# Cosmologia Teórica e Observacional

Carlos Herdeiro
Universidade de Aveiro
http://gravitation.web.ua.pt

6ª Escola de Gravitação e Astrofísica do Instituto Superior Técnico
Lisboa, Setembro de 2012

# Cosmologia Teórica e Observacional

**Tópicos:**

Aula 1 - Introdução e perspectiva histórica
Aula 2 - Cosmologia em Relatividade Geral
Aula 3 - Para além da Relatividade Geral

# Aula 1

## Introdução e perspectiva histórica

# Cosmologia

## é o estudo da estrutura e dinâmica do Universo em

## LARGA ESCALA

O "Ultra Deep Field" do Hubble Space Telescope.

**Quase todos os pontos luminosos desta imagem são uma galáxia inteira!**

Estima-se que esta pequena região do Universo contenha quase 200 mil milhões de galáxias.

Esta região é na constelação Fornax (Fornalha - Hemisfério Sul). Os dados foram obtidos pelo HST entre Sep 3, 2003 - Jan 16, 2004.

Esta região do céu foi escolhida por ter uma densidade baixa de estrelas brilhantes na região "near-field".

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tem origem etimológica no grego:
"Cosmos"=ordem + "Logia"=estudo, tratado

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A palavra **Cosmologia**

foi usada primeiro pelo filósofo alemão Christian Wolff

no seu tratado "Cosmologia Generalis" (1730)


Placa no edifício de Wroclaw (hoje Polónia)
onde Wolff nasceu e viveu de 1679-1699

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É pois natural que a generalidade das civilizações e culturas tenham
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A **Cosmologia científica moderna**
aborda esta questão usando o método científico,
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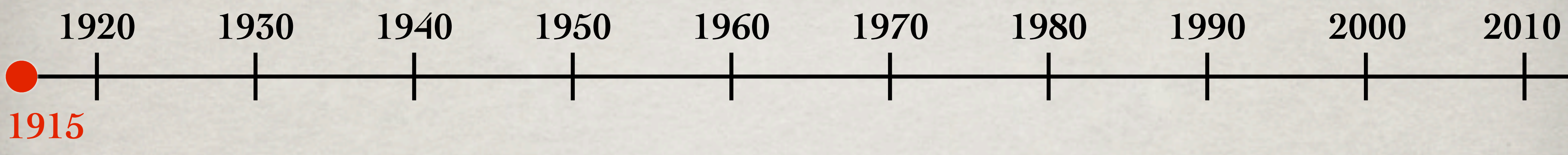
**Observações recentes de alta precisão**
restringiram consideravalmente as especulações teóricas
originando um extraordinário cenário para o que é o Universo:

Como construimos um tão extraordinário modelo?

# “Timeline”:



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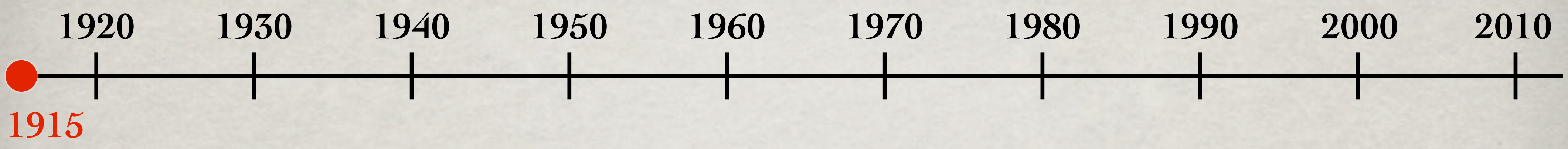
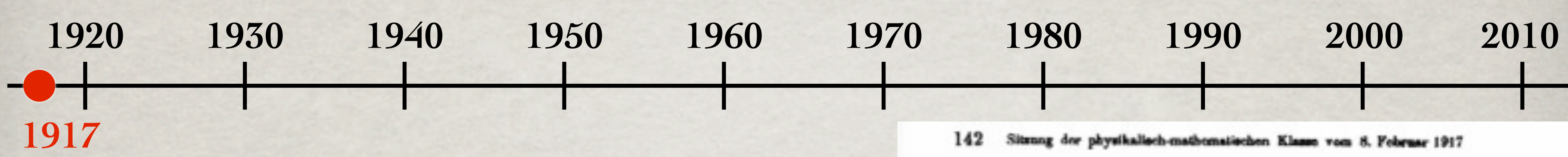



A construção da **Relatividade Geral** por A. Einstein

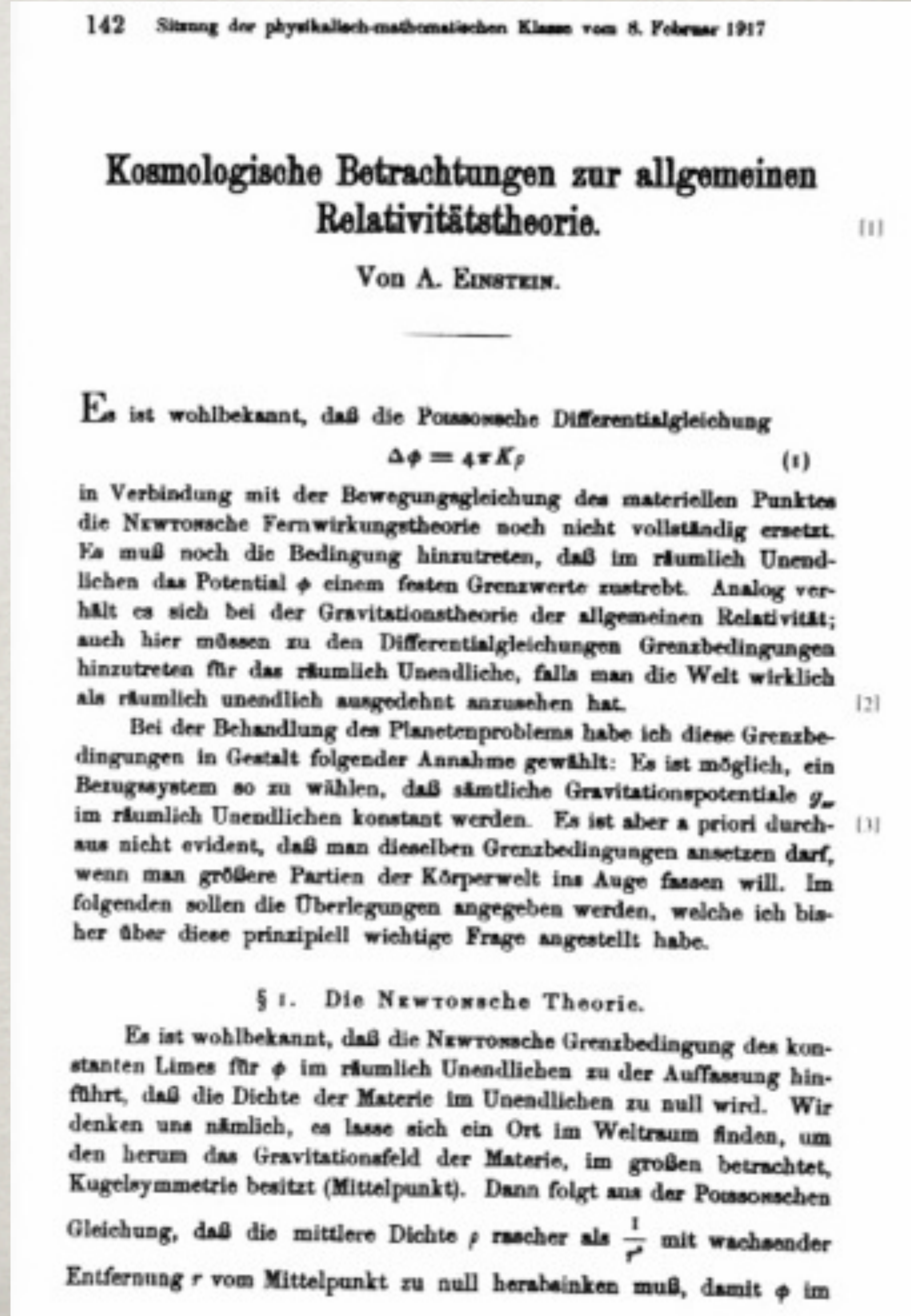
Pintura: Peter Wharton

O espaço-tempo é dinâmico

# "Timeline":




Insatisfeito com o facto de as soluções cosmológicas das suas equações terem singularidades, Einstein modifica-as introduzindo a **Constante Cosmologica**



142 Sitzung der physikalisch-mathematischen Klasse vom 8. Februar 1917

## Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie. [1]

Von A. Einstein.

Es ist wohlbekannt, daß die Poissonsche Differentialgleichung

$$\Delta\phi = 4\pi K\rho \quad (1)$$

in Verbindung mit der Bewegungsgleichung des materiellen Punktes die Newtonsche Fernwirkungstheorie noch nicht vollständig ersetzt. Es muß noch die Bedingung hinzutreten, daß im räumlich Unendlichen das Potential $\phi$ einem festen Grenzwerte zustrebt. Analog verhält es sich bei der Gravitationstheorie der allgemeinen Relativität; auch hier müssen zu den Differentialgleichungen Grenzbedingungen hinzutreten für das räumlich Unendliche, falls man die Welt wirklich als räumlich unendlich ausgedehnt anzusehen hat. [2]

Bei der Behandlung des Planetenproblems habe ich diese Grenzbedingungen in Gestalt folgender Annahme gewählt: Es ist möglich, ein Bezugssystem so zu wählen, daß sämtliche Gravitationspotentiale $g_{\mu\nu}$ im räumlich Unendlichen konstant werden. Es ist aber a priori durchaus nicht evident, daß man dieselben Grenzbedingungen ansetzen darf, wenn man größere Partien der Körperwelt ins Auge fassen will. Im folgenden sollen die Überlegungen angegeben werden, welche ich bisher über diese prinzipiell wichtige Frage angestellt habe. [3]

### § 1. Die Newtonsche Theorie.

Es ist wohlbekannt, daß die Newtonsche Grenzbedingung des konstanten Limes für $\phi$ im räumlich Unendlichen zu der Auffassung hinführt, daß die Dichte der Materie im Unendlichen zu null wird. Wir denken uns nämlich, es lasse sich ein Ort im Weltraum finden, um den herum das Gravitationsfeld der Materie, im großen betrachtet, Kugelsymmetrie besitzt (Mittelpunkt). Dann folgt aus der Poissonschen Gleichung, daß die mittlere Dichte $\rho$ rascher als $\frac{1}{r^2}$ mit wachsender Entfernung $r$ vom Mittelpunkt zu null herabsinken muß, damit $\phi$ im

"Cosmological considerations on the General Theory of Relativity"

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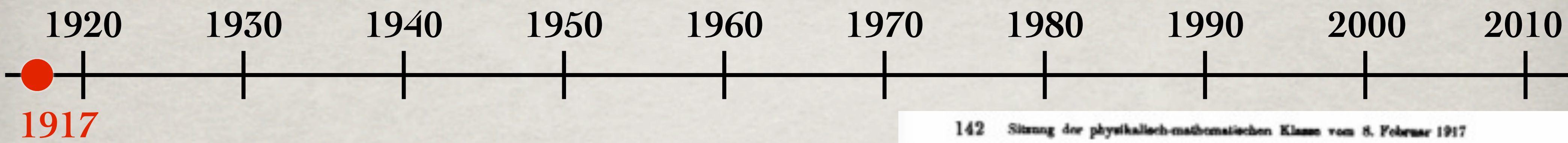


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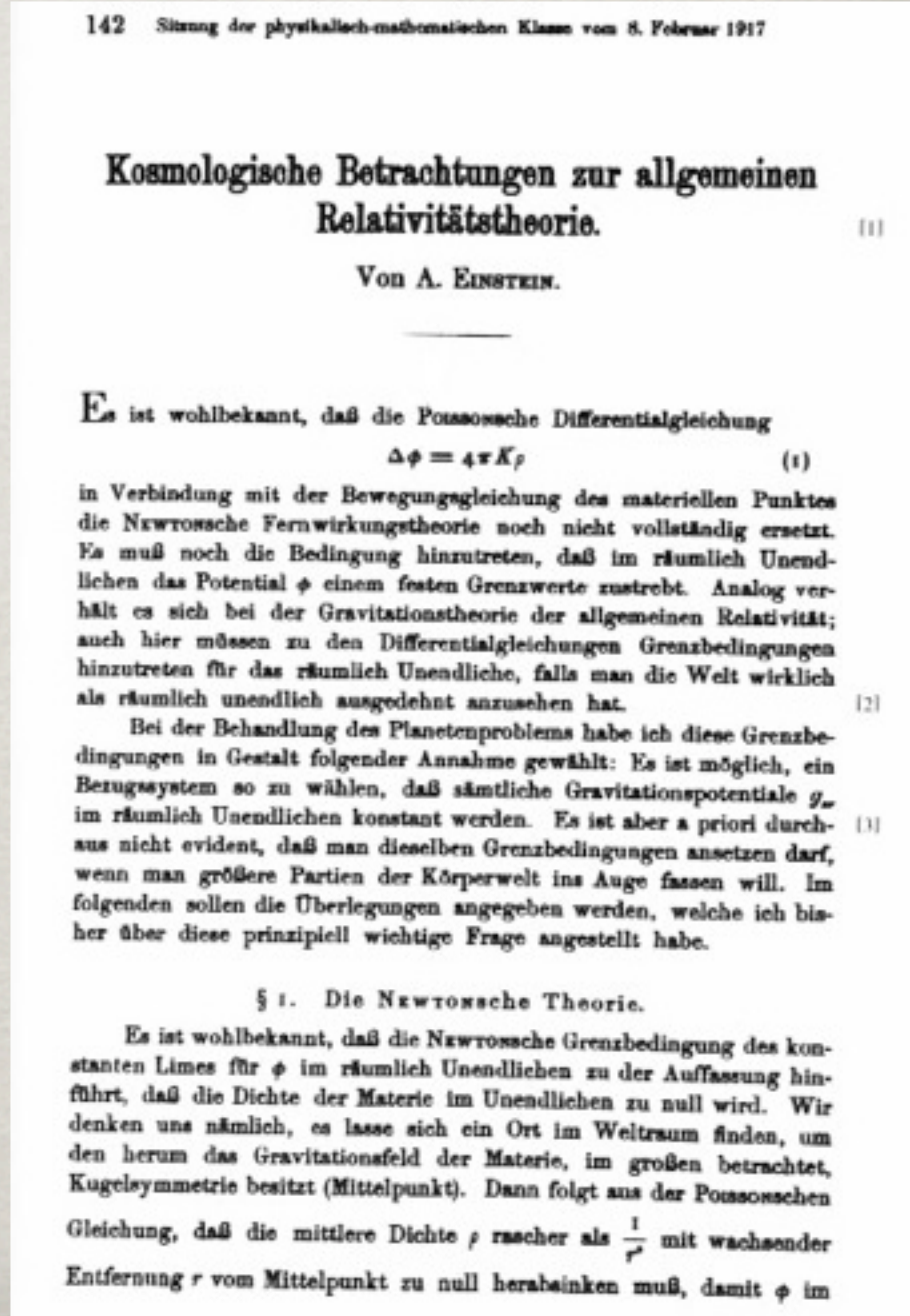
Com as novas equações, Einstein deduz uma nova solução cosmológica: **O Universo Estático de Einstein**



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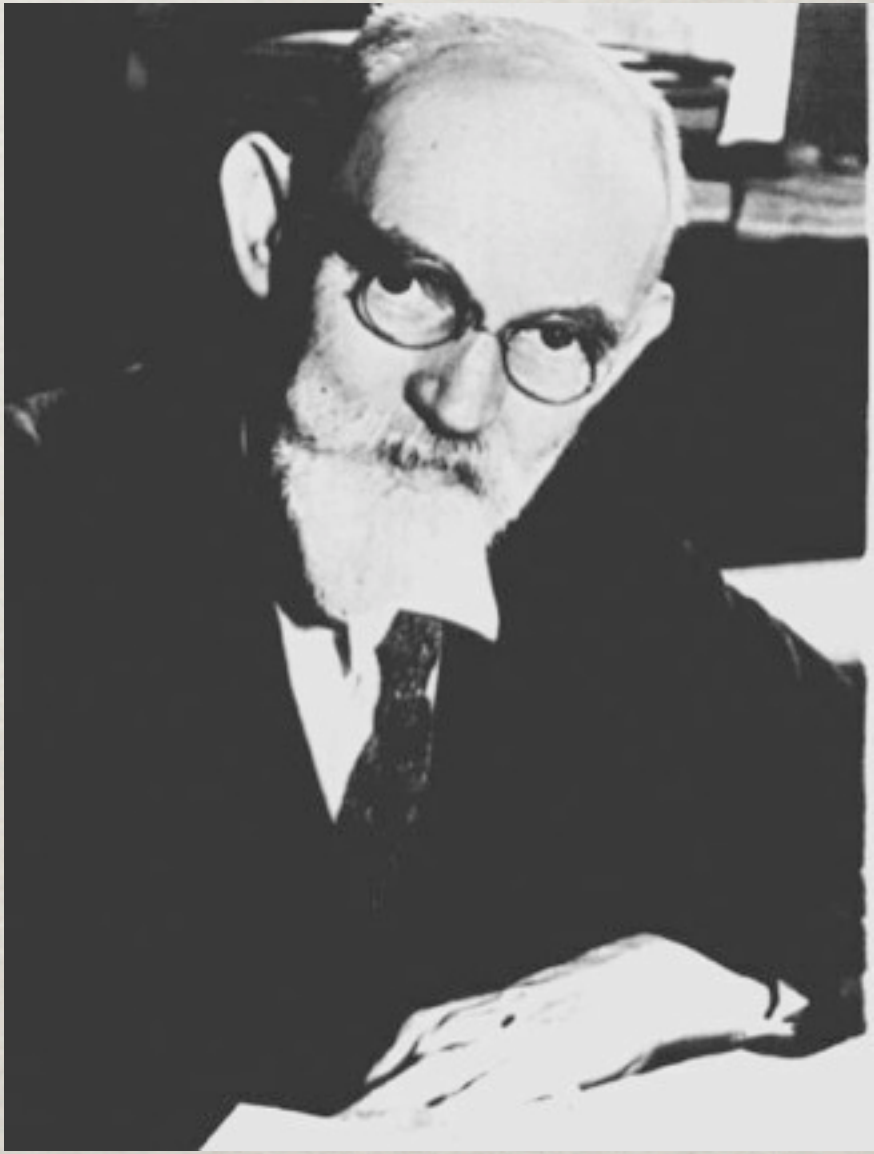
| 1920 | 1930 | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 | 2000 | 2010 |
|---|---|---|---|---|---|---|---|---|---|

1917

No mesmo ano Willem de Sitter a solução para um Universo vazio das novas equações de Einstein:

**o Universo de de Sitter.**

Este é o primeiro exemplo de um Universo inflacionário



# “Timeline”:

1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

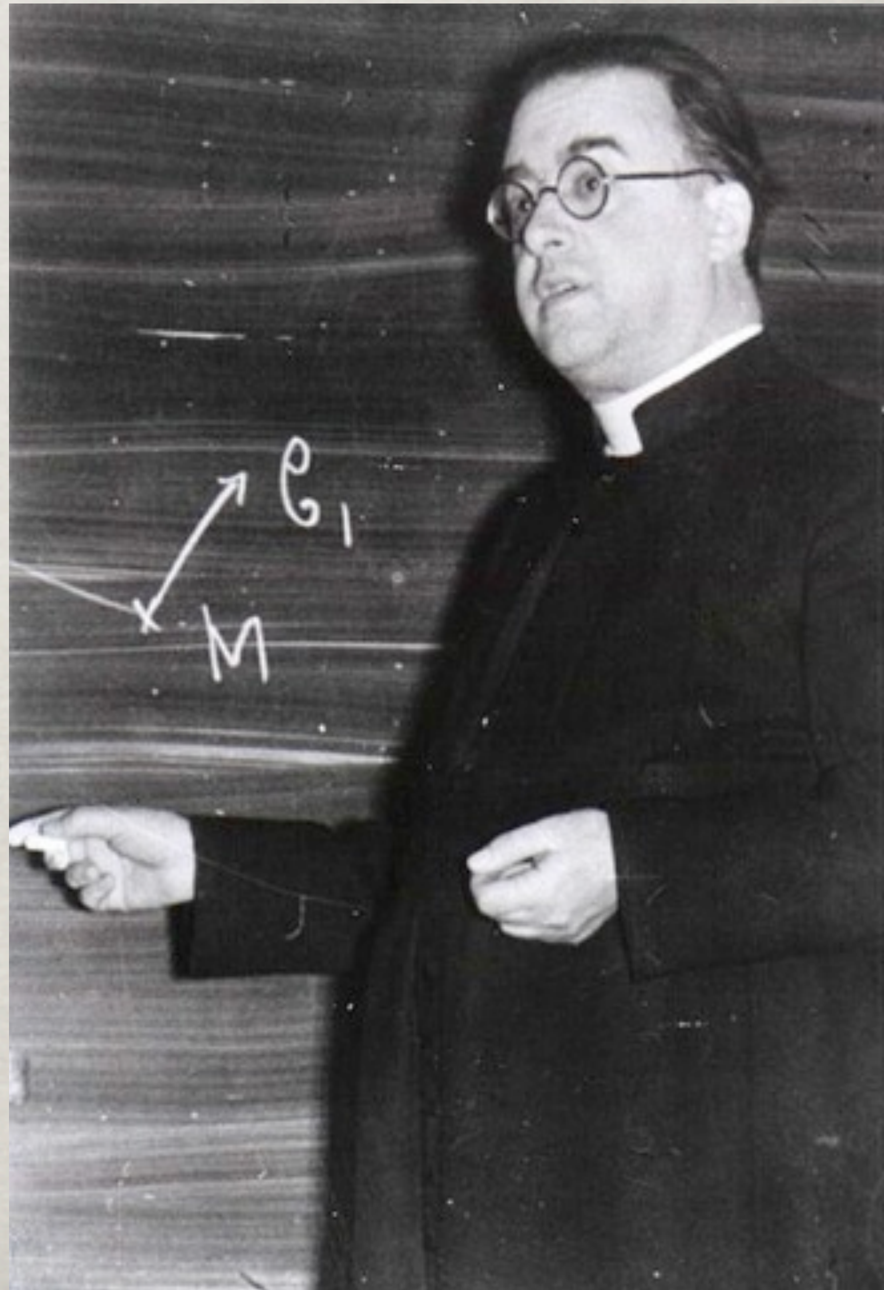
**1922-24**

Alexander Friedmann considerou modelos cosmológicos em Relatividade Geral com curvatura espacial (constante).
Os modelos cosmologicos homogéneos e isotrópicos são denominados **Universos de FRW ou FLRW** (Friedmann-(Lemaître-) Robertson-Walker) e uma ou ambas as equações de Einstein para estes modelos são chamadas “**equação de Friedmann**”.

# “Timeline”:

| 1920 | 1930 | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 | 2000 | 2010 |
|---|---|---|---|---|---|---|---|---|---|

1927




Georges Lemaître estudou os mesmos modelos e foi o primeiro a:

- prever a **expansão do Universo**;

- propôr a **“lei de Hubble”**;

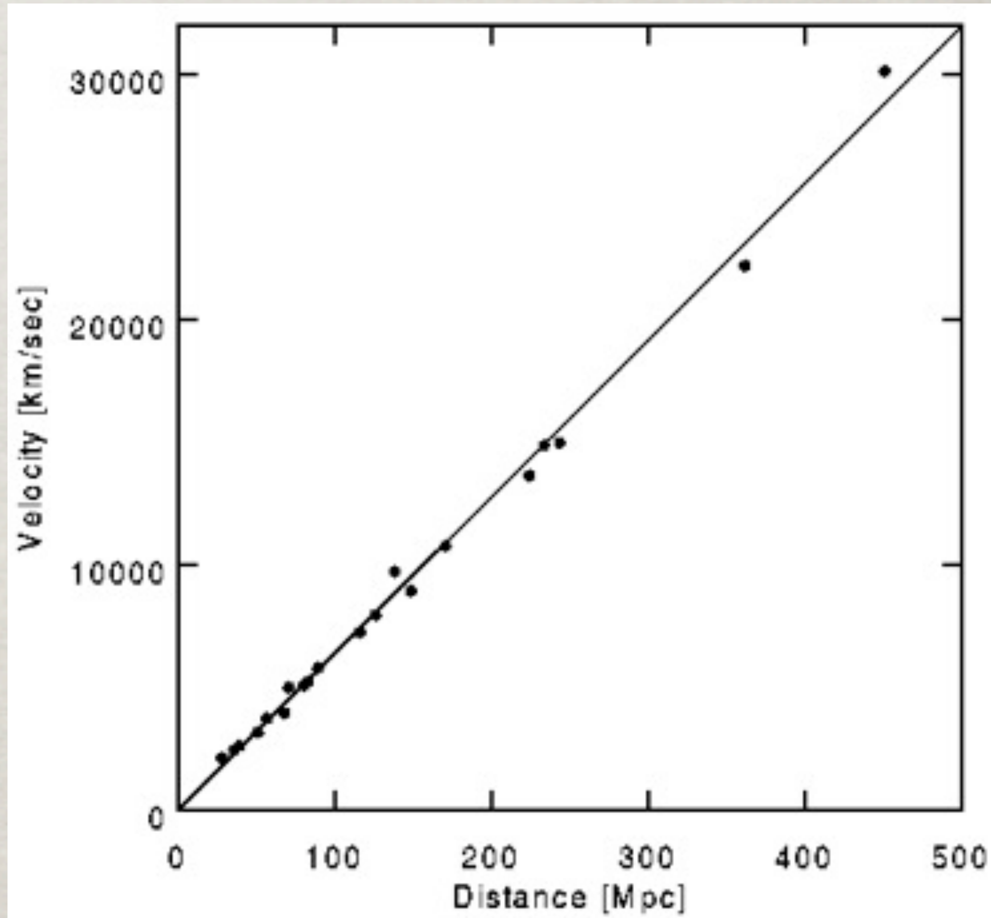
- estimar **“o parâmetro de Hubble”**;

- uma teoria para a origem do Universo do tipo “Big Bang”, a que ele chamou **“átomo primevo”** ou **“ovo cósmico”** (1931)

# “Timeline”:

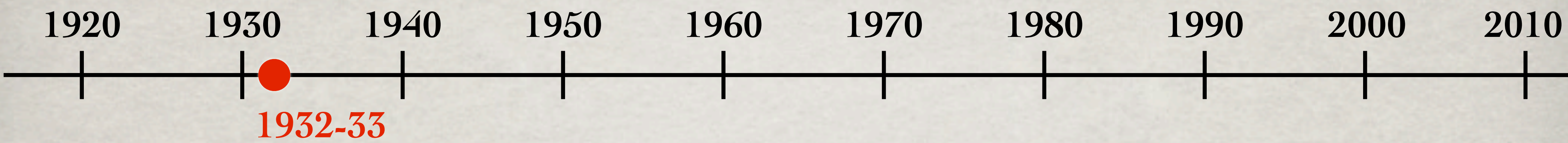
1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

1929

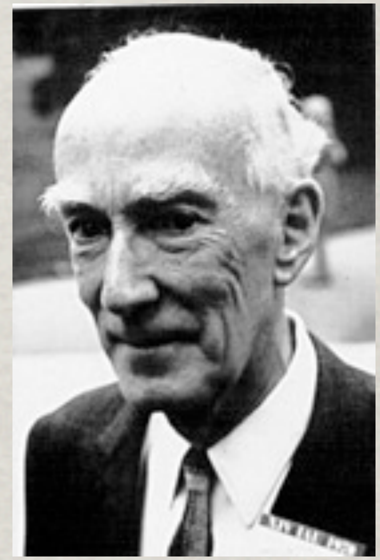



Edwin Hubble descobre a **EXPANSÃO DO UNIVERSO**

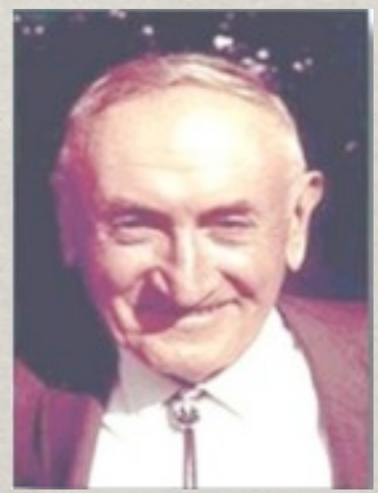
# “Timeline”:




Jan Oort e Fritz Zwicky
observeram que para tanto para
explicar as velocidades orbitais de estrelas
na Via Láctea como para explicar as
velocidades de galáxias em aglomerados
a massa “visível” não é suficiente.
Foi a primeira evidência da
**matéria escura**.

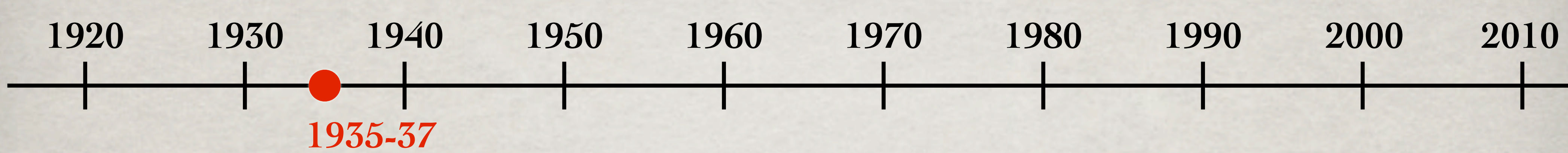


Jan Oort



Fritz Zwicky

# “Timeline”:




Howard Robertson (americano) e Arthur Walker (inglês) demonstram rigorosamente que a métrica de FLRW é única para Universos cujas secções espaciais sejam **homogéneas** e **isotropicas**.

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

# “Timeline”:

1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

**1946-48**

George Gamow desenvolve a teoria do “Big Bang” de Lemaître.

Assumindo que o Universo começa num estado muito denso e quente, Gamow iniciou a ideia de **NUCLEOSSÍNTESE PRIMORDIAL** e argumentou como as abundâncias de elementos leves como o deutério e Hélio (e erradamente também para elementos mais pesados do que o Hélio) podiam ser explicadas por reacções ocorridas nesta época.

”On the origin of Chemical Elements” Physcal Review, April 1 1948, Ralph Alpher, Hans Bethe, George Gamow

# “Timeline”:

1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

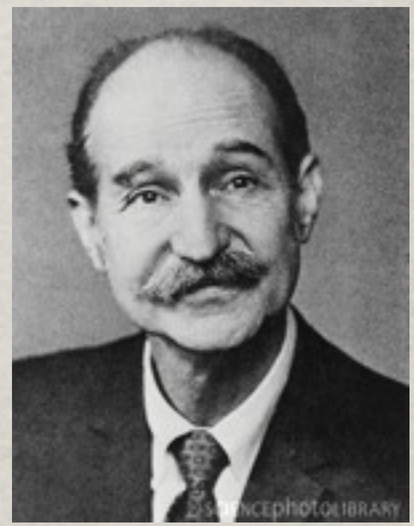
**1948**

Ralph Alpher e Robert Herman prevêem a temperatura da radiação residual do hipotético “Big Bang”, hoje denominada

**RADIAÇÃO CÓSMICA DE FUNDO (RCF)**

e obtêm um valor de 5°K (dois anos depois obtiveram 28°K)

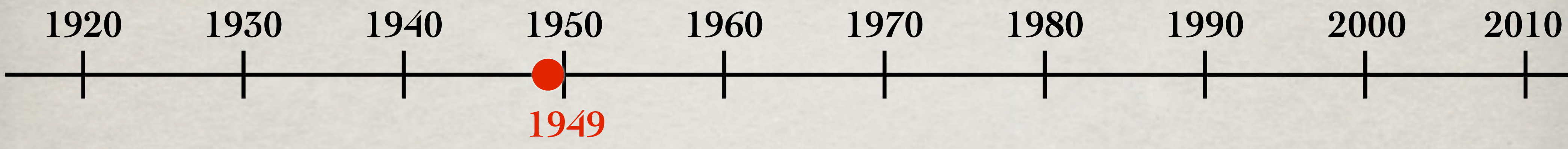
Ralph Alpher



Robert Herman

”On the relative abundance of the Elements” Physical Review, *74* (1948) 1577, R. Alpher, R. Herman

# “Timeline”:




Fred Hoyle cunhou o termo **“Big Bang”** para o modelo do átomo primevo de Lemaître. (No programa de rádio da BBC “Third Programme” emitido às 18H30 GMT de 28 de Março de 1949).

Hoyle aceitava a expansão do Universo observada por Hubble e descrita por Lemaître mas rejeitava a ideia de que o Universo tinha um princípio.

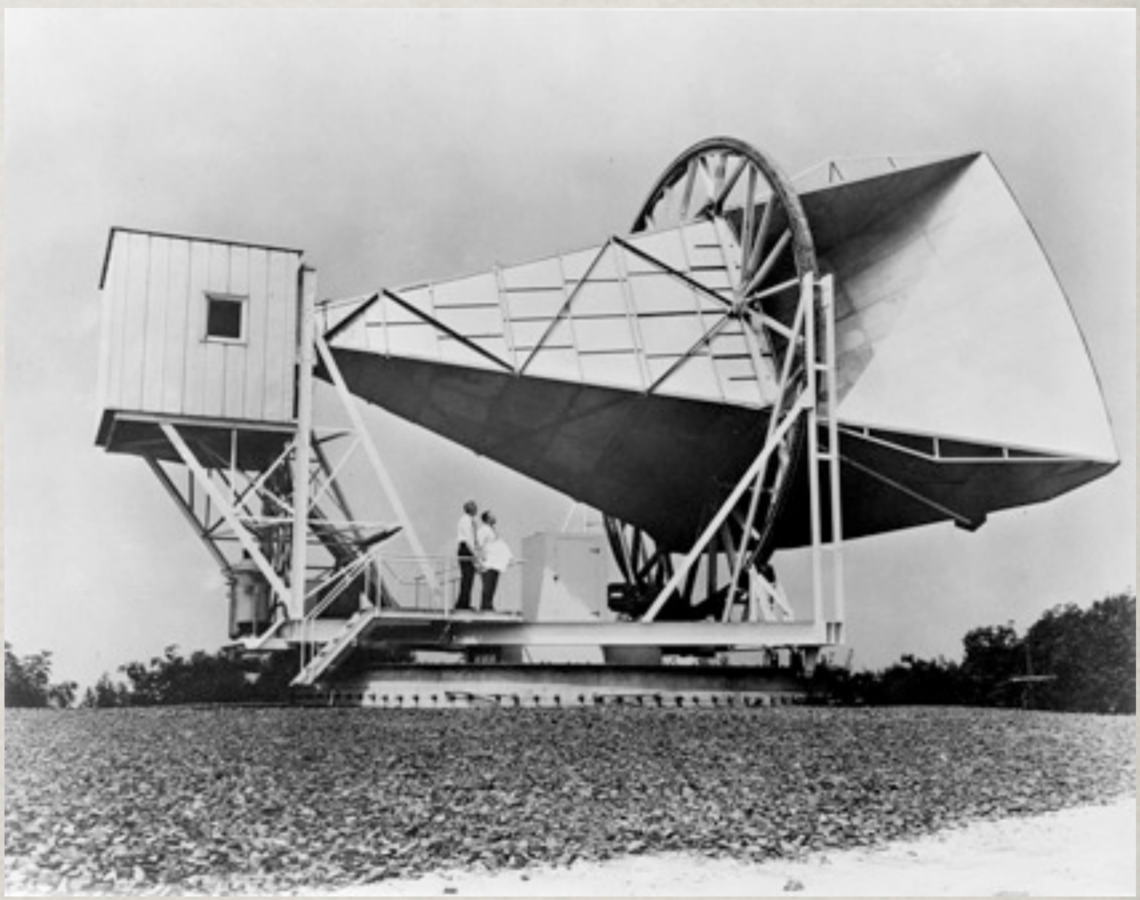
Propôs um modelo alternativo: **“Modelo do estado estacionário”**

# “Timeline”:

1920 | 1930 | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 | 2000 | 2010

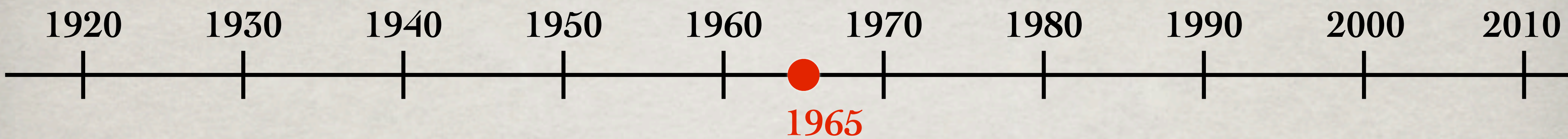
1964

Arno Penzias e Robert Wilson a trabalhar nos laboratórios Bell em Holmdel, New Jersey, com receptores de microndas criogénicos ultra-sensíveis (antena Horn) observaram inesperadamente um ruído rádio isotrópico. Inadvertidamente, tinham descoberto a **radiação cósmica de fundo**, prevista pelo modelo do “Big Bang”



Wilson, R. W.; Penzias, A. A. (1967). "Isotropy of Cosmic Background Radiation at 4080 Megahertz". *Science* **156** (3778): 1100–1101

# “Timeline”:




Robert Dicke e Jim Peebles rederivaram (alegadamente independentemente do grupo de Gamow) a radiação cósmica de fundo. Com David Wilkinson e Peter Roll, desenvolveram um detector para procurar a radiação mas foram ultrapassados pela detecção acidental de Penzia e Wilson (a apenas alguns kms de Princeton). O grupo de Dicke fez uma segunda medição da radiação concluindo uma **temperatura de 3.5ºK** e interpretaram a observação de Penzias e Wilson.

A cosmologia do Universo primordial **passou de especulação a uma ciência empírica**.

Dicke, R. H., Peebles, P. J. E., Roll, P. G., Wilkinson, D. T. (1965). "Cosmic Black-Body Radiation". *Astrophysical Journal* **142**: 414–419

# “Timeline”:

1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

1970

Vera Rubin mediu **curvas de rotação galácticas** para galáxias em espiral no plano de observação.



Rubin, V. C.; Ford, W. K. Jr. (1970). "Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions". *The Astrophysical Journal* **159**: 379

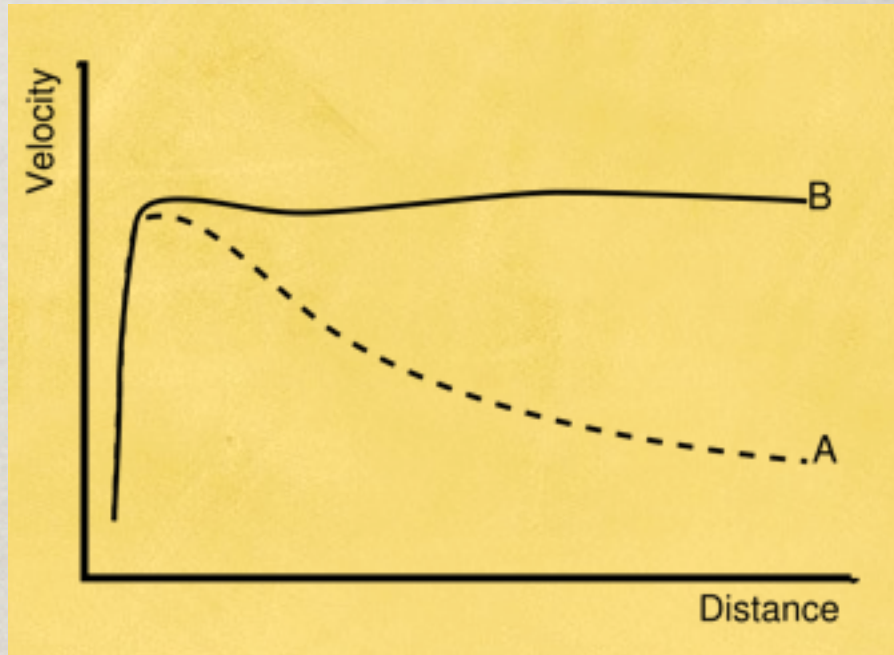
# "Timeline":

1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

**1975**

Vera Rubin anunciou num encontro da American Astronomical Society que a maior parte das estrelas em galáxias em espiral **orbitam com a mesma velocidade**.

Em gravidade Newtoniana isto implica que a densidade das galáxias deve ser aproximadamente constante, em contraste com a localização das estrelas visíveis - maioritariamente no "galactic bulge".



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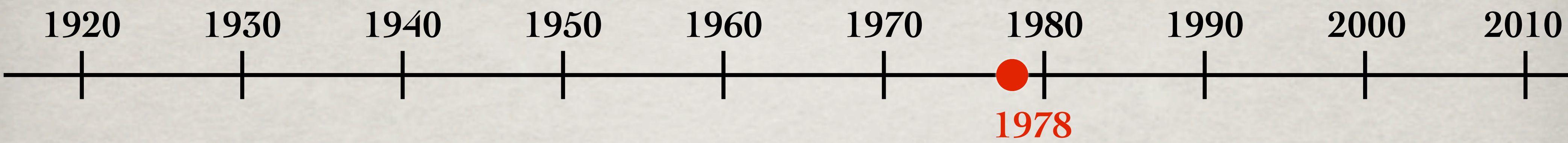
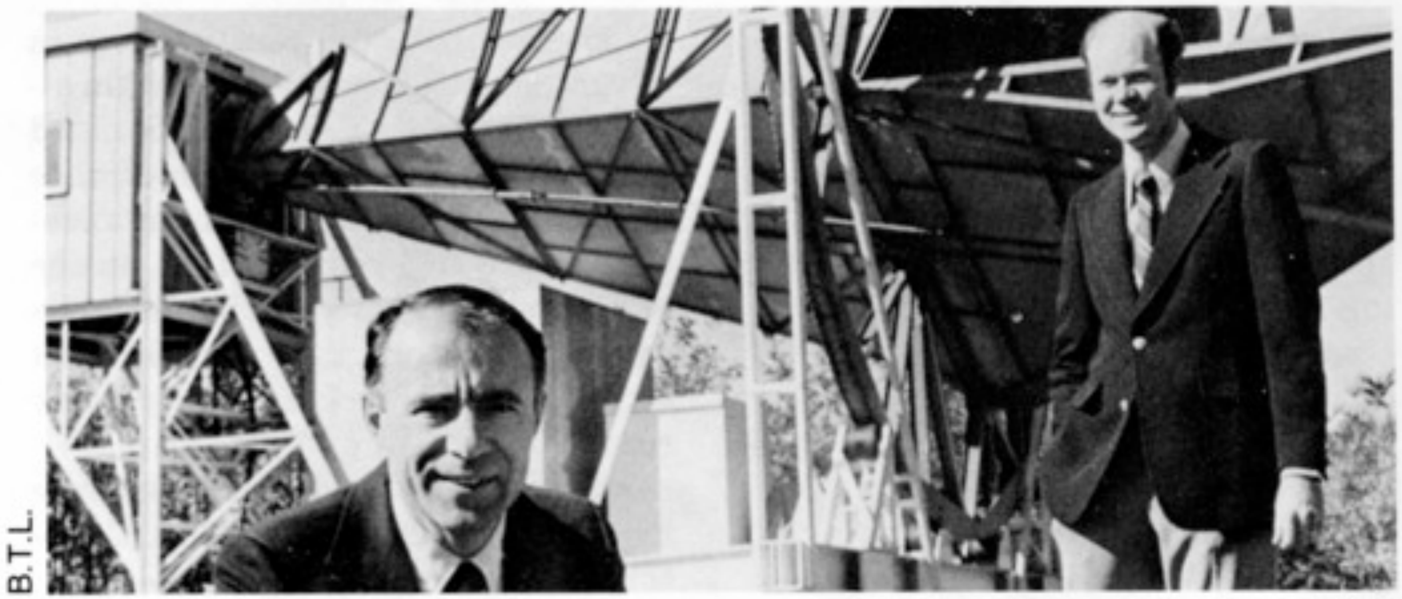


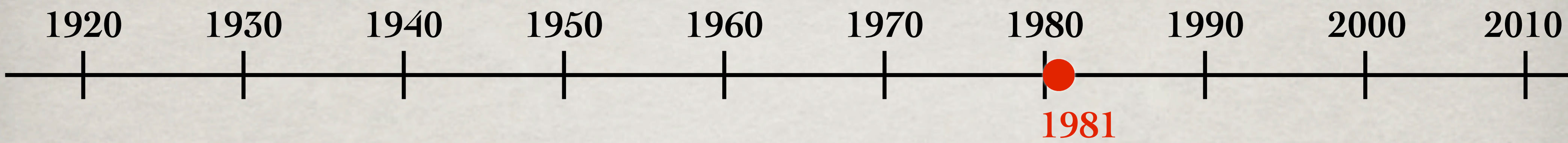

Prémio Nobel
da Física 1978

*"...for their discovery of cosmic microwave background radiation."*




Penzias (left) and Wilson. "A small discrepancy led them to the grandest of all possible answers."

# “Timeline”:




Alan Guth propõe a ideia de **inflação primordial**, uma época de expansão acelerada logo após o Big Bang, para resolver alguns problemas do modelo standard cosmológico (planura, horizonte, monopolos).

Alan Guth, “Inflationary universe: A possible solution to the horizon and flatness problems “, Phys. Rev. D 23, 347–356 (1981)

# “Timeline”:

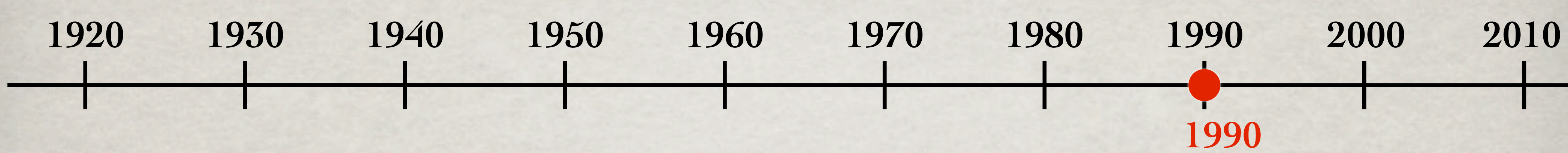
1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

1989

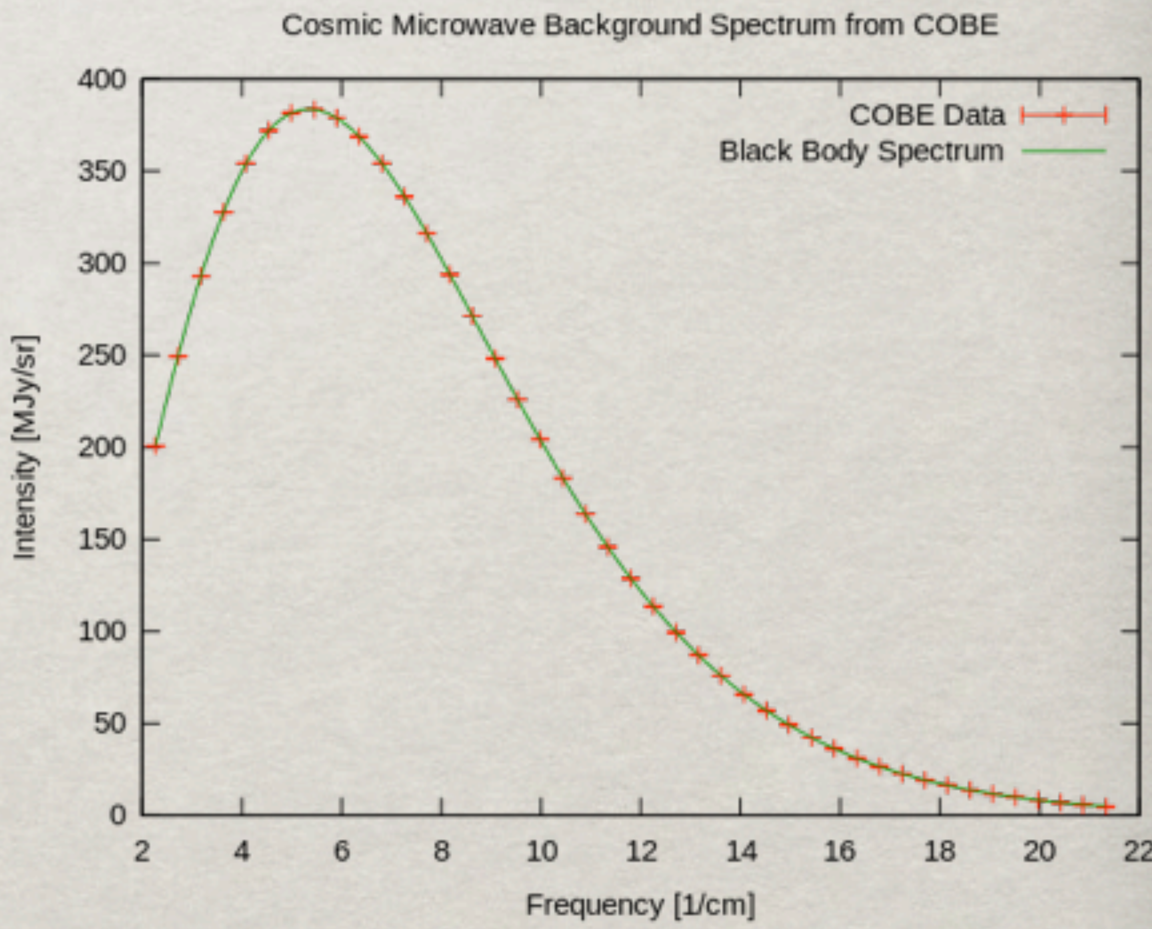
O satélite COBE
(COsmic Background Explorer)
é lançado com o objectivo de medir as propriedades da radiação cósmica de fundo com grande precisão.
Inicia uma nova era na Cosmologia:
**a das experiências de alta precisão**.


Dois instrumentos fundamentais:
- FIRAS (Far InfraRed Absolute Spectrophotometer) vai medir o espectro da RCF (Mather)
- DMR (Differential Microwave Radiometer) vai mapear as anisotropias da RCF; (Smoot)

# “Timeline”:

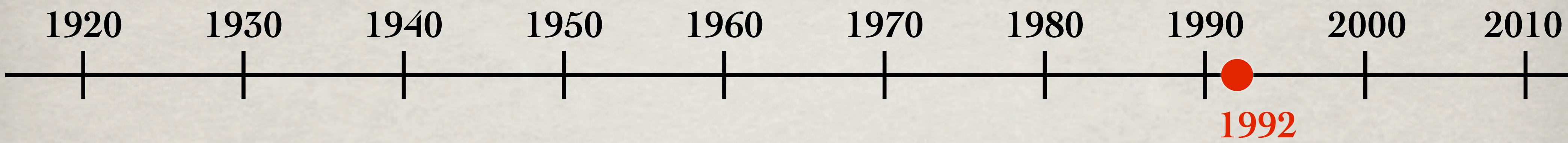



O resultado do FIRAS demonstrou que a RCF tem um espectro praticamente perfeito de radiação de corpo negro com temperatura 2.73ºK.

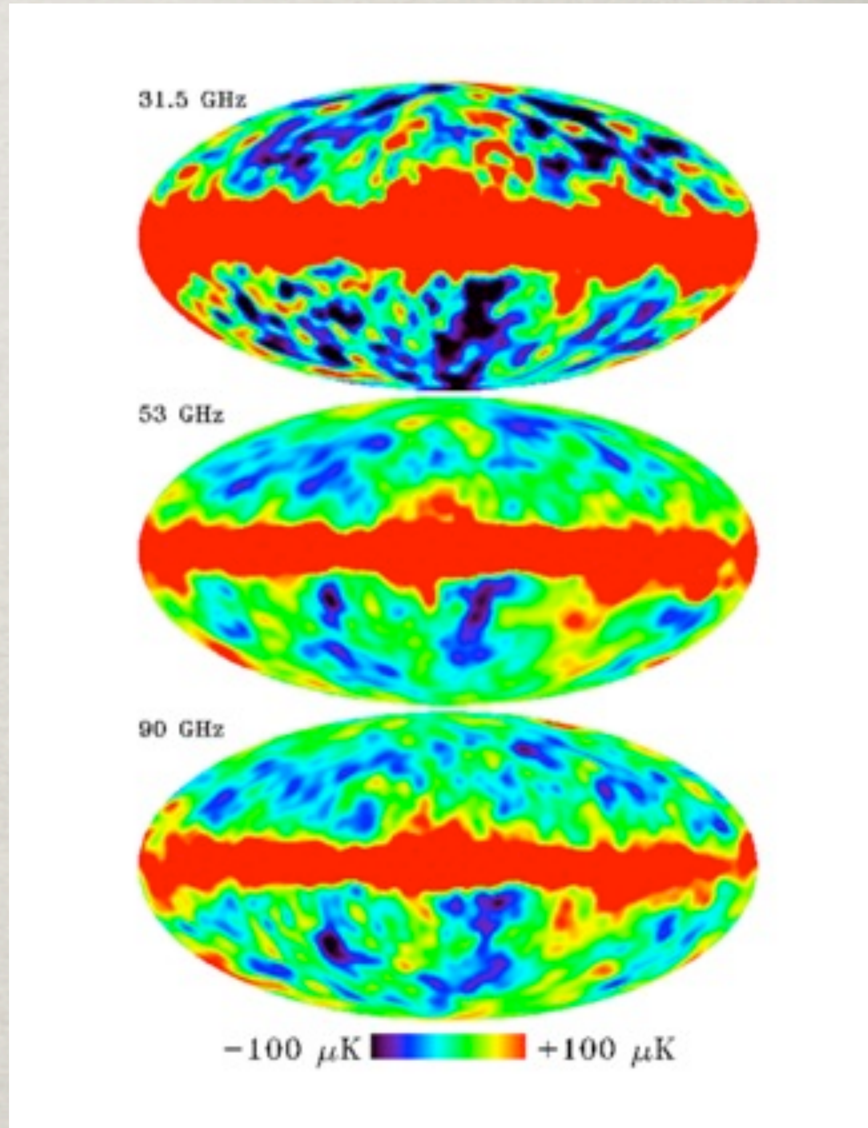



J. C. Mather, et al. (1990). "A Preliminary Measurement of the Cosmic Microwave Background Spectrum by the Cosmic Background Explorer (COBE) Satellite". *The Astrophysical Journal* 354: L37–40

# "Timeline":




O resultado do DMR exibiu flutuações (**anisotropias**) da RCF de cerca de 1 parte em 100 000 relativamente à temperatura média de 2.73ºK.

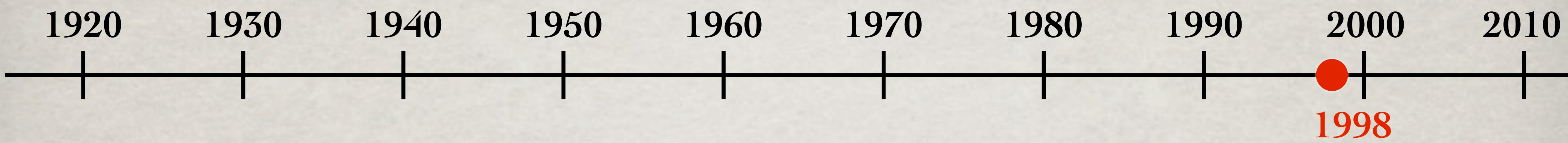



Smoot, G.F.; *et al.* (September 1992). "Structure in the COBE differential microwave radiometer first-year maps". *Astrophysical Journal* **396** (1): L1–L5

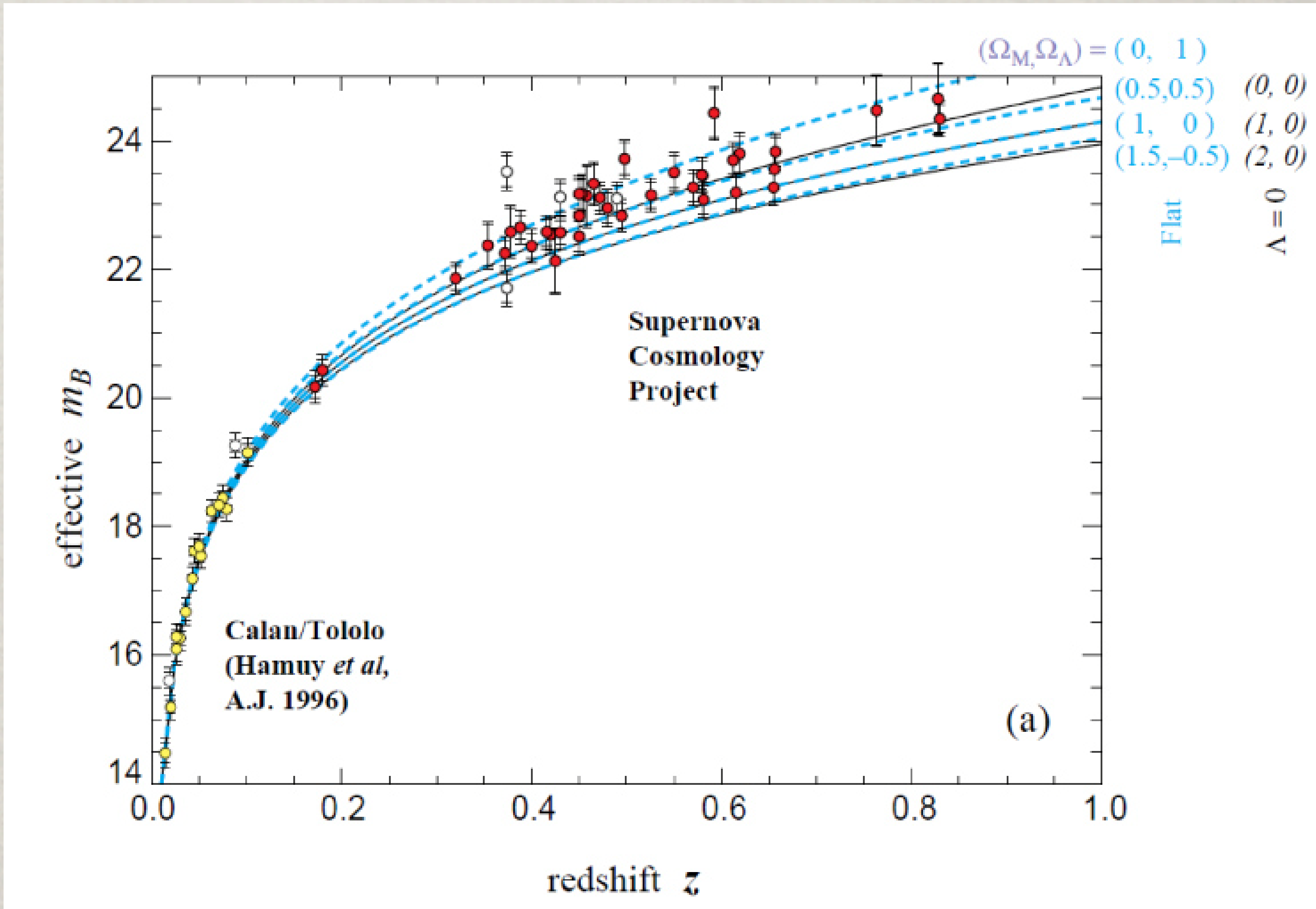
# Aula 2

## Introdução e perspectiva histórica (cont.)

# "Timeline":




Duas equipas independentes publicam evidência, usando supernovas Ia, que a **expansão do Universo é acelerada**.




**Riess, A., et al.** (1998) Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant, Astronomical Journal, 116, 1009-1038.
**Perlmutter, S., et al.** (1999) Measurment of Ω and Λ from 42 High-Redshift Supernovae, Astrophysical Journal, 517, 565-586.

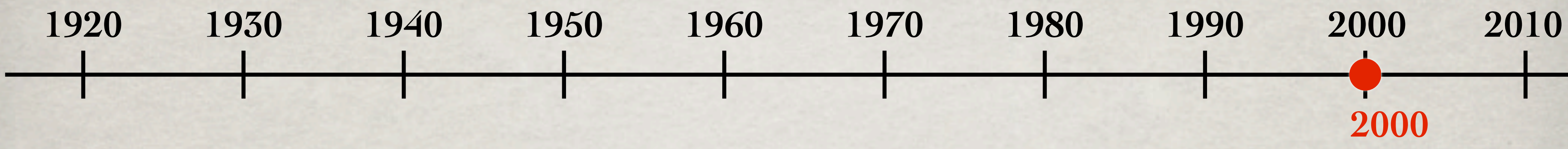
# “Timeline”:

1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

**2000**

Início da “**Sloane Digital Sky Survey**”, um varrimento do céu com um telescópio dedicado (2.5 metro grande angular, telescópio óptico do Observatório Apache Point, Novo México, EUA.

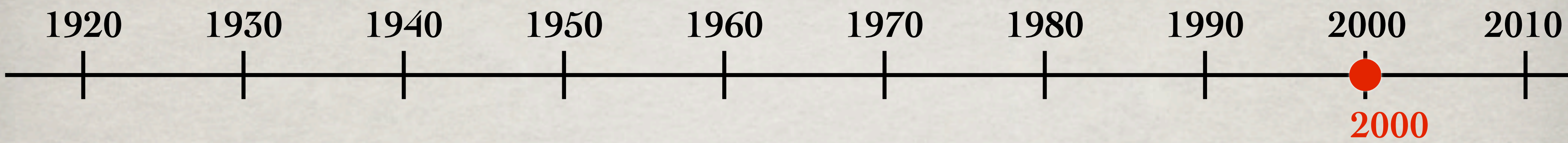
# “Timeline”:



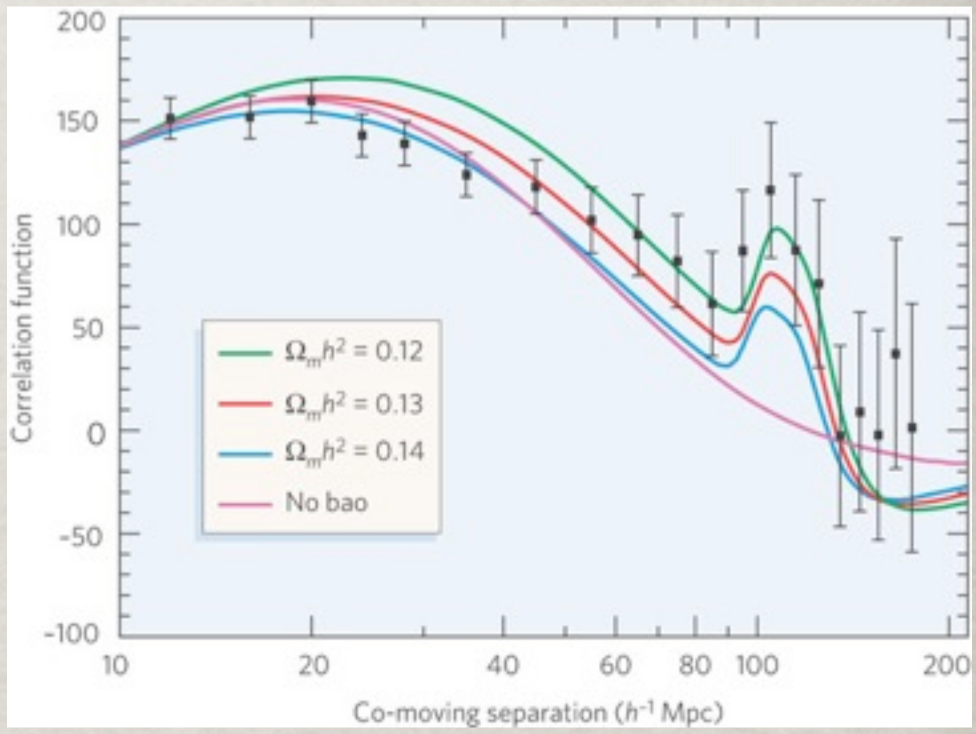

Início da “**Sloane Digital Sky Survey**”, um varrimento do céu com um telescópio dedicado (2.5 metro grande angular, telescópio óptico do Observatório Apache Point, Novo México, EUA.

Até 2011, catalogou observações fotométricas de 500 milhões de objectos e espectros de mais de um milhão, até quasares com z=6.

# "Timeline":




Ao calcular a probabilidade de encontrar uma galáxia a uma dada distânica de outra, encontrou um pico que é interpretado como a escala do **horizonte acústico (hoje - 150 Mpc)**. Este horizonte é uma manifestação das **Baryon Acoustic Oscillations (BAO)**.




D.J. Eisenstein et. al. "Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies" The Astrophysical Journal. 633, 560 (2005).

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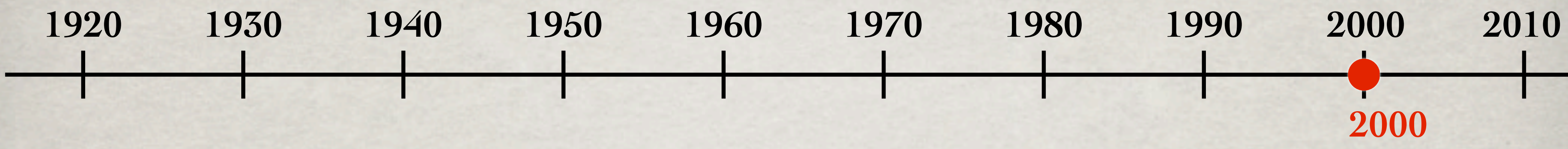
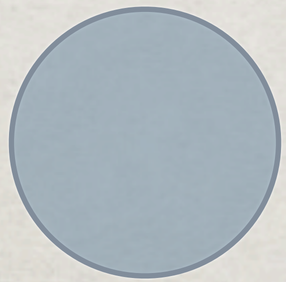
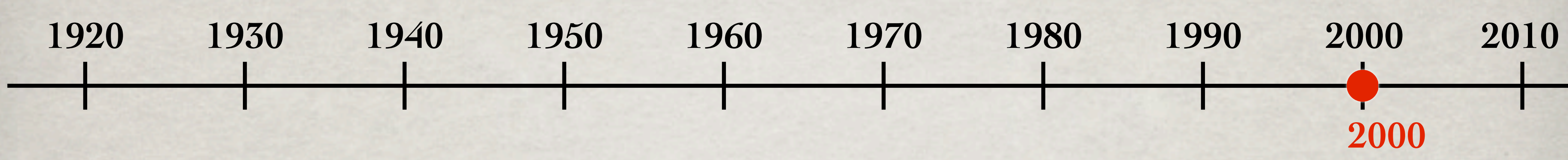
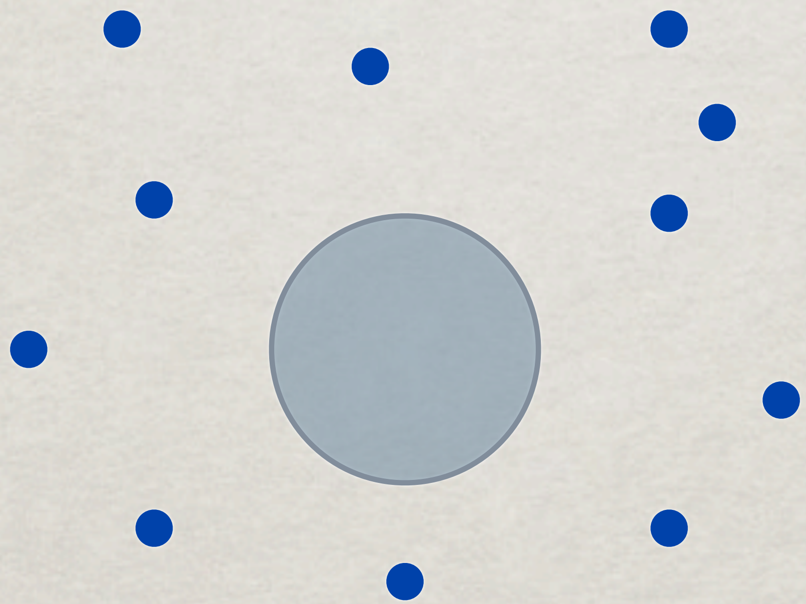


Região de sobre-densidade
(devido a matéria escura)

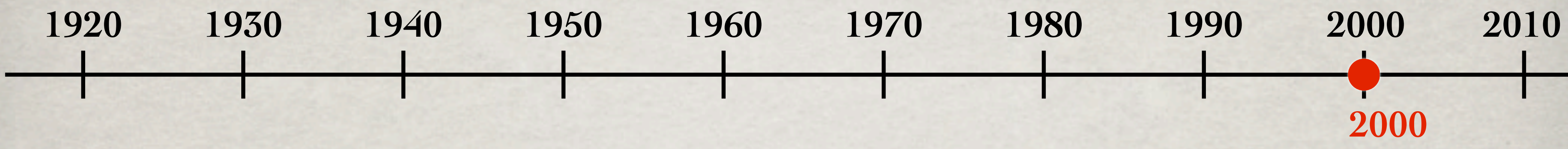
# “Timeline”:

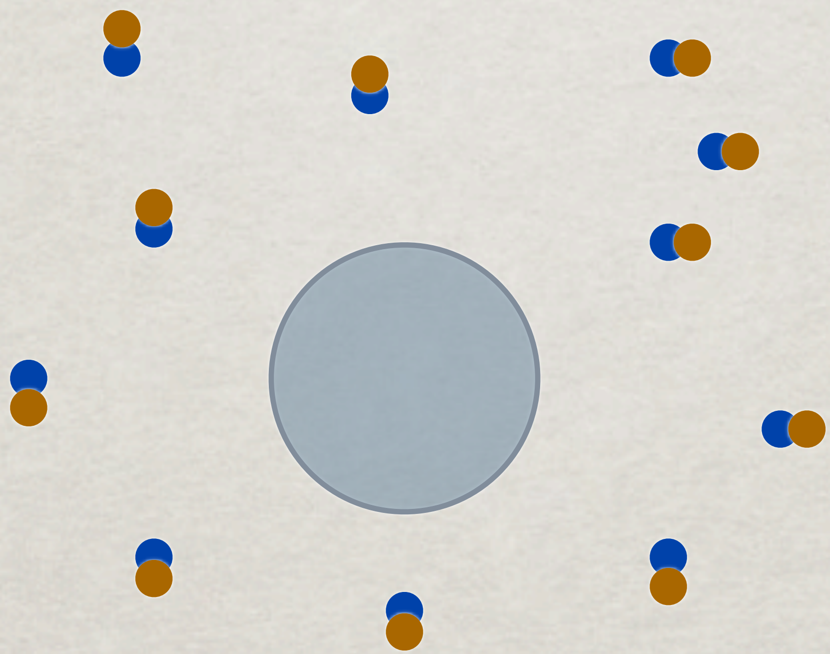


Bariões são atraidos gravitacionalmente para esta região.

# “Timeline”:

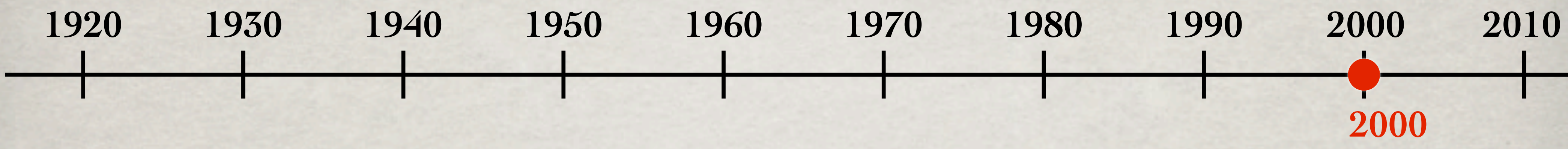


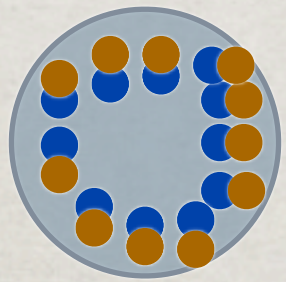



Bariões são atraidos gravitacionalmente para esta região.

Antes do desacoplamento matéria-radiação,
os bariões estão acoplados aos fotões.

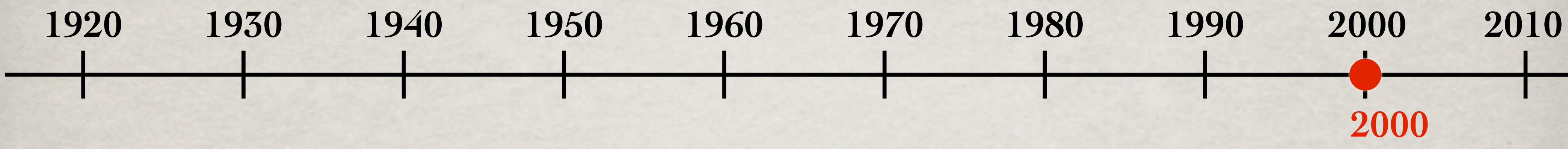
# "Timeline":

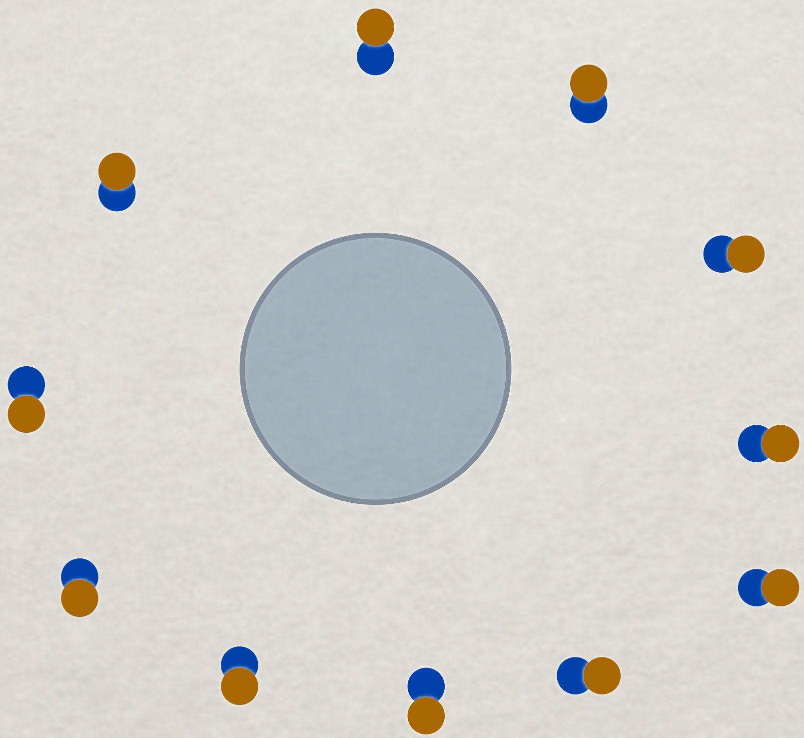


Ao colapsarem gravitacionalmente a pressão de radiação aumenta e domina, originando uma expansão.

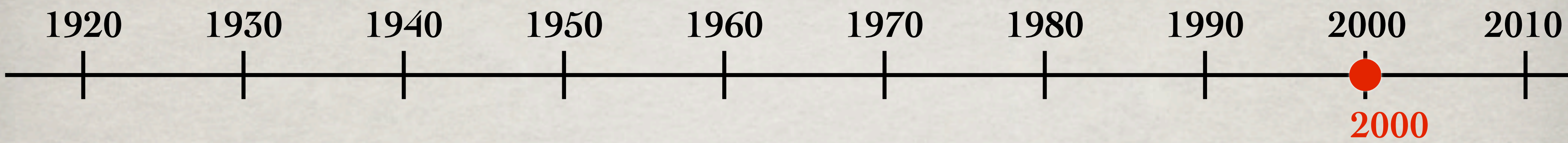
# "Timeline":

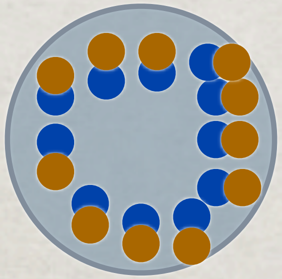


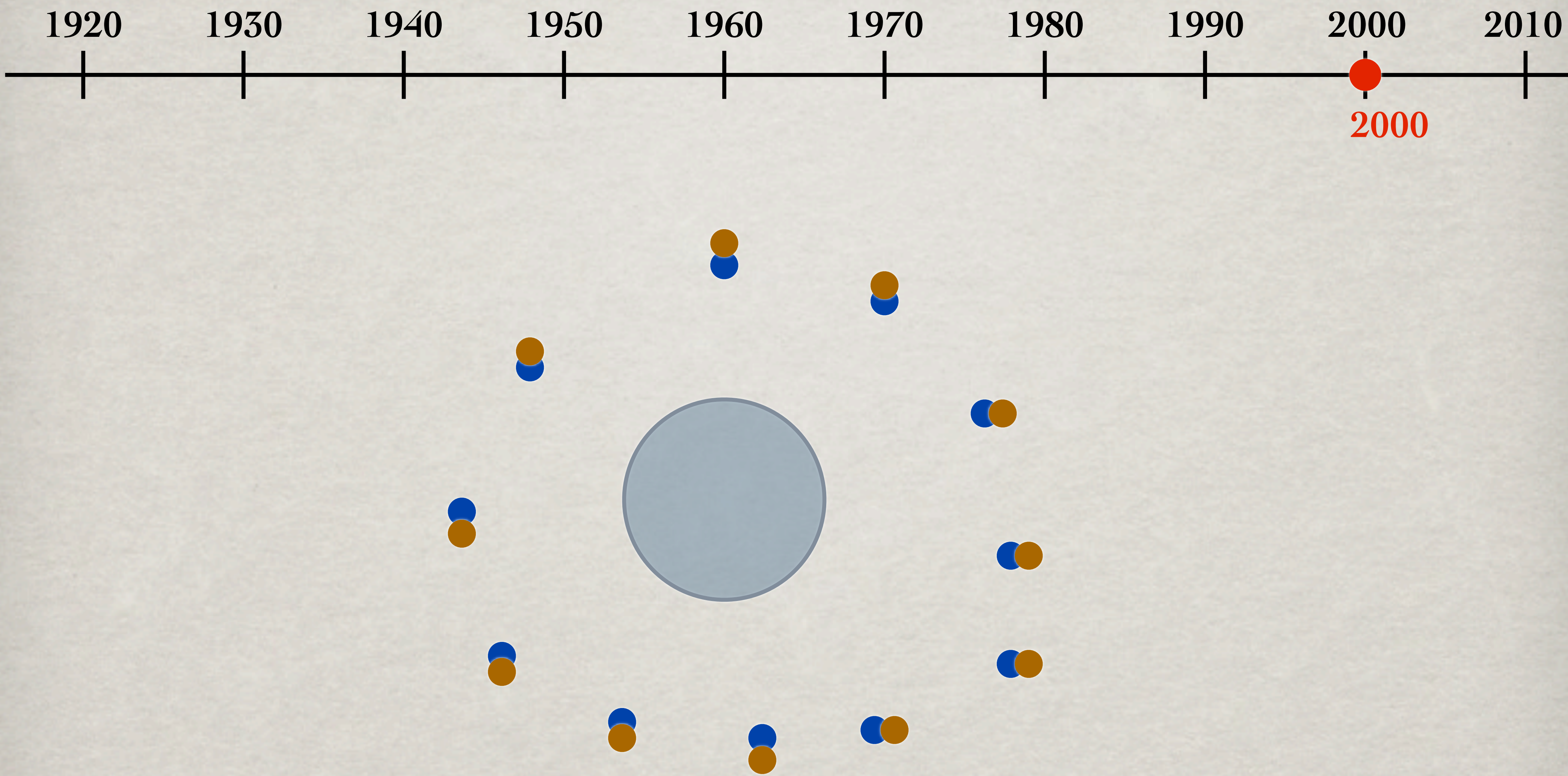
A expansão continua até a pressão da radiação se tornar subdominante relativamente à atração gravitacional dos bariões. Resulta assim um processo de oscilações acústicas bariónicas (BAO).

# "Timeline":

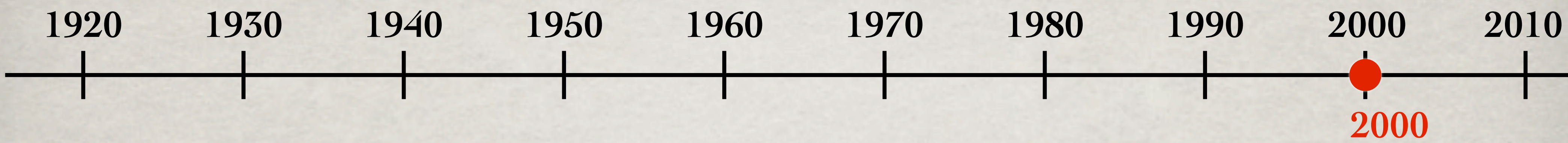


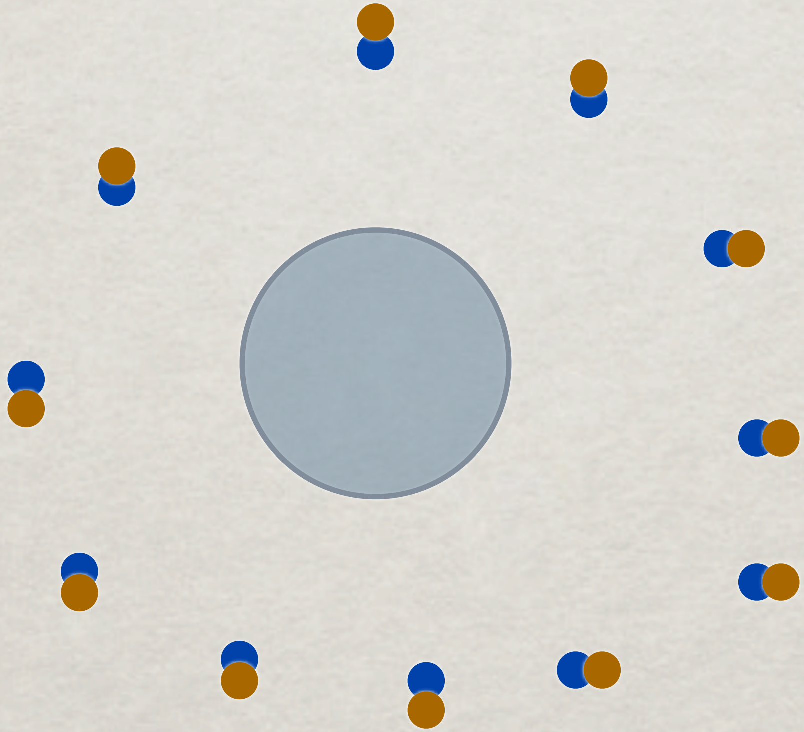



# “Timeline”:



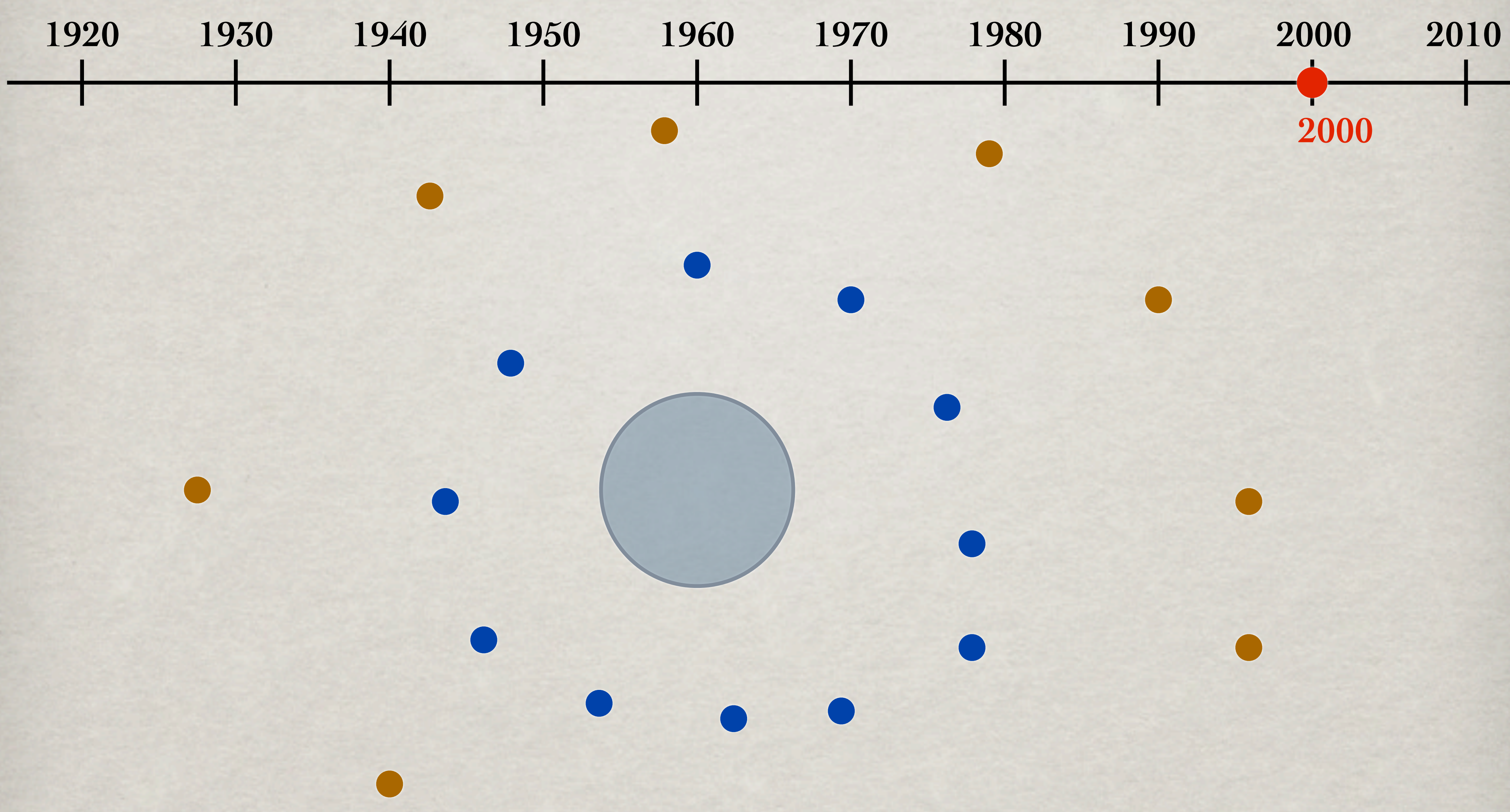
# “Timeline”:



Quando a radiação desacopla dos bariões (e é emitida a radiação cósmica de fundo, resulta um “snapshot” destas oscilações - que são visíveis na radiação cósmica de fundo.

# “Timeline”:

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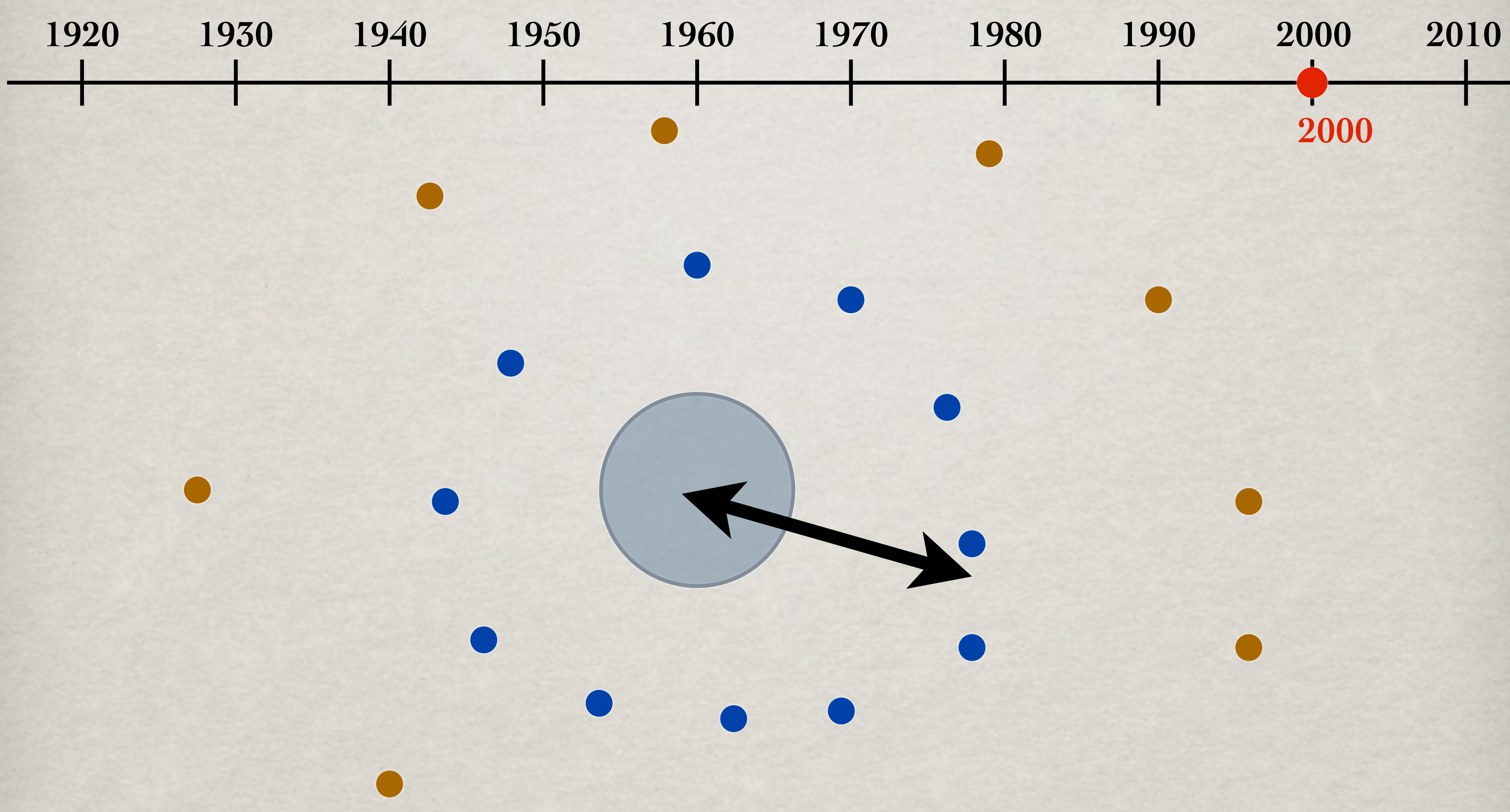



Em particular fica marcada na radiação cósmica de fundo uma escala - a do horizonte acústico na altura do desacoplamento.

# "Timeline":

1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

2000

Publicação dos dados da experiência BOOMERanG (Balloon Observations of Millimetric Extragalactic Radiation and Geomagnetics), um telescópio de microondas, lançado em Dezembro de 1998 e transportado a uma altitude de cerca de 38 km, sobre a Antártida, por um balão.

# "Timeline":

1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

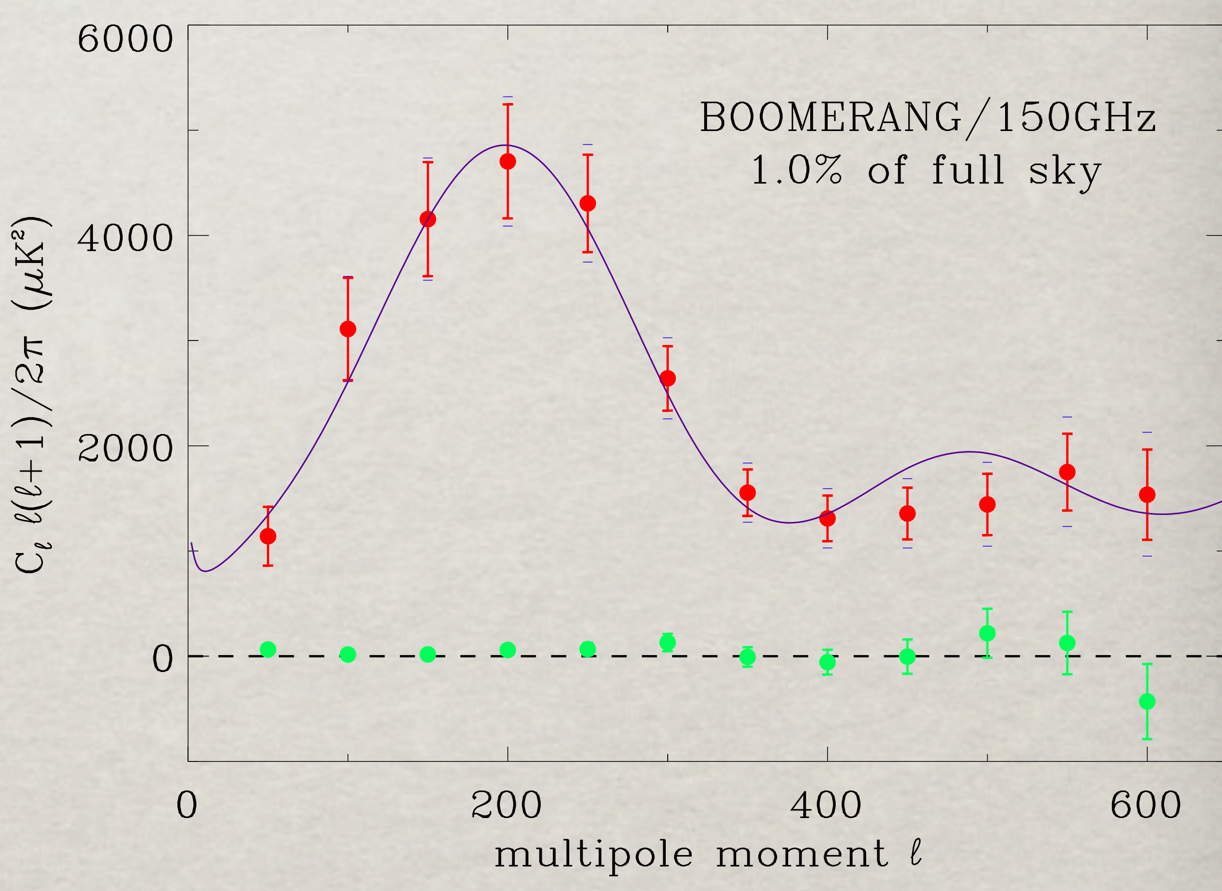
2000

Analizando as flutuações de temperatura em pares (correlador de dois pontos) e expressando-a numa expansão multipolar

$$\langle \delta T(\hat{n}) \delta T(\hat{n}') \rangle = \sum_{\ell} \frac{(2\ell+1)}{4\pi} C_\ell P_\ell(\cos\theta)$$

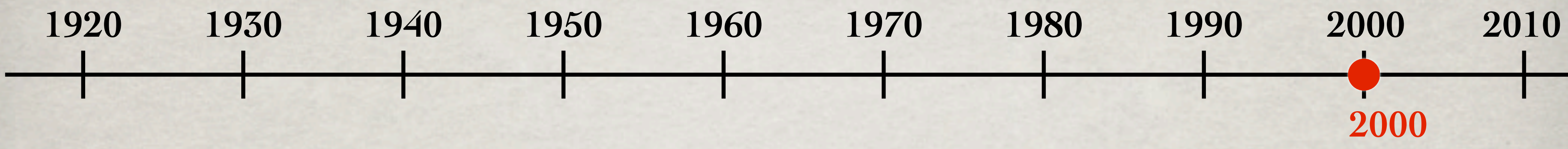
o espectro angular de potências revela um pico com

$$\ell_{pico} = 197 \pm 6$$



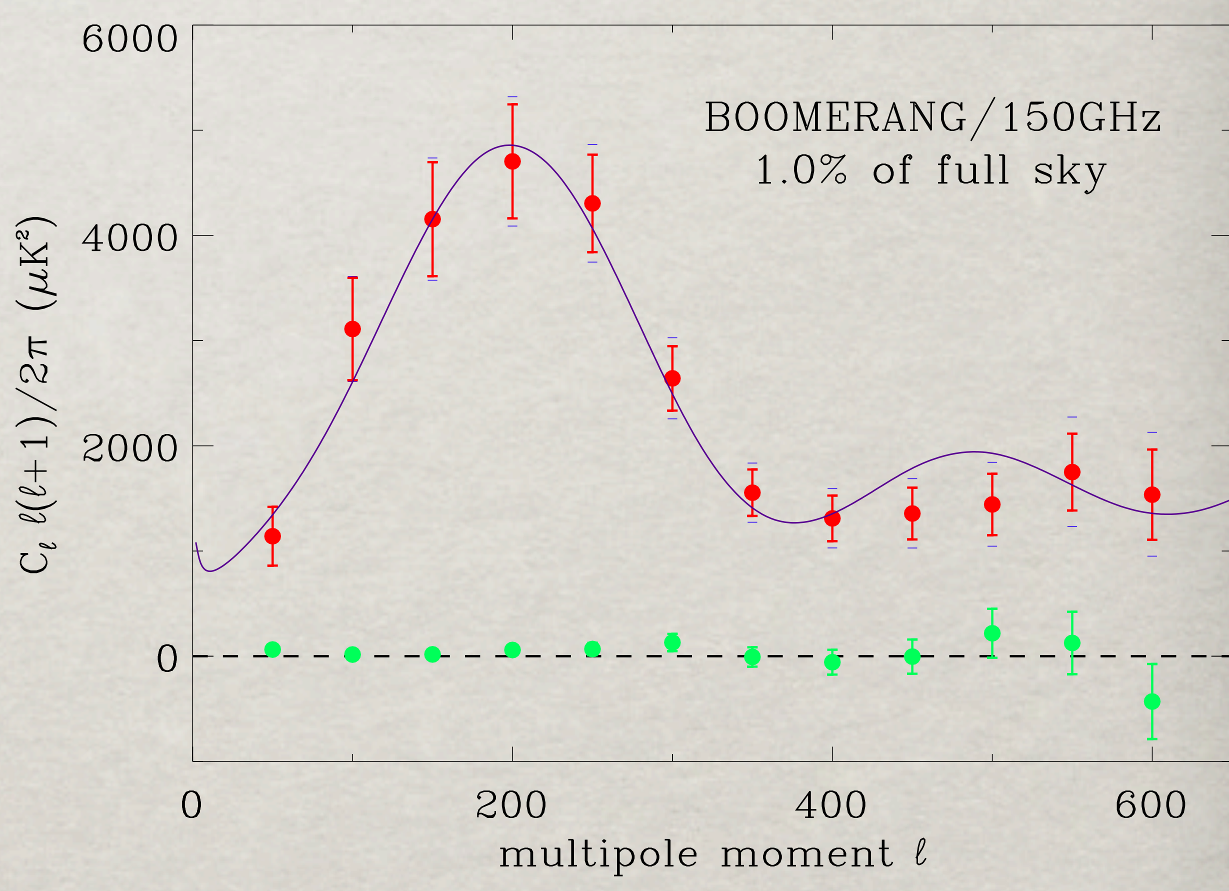

P. de Bernardis et. al. "A flat Universe from High resolution Maps of the Cosmic Microwave Background Radiation" Nature 404 (2000) 955-959

# "Timeline":




- Apoia modelos de matéria escura;

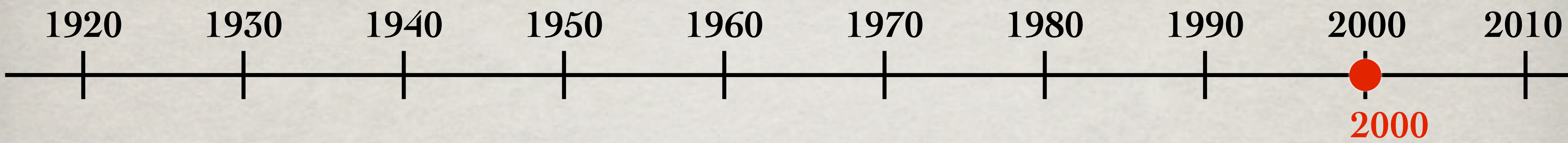
- Restringe parâmetros cosmológicos, dado que esta escala aparente no céu depende da escala física original mais a evolução do Universo ("distância" até nós)



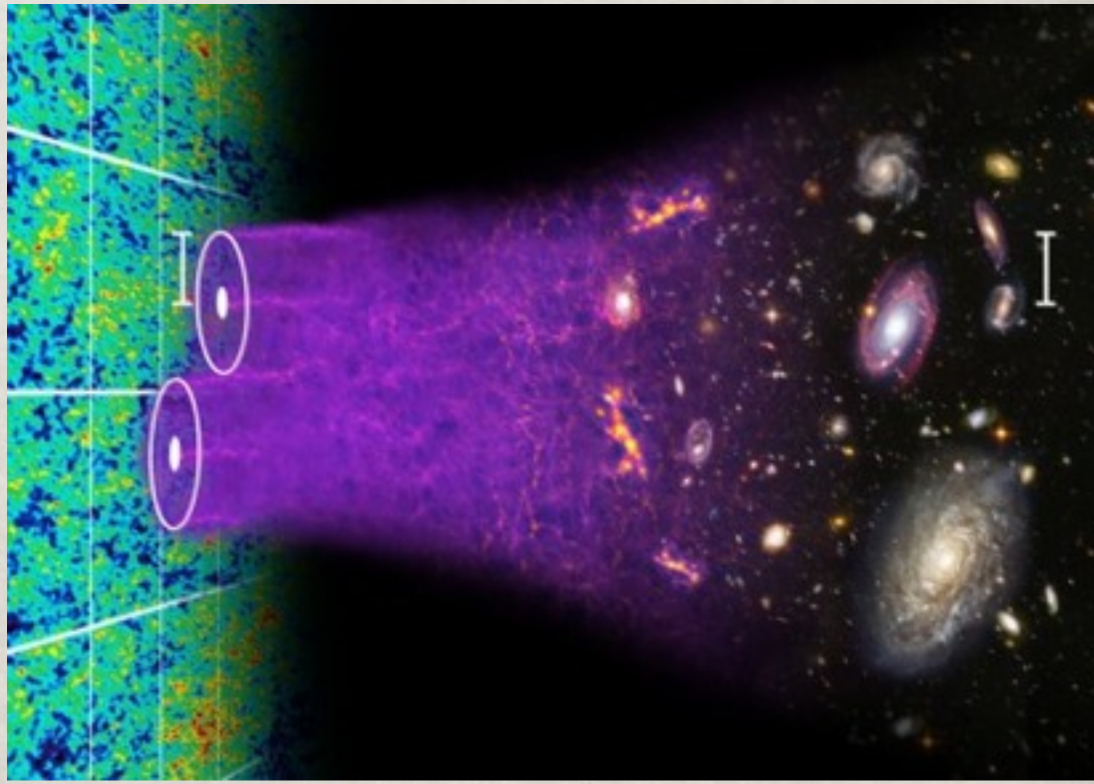

$$\ell \propto 1/\theta \qquad \theta_{HA} = \frac{r_{HA}}{d_{SLS}}$$

P. de Bernardis et. al. "A flat Universe from High resolution Maps of the Cosmic Microwave Background Radiation" Nature 404 (2000) 955-959

# “Timeline”:




Comparando a escala do horizonte acústico na recombinação - através do sinal presente na RCF -, com a escala do horizonte acústico na distribuição de galáxias obtém-se uma restrição para  a evolução do Universo  independente das supernovas.



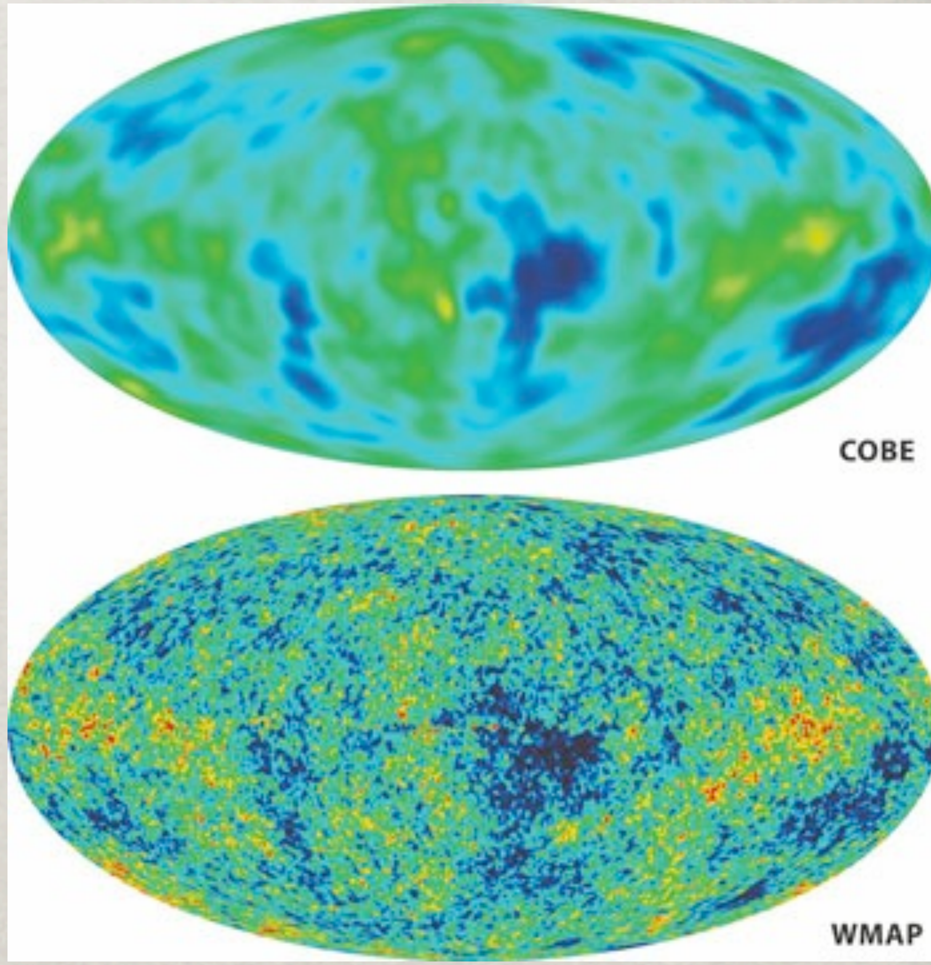
D.J. Eisenstein et. al. “Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies” The Astrophysical Journal. 633, 560 (2005).

# “Timeline”:

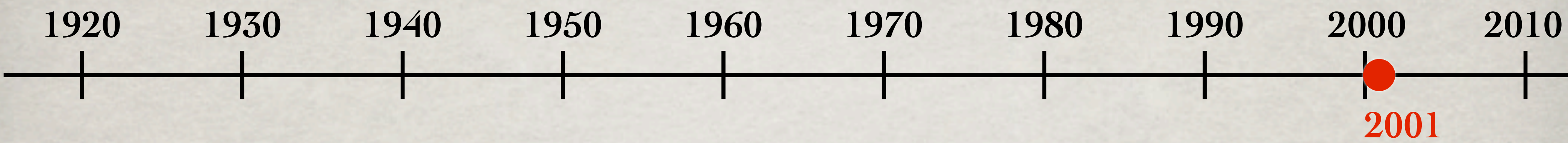
1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

2001

Foi lançado o satélite WMAP (Wilkinson Microwave Anisotropy Probe) para medir as anisotropias da RCF com 45 vezes a sensibilidade e 33 vezes a resolução angular do COBE.



# "Timeline":

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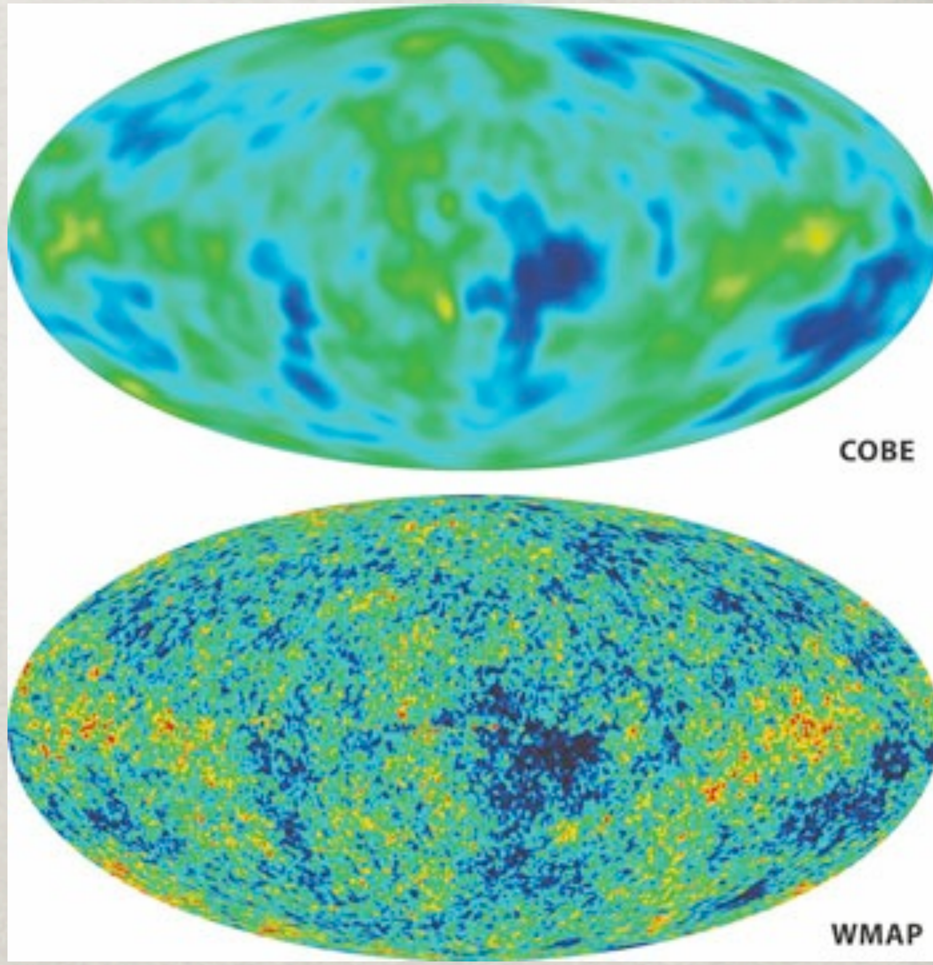
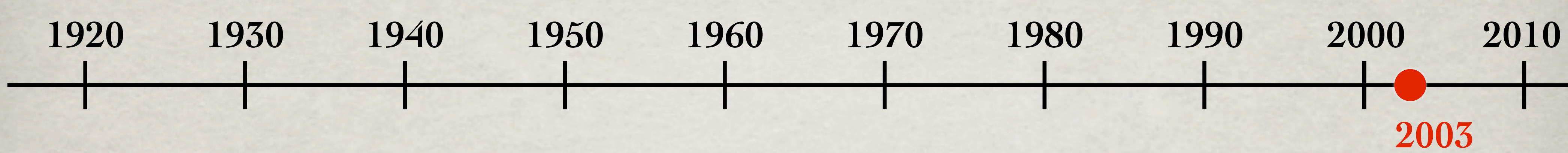
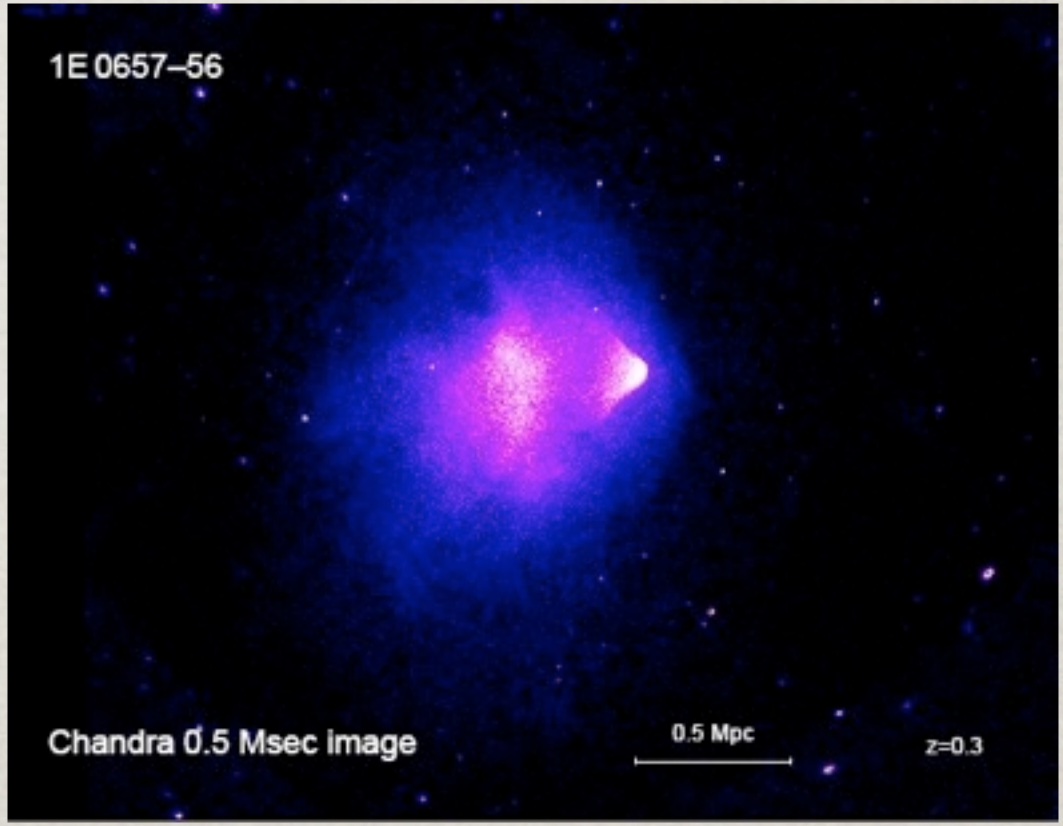



Durante os anos seguintes foram lançados dados com 1,3,5 e 7 anos que foram centrais em establecer o **modelo Lambda-CDM** para o Universo.

# “Timeline”:



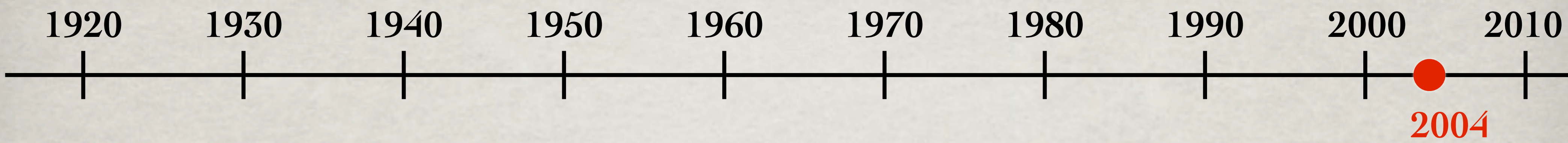

Evidência observacional do “Bullet Cluster” fornece a mais forte evidência para a matéria escura:



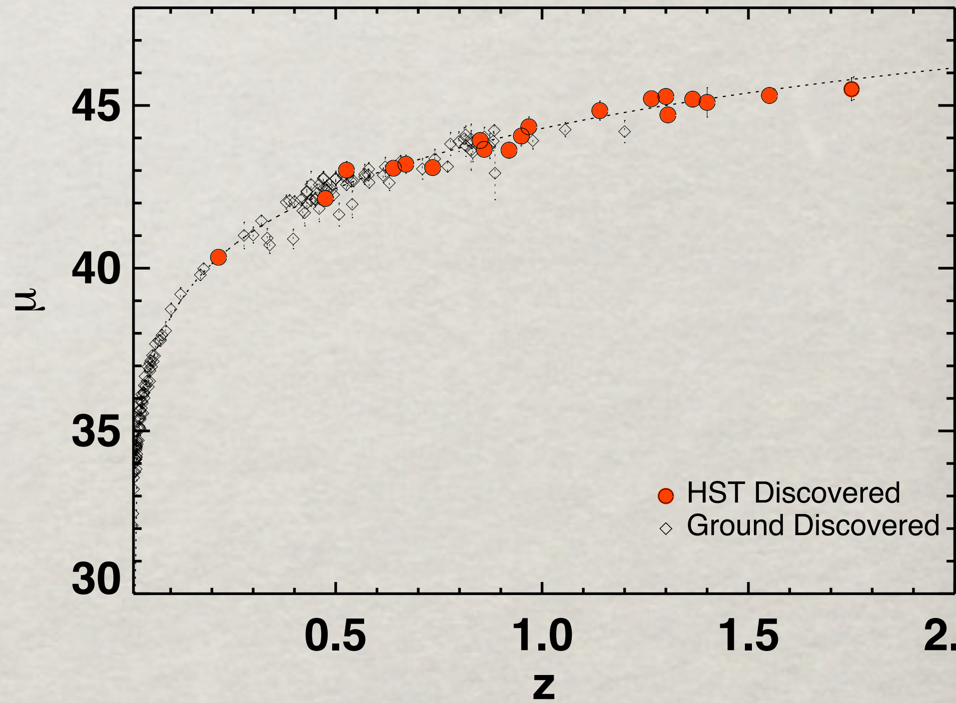

Fotografia (em rais X) do “Bullet Cluster” (1E0657-56) obitada pelo Chandra X-ray Observatory. A exposição foi de aproximadamente 140 horas e a escala mostrada é em megaparsecs. O redshift é ($z$) = 0.3, o que signifa que a luz tem comprimentos de onda esticados por um factor de 1.3. De acordo com os modelos de hoje o cluster está a 4 mil milhões de anos luz de distância.

M. Markevitch, A. H. Gonzalez, D. Clowe, A. Vikhlinin, L. David, W. Forman, C. Jones, S. Murray, and W. Tucker (2003). "Direct constraints on the dark matter self-interaction cross-section from the merging galaxy cluster 1E0657-56". *Astrophys.J.* **606** (2): 819–824

# "Timeline":

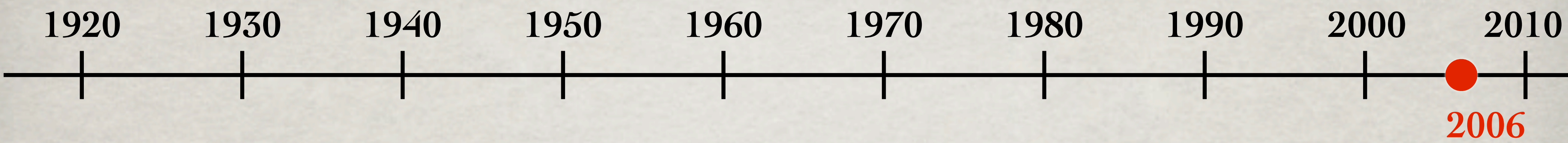



Um estudo pelo "Supernova Cosmology Project", usando o Hubble Space Telescope, encontra evidência para uma **fase de desaceleração** do Universo para z>1.




A.G. Riess et al., "Type Ia supernova discoveries at *z >1* from the Hubble Space Telecope: Evidence for past deceleration and constraints on dark energy evolution", Astrophys. J., **607**, 665-687, (2004)

# "Timeline":

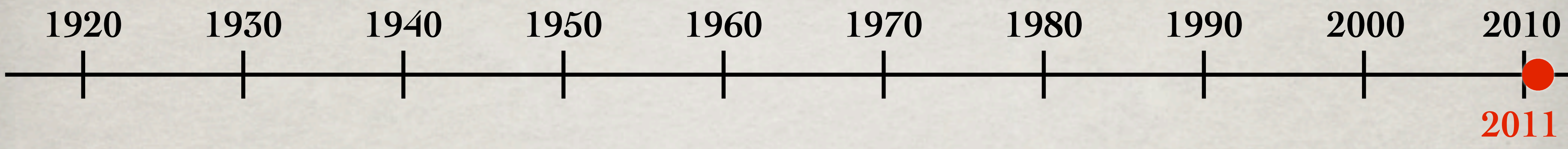



Prémio Nobel
da Física 2006

*"...for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation."*

John C. Mather    George F. Smoot

# “Timeline”:



# “Timeline”:

1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

2011

Prémio Nobel da Física 2011

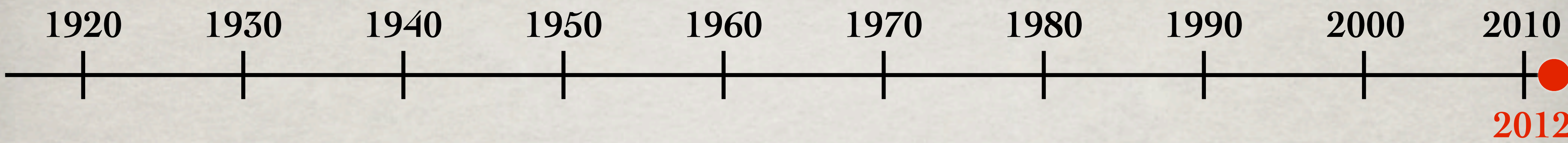
*“...for the discovery of the accelerated expansion of the Universe through observations of distant supernovae...”*

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory
Saul Perlmutter

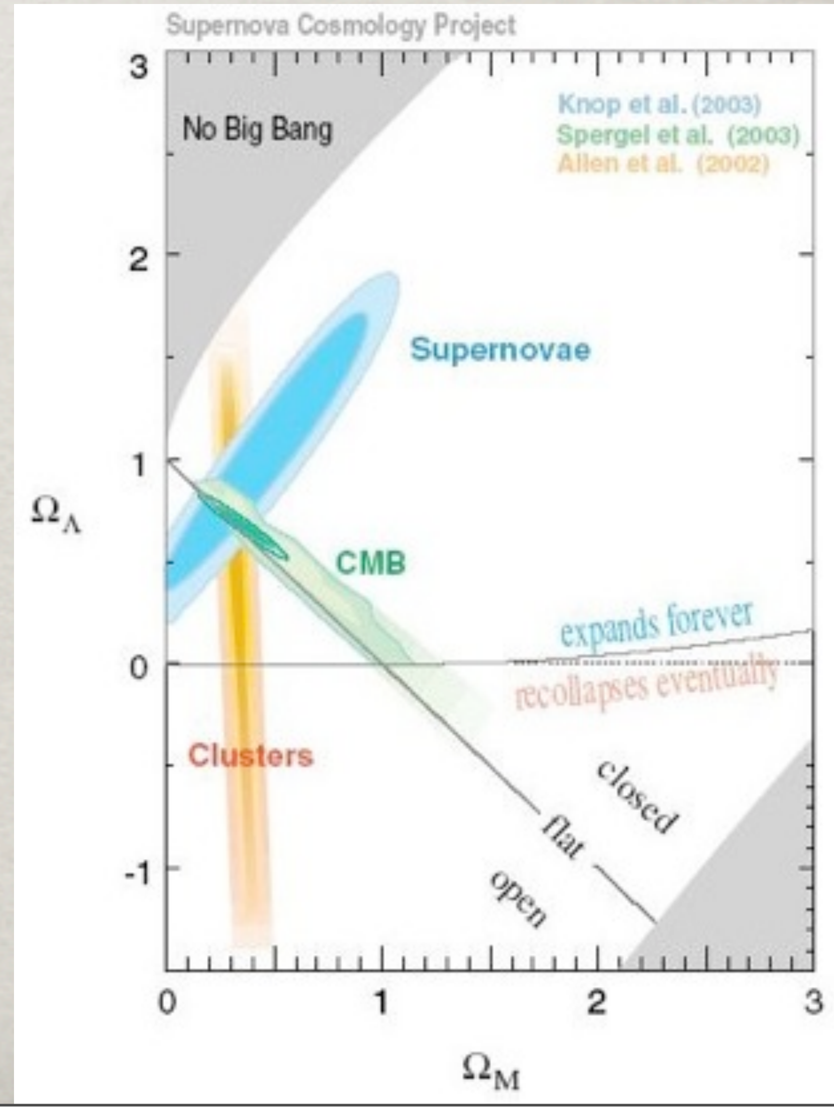
Photo: Belinda Pratten, Australian National University
Brian P. Schmidt

Photo: Homewood Photography
Adam G. Riess

# "Timeline":




Modelo resultante da combinação das observações:
- expansão do Universo (especialmente Supernovas);
- RCF (dados do WMAP)
- Estrutura de larga escala (Sloane digital Survey)



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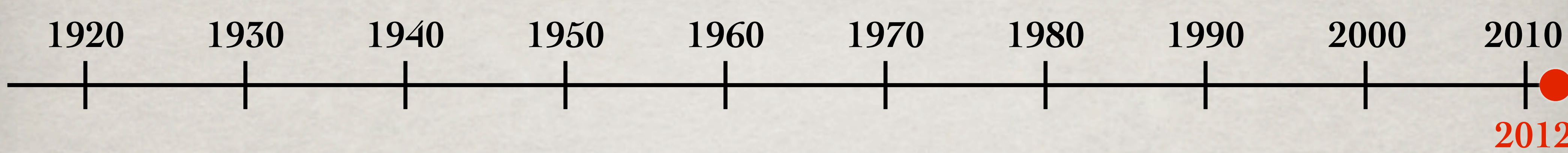


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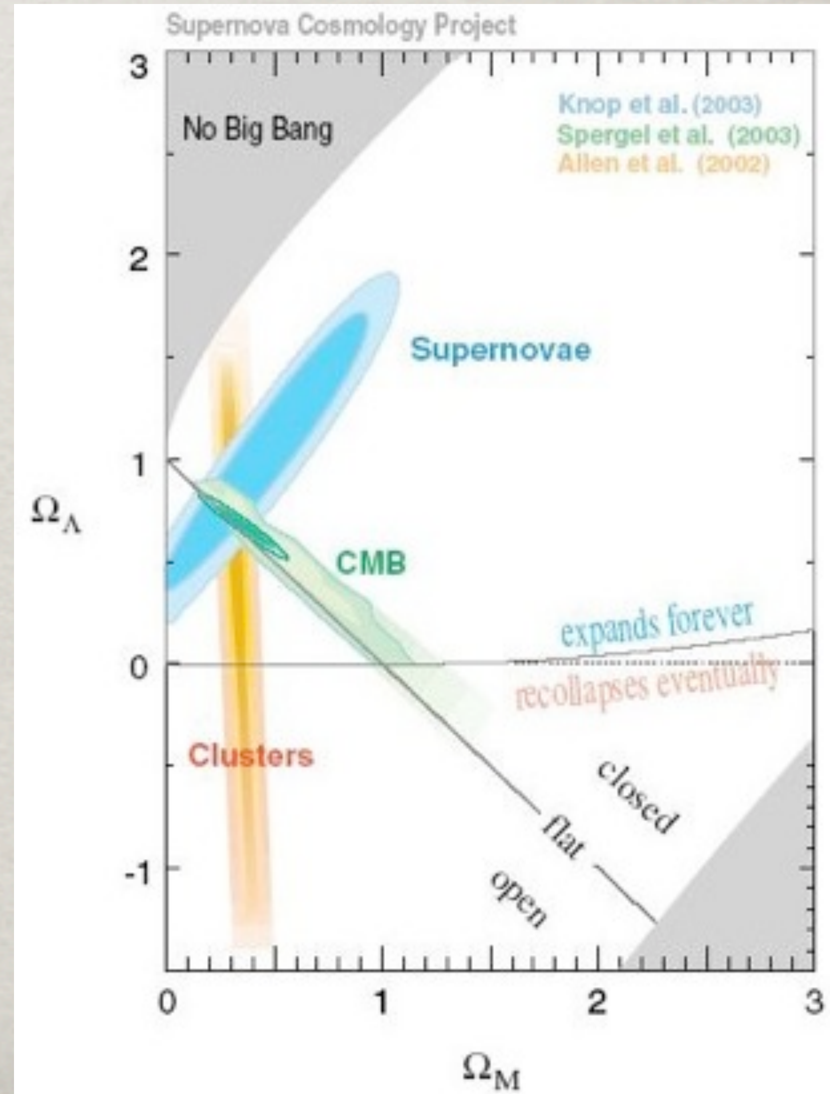


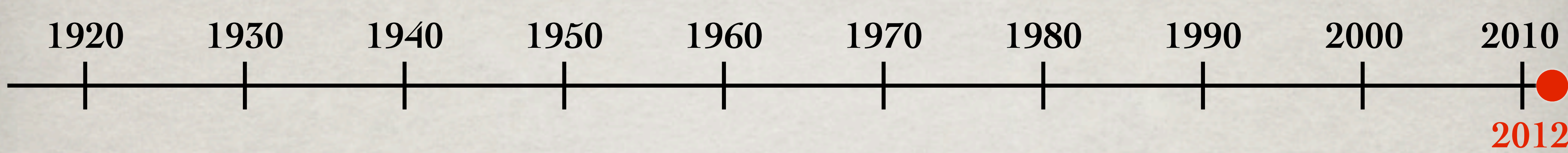

## Modelo Lambda-CDM

Universo Plano

Idade do Universo:
$13.75 \pm 0.11$ Giga anos

Parâmetro de Hubble:
$70.5 \pm 1.3$ km s$^{-1}$ Mpc$^{-1}$

# “Timeline”:

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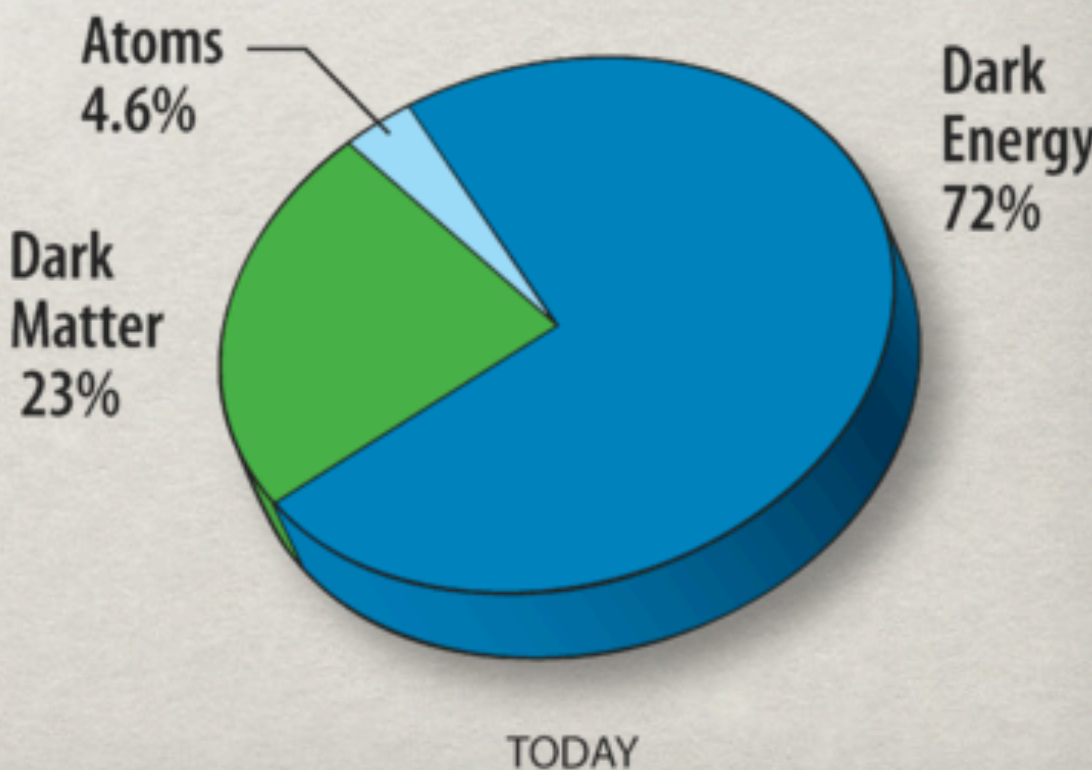
Conteúdo do Universo:



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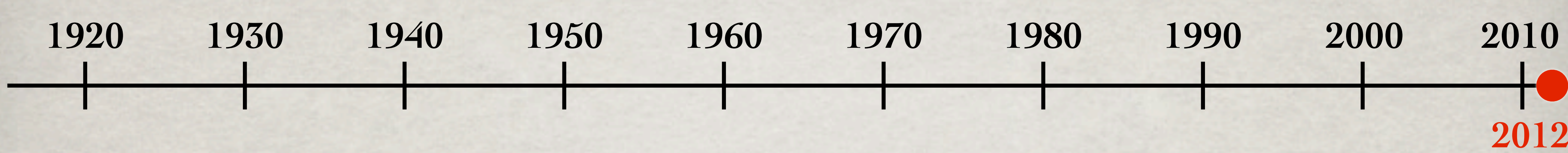


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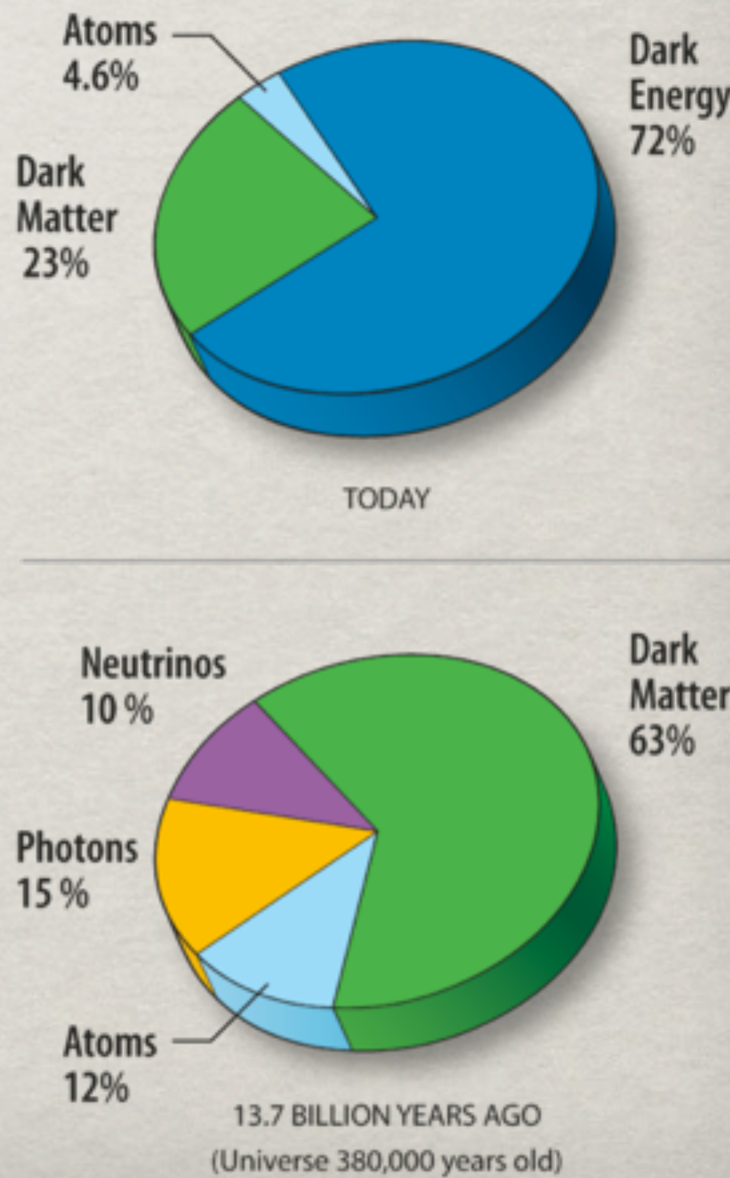


## Modelo Lambda-CDM

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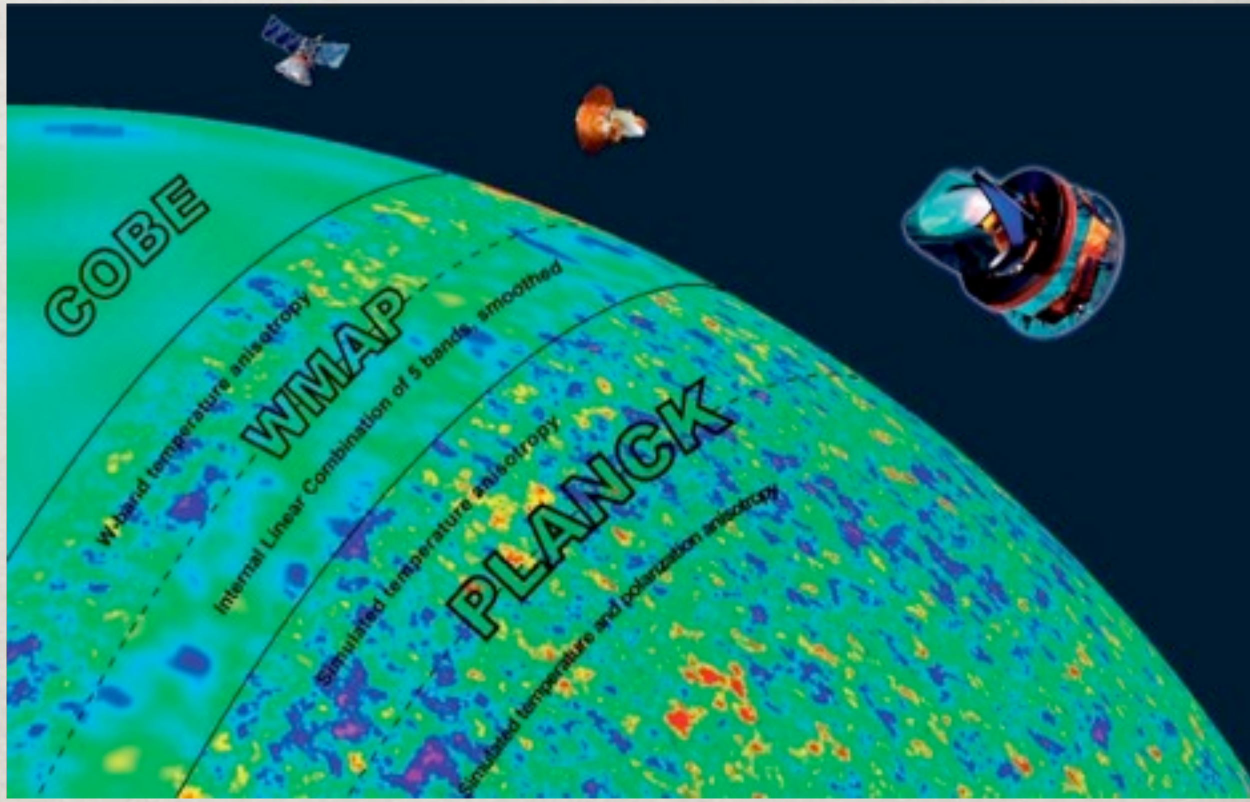
Conteúdo do Universo:

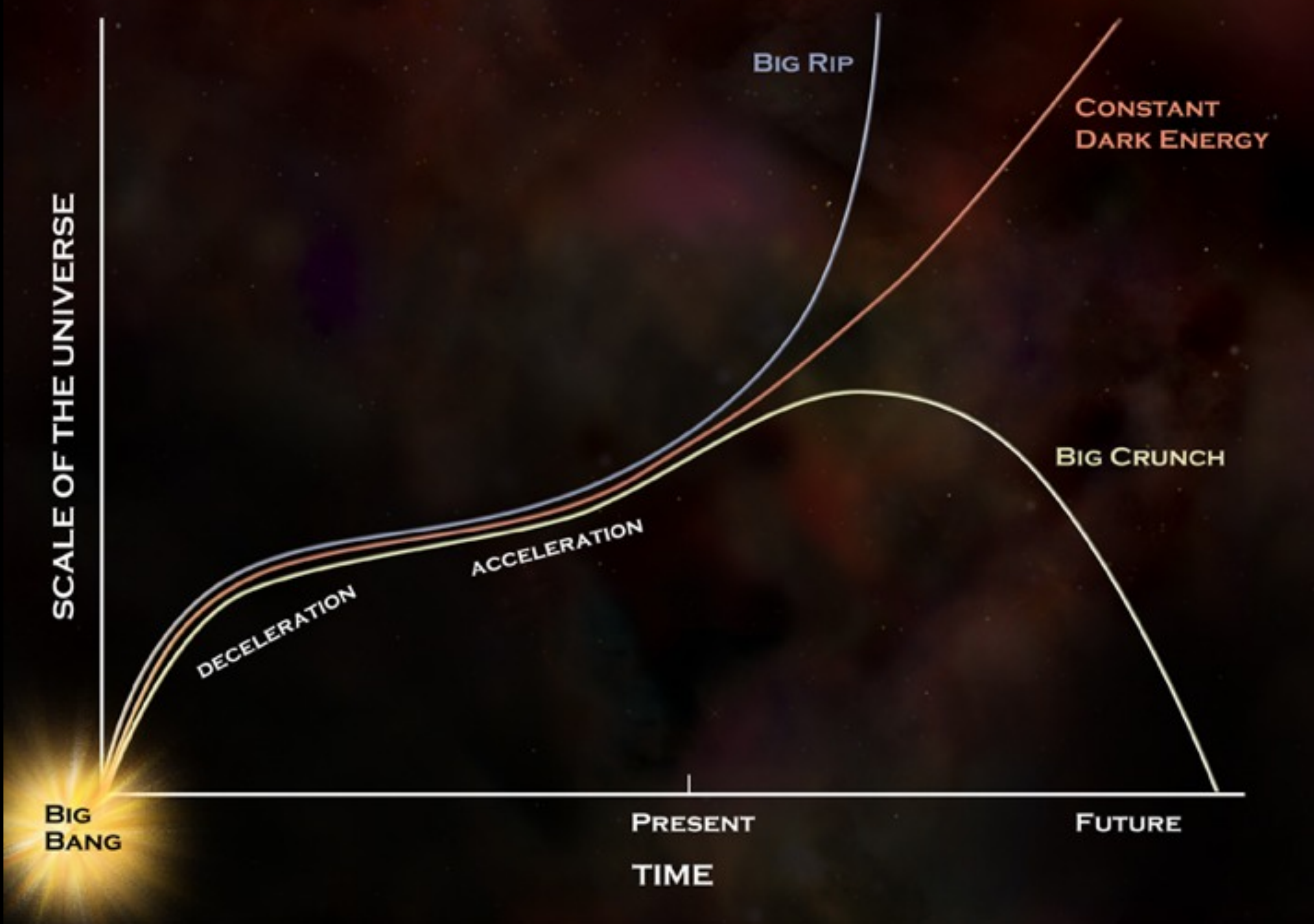
# “Timeline”:

1920 | 1930 | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 | 2000 | 2010 | **2013**

Primeiro anúncio dos resultados cosmológicos do **satélite Planck**, lançado em Maio de 2009. O Planck irá detectar com alta resolução tanto a intensidade como a polarização das anisotropias primordiais da RCF, com 10 vezes a sensibilidade e 3 vezes a resolução em escalas menores que o WMAP.

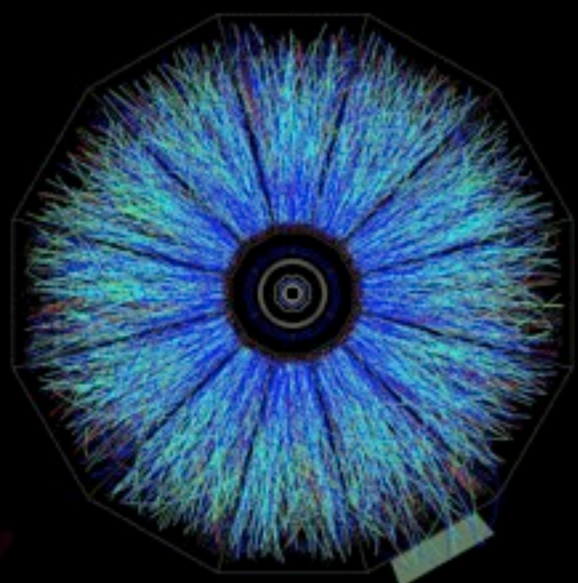


# A evolução do Universo:



O que são a matéria e a energia escura em termos de Física de Partículas ?

# A evolução do extraordinariamente GRANDE…



… é determinada pelo extraordinariamente pequeno !

# As escalas envolvidas são extraordinariamente díspares:

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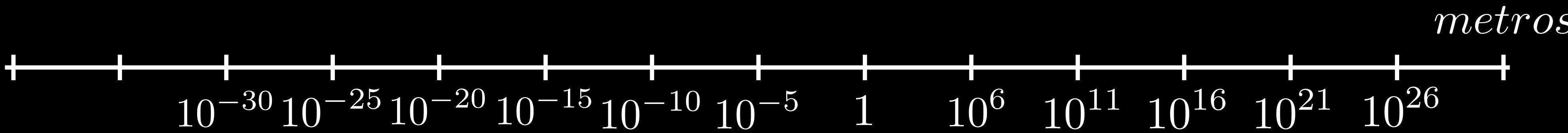
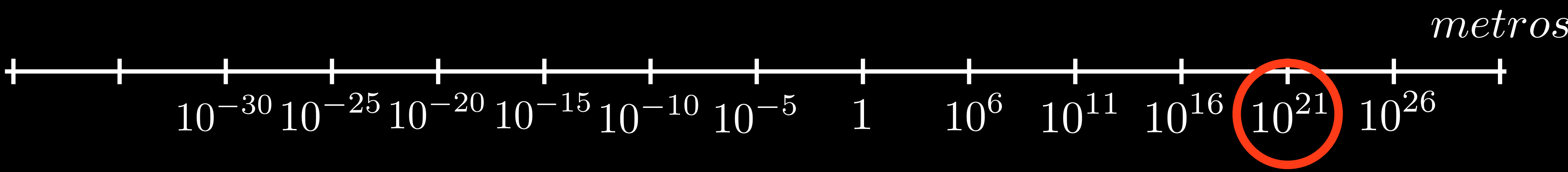


# As escalas envolvidas são extraordinariamente díspares:

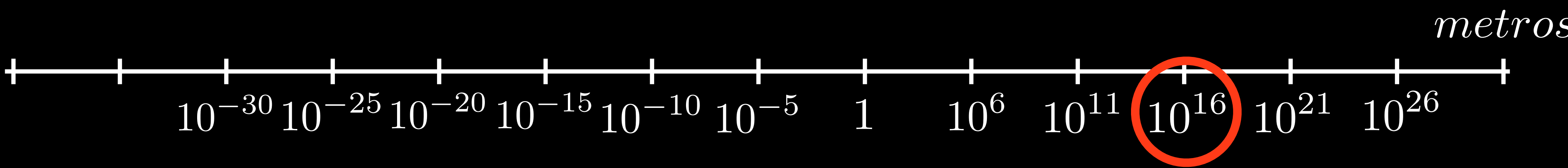
*metros*

$10^{-30}$ $10^{-25}$ $10^{-20}$ $10^{-15}$ $10^{-10}$ $10^{-5}$ $1$ $10^{6}$ $10^{11}$ $10^{16}$ $10^{21}$ $10^{26}$

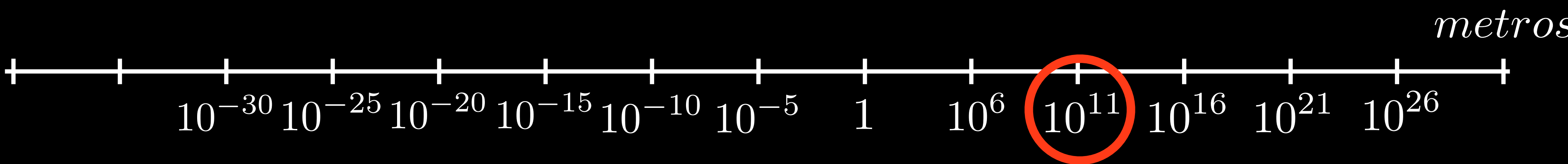
Universo observável
13.7 mil milhões de anos luz



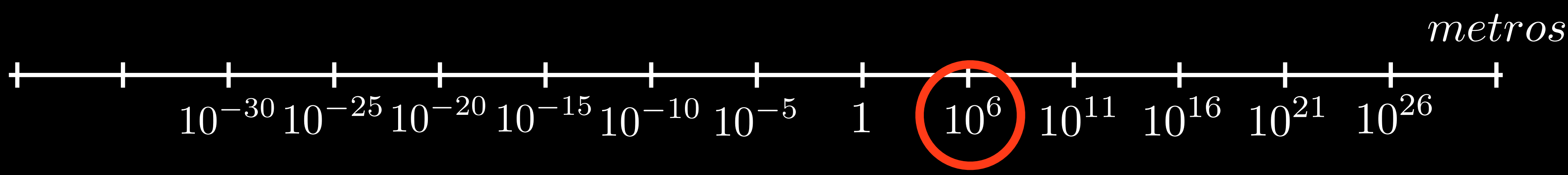

Via Láctea
100 mil de anos luz



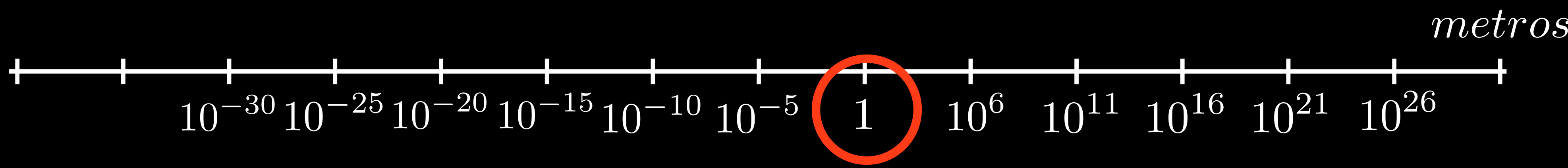

Estrela mais próxima
do Sol, Proxima Centaurus:
4 anos luz



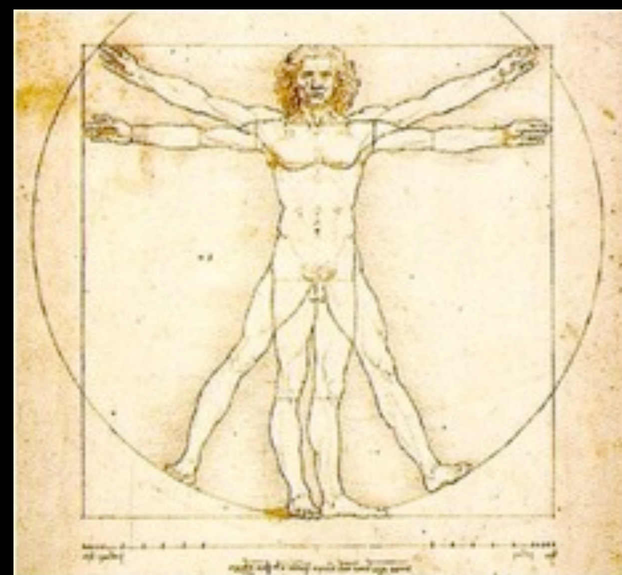

Distância Terra-Sol:
8 minutos luz

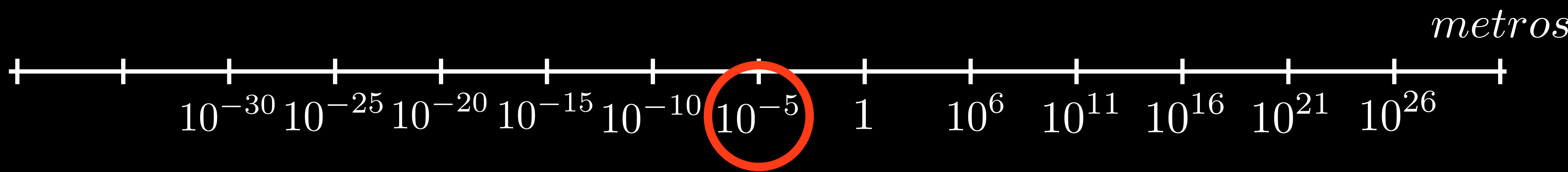



Raio Terra:
6.3 mil kilometros

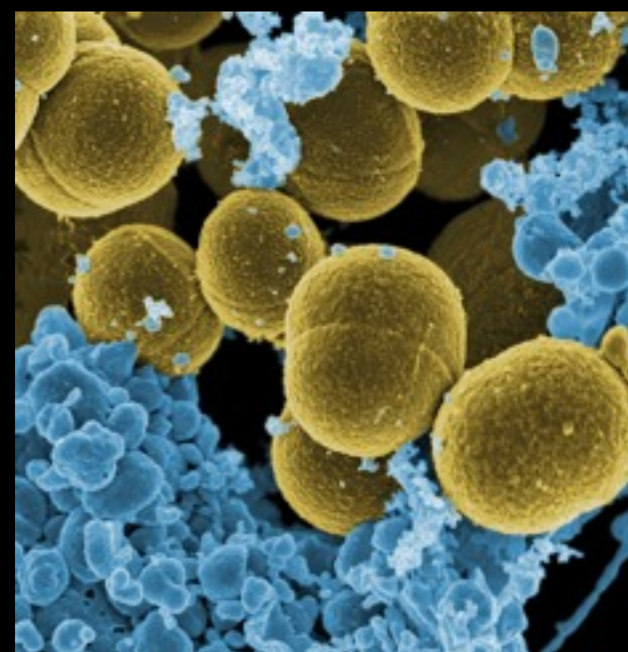


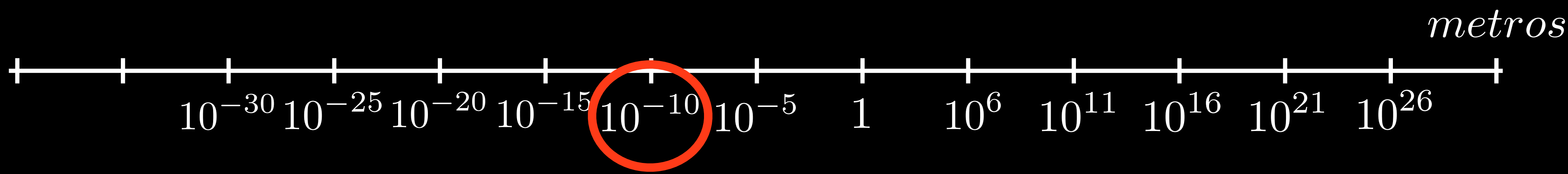

Homem:
1 metro



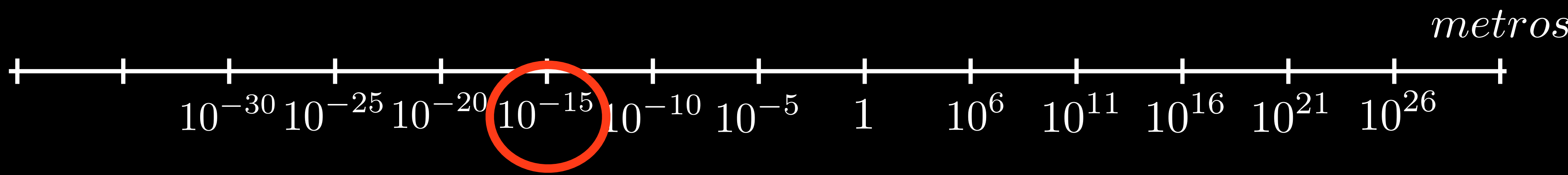



Bactérias:
1-10 micrometros

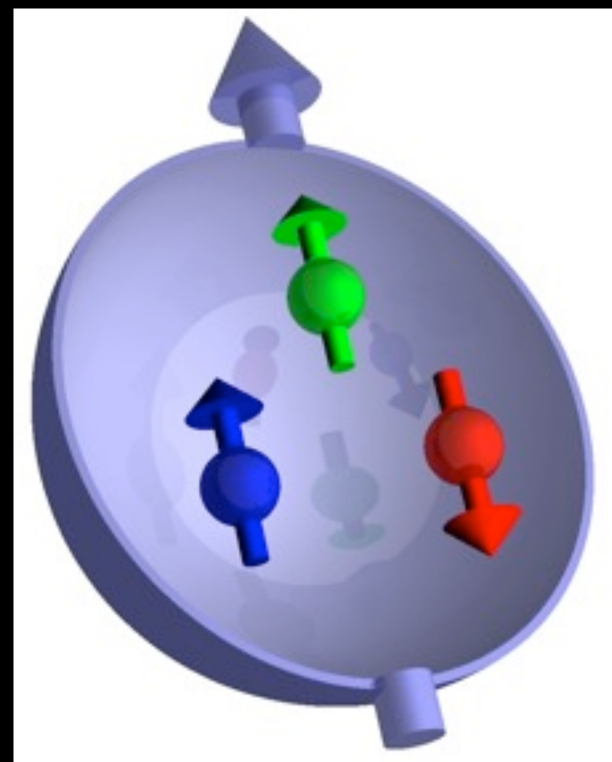


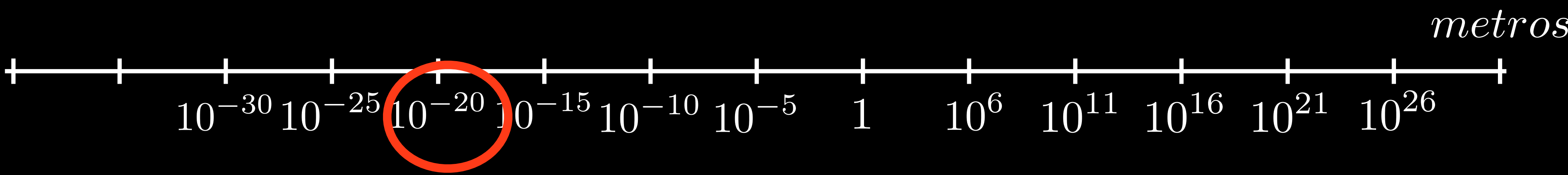



Átomo:
1 Angstrom

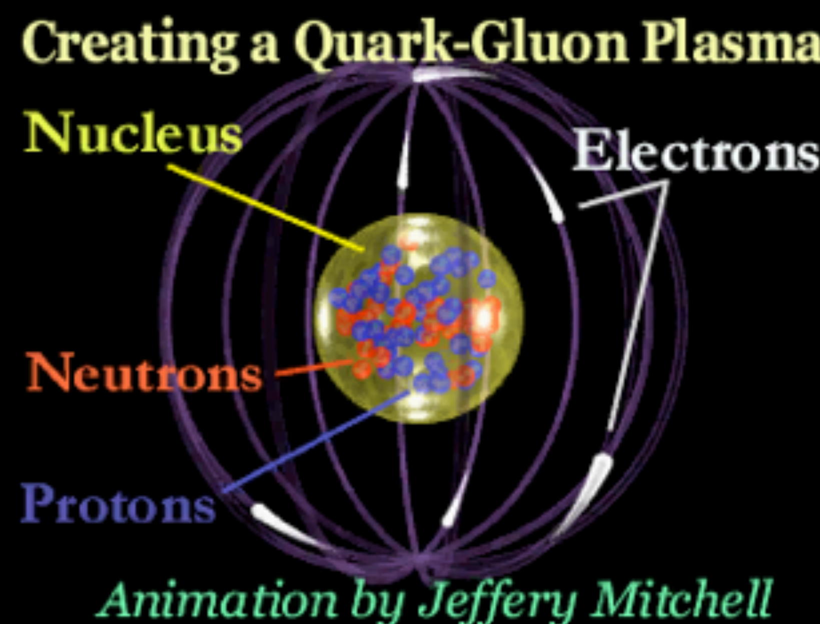



Nucleões:
1 Fermi

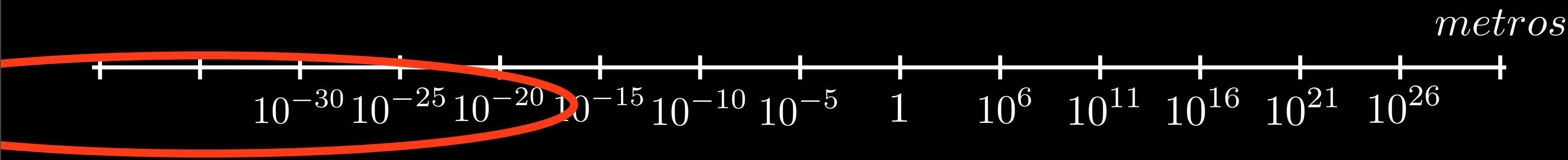




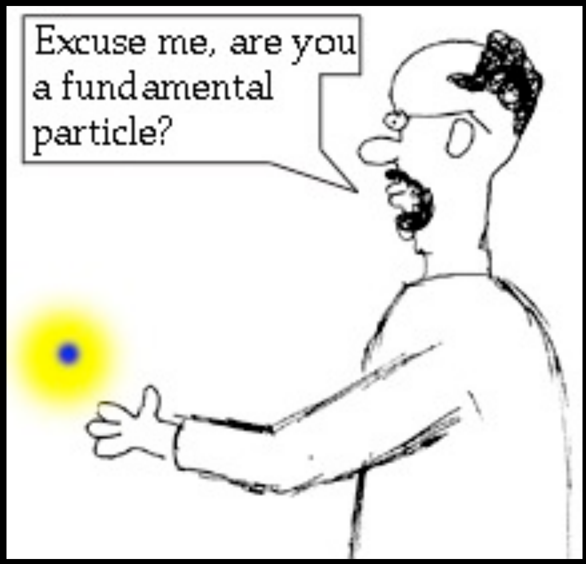

Quarks:
menos de 1 milésima de Fermi




Animation by Jeffery Mitchell (Brookhaven National Laboratory)




Para além dos quarks?



A dinâmica do Universo,
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Einstein 1915

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Einstein 1915

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Como é este conteúdo?

Standard Model of

# FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

## FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

**Leptons** spin = 1/2

| Flavor | Mass GeV/c² | Electric charge |
|---|---|---|
| $\nu_e$ electron neutrino | <1×10$^{-8}$ | 0 |
| e electron | 0.000511 | −1 |
| $\nu_\mu$ muon neutrino | <0.0002 | 0 |
| $\mu$ muon | 0.106 | −1 |
| $\nu_\tau$ tau neutrino | <0.02 | 0 |
| $\tau$ tau | 1.7771 | −1 |

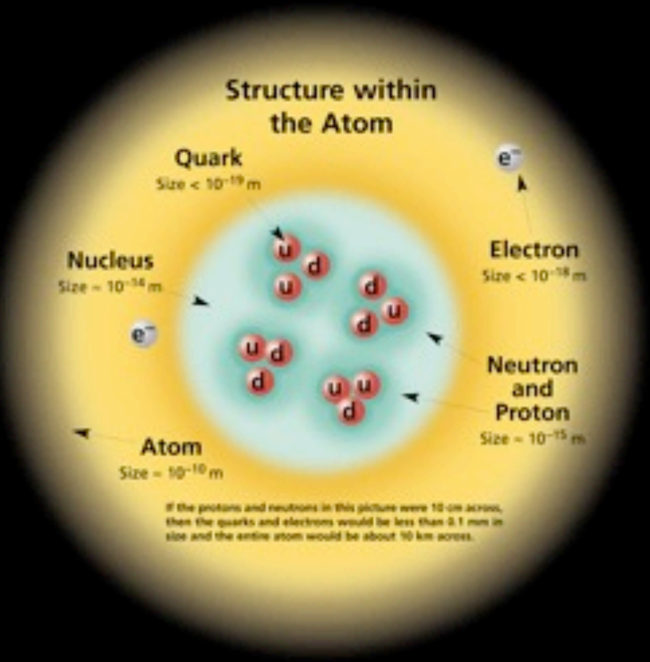
**Quarks** spin = 1/2

| Flavor | Approx. Mass GeV/c² | Electric charge |
|---|---|---|
| u up | 0.003 | 2/3 |
| d down | 0.006 | −1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | −1/3 |
| t top | 175 | 2/3 |
| b bottom | 4.3 | −1/3 |

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is $1.60\times10^{-19}$ coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c² (remember $E = mc^2$), where 1 GeV = $10^9$ eV = $1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c² = $1.67\times10^{-27}$ kg.




If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

## BOSONS force carriers spin = 0, 1, 2, ...

**Unified Electroweak** spin = 1

| Name | Mass GeV/c² | Electric charge |
|---|---|---|
| $\gamma$ photon | 0 | 0 |
| $W^-$ | 80.4 | −1 |
| $W^+$ | 80.4 | +1 |
| $Z^0$ | 91.187 | 0 |

**Strong (color)** spin = 1

| Name | Mass GeV/c² | Electric charge |
|---|---|---|
| g gluon | 0 | 0 |

**Color Charge**

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and **W** and **Z** bosons have no strong interactions and hence no color charge.

**Quarks Confined in Mesons and Baryons**

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

**Residual Strong Interaction**

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

## PROPERTIES OF THE INTERACTIONS

| Property \ Interaction | Gravitational | Weak (Electroweak) | Electromagnetic (Electroweak) | Strong: Fundamental | Strong: Residual |
|---|---|---|---|---|---|
| Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge | See Residual Strong Interaction Note |
| Particles experiencing: | All | Quarks, Leptons | Electrically charged | Quarks, Gluons | Hadrons |
| Particles mediating: | Graviton (not yet observed) | $W^+$ $W^-$ $Z^0$ | $\gamma$ | Gluons | Mesons |
| Strength relative to electromag for two u quarks at: $10^{-18}$ m | $10^{-41}$ | 0.8 | 1 | 25 | Not applicable to quarks |
| Strength relative to electromag for two u quarks at: $3\times10^{-17}$ m | $10^{-41}$ | $10^{-4}$ | 1 | 60 | |
| for two protons in nucleus | $10^{-36}$ | $10^{-7}$ | 1 | Not applicable to hadrons | 20 |

**Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$**

Baryons are fermionic hadrons. There are about 120 types of baryons.

| Symbol | Name | Quark content | Electric charge | Mass GeV/c² | Spin |
|---|---|---|---|---|---|
| p | proton | uud | 1 | 0.938 | 1/2 |
| $\bar{p}$ | anti-proton | $\bar{u}\bar{u}\bar{d}$ | −1 | 0.938 | 1/2 |
| n | neutron | udd | 0 | 0.940 | 1/2 |
| $\Lambda$ | lambda | uds | 0 | 1.116 | 1/2 |
| $\Omega^-$ | omega | sss | −1 | 1.672 | 3/2 |

**Mesons $q\bar{q}$**

Mesons are bosonic hadrons. There are about 140 types of mesons.

| Symbol | Name | Quark content | Electric charge | Mass GeV/c² | Spin |
|---|---|---|---|---|---|
| $\pi^+$ | pion | $u\bar{d}$ | +1 | 0.140 | 0 |
| $K^-$ | kaon | $s\bar{u}$ | −1 | 0.494 | 0 |
| $\rho^+$ | rho | $u\bar{d}$ | +1 | 0.770 | 1 |
| $B^0$ | B-zero | $d\bar{b}$ | 0 | 5.279 | 0 |
| $\eta_c$ | eta-c | $c\bar{c}$ | 0 | 2.980 | 0 |

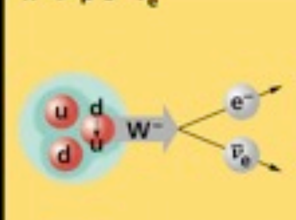
**Matter and Antimatter**

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., $Z^0$, $\gamma$, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

**Figures**

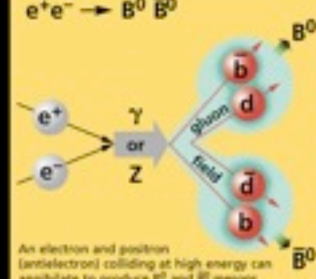
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$




A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$




An electron and positron (antielectron) colliding at high energy can annihilate to produce $B^0$ and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\,p \rightarrow Z^0Z^0$ + assorted hadrons


Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

**The Particle Adventure**

Visit the award-winning web feature *The Particle Adventure* at http://ParticleAdventure.org


**This chart has been made possible by the generous support of:**

U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.




**http://CPEPweb.org**

Conclusão:
A Física do micro-cosmos tem um papel determinante na dinâmica do macro-cosmos, quer das galáxias, quer do próprio universo.

# Moral da história:

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O nosso conhecimento do Universo depende crucialmente do nosso conhecimento da Física de Partículas;

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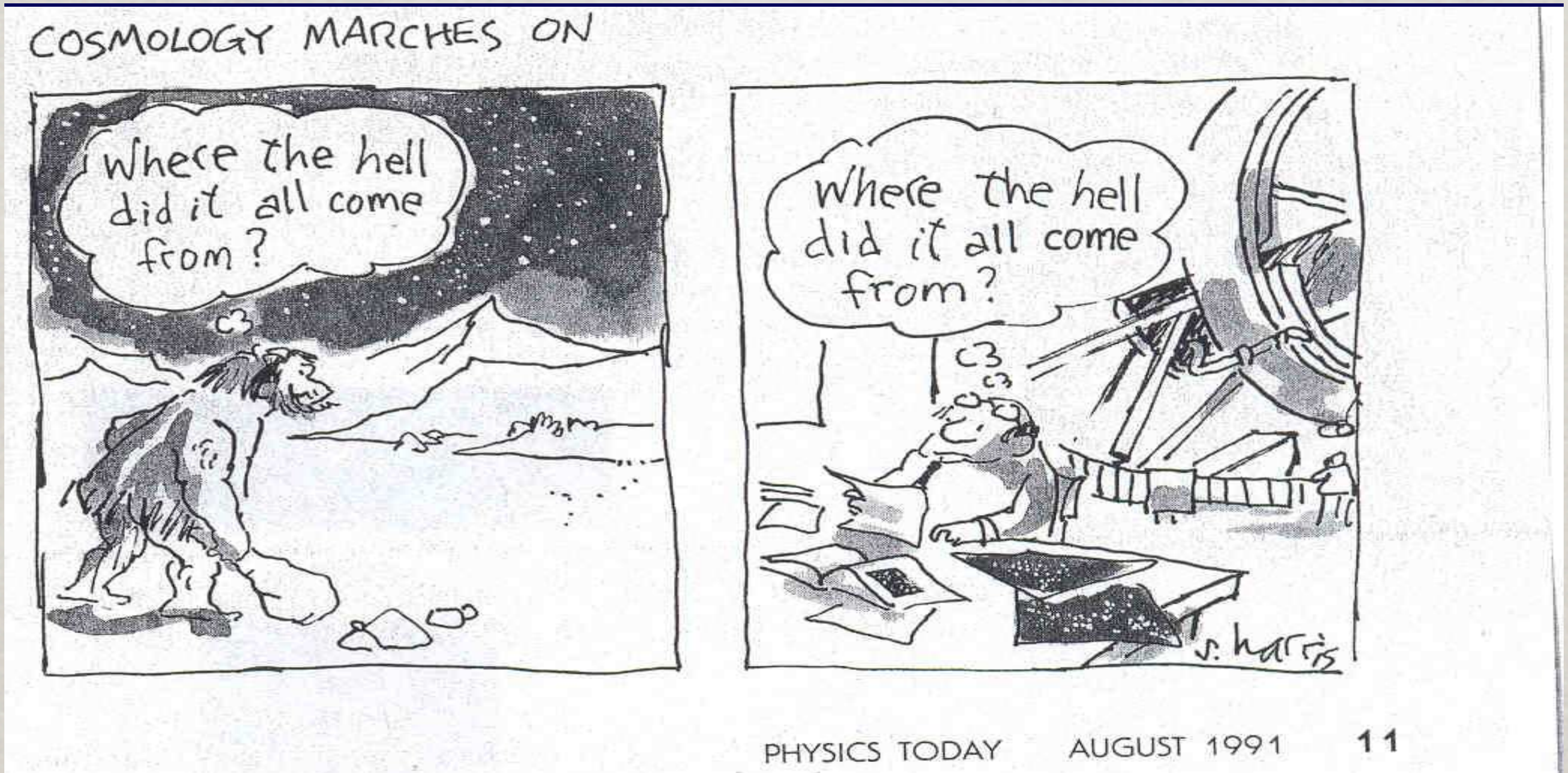
Simbiose!

# Aula 3

## Cosmologia em Relatividade Geral



# Formalismo Matemático

O formalismo natural para estudar Cosmologia é a Relatividade Geral, baseada nas equações de Einstein:

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As equações de Einstein são equações diferenciais de segunda ordem a derivadas parciais. Pretendemos encontrar soluções não triviais.

# Lado esquerdo das equções de Einstein:

Hipótese: **princípio cosmológico**:
o Universo é homogéneo e isotrópico

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Métrica que descreve o Universo tem a seguinte forma:

$$ds^2 = -dt^2 + a(t)^2 ds_3^2$$

onde a métrica espacial pode representar:
- uma esfera (modelo k=+1);
- um plano (modelo k=0);
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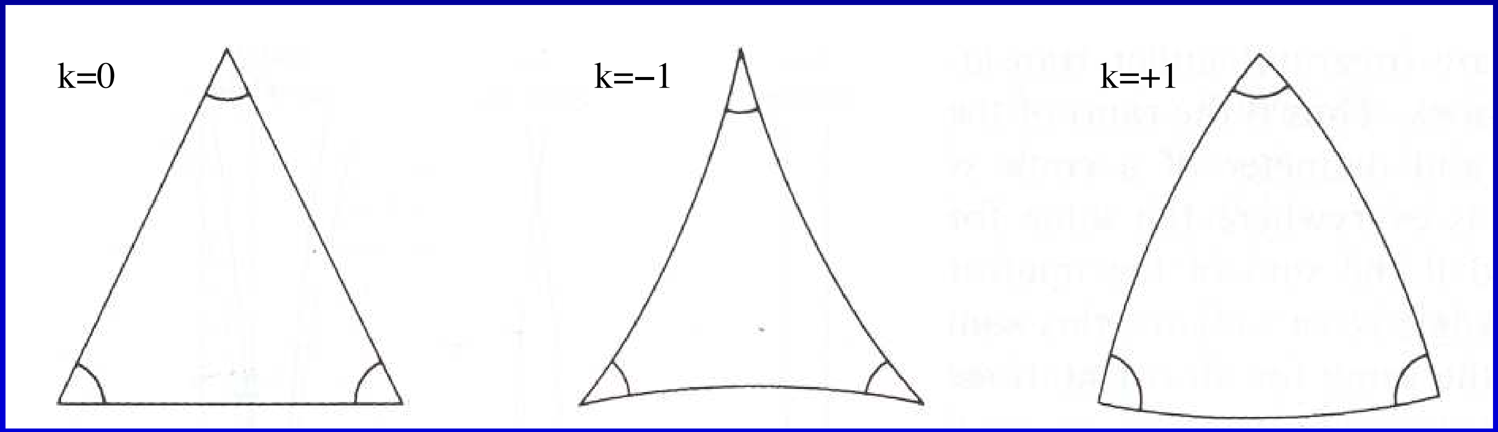
Estes são os modelos de Friedmann-Lemaître-Robertson-Walker (FLRW); a dinâmica do Universo é totalmente descrita pela função a(t), denominada factor de escala.

## Espaços maximalmente simétricos:

- Em n dimensões têm $n(n+1)/2$ campos de vectores de Killing independentes. Em $n=3$ temos 6 isometrias.
- São espaços de curvatura constante. Logo

$$R_{\mu\nu} = k(n-1)g_{\mu\nu}$$

- Marcando 3 pontos e as geodésicas entre eles obtemos triângulos com soma dos ângulos $=$, $<$ ou $>$ que $\pi$:




PLANO ABERTO FECHADO

# Lado direito das equções de Einstein:

Hipótese: conteúdo material do Universo pode ser representado por um **fluido perfeito**.

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Hipótese: conteúdo material do Universo pode ser representado por um **fluido perfeito**.

Tensor de impulsão-energia é:

$$T_{\mu\nu} = (\rho + p)u_\mu u_\nu + pg_{\mu\nu}$$

consideram-se diferentes fluidos, considerando diferentes equações de estado, isto é, relações entre densidade e pressão.

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consideram-se diferentes fluidos, considerando diferentes equações de estado, isto é, relações entre densidade e pressão.

No modelo Lambda-CDM consideram-se 3 tipos de fluido:
- matéria: $\rho > 0, \; p = 0;$
- radiação: $p = \rho/3, \; \rho = 0;$
- constante cosmológica: $p = -\rho$

# Dinâmica do Universo

Com os pressupostos anteriores, as equações de Einstein juntamente com a conservação de energia reduzem-se a:

- Equação de Friedmann

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho \,,$$

- equação de conservação de energia

$$\frac{d}{dt}\left(a^3(p+\rho)\right) = \dot{p}a^3 \,,$$

- que implicam a equação de Raychaudhuri

$$\frac{\ddot{a}}{a} = -\frac{8\pi G}{6}(\rho + 3p) \,.$$

## A equação de Raychaudhuri

A equação

$$\frac{\ddot{a}}{a} = -\frac{8\pi G}{6}(\rho + 3p) \ .$$

diz-nos que

$$\rho + 3p > 0 \Leftrightarrow \ddot{a} < 0 \ .$$

ou ainda

Condição de energia forte $\Leftrightarrow$ Expansão desacelerada

Esta condição é obedecida para matéria e radiação.

## A equação de Raychaudhuri

A equação

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diz-nos que

$$\rho + 3p > 0 \Leftrightarrow \ddot{a} < 0 \ .$$

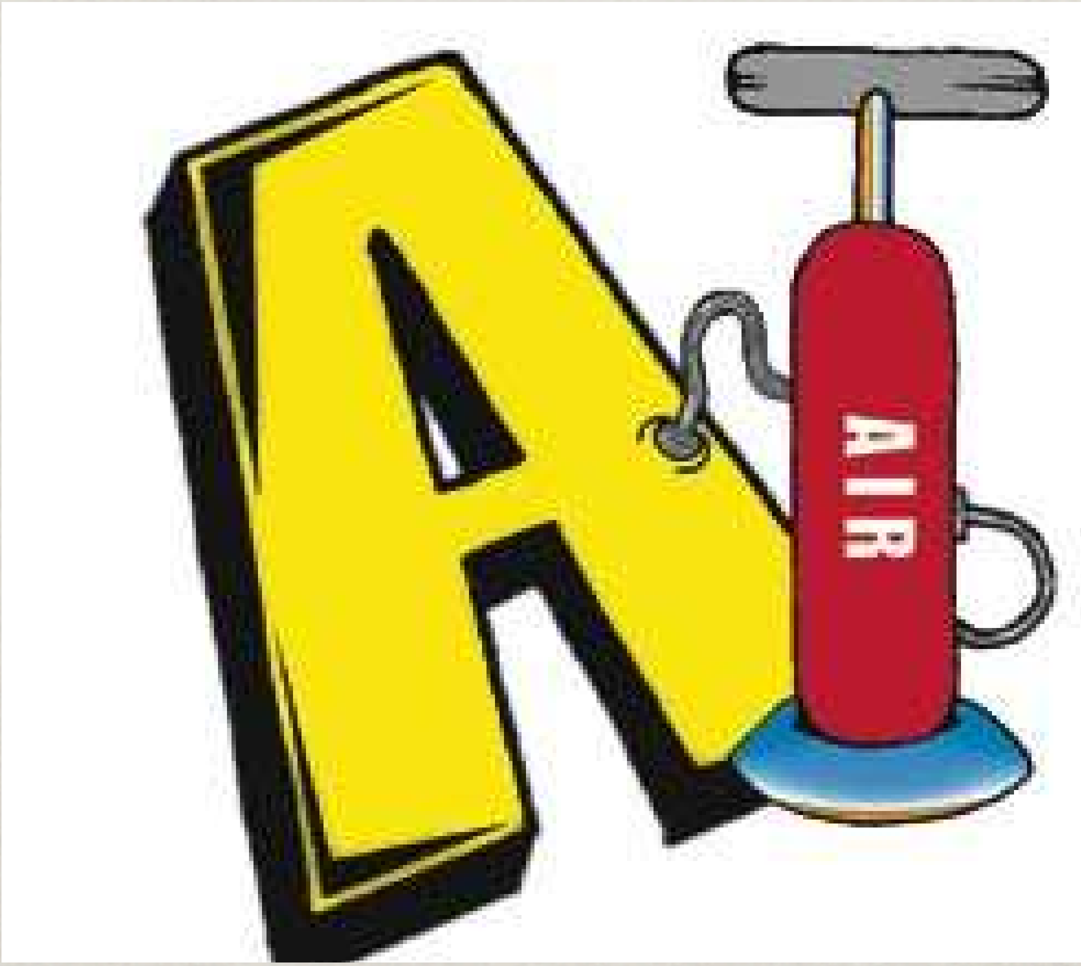
ou ainda

Condição de energia forte $\Leftrightarrow$ Expansão desacelerada

Esta condição é obedecida para matéria e radiação.

Matéria $a(t) \sim t^{2/3}$; Radiação $a(t) \sim t^{1/2}$.

Épocas inflacionárias são épocas que esta condição é violada:




Há um crescimento **acelerado** do factor de escala.

# Inflação Cosmológica

Inflação é uma época em que $\ddot{a} > 0$. Requer um tipo exótico de matéria que produza gravidade repulsiva.

Os modelos típicos de inflação consideram um campo escalar $\Phi$, com um potencial $V(\Phi)$ acoplado à gravidade. Estes modelos são descritos pela acção

$$\mathcal{S} = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left[R - \frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi - V(\Phi)\right] .$$

Ou seja, o conteúdo material - campo escalar - tem o tensor de impulsão energia

$$T_{\mu\nu} = \partial_\mu\Phi\partial_\nu\Phi - \frac{1}{2}g_{\mu\nu}\partial_\alpha\Phi\partial^\alpha\Phi - g_{\mu\nu}V(\Phi) .$$

# Dinâmica do Universo

As equações de movimento da acção anterior, com a hipótese $\Phi = \Phi(t)$ reduzem-se a:

- Equação de Friedmann

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{1}{6}\left[\frac{\dot{\Phi}^2}{2} + V(\Phi)\right] ,$$

- equação do campo escalar

$$\ddot{\Phi} + 3\frac{\dot{a}}{a}\dot{\Phi} + \frac{dV}{d\Phi} = 0 ,$$

- que implicam a equação de Raychaudhuri

$$\frac{\ddot{a}}{a} = \frac{1}{6}\left(-\dot{\Phi}^2 + V(\Phi)\right) .$$

## A equação de Raychaudhuri

A equação

$$\frac{\ddot{a}}{a} = \frac{1}{6}\left(-\dot{\Phi}^2 + V(\Phi)\right) .$$

diz-nos que

$$-\dot{\Phi}^2 + V(\Phi) > 0 \quad \Leftrightarrow \quad \ddot{a} > 0 .$$

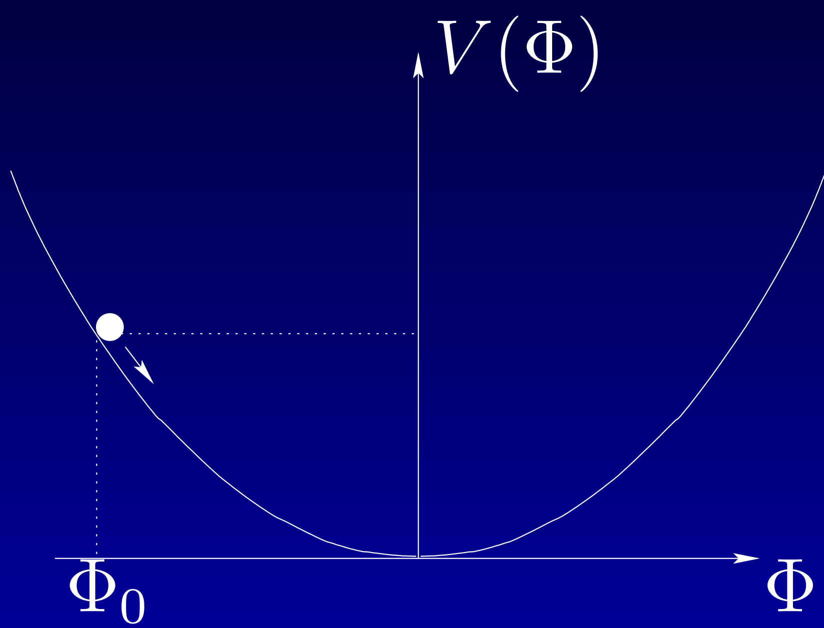
ou seja

$$V(\Phi) > \dot{\Phi}^2 \Leftrightarrow \text{Expansão acelerada}$$

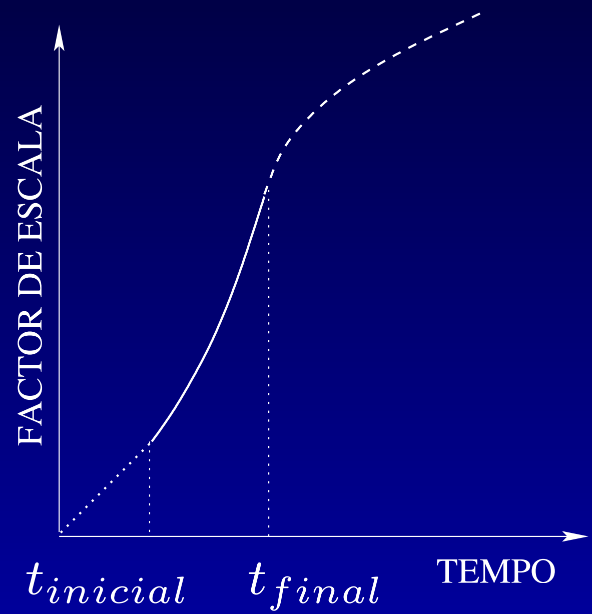
Se o inflatão ($\Phi$) rolar lentamente ao longo de um potencial positivo, a gravidade torna-se repulsiva.

# Dinâmica do Universo

Qualitativamente:




$\Longrightarrow$




Onde

$$\left(\frac{d\Phi}{dt}\right)(t_{inicial}) = 0 \;, \quad \Phi(t_{inicial}) = \Phi_0 \;, \quad V(\Phi_0) > 0 \;.$$

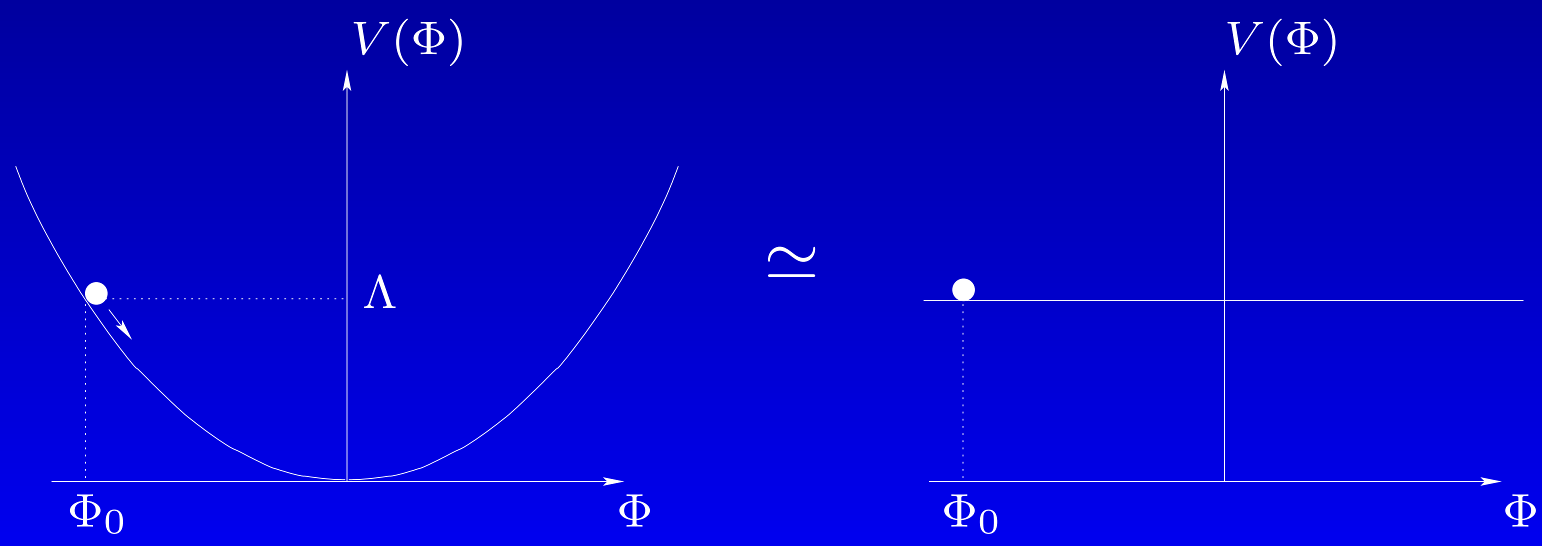
# A constante cosmológica

Se a dinâmica do campo escalar é dominada pela energia potencial de um potencial constante, então

$$\begin{aligned} T_{\mu\nu} &= \partial_\mu \Phi \partial_\nu \Phi - \tfrac{1}{2} g_{\mu\nu} \partial_\alpha \Phi \partial^\alpha \Phi - g_{\mu\nu} V(\Phi) \\ &\simeq -V(\Phi) g_{\mu\nu} = -\Lambda g_{\mu\nu} \ , \end{aligned}$$

onde $\Lambda > 0$ é denominada *constante cosmológica*.

Ou seja,



# O Universo de de Sitter

Se o tensor de impulsão energia for exactamente o de uma constante cosmológica positiva

$$T_{\mu\nu} = -\Lambda g_{\mu\nu} \ ,$$

a solução exacta das equações de Einstein é denominada o universo de de Sitter.

$$ds^2 = -dt^2 + e^{\pm\sqrt{\Lambda}t} ds^2(\mathbb{R}^3) \ .$$

Corresponde a um universo que inflaciona eternamente.

# Sobre a constante cosmológica

- Podemos pensar na constante cosmológica como um caso especial de fluido perfeito. De facto

$$T_{\mu\nu} = (\rho + p)u_\mu u_\nu + p g_{\mu\nu} \quad \overset{p=-\rho=-\Lambda}{\Rightarrow} \quad T_{\mu\nu} = -\Lambda g_{\mu\nu} \; ;$$

- Para $\Lambda > 0$, a condição de energia forte não é obedecida

$$\rho + 3p > 0 \overset{p=-\rho}{\Leftrightarrow} -2\rho > 0 \;\; (falso) \; .$$

- Da equação de conservação de energia vemos que a constante cosmológica é um conteúdo material especial

$$\frac{d}{dt}\left(a^3(p+\rho)\right) = \dot{p}a^3 \Rightarrow \begin{cases} Mat. & \frac{d}{dt}(a^3\rho) = 0 & \Rightarrow & \rho \sim 1/a^3 \\ Rad. & \frac{d}{dt}(a^4\rho) = 0 & \Rightarrow & \rho \sim 1/a^4 \\ \Lambda & \frac{d}{dt}(\rho) = 0 & \Rightarrow & \rho \sim const. \end{cases}$$

A constante cosmológica não se dilui com a expansão.

# Porque queremos inflação?

Nos modelos actuais consideram-se duas épocas inflacionárias:

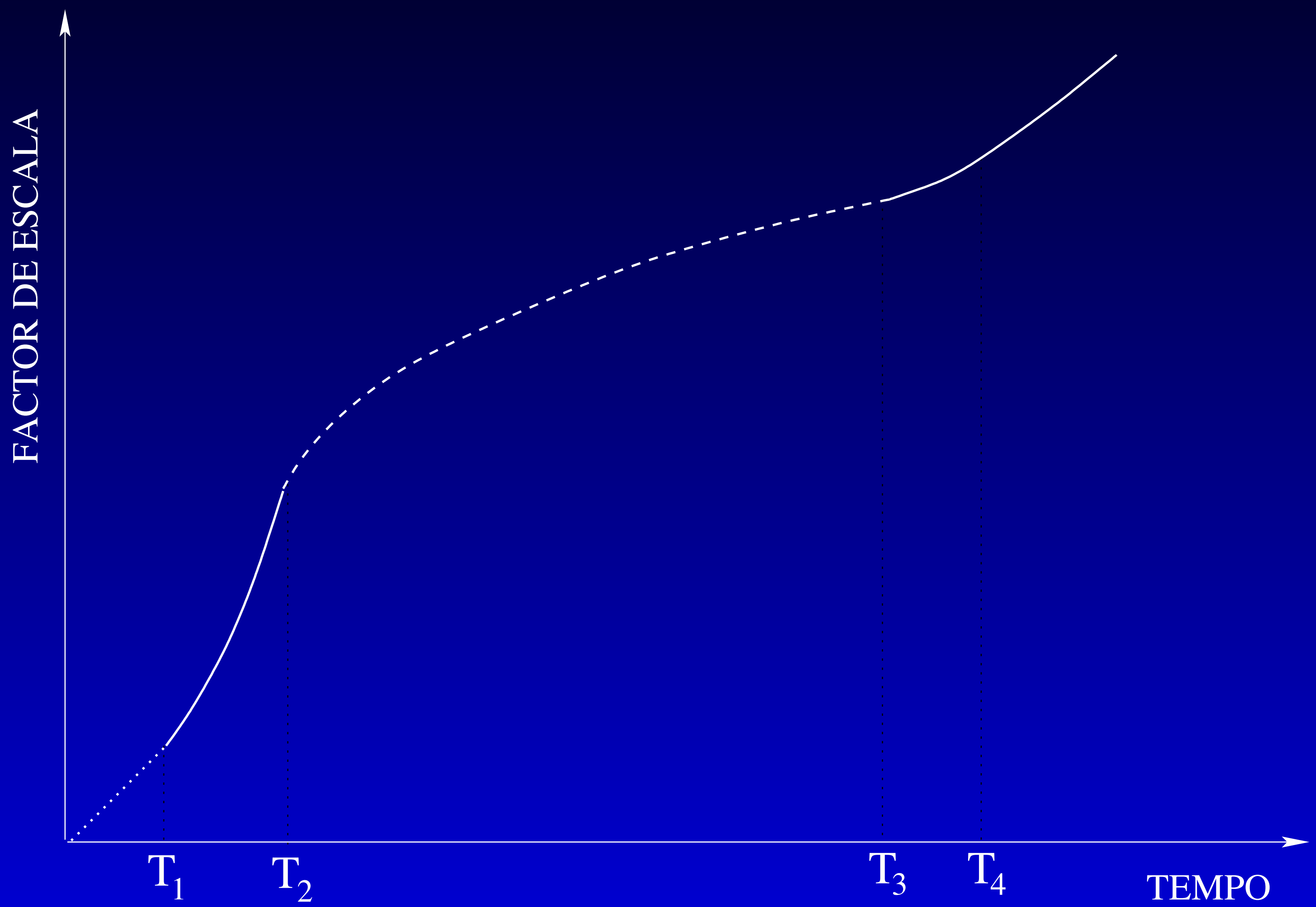
• Inflação primordial: terá acontecido pouco depois da época de Planck (entre $\simeq 10^{-37}$ até $\simeq 10^{-35}$ segundos). É importante para resolver alguns problemas teóricos do modelo padrão;

• Inflação actual: acontece agora. É importante porque é observada! (Riess et al. 1998)

De acordo com os dados do satélite WMAP, o conteúdo material do universo hoje é

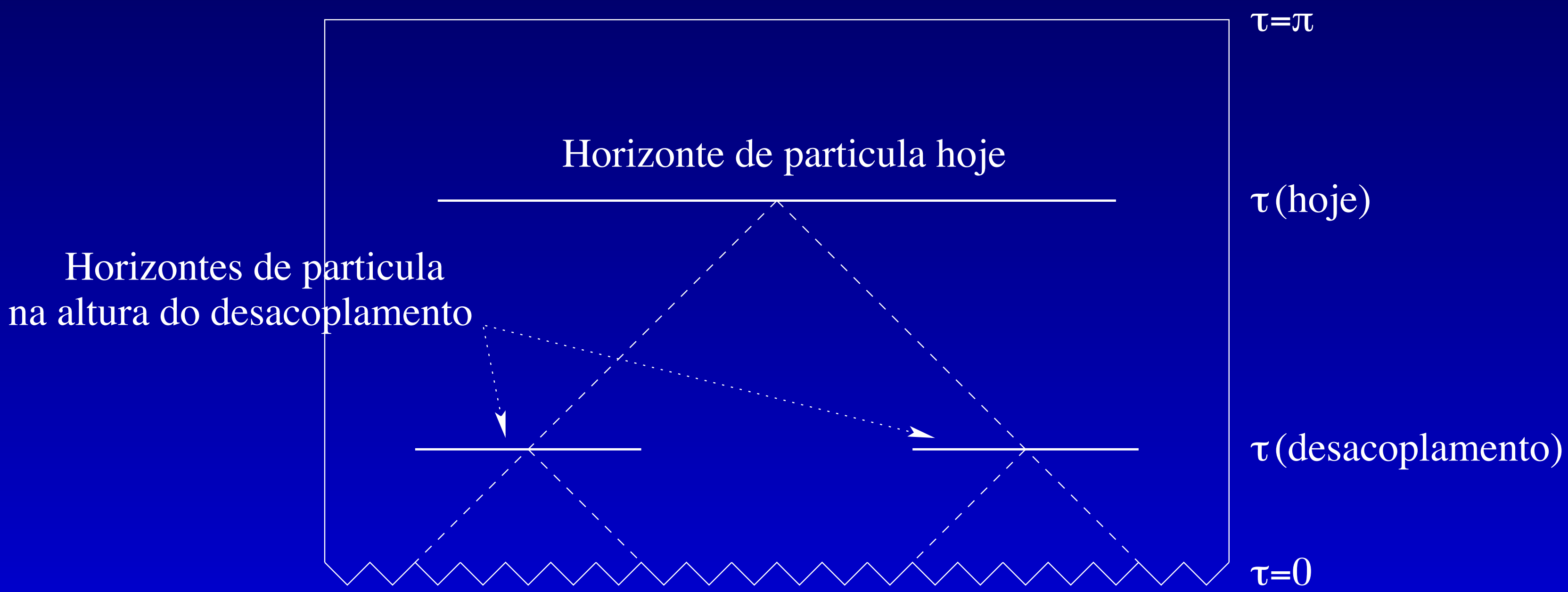
- Matéria bariónica: $\Omega_B \simeq 4.4\%$;
- Matéria escura: $\Omega_{DM} \simeq 22\%$;
- Energia escura: $\Omega_\Lambda \simeq 73\%$;

# Factor de Escala com Inflações:



# O problema do horizonte

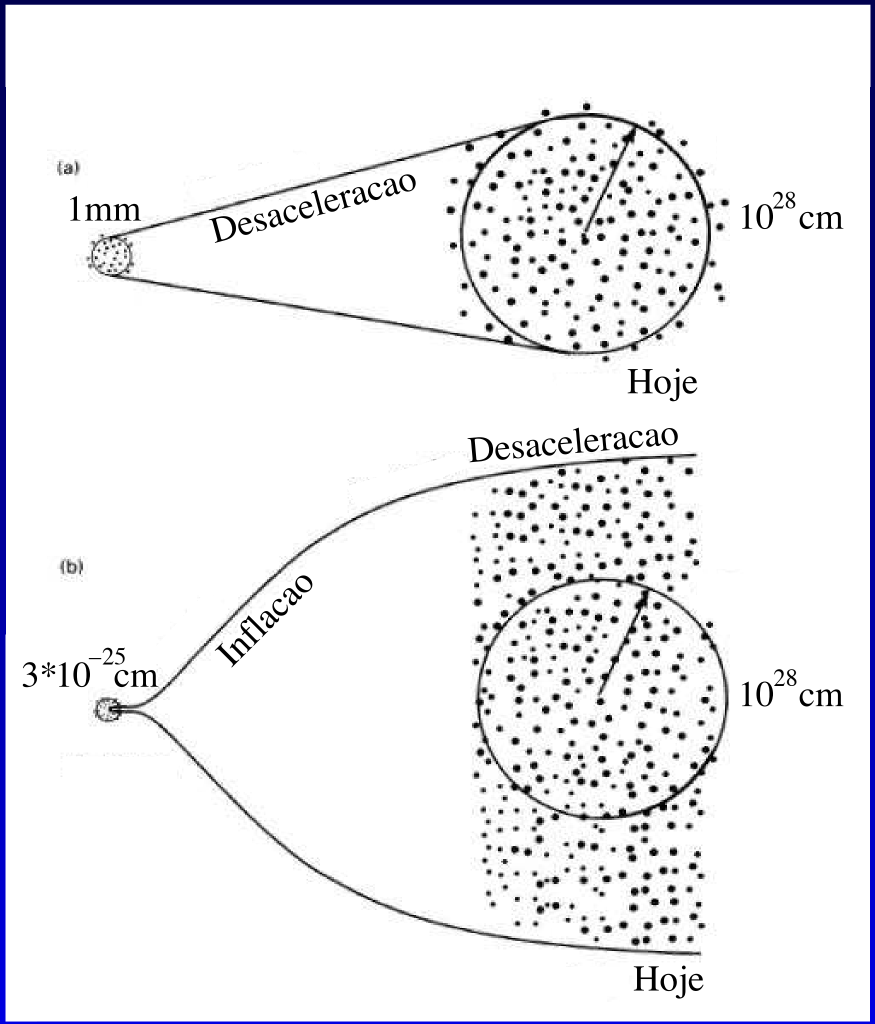
A radiação cósmica de fundo é extremamente isotrópica tendo um espectro de corpo negro. Termalização implica que todos os pontos de onde recebemos radiação tenham estado em contacto térmico. Contudo




O horizonte de partícula na altura do desacoplamento corresponde hoje a um ângulo de cerca de $2^o$ do céu!

# A solução da inflação

‘Inflacionando’ as escalas colocamos o horizonte actual dentro do horizonte causal antes de começar o período inflacionário.



# Sobre o Big Bang

O ponto onde o factor de escala se torna zero é, em geral, uma singularidade de curvatura. Por exemplo, o escalar de Ricci diverge

$$R = 6\frac{\left(\dot{a}^2 + a\ddot{a} + k\right)}{a^2} \; .$$

Isto signifi ca que a teoria de Einstein deixa de ser aplicável perto de $a = 0$.

Este ponto é sempre atingido algures no passado na cosmologia padrão. Genericamente, se a condição de energia forte é obedecida, em conjunto com certas hipóteses sobre causalidade, a singularidade do Big Bang é sempre atingida (Teoremas de Singularidades, Penrose e Hawking 1970).

*Excepção*: Para $t$ pequeno $a(t) \sim t \; , \;\; k = -1 \; , \;\; \Rightarrow \;\; R = 0.$

# Epílogo

## Para além da Relatividade Geral

Para além da Relatividade Geral clássica
consiste em considerar:

- modelos inspirados em descrições fundamentais;
- modelos semi-clássicos;
- modelos clássicos fenomenológicos;

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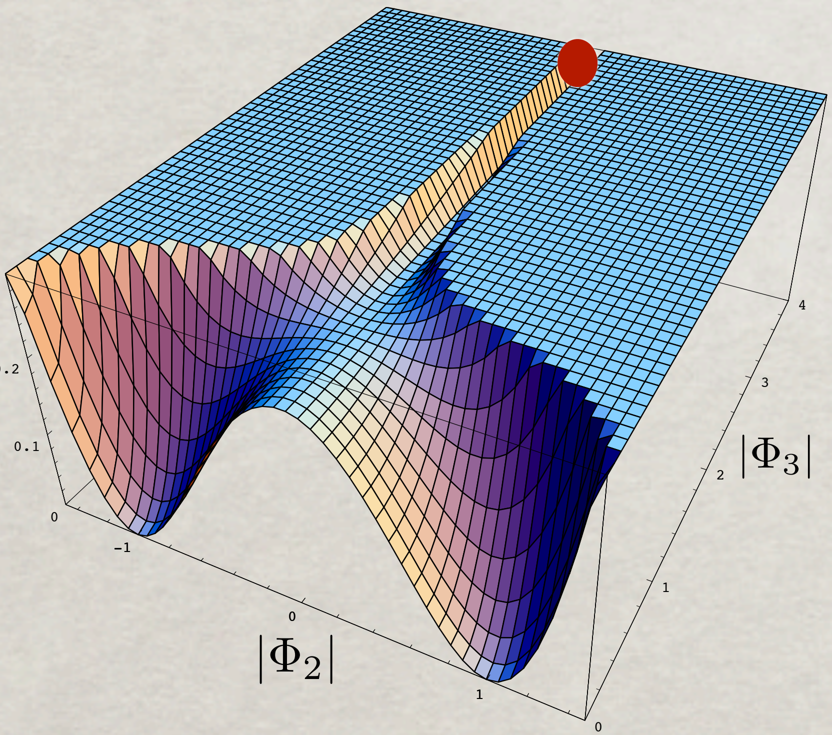


**PRD 65 (2002)126002**

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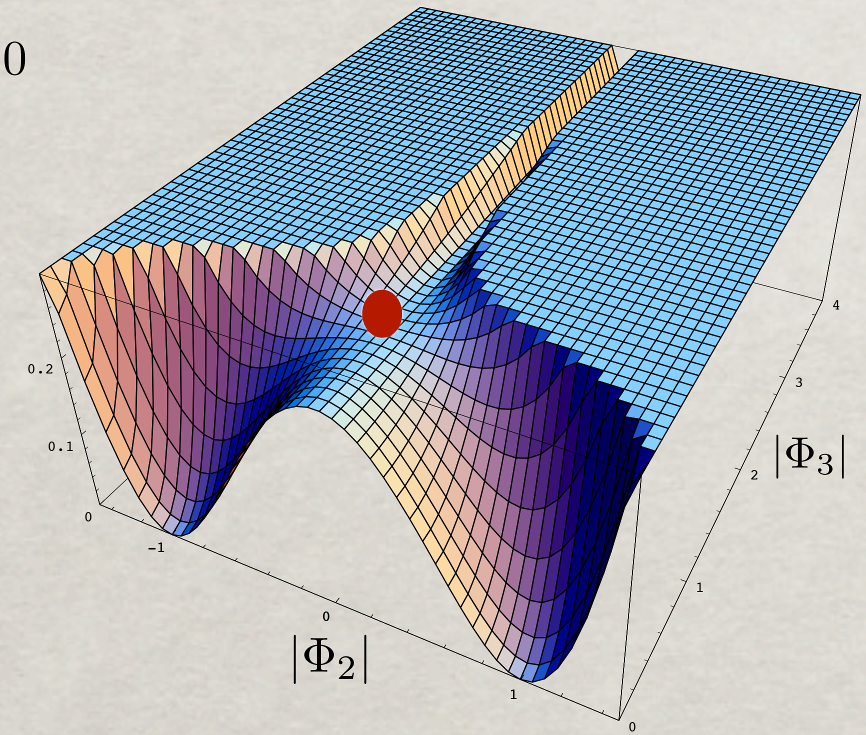


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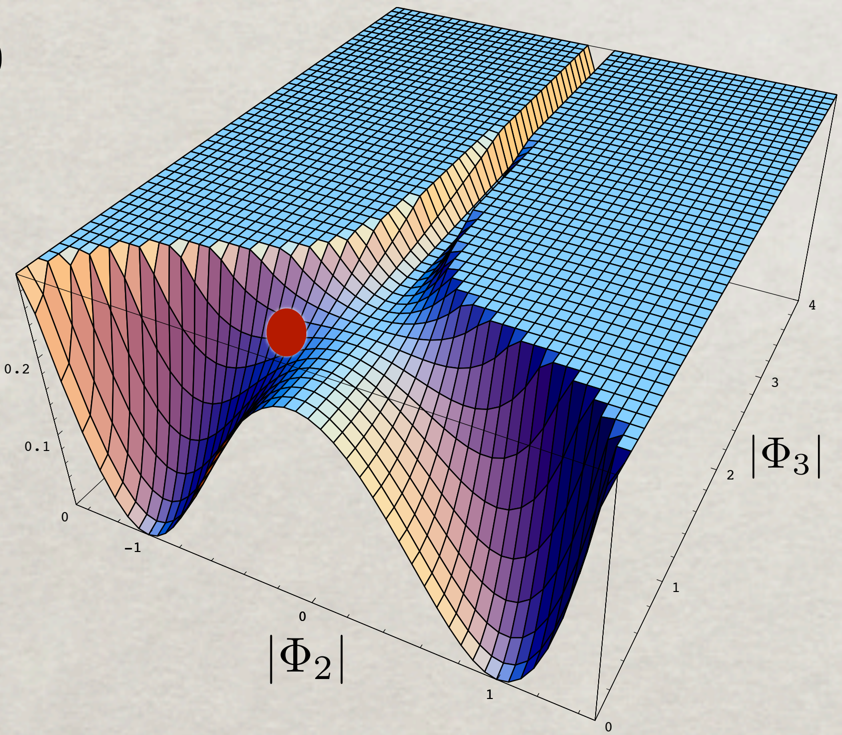


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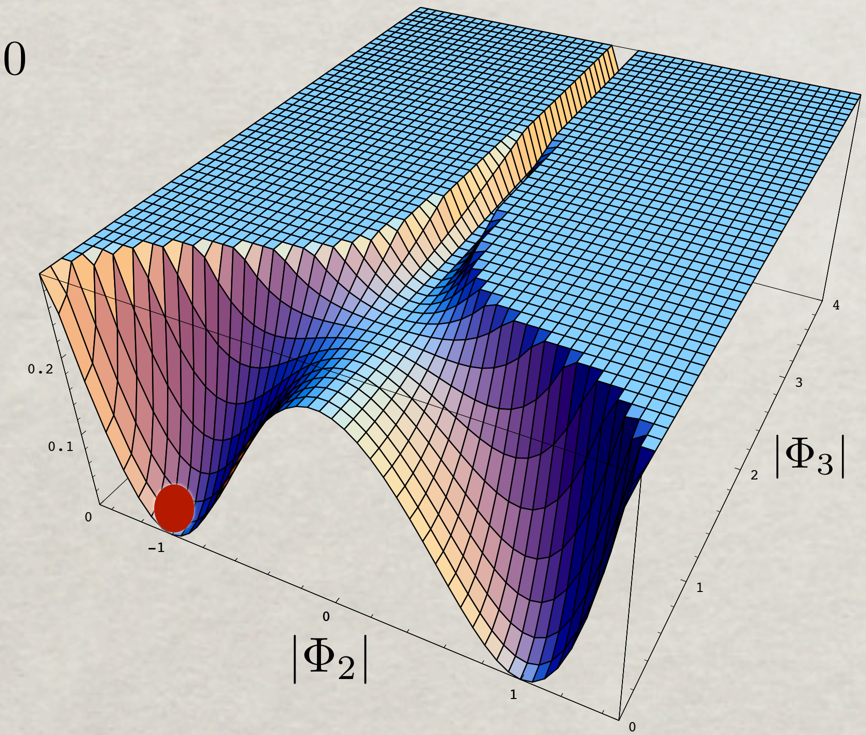


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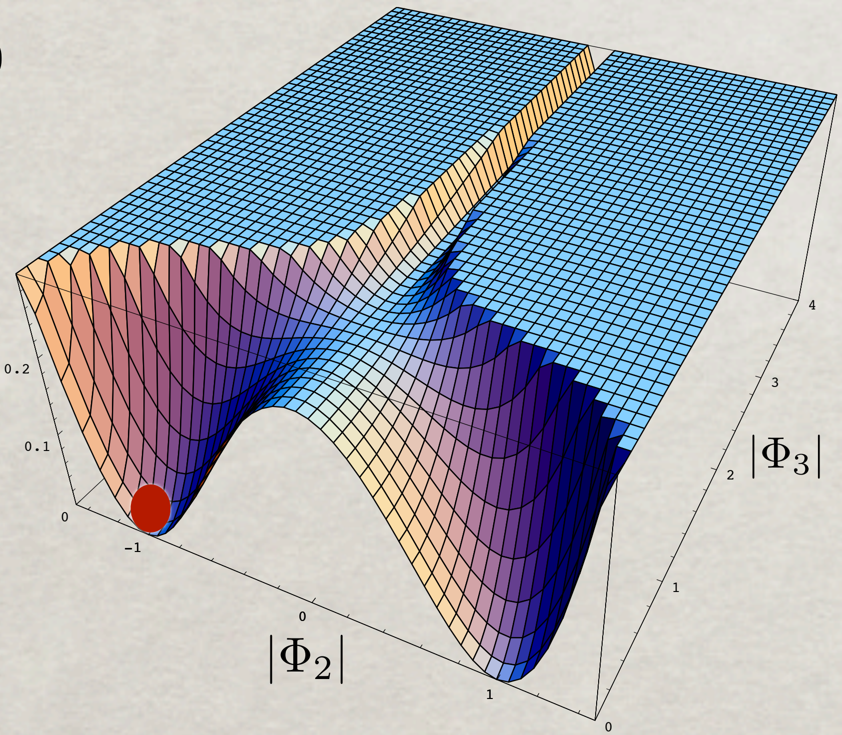


$$V = \frac{1}{2}\xi^2 + \frac{g^2}{16\pi^2}\xi^2 \ln\frac{|\Phi_3|^2}{|\Phi_3|_c^2}$$

correcção de 1-loop

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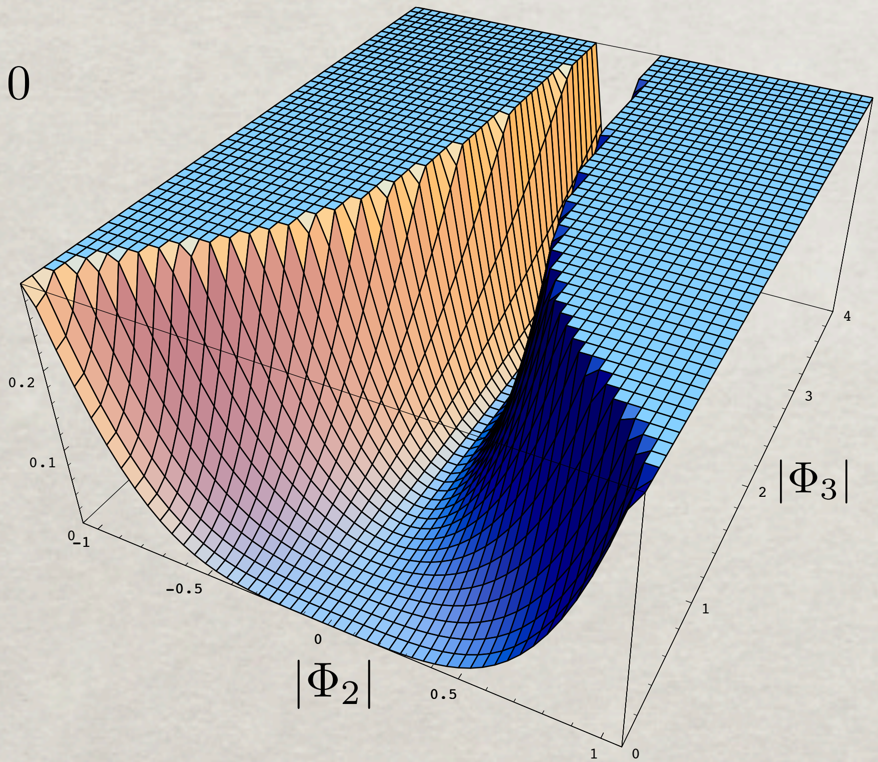


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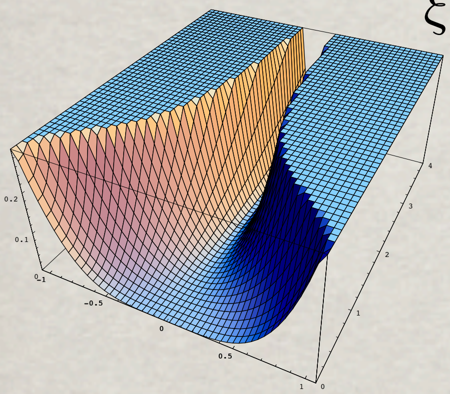

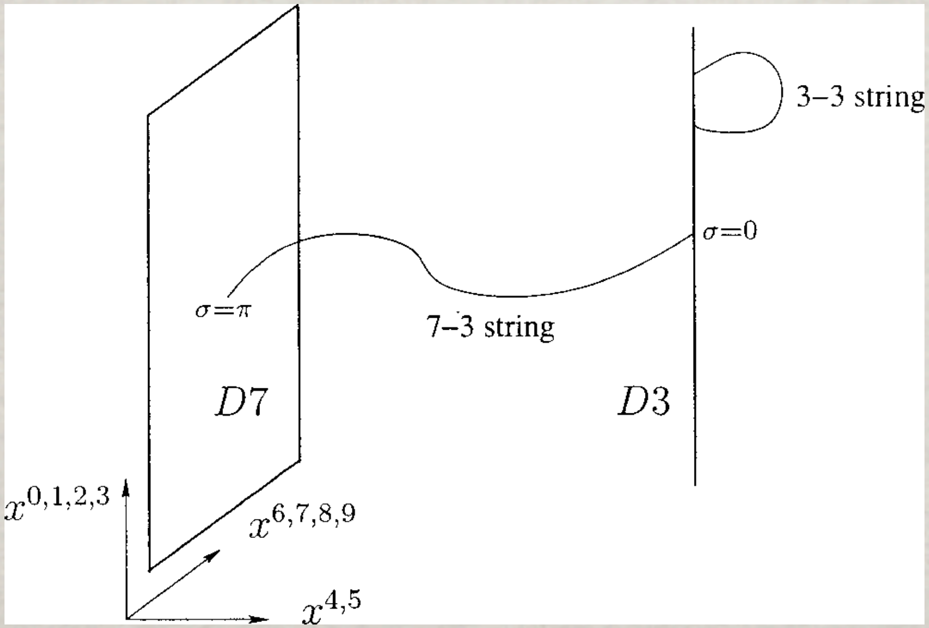


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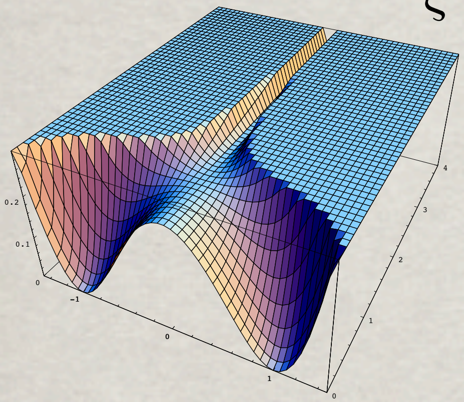

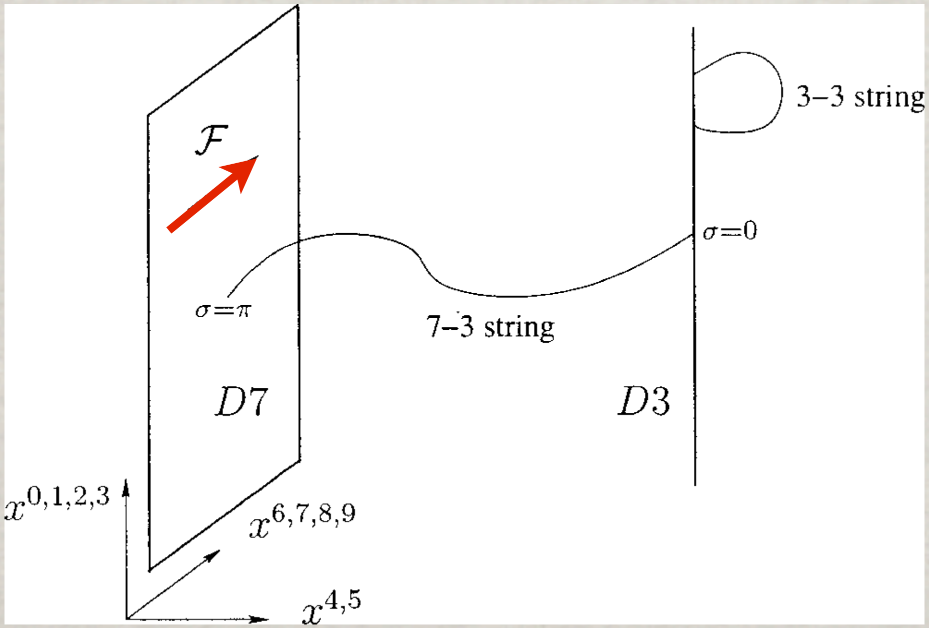


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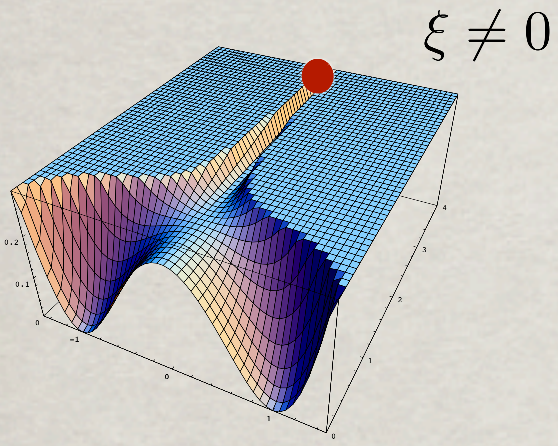


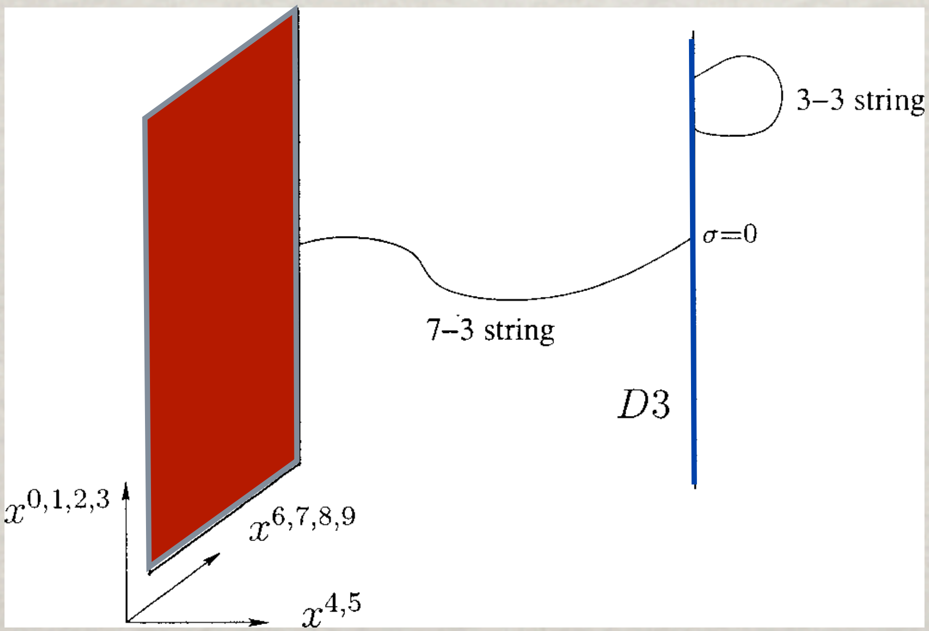


**PRD 65 (2002)126002**

PHYSICAL REVIEW D, VOLUME 65, 126002

**D3-D7 inflationary model and M theory**

Keshav Dasgupta,* Carlos Herdeiro,† Shinji Hirano,‡ and Renata Kallosh§
*Department of Physics, Varian Laboratory of Physics, Stanford University, Stanford, California 94305*
(Received 11 March 2002; published 23 May 2002)

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**JHEP 12 (2001)027**

JHEP HYPER VERSION
RECEIVED: *November 7, 2001*, ACCEPTED: *December 19, 2001*

**String theory and hybrid inflation/acceleration**

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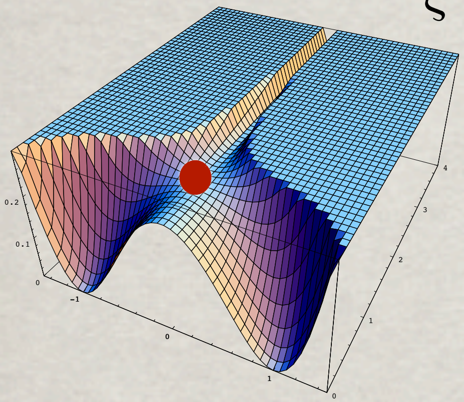


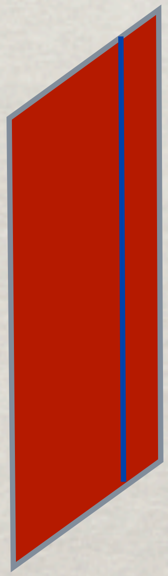

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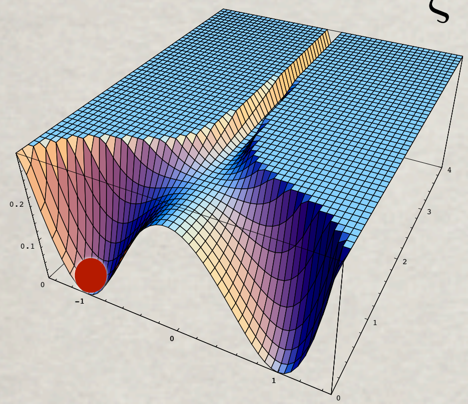


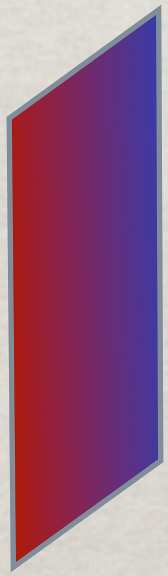

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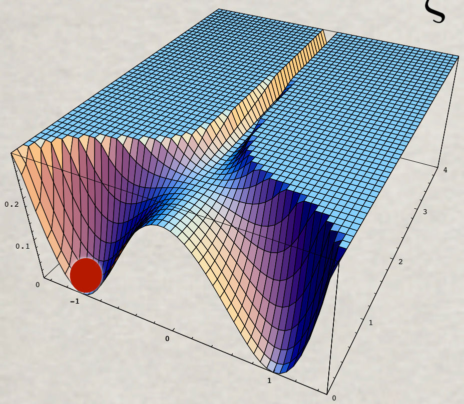


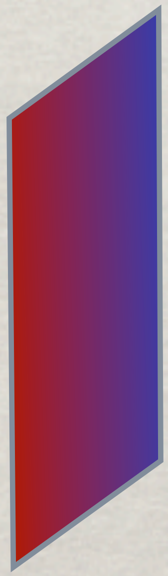

**Consegue-se:**

- Realizar a teoria de gauge com um sistema de branas;
- Reproduzir espectro e potencial de 1-loop com cálculos de cordas;
- Compactação é problemática;

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$$T_{ab} = \mathbf{k}_a \Phi \mathbf{k}_b \Phi - \frac{g_{ab}}{2} \mathbf{k}_c \Phi \mathbf{k}^c \Phi - \frac{\mu^2}{2} g_{ab} \Phi^2 + \xi (G_{ab} - \nabla_a \mathbf{k}_b + g_{ab} \Box) \Phi^2$$

**CQG 23 (2006) 473**

INSTITUTE OF PHYSICS PUBLISHING — CLASSICAL AND QUANTUM GRAVITY
Class. Quantum Grav. **23** (2006) 473–484 — doi:10.1088/0264-9381/23/2/012

## Casimir energy and a cosmological bounce

**Carlos A R Herdeiro and Marco Sampaio**

Departamento de Física e Centro de Física do Porto, Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre, 687, 4169-007 Porto, Portugal

Received 13 October 2005, in final form 17 November 2005
Published 28 December 2005
Online at stacks.iop.org/CQG/23/473

**Abstract**
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PACS numbers: 04.62.+v, 98.80.−k

(Some figures in this article are in colour only in the electronic version)

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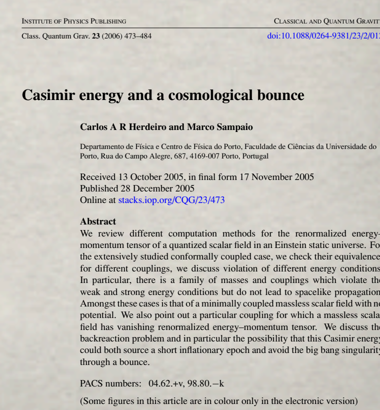
CQG 23 (2006) 473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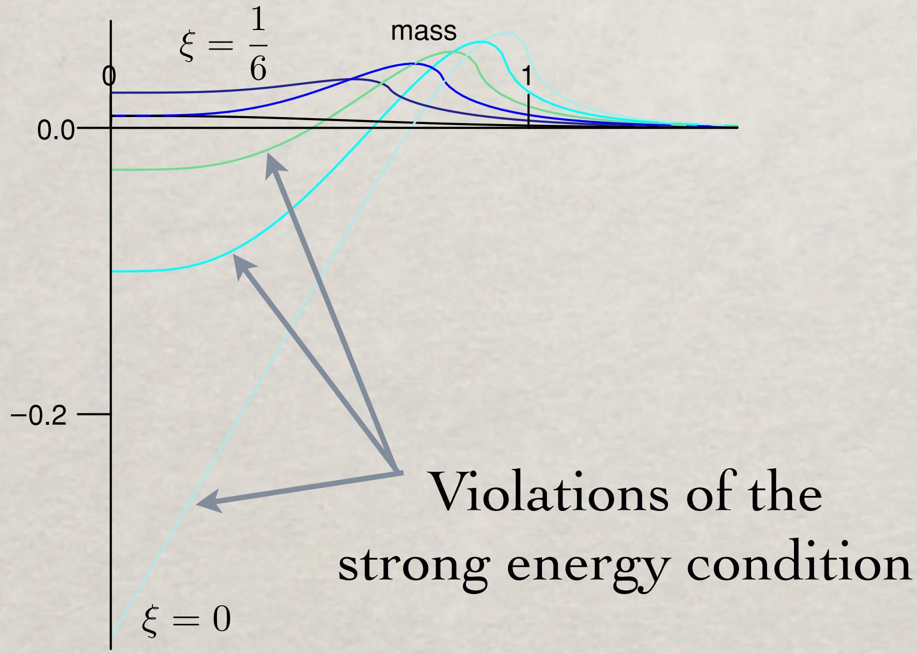
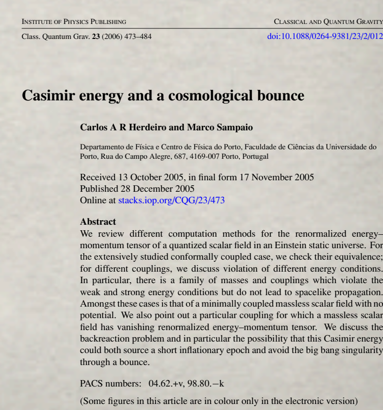



CQG 23 (2006) 473



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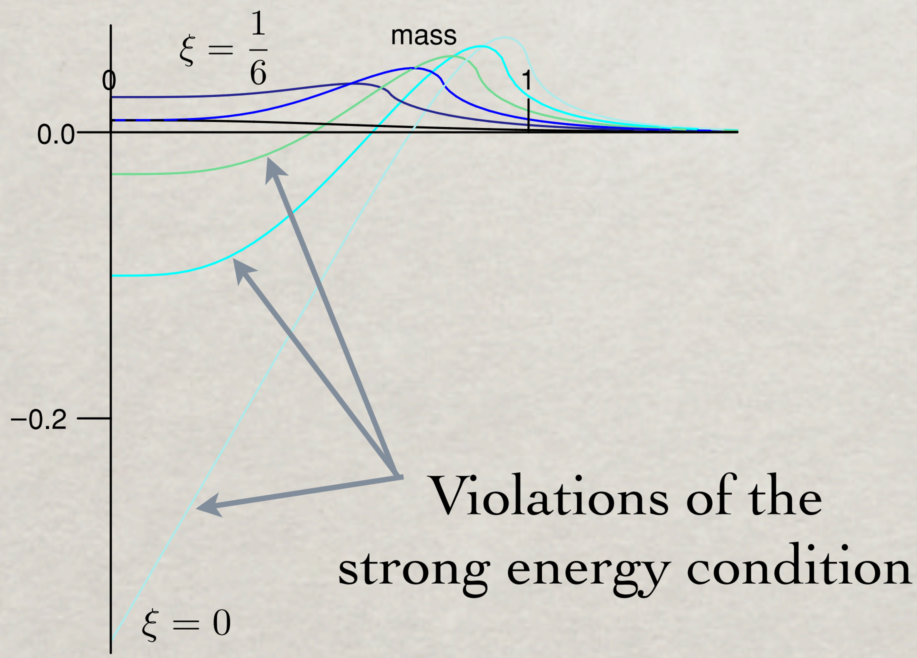
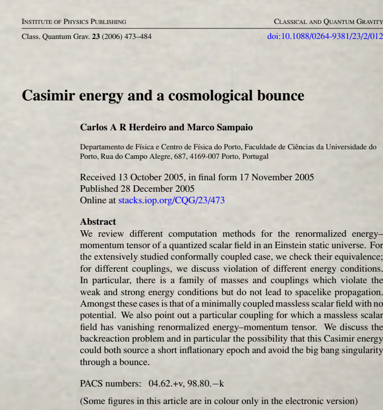



**Consegue-se:**

- Modelos simples originam repulsão, mas não uma constante cosmológica

CQG 23 (2006) 473



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# Uma descrição fenomenológica clássica

$$S = -\frac{3\lambda}{4\pi G_N^2}\int d^4x\sqrt{-g}\left[\sqrt{1+\frac{G_N}{6\lambda}(R+\mathcal{K})}-q\right]$$

$$\mathcal{K} := -\frac{2}{\sqrt{h}}\pounds_n\left(\sqrt{h}K\right) = -2(K^2+n^\sigma\partial_\sigma K)$$

## PRD 84 (2011)124048

PHYSICAL REVIEW D **84,** 124048 (2011)

**$n$-DBI gravity**

Carlos Herdeiro,[1,*] Shinji Hirano,[2,†] and Yuki Sato[2,3,‡]

[1] *Departamento de Física, Universidade de Aveiro and I3N Campus de Santiago, 3810-183 Aveiro, Portugal*
[2] *Department of Physics, Nagoya University, Nagoya 464-8602, Japan*
[3] *The Niels Bohr Institute, Blegdamsvej 17, DK-2100, Copenhagen, Denmark*
(Received 10 October 2011; published 27 December 2011)

$n$-DBI gravity is a gravitational theory introduced in [C. Herdeiro and S. Hirano, arXiv:1109.1468.], motivated by Dirac-Born-Infeld type conformal scalar theory and designed to yield noneternal inflation spontaneously. It contains a foliation structure provided by an everywhere timelike vector field **n**, which couples to the gravitational sector of the theory, but decouples in the small curvature limit. We show that any solution of Einstein gravity with a particular curvature property is a solution of $n$-DBI gravity. Among them is a class of geometries isometric to a Reissner-Nordström–(anti)-de Sitter black hole, which is obtained within the spherically symmetric solutions of $n$-DBI gravity minimally coupled to the Maxwell field. These solutions have, however, two distinct features from their Einstein gravity counterparts: (1) the cosmological constant appears as an integration constant and can be positive, negative, or vanishing, making it a *variable* quantity of the theory; and (2) there is a nonuniqueness of solutions with the same total mass, charge, and effective cosmological constant. Such inequivalent solutions cannot be mapped to each other by a foliation preserving diffeomorphism. Physically they are distinguished by the expansion and shear of the congruence tangent to **n**, which define scalar invariants on each leaf of the foliation.

## JCAP 05 (2012) 031

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

**Scale invariance and a gravitational model with non-eternal inflation**

**Carlos Herdeiro[a] and Shinji Hirano[b]**

[a] Departamento de Física da Universidade de Aveiro and I3N, Campus de Santiago, 3810-183 Aveiro, Portugal
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E-mail: herdeiro@ua.pt, hirano@eken.phys.nagoya-u.ac.jp

Received December 13, 2011
Revised April 19, 2012
Accepted April 24, 2012
Published May 25, 2012

**Abstract.** We propose a 3+1 dimensional model of gravity which results in inflation at early times, followed by radiation- and matter-dominated epochs and a subsequent acceleration at late times. Both the inflation and late time acceleration are nearly de Sitter with a large hierarchy between the effective cosmological constants. There is no scalar field agent of inflation, and the transition from the inflation to the radiation-dominated period is smooth. This model is designed so that it yields, at the cost of giving up on Lorentz invariance in the gravitational sector, the Dirac-Born-Infeld type conformal scalar theory when the universe is conformally flat. It, however, resembles Einstein's gravity with the Gibbons-Hawking-York boundary term in weakly curved space-times.

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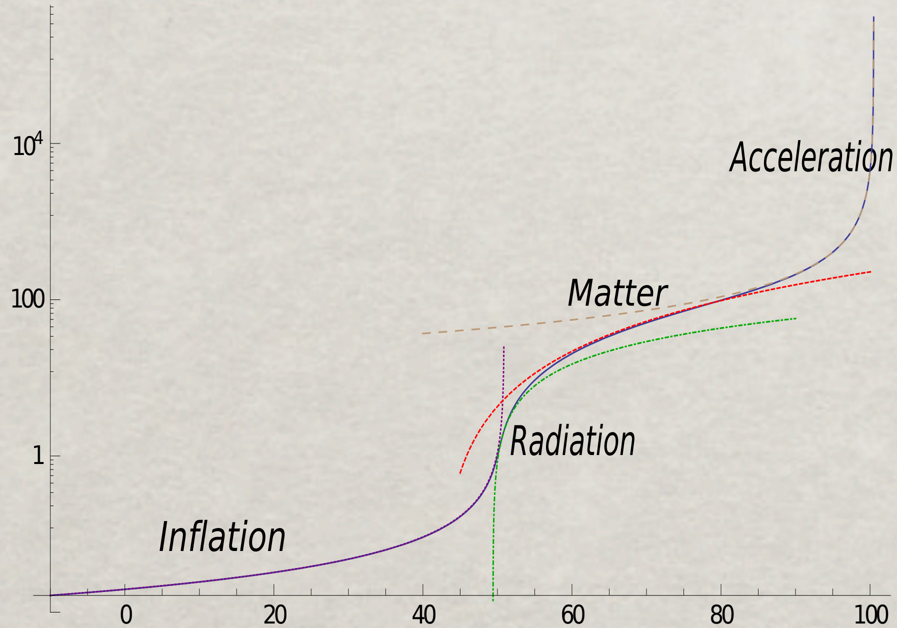


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[b]Department of Physics, Nagoya University,
Nagoya 464-8602, Japan

E-mail: herdeiro@ua.pt, hirano@eken.phys.nagoya-u.ac.jp

Received December 13, 2011
Revised April 19, 2012
Accepted April 24, 2012
Published May 25, 2012

**Abstract.** We propose a 3+1 dimensional model of gravity which results in inflation at early times, followed by radiation- and matter-dominated epochs and a subsequent acceleration at late times. Both the inflation and late time acceleration are nearly de Sitter with a large hierarchy between the effective cosmological constants. There is no scalar field agent of inflation, and the transition from the inflation to the radiation-dominated period is smooth. This model is designed so that it yields, at the cost of giving up on Lorentz invariance in the gravitational sector, the Dirac-Born-Infeld type conformal scalar theory when the universe is conformally flat. It, however, resembles Einstein's gravity with the Gibbons-Hawking-York boundary term in weakly curved space-times.

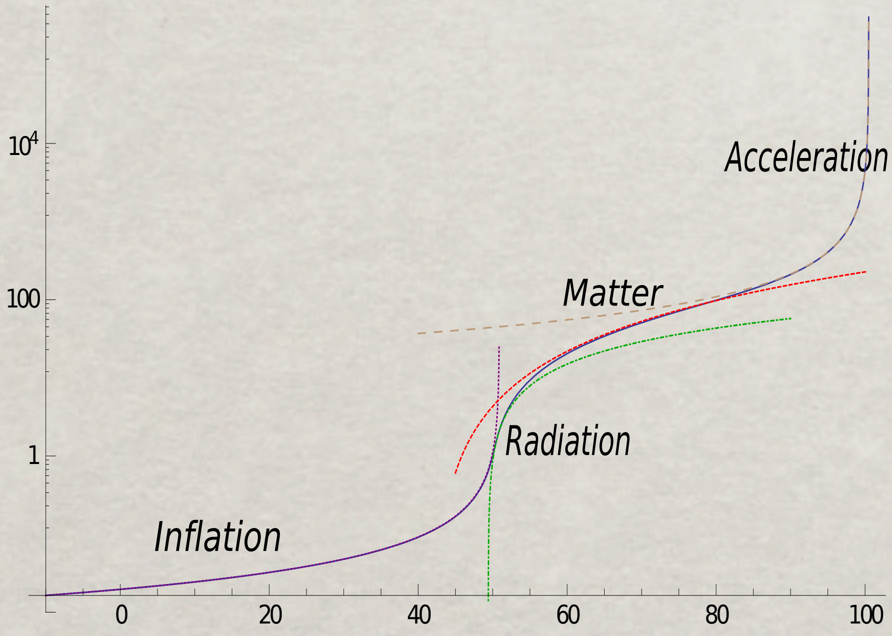
# Uma descrição fenomenológica clássica

$$S = -\frac{3\lambda}{4\pi G_N^2}\int d^4x\sqrt{-g}\left[\sqrt{1+\frac{G_N}{6\lambda}(R+\mathcal{K})}-q\right]$$

$$\mathcal{K} := -\frac{2}{\sqrt{h}}\pounds_n\left(\sqrt{h}K\right) = -2(K^2 + n^\sigma\partial_\sigma K)$$

**Achieved:**

- Duas épocas inflacionárias naturais com gravidade modificada




## PRD 84 (2011)124048

PHYSICAL REVIEW D **84**, 124048 (2011)

**$n$-DBI gravity**

Carlos Herdeiro,[1,*] Shinji Hirano,[2,†] and Yuki Sato[2,3,‡]

[1]*Departamento de Física, Universidade de Aveiro and I3N Campus de Santiago, 3810-183 Aveiro, Portugal*
[2]*Department of Physics, Nagoya University, Nagoya 464-8602, Japan*
[3]*The Niels Bohr Institute, Blegdamsvej 17, DK-2100, Copenhagen, Denmark*

(Received 10 October 2011; published 27 December 2011)

$n$-DBI gravity is a gravitational theory introduced in [C. Herdeiro and S. Hirano, arXiv:1109.1468.], motivated by Dirac-Born-Infeld type conformal scalar theory and designed to yield noneternal inflation spontaneously. It contains a foliation structure provided by an everywhere timelike vector field **n**, which couples to the gravitational sector of the theory, but decouples in the small curvature limit. We show that any solution of Einstein gravity with a particular curvature property is a solution of $n$-DBI gravity. Among them is a class of geometries isometric to a Reissner-Nordström–(anti)-de Sitter black hole, which is obtained within the spherically symmetric solutions of $n$-DBI gravity minimally coupled to the Maxwell field. These solutions have, however, two distinct features from their Einstein gravity counterparts: (1) the cosmological constant appears as an integration constant and can be positive, negative, or vanishing, making it a *variable* quantity of the theory; and (2) there is a nonuniqueness of solutions with the same total mass, charge, and effective cosmological constant. Such inequivalent solutions cannot be mapped to each other by a foliation preserving diffeomorphism. Physically they are distinguished by the expansion and shear of the congruence tangent to **n**, which define scalar invariants on each leaf of the foliation.

## JCAP 05 (2012) 031

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

**Scale invariance and a gravitational model with non-eternal inflation**

**Carlos Herdeiro[a] and Shinji Hirano[b]**

[a]Departamento de Física da Universidade de Aveiro and I3N,
Campus de Santiago, 3810-183 Aveiro, Portugal
[b]Department of Physics, Nagoya University,
Nagoya 464-8602, Japan

E-mail: herdeiro@ua.pt, hirano@eken.phys.nagoya-u.ac.jp

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# Relembrar a História:

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Anomalia de Úrano (1781)

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↓

Várias modificações da gravidade;
as simples falham;
RG (1915) resultou - mas é revolucionária!

# Cosmologia Teórica e Observacional

Carlos Herdeiro
Universidade de Aveiro
http://gravitation.web.ua.pt

6ª Escola de Gravitação e Astrofísica do Instituto Superior Técnico
Lisboa, Setembro de 2012