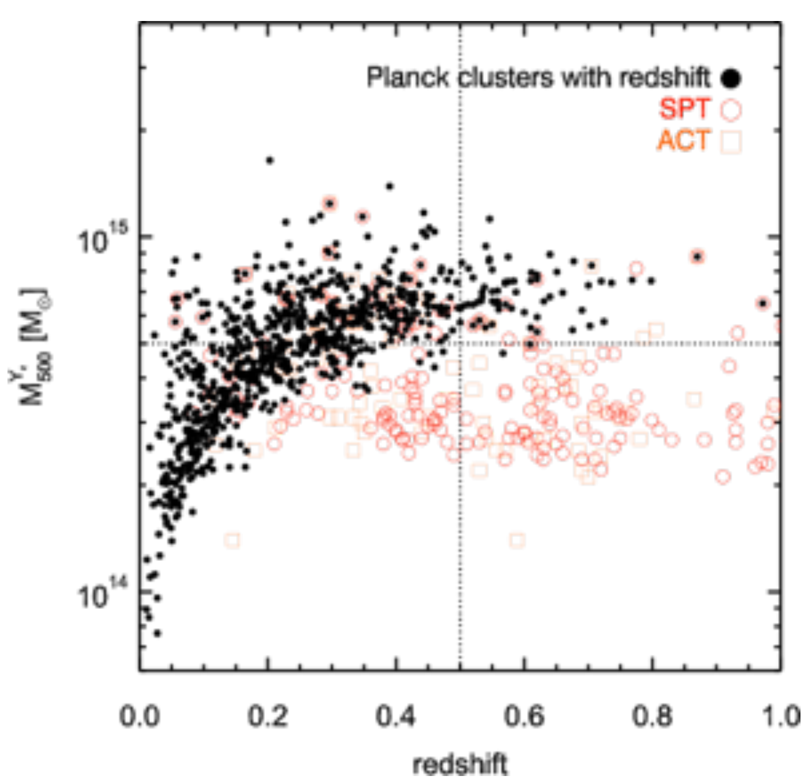


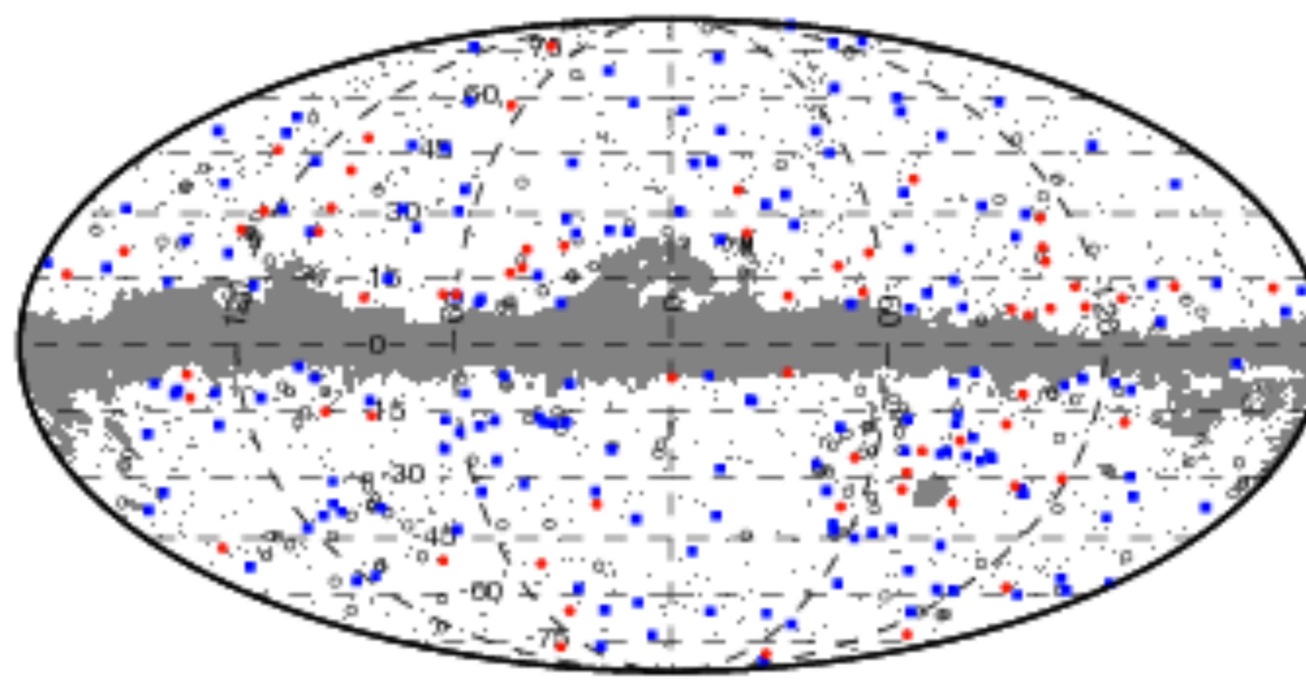


Planck SZ-clusters







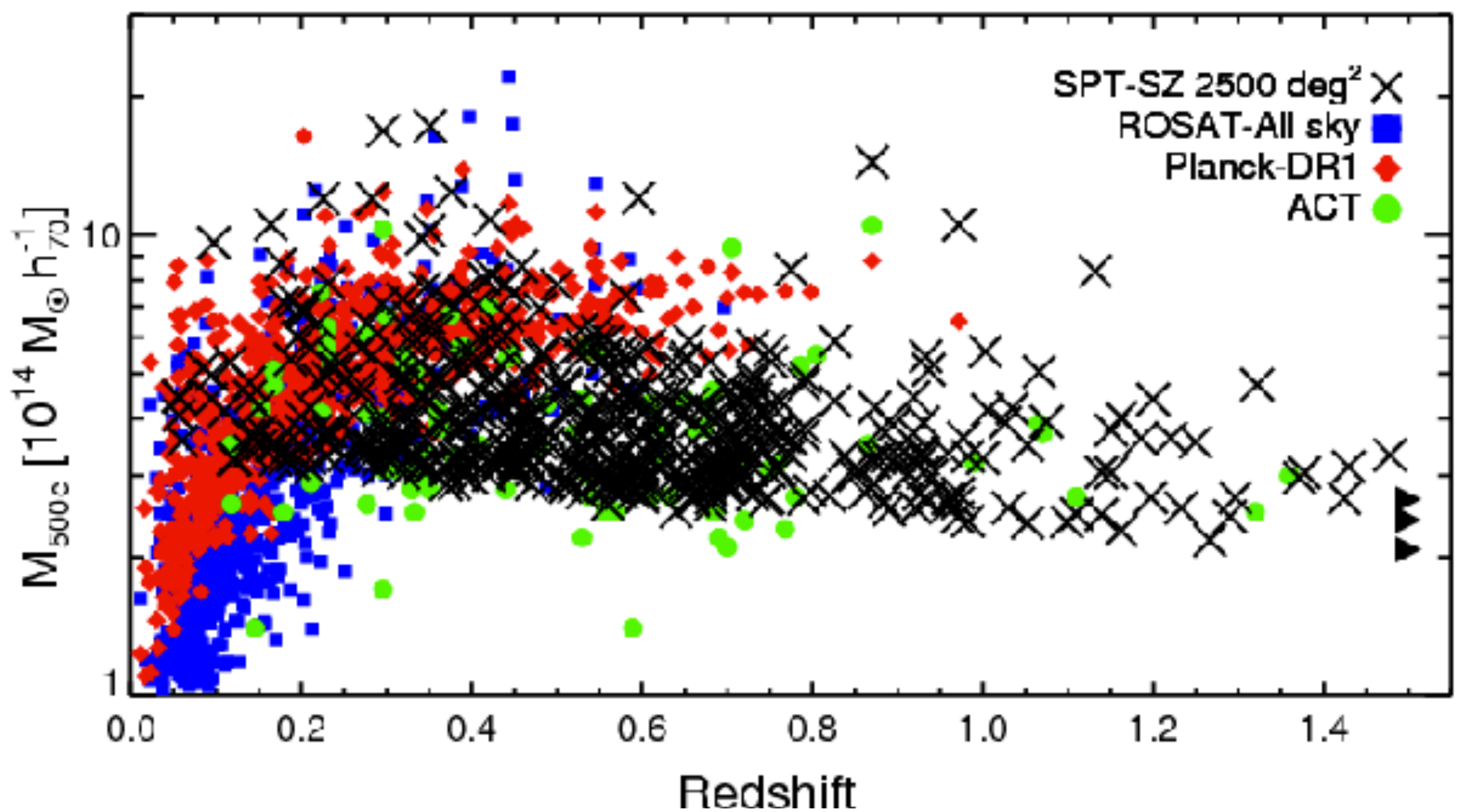


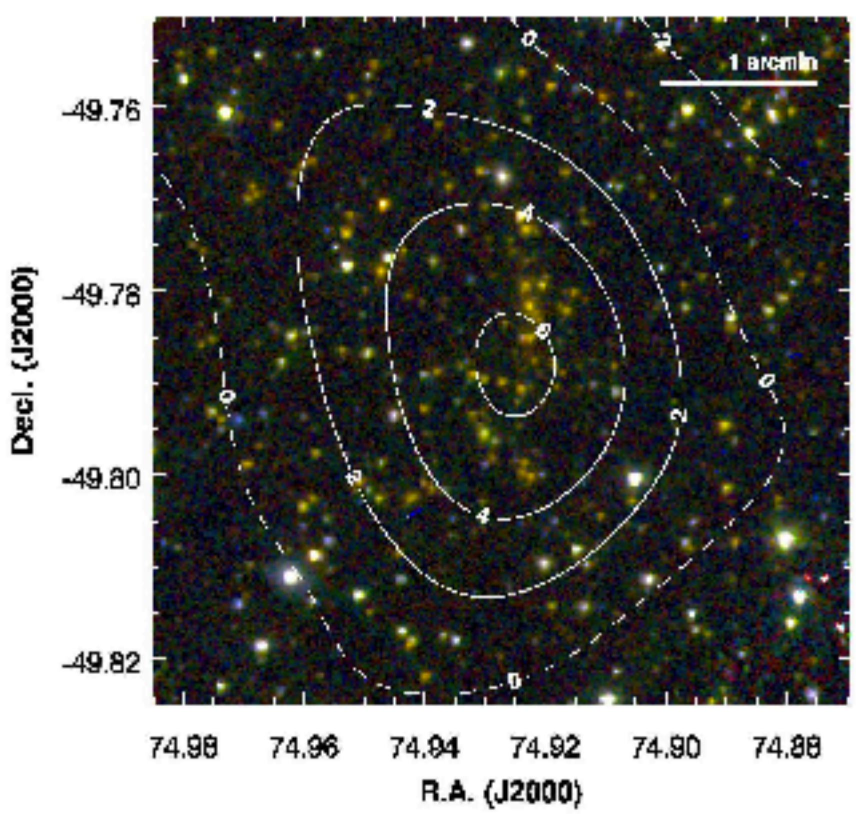
SZ clusters from Planck

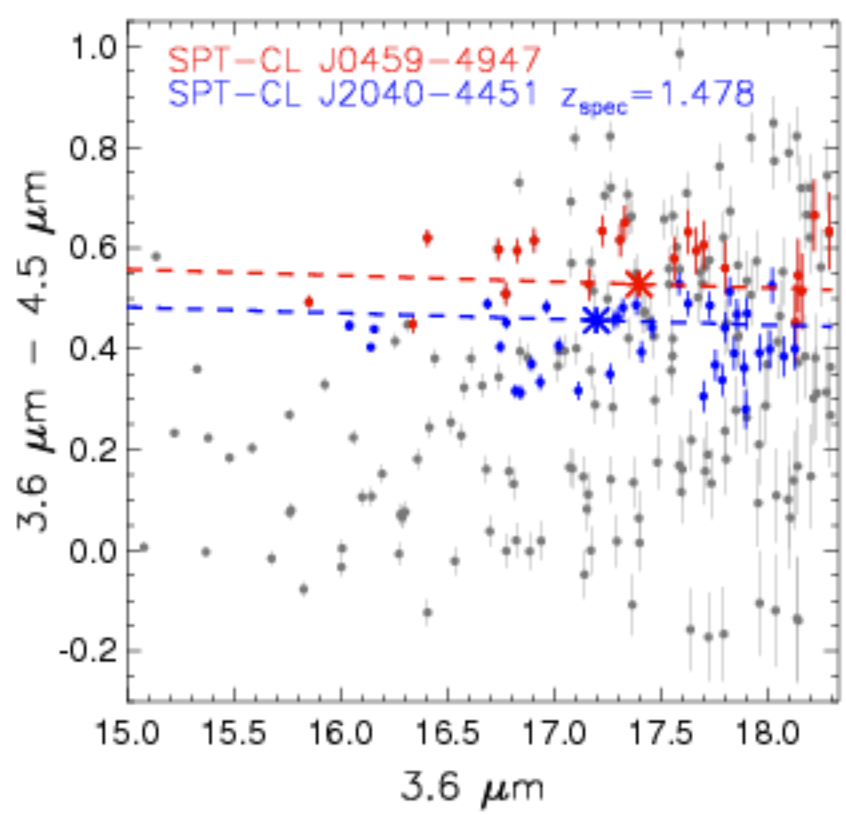
South Pole Telescopes

- South Pole station : CMB telescopes visible in the background include (left to right) the South Pole Telescope, the BICEP2 telescope, and the Keck Array telescope

SPT Clusters

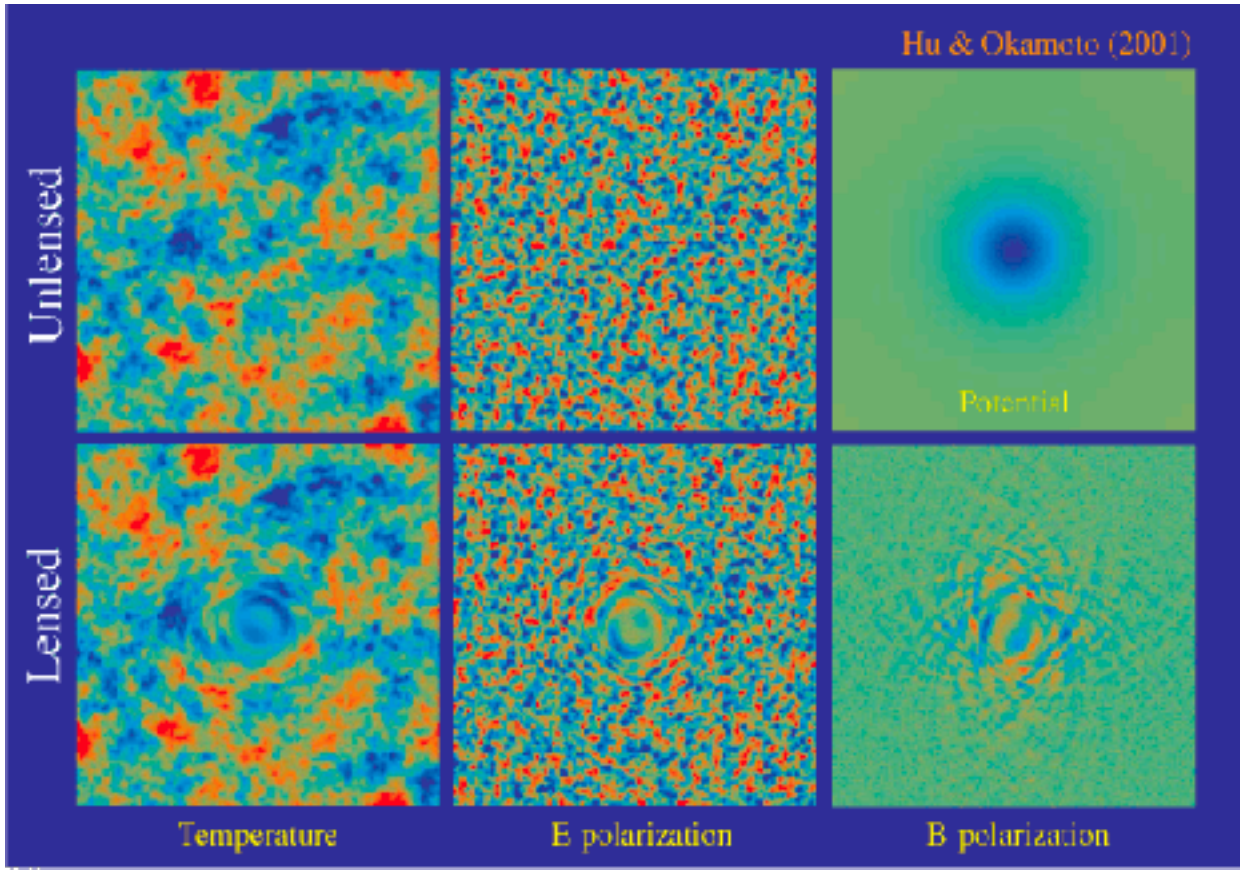


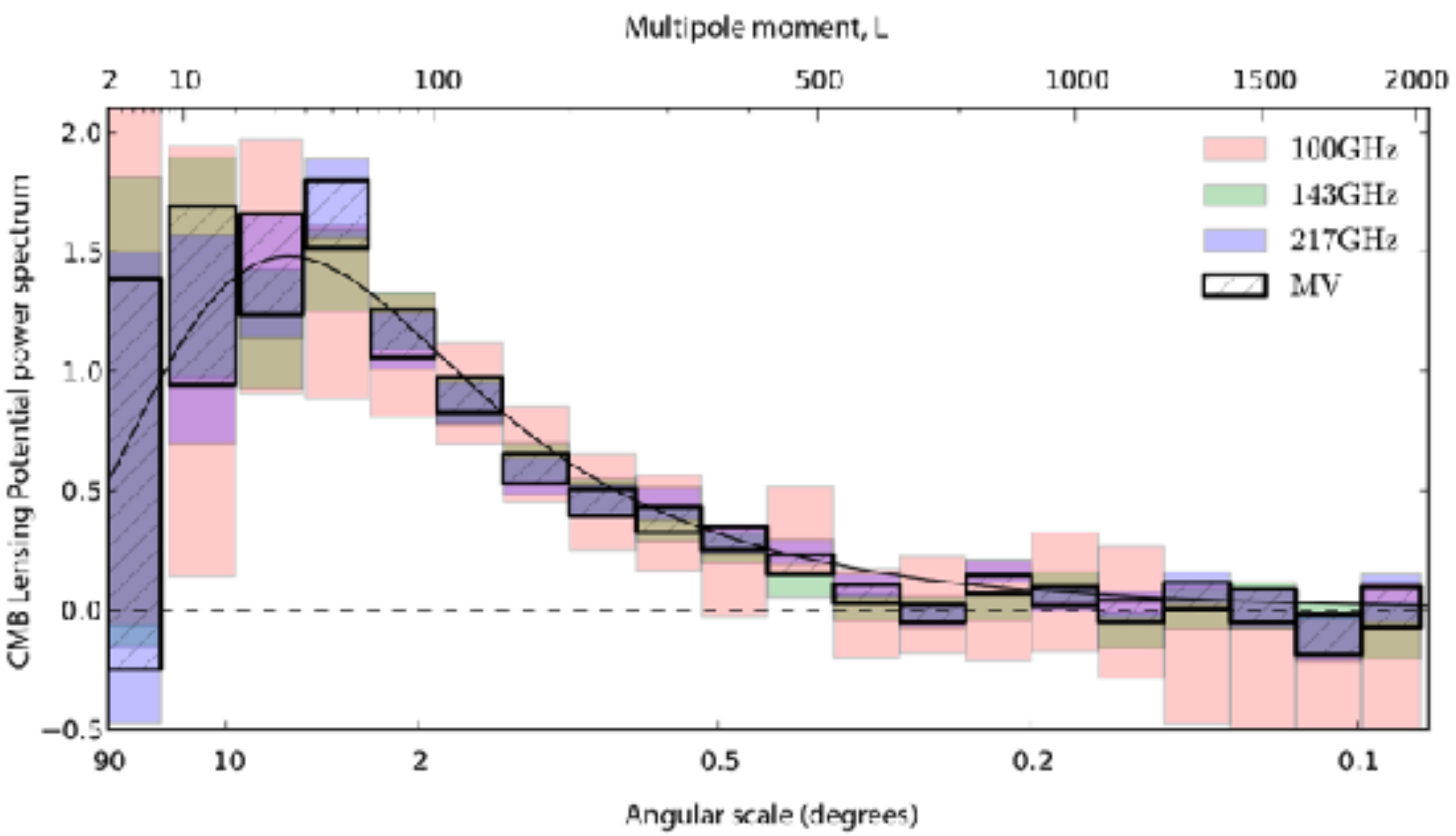




CMB Lensing

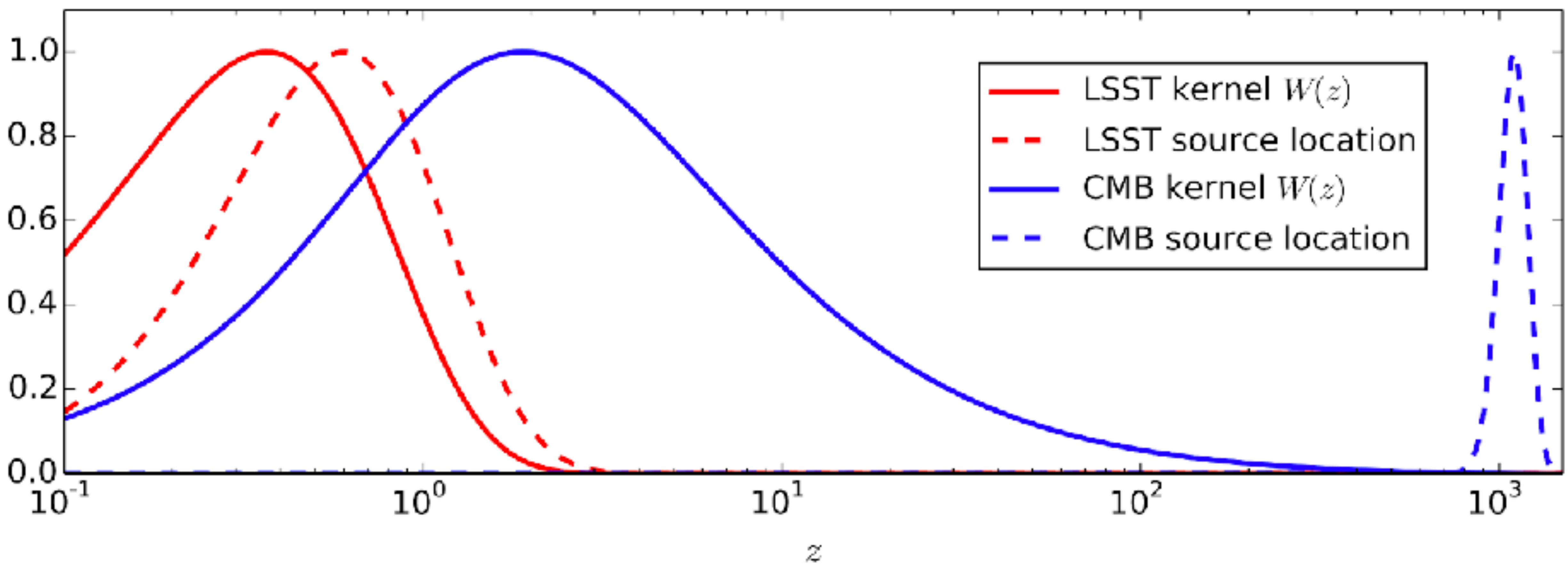
- Mass distribution on the line of sight will distort the CMB light
- Changes in T, E and B polarisation
- Detected in the Planck/SPT/ACT data





https://arxiv.org/abs/1502.01591

CMB and galaxy lensing



CMB S-4 Science book

https://arxiv.org/abs/1610.02743

Future of CMB observations

- Better polarisation measurement.
- Primordial B-modes? (test inflation)
- Higher resolution images (larger telescope)
- Space-based projects (proposed but not successful yet)
- Ground based project: "Stage-IV" project led/motivated by US DOE. (Simons Observatory in the near future)
- http://xxx.lanl.gov/abs/1610.02743 CMB-S4 Science Book https://cmb-s4.org/

LiteBIRD Space Mission

https://www.isas.jaxa.jp/en/missions/spacecraft/future/litebird.html