COSMOLOGIA

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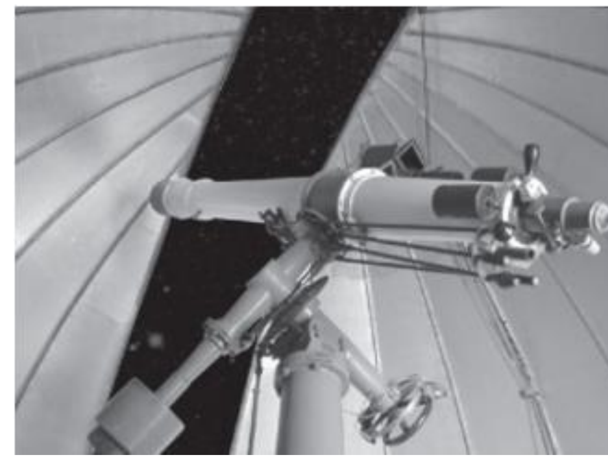
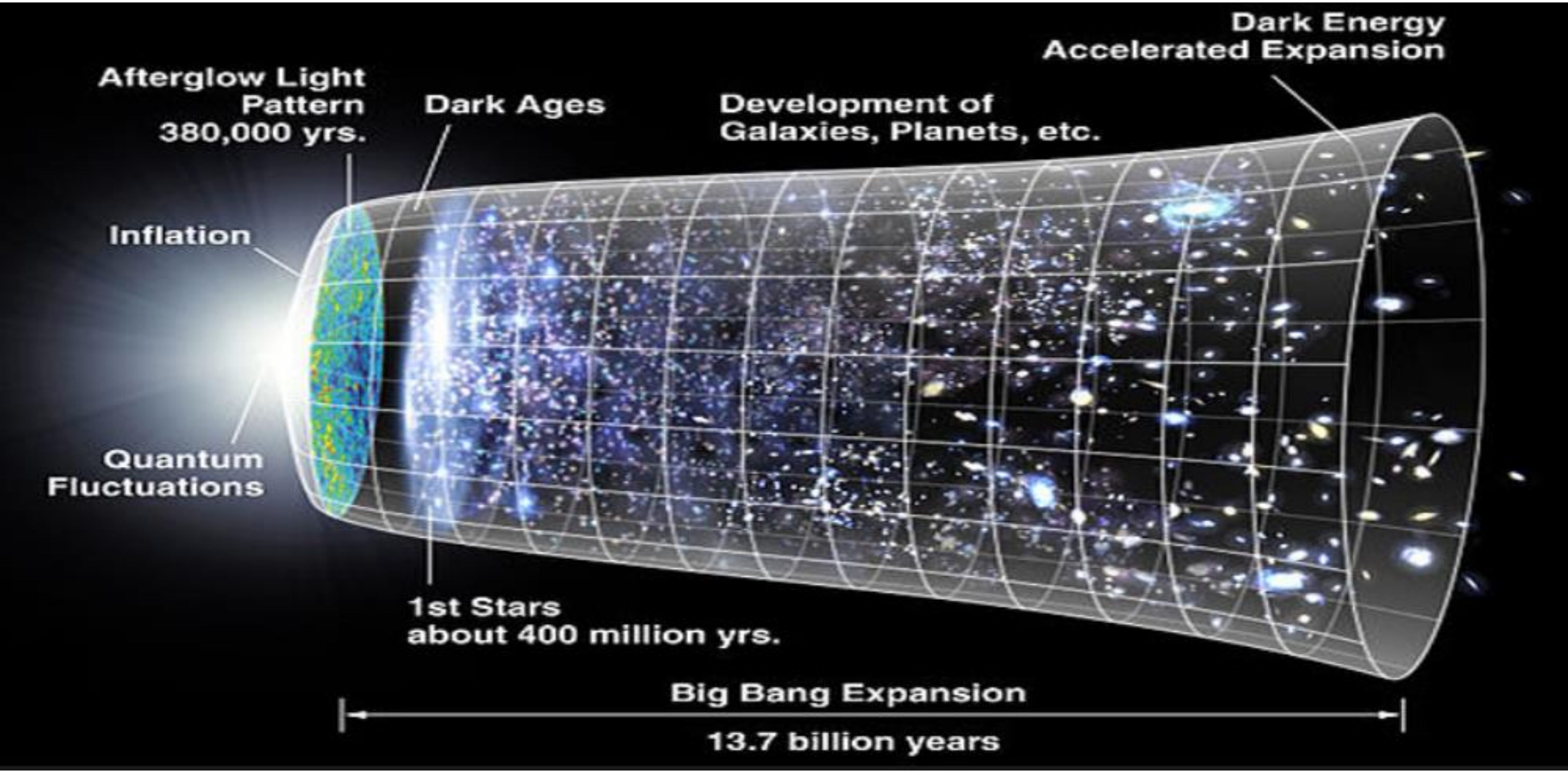
Mostra de Astronomia ES
2021

Ouro Preto possui um dos primeiros observatórios do Brasil.
Ensino de astronomia desde 1891 na Escola de Minas (criada em 1876).

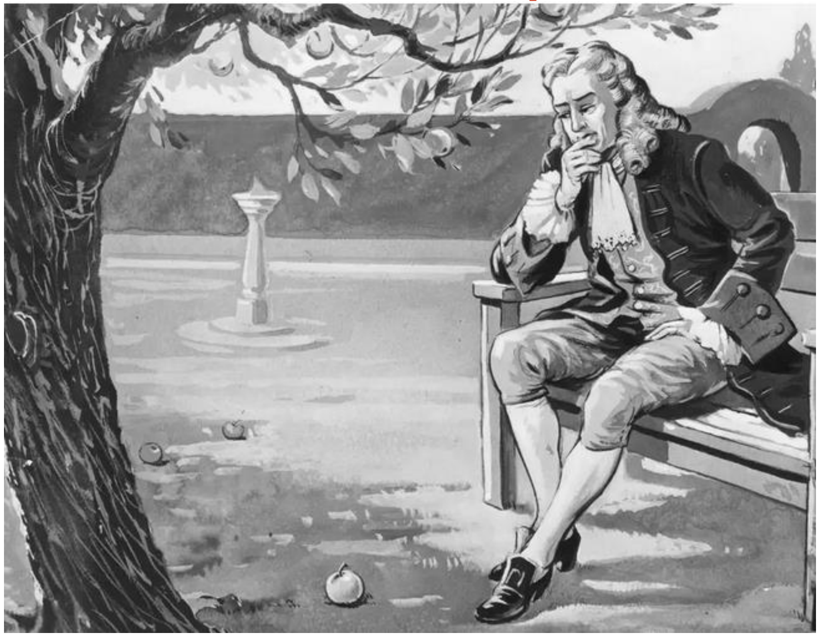



Fim da palestra. Vamos para a praia!

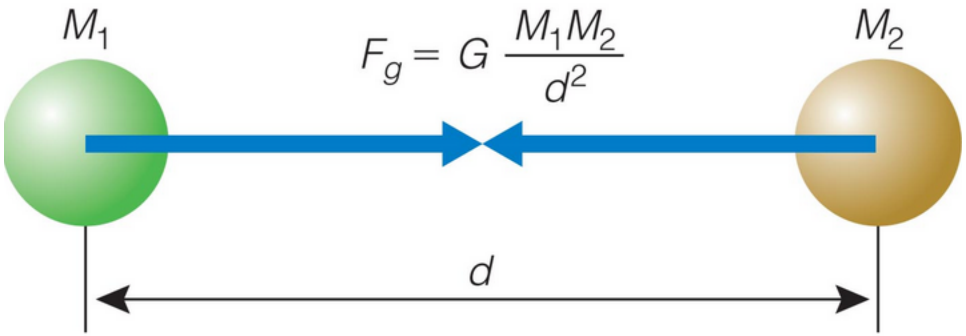


PRECISAMOS DE UMA TEORIA PARA A INTERAÇÃO GRAVITACIONAL

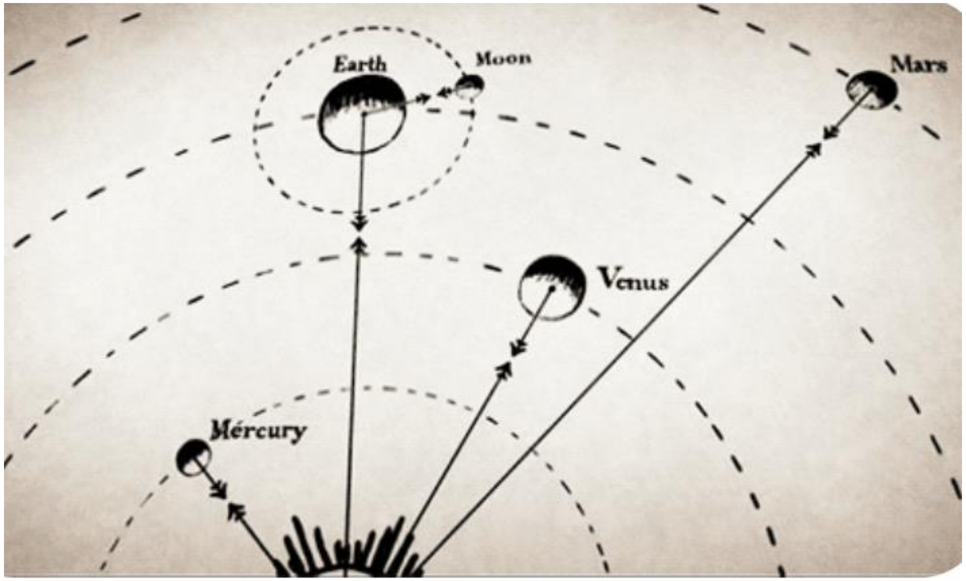
Gravitação Universal de Newton



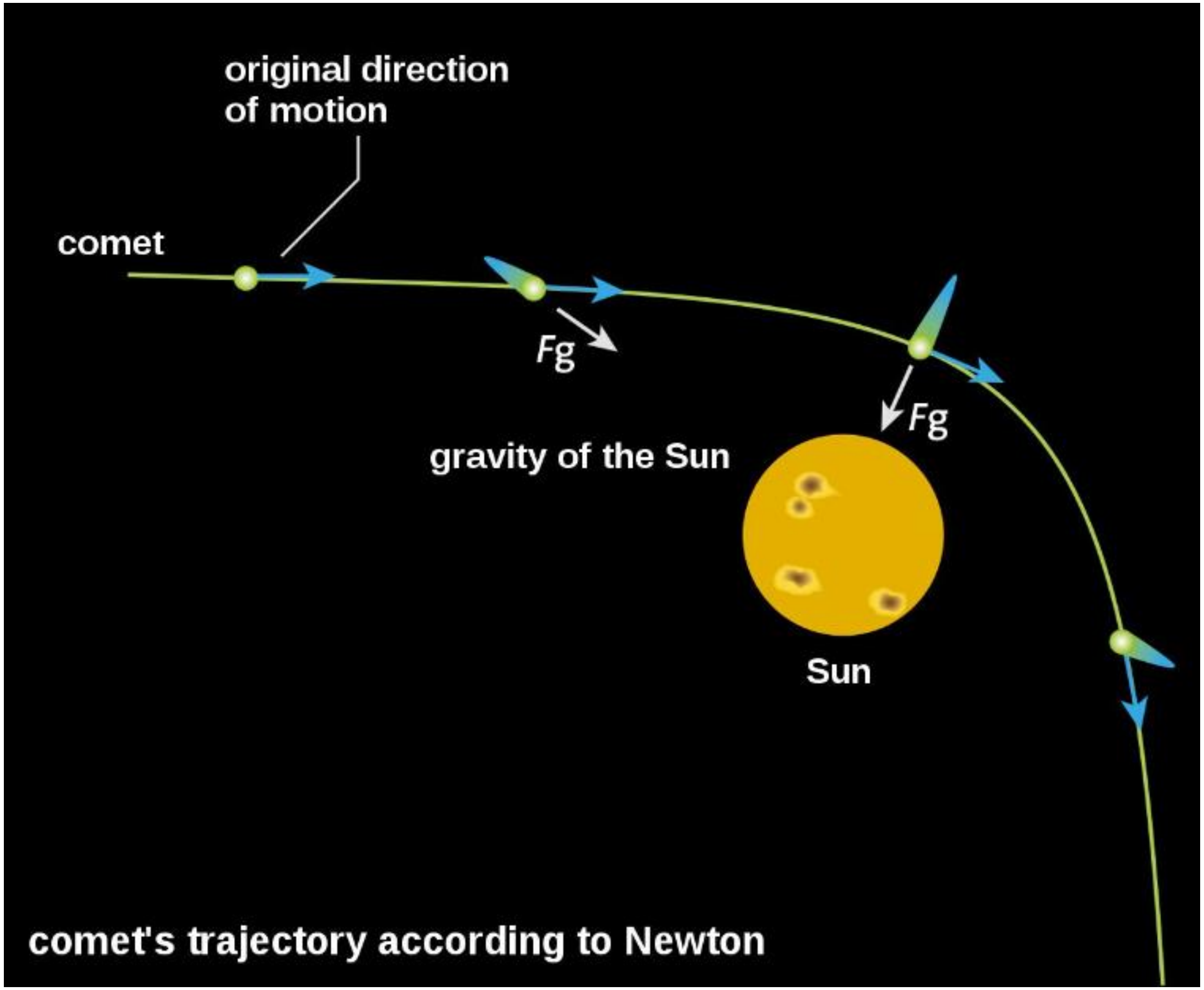
Isaac Newton
1643-1727



- A gravidade explica o mundo!
- 1) Leis de Kepler
- 2) Forma da Terra
- 3) Precessão dos equinócios
- 4) Marés dos oceanos
- 5) Ciclos de Milankovitch (século XX)
  6) ...



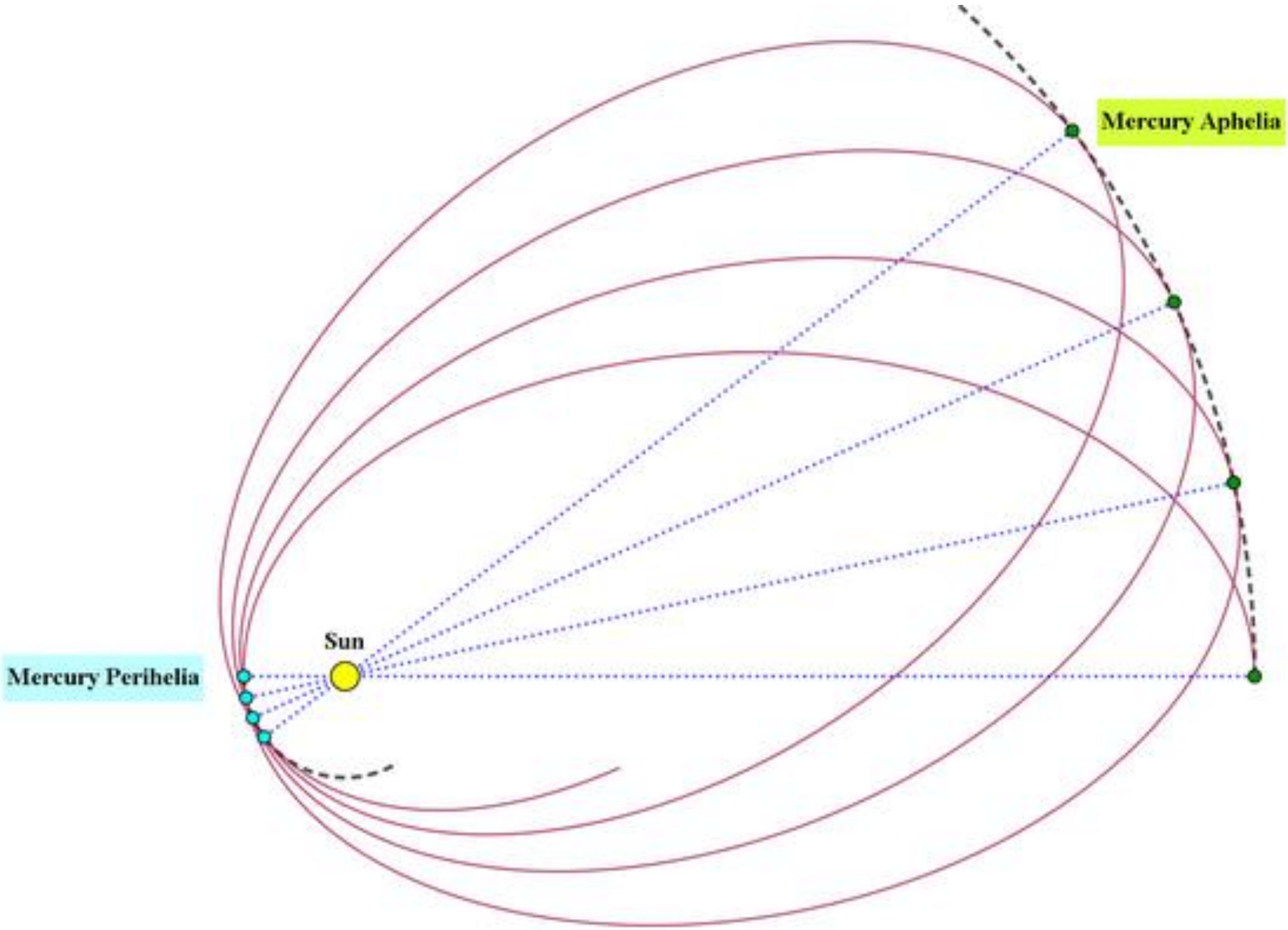
Trajetória de um cometa de acordo com Newton



Na primeira metade do século XIX a órbita de Urano apresentava anomalias. Em 1846, Le Verrier indica, por meio de cálculos, que deveria existir um planeta além da órbita de Urano. Assim o planeta Netuno foi descoberto!

Urbain Le Verrier

1811-1877



Le Verrier começou a observar Mercúrio. Também haviam anomalias na órbita. Na época, chegou-se cogitar a existência de um outro planeta, com órbita interior a Mercúrio: Vulcano. Até hoje Vulcano não foi observado!

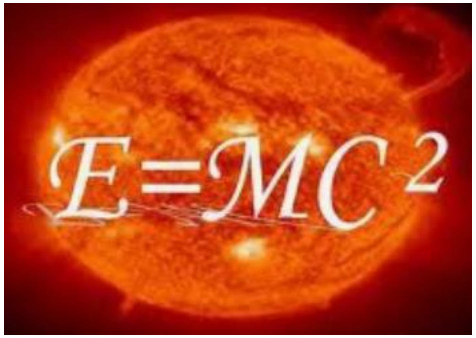
Relatividade Especial

1905

Uma teoria para a mecânica dos corpos

Postulado: a velocidade da luz no vácuo é uma velocidade limite;

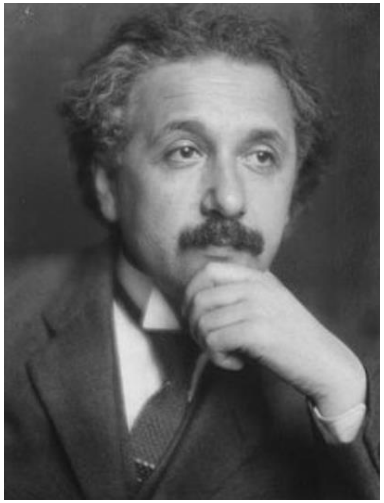
Um resultado:

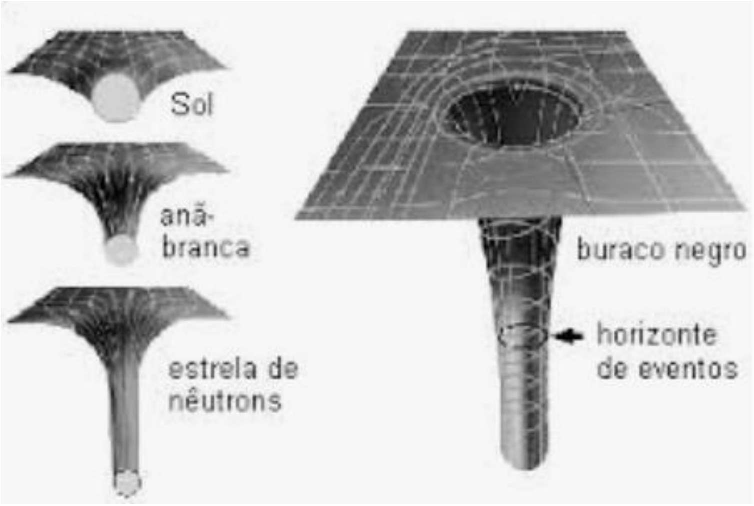


Relatividade Geral

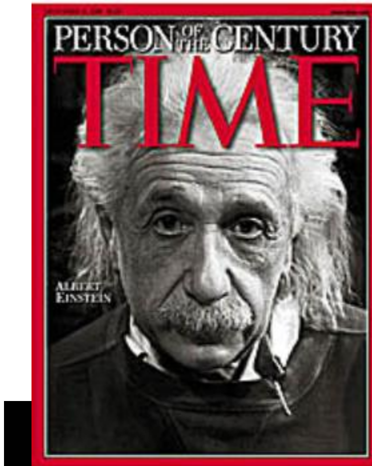
1915

Uma teoria para a gravitação

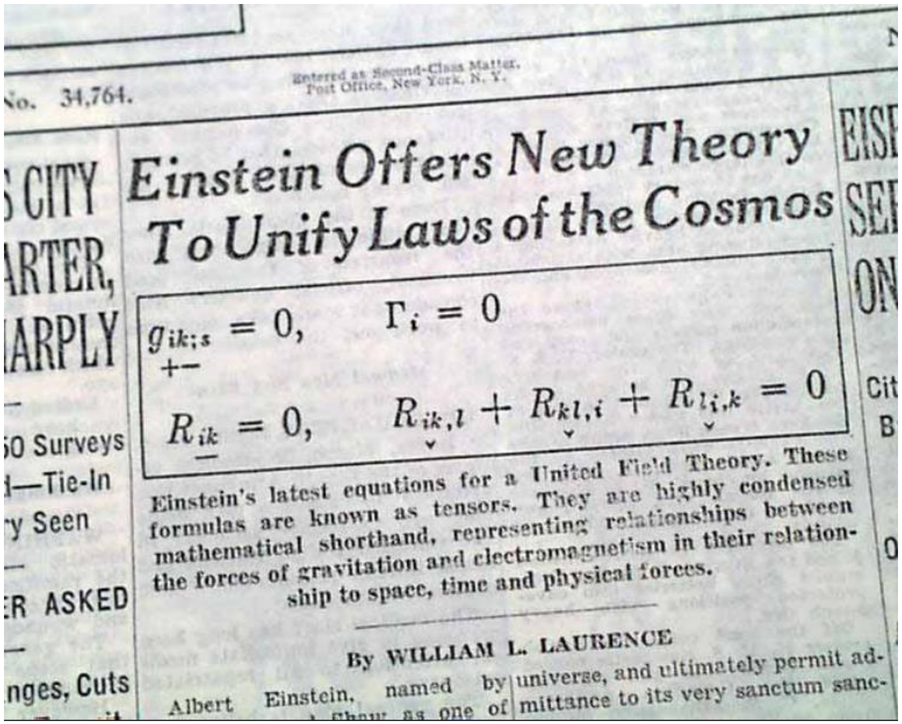




Relatividade Geral



1915



Entered as Second-Class Matter, Post Office, New York, N. Y.

No. 34,764.

Einstein Offers New Theory To Unify Laws of the Cosmos

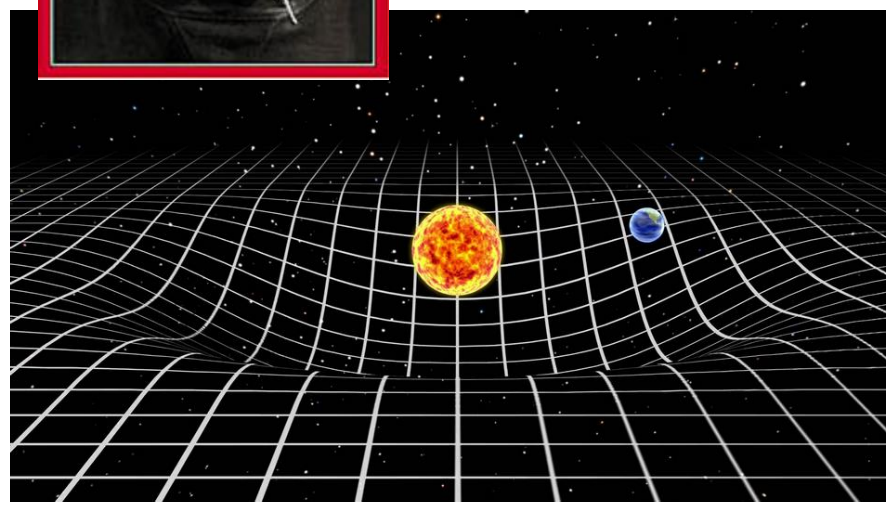
$$g_{ik;s} = 0, \qquad \Gamma_i = 0$$

$$R_{ik} = 0, \qquad R_{ik,l} + R_{kl,i} + R_{li,k} = 0$$

Einstein's latest equations for a United Field Theory. These formulas are known as tensors. They are highly condensed mathematical shorthand, representing relationships between the forces of gravitation and electromagnetism in their relationship to space, time and physical forces.

By WILLIAM L. LAURENCE

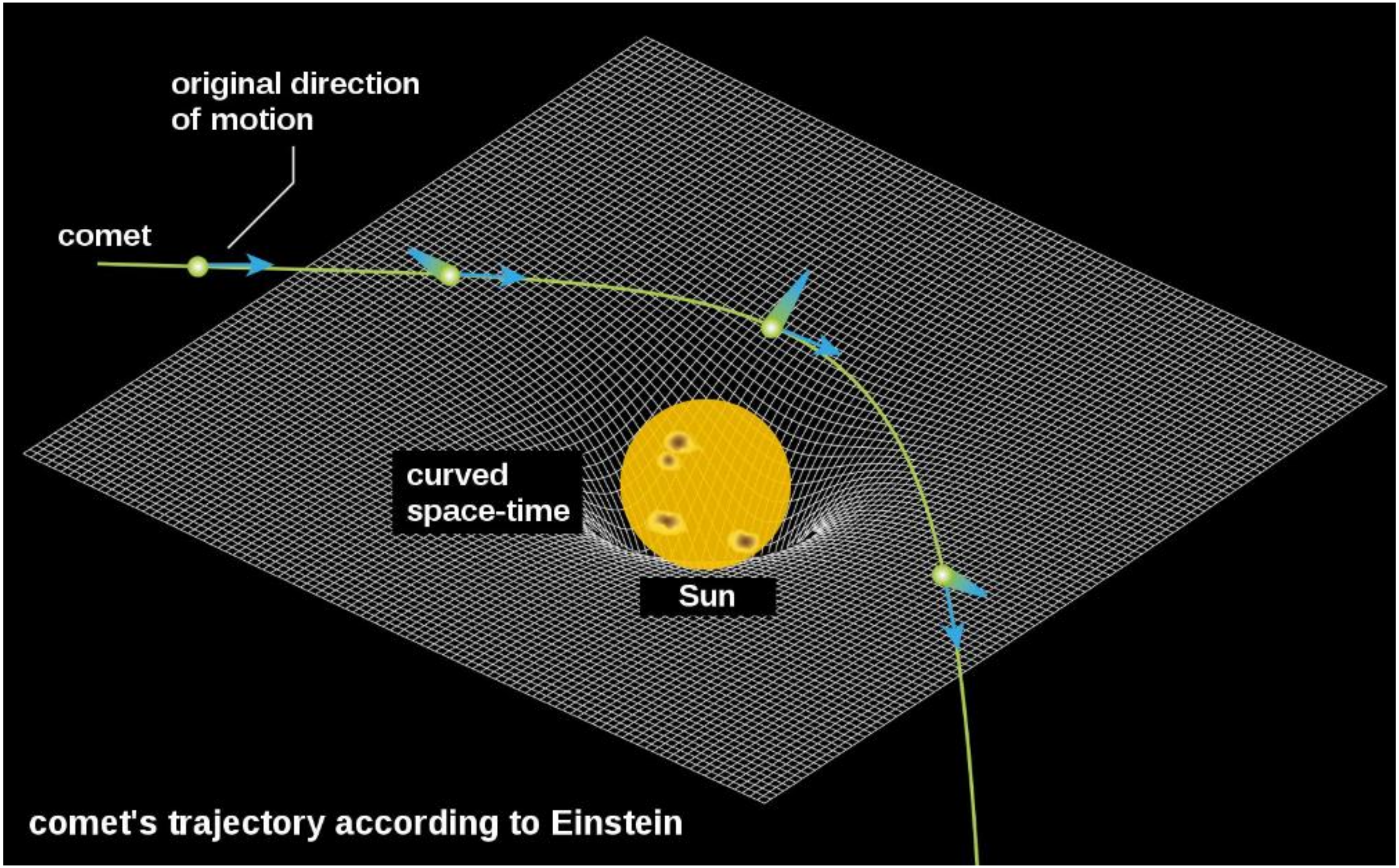
Albert Einstein, named by ... universe, and ultimately permit admittance to its very sanctum sanc-



Matéria curva o espaço-tempo:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Trajetória de um cometa de acordo com Einstein



Testes da Relatividade Geral

- Einstein propôs 3 testes (ditos Clássicos) :

    1) Precessão do perihélio da órbita de Mercúrio; ✓

    2) A deflexão de um feixe de luz em um campo gravitacional ; ✓

    3) O desvio para o vermelho de fótons ao viajar em um campo gravitacional. ✓

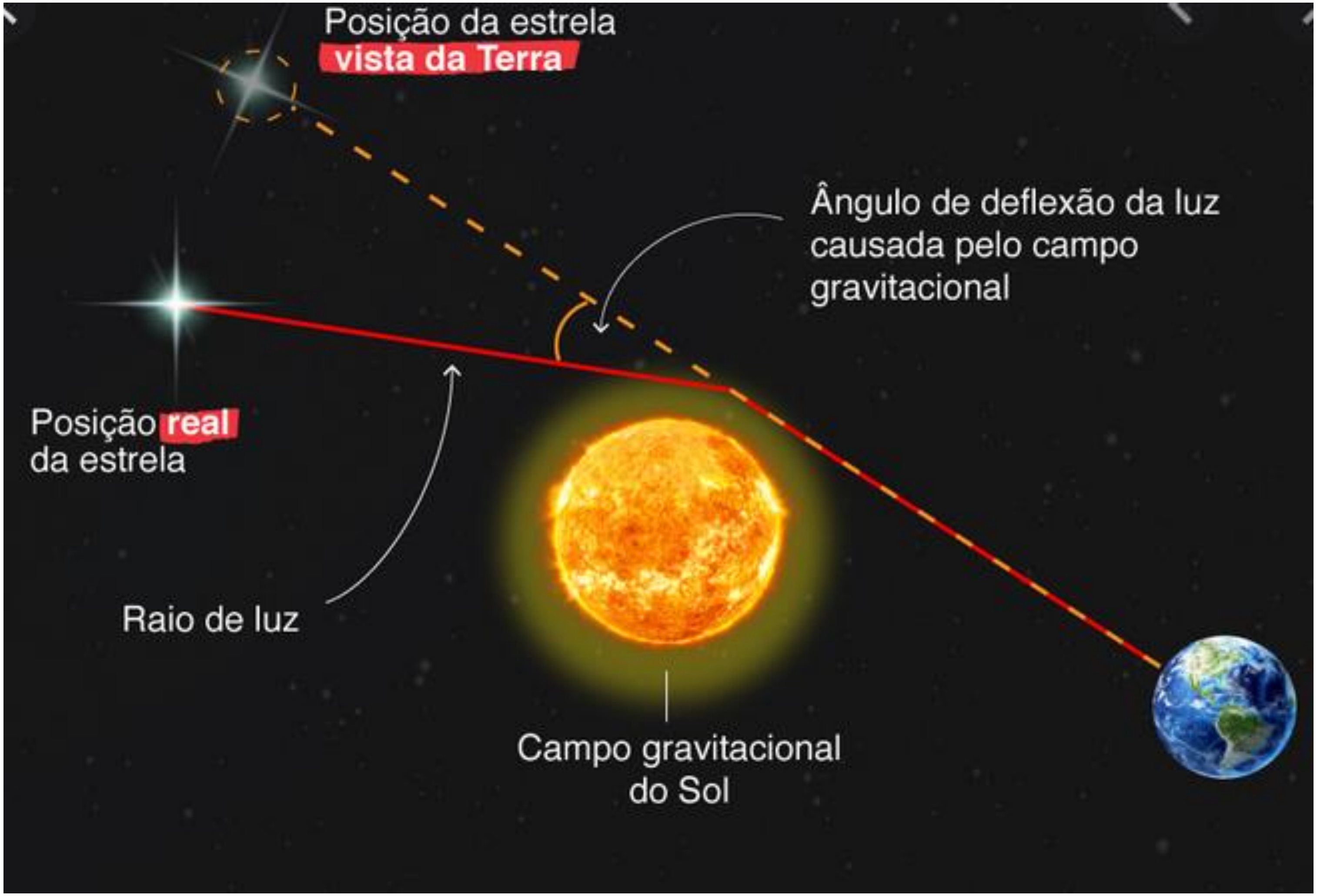
Outros testes:

Erwin Shapiro mediu, em 1970, o atraso temporal (de origem relativística) em sinais de radar que viajavam perto do Sol. ✓

Hulse e Taylor mediram o decaimento do período orbital de uma pulsar binário. ✓

Em 2016 a colaboração LIGO anuncia a detecção direta das Ondas Gravitacionais. ✓

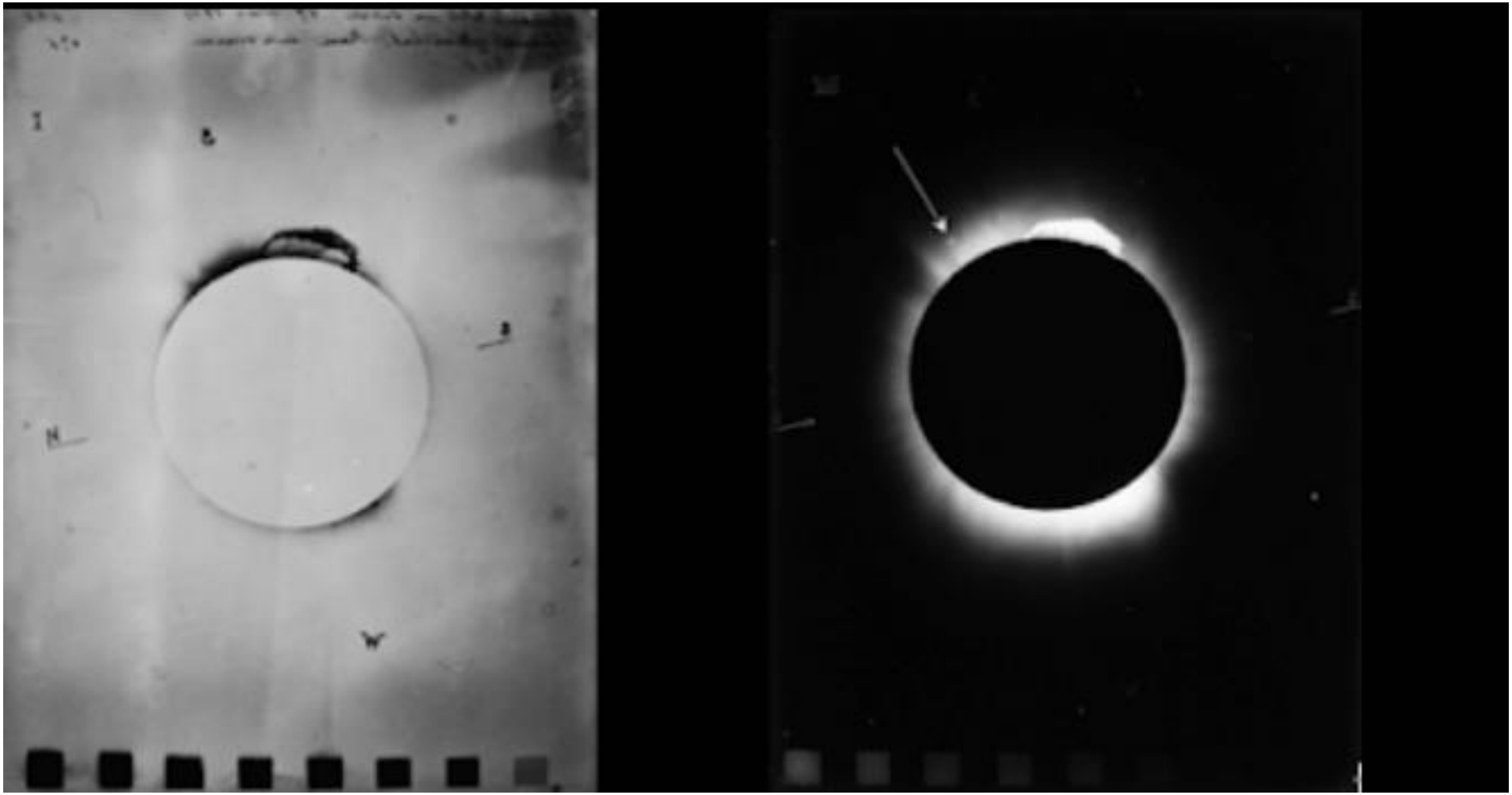
Deflexão da luz?



Como medir isso? Um eclipse do sol!
Eclipse de 1919

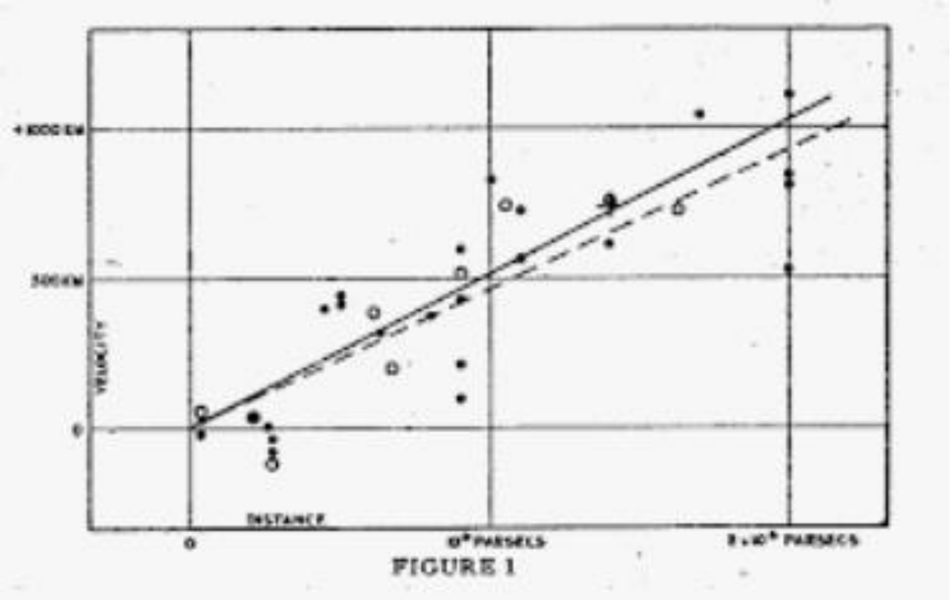
A teoria da relatividade geral de Einstein foi confirmada em solo brasileiro!

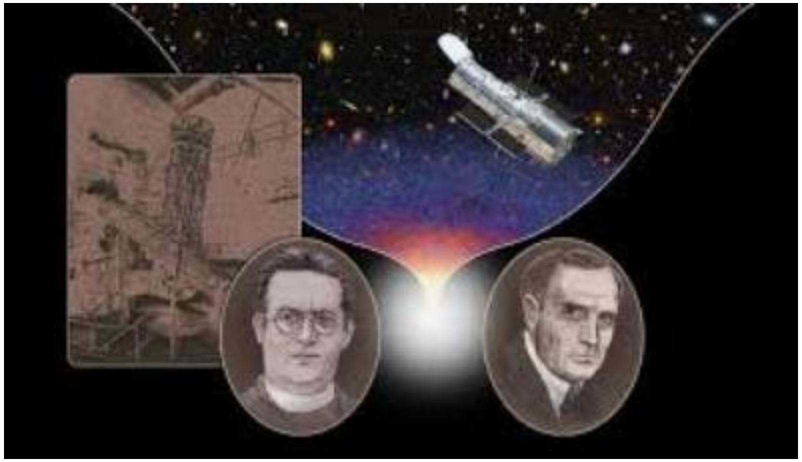


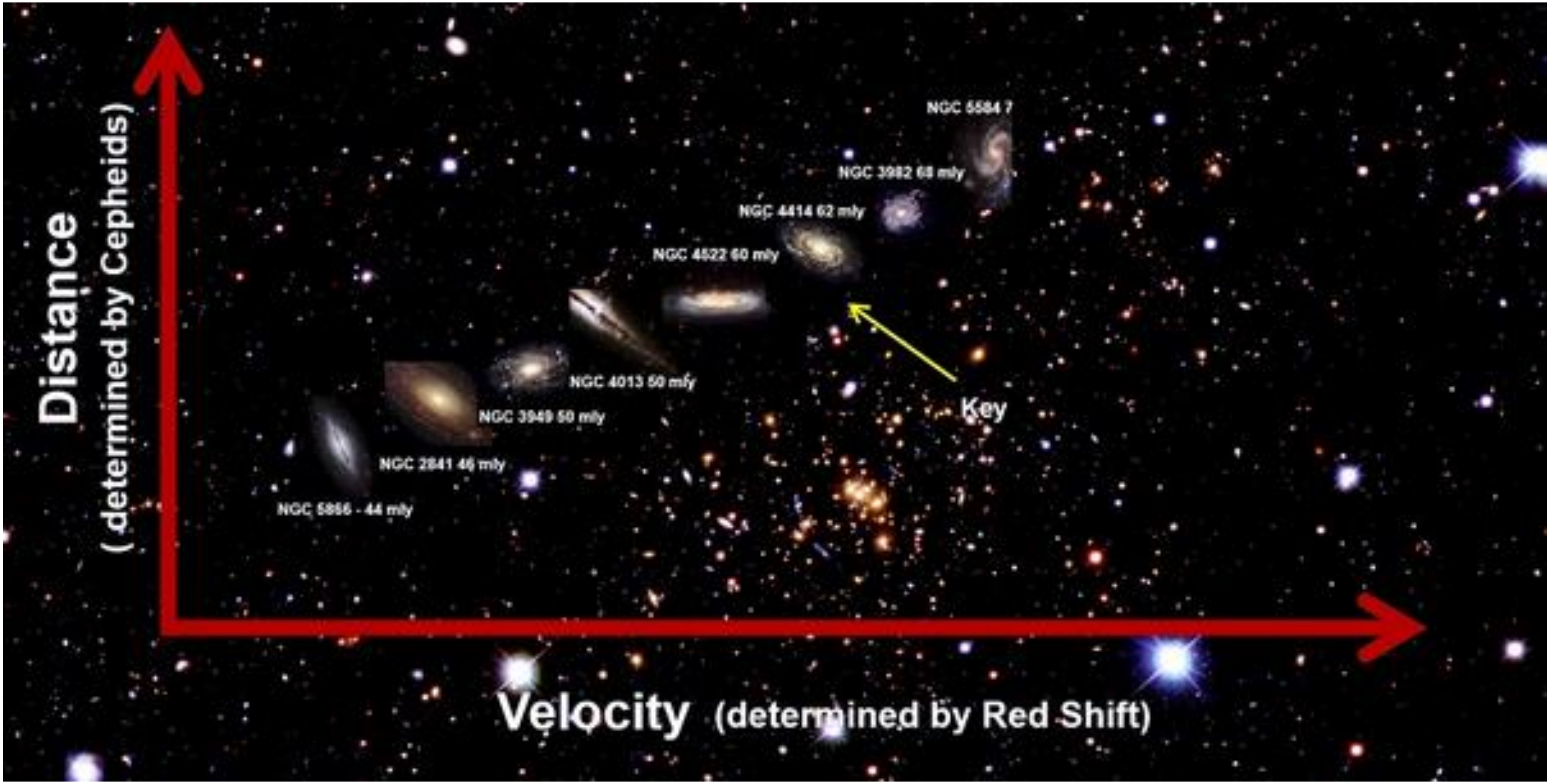


A expansão do Universo

Edwin Hubble (1889 - 1953)

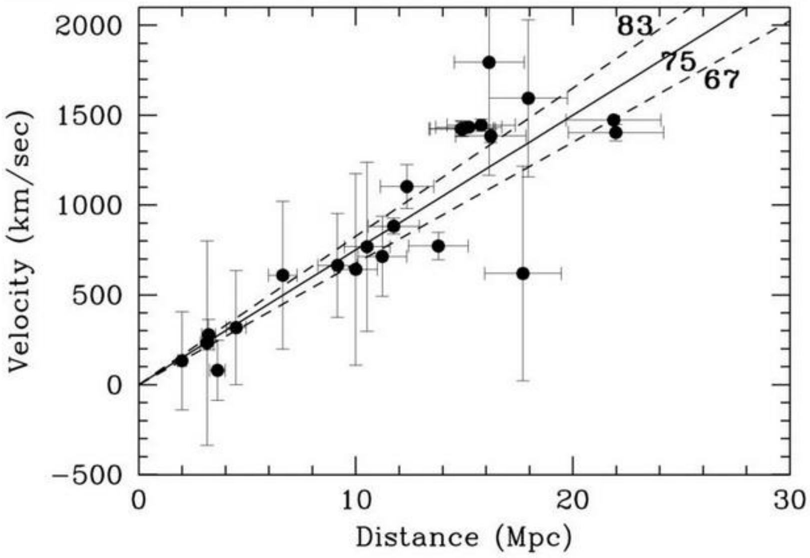


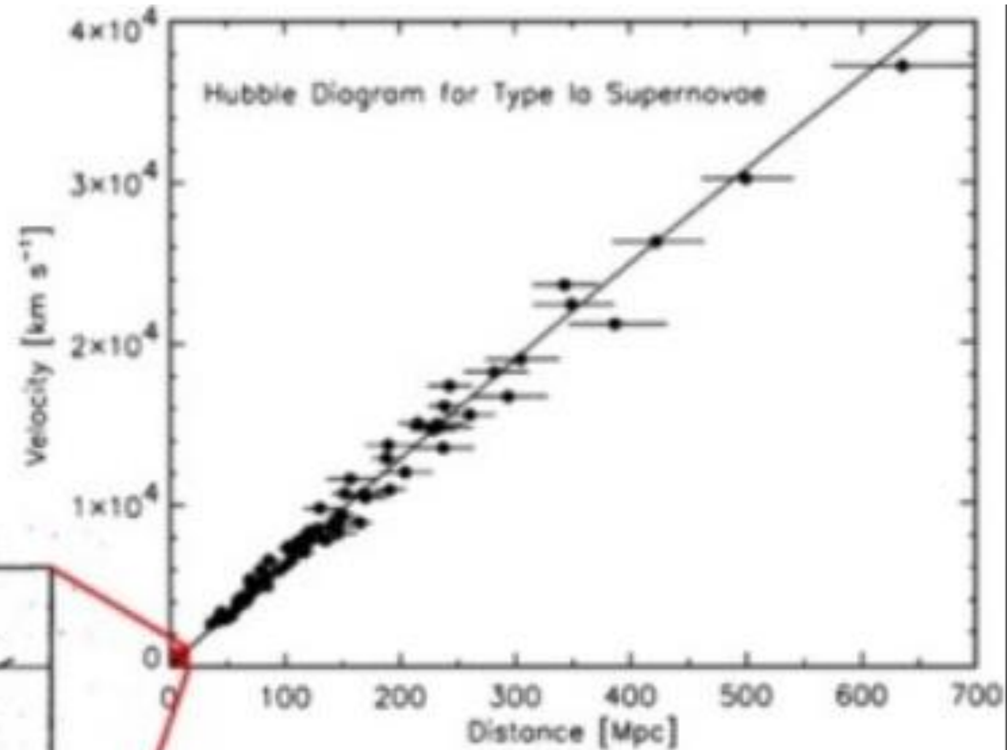


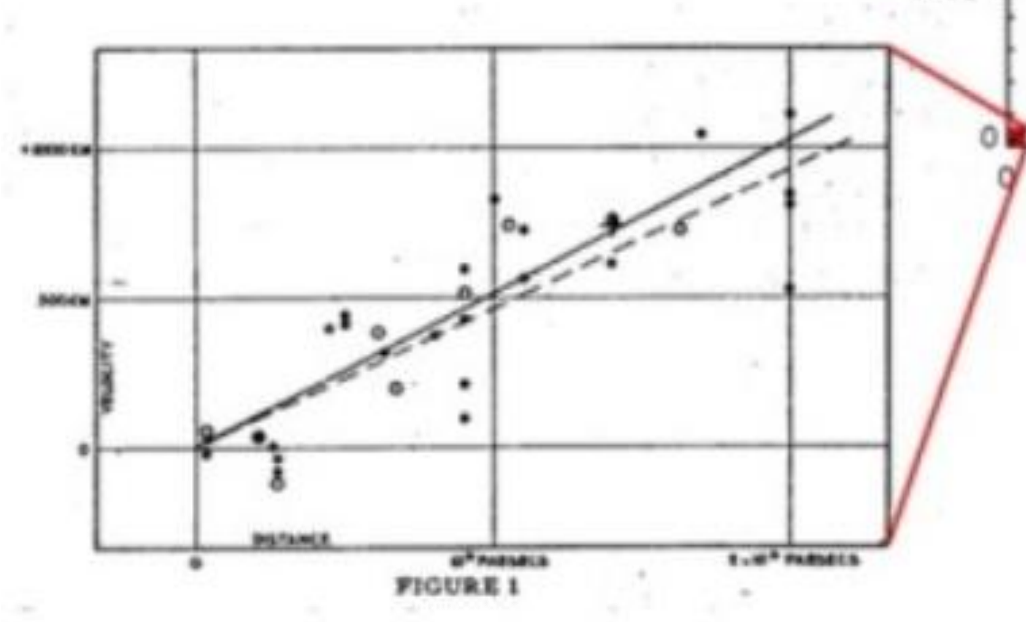


Distance
(determined by Cepheids)
NGC 5584 7
NGC 3982 68 mly
NGC 4414 62 mly
NGC 4522 60 mly
NGC 4013 50 mly
NGC 3949 50 mly
NGC 2841 46 mly
NGC 5866 - 44 mly
Key
Velocity (determined by Red Shift)

Hubble's Law (modern data)

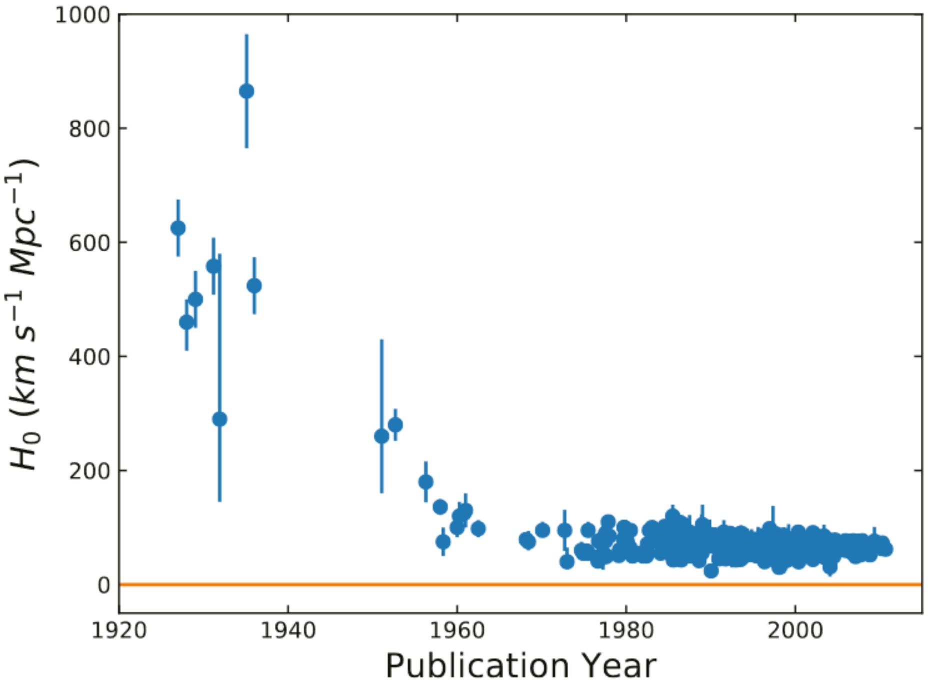


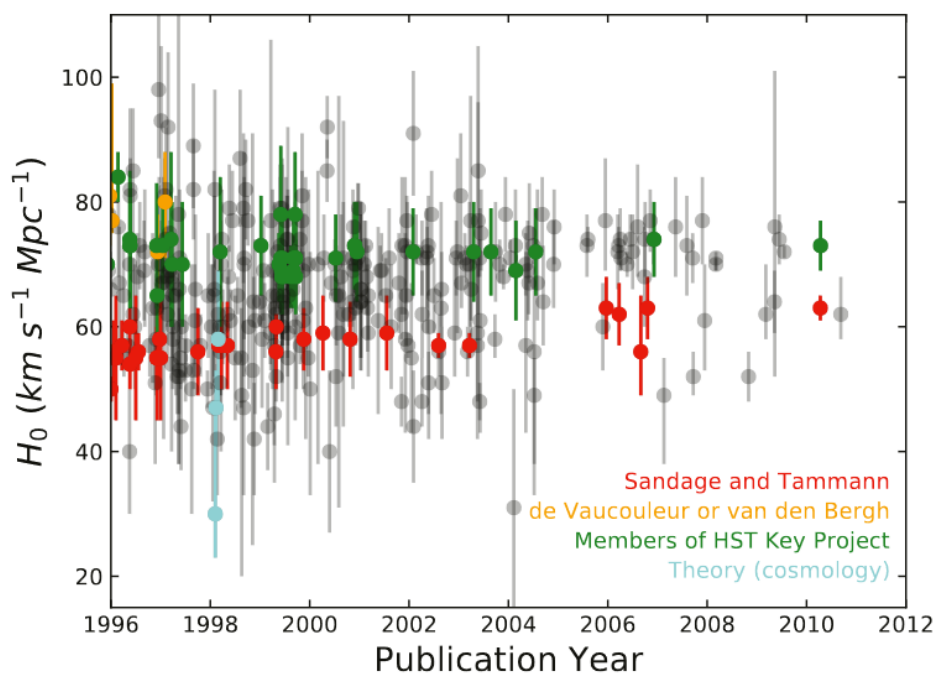




$$v = H_0 r$$

H0 é uma das principais quantidades cosmológicas

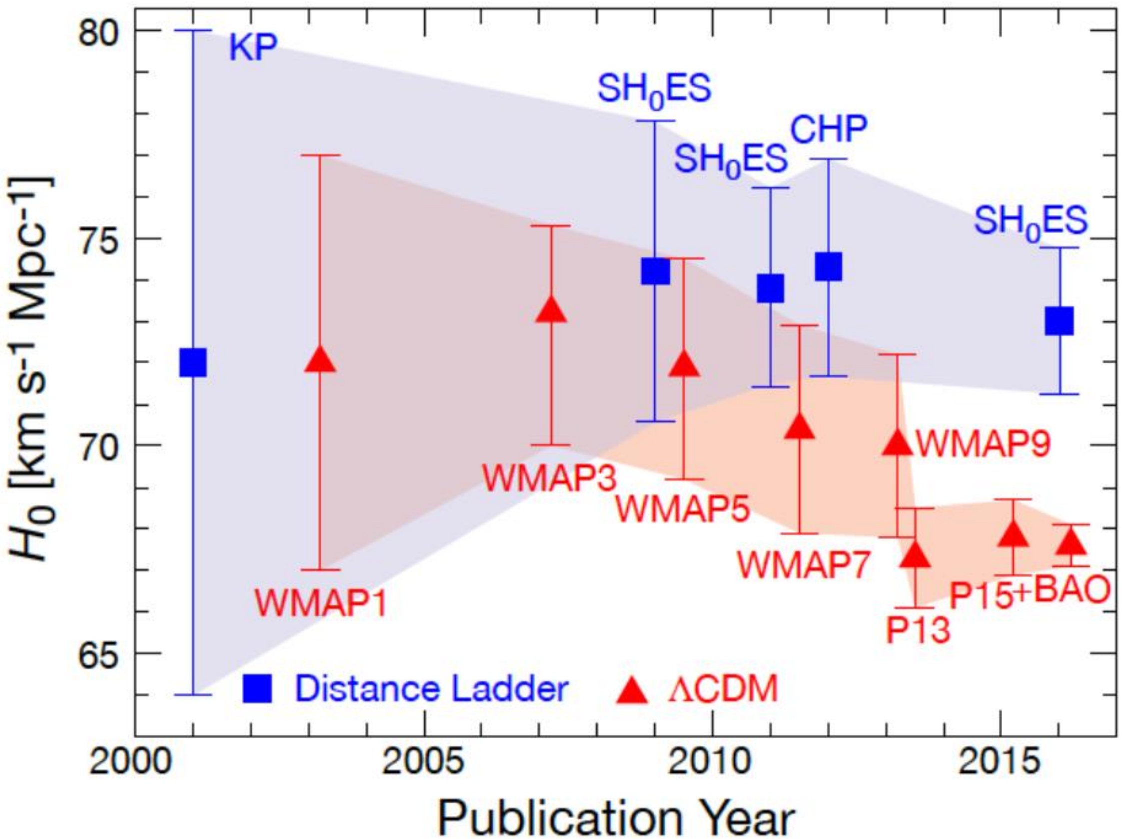




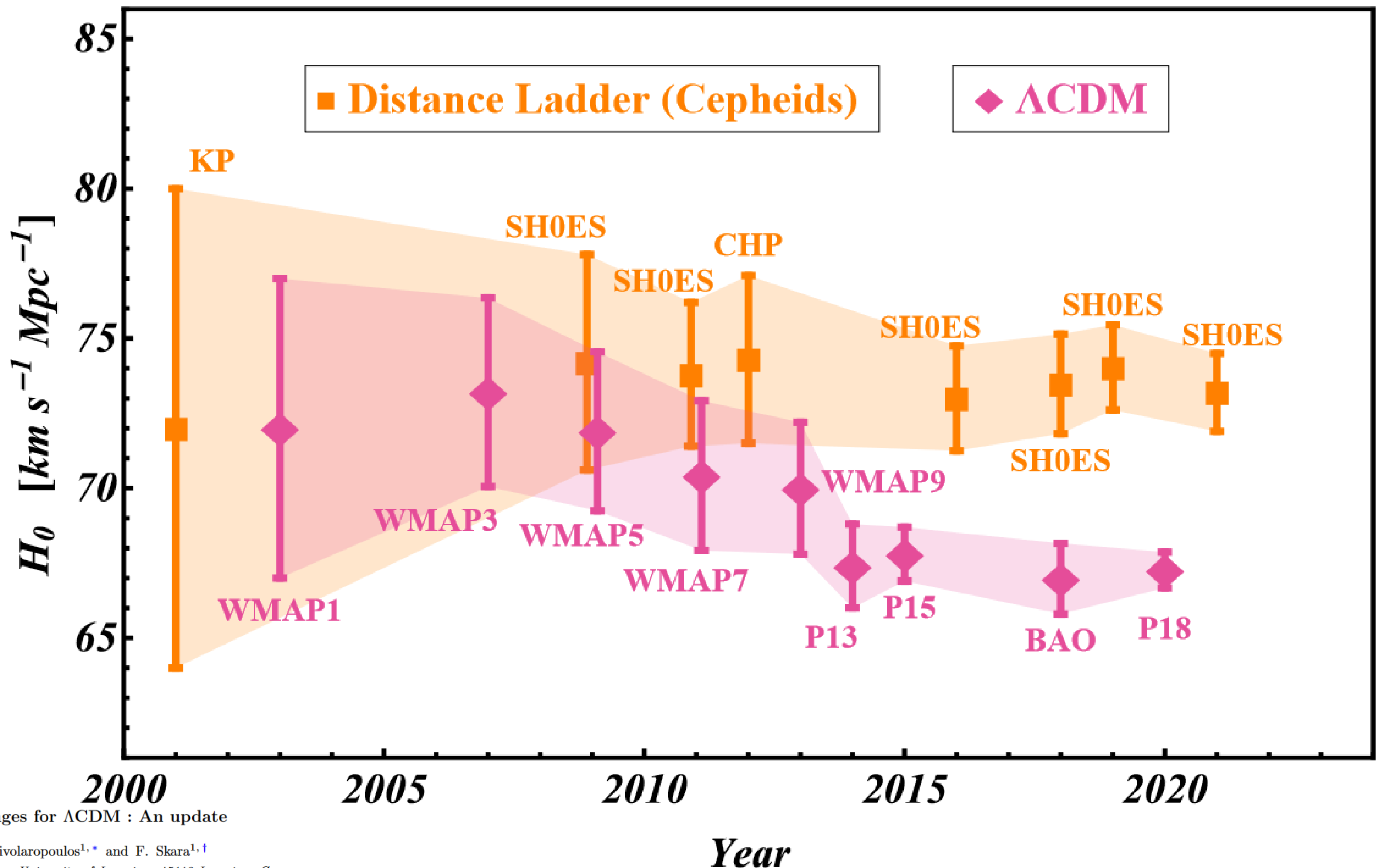
Bruno Leibundgut,

SPATIUM No. 47, May 2021

TENSÃO NAS MEDIDAS DE H0



Wendy L. Freedman *Nature Astronomy* **1**, Article number: 0121 (2017)



Challenges for ΛCDM : An update

L. Perivolaropoulos[1,*] and F. Skara[1,†]

[1] Department of Physics, University of Ioannina, 45110 Ioannina, Greece

(Dated: May 20, 2021)

Cosmologia

- Qual sistema queremos estudar? Universo (como um todo) como sistema físico e suas componentes.

- Quais são as estruturas que estamos querendo entender? Galáxias e aglomerados de galáxias e sua distribuição em grande escala.

Equações de Friedmann (1922)

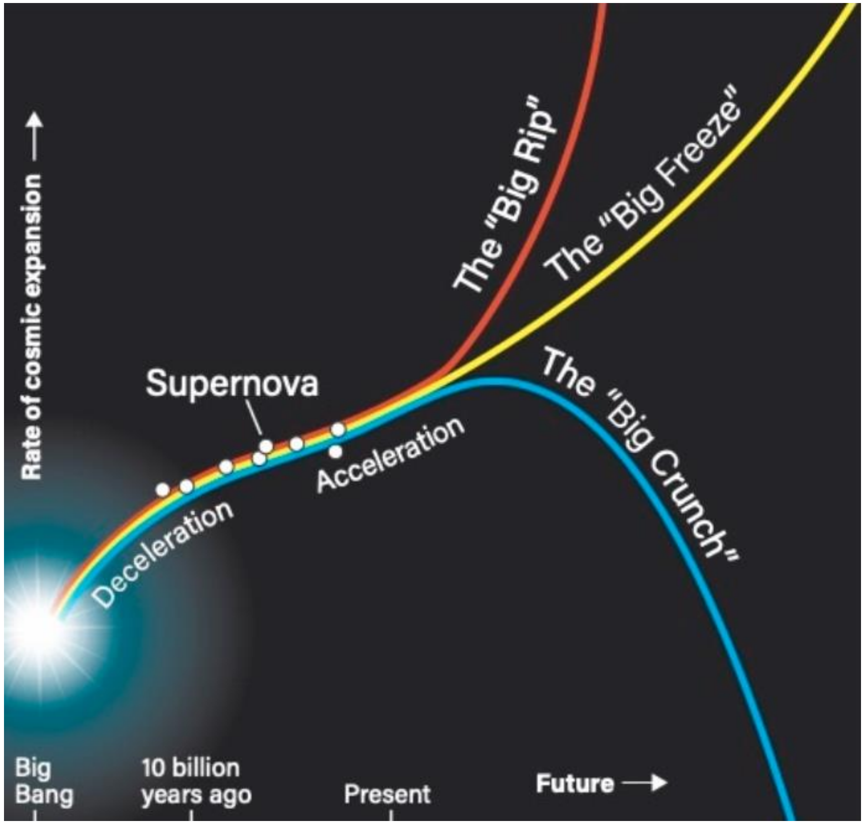
$$R_{00} = -3\left(H^2 + \dot{H}\right), \quad R_{0i} = R_{i0} = 0, \quad R_{ij} = a^2\left(3H^2 + \dot{H} + 2K/a^2\right)\gamma_{ij},$$
$$R = 6\left(2H^2 + \dot{H} + K/a^2\right).$$

$$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2},$$
$$3H^2 + 2\dot{H} = -8\pi G P - \frac{K}{a^2}$$

$$\Rightarrow \quad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

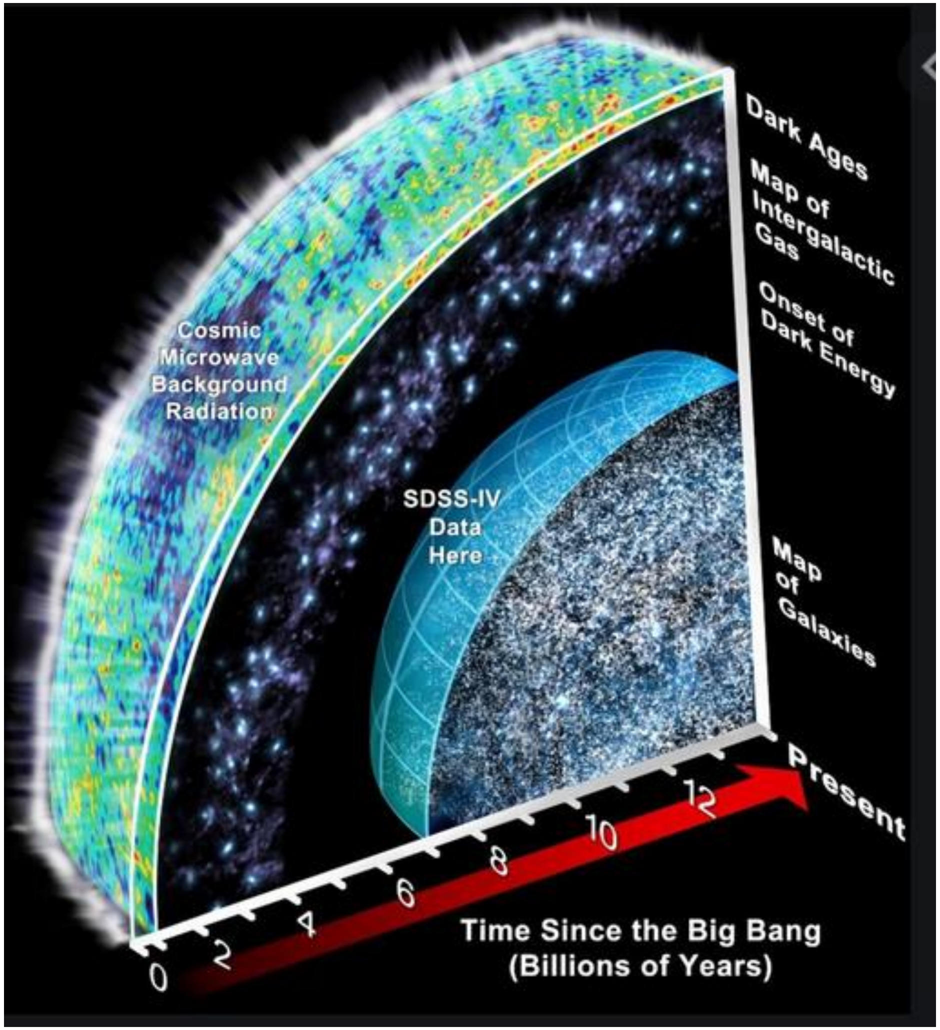
$$\Omega_M + \Omega_K = 1,$$

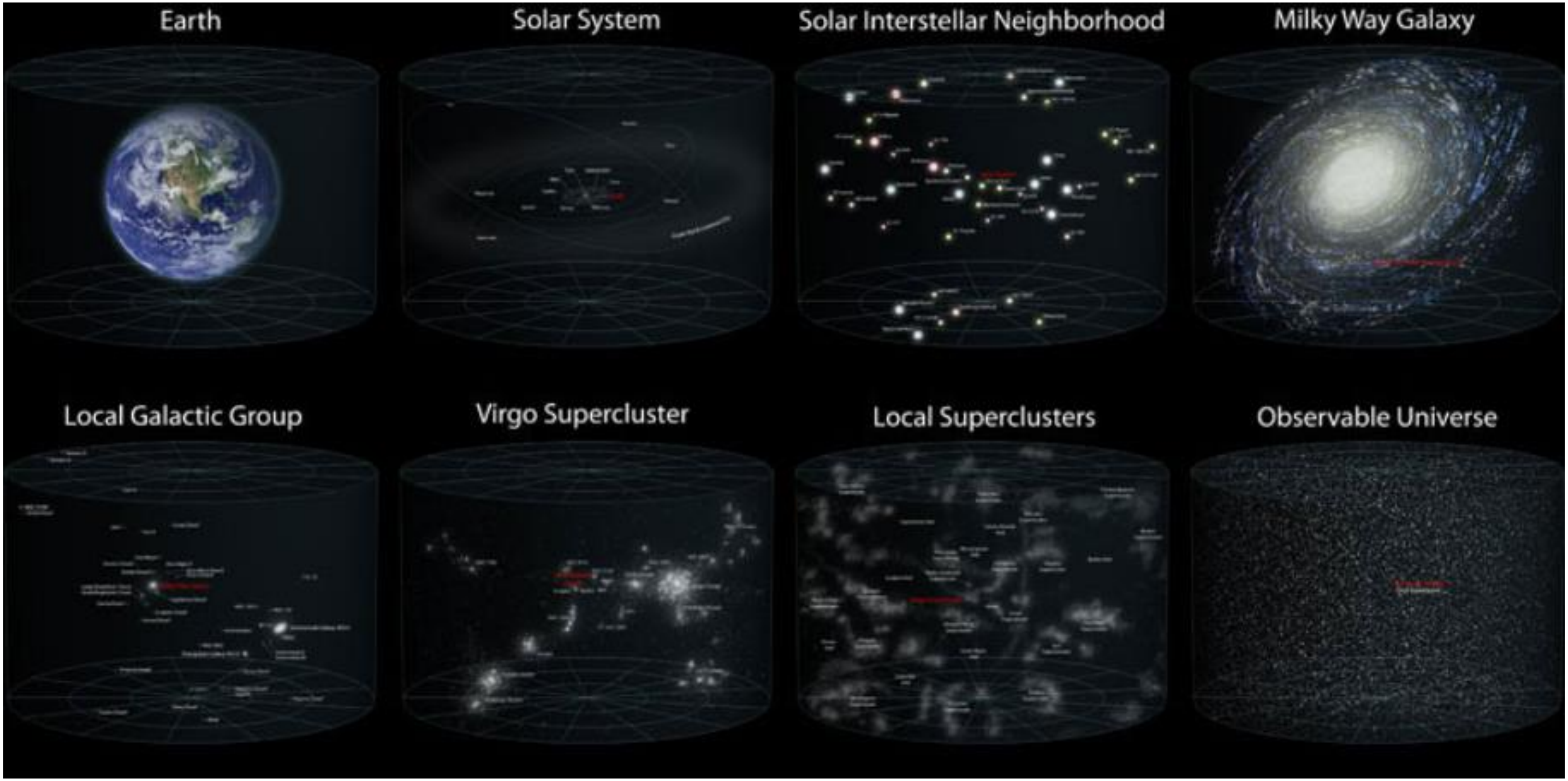
$$\Omega_M \equiv \frac{8\pi G\rho}{3H^2}, \qquad \Omega_K \equiv -\frac{K}{(aH)^2}$$



A dinâmica da evolução cósmica depende de seu conteúdo material

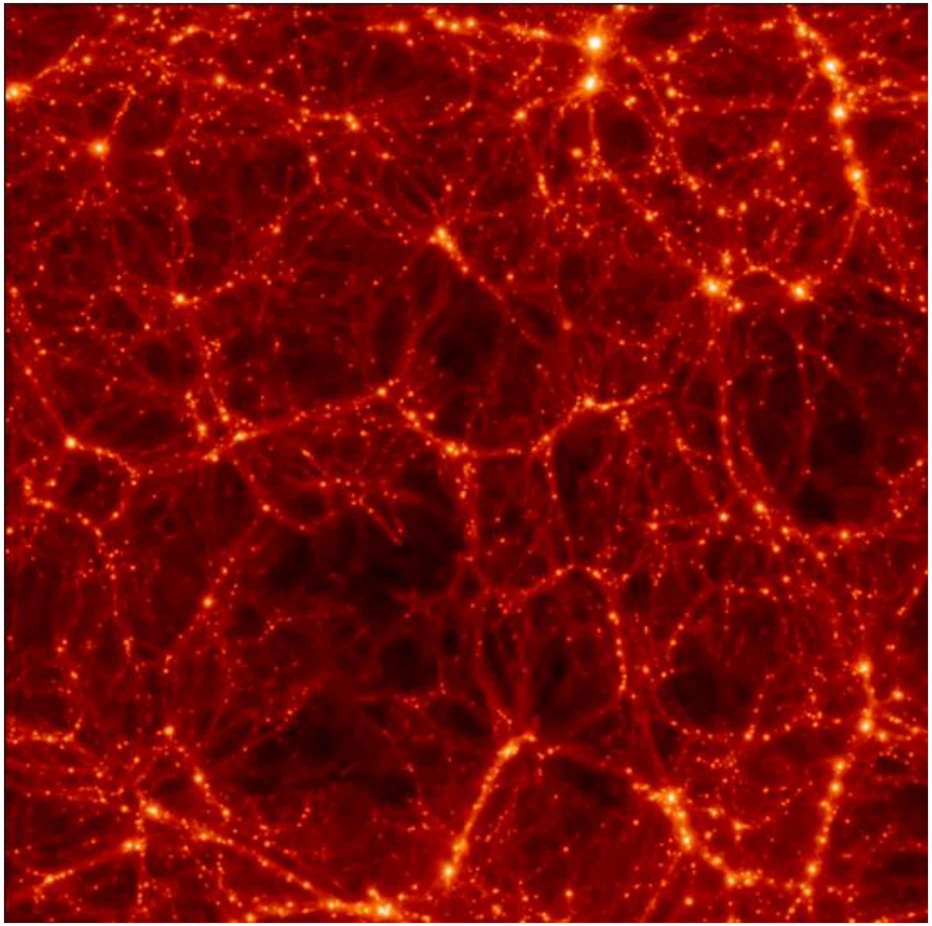
Grandes mapeamentos de galáxias

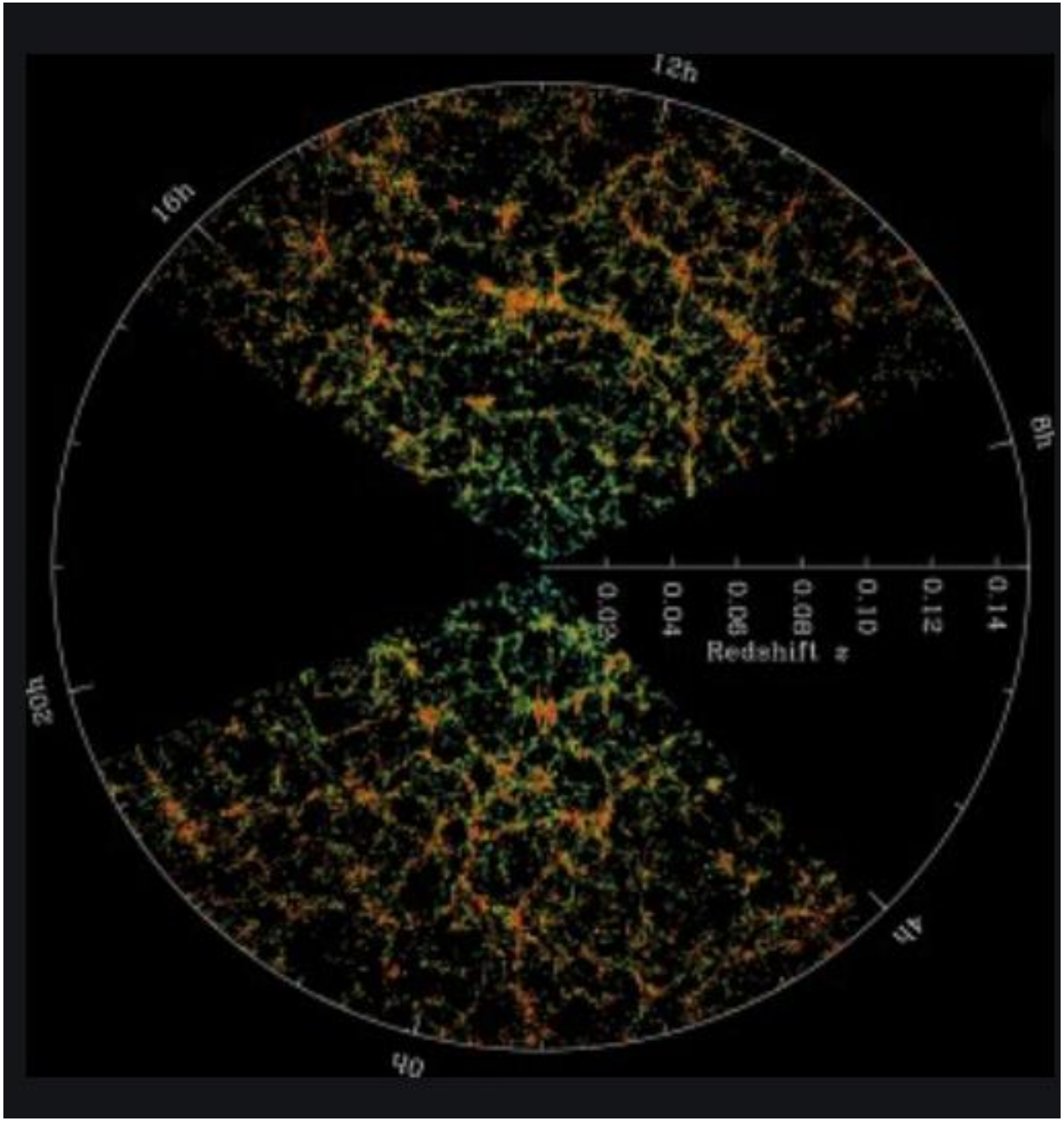



Earth
Solar System
Solar Interstellar Neighborhood
Milky Way Galaxy
Local Galactic Group
Virgo Supercluster
Local Superclusters
Observable Universe

Estrutura em grande escala

https://www.youtube.com/watch?v=RAiPZ_oUPI4&feature=emb_logo

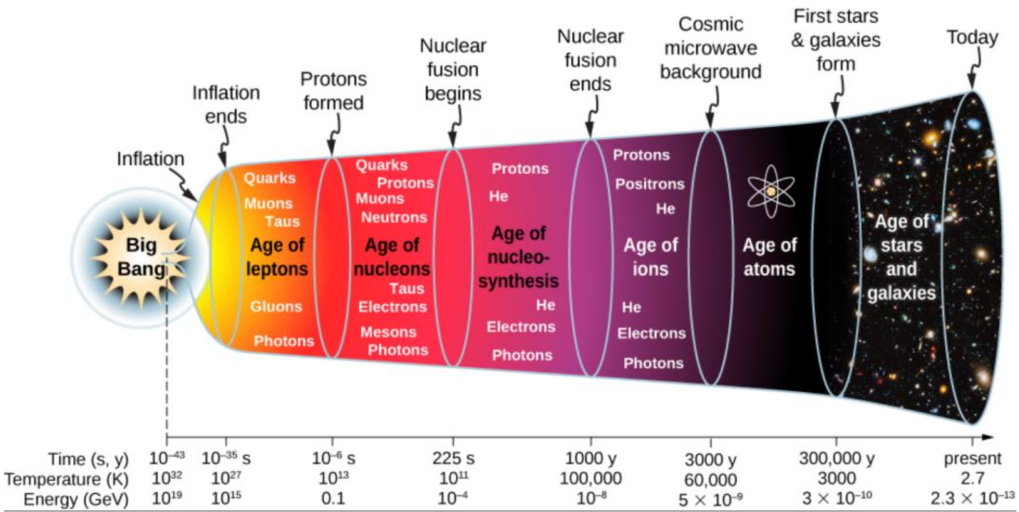




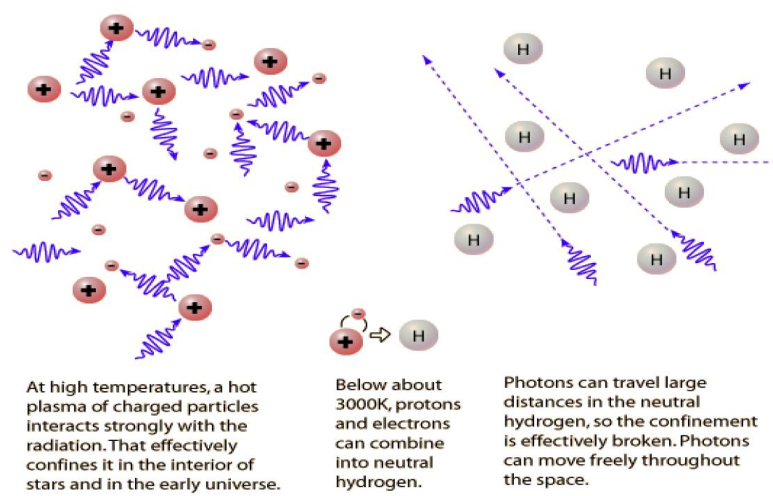
12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z

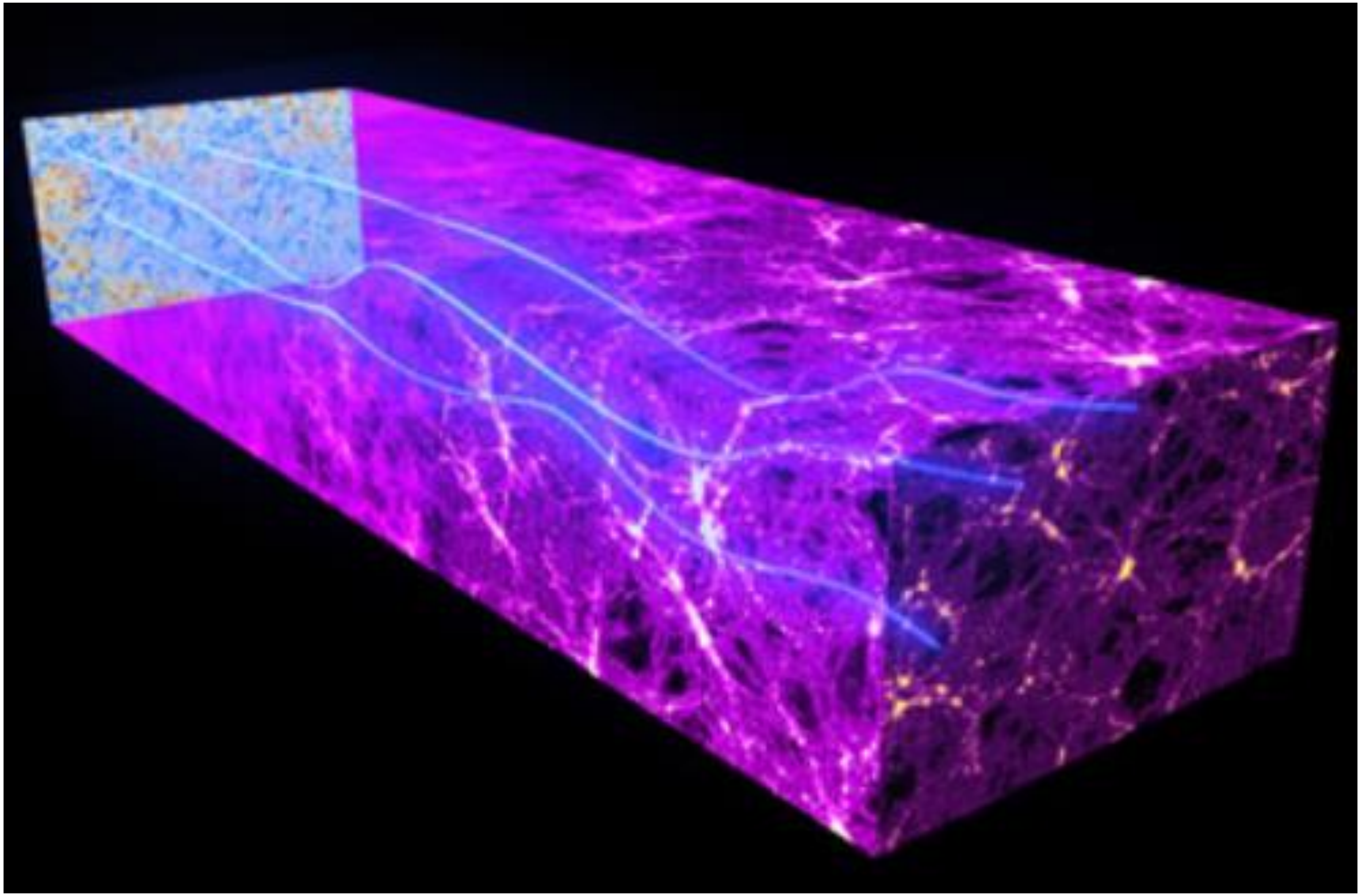
Radiação Cósmica de Fundo – Cosmic Microwave Background (CMB)

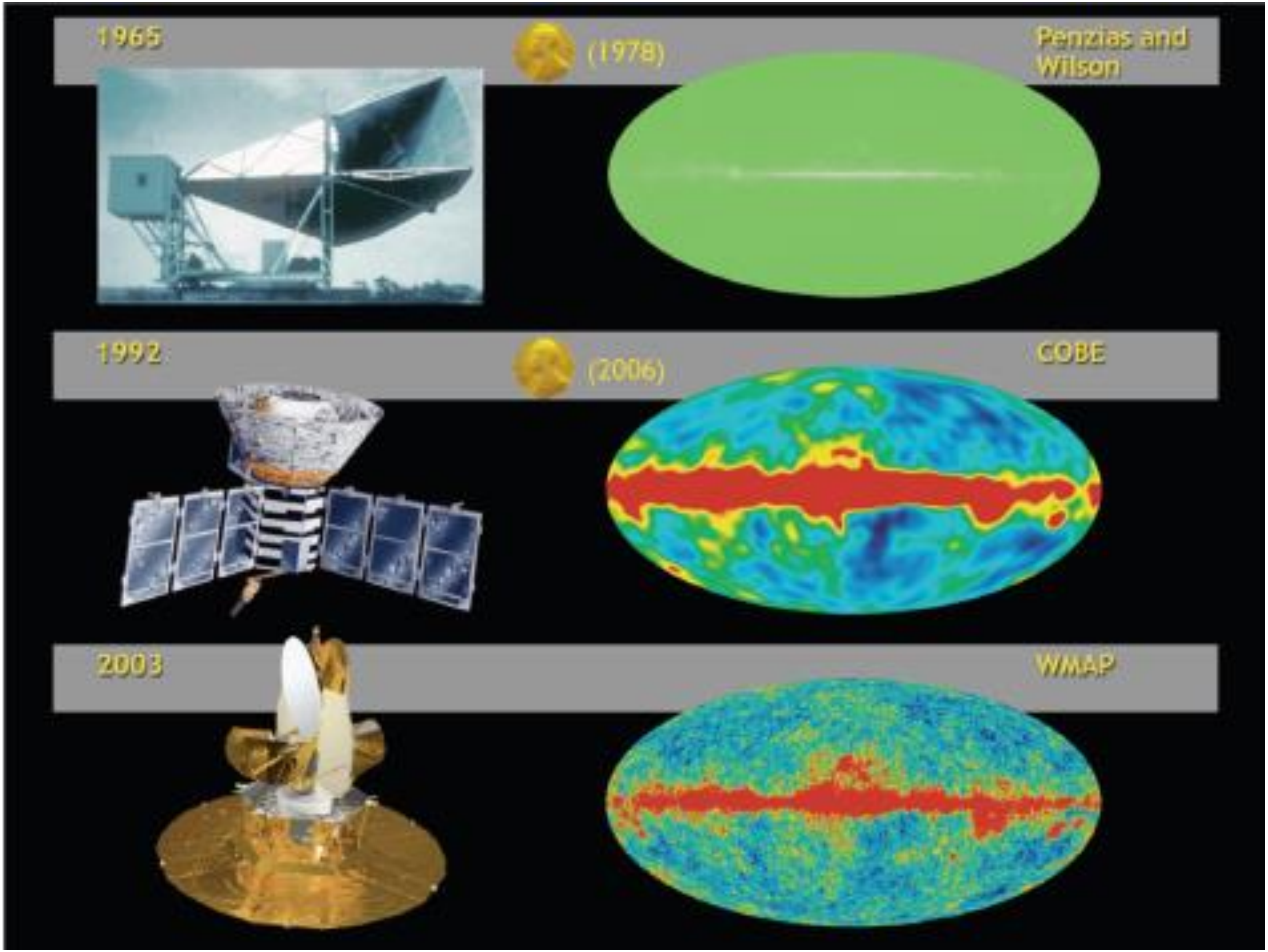
Hermano Velten



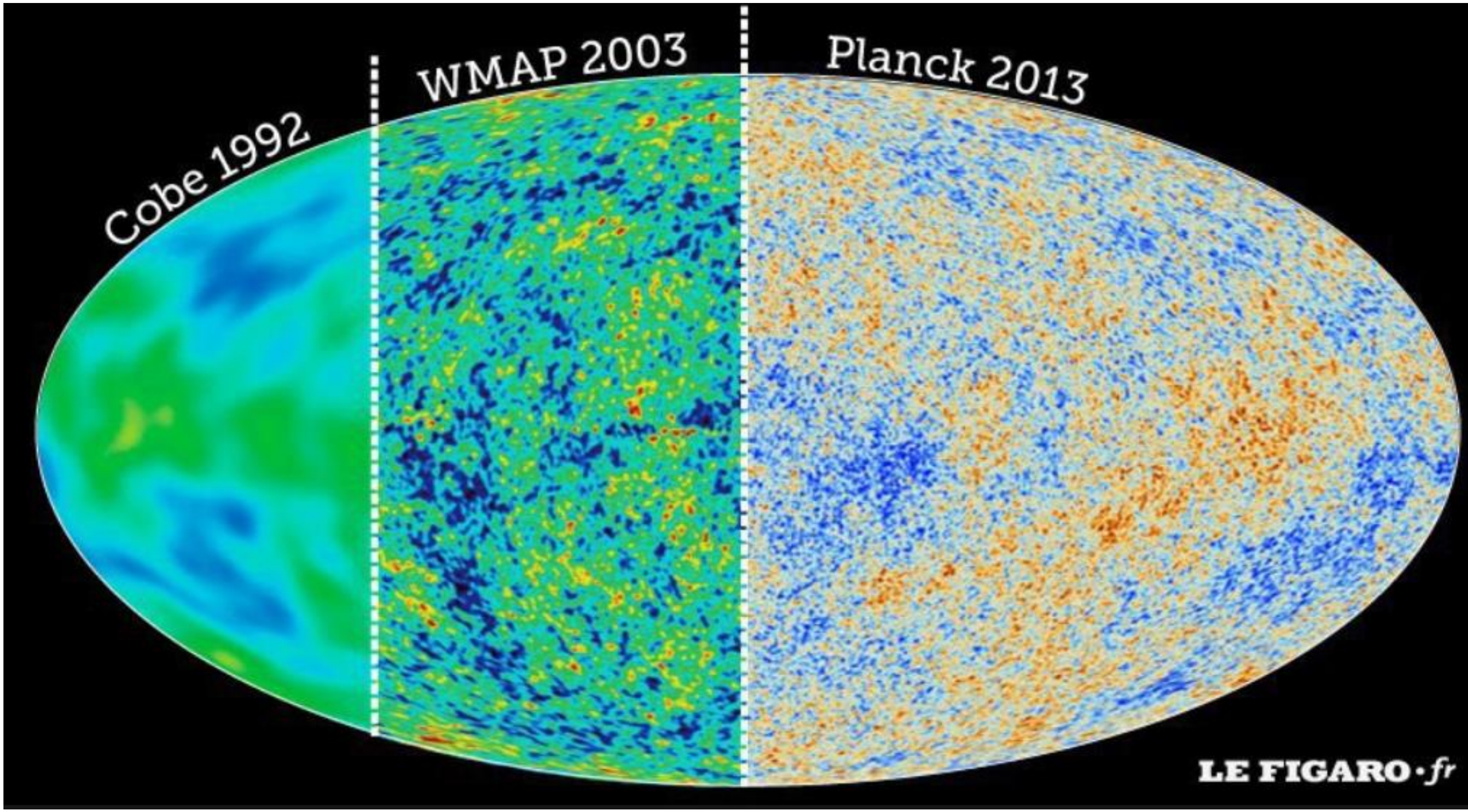
Radiação se desacopla dos elétrons







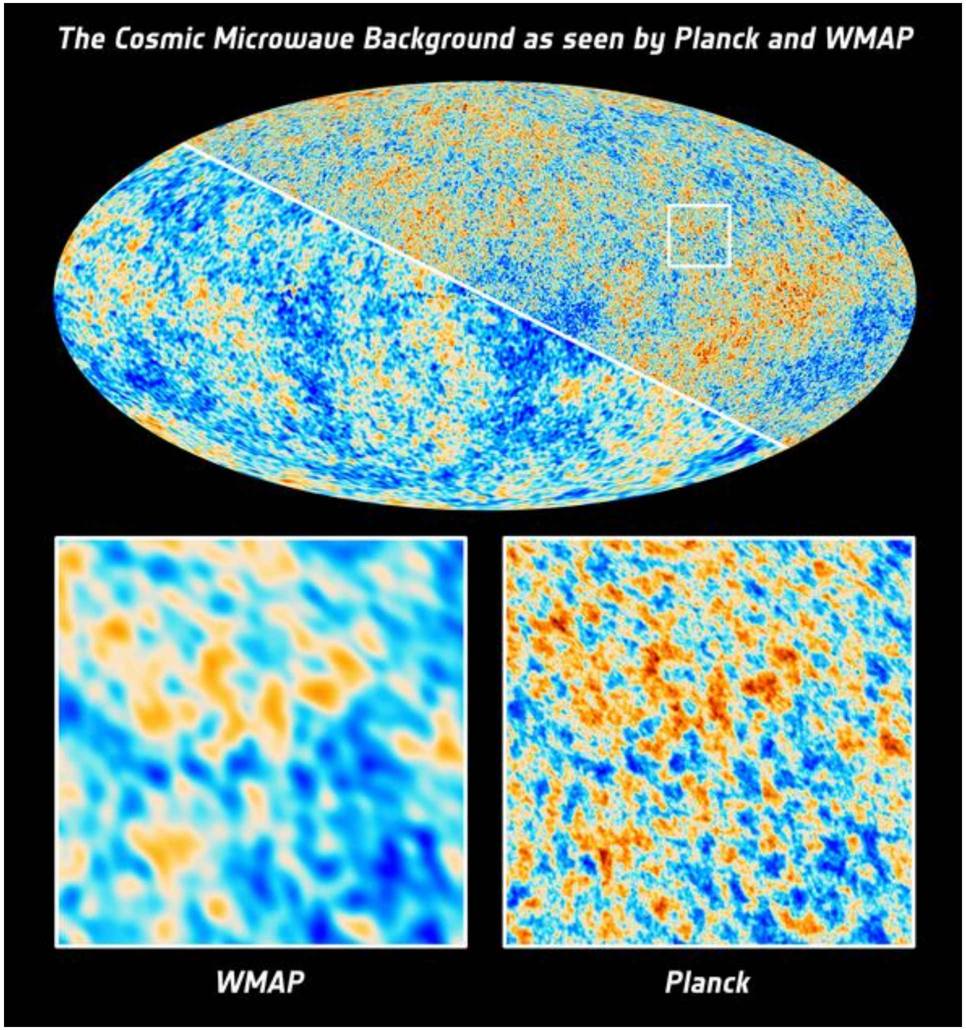
1965
(1978)
Penzias and Wilson
1992
(2006)
COBE
2003
WMAP


Cobe 1992
WMAP 2003
Planck 2013
LE FIGARO·fr

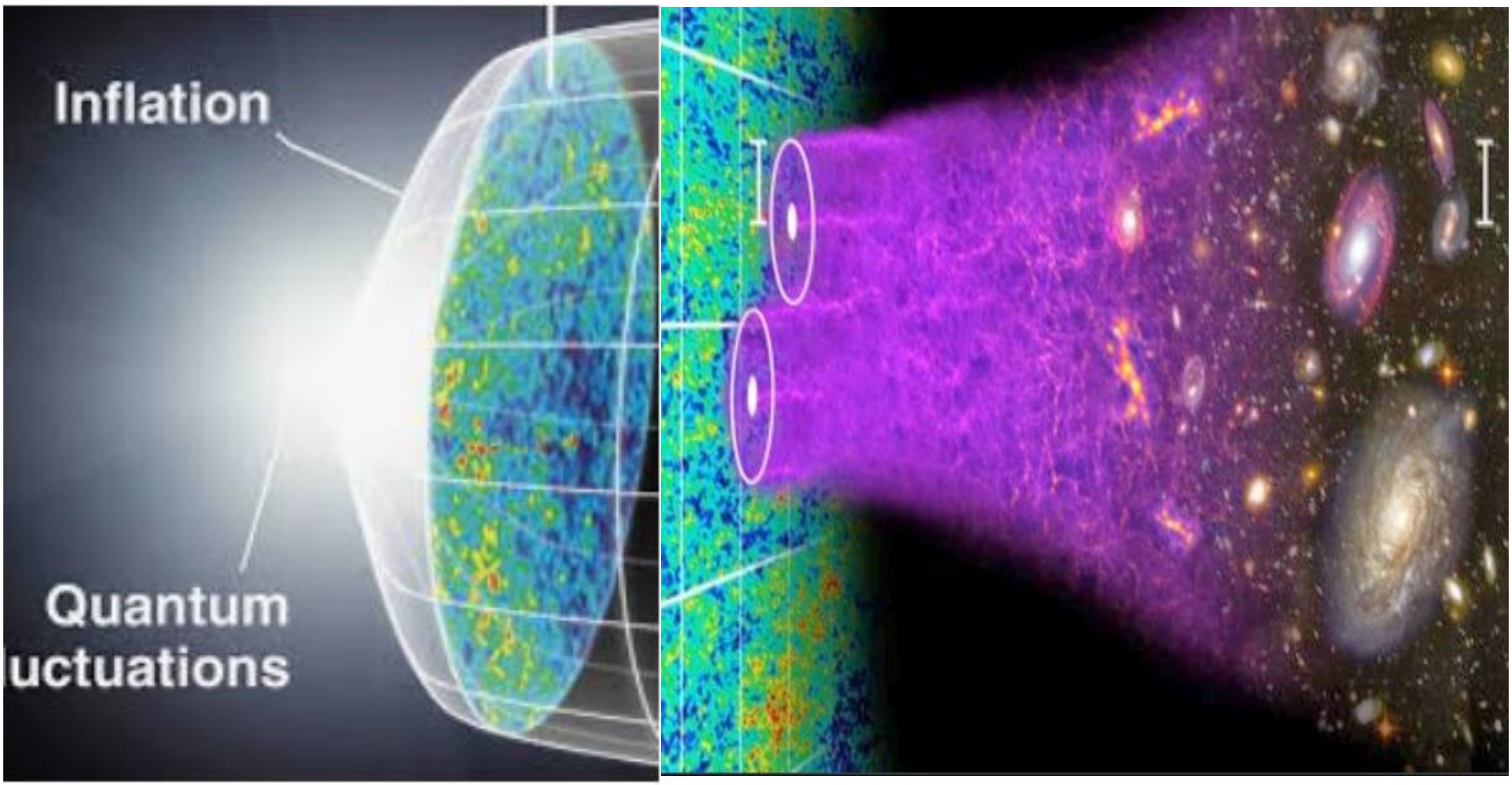
PLANCK satellite

Lauch: 2009.
Took data until 2013.

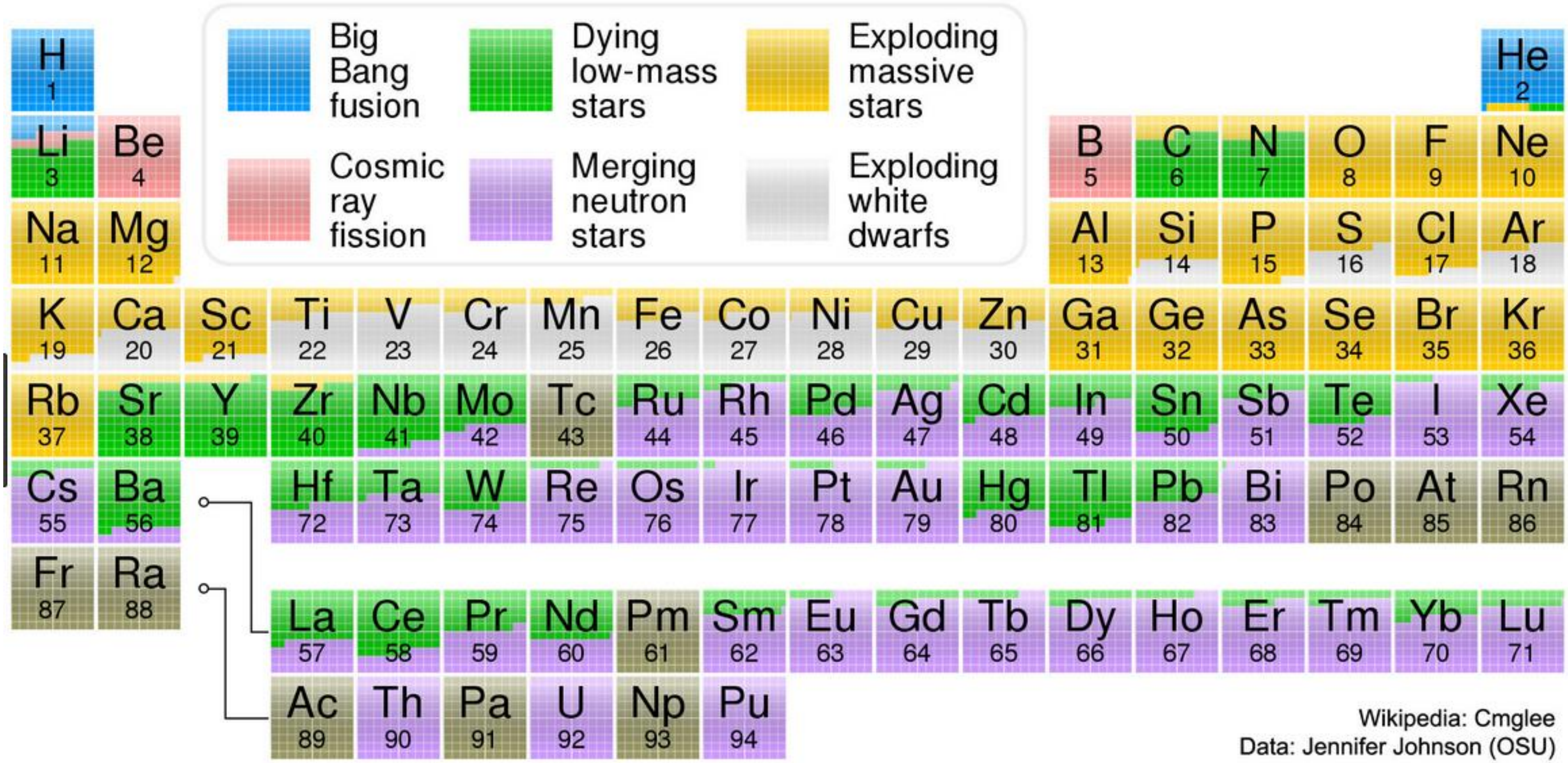
Data releases: 2013, 2016, 2018



As perturbações são criadas na inflação, deixam uma marca na CMB e na distribuição de galáxias:

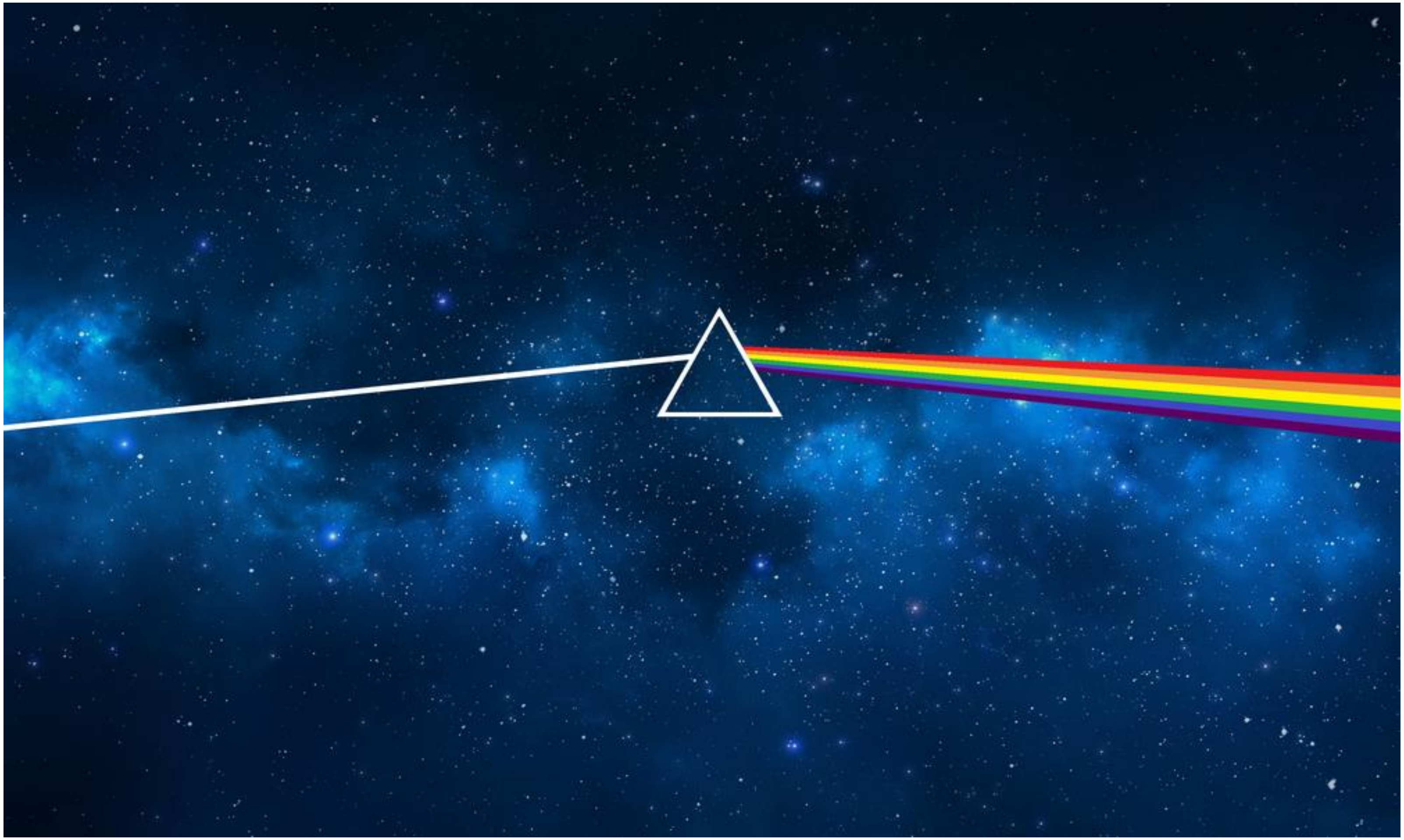


O que conhecemos do cosmos?
A origem dos elementos



E o que NÃO conhecemos de todo o Cosmos?

- O SETOR ESCURO DO UNIVERSO:
  - Matéria Escura e Energia Escura



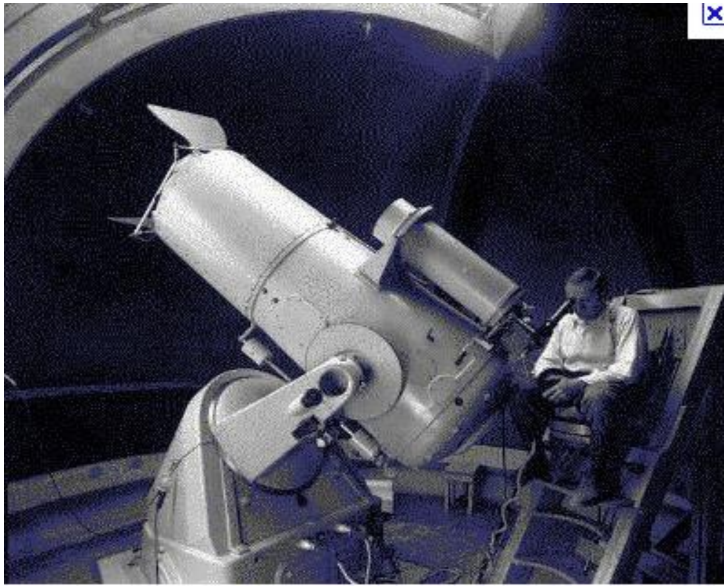
Matéria Escura

Evidências de Matéria Escura

- Evidências Astrofísicas:
- - Ocorrem em sistemas isolados como galáxias e aglomerados;

- Evidências Cosmológicas:
- - Levam em conta a expansão do Universo.
- - Matéria escura surge como elemento imprescindível

Fritz Zwicky 1898-1974: Primeira evidência sobre matéria escura



THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_{\odot}$ for the average mass of its member nebulae.

Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes of application. It is proposed, in particular, to investigate the distribution of nebulae in individual great clusters.

As a first step toward the realization of the proposed program, the Coma cluster of nebulae was photographed with the new 18-inch Schmidt telescope on Mount Palomar. Counts of nebulae brighter than about $m = 16.7$ given in section vi lead to the gratifying result that the distribution of nebulae in the Coma cluster is very similar to the distribution of luminosity in globular nebulae, which, according to Hubble's investigations, coincides closely with the theoretically determined distribution of matter in isothermal gravitational gas spheres. The high central condensation of the Coma cluster, the very gradual decrease of the number of nebulae per unit volume at great distances from its center, and the hitherto unexpected enormous extension of this cluster become here apparent for the first time. These results also suggest that the current classification of nebulae into relatively few *cluster nebulae* and a majority of

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

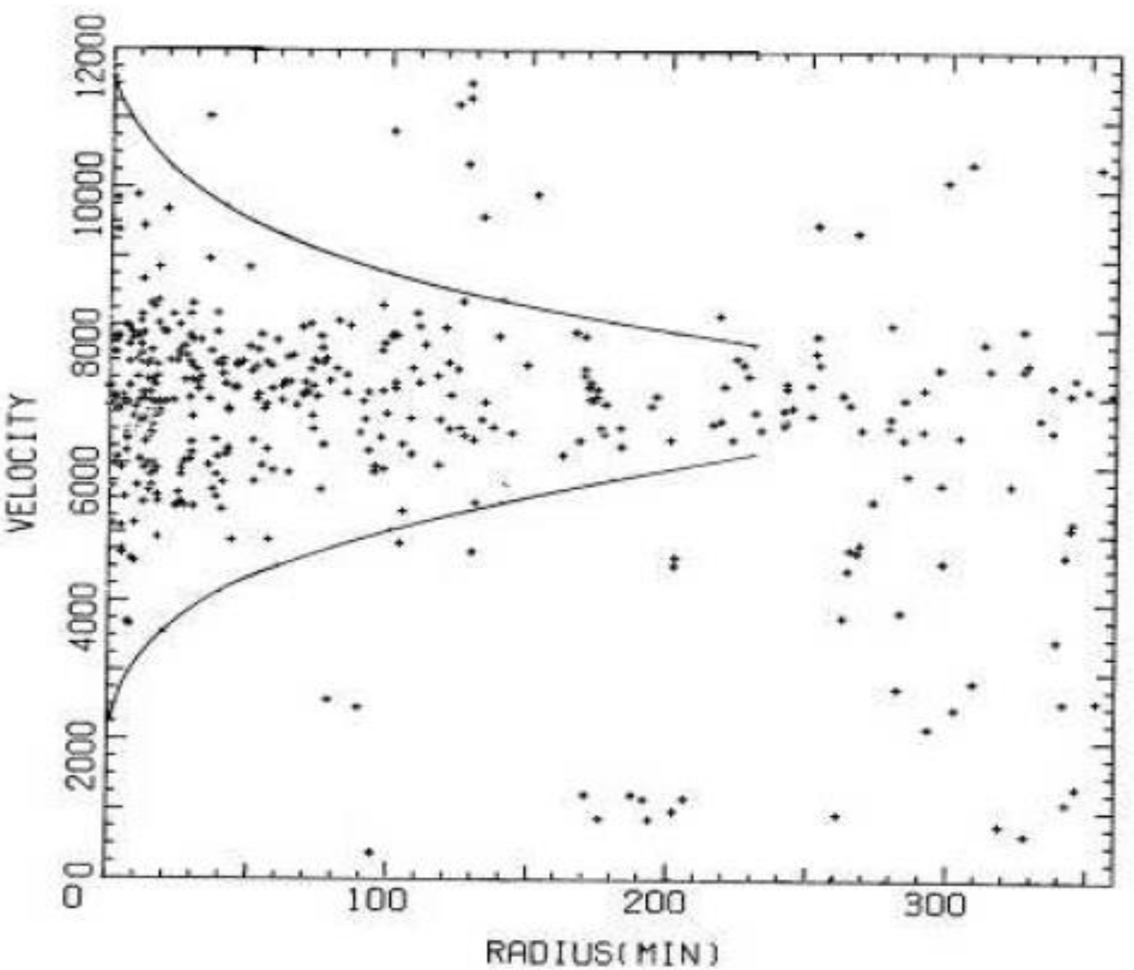
$$\overline{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_{\odot} . \tag{36}$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathcal{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500 , \tag{37}$$

as compared with about $\gamma' = 3$ for the local Kapteyn stellar system.

Aplicando o teorema do Virial (2K+W=0) ao aglomerado de galáxias de COMA
Resultado: a razão entre sua massa e luminosidade é M/L ~180 em unidades solares



$$\gamma = \sqrt{1 - \frac{v^2}{c^2}}$$

$$c = 299.729.458 m/seg.$$

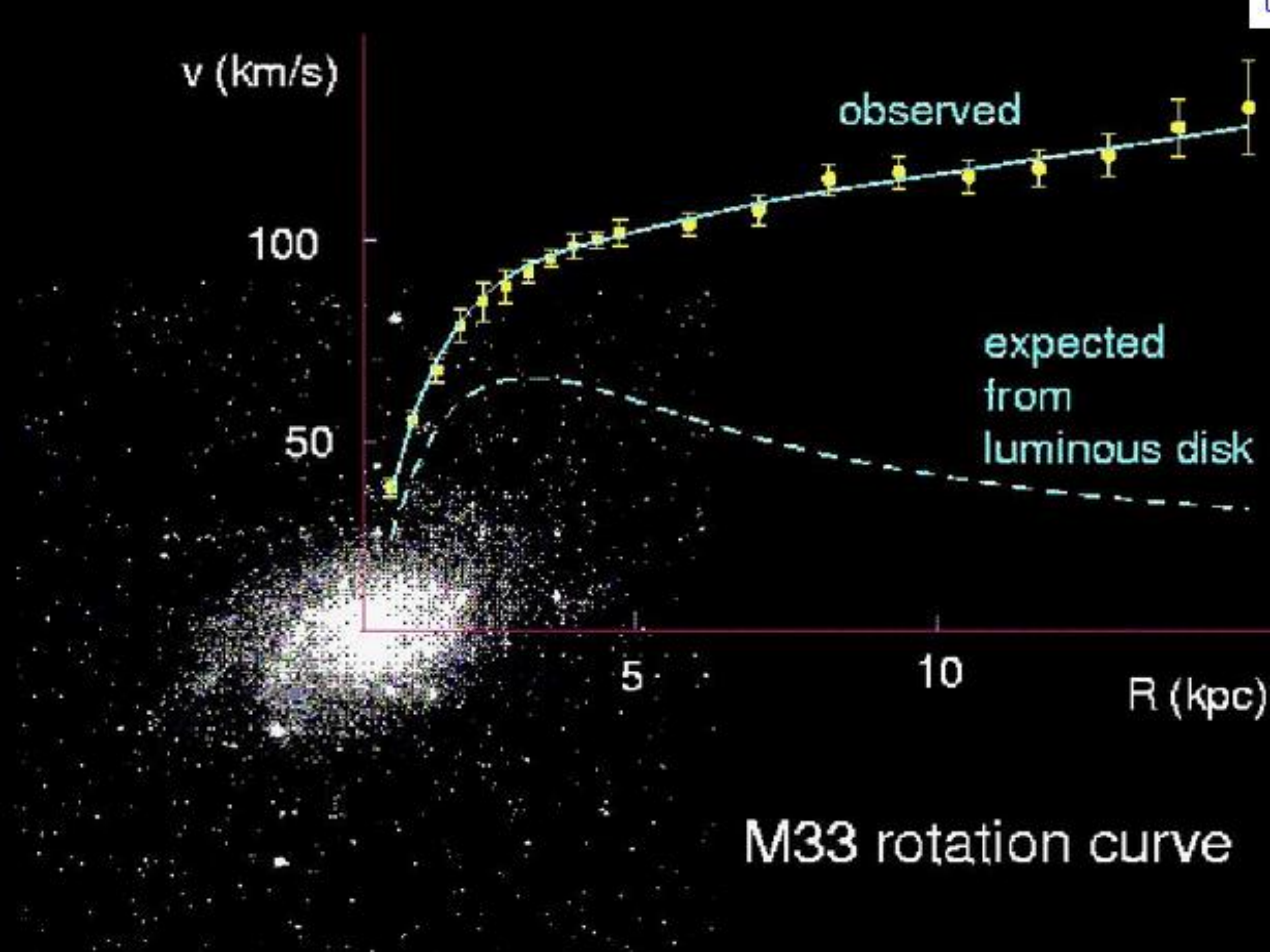
$$\gamma \sim 0,9997$$

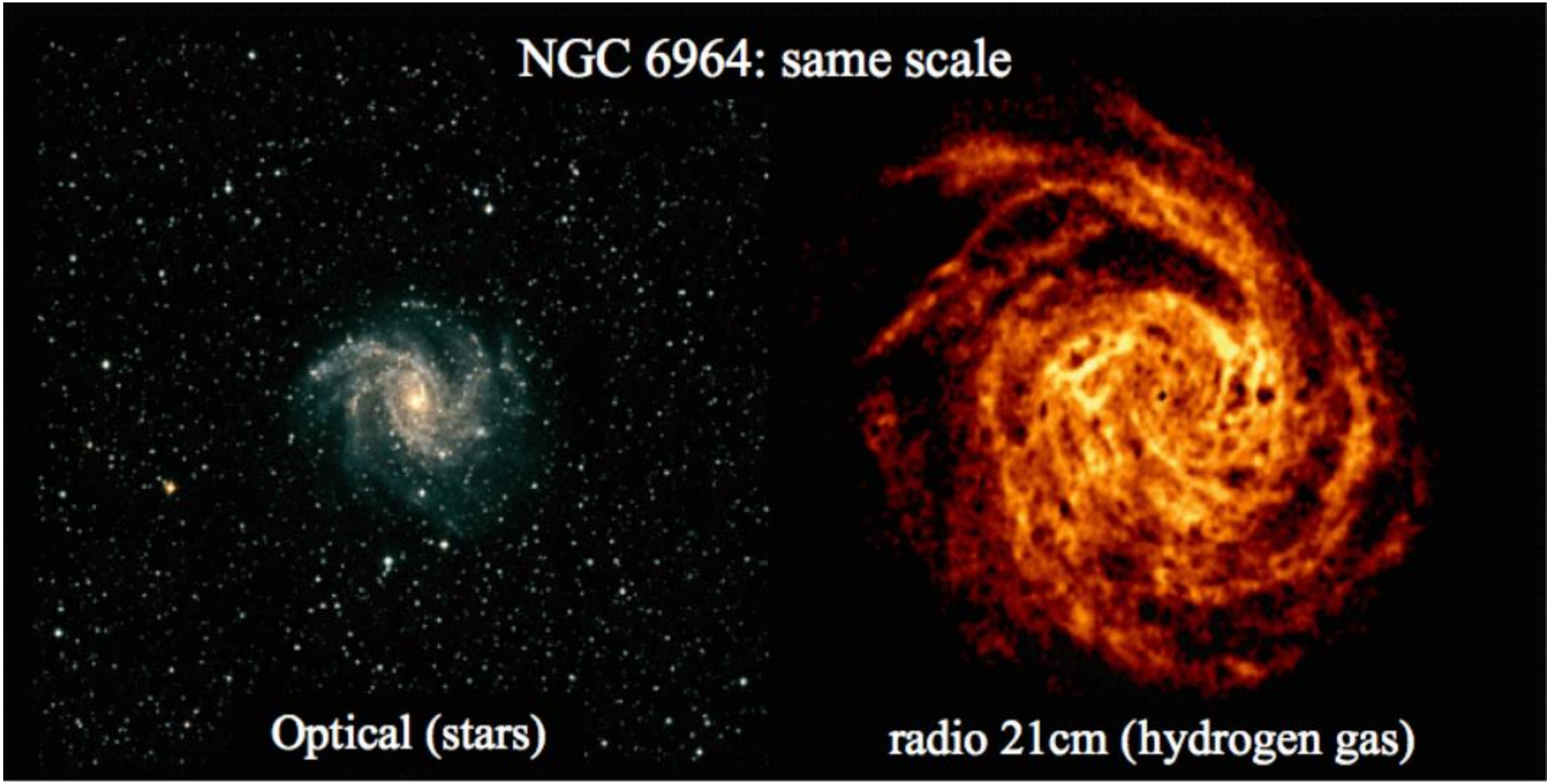
Sistema Newtoniano!

Curva de rotação de galáxias espirais

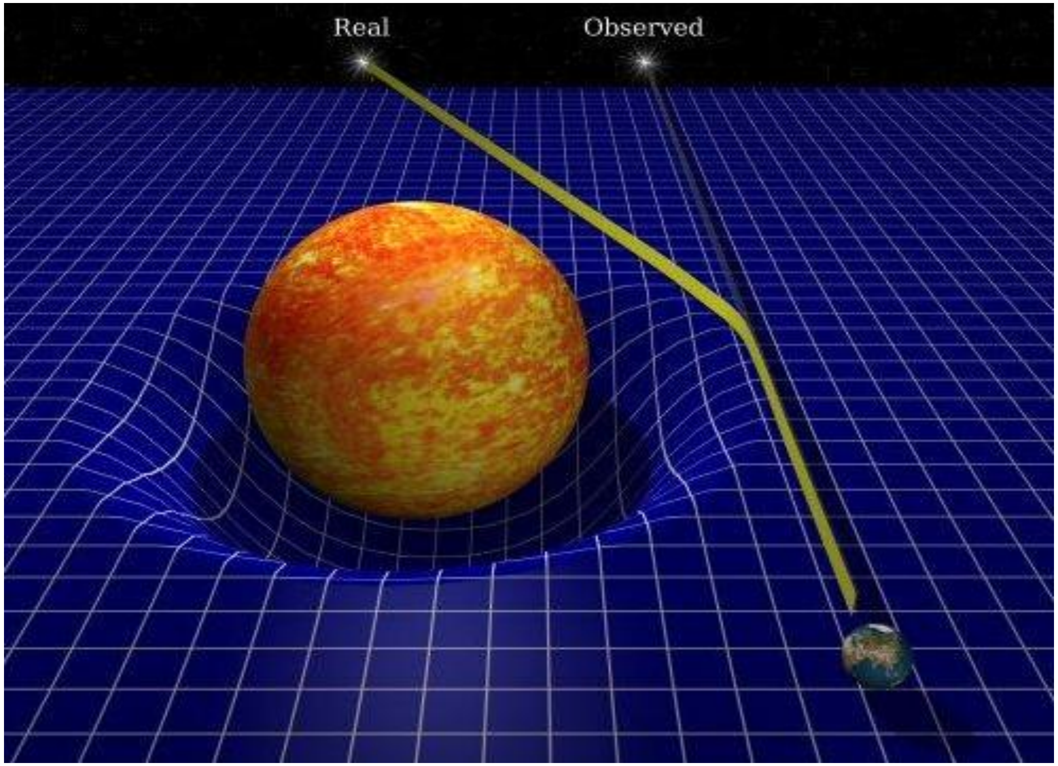
Vera Rubin ~1980

Qual o perfil de velocidade das estrelas e gases nesse sistema?


v (km/s)
observed
100
expected
from
luminous disk
50
5
10
R (kpc)
M33 rotation curve


NGC 6964: same scale
Optical (stars)
radio 21cm (hydrogen gas)

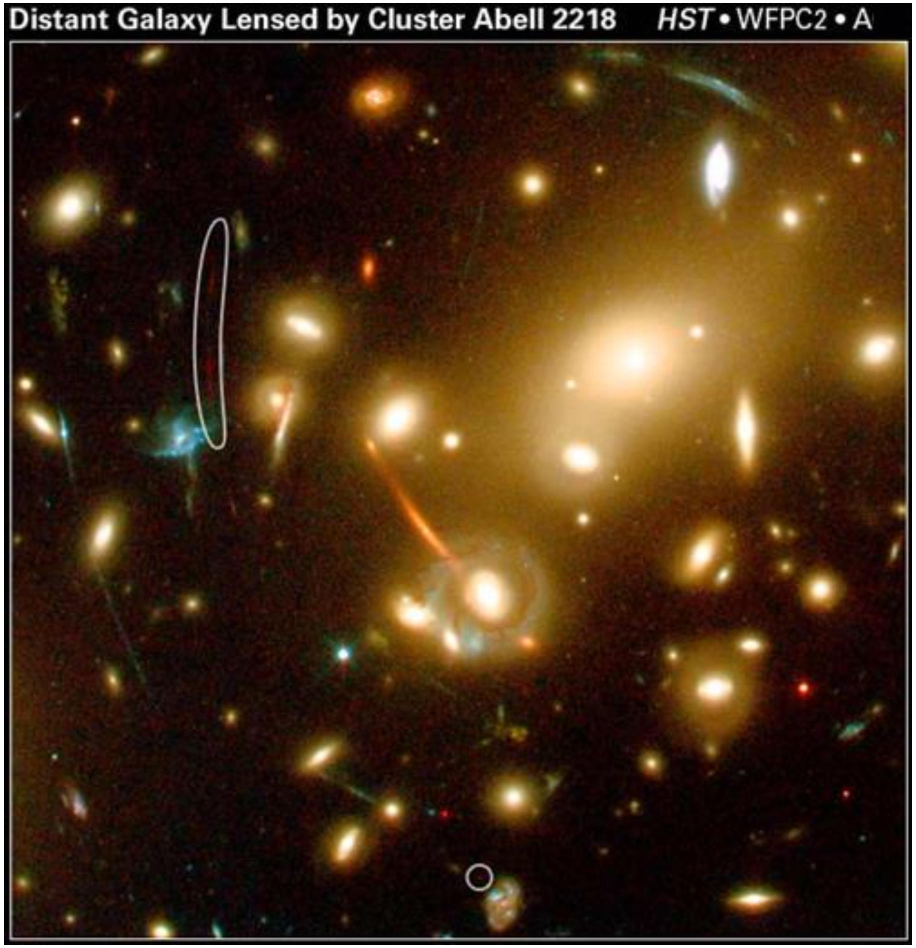
Fenômeno de lenteamento gravitacional



Medindo o ângulo de deflexão da luz de uma estrela distante é possível obter a massa do objeto de interesse

$$\theta = \frac{4GM}{rc^2}$$

Imagens reais e muito interessantes



Anéis de Einstein

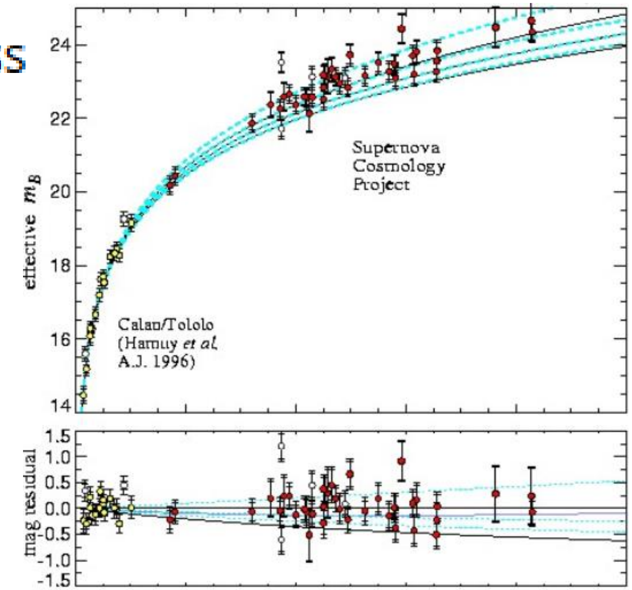
ENERGIA ESCURA

Supernovas e a expansão acelerada do Universo: o fenômeno ENERGIA ESCURA

The Nobel Prize in Physics 2011

Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"



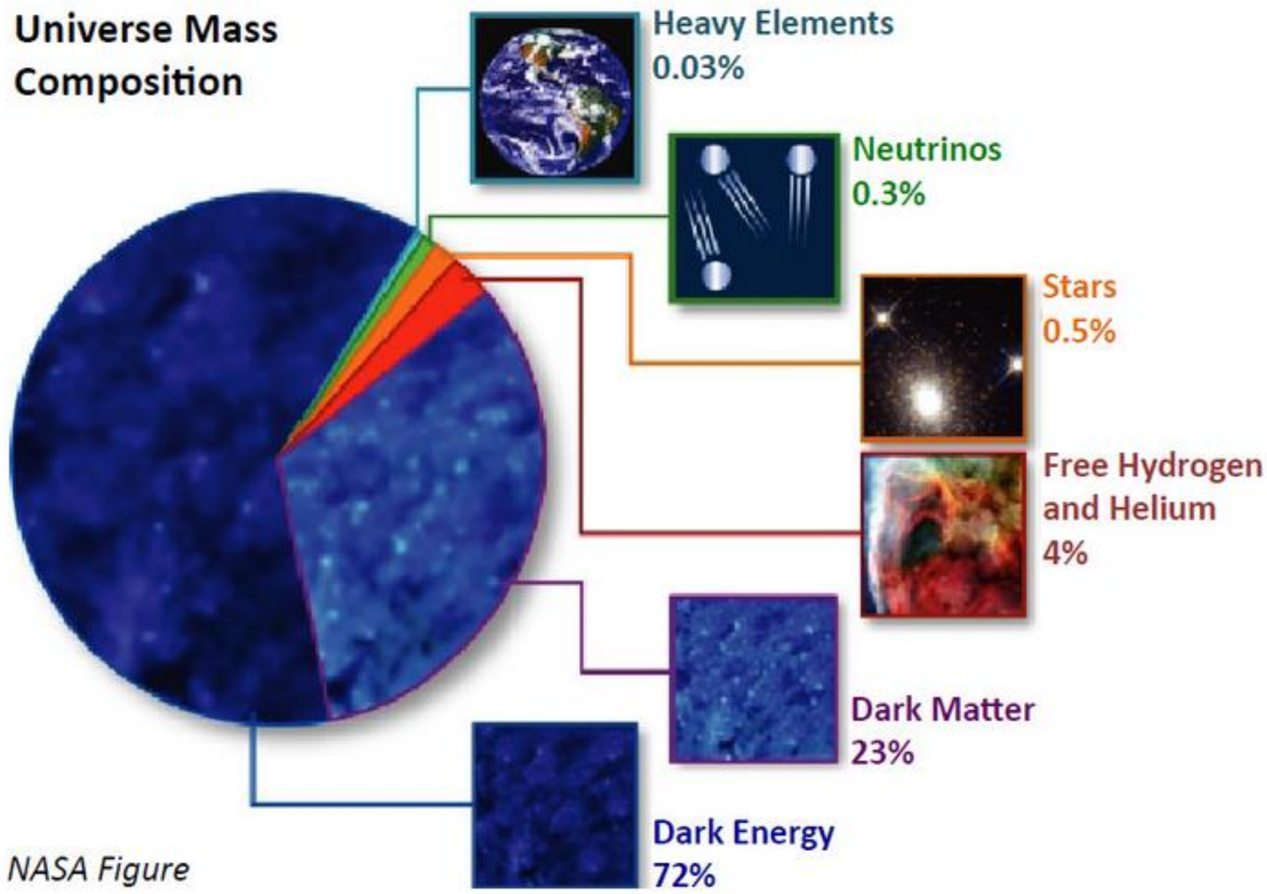
Brian Schmidt, Saul Perlmutter, & Adam Riess.

In 1998/9, published observations of ***Type Ia supernovae*** by

- The ***High-z Supernova Search Team***
- The ***Supernova Cosmology Project***

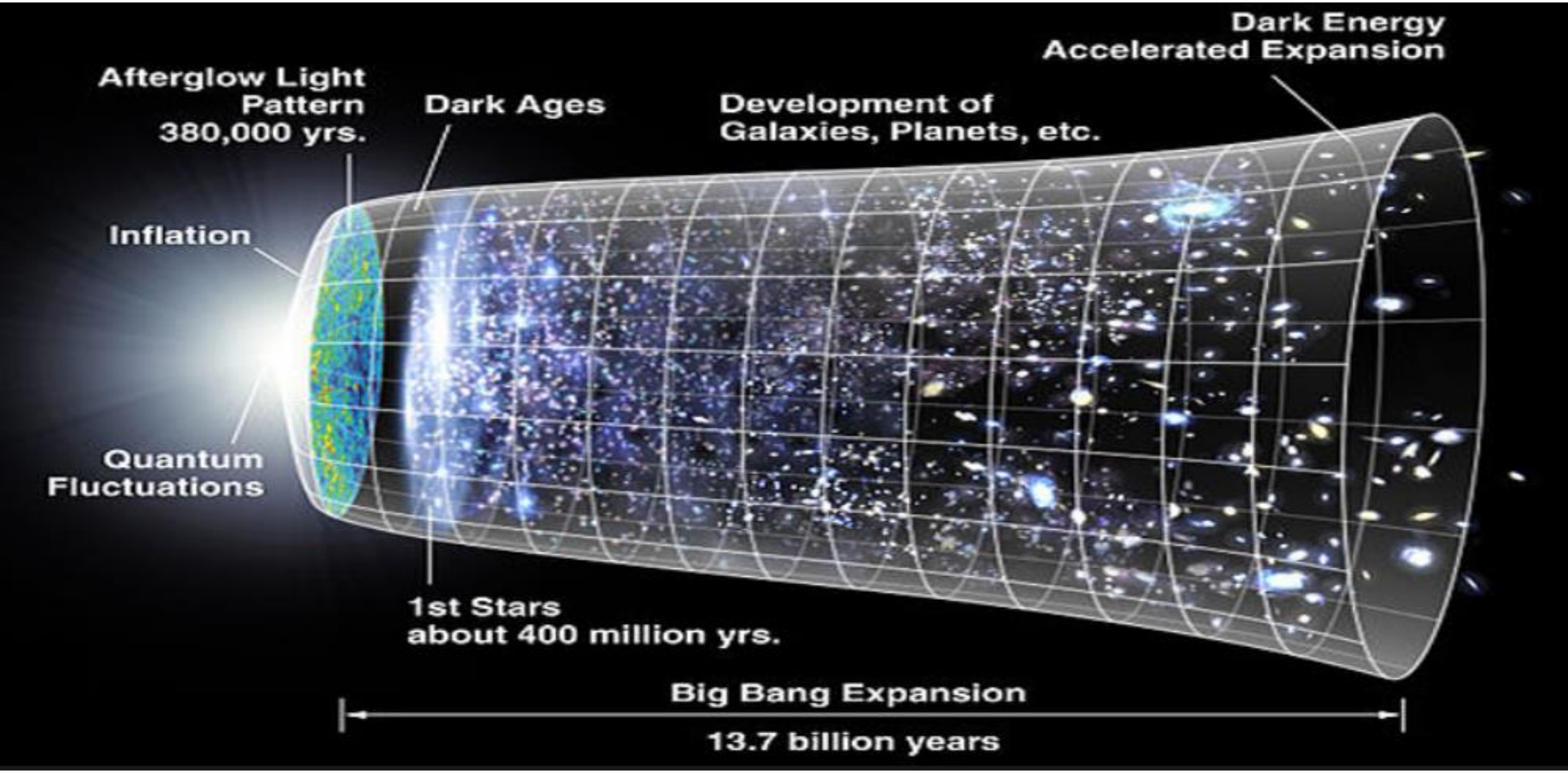
suggested that the expansion of the universe is *actually accelerating* – a total surprise to everyone.

The 2011 Nobel Prize in Physics was awarded for this work.



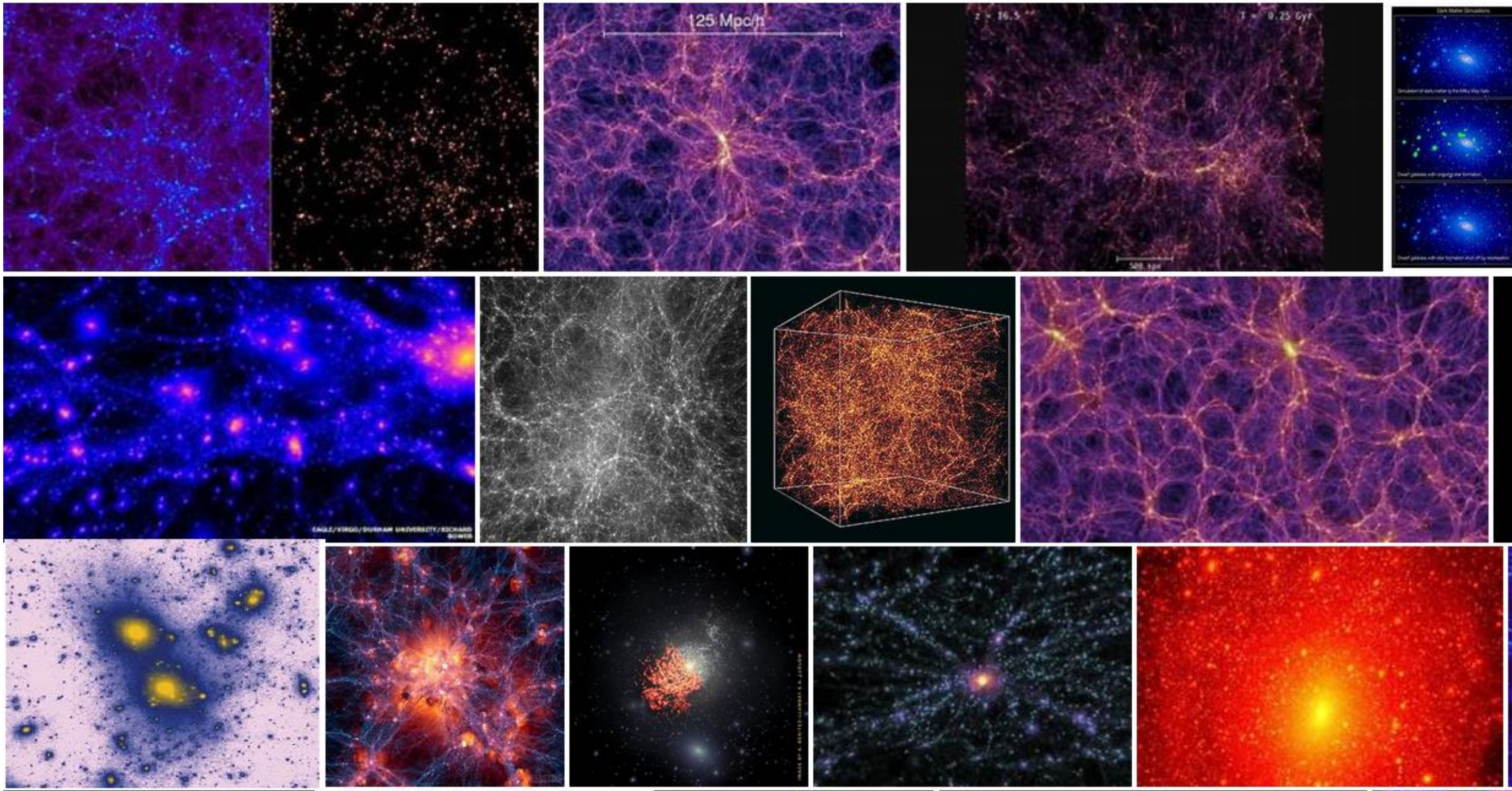
Matéria escura e Energia Escura correspondem a cerca de 95% do conteúdo do universo

Não há evidência dessas partículas!

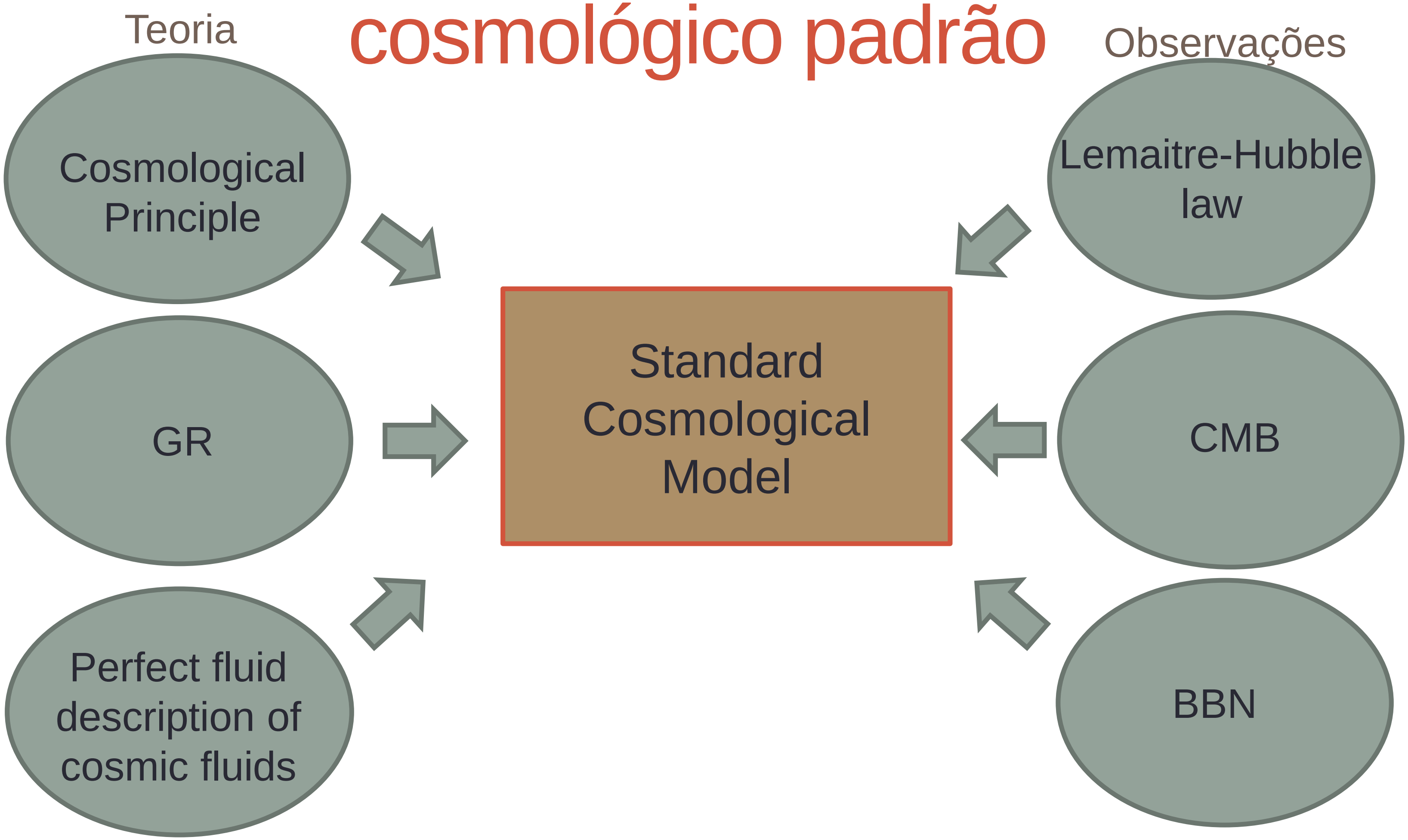


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Simulações numéricas



RESUMO: Pilares do modelo cosmológico padrão



NOSSAS PRINCIPAIS PERGUNTAS:

O QUE É A MATÉRIA ESCURA?
O QUE É A ENERGIA ESCURA?

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