MATÉRIA ESCURA E FORMAÇÃO DE ESTRUTURAS NO UNIVERSO

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Inverno Astrofísico
2019

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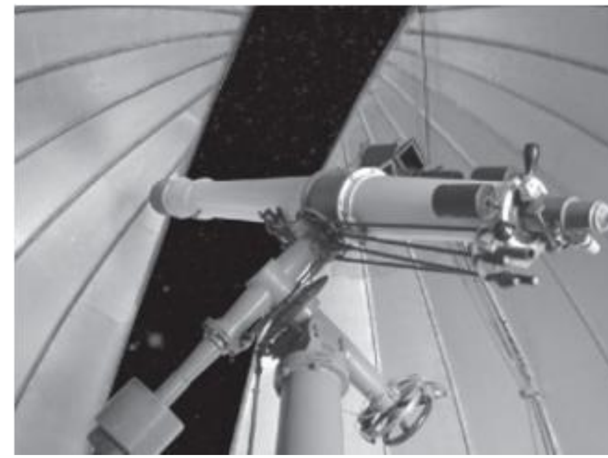
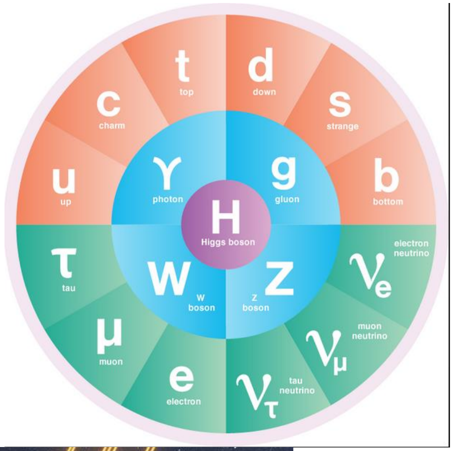
UFOP

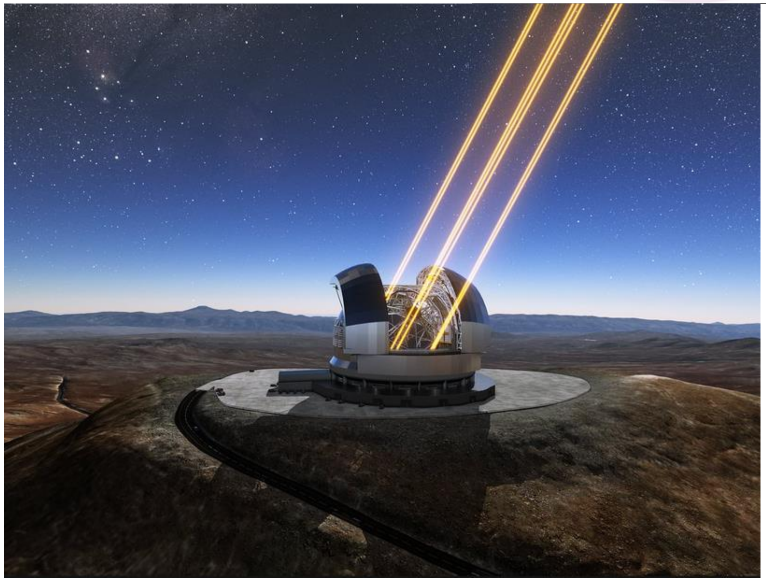
Ouro Preto possui um dos primeiros observatórios do Brasil.
Ensino de astronomia desde 1891 na Escola de Minas (criada em1876).



Aula I

- O que conhecemos de todo o cosmo?





Aula II

- E o que NÃO conhecemos...

- Quais são as evidências sobre a existência de matéria escura?

- Quais são as evidências sobre a existência de energia escura?

Aula III

- 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.

Aula IV

- Entender como pequenas perturbações existentes na distribuição quase homogênea de densidade de matéria no universo primordial evoluem até o ponto de formar uma estrutura como galáxias e aglomerados de galáxias.

Aula V

- Efeito Mészaros -> Bônus: Precisamos de matéria escura

- Estágio não-linear de formação de estruturas. Entender o porquê de um excesso de densidade na distribuição de matéria se desacopla do fluxo de Hubble e colapsa para formar um objeto astronômico.

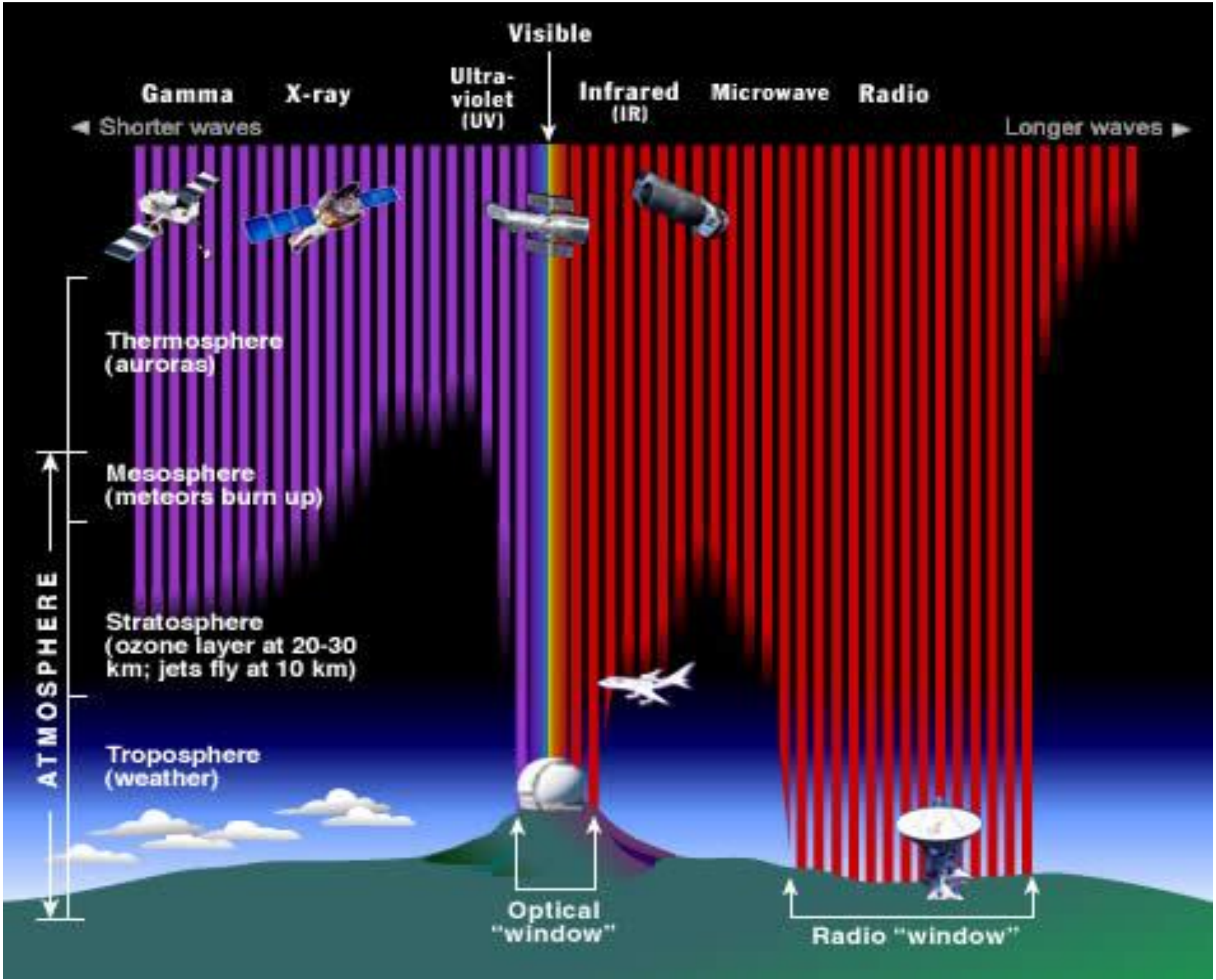
Aula I

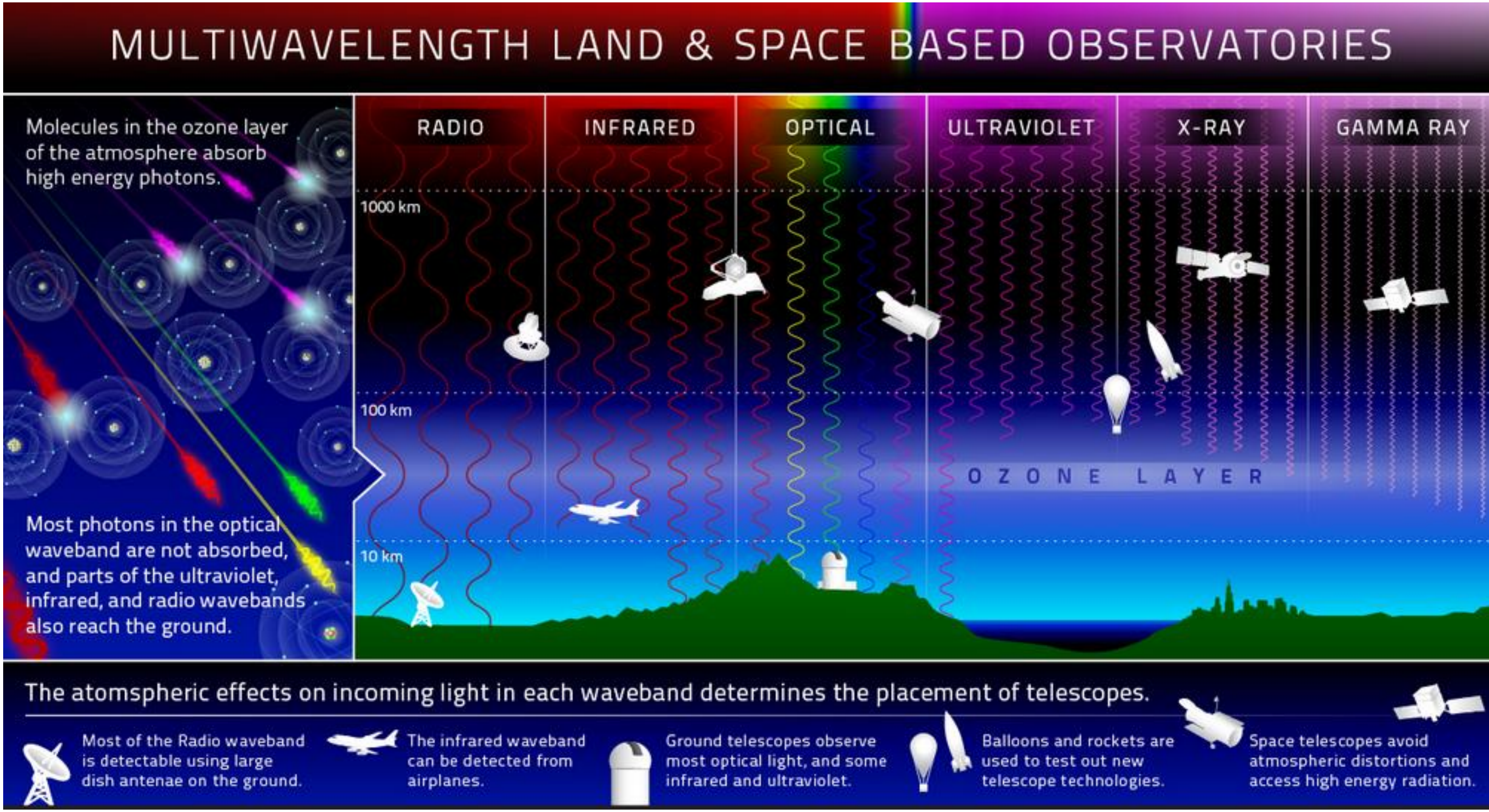

$\beta(p, q) = \frac{\Gamma(p)\Gamma(q)}{\Gamma(p+q)}$
$\sum_{x=0}^{\infty} P(x) = 1$
$\Gamma(y) = \int_0^{\infty} e^{-x} x^{y-1} dx$

Primeiro passo:

COMO OBSERVAMOS?

Como diferentes partes do espectro atravessam a atmosfera

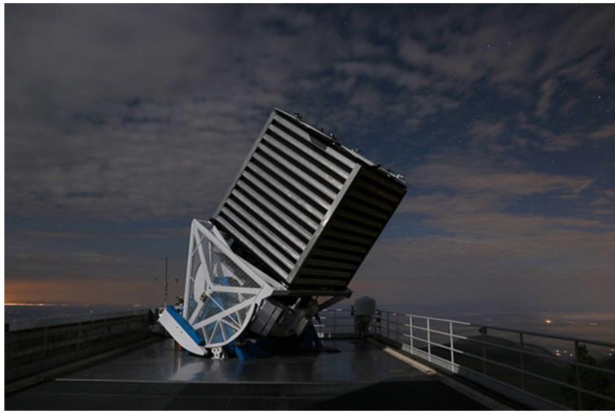



MULTIWAVELENGTH LAND & SPACE BASED OBSERVATORIES
Molecules in the ozone layer of the atmosphere absorb high energy photons.
RADIO
INFRARED
OPTICAL
ULTRAVIOLET
X-RAY
GAMMA RAY
1000 km
100 km
10 km
OZONE LAYER
Most photons in the optical waveband are not absorbed, and parts of the ultraviolet, infrared, and radio wavebands also reach the ground.
The atomspheric effects on incoming light in each waveband determines the placement of telescopes.
Most of the Radio waveband is detectable using large dish antenae on the ground.
The infrared waveband can be detected from airplanes.
Ground telescopes observe most optical light, and some infrared and ultraviolet.
Balloons and rockets are used to test out new telescope technologies.
Space telescopes avoid atmospheric distortions and access high energy radiation.

Fontes observacionais

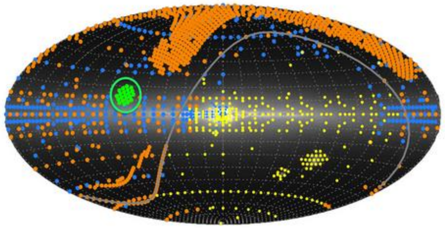
SDSS

The Sloan Digital Sky Survey: Mapping the Universe



The Sloan Digital Sky Survey has created the most detailed three-dimensional maps of the Universe ever made, with deep multi-color images of one third of the sky, and spectra for more than three million astronomical objects.

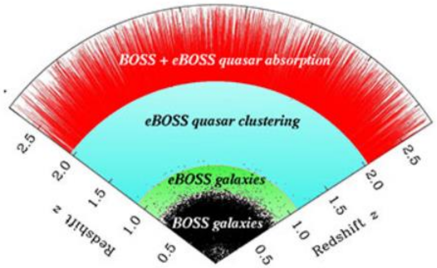
APOGEE-2



A stellar spectroscopic survey of the Milky Way, with two major components: a northern survey using the bright time at APO (APOGEE-2N), and a southern survey using the 2.5m du Pont Telescope at Las Campanas (APOGEE-2S).

Explore APOGEE-2

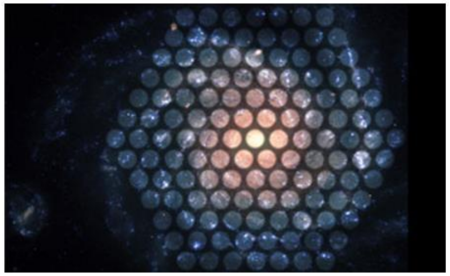
eBOSS



A cosmological survey of quasars and galaxies, also encompassing subprograms to survey variable objects (TDSS) and X-Ray sources (SPIDERS).

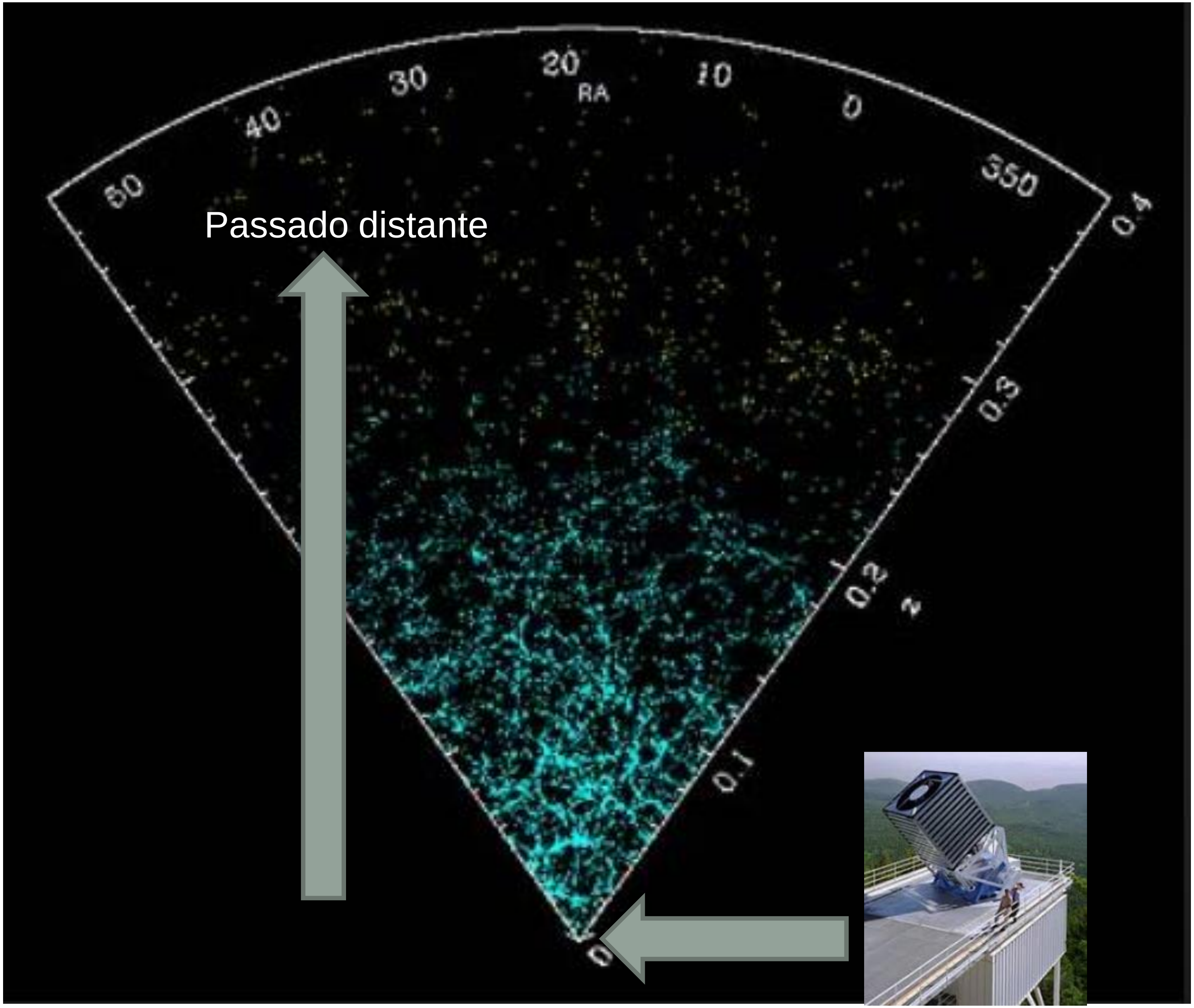
Explore eBOSS

MaNGA



The galaxy survey for people who love galaxies! MaNGA (Mapping Nearby Galaxies at Apache Point Observatory) will explore the detailed internal structure of nearly 10,000 nearby galaxies using spatially resolved spectroscopy.

Explore MaNGA



Passado distante
50
40
30
20
RA
10
0
350
0.4
0.3
0.2
z
0.1
0

THE DARK ENERGY SURVEY

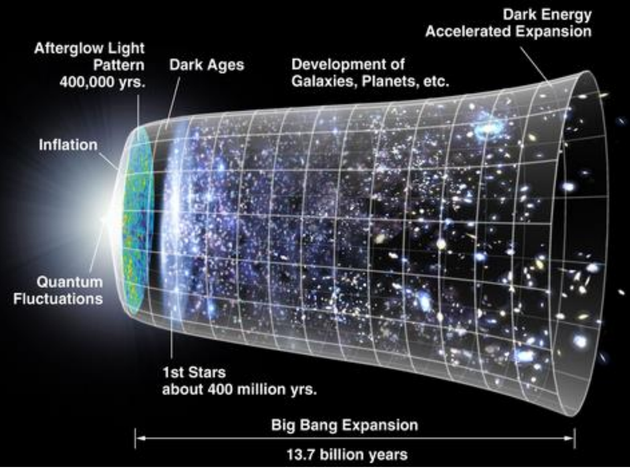
ESPAÑOL ENGLISH

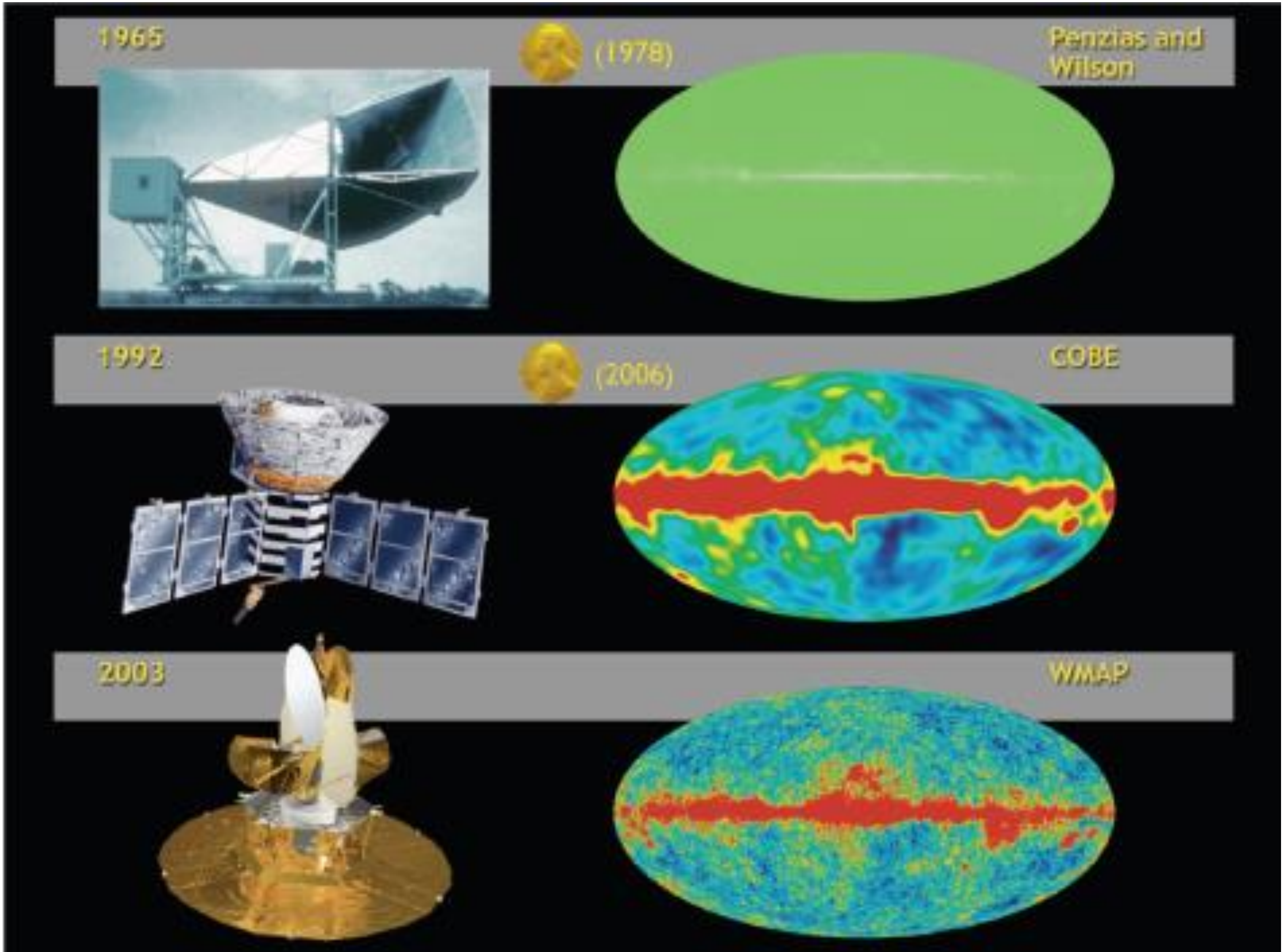
THE DES PROJECT NEWS AND RESULTS DATA ACCESS MULTIMEDIA EDUCATION CONTACT US SEARCH HERE

Overview

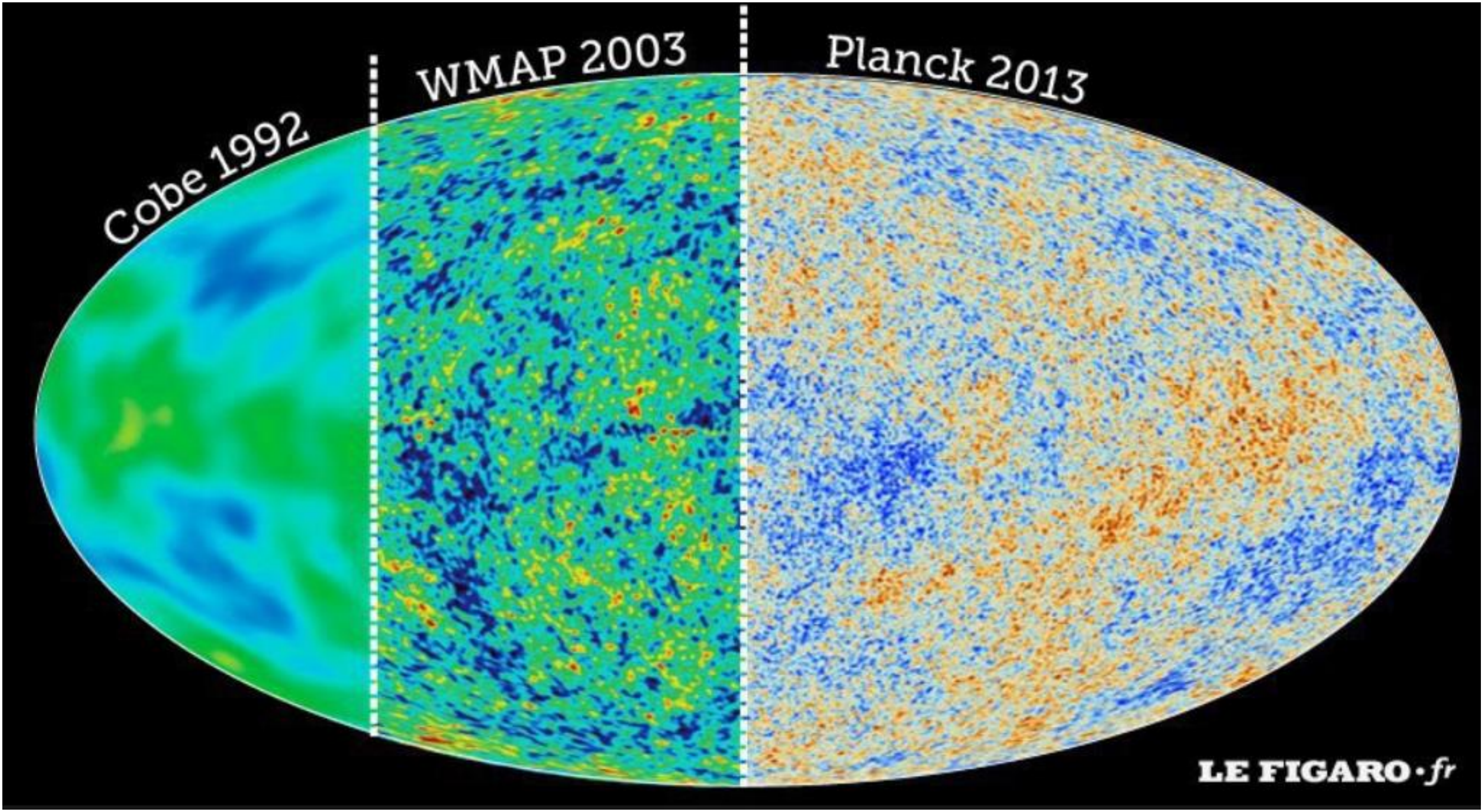
The Dark Energy Survey (DES) is an international, collaborative effort to map hundreds of millions of galaxies, detect thousands of supernovae, and find patterns of cosmic structure that will reveal the nature of the mysterious dark energy that is accelerating the expansion of our Universe. DES began searching the Southern skies on August 31, 2013.

According to Einstein's theory of General Relativity, gravity should lead to a slowing of the cosmic expansion. Yet, in 1998, two teams of astronomers studying distant supernovae made the remarkable discovery that the expansion of the universe is speeding up. To explain cosmic acceleration, cosmologists are faced with two possibilities: either 70% of the universe exists in an exotic form, now called dark energy, that exhibits a gravitational force opposite to the attractive gravity of ordinary matter, or General Relativity must be replaced by a new theory of gravity on cosmic scales.

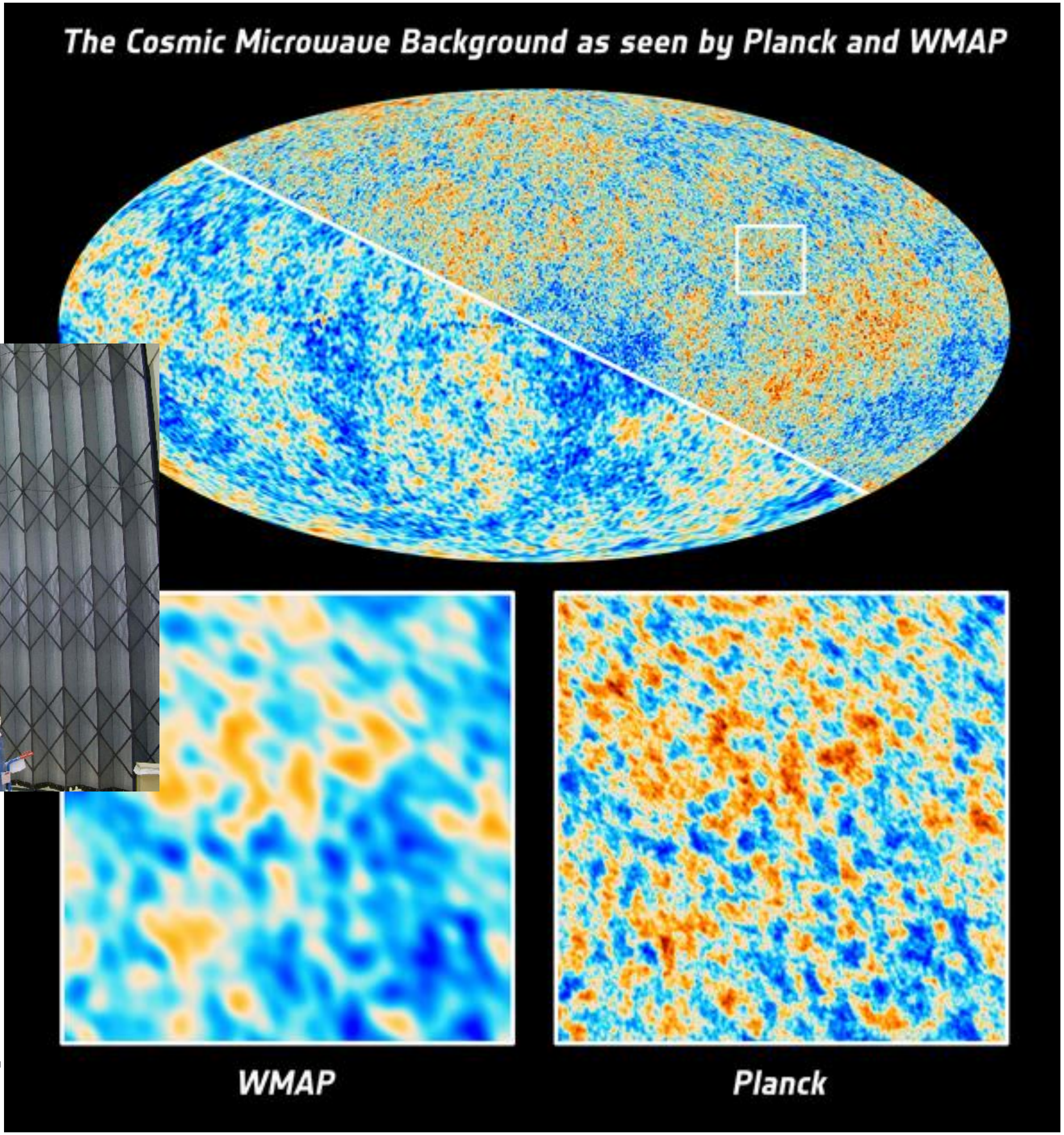



1965
(1978)
Penzias and Wilson
1992
(2006)
COBE
2003
WMAP

Distribuição da Radiação Cósmica de Fundo em Microondas

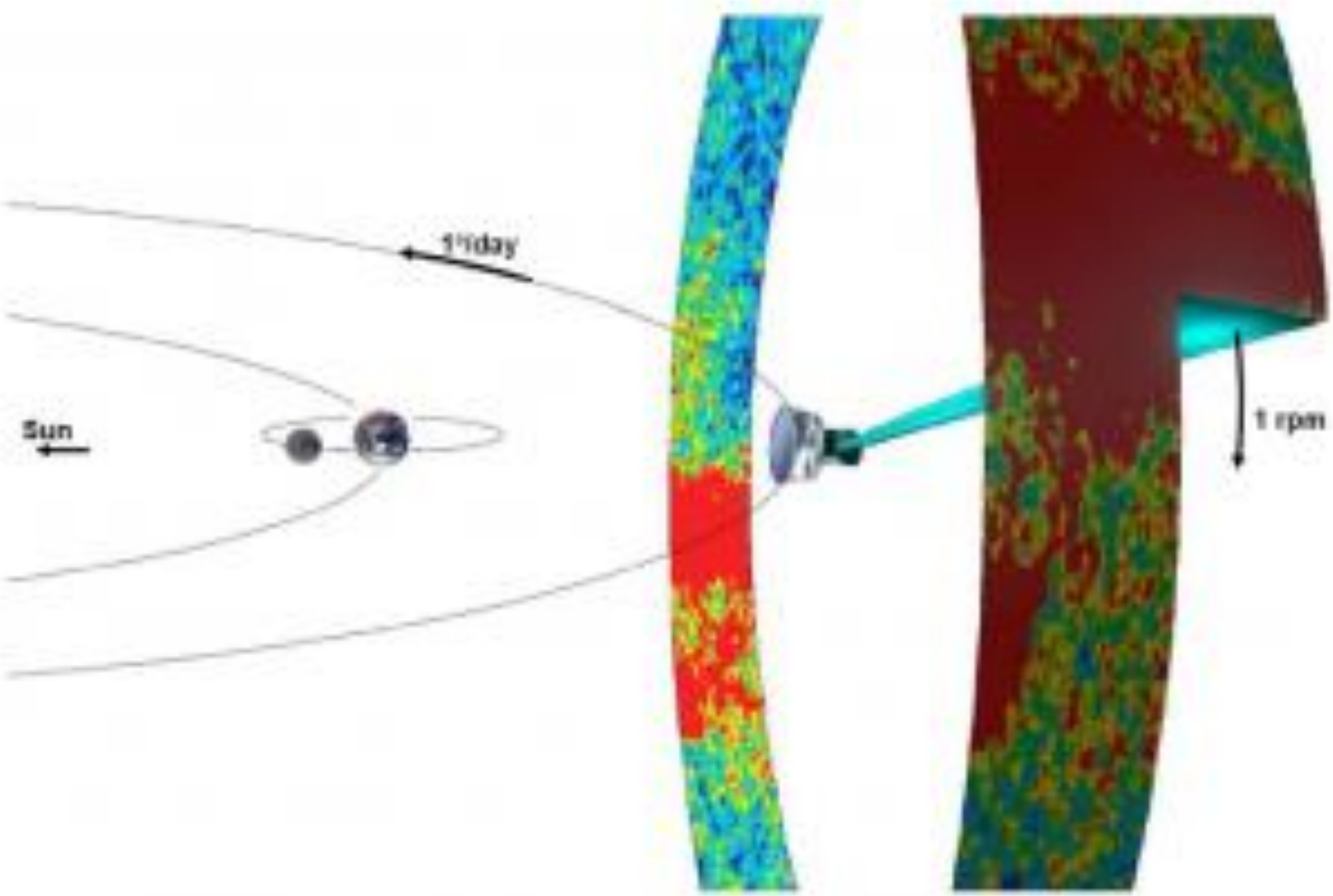


Satélite PLANCK

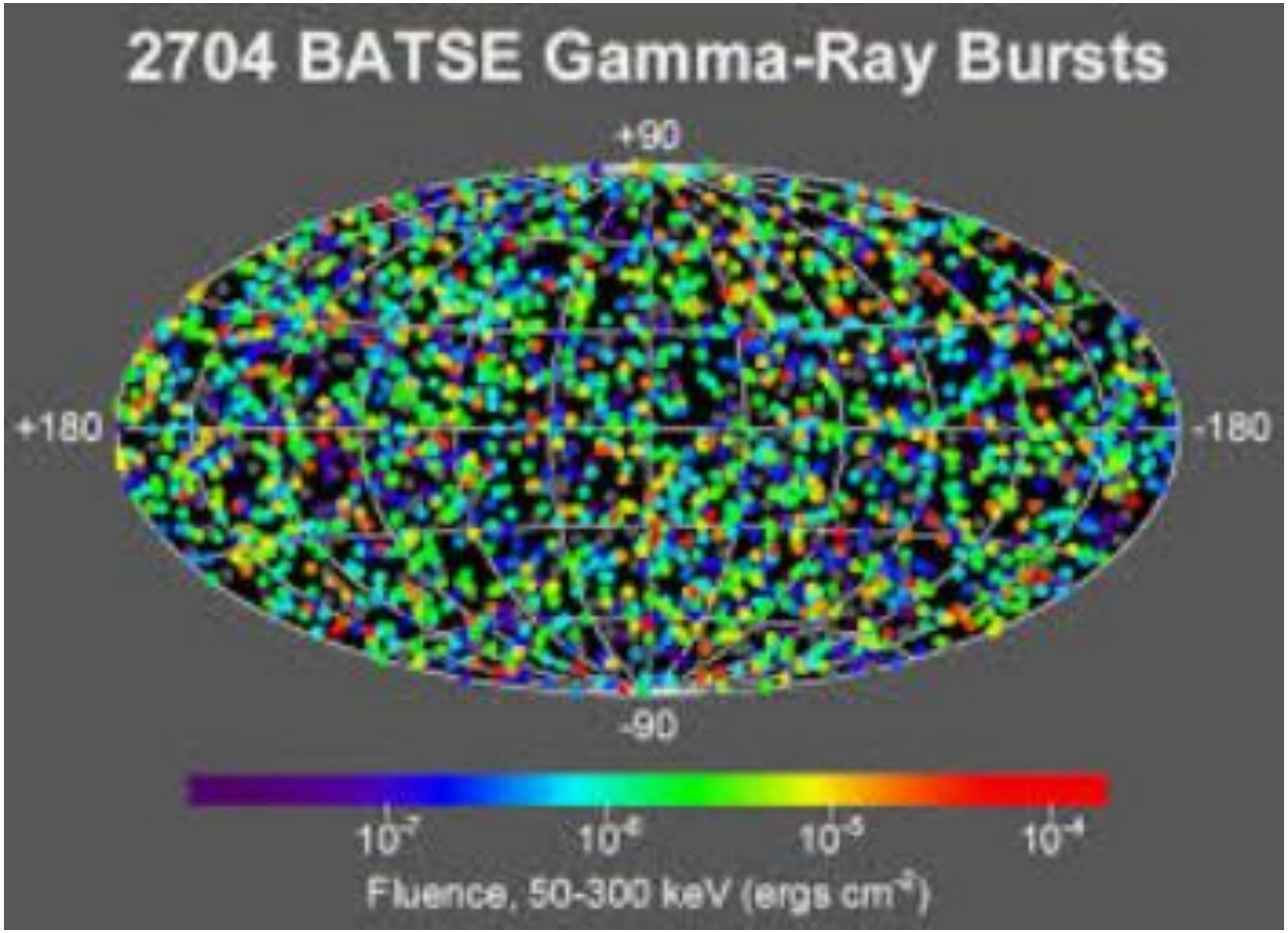


Lançado em 2009.
Coletou dados até 2013.

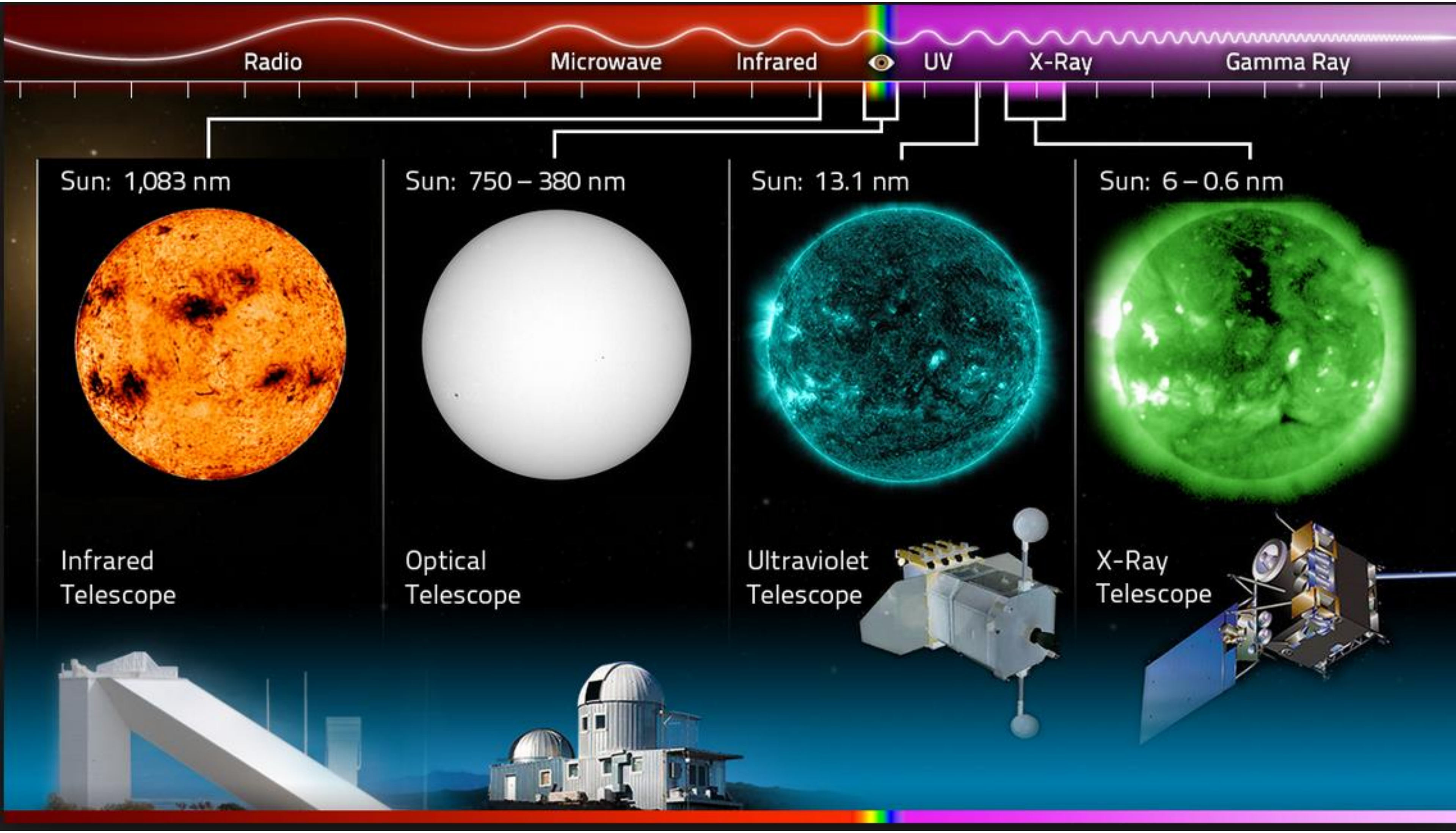
Estratégia de observação:
Satélite PLANCK - ESA

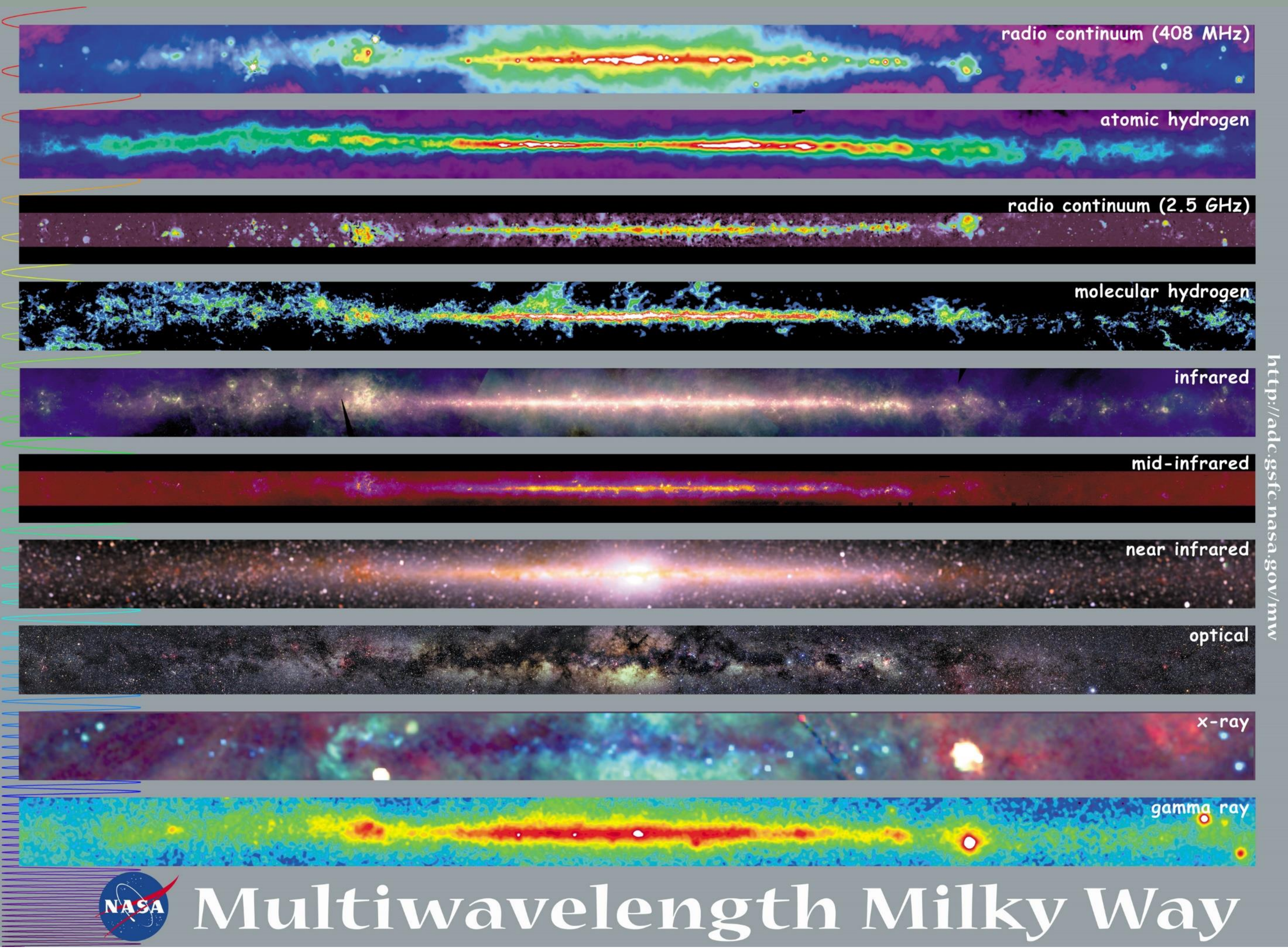


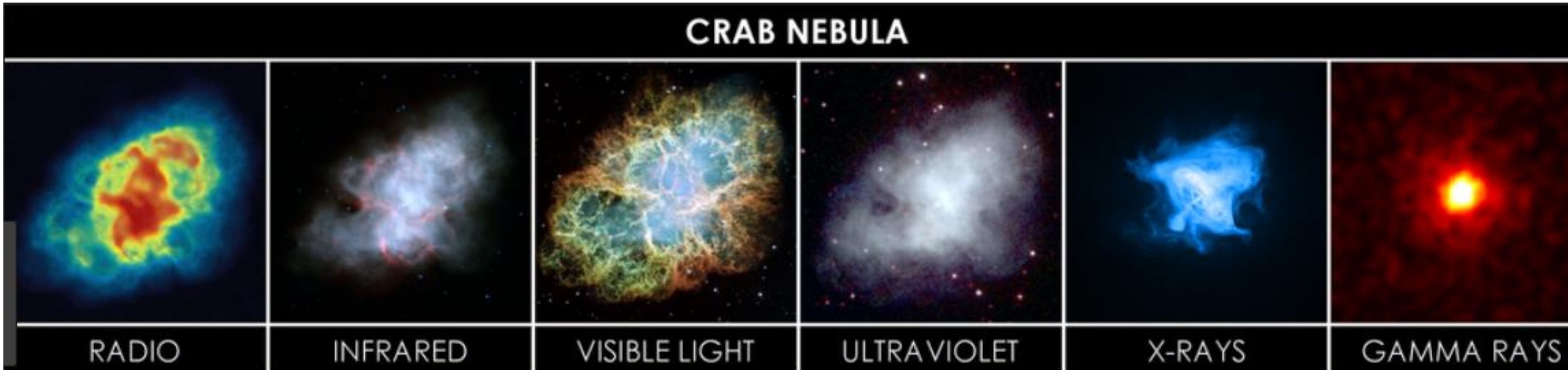
Radiação gama



O sol visto em diferentes frequências

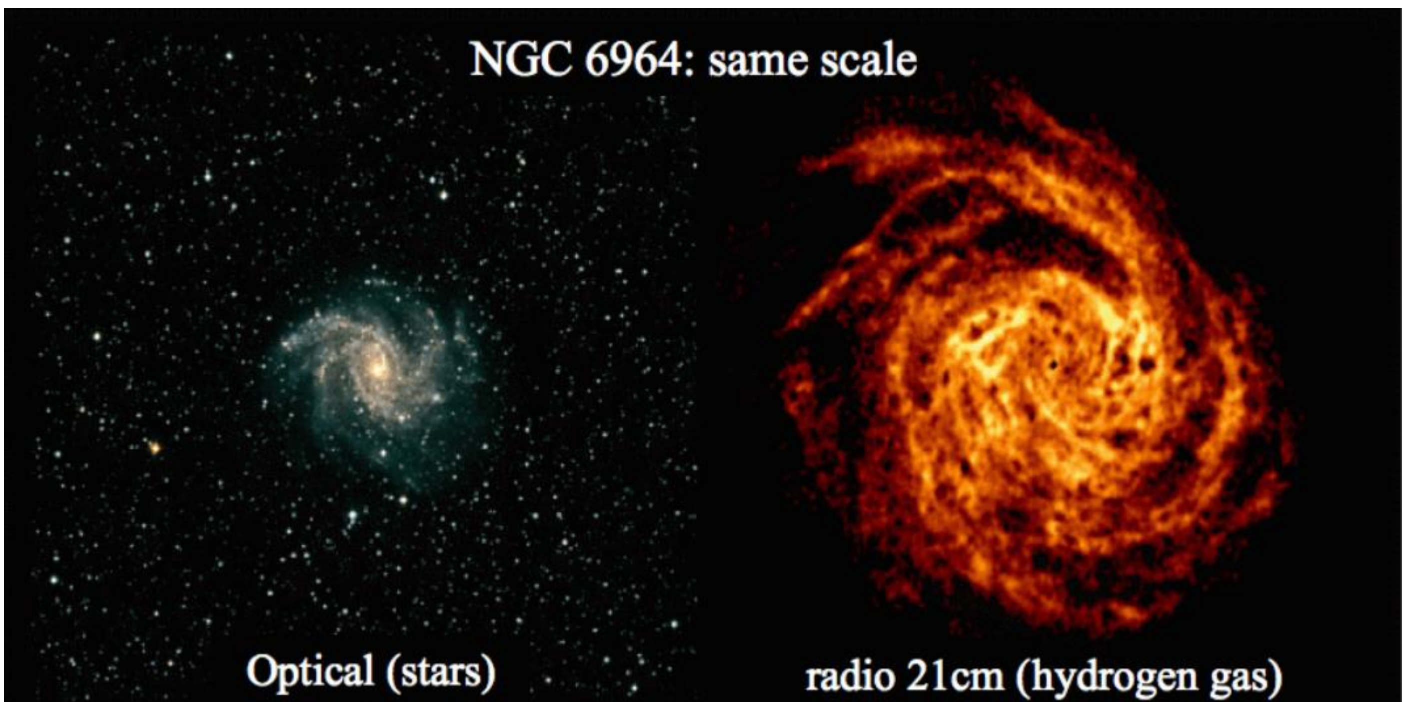



radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way



The crab nebula in radio, infrared, visible, ultraviolet, x-ray and gamma-ray wavelengths.

Sources: Radio: NRAO/AUI and M. Bietenholz, J.M. Uson, T.J. Cornwell; Infrared: NASA/JPL-Caltech/R. Gehrz (University of Minnesota); Visible: NASA, ESA, J. Hester and A.Loll (Arizona State University); Ultraviolet: NASA/Swift/E. Hoversten, PSU, X-ray: NASA/CXC/SAO/F. Seward et al.; Gamma: NASA/DOE/Fermi LAT/R. Buehler



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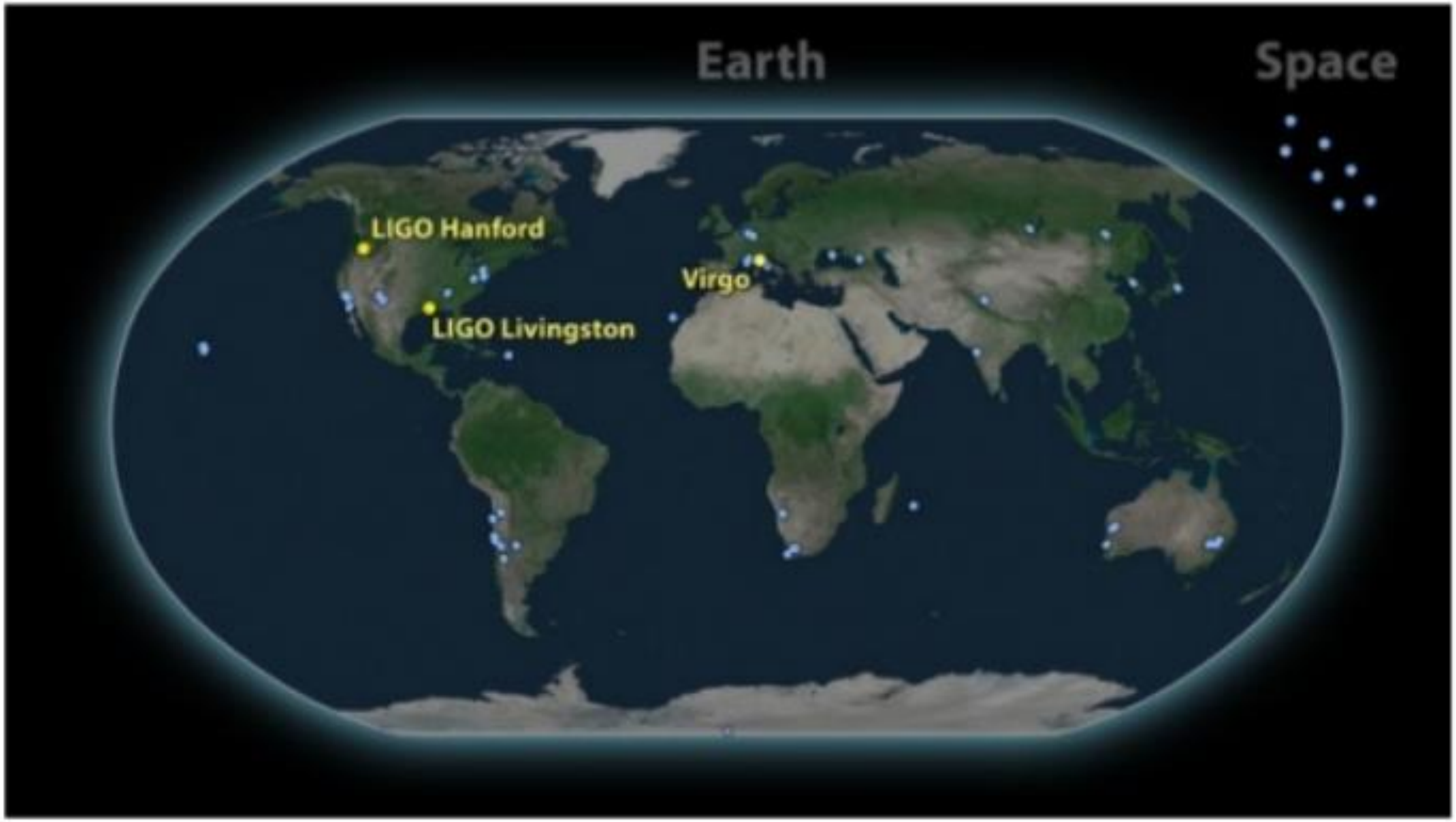
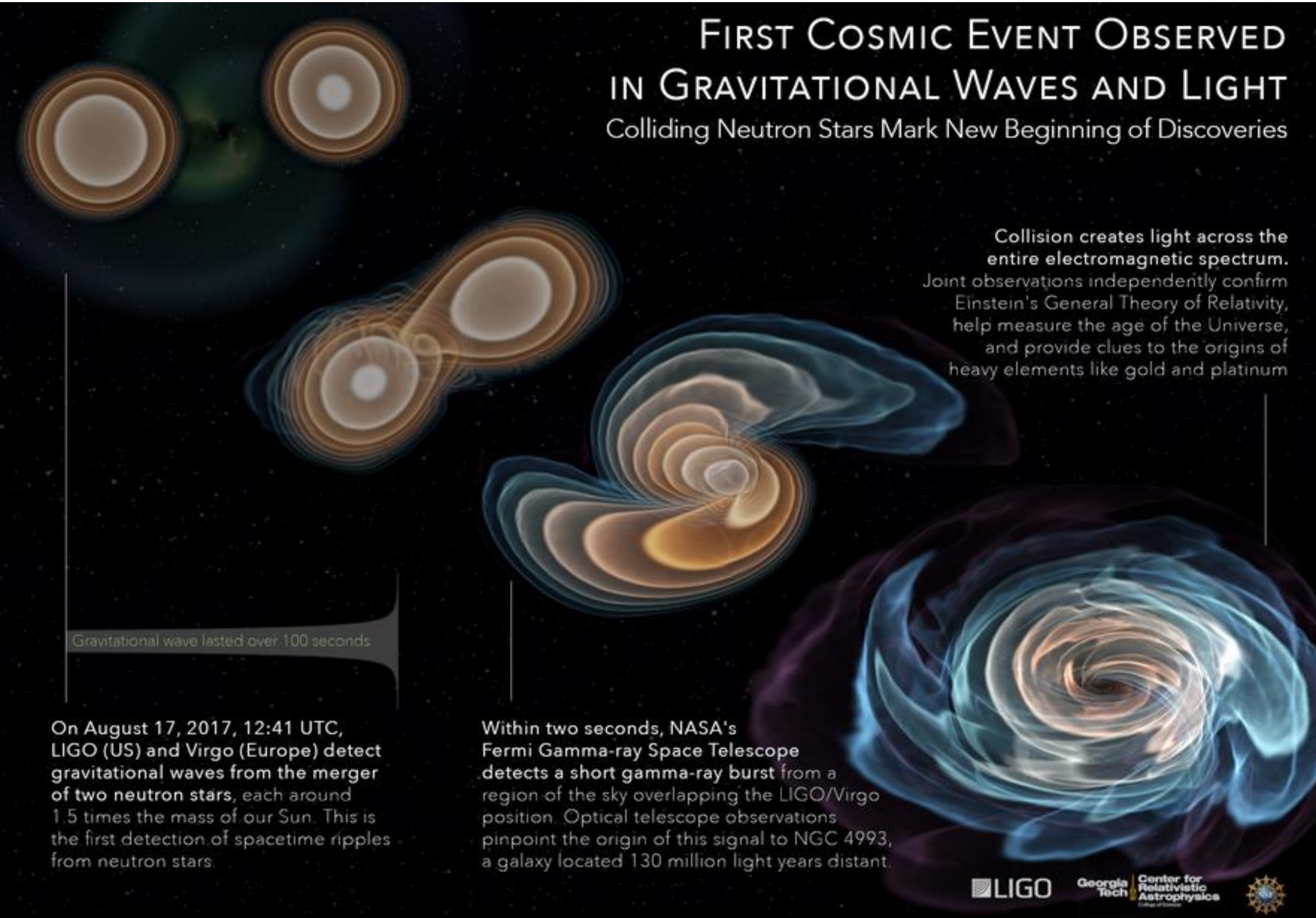
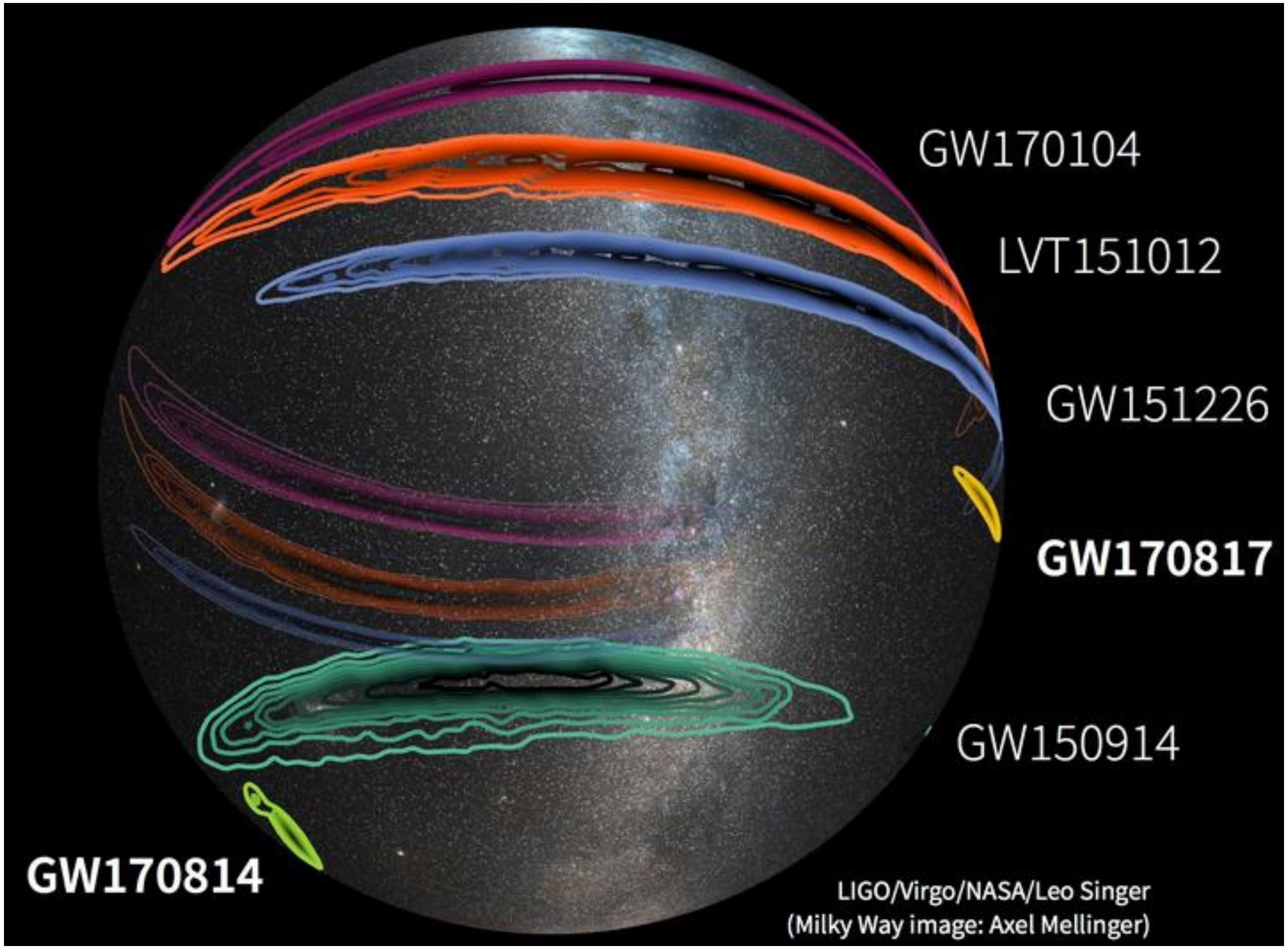


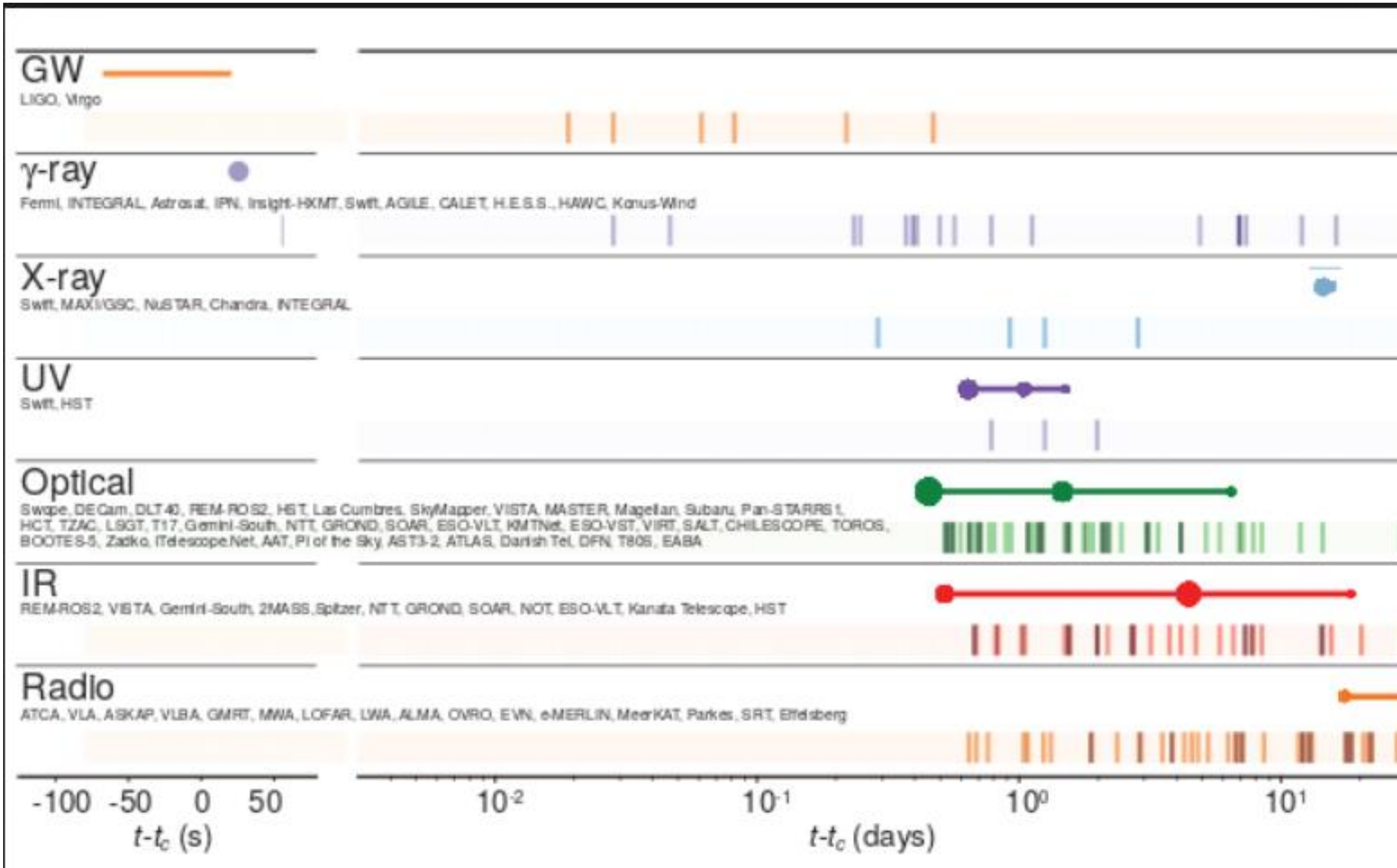
https://www.ligo.caltech.edu/image/ligo20171016e


FIRST COSMIC EVENT OBSERVED
IN GRAVITATIONAL WAVES AND LIGHT
Colliding Neutron Stars Mark New Beginning of Discoveries
Collision creates light across the entire electromagnetic spectrum. Joint observations independently confirm Einstein's General Theory of Relativity, help measure the age of the Universe, and provide clues to the origins of heavy elements like gold and platinum
Gravitational wave lasted over 100 seconds
On August 17, 2017, 12:41 UTC, LIGO (US) and Virgo (Europe) detect gravitational waves from the merger of two neutron stars, each around 1.5 times the mass of our Sun. This is the first detection of spacetime ripples from neutron stars.
Within two seconds, NASA's Fermi Gamma-ray Space Telescope detects a short gamma-ray burst from a region of the sky overlapping the LIGO/Virgo position. Optical telescope observations pinpoint the origin of this signal to NGC 4993, a galaxy located 130 million light years distant.
LIGO
Georgia Tech
Center for Relativistic Astrophysics



$$-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 7 \cdot 10^{-16}$$

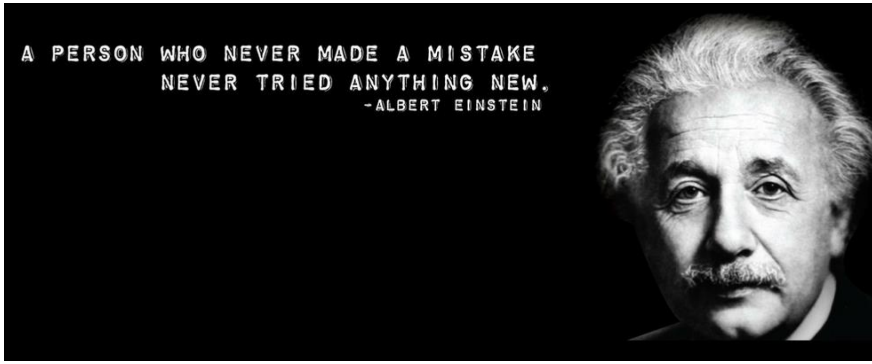
Astronomia multi-espectral

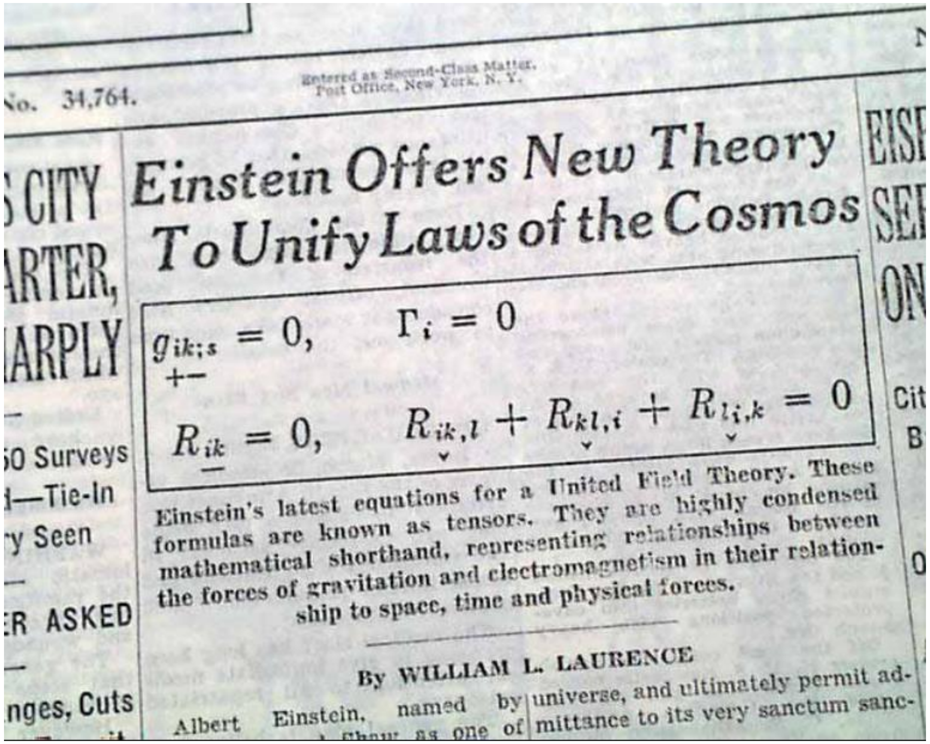


PRECISAMOS DE UMA TEORIA PARA A INTERAÇÃO GRAVITACIONAL

Relatividade Geral

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





No. 34,764.

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

Einstein Offers New Theory To Unify Laws of the Cosmos

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

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

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

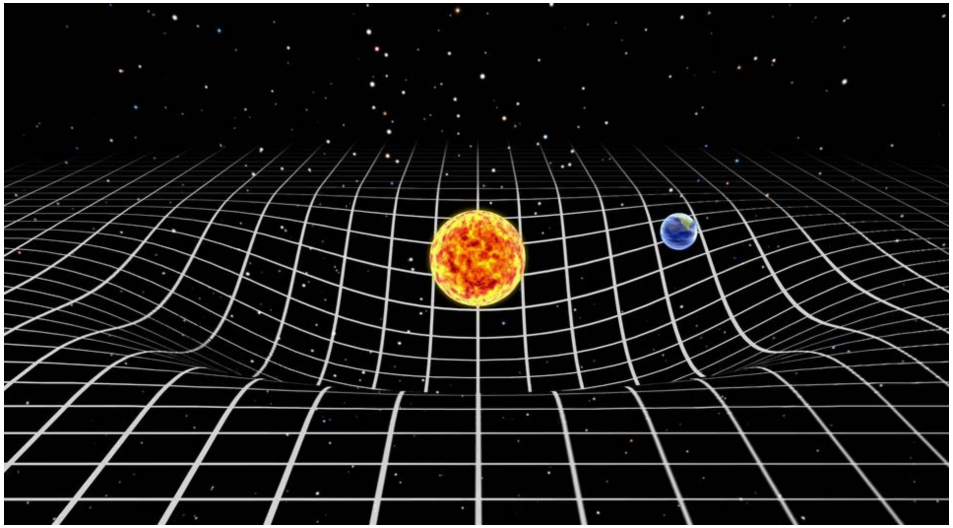
Albert Einstein, named by ... universe, and ultimately permit admittance to its very sanctum sanc-

CITY ... ARTER, ... ARPLY

50 Surveys ... —Tie-In ... y Seen

ER ASKED

nges, Cuts



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 gravitacinal ;

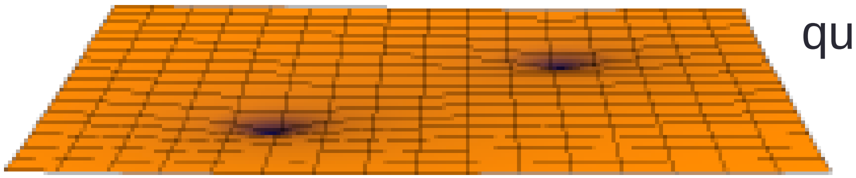
  3) O desvio para o vermelho de fótons ao viajar em um campo gravitacional.

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.

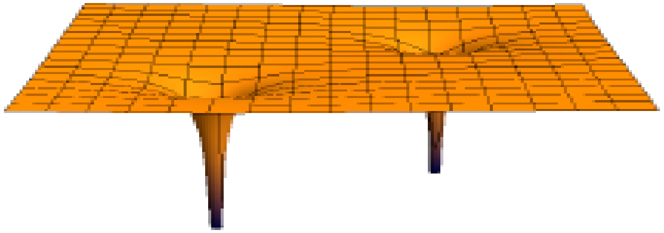
Em 2016 a colaboração LIGO anuncia a detecção direta das Ondas Gravitacionais.

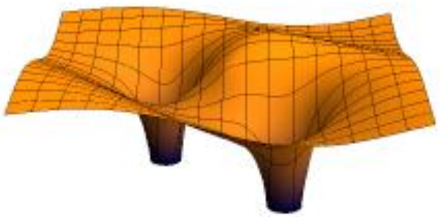
Como e onde testar a Relatividade Geral



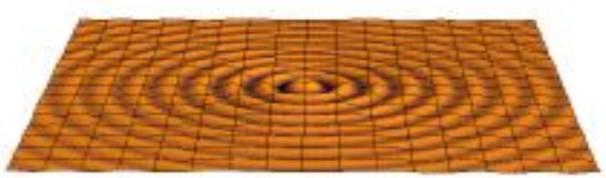
quase-estacionário/ CAMPO FRACO

Quase-estacionário/CAMPO FORTE



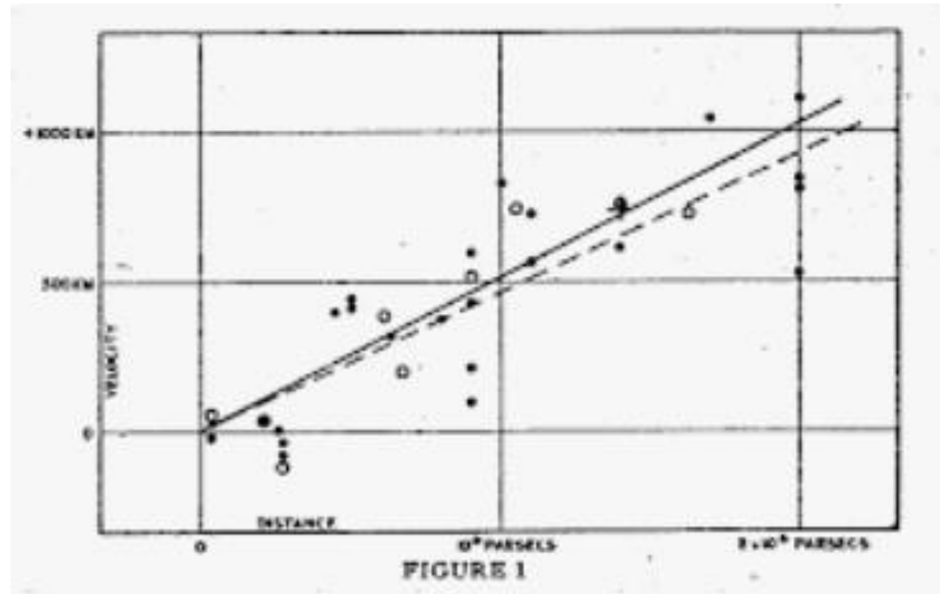


Altamente dinâmico/CAMPO FORTE

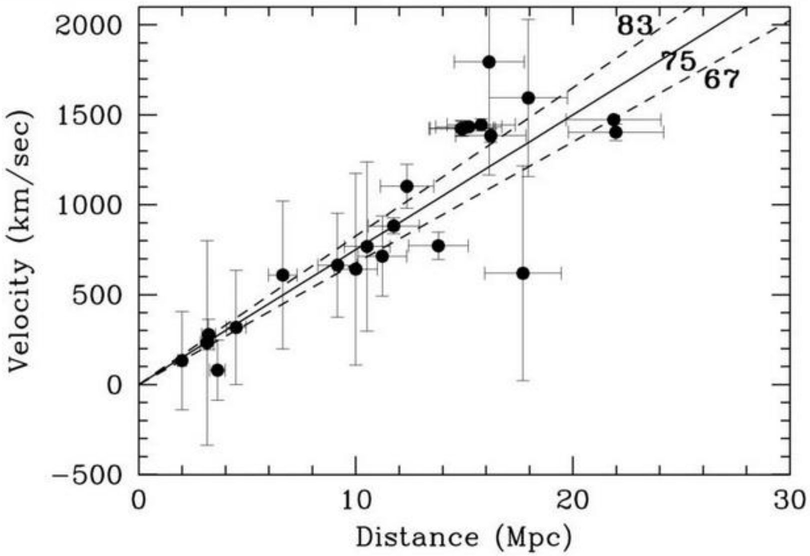


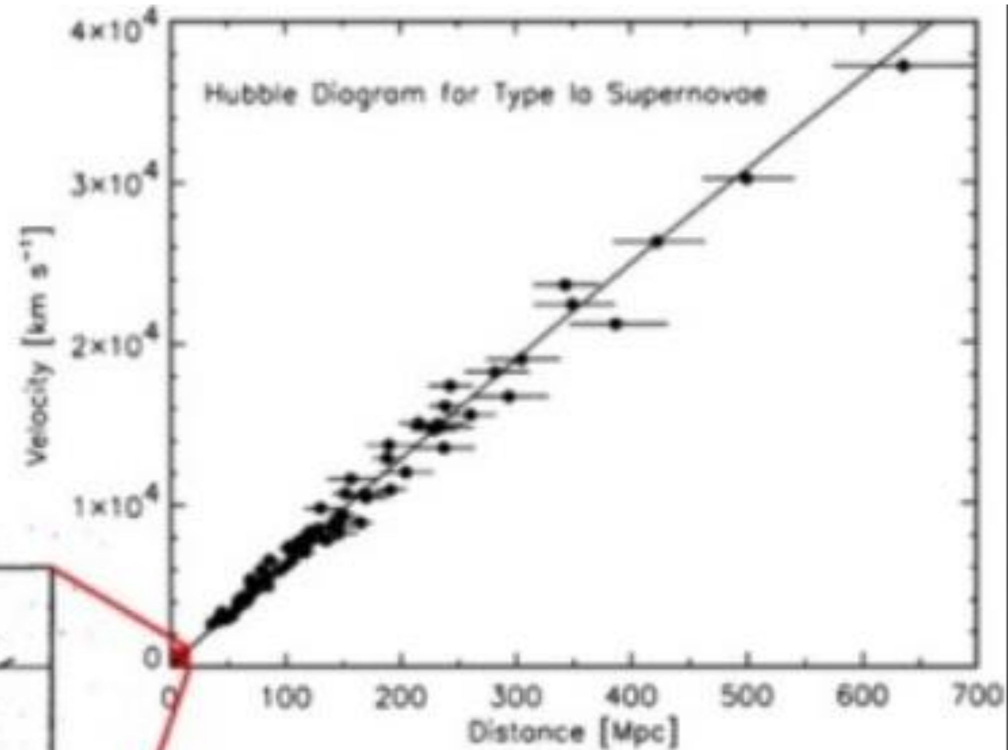
Regime Radiativo (ONDAS GRAVITACIONAIS)

A expansão do Universo



Hubble's Law (modern data)





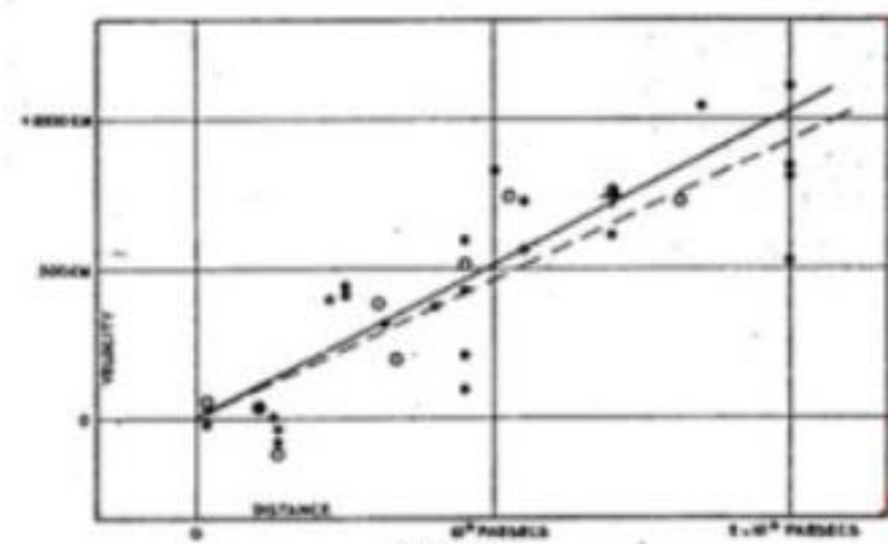
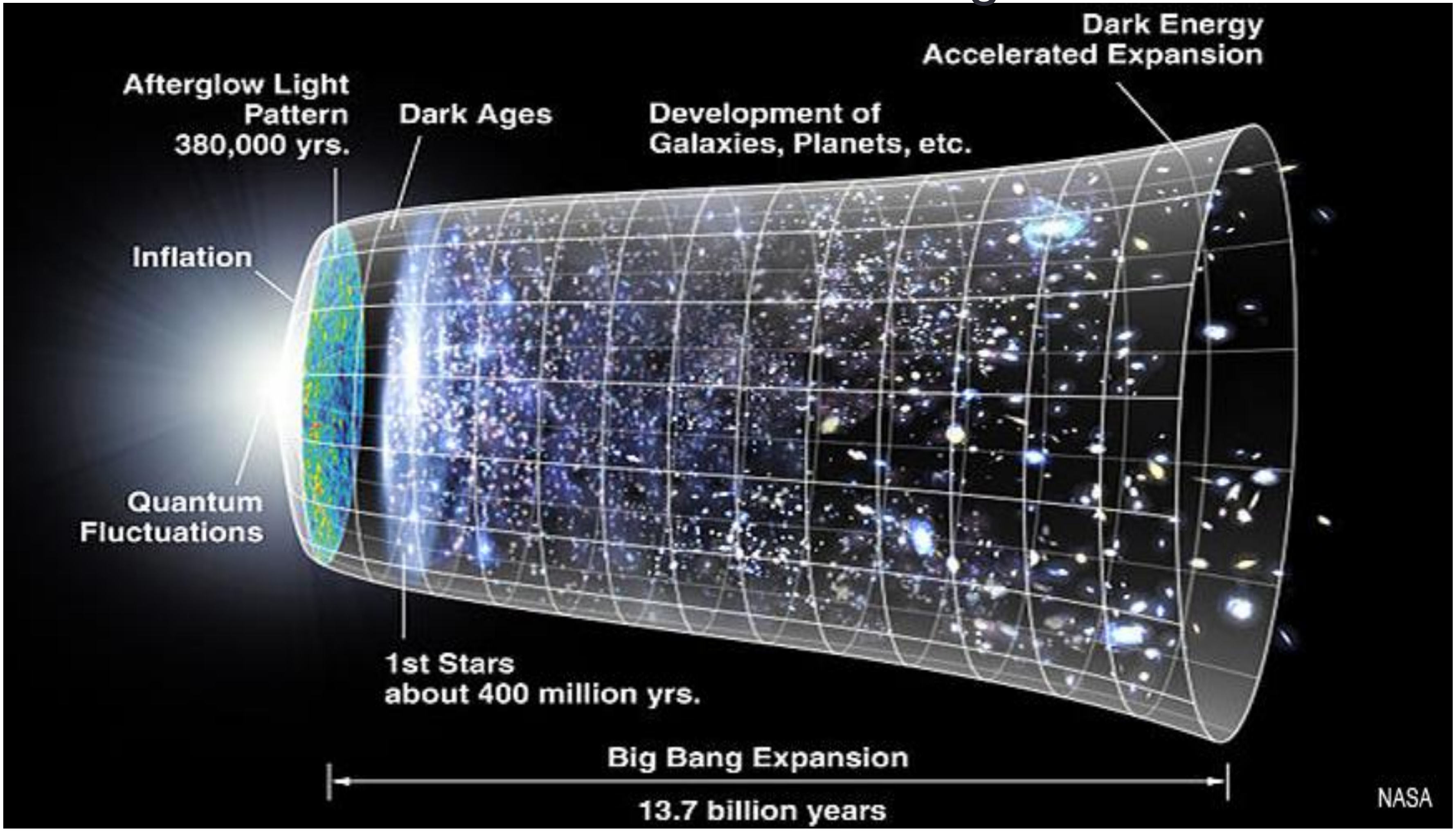
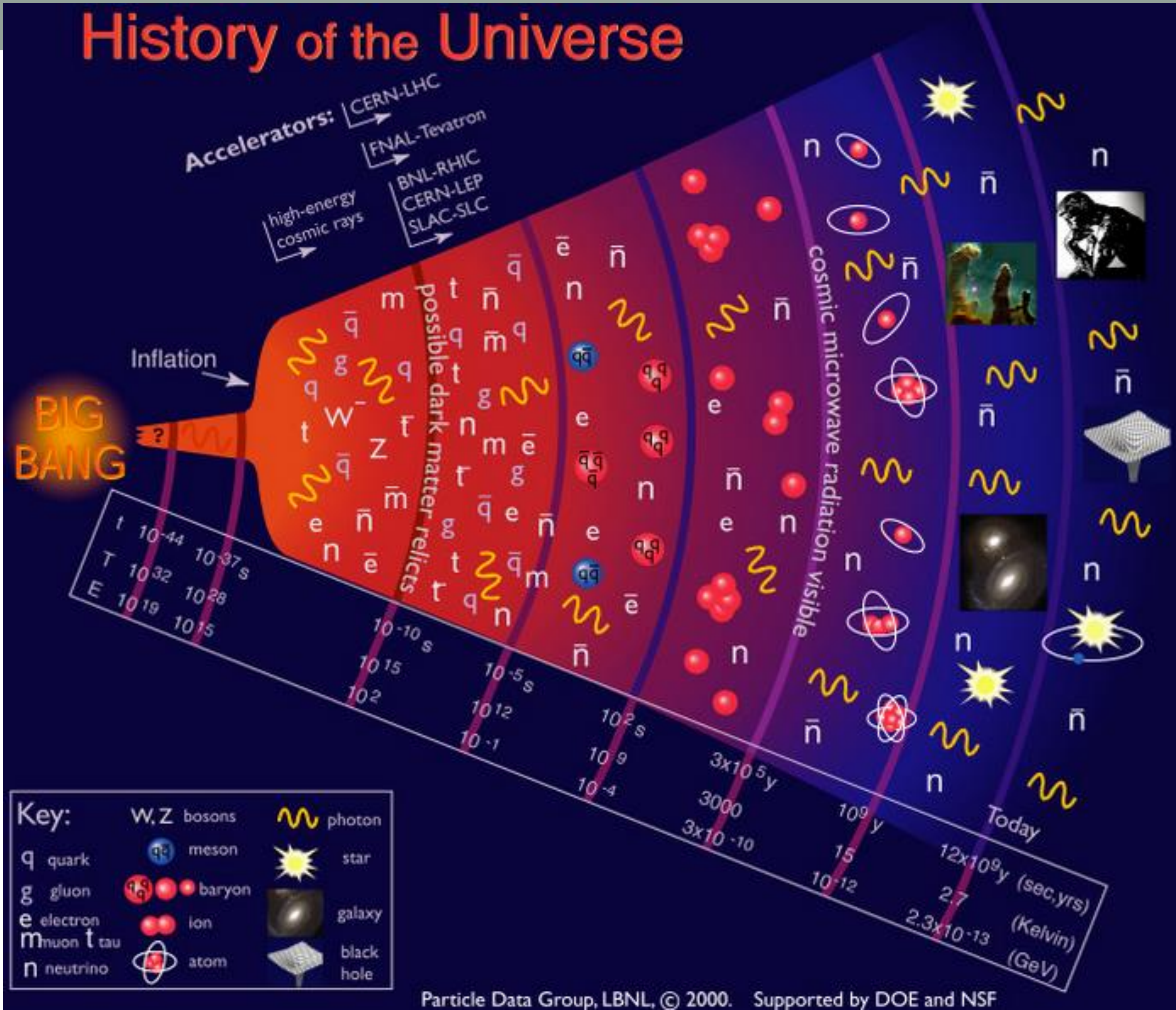


FIGURE 1

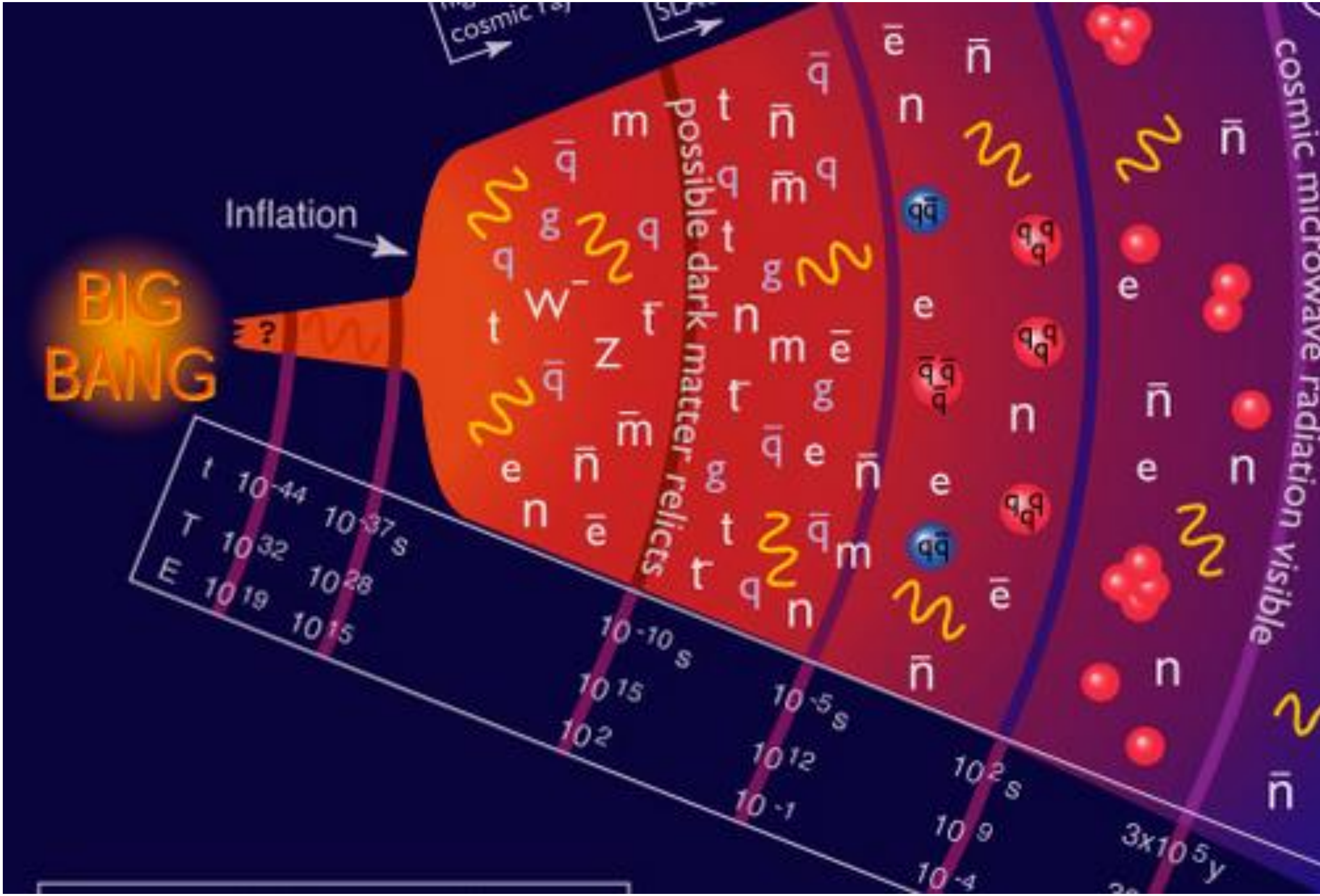
$$v = H_0 r$$

O que seria o Universo?
Que objeto estamos estudando?
Só é possível construir esta figura sabendo da existência de matéria e energia escuras.

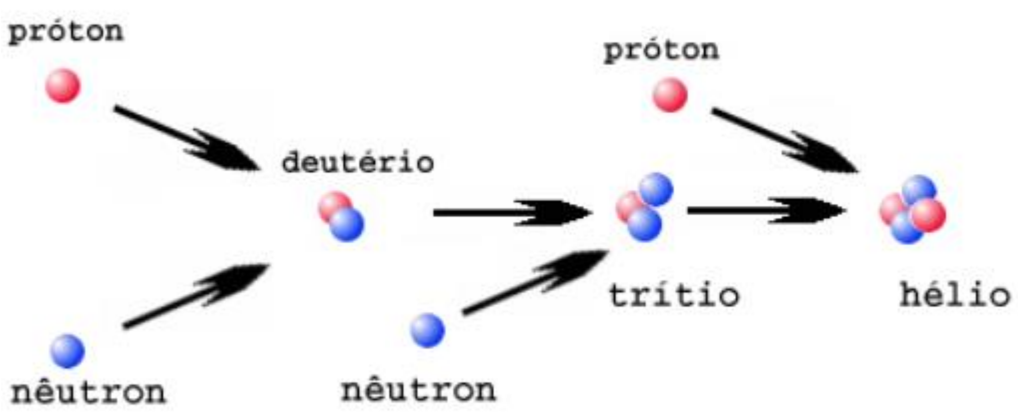




History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF


BIG BANG
Inflation
possible dark matter relicts
cosmic microwave radiation visible
cosmic ray
t
T
E
10-44
1032
1019
10-37 s
1028
1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y

Do que é feito tudo isso?
A origem dos elementos no início do universo.
Nucleossíntese Primordial. Primeiros 3 minutos!



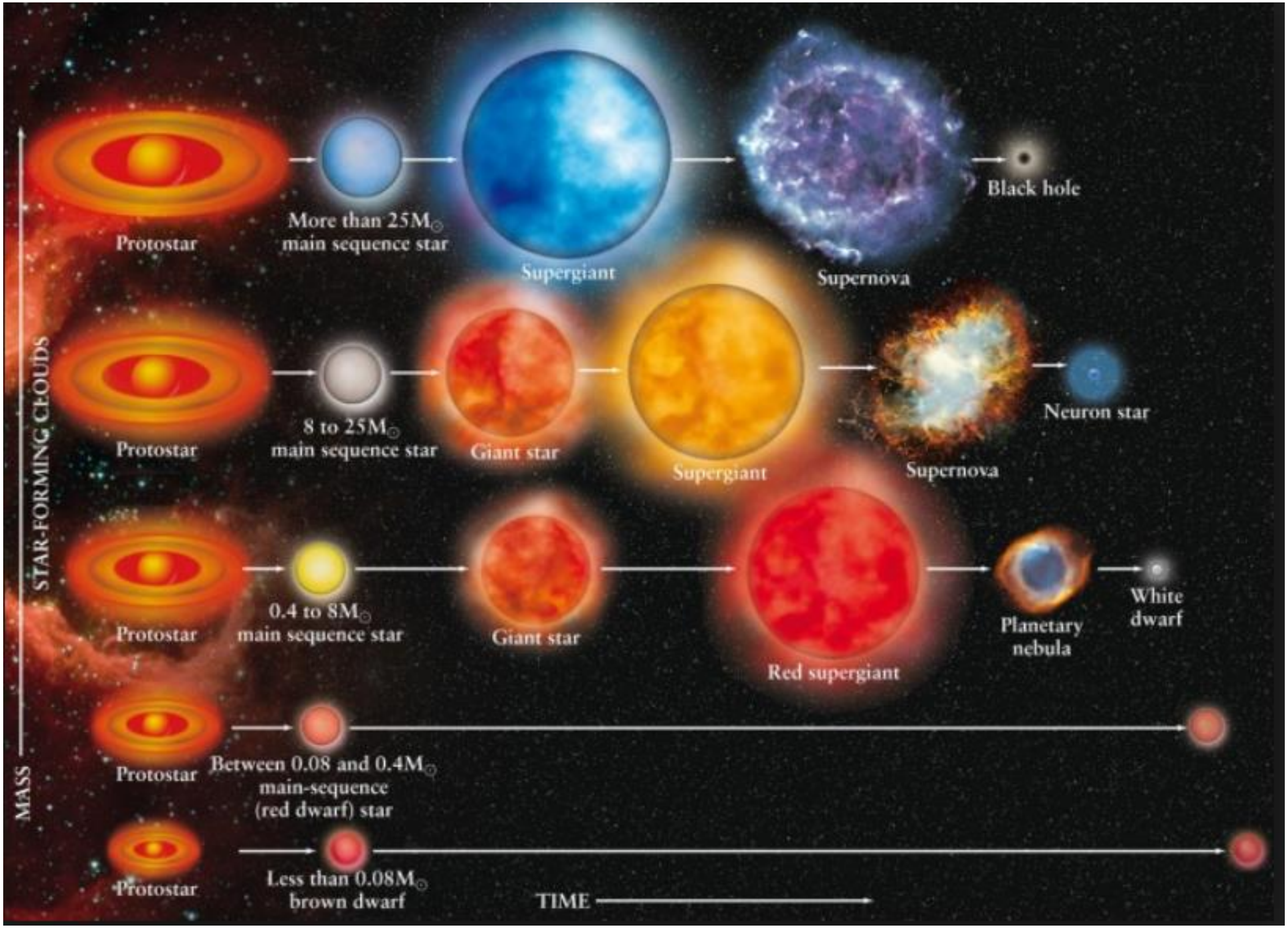
Fim:

1) Inexistência de núcleos estáveis 5<A<8
2) Expansão do universo amortecida, temperatura menor, não é possível fazer fusão dos Z>5

$n^0 \longrightarrow p^+ + e^- + \bar{\nu}_e$	$p^+ + n^0 \longrightarrow {}^2_1\mathrm{D} + \gamma$
${}^2_1\mathrm{D} + p^+ \longrightarrow {}^3_2\mathrm{He} + \gamma$	${}^2_1\mathrm{D} + {}^2_1\mathrm{D} \longrightarrow {}^3_2\mathrm{He} + n^0$
${}^2_1\mathrm{D} + {}^2_1\mathrm{D} \longrightarrow {}^3_1\mathrm{T} + p^+$	${}^3_1\mathrm{T} + {}^2_1\mathrm{D} \longrightarrow {}^4_2\mathrm{He} + n^0$
${}^3_2\mathrm{He} + {}^4_2\mathrm{He} \longrightarrow {}^7_3\mathrm{Li} + \gamma$	${}^3_2\mathrm{He} + n^0 \longrightarrow {}^3_1\mathrm{T} + p^+$
${}^3_2\mathrm{He} + {}^2_1\mathrm{D} \longrightarrow {}^4_2\mathrm{He} + p^+$	${}^3_2\mathrm{He} + {}^4_2\mathrm{He} \longrightarrow {}^7_4\mathrm{Be} + \gamma$
${}^7_3\mathrm{Li} + p^+ \longrightarrow {}^4_2\mathrm{He} + {}^4_2\mathrm{He}$	${}^7_4\mathrm{Be} + n^0 \longrightarrow {}^7_3\mathrm{Li} + p^+$

Principais reações termonucleares que ocorreram após o Big Bang.

Do que é feito tudo isso?
A origem dos elementos nas estrelas. Nucleosíntese estelar



7 Milhões

Duração do ciclo evolutivo

10 Bilhões

Do que é feito tudo isso?
A origem dos elementos nas estrelas.
Nucleosíntese estelar:

Ciclo próton-próton

$$p + p \rightarrow {}^{2}H + e^{+}\nu_e$$
$$p + {}^{2}H \rightarrow {}^{3}He + \gamma$$
$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + p + p$$

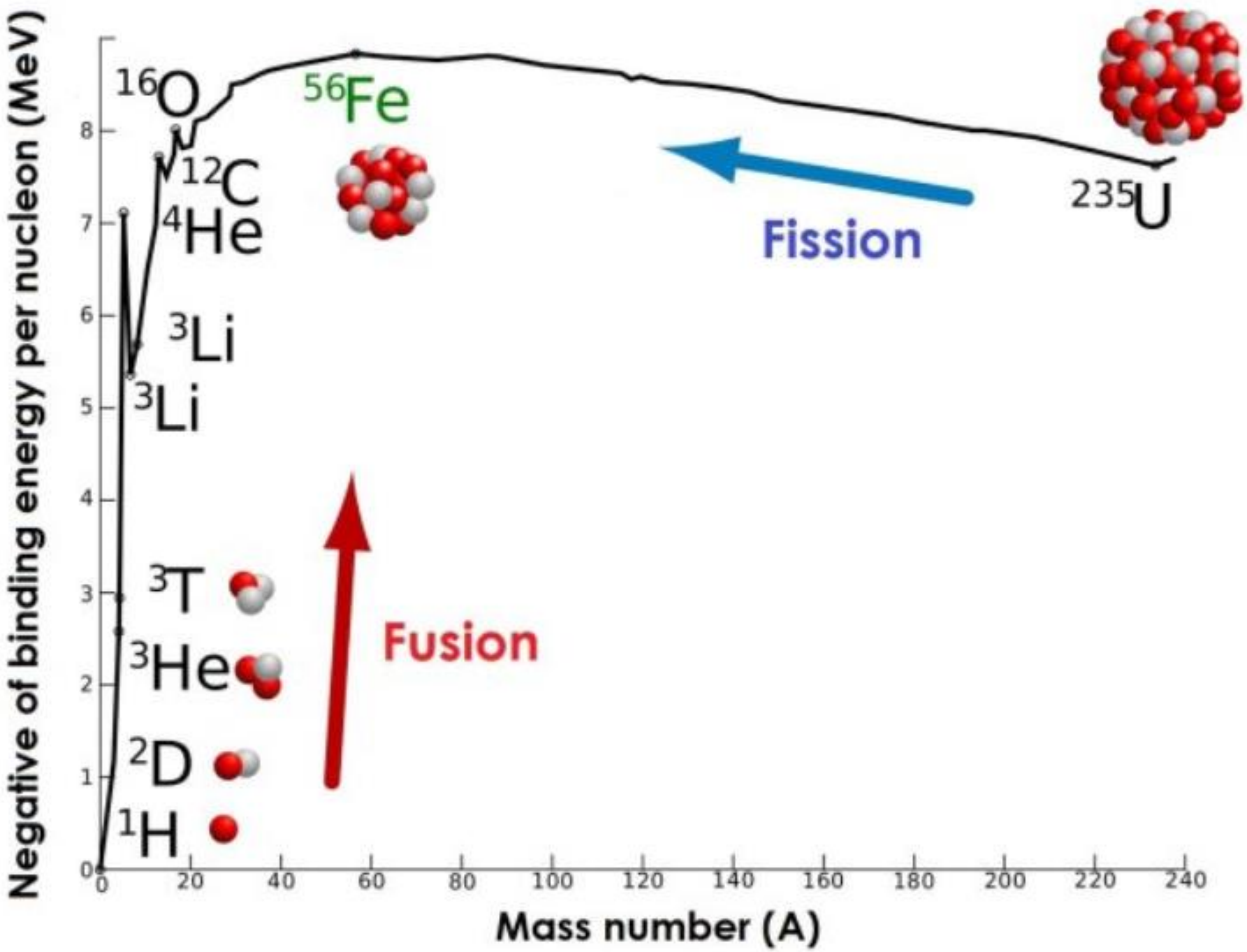
Ciclo CNO

$${}^{12}C + p \rightarrow {}^{13}N + \gamma$$
$${}^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$$
$${}^{13}C + p \rightarrow {}^{14}N + \gamma$$
$${}^{14}N + p \rightarrow {}^{15}O + \gamma$$
$${}^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$$
$${}^{15}N + p \rightarrow {}^{12}C + {}^{4}He$$

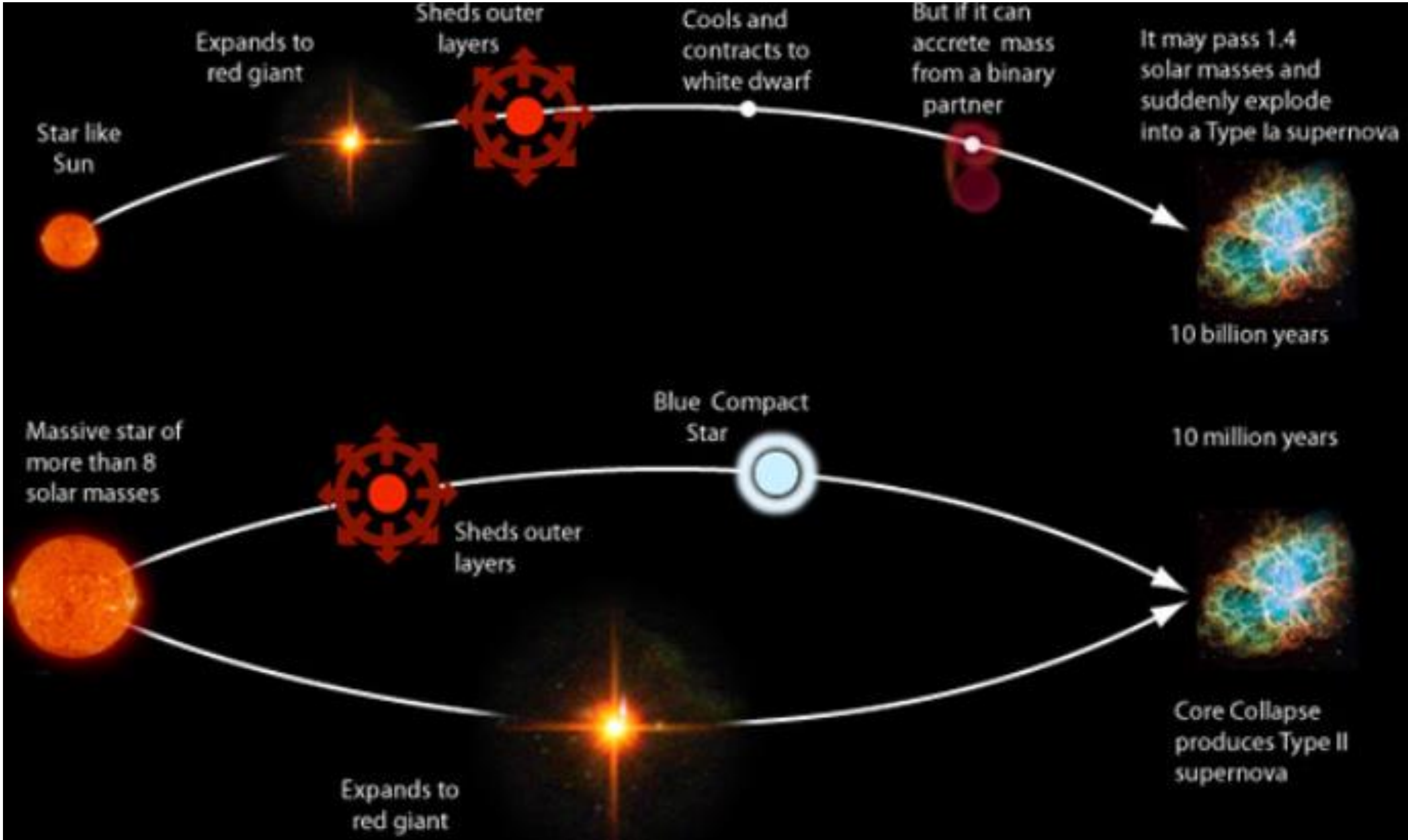
Ciclo Triplo alpha

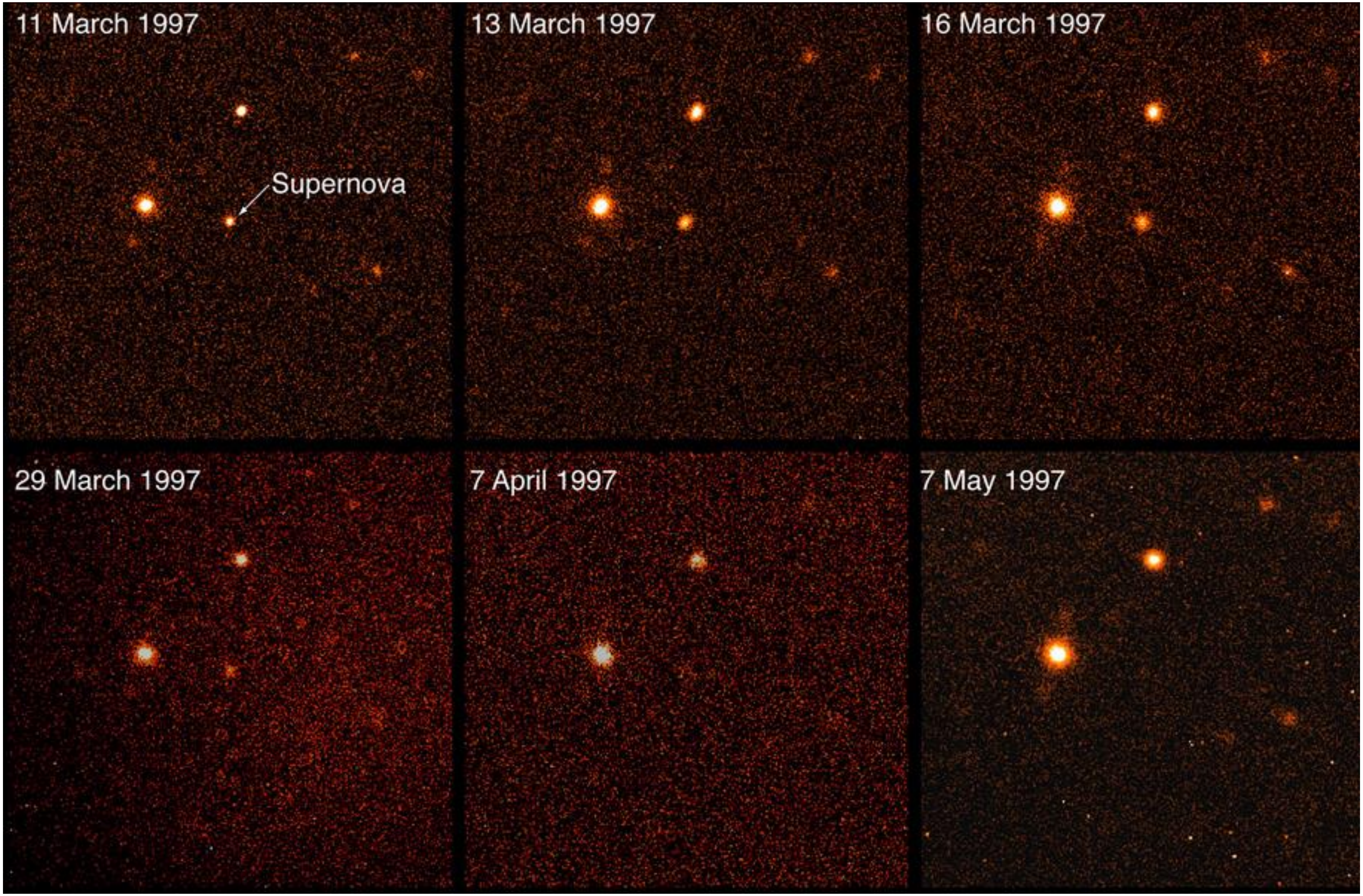
$$3 \times {}^{4}He \rightarrow {}^{12}C + e^{+} + e^{-} + \gamma$$

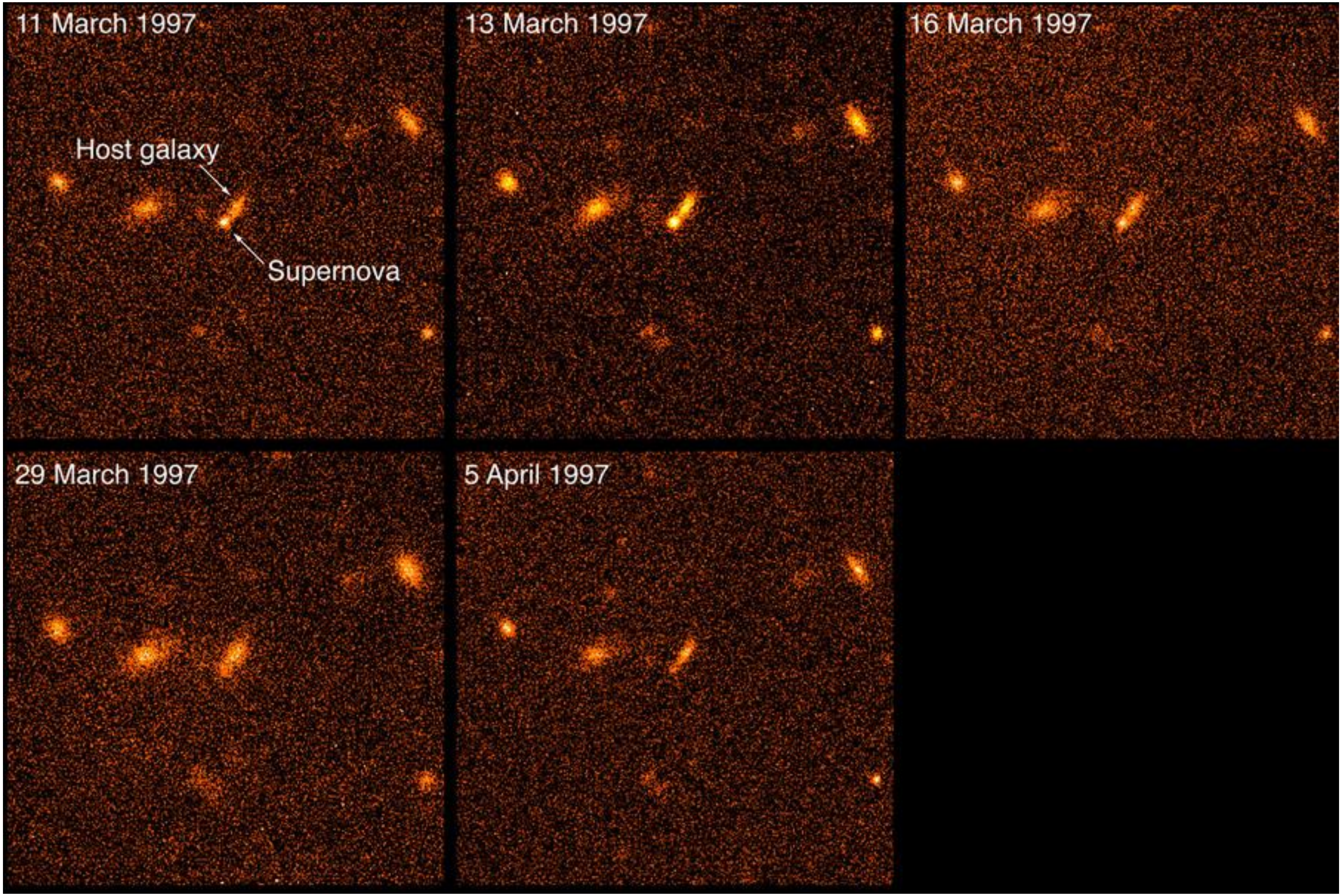
Produção dos elementos mais pesados que o Fe 56



Supernovas e a formação dos elementos pesados




11 March 1997
Supernova
13 March 1997
16 March 1997
29 March 1997
7 April 1997
7 May 1997


11 March 1997
Host galaxy
Supernova
13 March 1997
16 March 1997
29 March 1997
5 April 1997

Processos “S”

O “processo *s*” ocorre em ambientes em que existam nêutrons livres, porém com densidade relativamente baixa, tipicamente nos núcleos de estrelas massivas. Nessas condições, um núcleo-semente pode capturar um nêutron e a seguir emitir um elétron, o que se chama *decaimento beta nuclear*, antes de capturar mais um nêutron. Esse mecanismo permite a formação de uma sequência de elementos químicos que vai do ^{57}Fe até o ^{209}Bi. A cadeia de reações abaixo ilustra uma fase desse processo:

$$^{56}Fe + n \rightarrow {}^{57}Fe$$
$$^{57}Fe + n \rightarrow {}^{58}Fe$$
$$^{58}Fe + n \rightarrow {}^{59}Fe \rightarrow {}^{59}Co + e^-$$
$$^{59}Co + n \rightarrow {}^{60}Co \rightarrow {}^{60}Ni + e^-$$

Esse tipo de processo pode prosseguir até a síntese do ^{209}Bi. Todas as reações seguintes resultam em isótopos instáveis que decaem novamente no bismuto. Assim, os elementos radioativos de

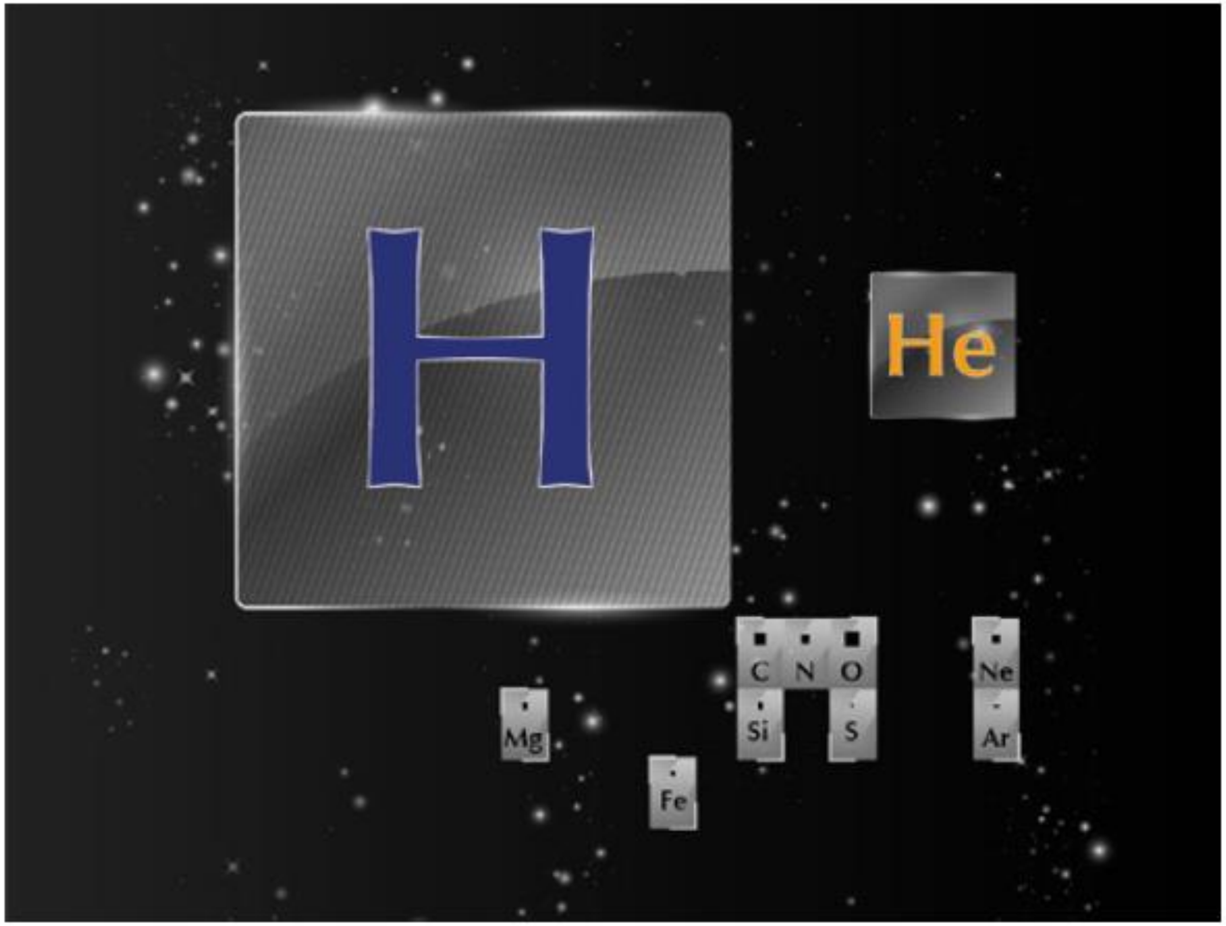
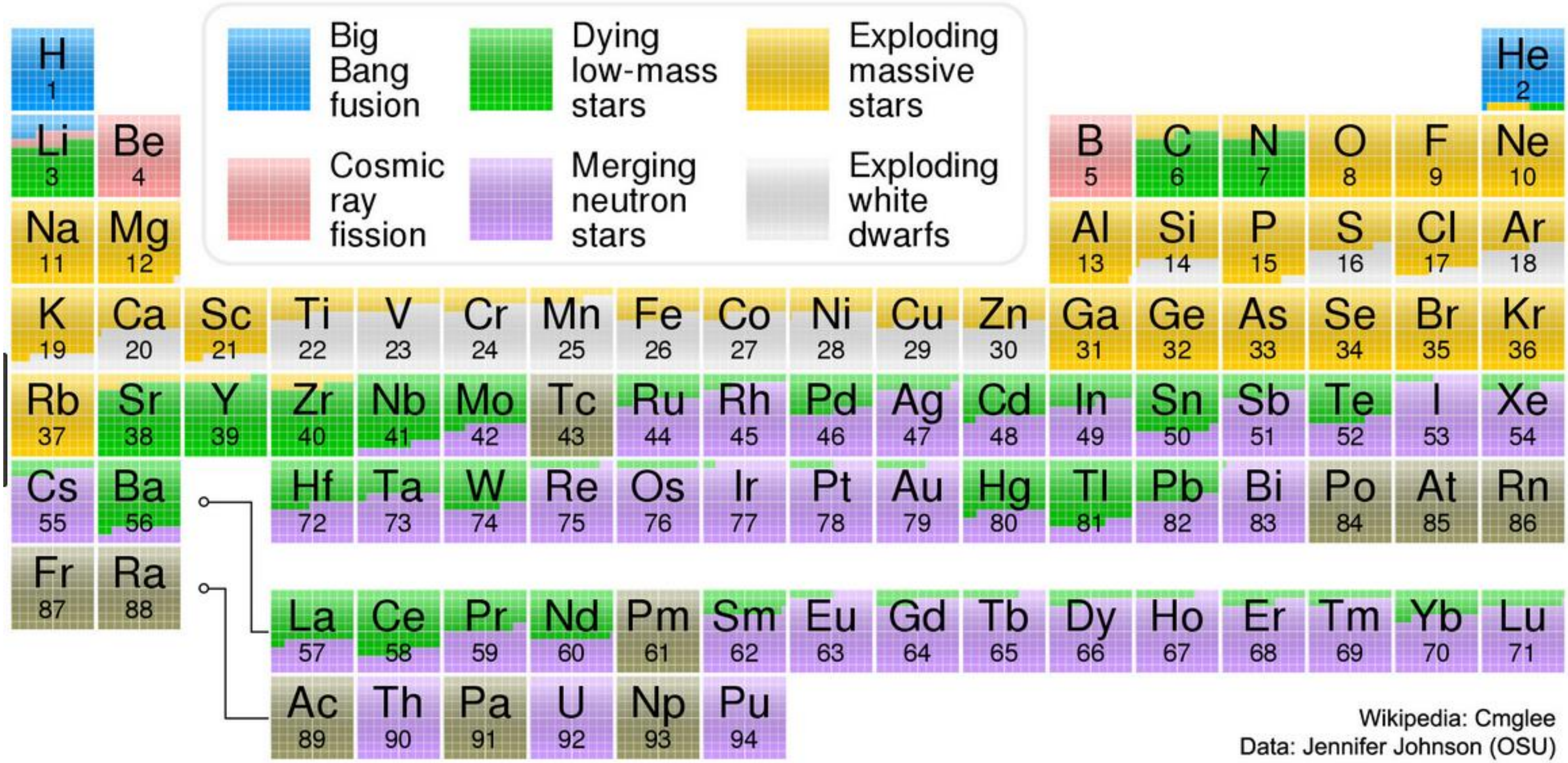


Figura 2.4. A tabela periódica do astrônomo. Contrariamente à representação convencional, o espaço de cada elemento é mostrado proporcionalmente à abundância cósmica medida. Note-se que todos os elementos alfa etc. não chegam, somados, a 1% do total. E outros – tão raros que nem aparecem na figura – são utilizados muito intensivamente pelos sistemas biológicos. Fonte: IAG

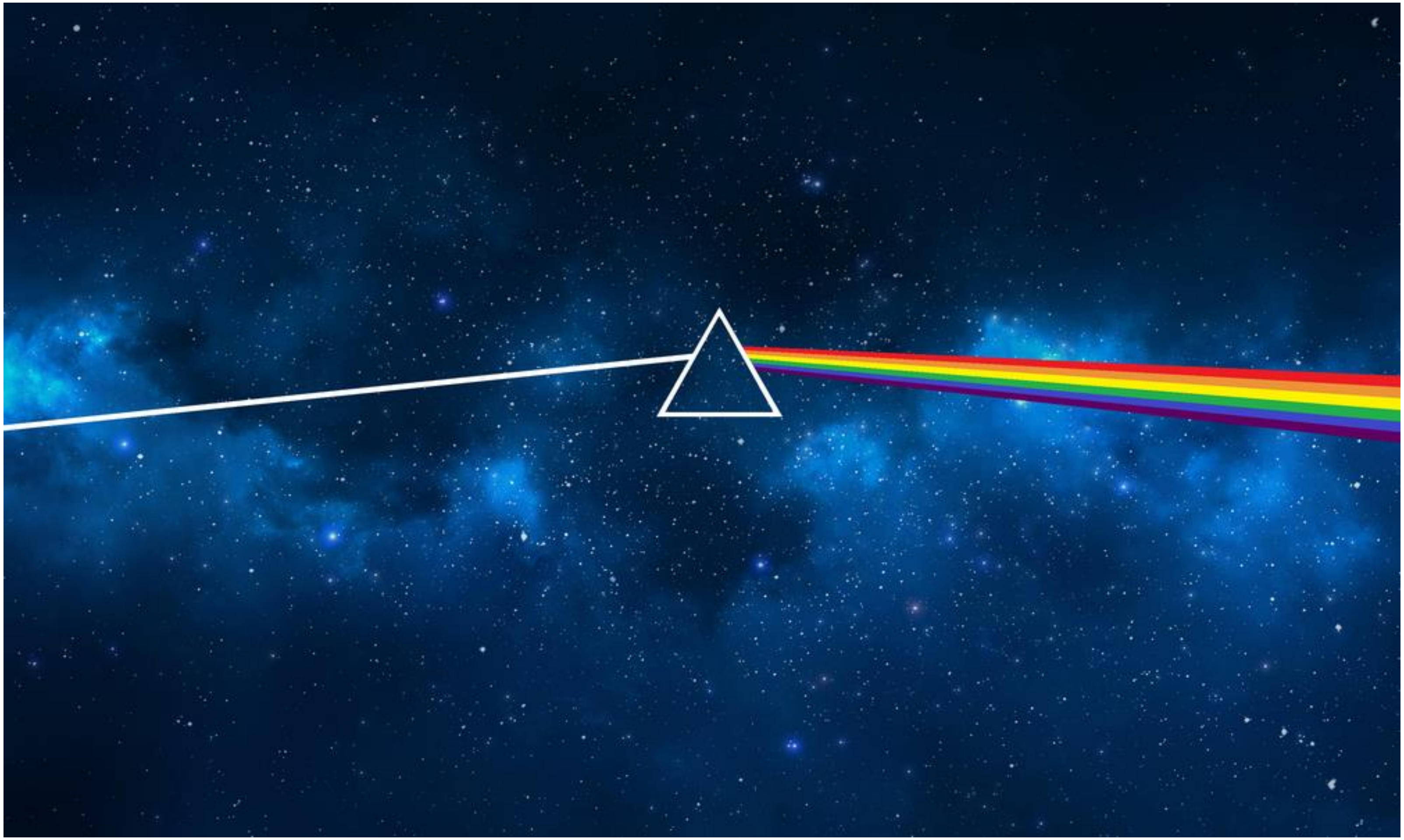
A origem dos elementos



E o que NÃO conhecemos de todo o Cosmos?

Aula II

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



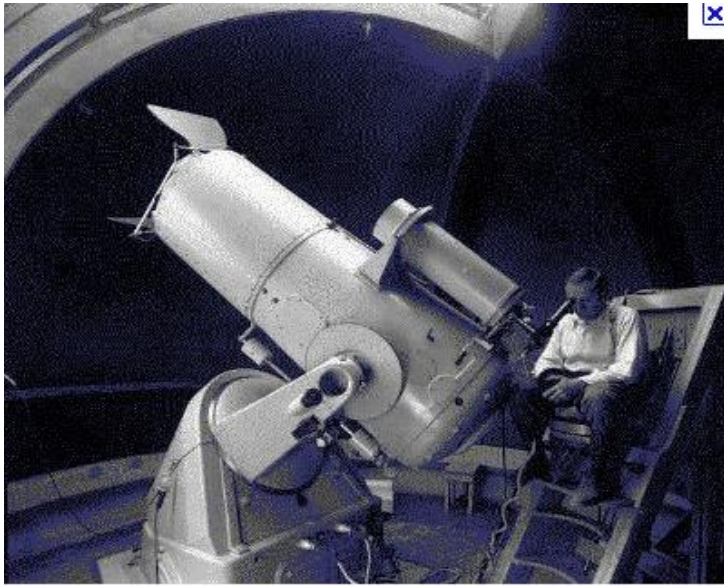
Matéria Escura

Evidências de Matéria Escura

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

- Evidências Cosmológicas:
- - Levam em conta a expansão do Universo.
- - Matéria escura surge como elemento imprescindível
- - Tema das aulas V e VI.

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

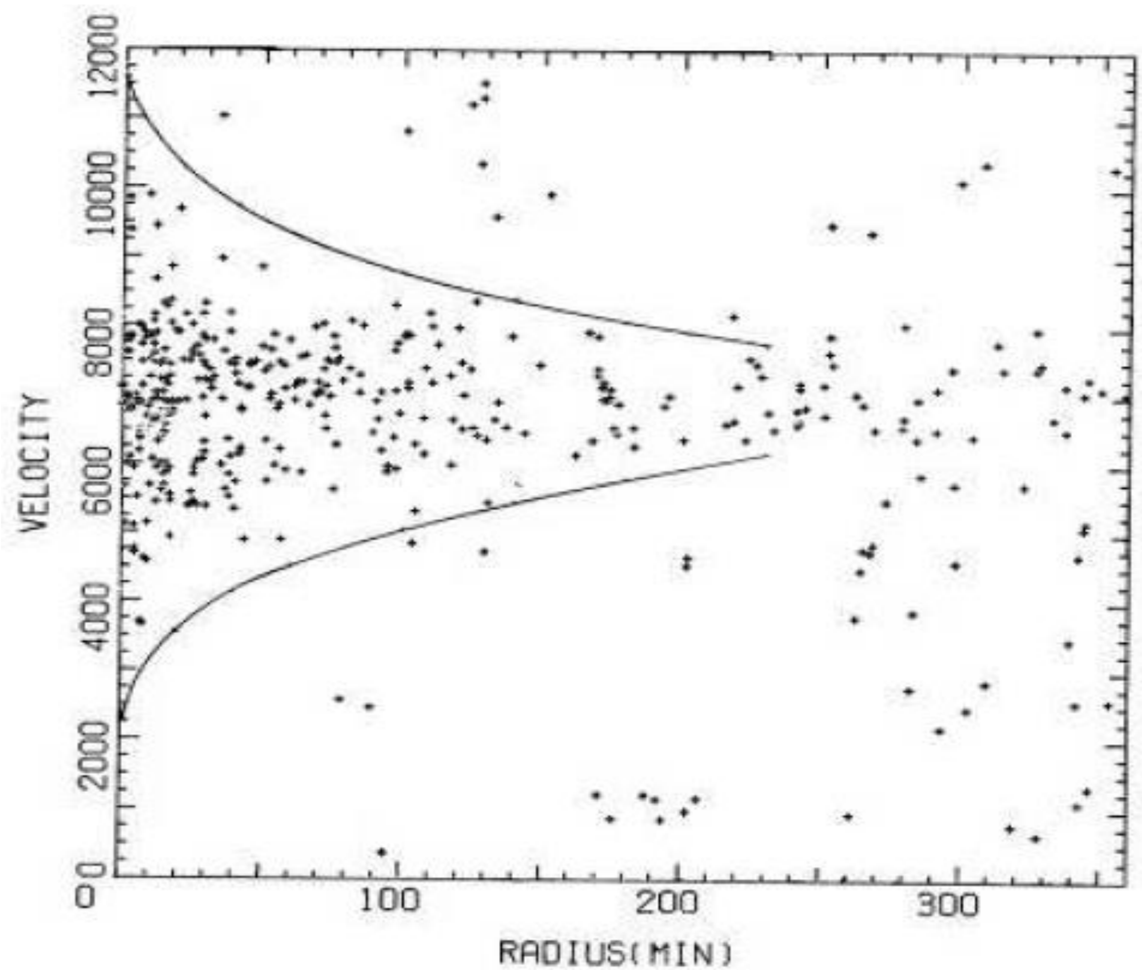
$$\overline{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_{\odot} . \tag{36}$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathscr{M}$, 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



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

$$c = 299.729.458 m/seg.$$

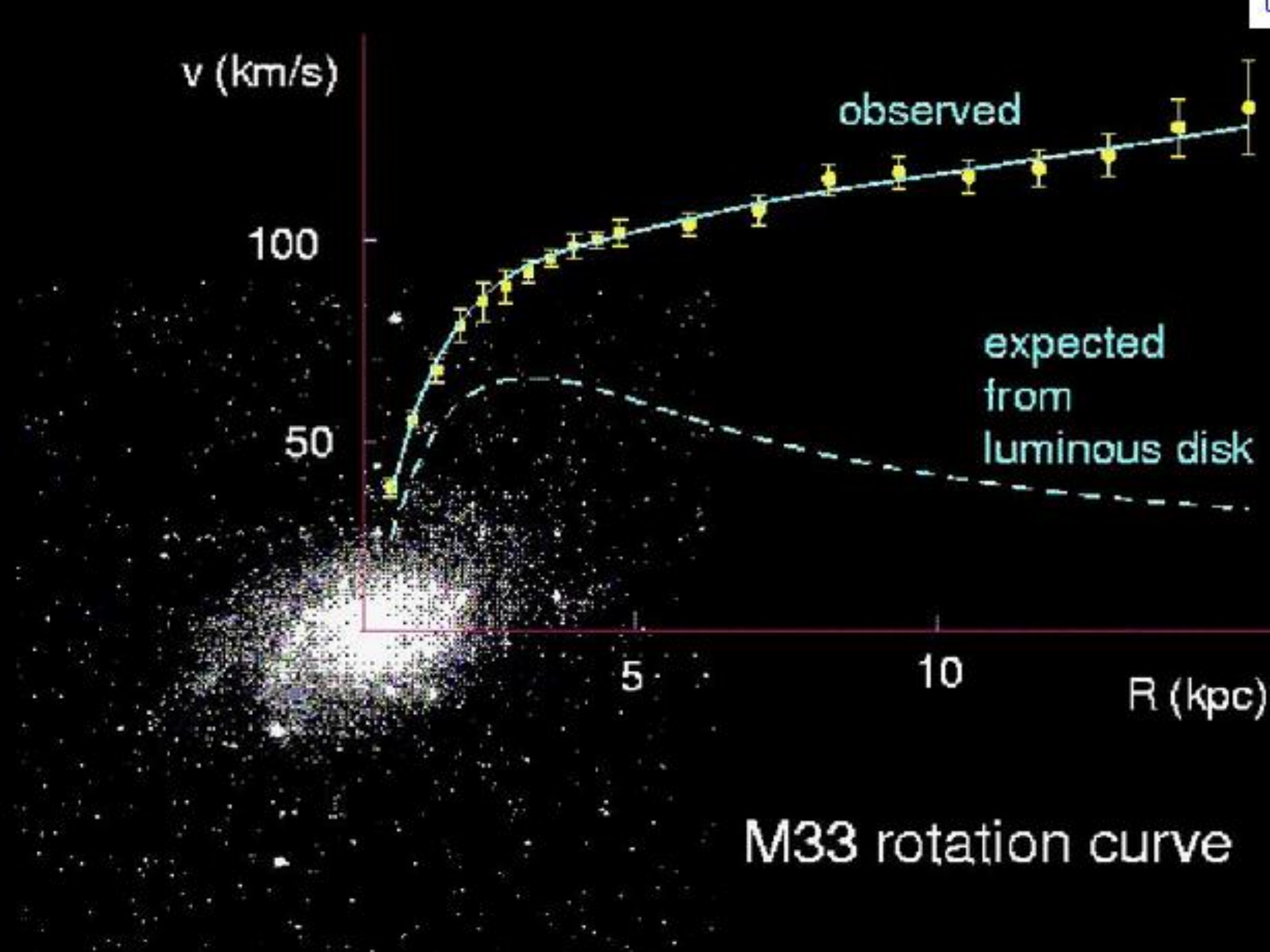
$$\gamma \sim 0,9997$$

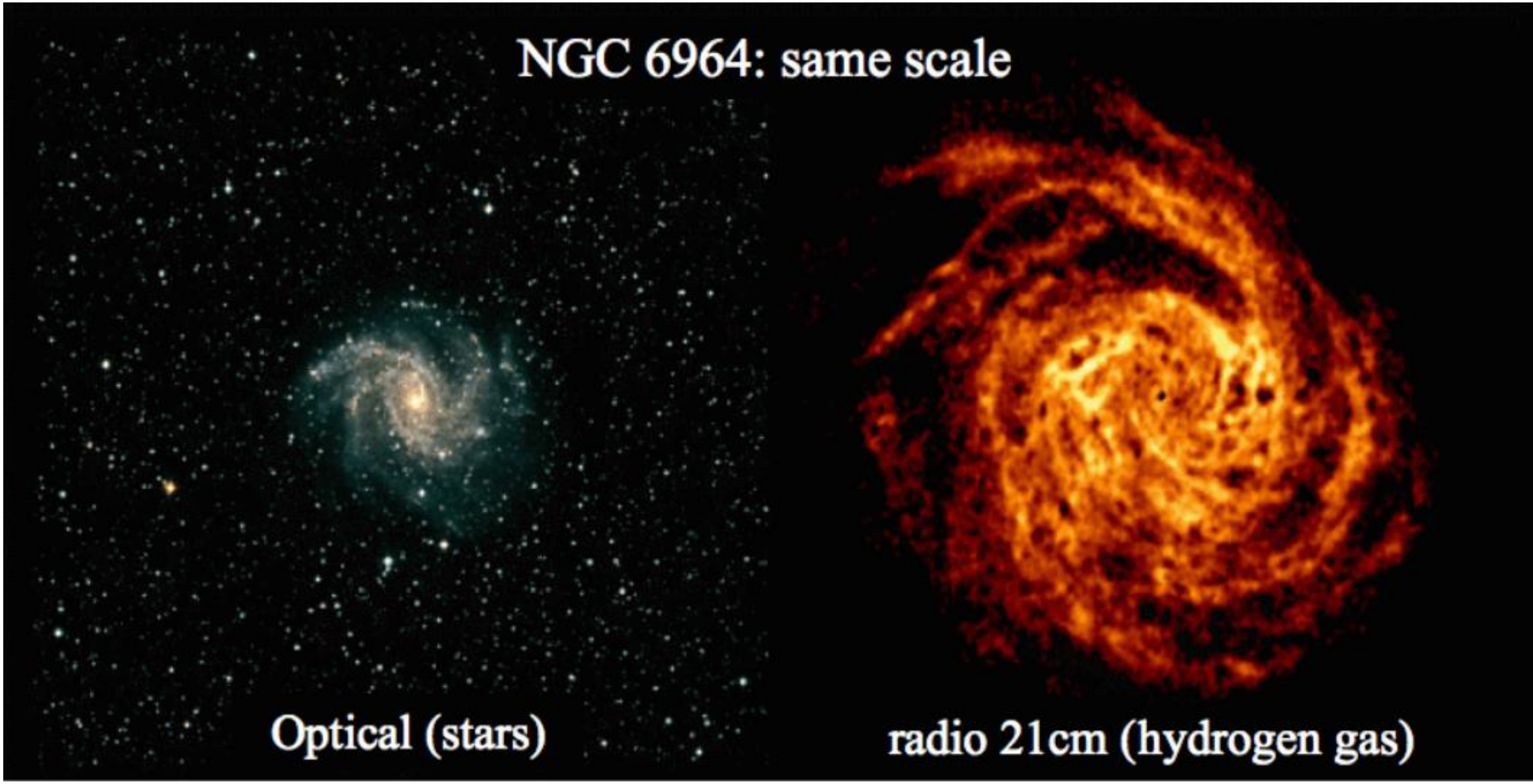
Sistema Newtoniano!

Curva de rotação de galáxias espirais

Vera Rubin ~1980

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


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


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

Uma alternativa Clássica à Matéria Escura
MOND – Modified Newtonian dynamics

THE ASTROPHYSICAL JOURNAL, **270**:365–370, 1983 July 15

A MODIFICATION OF THE NEWTONIAN DYNAMICS AS A POSSIBLE ALTERNATIVE TO THE HIDDEN MASS HYPOTHESIS[1]

M. MILGROM
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The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

ABSTRACT

I consider the possibility that there is not, in fact, much hidden mass in galaxies and galaxy systems. If a certain modified version of the Newtonian dynamics is used to describe the motion of bodies in a gravitational field (of a galaxy, say), the observational results are reproduced with no need to assume hidden mass in appreciable quantities. Various characteristics of galaxies result with no further assumptions.

In the basis of the modification is the assumption that in the limit of small acceleration $a \ll a_0$, the acceleration of a particle at distance r from a mass M satisfies approximately $a^2/a_0 \approx MGr^{-2}$, where a_0 is a constant of the dimensions of an acceleration.

A success of this modified dynamics in explaining the data may be interpreted as implying a need to change the law of inertia in the limit of small accelerations or a more limited change of gravity alone.

I discuss various observational constraints on possible theories for the modified dynamics from data which exist already and suggest other systems which may provide useful constraints.

Velocidade de rotação de uma partícula teste ao redor de uma esfera de raio R, massa M e densidade constante

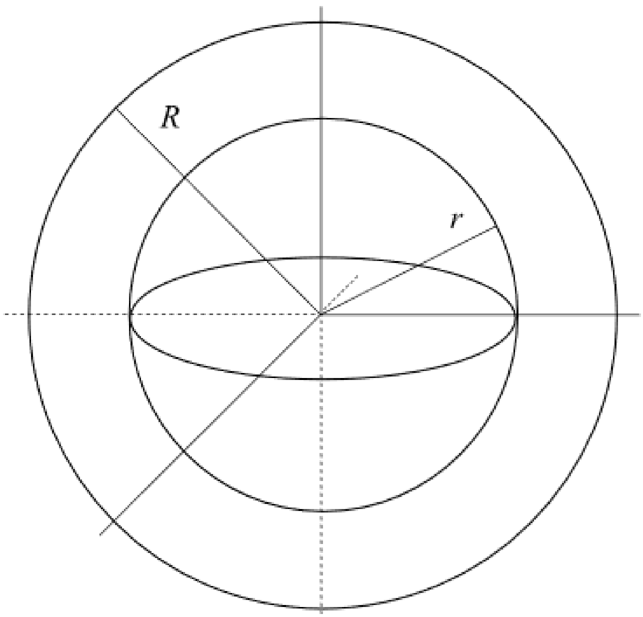


Figura 1 - Representação esfericamente simétrica para uma galáxia de raio R.

Região $r < R$

$$\frac{Gmm'}{r^2} = \frac{m'v_{ni}^2}{r};$$

$$m = Mr^3/R^3.$$

$$v_{ni} = \sqrt{\frac{GM}{R^3}}r.$$

Região $r > R$

$$\frac{GMm'}{r^2} = m'\frac{v_{ne}^2}{r}.$$

$$v_{ne} = \sqrt{\frac{GM}{r}}.$$

$$v_{ni} = v_{ne} = \sqrt{\frac{GM}{R}}$$

MOND: uma alternativa à mecânica newtoniana

(MOND: an alternative to Newtonian mechanics)

quenas. Basicamente, a teoria MOND é uma modificação da segunda lei de Newton, de tal forma que esta, para um corpo de prova de massa m', passa a ser escrita como

$$F = m'\mu\left(\frac{a}{a_0}\right)a, \tag{5}$$

onde $\mu(x)$ é uma função que assume a seguinte forma: $\mu(x) \approx 1$ para $x >> 1$ e $\mu(x) \approx x$ para $x << 1$. Existem na literatura várias formas para a função $\mu(x)$ [9], entretanto as implicações causadas pela teoria MOND não dependem de uma forma exata para esta função. Nesta modificação, $a_0 \sim 10^{-8}$ cm s^{-2} define o valor para a aceleração crítica da teoria. Para um corpo em movimento com uma aceleração abaixo deste valor a segunda lei de Newton usual não seria mais válida. A princípio, o valor estabelecido pela constante a_0 parece ser tão pequeno que talvez não existam situações física em que corpos possuam esta aceleração. No entanto, justamente em sistemas como galáxia e aglomerados de galáxias verificamos acelerações desta ordem. Com isso a segunda lei de Newton para uma partícula no regime MOND assume a forma

$$F = m'\frac{a^2}{a_0}. \tag{6}$$

Região $r < R$ $\quad v_{mi} = \left(\dfrac{GMa_0r^3}{R^3}\right)^{\frac{1}{4}}.$

Região $r > R$ $\quad v_{me} = (GMa_0)^{\frac{1}{4}}$

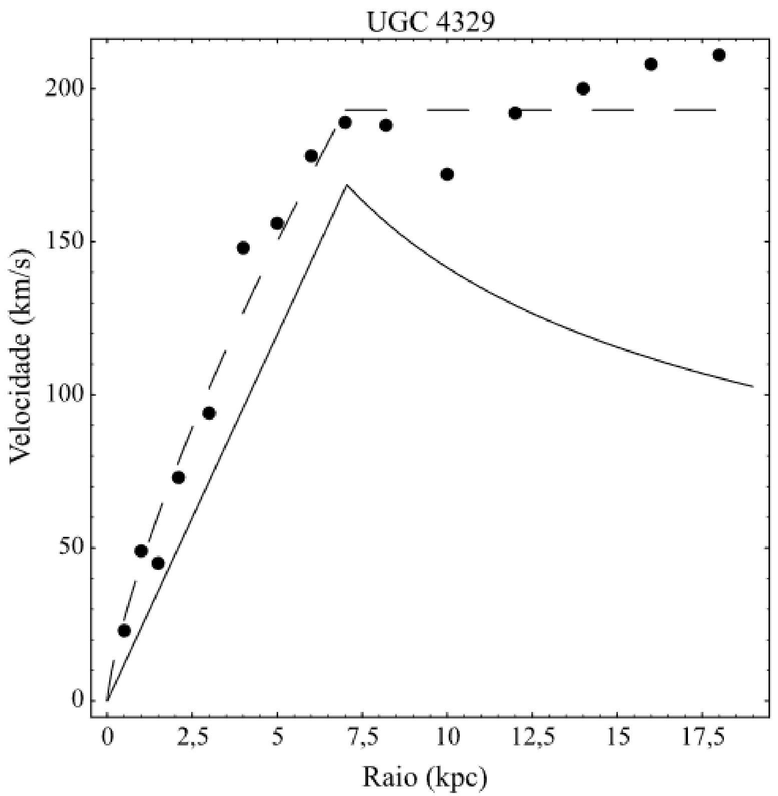


Figura 2 - Curva de rotação para a galáxia UGC4329. A teoria MOND (linha tracejada) e a teoria newtoniana (linha sólida) são comparadas com os dados observacionais (pontos).

MOND virial theorem applied to a galaxy cluster

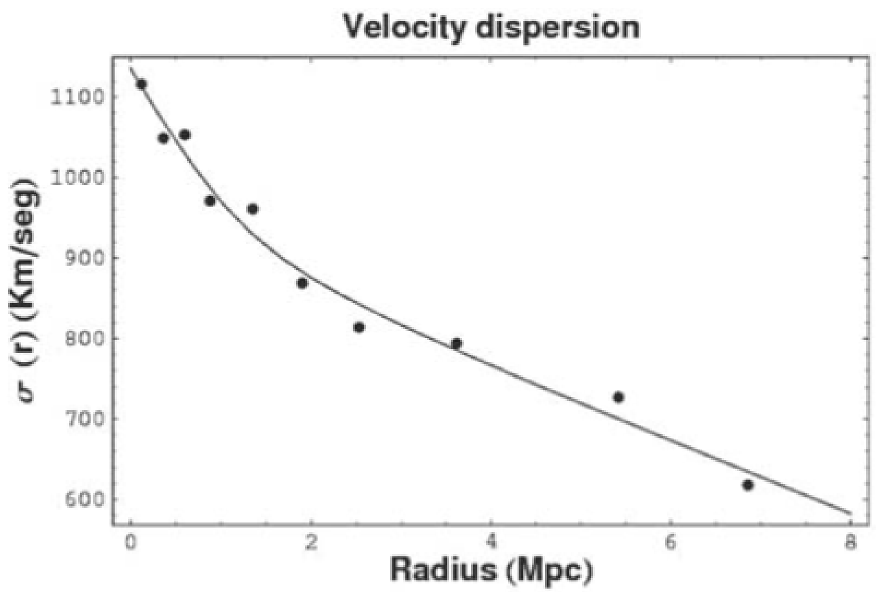
J.C. Fabris[1*] and H.E.S. Velten[1†]
[1] *Departamento de Física, Universidade Federal do Espírito Santo, Vitória, Espírito Santo, Brasil*
(Received on 30 May, 2009)

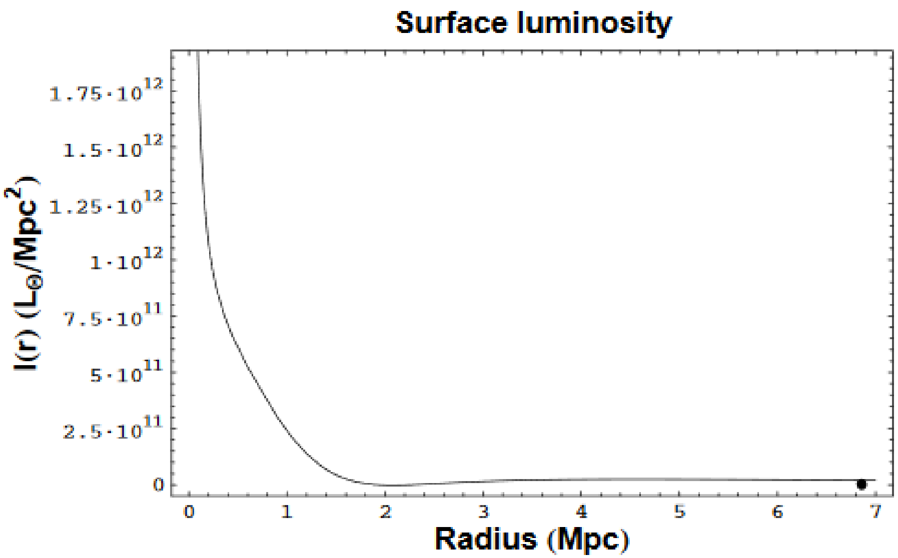
Large values for the mass-to-light ratio (Υ) in self-gravitating systems is one of the most important evidences of dark matter. We propose a expression for the mass-to-light ratio in spherical systems using MOND. Results for the COMA cluster reveal that a modification of the gravity, as proposed by MOND, can reduce significantly this value.

$$\Phi_M(r) = -GM\left\{\frac{\sqrt{1+\left(\frac{r}{r_c}\right)^2}}{r} - \frac{\sinh^{-1}\left(\frac{r}{r_c}\right)}{r_c}\right\}. \quad (8)$$

The potential has the usual newtonian form in the limit $r << r_c$, while it becomes logarithmic when $r >> r_c$, what corresponds to the full MOND regime.

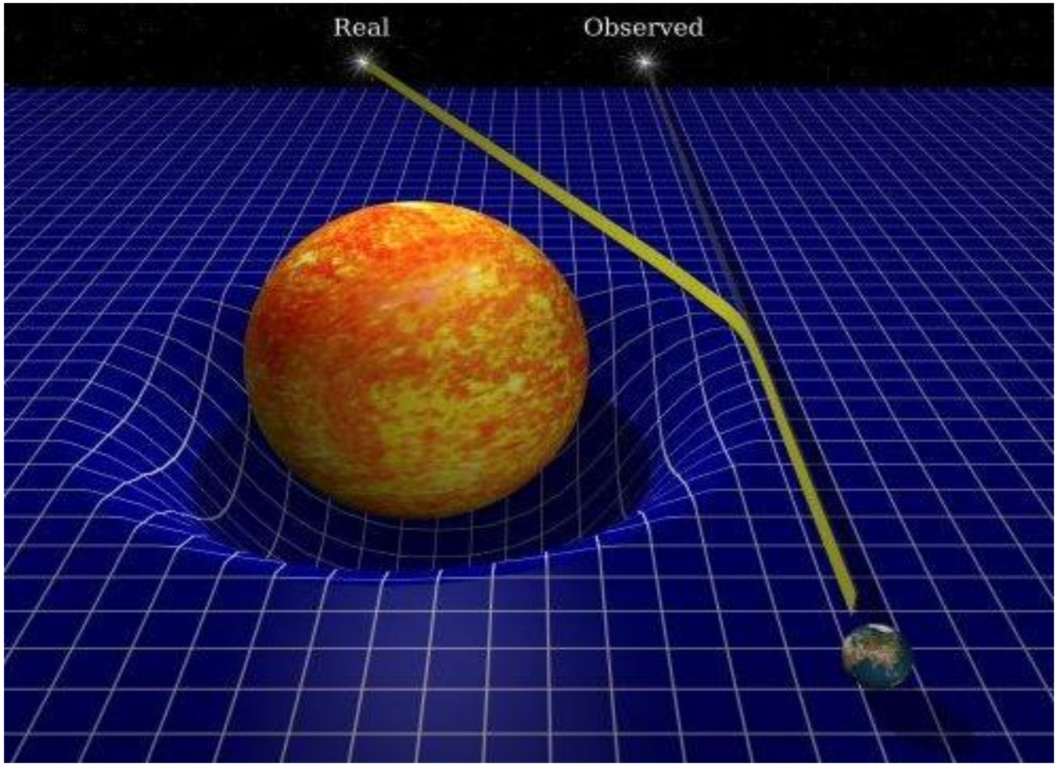
$$K = \frac{1}{2}\sum_i \left\langle \frac{\partial \Phi(r)}{\partial r} r \right\rangle m_i$$





$r_c\ (Mpc)$	Υ_M	$a_0\ (m/s^2)$
0.05	3.6	1.7×10^{-7}
0.1	7.2	7.0×10^{-7}
0.2	14.4	2.7×10^{-8}
0.3	21.6	1.5×10^{-8}
0.4	28.6	9.7×10^{-9}
0.5	35.5	6.8×10^{-9}
0.6	42.3	5.1×10^{-9}
0.7	48.9	4.0×10^{-9}
0.8	55.3	3.1×10^{-9}
0.9	61.6	2.6×10^{-9}

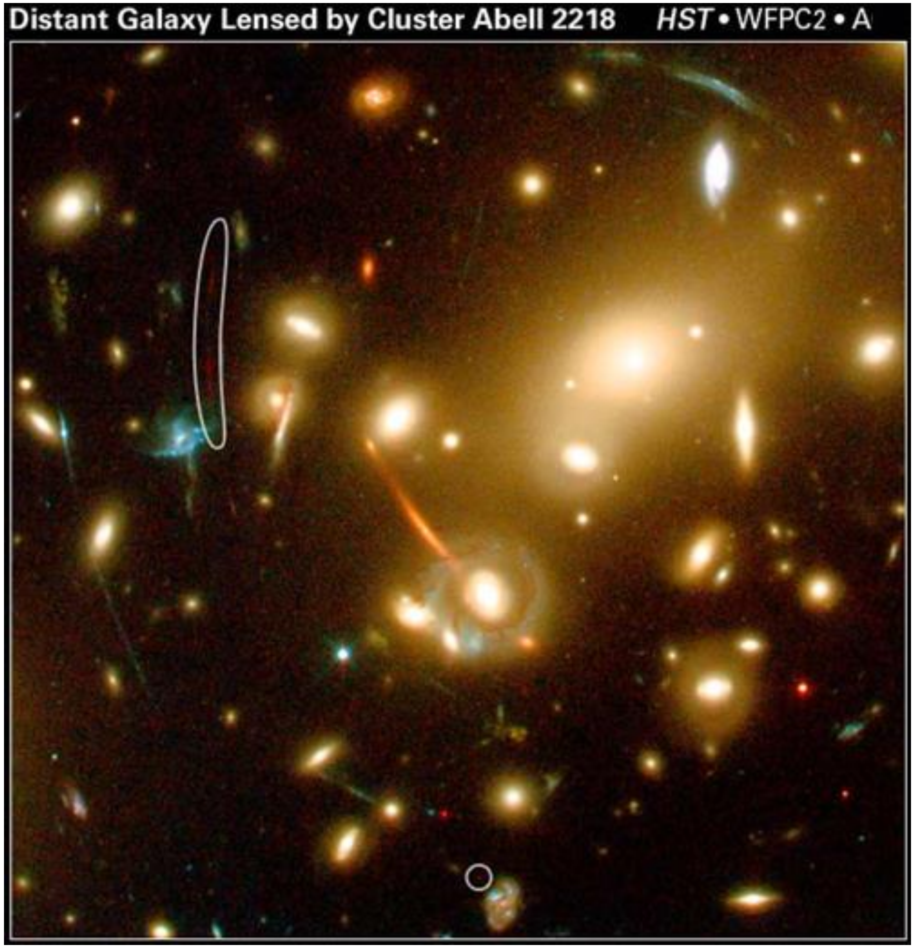
Fenômeno de lenteamento gravitacional

- 

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

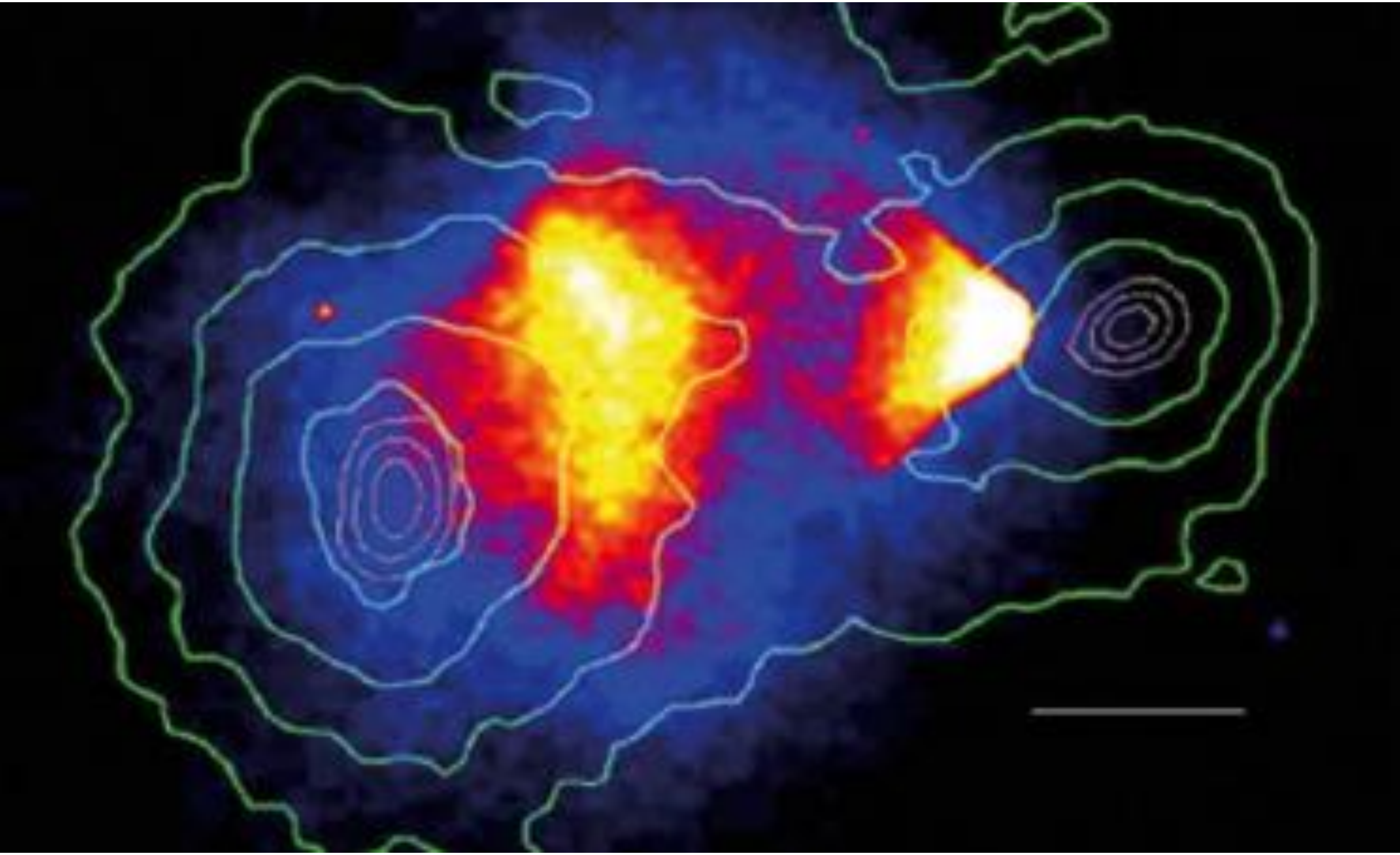
$$\theta = \frac{4GM}{rc^2}$$

Imagens reais e muito interessantes



Anéis de Einstein

Aglomerado da bala (2005)



Vídeo !!!!!!!

Qual partícula representaria a Matéria escura?

Se existe uma partícula para a Matéria escura seus requisitos mínimos:

1) Interagir gravitacionalmente;
2) Não possuir carga. Caso contrário já teria sido detectada;
3) Seção de choque com núcleons muito pequena;

Qual a massa essa partícula deveria ter?

Matéria escura quente: leve e rápida!

Matéria escura fria: pesada e lenta!

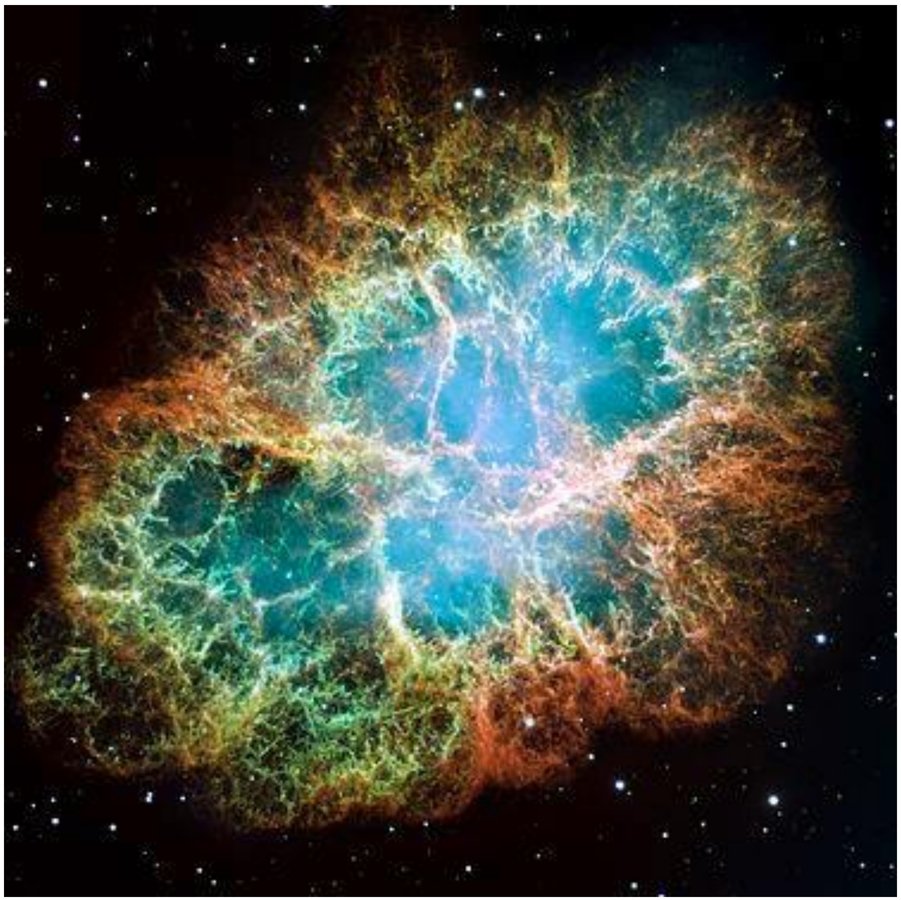
Matéria escura morna: Algo entre quente e frio!

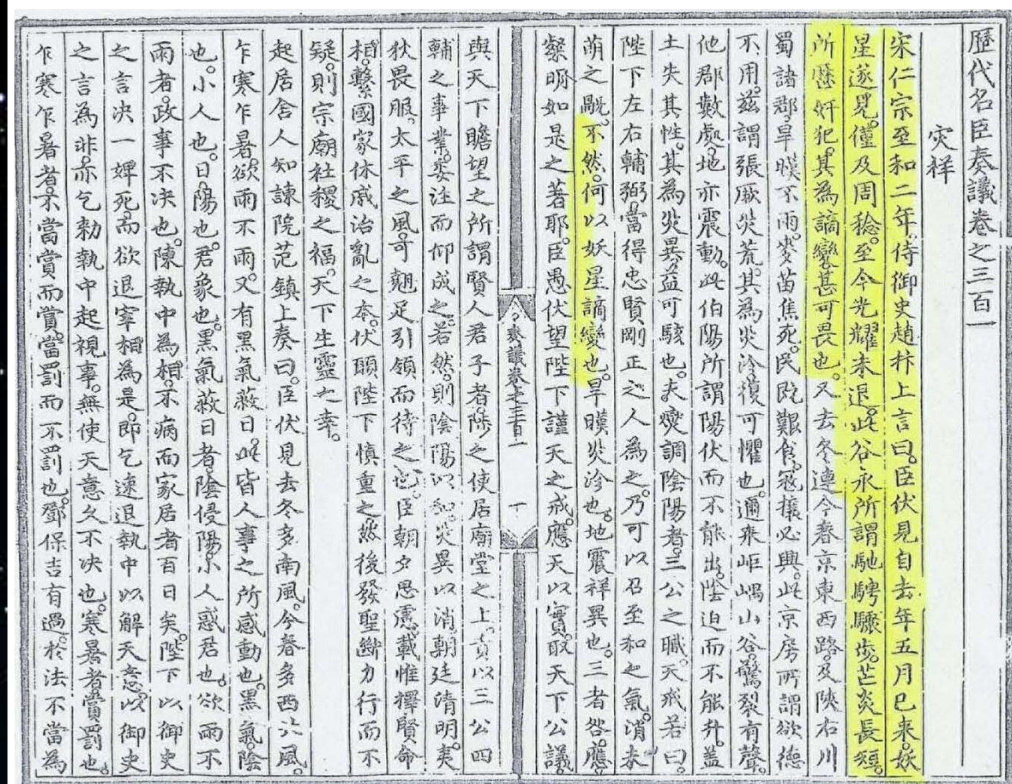
ENERGIA ESCURA

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

Astronomia oriental:

Chineses observaram uma supernova em 1054C





歷代名臣奏議卷之三百一

災祥

宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月己來妖
星遂見僅及周稔至今光耀未退此谷永所謂馳騁驟步芒炎長緩
所繇奸犯其為譎變甚可畏也又去冬逵今春京東西路及陝右川
蜀諸郡旱暵不雨麥苗焦死民既艱食寇攘必興此京房所謂欲德
不用茲謂張厥災荒其為災沴償可懼也通來峄嶧山谷驚裂有聲
他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋
土失其性其為災異益可駭也夫燮調陰陽者三公之職天戒若曰
陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消未
萌之亂不然何以妖星譎變也旱暵災沴也地震祥異也三者咎應
粲明如是之著耶臣愚伏望陛下謹天之戒應天以實取天下公議

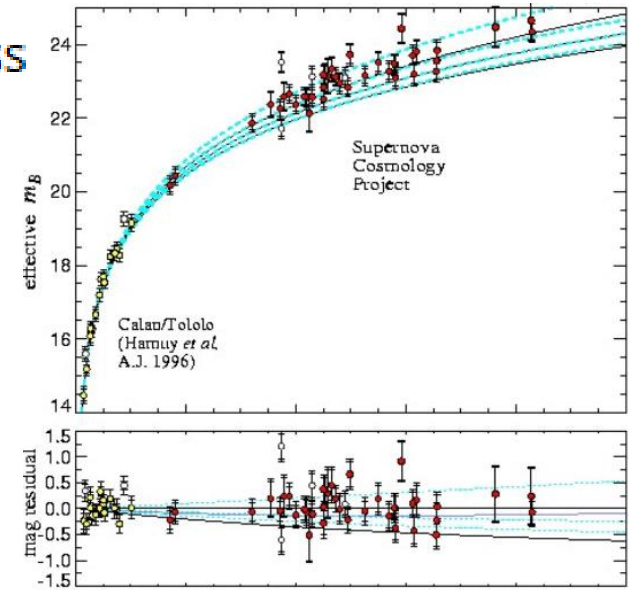
奏議卷之三百一 十

與天下瞻望之所謂賢人君子者陟之使居廟堂之上責以三公四
輔之事業委注而仰成之若然則陰陽以和災異以消朝廷清明夷
狄畏服太平之風可翹足引領而待之也臣朝夕思慮載惟擇賢命
相繫國家休戚治亂之本伏願陛下慎重之然後發聖斷力行而不
疑則宗廟社稷之福天下生靈之幸
起居舍人知諫院范鎮上奏曰臣伏見去冬多南風今春多西北風
乍寒乍暑欲雨不雨又有黑氣蔽日此皆人事之所感動也黑氣陰
也小人也日陽也君象也黑氣蔽日者陰侵陽小人惑君也欲雨不
雨者政事不決也陳執中為相不病而家居者百日矣陛下以御史
之言決一婢死而欲退宰相為是耶乞速退執中以解天意以御史
之言為非亦乞勅執中起視事無使天意久不決也寒暑者賞罰也
乍寒乍暑者不當賞而賞當罰而不罰也鄧保吉有過於法不當為

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.

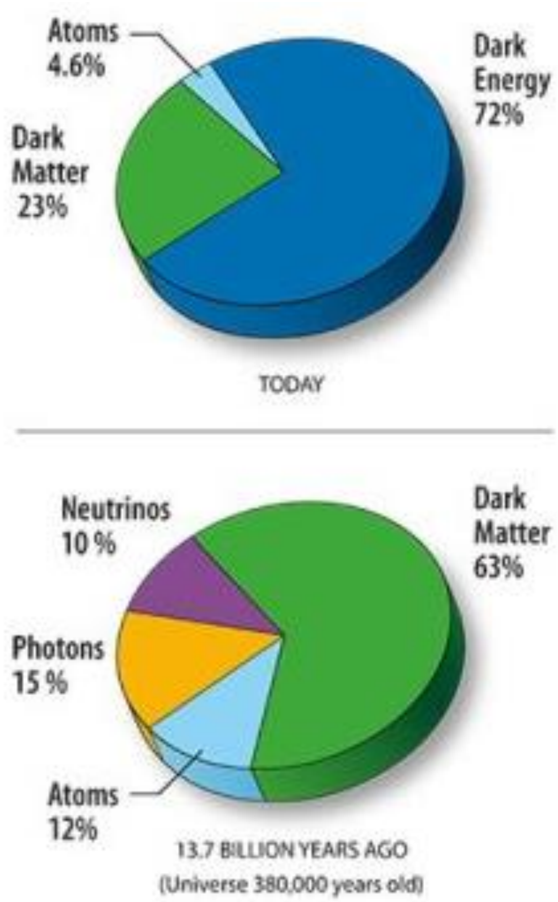
In 1998/9, published observations of ***Type Ia supernovae*** by

- 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.

O conteúdo material do Universo



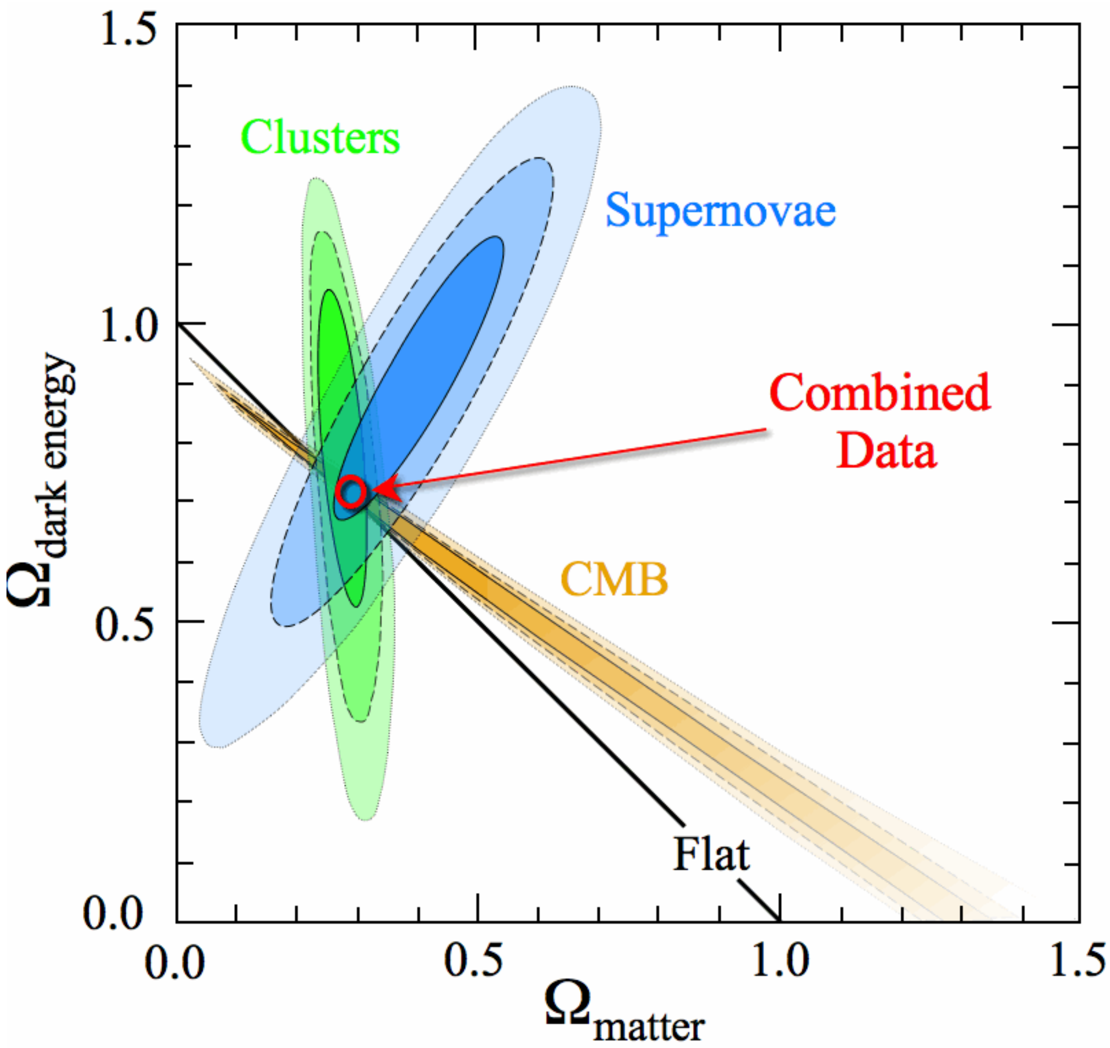
- Descrição padrão:

- Matéria Bariônica (~5%)
- Neutrinos & Fótons (~0.08%)
- Matéria Escura(~25%)
- Energia Escura (~70%)

$$H^2 = H_0^2 \{\Omega_{Bar} + \Omega_{Pho} + \Omega_{Neu} + \Omega_{DM} + \Omega_{DE}\}$$

$$H^2 = H_0^2 \left[\frac{\Omega_{b0} + \Omega_{dm0}}{a^3} + \frac{\Omega_{r0}}{a^4} + \Omega_\Lambda\right]$$

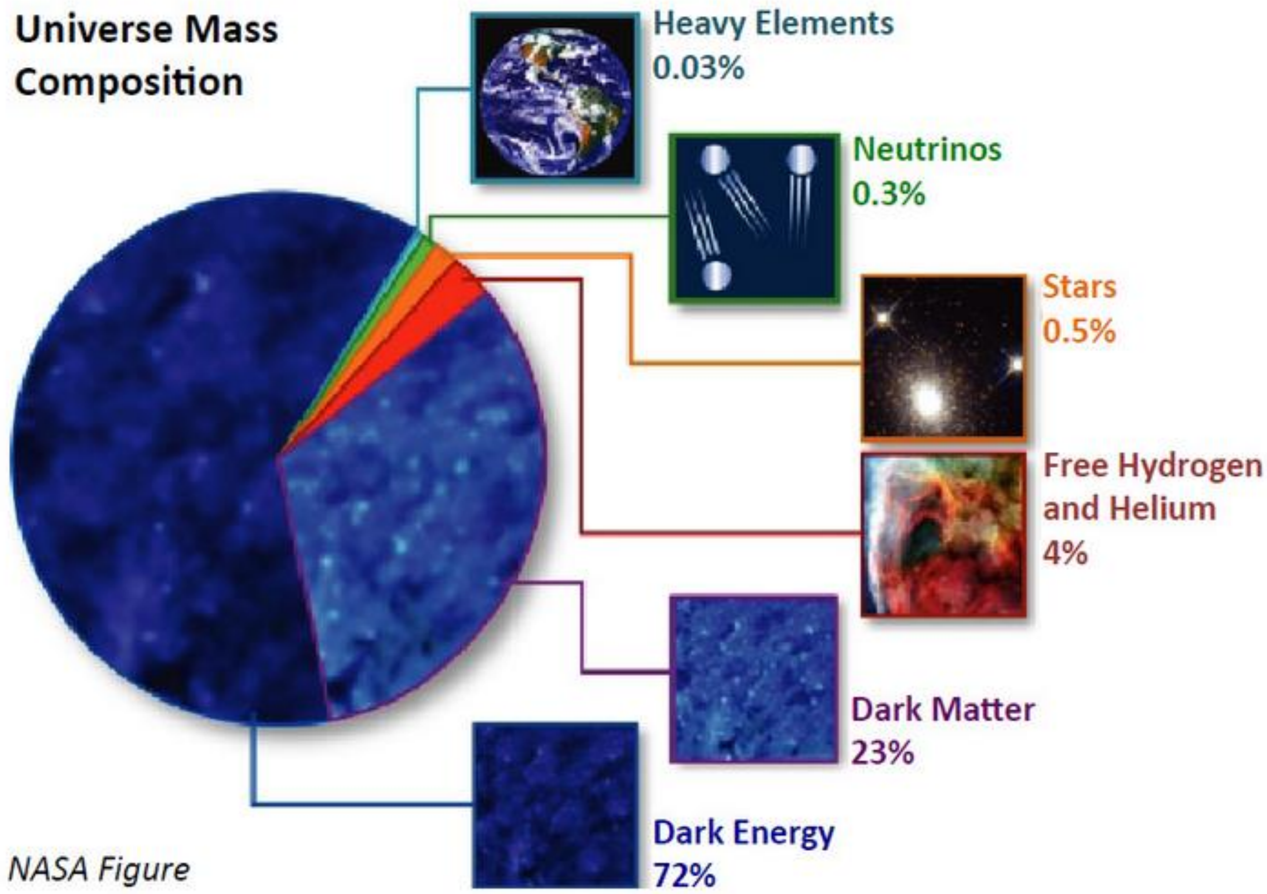
Os resultados da sonda PLANCK (2015) confirmam esse modelo padrão



ENERGIA ESCURA

A necessidade de explicar a expansão acelerada do Universo

https://www.astro.virginia.edu/class/whittle/astr553/Topic01/t1_cos_combined.gif



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

Não há evidência dessas partículas!

Alguns modelos de energia escura:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_{\rm tot} + 3p_{\rm tot}) = -\frac{4\pi G}{3}\sum \rho_w(1+3w)$$

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\rho_{\rm tot}$$

Em um universo com Matéria (Bárions + Matéria escura) e energia escura:

$$\frac{H^2(a)}{H_0^2} = \frac{\Omega_{\rm m0}}{a^3} + (1-\Omega_{\rm m0})\, e^{-\int da \frac{1+w_{\rm DE}}{a}}$$

Alguns modelos de energia escura:

Equação de estado:

$$w_{de} = p_{de}/\rho_{de}$$

- The constant EoS

$$w_{\rm DE} = w_0;$$

- The Chevallier-Polarski-Linder (CPL) [19, 20]

$$w_{\rm DE}(a) = w_0 + w_1(1-a);$$

- The Wetterich-logarithmic one [21]

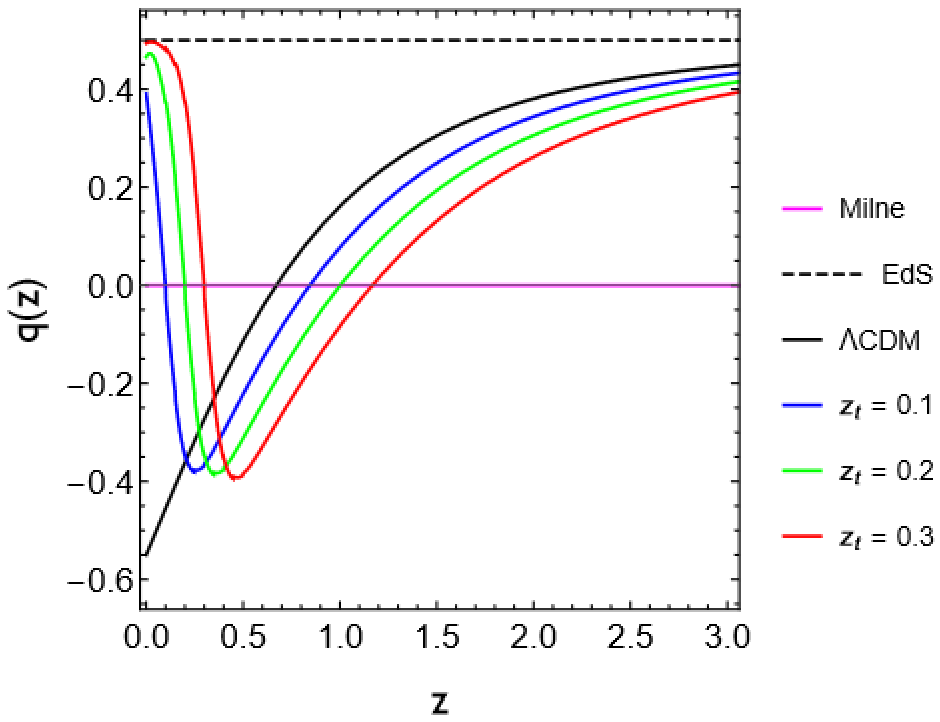
$$w_{\rm DE}(a) = \frac{w_0}{[1 + w_1 \ln(1/a)]^2}.$$

Equação da continuidade:

$$\dot{\rho} = -3H(\rho + p)$$

Parâmetro de desaceleração

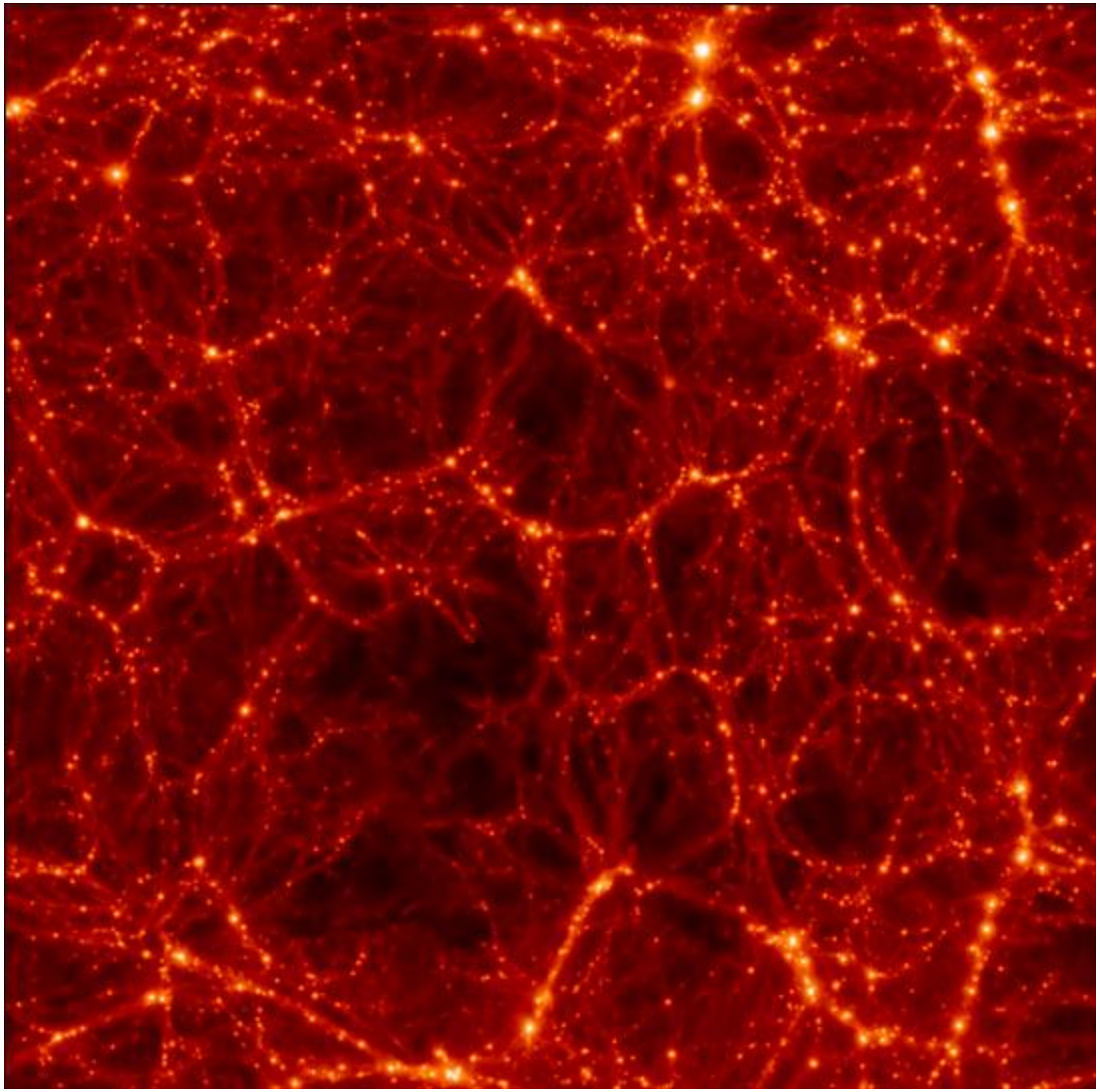
$$q(z) = \frac{H'(z)}{H(z)}(1+z) - 1$$

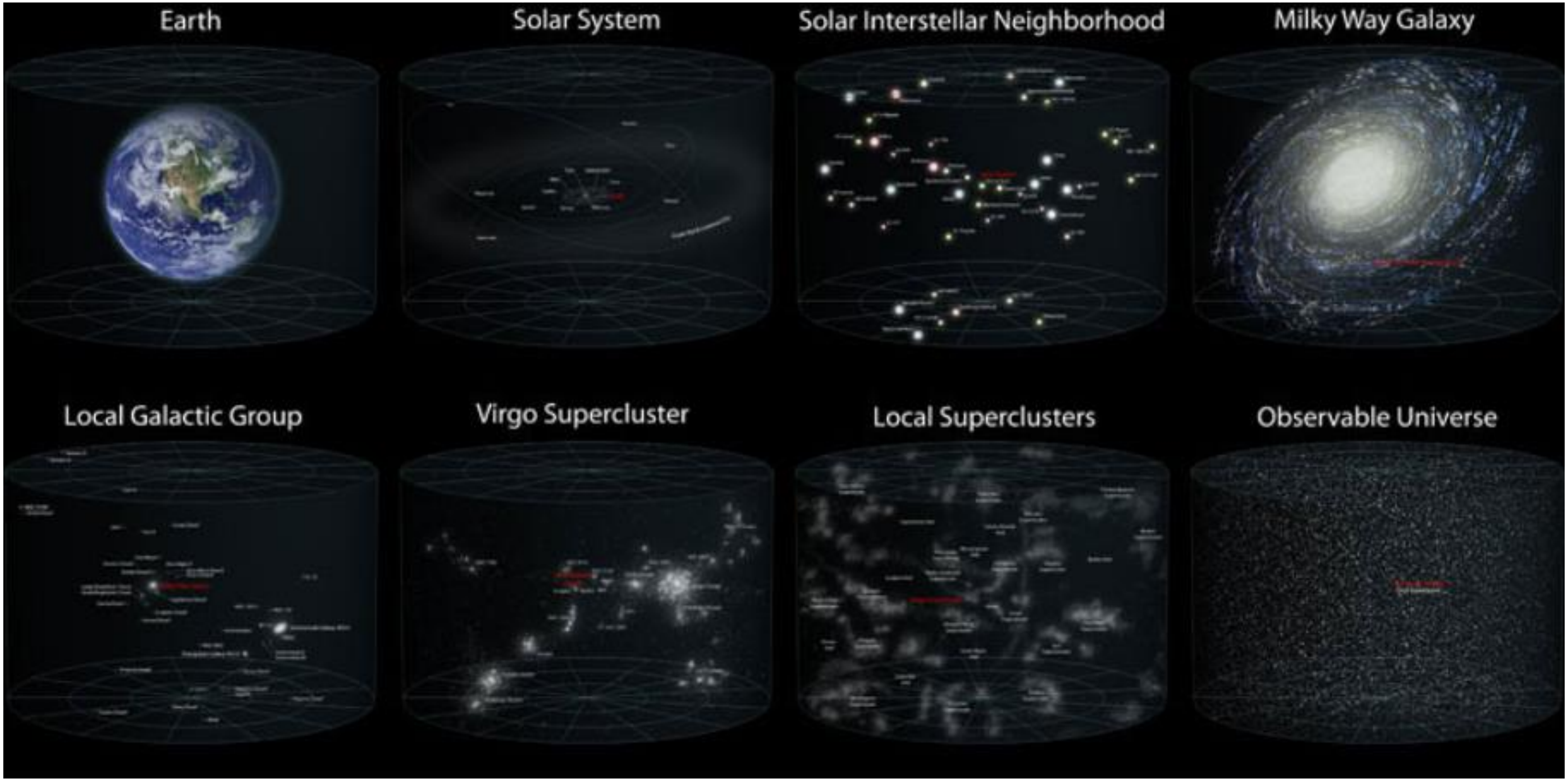


$$w(z) = -\frac{1 + \mathrm{Tanh}[(z - z_t)\Delta]}{2}$$

FIG. 1: Evolution of the deceleration parameter $q(z)$ as a function of the redshift for different models adopted in this work.

Aula III




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

Princípio cosmológico
vs
Escala de homogeneidade do universo

A structure in the early universe at $z \sim 1.3$ that exceeds the homogeneity scale of the R-W concordance cosmology

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Luis E. Campusano,[2] Ilona K. Söchting[3] and Matthew J. Graham[4]
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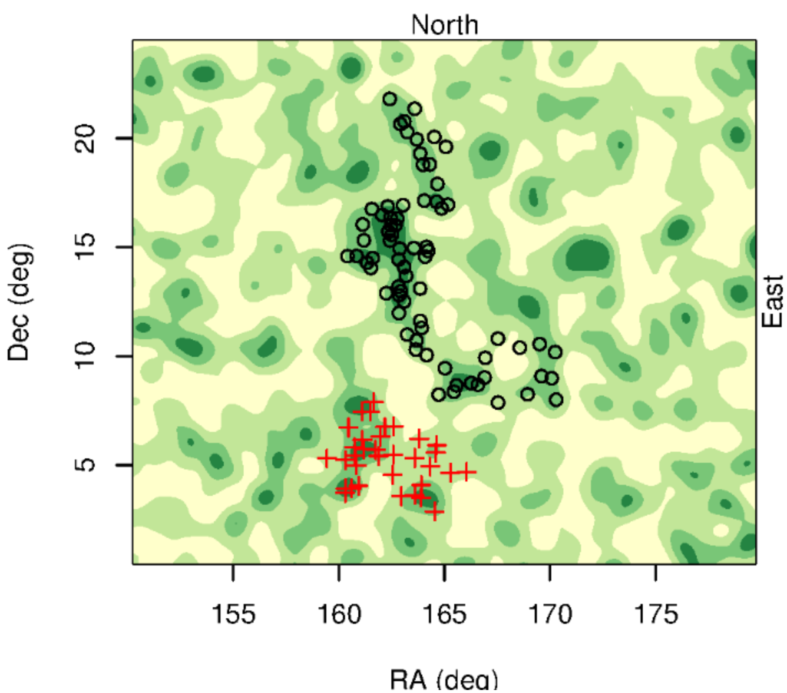
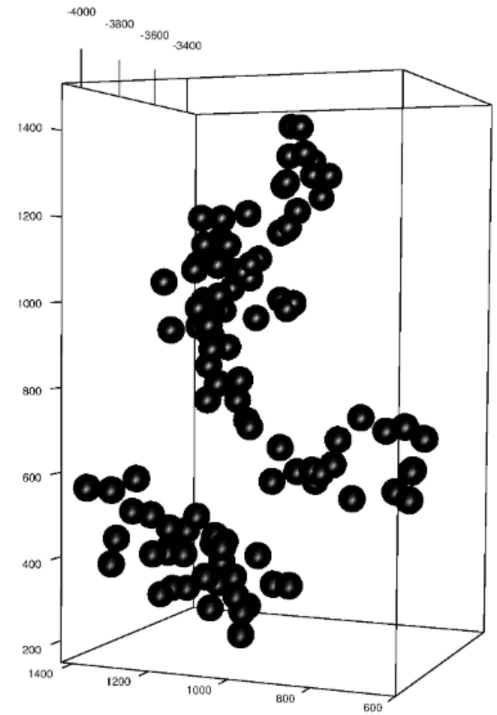
Clowes R. G., Harris K. A., Raghunathan S., Campusano L. E.,
Soechting I. K., Graham M. J., 2013, MNRAS, 429, 2910

ABSTRACT

A Large Quasar Group (LQG) of particularly large size and high membership has been identified in the DR7QSO catalogue of the Sloan Digital Sky Survey. It has characteristic size (volume$^{1/3}$) ~ 500 Mpc (proper size, present epoch), longest dimension ~ 1240 Mpc, membership of 73 quasars, and mean redshift $\bar{z} = 1.27$. In terms of both size and membership it is the most extreme LQG found in the DR7QSO catalogue for the redshift range $1.0 \leqslant z \leqslant 1.8$ of our current investigation. Its location on the sky is $\sim 8.8°$ north (~ 615 Mpc projected) of the Clowes & Campusano LQG at the same redshift, $\bar{z} = 1.28$, which is itself one of the more extreme examples. Their boundaries approach to within $\sim 2°$ (~ 140 Mpc projected). This new, huge LQG appears to be the largest structure currently known in the early universe. Its size suggests incompatibility with the Yadav et al. scale of homogeneity for the concordance cosmology, and thus challenges the assumption of the cosmological principle.





Mon.Not.Roy.Astr.Soc.434:398,2013

Seeing patterns in noise: Gigaparsec-scale 'structures' that do not violate homogeneity

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ABSTRACT
Clowes et al. (2013) have recently reported the discovery of a Large Quasar Group (LQG), dubbed the Huge-LQG, at redshift $z \sim 1.3$ in the Data Release 7 quasar catalogue of the Sloan Digital Sky Survey. On the basis of its characteristic size ~ 500 Mpc and longest dimension > 1 Gpc, it is claimed that this structure is incompatible with large-scale homogeneity and the cosmological principle. If true, this would represent a serious challenge to the standard cosmological model. However, the homogeneity scale is an average property which is not necessarily affected by the discovery of a single large structure. I clarify this point and provide the first fractal dimension analysis of the DR7 quasar catalogue to demonstrate that it is in fact homogeneous above scales of at most $130\,h^{-1}$ Mpc, which is much less than the upper limit for ΛCDM. In addition, I show that the algorithm used to identify the Huge-LQG regularly finds even larger clusters of points, extending over Gpc scales, in explicitly homogeneous simulations of a Poisson point process with the same density as the quasar catalogue. This provides a simple null test to be applied to any cluster thus found in a real catalogue, and suggests that the interpretation of LQGs as 'structures' is misleading.

3 TESTING HOMOGENEITY WITI CATALOGUES

3.1 Fractal analysis

The simplest test of homogeneity that ca set is based on the average of the numbe $N_i(< R)$ contained within a sphere of ra member of the point set, with the requiren lies within the distribution of points:

$$N(< R) = \frac{1}{M} \sum_{i=1}^{M} N_i(< R) \,,$$

where M is the number of sphere centres. For a homogeneous distribution $N(< R) \propto R^D$, where D is the number of dimensions, three in this case. The correlation dimension $D_2(R)$ is calculated as the derivative

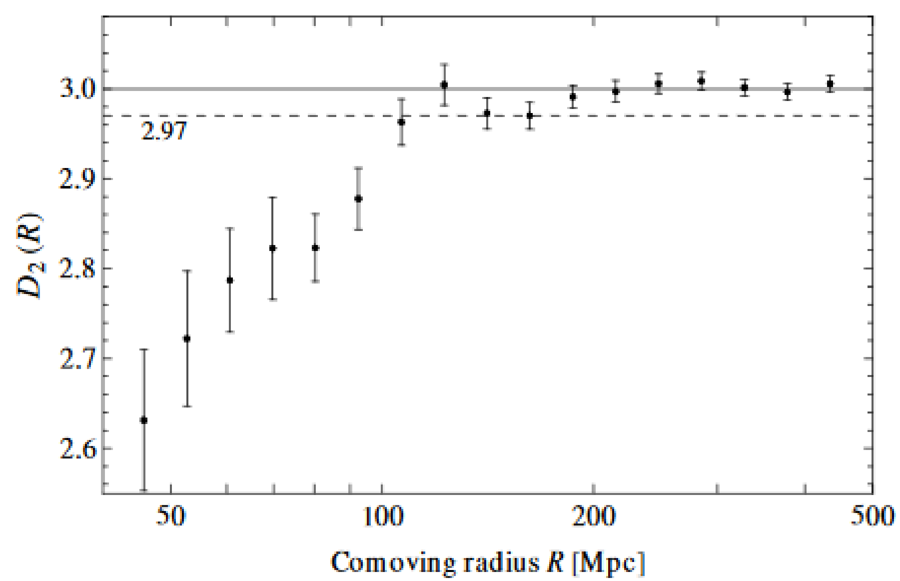
$$D_2(R) = \frac{d \ln N(< R)}{d \ln R} \,, \quad (2)$$

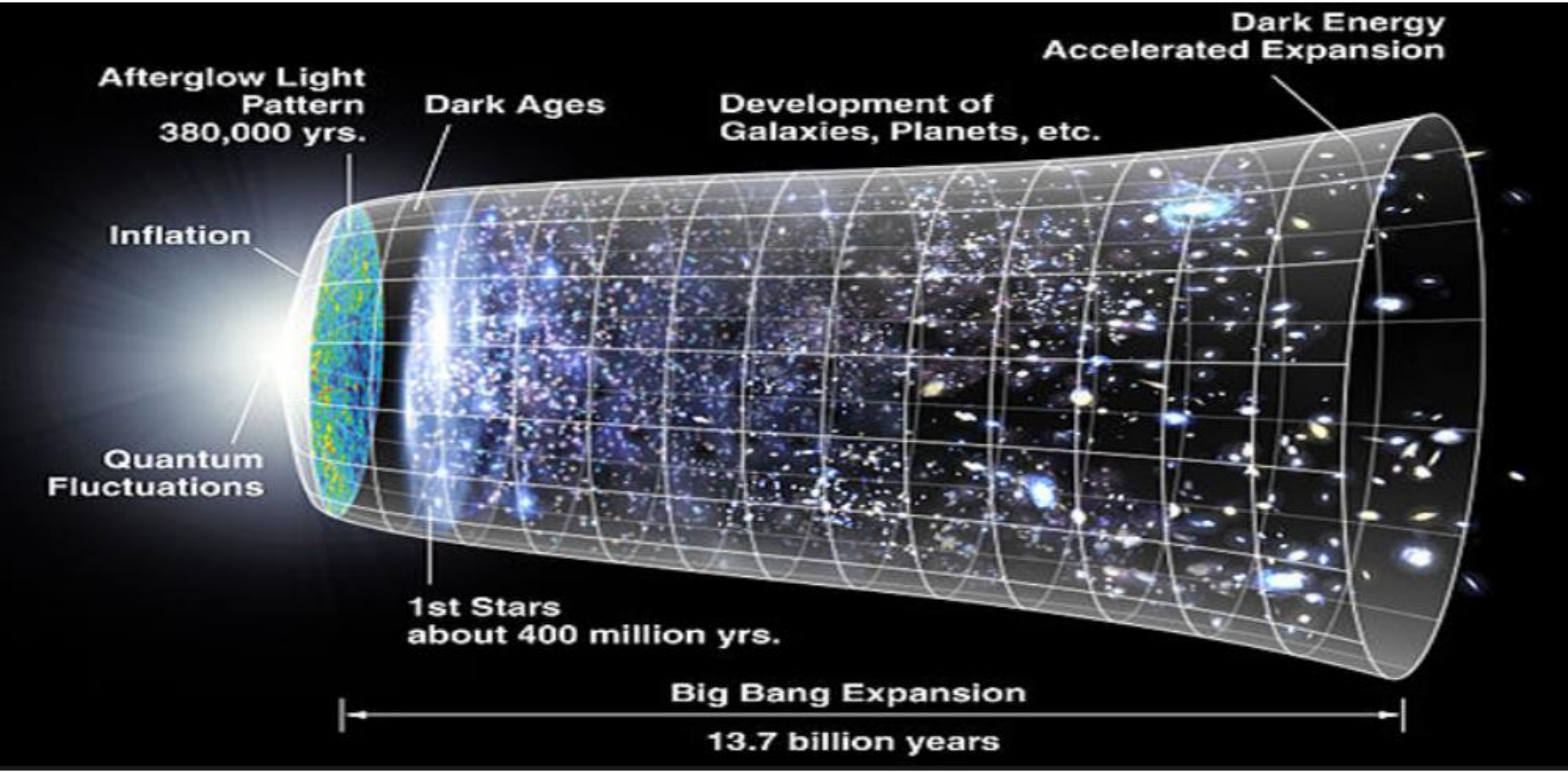
and quantifies the deviation from this homogeneous scaling.

For any given catalogue of objects that trace the matter density of the Universe, $N(< R)$ can be related to the two-point correlation function $\xi(r)$ by

$$N(< R) = \bar{\rho} \int_0^R \left(1 + b^2\xi(r)\right) 4\pi r^2 dr \,, \quad (3)$$

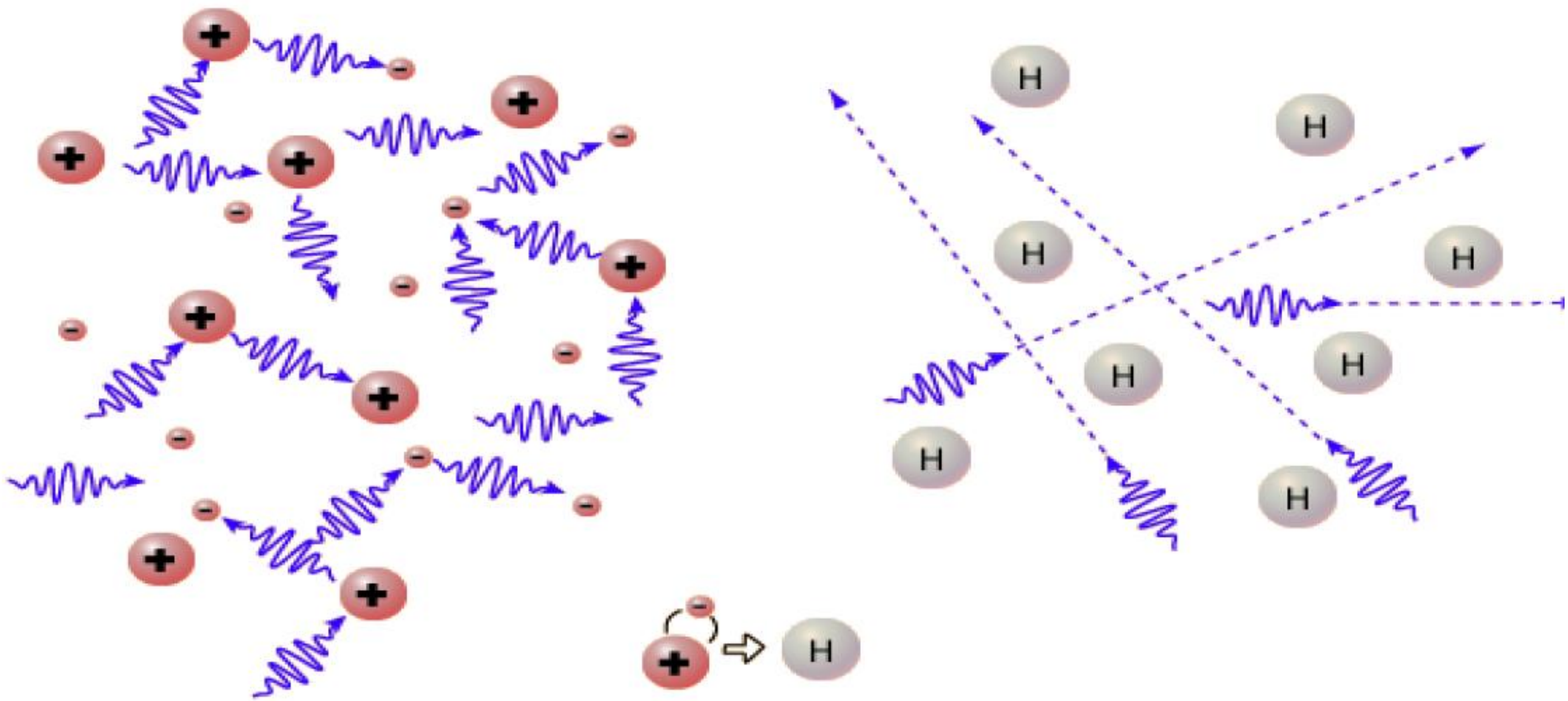
where $\bar{\rho}$ is the mean matter density and b is the bias of the tracer population. Note that the relationship in eq. (3) requires the as-





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

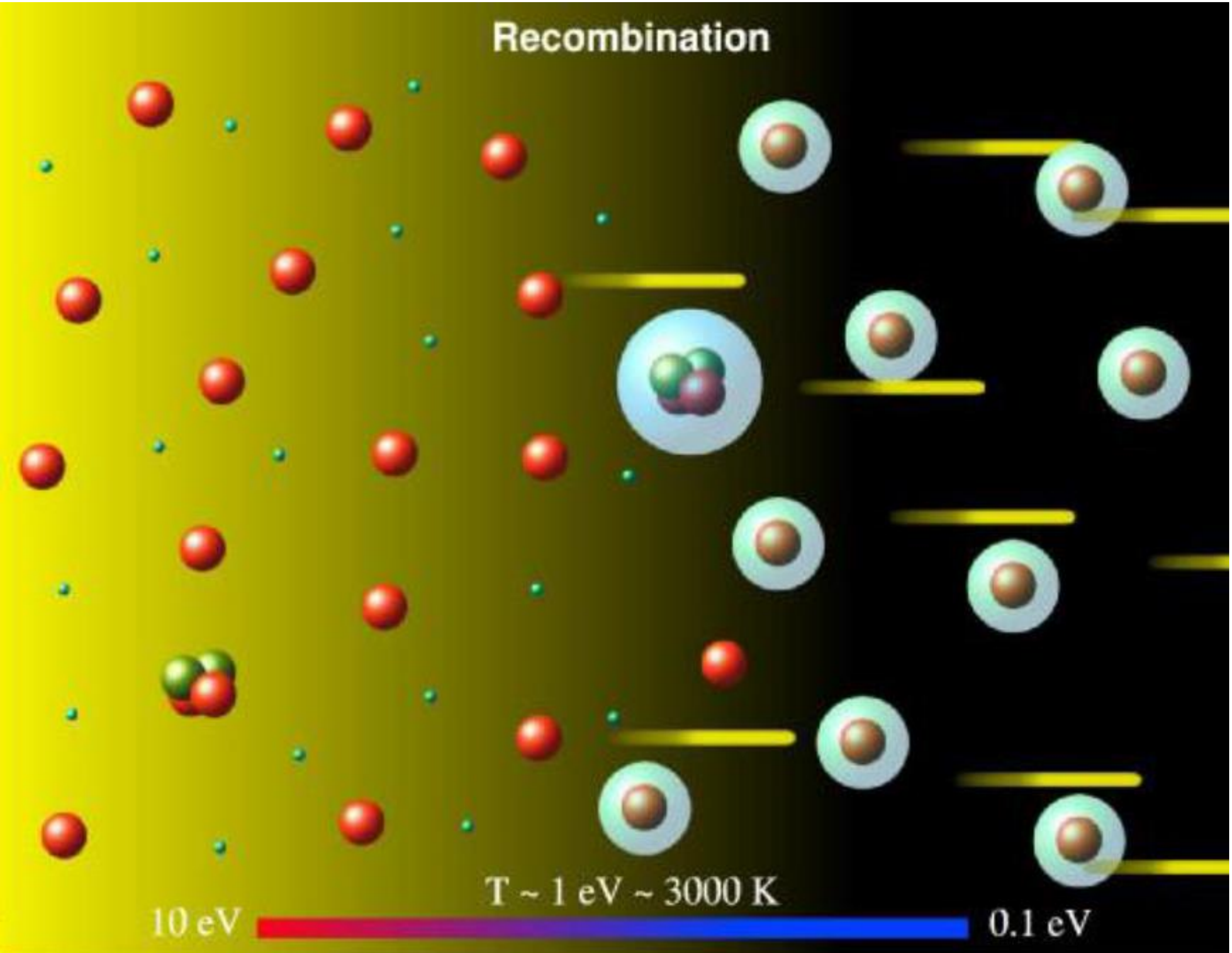
Superfície de último espalhamento

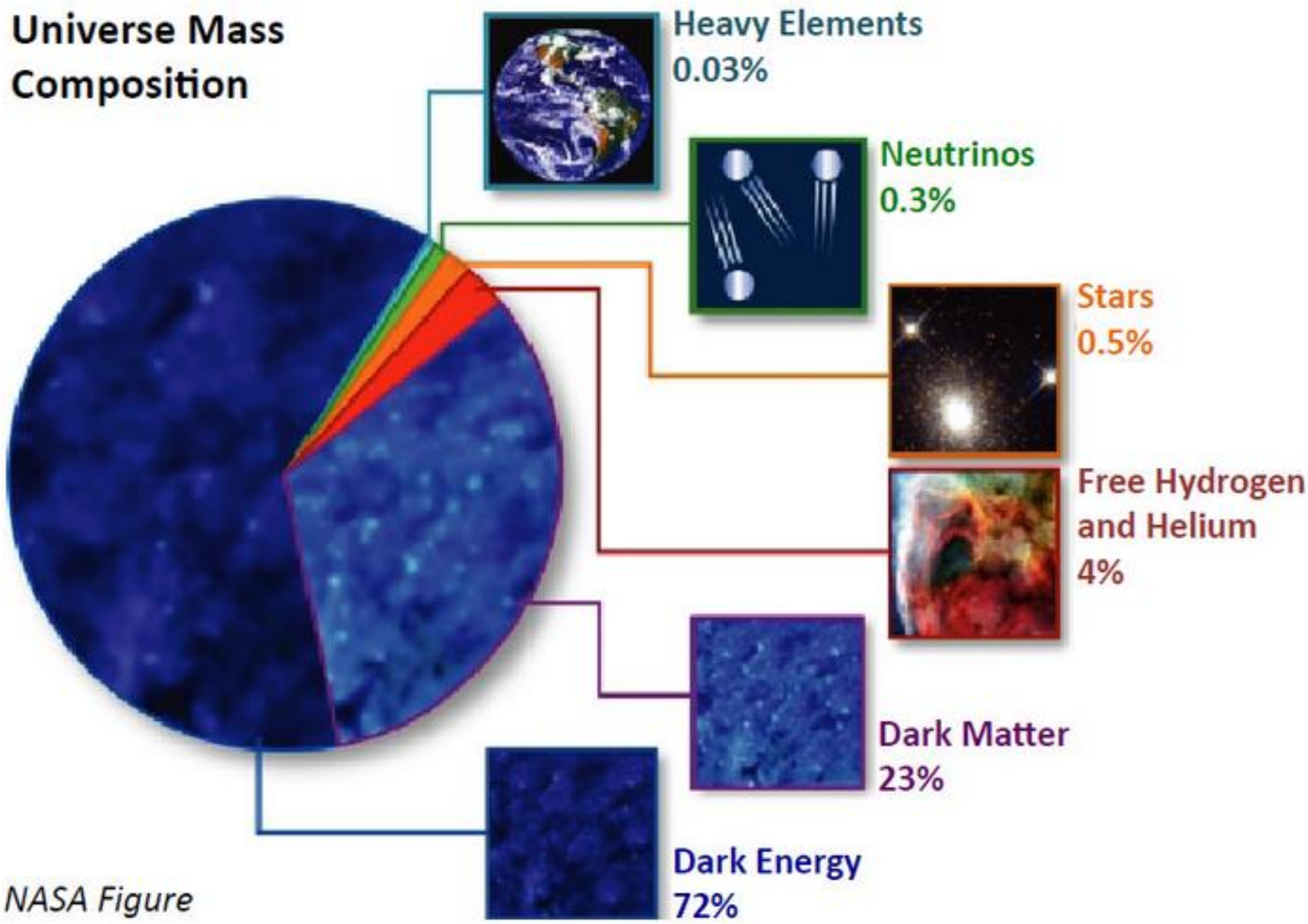


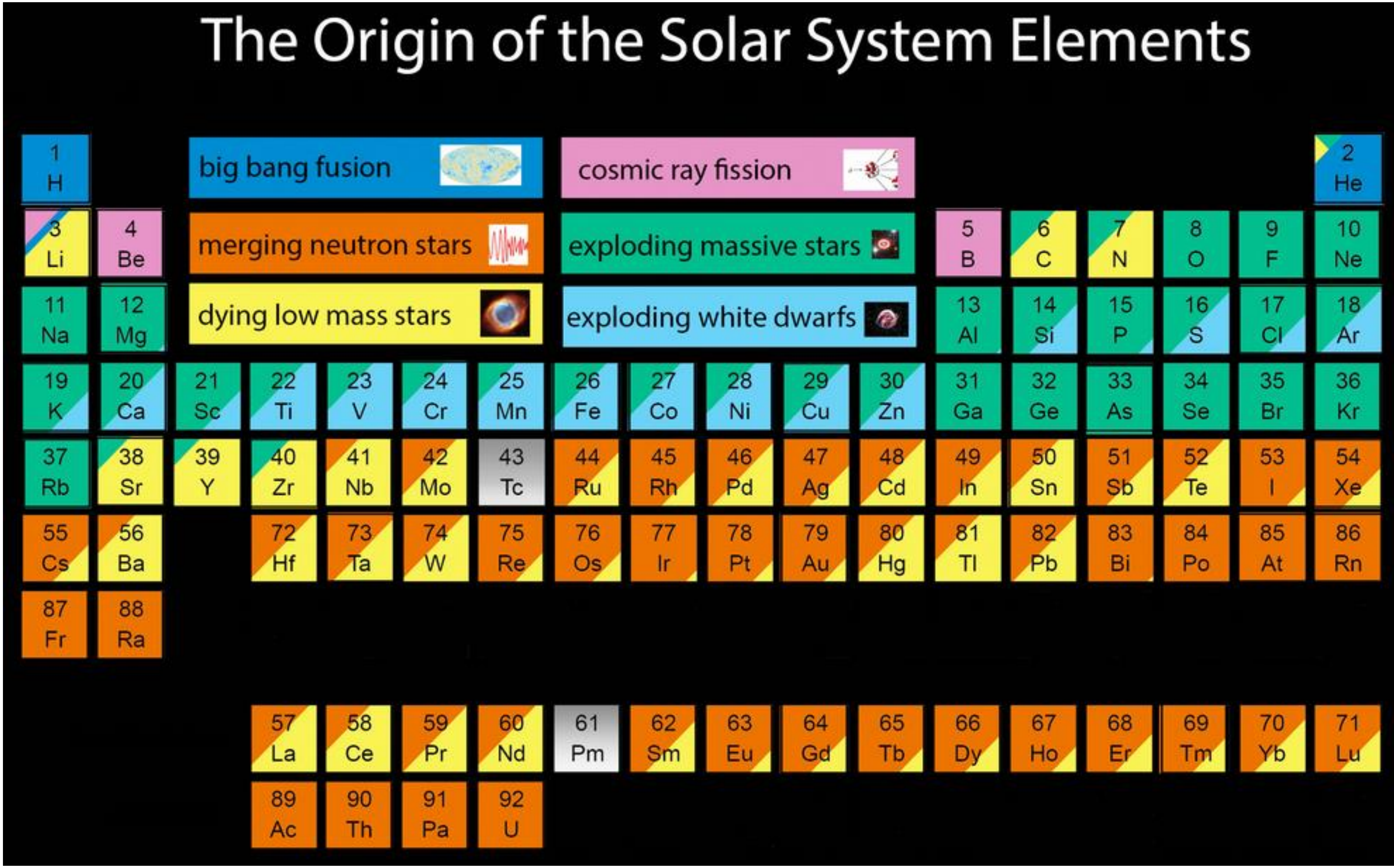
At high temperatures, a hot plasma of charged particles interacts strongly with the radiation. That effectively confines it in the interior of stars and in the early universe.

Below about 3000K, protons and electrons can combine into neutral hydrogen.

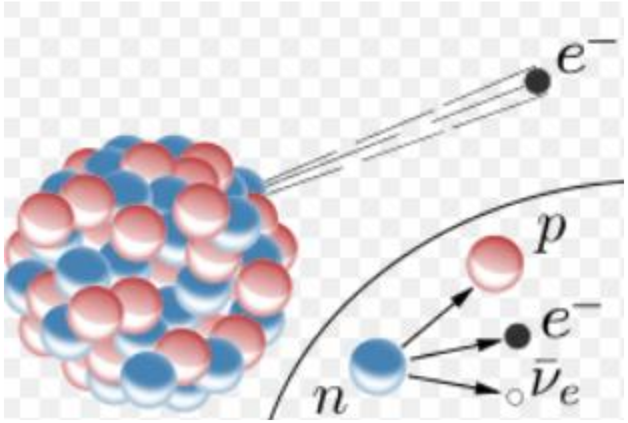
Photons can travel large distances in the neutral hydrogen, so the confinement is effectively broken. Photons can move freely throughout the space.

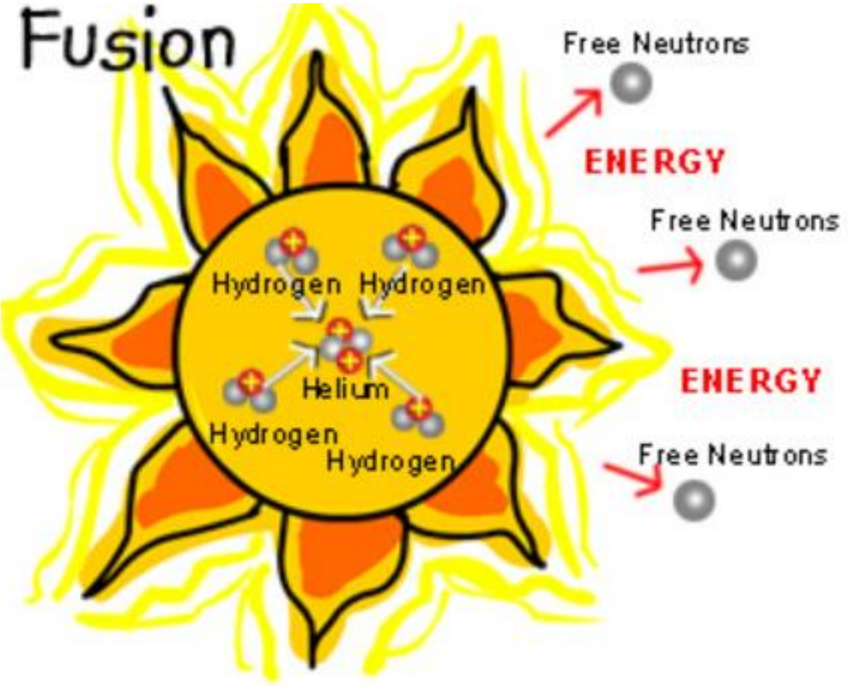

Recombination
T ~ 1 eV ~ 3000 K
10 eV
0.1 eV


Universe Mass Composition
Heavy Elements 0.03%
Neutrinos 0.3%
Stars 0.5%
Free Hydrogen and Helium 4%
Dark Matter 23%
Dark Energy 72%
NASA Figure


The Origin of the Solar System Elements
big bang fusion
cosmic ray fission
merging neutron stars
exploding massive stars
dying low mass stars
exploding white dwarfs
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U

Partículas: Neutrinos





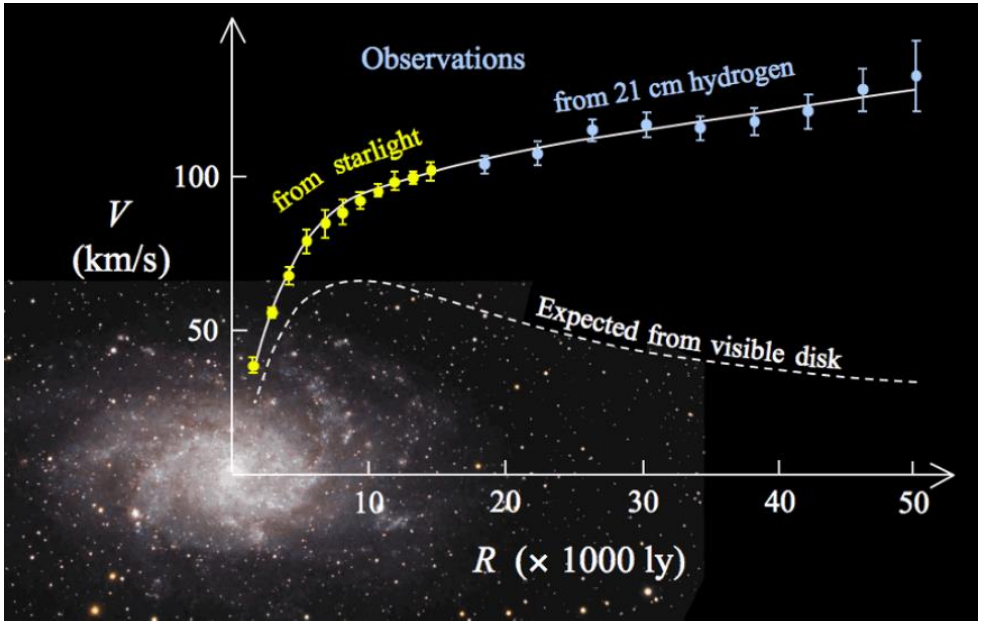
Partículas: Matéria Escura

Fritz Zwicky (~1930)

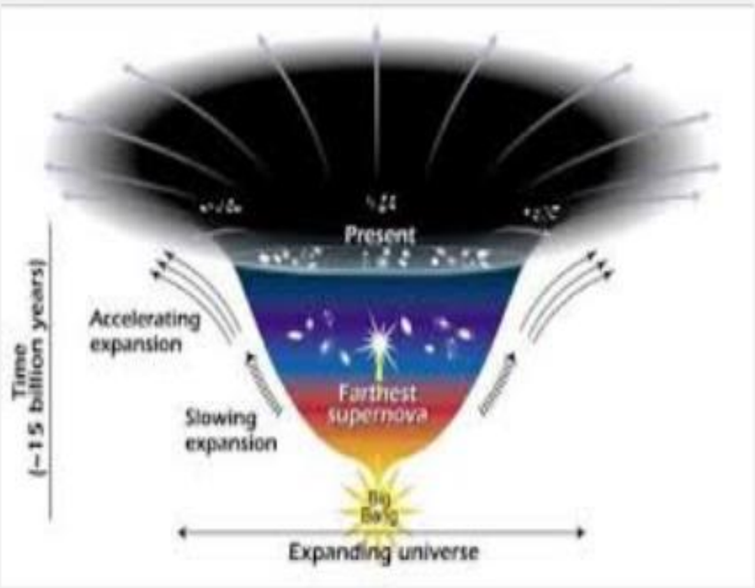
Aglomerados de Galáxias: Mais massa do que se podia ver

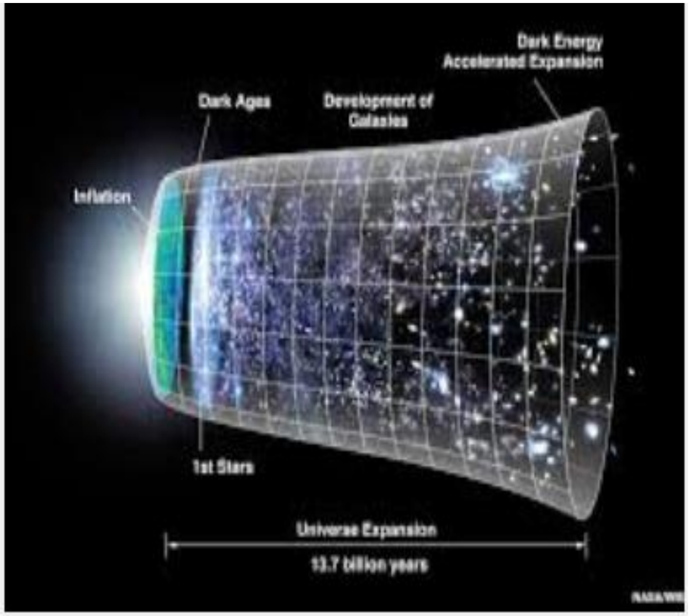
Anos de 1970

Rotação de Galáxias:



Energia: Energia escura





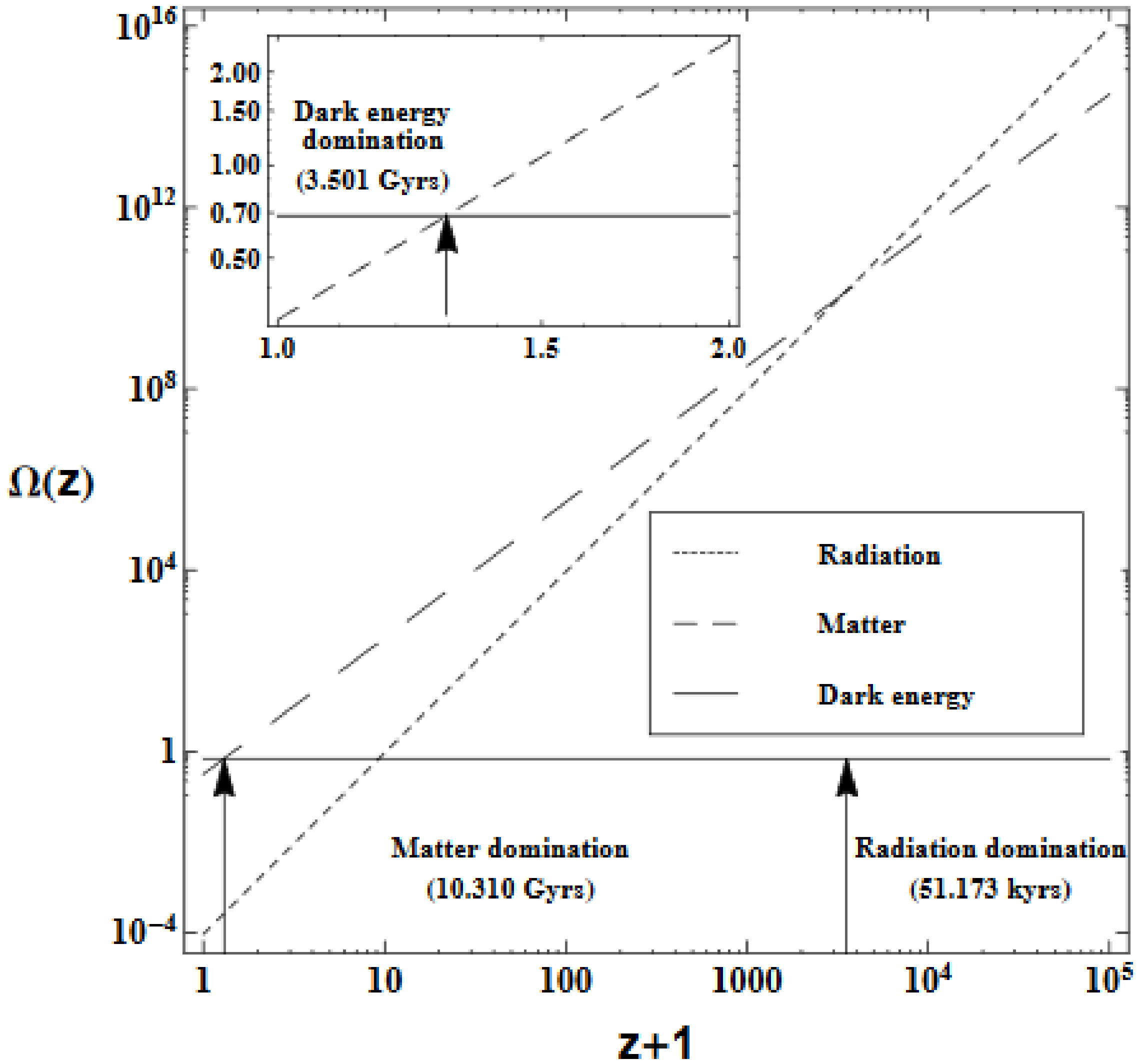
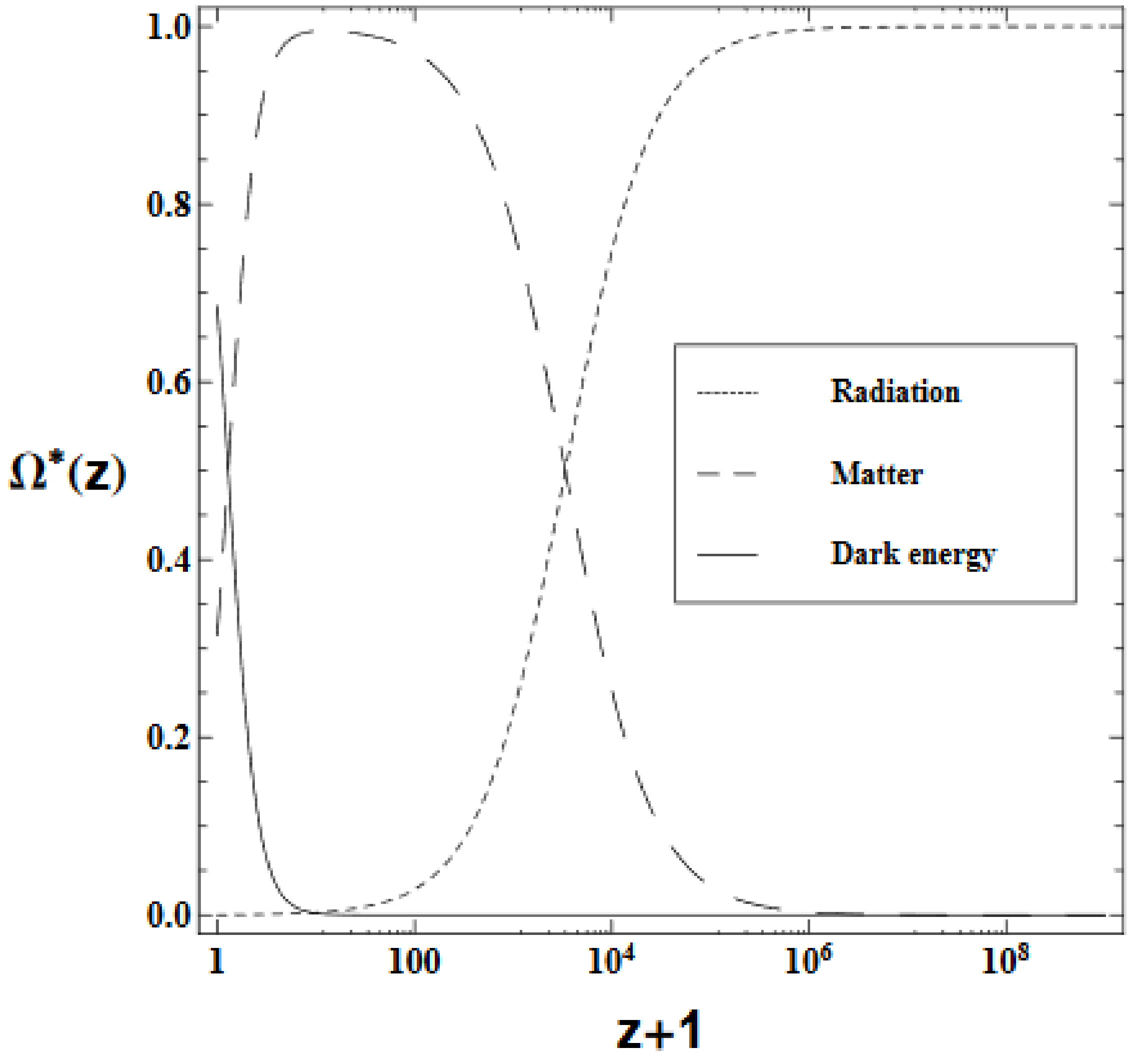


FIG. 1: Evolution of fractionary energy densities Ω as a function of redshift.

$$\Omega_i(z) = \frac{\rho_i(z)}{\rho_{c0}},$$

$$\rho_{c0} = \frac{3}{8\pi G} H_0^2,$$



$$\Omega_i^\star(z) = \frac{\rho_i(z)}{\rho_c(z)},$$

$$\rho_c(z) = \frac{3}{8\pi G} H^2(z)$$

FIG. 2: Evolution of fractionary energy densities $\Omega^\star$ as a function of redshift.

$$\Omega_r^\star(z) + \Omega_m^\star(z) + \Omega_k^\star(z) + \Omega_\Lambda^\star(z) = 1.$$

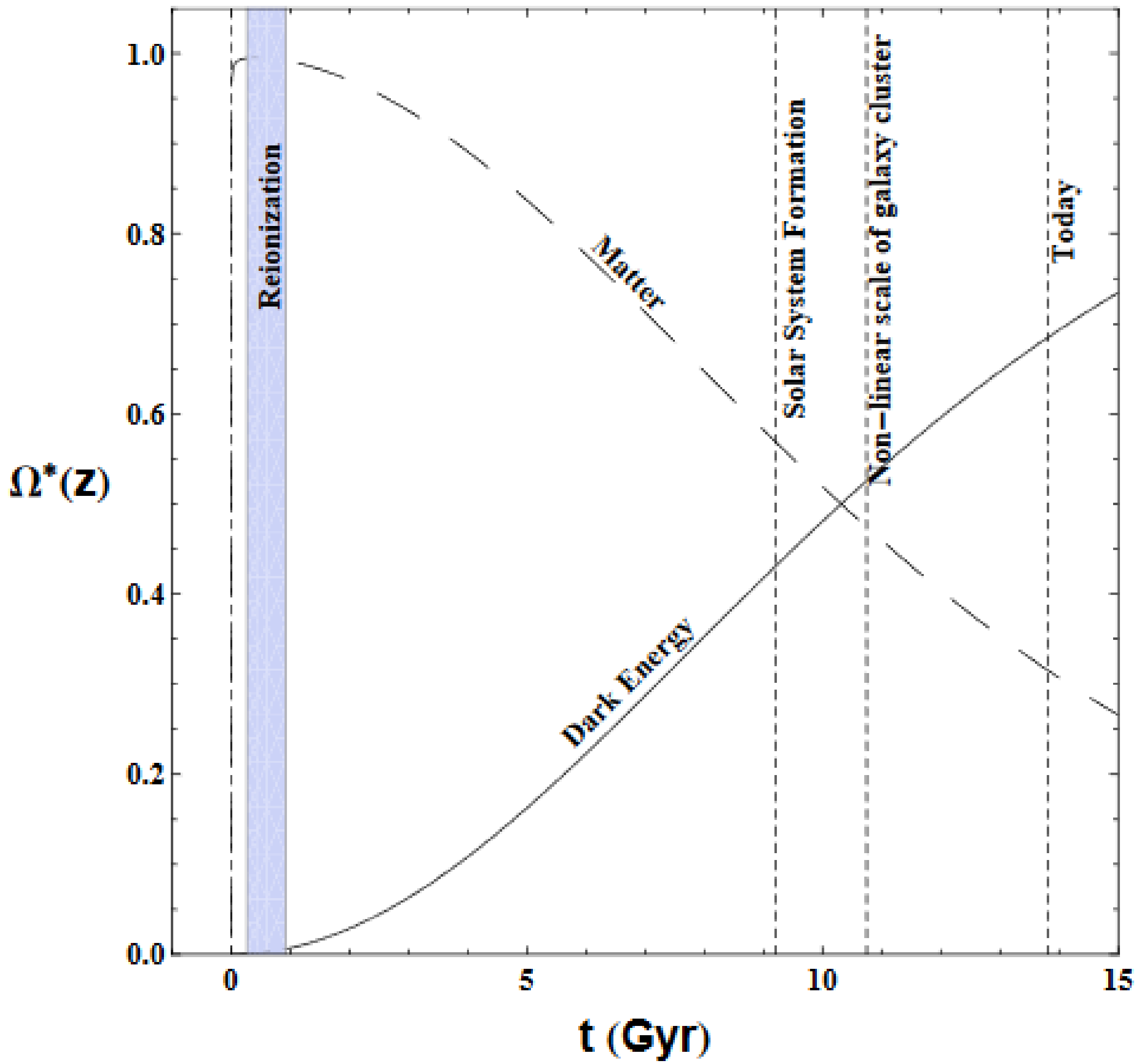


FIG. 3: Evolution of fractionary energy densities as a function of the cosmic time.

$$\int_0^t dt = \int_0^a \frac{da'}{a' H(a')} \, .$$

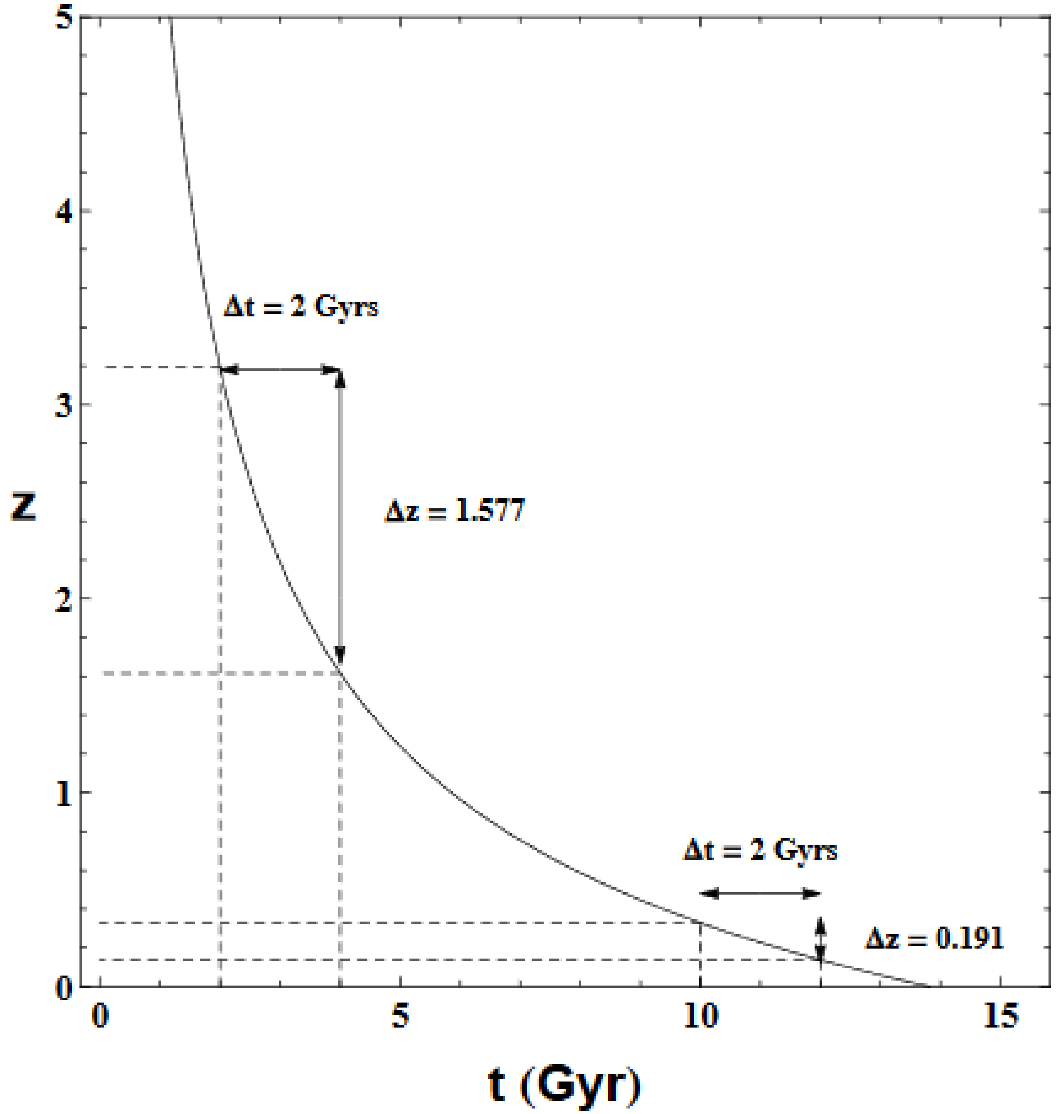


FIG. 4: Variation of the redshift as a function of the cosmic time.

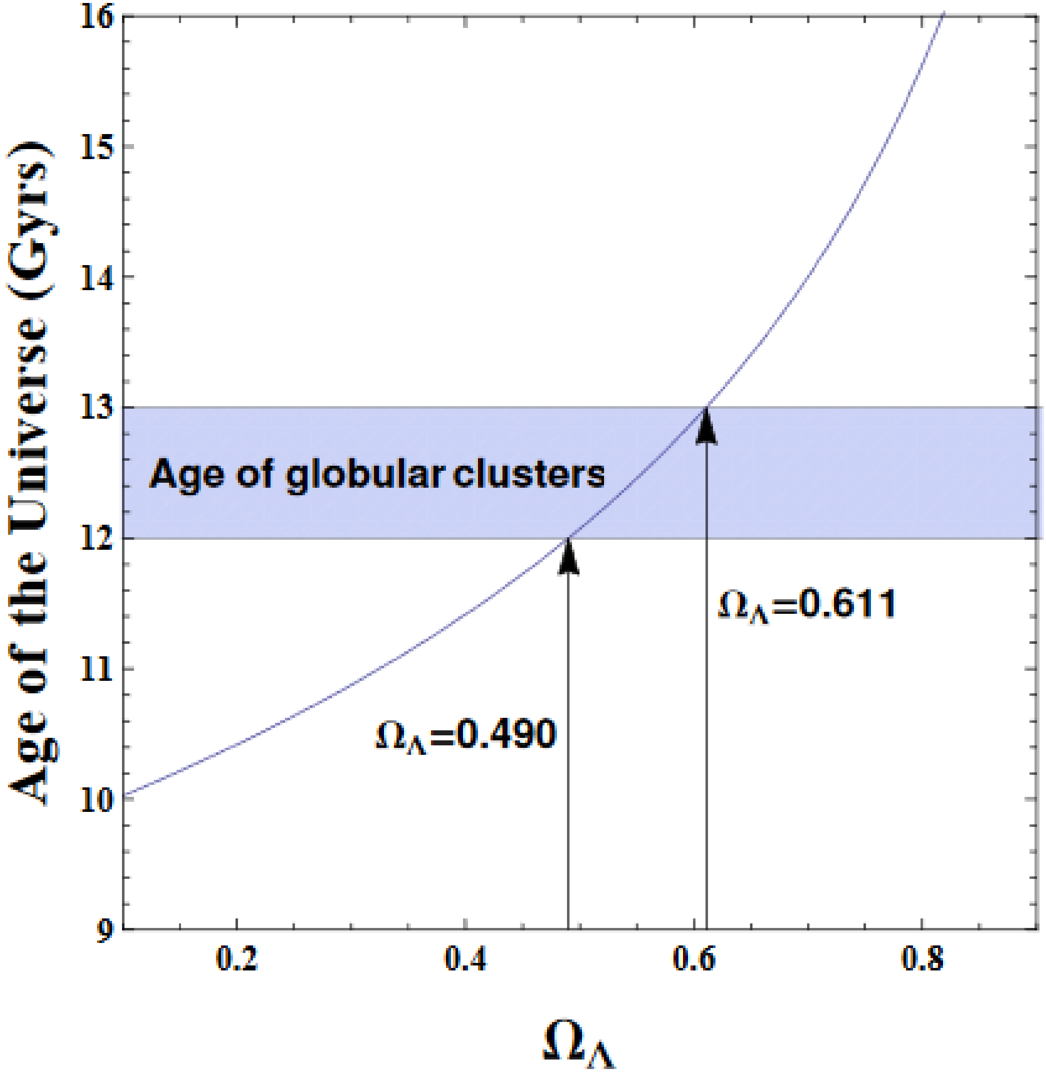
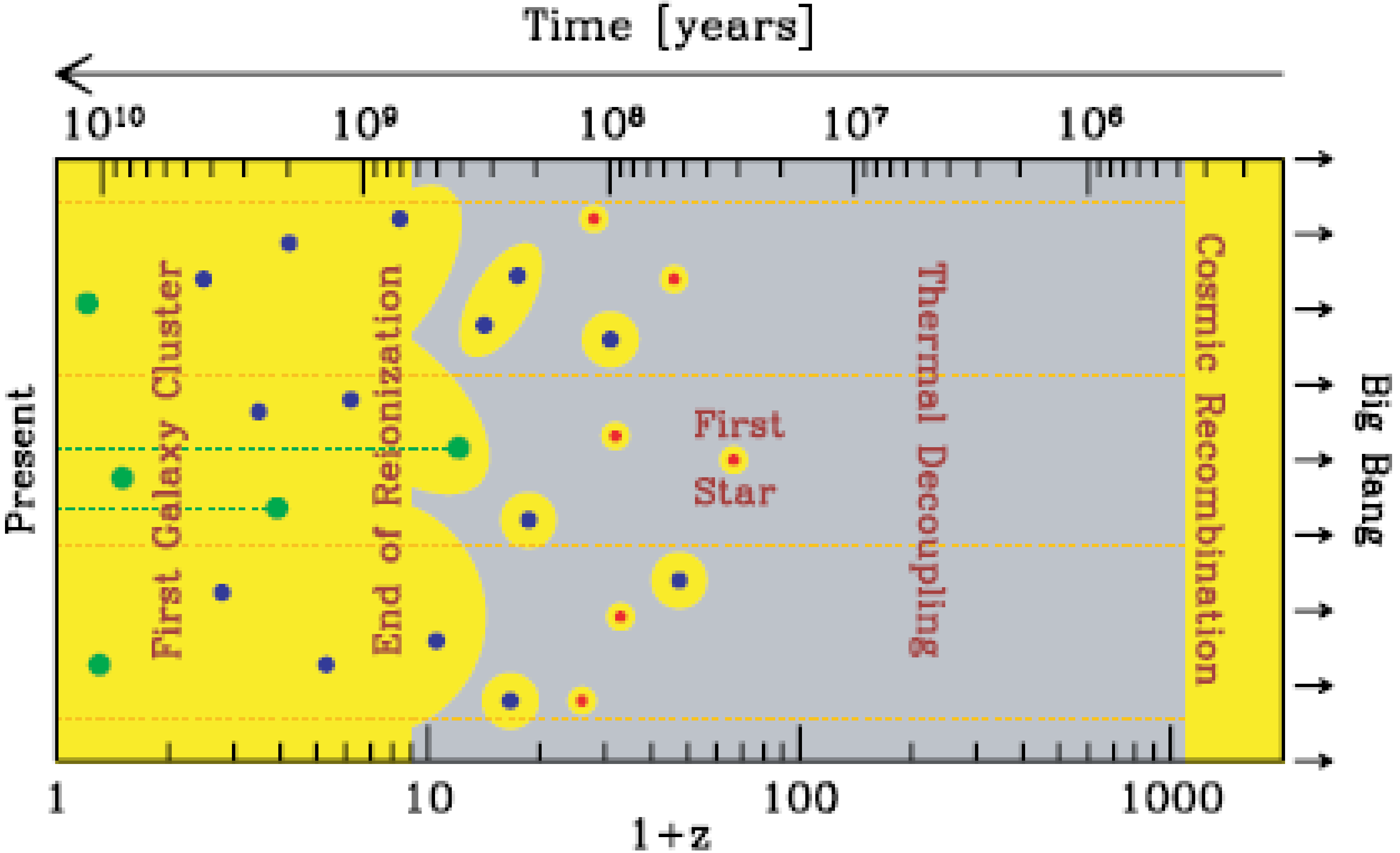
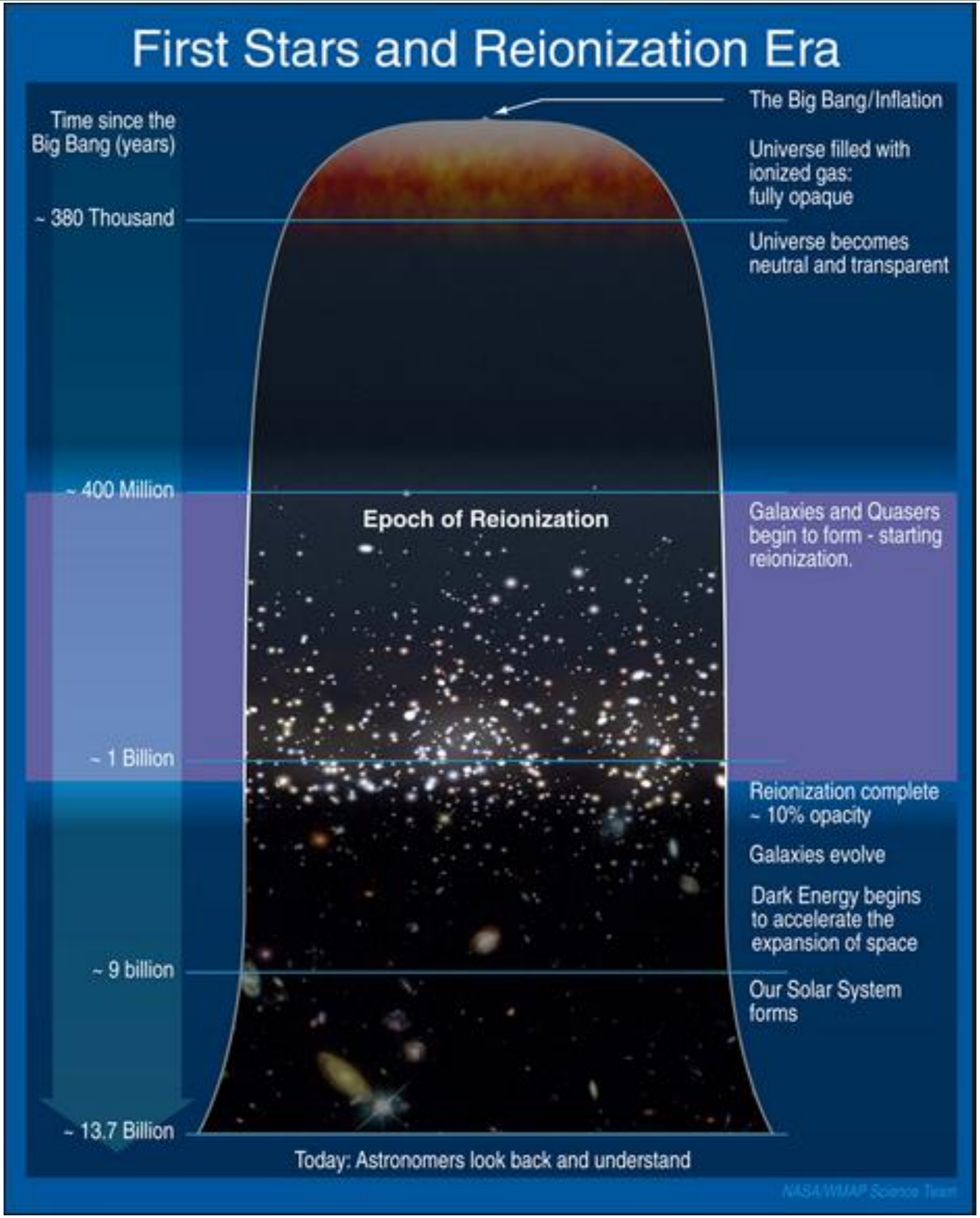
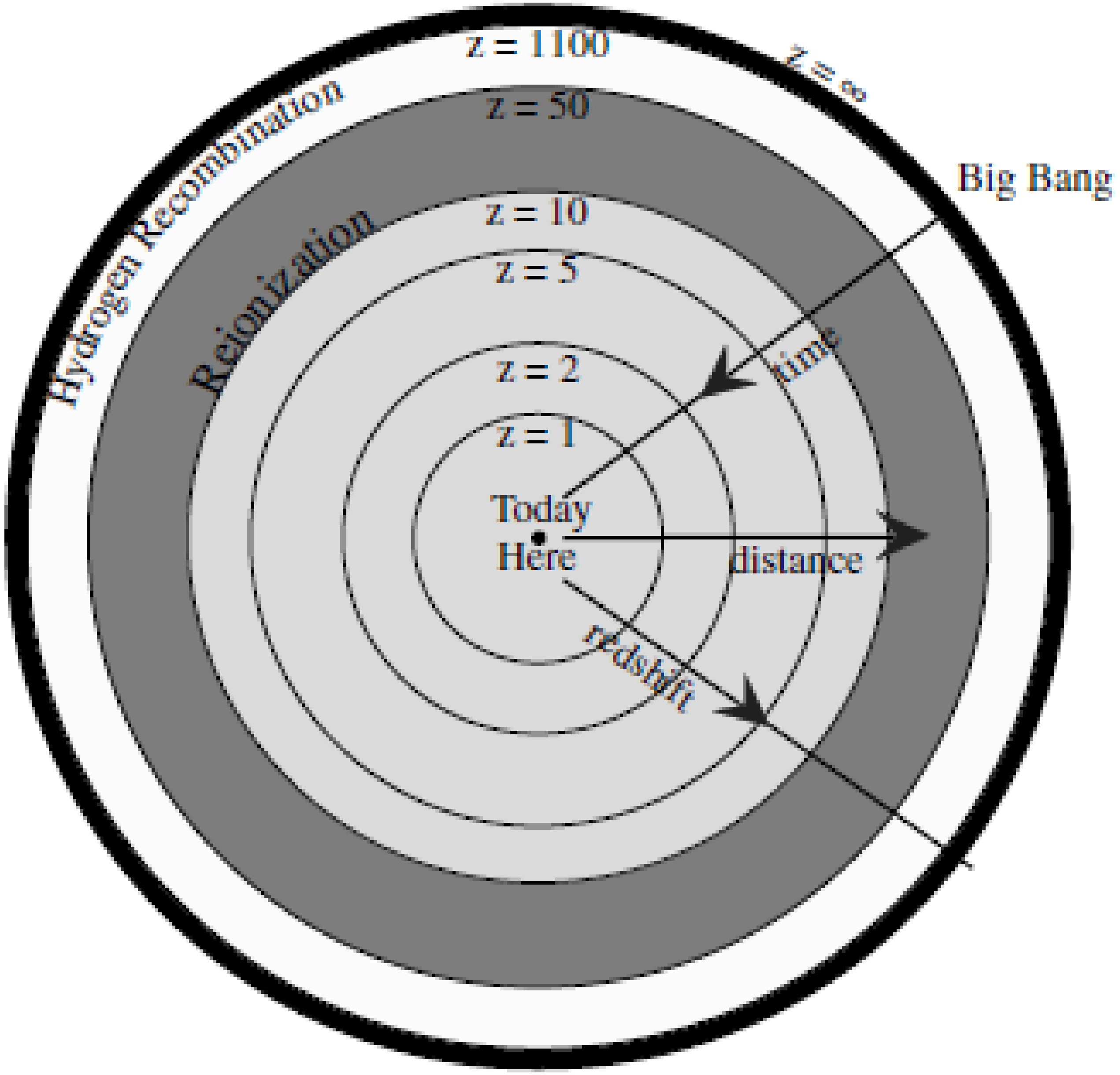


FIG. 6: Age of the Universe as a function of Ω_Λ. The horizontal stripe corresponds to the age of some known globular clusters.

Reionização do hidrogênio cósmico pelas primeiras estrelas



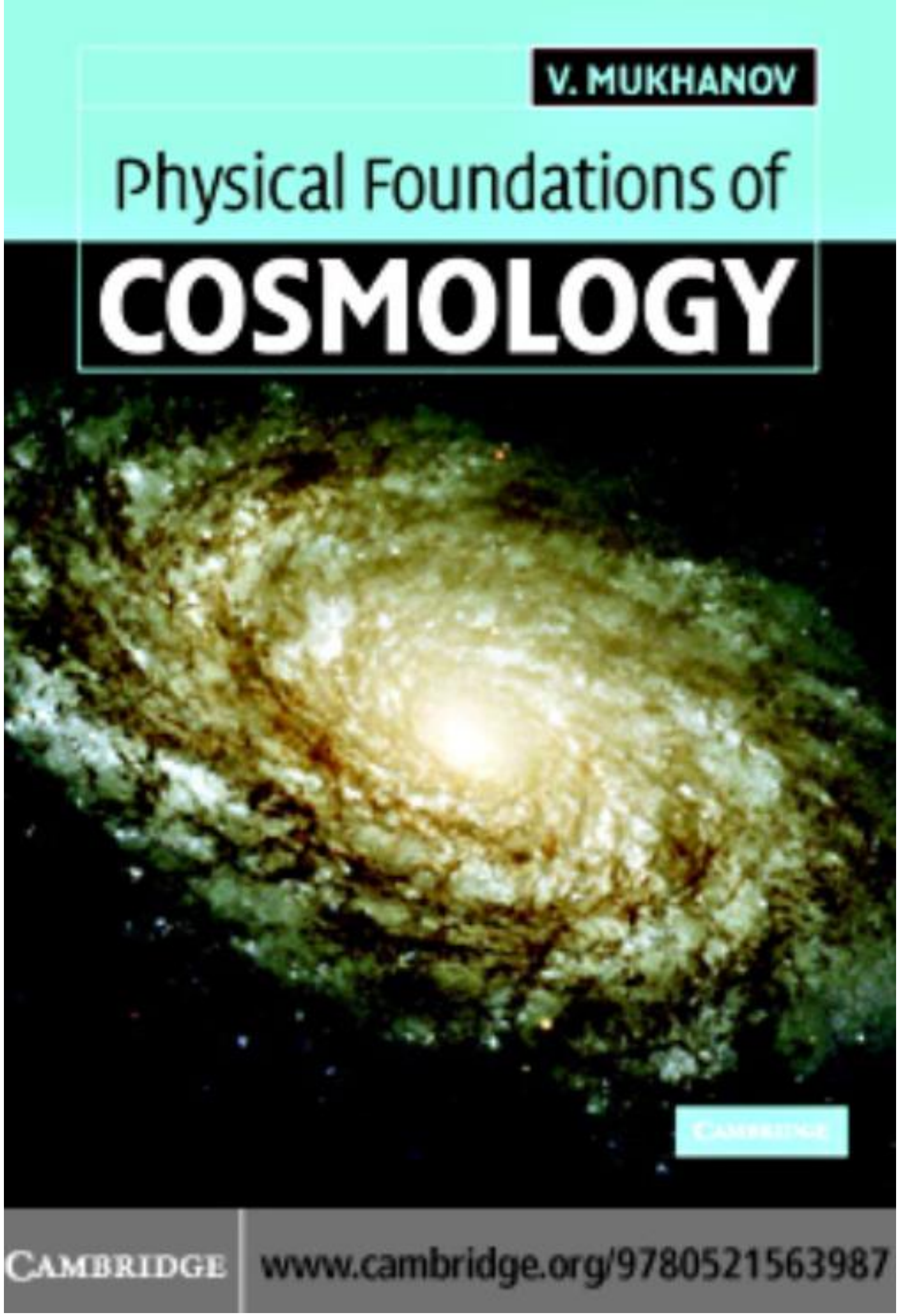

First Stars and Reionization Era
Time since the Big Bang (years)
~ 380 Thousand
~ 400 Million
~ 1 Billion
~ 9 billion
~ 13.7 Billion
The Big Bang/Inflation
Universe filled with ionized gas: fully opaque
Universe becomes neutral and transparent
Epoch of Reionization
Galaxies and Quasars begin to form - starting reionization.
Reionization complete ~ 10% opacity
Galaxies evolve
Dark Energy begins to accelerate the expansion of space
Our Solar System forms
Today: Astronomers look back and understand
NASA/WMAP Science Team



z = 1100
z = ∞
Hydrogen Recombination
z = 50
Big Bang
Reionization
z = 10
z = 5
time
z = 2
z = 1
Today
Here
distance
redshift

Aula IV

- Entender como pequenas perturbações existentes na distribuição quase homogênea de densidade de matéria no universo primordial evoluem até o ponto de formar uma estrutura como galáxias e aglomerados de galáxias.


V. MUKHANOV
Physical Foundations of
COSMOLOGY
CAMBRIDGE
www.cambridge.org/9780521563987

Perturbações cosmológicas

- 1) Perturbações Newtonianas
- 1.a) Modos escalares (Foco dos próximos slides)
- 1.b) Modos vetoriais

- 2) Perturbações relativísticas
- 2.a) Modos escalares
- 2.b) Modos vetoriais
- 2.c) Modos tensoriais -> Ondas gravitacionais

Continuity equation If we consider a *fixed volume element* ΔV in Euler (noncomoving) coordinates $\mathbf{x}$, then the rate of change of its mass can be written as

$$\frac{dM(t)}{dt} = \int\limits_{\Delta V} \frac{\partial \varepsilon(\mathbf{x}, t)}{\partial t} dV. \tag{6.1}$$

On the other hand, this rate is entirely determined by the flux of matter through the surface surrounding the volume:

$$\frac{dM(t)}{dt} = -\oint \varepsilon \mathbf{V} \cdot d\boldsymbol{\sigma} = -\int\limits_{\Delta V} \nabla(\varepsilon \mathbf{V})\, dV. \tag{6.2}$$

These two expressions are consistent only if

$$\frac{\partial \varepsilon}{\partial t} + \nabla(\varepsilon \mathbf{V}) = 0. \tag{6.3}$$

Euler equations The acceleration $\mathbf{g}$ of a small *matter element* of mass ΔM is determined by the gravitational force

$$\mathbf{F}_{gr} = -\Delta M \cdot \nabla\phi, \tag{6.4}$$

where ϕ is the gravitational potential, and by the pressure p:

$$\mathbf{F}_{pr} = -\oint p \cdot d\sigma = -\int_{\Delta V} \nabla p dV \simeq -\nabla p \cdot \Delta V. \tag{6.5}$$

With

$$\mathbf{g} \equiv \frac{d\mathbf{V}(\mathbf{x}(t)\,,t)}{dt} = \left(\frac{\partial \mathbf{V}}{\partial t}\right)_x + \frac{dx^i(t)}{dt}\left(\frac{\partial \mathbf{V}}{\partial x^i}\right) = \frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \boldsymbol{\nabla})\,\mathbf{V}, \tag{6.6}$$

Newton's force law

$$\Delta M \cdot \mathbf{g} = \mathbf{F}_{gr} + \mathbf{F}_{pr} \tag{6.7}$$

becomes the Euler equations

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \boldsymbol{\nabla})\,\mathbf{V} + \frac{\nabla p}{\varepsilon} + \nabla\phi = 0. \tag{6.8}$$

Conservation of entropy Neglecting dissipation, the entropy of a *matter element* is conserved:

$$\frac{dS(\mathbf{x}(t),t)}{dt} = \frac{\partial S}{\partial t} + (\mathbf{V}\cdot\nabla)\,S = 0. \tag{6.9}$$

Poisson equation Finally, the equation which determines the gravitational potential is the well known Poisson equation,

$$\Delta\phi = 4\pi G\varepsilon. \tag{6.10}$$

Equations (6.3), (6.8)–(6.10), taken together with the equation of state

$$p = p(\varepsilon, S)\,, \tag{6.11}$$

form a complete set of seven equations which, in principle, allows us to determine the seven unknown functions ε, $\mathbf{V}$, S, ϕ, p. Note that only the first five equations contain first time derivatives. Hence the most general solution of these equations should depend on five constants of integration which in our case are five arbitrary functions of the spatial coordinates $\mathbf{x}$. The hydrodynamical equations are nonlinear and in general it is not easy to find their solutions. However, to study the behavior of *small* perturbations around a homogeneous, isotropic background, it is appropriate to linearize them.

6.2 Jeans theory

Let us first consider a static nonexpanding universe, assuming the homogeneous, isotropic background with constant, time-independent matter density: $\varepsilon_0(t, \mathbf{x}) =$ const. This assumption is in obvious contradiction with the hydrodynamical equations. In fact, the energy density remains unchanged only if the matter is at rest and the gravitational force, $F \propto \nabla\phi$, vanishes. But then the Poisson equation $\Delta\phi = 4\pi G\varepsilon_0$ is not satisfied. This inconsistency can, in principle, be avoided if we consider a static Einstein universe, where the gravitational force of the matter is compensated by the "antigravitational" force of an appropriately chosen cosmological constant.

Slightly disturbing the matter distribution, we have:

$$\begin{aligned} &\varepsilon(\mathbf{x}, t) = \varepsilon_0 + \delta\varepsilon(\mathbf{x}, t), \quad \mathbf{V}(\mathbf{x}, \mathbf{t}) = \mathbf{V}_0 + \delta\mathbf{v} = \delta\mathbf{v}(\mathbf{x}, \mathbf{t}), \\ &\phi(\mathbf{x}, t) = \phi_0 + \delta\phi(\mathbf{x}, t), \quad S(\mathbf{x}, t) = S_0 + \delta S(\mathbf{x}, t), \end{aligned} \tag{6.12}$$

where $\delta\varepsilon \ll \varepsilon_0$, etc. The pressure is equal to

$$p(\mathbf{x}, t) = p(\varepsilon_0 + \delta\varepsilon, S_0 + \delta S) = p_0 + \delta p(\mathbf{x}, t), \tag{6.13}$$

and in linear approximation its perturbation δp can be expressed in terms of the energy density and entropy perturbations as

$$\delta p = c_s^2 \delta\varepsilon + \sigma \delta S. \tag{6.14}$$

Here $c_s^2 \equiv (\partial p/\partial\varepsilon)_S$ is the square of the speed of sound and $\sigma \equiv (\partial p/\partial S)_\varepsilon$. For nonrelativistic matter ($p \ll \varepsilon$), the speed of sound as well as the velocities $\delta\mathbf{v}$ are much less than the speed of light.

Substituting (6.12) and (6.14) into (6.3), (6.8)–(6.10) and keeping only the terms which are linear in the perturbations, we obtain:

$$\frac{\partial\delta\varepsilon}{\partial t} + \varepsilon_0 \nabla(\delta\mathbf{v}) = 0, \tag{6.15}$$

$$\frac{\partial\delta\mathbf{v}}{\partial t} + \frac{c_s^2}{\varepsilon_0}\nabla\delta\varepsilon + \frac{\sigma}{\varepsilon_0}\nabla\delta S + \nabla\delta\phi = 0, \tag{6.16}$$

$$\frac{\partial\delta S}{\partial t} = 0, \tag{6.17}$$

$$\Delta\delta\phi = 4\pi G\delta\varepsilon. \tag{6.18}$$

Equation (6.17) has a simple general solution

$$\delta S(\mathbf{x}, t) = \delta S(\mathbf{x}), \tag{6.19}$$

which states that the entropy is an arbitrary time-independent function of the spatial coordinates.

Taking the divergence of (6.16) and using the continuity and Poisson equations to express $\nabla \delta \mathbf{v}$ and $\Delta \delta \phi$ in terms of $\delta \varepsilon$, we obtain

$$\frac{\partial^2 \delta \varepsilon}{\partial t^2} - c_s^2 \Delta \delta \varepsilon - 4\pi G \varepsilon_0 \delta \varepsilon = \sigma \Delta \delta S(\mathbf{x}). \tag{6.20}$$

This is a closed, linear equation for $\delta \varepsilon$, where the entropy perturbation serves as a given source.

6.2.1 Adiabatic perturbations

First we will assume that entropy perturbations are absent, that is, $\delta S = 0$. The coefficients in (6.20) do not depend on the spatial coordinates, so upon taking the Fourier transform,

$$\delta \varepsilon(\mathbf{x}, t) = \int \delta \varepsilon_{\mathbf{k}}(t) \exp(i\mathbf{k}\mathbf{x}) \frac{d^3 k}{(2\pi)^{3/2}}, \tag{6.21}$$

we obtain a set of independent ordinary differential equations for the time-dependent Fourier coefficients $\delta \varepsilon_{\mathbf{k}}(t)$:

$$\delta \ddot{\varepsilon}_{\mathbf{k}} + \left(k^2 c_s^2 - 4\pi G \varepsilon_0\right) \delta \varepsilon_{\mathbf{k}} = 0, \tag{6.22}$$

where a dot denotes the derivative with respect to time t and $k = |\mathbf{k}|$.

Equation (6.22) has two independent solutions

$$\delta\varepsilon_{\mathbf{k}} \propto \exp(\pm i\omega(k)\,t), \tag{6.23}$$

where

$$\omega(k) = \sqrt{k^2 c_s^2 - 4\pi G\varepsilon_0}.$$

The behavior of these so-called adiabatic perturbations depends crucially on the sign of the expression under the square root. Defining the Jeans length as

$$\lambda_J = \frac{2\pi}{k_J} = c_s\left(\frac{\pi}{G\varepsilon_0}\right)^{1/2}, \tag{6.24}$$

so that $\omega(k_J) = 0$, we conclude that if $\lambda < \lambda_J$, the solutions describe sound waves

$$\delta\varepsilon \propto \sin(\omega t + \mathbf{kx} + \alpha), \tag{6.25}$$

propagating with phase velocity

$$c_{phase} = \frac{\omega}{k} = c_s\sqrt{1 - \frac{k_J^2}{k^2}}. \tag{6.26}$$

In the limit $k \gg k_J$, or on very small scales $(\lambda \ll \lambda_J)$ where gravity is negligible compared to the pressure, we have $c_{phase} \to c_s$, as it should be.

On large scales gravity dominates and if $\lambda > \lambda_J$, we have

$$\delta\varepsilon_{\mathbf{k}} \propto \exp(\pm |\omega| t) . \tag{6.27}$$

One of these solutions describes the exponentially fast growth of inhomogeneities, while the other corresponds to a decaying mode. When $k \to 0$, $|\omega| t \to t/t_{gr}$, where $t_{gr} \equiv (4\pi G\varepsilon_0)^{-1/2}$. We interpret t_{gr} as the characteristic collapse time for a region with initial density ε_0.

The Jeans length $\lambda_J \sim c_s t_{gr}$ is the "sound communication" scale over which the pressure can still react to changes in the energy density due to gravitational instability. Gravitational instability is very efficient in a static universe. Even if the adiabatic perturbation is initially extremely small, say 10^{-100}, gravity needs only a short time $t \sim 230 t_{gr}$ to amplify it to order unity.

6.3 Instability in an expanding universe

Background In an expanding homogeneous and isotropic universe, the background energy density is a function of time, and the background velocities obey the Hubble law:

$$\varepsilon = \varepsilon_0(t), \quad \mathbf{V} = \mathbf{V}_0 = H(t) \cdot \mathbf{x}. \tag{6.32}$$

Substituting these expressions into (6.3), we obtain the familiar equation

$$\dot{\varepsilon}_0 + 3H\varepsilon_0 = 0, \tag{6.33}$$

which states that the total mass of nonrelativistic matter is conserved. The divergence of the Euler equations (6.8) together with the Poisson equation (6.10) leads to the Friedmann equation:

$$\dot{H} + H^2 = -\frac{4\pi G}{3}\varepsilon_0. \tag{6.34}$$

Perturbations Ignoring entropy perturbations and substituting the expressions

$$\begin{aligned}
&\varepsilon = \varepsilon_0 + \delta\varepsilon(\mathbf{x}, t), \quad \mathbf{V} = \mathbf{V}_0 + \delta\mathbf{v}, \quad \phi = \phi_0 + \delta\phi, \\
&p = p_0 + \delta p = p_0 + c_s^2 \delta\varepsilon,
\end{aligned} \tag{6.35}$$

into (6.3), (6.8), (6.10), we derive the following set of linearized equations for small perturbations:

$$\frac{\partial \delta\varepsilon}{\partial t} + \varepsilon_0 \nabla \delta\mathbf{v} + \boldsymbol{\nabla}(\delta\varepsilon \cdot \mathbf{V}_0) = 0, \tag{6.36}$$

$$\frac{\partial \delta\mathbf{v}}{\partial t} + (\mathbf{V}_0 \cdot \nabla)\delta\mathbf{v} + (\delta\mathbf{v} \cdot \nabla)\mathbf{V}_0 + \frac{c_s^2}{\varepsilon_0} \nabla \delta\varepsilon + \nabla \delta\phi = 0, \tag{6.37}$$

$$\Delta \delta\phi = 4\pi G \delta\varepsilon. \tag{6.38}$$

The Hubble velocity $\mathbf{V}_0$ depends explicitly on $\mathbf{x}$ and therefore the Fourier transform with respect to the Eulerian coordinates $\mathbf{x}$ does not reduce these equations to a decoupled set of ordinary differential equations. This is why it is more convenient to use the Lagrangian (*comoving with the Hubble flow*) coordinates $\mathbf{q}$, which are related to the Eulerian coordinates via

$$\mathbf{x} = a(t)\,\mathbf{q}, \tag{6.39}$$

where $a(t)$ is the scale factor. The partial derivative with respect to time taken at constant $\mathbf{x}$ is different from the partial derivative taken at constant $\mathbf{q}$. For a general function $f(\mathbf{x}, t)$ we have

$$\left(\frac{\partial f(\mathbf{x} = a\mathbf{q}, t)}{\partial t}\right)_{\mathbf{q}} = \left(\frac{\partial f}{\partial t}\right)_{\mathbf{x}} + \dot{a}q^i\left(\frac{\partial f}{\partial x^i}\right)_t \tag{6.40}$$

and therefore

$$\left(\frac{\partial}{\partial t}\right)_{\mathbf{x}} = \left(\frac{\partial}{\partial t}\right)_{\mathbf{q}} - (\mathbf{V}_0 \cdot \nabla_{\mathbf{x}}). \tag{6.41}$$

The spatial derivatives are more simply related:

$$\nabla_{\mathbf{x}} = \frac{1}{a}\nabla_{\mathbf{q}}. \tag{6.42}$$

Replacing the derivatives in (6.36)–(6.38) and introducing the fractional amplitude of the density perturbations $\delta \equiv \delta\varepsilon/\varepsilon_0$, we finally obtain

$$\left(\frac{\partial\delta}{\partial t}\right) + \frac{1}{a}\nabla\delta\mathbf{v} = 0, \tag{6.43}$$

$$\left(\frac{\partial\delta\mathbf{v}}{\partial t}\right) + H\delta\mathbf{v} + \frac{c_s^2}{a}\nabla\delta + \frac{1}{a}\nabla\delta\phi = 0, \tag{6.44}$$

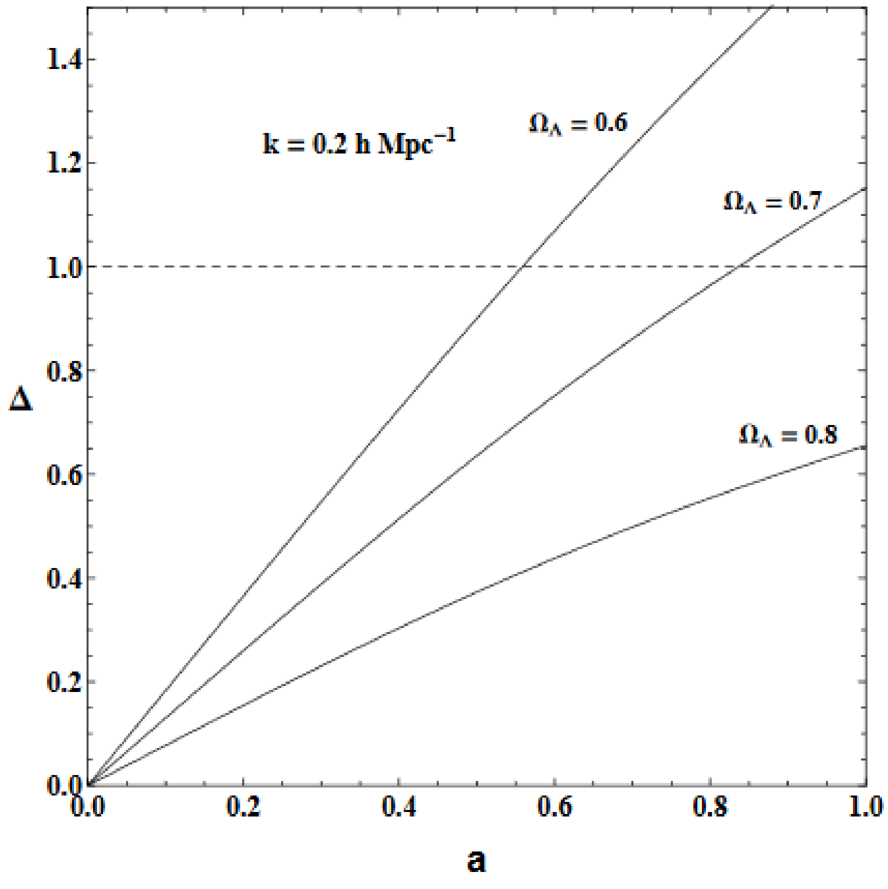
$$\Delta\delta\phi = 4\pi G a^2\varepsilon_0\delta, \tag{6.45}$$

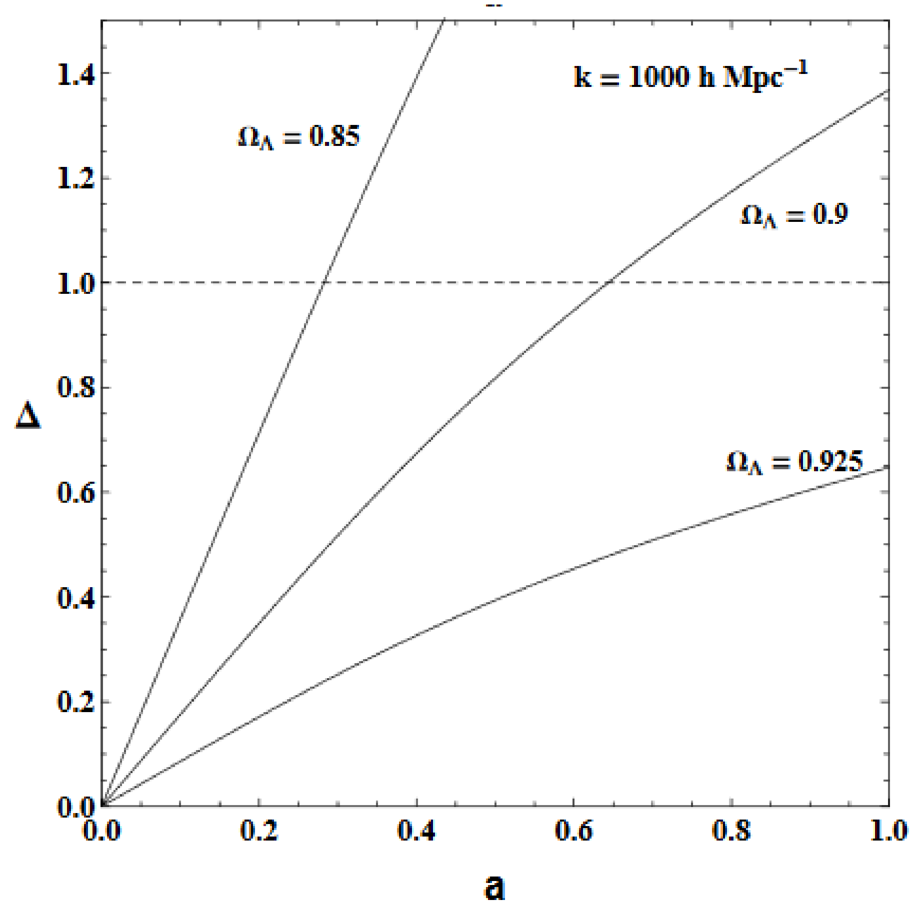
where $\nabla \equiv \nabla_{\mathbf{q}}$ and Δ are now the derivatives with respect to the Lagrangian coordinates $\mathbf{q}$ and the time derivatives are taken at constant $\mathbf{q}$. In deriving (6.43) we have used (6.33) for the background and noted that $\nabla_{\mathbf{x}}\mathbf{V}_0 = 3H$ and $(\delta\mathbf{v}\cdot\nabla_{\mathbf{x}})\mathbf{V}_0 = H\delta\mathbf{v}$. Taking the divergence of (6.44) and using the continuity and Poisson equations to express $\nabla\delta\mathbf{v}$ and $\Delta\delta\phi$ in terms of δ, we derive the closed form equation

$$\ddot{\delta} + 2H\dot{\delta} - \frac{c_s^2}{a^2}\Delta\delta - 4\pi G\varepsilon_0\delta = 0, \tag{6.46}$$

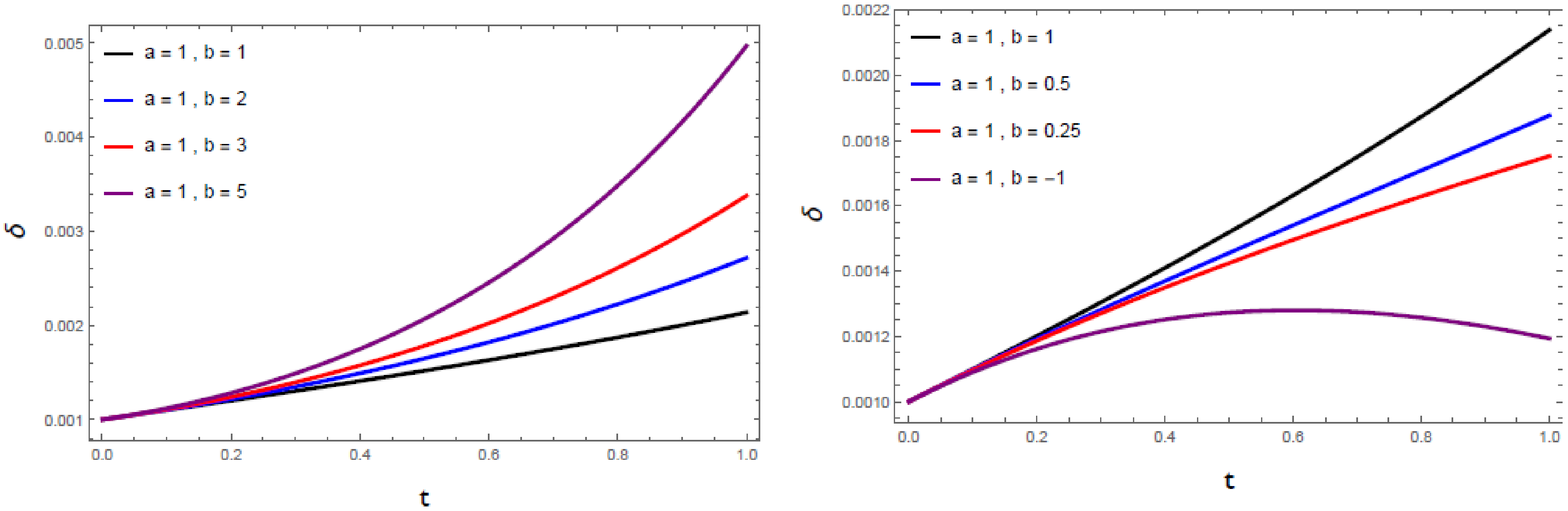
which describes gravitational instability in an expanding universe.

$$\ddot{\Delta} + 2H\dot{\Delta} + \left(\frac{c_s^2 k^2}{a^2} - 4\pi G\rho\right)\Delta = 0,$$





$$\ddot{\delta} + a\dot{\delta} - b\delta = 0$$



Time

Just after Inflation

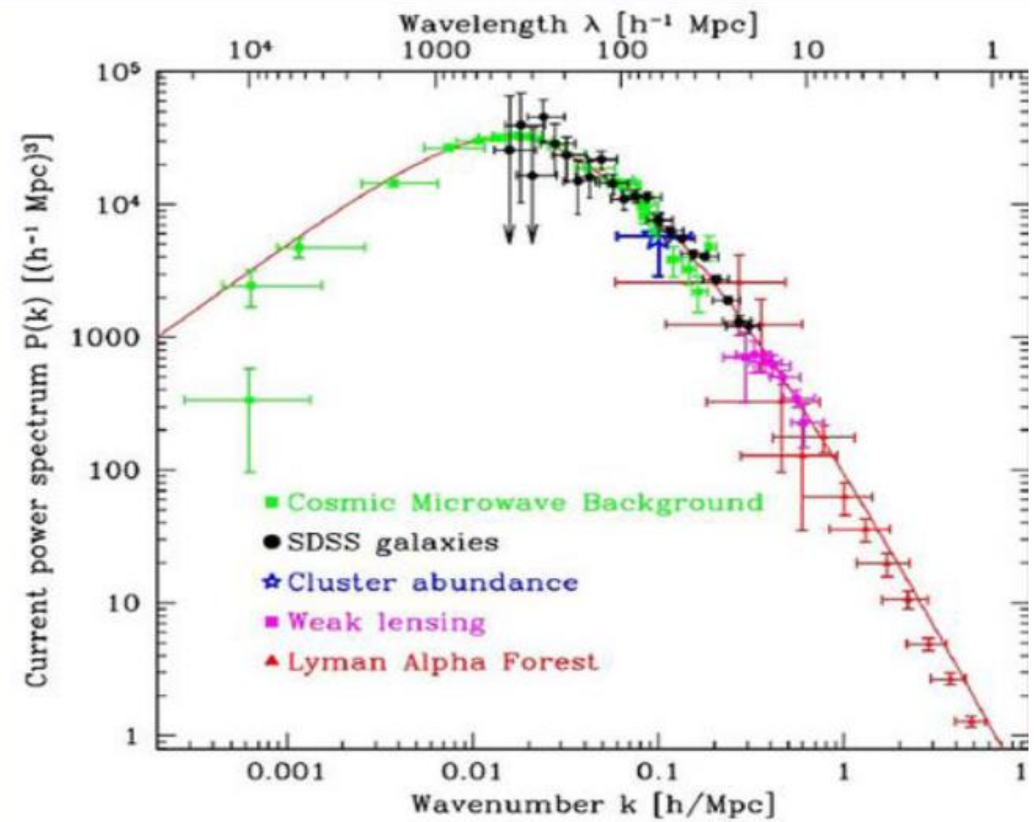
z=0 (Today)

The Initial Power Spectrum

$$P(k) = |\Delta_k|^2 \propto k^n$$

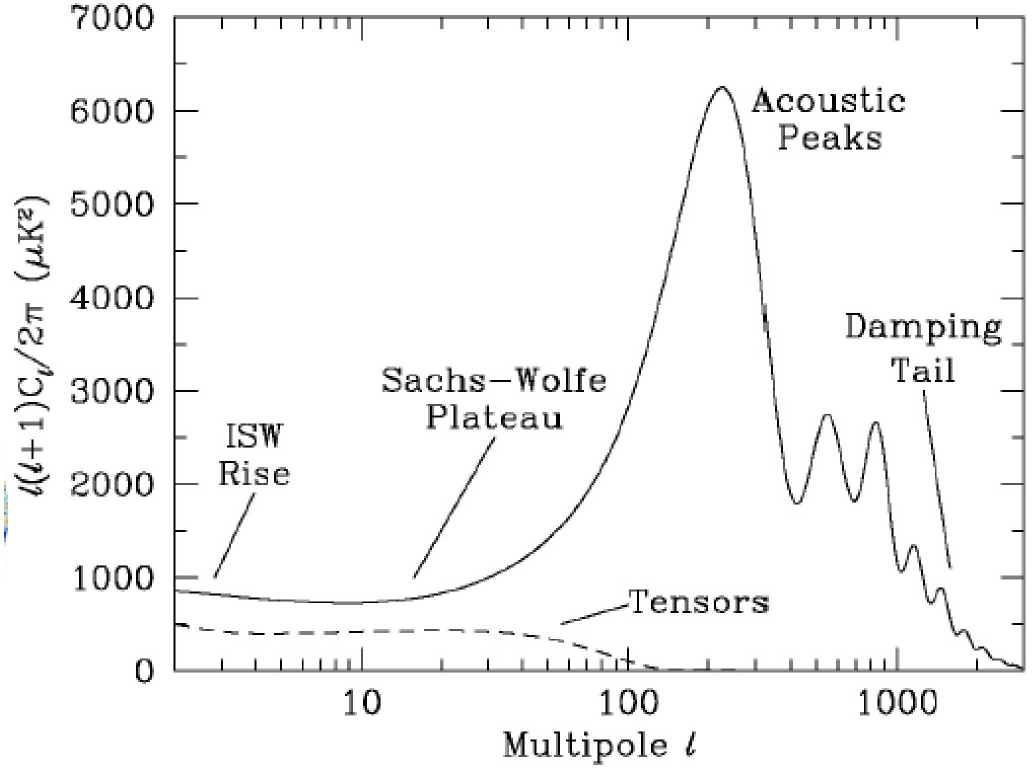
The Harrison–Zeldovich power spectrum has $n = 1$

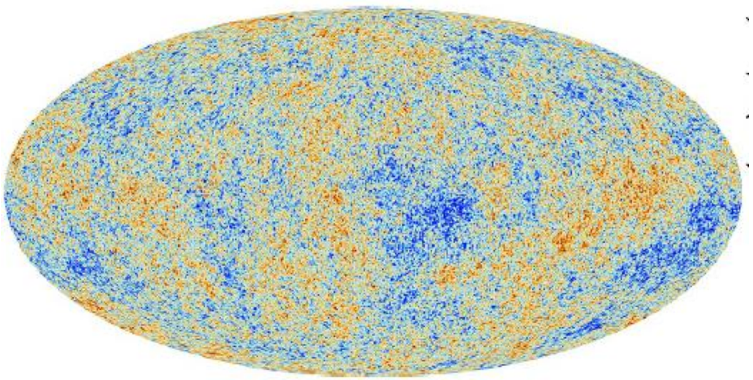
T(k) modifies the shape of P(k).



$$\Delta_k(z=0) = T(k)\ f(z)\ \Delta_k(z)$$

Efeito da energia escura no efeito Sachs-Wolfe integrado

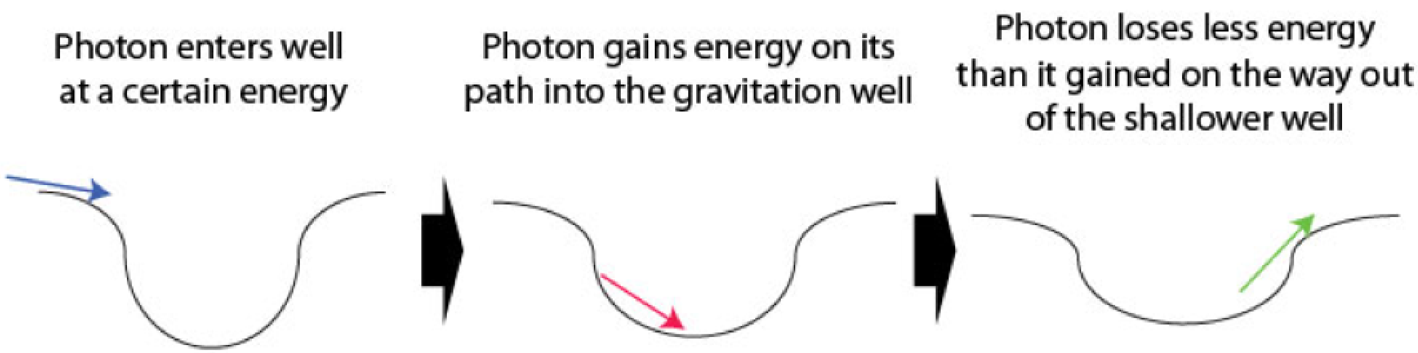




$$\frac{\delta T}{T}(\vec{e}) = \left[\frac{\delta T_\gamma}{T} + \phi - \vec{e}\cdot\vec{v_\gamma}\right]_{dec} + \int_{\eta_{dec}}^{\eta_0} d\eta \frac{\partial}{\partial\eta}(\phi+\psi)$$

Flutuações de temperatura relacionadas ao potencial que varia no tempo:

$$\left(\frac{\Delta T}{T}\right)_k^{ISW} = 2\int_{a_d}^{a_0} \frac{\partial \Phi_k}{\partial a} da = 2\left(\Phi_k(a_0) - \Phi_k(a_d)\right)$$



Gravitational well of galaxy supercluster - the depth shrinks as the universe (and cluster) expands

Aula V

- Efeito Mészaros -> Bônus: Precisamos de matéria escura

- Estágio não-linear de formação de estruturas. Entender o porquê de um excesso de densidade na distribuição de matéria se desacopla do fluxo de Hubble e colapsa para formar um objeto astronômico.

Evolução das perturbações na matéria escura e bárions

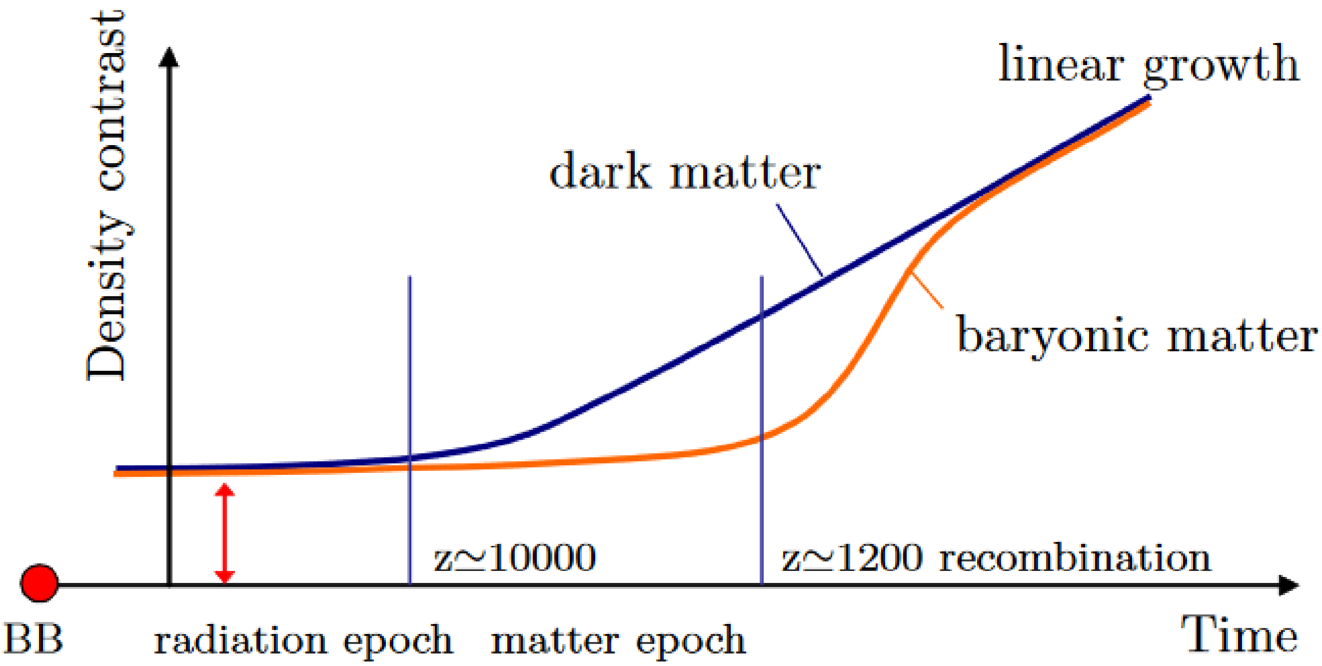
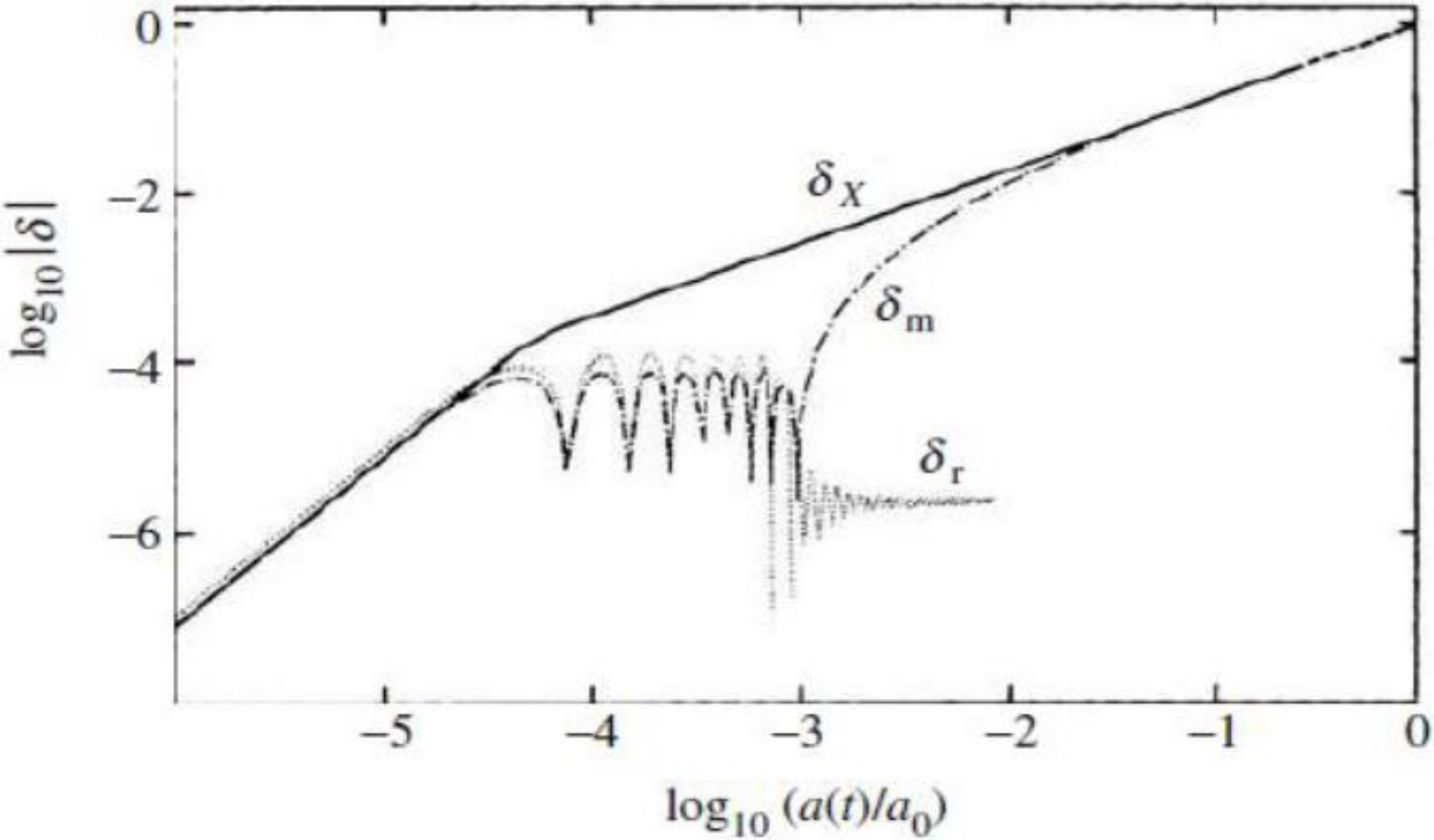


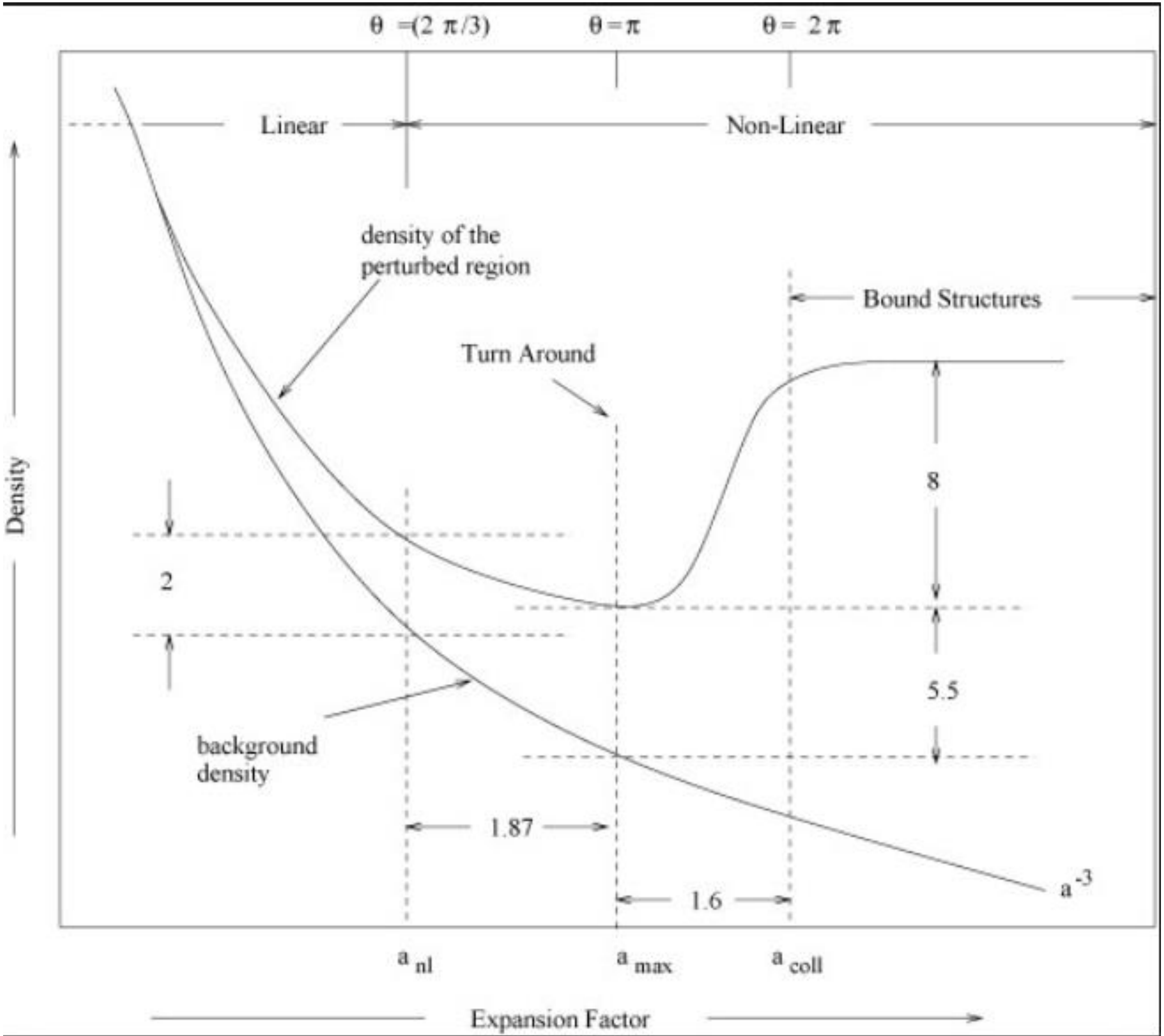
Figure 2.4: Growth of matter density contrast. After the recombination the baryonic is free to evolve and fall into the dark mater halos which formed earlier. Afterward both matter grow together.



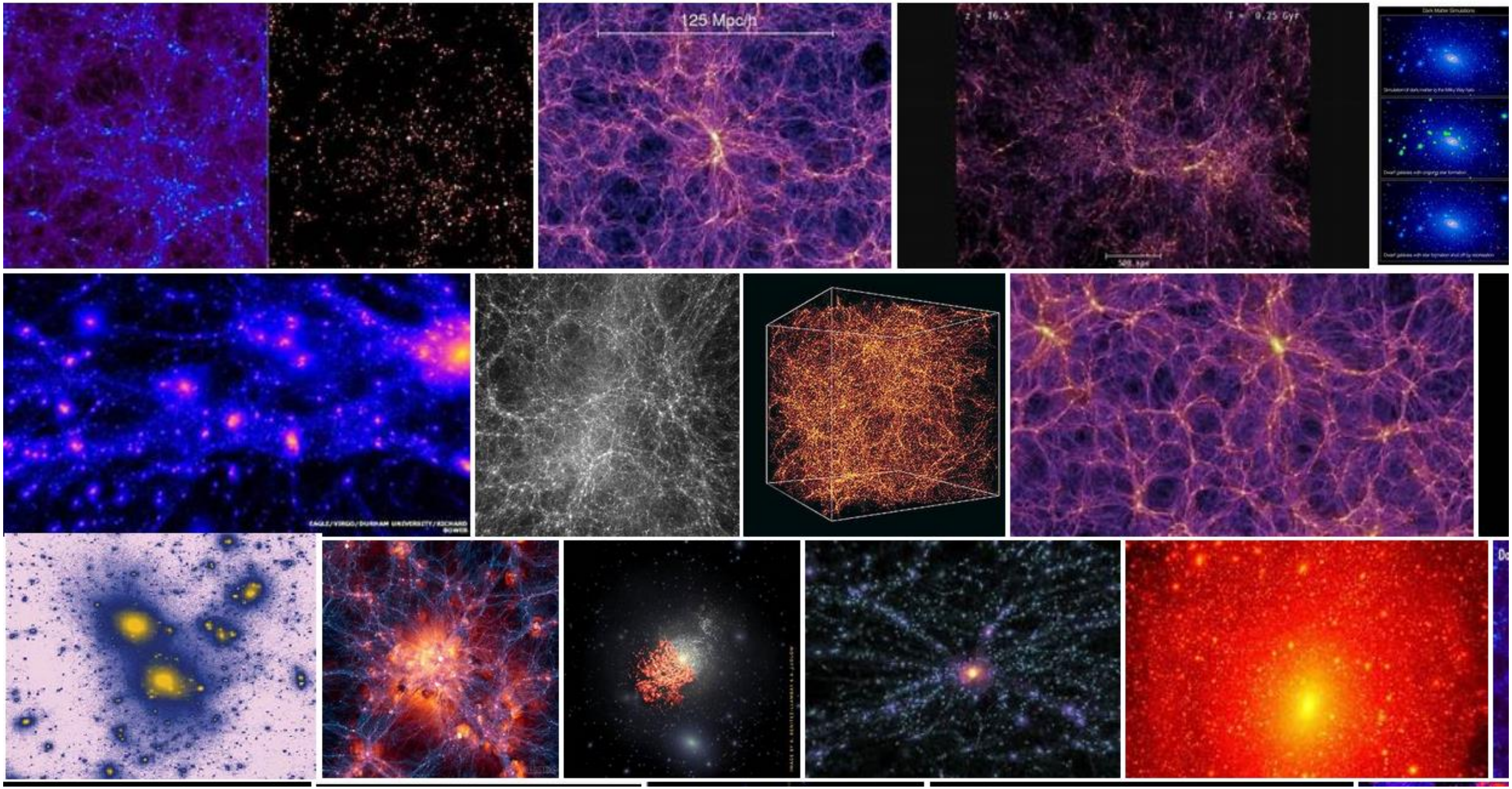
0
−2
−4
−6
$\log_{10}|\delta|$
δ_X
δ_m
δ_r
−5
−4
−3
−2
−1
0
$\log_{10}(a(t)/a_0)$

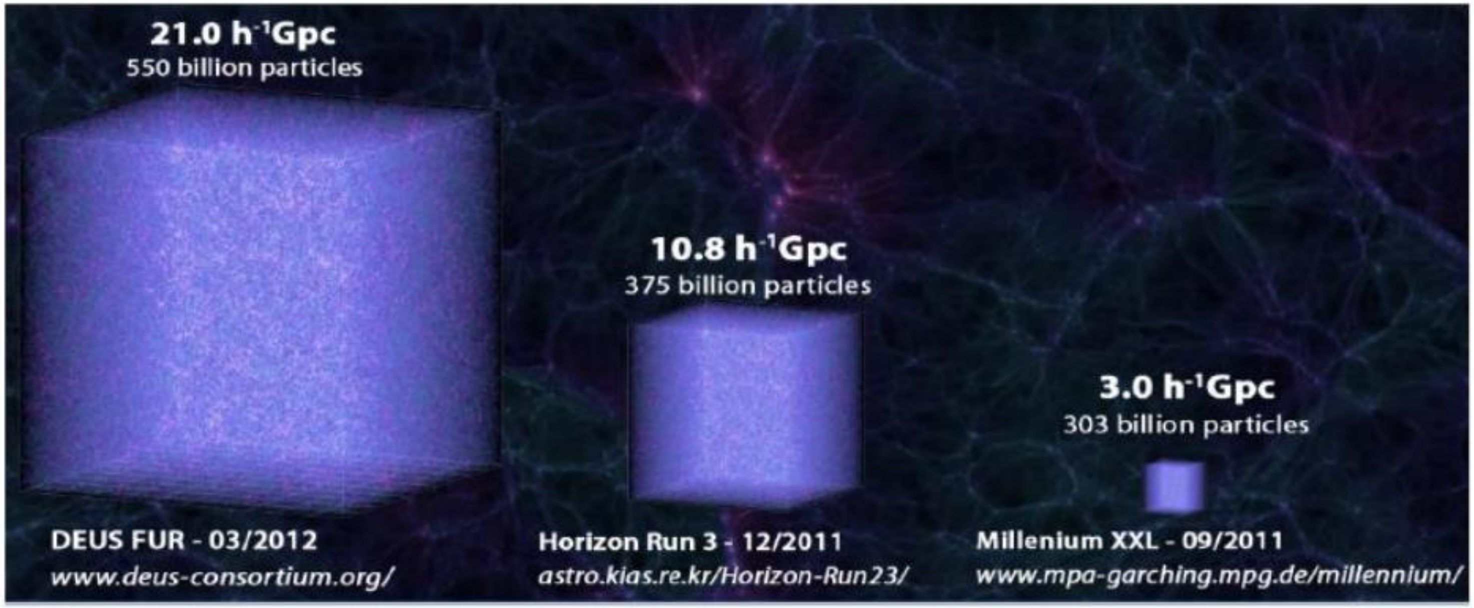
As perturbações lineares finalmente chegaram ao estágio não-linear.

E agora?


θ =(2 π/3)
θ = π
θ = 2 π
Linear
Non-Linear
density of the
perturbed region
Bound Structures
Turn Around
Density
8
2
5.5
background
density
1.87
1.6
a -3
a nl
a max
a coll
Expansion Factor

Simulações numéricas





Comparison of some N-Body simulations in terms of particles and volume sizes.

Mean Field approximation: Vlasov-Poisson equations and N-body system

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + \vec{v}.\frac{\partial f}{\partial \vec{r}} - \frac{\partial \phi}{\partial \vec{r}}.\frac{\partial f}{\partial \vec{v}} = 0,$$

$$\nabla^2 \phi(\vec{r}, t) = 4\pi G \rho(\vec{r}, t),$$

where the density of finding a particle is

$$\rho(\vec{r}, t) = \int f(\vec{r}, \vec{v}, t) d\vec{v}.$$

velocity/acceleration equation

$$\frac{d\vec{r}}{dt} = \vec{v} \quad \rightarrow \quad \frac{d\vec{v}}{dt} = -\nabla \phi.$$

The potential ϕ is given by,

$$\phi(\vec{r}) = -\sum_{j \neq i} G \frac{m_j}{\sqrt{|\vec{r} - \vec{r}_j|^2 + \epsilon^2}} \quad \text{or} \quad \nabla^2 \phi = 4\pi G \rho_T$$

From the particle distribution,
compute the mass **density field** on the grid

↓

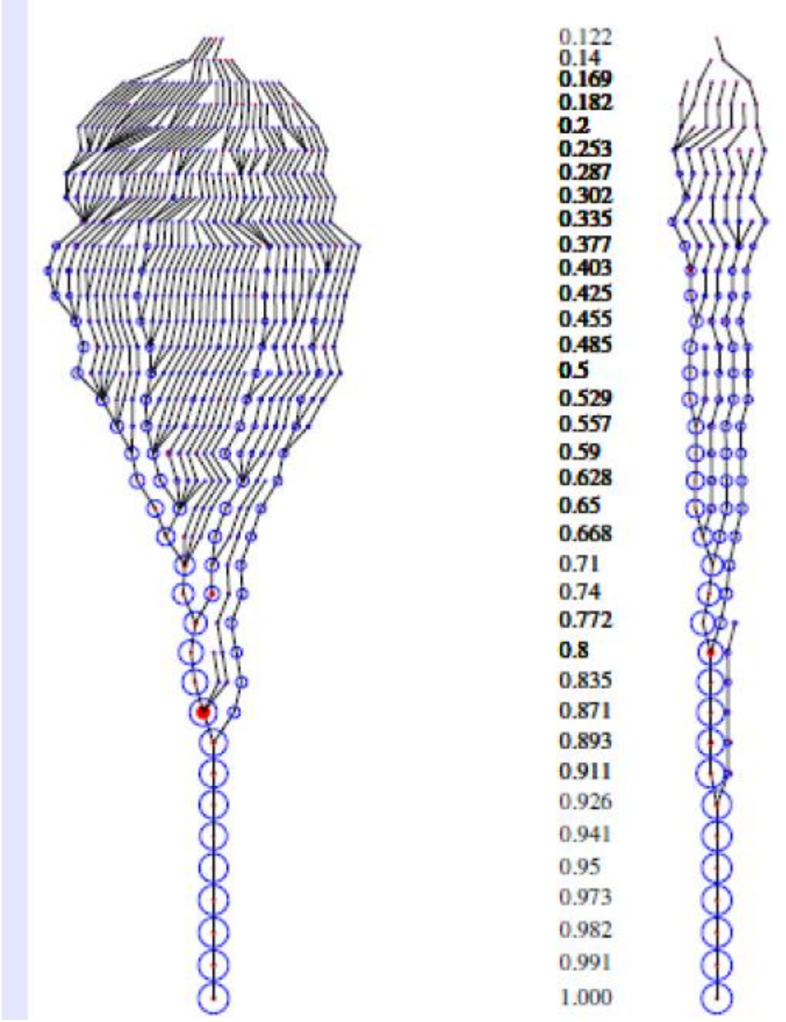
Solve for fields equation (e.g. Poisson eq) on the grid
Potencialis developedon harmonic functions
(Plane waves, Fourier Trasform)

↓

Interpolate the force back to the particle position

↓

Move the particles (Time Integrator)



O que as simulações revelam? Existem problemas com nosso modelo padrão para a matéria escura?

- Distribuição da matéria ao longo do halo: Core/cusp
- Muitos satélites preditos! Mas não vemos todos eles.

Cold dark matter: controversies on small scales

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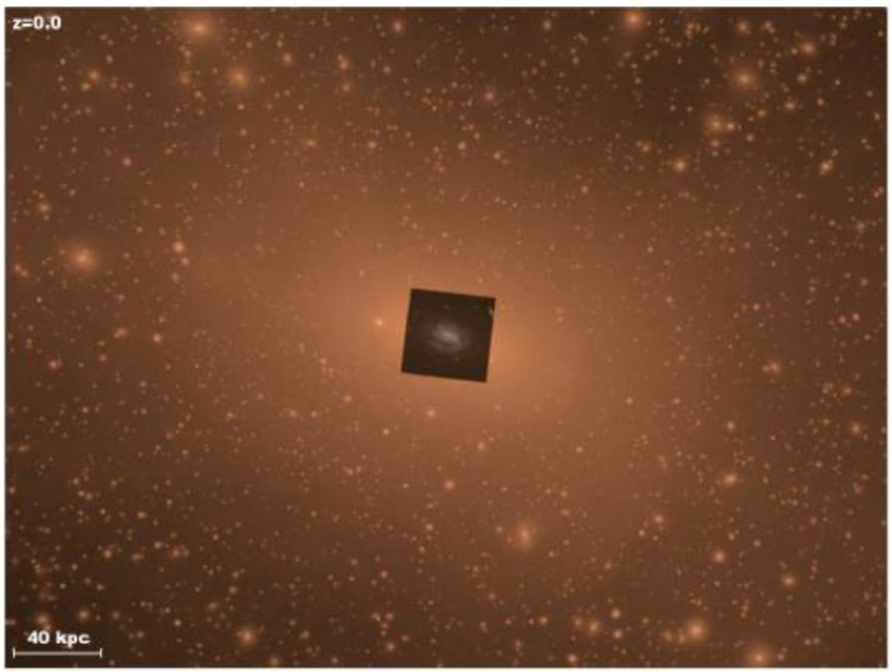
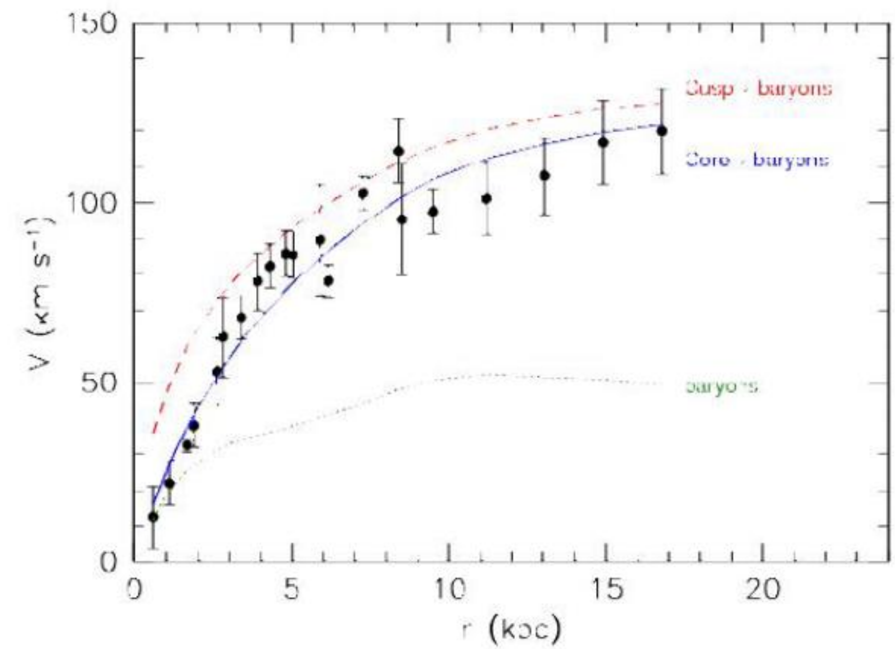
1) The CUSP-CORE Problem





2) The Missing Satellites Problem
2.1) Too Big to Fail Problem