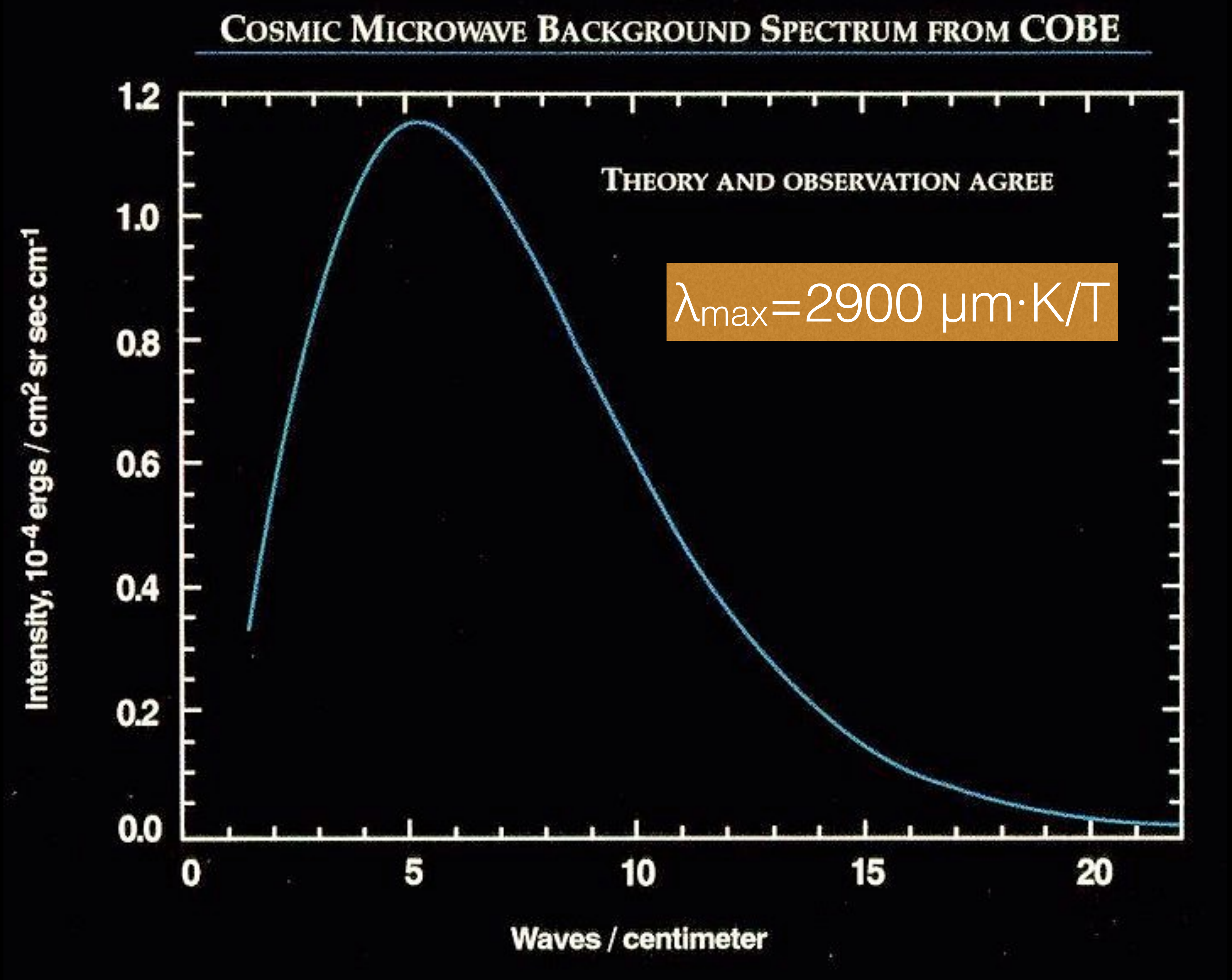
Observation of the Evolution of the Temperature of the Universe

Jan. 26, 2017

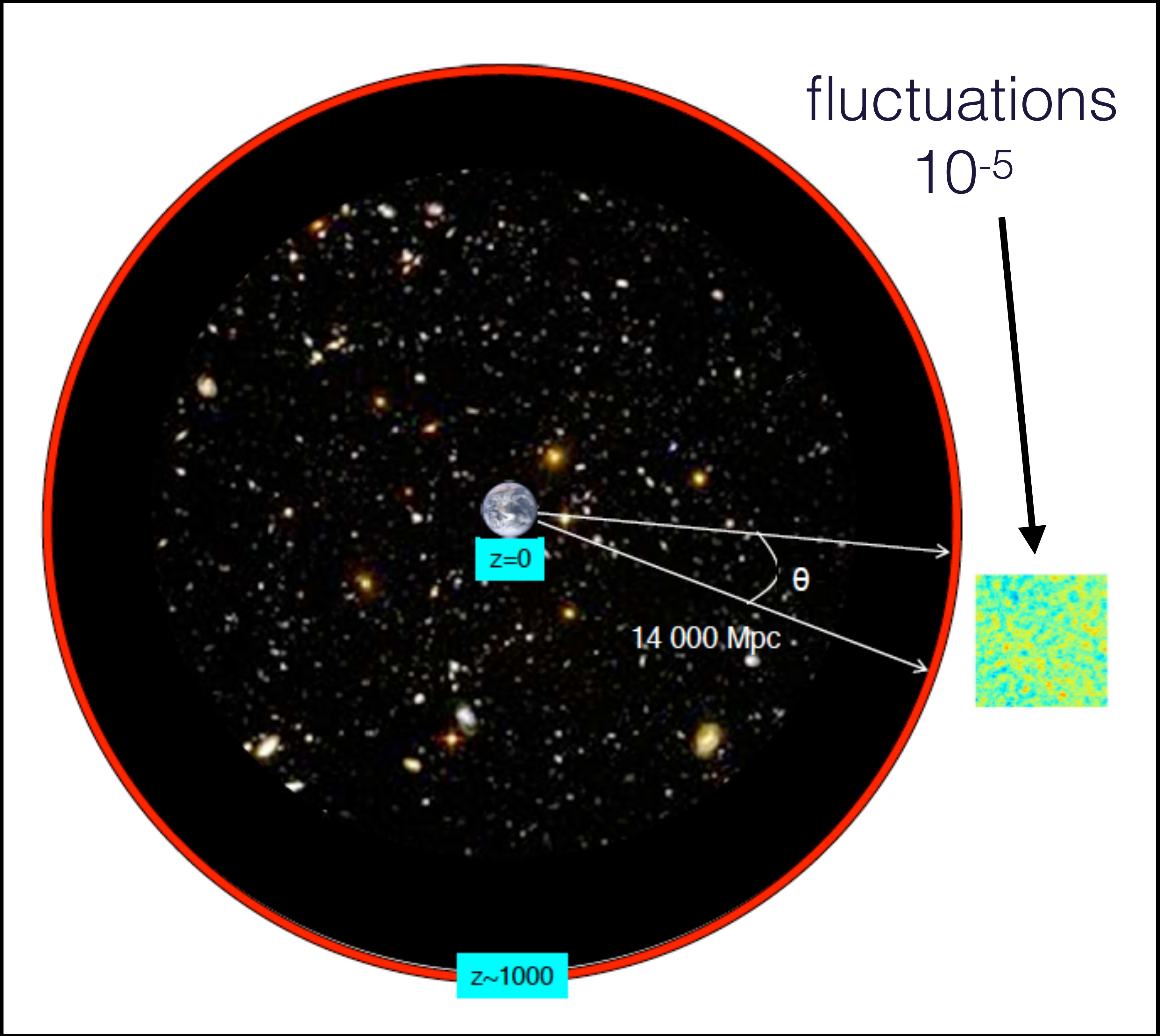
Friday Feature™, M. Gold

CMB is a Perfect Black Body T=2.725 K

errors are so small as to be invisible on this scale!



z is a proxy for distance



3D print of universe at t_{CMB} = 380,000 y

note that this does not mean that the total universe is finite!

http://www3.imperial.ac.uk/newsandeventspggrp/imperialcollege/newssummary/news_27-10-2016-11-42-11

Cosmological red shift (z)

$$1 + z = \lambda_{obs}/\lambda_{emit} = a_{now}/a_{then}$$

where “a” is expansion factor

age of universe:
13.799±0.021 Gy
ΛCDM concordance model.

CosmoCalc.html

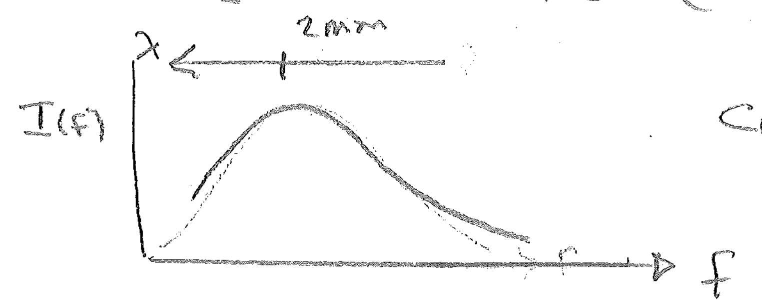
$H_0 = 71$, $\Omega_m = 0.27$ Ω_{vac} 0.73 (flat)

Z	Age (Gyr)	Light Travel (Gyr)
0	13.7	0
0.1	12.4	1.3
1	5.9	7.7
2	3.3	10.3
3	2.2	11.5

λ_o observed wavelength } $a(t)$ scale
λ_e emitted wavelength } parameter

$$Z = \frac{\lambda_o}{\lambda_e} - 1 \qquad \frac{\lambda_o}{\lambda_e} = \frac{a_o}{a_e}$$

$$a_e = \frac{a_o}{1+Z} \qquad \lambda_o = (1+Z)\lambda_e$$

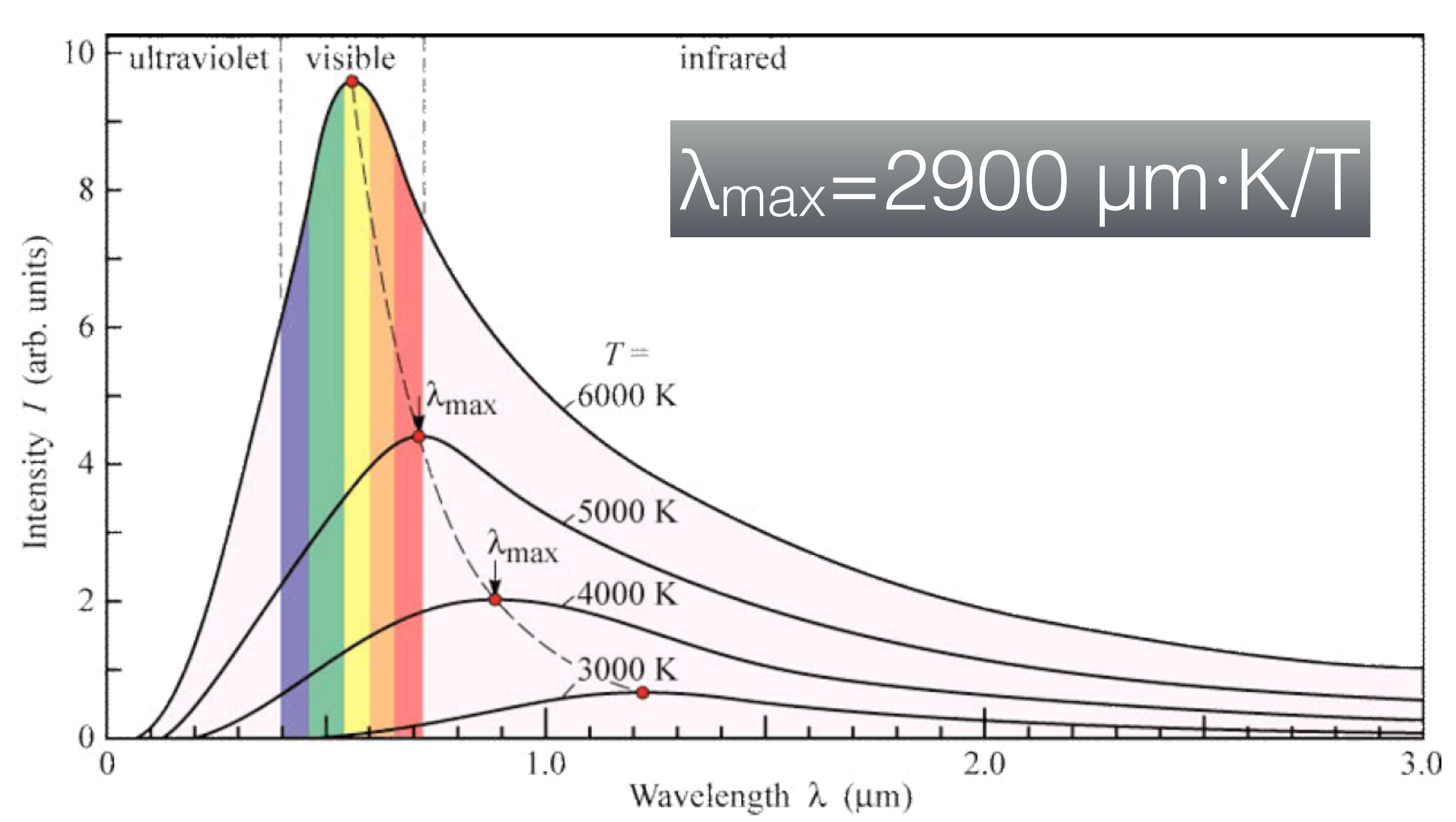


CMB thermal spectrum (black body)

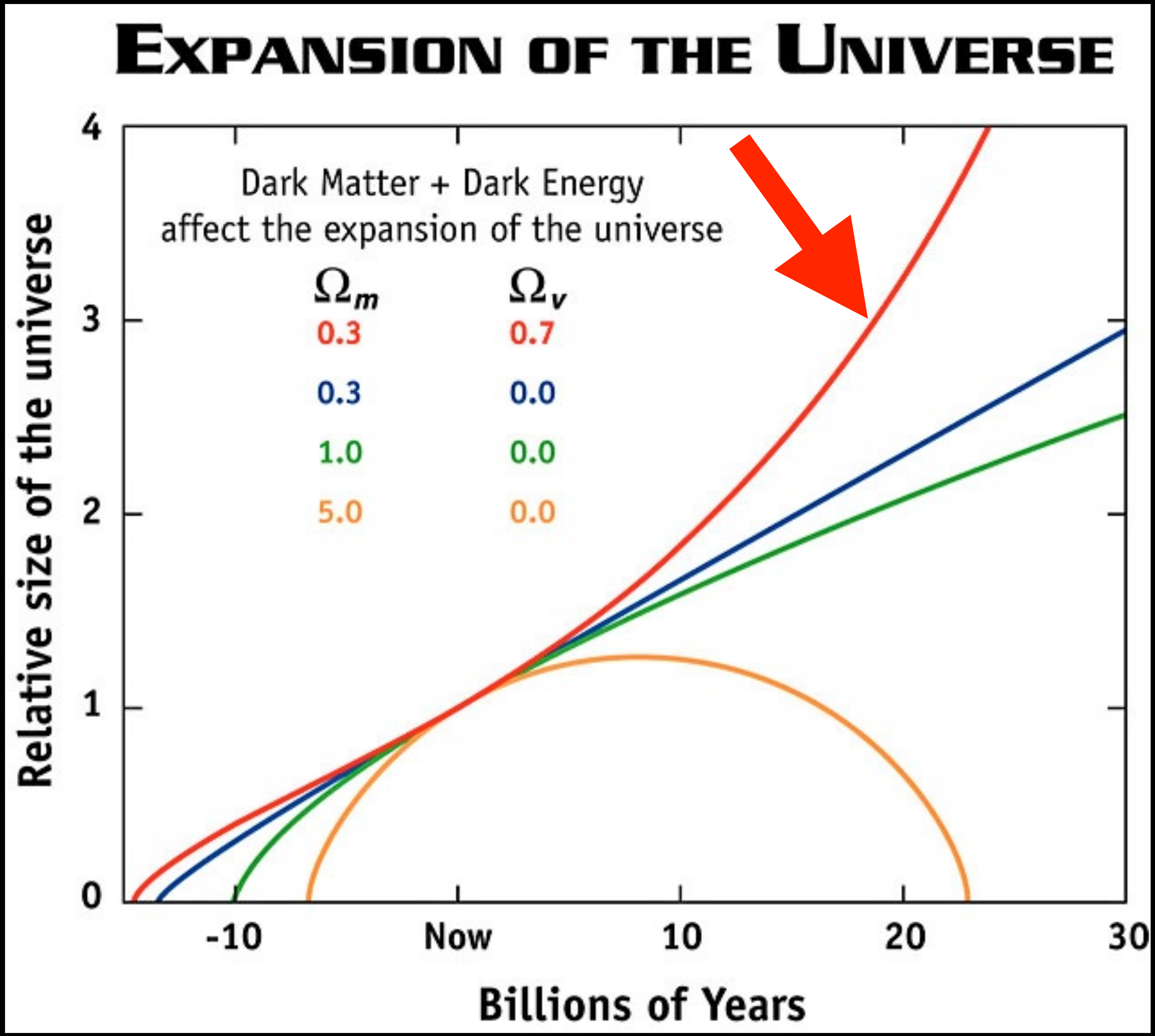
$$I(f) = \frac{4\pi\hbar}{c^2}\left(\frac{f^3}{e^{hf/k_BT} - 1}\right) \qquad T = 2.7\,K$$

$Z_{CMB} \cong 1100$ ($t \approx 400{,}000$ y from big bang)

CMB black body spectrum should evolve with red shift according to Wien's law



Red line is our universe in which expansion is accelerating



Astronomy & Astrophysics manuscript no. TCMB˙astroph © ESO 2010
December 16, 2010

LETTER TO THE EDITOR

The evolution of the Cosmic Microwave Background Temperature*

Measurements of $T_{\rm CMB}$ at high redshift from carbon monoxide excitation

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ABSTRACT

A milestone of modern cosmology was the prediction and serendipitous discovery of the Cosmic Microwave Background (CMB), the radiation left over after decoupling from matter in the early evolutionary stages of the Universe. A prediction of the standard hot Big-Bang model is the linear increase with redshift of the black-body temperature of the CMB ($T_{\rm CMB}$). This radiation excites the rotational levels of some interstellar molecules, including carbon monoxide (CO), which can serve as cosmic thermometers. Using three new and two previously reported CO absorption-line systems detected in quasar spectra during a systematic survey carried out using VLT/UVES, we constrain the evolution of $T_{\rm CMB}$ to $z \sim 3$. Combining our precise measurements with previous constraints, we obtain $T_{\rm CMB}(z) = (2.725 \pm 0.002) \times (1+z)^{1-\beta}$ K with $\beta = -0.007 \pm 0.027$, a more than two-fold improvement in precision. The measurements are consistent with the standard (i.e. adiabatic, $\beta = 0$) Big-Bang model and provide a strong constraint on the effective equation of state of decaying dark energy (i.e. $w_{eff} = -0.996 \pm 0.025$).

Key words. Cosmology: Observations – Cosmic background radiation – Quasars: Absorption lines

phenomenologically parametrize possible deviations by

$$T_{\rm CMB}(z) = T_0(1+z)^{1-\beta} ,$$

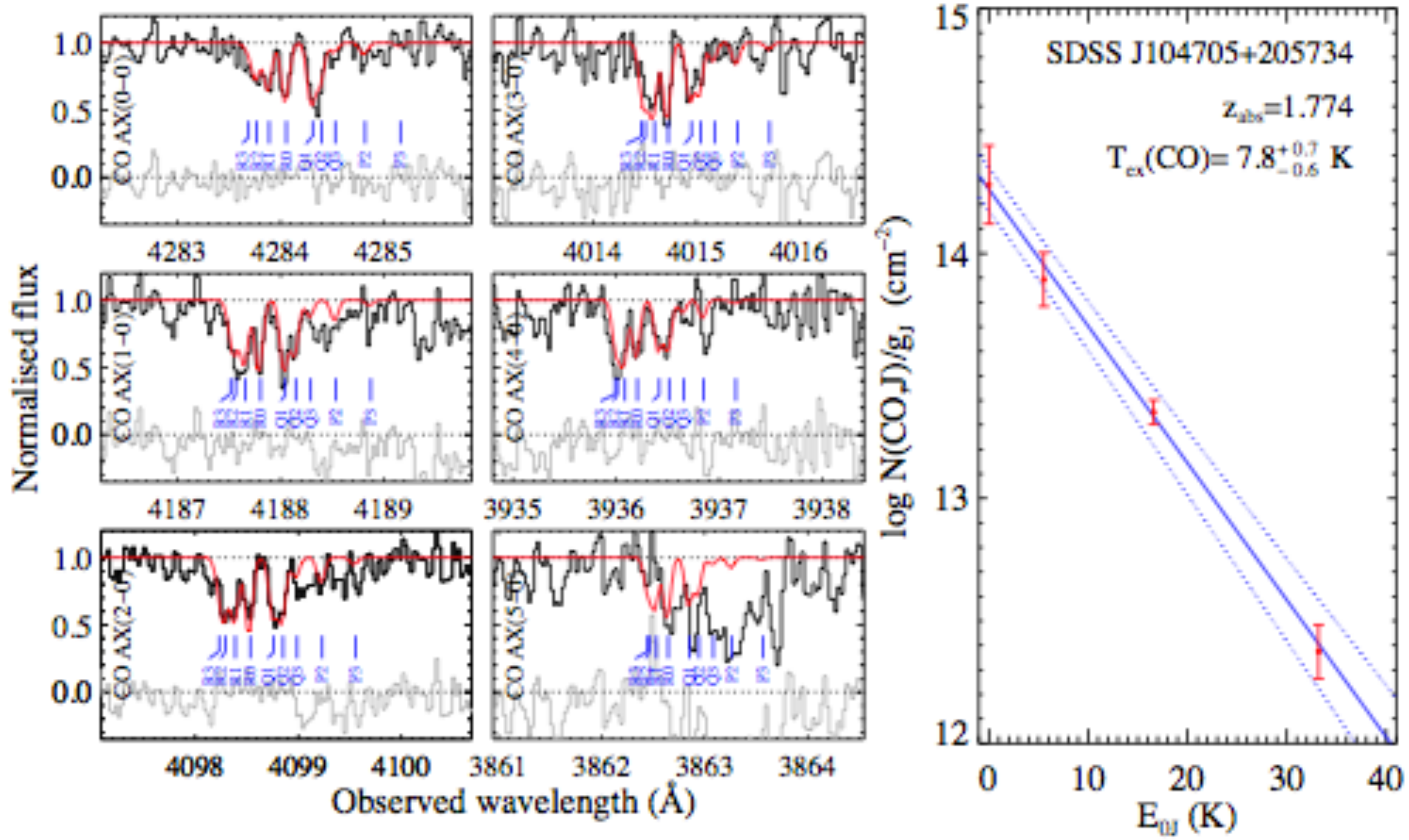

Fig. 1. Left: $A^1\Pi(\nu') \leftarrow X^1\Sigma^+(\nu{=}0)$ electronic bands of CO detected at $z_{abs} = 1.774$ toward the quasar SDSS J104705+205734. The modelled profile is over-plotted in red with the fitting residuals shown in grey. Short vertical lines indicate the branch ('R', 'P' or 'Q') and the rotational level of the transition (J=0-3). Right: The corresponding excitation diagram of CO gives the column density of the rotational levels J weighted by their quantum degeneracy (g_J) versus the energy of these levels relative to the ground state. The excitation temperature is directly given by $-1/(a \ln 10)$ where a is the slope of the linear fit (solid blue line, with 1 σ errors represented by the dotted curves).

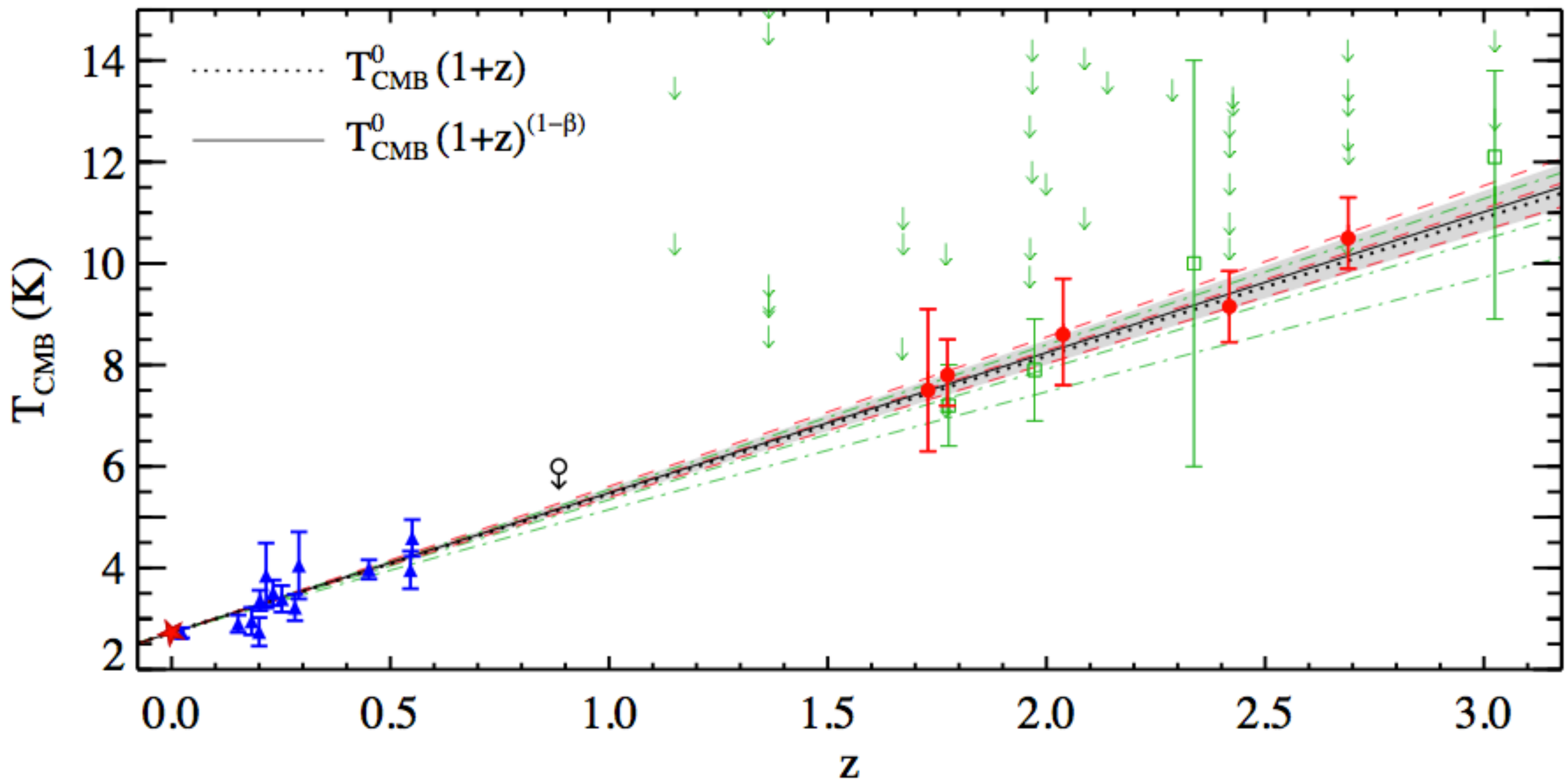

Fig. 4. The black-body temperature of the Cosmic Microwave Background radiation as a function of redshift. The star represents the measurement at $z = 0$ (Mather et al., 1999). Our measurements based on the rotational excitation of CO molecules are represented by red filled circles at $1.7 < z < 2.7$. Other measurements at $z > 0$ are based (i) on the S-Z effect (blue triangles at $z < 0.6$, Luzzi et al. 2009) and (ii) on the analysis of the fine structure of atomic carbon (green open squares: $z = 1.8$, Cui et al. 2005; $z = 2.0$, Ge et al. 1997; $z = 2.3$, Srianand et al. 2000; $z = 3.0$, Molaro et al. 2002). Upper-limits come from the analysis of atomic carbon (from the literature and our UVES sample, see Srianand et al. 2008) and from the analysis of molecular absorption lines in the lensing galaxy of PKS 1830-211 (open circle at $z = 0.9$, Wiklind & Combes, 1996). The dotted line represents the adiabatic evolution of T_{CMB} as expected in standard hot Big-Bang models. The solid line with shadowed errors is the fit using all the data and the alternative scaling of $T_{CMB}(z)$ (Lima et al., 2000) yielding $\beta = -0.007 \pm 0.027$. The red dashed curve (resp. green dashed-dotted) represents the fit and errors using S-Z + CO measurements (resp. S-Z + atomic carbon).

Constraining the evolution of the CMB temperature with SZ measurements from Planck data

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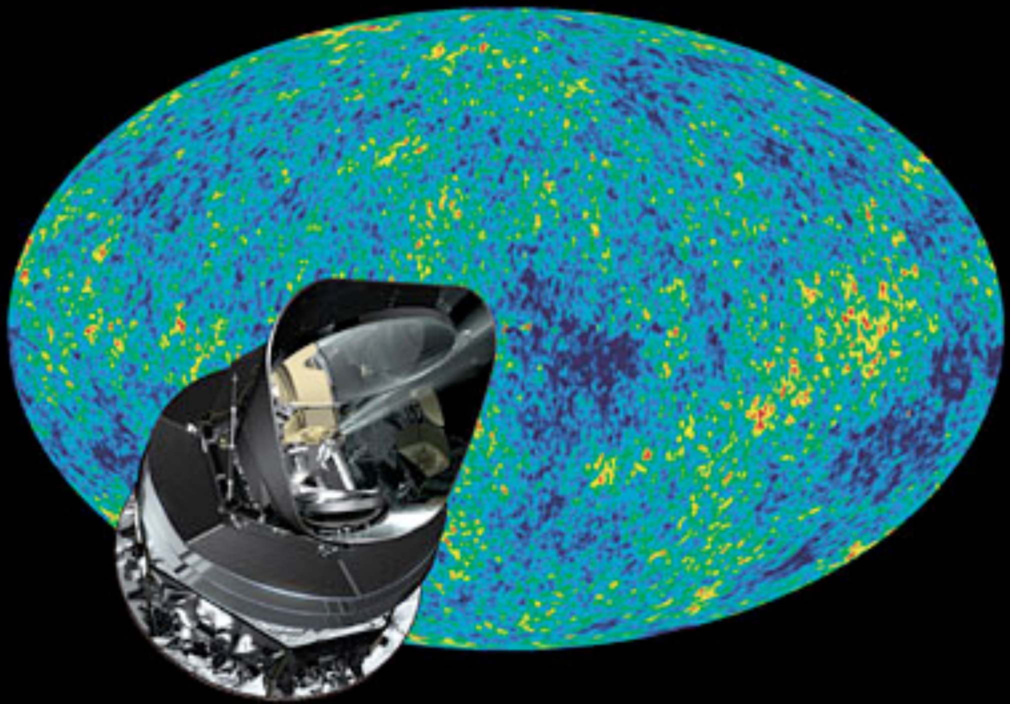
Feb. 27, 2015 https://arxiv.org/abs/1502.07858

https://www.cosmos.esa.int/web/planck

Planck launched 2009
Ariane 5 from Europe's
Spaceport in French Guiana



CMB fluctuations ~10^{-5}

The SZ effect:

https://ned.ipac.caltech.edu/level5/Sept05/Carlstrom/Carlstrom_contents.html

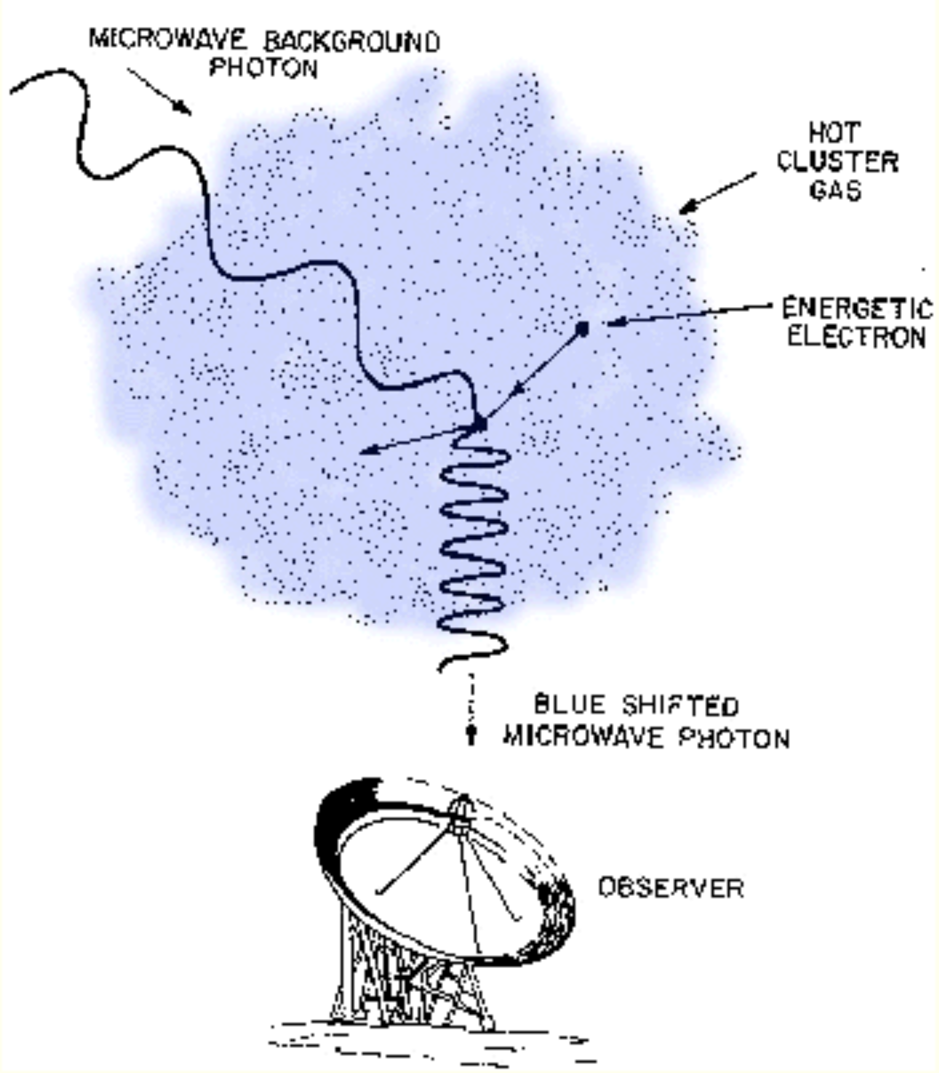
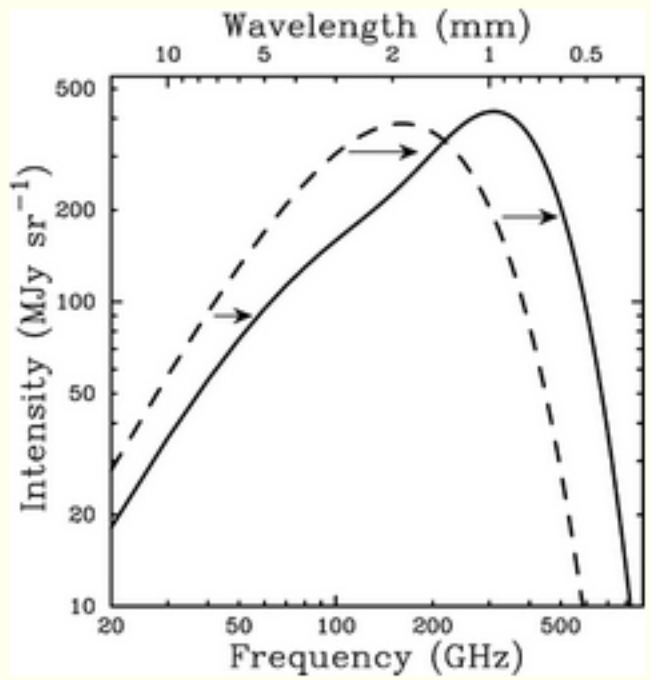
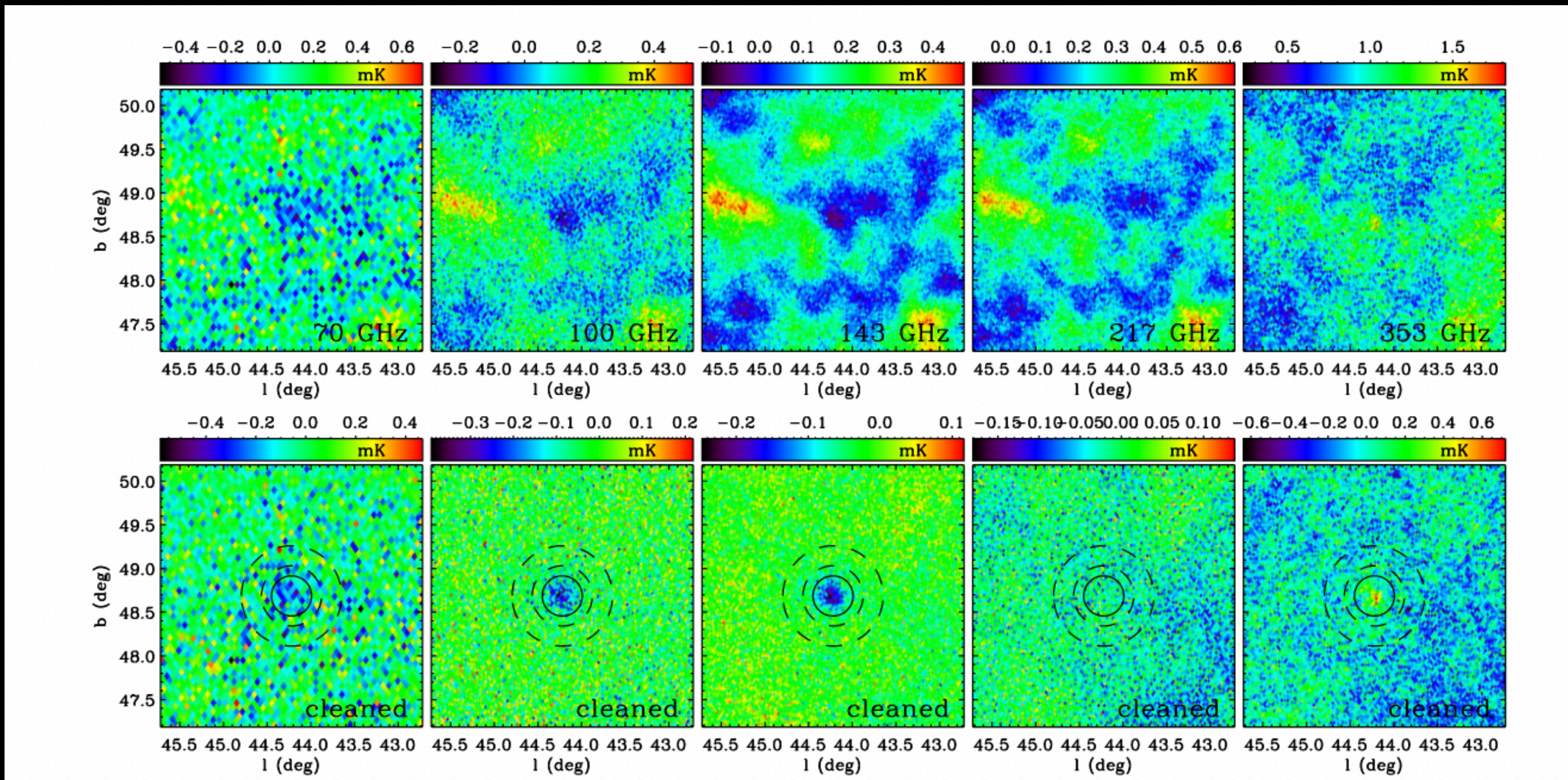


Figure 1: Schematic of the Sunyaev-Zeldovich effect that results in an increase in higher energy (or blue shifted) photons of the cosmic background when seen through the hot gas present in cluster of galaxies. (Adapted from L. Van Speybroeck)



<u>Figure 2:</u> The dashed line represents the intensity of the cosmic microwave background with radio frequency. The solid line is the distortiong in the cosmic background intensity due to inverse-Compton scattering of photons through the gas presents in a cluster of galaxies. This is a schematic representation: the actual distortion is much smaller. (Credit: Carlstrom et al., Annual Reviews of Astronomy & Astrophysics vol 40, pg 643, 2002)

The steep frequency dependence of the change in the CMB spectral intensity, ΔI_{SZ}, due to the SZ effect allows the CMB temperature to be estimated at the redshift of the cluster.



The maps, and the second line to the maps after cleaning for the thermal dust and CMB using our methodology (see section 3.1). The maps clearly show the expected SZ decrements at frequencies below 217 GHz, no effect at 217 GHz, and a positive signal at 353 GHz. The solid circle depicts the aperture we use to integrate the SZ flux, and the two concentric dashed rings the annulus used for background subtraction.

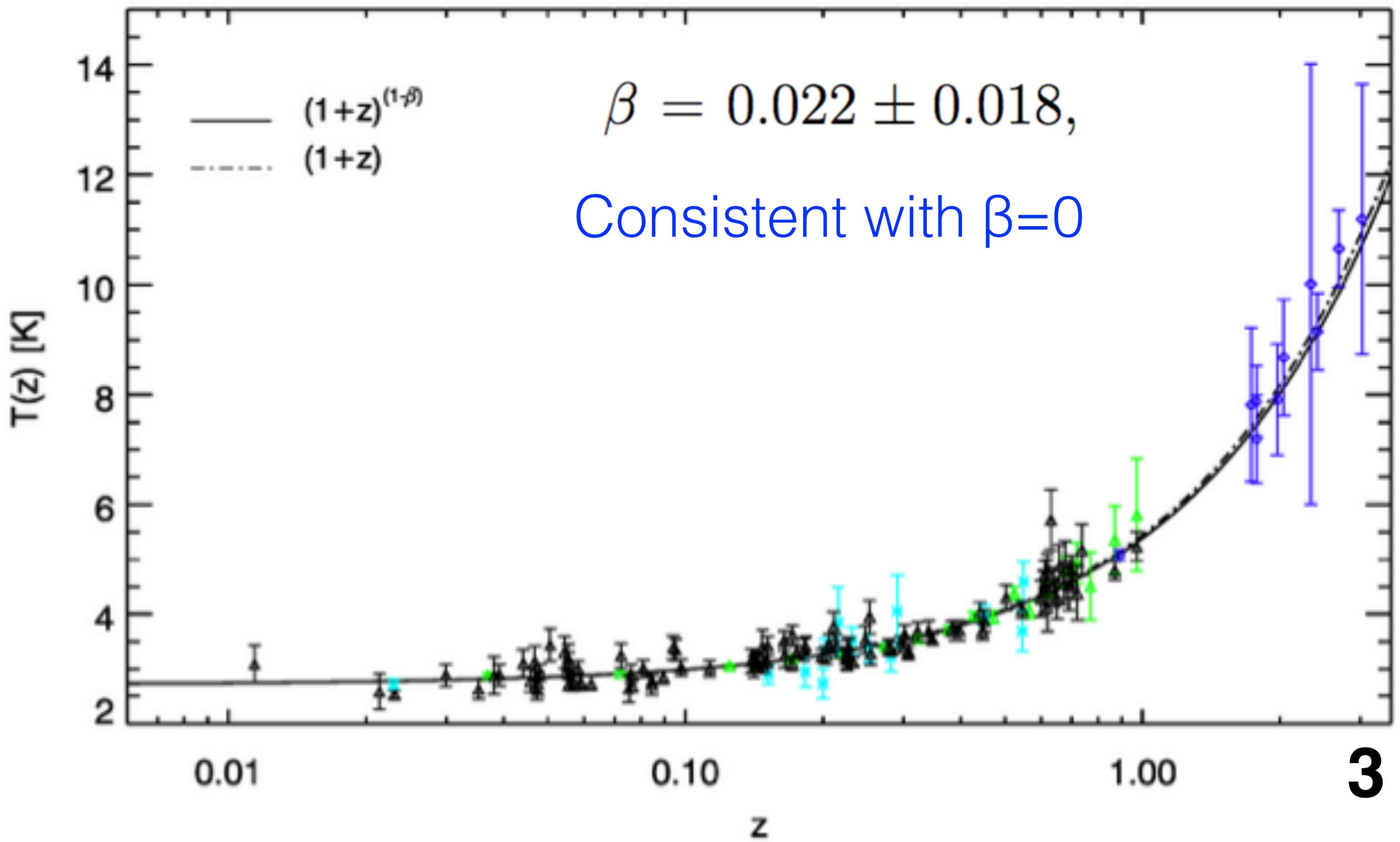


Figure 8. Measurements of the CMB temperature as a function of redshift. Black points are measurements from SZ spectra of individual clusters (104 Planck-selected clusters); blue points are absorption lines measurements (Muller et al 2013 and references therein); T(z) data points from Saro et al. (2014) are not available. The solid line is the best fit to the scaling $T_{\rm CMB}(z)=T_0(1+z)^{1-\beta}$ obtained by combining our result with Muller et al. (2013) and with Saro et al. (2014). The dot-dashed line is the standard scaling. For visualization purpose we also plot in cyan previous SZ measurements toward galaxy clusters (Luzzi et al. 2009) and in green stacked Planck SZ selected clusters (Hurier et al. 2014). We haven't used these two last datasets for our combined constraints on β, due to common clusters in our sample.