Astroparticle physics – the History of the Universe

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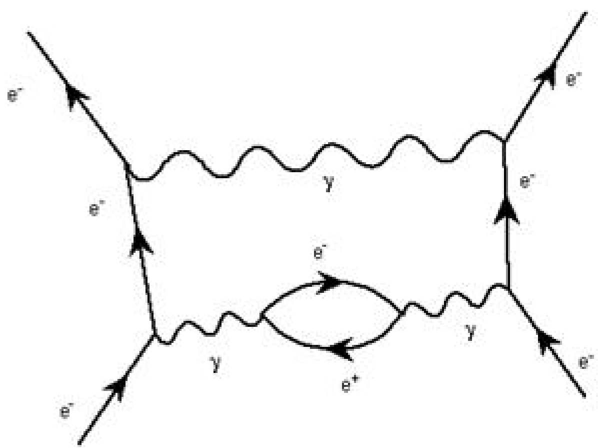
The History of the Universe

The two pillars of modern physics

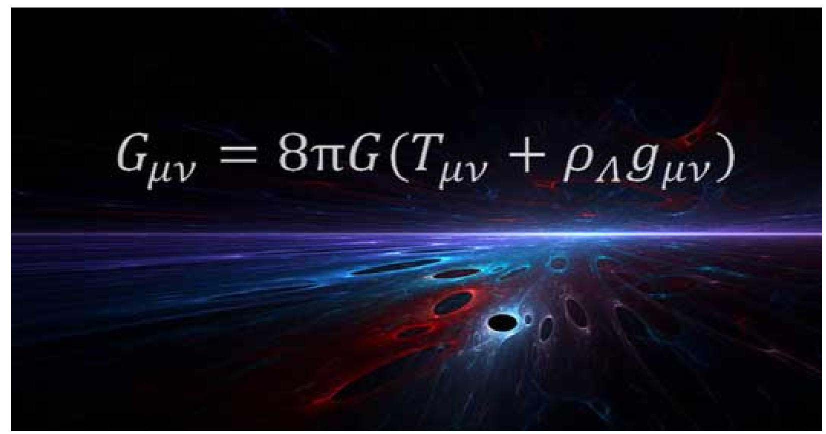
From a theoretical perspective, modern physics stands on two pillars:

Quantum field theories



for the description of the subatomic regime:
- electroweak force
- strong force

General relativity



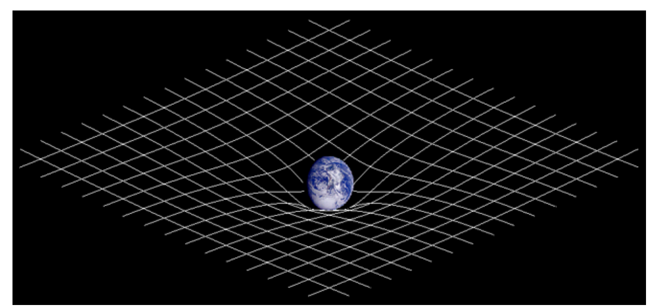
for the description of the large scales of the universe
- gravity

General relativity

- General relativity knows only of an attractive gravitational force $\rightarrow$ a collapsing universe?

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

$G_{\mu\nu}$ . . . Geometry of space-time (Einstein tensor)
G . . . Newton's gravitational constant
$g_{\mu\nu}$ . . . metric tensor
Λ . . . cosmological constant
$T_{\mu\nu}$ . . . Distribution of mass and energy in the Universe (stress-energy tensor)



General relativity

- General relativity knows only of an attractive gravitational force $\longrightarrow$ a universe that collapses immediately on itself?

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

Two ways out:

- a static universe with a cosmological constant
- an ever expanding universe

Two ways out

Georges Lemaître (expanding universe, 1927) and Albert Einstein (cosmological constant, the “greatest blunder of his life”), standing for the two ways to reconcile general relativity with a universe that does not immediately collapse on itself.

Cosmological constant

Einstein's proposal of cosmological constant λ:

- Repulsive force: vacuum exerts pressure
- Vacuum acts like a gas of negative pressure
- Repulsive force compensates gravity, static Universe is possible (but it does not remain static)
- Today's formulation: constant uniform density of dark energy throughout all of space that is independent of time or the Universe's expansion

(Was Einstein really wrong … ?)

Edwin Hubble

- Most galaxies recede from us
- Recession speed is larger for more distant galaxies
- Linear relation between recess velocity *v* and distance *d*

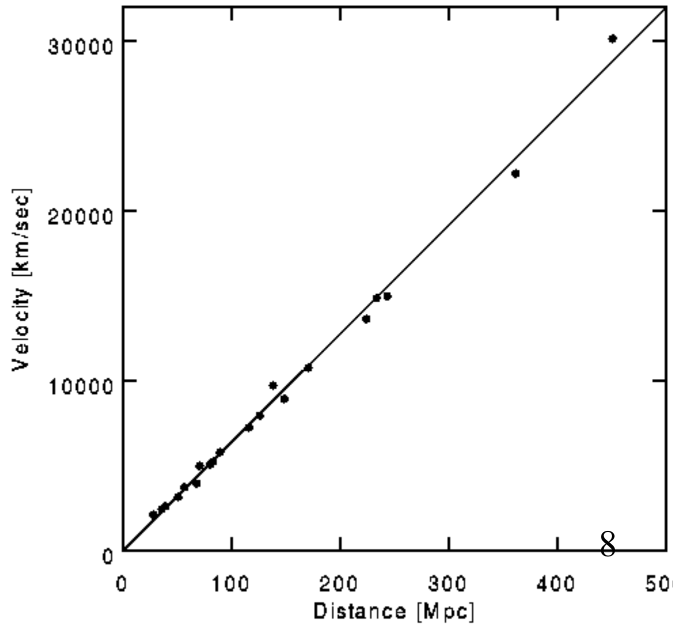
$$v = H_0\, d$$

$H_0 \sim 68$ km s^{-1} Mpc^{-1}

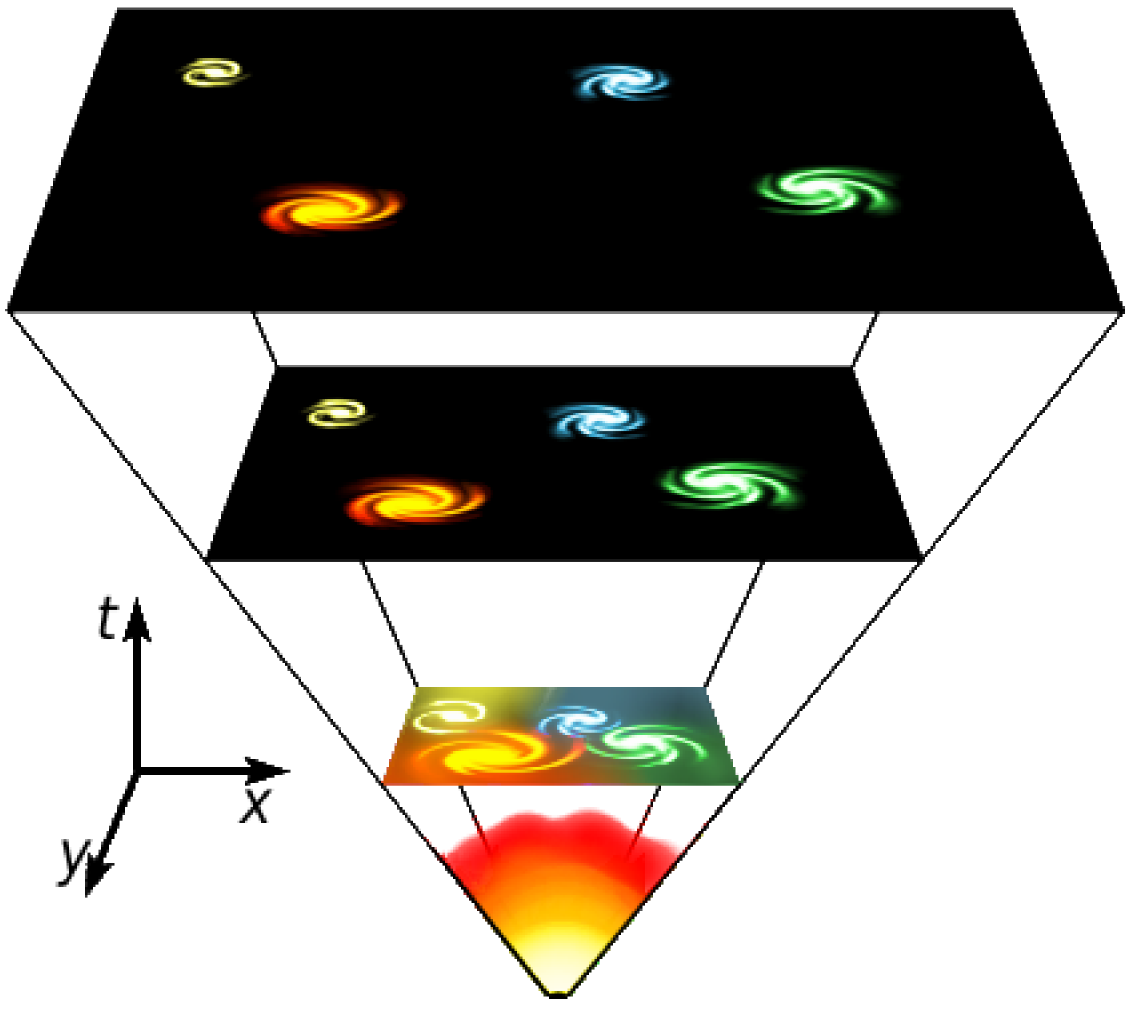
H_0 … Hubble constant (Hubble parameter)

Edwin Hubble (1889-1953)

Hooker Telescope
Mt. Wilson



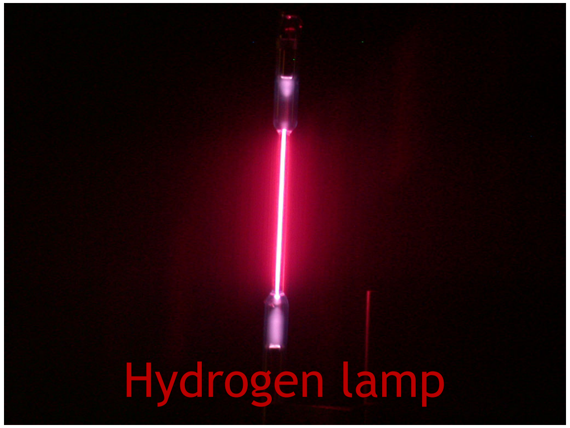
An expanding universe

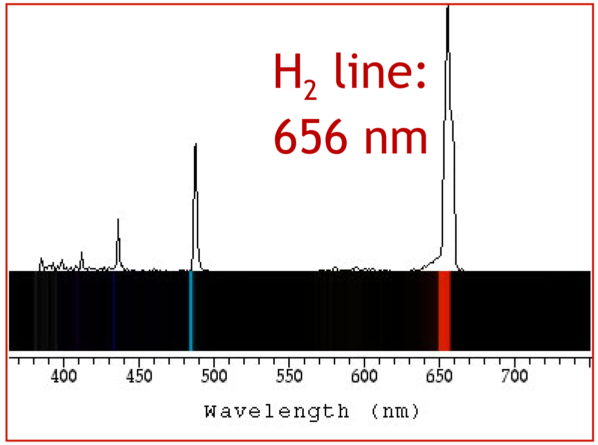


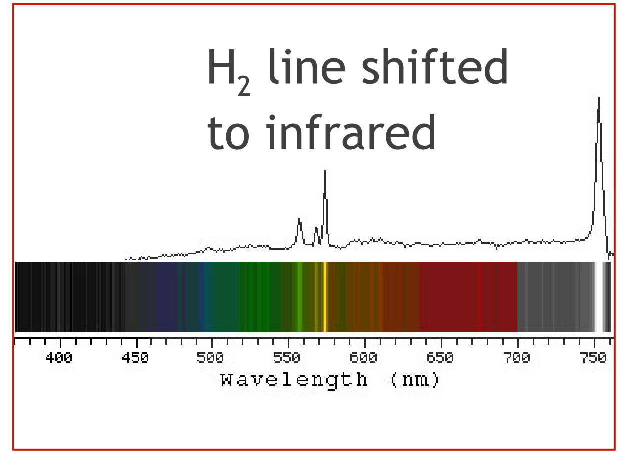
How can we know that galaxies recede from us?

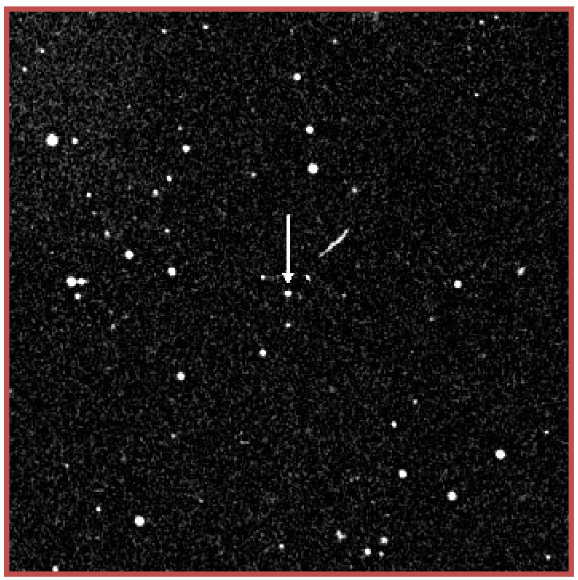
How can we measure the velocities at which they recede from us? And their distance?

Redshift as instrument to measure velocity of recession of galaxies





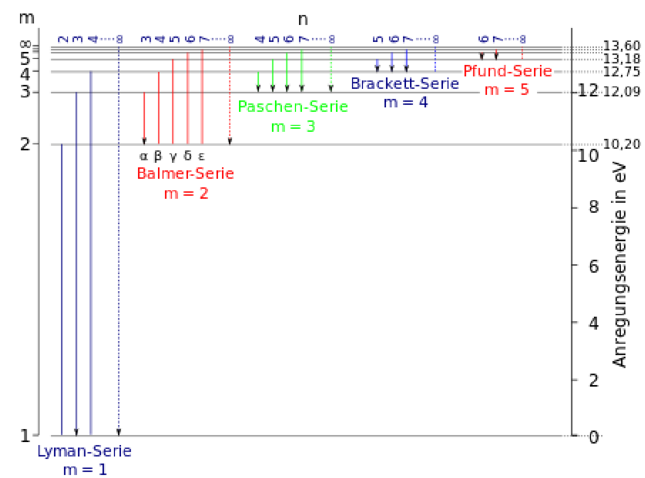




Galaxy IRAS F09159

$$z = \sqrt{\frac{1+\beta}{1-\beta}} - 1$$

$$z = \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}}$$



Light flux as a measure of distance

Distance *r* of a galaxy can be calculated from light flux *F* from objects with defined luminosity *L* (Standard Candles e.g. Cepheid variable stars, supernovae Ia):

Henrietta Leavitt
(cepheid variable stars)

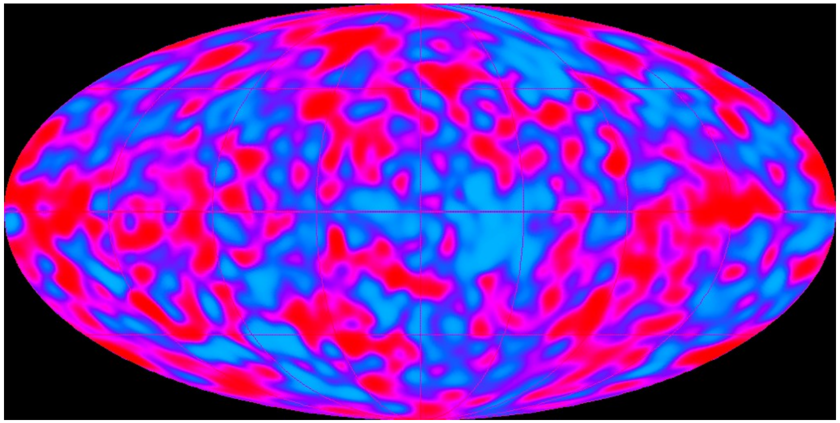
$$F = \frac{L}{4\pi r^2}$$

$$\boxed{r = \sqrt{\frac{L}{4\pi F}}}$$

NGC-4526

The cosmological principle

Temperature fluctuations



COBE

Homogeneous: the universe looks the same everywhere on large scales
→ there is no special place (center)

Isotropic: the universe looks the same in all directions on the sky
→ there is no special direction (axis)

Does the cosmological principle hold?
The cosmological principle is valid for our Universe on the largest scales.
One very direct evidence for the principle to hold is the
cosmic microwave background, which is homogeneous to 1 part in 10^5!

… and now back to our cosmological model of the universe:

Ingredients:

- general relativity

- cosmological principle

- an expanding universe

...

Metric of an Expanding Universe

Flat (static) space: $$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = dt^2 - dx^2 - dy^2 - dz^2$$

Spherical coordinates: $$ds^2 = dt^2 - (dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2)$$

Expanding space: $$ds^2 = dt^2 - R^2(t)(dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2)$$

R(t) ... scale factor, *ds* ... space-time interval

Most general form of metric for homogeneous, isotropic universe:

Robertson-Walker metric: $$\boxed{ds^2 = dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right)}$$

k ... curvature constant

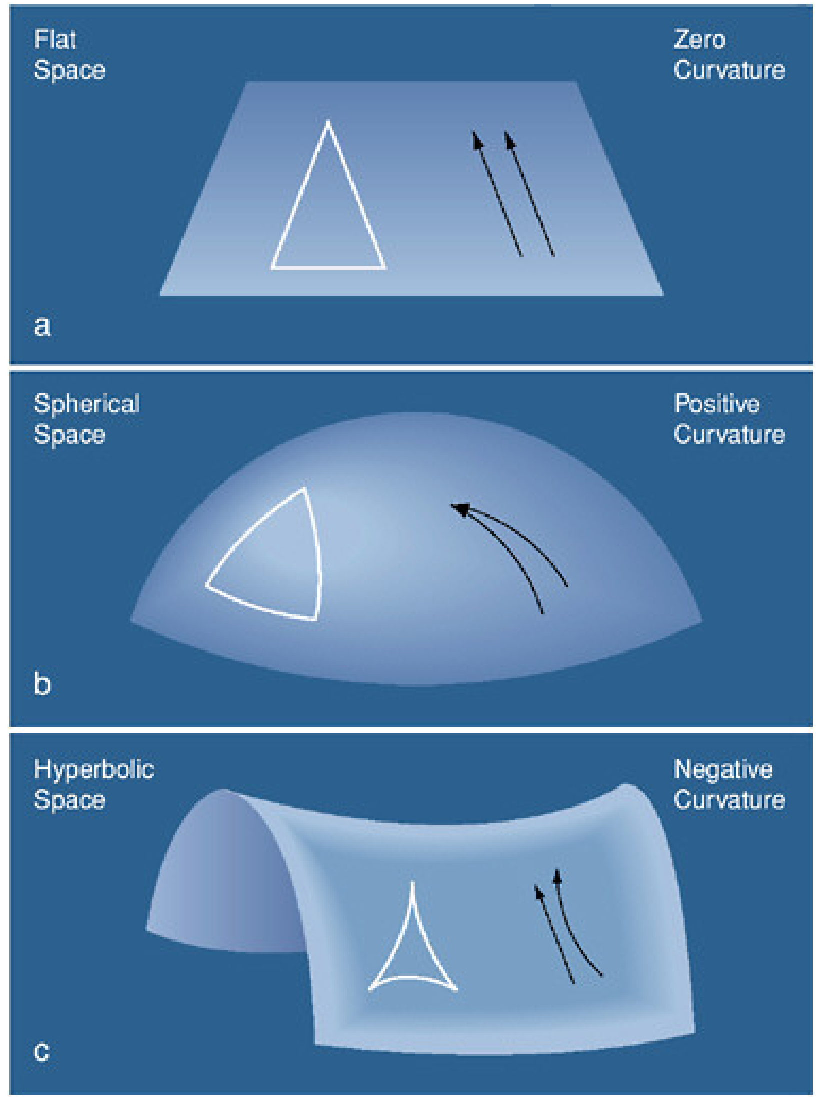
k = 0: flat space
k > 0: spherical geometry
k < 0: hyperbolic geometry

Topology of the Universe

k = 0: flat space

k > 0: spherical geometry

k < 0: hyperbolic geometry



Friedmann equation

The solution of Einstein's field equations for general relativity, assuming homogeneous and isotropic distribution of matter and radiation behaving like a perfect, frictionless fluid, describes the evolution of the Universe.

This solution for the temporal development of the Universe was first found by Alexander Friedmann, with *r* being the average density:

$$H_0^2 = \frac{v^2}{R^2} = \frac{8\pi G}{3}\rho - \frac{k}{R^2}$$

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(for special case of non-relativistic matter the equation can be understood with simple Newtonian mechanics: a point mass m is accelerated by gravity at the surface of a sphere of radius R, density ρ, mass M = 4 π R^3 ρ / 3:

$$H_0^2 = \frac{v^2}{R^2} = \frac{8\pi G}{3}\rho - \frac{k}{R^2}$$

total energy

kinetic energy

- potential energy

Friedmann equation

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$$H_0^2 = \frac{v^2}{R^2} = \frac{8\pi G}{3}\rho - \frac{k}{R^2}$$

Critical density for $k = 0$: $$\rho_{crit} = \frac{3H_0^2}{8\pi G}$$

$\rho_{crit} = 8 \times 10^{-30}$ g/cm^3 ~1 atom per 200 l

$\rho = \rho_{crit}$: Universe expands forever
$\rho > \rho_{crit}$: Universe recollapses
$\rho < \rho_{crit}$: Universe expands forever

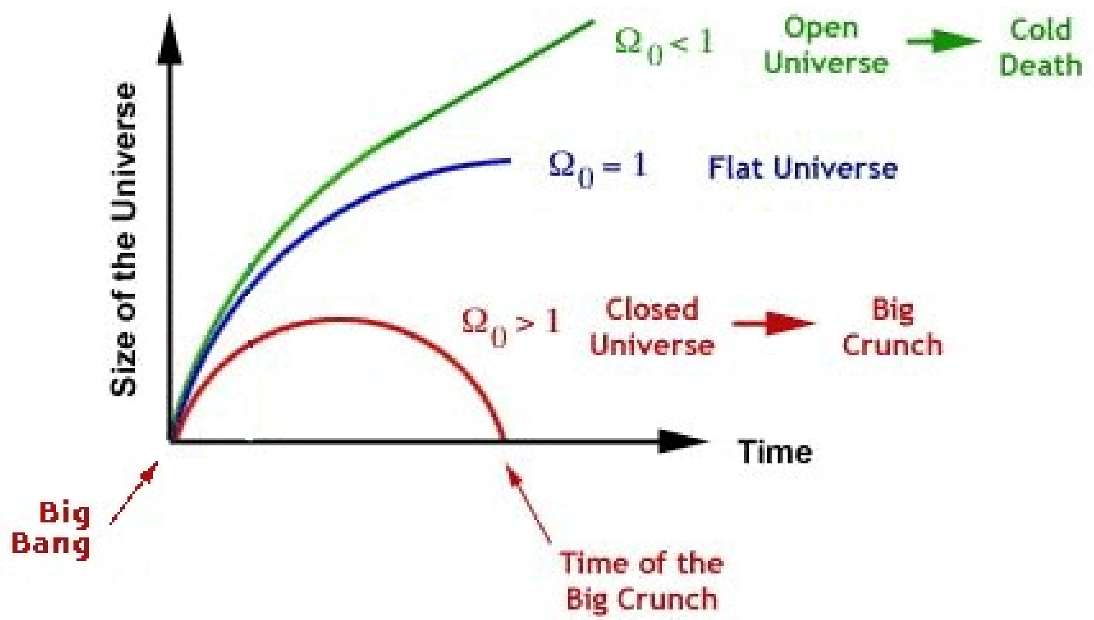
Fate of the Universe

Density parameter $\Omega_0 = \rho / \rho_{crit}$

$\Omega_0 = 1$: flat space, forever expanding (open)

$\Omega_0 > 1$: spherical geometry, recollapsing (closed)

$\Omega_0 < 1$: hyperbolic geometry, forever expanding



Fate of the Universe

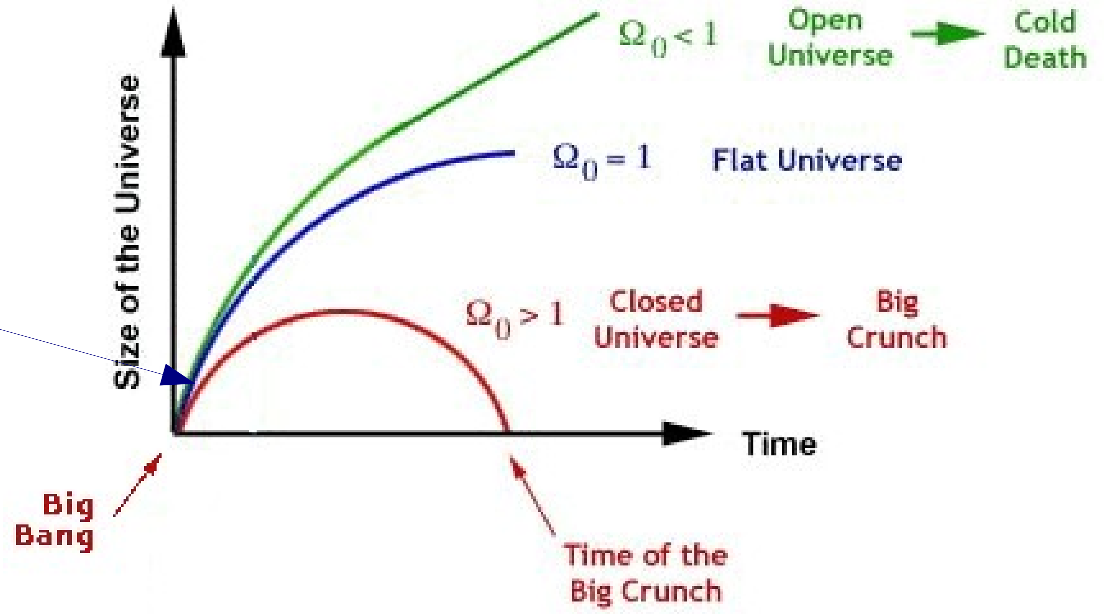
Density parameter $\Omega_0 = \rho / \rho_{crit}$

Ω_0 = *1*: flat space, forever expanding (open)

Ω_0 > *1*: spherical geometry, recollapsing (closed)

Ω_0 < *1*: hyperbolic geometry, forever expanding

you are here



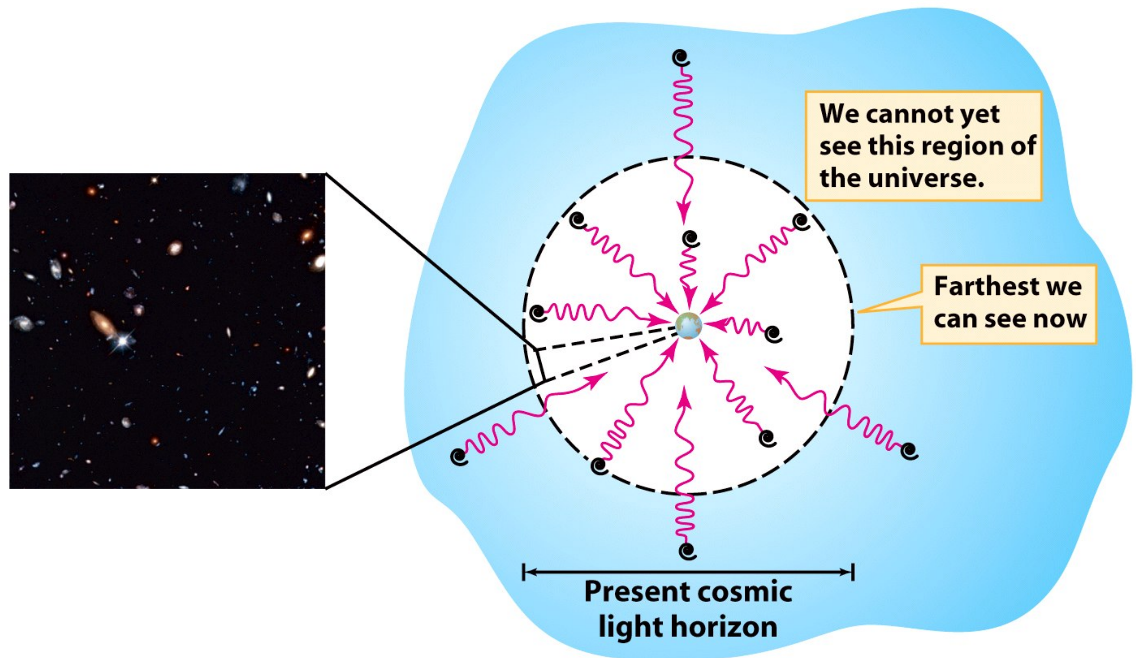
Age and size of the universe

If the exansion rate of the universe $H = \frac{\dot{R}}{R}$ was constant H_0, we could compute the age of the universe as

$$t_{Hubble} = \frac{d}{v} = \frac{1}{H_0}$$

we shall see later that the H is not constant with time. Taking this into account we end up with the age of the universe of **about 14 billion years**

We can only see the part of the Universe that is closer than the distance that light can travel in a time corresponding to the age of the universe.



Size of the Observable Universe

The radius of the observable universe is determined by the distance to the optical horizon, beyond which no light signals could reach the Earth at the present time.

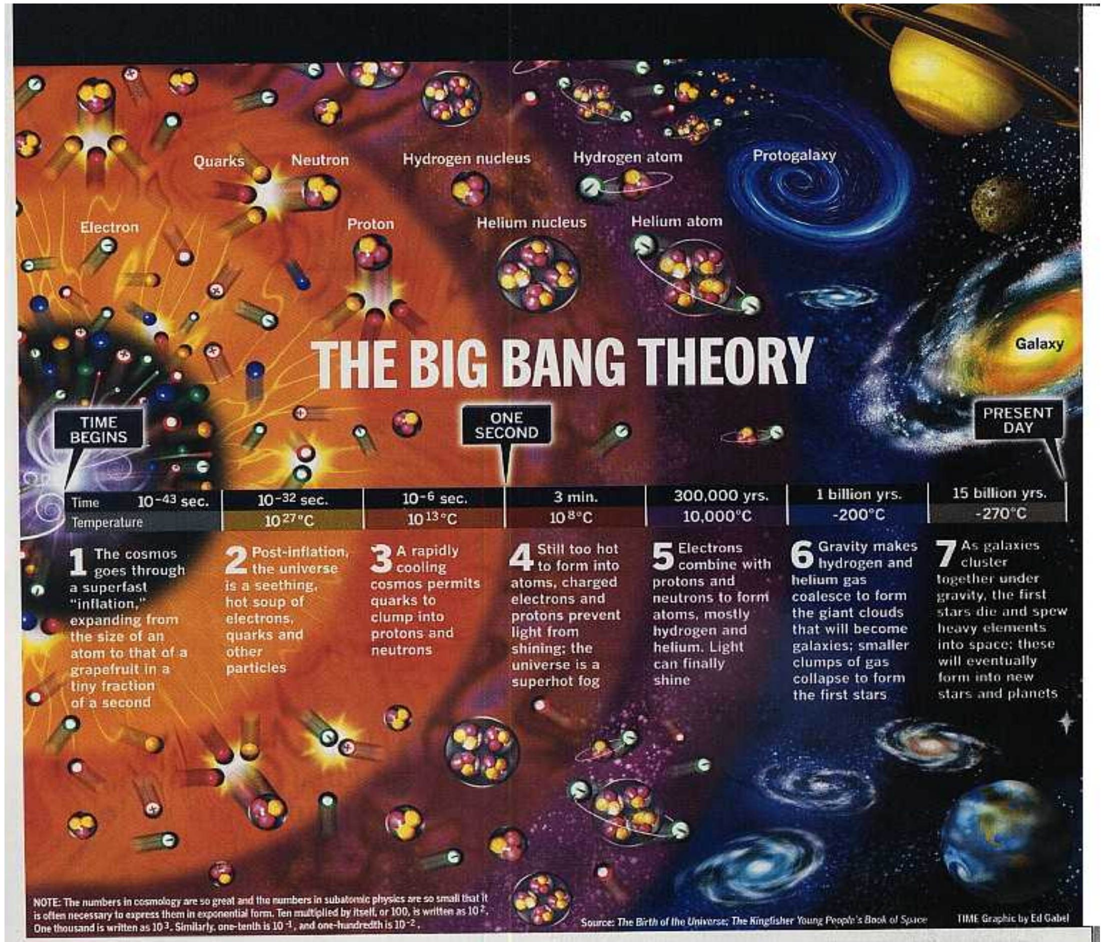
If the universe was static, flat:

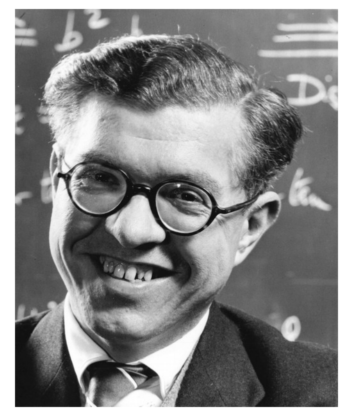
$$d_{Hubble} = ct_{Hubble} = \frac{c}{H_0} \approx 4.2 \text{ Gpc}$$

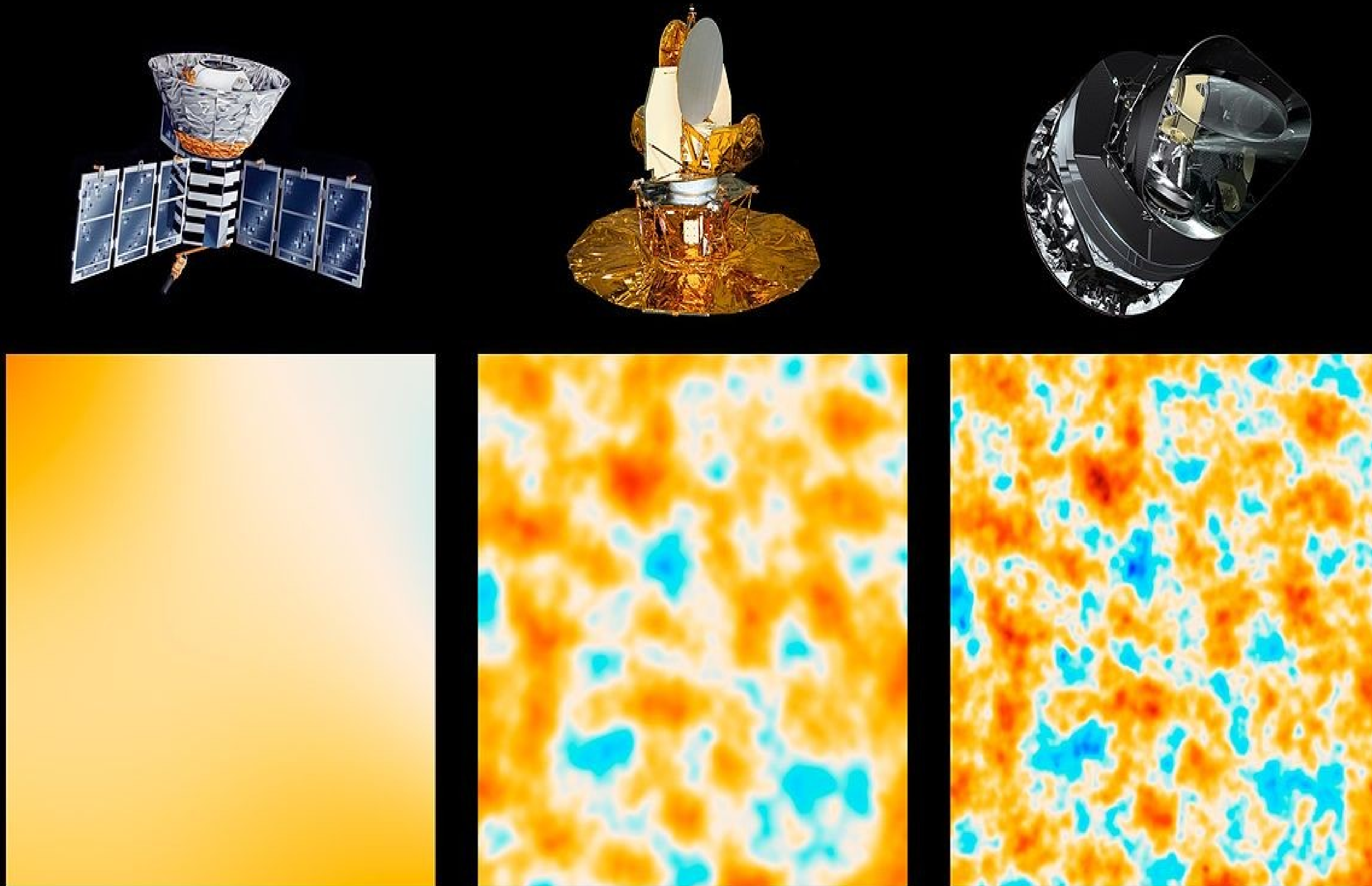
Expansion of the universe enlarges this number, such that (under reasonable assumptions):

$$H \approx 3.3 \frac{c}{H_0} \approx 14 Gpc \approx 45 Gly$$

The Big Bang Theory





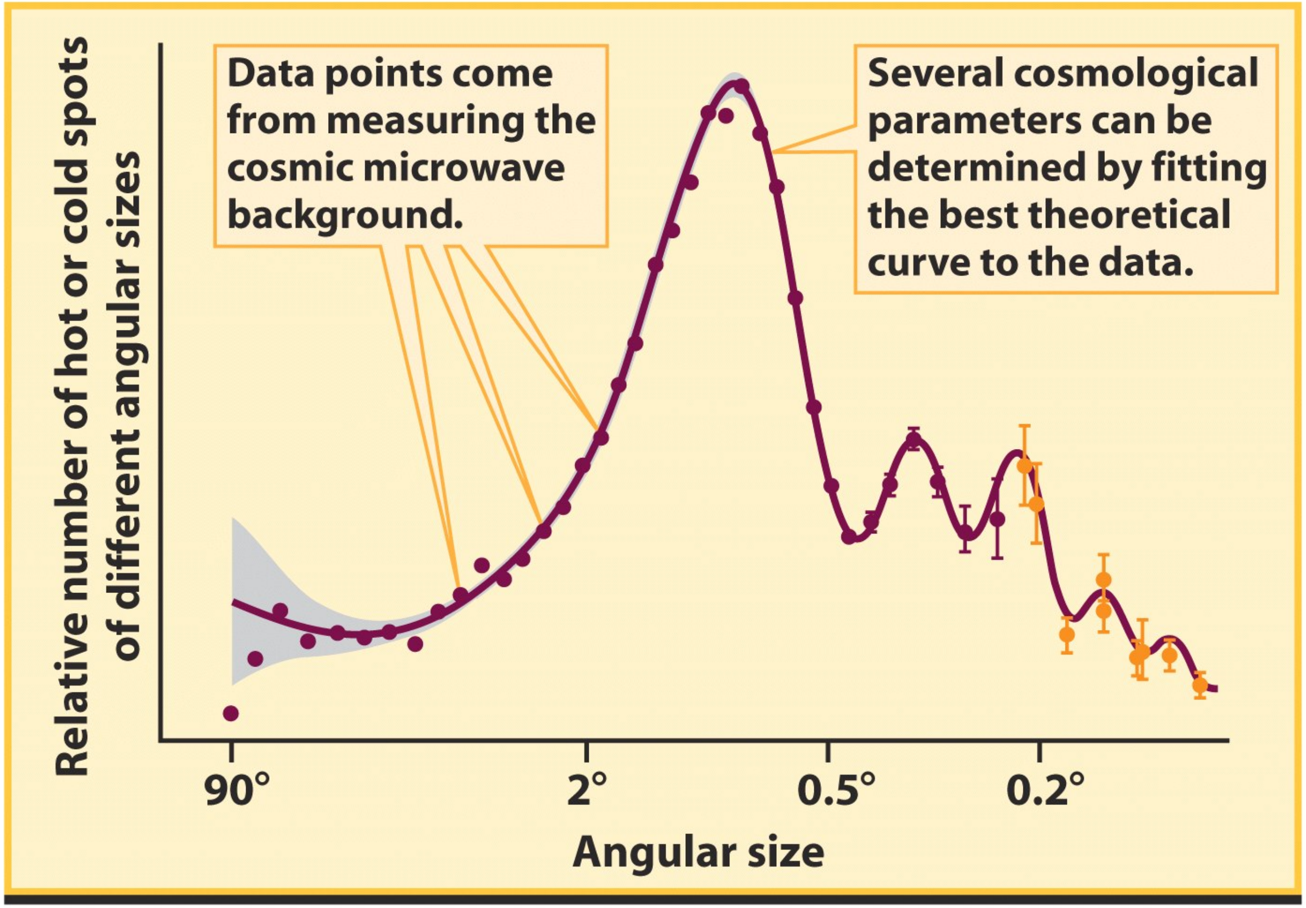


COBE

WMAP

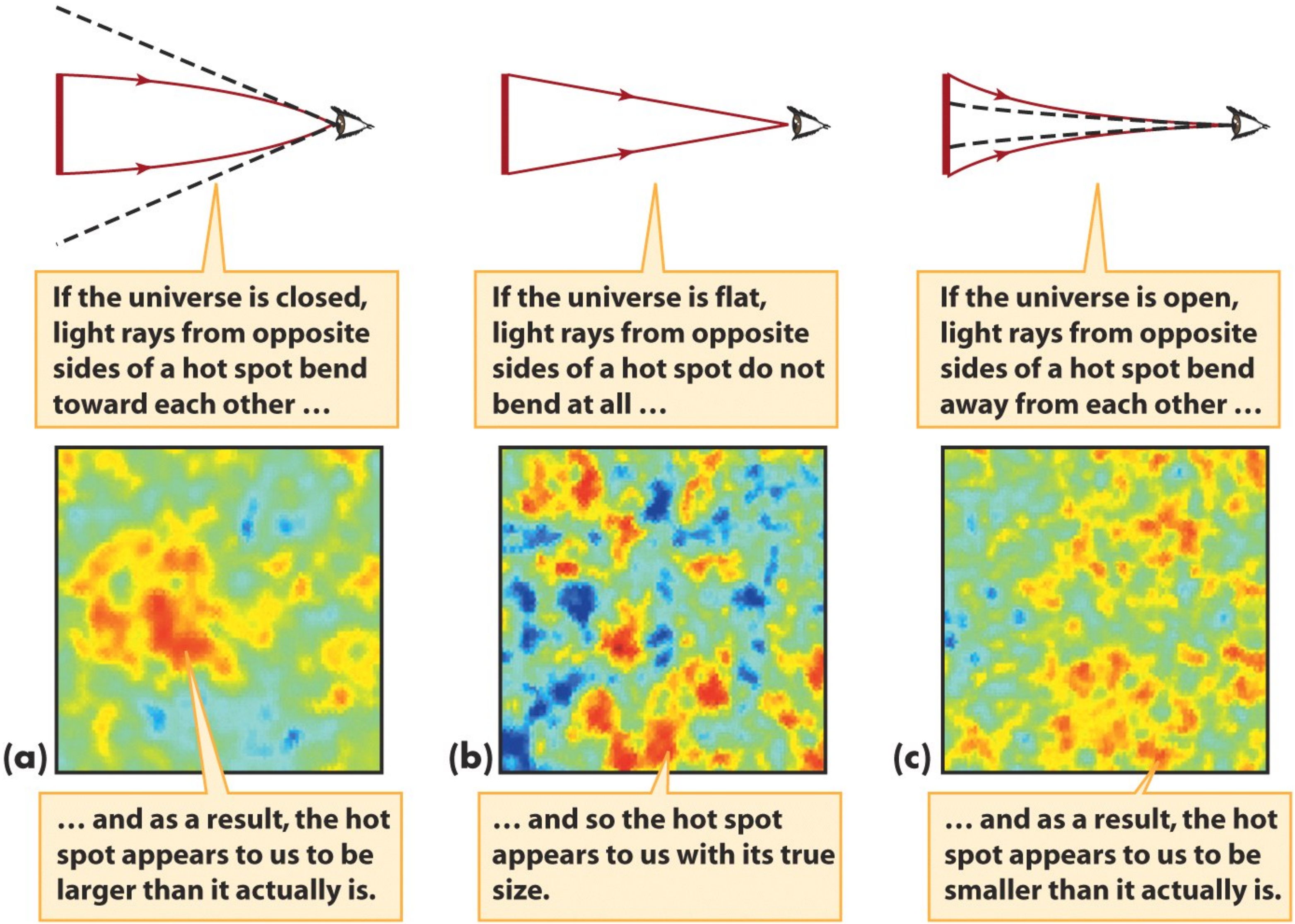
Planck

Baryonic Acoustic Oscillations – Primordial sound waves

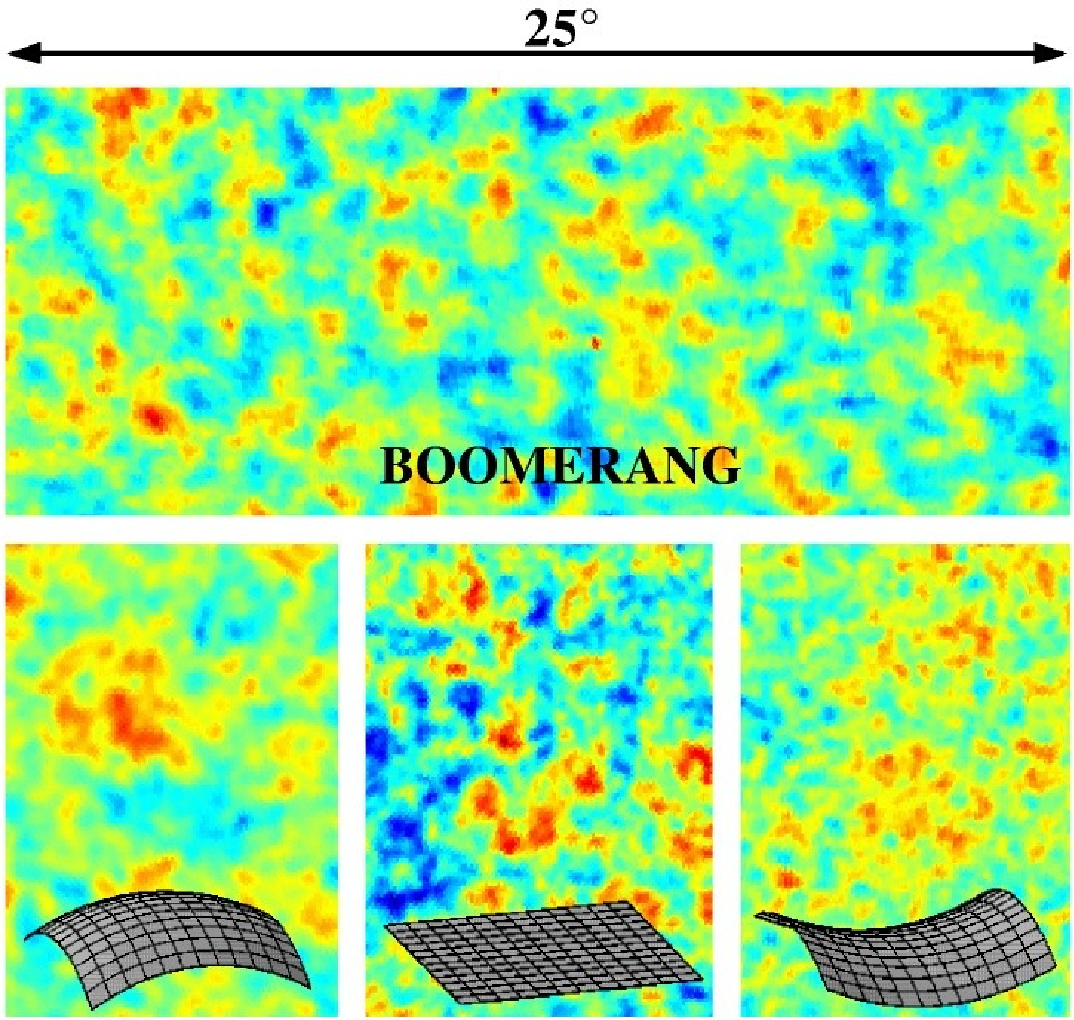


- Temperature variations in the cosmic background radiation are a record of sound waves in the early universe
- Studying the character of these sound waves, and the polarization of the background radiation that they produce, helps constrain models of the universe
- The three major peaks show the relative contributions of dark energy, ordinary matter, and dark matter.

Curvature of the Universe



Universe is flat



Boomerang experiment

Measurement of Ω_0

1: Count all mass we "see" (tricky …)

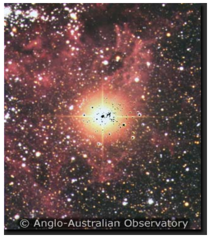
2: measure rate at which expansion is slowing down

- More massive Universe will slow down faster

3: measure geometry of the Universe

1998: 2 projects of supernova Ia measurements to determine the Hubble constant accurately -> surprise!

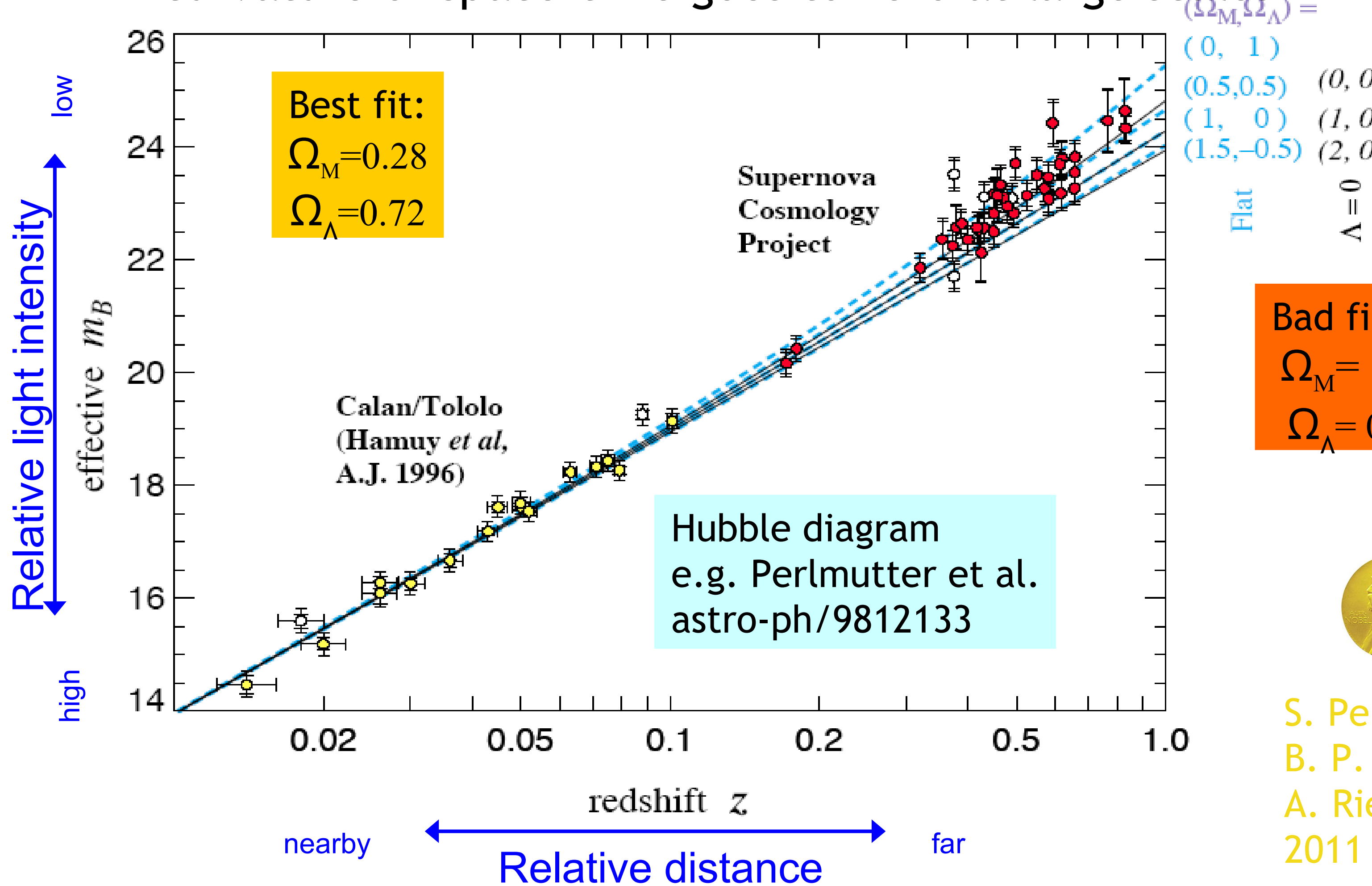
Most accurate measurement today: cosmic microwave background



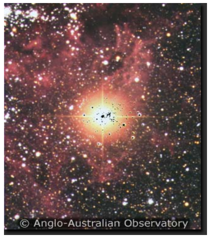
Accelerated expansion of the Universe

$\Omega_M + \Omega_\Lambda = 1$ **… Universe is "flat":**

curvature of space-time goes to zero at large scales

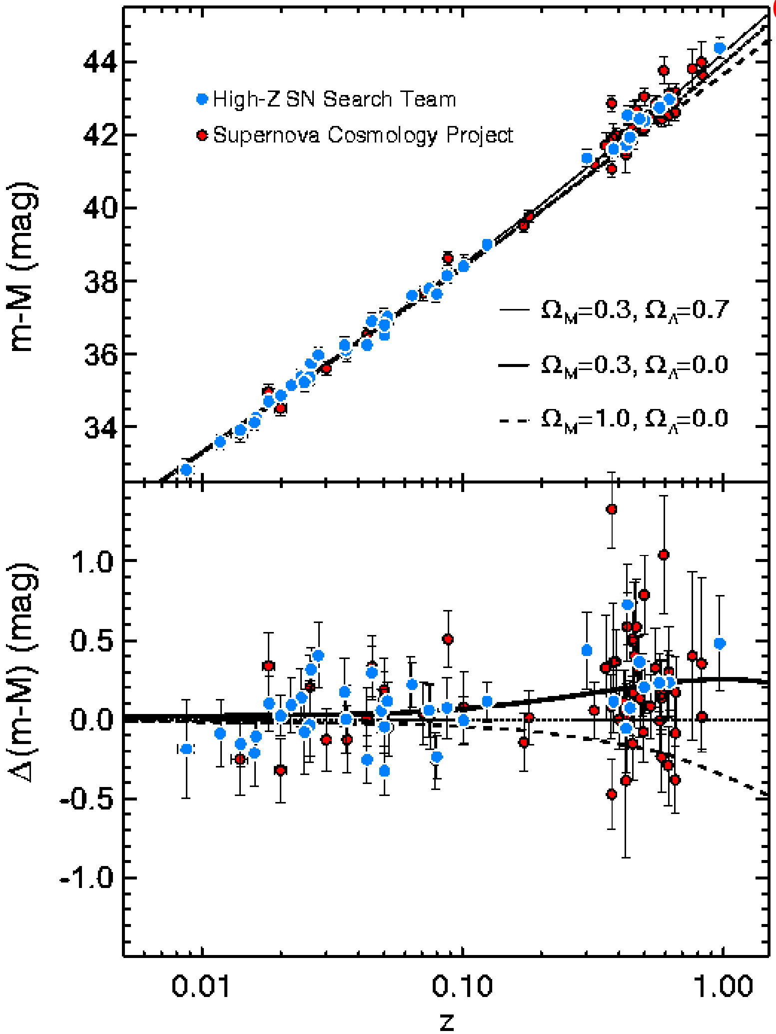


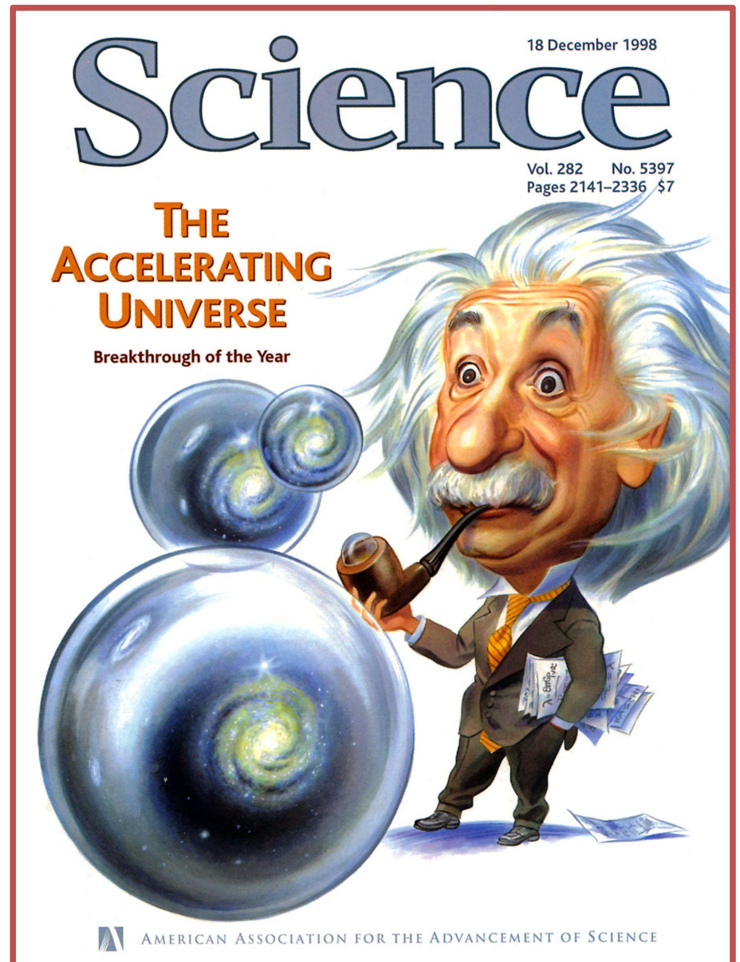
S. Perlmutter
B. P. Schmidt
A. Riess
2011



Accelerated expansion of the Universe

Einstein's cosmological constant revived -> vacuum energy, "dark energy"!





Friedmann equation revisited

$$H_0^2 = \frac{v^2}{R^2} = \frac{8\pi G}{3}\rho - \frac{k}{R^2} + \frac{\Lambda}{3}$$

$$\Omega_\Lambda = \frac{\Lambda}{3H_0^2} \approx 0.7$$

$$\Omega_M = \Omega_0 \approx 0.3$$

k = 0: flat space
k > 0: spherical geometry
k < 0: hyperbolic geometry

Note: for sufficiently large Λ a spherical Universe may also expand forever

Fate of the Universe revisited ($\Lambda > 0$)

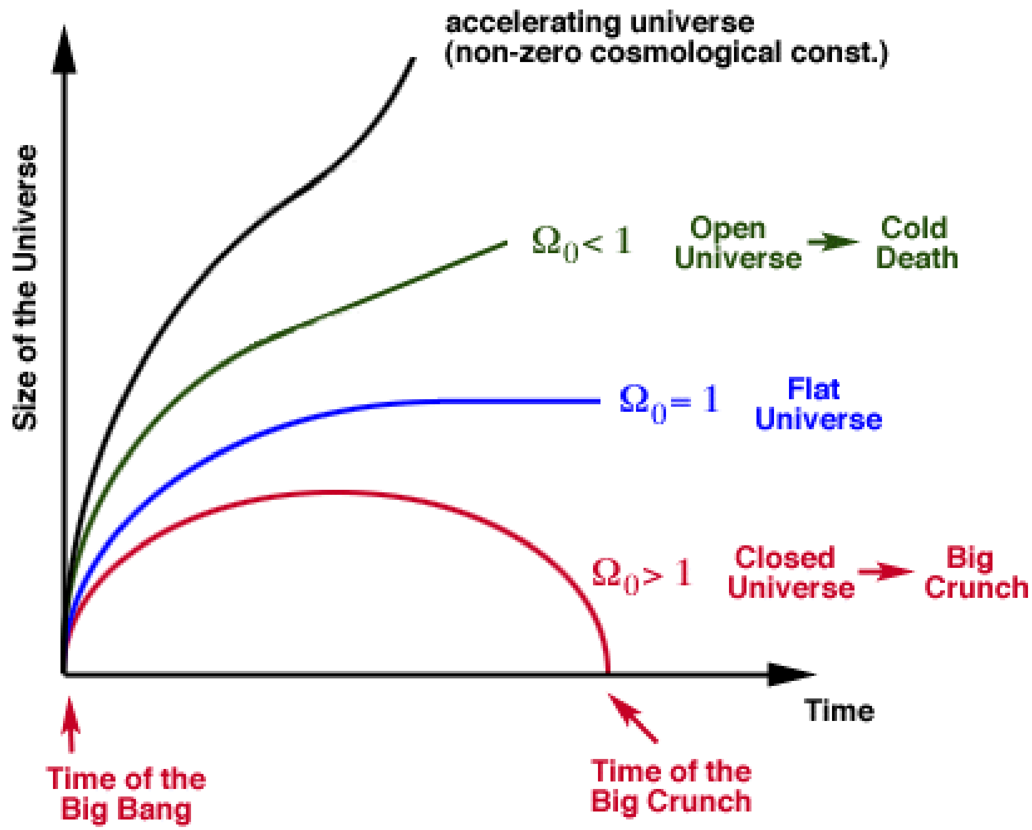
$\Omega_\Lambda + \Omega_0 = 1$: flat

$\Omega_\Lambda + \Omega_0 < 1$: hyperbolic

$\Omega_\Lambda + \Omega_0 > 1$: spherical

$\Omega_0/2 - \Omega_\Lambda > 0$: decelerating

$\Omega_0/2 - \Omega_\Lambda < 0$: accelerating

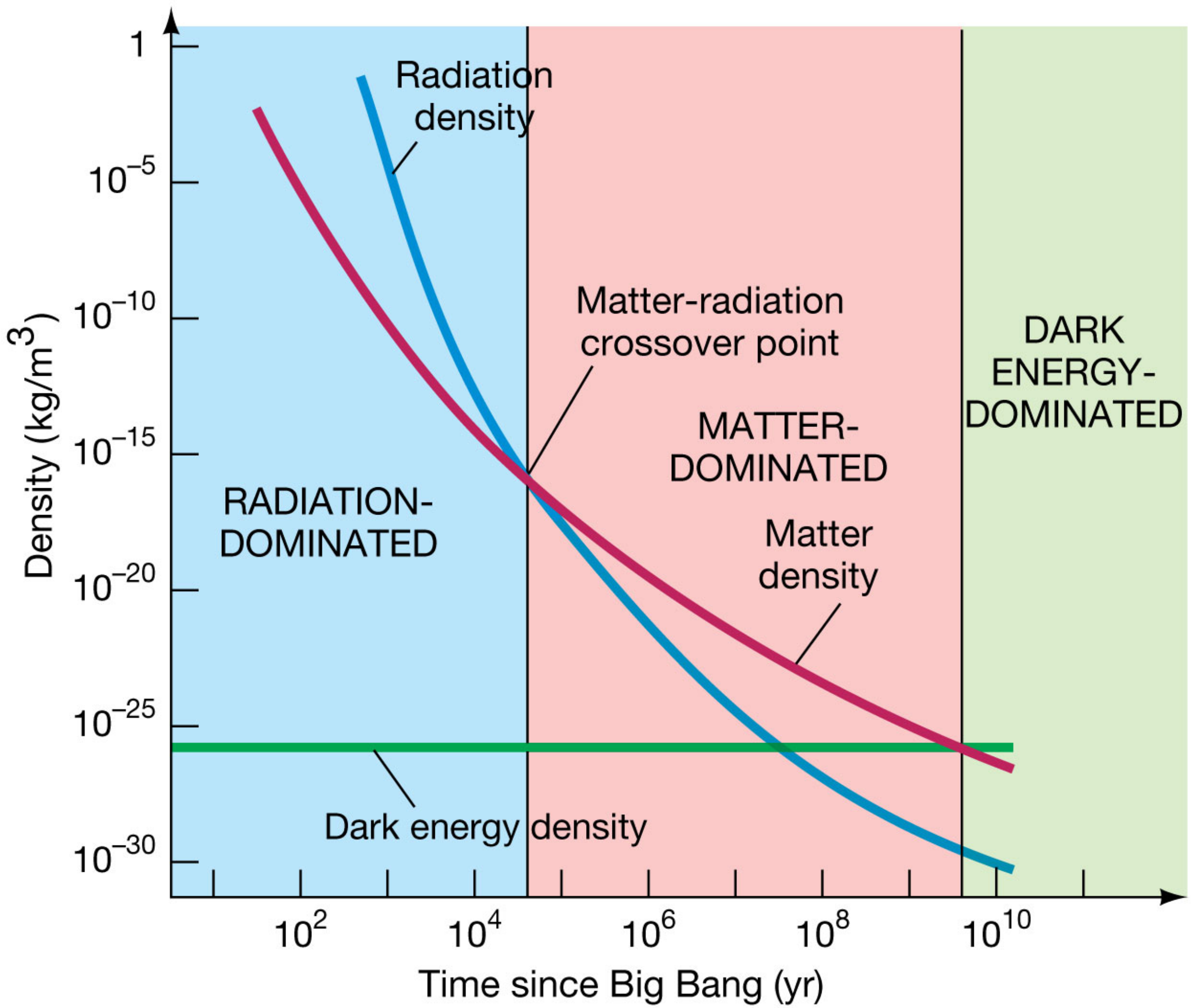


General relativity +
cosmological principle +
Robinson-Walker metric +
Friedmann equation +
cold dark matter +
cosmological constant =

(theoretical framework of)

Standard model of cosmology
= Λ-CDM-model

Evolution of density



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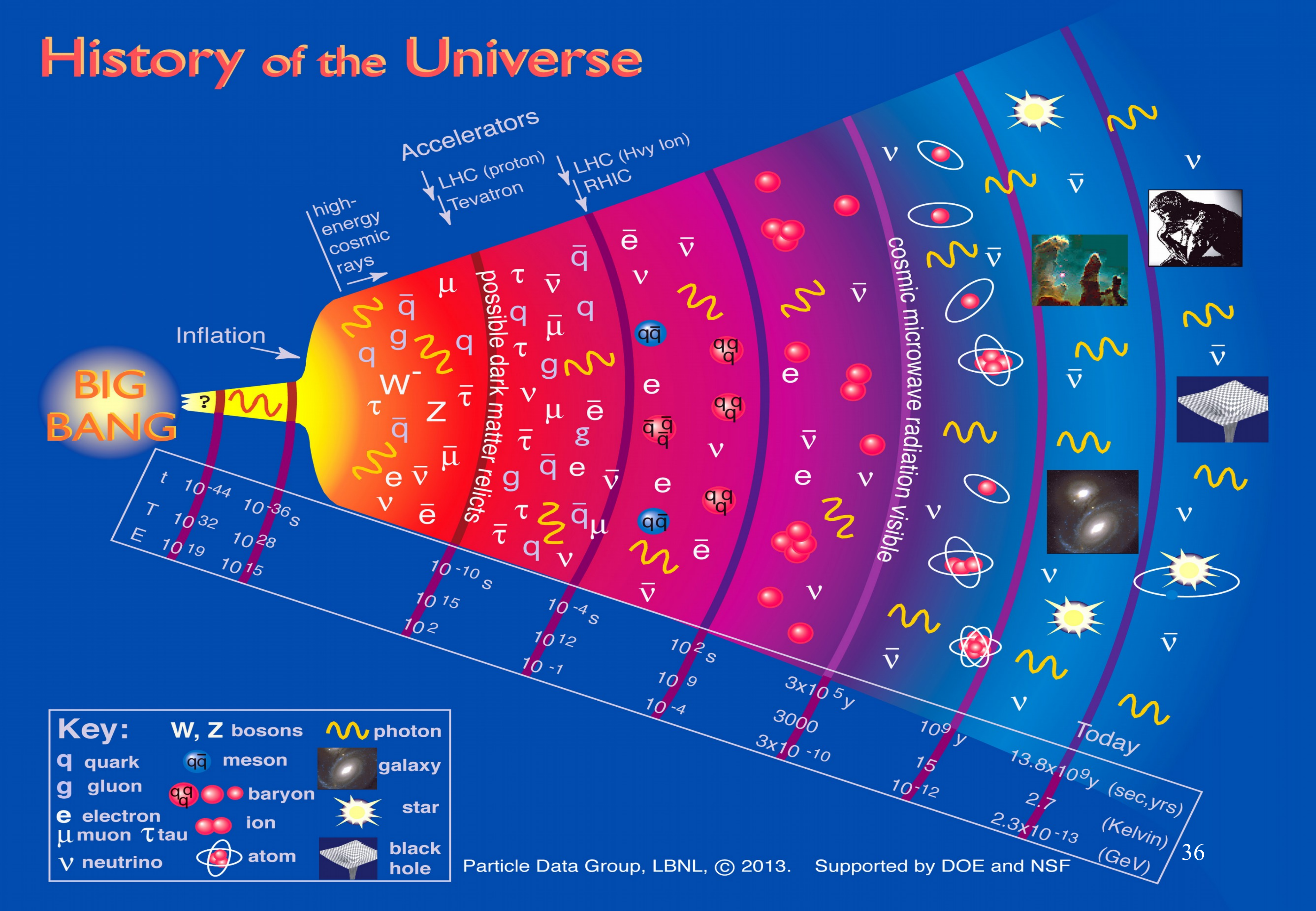
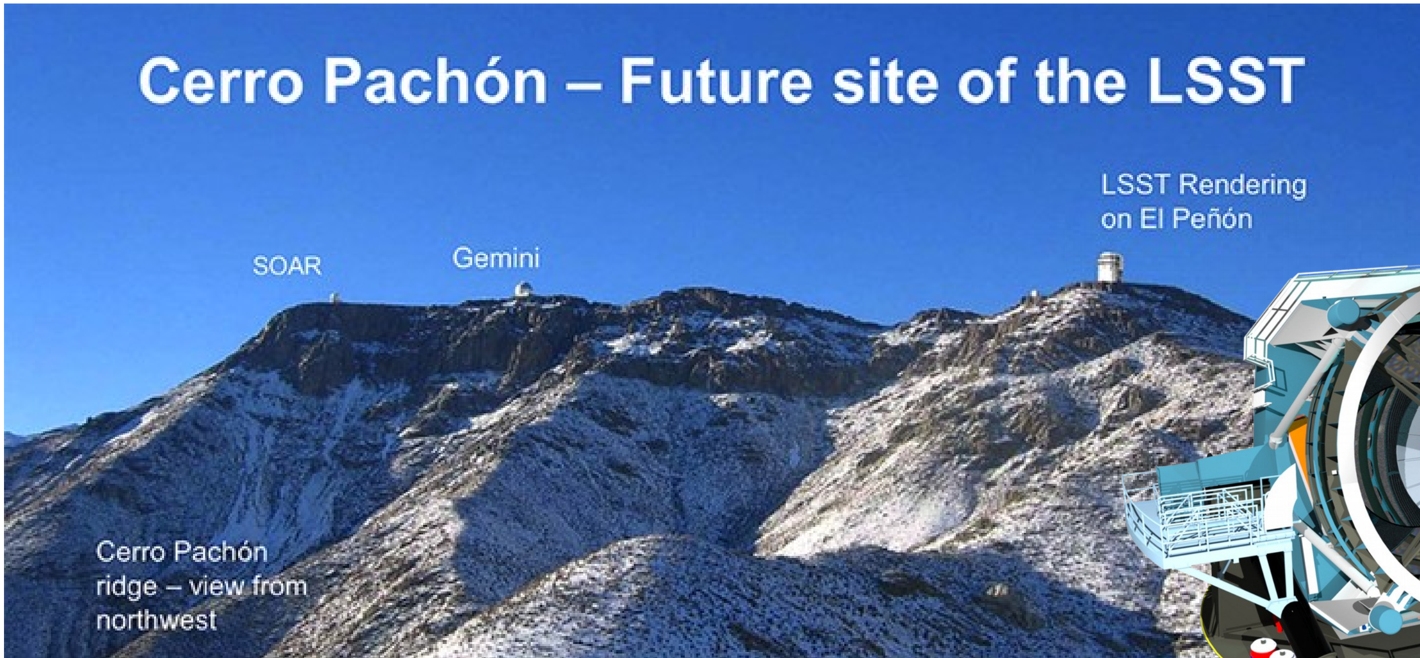
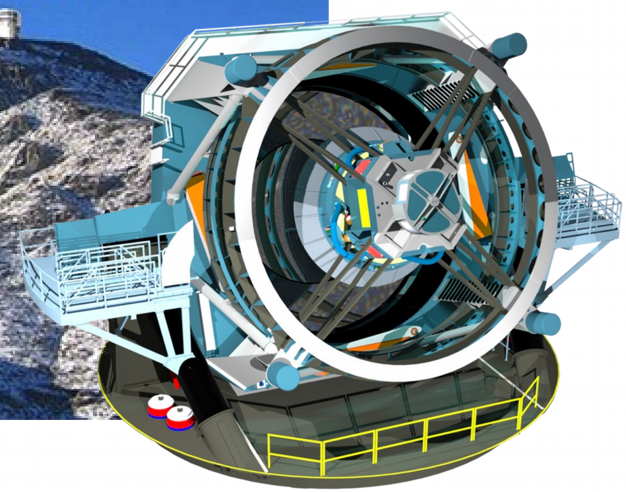

History of the Universe
Accelerators
LHC (proton)
Tevatron
LHC (Hvy Ion)
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10 -44 10 -36 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -4 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
13.8x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

Sloane Digital Sky Survey

Baryonic Acoustic Oscillations, Dark Energy

LSST (Large Synoptic Survey Telescope)

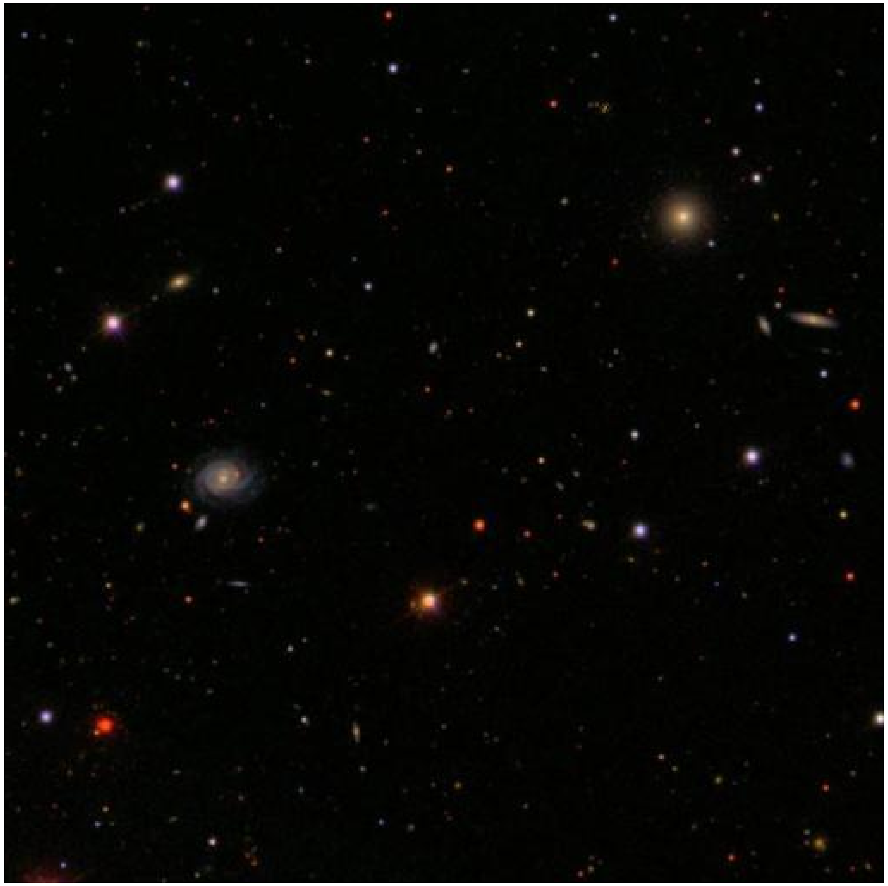




- Dark energy signatures in a single data set
- Separately measure geometry and growth of dark matter structure versus cosmic time.
- first light in 2019

http://www.lsst.org/lsst/

SDSS – LSST comparison



Sloan Digital Sky Survey

LSST

Baryogenesis

Baryogenesis

Baryogenesis: process that produced dominance of matter over antimatter observed in the Universe.

We know there is a paucity of anti-matter in our galaxy, in the local cluster, and in our universe.

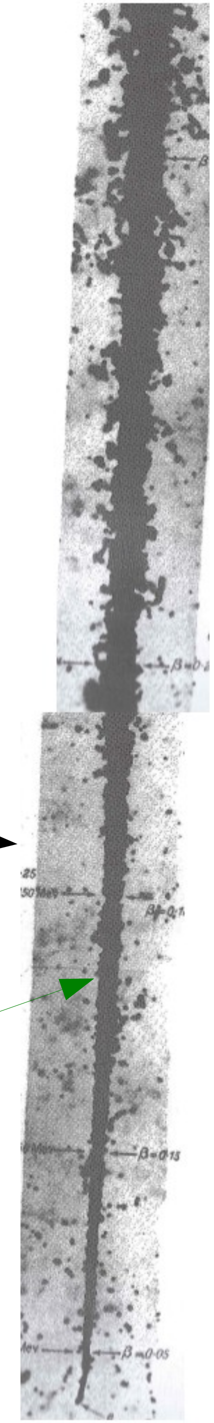
How do we know this?

Several hints:

- primary cosmic ray nuclei are mostly baryons rather than anti-baryons

- no evidence for intense gamma ray emission following from annihilation of matter in distant galaxies with clouds of antimatter

- no signs for nucleon-antinucleon annihilation in the black body distribution of the CMB background



a chromium nucleus, observed in nuclear emulsion flown in a balloon, as it slowly collects all electrons needed to form a chromium atom. An anti-chromium would have produced O(100) pions – a much, much more violent reaction!

Where are the anti-baryons?

If we assume an initial Baryon number of ≈ 0,
and strict Baryon conservation, then
a naïve calculation would lead to

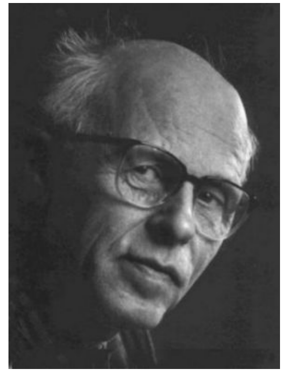
$$\frac{N_B}{N_\gamma} = \frac{N_{\bar{B}}}{N_\gamma} \approx 10^{-18}$$

However, we observe

$$\frac{N_B}{N_\gamma} \approx 10^{-9}, \frac{N_{\bar{B}}}{N_B} < 10^{-4}$$

Sacharov conditions and possible reasons for baryon asymmetry

Three conditions must be met for a universe with non-zero baryon number to evolve from an initial B=0 state, A. Sacharov 1967:



1) Baryon number violating interactions
2) Deviation from thermal equilibrium
3) C (charge) and CP (charge-parity) violation

C … charge conjugation, P … parity

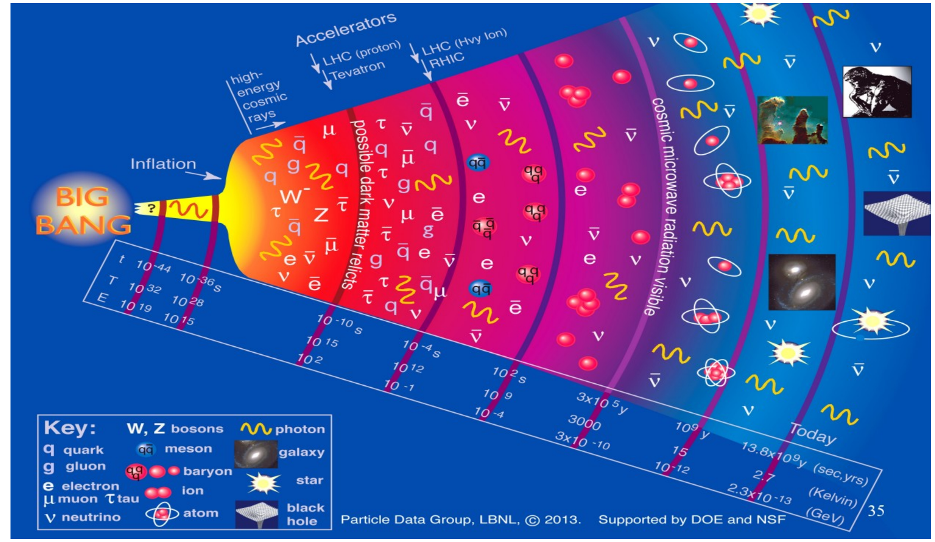
1) evidently
2) in thermal equilibrium reverse process would occur as much as baryon-destruction process
3) needed in order for anti-baryon to significantly differ from baryon

→ leptoquarks at the scale of the Grand Unified Theory (GUT)?
→ Proton decay?

An unsolved puzzle!

Nucleosynthesis

Nucleosynthesis



Nucleosynthesis ≡ synthesis of the nuclei of the light elements: ^{4}He, ^{2}H, ^{3}He, ^{7}Li.

At t> 10^{-4} s, kT becomes < 100 MeV, and all hadrons with exception of neutrons and protons have died.

What are the relative numbers of neutrons to protons?

Given the ratio of neutrons to protons, what do we expect the ratio of hydrogen to helium mass to be? Is this compatible with what we see?

Nucleosynthesis

What's the relative numbers of neutrons and protons?

Ratio determined by the weak reactions:

$$n \rightarrow p + e^- + \nu_e \text{ (Neutron decay)}$$
$$p + \nu_e \leftrightarrow n + e^+$$
$$n + \nu_e \leftrightarrow p + e^-$$

Initial ratio at freeze-out governed by Boltzmann equation: $$\frac{N_n}{N_p} = exp\left(\frac{-Q}{kT}\right)$$

$Q = (m_n - m_p)c^2$
kT = freeze-out temperature approx 0.8 MeV

$$\frac{N_n(t=0)}{N_p(t=0)} \approx \frac{1}{5}$$

a few more neutrons die out such that eventually $$\frac{N_n(t=300s)}{N_p(t=300s)} \approx \frac{1}{7}$$

Nucleosynthesis

Given the ratio of neutrons to protons, what do we expect the ratio of hydrogen to helium mass to be?

Setting the mass of a helium nucleus = 4 * mass of proton:

$$Y = \frac{4N_{He}}{N_H + 4N_{He}} = \frac{2r}{1 - r + 2r} \approx 0.24$$

Is this compatible with what we measure?

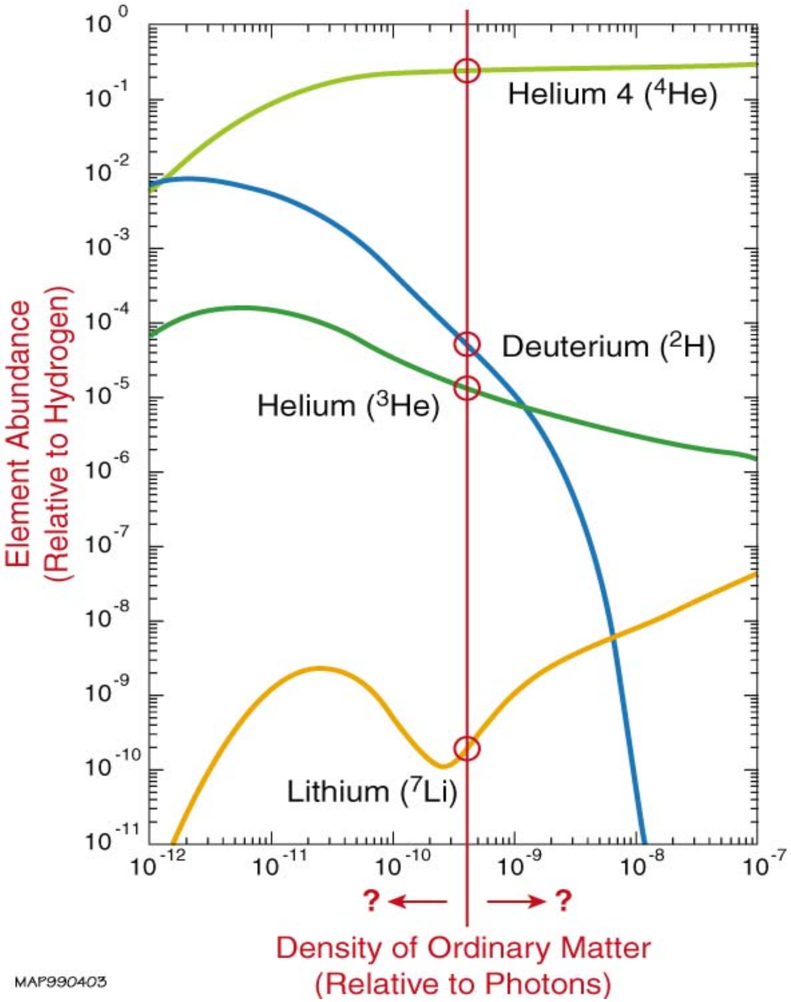
Measured in a variety of celestial sites: nebulae, gas clouds, clusters:

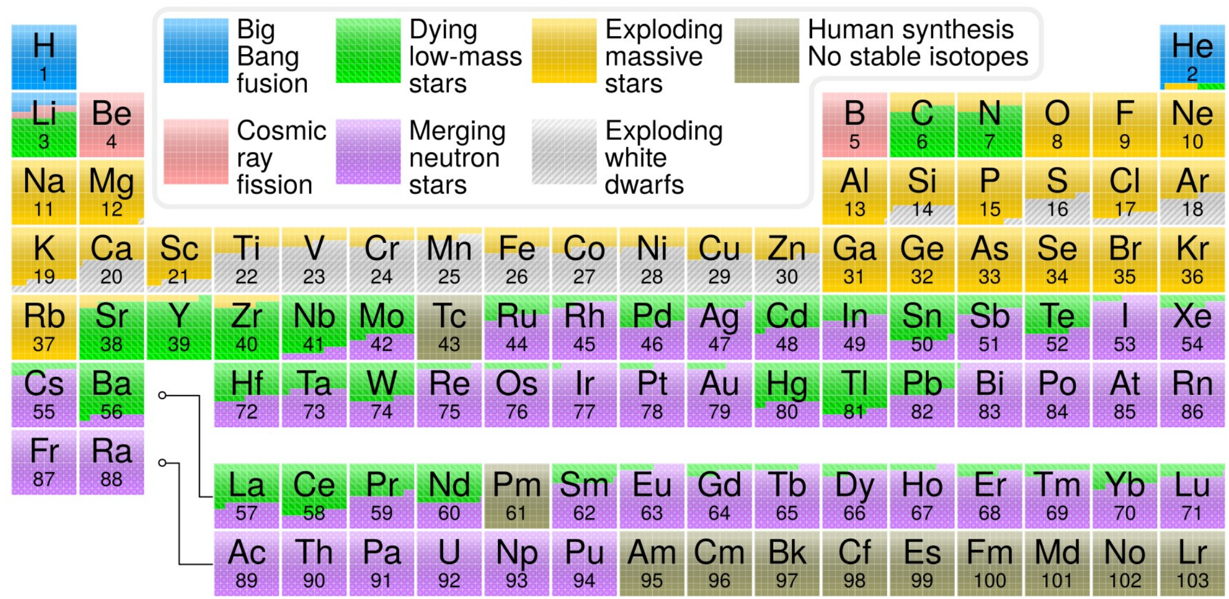
Y = 0.238 +- 0.006

Early success for the Big Bang model!

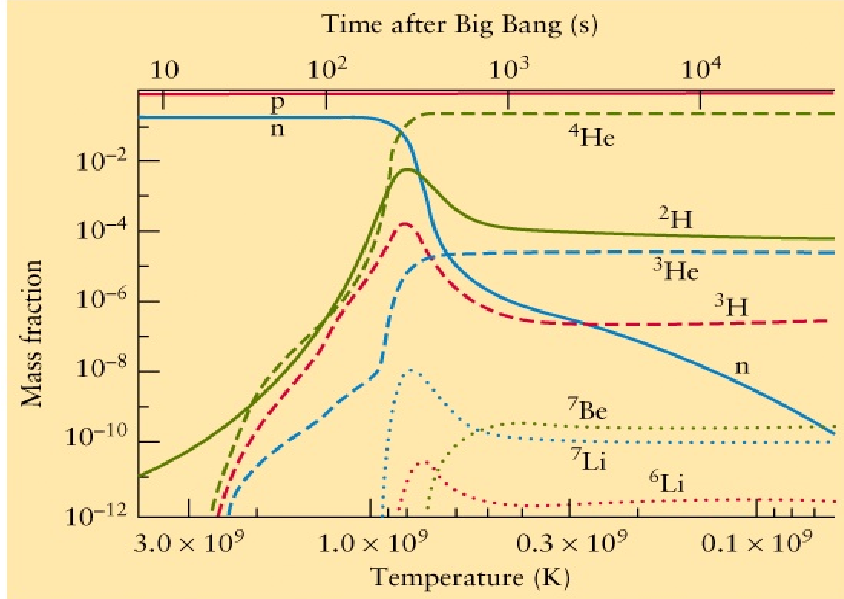
Similar but more complicated considerations hold for the abundance of D, ^{3}He, ^{7}Li.

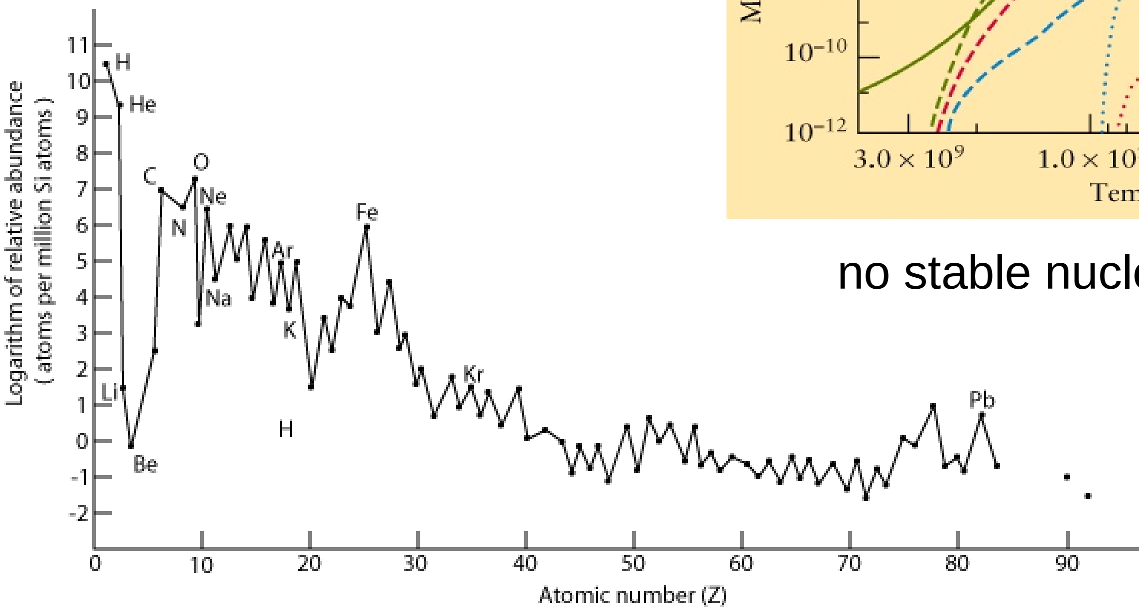
Nucleosynthesis





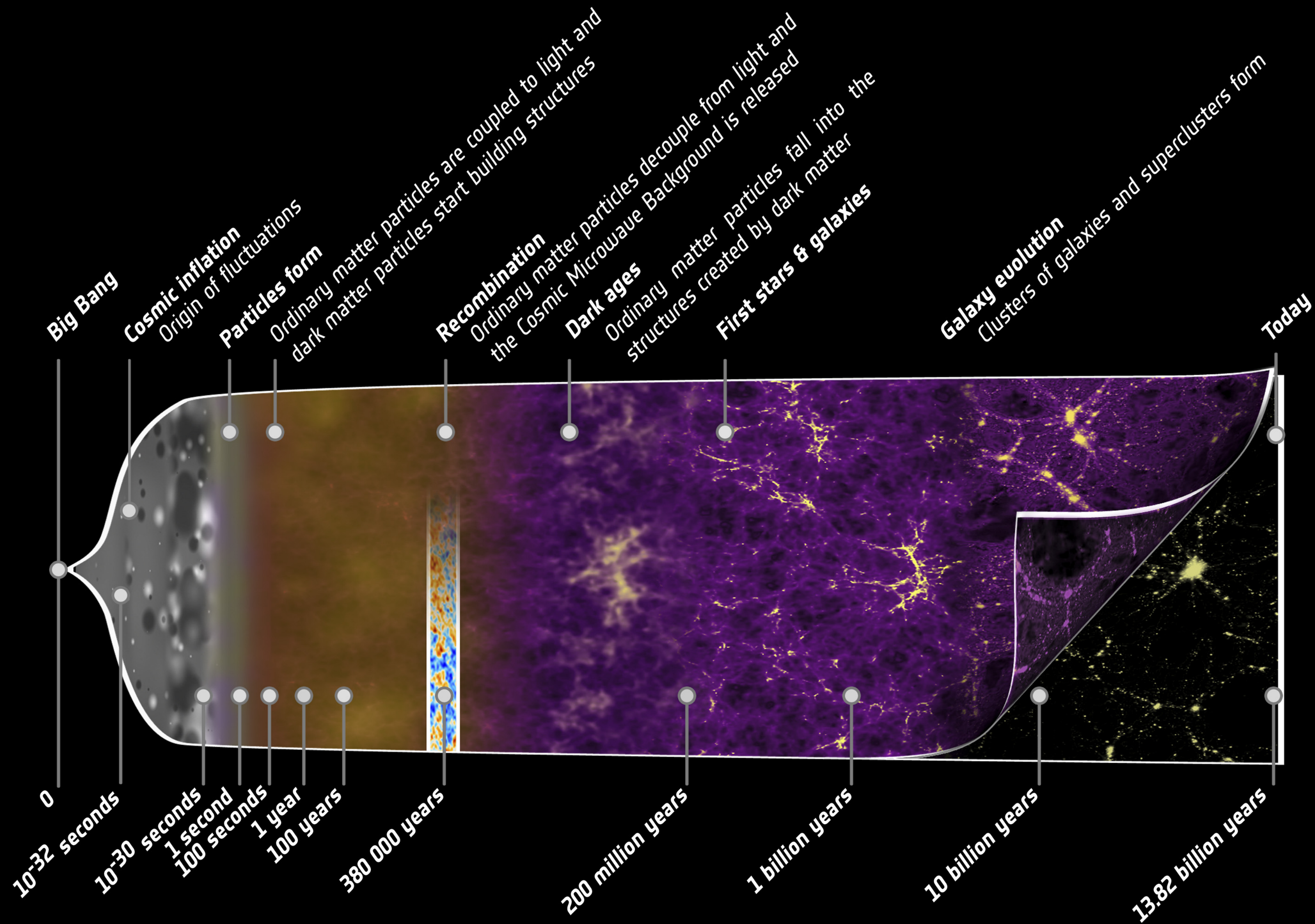
Nucleosynthesis





no stable nuclei with A=5, 6, 8

Theory of nucleosynthesis predicts light element abundances correctly.
Fails in predicting heavier elements (different mechanism: burning in stars, supernova explosions, …)


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and
dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and
the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the
structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years