

LA RADIAZIONE COSMICA DI FONDO

Mario Zannoni

Antefatto:

All'epoca della pubblicazione della RG (1915), il modello di Universo accreditato era costituito da una visione statica della nostra galassia.

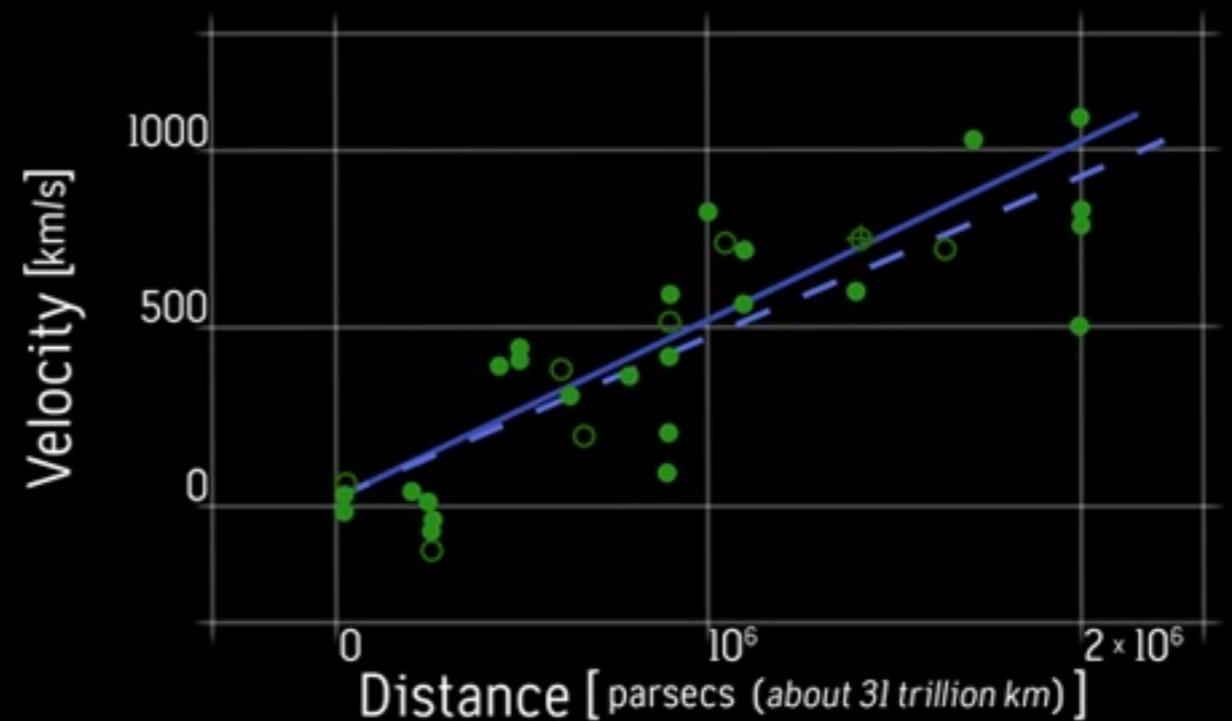
Le altre galassie sono nebulose facenti parte della Via Lattea.

Einstein introduce la Costante Cosmologica Λ nelle equazioni di campo allo scopo di avere una soluzione **STATICA**

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Nel **1929** Edwin Hubble scopre la recessione delle galassie (**UNIVERSO IN ESPANSIONE**), che nel frattempo aveva stabilito essere oggetti esterni alla Via Lattea.

Einstein considera Λ il suo più clamoroso errore.



L'Universo non è statico: si espande

2 cosmologie rivali

Big Bang

vs

Steady State

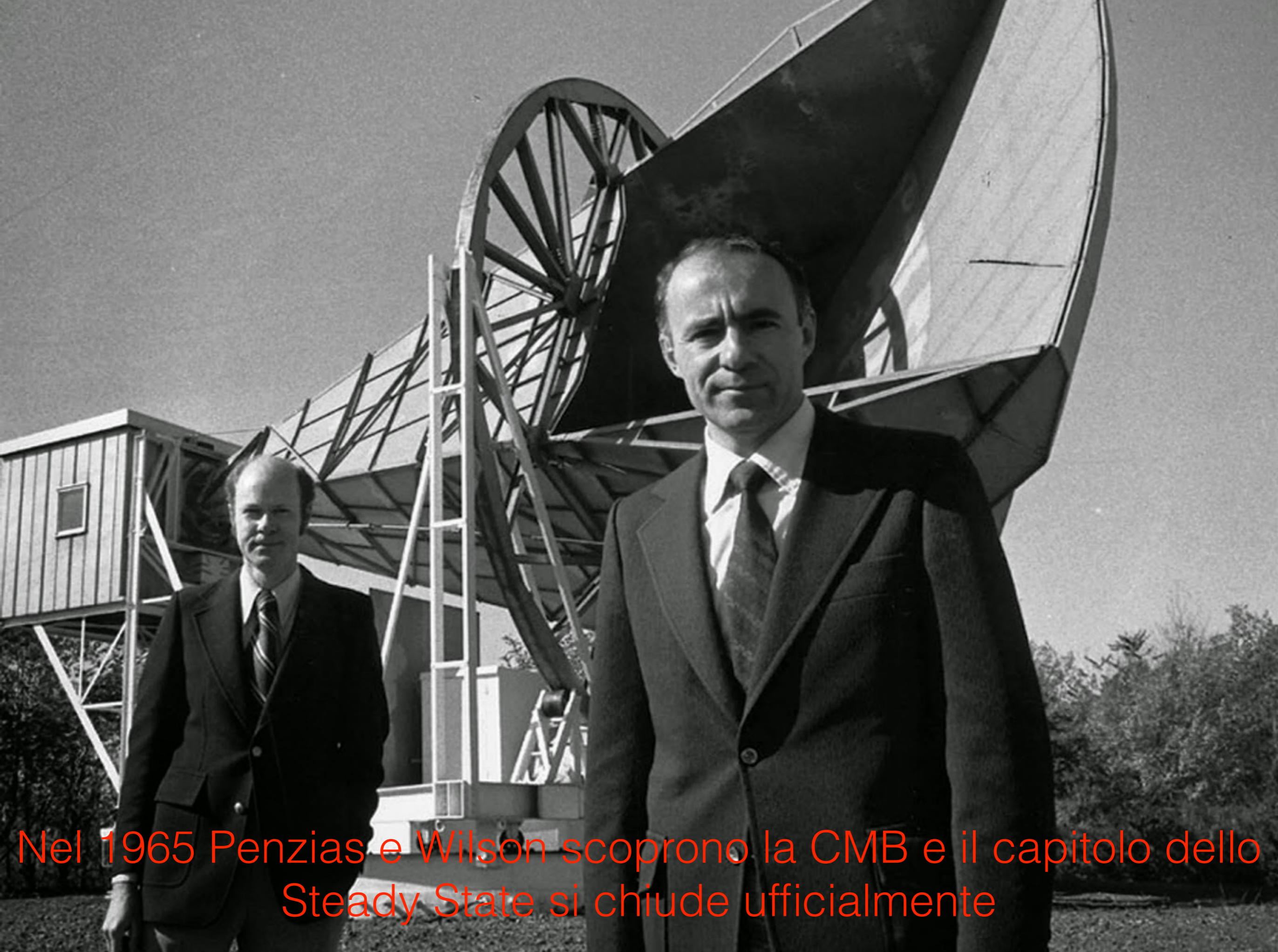
George Gamow, Ralph Alpher, Robert Herman

Fred Hoyle, Herman Bondi, Thomas Gold

- Modello per la nucleosintesi fallimentare (a parte gli elementi leggeri)
- Nucleosintesi stellare sembra lavorare meglio
- Predizione del fondo cosmico **DIMENTICATA!**
- Predizioni quantitative difficili a causa dei molti parametri liberi

- Assume solo nucleosintesi stellare elio, litio, deuterio possibili problemi
- Richiede nuova fisica
Creazione continua di materia (non osservabile!)
- Limitazioni estremamente alte no evoluzione, no inhomogeneità
- Fornisce previsioni affidabili
- **Totalmente incompatibile con la CMB**

All'inizio degli anni '60 non è chiaro chi abbia ragione

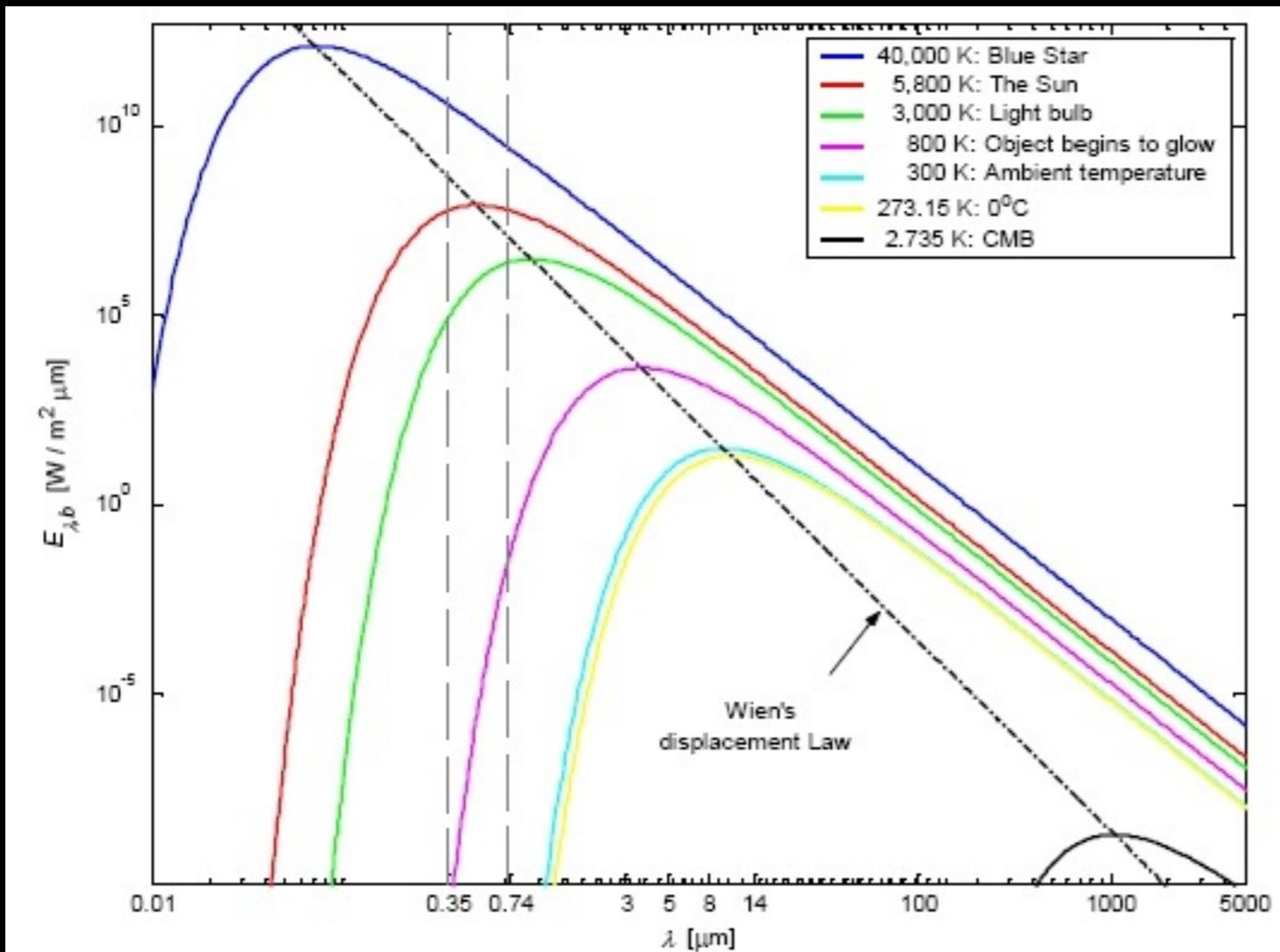


Nel 1965 Penzias e Wilson scoprono la CMB e il capitolo dello Steady State si chiude ufficialmente

Nota:

La CMB (Cosmic Microwave Background) è nota come radiazione a 3 gradi Kelvin (2.726 ± 0.010 K) perché ha uno spettro di **corpo nero** (o spettro di Planck) a questa temperatura.

Caratteristica del corpo nero infatti è quella di essere univocamente determinato da un solo parametro: la temperatura



$$E(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

La CMB, senza che venisse riconosciuta come tale, ha fatto capolino diverse volte nella ricerche astronomiche prima della scoperta ufficiale del 1965: vediamo quando



Nel 1941 S.W.Adams osserva righe di assorbimento del cianogeno (CN) interstellare per le quali A. McKeller stima una temperatura di eccitazione $T=2.3$ K che viene così commentata dallo stesso McKeller: “which has of course a very restricted meaning” ...

Nel 1946 Dicke aveva usato un radiometro di sua invenzione per misurare l'emissione nelle microonde dell'atmosfera e della luna stabilendo un limite superiore ($T<20$ K) alla radiazione termica di origine celeste. Un risultato sostanzialmente dimenticato anche dopo la scoperta del 1965...

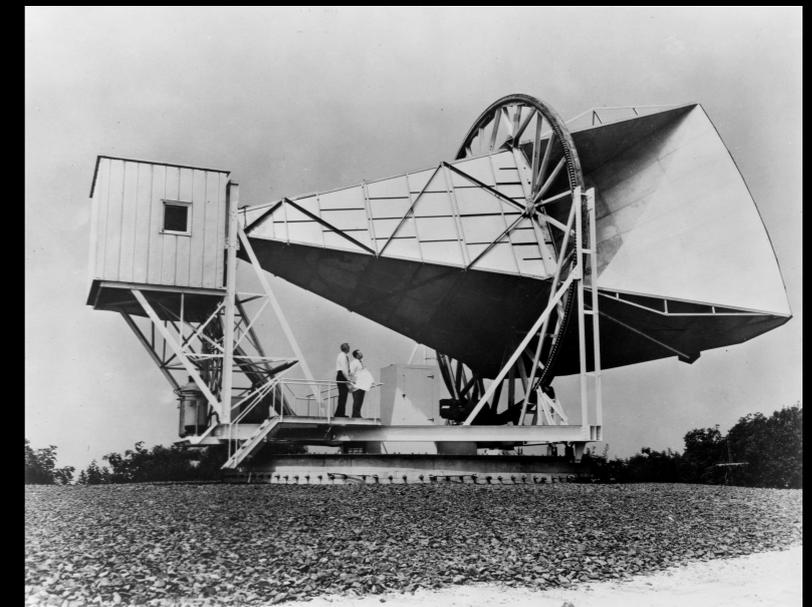
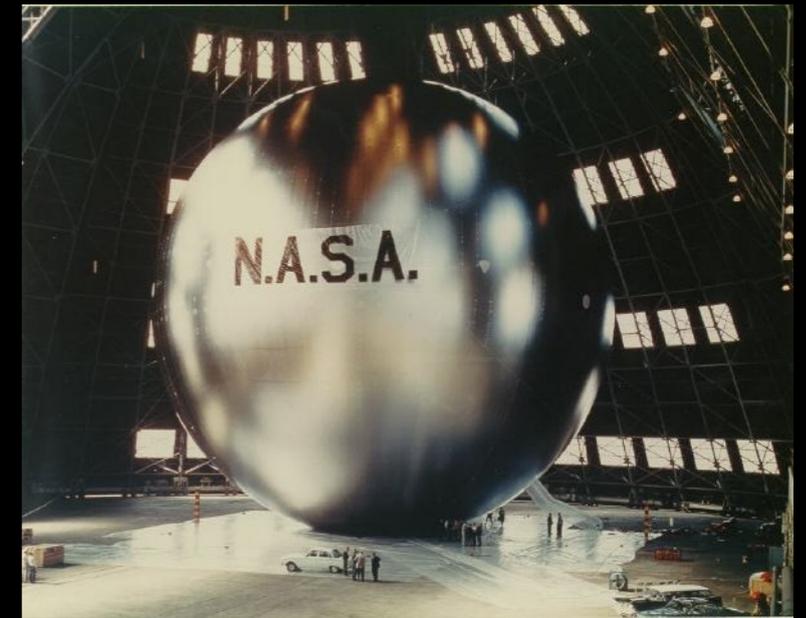
Nel 1948 compare il famoso articolo α - β - γ a firma di G. Gamow, R. Alpher e R. Herman sulla sintesi primordiale degli elementi leggeri in cui viene calcolata la presenza di un fondo di radiazione elettromagnetica con spettro di corpo nero con una temperatura attuale $T=10$ K, poi meglio stimata in 5K. Sostanzialmente viene dimenticato.

Nel 1957 T. A. Shmaonov osservando a 3.2cm con il radiotelescopio da 22m di Pushkino trova un risultato simile $T=4\pm 3$ K

Nel 1959 Emile Le Roux dell'osservatorio di Nancay vicino a Parigi, eseguendo una survey a 33cm riporta un fondo di segnale isotropo con $T=3\pm 2$ K

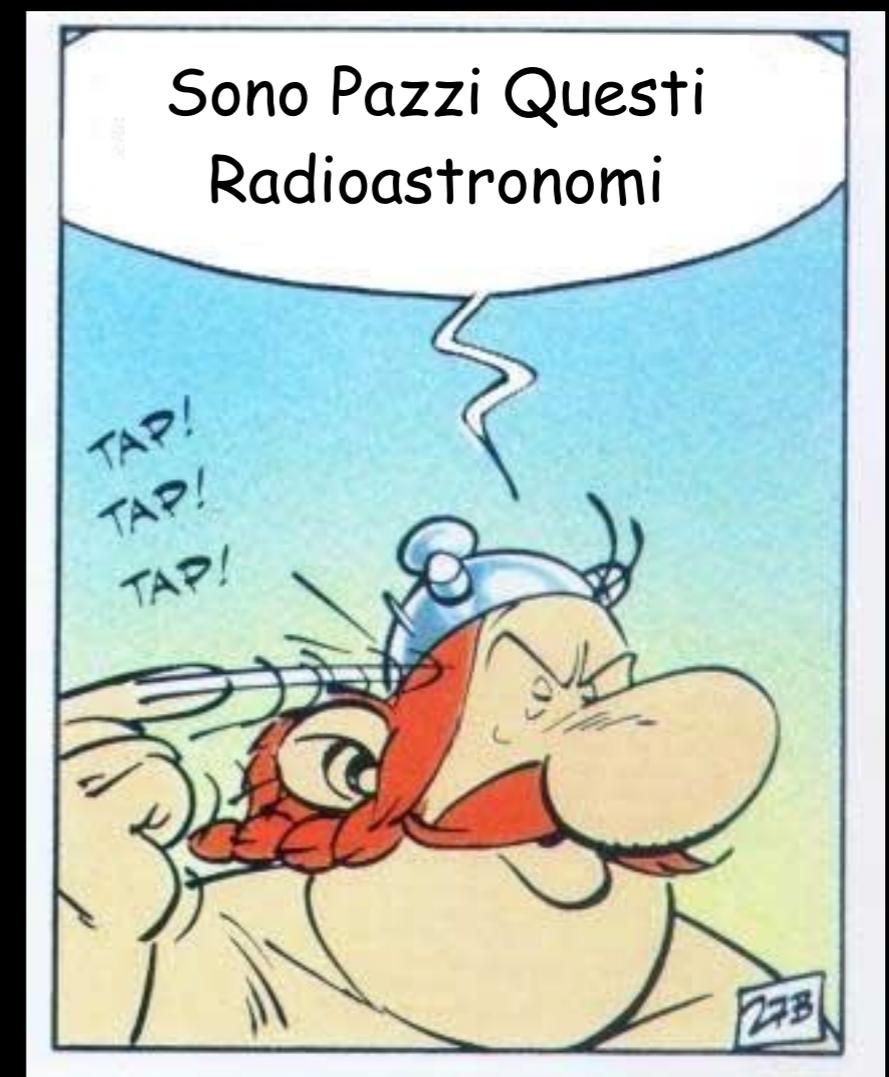
Ma torniamo a Penzias e Wilson

- Nel 1960 la NASA lancia il satellite per telecomunicazioni ECHO
- I Bell-Lab costruiscono l'ormai famosa antenna di Holmdel (NJ) per testare il principio di funzionamento di ECHO



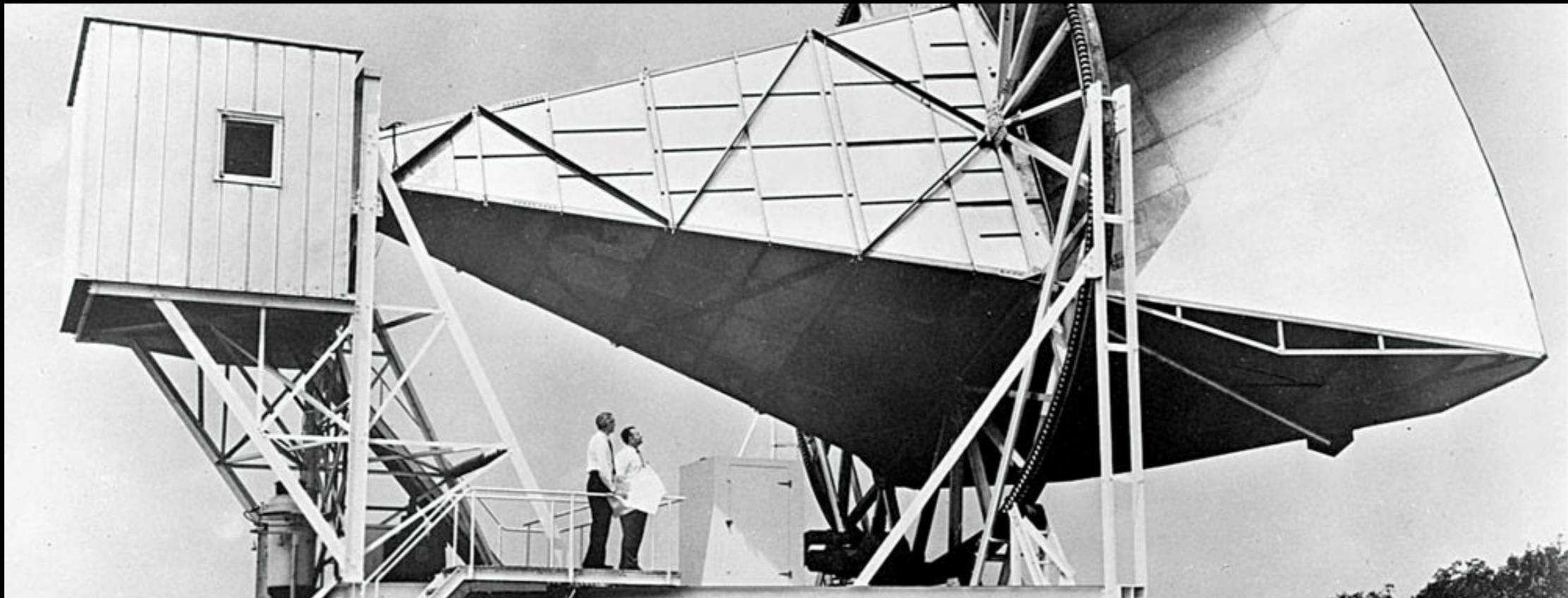
- **1961** Ed Ohm, ingegnere dei Bell Labs, nel calibrare l'antenna di Holmdel riporta un eccesso di segnale pari a 3.3K che attribuisce all'antenna anziché al cielo
- Due cosmologi sovietici, Doroshkevich e Novikov, notano nel **1964** il lavoro di Ohm ma considerano il segnale visto come proveniente dall'atmosfera terrestre

Ancora una volta gli scienziati
si fanno sfuggire la Primula Rossa...



Nel **1964** Arno Penzias e Robert Wilson iniziano una campagna osservativa con l'antenna di Holmdel riscontrando lo stesso eccesso di segnale trovato da Ohm e proveniente apparentemente da TUTTO IL CIELO:

Che davvero si generi all'interno dell'antenna?



- Danno perciò il via a quella che 35 anni dopo si chiamerà **COSMOLOGIA DI PRECISIONE**



Contemporaneamente il gruppo di Dicke stava iniziando le misure...



"Well boys, we've been scooped!"

of the first four interlopers, provided the initial clue to the existence of radio-quiet, blue, quasi-stellar galaxies (QSG) whose optical properties are similar to those of QSS's (Sandage 1965).

Spectrograms were subsequently obtained for BSO 1, BSO 8, and BSO 16 by Schmidt and by Sandage in an attempt to verify the existence of QSG. The spectrum of BSO 16 shows that this object is a hot star having the Balmer lines in absorption near their rest wavelengths. This was expected on the basis of the non-peculiar $U - B$, $B - V$ colors. The spectrum of BSO 8 (called "BSO 105" by Sandage 1965 on an older numbering system) is continuous with no prominent absorption or emission lines. BSO 1 has a large redshift of $\Delta\lambda/\lambda_0 = 1.2410$, as described elsewhere (Sandage 1965).

Table 1 lists the precise optical positions of the first four interlopers, and estimated positions, accurate to perhaps $\pm 20''$, for the thirty-one survey objects. Where available, the colors and magnitudes determined photoelectrically at the 200-inch are also shown.

These blue objects are undoubtedly of the same class as the faint objects in the catalogues of Iriarte and Chavira (1957), Chavira (1958), and Haro and Luyten (1962). With the identification of most of these objects as intrinsically bright stellar-appearing galaxies, these catalogues provide a large finding list that can be surveyed by radio techniques to determine if the QSG's are weak radio emitters. It is expected that such study will shed light on the evolutionary process of radio decay after the intense QSS radio phase.

ALLAN SANDAGE
PHILIPPE VÉRON

May 21, 1965

MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

REFERENCES

- Chavira, E. 1958, *Bull. Obs. Ton*, No. 17, p. 15.
Haro, G., and Luyten, W. J. 1962, *Bull. Obs. Ton*, No. 22, p. 1.
Iriarte, B., and Chavira, E. 1957, *Bull. Obs. Ton.*, No. 16, p. 3.
Ryle, M., and Sandage, A. 1964, *Ap. J.*, **139**, 419.
Sandage, A. 1965, *Ap. J.*, **141** (in press).

COSMIC BLACK-BODY RADIATION*

One of the basic problems of cosmology is the singularity characteristic of the familiar cosmological solutions of Einstein's field equations. Also puzzling is the presence of matter in excess over antimatter in the universe, for baryons and leptons are thought to be conserved. Thus, in the framework of conventional theory we cannot understand the origin of matter or of the universe. We can distinguish three main attempts to deal with these problems.

1. The assumption of continuous creation (Bondi and Gold 1948; Hoyle 1948), which avoids the singularity by postulating a universe expanding for all time and a continuous but slow creation of new matter in the universe.
2. The assumption (Wheeler 1964) that the creation of new matter is intimately related to the existence of the singularity, and that the resolution of both paradoxes may be found in a proper quantum mechanical treatment of Einstein's field equations.
3. The assumption that the singularity results from a mathematical over-idealization,

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high pressure, such as the zero-mass scalar, capable of speeding the universe through the period of helium formation. To have a closed space, an energy density of 2×10^{-29} gm/cm³ is needed. Without a zero-mass scalar, or some other "hard" interaction, the energy could not be in the form of ordinary matter and may be presumed to be gravitational radiation (Wheeler 1958).

One other possibility for closing the universe, with matter providing the energy content of the universe, is the assumption that the universe contains a net electron-type neutrino abundance (in excess of antineutrinos) greatly larger than the nucleon abundance. In this case, if the neutrino abundance were so great that these neutrinos are degenerate, the degeneracy would have forced a negligible equilibrium neutron abundance in the early, highly contracted universe, thus removing the possibility of nuclear reactions leading to helium formation. However, the required ratio of lepton to baryon number must be $> 10^9$.

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. DICKE
P. J. E. PEEBLES
P. G. ROLL
D. T. WILKINSON

May 7, 1965

PALMER PHYSICAL LABORATORY
PRINCETON, NEW JERSEY

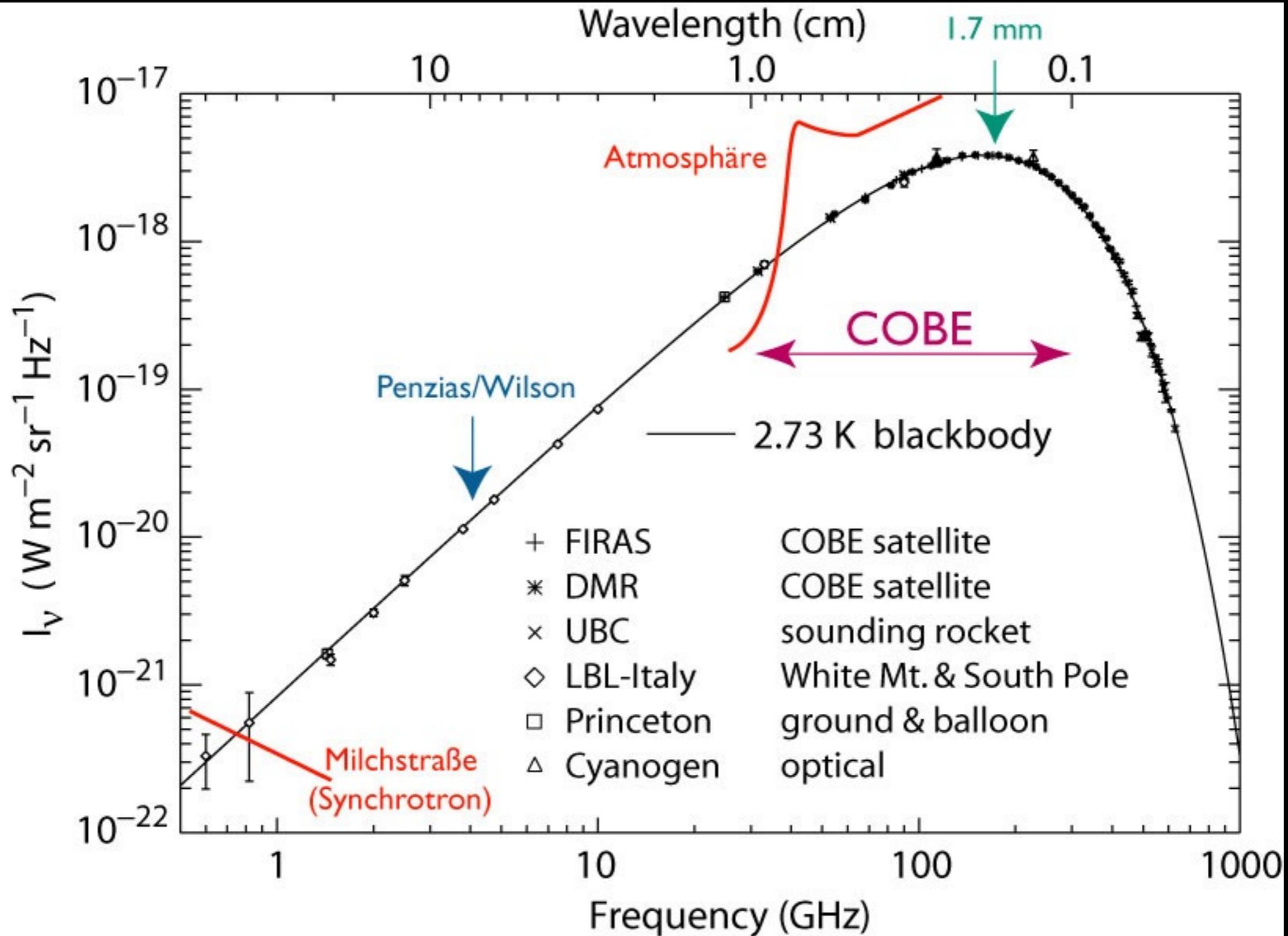
REFERENCES

- Alpher, R. A., Bethe, H. A., and Gamow, G. 1948, *Phys. Rev.*, **73**, 803.
Alpher, R. A., Follin, J. W., and Herman, R. C. 1953, *Phys. Rev.*, **92**, 1347.
Bondi, H., and Gold, T. 1948, *M. N.*, **108**, 252.
Brans, C., and Dicke, R. H. 1961, *Phys. Rev.*, **124**, 925.
Dicke, R. H. 1962, *Phys. Rev.*, **125**, 2163.
Dicke, R. H., Berlinger, R., Kyhl, R. L., and Vane, A. B. 1946, *Phys. Rev.*, **70**, 340.
Einstein, A., 1950, *The Meaning of Relativity* (3d ed.; Princeton, N.J.: Princeton University Press), p. 107.
Hoyle, F. 1948, *M. N.*, **108**, 372.
Hoyle, F., and Tayler, R. J. 1964, *Nature*, **203**, 1108.
Liftshitz, E. M., and Khalatnikov, I. M. 1963, *Adv. in Phys.*, **12**, 185.
Oort, J. H. 1958, *La Structure et l'évolution de l'univers* (11th Solvay Conf. [Brussels: Éditions Stoops]), p. 163.
Peebles, P. J. E. 1965, *Phys. Rev.* (in press).
Penzias, A. A., and Wilson, R. W. 1965, private communication.
Wheeler, J. A., 1958, *La Structure et l'évolution de l'univers* (11th Solvay Conf. [Brussels: Éditions Stoops]), p. 112.
——— 1964, in *Relativity, Groups and Topology*, ed. C. DeWitt and B. DeWitt (New York: Gordon & Breach).
Zel'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, **14**, 1143.

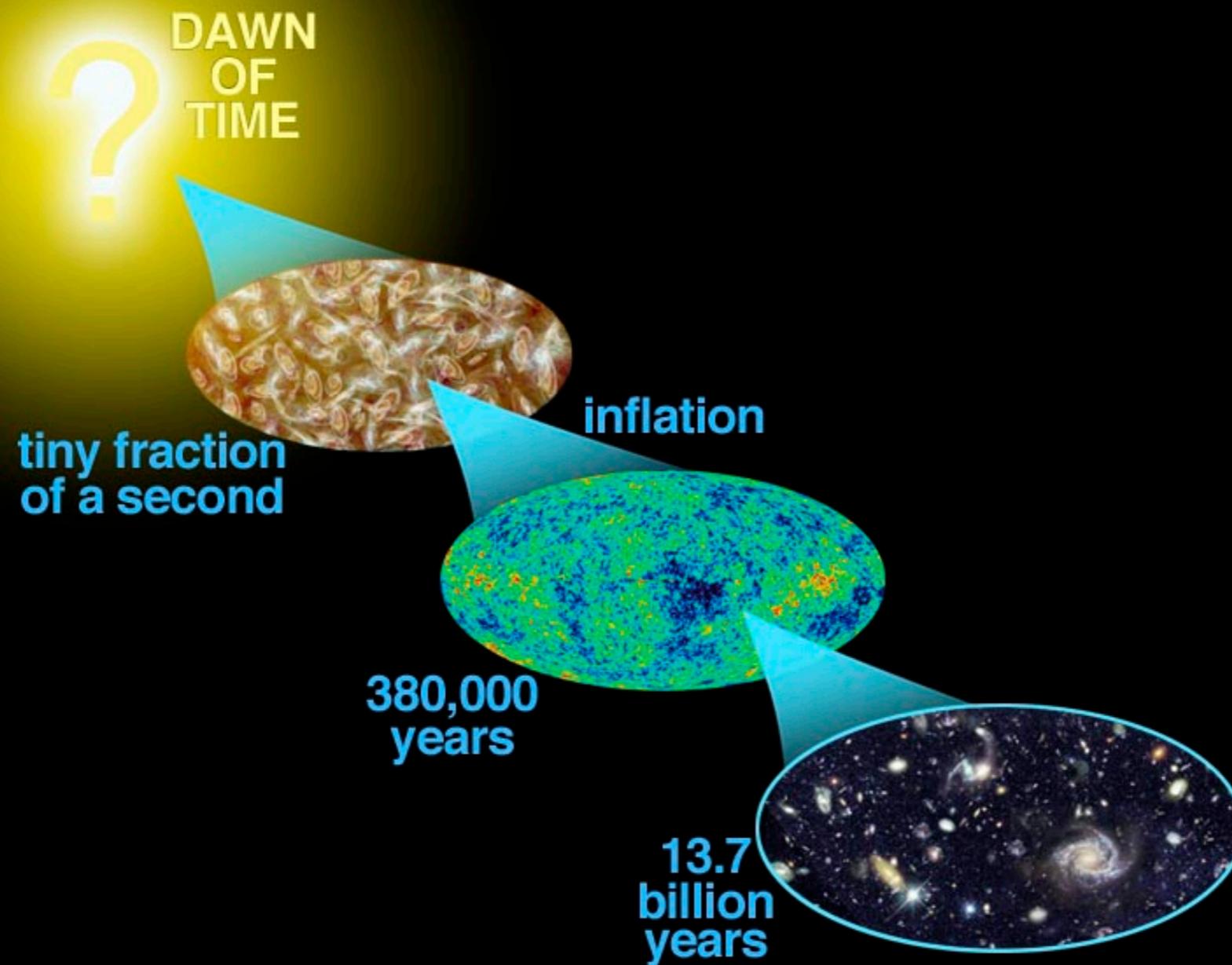
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

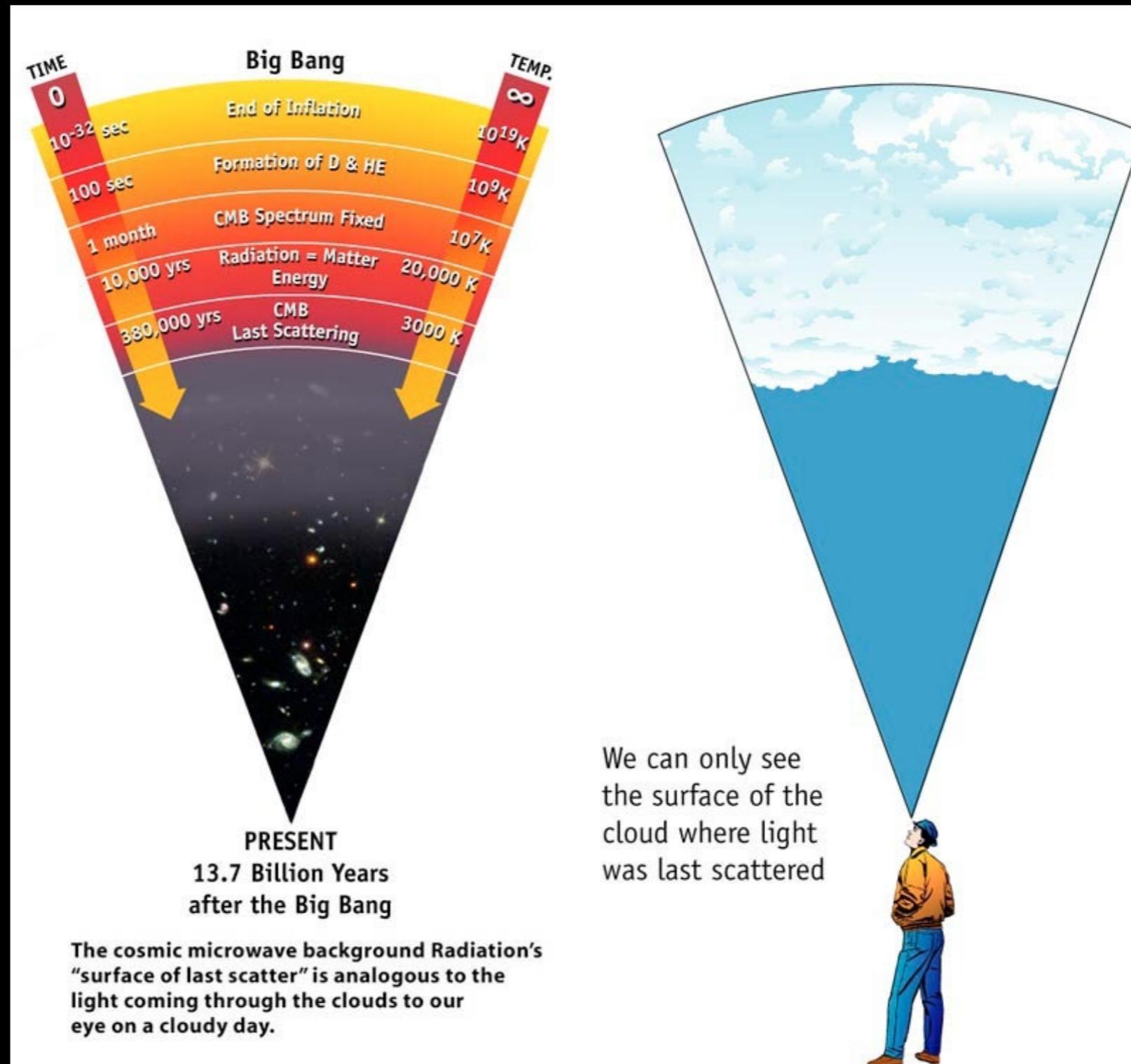
Spettro in frequenza



La CMB è un'istantanea dell'Universo 380000 anni dopo il Big Bang



La CMB è un'istantanea dell'Universo 380000 anni dopo il Big Bang



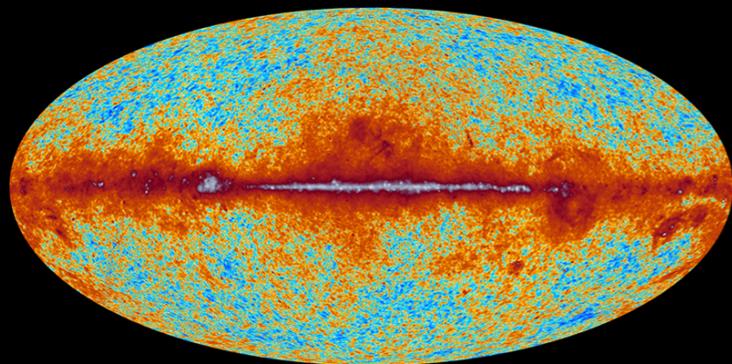
Anche se c'è modo di "vedere" ancora più indietro

In cielo però non c'è solo la CMB, anzi...

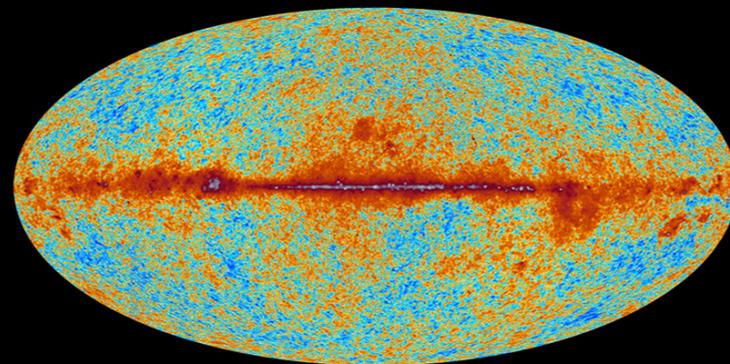


planck

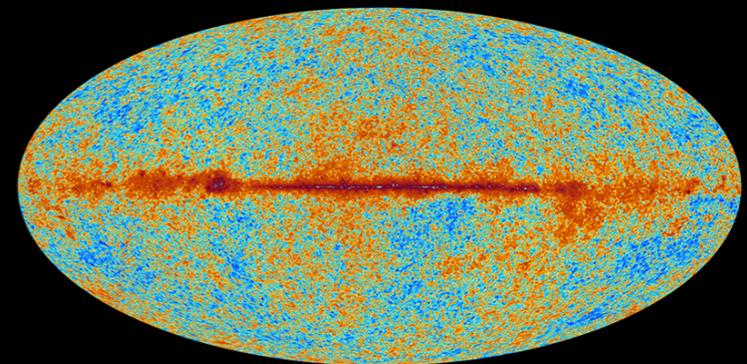
The sky as seen by Planck



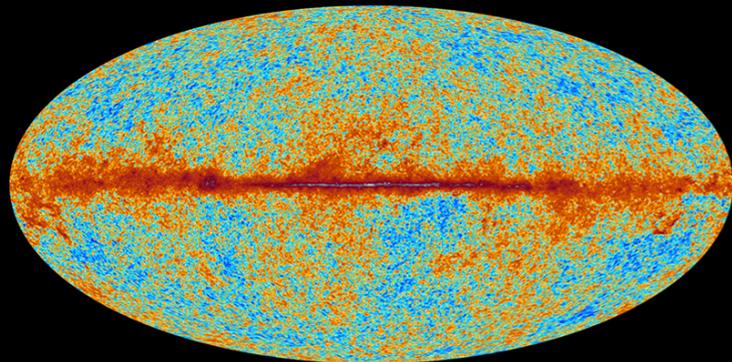
30 GHz



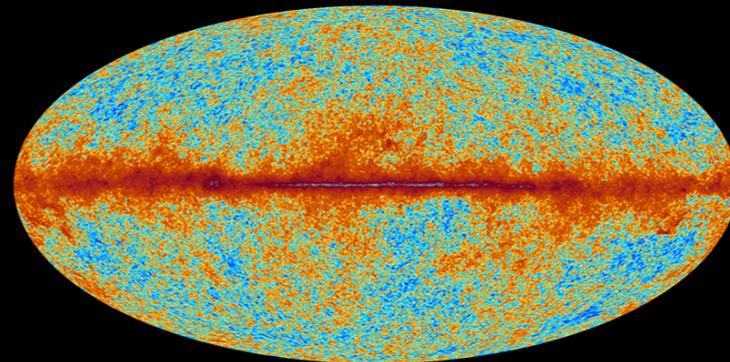
44 GHz



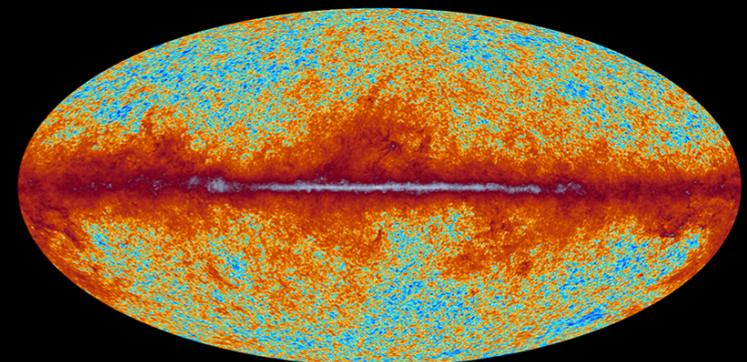
70 GHz



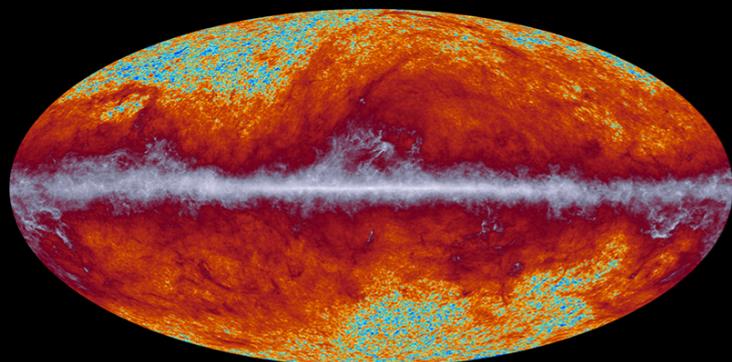
100 GHz



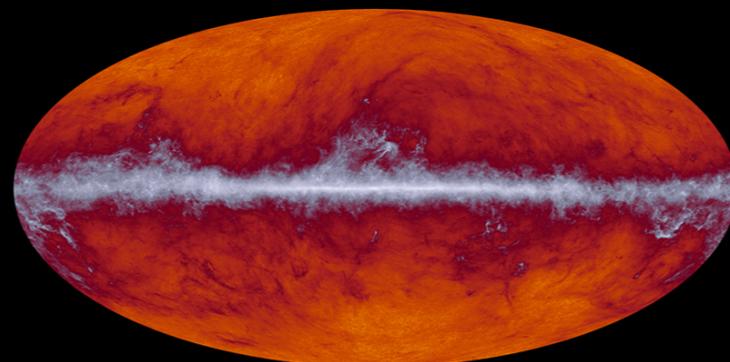
143 GHz



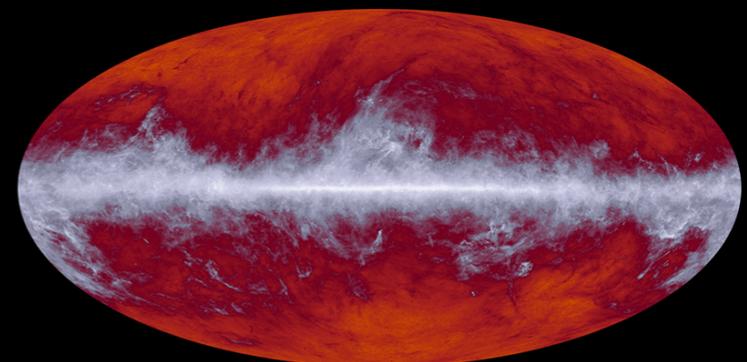
217 GHz



353 GHz



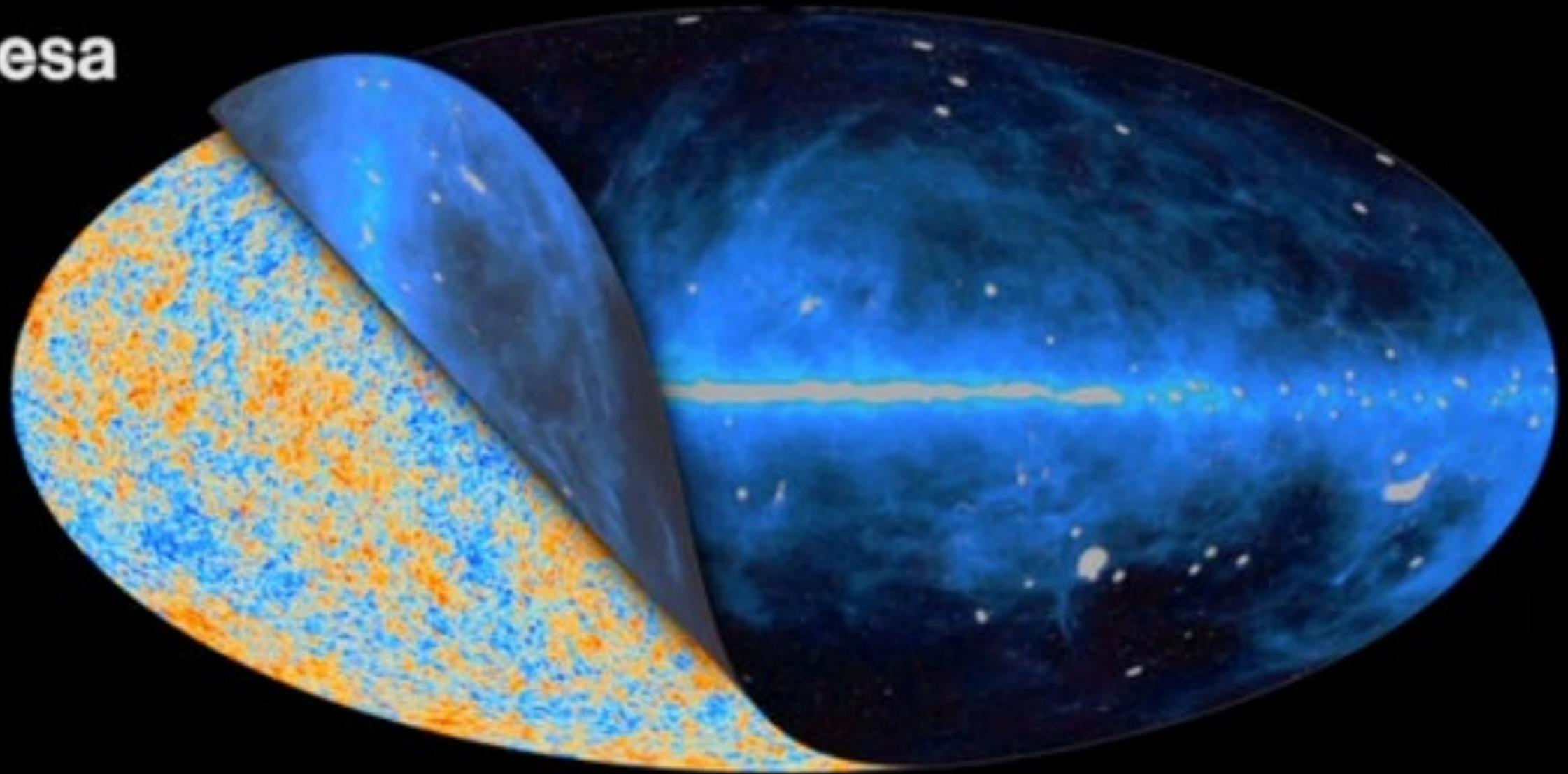
545 GHz



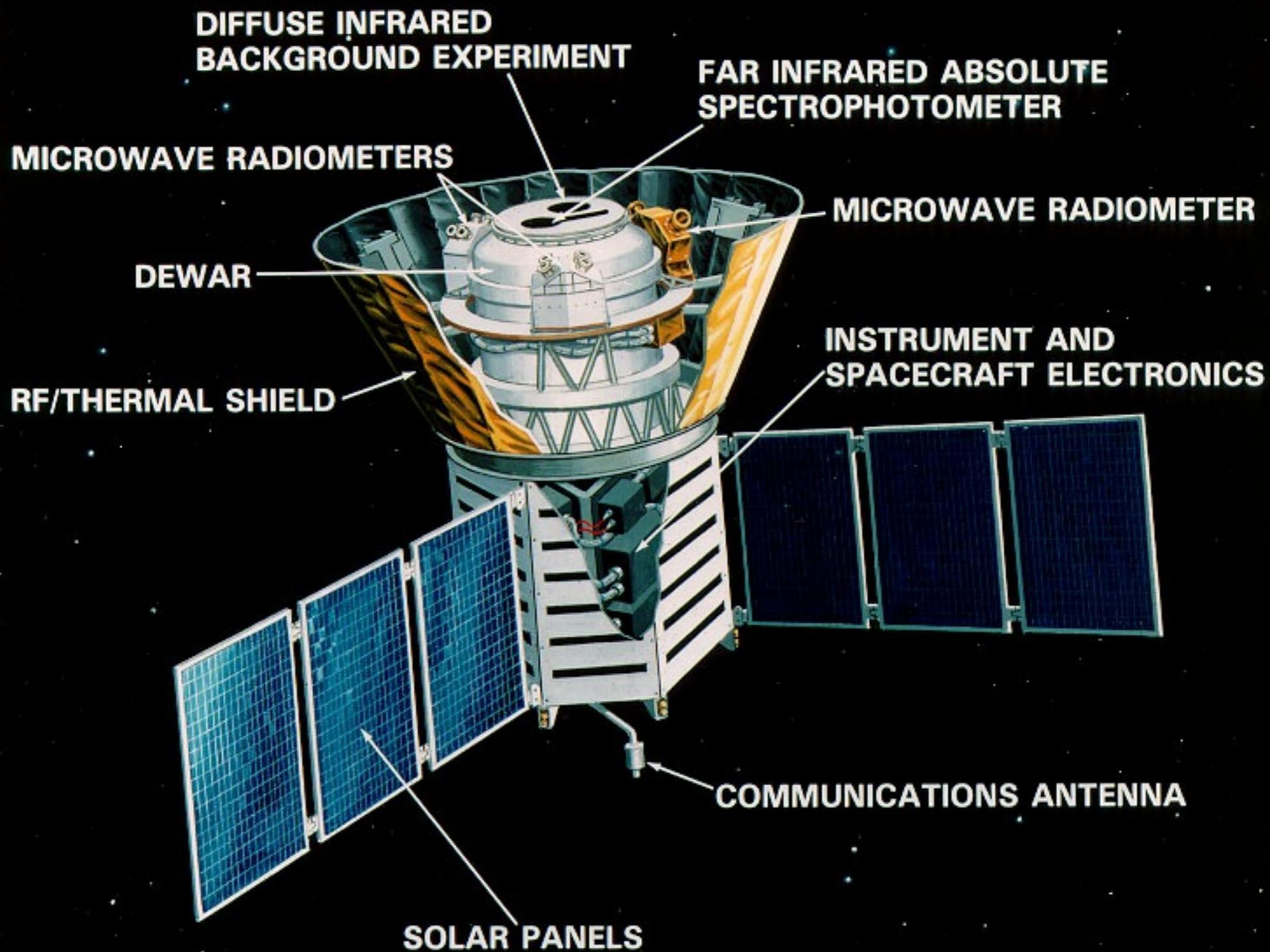
857 GHz

In cielo però non c'è solo la CMB, anzi...

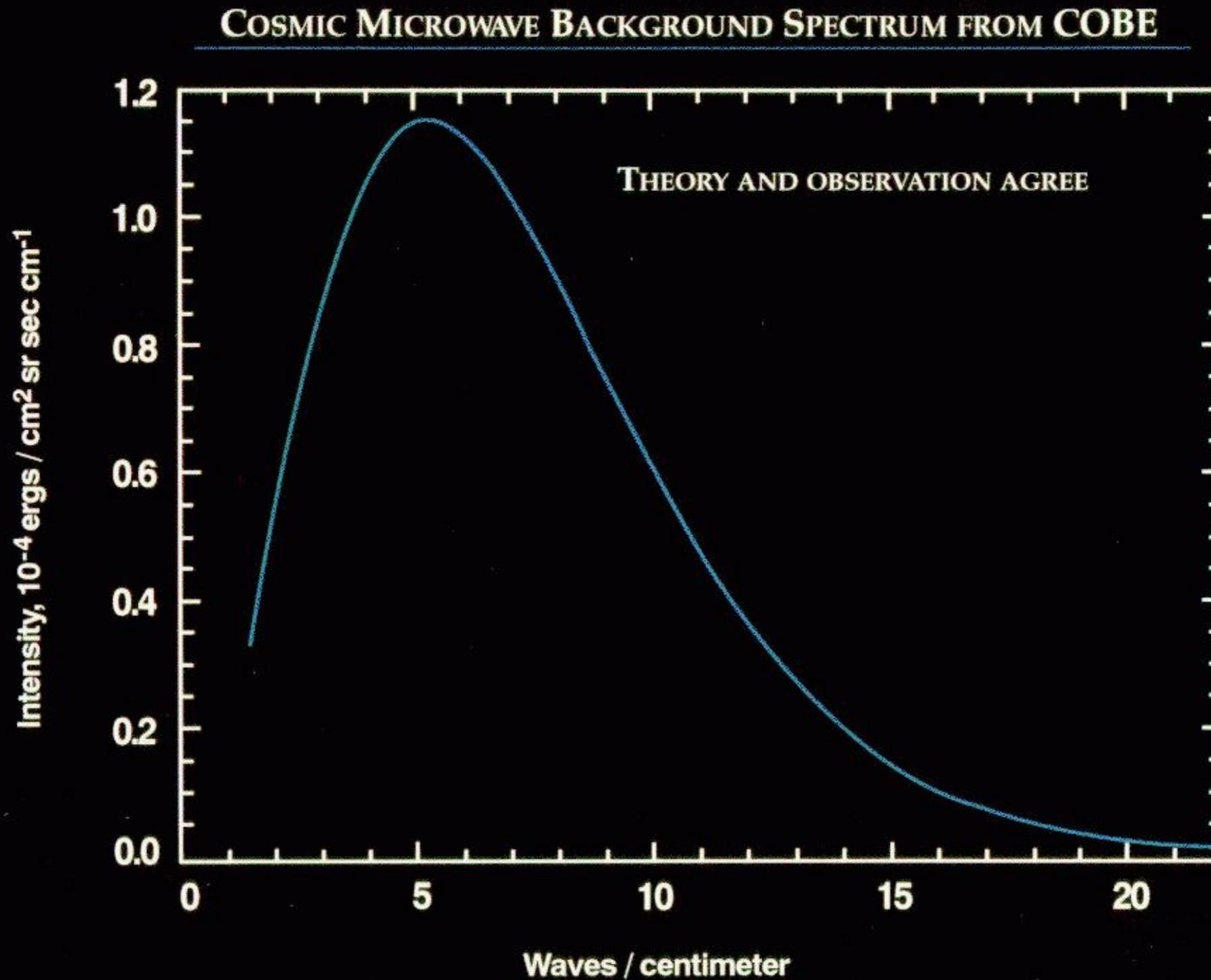
esa



Gli anni di COsmic Background Explorer (1989-1993)



Gli anni di COsmic Background Explorer (1989-1993)



Più preciso spettro di corpo nero mai misurato (Premio Nobel!)

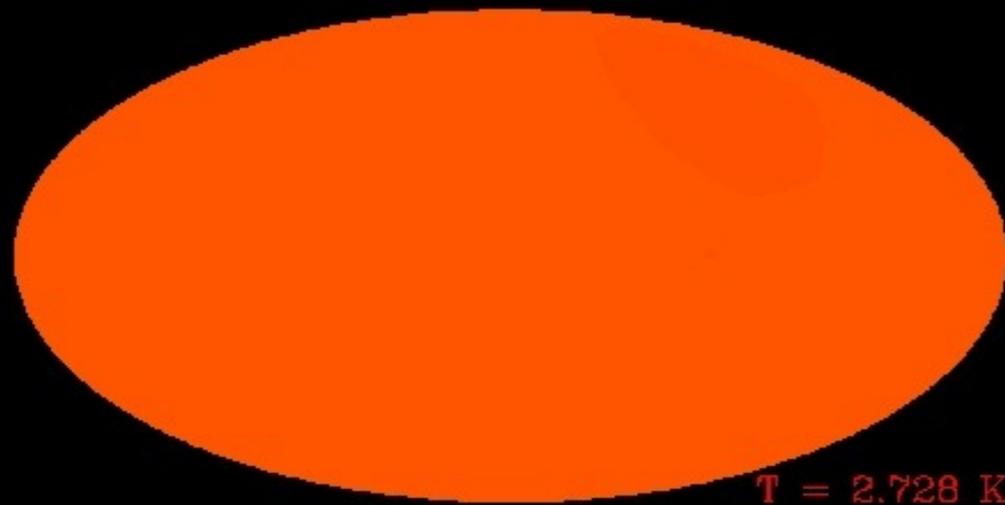
Gli anni di COsmic Background Explorer (1989-1993)

Se la CMB fosse esattamente un corpo nero uguale dappertutto, l'Universo sarebbe fatto di H ed He freddi ed uniformemente distribuiti. Per fortuna non è così!



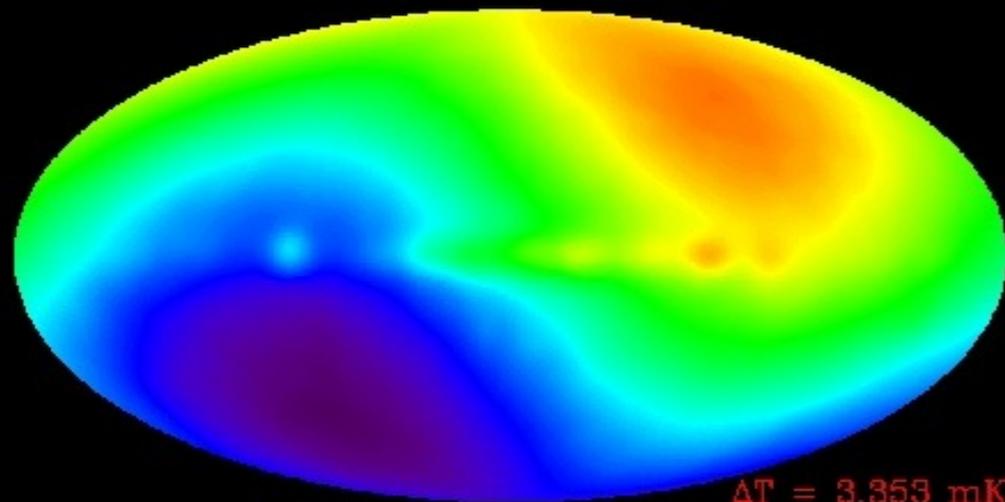
Gli anni di COsmic Background Explorer (1989-1993)

Se guardiamo il cielo a 53 GHz con una sensibilità di



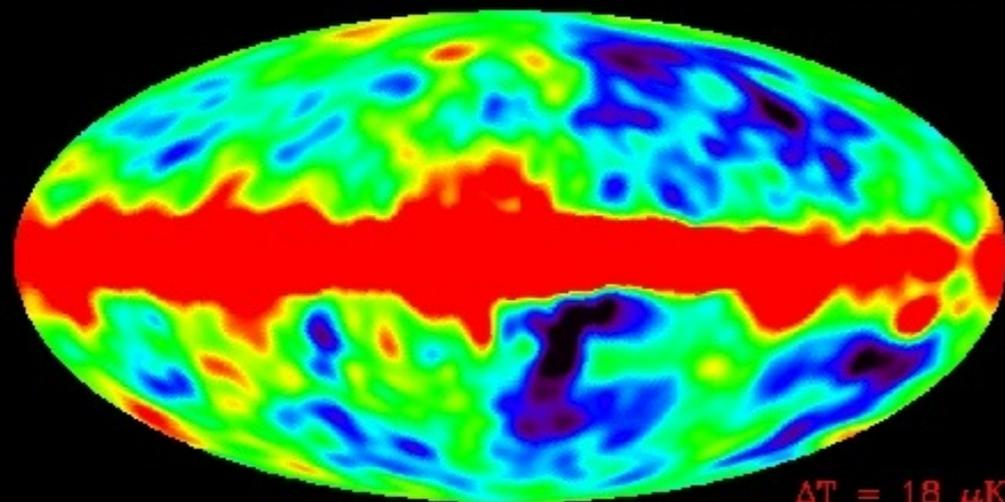
$T = 2.728 \text{ K}$

100mK



$\Delta T = 3.353 \text{ mK}$

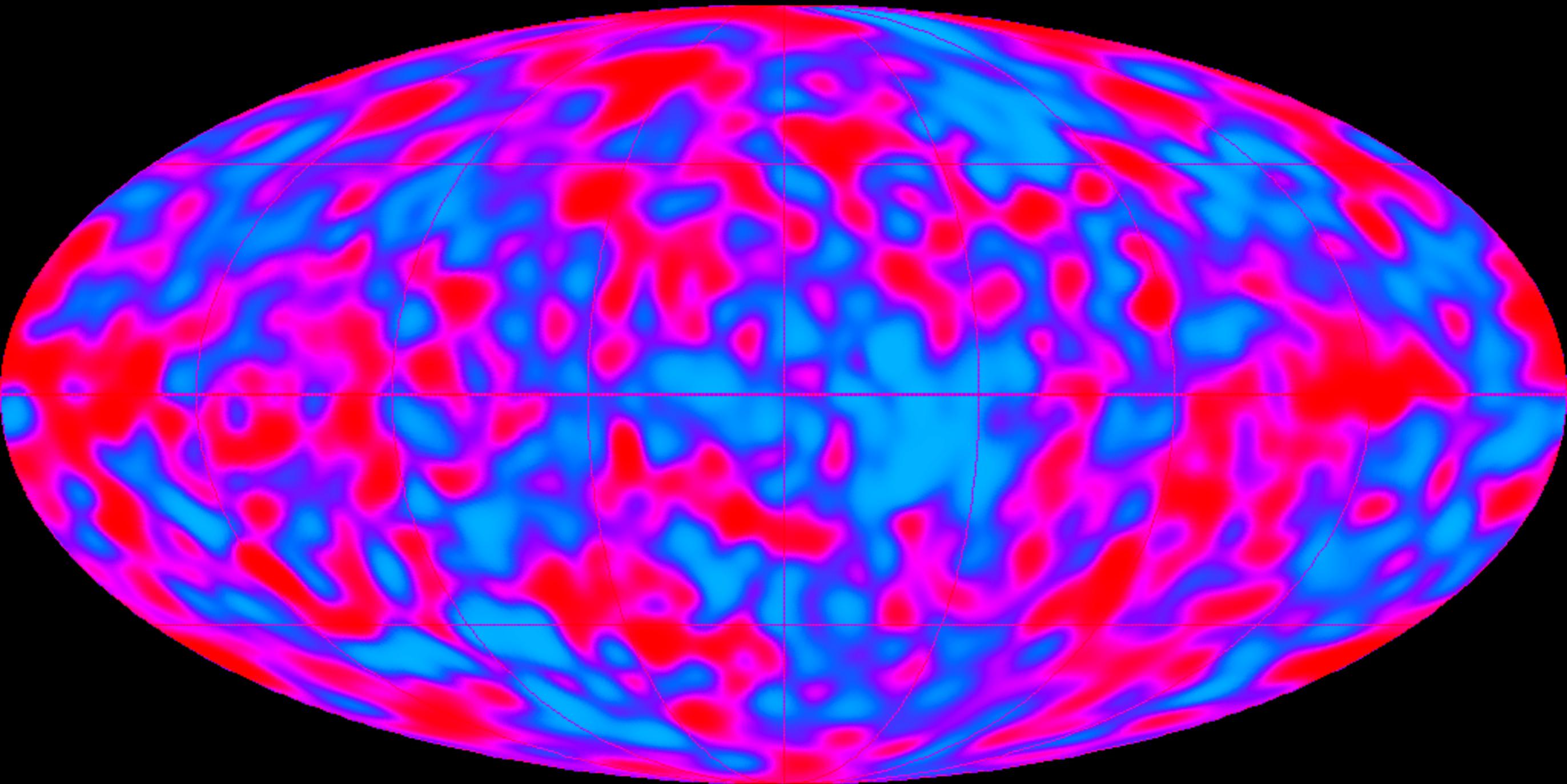
100 μ K



$\Delta T = 18 \mu\text{K}$

10 μ K

Gli anni di COsmic Background Explorer (1989-1993)



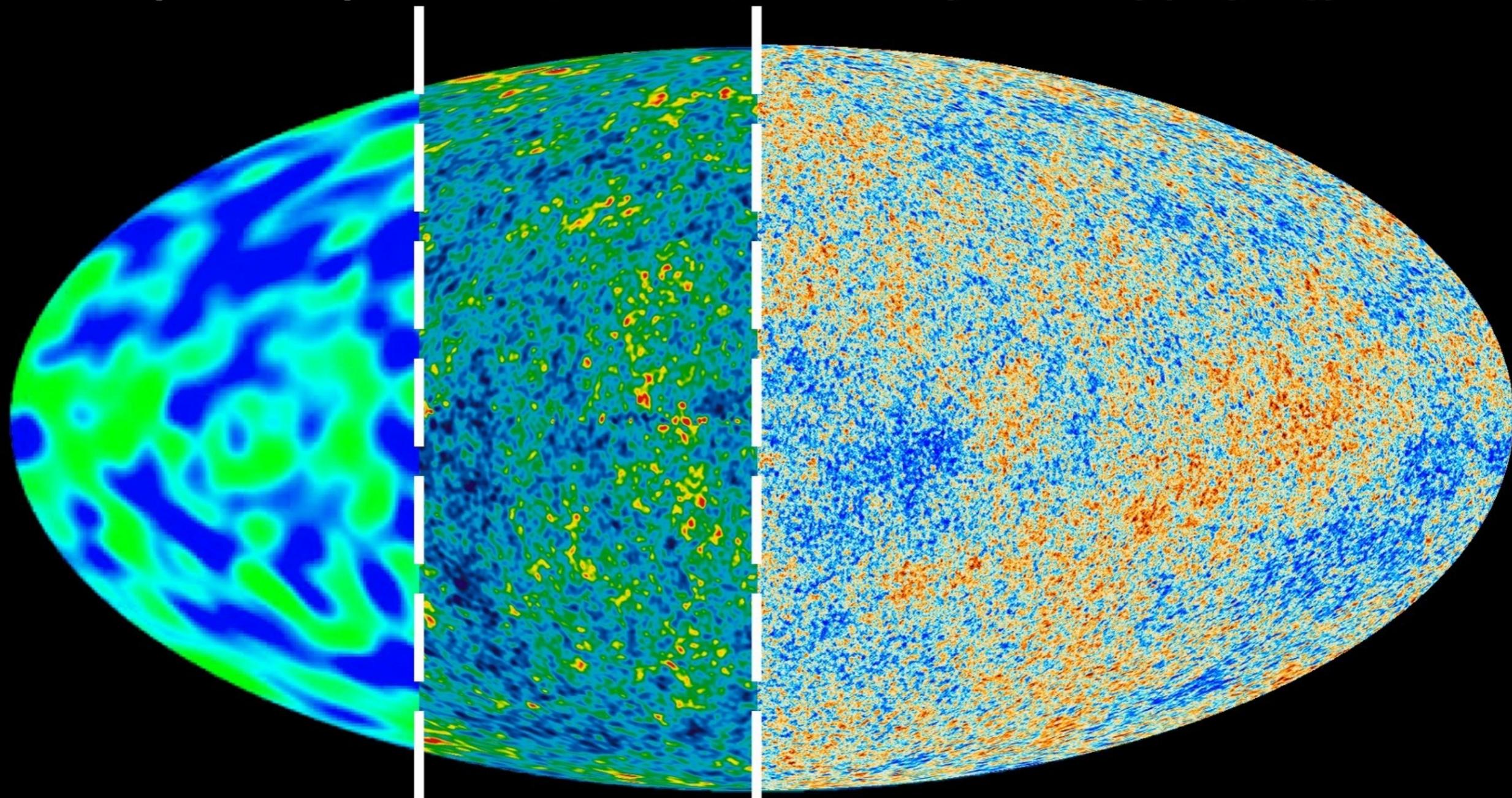
Prima "mappa" delle anisotropie della CMB (premio Nobel!)

I satelliti WMAP e PLANCK

COBE (1989-1993)

WMAP (2003-2012)

Planck (2009-2013) (ongoing)



7°

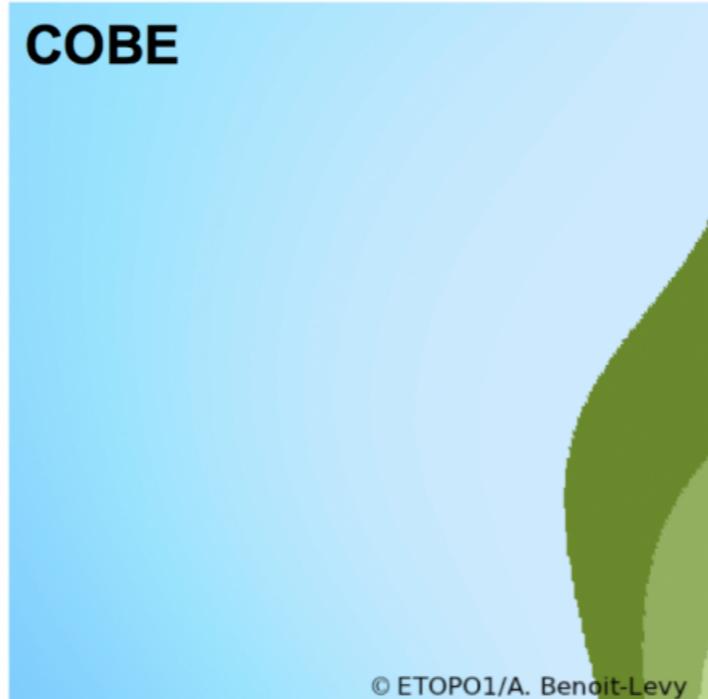
$14'$

$5'$

Anisotropia della CMB

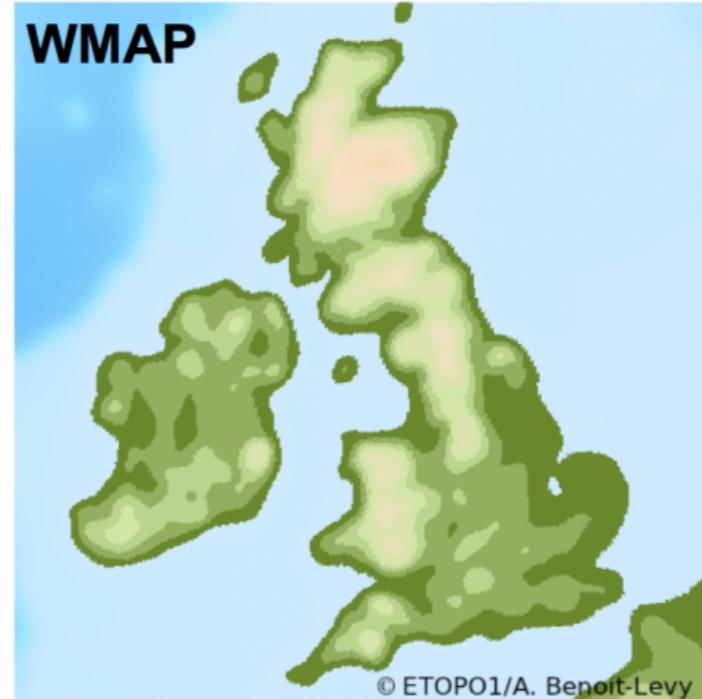
Resolution = 7.00 degrees

COBE



Resolution = 14.00 arcminutes

WMAP



Resolution = 5.00 arcminutes

Planck



Full resolution



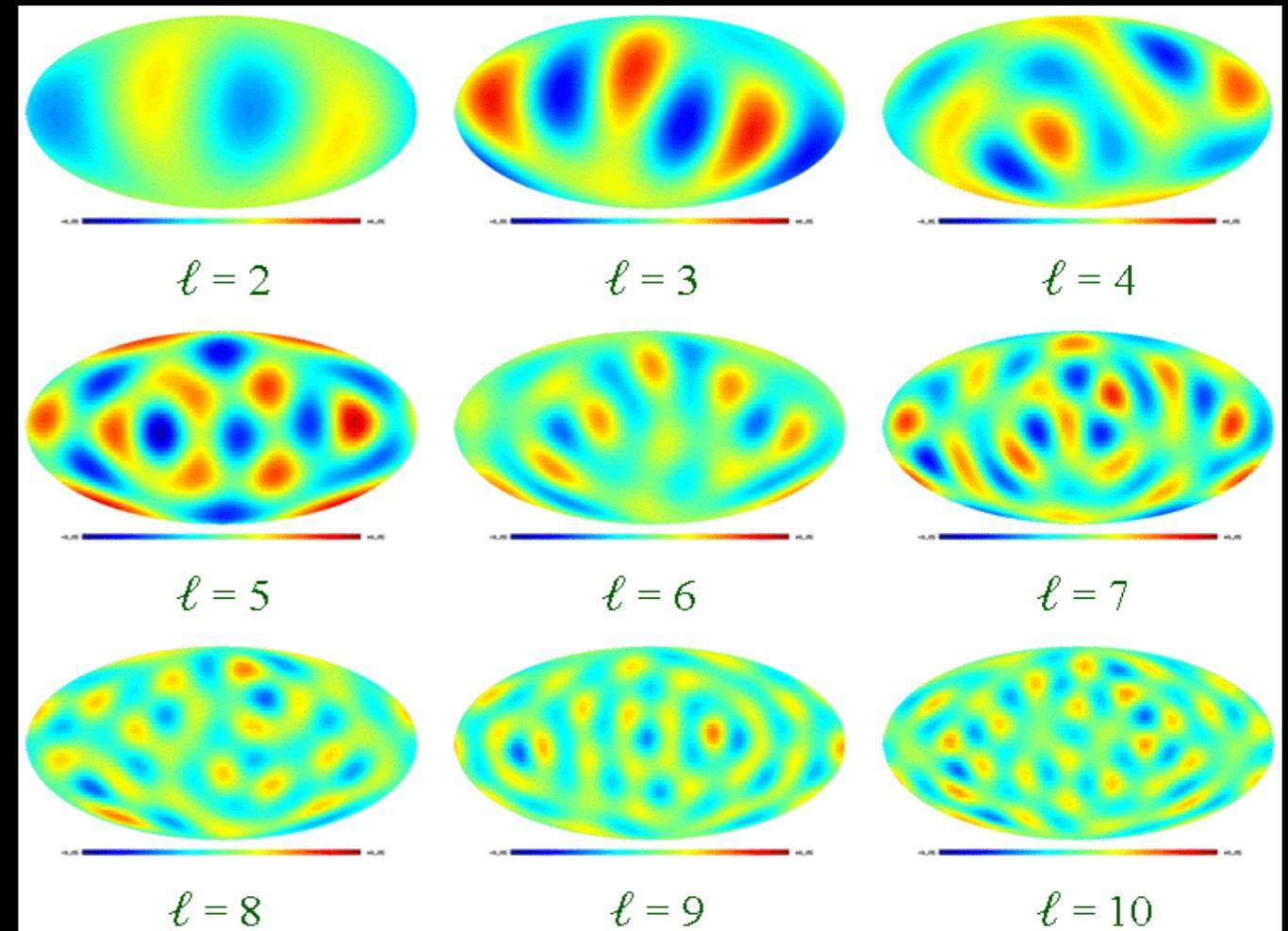
Anisotropia della CMB

$$T(\alpha, \delta) = T_0 + \Delta T(\alpha, \delta)$$

$$\Delta T(\alpha, \delta) = \sum_{\ell, m} a_{\ell, m} Y_{\ell}^m(\alpha, \delta)$$

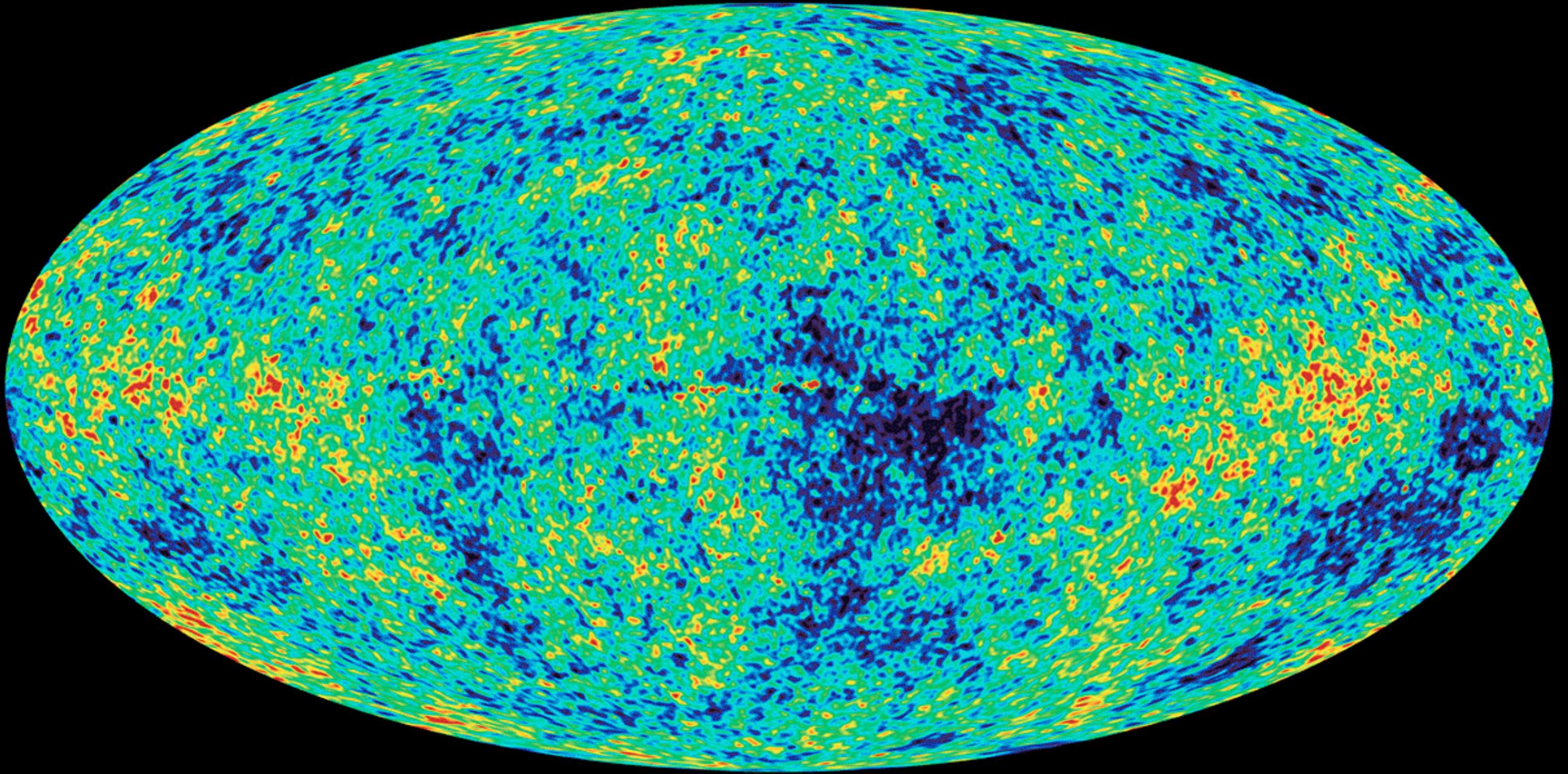
$$c_{\ell} = \left\langle |a_{\ell, m}|^2 \right\rangle$$

$$\theta = \frac{180^\circ}{\ell}$$

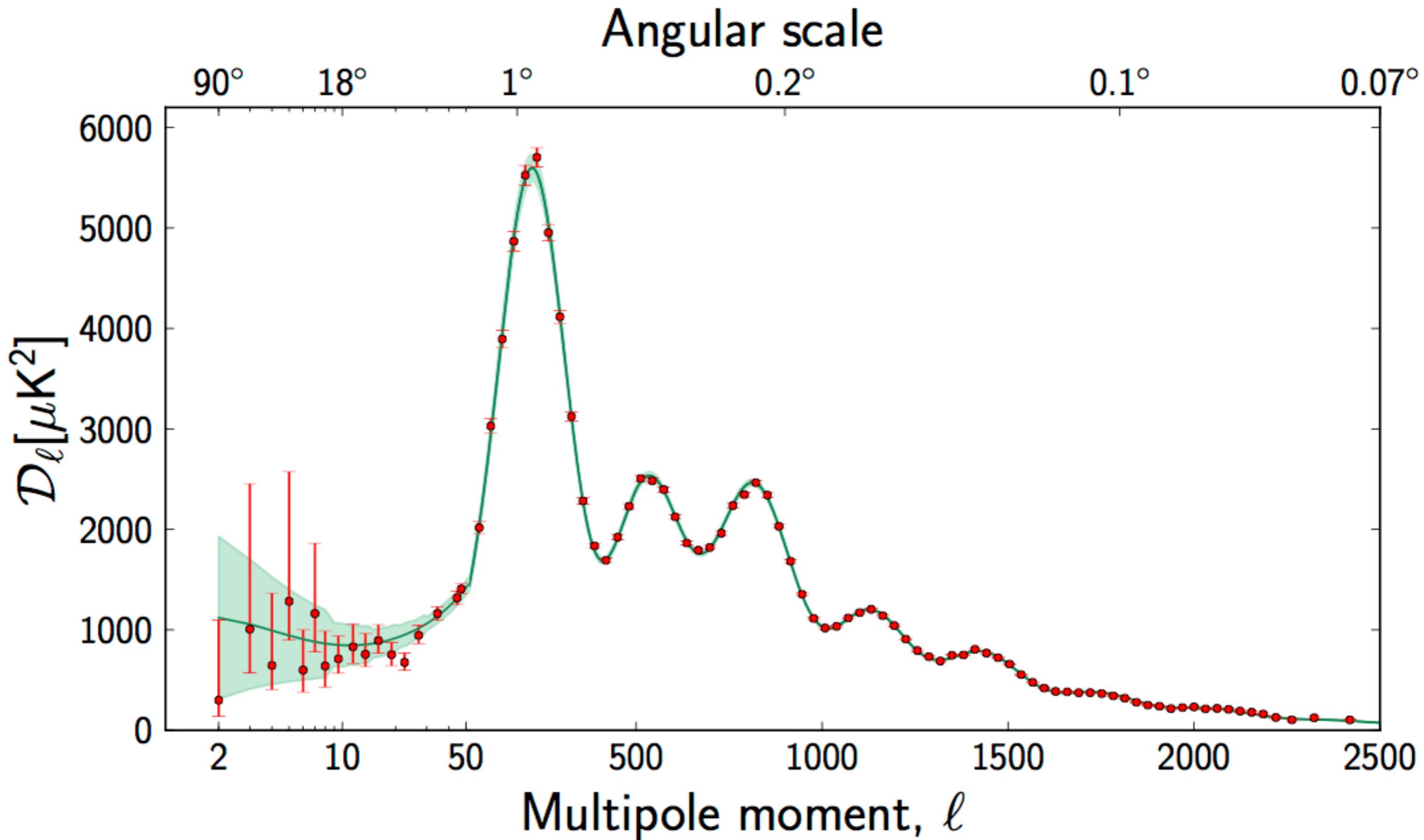


Sviluppo in armoniche sferiche

Anisotropia della CMB



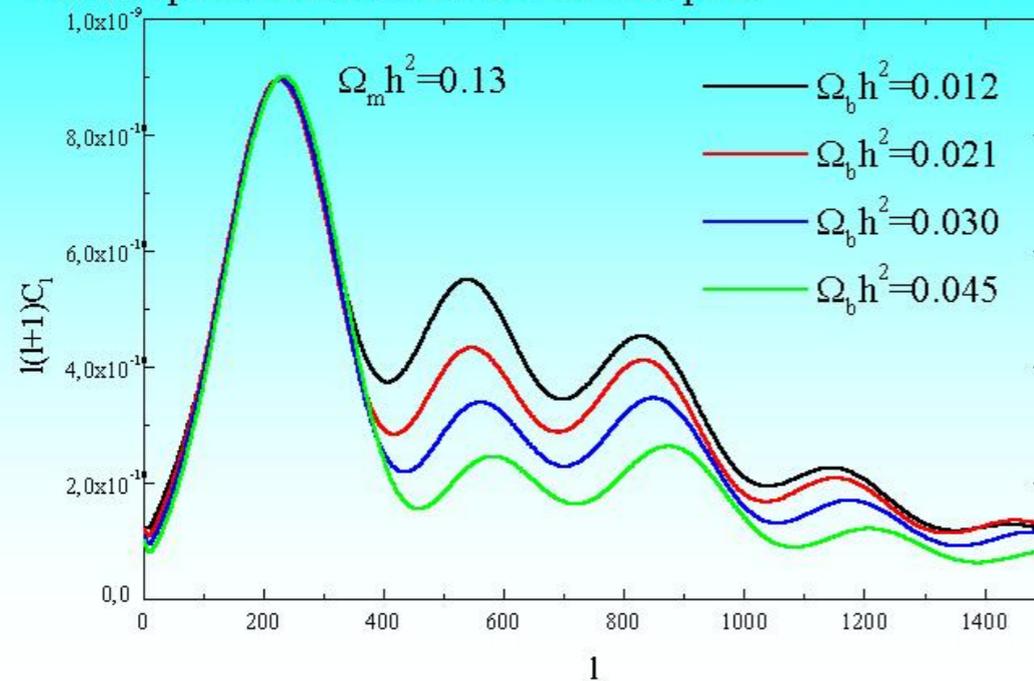
Anisotropy della CMB



Anisotropia della CMB e parametri cosmologici

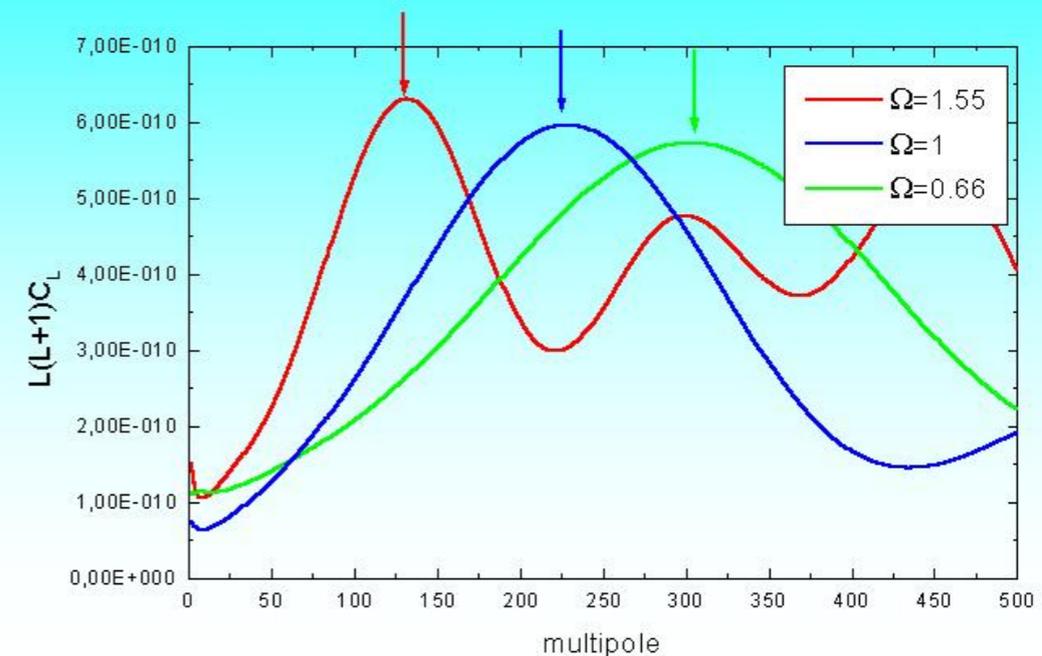
Examples

Dependance on Ω_b (Relative amplitudes second to first peak):
All the spectra are normalized to the first peak.



Examples

Dependance on Ω (curvature drives the location of first peak).
Not as simple as in these examples (see S.Weinberg, astro-ph/0006276)



Anisotropia della CMB e parametri cosmologici

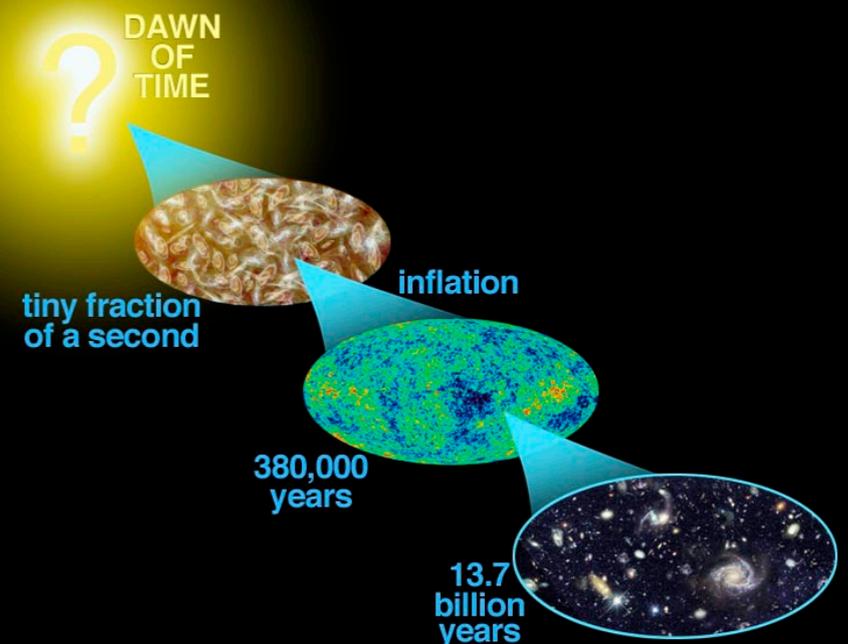
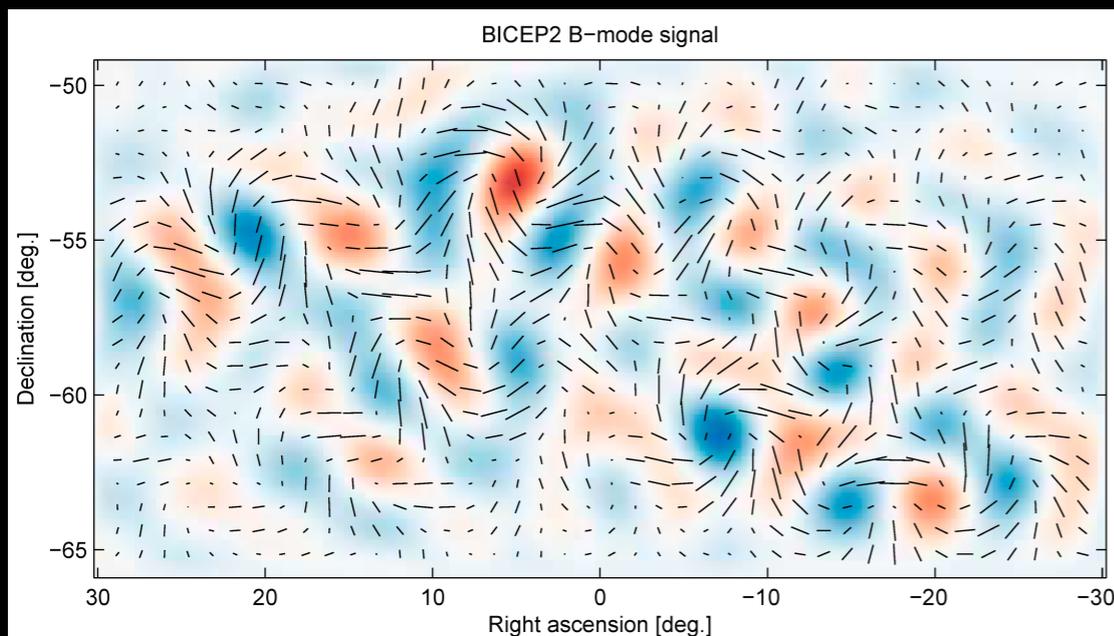
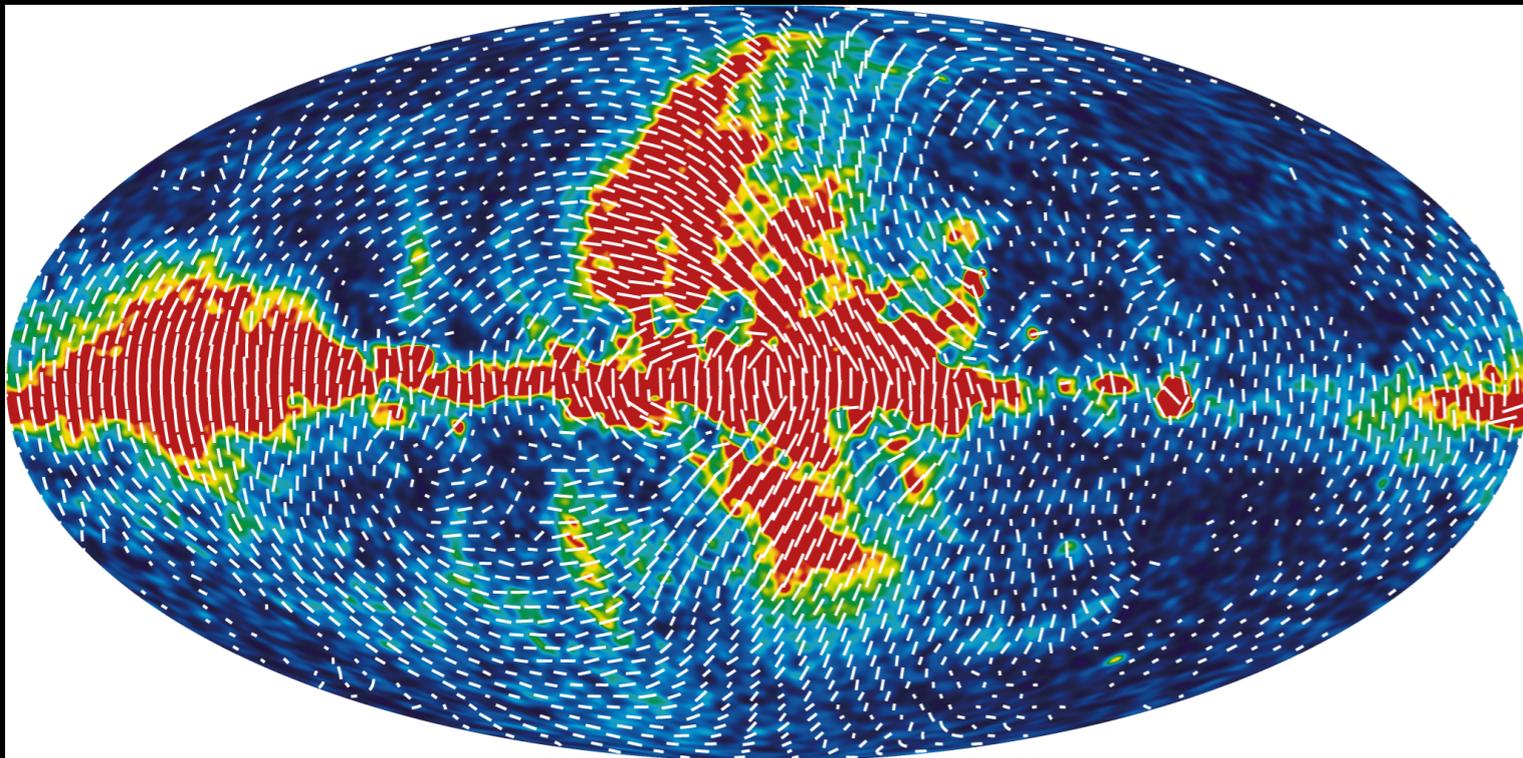
Parameter	<i>Planck</i>		<i>Planck+lensing</i>		<i>Planck+WP</i>	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_p	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

Table 2. Cosmological parameter values for the six-parameter base Λ CDM model. Columns 2 and 3 give results for the *Planck* temperature power spectrum data alone. Columns 4 and 5 combine the *Planck* temperature data with *Planck* lensing, and columns 6 and 7 include *WMAP* polarization at low multipoles. We give best fit parameters as well as 68% confidence limits for constrained parameters. The first six parameters have flat priors. The remainder are derived parameters as discussed in Sect. 2. Beam, calibration parameters, and foreground parameters (see Sect. 4) are not listed for brevity. Constraints on foreground parameters for *Planck*+WP are given later in Table 5.

Il futuro degli studi della CMB?

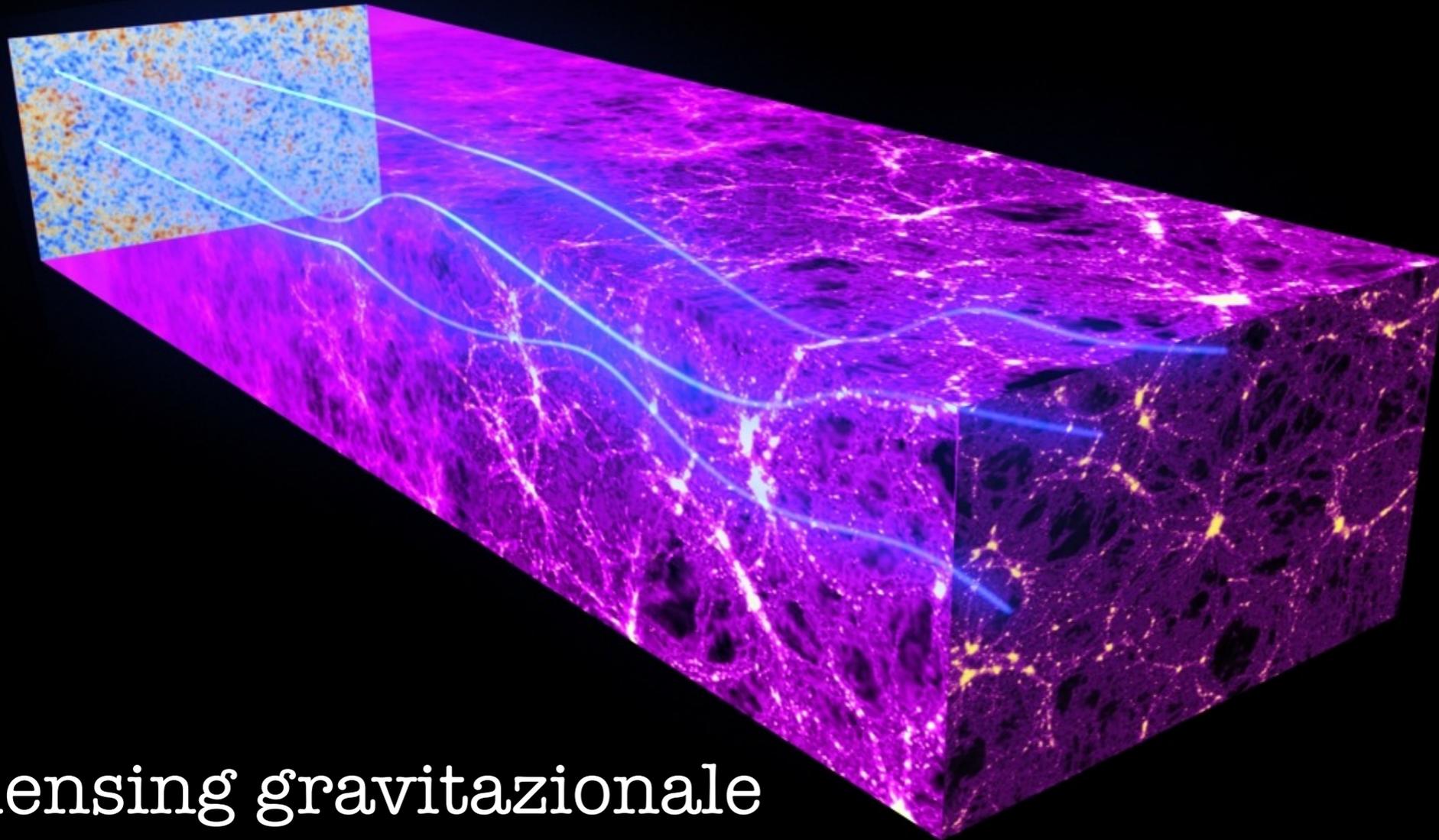
La Polarizzazione

I modi B sono direttamente riconducibili all'inflazione

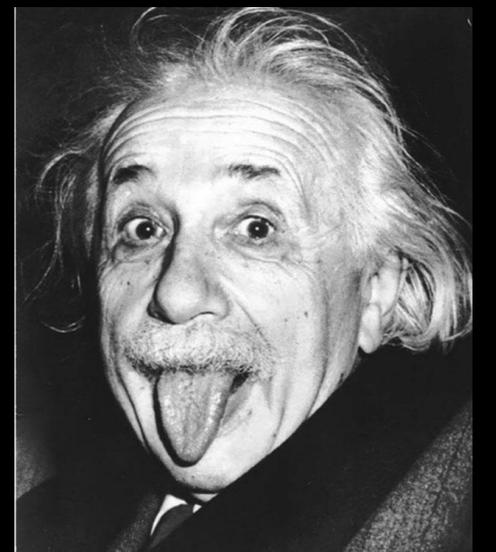


Il futuro degli studi della CMB?

La Polarizzazione



Il lensing gravitazionale
mima i modi B



La CMB, a più di 50 anni dalla sua scoperta
(e 13.8 miliardi dalla sua nascita)
è ancora giovane e attraente!

