Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

Einstein i la Cosmologia

El naixement de la Cosmologia Moderna: l'important aportació d'Einstein

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www.ice.csic.es/personal/elizalde/eli/eli.htm www.enciclopedia.cat/divulcat/Emili-Elizalde

Universitat Catalana d'Estiu 2023, Prada de Conflent, Ciència i Tecnologia

22 d'agost del 2023

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

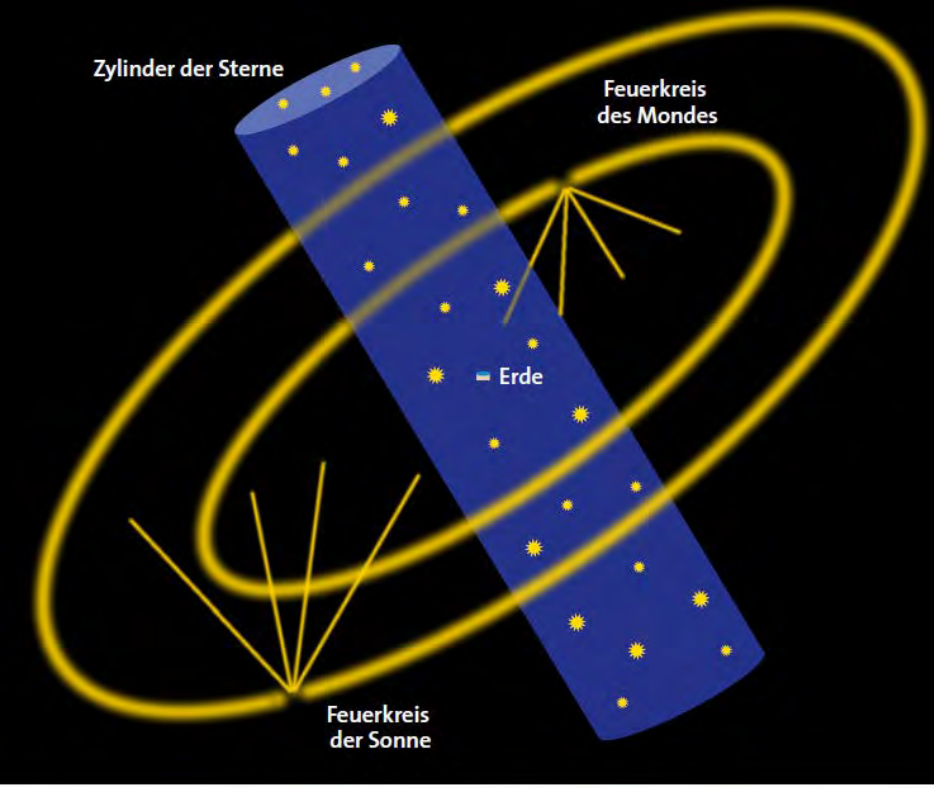
CSIC IEEC

El despertar de la consciencia còsmica

Above us, only sky …

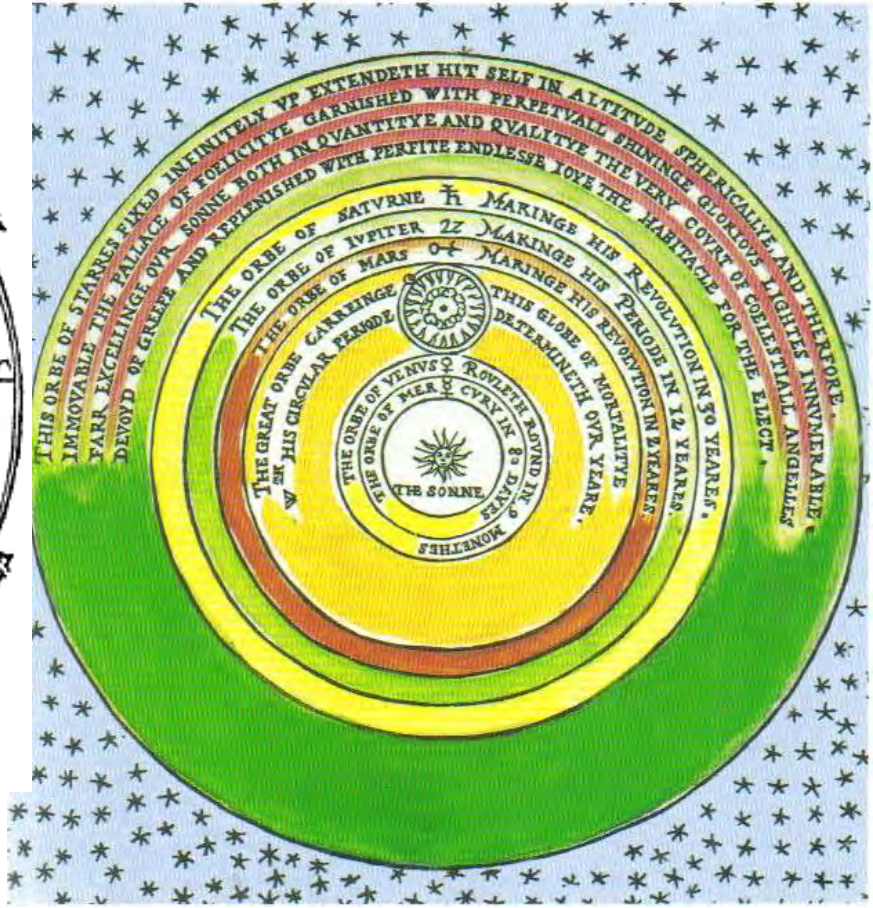
You may say I'm a dreamer …

John Lennon & Yoko Ono

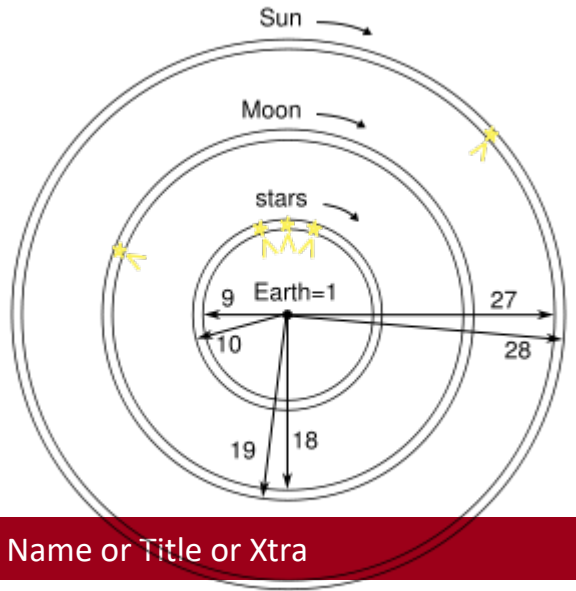


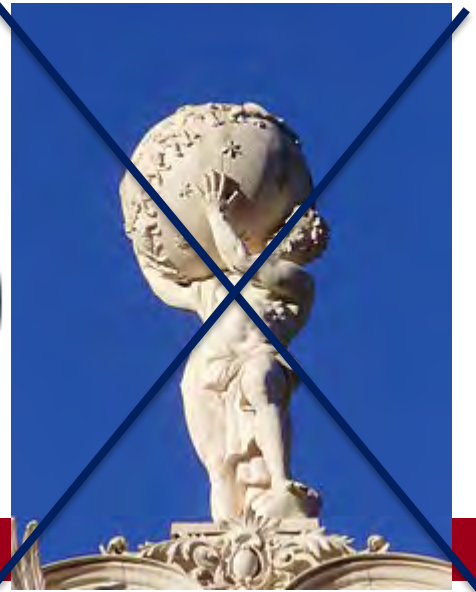
Univers d'Anaximandre 610–546 BC

Univers de Ptolomeu, s.II



Univers de Copèrnic, Thomas Digges 1576



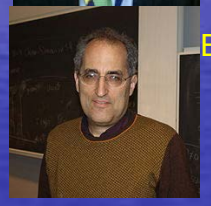


Diversos models d'Univers

Ciència

- Observació de la natura, exp. laboratori
  - No és suficient
- Teoria
  - No és suficient

Samuel Ting, Premi Nobel 76



Edward Witten, Fields Medal 90

Observacions + Teoria →

Comprensió de l'Univers !

Sir Isaac Newton (left) and Gottfried Wilhelm von Leibniz (right)

»Il libro della natura é scritto in lingua matematica»
Galileo Galilei (1564-1642)

Any 1912

Els inicis de la Cosmologia Moderna

- ✓ Distàncies Henrietta S. Leavitt (Cefeides)
- ✓ Velocitats Vesto M. Slipher (redshifts)

7 Abril 1912: Victor Hess descobriment dels raigs còsmics

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La 1era revolució cosmológica 1912-32

Observatori Lowell, Flagstaff, Arizona, EEUU

Vesto Slipher

Henrietta Leavitt

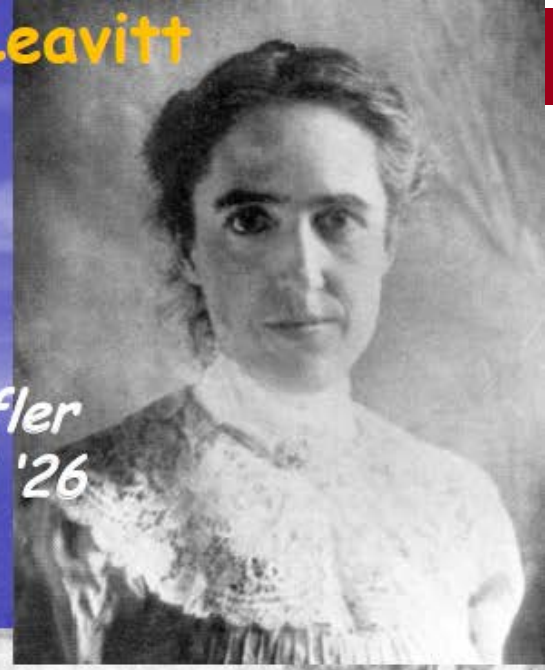
Edwin Hubble

Observatori Mount Wilson, Angeles National Forest, California, EEUU

Ed Pickering's Harvard Harem

Henrietta Leavitt

Mittag-Leffler
NP proposal '26



or Harvard
Computers

1913

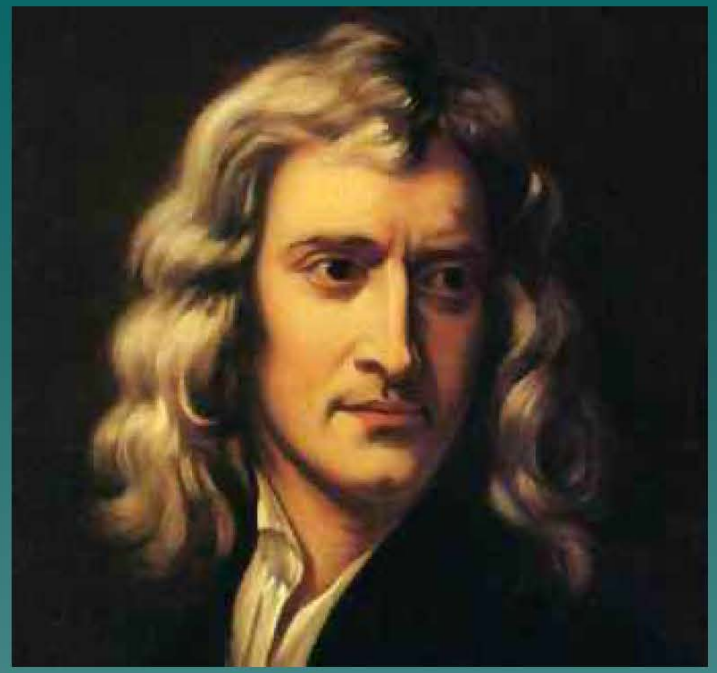
Henrietta S Leavitt 1912 period-luminosity relationship of Cepheid variable stars: linear dep luminosity vs log of period of variab stars (Eddington valve) "standard candles" for measuring H

SLIPHER

Vesto
Slipher

On September 17, 1912, obtained the first radial velocity of a "spiral nebula" - Andromeda. Using the 24-inch telescope at Lowell Observatory, AZ, he got more Doppler shifts, establishing that large velocities, usually in recession, were a general property of the spiral nebulae.

Slipher presented his results of the speed of 15 nebulae to the Am Astronomical Society in 1914, and received a standing ovation.



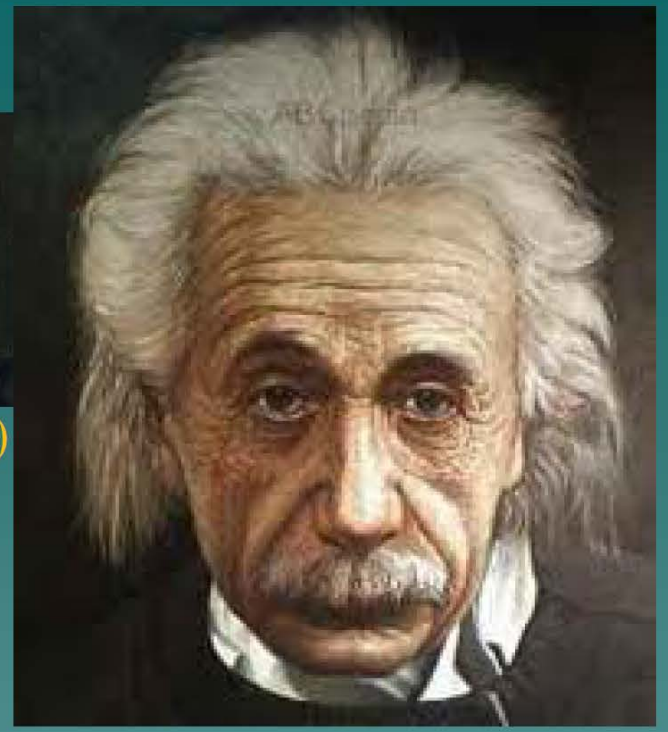
Isaac Newton (1642–1727)

$$F = G\frac{Mm}{r^2}$$

Leibniz (1646–1716)

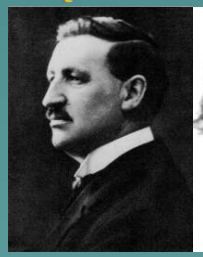
Galileo (1564–1642)

$$E = mc^2$$



Albert Einstein (1879-1955)

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



M Grossmann M Maric

$$\Omega_{tot} = \Omega_r + \Omega_m + \Omega_k + \Omega_\lambda$$

1917

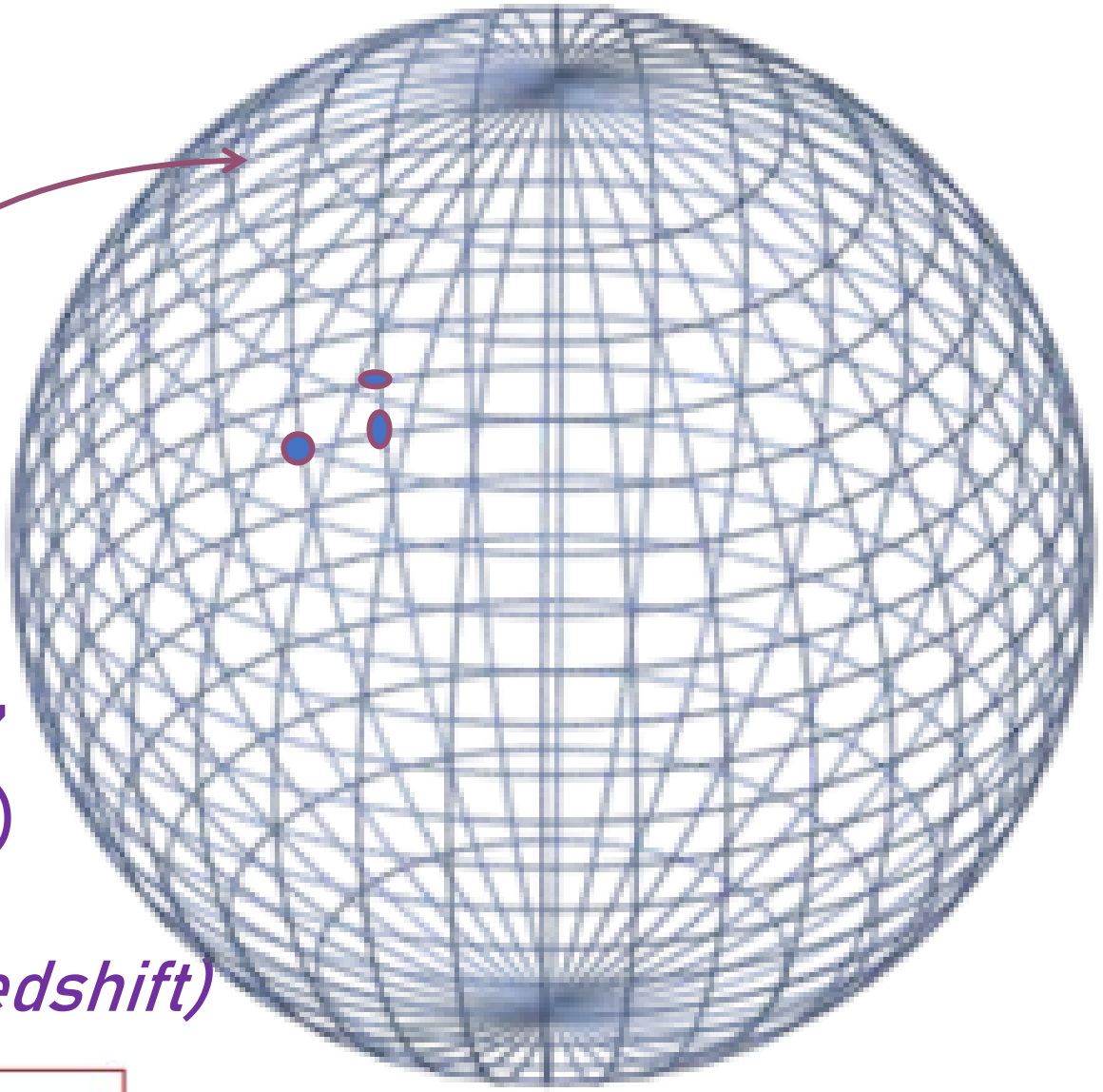
- ✓ Univers: etern
- ✓ Univers: estàtic *per què?*
- ✓ Univers = Via Làctia

Equacions de camp d'Einstein amb Λ

"Die Größte Eselei meines Lebens"

➡ Inicis de la Cosmologia Teòrica Moderna

L'UNIVERS



Model

- Superfície (2 dimensions, globus goma)
- Res a dins, res per fora; no hi ha 'centre'
- El 'globus' s'expandeix (acceleradament)
- El radi del globus és el temps
- Tot objecte al voltant nostre s'allunya *(redshift)*

November 23, 1924

The New York Times

FINDS SPIRAL NEBULAE ARE STELLAR SYSTEMS; Dr. Hubbell Confirms View That They Are 'Island Universes' Similar to Our Ow

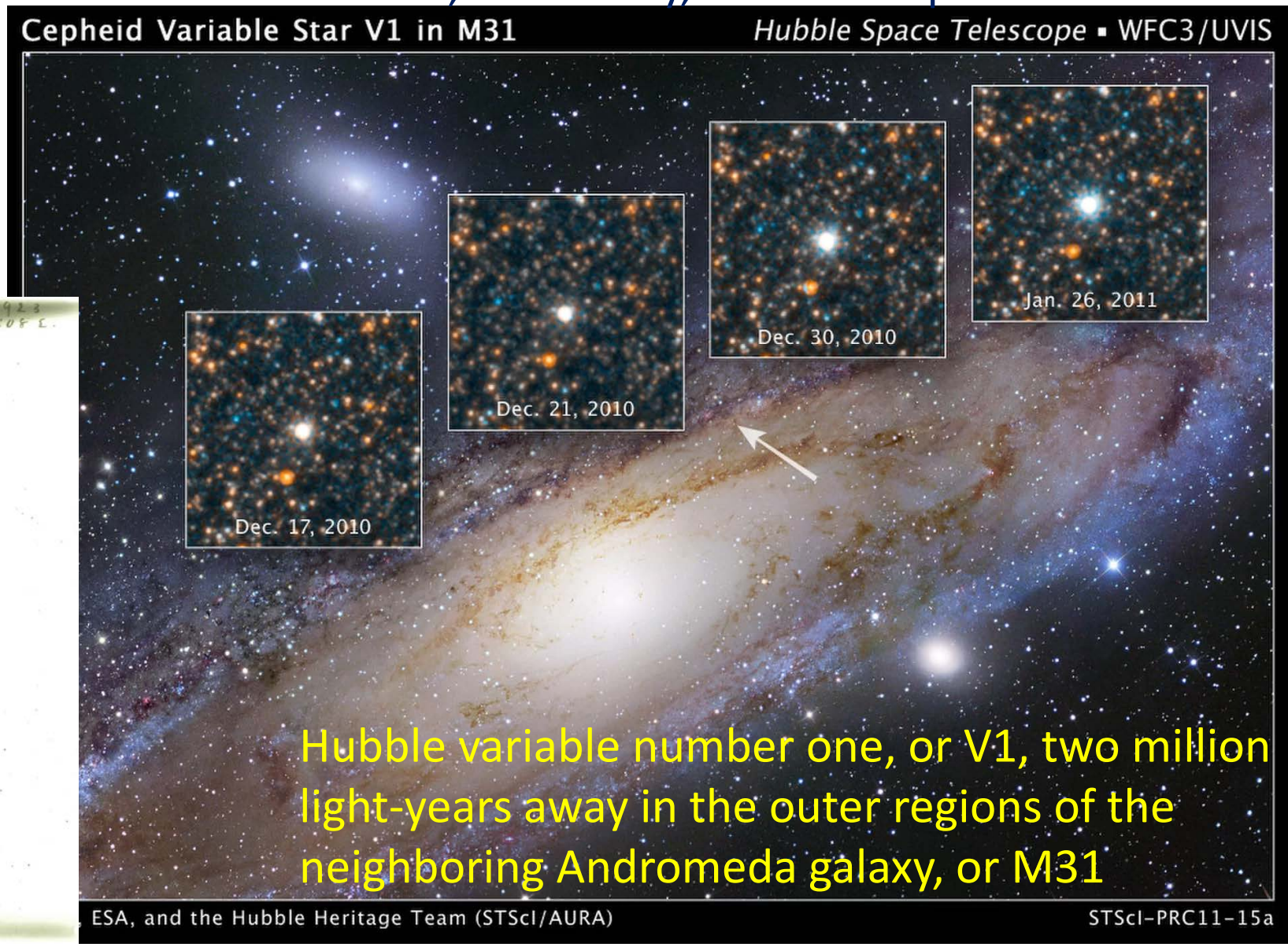
WASHINGTON, Nov. 22. -- Confirmation of the view that the spiral nebulae, whic appear in the heavens as whirling clouds, are in reality distant stellar systems, or "island universes," has been obtained by Dr. Edwin Hubbell of the Carnegie Institution's Mount Wilson observatory, through investigations carried out with tl observatory's powerful telescopes.


The New York Times.

In 1929 Hubble formulated the Redshift Distance Law, Hubble's law

Edwin Hubble (1929), *"A relation between distance and radial velocity among extra-galactic nebulae",* PNAS 15, 168–173

Image of H335H shows the glass side of the photographic plate, on which Hubble marked novae and, eventually, the first Cepheid in ink



Hubble variable number one, or V1, two million light-years away in the outer regions of the neighboring Andromeda galaxy, or M31

Ernst J. Öpik

Estonian astronomer and astrophys. (1893-1985) worked at the Armagh Observatory in Northern Ireland. In 1922 published a paper estimating the distance to Andromeda using an original method based on observed rotational velocities of the galaxy: 450 kpc. Was the first to calculate the density of a white dwarf.

His result was closer to recent estimates (775 kpc) than Hubble's result (285 kpc) of Nov 23, 1924; E Öpik, ApJ 55, 406, 1922.

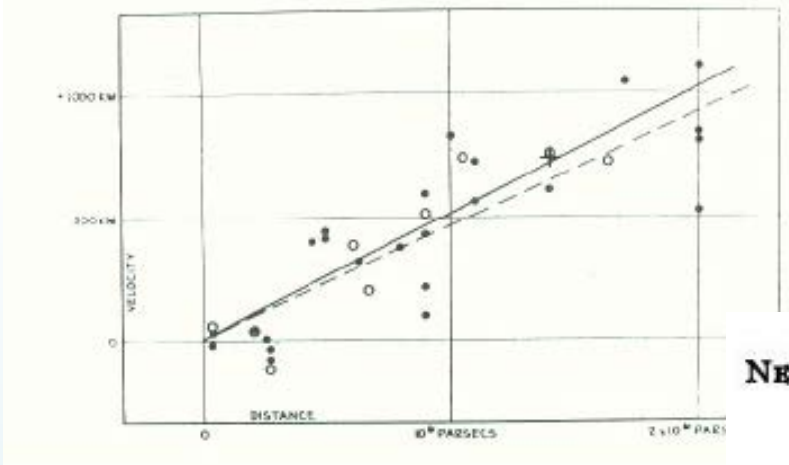


Table 1: Radial velocities in km/s of 25 spiral nebulae published by VM Slipher in 1917

RADIAL VELOCITIES OF TWENTY-FIVE SPIRAL NEBULÆ.

Nebula.	Vel.	Nebula.	Vel.
N.G.C. 221	− 300 km.	N.G.C. 4526	+ 580
224	− 300	4565	+1100
598	− 260	4594	+1100
1023	+ 300	4649	+1090
1068	+1100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

"... your velocities and my distances". Letter of E.P. Hubble to V.M. Slipher, Mar 6, 1953. Biographical Memoirs, Vol 52, National Academy of Sciences (U.S.)

Table 1: Distances in Mpc of spiral nebulae published by E Hubble in 1929

TABLE 1

NEBULAE WHOSE DISTANCES HAVE BEEN ESTIMATED FROM STARS INVOLVED OR FROM MEAN LUMINOSITIES IN A CLUSTER

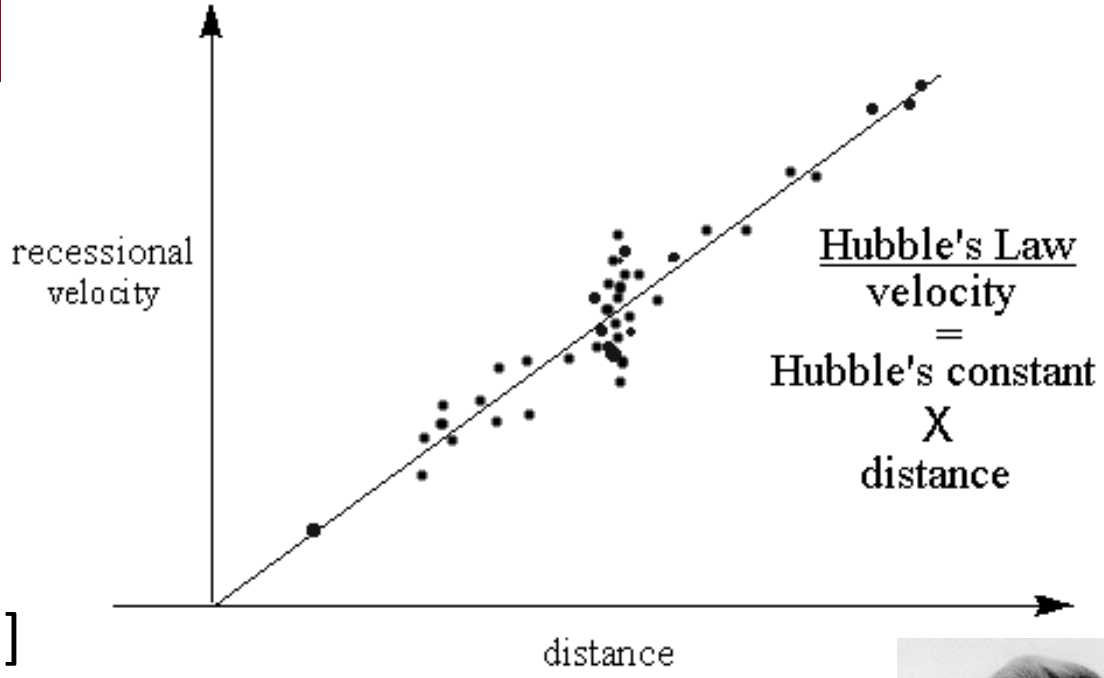
OBJECT	m_s	r	v	m_t	M_t
S. Mag.	..	0.032	+ 170	1.5	−16.0
L. Mag.	..	0.034	+ 290	0.5	17.2
N. G. C. 6822	..	0.214	− 130	9.0	12.7
598	..	0.263	− 70	7.0	15.1
221	..	0.275	− 185	8.8	13.4
224	..	0.275	− 220	5.0	17.2
5457	17.0	0.45	+ 200	9.9	13.3
4736	17.3	0.5	+ 290	8.4	15.1
5194	17.3	0.5	+ 270	7.4	16.1
4449	17.8	0.63	+ 200	9.5	14.5
4214	18.3	0.8	+ 300	11.3	13.2
3031	18.5	0.9	− 30	8.3	16.4
3627	18.5	0.9	+ 650	9.1	15.7
4826	18.5	0.9	+ 150	9.0	15.7
5236	18.5	0.9	+ 500	10.4	14.4
1068	18.7	1.0	+ 920	9.1	15.9
5055	19.0	1.1	+ 450	9.6	15.6
7331	19.0	1.1	+ 500	10.4	14.8
4258	19.5	1.4	+ 500	8.7	17.0
4151	20.0	1.7	+ 960	12.0	14.2
4382	..	2.0	+ 500	10.0	16.5
4472	..	2.0	+ 850	8.8	17.7
4486	..	2.0	+ 800	9.7	16.8
4649	..	2.0	+1090	9.5	17.0

Hubble's Law

At large scale, the dominant movement of our Universe is dictated by the law:

$$V = H_o D$$

H_o = (67.8 +/- 0.9) km/s/Mpc [500 Hubble, 1929]



Interpretation:

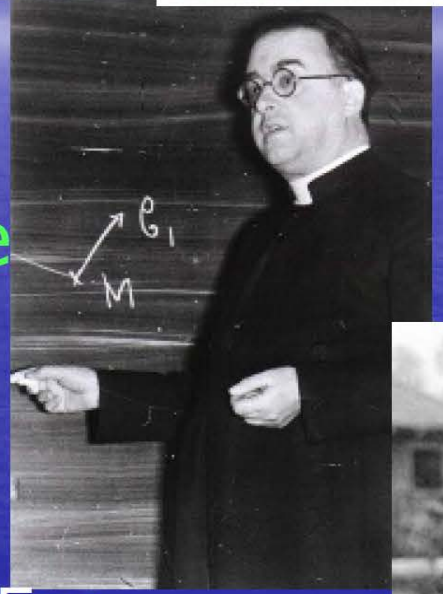
1. Proper movement of the galaxies
2. Movement of the reference system, of space-time

Both are right! –But the second prevails at large distances

Big Bang

"Condició primigènia en la qual existien unes condicions d'una infinita densitat i temperatura" [Wikipedia CAT]

"At some moment all matter in the universe was contained in a single point" [Wikipedia]

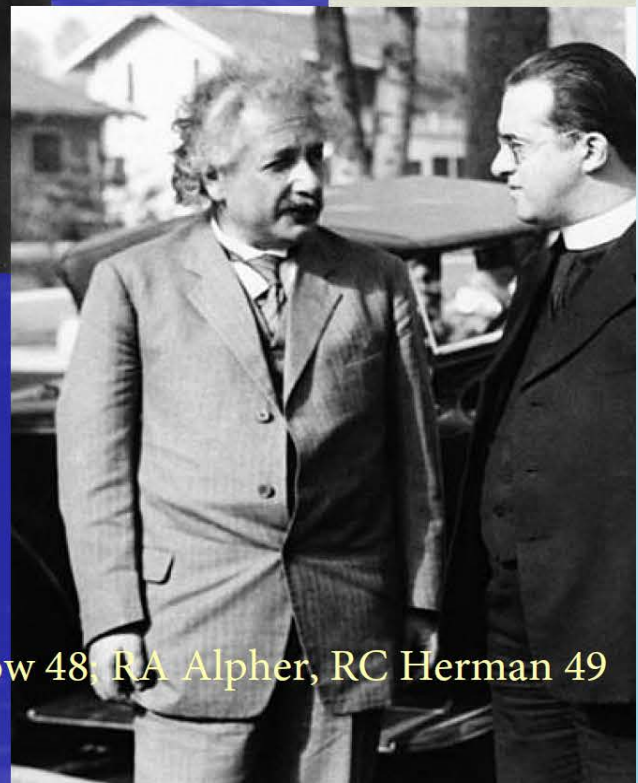


Georges Lemaître (1894-1966)

Theory, 1927: Solution (Friedmann's) of Einstein's Eqs
Annales Société Scientifique Bruxelles **47**, 49 (1927), Eddington *MNRAS* (1930)

Observational evid.: V. Slipher redshifts + E. Hubble distancies

"hypothèse de l'atome primitif" *Nature* **127**, 706 (1931)
primeval atom, cosmic egg



WS Adams i T Dunham Jr 37-41; G Gamow 48; RA Alpher, RC Herman 49

James Peebles: *"The discovery that the U is expanding"*, Madrid 21/4/15

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Solvay Conference, Brussels, Belgium, 1927

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L'expansió de l'Univers:

Un dels descobriments més importants en tota la Història de la Humanitat

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Electronic vote on the Resolution B4 "on a suggested renaming of the Hubble Law"

The Chair of the Resolution Committee presenting the Resolution B4

Voting Results for the Vote on Resolution B4 "on a suggested renaming of the Hubble Law"

Option	No. of Votes	
I approve the Resolution B4	3169	78%
I reject the Resolution B4	798	20%
Abstain	93	2%
Total Number of Votes	4,060	

Background

Five Resolutions were proposed for approval at the XXXth IAU General Assembly (Vienna, August 20th – 31st, 2018). They were announced and posted on the IAU web site on June 20th (see https://www.iau.org/news/announcements/detail/ann18029/) and initially they did not generate any comments by the members.

"Big Bang" BBC 28 març 1949

Fred Hoyle (1915-2001)

"... all matter in the universe was created in one big bang at a particular time ..."

Impossible!

La primera revolució cosmològica:

canvià del tot la nostra visió de l'Univers; de ser estàtic, immutable i etern va passar a tenir un origen –a partir del no-res– i a expansionar-se

Miracle de la Física No. 1

[Alan Guth, MIT]

"La gravetat pot ser repulsiva"

2ona Equació de Friedmann

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

$$p = w\,\rho$$

Miracle de la Física No. 2

[Alan Guth, MIT]

"Les energies no són sempre positives: el camp gravitatori te energia negativa"

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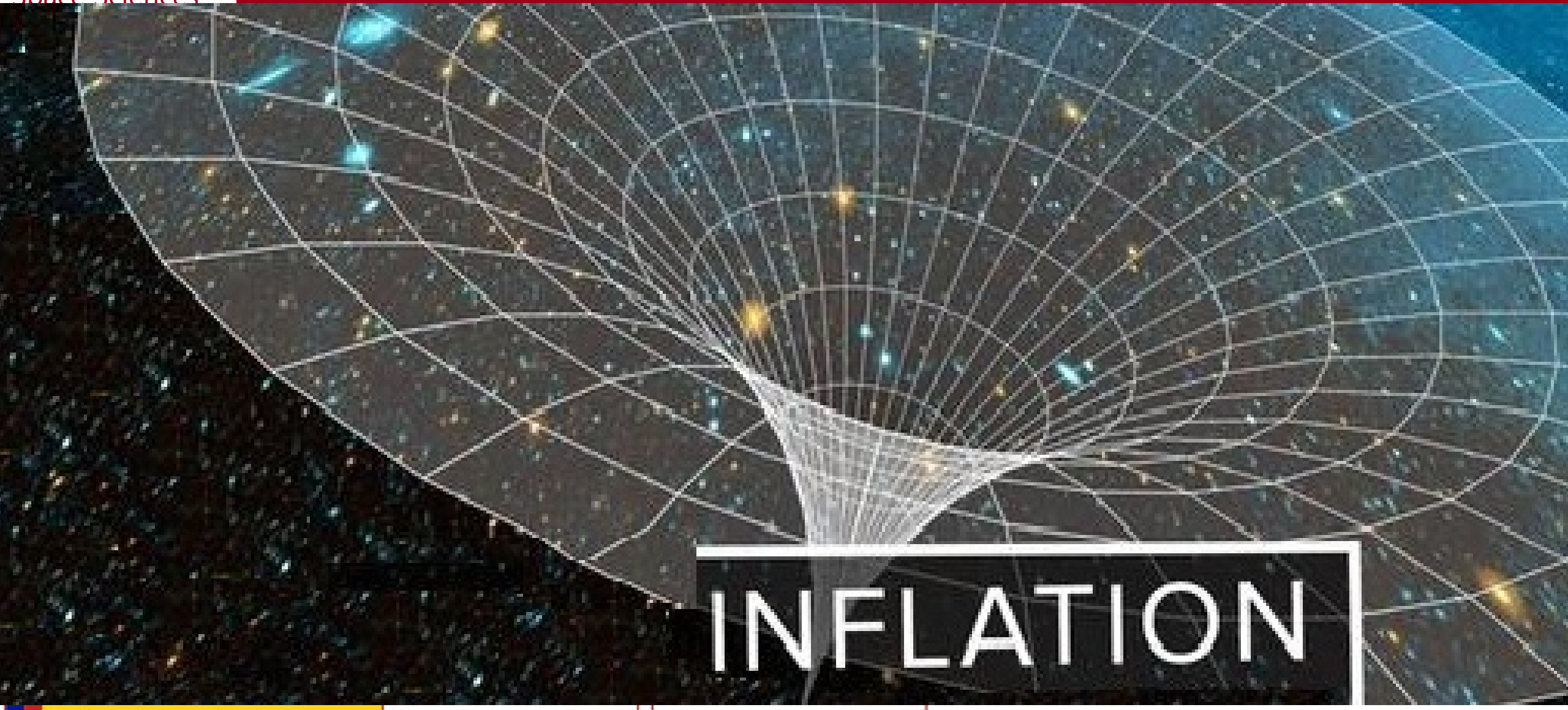

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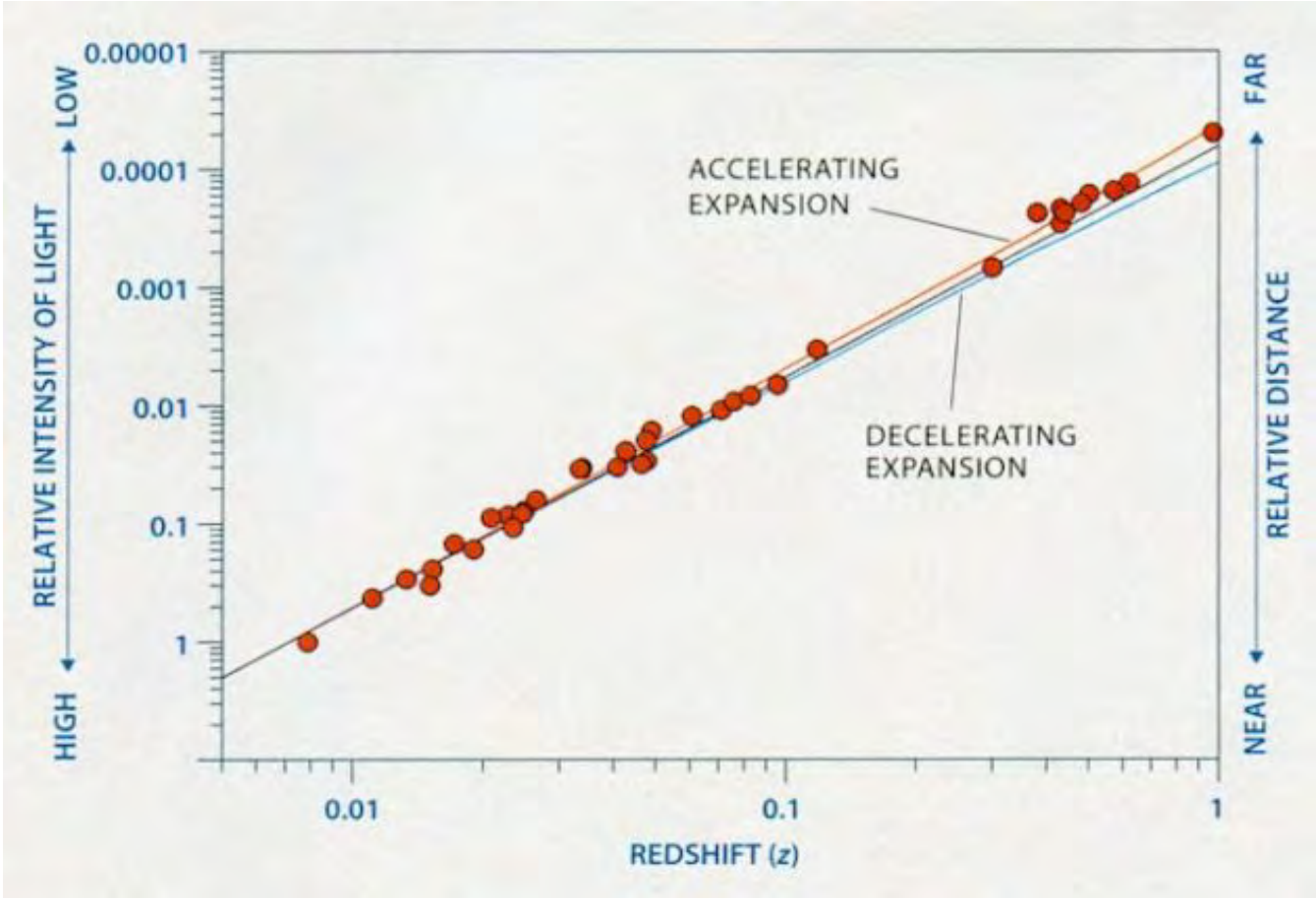
Adam Riess Saul Perlmutter Brian Schmidt
Nobel Prize in Physics 2011

A Riess, B Schmidt, et al. "Observational evidence from supernovae for an accelerating universe and a cosmological constant". Astronomical Journal 116, 1009–38 (1998).

S Perlmutter, ..., P Ruiz-Lapuente, et al. "Measurements of Omega and Lambda from 42 high redshift supernovae". Astrophysical Journal 517, 565–86 (1999).

L'expansió de l'Univers no es frena per la gravetat, sino que, contrariament, s'accelera



- Per als especialistes cap sorpresa: molts indicis de Λ implicaven que l'expansió de l'univers s'accelerava
- Les observacions de les SNIa es van haver de confirmar independentment: CMB, formació primerenca de galàxies, distribucions de galàxies properes, BAO, i moltes altres
- Roman la gran pregunta: quin és el motiu físic d'aquesta acceleració universal? S'han proposat
    - Einstein RG amb Λ
    - Altra possibilitat: modificar la RG

La segona revolució cosmològica:

hem après, a més, que l'expansió s'accelera constantment, creant així un misteri absolut on abans hi havia completa certesa

Dues revolucions cosmològiques s. XX

- Primera (1912-1932):

  Univers petit, etern, estàtic **esdevingué**

  immens, origen (de 'quasi res'), expansió

- Segona (1985-2005):

  expansió accelerada (!?)

THE TRUE STORY OF MODERN COSMOLOGY

Origins, Main Actors and Breakthroughs

This book tells the story of how, over the past century, dedicated observers and pioneering scientists achieved our current understanding of the universe. It was in antiquity that humankind first attempted to explain the universe often with the help of myths and legends. This book, however, focuses on the time when cosmology finally became a true science. As the reader will learn, this was a slow process, extending over a large part of the 20th century and involving many astronomers, cosmologists and theoretical physicists. The book explains how empirical astronomical data (e.g., Leavitt, Slipher and Hubble) were reconciled with Einstein's general relativity; a challenge which finally led Friedmann, De Sitter and Lemaître, and eventually Einstein himself, to a consistent understanding of the observational results.

The reader will realize the extraordinary implications of these achievements and how deeply they changed our vision of the cosmos: From being small, static, immutable and eternal, it became vast and dynamical — originating from (almost) nothing, and yet now, nearly 14 billion years later, undergoing accelerated expansion. But, as always happens, as well as precious knowledge, new mysteries have also been created where previously absolute certainty had reigned.

ISBN 978-3-030-80653-8

▶ springer.com

EMILIO ELIZALDE

THE TRUE STORY OF MODERN COSMOLOGY

THE TRUE STORY OF MODERN COSMOLOGY

Origins, Main Actors and Breakthroughs

EMILIO ELIZALDE

Springer

Cosmología moderna desde sus orígenes

No resulta difícil imaginar a nuestros ancestros contemplando admirados el maravilloso cielo nocturno. Y fue ya en la Antigüedad cuando empezaron a elaborarse las primeras teorías sobre los componentes constitutivos del universo, material y etéreo, que nos envuelve. Este libro se centra sobre todo en un punto concreto: investigar el momento en que la cosmología se convirtió por fin en una verdadera ciencia, en que las teorías sobre el cosmos devinieron teorías científicas. Eso no sucedió de la noche a la mañana, ya que fue un proceso lento, que ocupó gran parte del siglo XX y en el que intervinieron numerosos astrónomos, cosmólogos y teóricos de la física fundamental, con sus grandes aciertos y, en ocasiones, crasos errores.

Todo este proceso se fundamentó en conciliar los datos empíricos obtenidos de las observaciones astronómicas (Leavitt, Slipher, Hubble) con un marco teórico muy sólido: la relatividad general de Einstein. Teoría que finalmente permitió (Friedmann, De Sitter, Lemaître) interpretar y entender los resultados obtenidos por los astrónomos. Visto en perspectiva, las aportaciones del pasado siglo tuvieron unas implicaciones extraordinarias, casi increíbles, que cambiaron por completo nuestra visión del universo: de ser pequeño, estático, inmutable y eterno pasó a ser enorme, a tener un principio, a partir de casi nada, y a expandirse aceleradamente. Lo que ha creado, a su vez, un nuevo misterio donde por un tiempo reinó la certeza absoluta.

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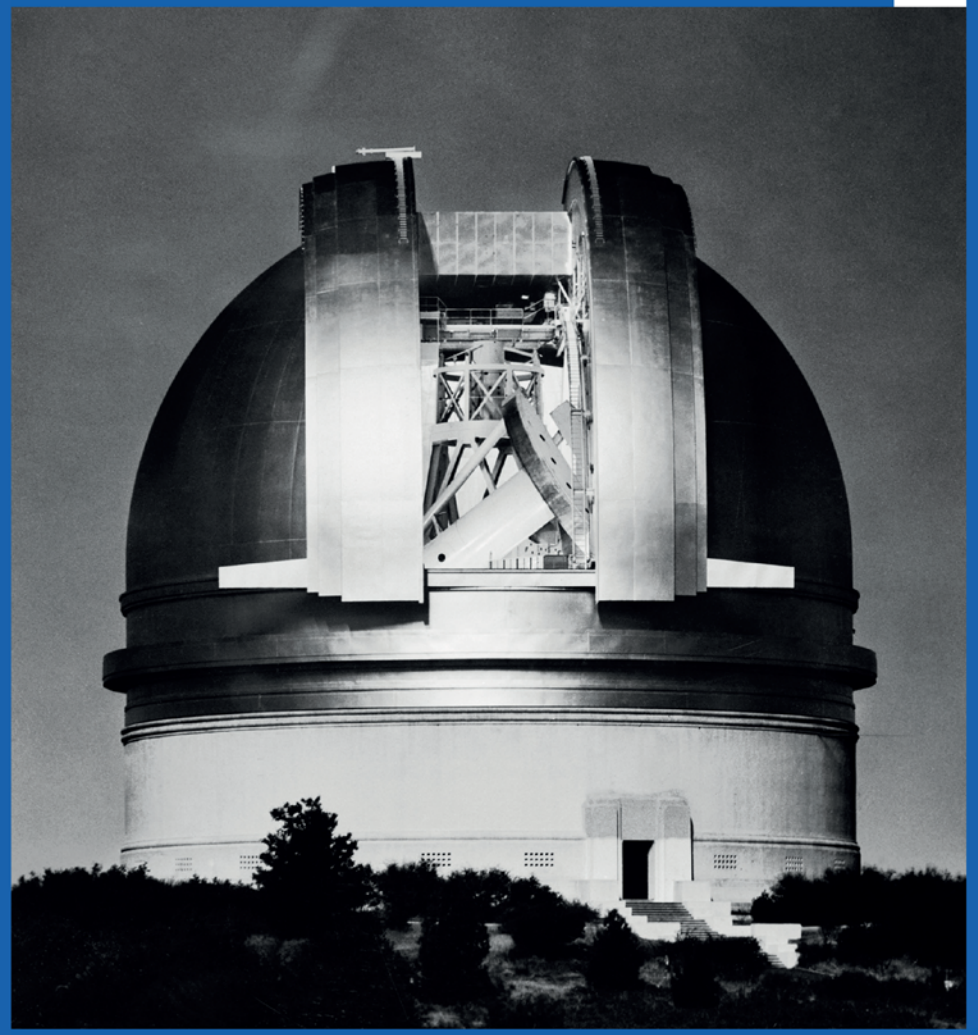
9 788413 521251
17 € ISBN: 978-84-1352-125-1

Emilio Elizalde Cosmología moderna desde sus orígenes

Emilio Elizalde

Cosmología moderna
desde sus orígenes

FÍSICA Y CIENCIA PARA TODOS

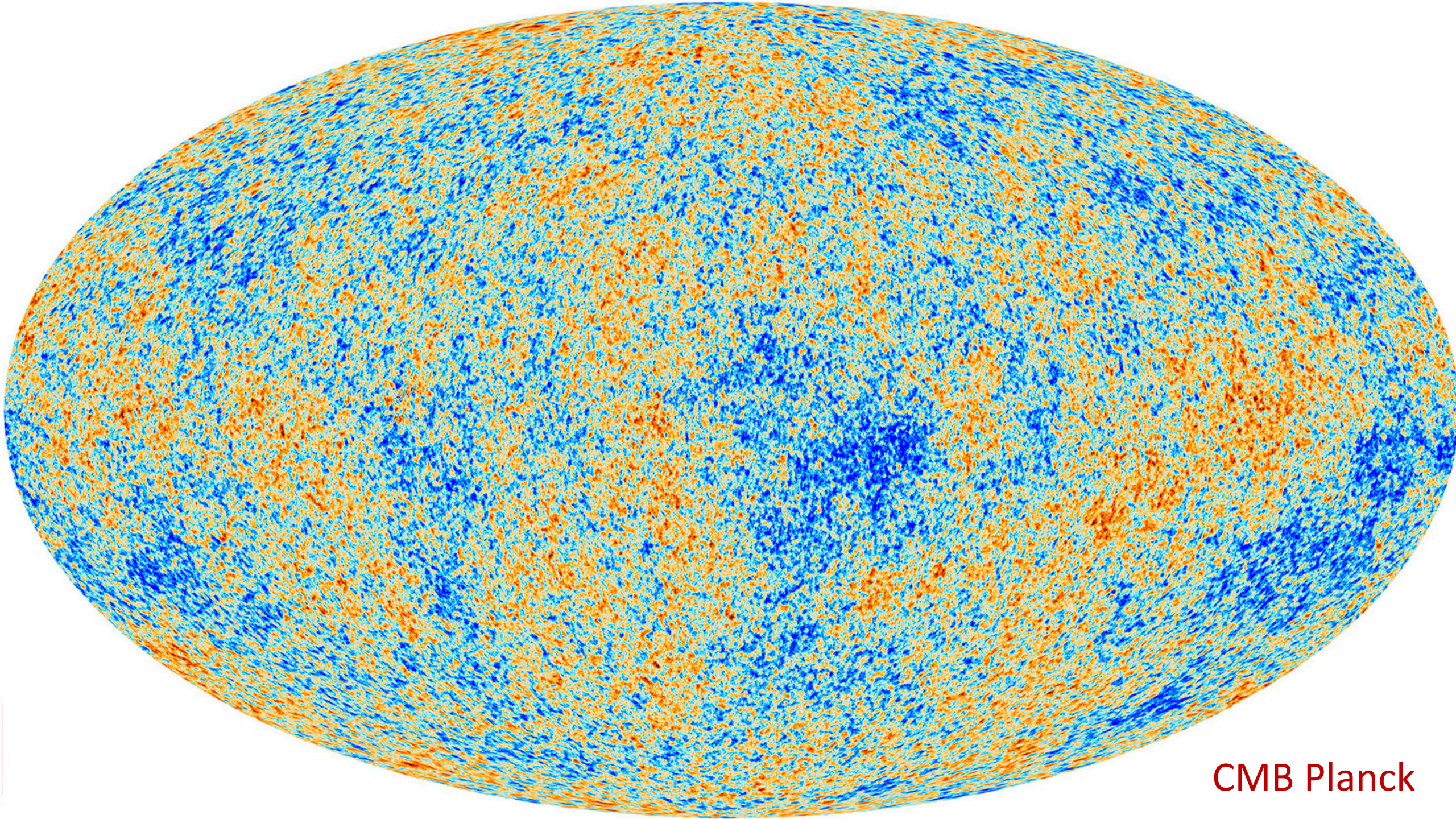


Real Sociedad Española de Física
frA FUNDACIÓN RAMÓN ARECES
CATARATA

Emilio Elizalde es físico y matemático. Doctor en Física por la Universidad de Barcelona, fue Humboldt *fellow* en Hamburgo y Berlín, y SEP *fellow* en Japón. Posteriormente, ha sido profesor de la Universidad de Barcelona y *visiting scholar* de prestigiosas universidades en Europa, Asia y América. Ha sido nombrado profesor *honoris causa* por dos universidades extranjeras y, desde hace poco, profesor de investigación *ad honorem* del Consejo Superior de Investigaciones Científicas, tras haber recibido cuatro distinciones al mérito científico por parte de esta institución, en sus años de pertenencia a la misma.

Reputado especialista, con libros de referencia, en funciones zeta y sus aplicaciones a las teorías de campos cuánticos y al efecto Casimir, ha dedicado parte de su trayectoria científica a la cosmología teórica y a las teorías de gravedad. Se siente profundamente orgulloso de sus estudiantes de doctorado y post-docs, varios de los cuales son ahora científicos de altísimo nivel en campos diversos, que abarcan desde los quarks e iones pesados al análisis funcional, la energía oscura y la cosmología observacional a gran escala.

Gràcies !


CMB Planck