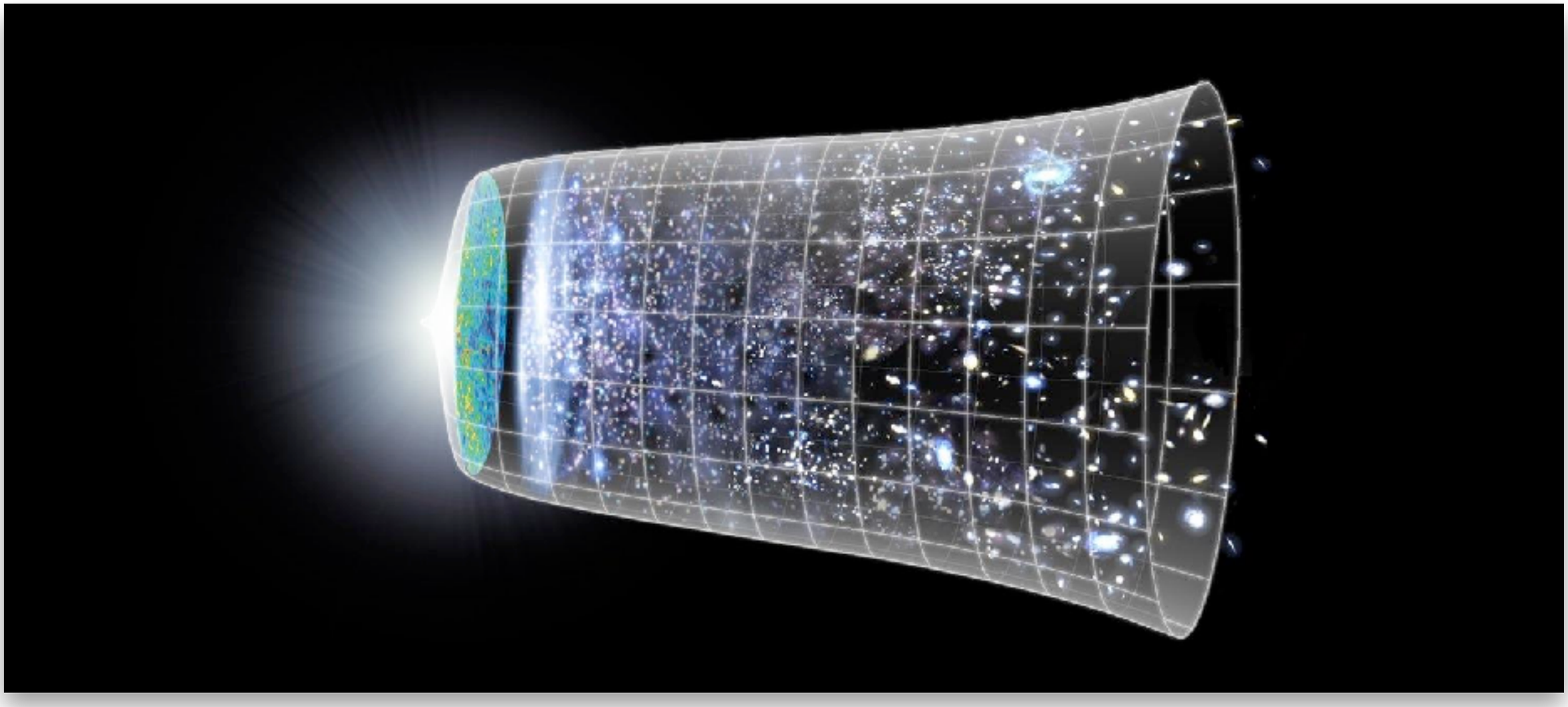


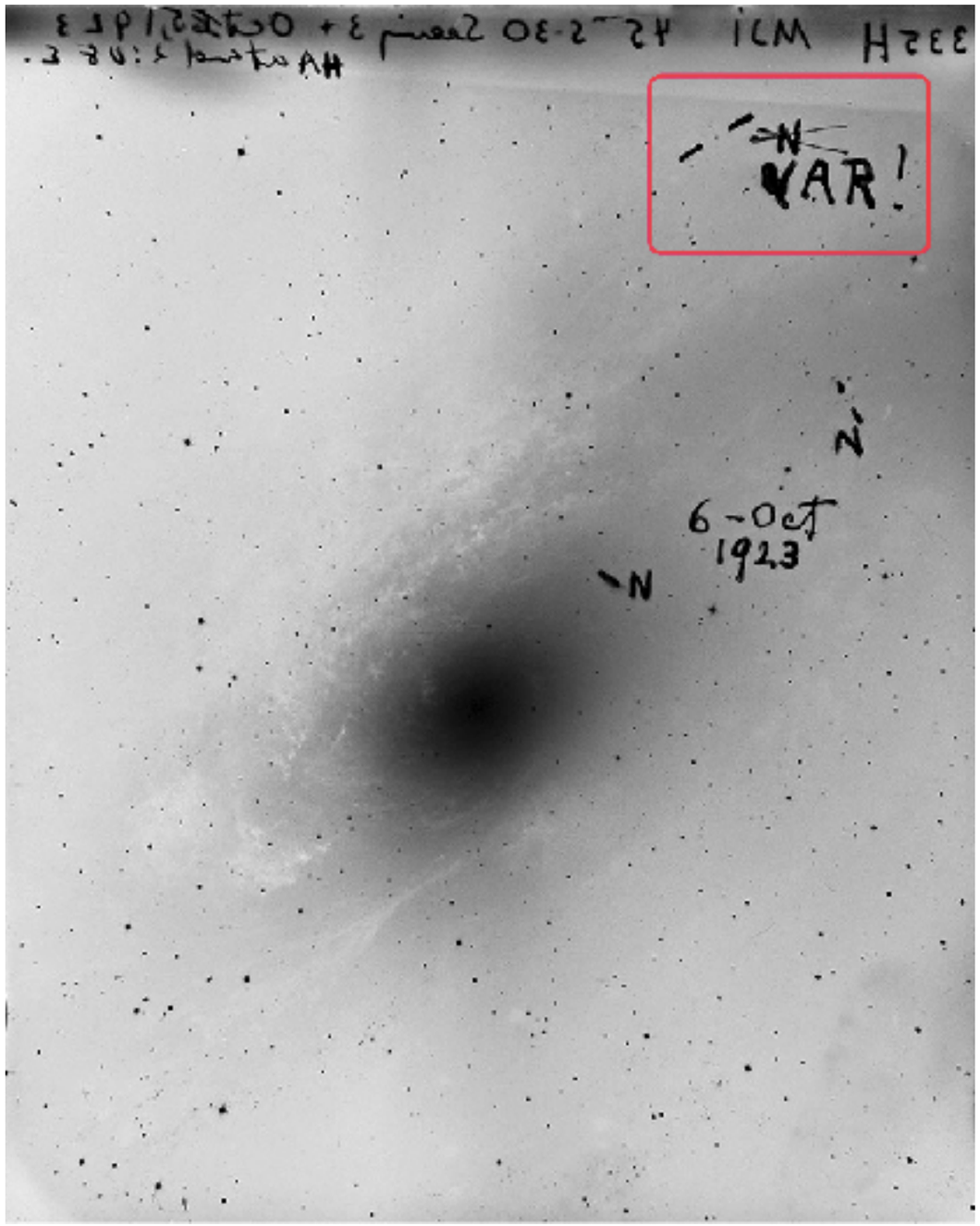
COSMOLOGÍA

Dr. Bernardo Cervantes Sodi

IRyA-UNAM

EDWIN HUBBLE (1923)

Henrietta Swan Leavitt



EDWIN HUBBLE (1929)

Velocidad a la que se alejan de nosotros

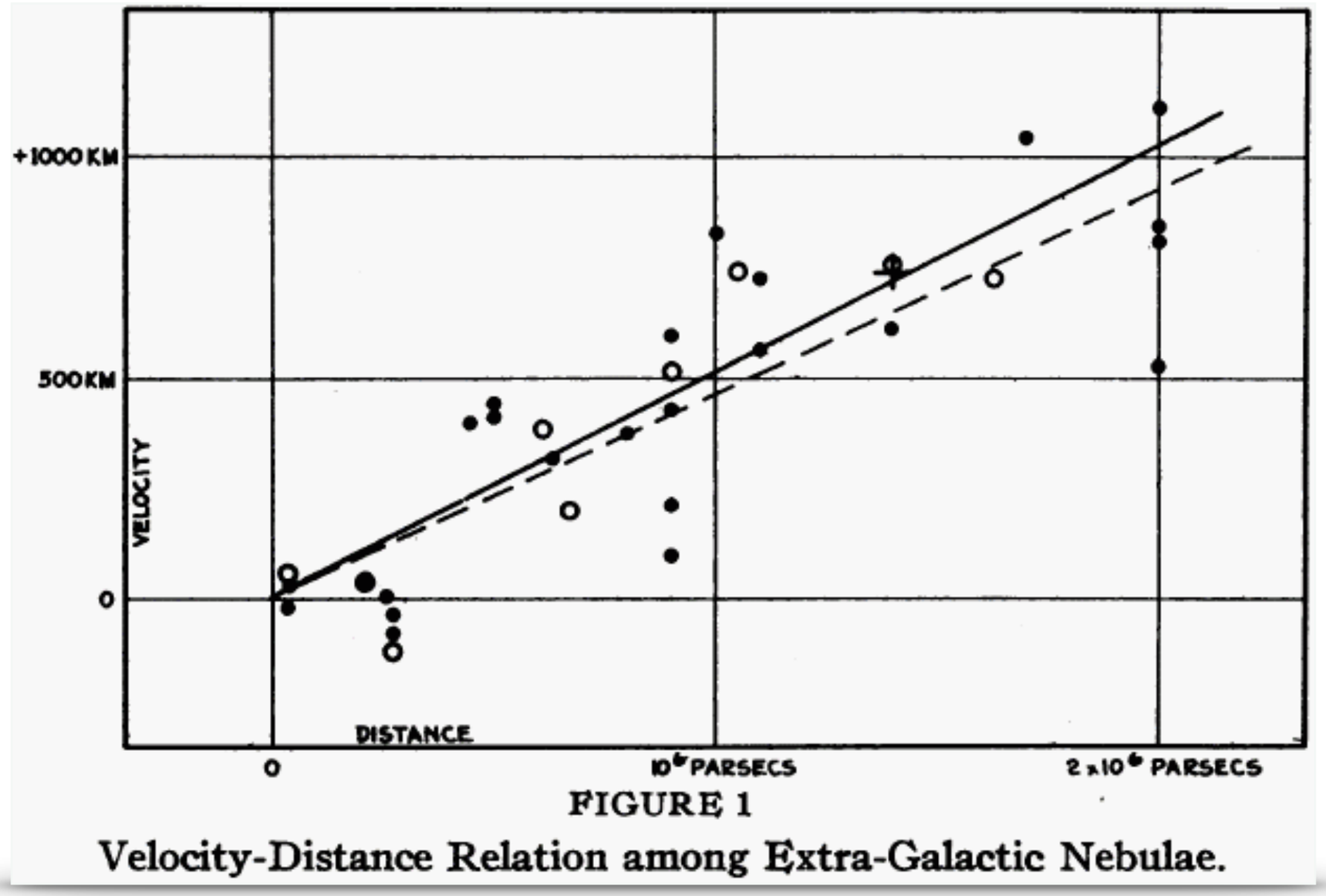


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

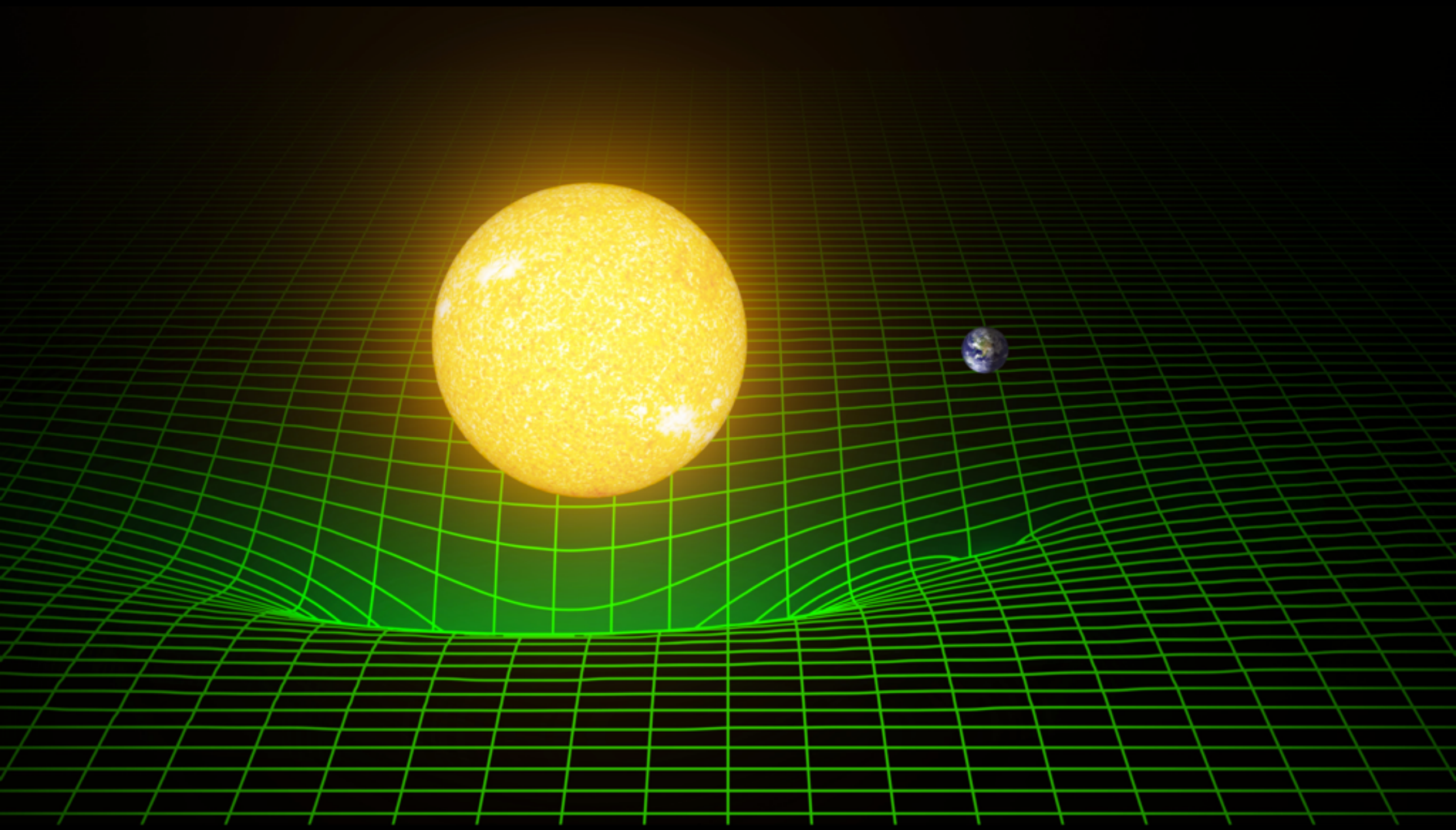
Distancia

ALBERT EINSTEIN

- En 1915 publica su Teoría de Relatividad General

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

Geometría del espacio-tiempo ⟷ Contenido de masa / energía



Einstein considera que no se pueden encontrar soluciones exactas a sus ecuaciones de campo

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

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right].$$

$$\begin{aligned} R^1_{010} &= \Gamma^1_{00,1} + \Gamma^1_{01,0} + \Gamma^1_{\beta 1}\Gamma^\beta_{00} - \Gamma^1_{\beta 0}\Gamma^\beta_{01} \\ R^1_{010} &= 0 + \frac{\ddot{a}}{a} + 0 + 0 \\ R^1_{010} &= \frac{\ddot{a}}{a}. \end{aligned}$$

$$\begin{aligned} R^0_{110} &= \frac{a\ddot{a}}{kr^2-1} \\ R^0_{220} &= -r^2 a\ddot{a} \\ R^0_{330} &= -r^2 a\ddot{a}\sin^2\theta \\ R^1_{010} &= -\frac{\ddot{a}}{a} \\ R^1_{221} &= -r^2(k+\dot{a}^2) \\ R^1_{331} &= -r^2\sin^2\theta(k+\dot{a}^2) \\ R^2_{020} &= -\frac{\ddot{a}}{a} \\ R^2_{121} &= \frac{k+\dot{a}^2}{1-kr^2} \\ R^2_{332} &= -r^2\sin^2\theta(k+\dot{a}^2) \\ R^3_{030} &= -\frac{\ddot{a}}{a} \\ R^3_{131} &= \frac{k+\dot{a}^2}{1-kr^2} \\ R^3_{232} &= r^2(k+\dot{a}^2) \end{aligned}$$

$$\begin{aligned} g_{0\delta}\Gamma^\delta_{11} &= \frac{1}{2}\left(\frac{\partial g_{01}}{\partial x^1} + \frac{\partial g_{01}}{\partial x^1} - \frac{\partial g_{11}}{\partial x^0}\right) \\ &= \frac{1}{2}\left(-\frac{2a\dot{a}}{1-kr^2}\right) \\ &= -\frac{a\dot{a}}{1-kr^2}. \end{aligned}$$

$$T_{\mu\nu} = \begin{pmatrix} 8\pi\rho & 0 & 0 & 0 \\ 0 & 8\pi p & 0 & 0 \\ 0 & 0 & 8\pi p & 0 \\ 0 & 0 & 0 & 8\pi p \end{pmatrix}.$$

$$R_{\mu\nu} = \begin{pmatrix} -\frac{3\ddot{a}}{a} & 0 & 0 & 0 \\ 0 & \frac{2k+2\dot{a}^2+a\ddot{a}}{1-kr^2} & 0 & 0 \\ 0 & 0 & r^2\left[2(k+\dot{a}^2)+a\ddot{a}\right] & 0 \\ 0 & 0 & 0 & r^2\sin^2(\theta)\left[2(k+\dot{a}^2)+a\ddot{a}\right] \end{pmatrix}$$

$$G_{\hat{t}\hat{t}} = \frac{3(k+\dot{a}^2)}{a^2} = 8\pi\rho$$

$$G_{\hat{r}\hat{r}} = G_{\hat{\theta}\hat{\theta}} = G_{\hat{\phi}\hat{\phi}} = -\frac{(k+\dot{a}^2+2a\ddot{a})}{a^2} = 8\pi p.$$

- Einstein introduce su constante cosmológica para obtener una solución de Universo estático

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

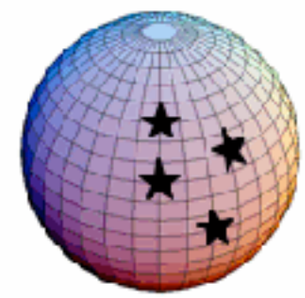
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

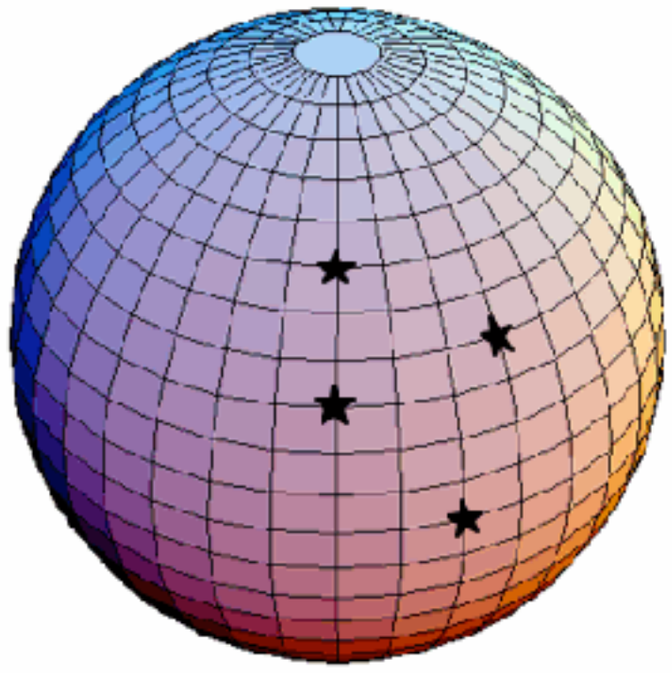
Alexander Friedmann (1922)

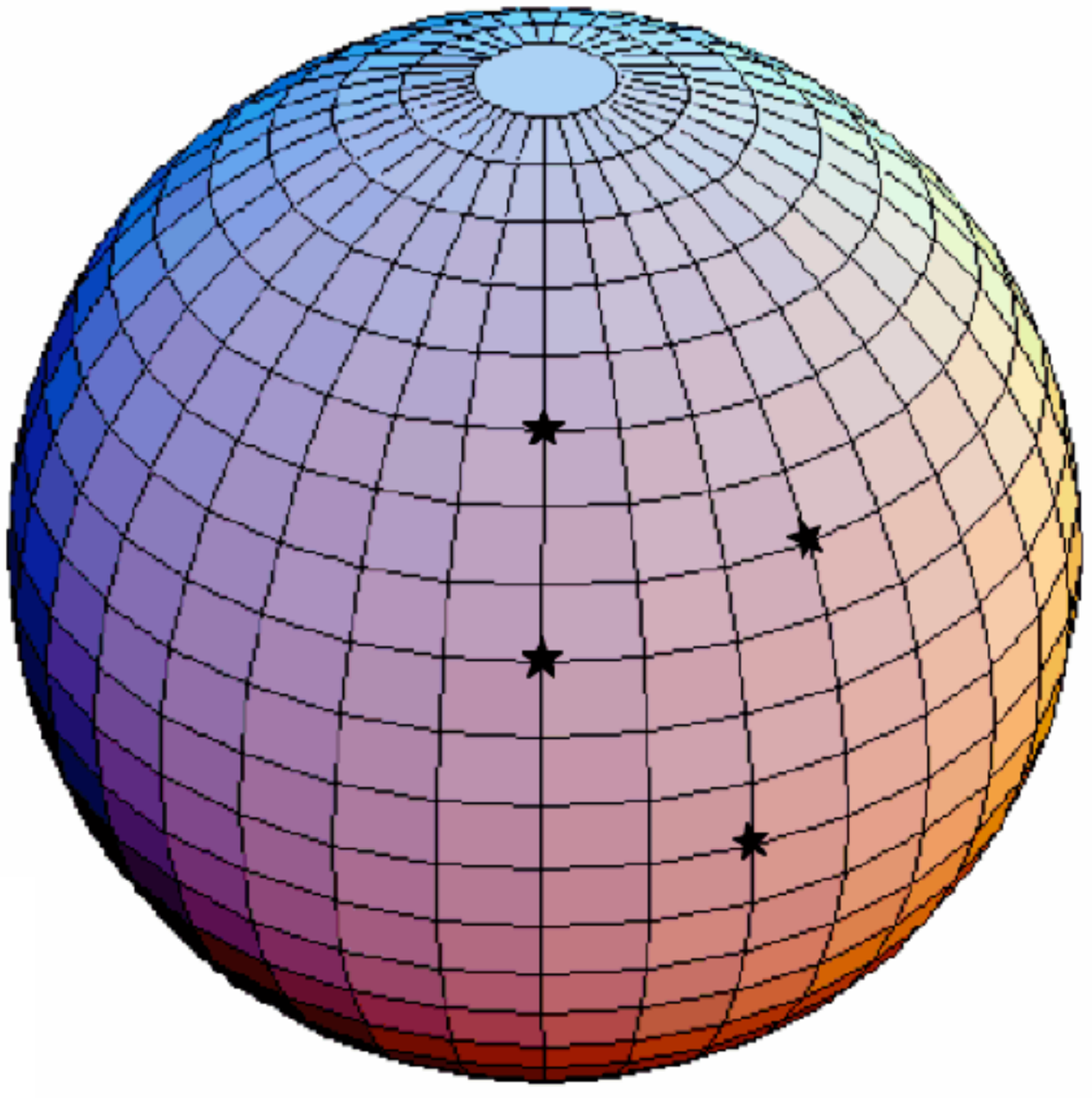
Publica una serie de artículos proponiendo soluciones dinámicas para el Universo

George Lemaitre (1927)

Resuelve las ecuaciones de Einstein y compara con observaciones de galaxias que muestran un Universo en expansión.







Ley de Hubble-Lemaitre

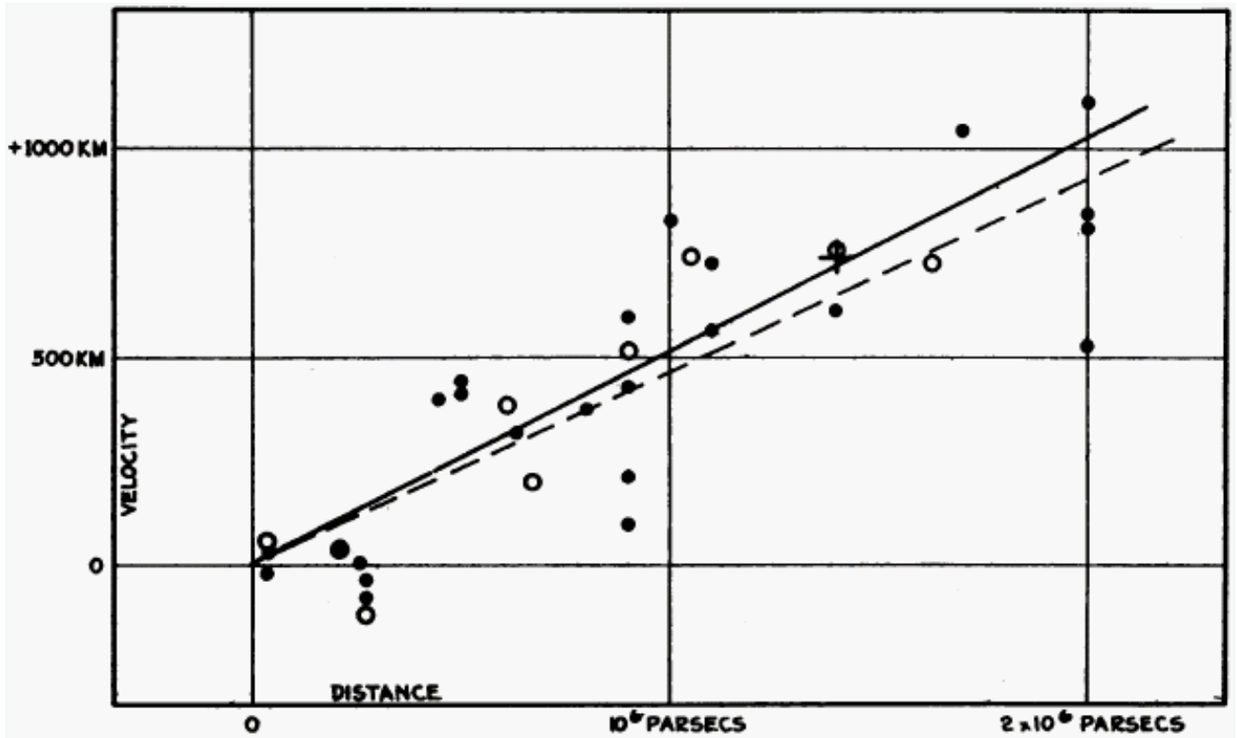


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble
1929

Lemaitre
1927

Utilisant les 42 nébuleuses figurant dans les listes de Hubble et de Strömberg (¹), et tenant compte de la vitesse propre du soleil (300 Km. dans la direction $\alpha = 315°$, $\delta = 62°$), on trouve une distance moyenne de 0,95 millions de parsecs et une vitesse radiale de 600 Km./sec, soit 625 Km./sec à 10^6 parsecs (²).

Nous adopterons donc

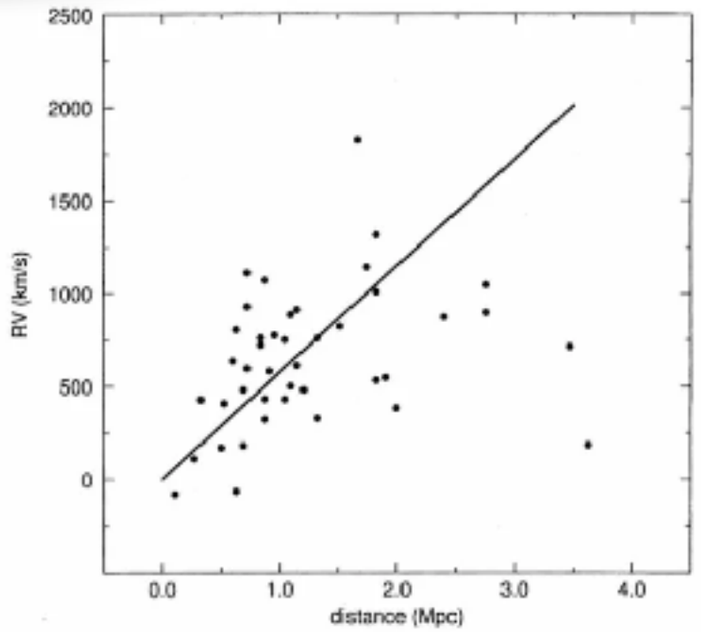
$$\frac{R'}{R} = \frac{v}{rc} = \frac{625 \times 10^5}{10^6 \times 3{,}08 \times 10^{18} \times 3 \times 10^{10}} = 0{,}68 \times 10^{-27}\ \text{cm}^{-1} \qquad (24)$$

Cette relation nous permet de calculer R_o. Nous avons en effet par (16)

$$\frac{R'}{R} = \frac{1}{R_o\sqrt{3}}\sqrt{1 - 3y^2 + 2y^3} \qquad (25)$$

où nous avons posé

$$y = \frac{R_o}{R} \qquad (26)$$



SOLVAY 1927

colourized by postincolour.com

SOLVAY CONFERENCE 1927

A. PICARD E. HENRIOT P. EHRENFEST Ed. HERSEN Th. DE DONDER E. SCHRÖDINGER E. VERSCHAFFELT W. PAULI W. HEISENBERG R.H FOWLER L. BRILLOUIN

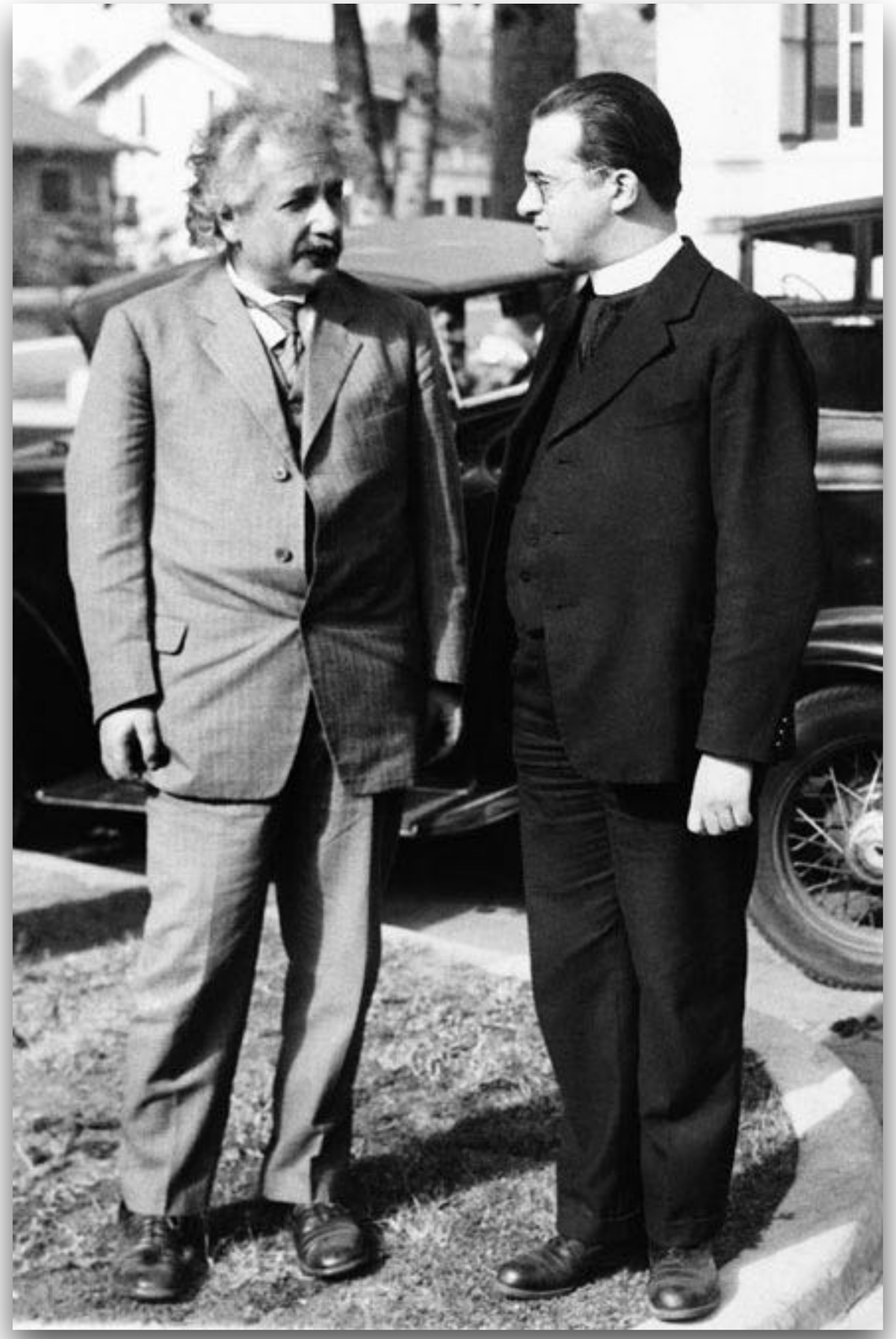
P. DEBYE M. KNUDSEN W.L. BRAGG H.A. KRAMERS P.A.M. DIRAC A.H. COMPTON L. de BROGLIE M. BORN N. BOHR

I. LANGMUIR M. PLANCK Mme CURIE H.A. LORENTZ A. EINSTEIN P. LANGEVIN Ch.E. GUYE C.T.R. WILSON O.W. RICHARDSON

Absents : Sir W.H. BRAGG, H. DESLANDRES et E. VAN AUBEL

1927

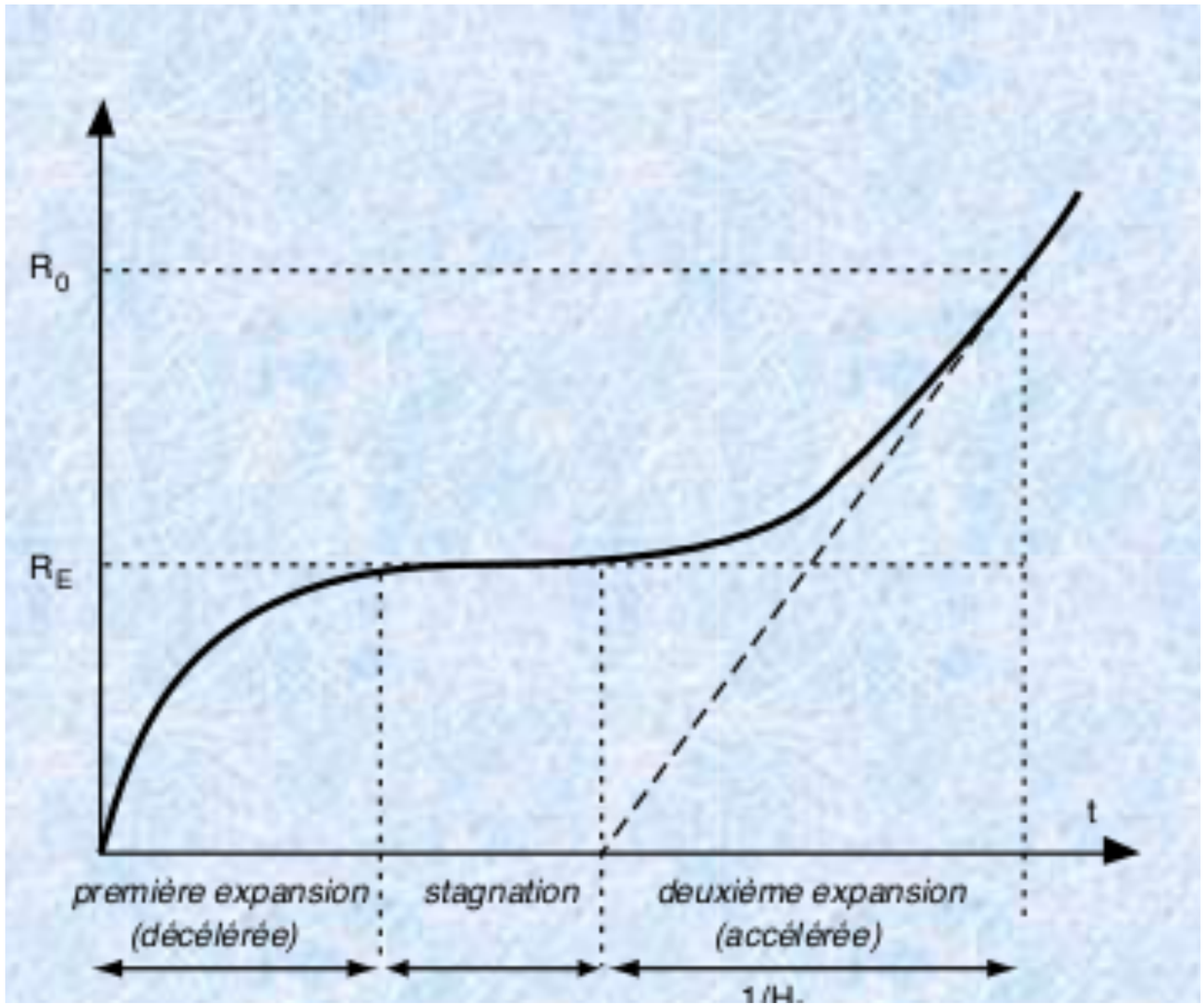
Sus cálculos son correctos pero su entendimiento de la física es ¡abominable!

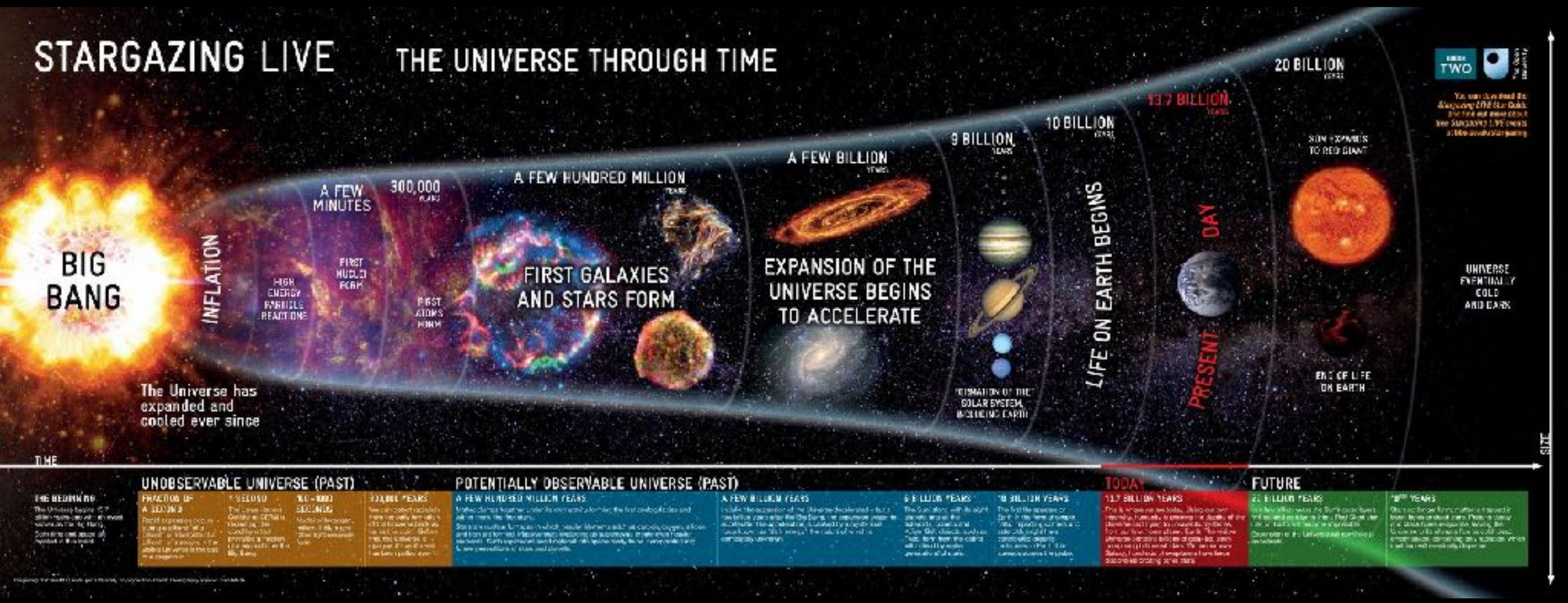


The Expanding Universe. By Abbé G. Lemaître.

(*Communicated by Sir A. S. Eddington.*)

- por George Lemaitre
- Publicado en 1931 en MNRAS.
- Primer modelo físico del origen del Universo.
- Publicó otros dos artículos desde el punto de vista de la Mecánica Cuántica y la Termodinámica.





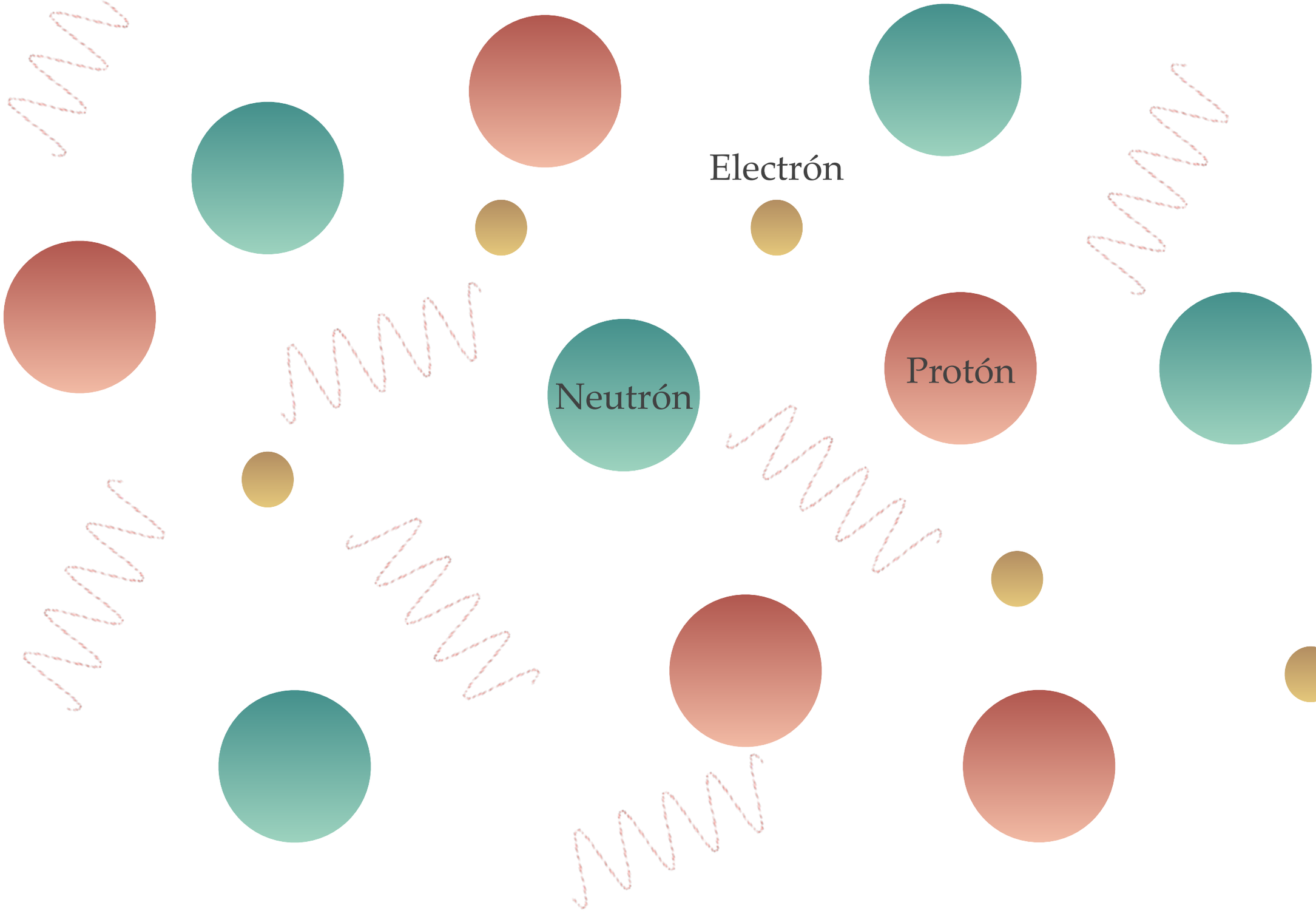
Evidencias:

Universo en expansión

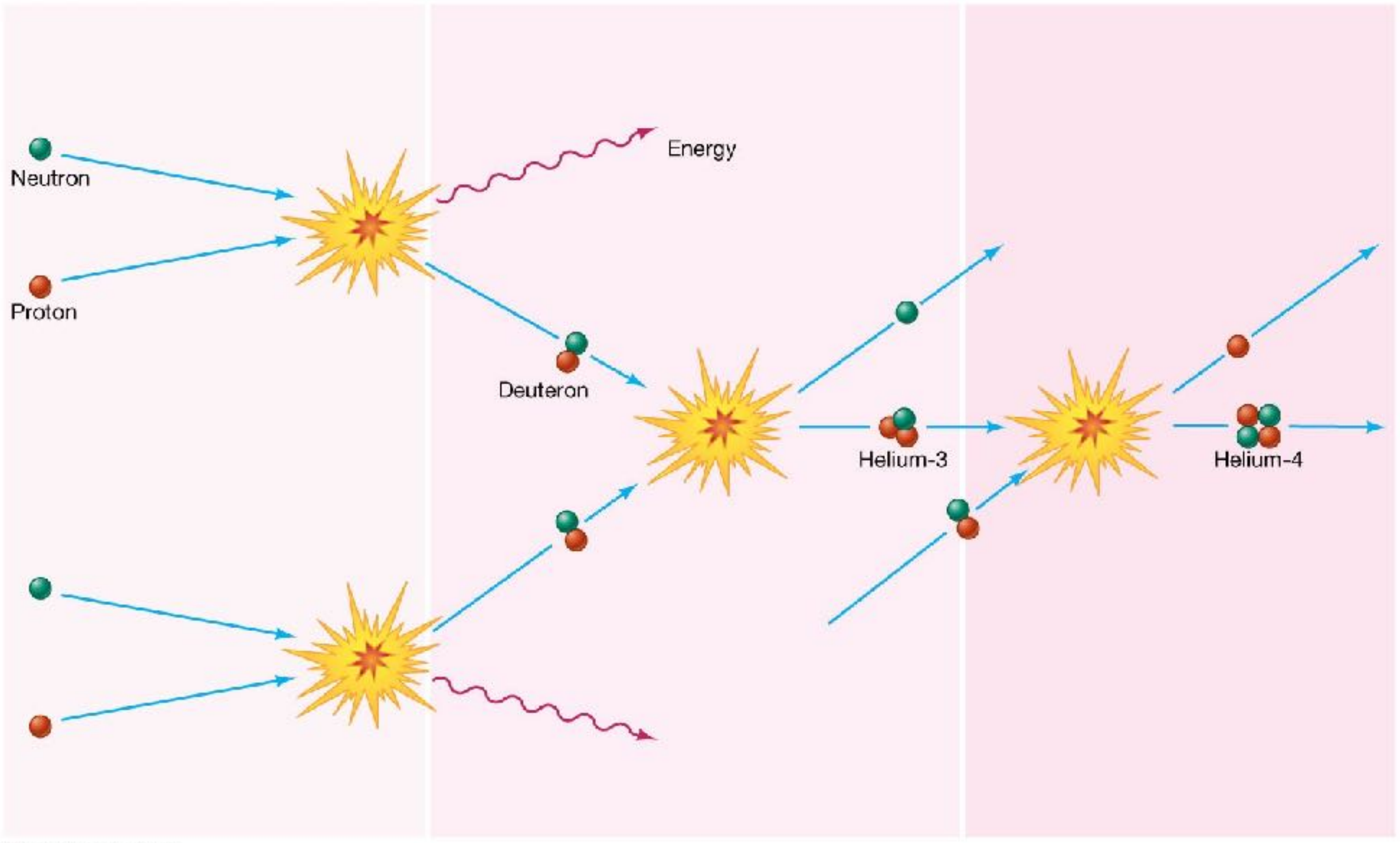
Fondo cósmico de radiación

Nucleosíntesis primordial

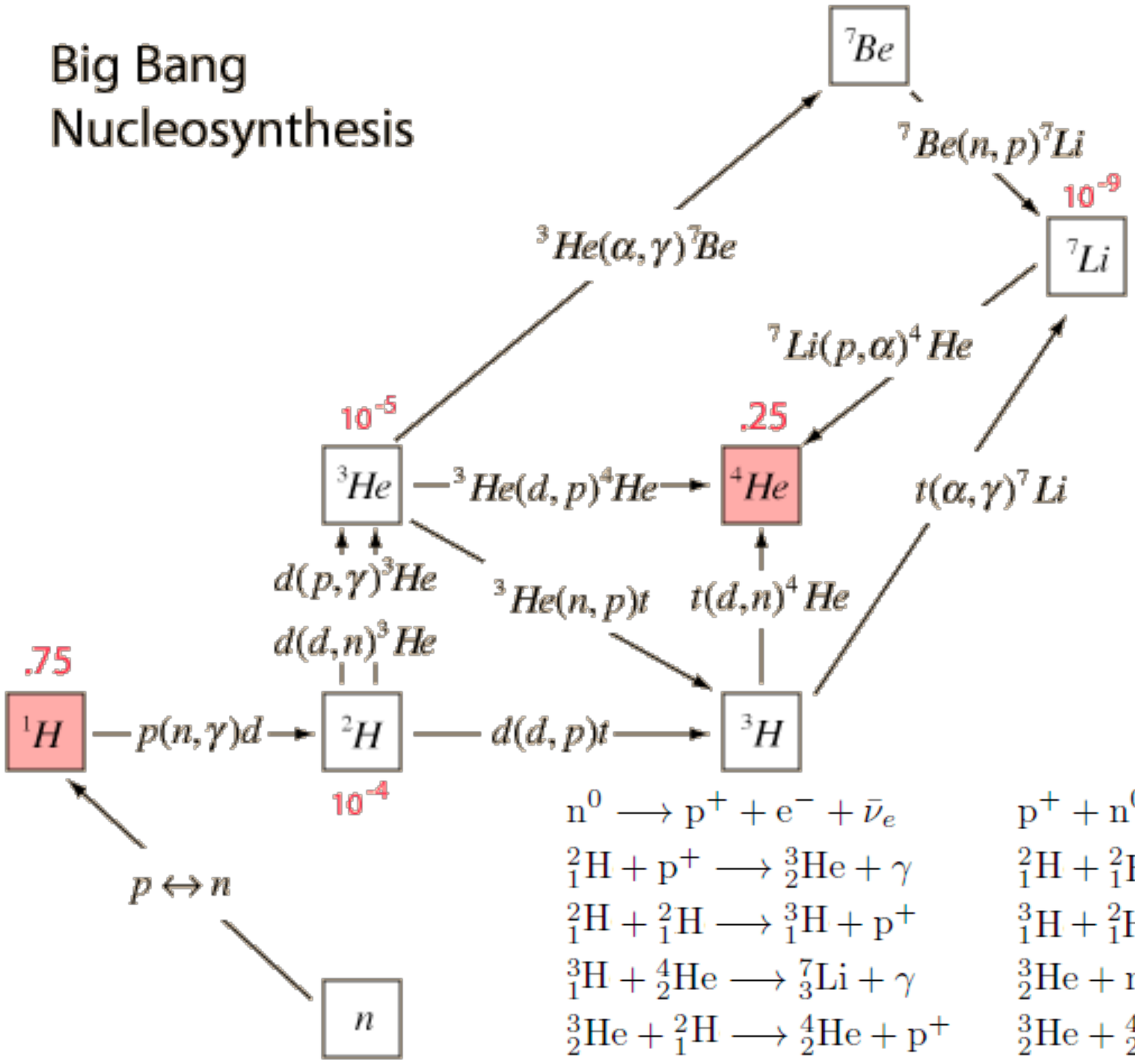
~unos cuantos minutos después del Big Bang
Temperatura de millones de grados C



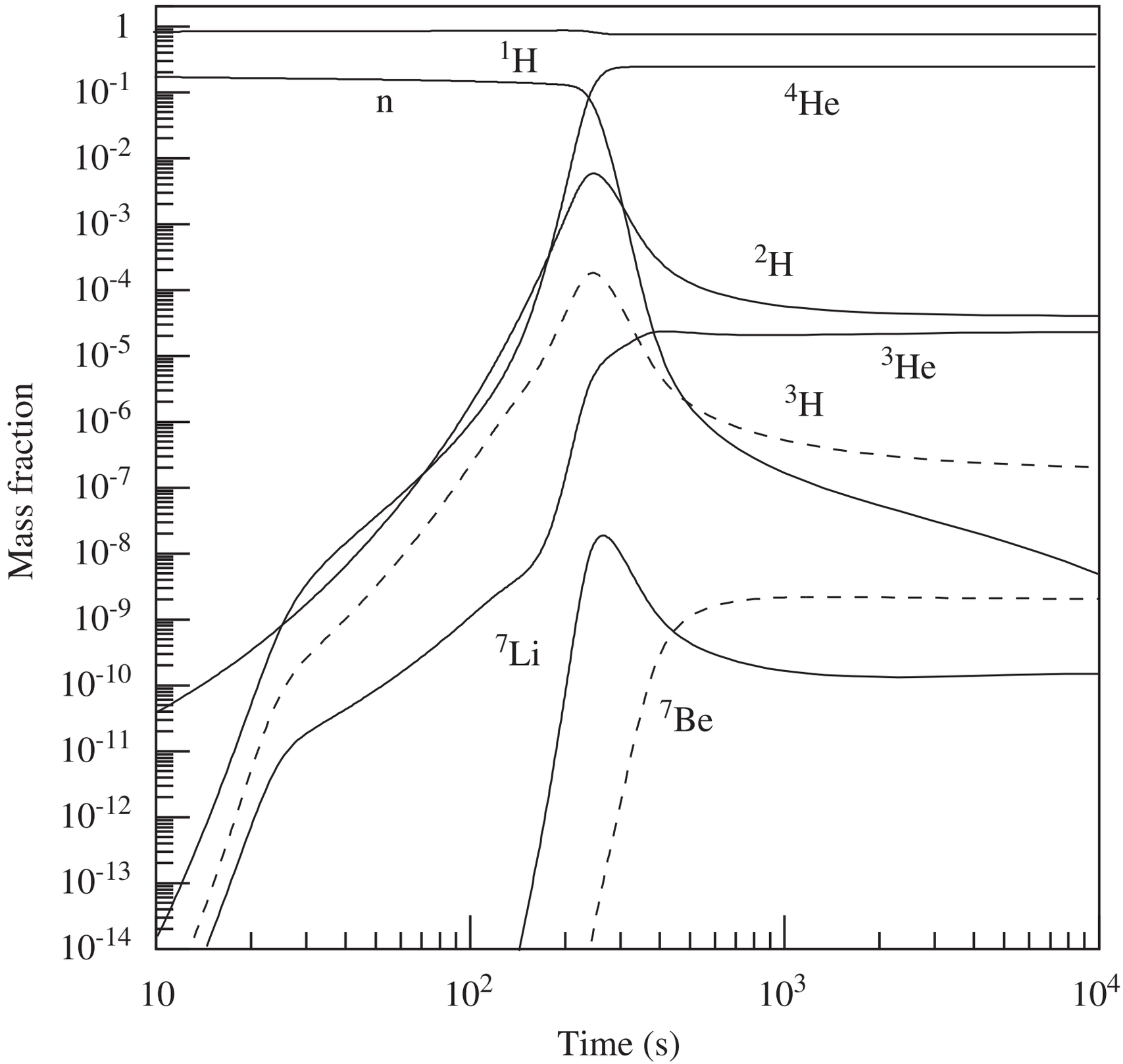
~unos cuantos minutos después del Big Bang



Big Bang Nucleosynthesis



$$n^0 \longrightarrow p^+ + e^- + \bar{\nu}_e$$
$$p^+ + n^0 \longrightarrow {}^2_1H + \gamma$$
$${}^2_1H + p^+ \longrightarrow {}^3_2He + \gamma$$
$${}^2_1H + {}^2_1H \longrightarrow {}^3_2He + n^0$$
$${}^2_1H + {}^2_1H \longrightarrow {}^3_1H + p^+$$
$${}^3_1H + {}^2_1H \longrightarrow {}^4_2He + n^0$$
$${}^3_1H + {}^4_2He \longrightarrow {}^7_3Li + \gamma$$
$${}^3_2He + n^0 \longrightarrow {}^3_1H + p^+$$
$${}^3_2He + {}^2_1H \longrightarrow {}^4_2He + p^+$$
$${}^3_2He + {}^4_2He \longrightarrow {}^7_4Be + \gamma$$
$${}^7_3Li + p^+ \longrightarrow {}^4_2He + {}^4_2He$$
$${}^7_4Be + n^0 \longrightarrow {}^7_3Li + p^+$$

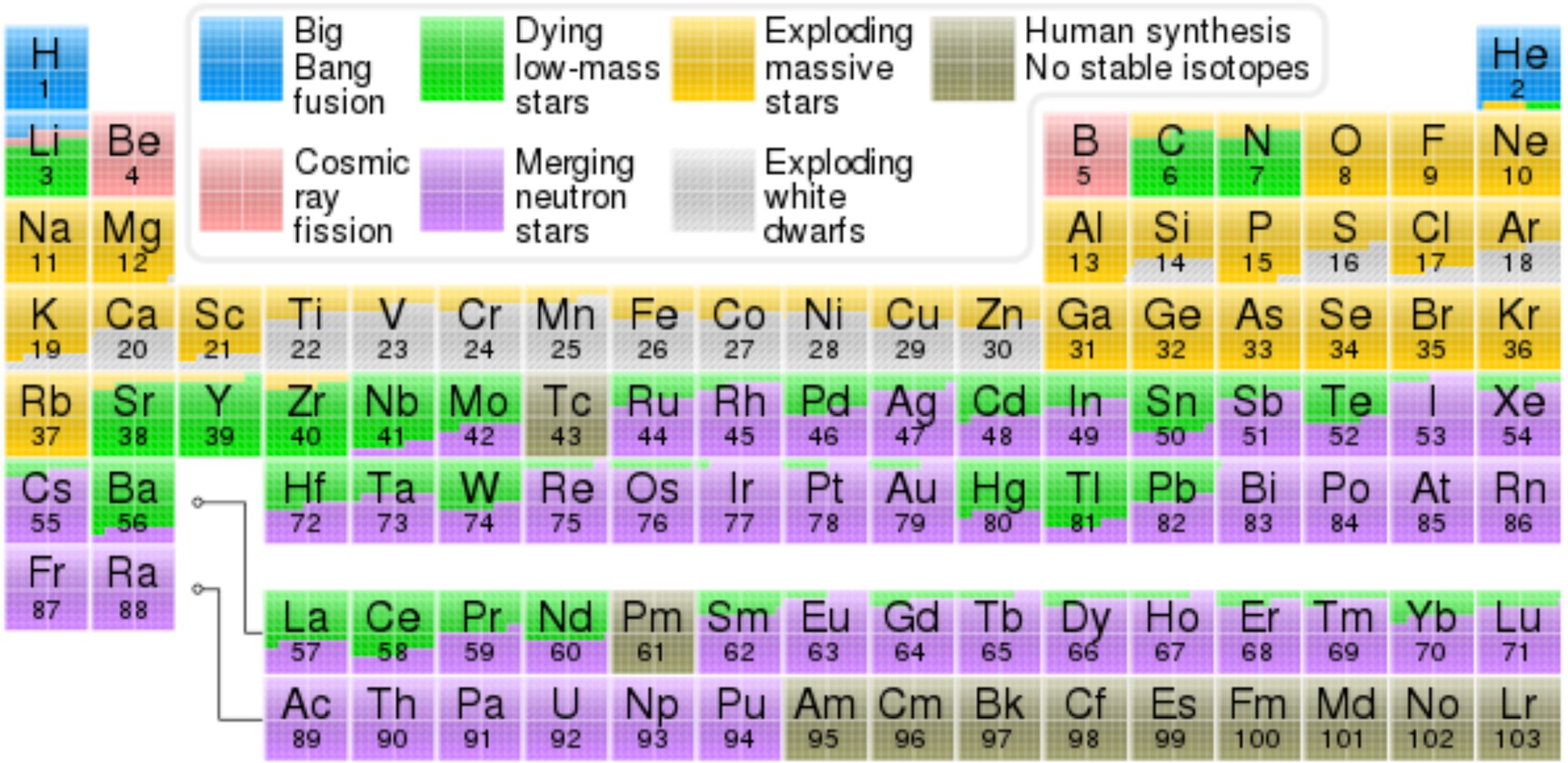


~75% H

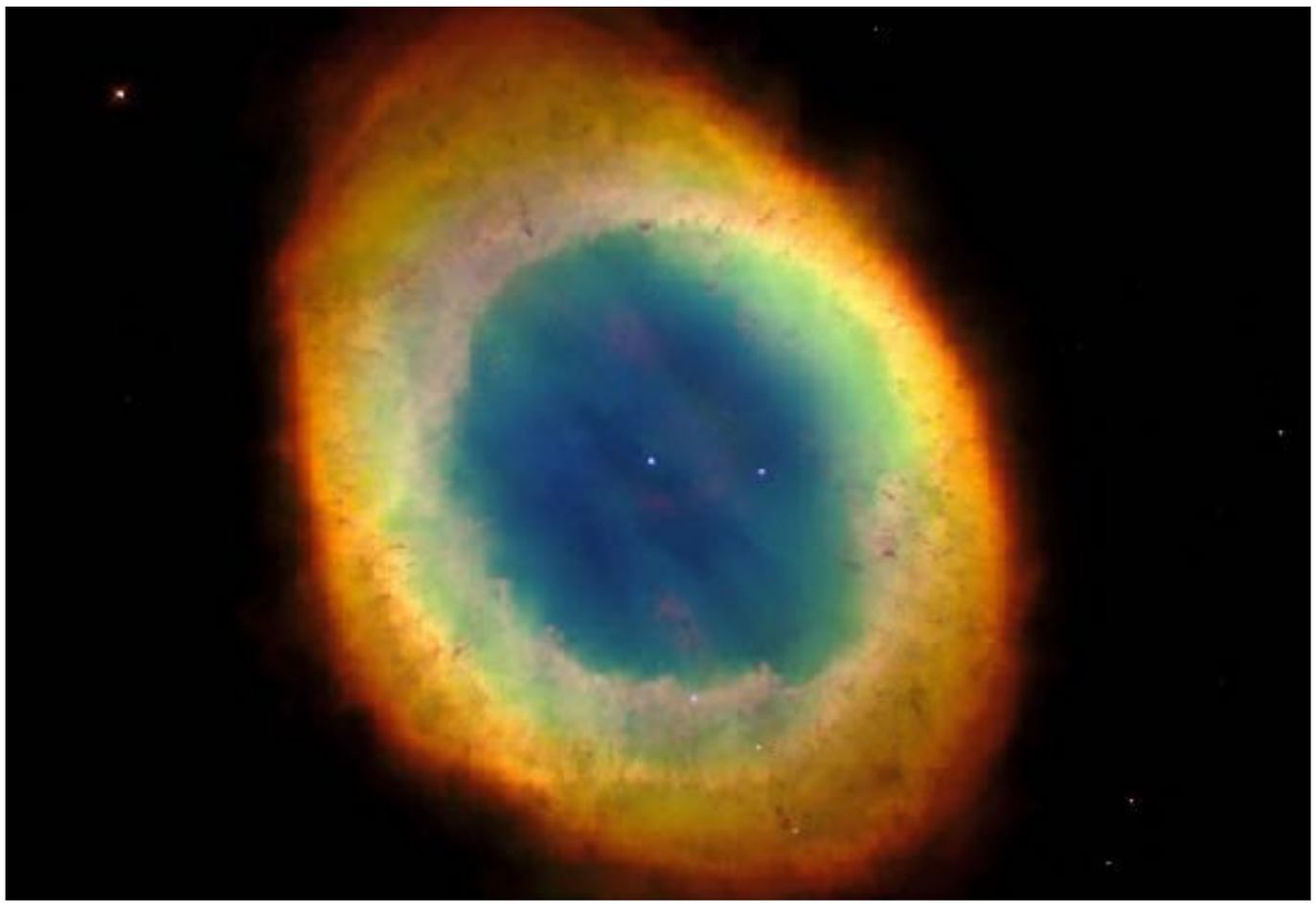
~25% He

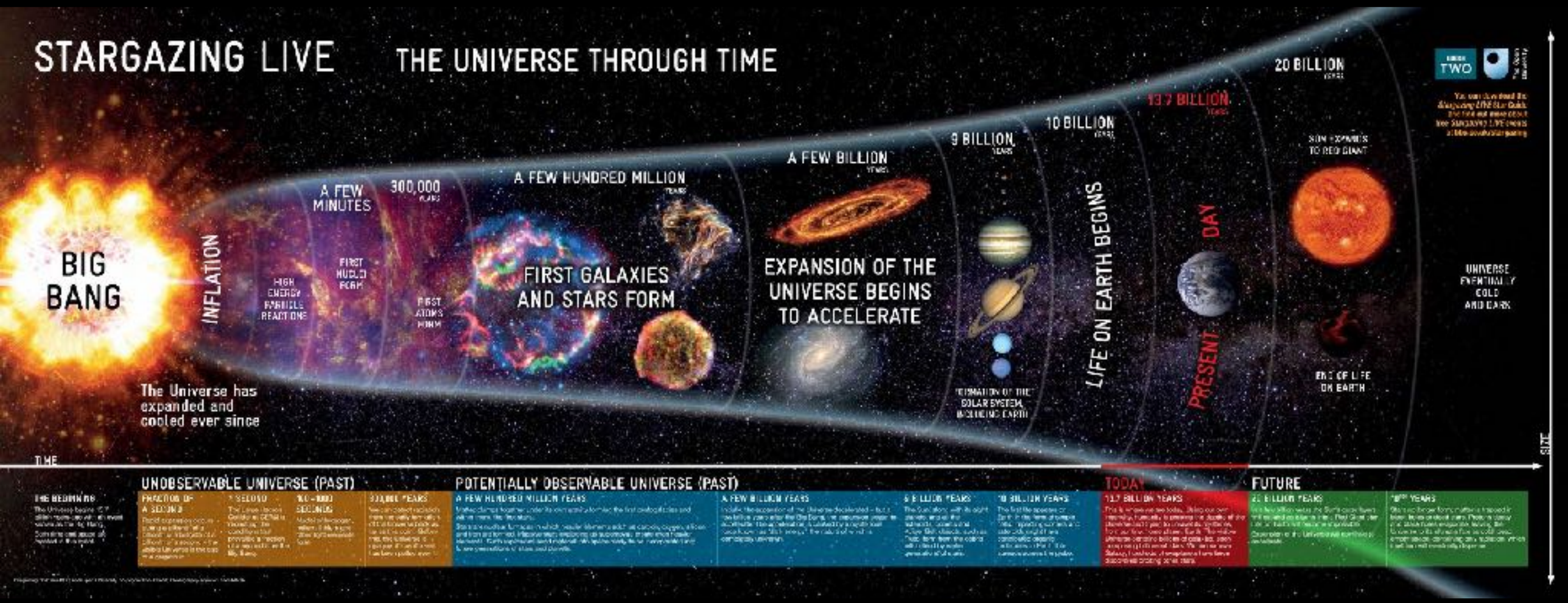
Minúsculas fracciones de Li, Be

Coc et al. 2009


Big Bang fusion
Dying low-mass stars
Exploding massive stars
Human synthesis No stable isotopes
Cosmic ray fission
Merging neutron stars
Exploding white dwarfs
H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
K 19
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Tc 43
Ru 44
Rh 45
Pd 46
Ag 47
Cd 48
In 49
Sn 50
Sb 51
Te 52
I 53
Xe 54
Cs 55
Ba 56
Hf 72
Ta 73
W 74
Re 75
Os 76
Ir 77
Pt 78
Au 79
Hg 80
Tl 81
Pb 82
Bi 83
Po 84
At 85
Rn 86
Fr 87
Ra 88
La 57
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Ac 89
Th 90
Pa 91
U 92
Np 93
Pu 94
Am 95
Cm 96
Bk 97
Cf 98
Es 99
Fm 100
Md 101
No 102
Lr 103

Silvia Torres y Manuel Peimbert





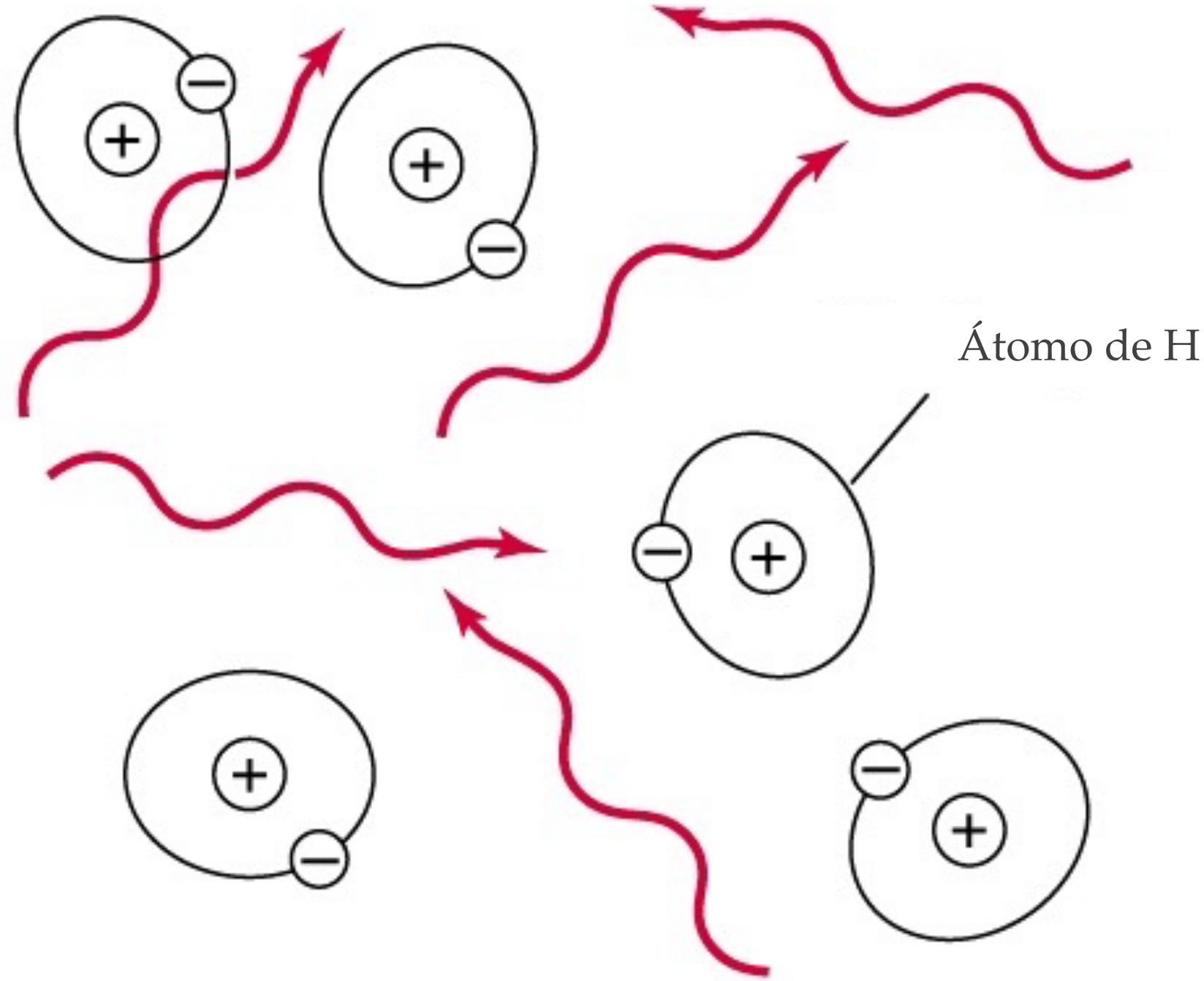
Evidencias:

Universo en expansión

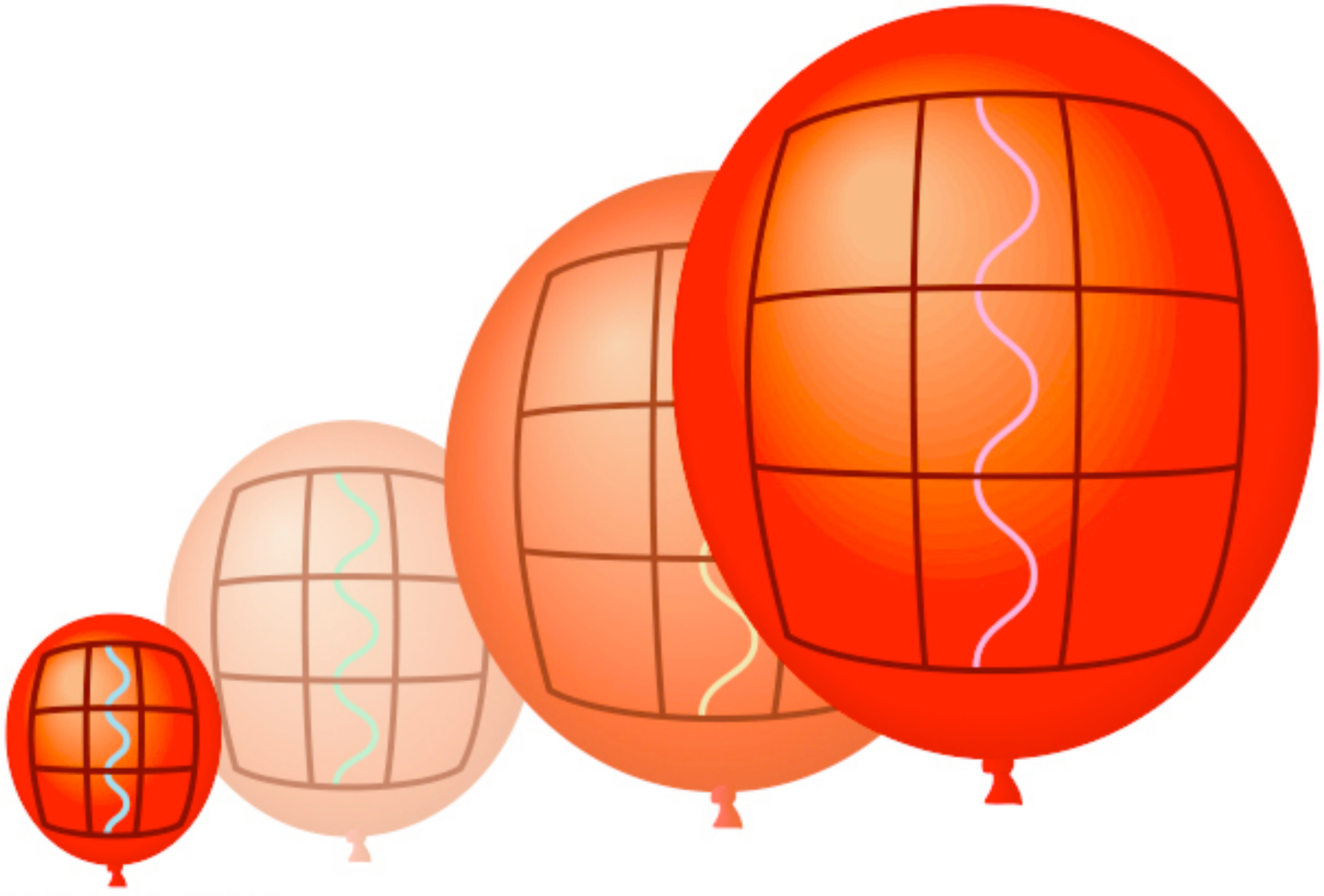
Fondo cósmico de radiación

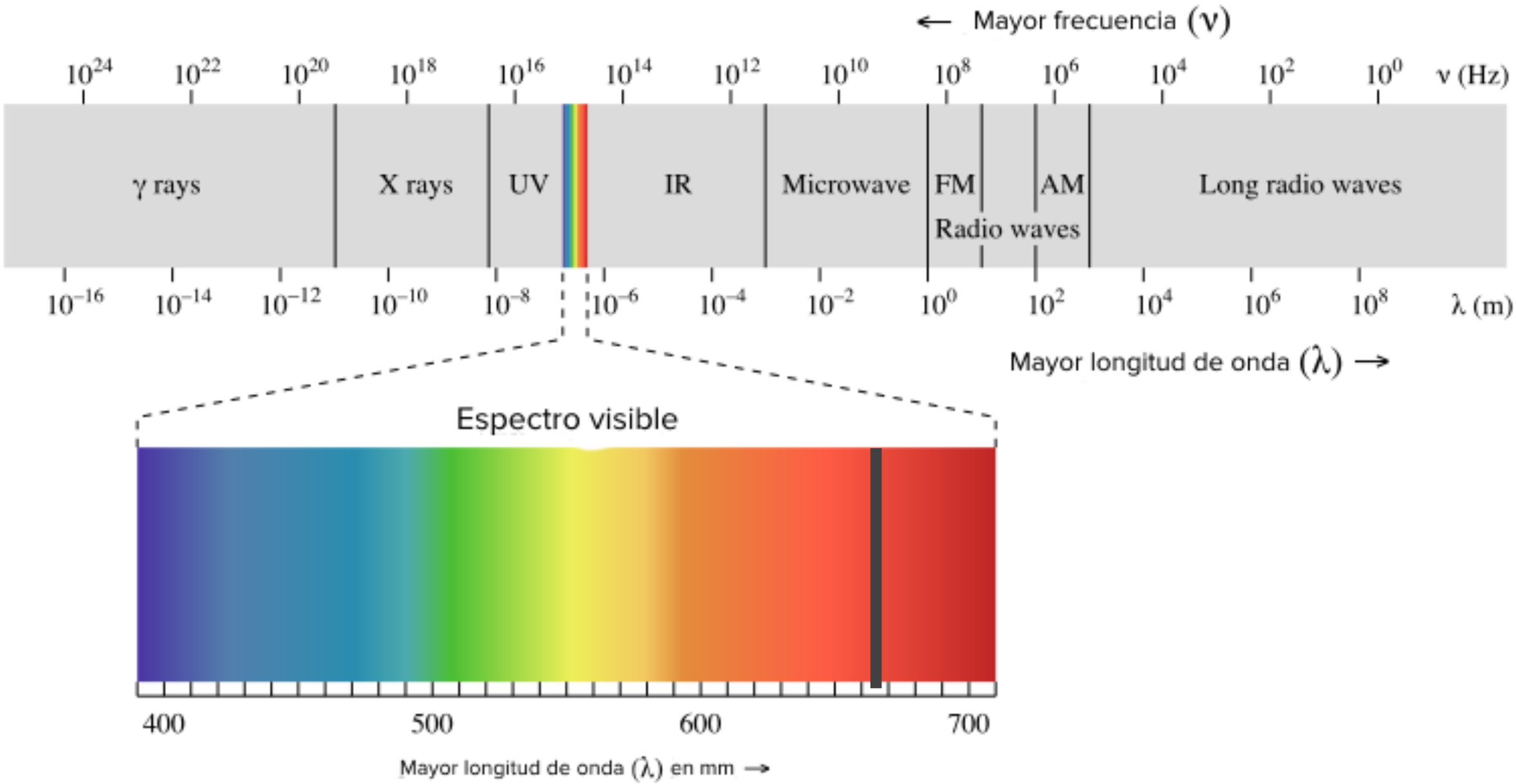
Nucleosíntesis primordial

~300,000 años después del Big Bang
Temperatura de unos 3000 grados C



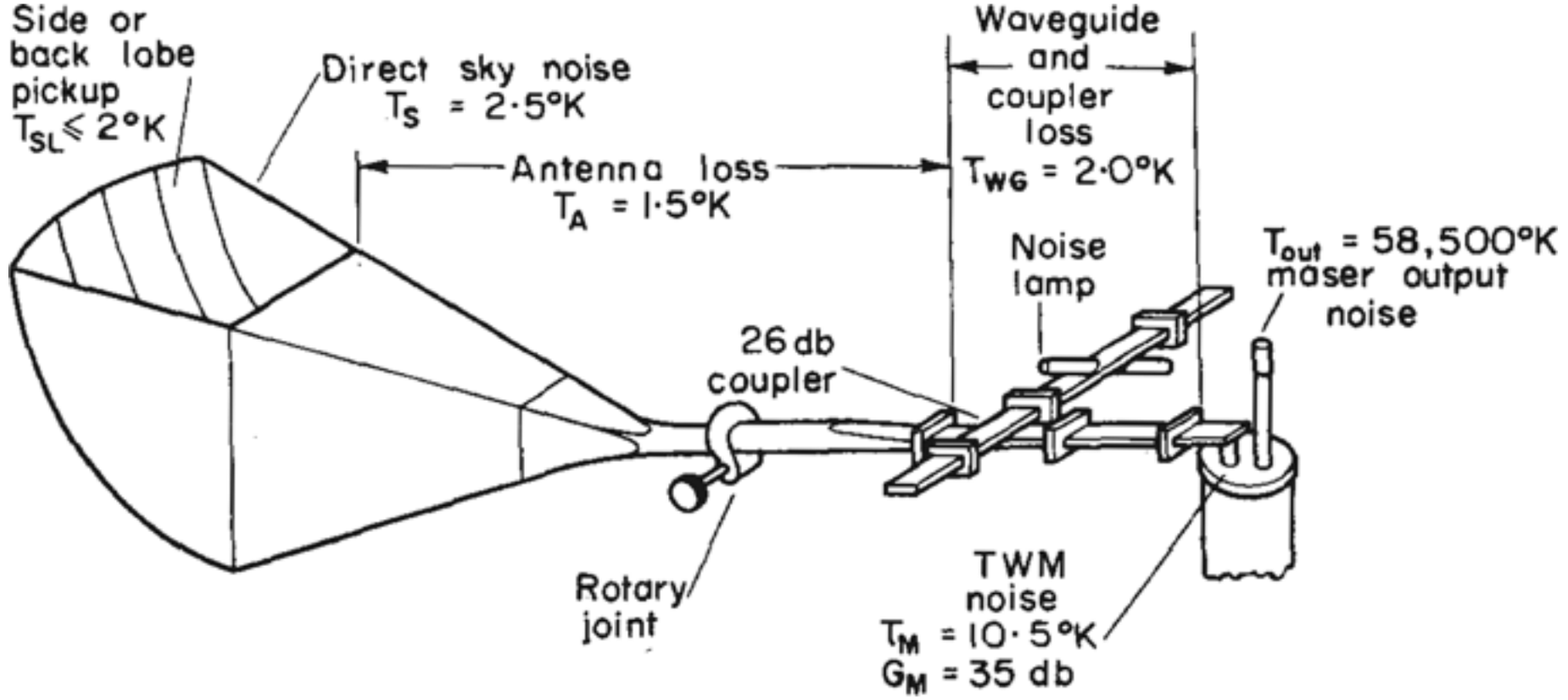

Betelgeuse



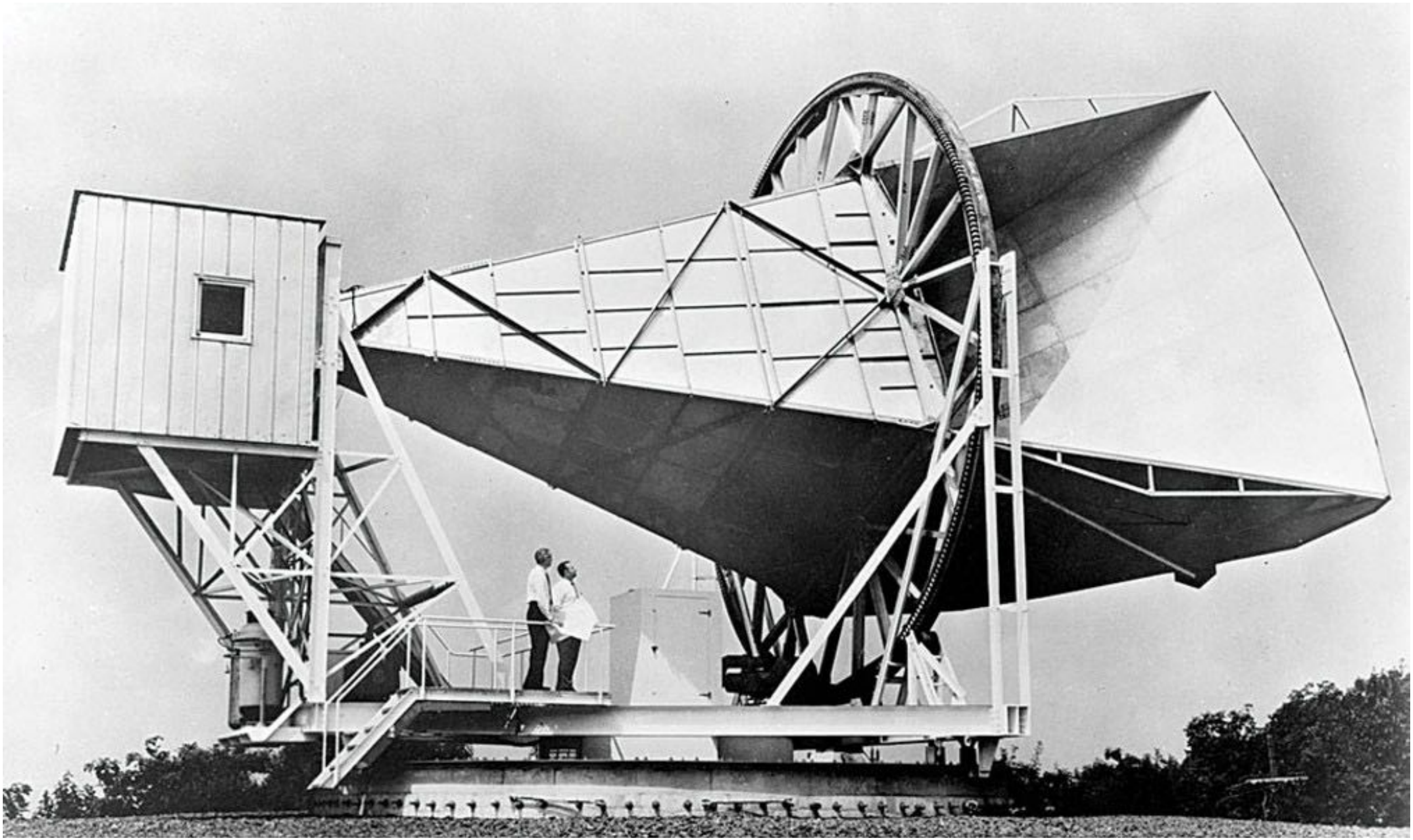

← Mayor frecuencia (ν)
10^24 10^22 10^20 10^18 10^16 10^14 10^12 10^10 10^8 10^6 10^4 10^2 10^0 ν (Hz)
γ rays
X rays
UV
IR
Microwave
FM
AM
Radio waves
Long radio waves
10^-16 10^-14 10^-12 10^-10 10^-8 10^-6 10^-4 10^-2 10^0 10^2 10^4 10^6 10^8 λ (m)
Mayor longitud de onda (λ) →
Espectro visible
400
500
600
700
Mayor longitud de onda (λ) en mm →

Dicke, Peebles, Roll & Wilkinson (Princeton 1964)

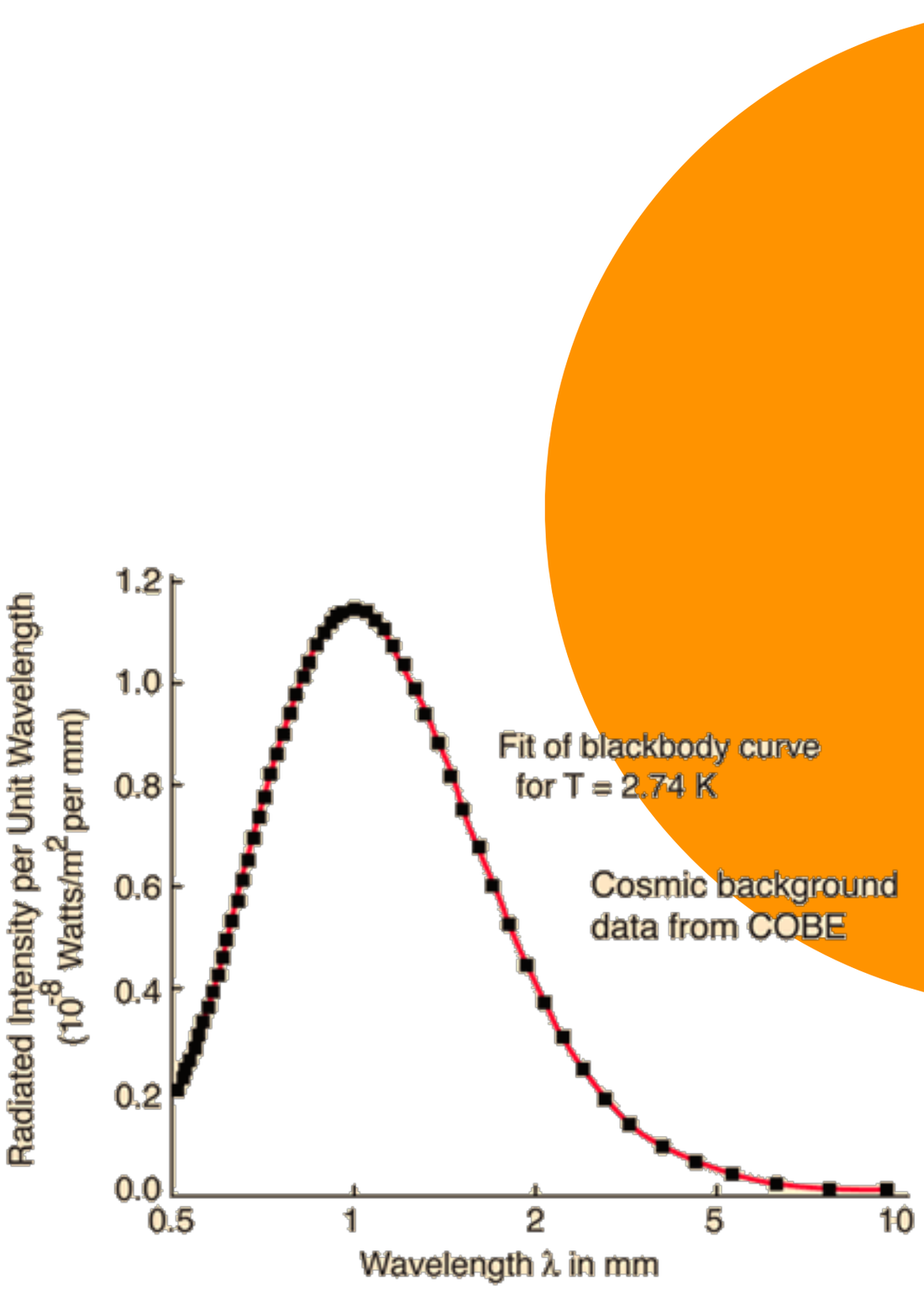
Dave Wilkinson, Bob Dicke, Ed Groth y Jim Peebles

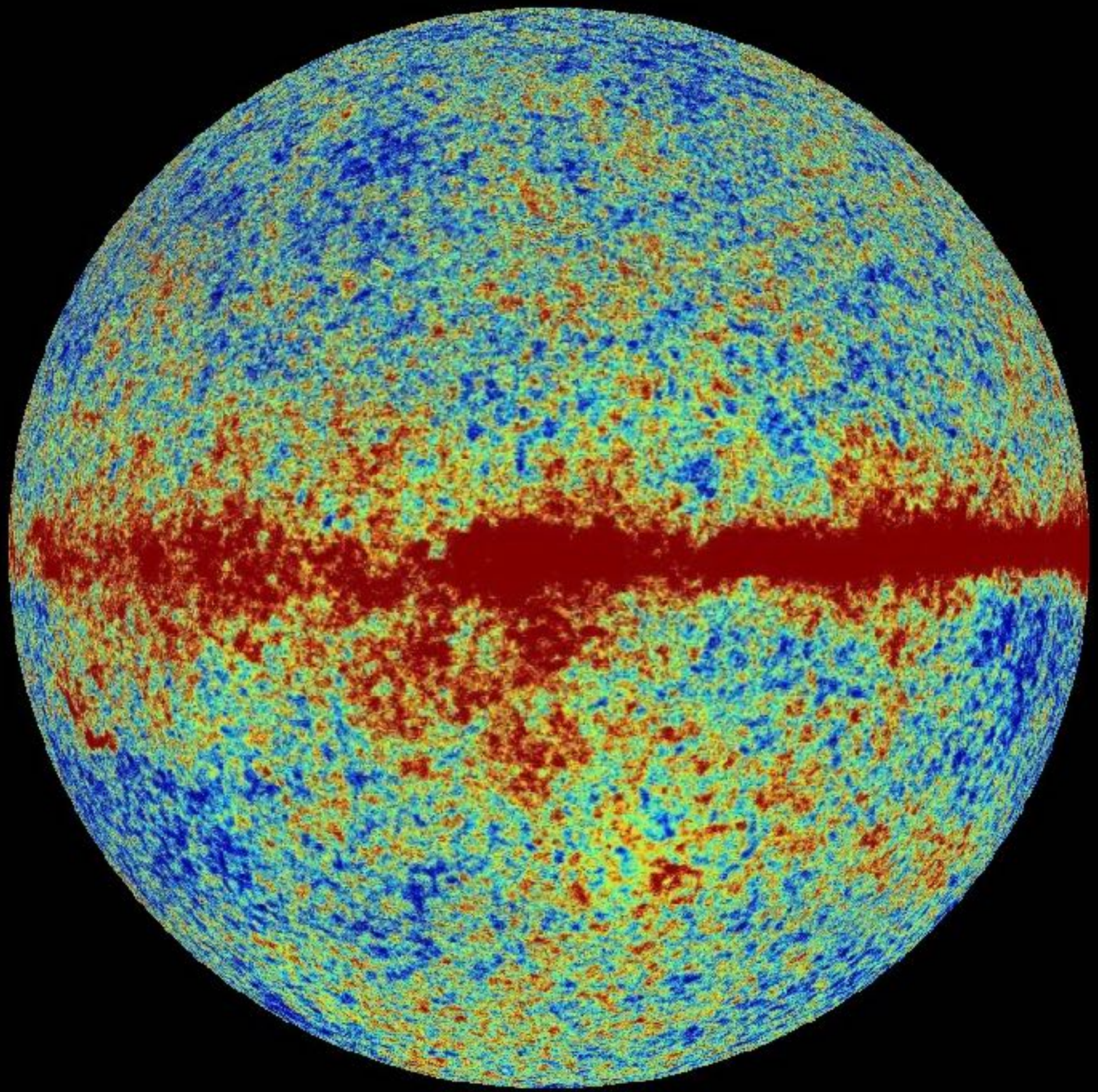


Arno Allan Penzias y Robert Woodrow Wilson de los laboratorios Bell

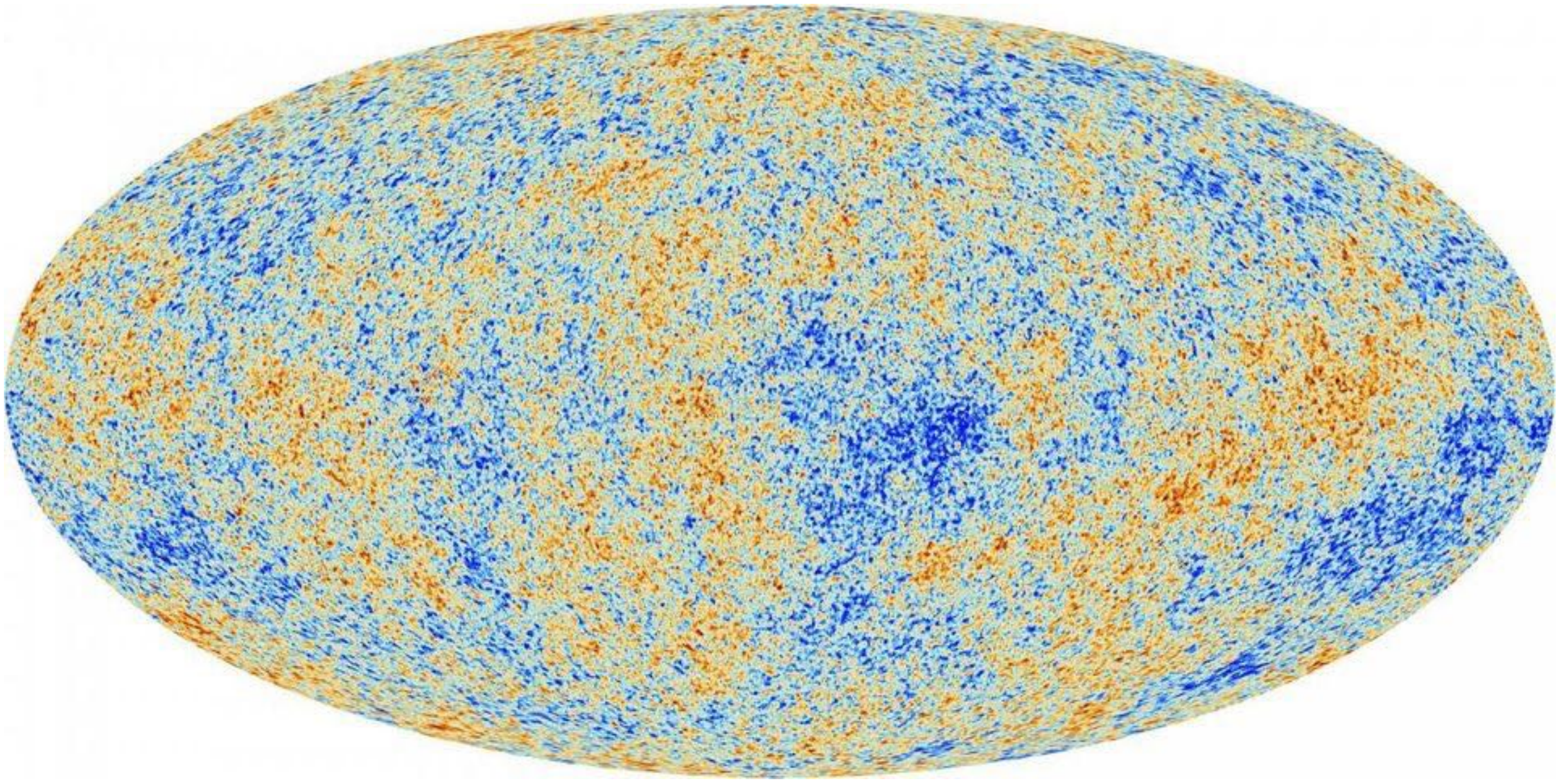


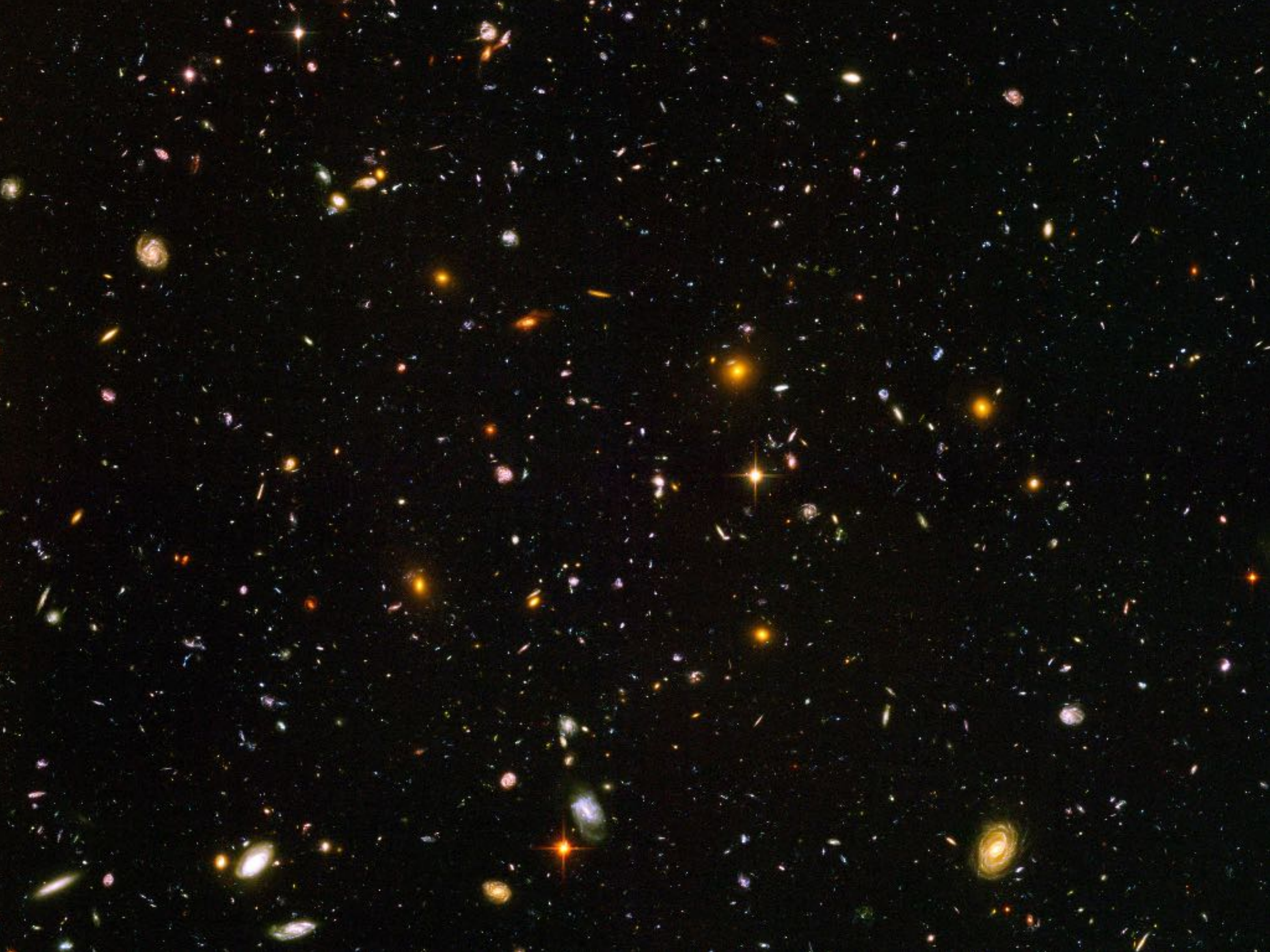
Temperatura de 2.725 K o -270.425 C

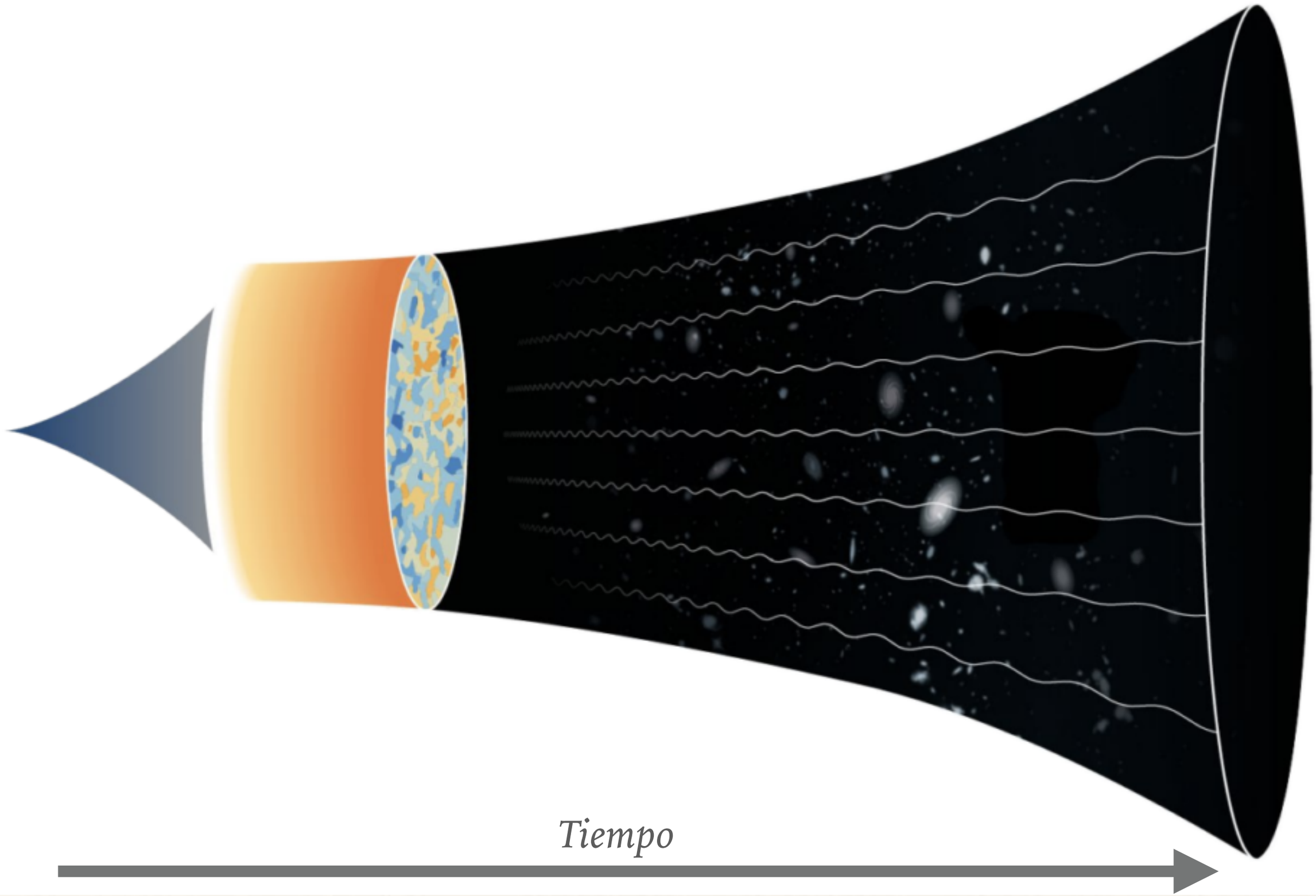


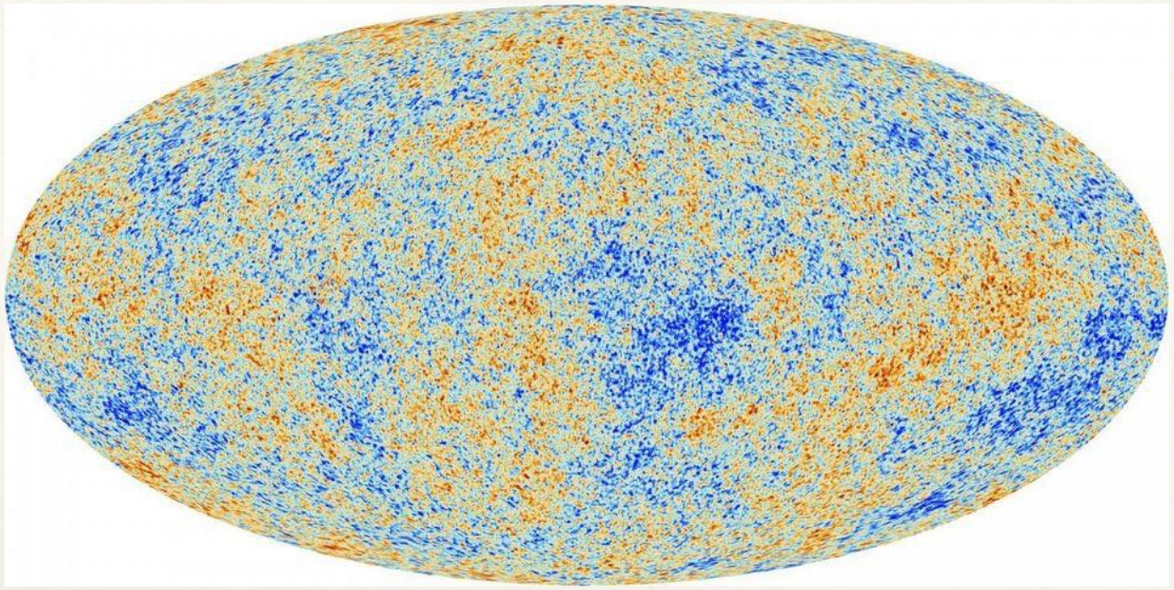


Fluctuaciones de temperatura de menos de 0.0005 grados C

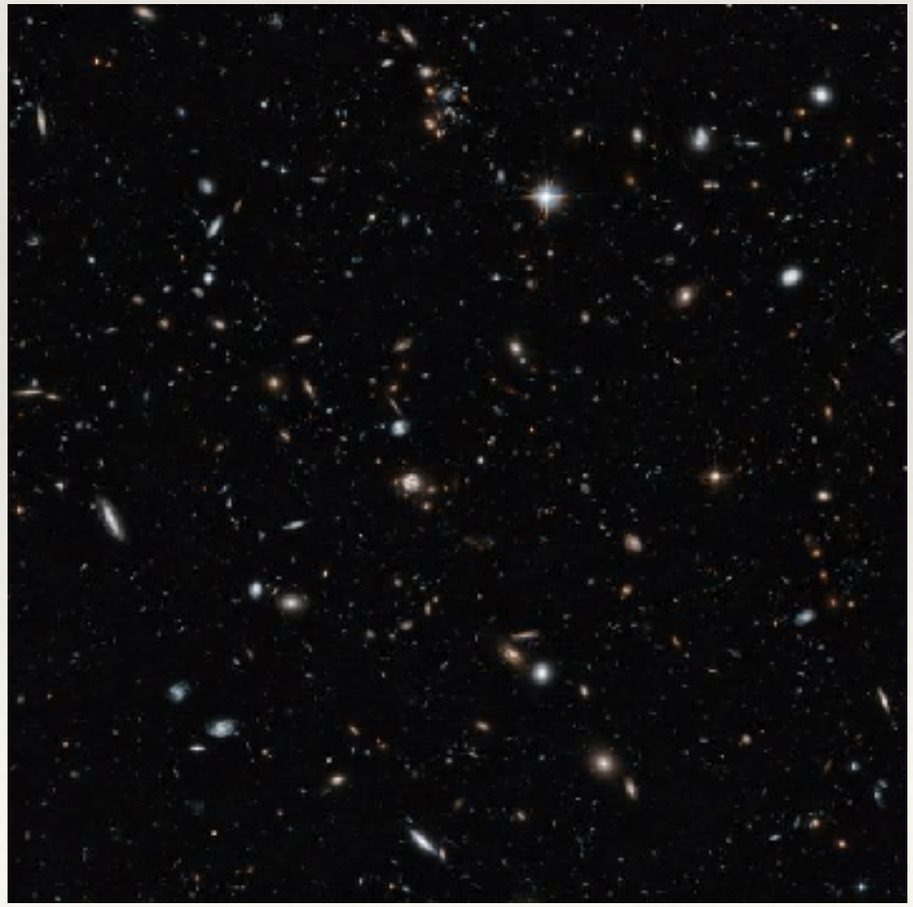




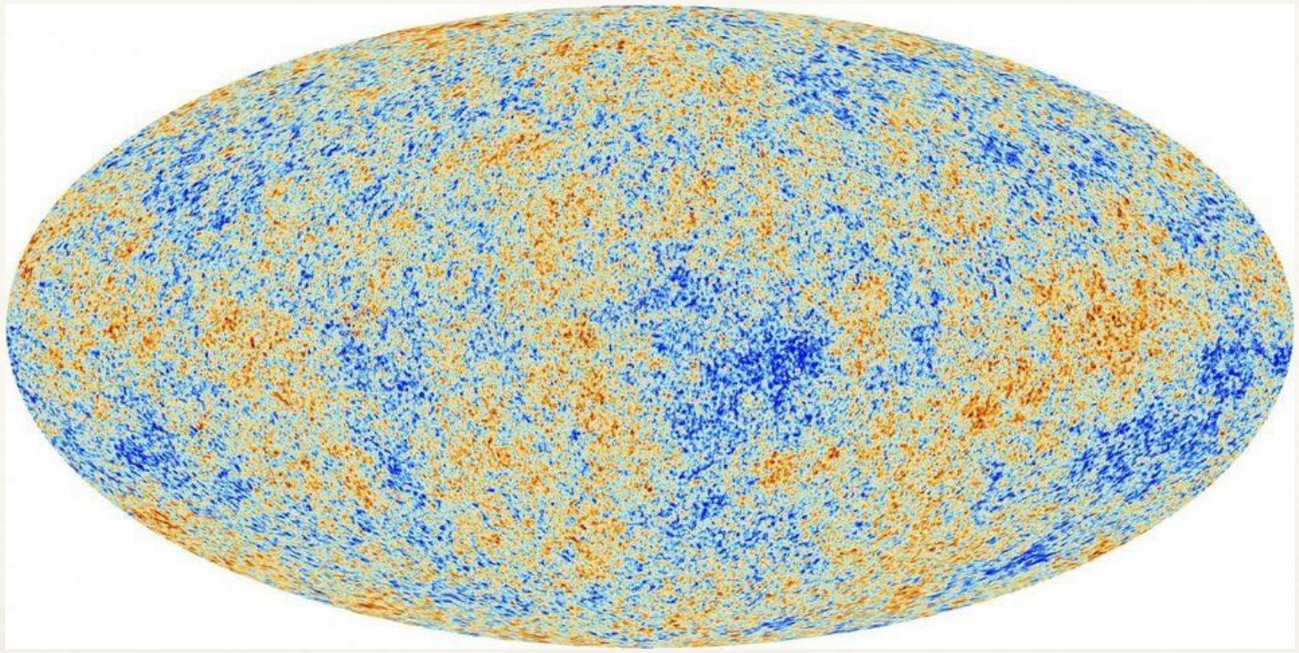

Tiempo

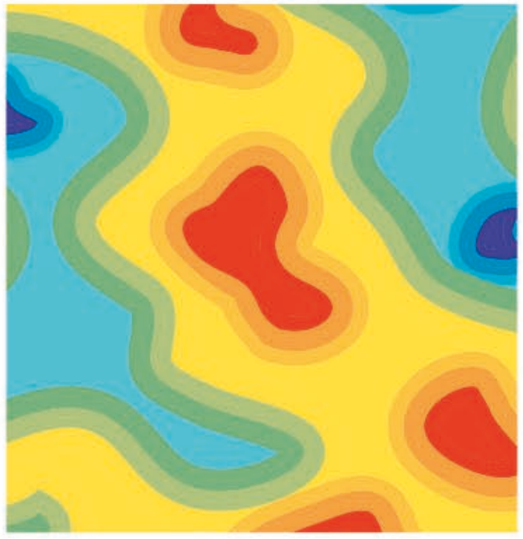


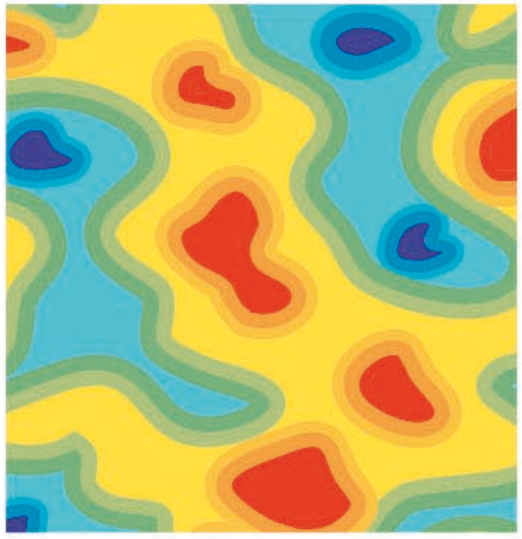
~13,000 millones de años

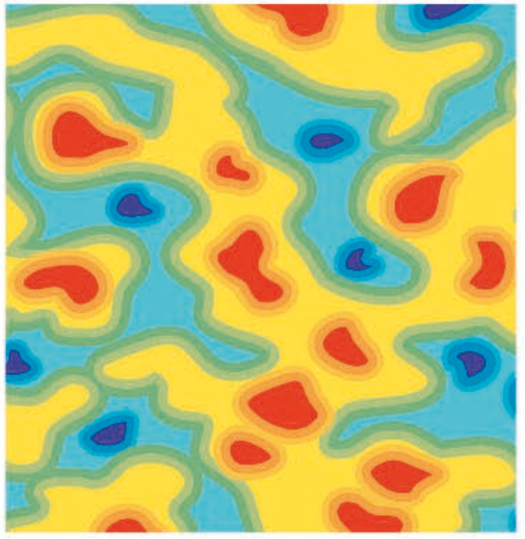


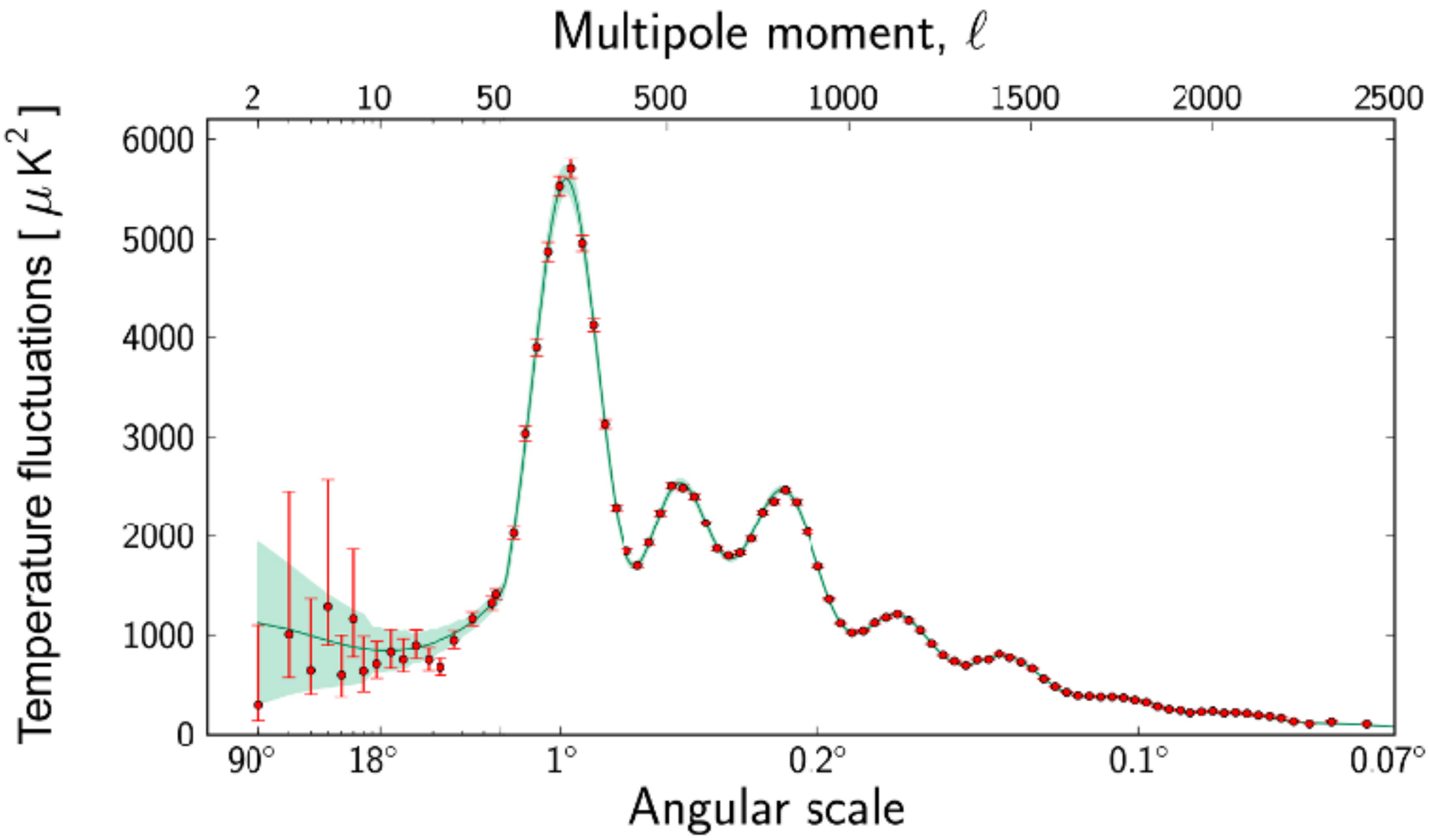
\+ materia

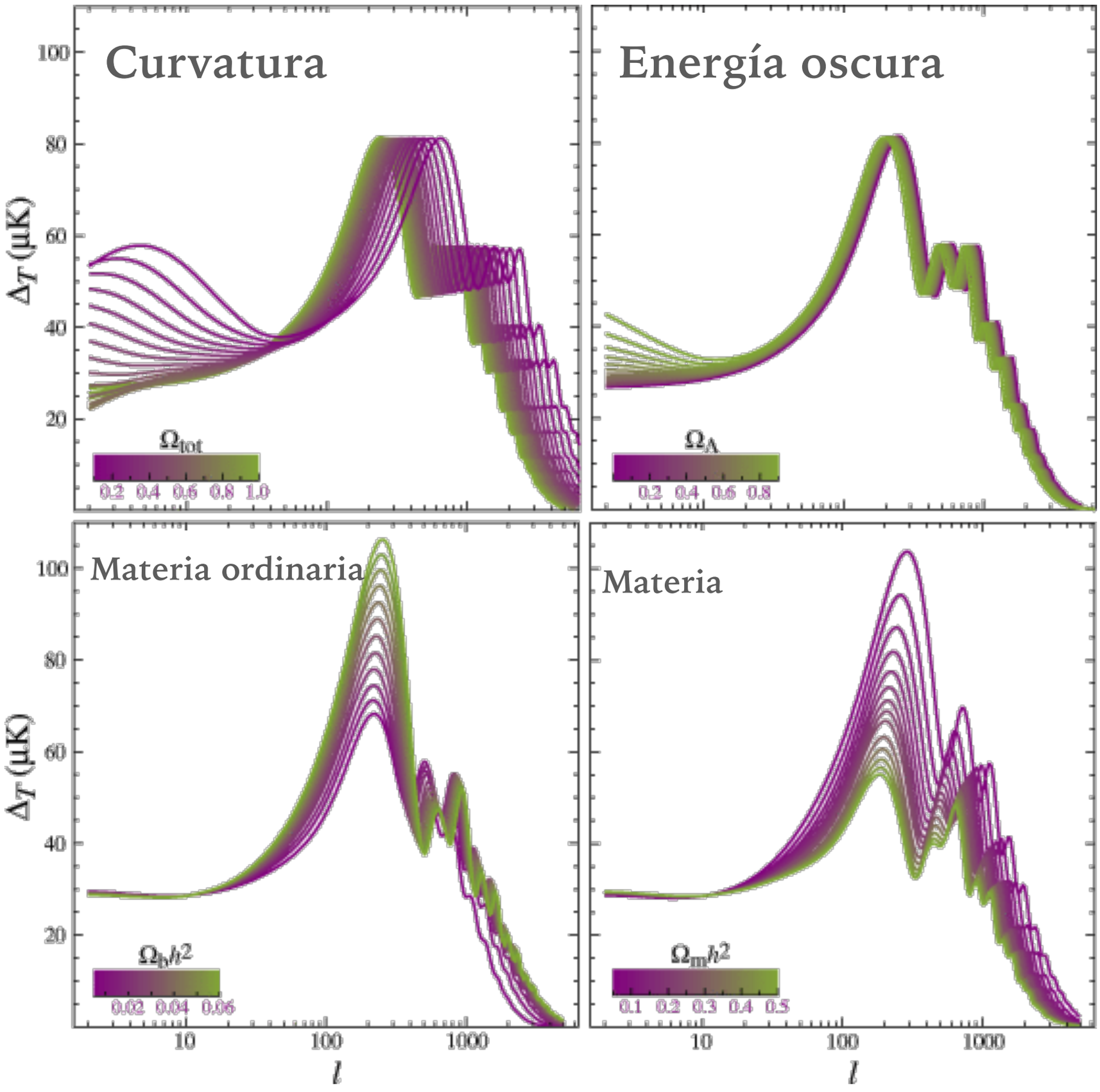




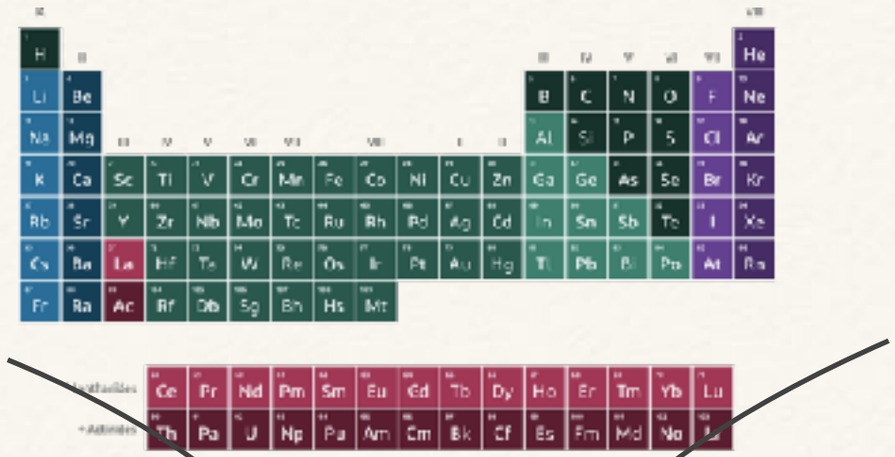


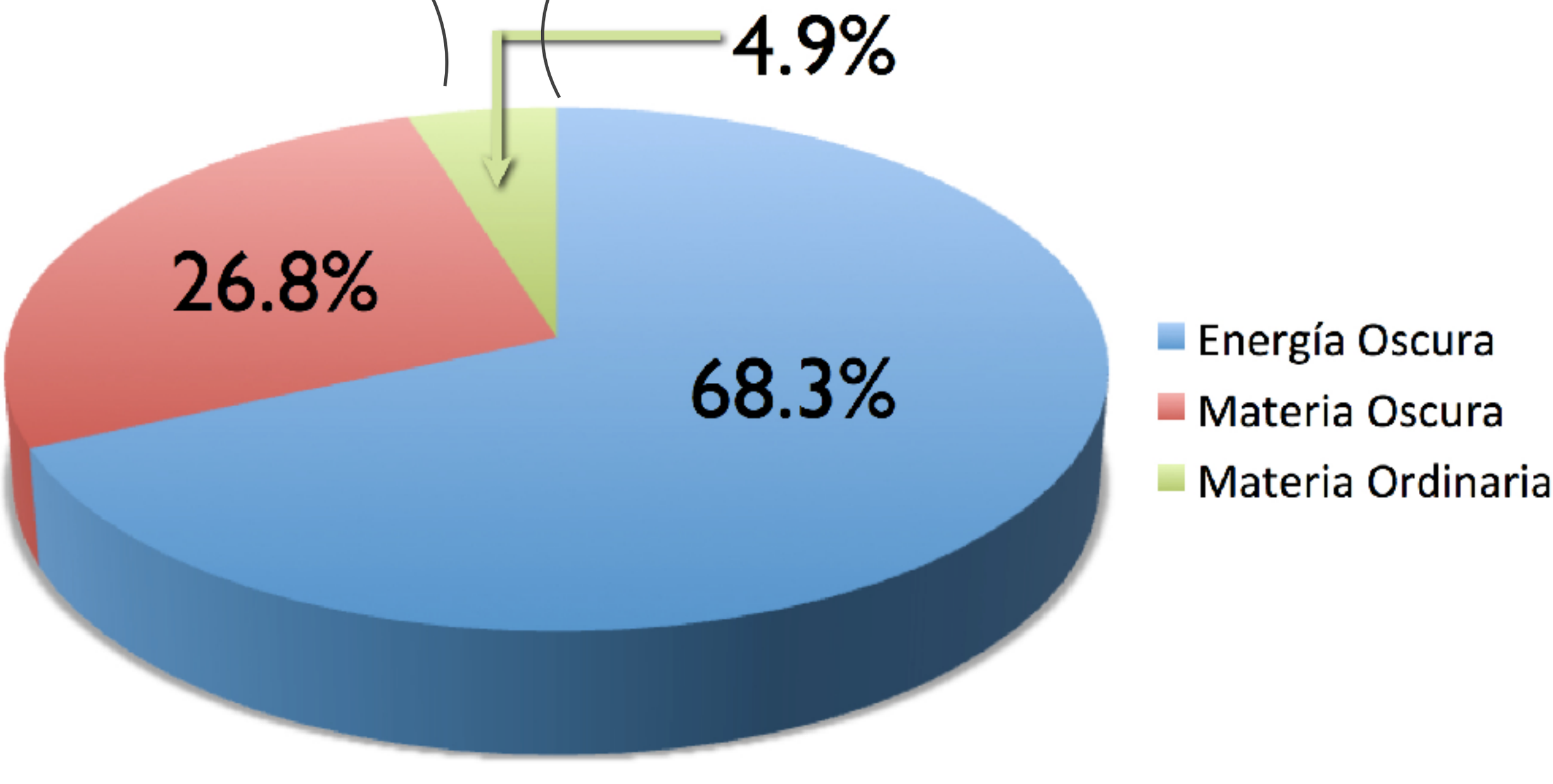


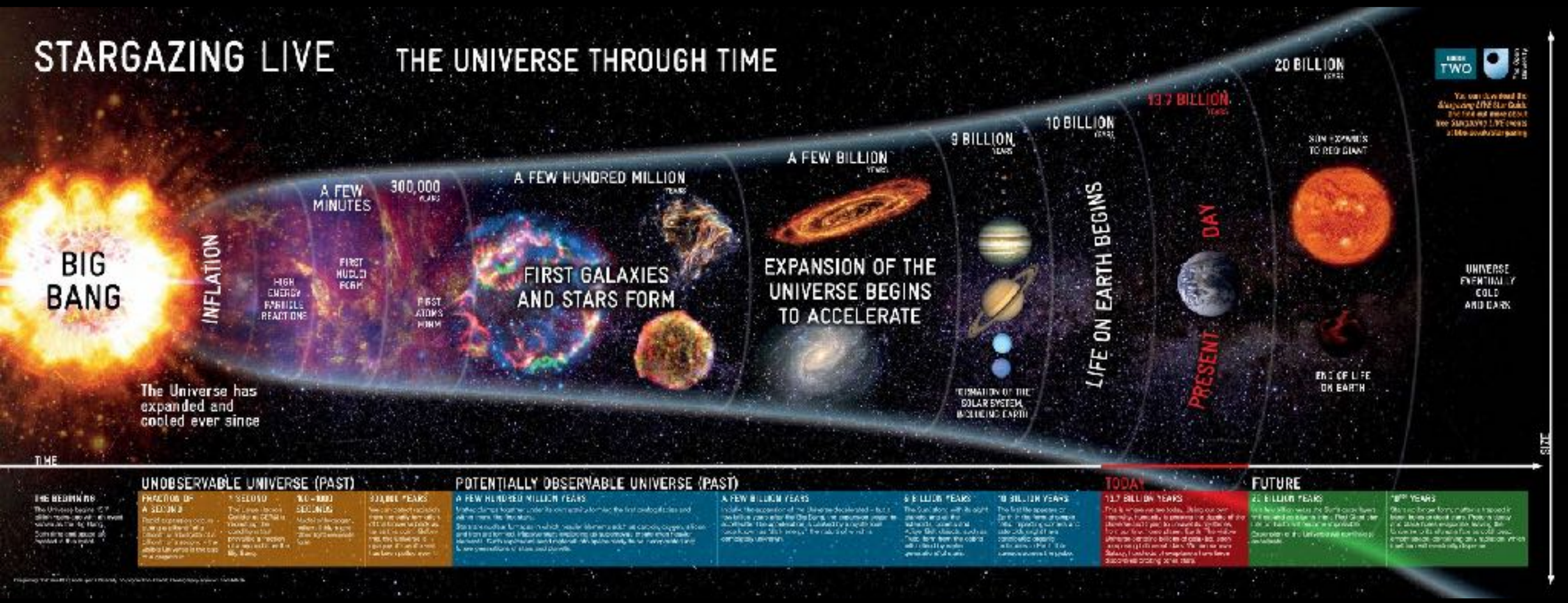

Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μ K^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale



Wayne Hu, U. of Chicago




4.9%
26.8%
68.3%
Energía Oscura
Materia Oscura
Materia Ordinaria



Evidencias:

Universo en expansión

Fondo cósmico de radiación

Nucleosíntesis primordial

EDWIN HUBBLE (1929)

Velocidad a la que se alejan de nosotros

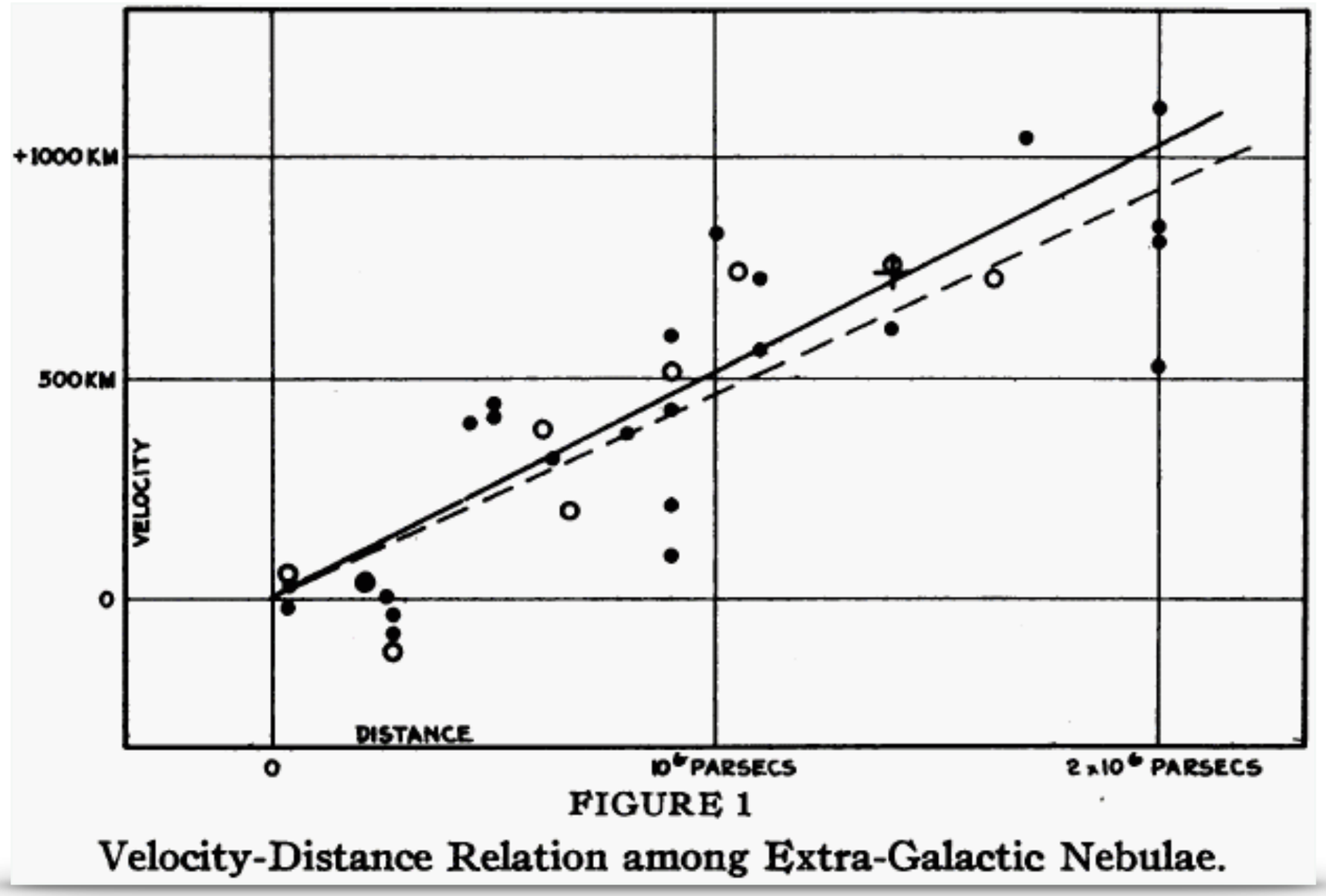
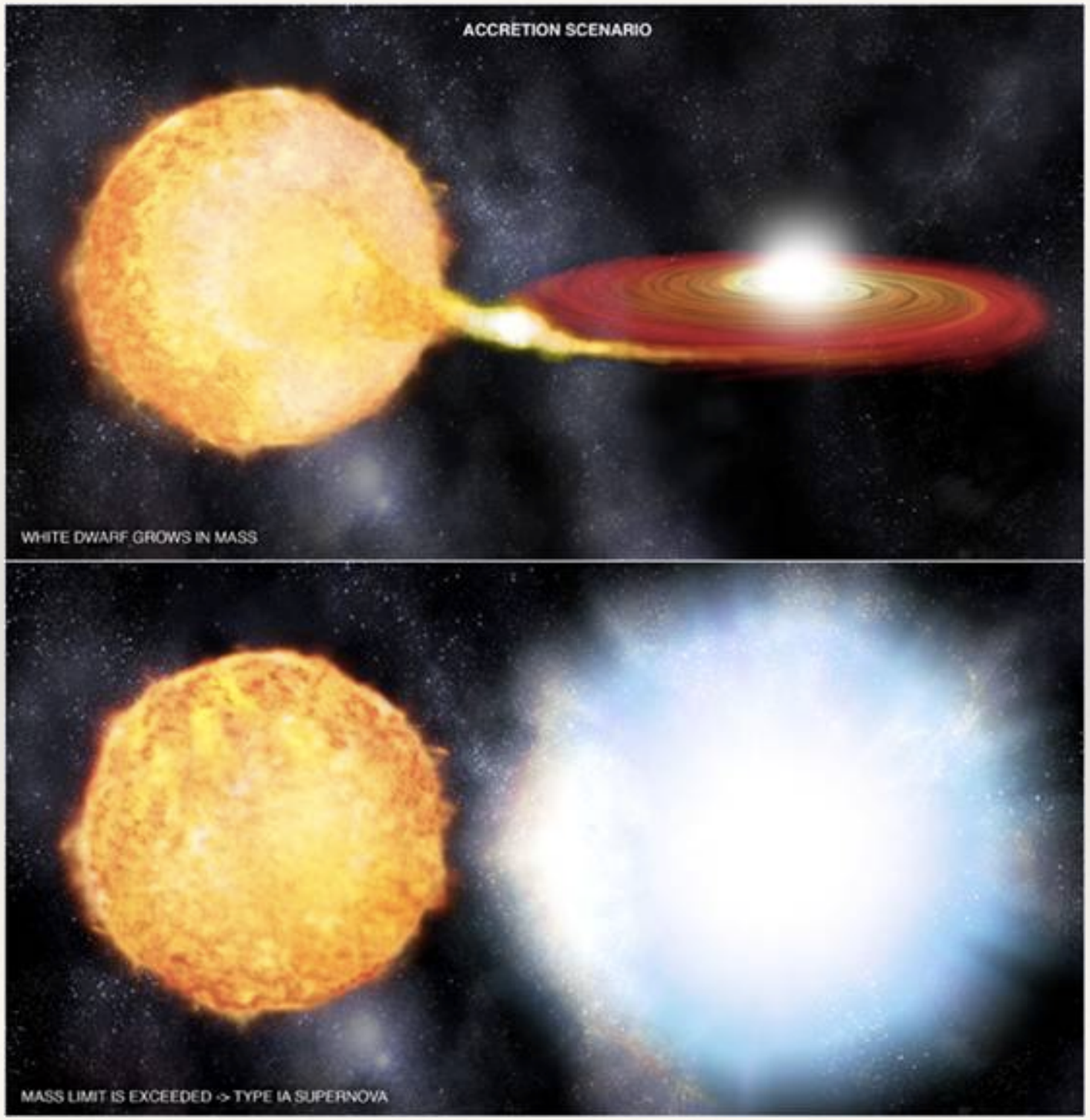


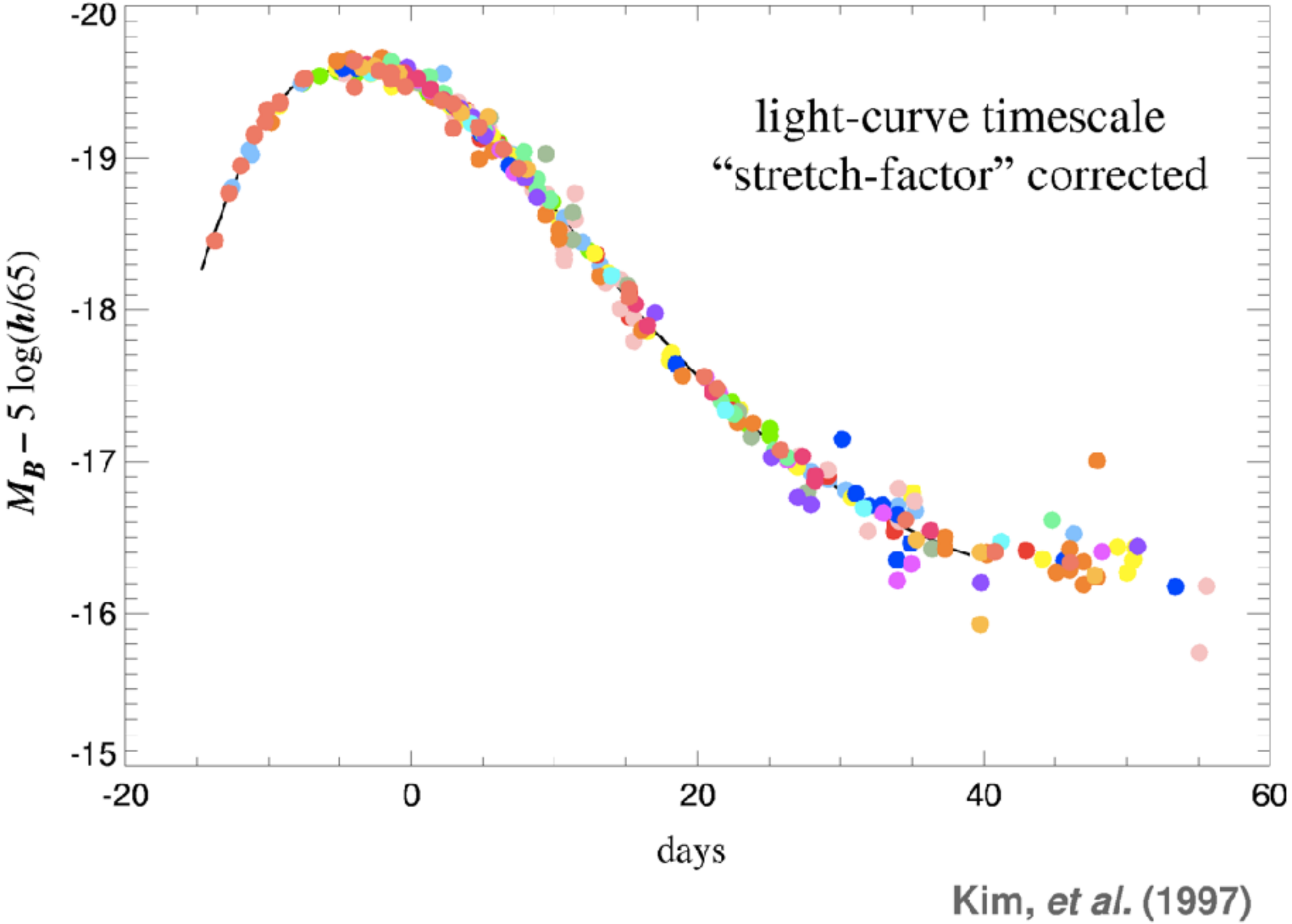
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

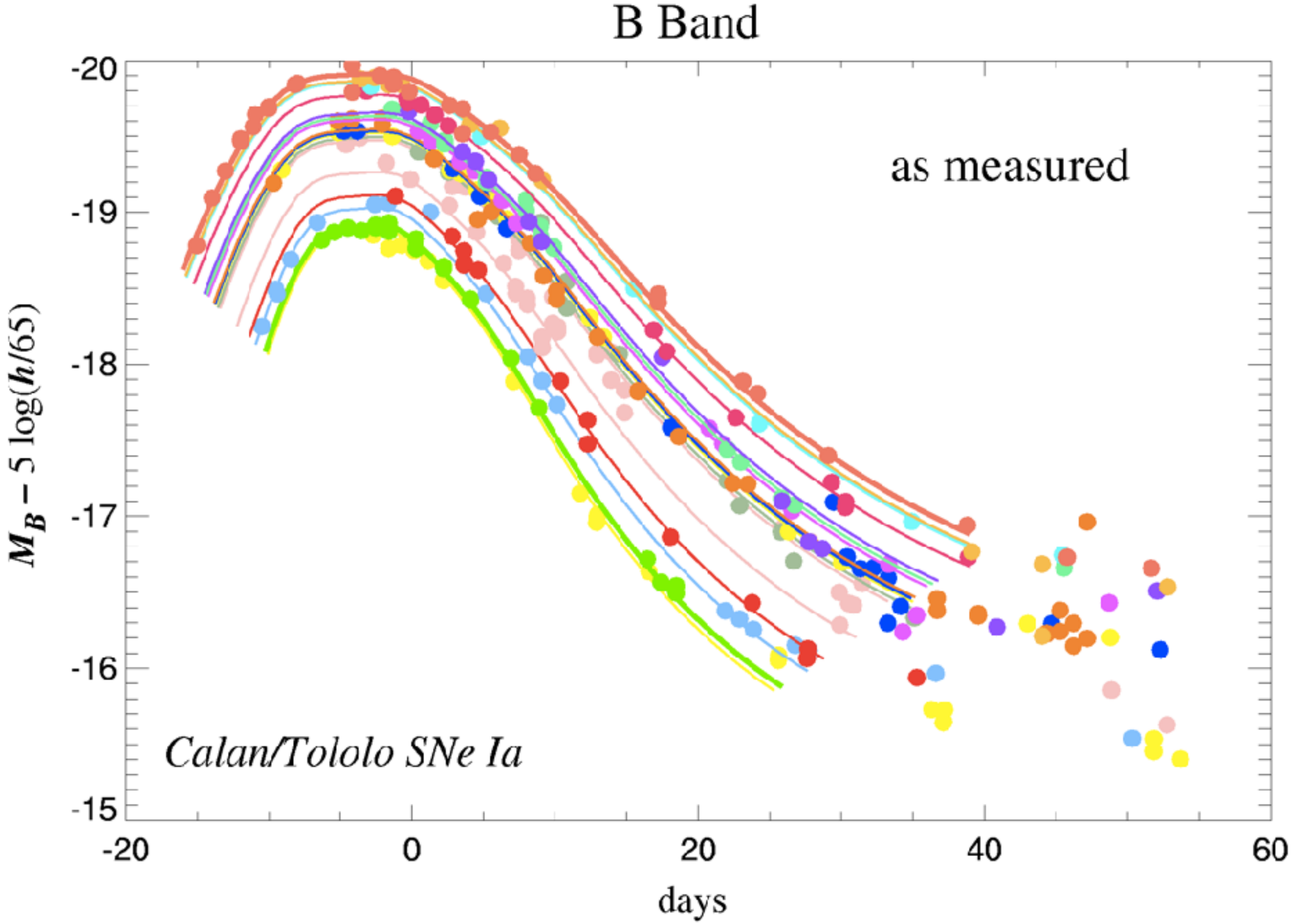
Distancia

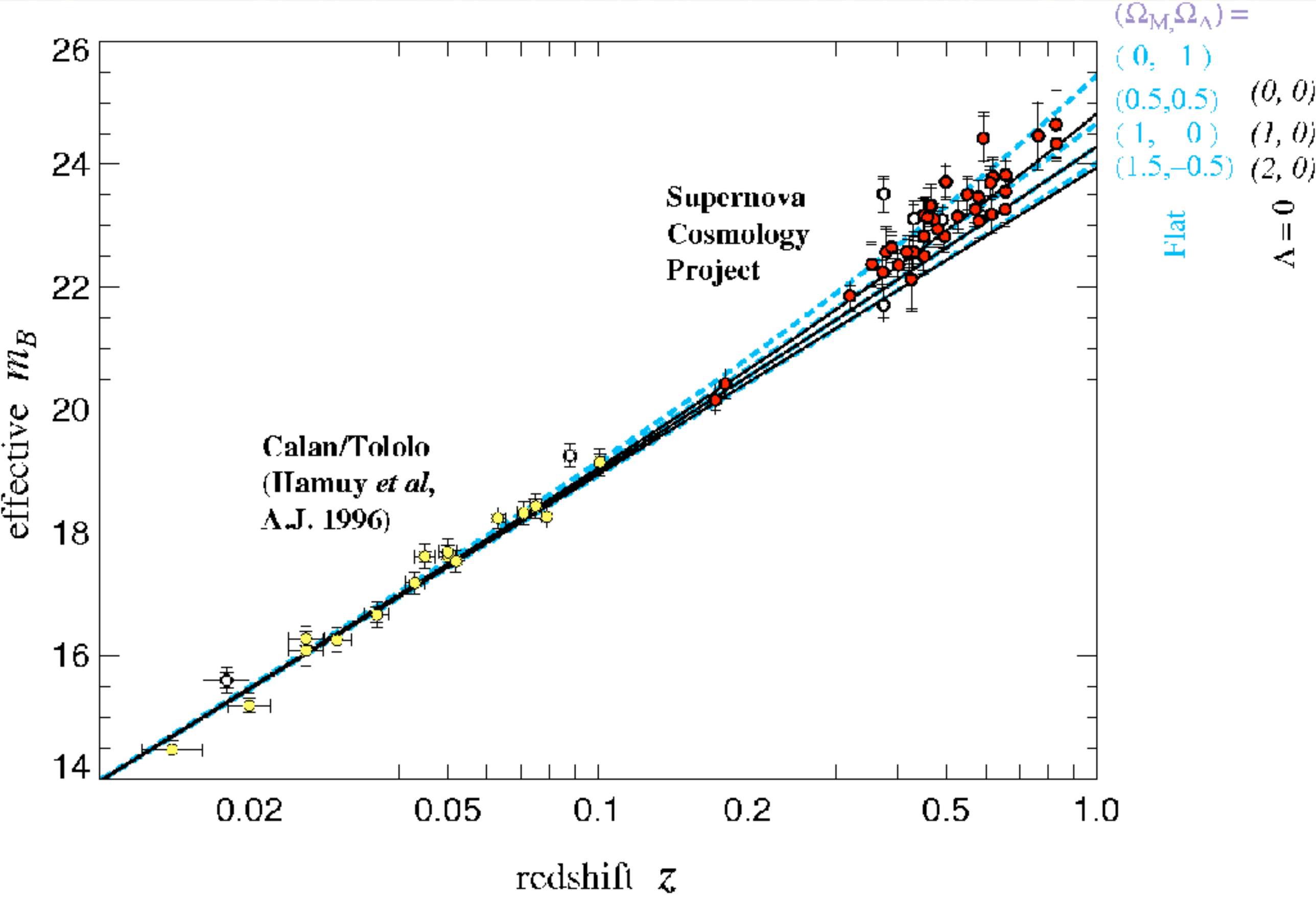
Supernovas tipo 1a





Kim, *et al.* (1997)


B Band
as measured
Calan/Tololo SNe Ia
$M_B - 5\log(h/65)$
-20
-19
-18
-17
-16
-15
-20
0
20
40
60
days


Supernova
Cosmology
Project
Calan/Tololo
(Hamuy et al,
A.J. 1996)
effective m_B
redshift z
26
24
22
20
18
16
14
0.02
0.05
0.1
0.2
0.5
1.0
$(\Omega_M,\Omega_\Lambda)$ =
(0, 1)
(0.5,0.5)
(1, 0)
(1.5,–0.5)
Flat
(0, 0)
(1, 0)
(2, 0)
$\Lambda = 0$