O que é a energia escura?

Jailson Alcaniz

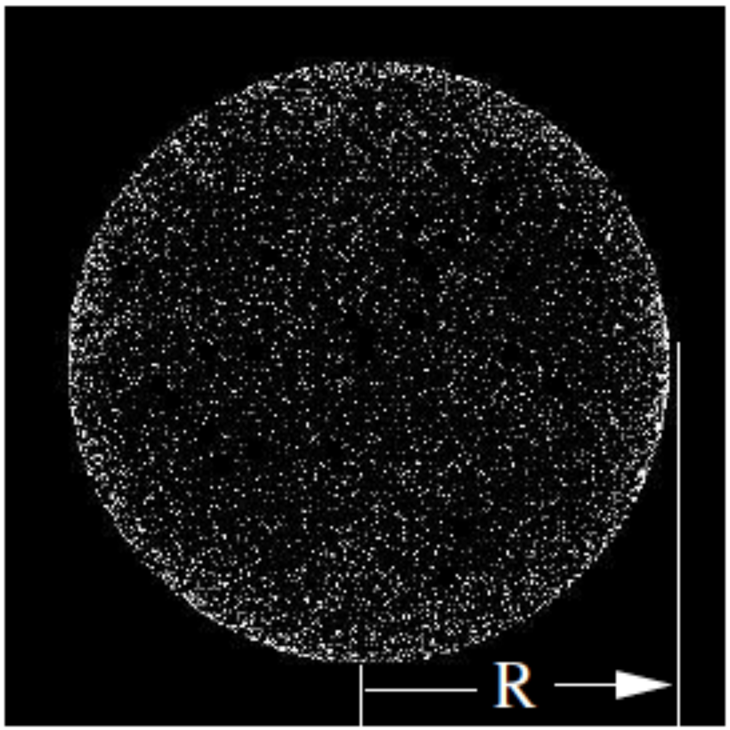
Observatório Nacional

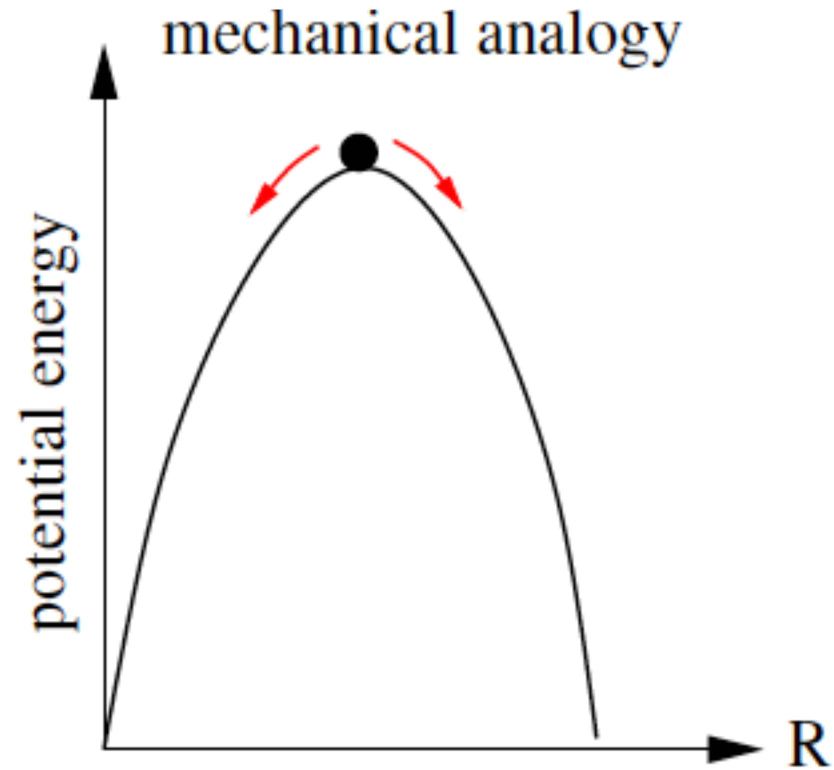
Sociedade Brasileira de Física
14 de Abril de 2021

Einstein (1917)

Cosmological Considerations in the General Theory of Relativity

Einstein's universe is a three-sphere with radius R and uniform mass density ρ. A static solution is found for $\Lambda = 8\pi G\rho/2 = R^{-2}$.





Cline (2016)

https://einsteinpapers.press.princeton.edu/vol8-trans/329

Friedmann (1922;1924)

Expansão do Universo

A. Friedmann

ON THE CURVATURE OF SPACE

A. Friedmann
Petersburg

Received: June 29, 1922

§1. In their well known works on cosmological questions Einstein (1917) and de Sitter (1917) have arrived at two types of world structure; Einstein discovered the so-called "cylindrical world", with a time independent curvature; the spatial[1] radius of curvature depending on the total mass in the space; de Sitter has developed a spherical world in which not only space but also, in a certain sense, space-time has a constant curvature (Klein 1918). To this end, Einstein, and also de Sitter, have made assumptions about the matter tensor; namely that the matter is incoherent and nearly at rest; i.e., that the velocity of the matter is sufficiently small compared to the velocity of light.

ON THE POSSIBILITY OF A WORLD WITH CONSTANT NEGATIVE CURVATURE

A. Friedmann
Petersburg

Received January 7, 1924

§1.1 In our note "On the Curvature of Space" (Friedmann 1922) we have treated solutions to Einstein's 'world' equations which have as a common feature that they lead to a space of constant positive curvature; we discussed all possible cases which lead to such a solution. According to the equations the possibility of having a world of positive curvature depends on the finiteness of space. For that reason it is interesting to see if these same equations can lead to a world with constant negative curvature and thus, so to speak, free our discourse from this 'finiteness'.

A NOTE ON THE WORK OF A. FRIEDMANN "ON THE CURVATURE OF SPACE"

A. Einstein
Berlin

Received May 31, 1923

I have in an earlier note (Einstein 1922) criticized the cited work (Friedmann 1922). My objection rested however - as Mr. Krutkoff in person and a letter from Mr. Friedmann convinced me - on a calculational error. I am convinced that Mr. Friedmann's results are both correct and clarifying. They show that in addition to the static solutions to the field equations there are time varying solutions with a spatially symmetric structure.

REFERENCES

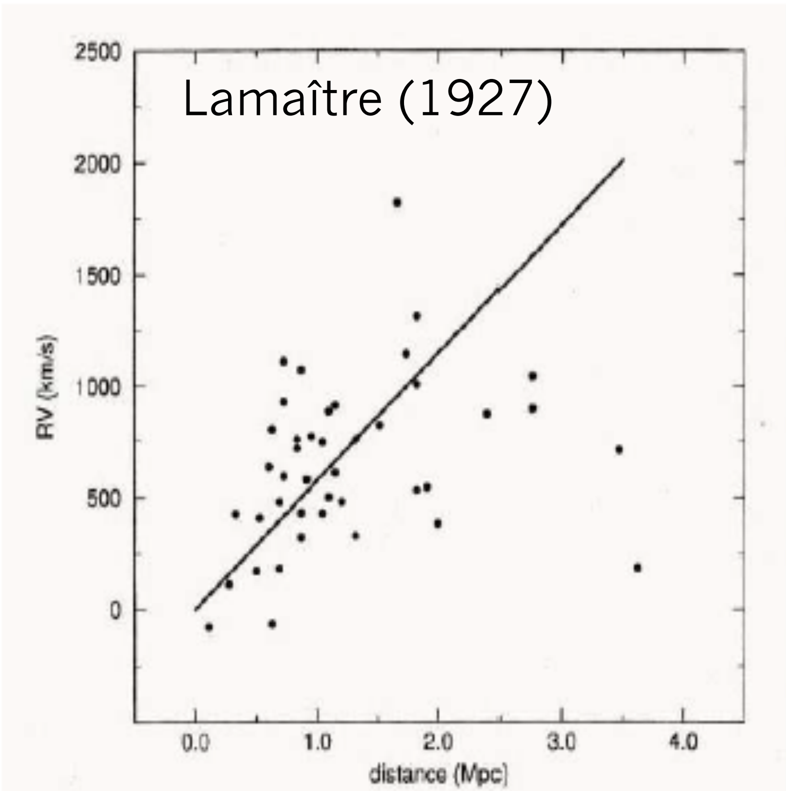
Einstein, A. 1922, Zs. f. Phys., **11**, 326.
Friedmann, A. 1922, Ebenda, **10**, 377.

Lamaître (1927) & Hubble (1929)

D. Block (2011) arXiv:1106.3928 [physics.hist-ph]

Vesto Slipher

Lamaître (1927)



Hubble (1929)

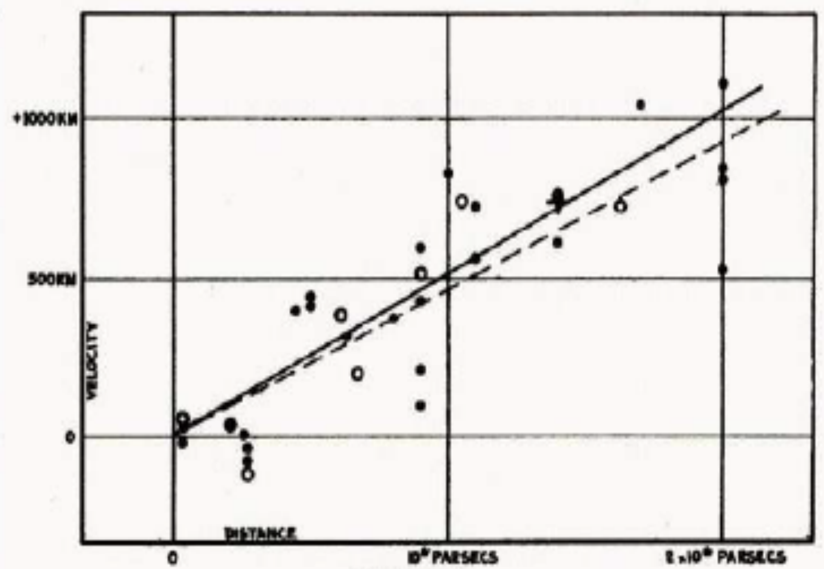


FIGURE 1

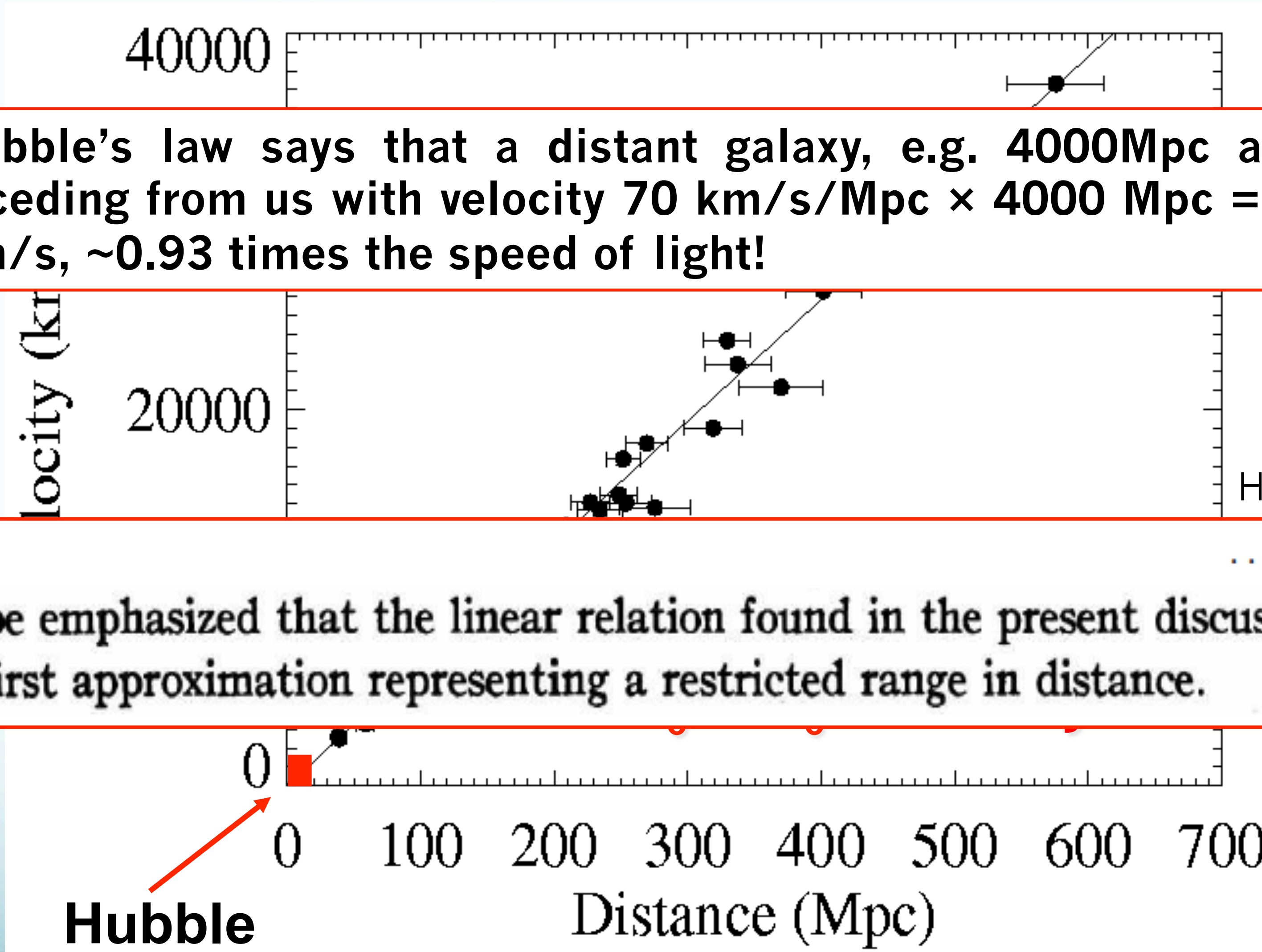
1 Mpc = 3.26 millions of light-years

speed = H_o x distance

$H_0 \sim 600$ km.s^{-1}.Mpc^{-1}

Hubble's data were corrected for peculiar motions of the galaxies and so look more linear. In his paper, Lamaître gave a theoretical explanation of the "Hubble law".

Hubble-Lamaître Law



Hubble's law says that a distant galaxy, e.g. 4000Mpc away, it is receding from us with velocity 70 km/s/Mpc × 4000 Mpc = 280, 000 km/s, ~0.93 times the speed of light!

Hubble 1929

… it may be emphasized that the linear relation found in the present discussion is a first approximation representing a restricted range in distance.

Riess *et al. (2010)*

speed = H_o x distance

"...o maior erro da minha vida."

Albert Einstein

"Um gênio não comete erros. Seus erros são como portais para novas descobertas."

James Joyce

Einstein's Mistakes - S. Weinberg, Physics Today, 58, 11 (2005)

Einstein and Λ

"If Hubble's expansion had been discovered at the time of the creation of the general theory of relativity, the cosmological member would never have been introduced. It seems now so much less justified to introduce such a member into the field equations, since its introduction loses its sole original justification."

A. Einstein, The Meaning of Relativity

PROCEEDINGS
OF THE
NATIONAL ACADEMY OF SCIENCES

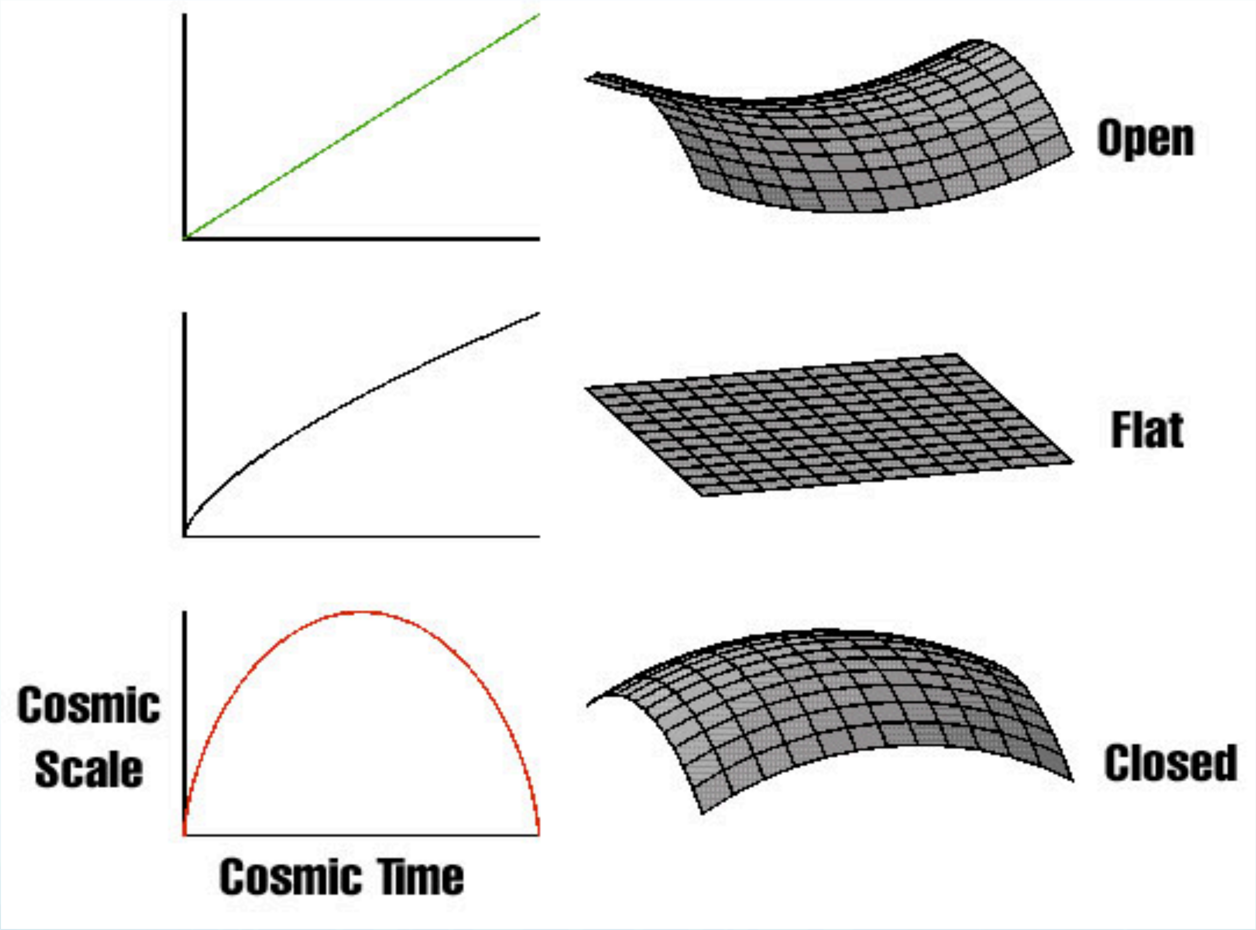
Volume 18 March 15, 1932 Number 3

ON THE RELATION BETWEEN THE EXPANSION AND THE MEAN DENSITY OF THE UNIVERSE

By A. Einstein and W. de Sitter

Communicated by the Mount Wilson Observatory, January 25, 1932

Geometry and Destiny



$\Omega < 1$

$\Omega = 1$

$\Omega > 1$

- Friedmann (1922): $\Omega > 1$
- Friedmann (1924): $\Omega < 1$
- Einstein-de Sitter (1932): $\Omega = 1$

$$\Omega = \frac{\rho}{\rho_{crit}}$$

Next decades...

- In the 30s, Zwicky postulated the existence of Dark Matter;
- In the 40's, Gamow and collaborators investigated the physics of the Hot Big-Bang and made predictions about primordial nucleosynthesis and the Cosmic Microwave Background (CMB);
- In 1965, Penzias and Wilson discovered the 3K CMB;
- Measurements of abundance of light nuclei in agreement with theoretical predictions.
- In the 70's, strong evidence was found for the existence of DM from galaxy's rotation curves (Rubin & Ford);
- In 1981, Guth proposed the so-called inflationary scenario. The original model predicted a flat universe.

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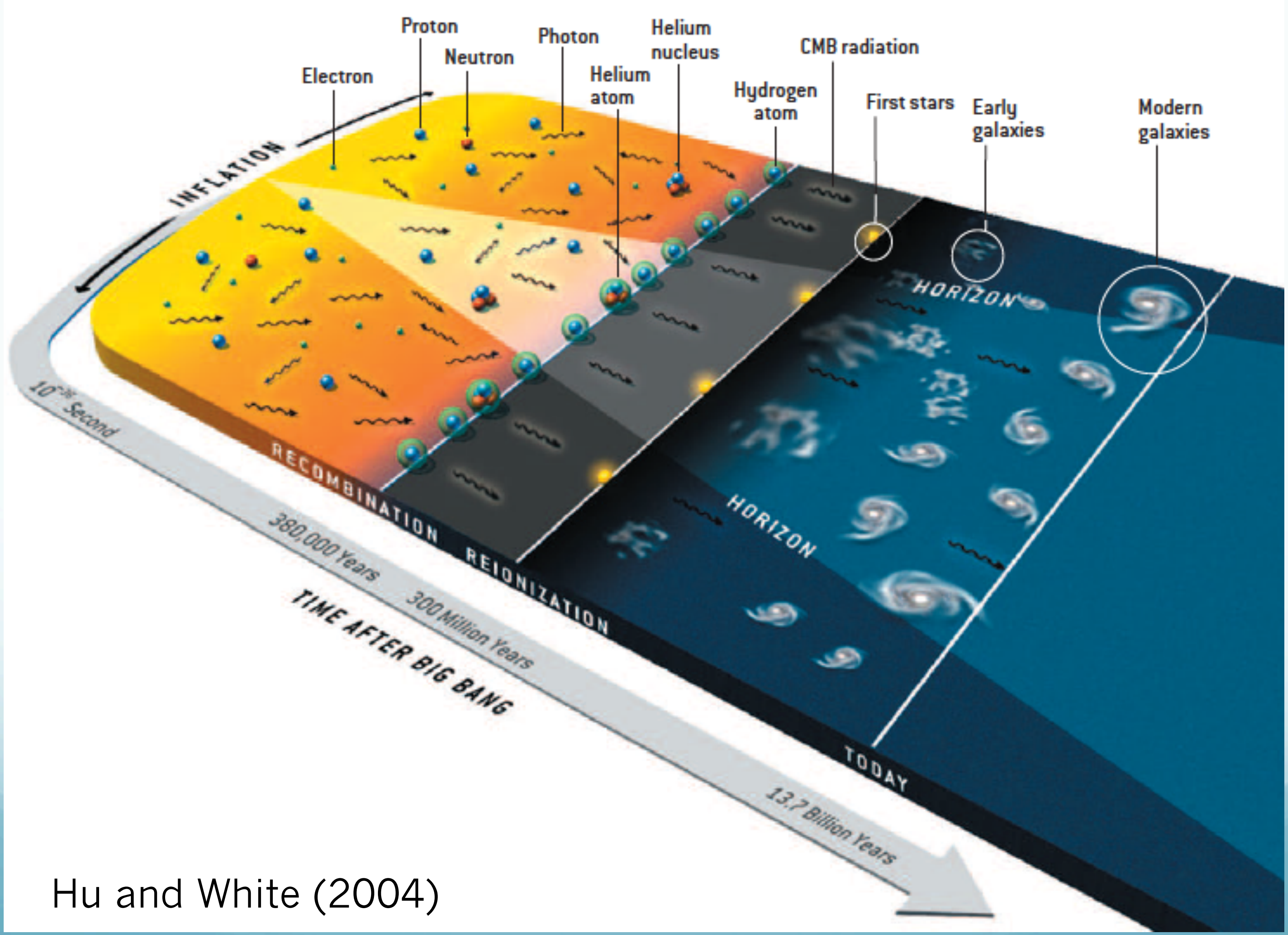
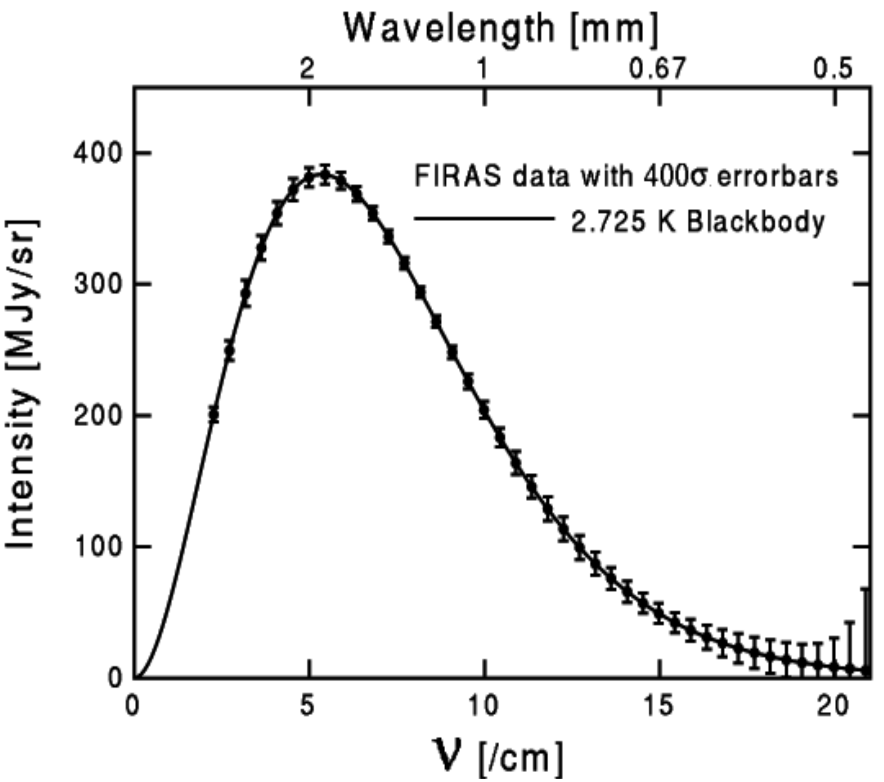
Thermal history

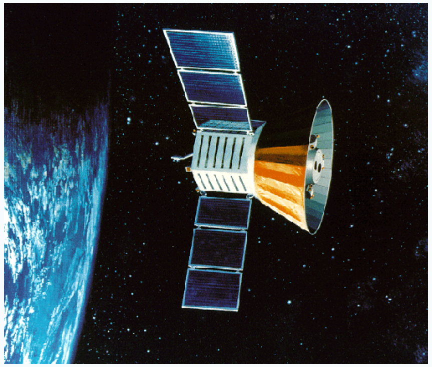


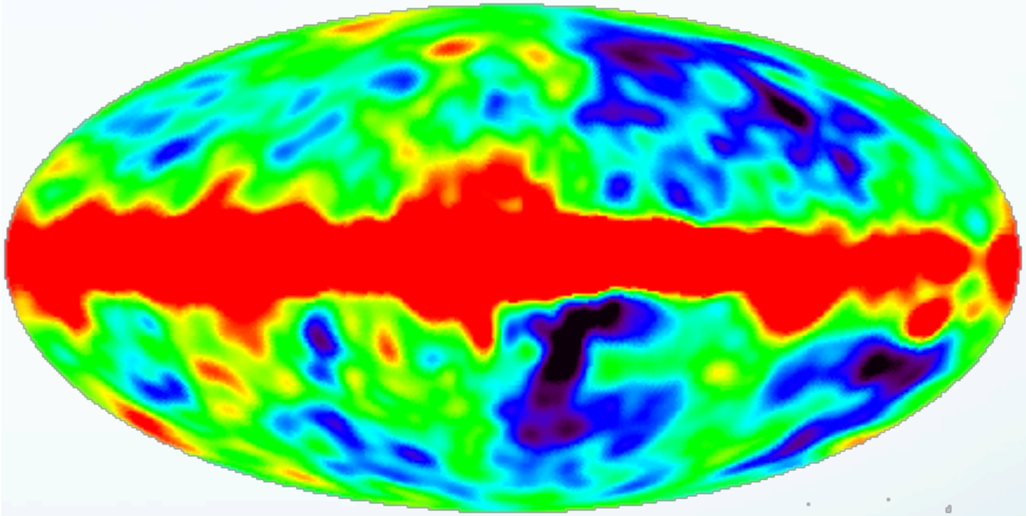
Hu and White (2004)

COBE (1992)

Cosmic microwave background



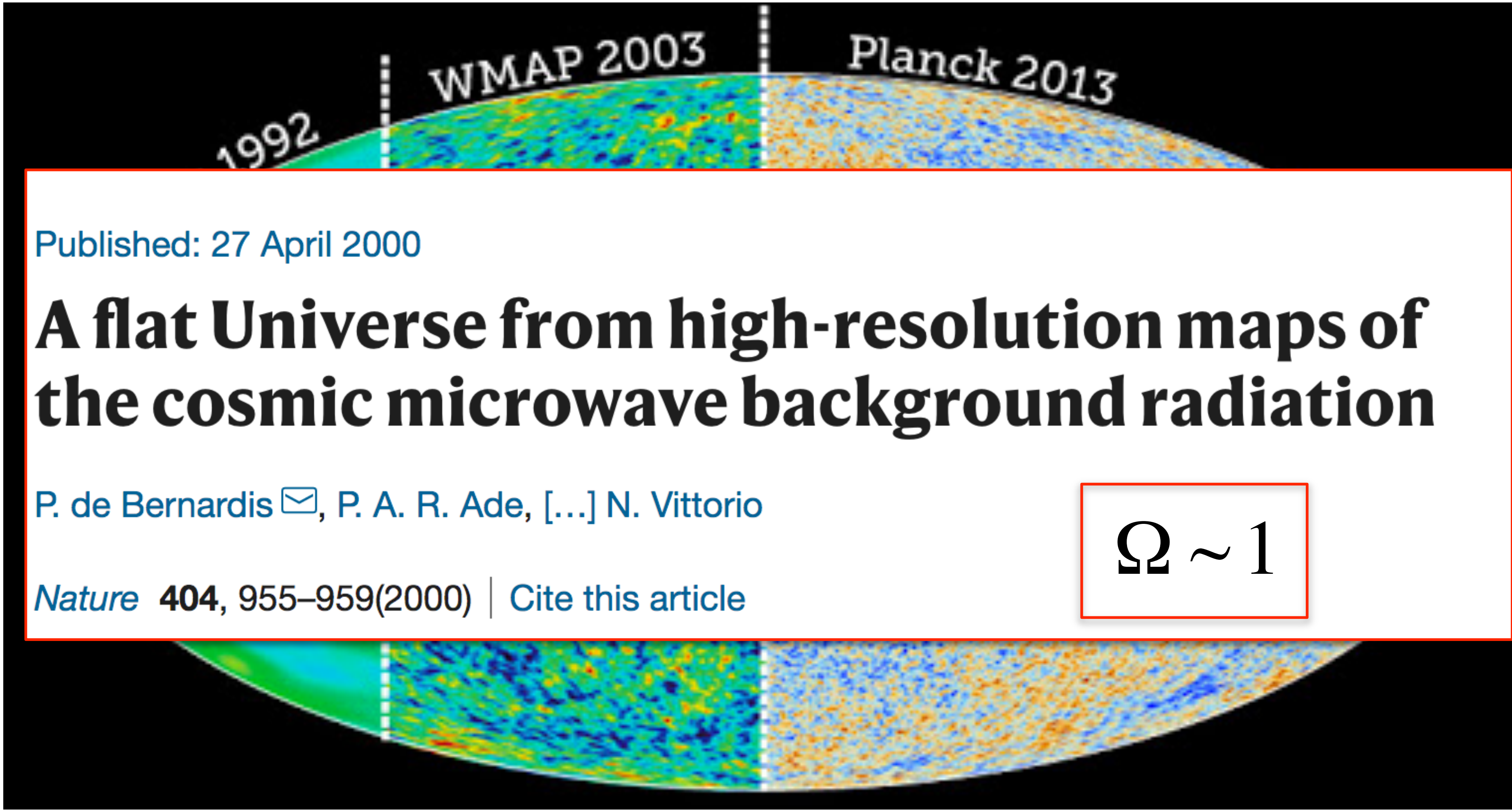




Average energy that corresponds to a black-body spectrum of T = 2.72548 ± 0.00057 K

$$\frac{\Delta T}{T} \approx 10^{-5}$$

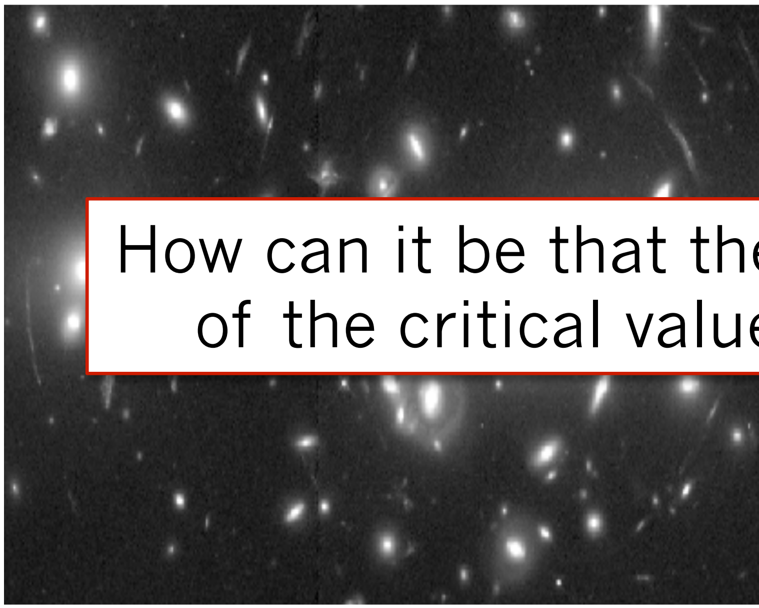
CMB Experiments



- Primordial Universe;
- Cosmological Parameters;
- Age of the Universe;
- Topological defects;
- Thermal history;
- Geometry, etc.

The large-scale structure

Gravitational Lensing



Galaxy Clusters

How can it be that the matter density is only 1/3 of the critical value, yet the universe is flat?

$$\Omega_m \approx 0.3; \quad \Omega = 1 - \Omega_m \approx 0.7$$

Trimble (1987)
Calberg et al. (1996)
Bahcall et al. (1996)

LETTERS TO NATURE (1990)

The cosmological constant and cold dark matter

G. Efstath

Department

THE cold
distribution
density is t
but recent
ture on very
constant *H*
of the CDN
the CDM
accommoda
80% of the
constant, w
with a non-
dominated
the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background and the large number of certain kinds of object found at high redshift.

LETTERS TO NATURE (1995)

The observational case for a low-density Universe with a non-zero cosmological constant

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imposed by
suggestions[6]
ere remains
rdance with
o models in
the critical
also permit
the vacuum
recover the
critical density favoured by the simplest inflationary models. The observations do not yet rule out the possibility that we live in an ever-expanding 'open' Universe, but a Universe having the critical energy density and a large cosmological constant appears to be favoured.

The Cosmological Constant Is Back†

Lawrence M. Krauss[1] and Michael S. Turner[2,3]

A diverse set of observations now compellingly suggest that the universe possesses a nonzero cosmological constant. In the context of quantum-field theory a cosmological constant corresponds to the energy density of the vacuum, and the favored value for the cosmological constant corresponds to a very tiny vacuum energy density. We discuss future observational tests for a cosmological constant as well as the fundamental theoretical challenges — and opportunities — that this poses for particle physics and for extending our understanding of the evolution of the universe back to the earliest moments.

General Relativity and Gravitation, Vol. 27, No. 11, 1995

SNe are bright, standardizable candles; They are almost as bright as a typical galaxy when they peak.

SN 1994D observed with the HST

High-z Supernovae Search

Discovered between October and November 1999. This Supernova is more than 9 billion light years in distance.

Accelerating Universe

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4] PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2] B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7] R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4] NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]
Received 1998 March 13; revised 1998 May 6

THE ASTROPHYSICAL JOURNAL, 517:565–586, 1999 June 1

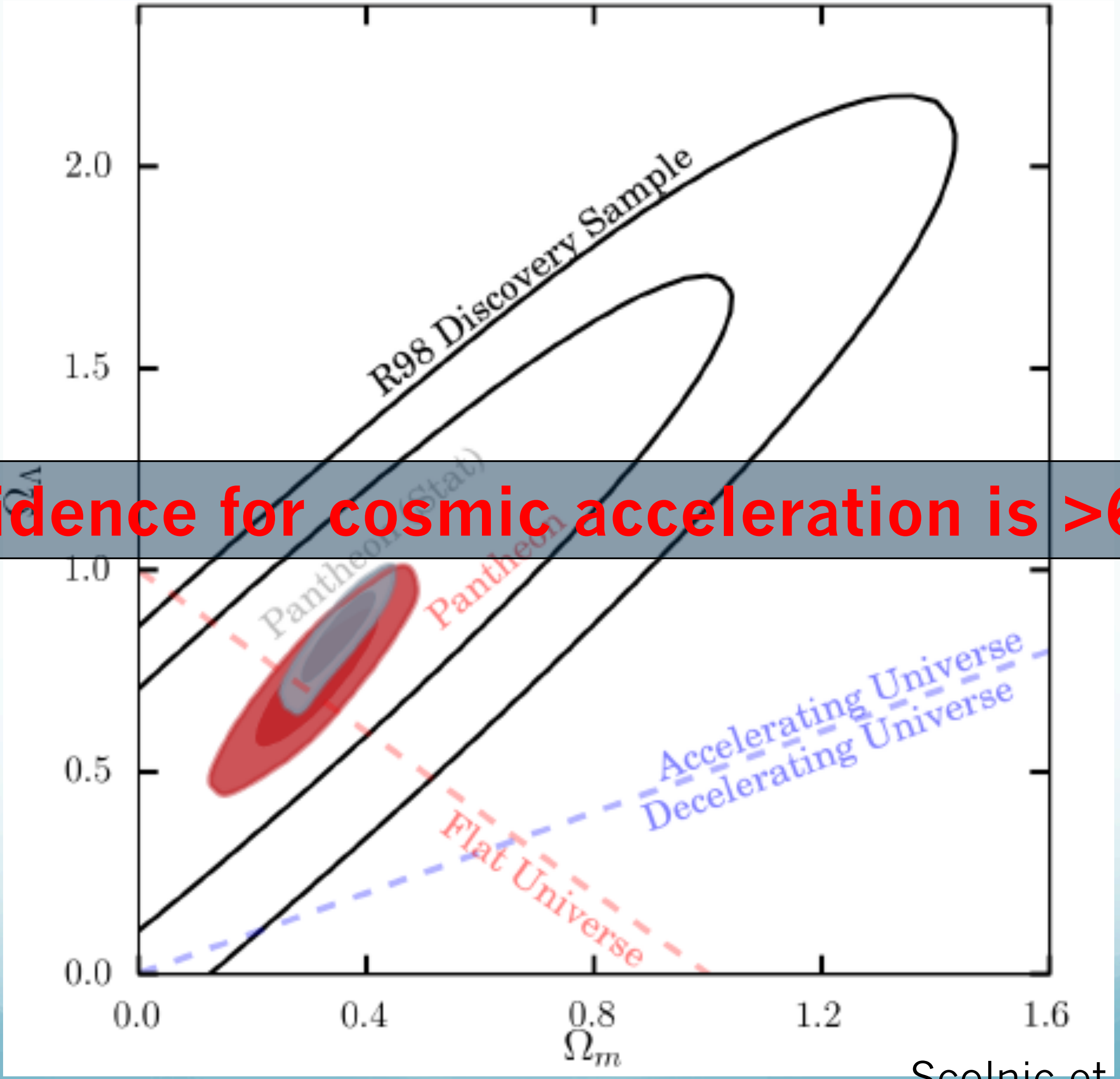
MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. PERLMUTTER,[1] G. ALDERING, G. GOLDHABER,[1] R. A. KNOP, P. NUGENT, P. G. CASTRO,[2] S. DEUSTUA, S. FABBRO,[3] A. GOOBAR,[4] D. E. GROOM, I. M. HOOK,[5] A. G. KIM,[1,6] M. Y. KIM, J. C. LEE,[7] N. J. NUNES,[2] R. PAIN,[3] C. R. PENNYPACKER,[8] AND R. QUIMBY
Institute for Nuclear and Particle Astrophysics, E. O. Lawrence Berkeley National Laboratory, Berkeley, CA 94720

SN and cosmic acceleration

- Distances between two points are smaller in a decelerated Universe.
- Example: The Einstein-de Sitter model ($\Omega_m = 1$) predicts that the flux of a SN observed when the Universe was 2/3 of its present size should be 25% brighter than what is predicted by an empty universe ($\Omega_m = 0$) expanding at a constant rate.
- But the distant supernovae are not brighter than expected in an empty universe, they are dimmer. For this to happen, the universe must be accelerating while the light from the supernova is in transit to our observatories.

Past and present SNe results



Evidence for cosmic acceleration is >60 σ !

Scolnic et al. (2018)

O que acelera o universo?

Matéria usual implica desaceleração.

tiva!

Pressão N o Universo!

EFE TICO!

Λ ?

Newton

nergia Escura

$$\text{aceleração} \propto -(\rho + 3p)$$

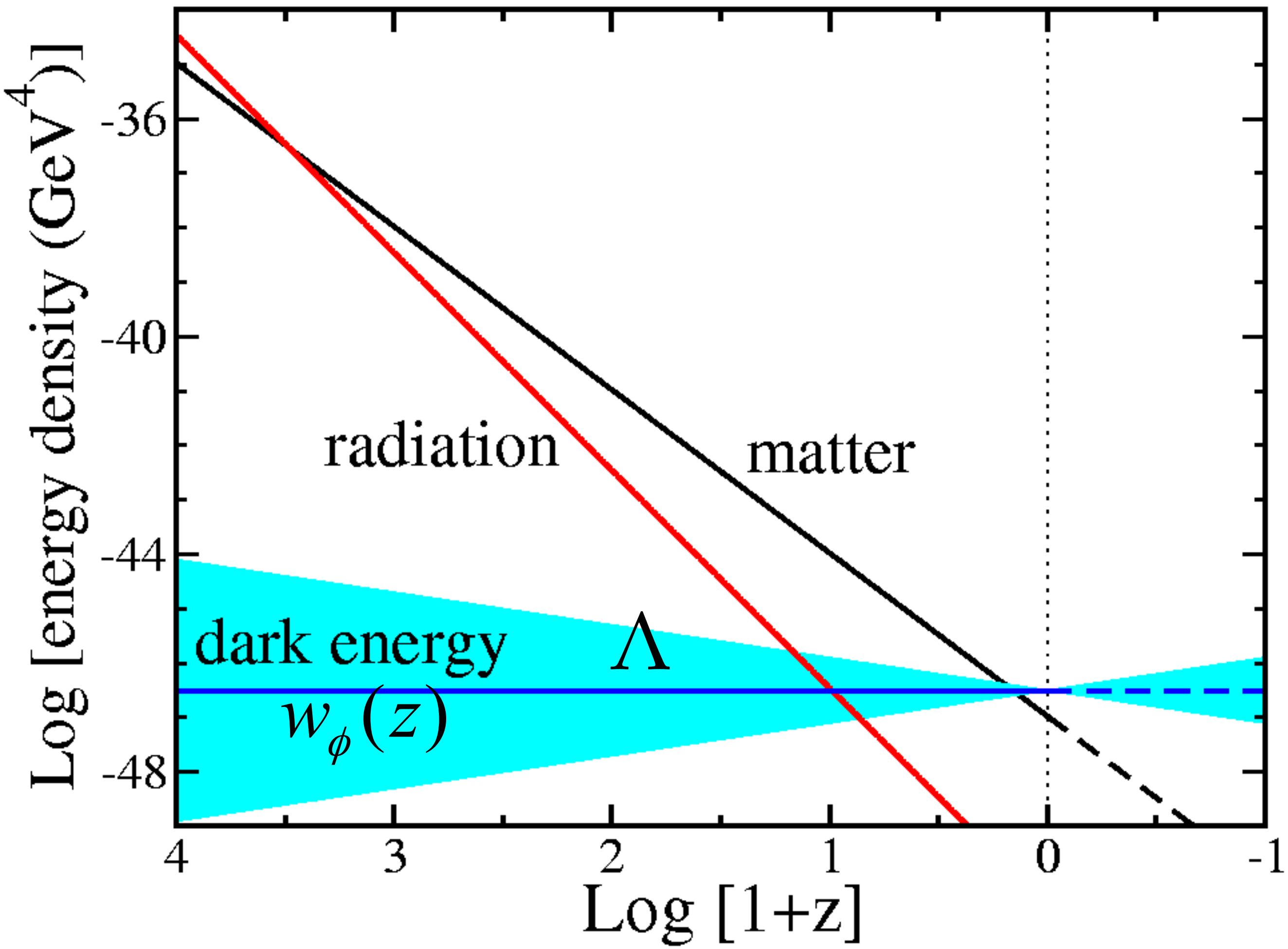
Einstein

A densidade de energia é positiva, mas a pressão é negativa.

Evolution of radiation, matter and dark energy densities with redshift/time.

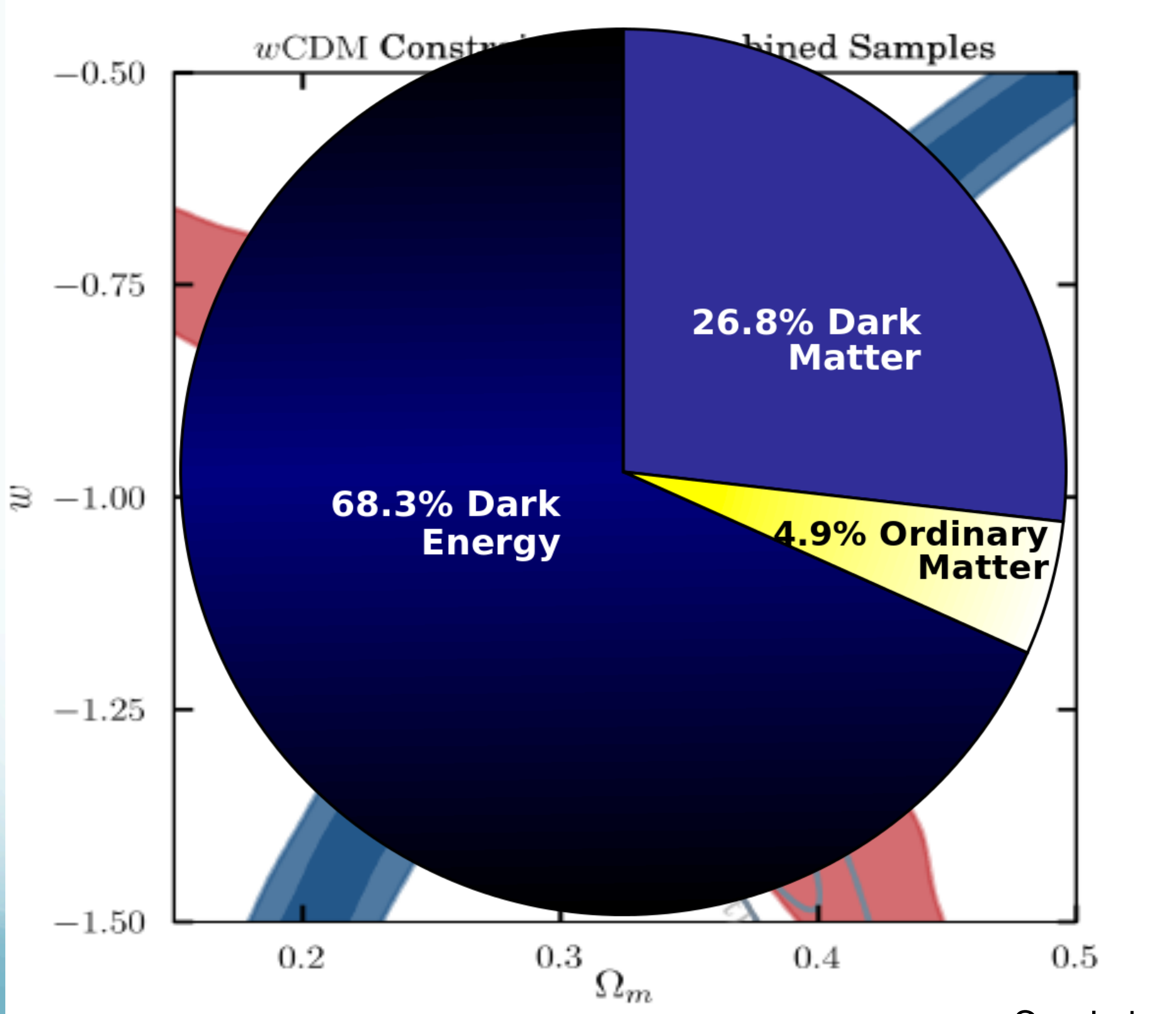
$$\rho_\gamma \propto a^{-4} \quad \text{and} \quad \rho_m \propto a^{-3}$$

$$\rho_{\rm DE} \sim 0.7\times10^{-29}\,{\rm g/cm^3} \approx 6.3\times10^{-10}\,{\rm erg/cm^3}$$



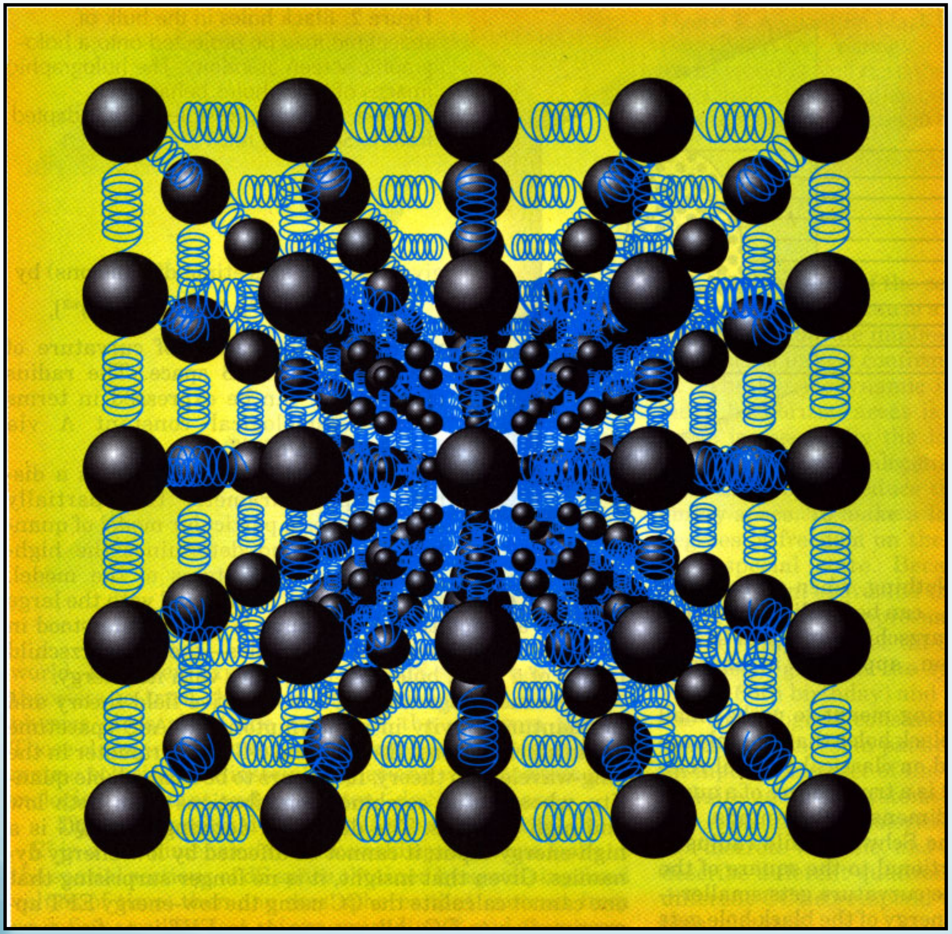
$\Lambda: w \;\; -1$

$w = -1.047 \pm 0.038\,(1\,\sigma)$



Scolnic et al. (2018)

The cosmological Constant Problem



$$\rho_\Lambda^{obs} \approx 10^{-10}\,\mathrm{erg/cm^3}$$

$$\rho_\Lambda^{theo} \approx 10^{+110}\,\mathrm{erg/cm^3}$$

$$\rho_\Lambda^{theo} \approx 10^{120}\,\rho_\Lambda^{obs}$$

S. Weinberg, Rev. Mod. Phys., 61, 1 (1989)
T. Padmanabhan, Phys. Rept. 380, 235 (2003)

Dark energy: ill-motivated candidates

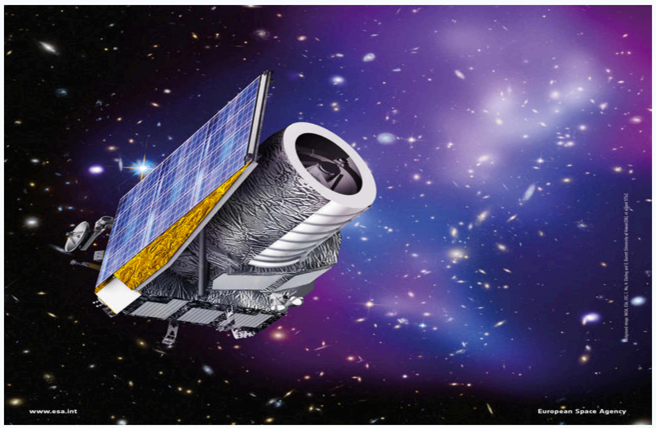
The discovery of cosmic acceleration indicated the presence of a new component in the universe, one that dominates the energy density today, or of a modification of the laws of gravity.

- Vacuum energy (Λ): aka cosmological constant – a strictly constant energy density inherent in empty space;
- Dynamical dark energy (Φ): evolution characterized by an equation-of-state $w(t) = p(t)/\rho(t)$.
- Modified Gravity: Friedmann equations are not valid at late times.

Next generation of Surveys

The Dark Energy Spectroscopic Instrument (DESI)

The Euclid Consortium



Square Kilometre Array (SKA)

Javalambre Physics of the Accelerating Universe Astrophysical Survey (J-PAS)

Conclusions

"To see what is in front of one's nose requires a constant struggle."

George Orwell

Dark energy is the mechanism that drives the current cosmic acceleration. Einstein's Λ? – CC problem. A dynamical field? Modification of Gravity?

Several experiments are underway or planned, and will probe the history of cosmic expansion and of the growth of structures.

XIX C: electricity, magnetism and light: electromagnetic theory.
XXI C: Gravity, dark matter and dark energy: ?