Trends in High Energy Physics

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CONTEMPORARY COSMOLOGY

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The subject of *Cosmology* is the description of the physical properties and the evolution of the Universe as a whole.

The most widely accepted scenario is the ΛCDM – a contemporary version of the Big Bang Model .

based on the Einstein's general theory of relativity and

supported by the contemporary observational data

studies the biggest scales now

just our Universe available for observations (not experiments)

Modern cosmology landmarks:

1917 Einstein mathematical model: static Universe, GTR modified with a "cosmological constant"

1917 de Sitter model of empty (vacuum) Universe

1922-24 Friedmann mathematical models of nonstatic expanding Universe (closed, open)

"О кривизне пространства" 1922 (closed Universe),

"О возможности мира с постоянной отрицательной кривизной" 1924

1927 Lemaître model of expanding Universe accounting for the extragalactic nebulae redshift

"Un Univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extragalactiques"

1931 *"The expanding Universe" 1946 " L'Hypothèse de l'atome primitif "*

1932 Einstein& de Sitter model (flat Universe)

Modern cosmology landmarks:

1917 Vesto Slipher measures redshifts of nebulae: receding of nebulae

1924 Edwin Hubble observes stars in the spiral nebulae, finds distances to NGC 6822, M31 and M33 using Cepheids and shows that they are galaxies, Universe of galaxies

1929 Edwin Hubble & Milton Humason observational work on nebular redshifts and distances to them, v-r relation, expanding Universe

1946 George Gamow's concept of Big Bang, CMB prediction, BBN

1948 steady state theory of Hermann Bondi, Thomas Gold& Fred Hoyle introduced a controversy leading to many observational tests

1965 Arno Penzias & Robert Wilson discovery of CMB (revived Gamow's BB concept)

1992 Relikt and COBE found the CMB anisotropy

1998 SN results pointed to accelerated expansion

2001 WMAP precision cosmological data

Outline

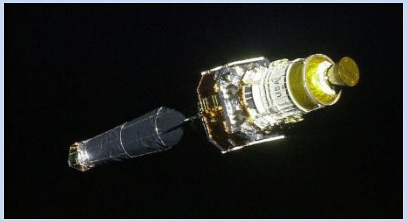
Introduction: Pecularities. Our place in the Universe.
Homogeneity, isotropy and structure in the Universe.

Standard Cosmological Model

Universe Dynamics

Early Universe theory and relics: CNB, BBN, CBR.

Matter Content of the Universe. Baryogenesis and antimatter.



Pecularities

❖ Main information source – observations

Research from ground-based and satellite-based telescopes and other instruments in the ***entire electromagnetic spectrum*** (*achieved in 20th c*) ***and beyond***:

Detection of neutrinos from stars, SN, hopefully relic neutrinos (neutrino telescopes)

Gravitational waves detection

Cosmic Ray searches (electrons, protons, heavier nucleus and anti-particles) detectors on balloons at the higher part of the atmosphere, spacecraft searches (AMS, PAMELA , SOHO collaborations)

❖ Looks back in time

The light travels with huge but finite speed: $c \approx 300000 km/s$

Hence, observing distant objects, we are observing the distant past of the Universe!

 - 1 s,  - 8 m 23 s, The Milky Way - 10 000 y, M31 - 2 million y (the furthest object you can see with your naked eye), the furtherst galaxies billion y

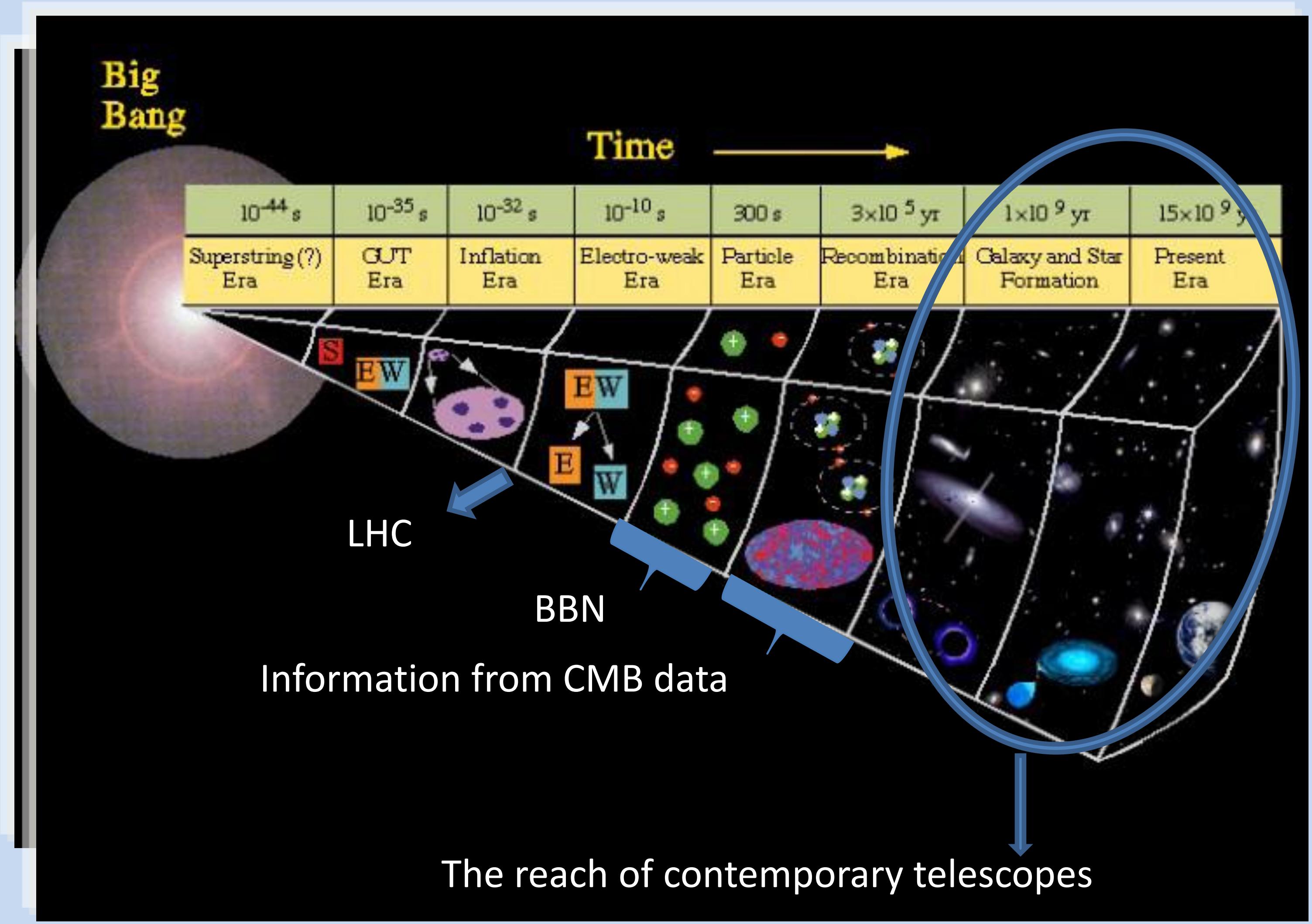
The telescope is a kind of a time machine; it lets us see our distant past.

Radiation may come to us from epochs not earlier than CMB formation time . Before that the Universe was not transparent for radiation.

In neutrino CNB may reach considerably earlier epoch –1sec (CNB not directly detected yet).

LHC – 10^{-12} s

Main information source – observations



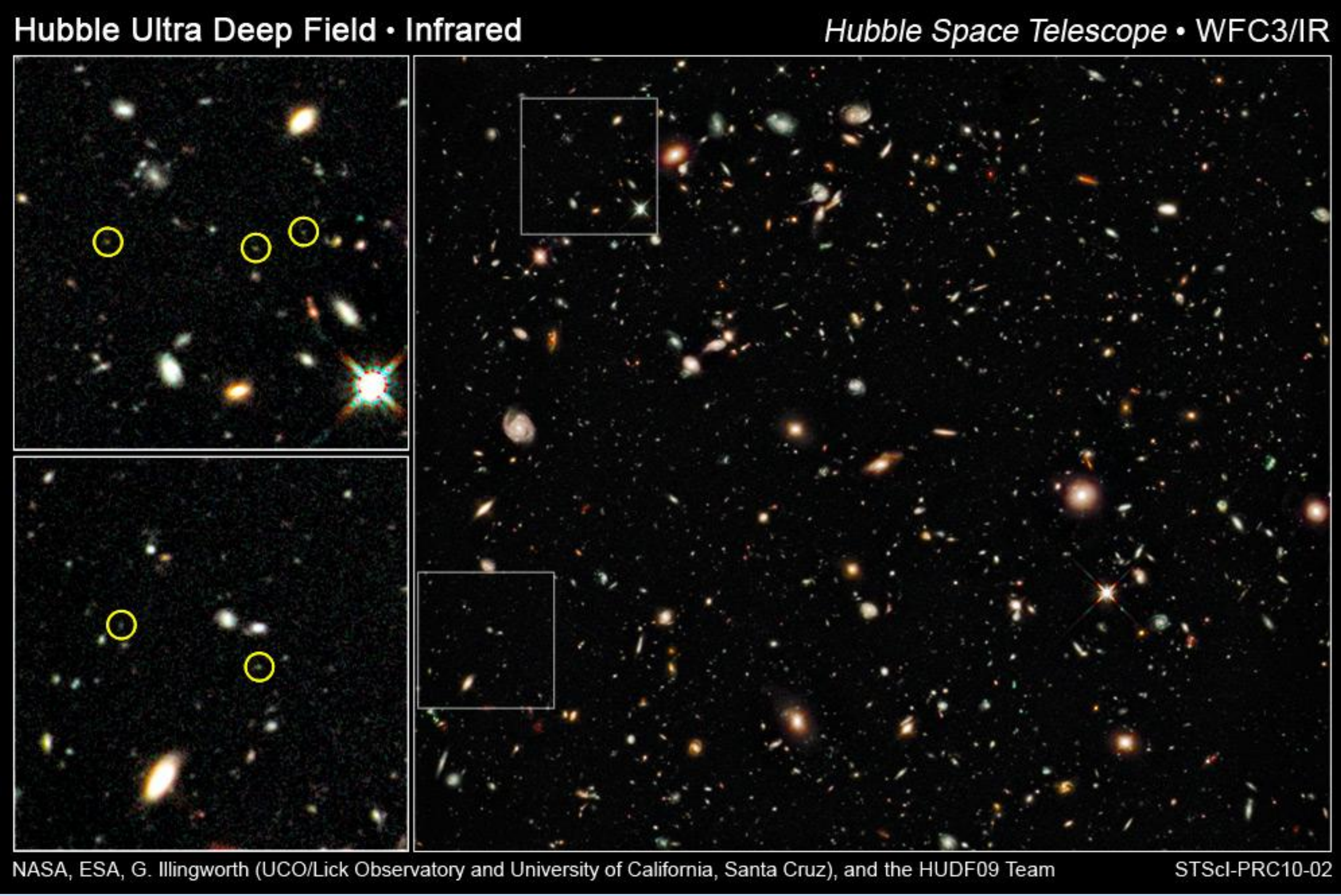
Galaxy History Revealed by Multi-Color View of 7500 galaxies by HST

Image made from mosaics taken in 2009 with the Wide Field Camera 3 and in 2004 with the Advanced Camera for Surveys of HST.

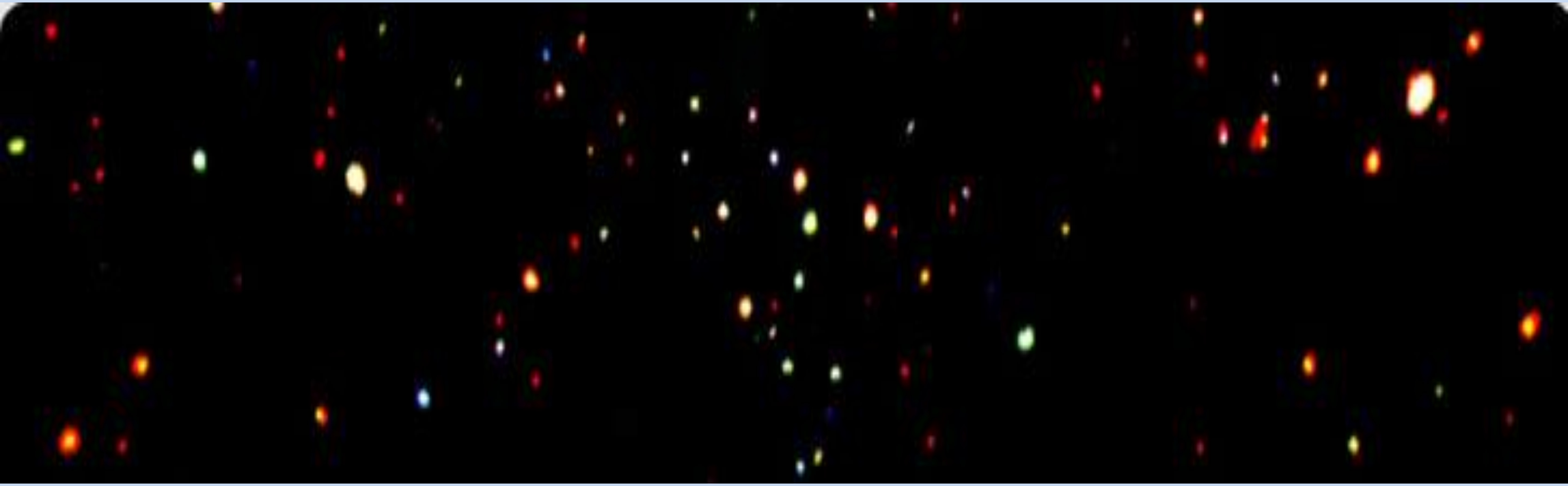
Astronomers used 96 Hubble orbits to make the ACS optical observations of this slice of the GOODS field and 104 orbits to make the WFC3 ultraviolet and near-infrared exposures. The image combines a broad color range from the ultraviolet, through visible light, and into the near-infrared. The closest galaxies seen in the foreground emitted their observed light about a billion years ago. The farthest galaxies, a few of the very faint red specks, are seen as they appeared more than 13 billion years ago, or roughly 650 million years after the Big Bang. This mosaic spans 10 arcminutes.

Ultraviolet light taken by WFC3 shows the blue glow of hot, young stars in galaxies teeming with star birth. The orange light reveals the final buildup of massive galaxies about 8 billion to 10 billion years ago. The near-infrared light displays the red glow of very distant galaxies — in a few cases as far as 12 billion to 13 billion light-years away — whose light has been stretched from ultraviolet light to longer-wavelength infrared light due to the expansion of the universe.

WFC3 peered deeper into the universe in this study than comparable near-infrared observations from ground-based telescopes. This set of unique new Hubble observations reveals galaxies to about 27th magnitude in brightness over a factor of 10 in wavelength. That's over 250 million times fainter than the unaided eye can see in visual light from a dark ground-based site.



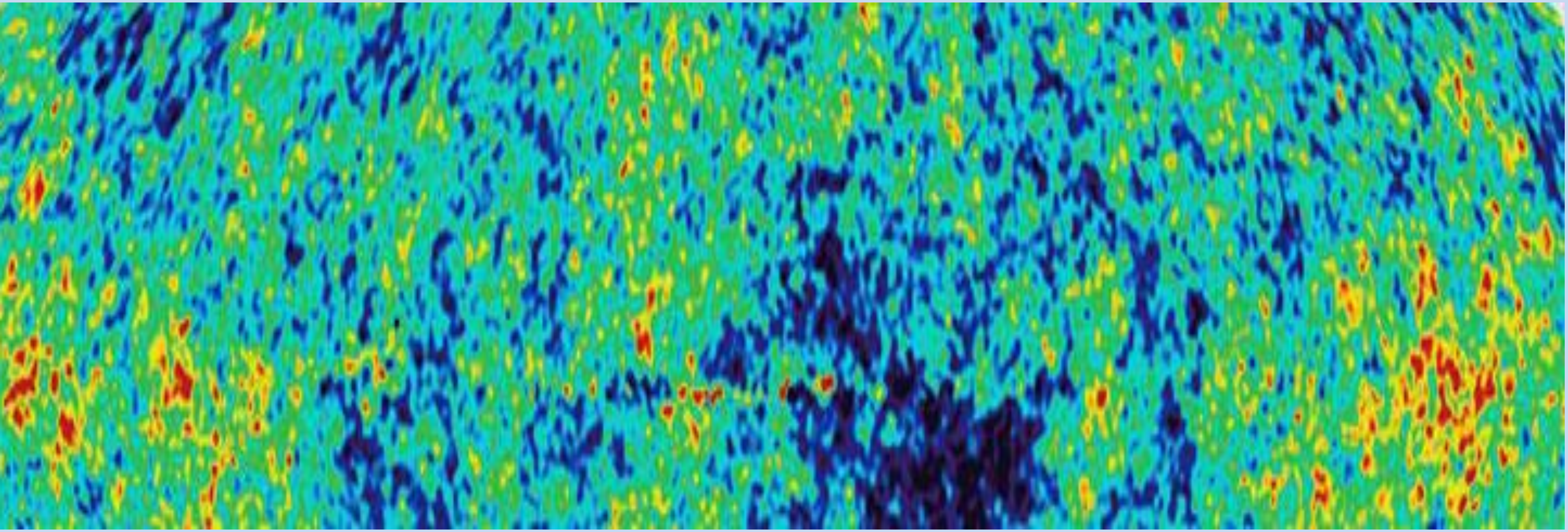
The ultra deep field the deepest image of the universe ever taken in near-infrared by Hubble Space Telescope.
The faintest and reddest objects are galaxies with “look-back times” 12.9 – 13.1 billion y   - protogalaxies .



The Dark Ages

The image, taken with Chandra X-ray Observatory in space, shows the most distant (and ancient) galaxies we can see. The dots are thought to be x-rays emitted by enormously powerful black holes at the centers of galaxies that are just beginning to form. In fact, the galaxies may not yet contain stars that have begun to shine — or they may be so distant that their starlight has been absorbed by dust.

The furthest we can see…13.7 billion ly



Very wide-angle view of almost the entire night sky, by WMAP satellite, shows the furthest light we can see. It is also the oldest: The light was emitted shortly after the Big Bang, and has been traveling through space for 13.7 billion years to us.

Pecularities

❖ Deals with enourmous space and time scales

History of the Universe

Inflation

Unified interactions (10^{-35} sec)

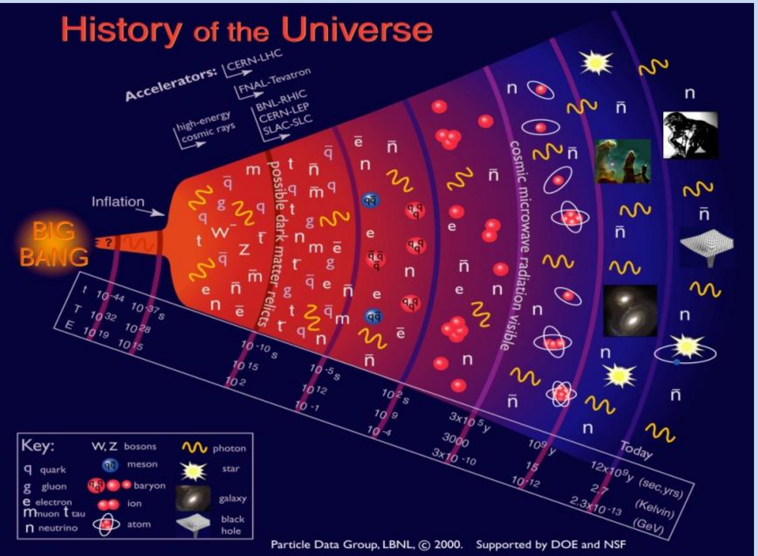
Generation of matter-antimatter asymmetry

Primordial Nucleosynthesis (first minutes).

CMB formation (380 000 years)

Galaxy formation (10^9 years)

Today (~ $1.4\ 10^{10}$ y)



Space scales

Astronomical Unit - defined by the semimajor axis of the Earth's orbit around the Sun.

1 AU = 149 600 000 km

A parsec defined as the distance from the Sun which would result in a parallax of 1 second of arc as seen from Earth.

Distances of nearby objects can be determined directly using parallax observations combined with elementary geometry, hence pc was historically used to express the distances of astronomical objects from the Earth.

light year – the distance, the light travels per year propagating in vacuum = 9460 billion km!!

1 pc = 3.26 lys

Mpc - most comonly used unit in cosmology

1 Mpc = 10^6 pc

Because of the enormous extrapolations of the standard physics, surprises may be expected: beyond GTR? Evolution of parameters?

Pecularities

- ❖ Cosmic laboratory of bizzare objects
- ❖ Multidisciplinary Science: close conection with Physics, Mathematics, Astroparticle Physics, Chemistry,…

Fascinating

Etc….

Basic Assumptions

1. The **universality** of physical laws

There is no observation which indicates a departure from the laws of physics in the accessible Universe!

2. The cosmos is **homogeneous.**

A belief that the place we occupy is no way special

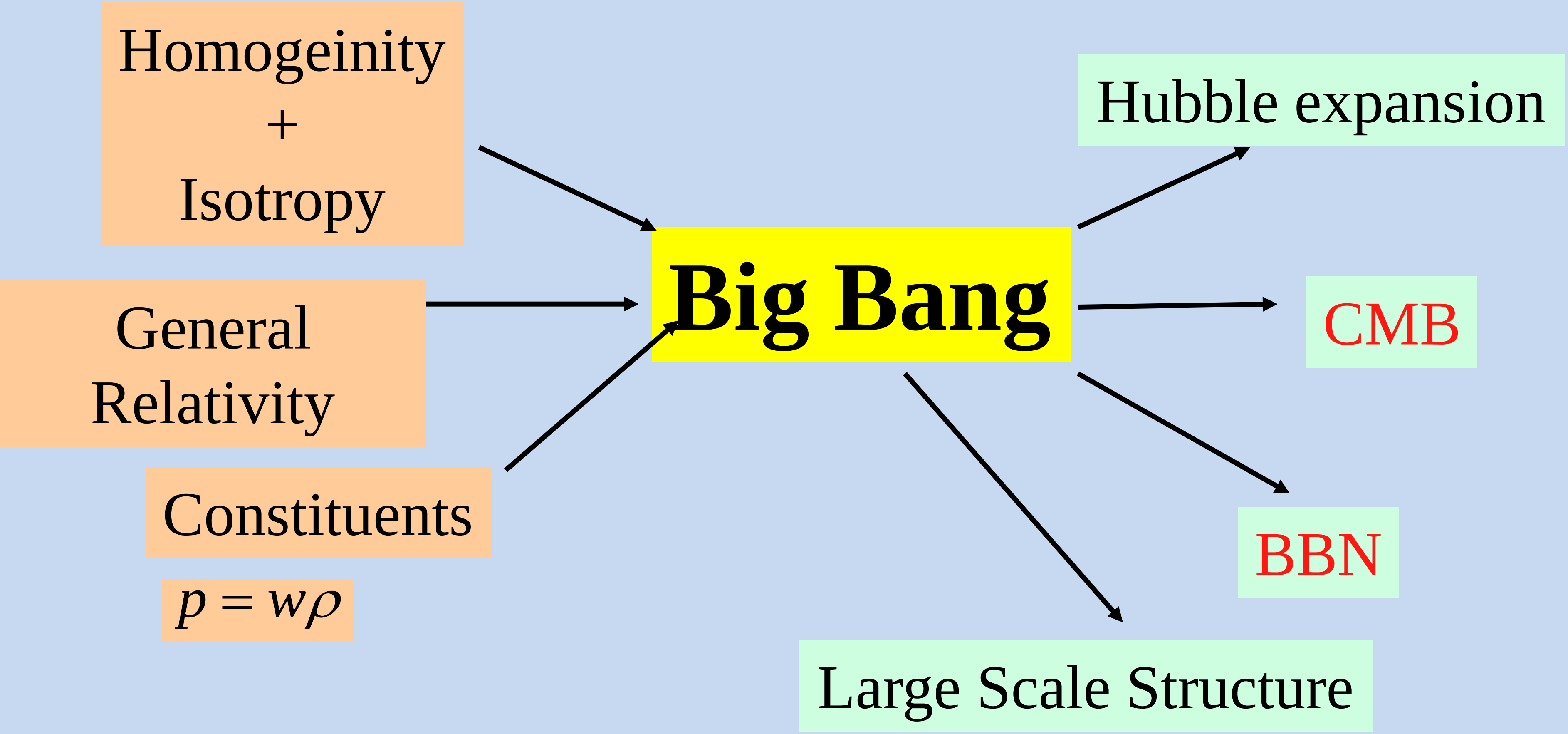
3. The universe is **isotropic**

There is no prefered direction (confirmed by recent CMB measurements)

Cosmological Principle states that all spatial positions and directions in the Universe are essentially equivalent or matter in the Universe is homogeneous and isotropic when averaged over very large scales.

Standard Cosmological Model

$$H_0, q_0, \Omega_i(\Omega_0, \Omega_\Lambda, \Omega_M, \Omega_B, \Omega_\gamma, \Omega_\nu, \ldots), t_0, T_0, P(k), C_l$$



Observational Milestones of Hot Big Bang Cosmology

- Homogeneity and isotropy and structures in the Universe

- The expansion of the Universe

Observation that galaxies were generally receding from us provided the first evidence for the Universe expansion.

SN observations pointed to an accelerated expansion.

- The abundance of the light elements

The light elements abundances provide evidence for a hotter and denser early Universe, when these elements have been fused from protons and neutrons. Point to non-baryonic DM.

- The cosmic microwave background radiation

The cosmic microwave background radiation is the remnant heat left over from the Big Bang. It is an evidence for a hot early Universe.

Points to a flat LambdaCDM dominated Universe now.

Our Place in the Universe

Ptolemy's geocentric model

16th-century representation of the Ptolemy's geocentric model

It is intriguing that for the bulk of the history of civilization it was believed that we occupy the most special location – the center.

Geocentric system

Ptolemy of Alexandria, 150 CE

Almagest

The celestial realm is spherical, and moves as a sphere.

The Earth is a sphere.

The Earth is at the center of the cosmos, it does not move

However, Ἀρίσταρχος; 310–230 BC

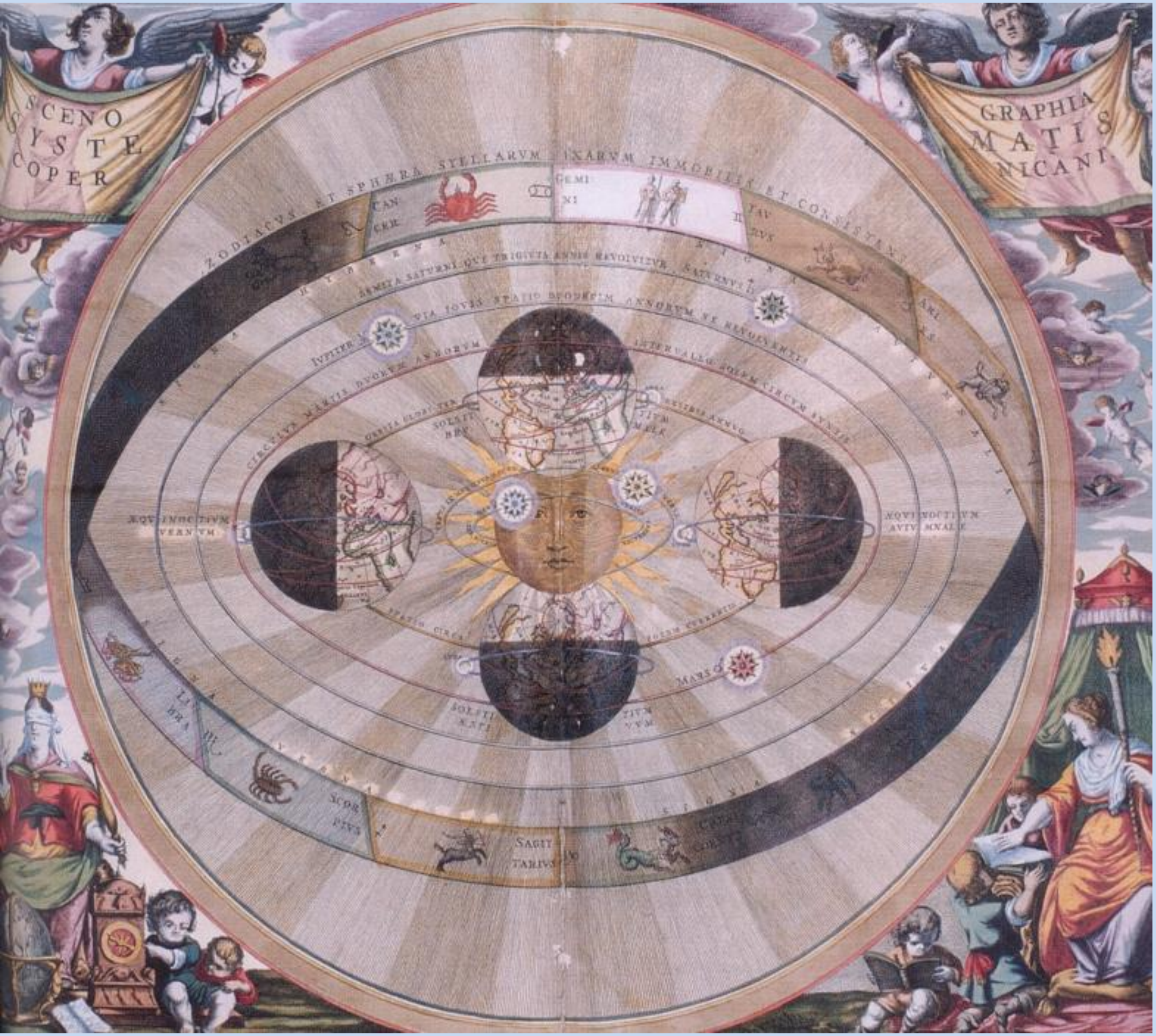
"Greek Copernicus"

heliocentric model

Biruni XI CE

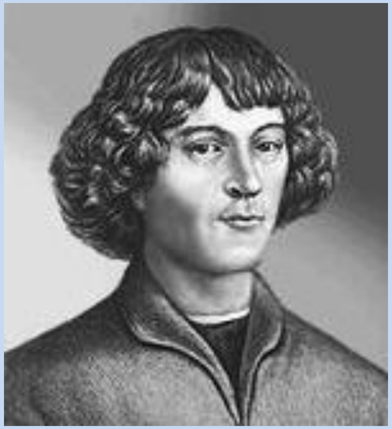
heliocentric model

Copernicus rediscovered after18 centuries
the heliocentric system



Scenographia systematis copernicani, 1660

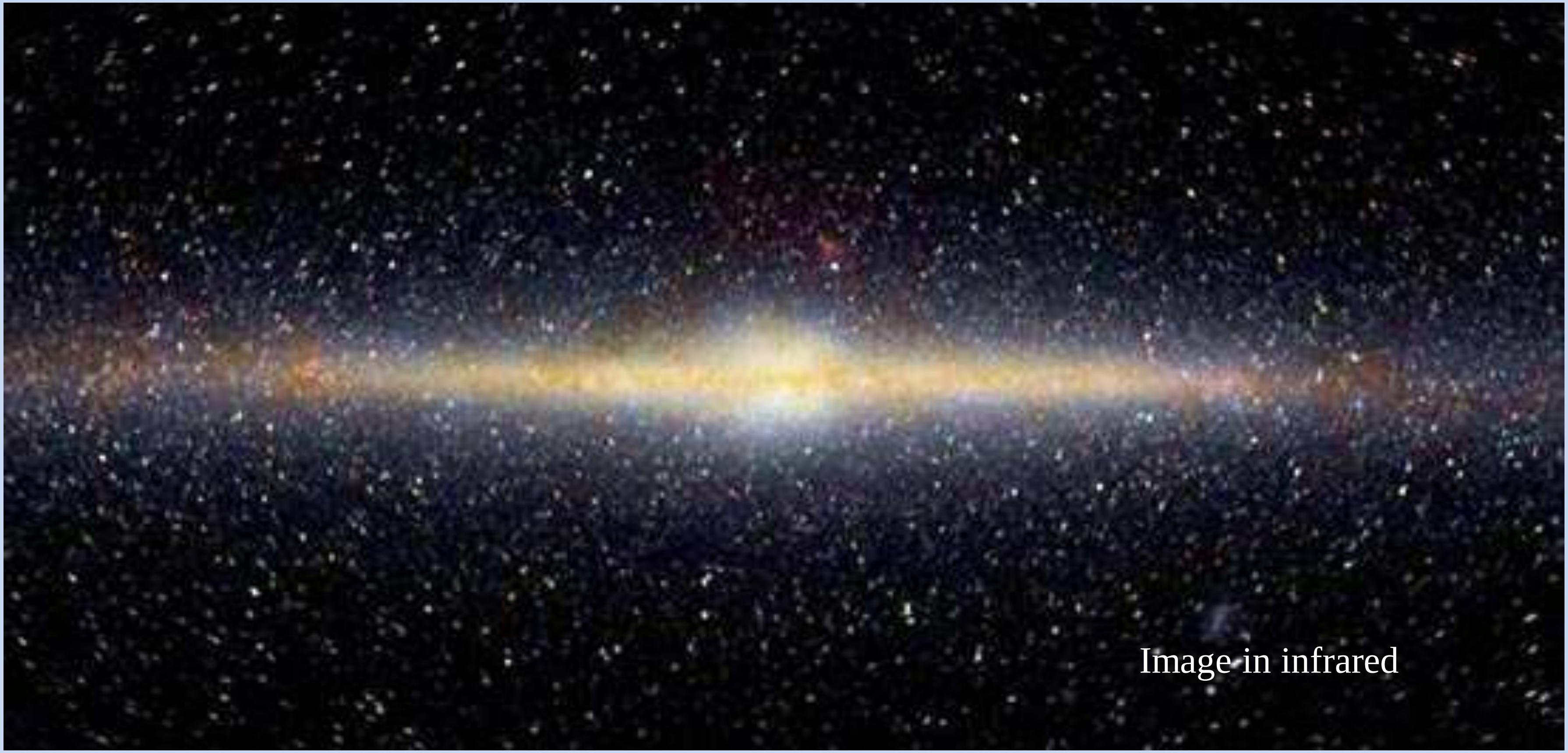
- The Sun is at the center of the Universe.
- What appear to us as motions of the sun arise not from its motion but from the motion of the earth



1543 *On the Revolutions of the Celestial Spheres*
The Earth is not the center of the Universe!

Newtonian static Universe of stars distributed evenly through infinite space

Our Galaxy – the Milky Way



Our galaxy contains billions of stars with mass range b/n 0.1-20 solar masses. It is a tyical Sb galaxy. All Sb galaxies have a bulge, disc and halo

Hershels identified the disc structure (Sun still at the center) 1700s Stars are located in a disc-shaped assembly (MW)
MW believed to be the center of the Universe in 1900s
1915 Shapley: The Solar system is not at the center of the Galaxy:
Sun is 2/3 of radius away from the Galaxy center (at 8 kpc) .

The Universe is inhomogeneous at galaxy scales

Shapley-Curtis Debate:
Are the spiral nebulas within the Milky Way or extra Galactic objects?

1923 - 25 Hubble identified Cepheids in “nebulae” proving that they are at extragalactic distances.

W. Baade: resolve stars in the center of M31 for the first time.
MW is a typical galaxy.

M 31 image of the cosmic telescope GALEX.

Andromeda 2.5 million ly

M31 is seen with naked eye in the constellation Andromeda. It is the biggest galaxy in the Local Group,
The Milky Way is approaching M31 at a v>100 km/s and in million years the two galaxies will merge.

The Universe is inhomogenious at the scale of galaxy groups

1923 - 25 Hubble identified Cepheids in “nebulae” NGC 6822, M31, and M33 proved that they are outside the Galaxy, i.e.
Our Galaxy is not the whole Universe.

The Universe consists of galaxies !

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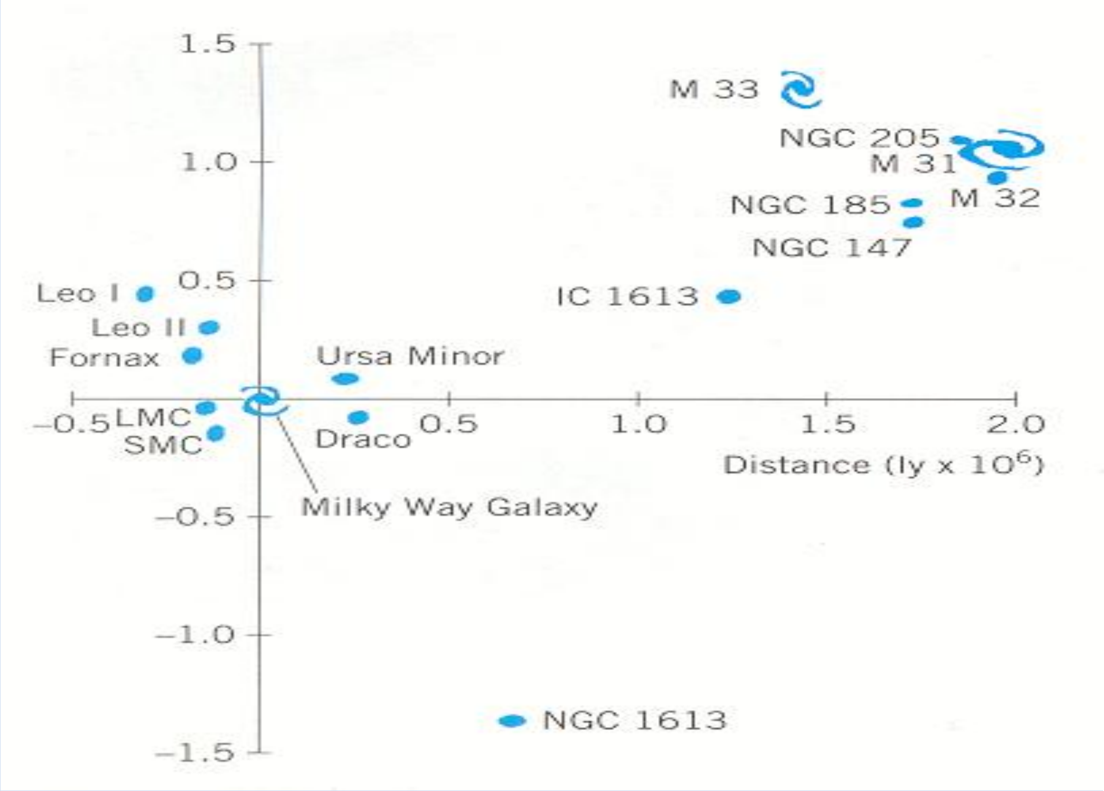
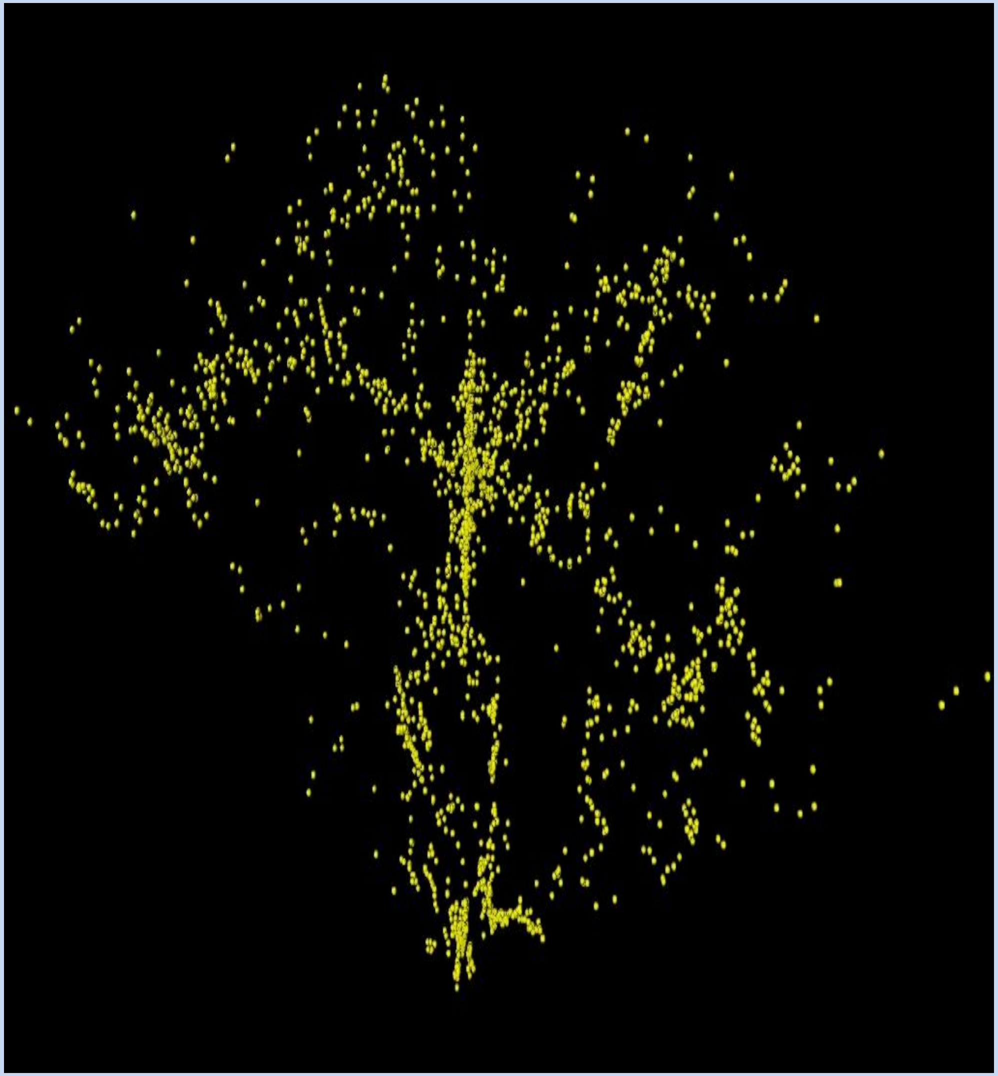


MW resides within a small concentrated group of galaxies known as the Local group.
The nereast to MW is LMC.
Galaxy groups occupy a typical volume of a few cubic Mpc.

inhomogenious at the scale of galaxy clusters

The cluster of galaxies, Abell 1689, 2 billion ly from Earth in the constellation Virgo.
Clusters of galaxies are the largest gravitationally-collapsed objects.
The Local group is in Virgo cluster.

LSS of the Universe



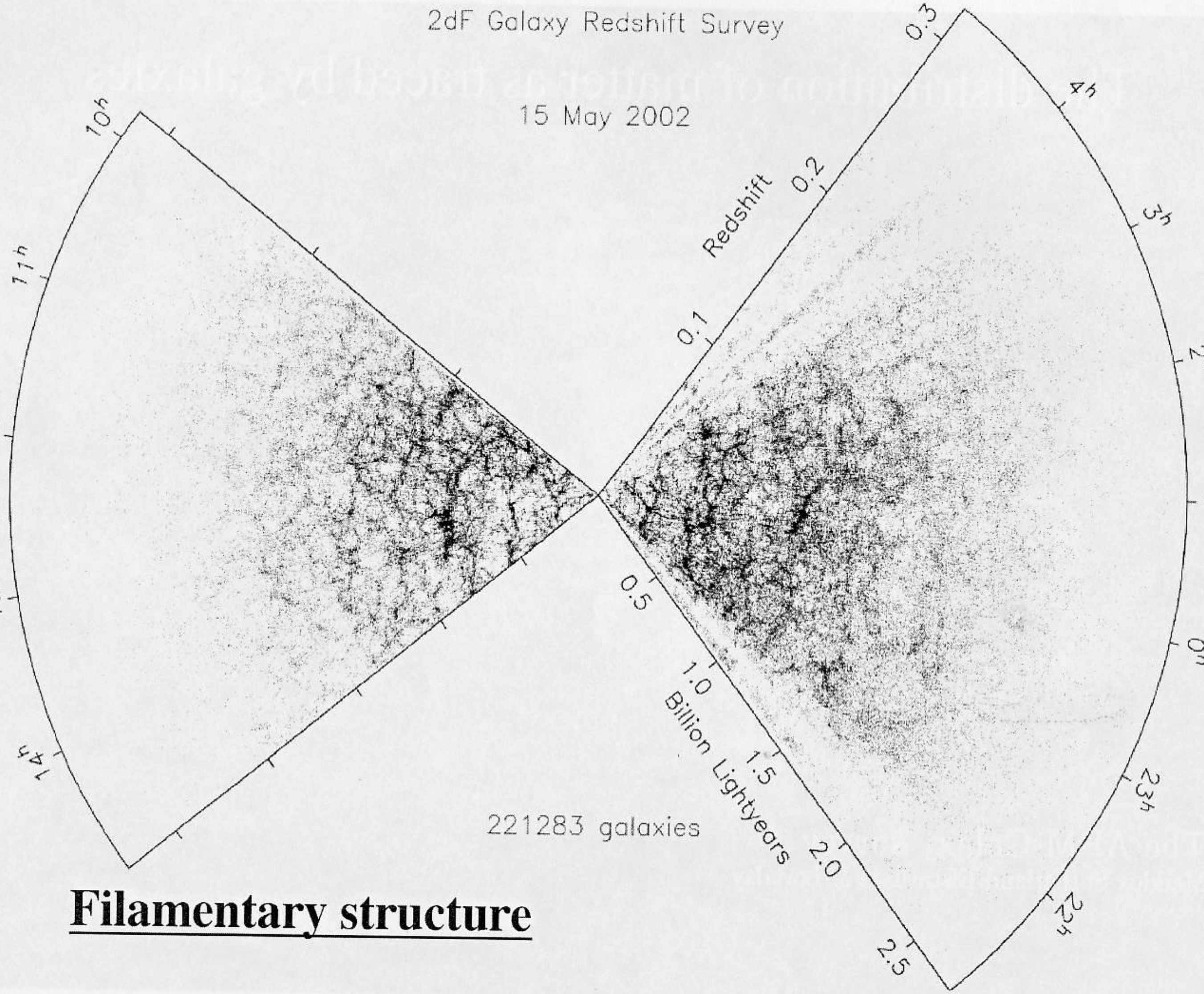
Clusters are grouped into superclusters of galaxies, joined by filaments and walls of galaxies. In b/n lie large voids, deprived of galaxies, almost 50 Mpc across.

The superclusters and voids are the largest structures in the Universe.

On a scale of 100 Mpc variety of large scale structures exist: clusters of galaxies, superclusters and voids.

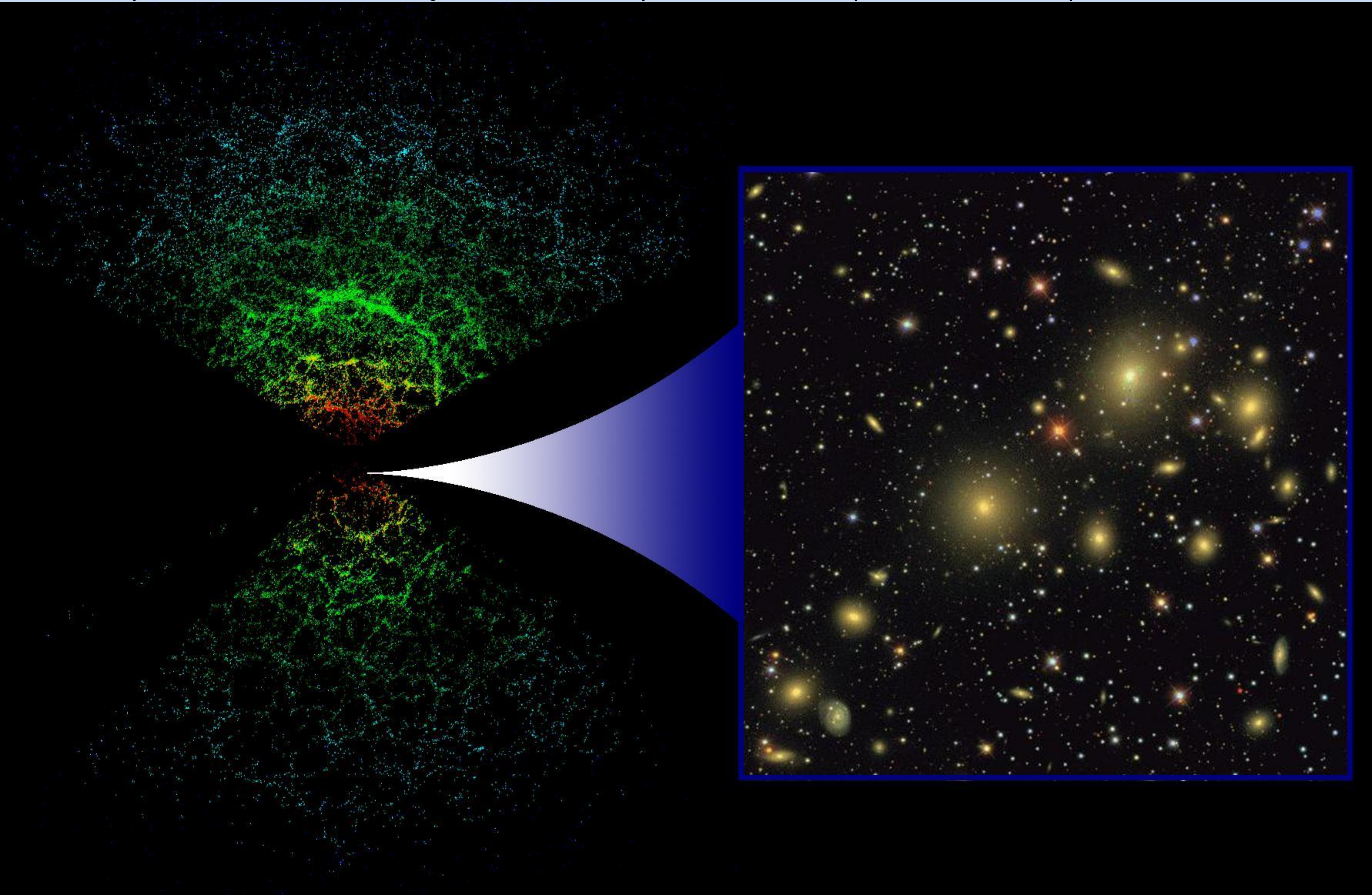
A map of galaxy positions in a narrow slice of the Universe, as identified by the CfA (Center for Astrophysics) redshift survey. The radius is around 200 Mpc. The galaxy positions were obtained by measurement of the shift of spectral lines.

[Figure courtesy Lars Christensen]



Filamentary structure

The SDSS (Slone Digital Sky Survey**) studies ¼ of the sky, millions galaxies and quasars.**
SDSS is two separate surveys in one: studies 2D images of galaxies (right), then have their distance determined from their spectrum to create a 2 billion ly deep 3D map (left), where the color representing the luminosity - this shows only 66,976 out of 205,443 galaxies in the map that lie near the plane of Earth's equator.



Sloan Digital Sky Survey

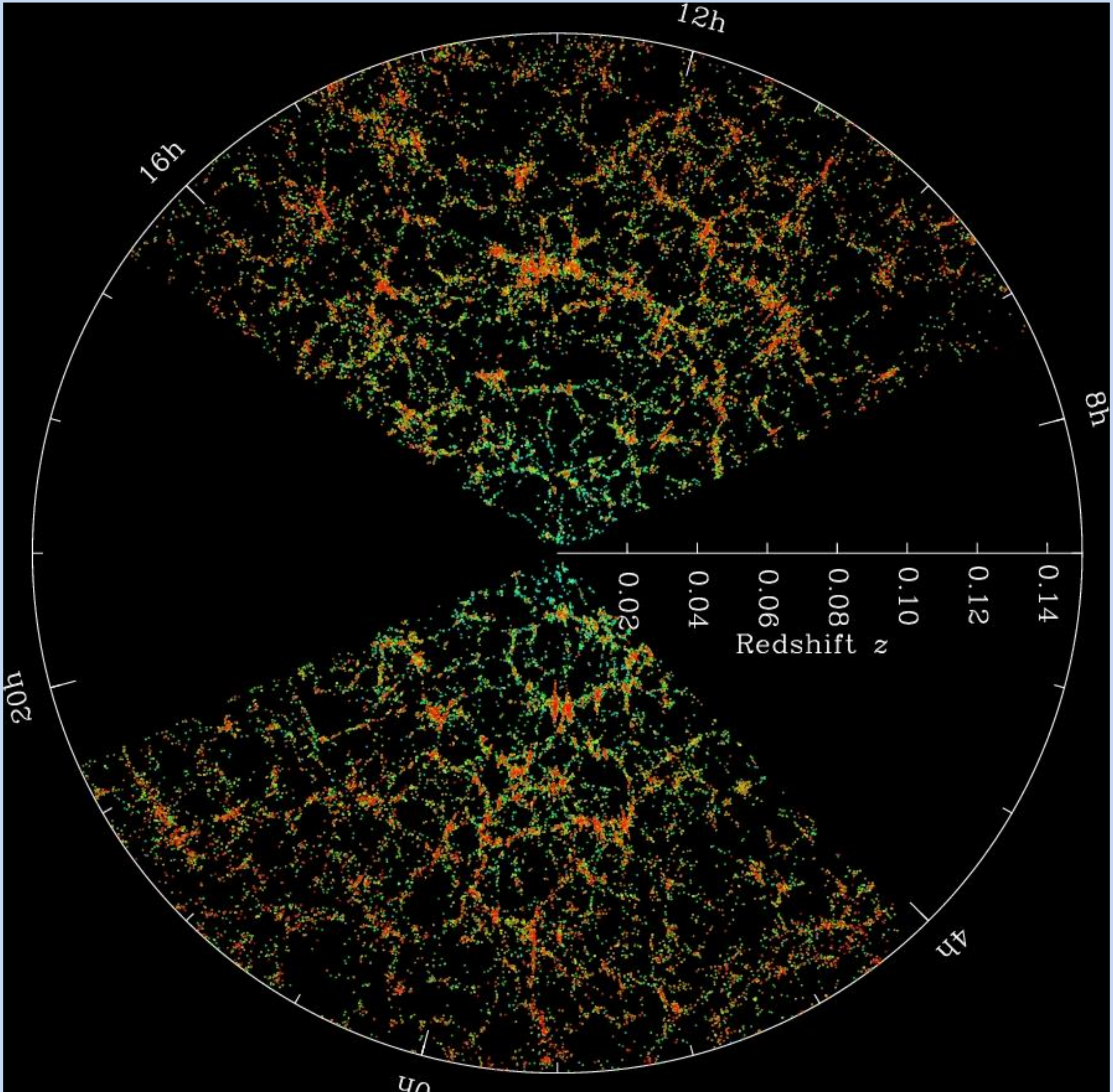
Apache Point Observatory in the Sacramento Mountains of New Mexico. The Sloan Digital Sky Survey's 2.5-meter telescope on the left, the monitor telescope, used for calibrations, inside the small dome to the right of center.

SDSS uses 2.5-meter telescope on Apache Point, NM, equipped with two powerful instruments:
120-megapixel camera imaging 1.5 square degrees of sky at a time (about eight times the area of the full moon),
a pair of spectrographs fed by optical fibers measuring spectra of more than 600 galaxies and quasars in a single observation.

SDSS is the most ambitious astronomical survey ever undertaken. Over eight years of operations (SDSS-I, 2000-2005; SDSS-II, 2005-2008), it obtained deep, multi-color images covering more than a quarter of the sky and created 3-dimensional maps containing more than 930,000 galaxies and more than 120,000 quasars.

SDSS-III, a program of four new surveys using SDSS facilities, began observations in July 2008, and will continue through 2014. It will provide detailed optical images covering more than a quarter of the sky, and a 3-dimensional map of about a million galaxies and quasars.

The Sloan Supernova Survey carried out repeat imaging of the 300 square degree southern equatorial stripe to discover and measure supernovae and other variable objects. In the course of three 3-month campaigns, the supernova survey discovered nearly 500 spectroscopically confirmed Type Ia supernovae, which are being used to determine the history of the accelerating cosmic expansion over the last 4 billion years.

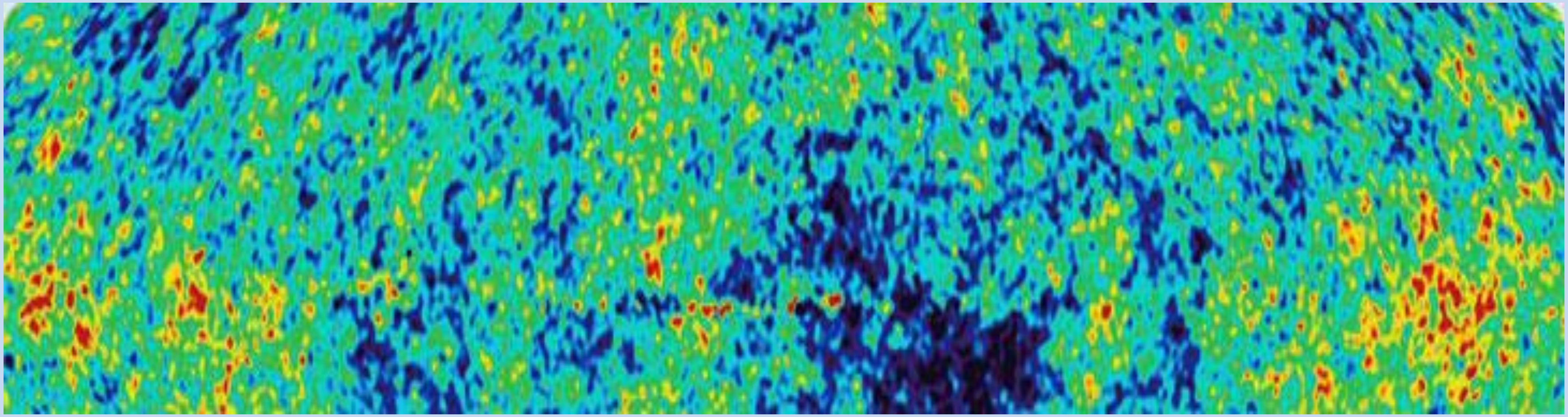


Slices through the SDSS 3-dimensional map of the distribution of galaxies.

Earth is at the center, each point represents a galaxy. Galaxies are colored according to the ages of their stars, with the redder, more strongly clustered points showing galaxi made of older stars. The outer circle is at a distance of two billion light years. The region between the wedges was not mapped because dust in our own Galaxy obscures the view in these directions. Both slices contain all galaxies within -1.25 and 1.25 degrees declination.

Credit: M. Blanton and the Sloan Digital Sky Survey.

Isotropy …13.7 billion years ago

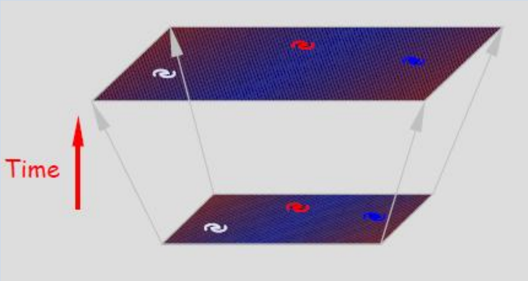


Very wide-angle view of almost the entire night sky, by NASA's WMAP satellite, shows the furthest light we can see. It is also the oldest: The light was emitted shortly after the Big Bang, and has been traveling through space for 13.7 billion years to us.

In this "baby picture" of the universe, the red and yellow patches are regions that are just a few millionths of a degree hotter than the blue and black areas. This tiny difference helped seed the formation of galaxies out of the shapeless gas that filled the early universe.

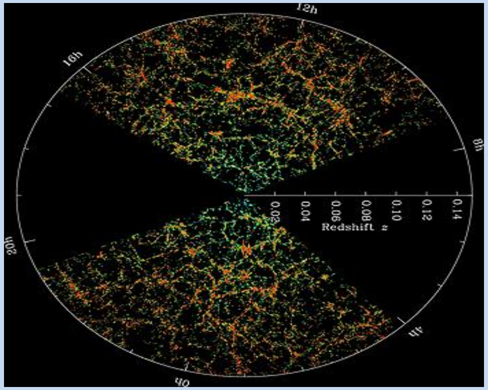
CMB, the remnant heat from the Big Bang, has a temperature which is highly uniform over the entire sky. This fact strongly supports the notion that the gas which emitted this radiation long ago was very uniformly distributed.

Homogeneity and Isotropy



Convincing observations about the smoothness of matter distribution on large scales exist :

✓ Homogeneous and isotropic expansion



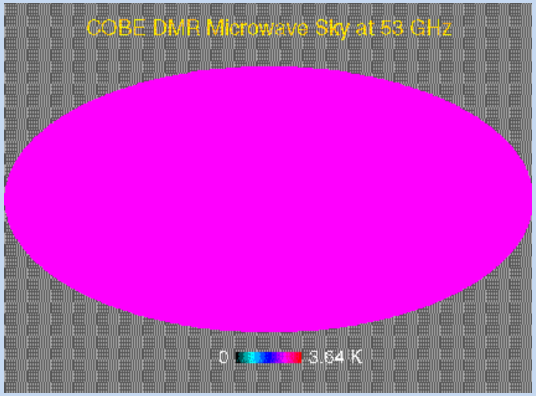
✓ Recent extremely large surveys 2dF, SDSS

have surveyed large volumes of few Gps.

Superclusters and voids are likely to be the biggest structures.

At scales 100-200 Mpc the Universe begin to appear smooth.

Universe 380 000 y old



✓ CMB observations:

RELIKT , COBE, WMAP and other CMB explorers

have found extremely high isotropy,

i.e. the Universe was isotropical also 14 bln y ago!

Cosmological Principle is exact at large scales >200 Mpc (mlns galaxies).

It is a property of the global Universe. It holds through the entire Universe evolution.

Standard Cosmological Model

Robertson-Walker metric

In case Cosmological Principle holds the most general expression for a space-time metric which has a (3D) maximally symmetric subspace of a 4D space-time is the Robertson-Walker metric:

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

R(t) – scale factor; *r, θ, φ* - comoving polar coordinates

c = 1, curvature index *k* = +1, −1, 0 closed, open, flat geometry

$${}^{(3)}R = 6k / R^2(t)$$

The observed homogeneity and isotropy enable us to describe the overall geometry and evolution of the Universe in terms of two cosmological parameters: k accounting for the spatial curvature and R(t) - for the overall expansion (or contraction) of the Universe

Consider two points with a fixed comoving distance *r* .

The physical distance for k=0 is $d = R(t)r$ the relative velocity is $v = r\dot{R} + R\dot{r} = Hd + Rv_p$

This is the famous Hubble's law $v = Hd$ where $H = \dot{R}(t)/R(t)$ Hubble parameter

redshift of light $z = \frac{\lambda_0 - \lambda}{\lambda}$ $\frac{\lambda_0}{\lambda} = \frac{R(t_0)}{R}$ $1 + z = R(t_0)/R(t)$

Theoretical Milestones

Dynamics is provided by General Relativity

Einstein field equations read:

$$\mathcal{R}_{\mu\nu} - \frac{1}{2} g_{\mu\nu}\mathcal{R} = 8\pi G_N T_{\mu\nu} + \Lambda g_{\mu\nu}$$

stress energy tensor

complicated function of the metric and its first and second derivatives

The space-time curvature is defined by the presence and distribution of the matter - its density and momentum.

- Friedman equations Non-stationary Universe

rate of expansion

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3}$$

$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}(\rho + 3p) ,$$

$$\Omega = 1 + k / H^2 R^2$$

$$\Omega_\Lambda = \Lambda / 3H^2$$

Space curvature k depends on the energy density.

$$\Omega = \frac{8\pi G}{3H^2}\rho$$

$$\rho_C \equiv 3H_0^2 / 8\pi G = 1.88 \times 10^{-26} h^2 \text{ kg m}^{-3}$$

6 atoms H/ m^{-3}

NB: not only energy, but also pressure contributes to the gravitational force. $p<-1/3\rho$ may lead to anti-gravity and to accelerated expansion.

$$q_0 = -\left.\frac{R\ddot{R}}{\dot{R}^2}\right|_0 = \frac{1}{2}\Omega_m + \Omega_r + \frac{(1+3w)}{2}\Omega_v .$$

$$\Omega < 1 \quad \Omega = 1 \quad \Omega > 1$$

$$\kappa < 0. \quad \kappa = 0. \quad \kappa > 0.$$

The density defines the geometry.

$$\Omega_{total} \sim 1.0$$

Finding a general solution to a set of equations as complex as the Einstein field equations is a hopeless task. The problem is simplified greatly by considering mass distributions with special symmetries.

- Contemporary Physics, Astrophysics, Thermodynamics, Quantum Field Theory

Theoretical Basis

The matter content is usually modeled as a perfect fluid with a stress-energy tensor in the rest frame of the fluid:

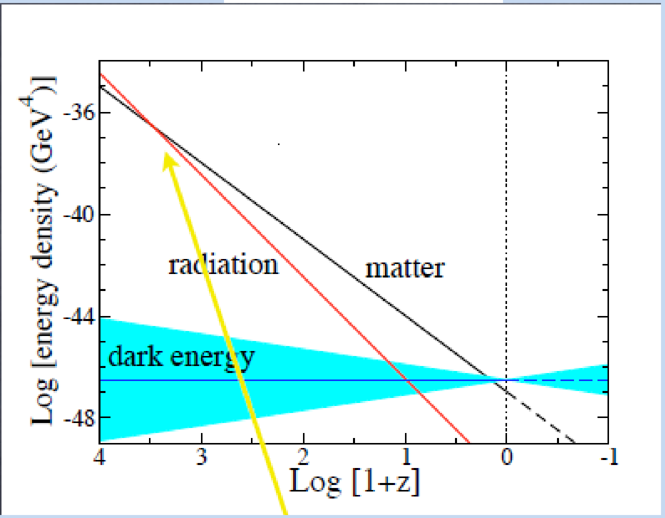
$$T_\mu^{\ \nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & -p & 0 & 0 \\ 0 & 0 & -p & 0 \\ 0 & 0 & 0 & -p \end{pmatrix}$$

$$\rho = \rho_M + \rho_R + \rho_\Lambda + \rho_w + \ldots\ldots$$

To solve the equations one should know the matter content of the Universe and the equations of state of each component $w \equiv \frac{p}{\rho}$.

- From energy-momentum conservation $T_{\mu\ ;\nu}^{\ \nu} = 0$ ⇨ $\dot{\rho} = -3H(\rho + p)$

⇨ $\rho \propto R^{-3(1+w)}$



$p_R = \rho_R/3$	radiation	$w = 1/3$	$\rho_R \sim R^{-4}$
$p_M = 0$	dust	$w = 0$	$\rho_M \sim R^{-3}$
$p_k = -\rho_k/3$		$w = -1/3$	$\rho_k \sim R^{-2}$
$p_V = -\rho_V$	vacuum	$w = -1$	$\rho_V \sim R^0$

$$w = -0.967^{+0.073}_{-0.072}$$

No matter how small is the radiation component today, having in mind the different dependence of radiation and matter density on R(t) and T~ 1/R, radiation dominated at early stage .

Universe Matter Content

Current observations point to at least four components:

$$\Omega_r = 2.47 \times 10^{-5} h^{-2}$$

$$\Omega_\nu h^2 \leq 0.0076 \quad 95\% \text{ CL}$$

Radiation (relativistic degrees of freedom) ~0.002%

Today this component consists of the photons and neutrino and gives negligible contribution into total energy density. However, it was a major fraction at early times.

Baryonic matter ~4% $\quad \Omega_b h^2 = 0.022 \pm 0.001$

Dark matter ~23% $\quad \Omega_{nbm} h^2 = 0.106 \pm 0.008$

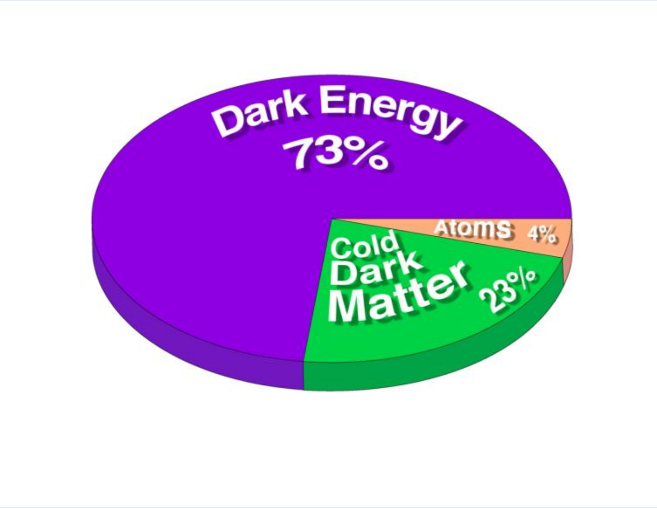
Was not directly detected yet, but should be there.

Constitutes major matter fraction today.

Dark energy ~73%

It provides the major fraction of the total energy density.

Was not anticipated and appears as the biggest surprise and challenge for particle physics, though conceptually it can be very simple, being just a `cosmological constant' or vacuum energy.



$$\Omega_m + \Omega_v = 1.011 \pm 0.012$$

- 4% - H+He, 0.0025% heavy elements, 0.5% stars, 0.005% CMB
- 23% - DM, 73% DE, 0.47% neutrino

Contribution of neutrinos to total energy density today (3 degenerate masses)

$$\Omega_\nu = \frac{3m_0}{93.14h^2 \text{ eV}^2}$$

RD stage:

Thermodynamic relations for the energy density, S and number densities n:

$$\rho = \frac{\pi^2}{30} g_* T^4 ,$$
$$n = \frac{\zeta(3)}{\pi^2} (g_B + \frac{3}{4} g_F) T^3 ,$$

$$S = \frac{2\pi^2}{45} g_* T^3$$

$$dE + p\,dV = T\,dS$$

$$g_* = \sum_{i=\text{bosons}} g_i + \frac{7}{8} \sum_{j=\text{fermions}} g_j \equiv (g_B + \frac{7}{8} g_F)$$

$$\rho_r = \rho_\gamma + \rho_\nu + \rho_x = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right] \rho_\gamma$$

Friedmann expansion driven by an ideal fluid is isentropic, dS=0

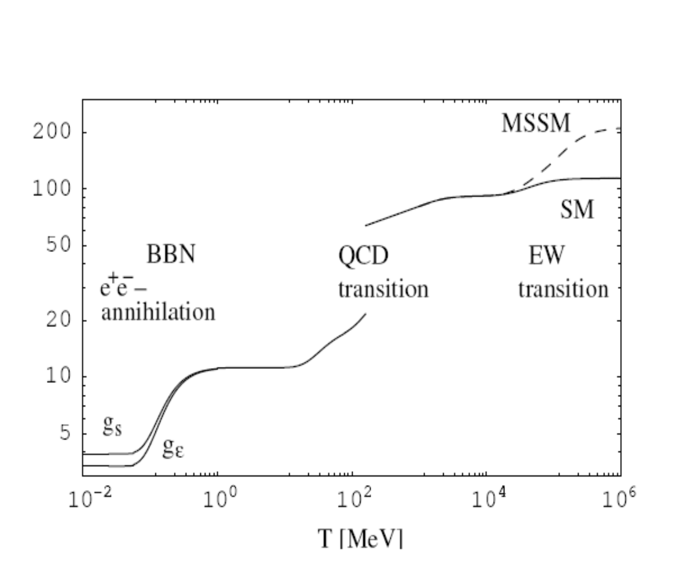
Relation between the scale factor and temperature in an expanding Universe : R(t)~1/T

These relations are a consequence of the integration of the Bose-Einstein or Fermi-Dirac distributions:

$$\frac{g}{(2\pi)^3} \int \frac{d^3q}{e^{q/T} \pm 1} q^a$$

Radiation era:

$$t[\text{s}] \approx \frac{2.4\times10^{-6}}{\sqrt{g(t)}\, T^2[\text{GeV}]}$$



Number of relativistic degrees of freedom g as a function of T

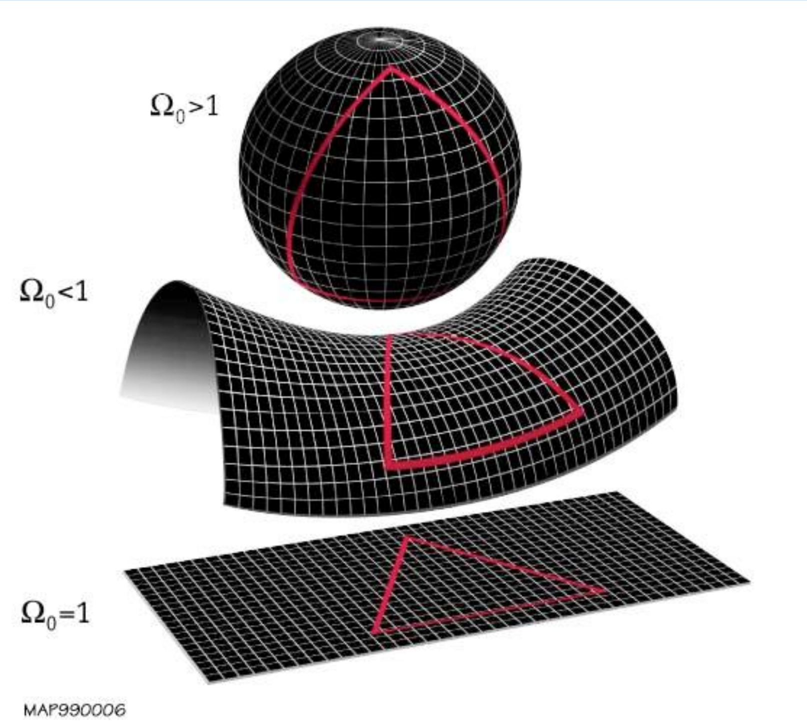
The Friedmann equation can be interpreted within Newtonian mechanics. It takes the form of energy conservation for test particles bounded in the gravitational potential created by mass

$$M = \frac{4\pi}{3}\rho r^3 \qquad \frac{1}{2}\dot{r}^2 - \frac{G M}{r} = -\frac{k r_0^2}{2} .$$

k=1 corresponds to negative binding energy, recollapse and over-critical density

k=-1 positive binding energy, expansion, under-critical density

Three cases should be distinguished which foreordain **the type geometry of the universe**:



$\rho > \rho_{cr}$ Spherical, closed universe, finite but unbounded in space and finite in time.

$\rho < \rho_{cr}$ Hyperbolic, again an open universe, infinite in space and in time, but curved.

$\rho = \rho_{cr}$ Flat, open universe, having Euclidean geometry, infinite in space and time.

Main expansion laws

$$R(t) \propto t^{\frac{2}{3(1+w)}} \begin{cases} \sqrt{t}; & \text{rad } (w = 1/3) \\ \sqrt[3]{t^2}; & \text{mat } (w = 0) \\ e^{\sqrt{\Lambda/3}t}; & \text{vac } (w = -1) \end{cases}$$

H=1/2t

H=2/3t

H=const

In the past the Universe was denser

$\rho \propto R^{-3(1+w)}$ and hotter T~1/R(t).

Cosmological singularity at T, ρ, H→∞

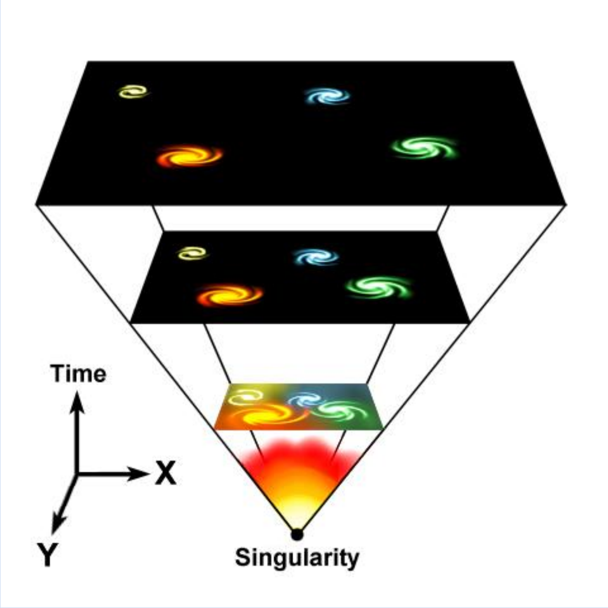
SCM predicts relic microwave background

from the early hot stage – CMB detected !

The future fate of the Universe depends on Λ:

If Λ<0 the Universe will recollapse independent of k sign.
For Λ> Λs even a closed Universe will expand forever.

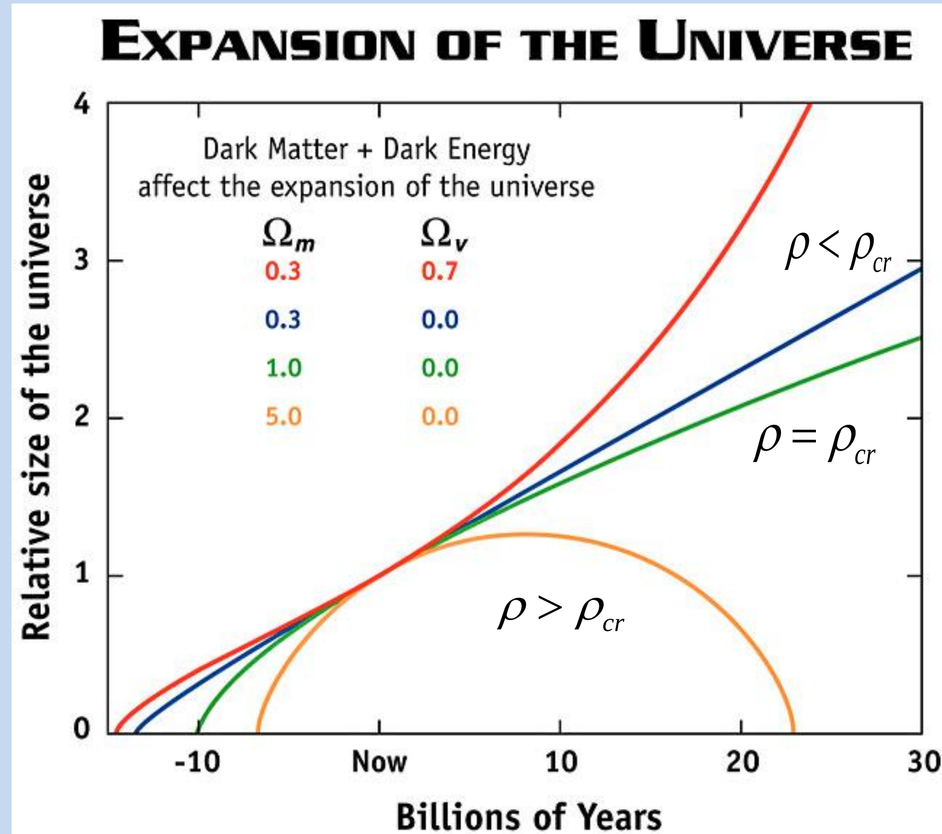
The Universe now shows accelerating expansion.



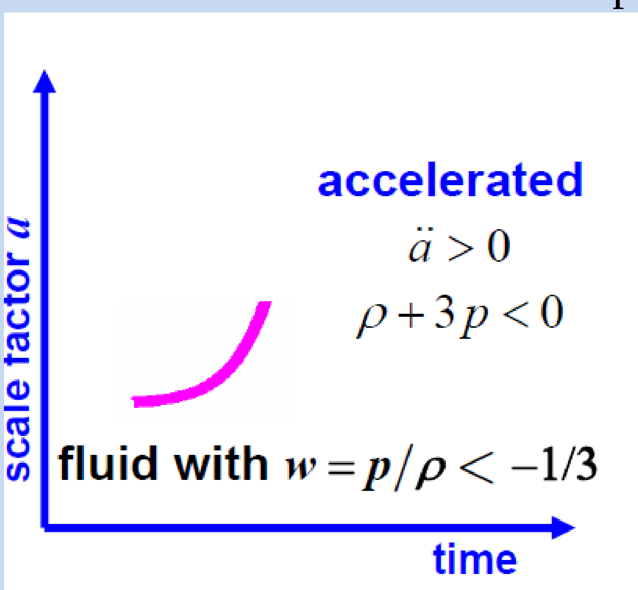
The Big Bang

If Λ is non-zero the geometry and Universe fate are not connected

Possible scenarios:
Orange – closed, overcritical density, will collapse
green - a flat, critical density universe in which the expansion is continually slowing down;
blue - an open, low density universe, expansion is slowing down, but not as much because the pull of gravity is not as strong.
red - a universe with a large fraction of matter in a form of dark energy, causing an accelerated expansion .



Observations:
The Universe has accelerated expansion.



$$q_0 = -\left.\frac{R\ddot{R}}{\dot{R}^2}\right|_0 = \frac{1}{2}\Omega_m + \Omega_r + \frac{(1+3w)}{2}\Omega_v \ .$$

Universe Dynamics

Observational Milestones of Hot Big Bang Cosmology

- Homogeneity and isotropy and structures in the Universe

- The expansion of the Universe

Observation that galaxies were generally receding from us provided the first evidence for the Universe expansion.
SN observations pointed to an accelerated expansion.

$$H_0, q_0, t_0$$

- The abundance of the light elements

The light elements abundances provide evidence for a hotter and denser early Universe, when these elements have been fused from protons and neutrons.
Point to non-baryonic DM.

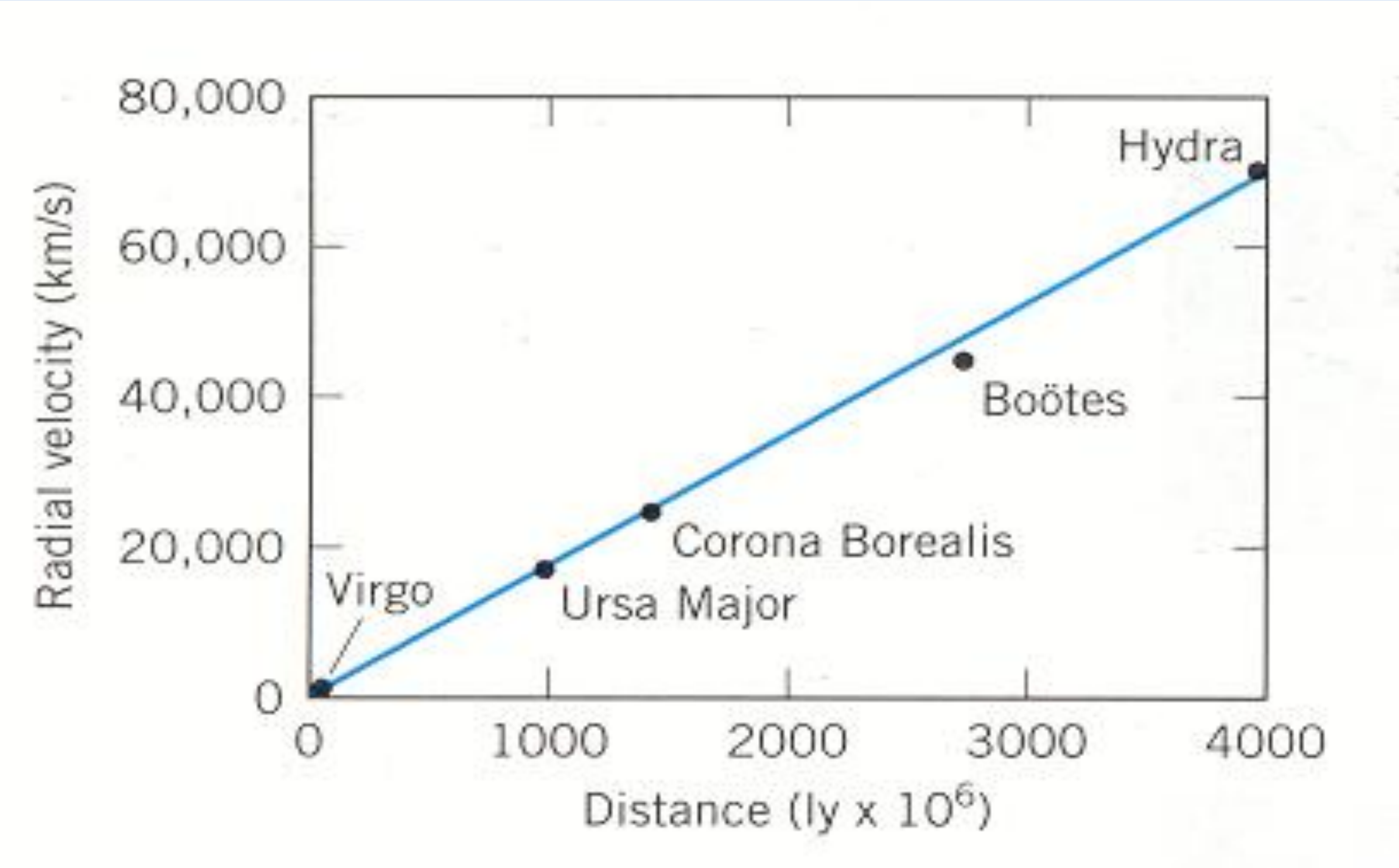
- The cosmic microwave background radiation

The cosmic microwave background radiation is the remnant heat left over from the Big Bang. It is an evidence for a hot early Universe.
Points to a flat LambdaCDM dominated Universe now.

The Expanding Universe - Observations

1912-1917 Slipher: spiral nebula are receding

1920's- Hubble: velocity-distance proportionality



Hubble's Law

$$v \sim cz = H\,d$$

The receding velocity increases with the distance.

$$z \equiv \frac{\lambda_d - \lambda_e}{\lambda_e} \approx \frac{v}{c}$$

Distances to Galaxies:

If we know the apparent magnitude m and the absolute magnitude *M* we can evaluate *d* (photometric distance):

$$m - M = 5 \log d - 5$$

[d] in parsecs

$$m \sim -2.5 \log f \qquad M \sim -2.5 \log L$$

Step by step approach (the distance ladder) based on the assumption that cepheids, RR Lyrae stars have the same properties in other galaxies. The same for the SN explosions. These assumptions are supported by essentially the same spectra and light curves.

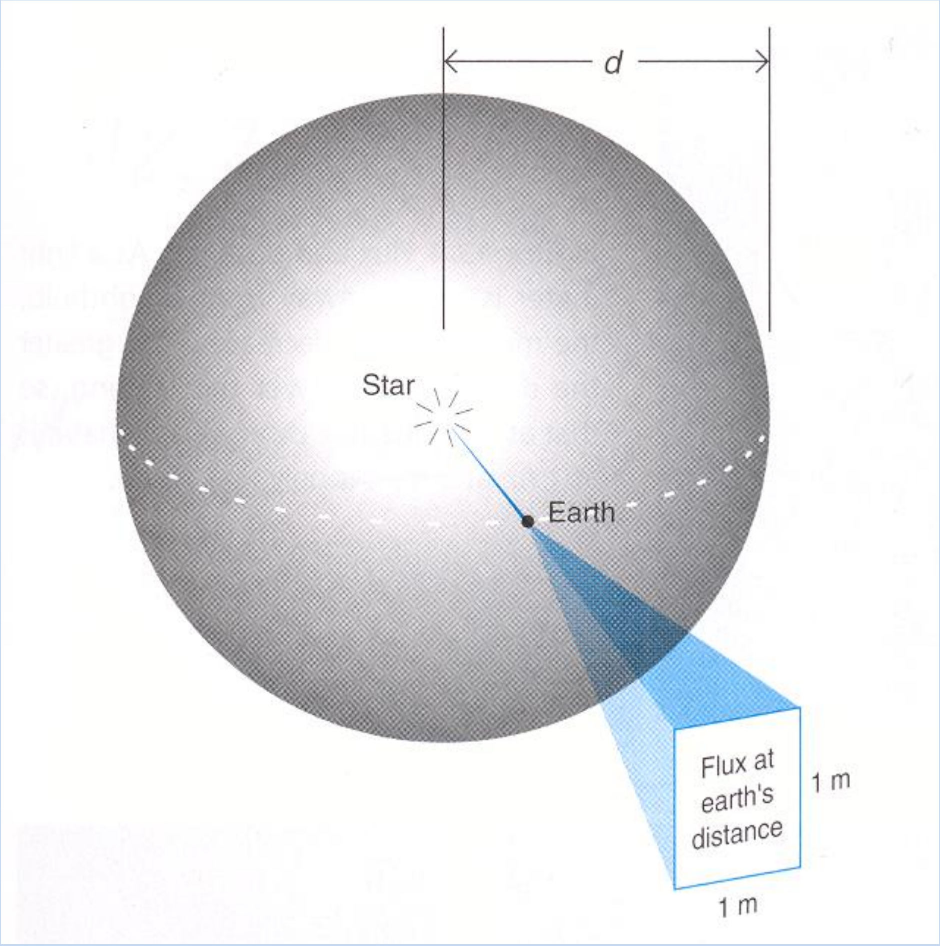
variable stars: up to 20 Mpc;

SN I (had nearly the same peak luminosity): up to 400 Mpc;

brightest Sc I spirals, which have about the same luminosity

Tully-Fisher relation, between the rotational velocity of a spiral galaxy and its luminosity - 400 – 600 Mpc.

Flux from a star f: $L=4\pi d^2 f$

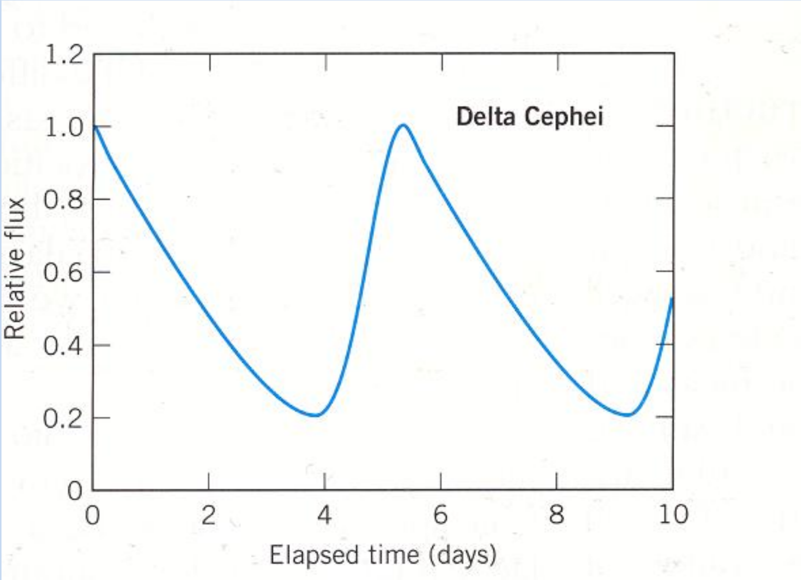


Cepheid variables:

These stars pulsate at a rate that is matched closely to their intrinsic brightness.This makes them ideal for measuring intergalactic distances.

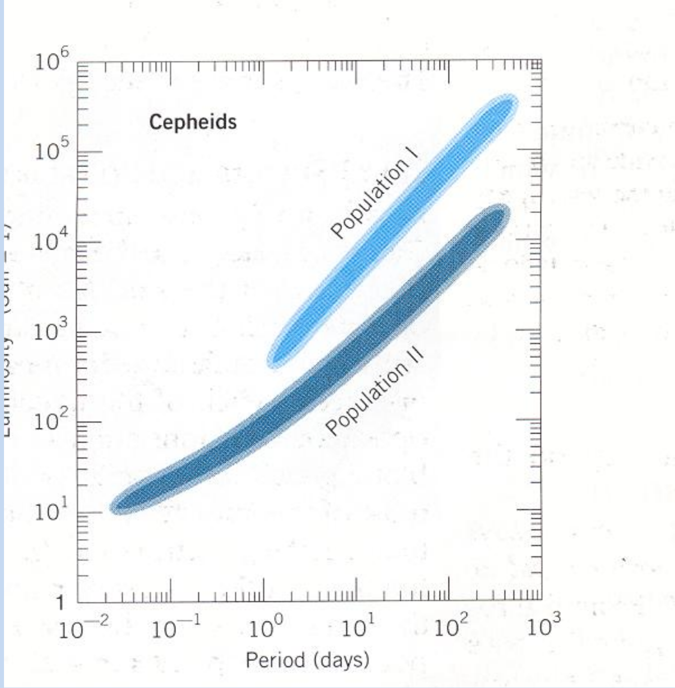
Classical cepheids (Population I): period of typically 5 to 10 days.

Population II cepheids: periods of 12 to 20 days.



RR Lyrae stars:

Periods typically of 12 hours. Population II stars and have luminosities of about 100 time the luminosity of the sun.



Galaxies Velocities

Systematic recession of objects, or cosmological expansion, leads to redshift.

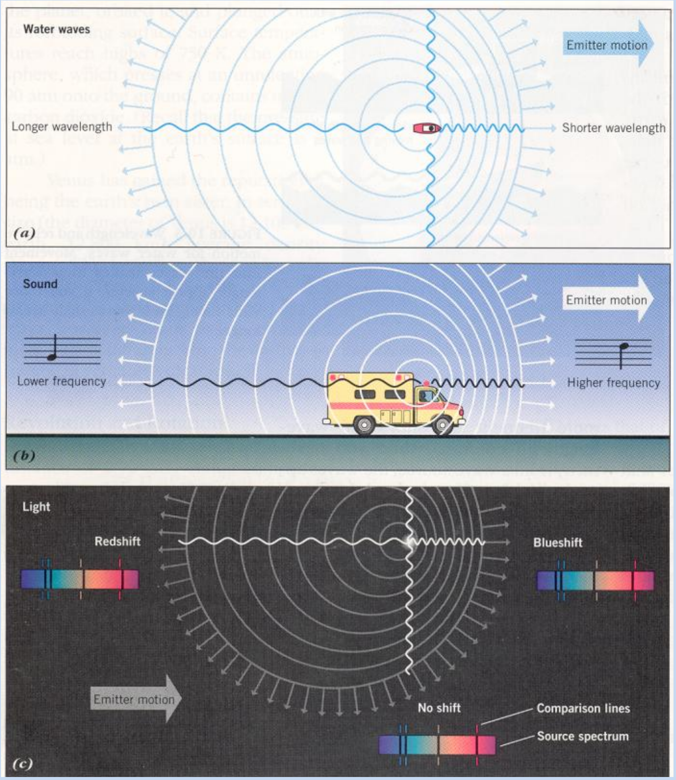
The shift of emission lines with respect to the frequency measurements by the local observer is related to velocity, and is used as an observable instead of the velocity. Note that cosmological redshift is not entirely due to Doppler effect, but, rather, can be interpreted as a mixture of Doppler effect and of gravitational redshift.

for z<0.2,

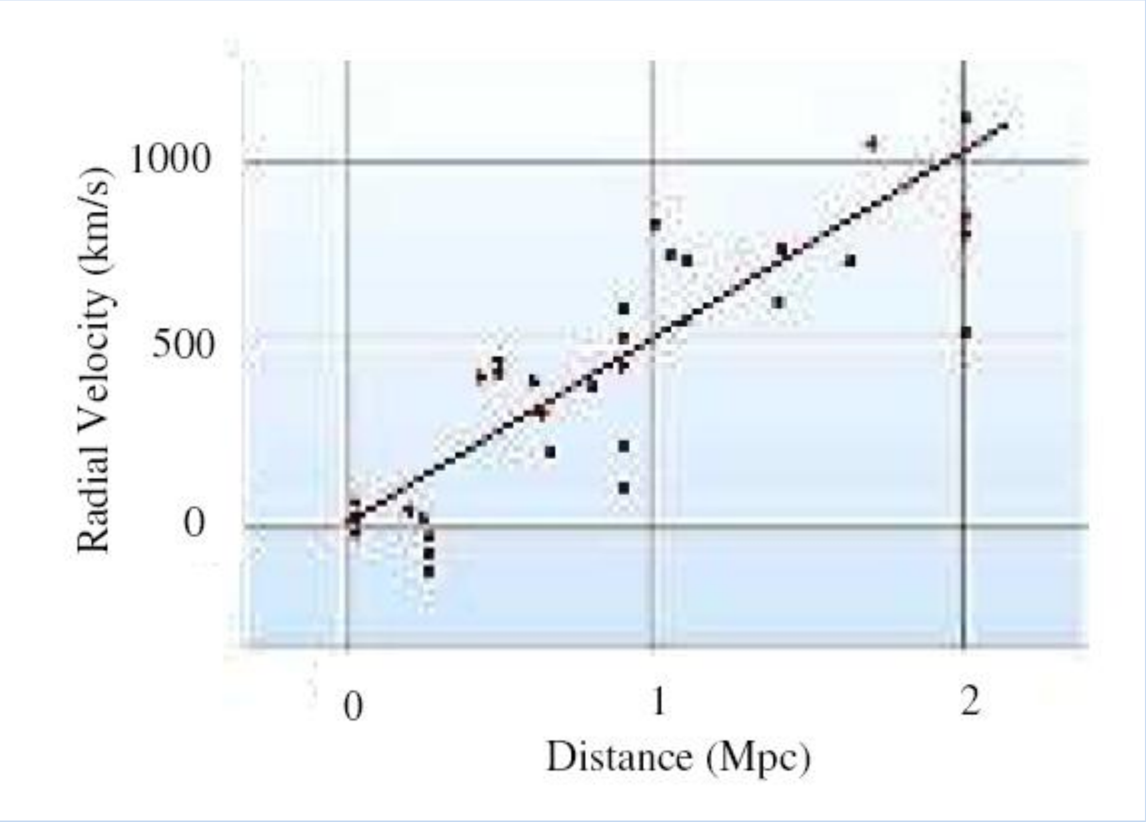
$$z \equiv \frac{\lambda_d - \lambda_e}{\lambda_e} \approx \frac{\mathrm{v}}{c}$$

otherwise

$$z = \sqrt{\frac{1+\frac{\mathrm{v}}{c}}{1-\frac{\mathrm{v}}{c}}} - 1$$



Hubble’s Original Diagram



From the Proceedings

of the National Academy of Sciences
Volume 15 : March 15, 1929 : Number 3

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

By Edwin Hubble

Mount Wilson Observatory, Carnegie Institution of Washington

Communicated January 17, 1929

………………………………

…..The results establish a roughly linear relation between velocities and distances among nebulae

…………………… The outstanding feature, is the possibility that the velocity-distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space. In the de Sitter cosmology, displacements of the spectra arise from two sources, an apparent slowing down of atomic vibrations and a general tendency of material particles to scatter. ……. ….. the linear relation found in the present discussion is a first approximation representing a restricted range in distance.

The Hubble Law

$$H_0 = 100 \cdot h \frac{km}{s \cdot Mpc}$$

cz = H d

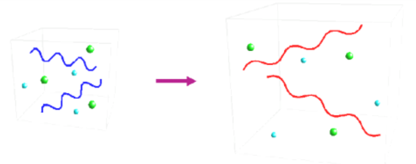
v [km/s], d [Mpc], hence H [km/s/Mpc].

H_0 = 100h km/s/Mpc, 0.4 < h < 1.0

Corresponds to a *homogeneous* expanding universe (ρ, T decrease)

- Not applicable for gravitationally bound systems.
  Space itself expands
- Matter density decreases with volume increase,
  radiation – faster due to the decrease of photons energy
  while vacuum energy $\rho_{vac} \propto a^0 = constant$

$$\rho_M \propto a^{-3}$$
$$\rho_R \propto a^{-4}$$



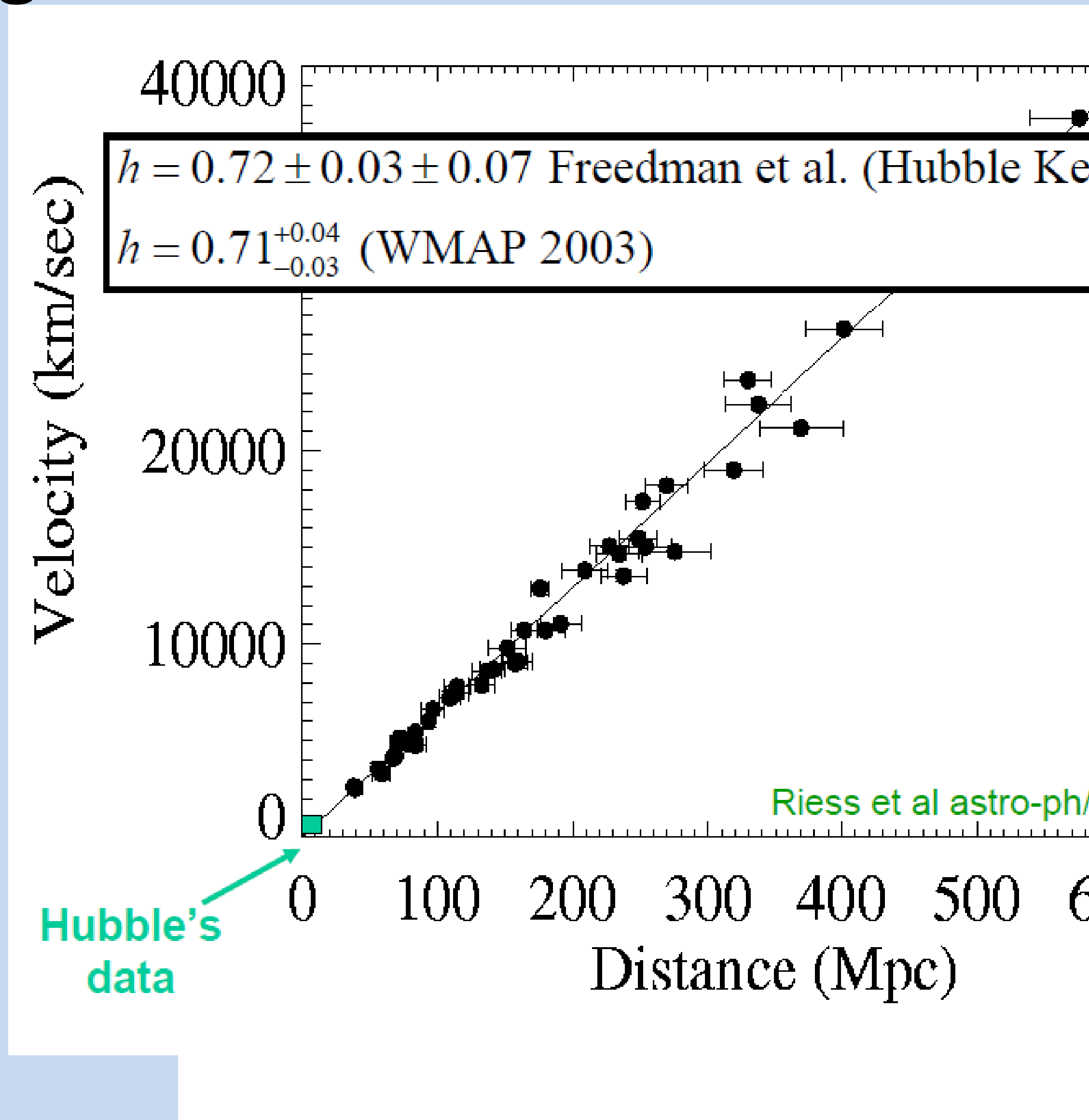
- Applicable for distances higher than those
  corresponding to peculiar velocities.
- d=3000h^{-1} z Mpc
- $d_H(t)$ =3t=2/H(t) at MD, $d_H(t)$ =2t=1/H(t) at RD
- Hubble age 1/H_0
- If ρ(t) and H(t) at any moment t, then $\dot{\rho}(t)$ and $\dot{H}(t)$
- Provides a scheme to find the distance to a distant galaxy by measuring z.

$$H \equiv 100\,h \text{ km s}^{-1}\text{ Mpc}^{-1}$$
$$\Rightarrow H^{-1} = 9.78\,h^{-1}\text{ Gyr}$$
$$= 2998\,h^{-1}\text{ Mpc}\,.$$

Measuring Hubble Constant

One of the "key projects" of the Hubble Space Telescope is the
 Edwin Hubble's program of
measuring distances to nearby galaxies.

H_0 = 72 km/sec/Mpc
$\approx (10^{10}\ \text{years})^{-1}$
$\approx (10^{18}\ \text{sec})^{-1}$
$\approx (10^{28}\ \text{cm})^{-1}$ $(c = 1)$
$\approx 10^{-33}$ eV

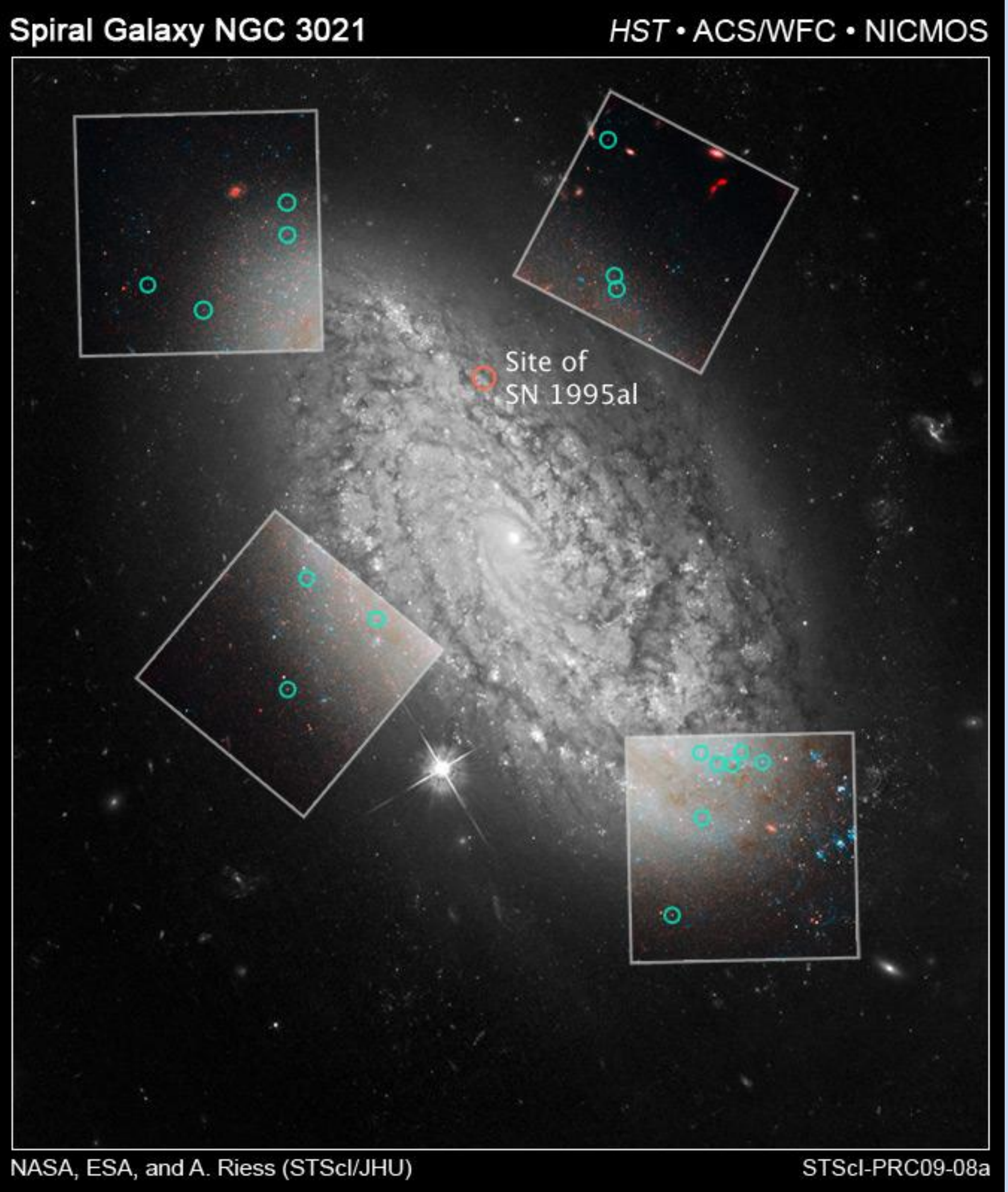


WMAP5: H=72 +/-3. (km/sec)/Mpc

HST 240 Cepheids:

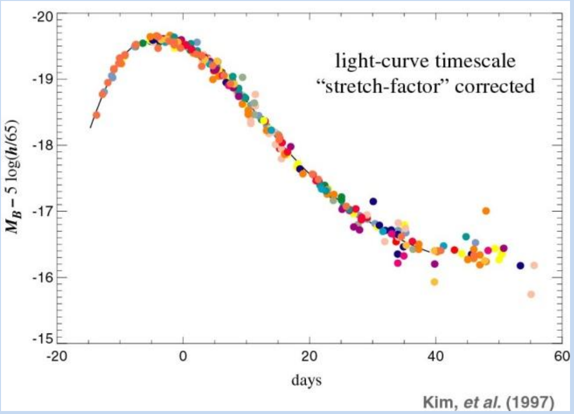
$$H_0 = 74 \pm 4\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

WMAP5 +BAO+SN+ …= 70.5 +/- 1.3 (km/sec)/Mpc



Hubble Space Telescope photo of the spiral galaxy NGC 3021.

Hubble made precise measurements of Cepheid variable stars in the galaxy, highlighted by green circles in the four inset boxes.
The Cepheids are then used to calibrate SN 1995aI.

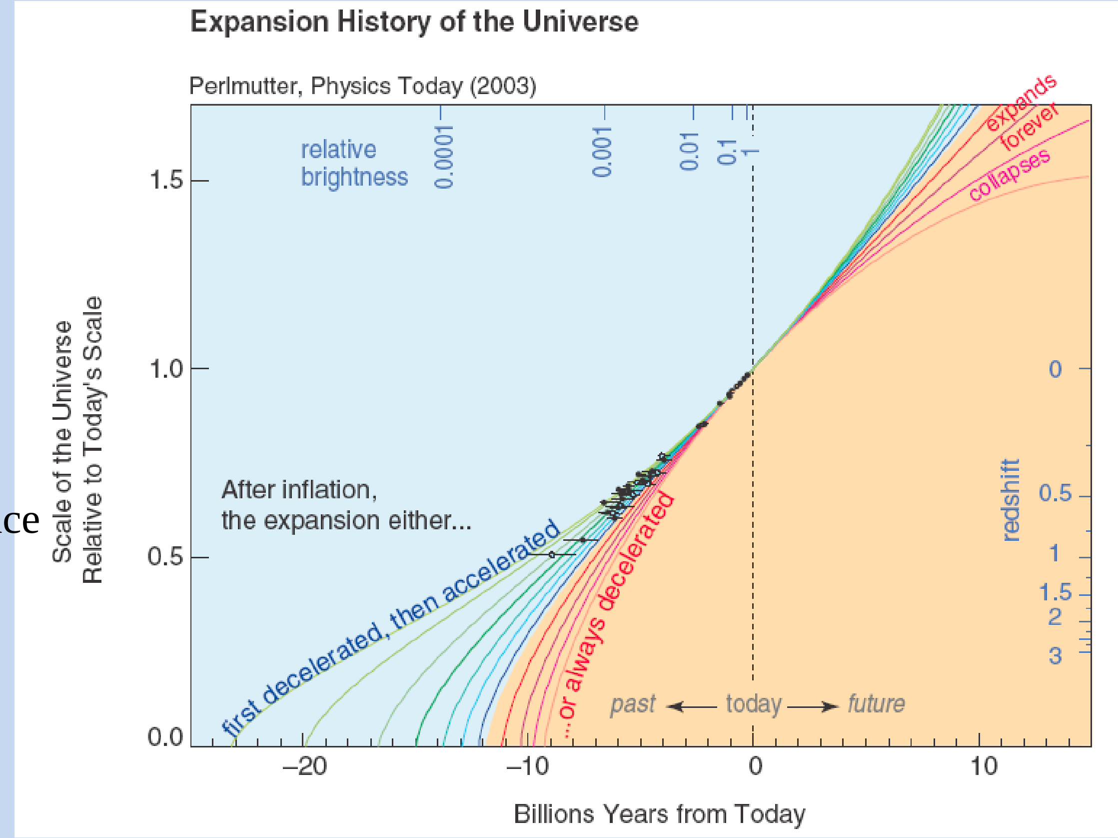


SN1a explodes with a spectacular flash whose inherent brightness is known

The images in the boxes were taken with the Near Infrared Camera and Multi-Object Spectrometer (NICMOS).

Universe Expansion

To measure how expansion slowed down over time, 12 years ago astronomers measure velocities of galaxies at different distances



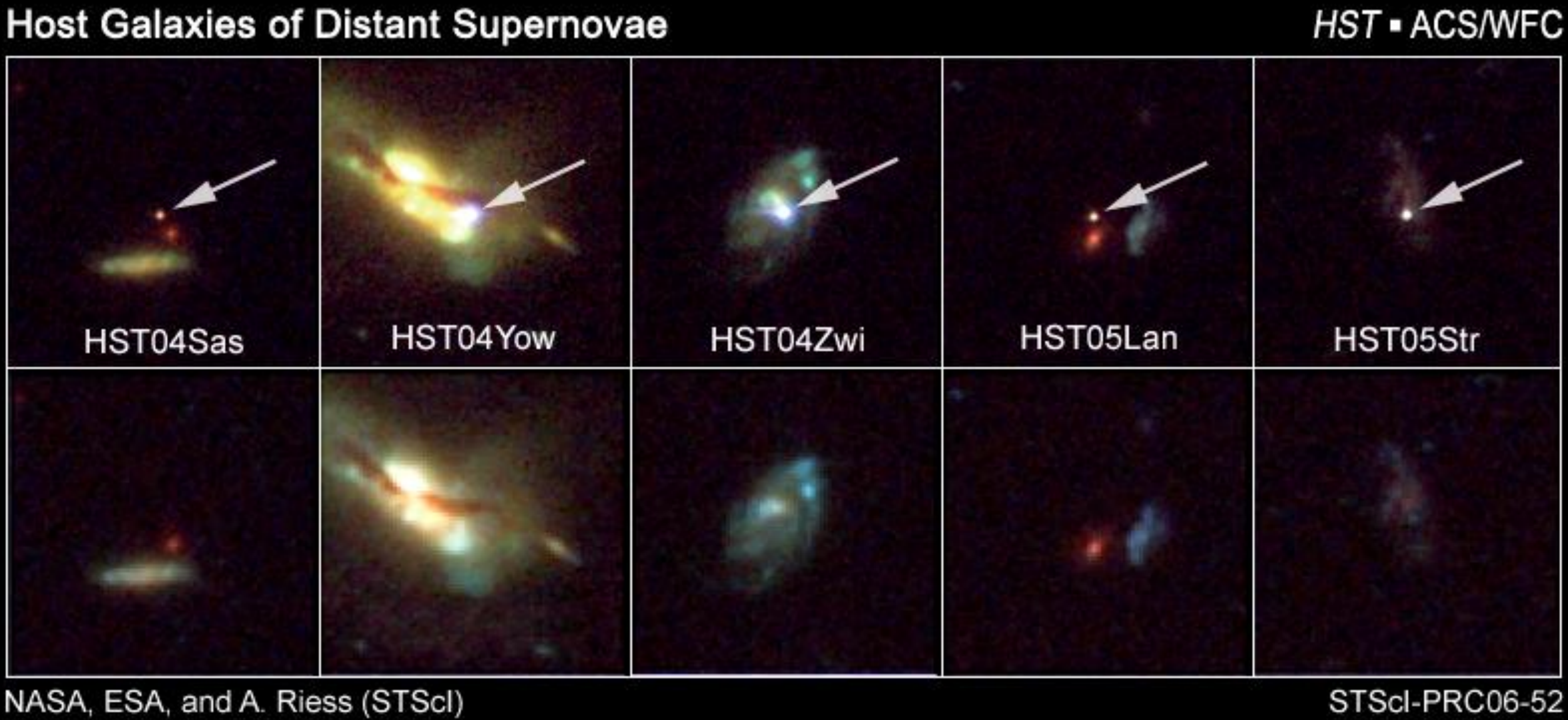
2 studies "SN cosmology project"
" High z SN search team"
lead by Adam Riess (Space Telescope Science Inst.) & Brian Schmidt (Mount Stromlo Observatory)

Saul Perlmutter (Lawrence Berkeley National Laboratory)
discovered accelerated expansion,
i.e. dark energy, with a behavior of Λ.

Combined data of HST and WMAP 2003 were used to define the universe's expansion rate to a precision of 3%!
That's a big step from 20 years ago when astronomers' estimates for H disagreed by a factor of two.
At present data of 300 SN Ia is available "Union sample"

HST, SN and DE

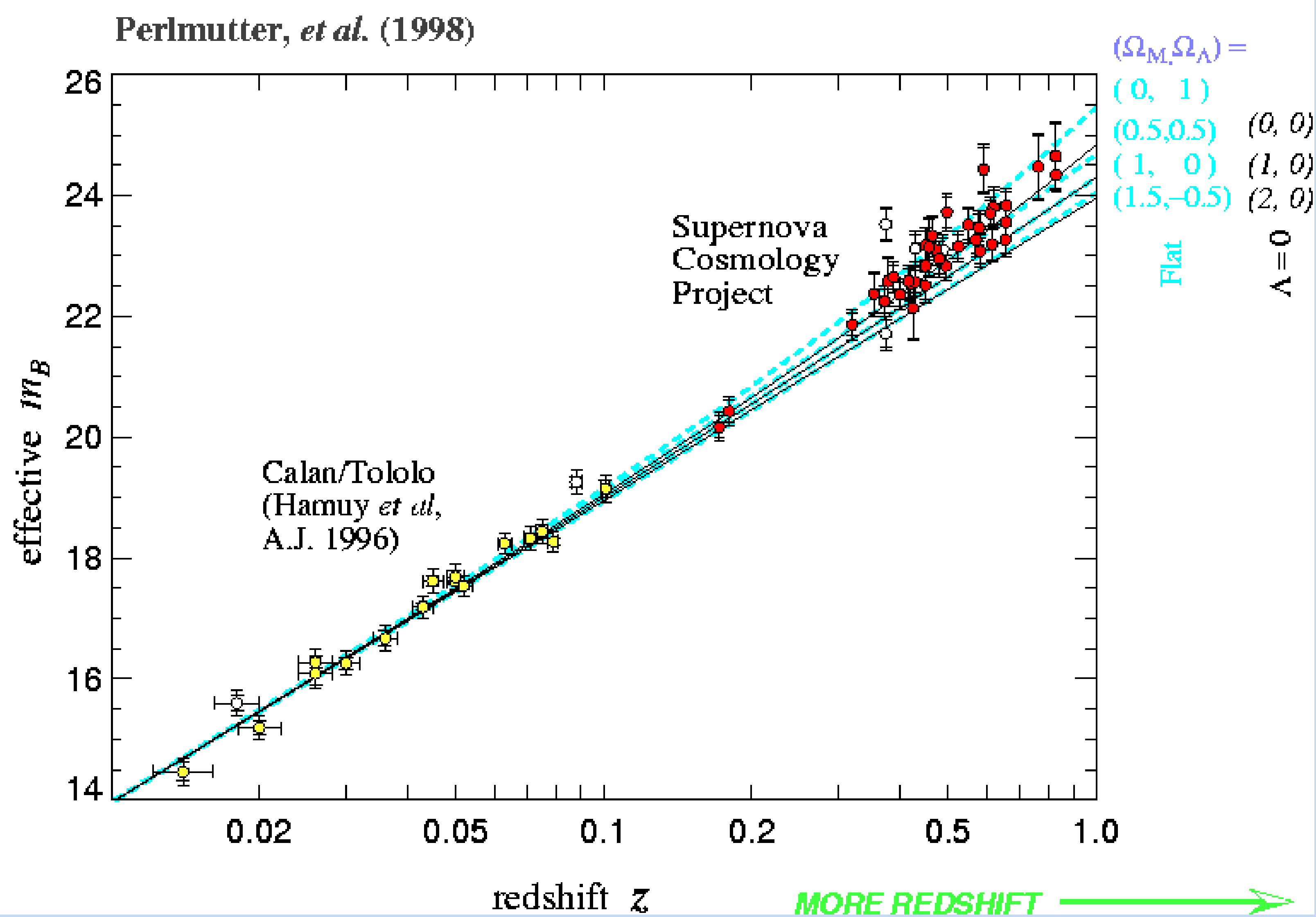
Hubble observations show for the first time that dark energy has been a present force for most of the universe's history.



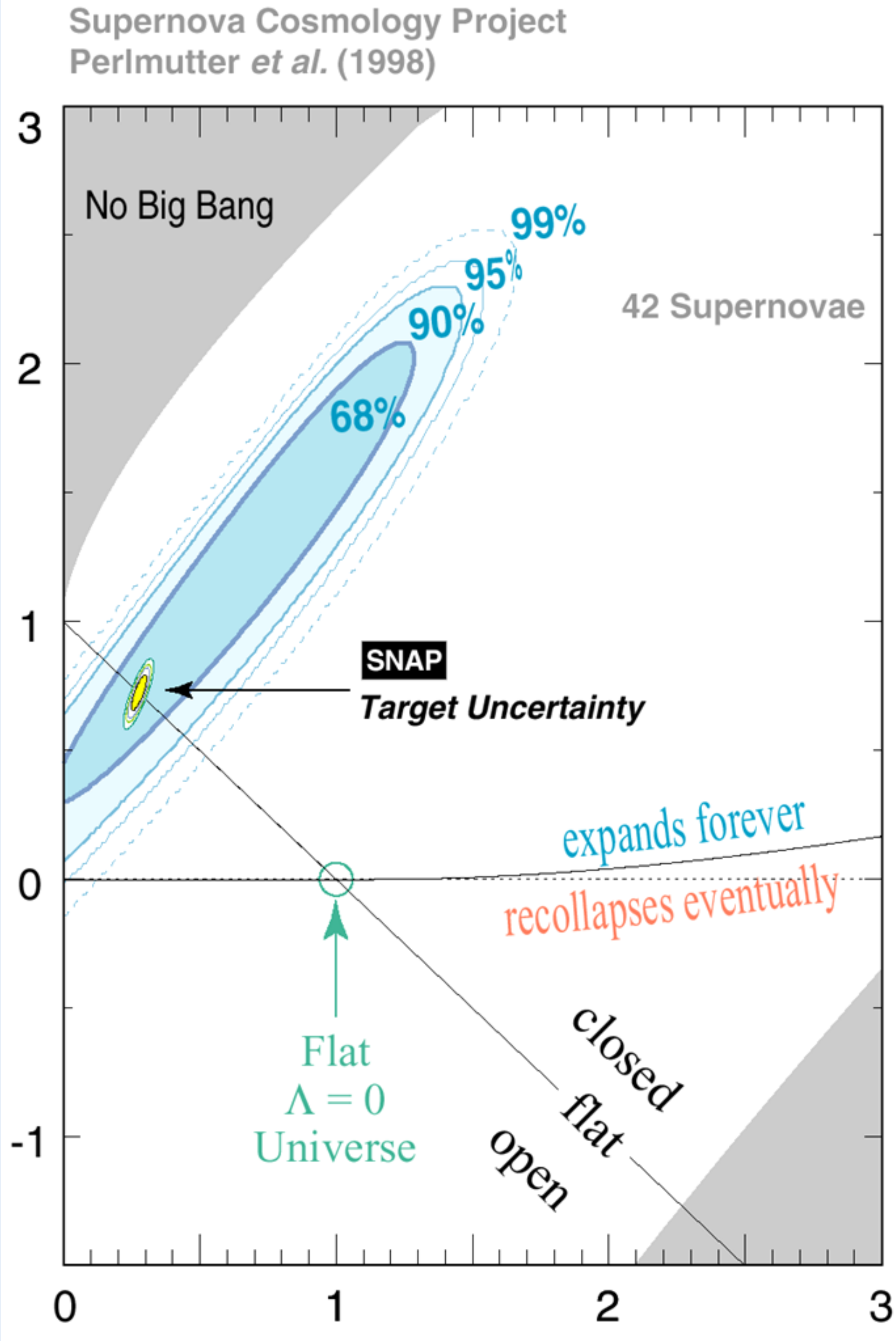
Snapshots, taken by NASA's Hubble Space Telescope, reveal five supernovae and their host galaxies. The supernovae exploded between 3.5 and 10 billion years ago. Only Hubble can measure these supernovae because they are too distant, and therefore too faint, to be studied by the largest ground-based telescopes.

Astronomers used the supernovae to measure the expansion rate of the universe and determine how the expansion rate is affected by the repulsive push of dark energy. Supernovae provide reliable measurements because their intrinsic brightness is well understood. They are therefore reliable distance markers.

Hubble Diagram SNIa



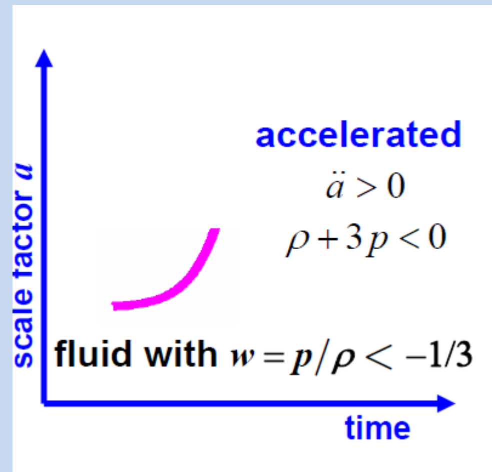
Sometime around 5 billion years ago, the universe began accelerating - its expansion getting faster and faster, rather than gradually slowing down.



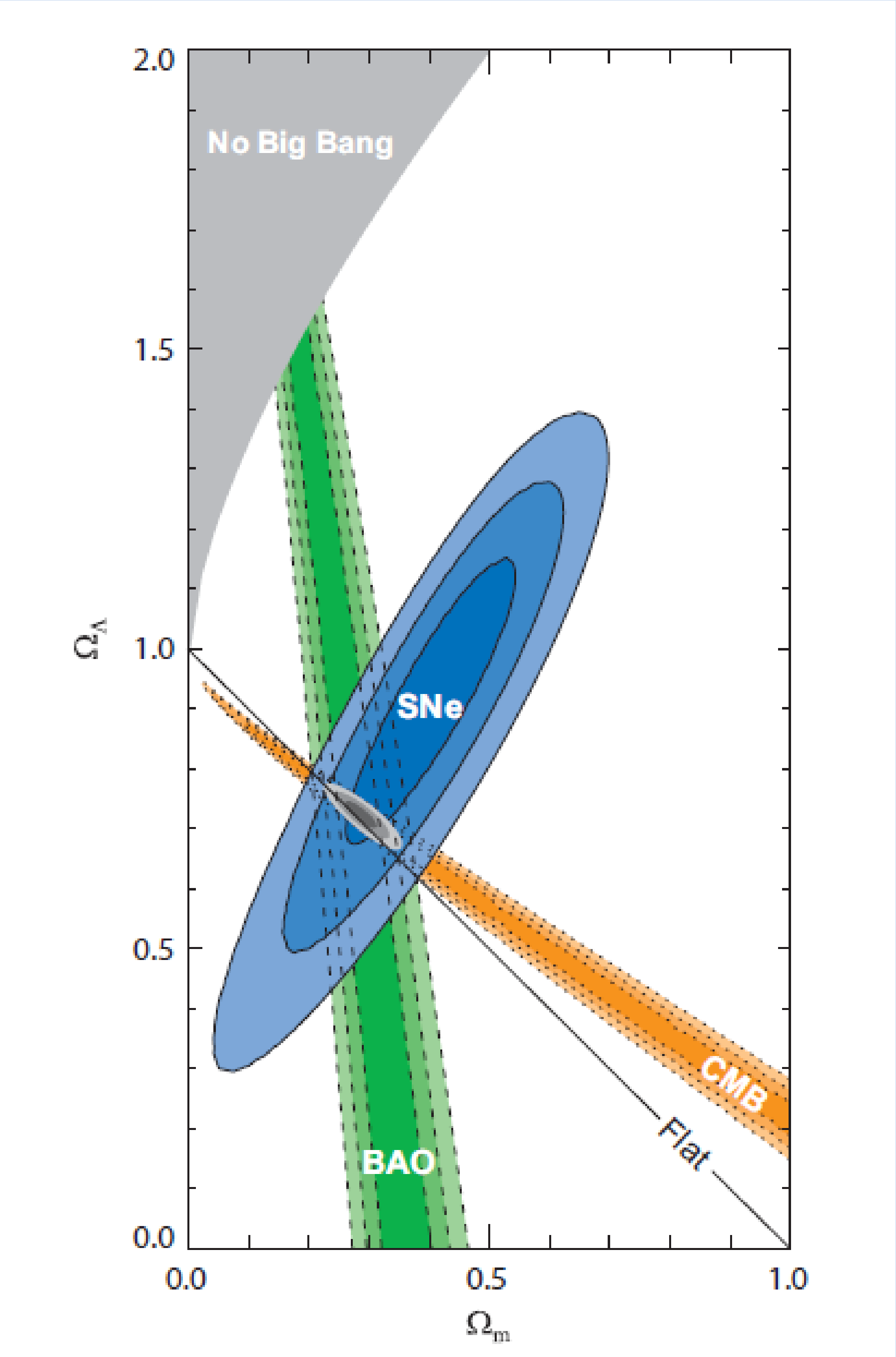
Ordinary matter gravitates.

Antigravity requires unusual medium with

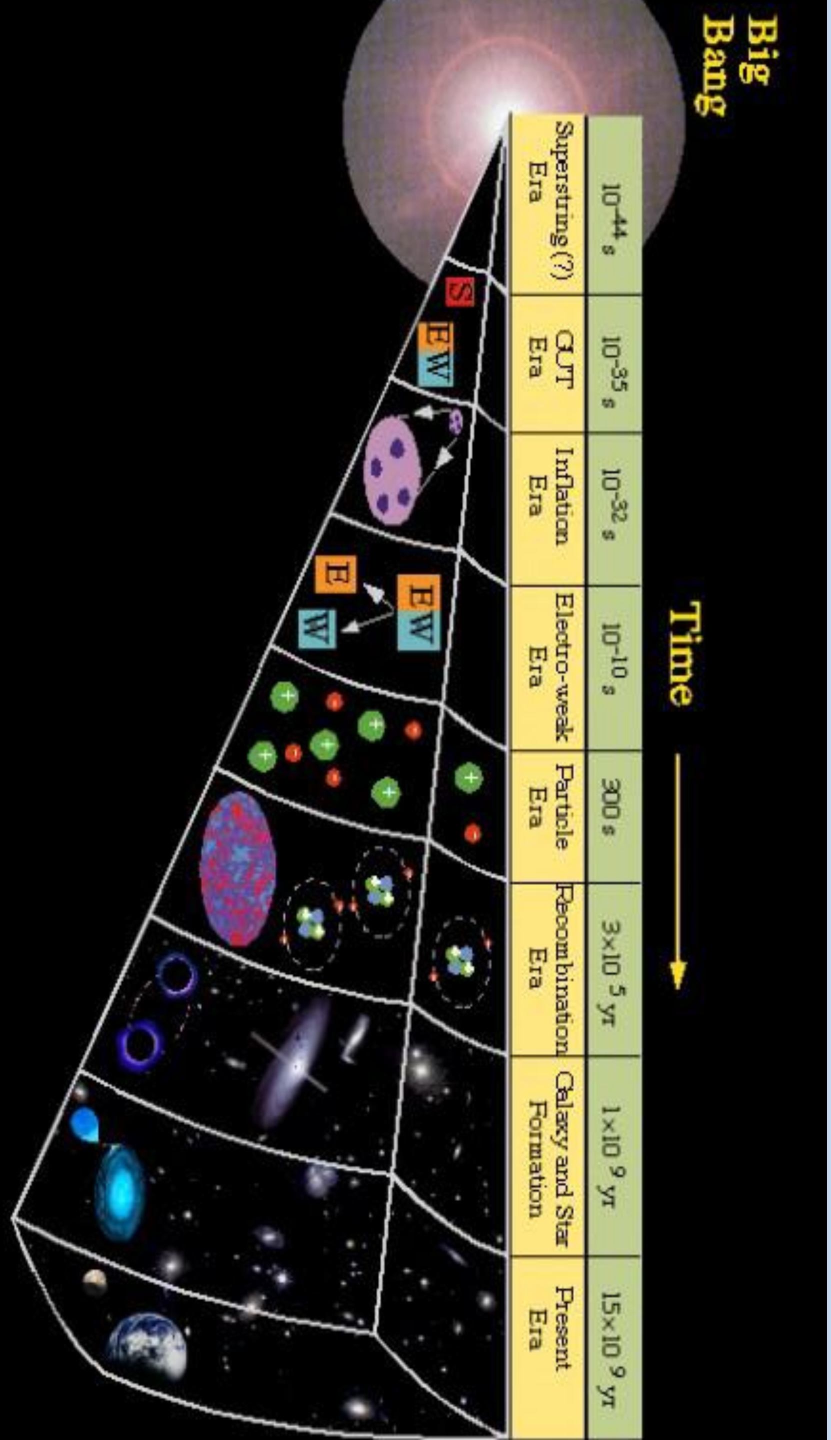
$P < 0$ and $p/\rho = \omega < -1/3$



- cosmological constant
- non-zero vacuum energy
- systematic effects
- ....



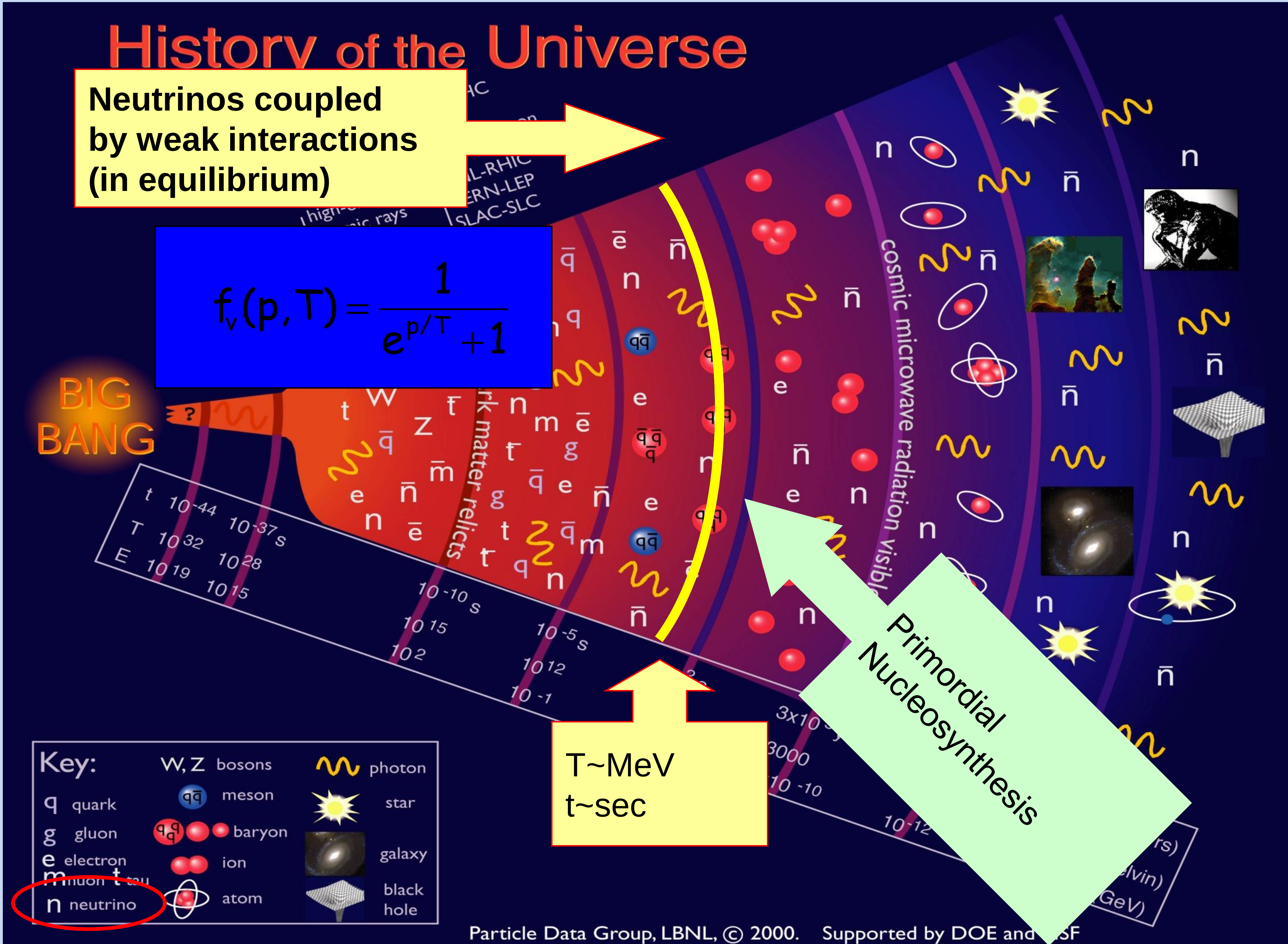
Union 300 SN Ia
&
КМФ
&
БАО



UNIVERSE HISTORY

Processes	**cosmic time**	**T**
GUT	10^{-35} s	10^{15} GeV
Inflation		
BA generation		
EW symmetry breaking		
	10^{-10} s	100 GeV
QCD	10^{-5} s	0.3 GeV
BBN	1 s – 3 m	1 - 0.1 MeV
CMB formation	300 000 y	0.3 eV
Galaxy formation	~10^{9} y	
Today	13.7 10^{9} y	0.0003 eV
		~ 3K

Relic Neutrino


History of the Universe
Neutrinos coupled by weak interactions (in equilibrium)
$f_\nu(p,T) = \frac{1}{e^{p/T}+1}$
BIG BANG
T~MeV
t~sec
Primordial Nucleosynthesis
cosmic microwave radiation visible
dark matter relicts
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
Key:
W, Z bosons
q quark
g gluon
e electron
m muon t tau
n neutrino
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Neutrino in SCM

- Universe is filled with massless non-oscillating neutrinos $\nu_{e,} \nu_{\mu} \nu_{\tau}$ (*an assumption*),

three neutrino flavours exist (confirmed for weakly interacting species lighter than Z/2 by LEP).

N_{eff} is *not exactly* 3 for standard neutrinos if non-instantaneous decoupling is considered, N_{eff} =3.046.

CMB+LSS constraints sensitive to the total energy density can be obtained $1<\delta N_s<5$

- The lepton asymmetry is zero (*an assumption*).
- Neutrino spectra have the equilibrium Fermi-Dirac distribution (*an assumption*).

$$n_\nu^{eq} = \exp(-E/T)/(1+\exp(-E/T))$$

$n_\nu = 3/11\, n_{cmb}$ $\quad$ $n_\nu = 113\ cm^{-3}$ $\quad$ $T_\nu = (4/11)^{1/3}\, T_{cmb}$

❖ **Neutrino contribution to the energy density of the Universe**

At $T<m_e$,

$$\rho_r = \rho_\gamma + \rho_\nu = \frac{\pi^2}{15} T_\gamma^4 + 3 \times \frac{7}{8} \times \frac{\pi^2}{15} T_\nu^4 = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} 3\right] \rho_\gamma$$

Traditional parametrization of the energy density stored in rel. particles

Effective number of relativistic neutrino species

$$\rho_r = \rho_\gamma + \rho_\nu + \rho_x = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right] \rho_\gamma$$

Neutrino effects the expansion rate of the Universe

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi\, G_N\, \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3} ,$$

Relic Neutrino Background

T>> 1 MeV equilibrium due to weak interactions

$$\Gamma \sim G_F^2 E_\nu^2 N_\nu \gg H \sim \sqrt{g_{eff} G} T^2$$

$$\nu_\alpha \nu_\beta \leftrightarrow \nu_\alpha \nu_\beta$$
$$\nu_\alpha \bar{\nu}_\beta \leftrightarrow \nu_\alpha \bar{\nu}_\beta$$
$$\nu_\alpha e^- \leftrightarrow \nu_\alpha e^-$$
$$\nu_\alpha \bar{\nu}_\alpha \leftrightarrow e^+ e^-$$

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3},$$

$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}(\rho + 3p),$$

As the Universe expands, particle densities are diluted and temperatures fall.
Weak interactions become ineffective to keep neutrinos in good thermal contact with the e.m. plasma.

$T_{dec}(\nu_e) \sim 2$ MeV $T_{dec}(\nu_{\mu,\tau}) \sim 3$ MeV $\Gamma \sim G_F^2 E_\nu^2 N_\nu \sim H \sim \sqrt{g_{eff} G} T^2$

Since decoupling neutrino were free streaming, i.e. cosmological neutrino background.

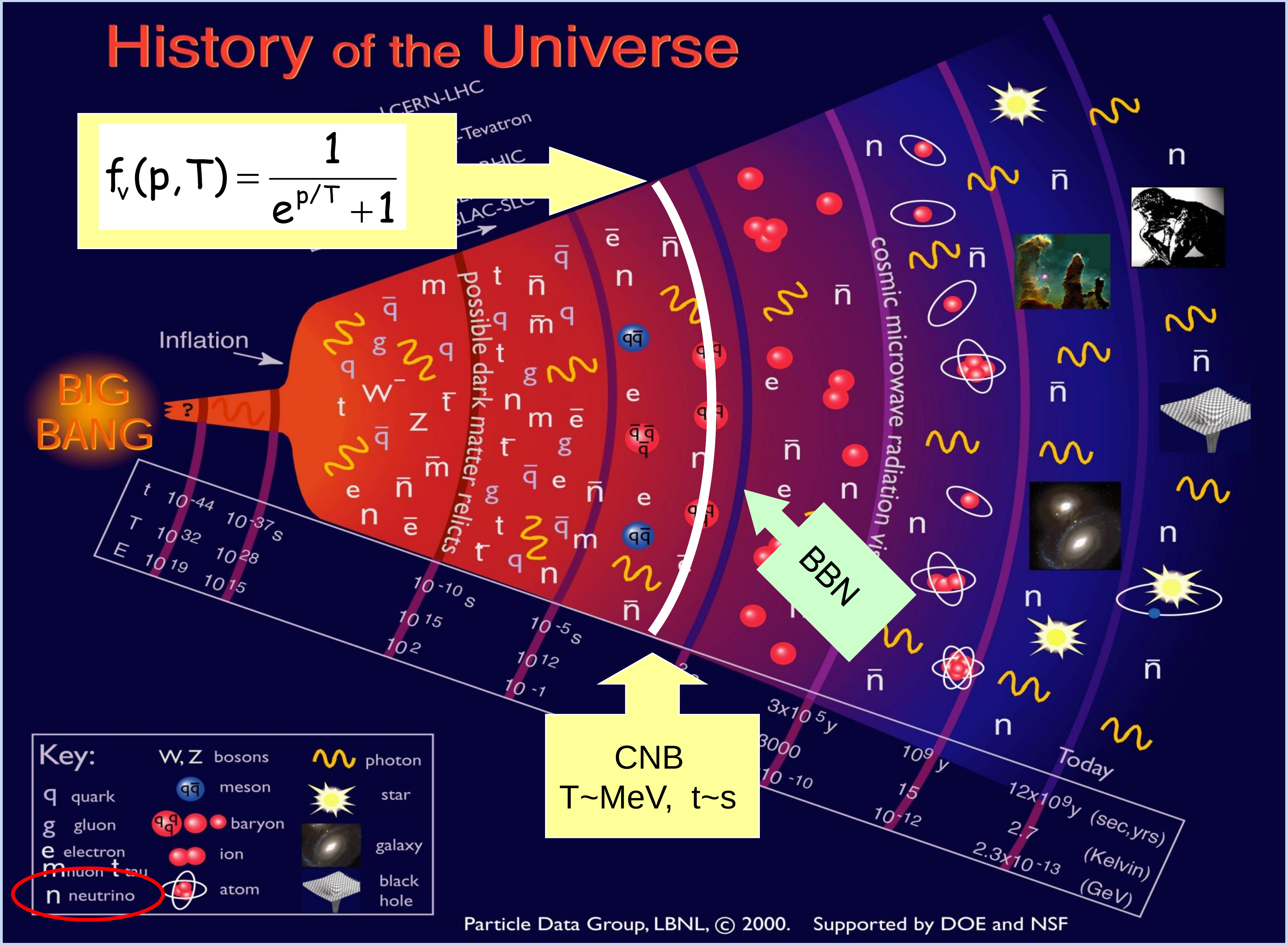
- $T \sim m_e$, $e^+e^- \rightarrow \gamma\gamma$, photons but not the neutrinos were heated $T_\nu = (4/11)^{1/3} T_{cmb}$.
  CNB today is expected with temperature ~ 1.9 K, $n_\nu = 3/11\, n_{cmb}$

*S*ince **$T_{dec}(\nu)$** is close to **m_e**, neutrinos shared a small part of the entropy release) *:*
neutrino species – 3.046 instead of 3 (not observable by present observational data)

Dolgov, Hansen & Semikoz,1997,Mangano et al,02,05

- Today relic neutrino (CNB) is expected to be the most numerous particle after CMB photons.

$n_\nu = 339.3\ \mathrm{cm}^{-3}$ $n_{cmb} = 411\ \mathrm{cm}^{-3}$ $\Omega_\nu = \dfrac{3m_0}{93.14 h^2\ \mathrm{eV}^2}$



History of the Universe
$$f_\nu(p,T)=\frac{1}{e^{p/T}+1}$$
CERN-LHC
Tevatron
RHIC
SLAC-SLC
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation
BBN
CNB
T~MeV, t~s
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
3x10^5 y
3000
10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Relic Neutrino Background

Neutrinos decoupled at T~MeV, keeping a spectrum as that of a relativistic species

$$f_\nu(p,T) = \frac{1}{e^{p/T_\nu}+1}$$

- Number density

$$n_\nu = \int \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) = \frac{3}{11} n_\gamma = \frac{6\zeta(3)}{11\pi^2} T_{CMB}^3$$

- Energy density

$$\rho_{\nu_i} = \int \sqrt{p^2+m_{\nu_i}^2} \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) \to \begin{cases} \frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T_{CMB}^4 & \text{Massless} \\ m_{\nu_i} n_\nu & \text{Massive } m_\nu \gg T \end{cases}$$

Though numerous, CNB direct detection is very difficult because it is an extremely elusive particle due to its weak interactions and extremely low energy expected for neutrinos today.

$$n_\nu = 339.3\ \mathrm{cm}^{-3} \qquad \Omega_\nu = \frac{3m_0}{93.14h^2\ \mathrm{eV}^2} \qquad 0.001 < \Omega_\nu < 0.02$$

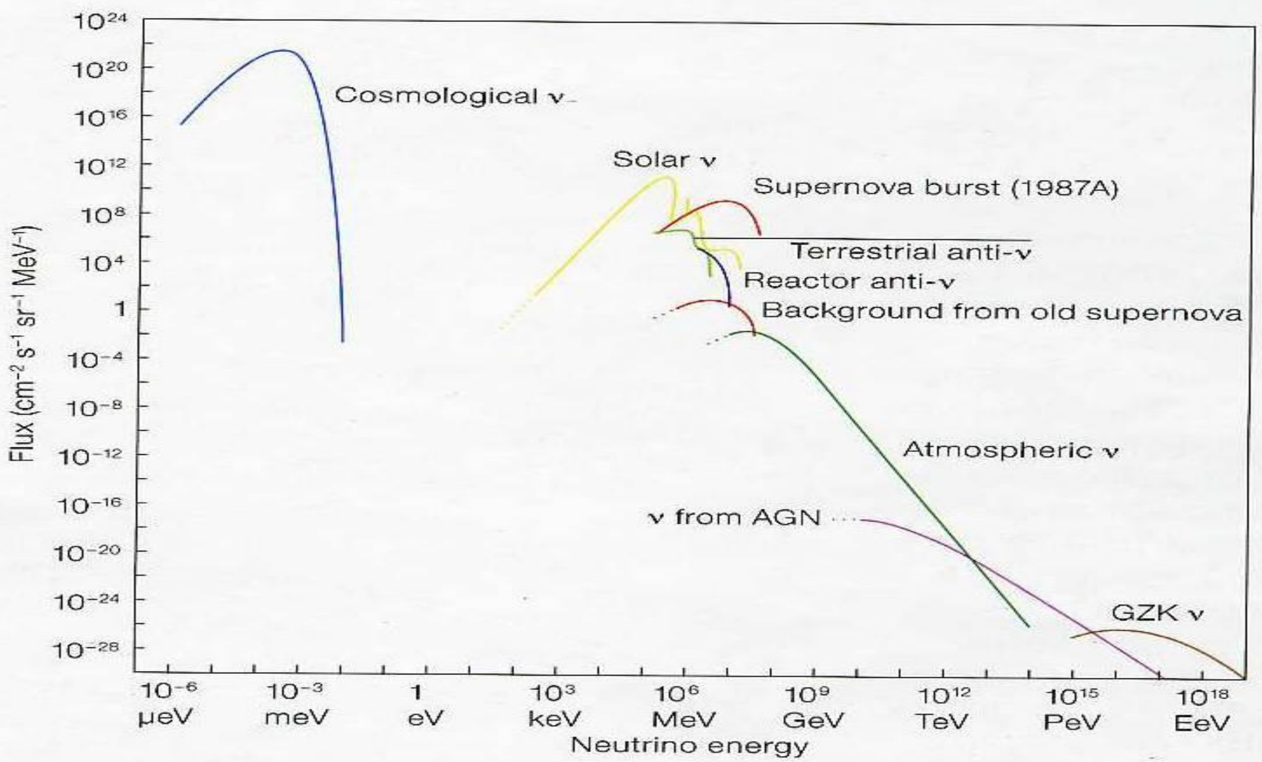


Figure 2: The 'grand unified' neutrino spectrum.

Figure from ASPERA roadmap

Indirect CNB detection is possible due to its effect on BBN,CMB, LSS.
CMB&LSS feel the total neutrino density. BBN is precise probe also of neutrino energy distribution, mass differences and mixing, chemical potential, etc.

OSCILLATING NEUTRINOS

$\nu_m = U_{mf} \nu_f$, $(f = e, \mu, \tau)$

$P(\theta, \delta m^2, E, t)$

Evidence for oscillations of neutrino were obtained at the greatest neutrino experiments: solar, atmospheric and terrestrial **LSND, KAMLAND, K2K.....**

Solar neutrino problem, atmospheric neutrino anomaly and the results of terrestrial neutrino oscillations experiments can be resolved by the phenomenon of neutrino oscillations.

It has been observationally and experimentally proved that neutrinos oscillate . Then

- ✓ non-zero neutrino mass and mixing
- ✓ LA may be non-zero
  Initially present, or generated in resonant active-sterile oscillations
- ✓ Relic neutrino n(E) may differ from the equilibrium form

$$n_\nu^{eq} \neq \exp(-E/T)/(1+\exp(-E/T))$$

$N_e < N_{eq}$

Solar neutrino anomaly: $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

$\delta m^2 \sim 7.6 \cdot 10^{-5}\ eV^2 \quad \sin^2\theta \sim 0.3$

Atmospheric neutrino anomaly: $\nu_\mu \leftrightarrow \nu_\tau$

$\delta m^2 \sim 2.4 \cdot 10^{-3} eV^2$ maximal mixing

$\delta m^2 \neq 0 \Longrightarrow$ at least 2 neutrino with $m_\nu \neq 0$

$$\Omega_\nu = \frac{3m_0}{93.14 h^2\ \text{eV}^2}$$

$$0.001 < \Omega_\nu$$

Flavor neutrino does not play an important role for DM and the formation of structure.

$$0.001 < \Omega_\nu < 0.02$$

Eventual sterile neutrino may be a good DM representative.

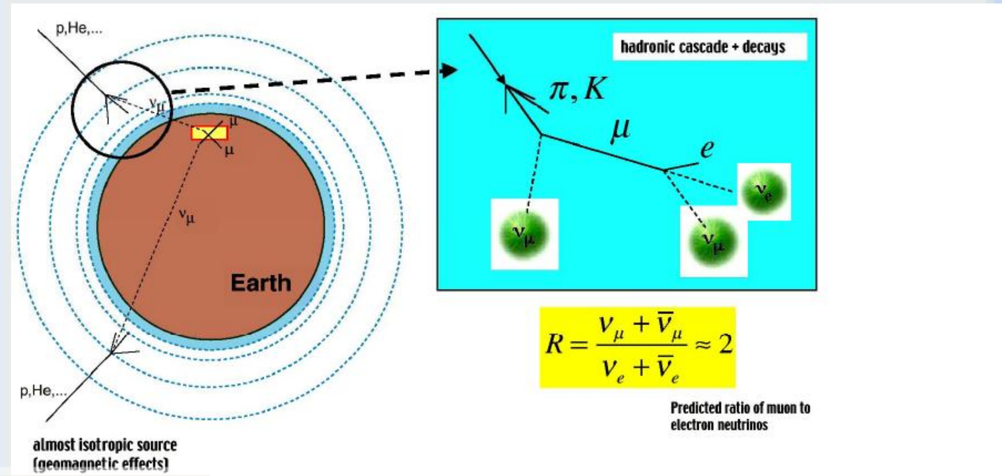
Solar neutrino problem
Homestake+Gallium+Kam+SK+SNO

1968 Homestake Ray Davis

ν_e + 37Cl → 37Ar + e

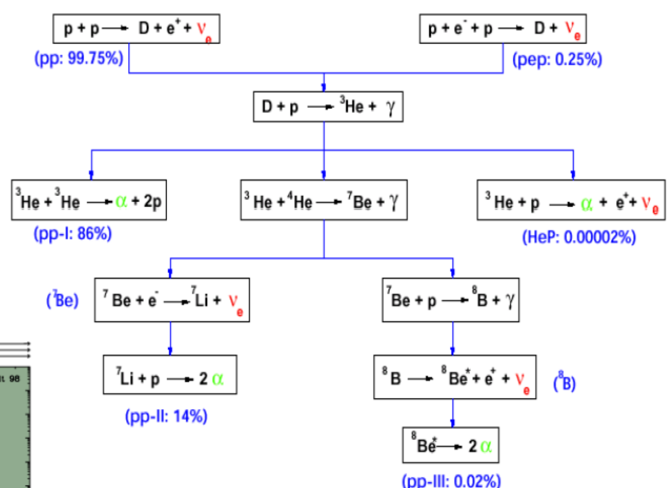
SK 1996: Neutrino is coming from the Sun
SNO 2002: SMA and the sterile neutrino channel are disfavored.
Sun shines due to nucleosynthesis in its core!
Muon and tau neutrino observed from the Sun,
Total neutrino flux from the Sun is measured.
KAMLAND: distortion typical for oscillations
SNO-II, Kamland: LMA solution of the solar anomaly
Solar neutrino anomaly confirmed by terrestrial experiments.

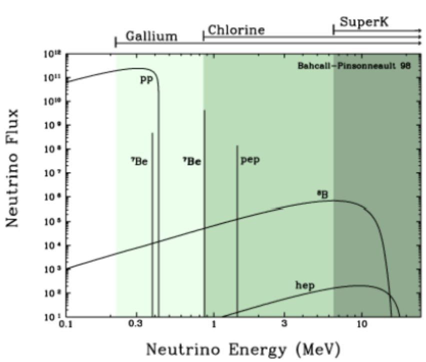
Atmospheric neutrino anomaly



ν_e solar neutrinos

Sun = Fusion reactor
Only ν_e produced
Different reactions
Spectrum in energy





Counting experiments vs flux calculated by SSM

BUT ...

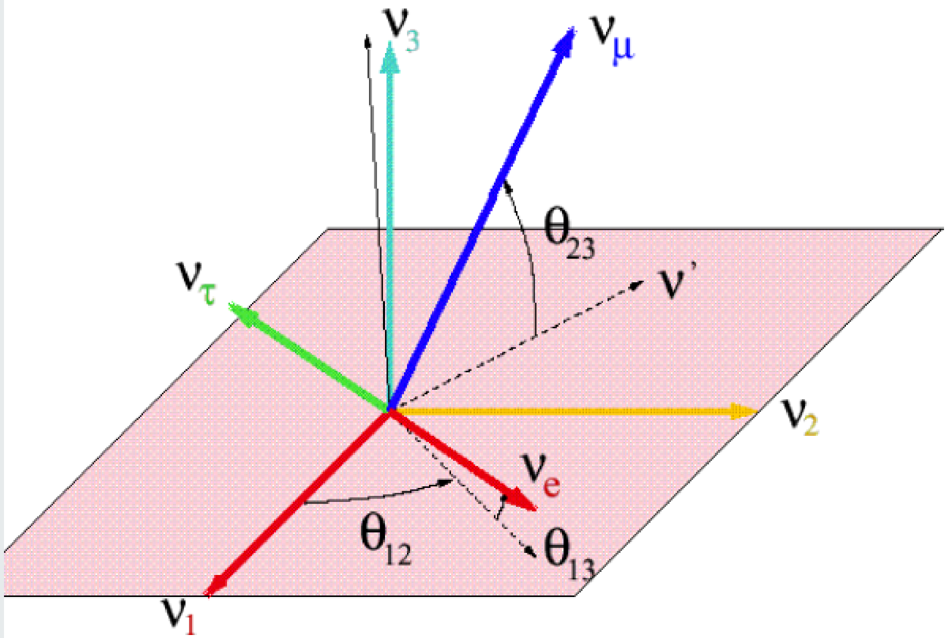
Atmospheric neutrino (ν_μ −> ν_τ) oscillations are established *(IMB+Kam+SK+Macro+Sudan)*

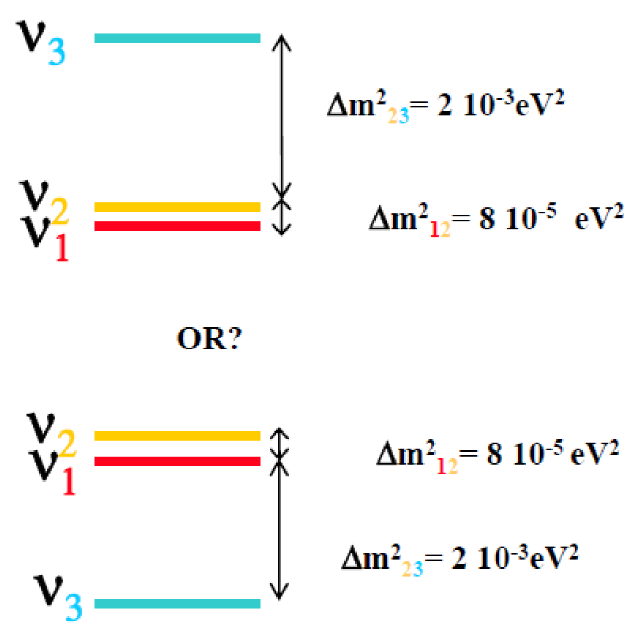
This allows a consistent picture with 3-family oscillations preferred.

$$\Omega_\nu = \frac{3m_0}{93.14h^2\ \mathrm{eV}^2}$$

$$0.001 < \Omega_\nu$$

The neutrino mixing matrix: 3 angles and a phase δ





θ_{23} (atmospheric) = 45^0 , θ_{12} (solar) = 32^0 , θ_{13} (Chooz) < 13^0

$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

Unknown or poorly known even after approved program:
θ_{13} , phase δ , sign of Δm^2_{13}

OSCILLATING NEUTRINOS

$\nu_m = U_{mf}\,\nu_f$, $(f = e, \mu, \tau)$ $P(\theta, \delta m^2, E, t)$

Evidence for oscillations of neutrino were obtained at the greatest neutrino experiments: solar, atmospheric and terrestrial **LSND, KAMLAND, K2K…..**

Solar neutrino problem, atmospheric neutrino anomaly and the results of terrestrial neutrino oscillations experiments can be resolved by the phenomenon of neutrino oscillations.

It has been observationally and experimentally proved that neutrinos oscillate . Then

- ✓ non-zero neutrino mass and mixing
- ✓ LA may be non-zero

  Initially present, or generated in resonant active-sterile oscillations
- ✓ Relic neutrino n(E) may differ from the equilibrium form

$$n_\nu^{eq} \neq \exp(-E/T)/(1+\exp(-E/T))$$

$N_e < N_{eq}$

Solar neutrino anomaly: $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

$\delta m^2 \sim 7.6\,.10^{-5}\,eV^2$ $\sin^2\theta \sim 0.3$

Atmospheric neutrino anomaly: $\nu_\mu \leftrightarrow \nu_\tau$

$\delta m^2 \sim 2.4.10^{-3} eV^2$ maximal mixing

$\delta m^2 \neq 0 \Longrightarrow$ at least 2 neutrino with $m_\nu \neq 0$

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$$0.001 < \Omega_\nu$$

Flavor neutrino does not play an important role for DM and the formation of structure.

$$0.001 < \Omega_\nu < 0.02$$

Eventual sterile neutrino may be a good DM representative.

The role of neutrino

There exist robust experimental and observational evidence for the existence of neutrino oscillations, pointing to at least 2 non-zero neutrino masses.

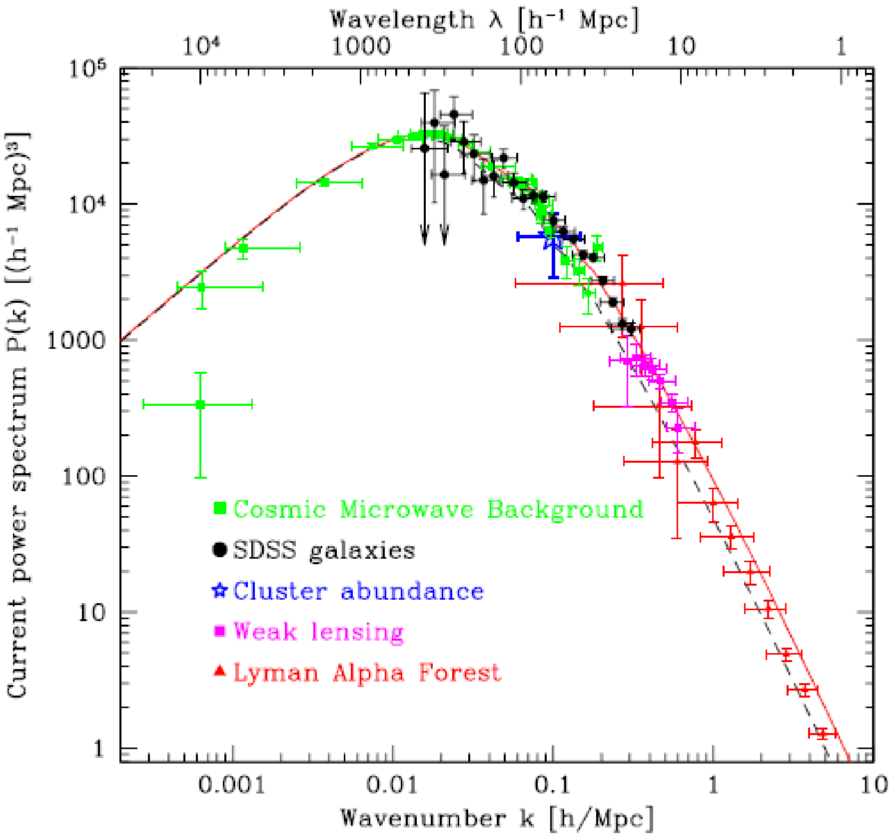
Contribution of neutrinos to total energy density today (3 degenerate masses)

$$\Omega_\nu = \frac{3m_0}{93.14h^2 \text{ eV}^2} \qquad n_\nu = 339.3 \text{ cm}^{-3}$$

In case neutrino masses are in the eV range they can constitute several % of the DM, they can influence matter clustering (suppressing small-scale power of the matter power spectrum) providing better correspondence between models and observational data (from SDSS, cluster abundance, weak lensing, Lyman Alpha forest, CMB). *Tegmark et al., 2004*

Fast moving neutrinos do not play any major role in the evolution of structure in the universe. They would have prevented the early clumping of gas in the universe, delaying the emergence of the first stars, in conflict with the new WMAP data.

Power Spectrum of Density Fluctuations



[Tegmark, hep-ph/0503257]

Solid Curve: flat ΛCDM model

$(\Omega_M^0 = 0.28\,,\ h = 0.72\,,\ \Omega_B^0/\Omega_M^0 = 0.16)$

Dashed Curve: $\sum_{k=1}^{3} m_k = 1\,\text{eV}$

hot dark matter
prevents early galaxy formation

$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \overline{\rho}}{\overline{\rho}}$$

$$\langle \delta(\vec{x}_1)\delta(\vec{x}_2) \rangle = \int \frac{d^3k}{(2\pi)^3}\, e^{i\vec{k}\cdot\vec{x}}\, P(\vec{k})$$

small scale suppression

$$\frac{\Delta P(k)}{P(k)} \approx -8\,\frac{\Omega_\nu}{\Omega_m} \approx -0.8 \left(\frac{\sum_k m_k}{1\,\text{eV}}\right)\left(\frac{0.1}{\Omega_m h^2}\right)$$

for

$$k \gtrsim k_{\text{nr}} \approx 0.026 \sqrt{\frac{m_\nu}{1\,\text{eV}}}\sqrt{\Omega_m}\, h\,\text{Mpc}^{-1}$$

[Hu, Eisenstein, Tegmark, PRL 80 (1998) 5255]

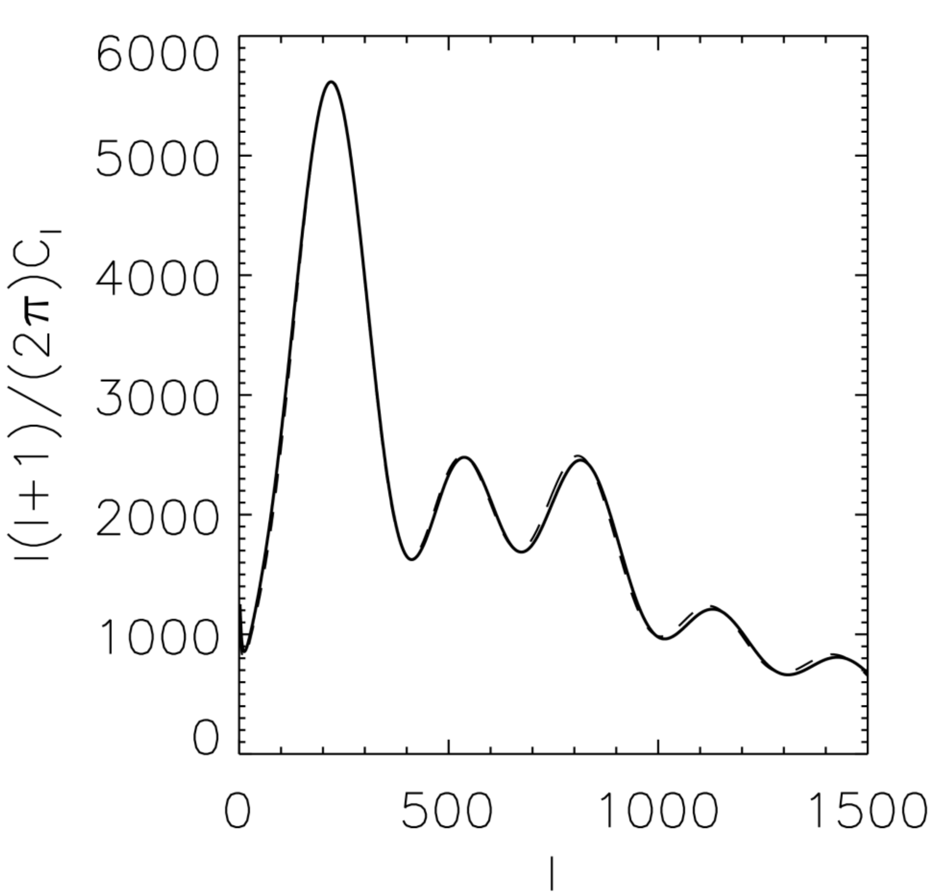
How comparing the CMB and galaxy surveys constrains the neutrino mass:

CMB +LSS: total neutrino mass < 0.6 eV

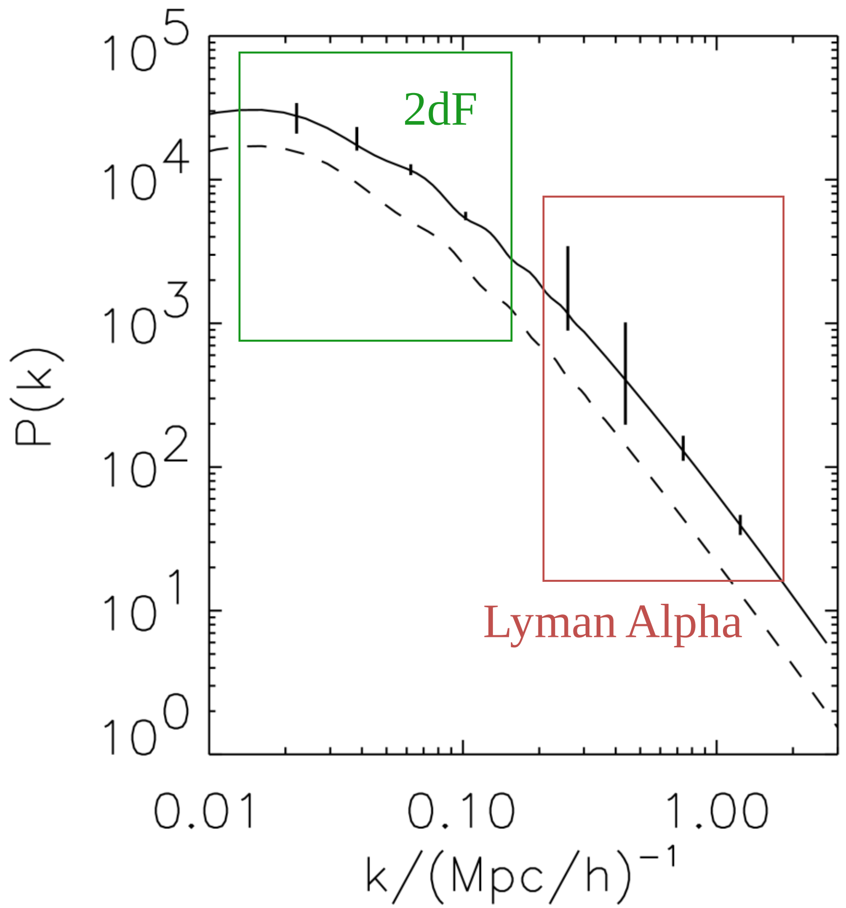
Massive neutrinos can hide in the CMB…

Solid: h=0.71 neutrino density=0

Dashed: h=0.60 neutrino density=0.02



… but at low redshift they are no longer relativistic and have a big effect on galaxy clustering.



Fogli, Lisi, Marrone, Melchiorri, Palazzo, Rotunno, Serra, Silk, Slosar

[PRD 78 (2008) 033010, hep-ph/0805.2517]

Flat ΛCDM

Case	Cosmological data set	Σ (at 2σ)
1	CMB	< 1.19 eV
2	CMB + LSS	< 0.71 eV
3	CMB + HST + SN-Ia	< 0.75 eV
4	CMB + HST + SN-Ia + BAO	< 0.60 eV
5	CMB + HST + SN-Ia + BAO + Lyα	< 0.19 eV

2σ (95% C.L.) constraints on the sum of ν masses Σ.

Sterile Neutrinos Status

- Sterile neutrino is not constrained by LEP
- Required for producing non-zero neutrino masses by most models
- Predicted by GUT models
- Welcomed by oscillations data for better fit (subdominant sterile oscillations channel required by Homestake data, *Holanda, Smirnov, 2004*), *Chauhan, Pulido, 2004,* variation of the flux with B, *Caldwell D, Sturrock P.,2005*
- required for explanation of LSND in combination with other expts
- Wellcomed by cosmology:

  * may be the particle accounting for all DM (m<3.5 KeV if MSM produced)
  * may play subdominant role as DM component (eV, KeV)
  * Fast moving neutrinos do not play major role in the evolution of structure in the universe.
  * may play a role in LSS formation (when constituting few % of the DM it suppresses small scale power in the matter power spectrum and better fits the observational data from SDSS, cluster abundance, weak lensing, Lyman Alpha forest, CMB) *Tegmark et al., 2004*
  * plays major role in natural baryogenesis through leptogenesis

Sterile Neutrinos

- The X ray photons from sterile neutrino decays may catalize the production of molecular H and speed up the star formation, causing earlier reionization

X ray photons from sterile neutrino decays – observational feature

- CMB feels the increase in the density due to additional particles
- Sterile neutrino is constrained by BBN, because it increases the expansion rate and hence dynamically influences He production, in case it is brought into equilibrium
- In case of oscillations with active neutrino it exerts major effect on nucleons kinetics during pre-BBN and its mixing parameters are constrained by BBN+CMB
- In case of radiative decays its decay products may distort CMB
- In case of non-raditive decays, the decay poducts may influence

nucleons kinetics and hence BBN constraints on its decay time, mass and number densities hold

Et cetera…..

Neutrinos in the Universe:

Effect the energy density expansion rate of the Universe

Constraints on number of neutrino species

Matter/radiation equality shift

Constraints on neutrino masses and number densities < 0.6 eV

DM candidate

Effect BBN kinetics

Spectrum distortion asymmetry constraints

Constraints on oscillation parameters
Constraints on sterile neutrino population

baryogenesis through leptogenesis

Effect on CMB and LSS

Feel total energy density stored in neutrinos

Constraints on neutrino masses
Constraints on lepton asymmetry

not sensitive to different species or spectrum distortions

Primordial Nucleosynthesis

Chemical composition of the baryonic component

Observational Milestones of Hot Big Bang Cosmology

- Homogeneity and isotropy and structures in the Universe

- The expansion of the Universe

- The abundance of the light elements

The light elements abundances provide evidence for a hotter and denser early Universe, when these elements have been fused from protons and neutrons. Point to non-baryonic DM.

$$H_0, \Omega_B, \Omega_\nu$$

- The cosmic microwave background radiation

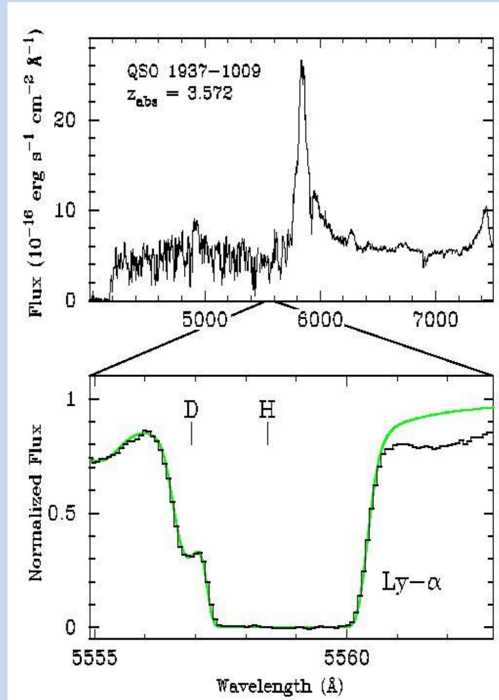
The Abundances of Light Elements

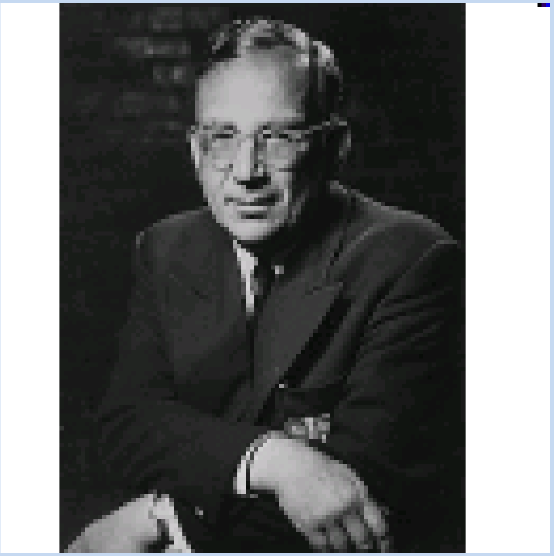
D measured in highredshift,
low-metallicity
quasar absorption systems

$$D/H|_p = (2.78 \pm 0.29) \times 10^{-5}$$

He in clouds of ionized hydrogen (H II regions), the most metal-poor of which are in dwarf galaxies. Z

$$Y_p = 0.249 \pm 0.009$$





George Gamow

1904 – 1968

In 1946–1948 develops BBN theory.

In the framework of this model predicts CMB and its T.

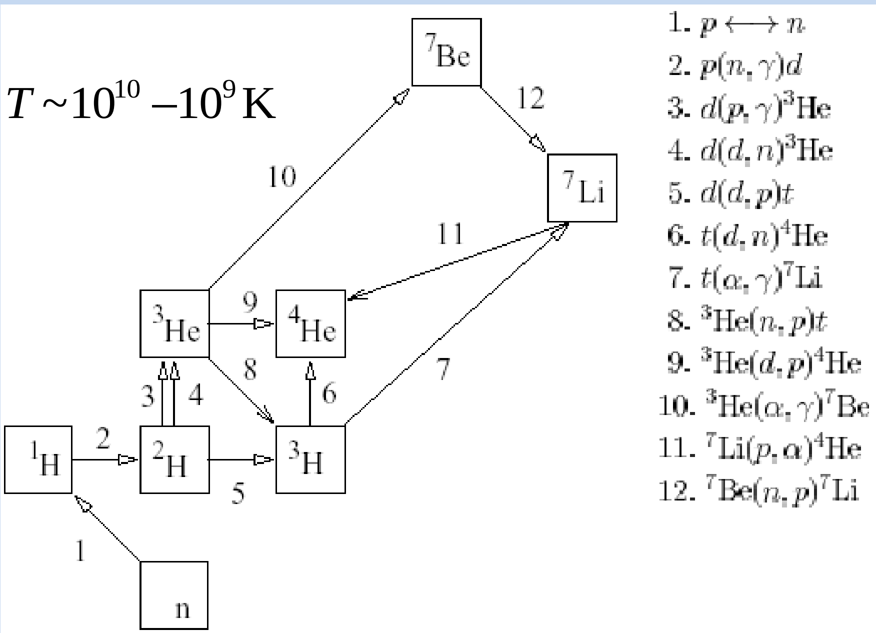
Pop II (metal-poor) stars in the spheroid of our Galaxy, which have Z<1/10 000 $Z_{☼}$)

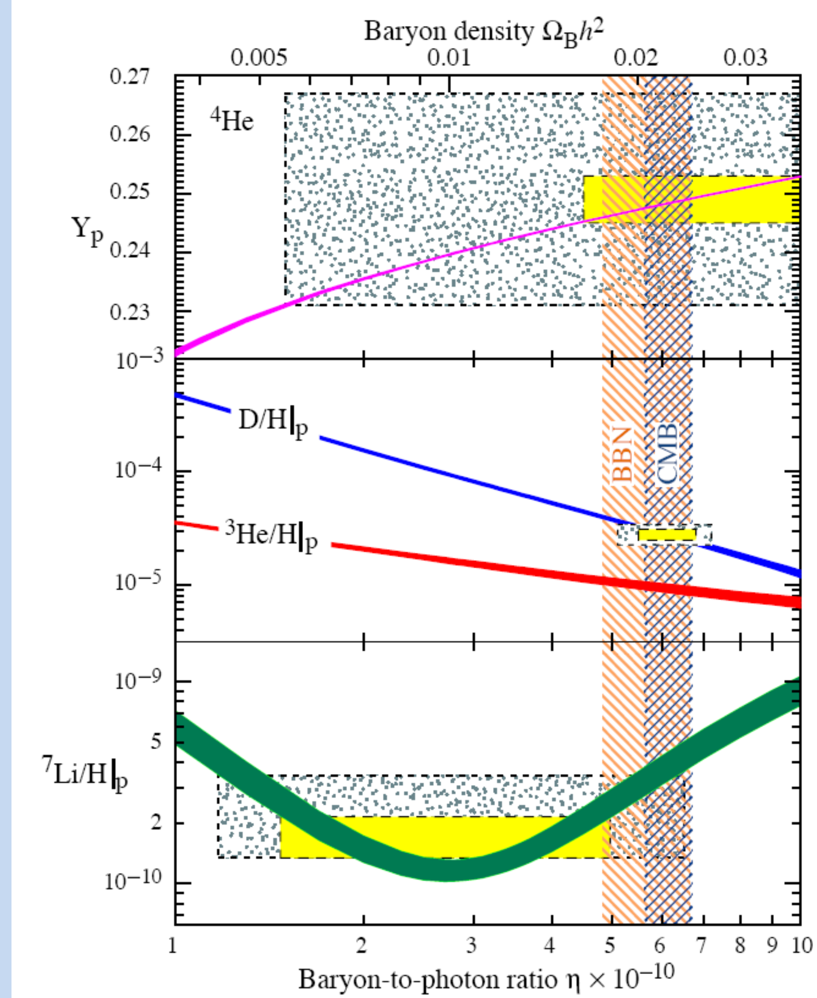
$$Li/H|_p = (1.7 \pm 0.02^{+1.1}_{-0}) \times 10^{-10}.$$

BBN theory predictions are in excellent agreement with the observational data, spanning 9 orders of magnitude!

Big Bang Nucleosynthesis

According to the Standard Big Bang Nucleosynthesis 4 light elements: D, He-3, He-4, Li-7 were produced during the early hot stage of the Universe evolution





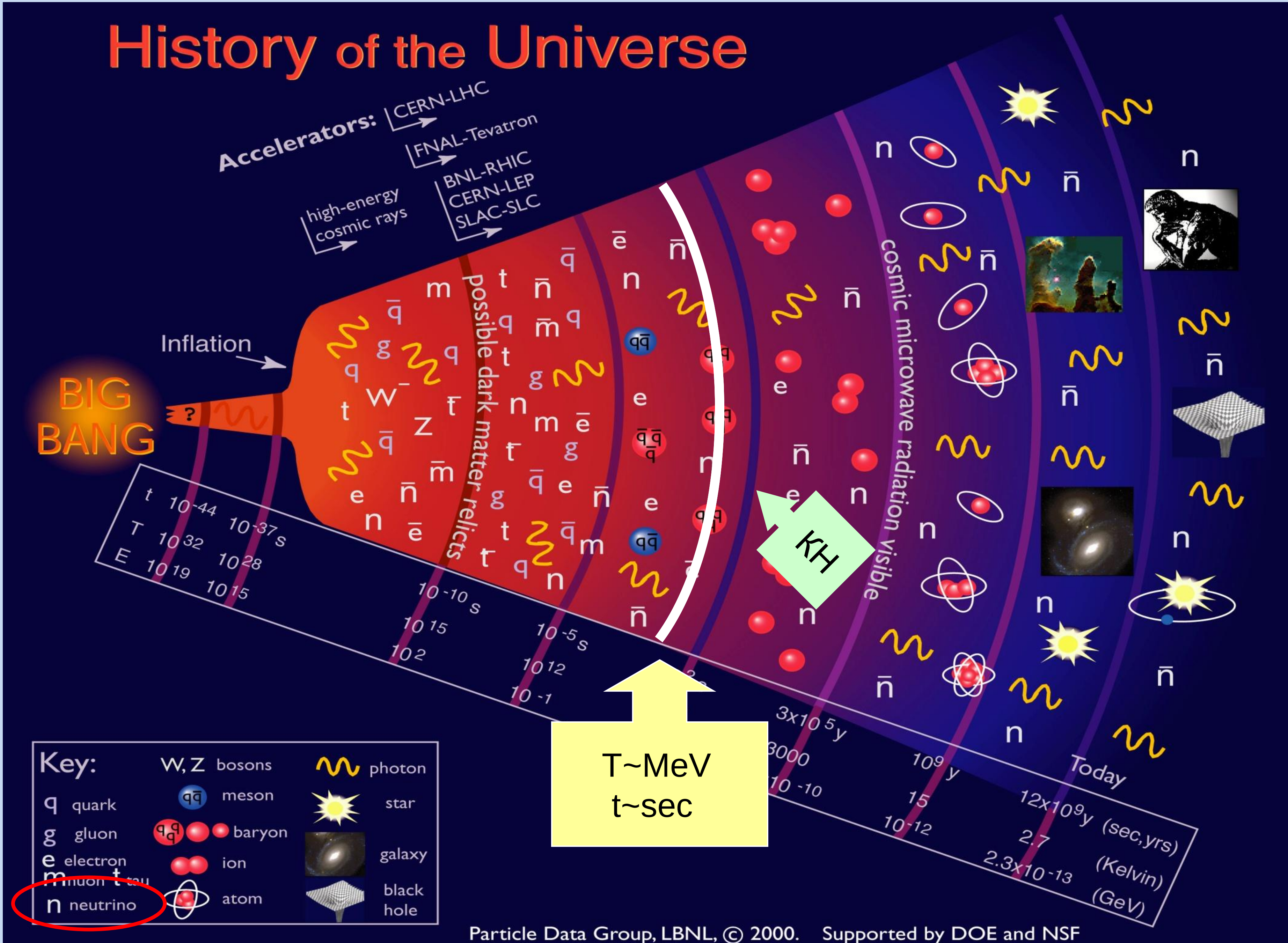
Observational data in yellow (2σ statistical error), bigger boxes (2σ statistical+systematic error). Vertical band give baryon density measured by CMB and BBN.

BBN predictions are in excellent agreement With observational data for $\Omega_B \sim 0.05$.

The primordially produced abundances of these elements are functions of only one parameter - the baryon-to-photon ratio η. (now determined by CMB anisotropy measurements)

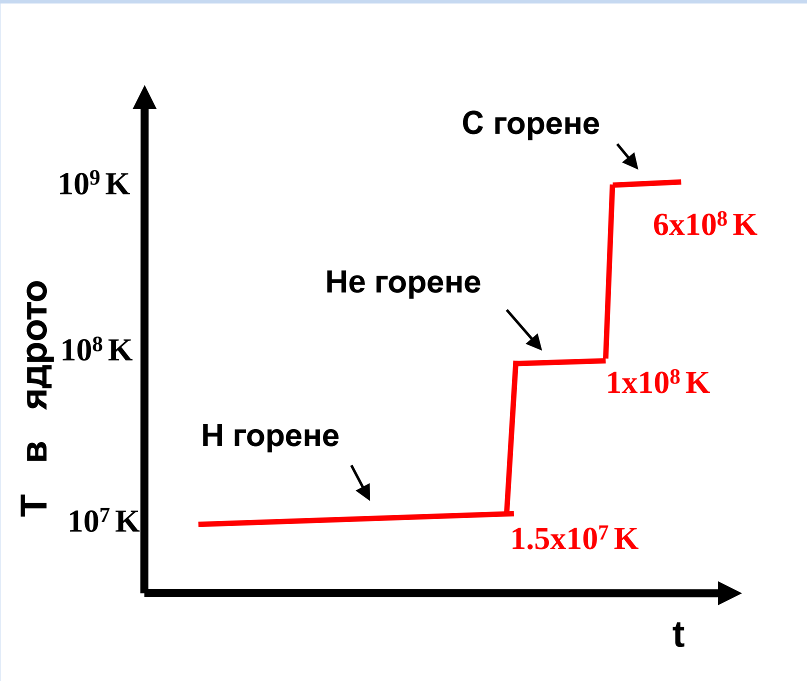
$$0.017 \leq \Omega_b h^2 \leq 0.024$$

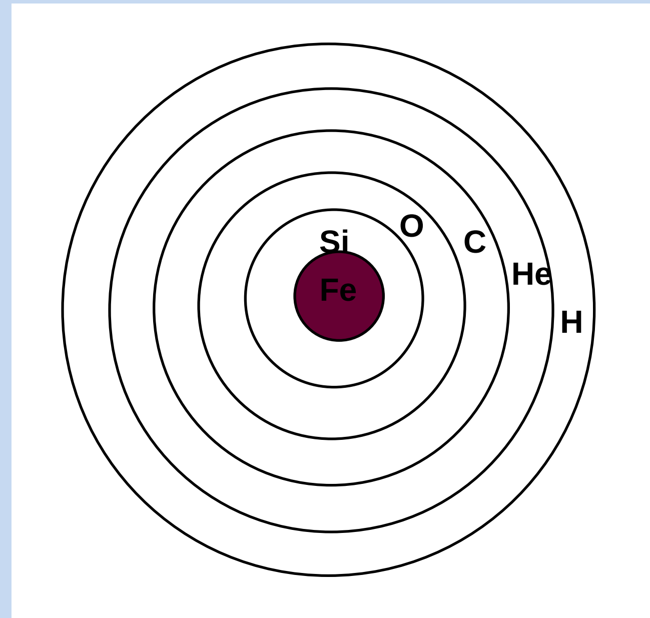
BBN is the most early and most precision probe for physical conditions in the early Universe, and for constraining new physics, relevant at BBN energies.


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

Stellar Nucleosynthesis of Heavy Elements

По-тежките от Li елементи са синтезирани в звездите. В масивните звезди H гори в He, C, O, Si и Fe. По-тежките от Fe елементи – при SN избухвания и в обвивките на свръх-гиганти.

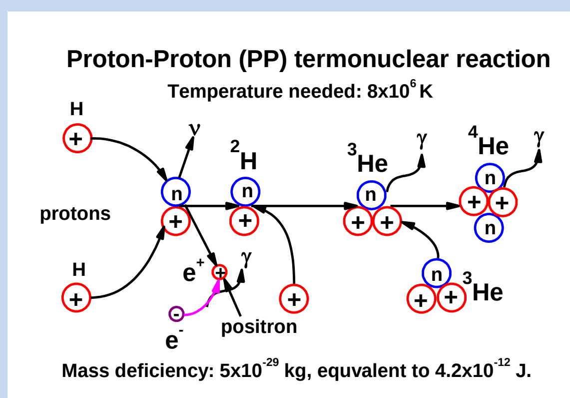


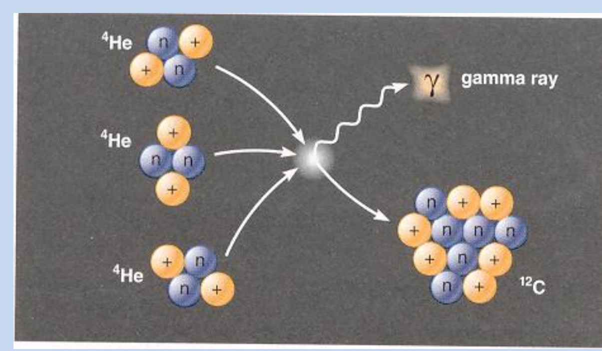


Отличия:

• pp – реакции
при синтез на He

• 3α процеси при синтез на C
т.е. голяма плътност
в отличие от условията в
 бързо изстиващата Вселена





BBN Constraints

BBN is the most early and most precision probe for physical conditions in the early Universe, and for constraining new physics, relevant at $T \sim 10^{10}$K

❖ The baryon density is measured with very high precision. Among light elements D is the best baryometer.

$$4.7 \leq \eta_{10} \leq 6.5 \ (95\% \ \mathrm{CL})$$

$$\Omega_b h^2 = 3.65 \times 10^7 \eta, \quad \Omega_b = \frac{\rho_b}{\rho_c}, \quad \rho_c = \frac{3H^2}{8\pi G_N}$$

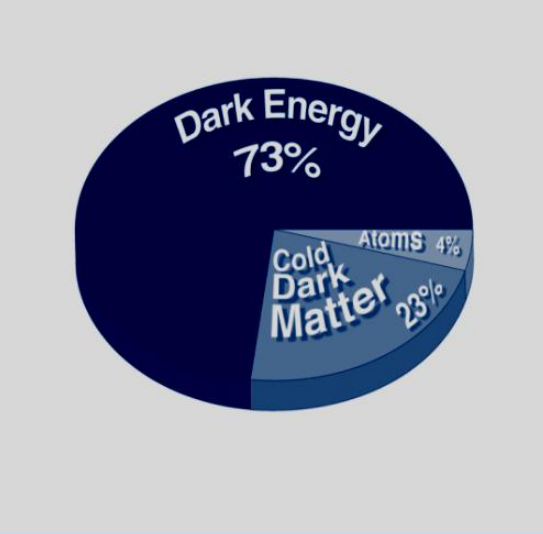
$$0.017 \leq \Omega_B h^2 \leq 0.024 \ (95\% \ \mathrm{CL})$$

BBN + D measurements
Towards quasars with big z
and low metalicity Z

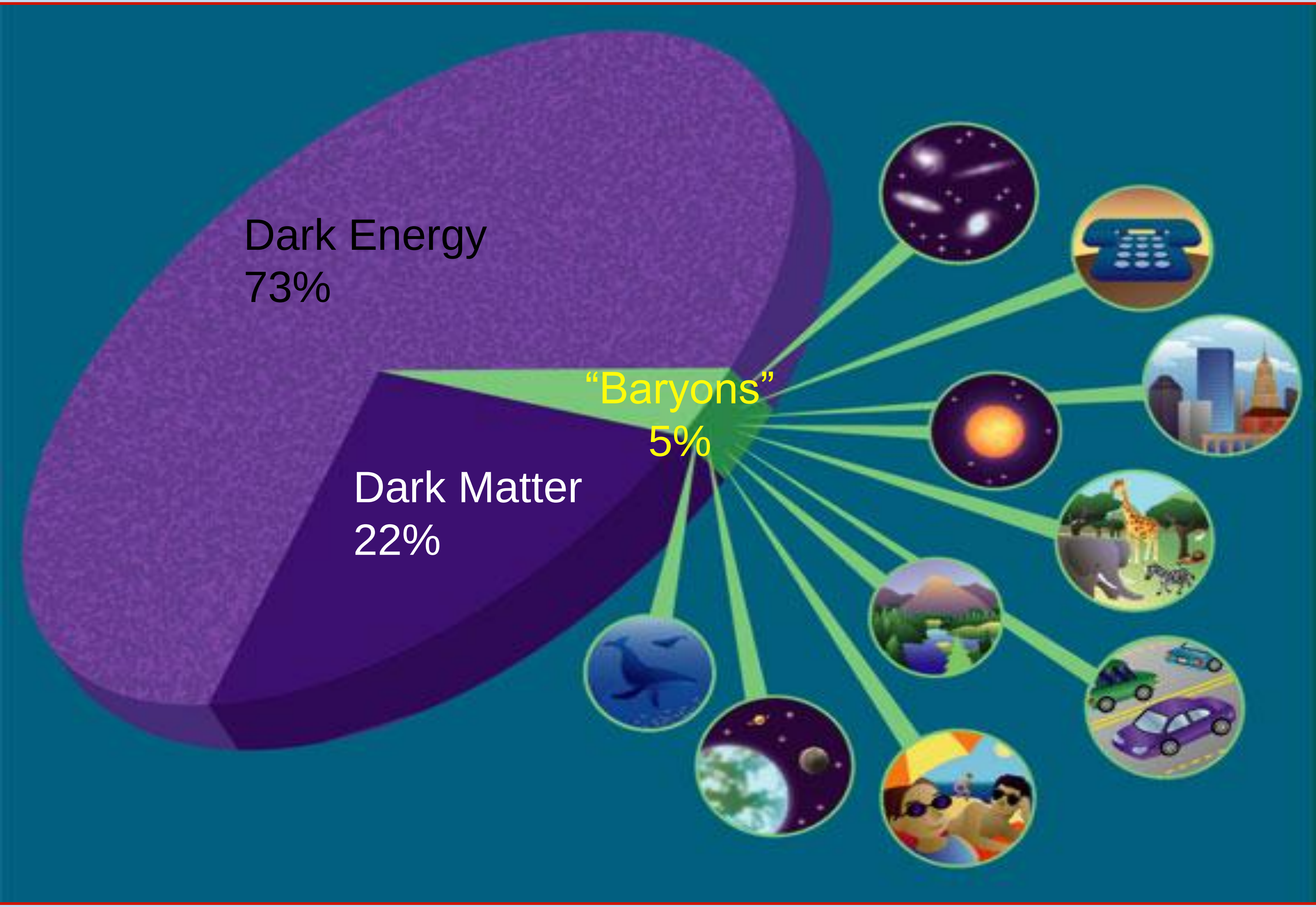
$$\Omega_b h^2 = 0.0216^{+0.0020}_{-0.0021}$$

CMB:

$$\Omega_b h^2 = 0.0223 \pm 0.0007$$

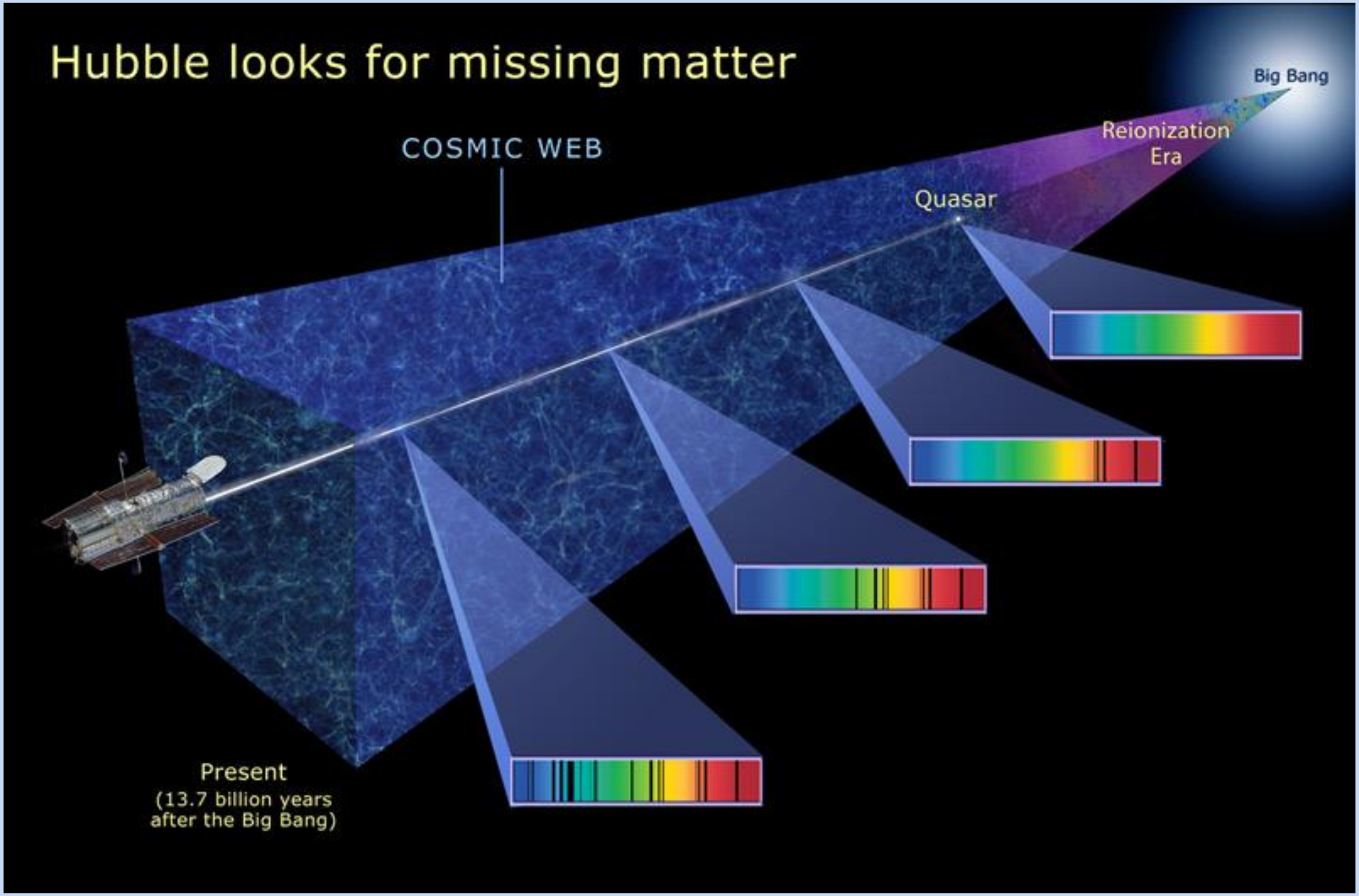


Baryons are not enough to close the Universe.
Most of the baryons are optically dark.



Baryonic matter building the planets, the stars , etc. is a negligible fraction <5% !

Half of the missing baryons are in the space between galaxies



In the spectra of the light from distant quasars (several billion ly away) the absorption lines of ordinary baryonic matter were found. The missing baryonic matter helps trace out the structure of intergalactic space, the "cosmic web."

C. Danforth & M. Shull, ApJ, 2008

The analysis of HST FUSE observations taken along sight-lines to 28 quasars represents how the intergalactic medium looks within 4 billion ly of Earth.

^{4}He – the preferred element

BBN - the most early and precision probe for physical conditions in the early Universe, and for constraining new physics, relevant at this E**.**

The most reliable and abundant data now available are for that element. He-4 is abundantly produced (25% by mass), precisely measured (3-5 % uncertainty) and calculated (0.1% uncertainty) and has simple post-BBN chemical evolution.

- Observed in HII low metalicity regions of dwarf galaxies
- Extrapolated towards zero metalicity

Y_p=0,2429$\pm$ 0,009 *Izotov, Thuan 2004*

Y_p=0,2472$\pm$ 0,0012 *Izotov, Thuan 2007 (93 spectra of 86 low-metalicity HII regions)*

Y_p=0,2491$\pm$ 0,0091 *Olive, Skillman 2004*

Y_p=0,2384$\pm$ 0,0025 *Peimbert et al 2002*

Y_p=0,2474$\pm$ 0,0028 *Peimbert, Luridiana. Peimbert 2007, new atomic data*

dispersion of detrerminations

$$Y_{\rm p} = 0.249 \pm 0.009.$$

Determinations indicate 3-5% uncertainty (systematic errors). *Sasselov, 95*

Possibly related with the evaluation of ionization level, stellar absorption, .. *Luridiana, 2002*

The primordial abundance Y_p, predicted from SBBN, is calculated with great precision: the theoretical uncertainty is less than 0.1% within a wide range of baryon density. Y_p=0,2482$\pm$ 0,0007

Fuse View of Primordial Helium

- As the universe evolves, density fluctuations in the intergalactic gas (H and He) grow into clumps and filaments under gravity's pull. The densest clumps form galaxies and quasars whose radiation reionizes the remaining intergalactic gas.
- 2001: Observations with NASA's Far Ultraviolet Spectroscopic Explorer (FUSE) reveal the structure of ionized helium that traces the lowest density regions of the intergalactic medium.

  First direct observations of primordially synthesised He.
- This helium gas left over from the big bang underlies the universe's structure at very early times. These FUSE observations confirm theoretical models of a web-like structure pervading all of the space between galaxies.

The FUSE observations were accomplished by collecting the light from a distant quasar, at 10 billion ly from Earth, for twenty days. Along the trajectory to Earth intervening clouds containing hot helium gas modified the quasar's light, He atoms absorb in the far-ultraviolet range of the spectrum. Simultaneous observations using NASA's Hubble Space Telescope showed the brightness of the quasar at longer ultraviolet wavelengths where the spectrum is unaffected by He.

By comparing the absorption caused by intergalactic hydrogen, which is visible in spectra from ground- based telescopes to the helium absorption seen with FUSE, astronomers are able to achieve a better understanding of the energy source of reionization.

Though more abundant, intergalactic H is less easily detected because it is so highly ionized. The FUSE comparison of helium to hydrogen absorption favors an energy source that is a mix of quasars powered by supermassive black holes and the light from newly formed stars.

^{4}He – the best speedometer

- T > 1 MeV

$$\nu_e + n \leftrightarrow p + e^-$$
$$e^+ + n \leftrightarrow p + \tilde{\nu}_e$$
$$n \rightarrow p + e^- + \tilde{\nu}$$

$$\frac{n}{p} \sim e^{-\frac{\Delta m}{T}}$$

$\Delta m = 1.293 MeV$

- T < 1 MeV

$$\Gamma \sim G_F^2 T^5 \qquad H \sim \sqrt{g_{eff} G} T^2 \qquad g_{eff} = \frac{11}{2} + \frac{7}{4} N_\nu = 10{,}75$$

$$T_f \sim \left(\frac{g_{eff} G}{G_F} \right)^{1/6} \sim 0{,}7 MeV \qquad \left(\frac{n}{p} \right)_f \sim e^{-\frac{\Delta m}{T_f}} \sim \frac{1}{6}$$

- T < 80 KeV

$$p + n \rightarrow D + \gamma \qquad D + D \rightarrow {}^4He + \gamma$$

$$(X_n)_f = \left(\frac{N_n}{N_{nuc}} \right)_f = \frac{\left(\frac{n}{p} \right)_f}{1 + \left(\frac{n}{p} \right)_f}$$

$$Y_p = 2 (X_n)_f e^{-\frac{t}{\tau_n}} \sim 0.24 \qquad \tau_n = 885{,}7 s$$

$Y_T = 0{,}2482 \pm 0{,}0007$ $\quad Y_O = 0{,}249 \pm 0{,}009$

BBN constraints

He-4 е най-обилно произведения елемент (25%), най-точно измерен (3-5 %) и пресметнат (0.1% неточност) и има проста еволюция след КН.

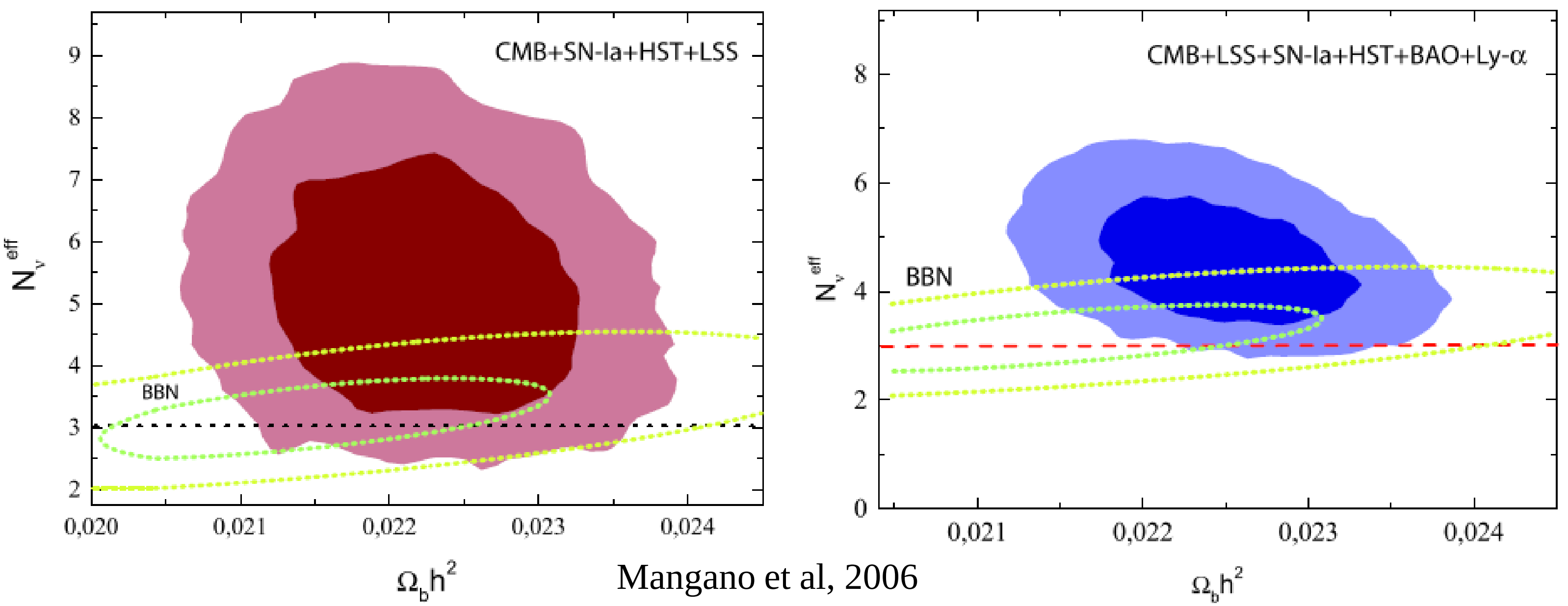
- BBN provides the stringest constraints on additional types of relativistic particles:

  $1.8 < N < 4.5$.

Having in mind LEP results confirming the number of neutrino families equal to 3, this constraints actually points to the possibility of existence of very weakly interacting particles.

WMAP +BBN:

$$5.66 < \eta_{10} < 6.58 \ (\Omega_B h^2 = 0.0226 \pm 0.0017) \text{ and } N_\nu = 3.24 \pm 1.2 \text{ at } 95\%$$



Mangano et al, 2006

BBN constraints

- **Constrains the effective number of relativistic species**

$$\rho_r = \rho_\gamma + \rho_\nu + \rho_x = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right] \rho_\gamma$$

$\delta Y_{KH} \sim 0.013\ \delta N_{eff}$

Non-zero ΔN_{eff} will indicate extra relativistic component, like sterile neutrino, neutrino oscillations, lepton asymmetry, neutrino decays, nonstandard thermal history, etc

$\Delta N_{eff} < 1\ (0.3)$

CMB $1 < N_{eff} < 8$

WMAP,ACBAR,CBI,BOOMERANG

- **Constrains lepton asymmetry**

$\Delta N_{eff} \sim 3$ (WMAP)

$\Delta N_{eff} \sim 0.2$ (Planck)

$$\Delta N_{eff} = 15/7[([\mu/T)/\pi]^4 + 2[(\mu/T)/\pi]^2\}$$

$\mu/T < 0.07$

BBN + LMA restricts chemical potential of all neutrino flavors

- **Constrains sterile neutrino decoupling** $T_R > 130$ MeV **production, right handed bosons**

$$\frac{\Gamma_R}{H} = \left(\frac{T_R}{T_L}\right)^3 \left(\frac{G_T}{G_F}\right)^2 \sim 1; \quad G_T \leq 10^{-2} G_F$$

- **Constrains neutrino magnetic moment** $\mu_\nu < 3\,10^{-10}\,\mu_B$

Constrains neutrino oscillations parameters BBN with $\nu \leftrightarrow \nu_s$ neutrino spectrum and densities differ, thus influencing kinetics of nucleons in BBN epoch, reducing weak processes rates overproducing He-4. The abundance of helium is known with 3% accuracy. This allows to constrain $\nu \leftrightarrow \nu_s$

Lepton asymmetry $L \neq 0$

$$L = \sum_{e,\mu,\tau} L_\ell \qquad L_\ell = \frac{N_{\nu_\ell} - N_{\bar\nu_\ell}}{N_\gamma} = \frac{1}{12\zeta(3)} \left(\frac{T_\nu}{T_\gamma}\right)^3 \left(\pi^2 \xi_\ell + \xi_\ell^3\right)$$

$$N_{\nu_e} = \frac{1}{2\pi^2} \int_0^\infty dp\, p^2\, n_{\nu_e}(p) \qquad n_{\nu_e}^{\bar{}}(p) = \left[\exp\left(\frac{E}{T_\nu} \pm \xi_\nu\right) + 1\right]^{-1}$$

$$\rho_{\nu_e} = \frac{1}{2\pi^2} \int dp\, p^2 E_{\nu_e}\, n_{\nu_e}(p) \qquad N_{\nu_{eff}} = 3 + \sum \frac{30}{7\pi^2}\left(\xi_\ell^2 + \xi_\ell^4/2\pi^2\right)$$

$\xi = \frac{\mu}{T} \neq 0 \Longrightarrow$ increase of number of massless ν species independent on sign ξ

$L_\nu \uparrow \quad \rho_\nu \uparrow \quad H \uparrow \quad T_F \uparrow \quad Y_p \uparrow$

Wagoner et al., 1967
Terasawa & Sato, 1988

- L effects the expansion rate

$$n/p = \exp\left[-\left(\frac{\Delta m}{T^F}\right) - \xi_{\nu_e}\right]$$

$\xi_{\nu_e} > 0 \quad \frac{n}{p} \downarrow \quad Y_p \downarrow \qquad |\xi_e| \leq 0.07$

$\xi_{\nu_e} < 0 \quad \frac{n}{p} \uparrow \quad Y_p \uparrow \qquad \xi_{\mu,\tau} < 1.5$

- L effects n-p kinetics due to change of neutrino distribution function

if $\xi_{\nu_{\mu,\tau}} \geq 9 \rightarrow$ earlier ν decoupling $\quad \frac{T_\nu}{T_\gamma} \downarrow \quad \rho_\nu \downarrow \quad H \downarrow \quad Y_p \downarrow$

Orito et al., a/0005446

- L effects ν decoupling

$L \uparrow \quad H \uparrow$ but enough Δt is necessary for LSS formation

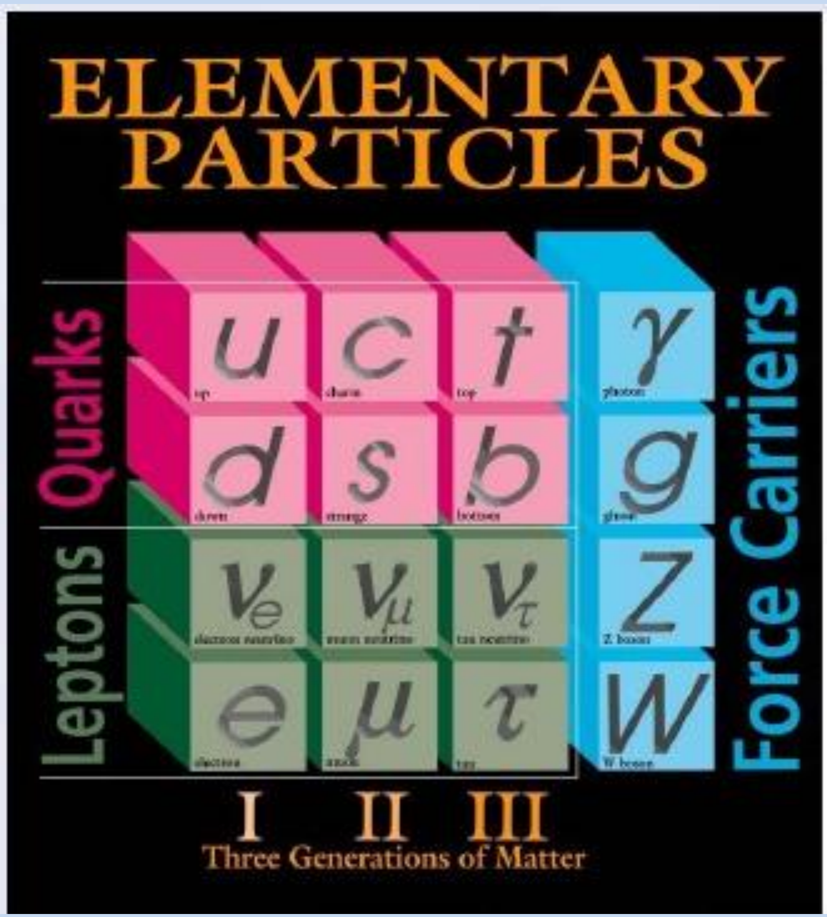
$-0.06 < \xi_e \leq 1.1 \qquad \xi_{\mu,\tau} \leq 6.9$

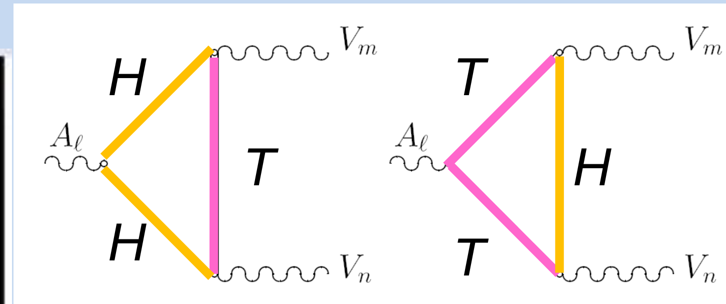
- L speeds up the expansion and affects structure formation

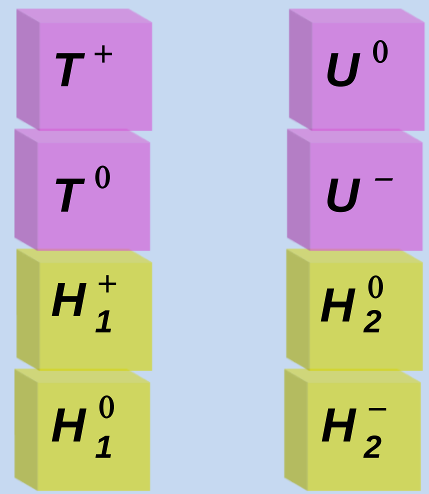

Chiral Bosons Search
at LHC

An example: Standard Model extension

M. C., Mod. Phys. Lett. A 8 (1993) 2753







$$\tan\beta \equiv \frac{\upsilon_2}{\upsilon_1} \sim \sqrt{2}$$

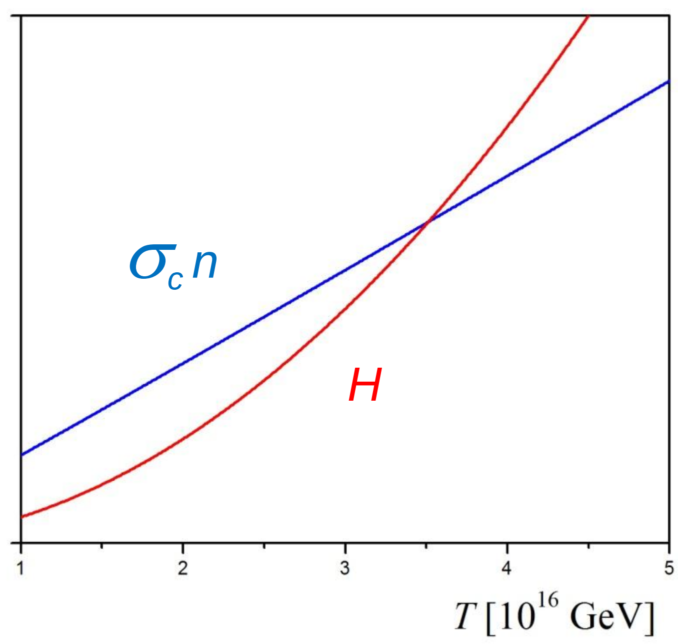
M_T ~ 1 TeV, M_U ~ 700 GeV

$$g_*^{new} = 106.75 + 4_T + 4_U + 4_{H_2} = 118.75$$

Process efficiency vs. expansion

$$\Gamma_{\text{int}} \equiv \sigma(T) \times n(T) \geq H(T) = \frac{1}{2t}, \text{ where } n_\nu(T) = \frac{3}{4}\frac{\zeta(3)}{\pi}T^3$$

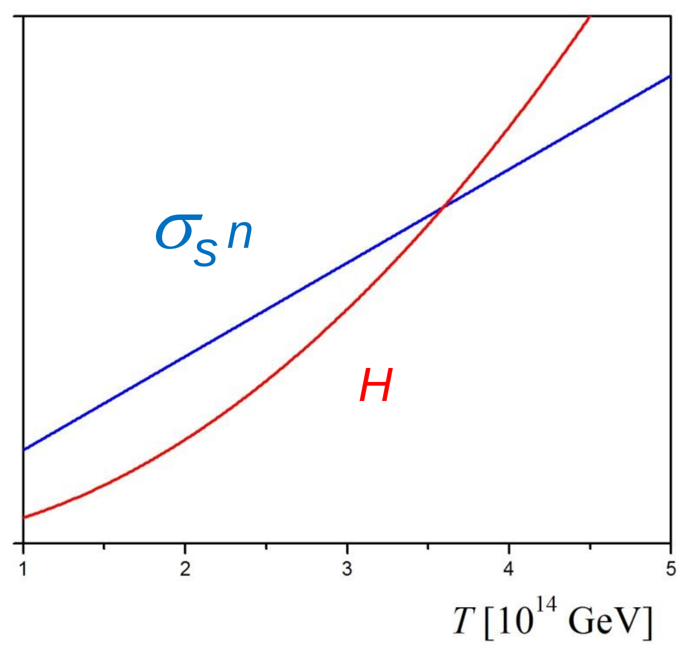
creation



$T_c = 3.5 \times 10^{16}$ GeV

$t_c = 1.8 \times 10^{-40}$ s

scattering



$T_s = 3.6 \times 10^{14}$ GeV

$t_s = 1.7 \times 10^{-36}$ s

Decay and annihilation of chiral tensor particles

$$\Gamma_d = \frac{\alpha}{\sin^2\theta_W} M \approx 17\ \text{GeV} \qquad T_d = 3.4\times 10^9\ \text{GeV}; \quad t_d = 1.9\times 10^{-26}\ \text{s}$$

end of the annihilation at $t_a = \dfrac{2.42\times 10^{-6}}{\sqrt{g_*}(2M)^2[\text{GeV}]} = 2.2\times 10^{-13}\ \text{s}$

as far as $t_d << t_a$ the tensor particles mainly decay

Conclusions: The provided analysis of the cosmological place of the chiral tensor particles showed, that

- cosmology allows the presence of tensor particles
- their direct interactions with the components of the high temperature plasma are effective for a short period $1.8\text{x}10^{-40}$ s < t < $1.9\text{x}10^{-26}$ s during the Universe evolution
- they increase the effective degrees of freedom and hence speed the expansion of the Universe during that period

Cosmological constraint on new coupling constant

- Constrains sterile neutrino decoupling, new coupling constant strength

From $\Delta N_\nu < 1$ at BBN epoch, and entropy conservation, we can calculate T_R decoupling of right-handed neutrino production:

$$\left(\frac{g_*(T_R)}{g_*(T_L)}\right)^{4/3} > 3; \quad g_*(T_R) > 2.28\times 10.75 = 24.5,$$

which corresponds to T_R > 130 MeV. On the other side T_R depends on G_T :

- (in case of 3 light right-handed neutrinos) $\frac{\Gamma_R}{H} = \left(\frac{T_R}{T_L}\right)^3 \left(\frac{G_T}{G_F}\right)^2 \sim 1; \quad G_T \le 10^{-2} G_F$

DK&Chizhov, 2009

Neutrino oscillations effects

❖ **Flavor Matter Oscillations** corresponding to the regions favored by the atmospheric and solar neutrino data establish an equilibrium between active neutrino species before BBN epoch. No considerable influence on BBN, CMB, CNB.

Account for flavour oscillations : 113 per cubic cm instead 112 in SCM.

❖ **Active-sterile oscillations** may have considerable cosmological influence!

✓ BBN with fast $\nu_a \leftrightarrow \nu_s$: $H \sim \sqrt{g_{eff} G} T^2$ increase $g_{eff} = 10.75 + \frac{7}{4}\delta N_s$ $\delta N_s = N_\nu - 3$

effective before ν_a decoupling - effect BBN and CMB

He-4 mass fraction is a strong function of the effective number of light stable particles at BBN epoch $\delta Y_d \sim 0.013\, \delta N_s$ (the best speedometer). δN_s

✓ BBN with $\nu_a \leftrightarrow \nu_s$ $\delta m^2 \sin^4 2\theta \leq 10^{-7}$ ν_e spectrum distortion

effective after ν_a decoupling and $\delta N_s<1$ BBN, CNB effect

Effect both expansion rate and the weak interactions rates, may distort ν_e energy spectrum, causing ν_e depletion, neutrino-antineutrino asymmetry generation and influences the neutrino involved processes in Universe, like BBN Kinetics, CMB, etc.

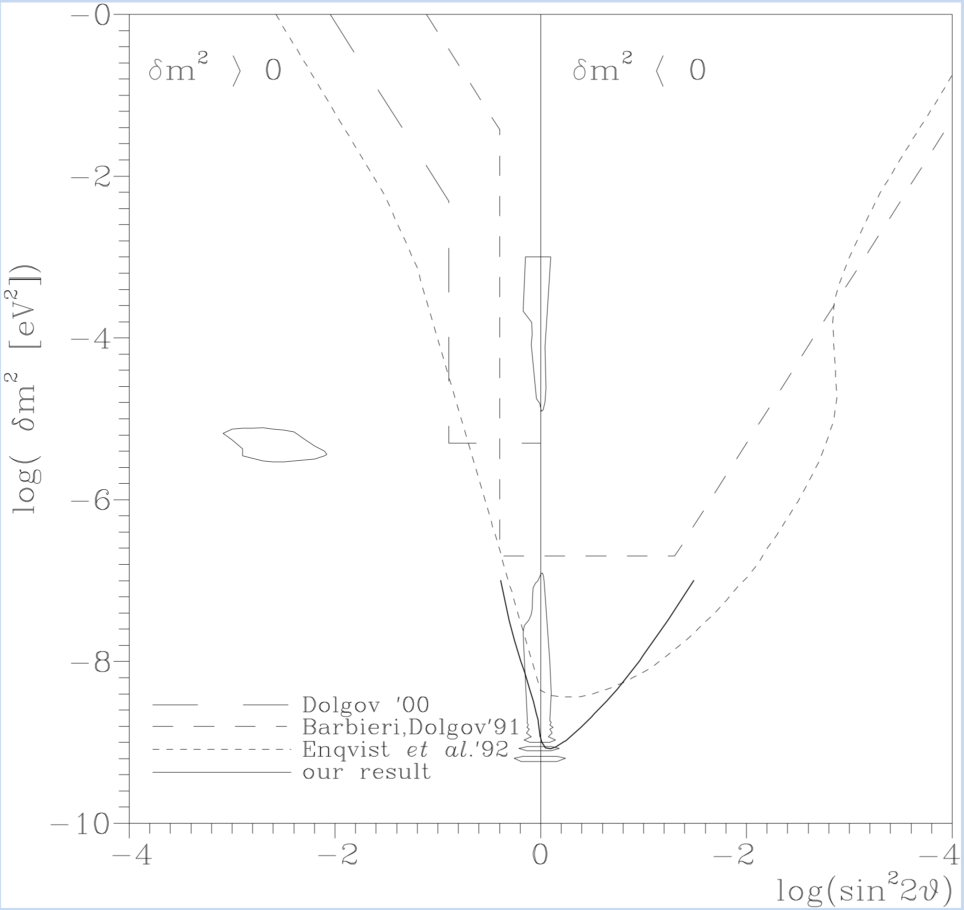
He-4 depends also on the ν_e characteristics $\Gamma \sim G_F^2 E_\nu^2 N_\nu$

decrease $\rightarrow$ n/p freezes earlier $\rightarrow$ ^{4}He is overproduced

Dolgov 81. DK 88, Barbieri, Dolgov 90, Kainulainen 91, Enqvist et al.,92, Foot&Volkas 95,96; D.K&Chizhov,96-98,2000-01, Dolgov&Villante 03; DK 04, DK&Panayotova 06, DK 07,08

BBN constraints on oscillations

BBN with neutrino oscillations between initially empty ν_s and ν_e



BBN constraints on $\nu_e \leftrightarrow \nu_s$:

Barbieri, Dolgov 91 – depletion account
Dolgov 2000 – dashed curve;
DK, Enqvist et al. 92 – one p approx.
Dolgov, Villante, 2003 - spectrum distortion

$\delta m^2 > 10^{-6}$ eV^2

$$\delta m_{es}^2 \sin^4 2\theta_{es} \leq 3.16\times10^{-5} eV^2 \left(\Delta N_\nu\right)^2$$

$$\delta m_{\mu s}^2 \sin^4 2\theta_{\mu s} \leq 1.74\times10^{-5} eV^2 \left(\Delta N_\nu\right)^2$$

$$\delta m^2 \sin^4 2\theta \leq 10^{-7}$$

DK.,Chizhov 2001 – distortion and asymmetry growth account

$$\delta m^2 \left(\sin^2 2\theta\right)^4 \leq 1.5\times10^{-9} eV^2 \quad \delta m^2 > 0$$

$$\delta m^2 < 8.2\times10^{-10} eV^2 \quad \text{large } \theta,\ \delta m^2 < 0$$

- ✓ BBN constraints are by 4 orders of magnitude more stringent than experimental ones
- ✓ Excluded 2 LMA and LOW active-sterile solutions (1990, 1999) years before experimental results.