Trends in High Energy Physics
12 June 2012, Primorsko

Cosmology

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Outline

Homogeneity, isotropy and structures of the Universe

Universe Dynamics: Theory and Observations
Friedmann Equations. Expansion Characteristics.

Early Universe theory and relics: CNB, BBN, CMB

Universe Puzzles

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

supported by the contemporary observational data

Modern cosmology landmarks:

1915 Einstein GTR

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)

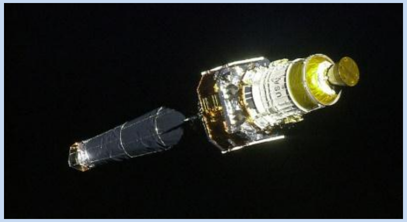
1992 Relikt and COBE found the CMB anisotropy

deep surveys CfA, IRAS, 2dF, SDSS, modern telescopes HST, X-ray, γ-ray, IR

1998 SN results pointed to accelerated expansion

2001 WMAP precision cosmological data

20?? - cosmology golden age: DM, DE, Baryogenesis, Inflation



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

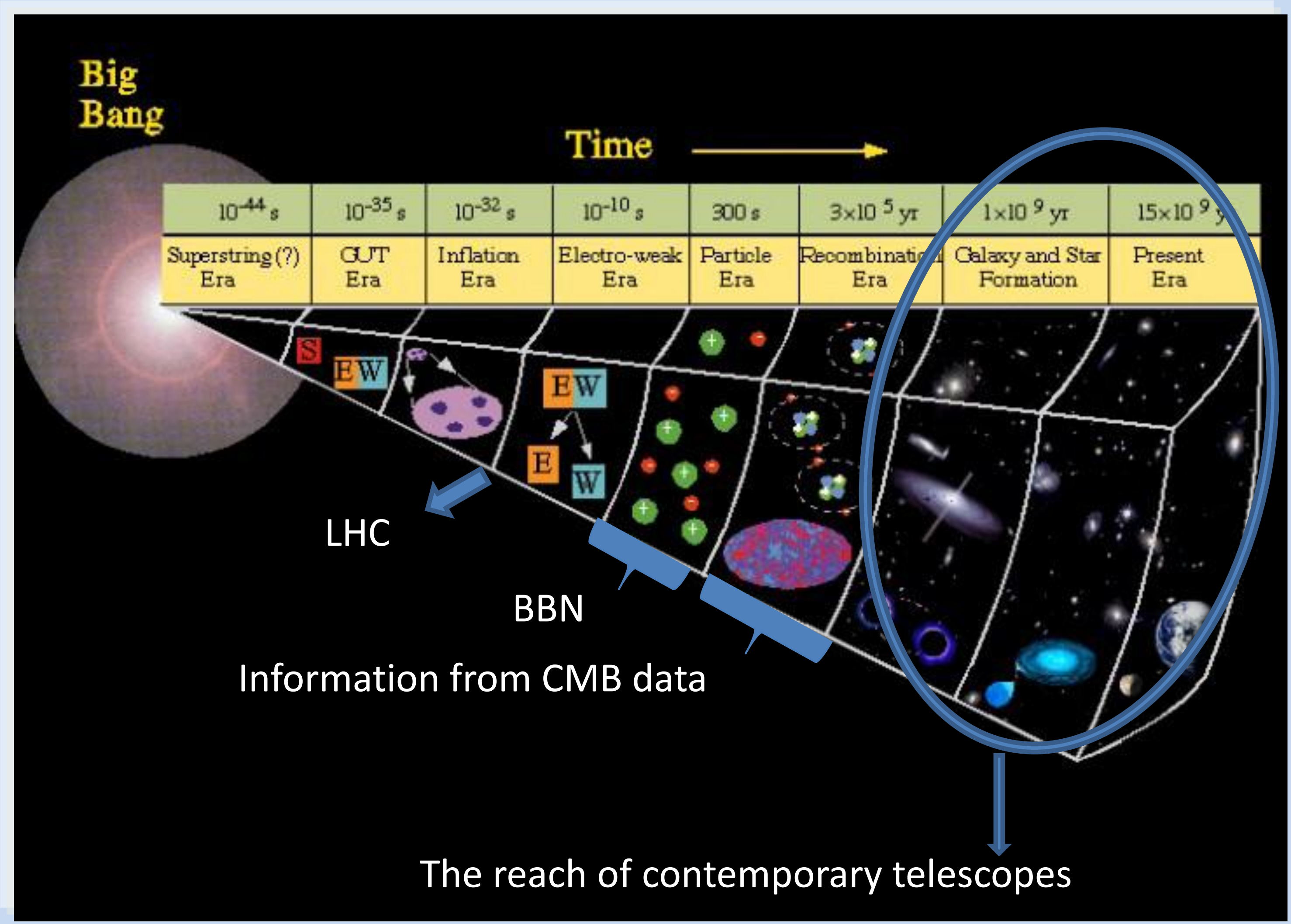
The telescope is a kind of a time machine; it lets us see our distant past.

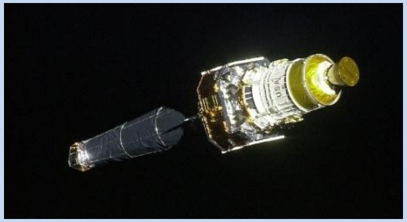
Radiation may come to us from epochs not earlier than CMB formation time . Before that the Universe was not transparent for radiation.

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

LHC – 10^{-12} *s*

Main information source – observations





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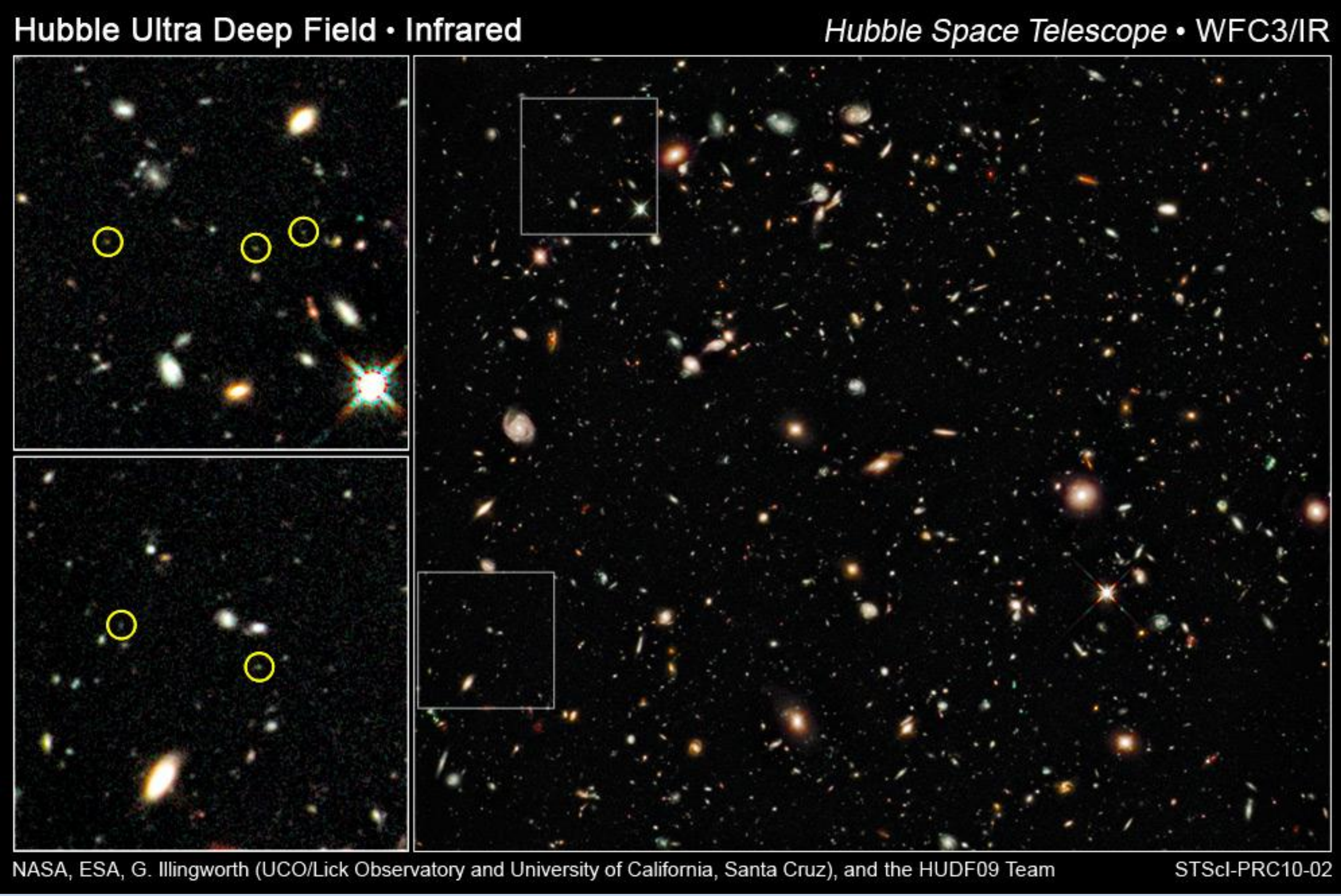
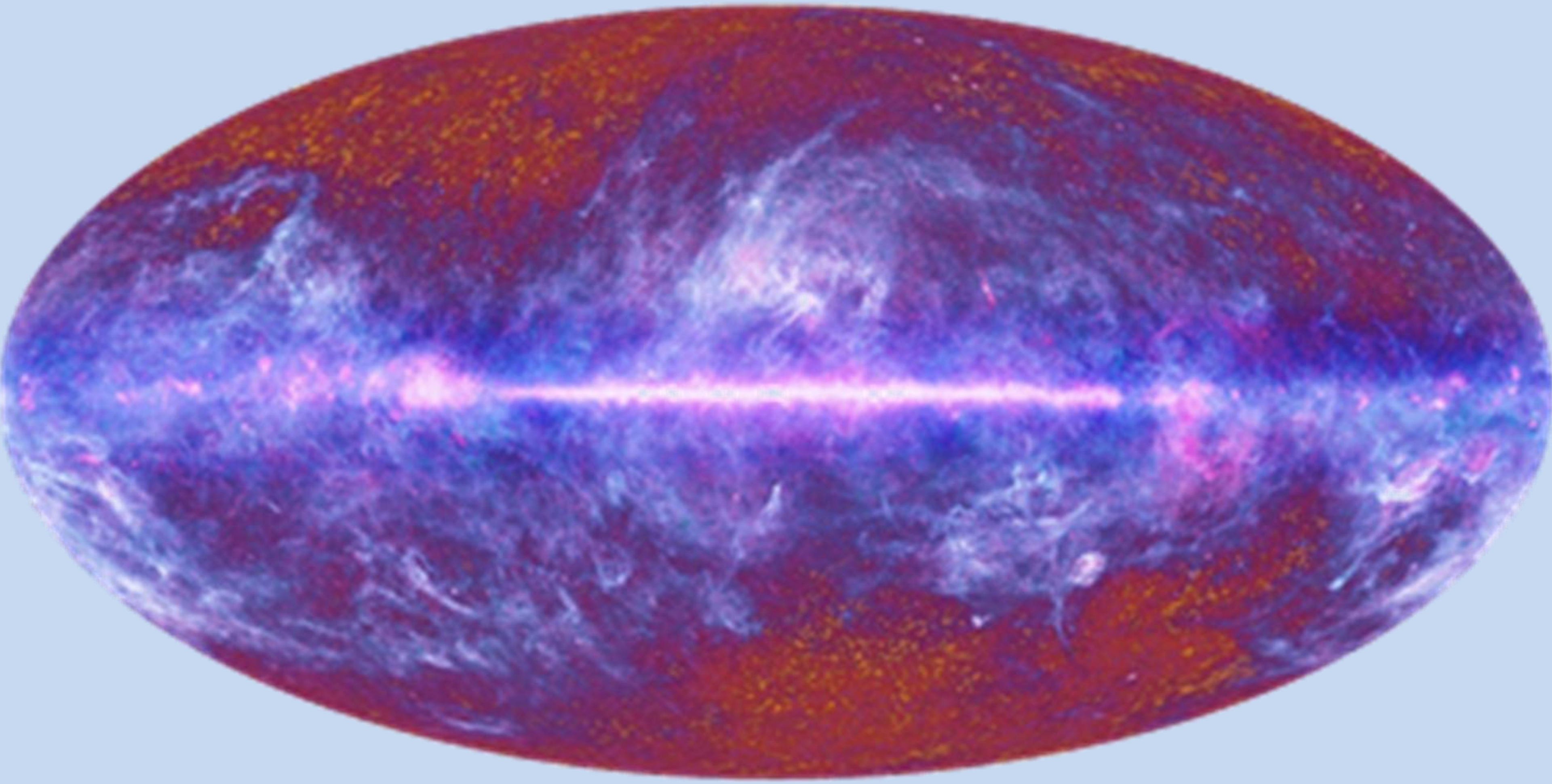


The ultra deep field the deepest image of the universe ever taken in near-infrared by Hubble Space Telescope.
The faintest and reddest objects are galaxies with “look-back times” 12.9 – 13.1 billion y - protogalaxies.

The furthest we can see…13.7 billion ly



View of a the entire night sky, by Planck 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 travelling 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) 10^{15} GeV

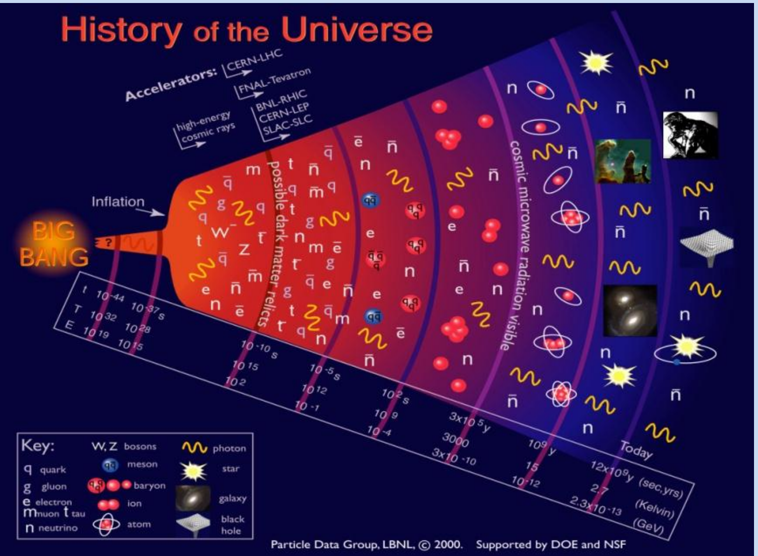
Generation of matter-antimatter asymmetry

Primordial Nucleosynthesis (first minutes).

CMB formation (380 000 years)

Galaxy formation (10^{9} years)

Today (~ 1.4 10^{10} y) 0.0003 eV



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

1 Mpc = 10^{6} pc

Cosmology studies the biggest scales.

Pecularities

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

Fascinating

Etc….

Because of the enormous extrapolations of the standard physics, surprises may be expected:

Beyond GTR? ***Beyond SM?***

Evolution of parameters?

Standard Cosmological Model

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

Homogeinity
+
Isotropy

General Relativity

Constituents

$p = w\rho$

Big Bang

Hubble expansion

CMB

BBN

Large Scale Structure

Observational Milestones of SCM

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

- 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.

LSS and Homogeneity and Isotropy of the Universe

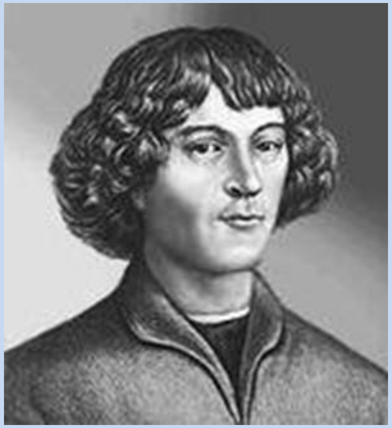
Our place in the Universe

Structures in the Universe

Homogeneity and Isotropy of the Universe:
observations in X, UV, I, visible and radio range

HI Scale

Our place in the Universe

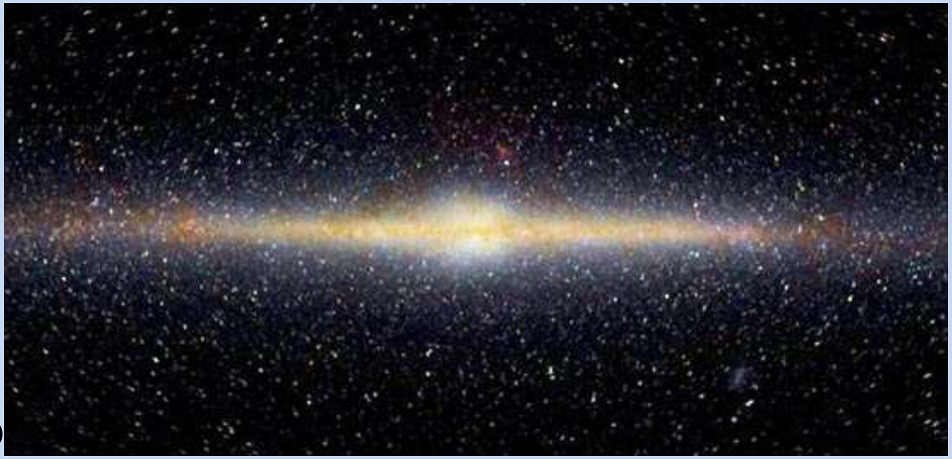


1543 *On the Revolutions of the Celestial Spheres*

The Earth is not the center of the Universe!

Copernicus rediscovered after18 centuries the heliocentric system.

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) .



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 extragalactic.

W. Baade: resolve stars in M31 center

MW is a typical galaxy.

MW is within a group of galaxies Local Group

MW is not the center of LG.

LG is close to Virgo cluster, not its center.

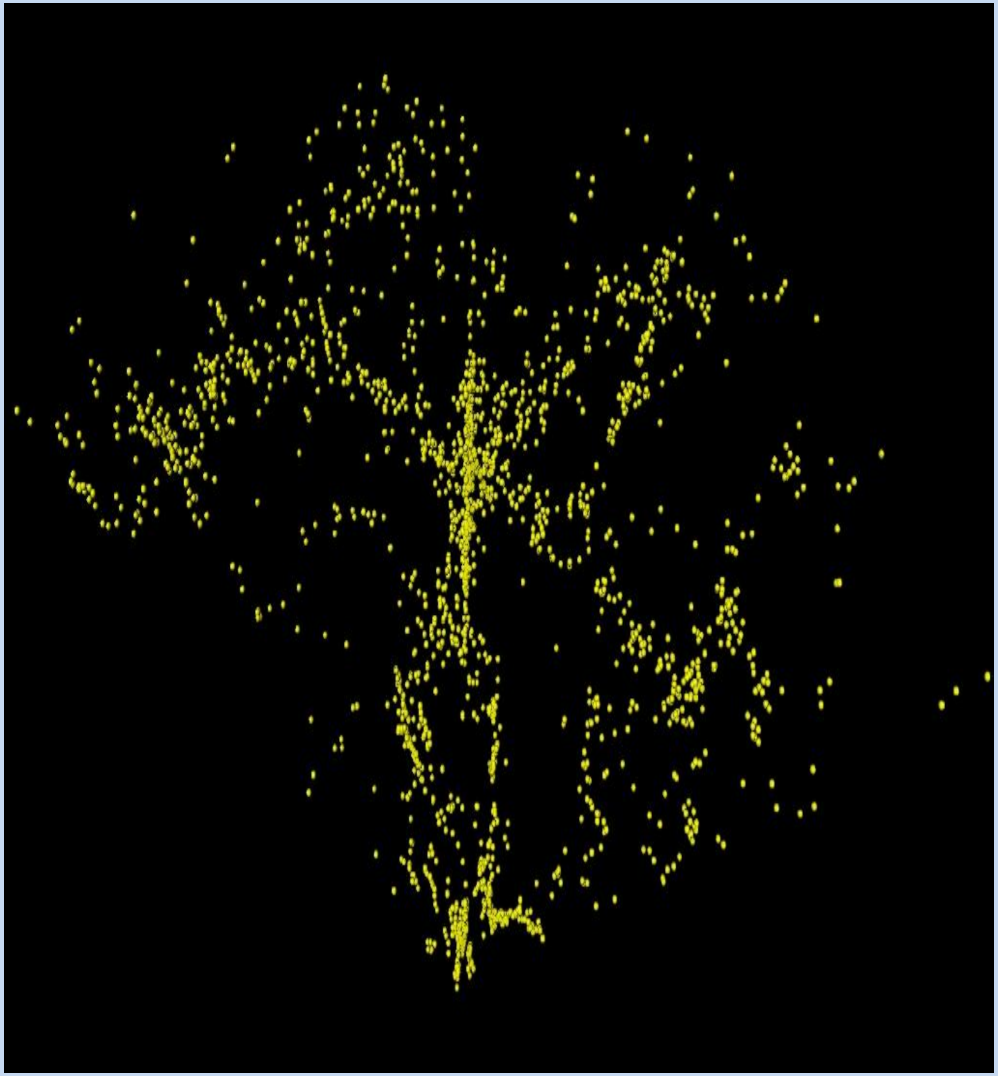
Clusters are grouped into superclusters of galaxies

LG belongs to Virgo SC, not in its center.

At larger scales, galaxy associations form sheets and fillaments, surrounded by immense voids.

Above this scale, the universe appears isotropic and homogeneous. NO center!

LSS of the Universe

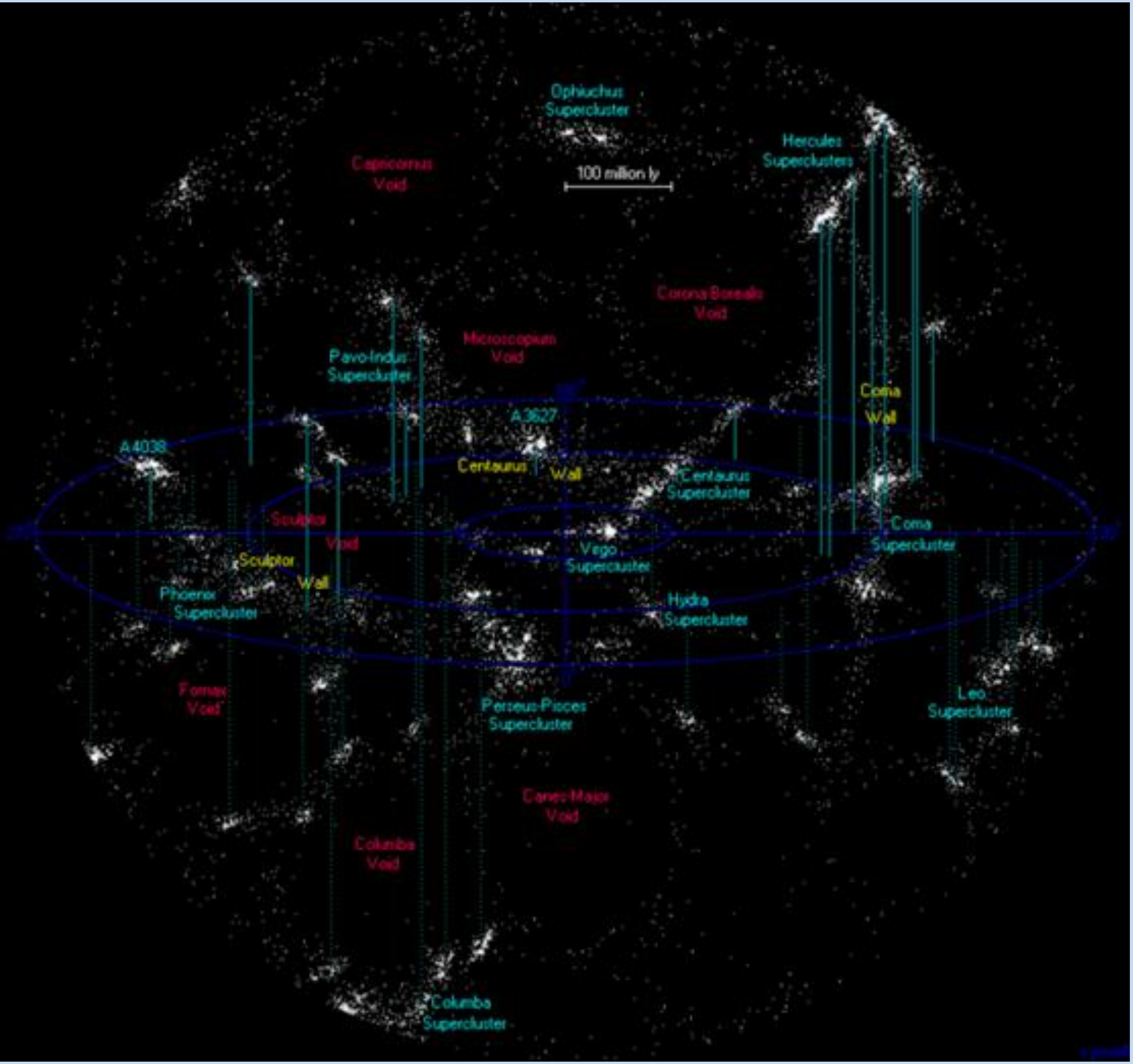


Clusters are grouped into superclusters of galaxies, joined by filaments and walls of galaxies. In b/n lie large voids, deprived of galaxies, almost 50 Mpc across.
The superclusters and voids are the largest structures in the Universe.

On a scale ~100 Mpc
a 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]

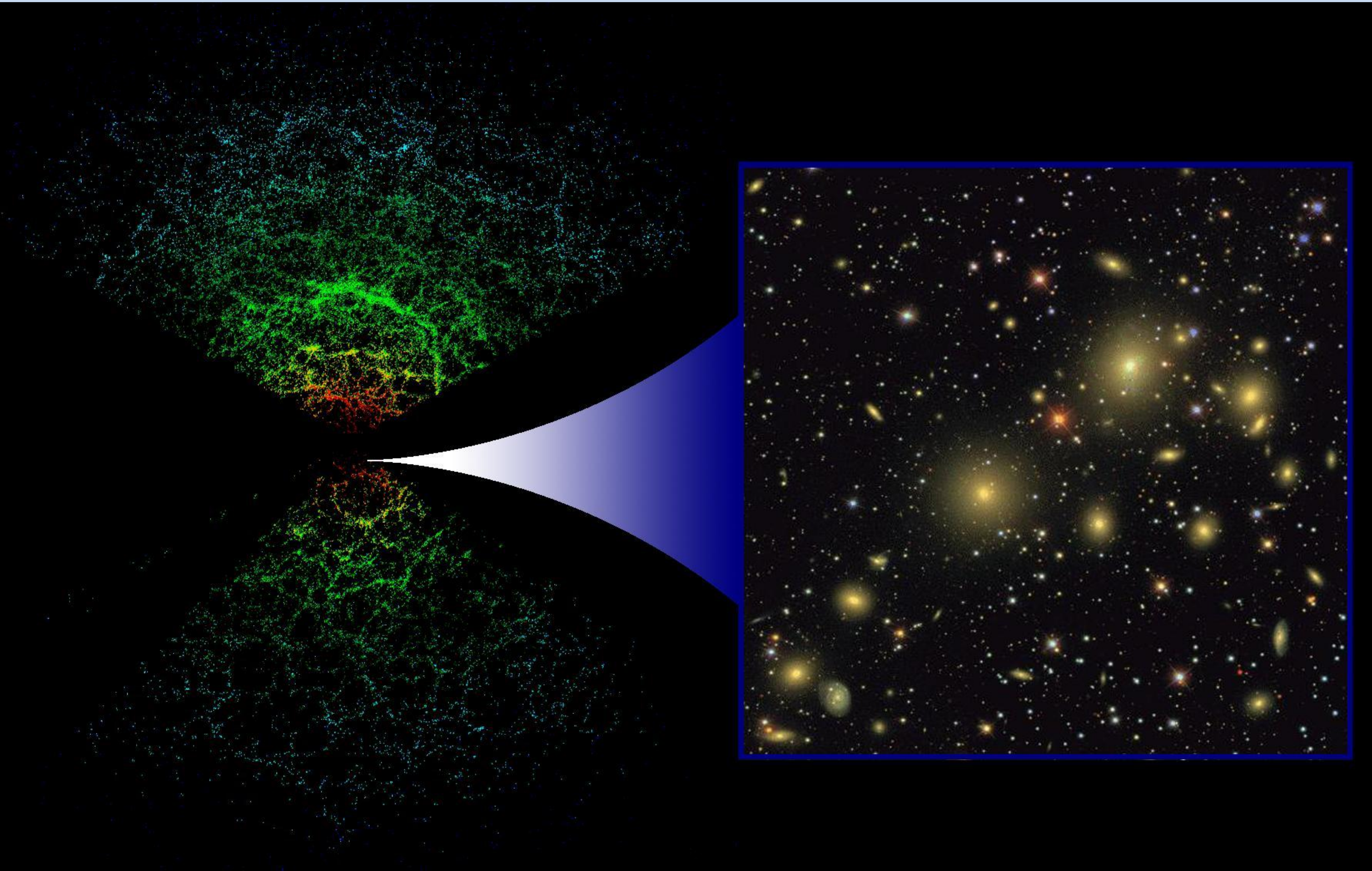


Nearest Superclusters

A map of the universe within 500 million ly. The superclusters are not isolated in space but together with other smaller concentrations of galaxies they form parts of extensive walls of galaxies surrounding large voids. Three of the biggest walls near us are marked on the map as well as several of the largest voids. There are several hundred thousand large galaxies within 500 million ly, so even on this scale our galaxy is a very insignificant object.

http://www.atlasoftheuniverse.com/nearsc.html

The SDSS (Slone Digital Sky Survey**) studies > ¼ of the sky, millions galaxies and quasars.**
SDSS 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 represents the luminosity. Only 66,976 out of 205,443 galaxies in the map that lie near the plane of Earth's equator are shown.



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.

Sloan Digital Sky Survey

SDSS is the most ambitious astronomical survey ever undertaken. Over eight years of operation (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.

HE of the Universe

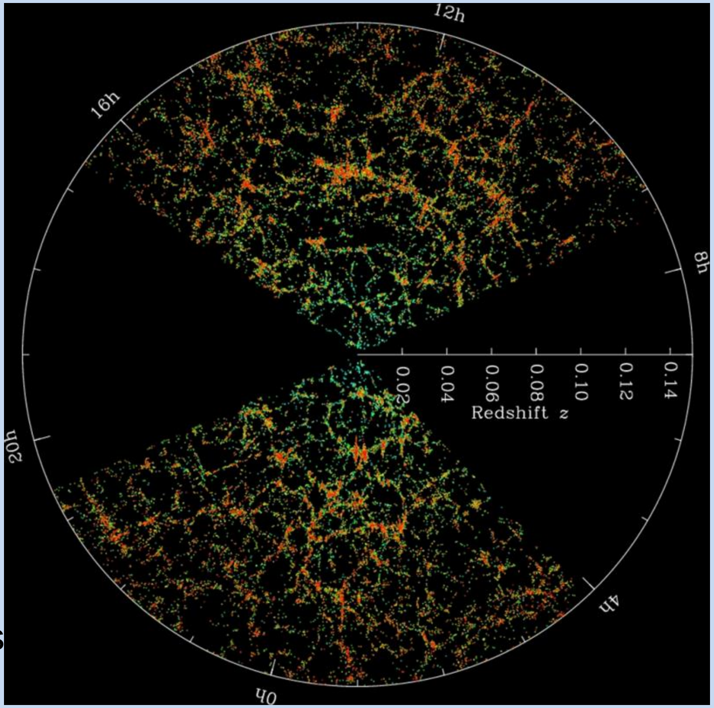
The Universe is inhomogeneous at galaxy scales.

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 !

Galaxy groups occupy a typical volume of a few cubic Mpc.
The Universe is inhomogenious at scale of galaxy groups.
galaxy clusters and superclusters.

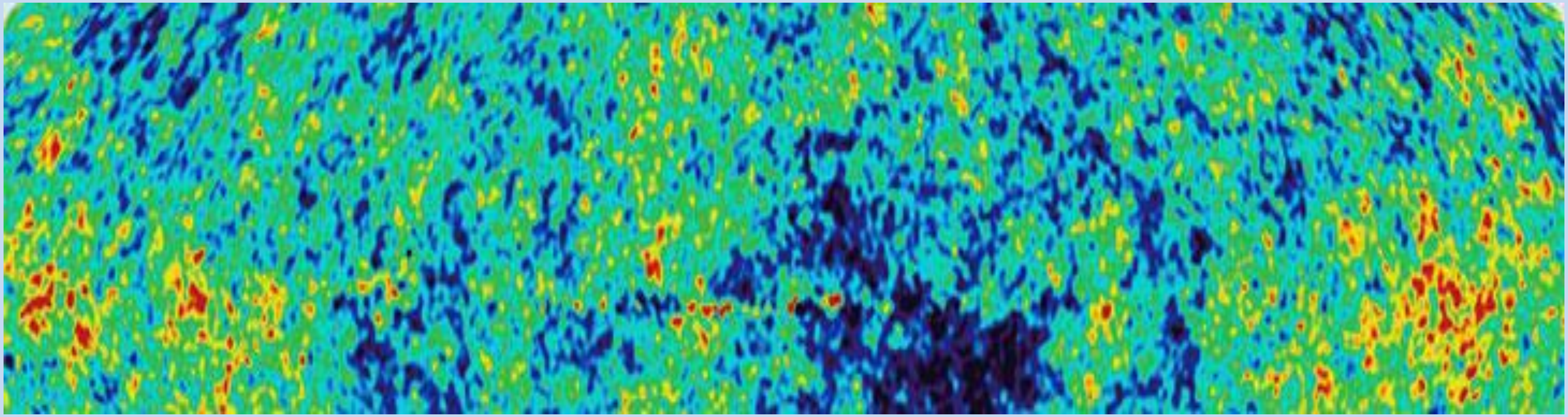
Clusters of galaxies are the largest gravitationally-collapsed objects., comprising thousands of galaxies, d~ 10 Mpc. Superclusters contain tens of thousands of galaxies, d~ 50 Mpc.

Slices through the SDSS :
3-d map distribution of galaxies



At scales > 200 Mpc the Universe appears smooth.

Isotropy to 1 part in 100 000…13.7 billion years ago

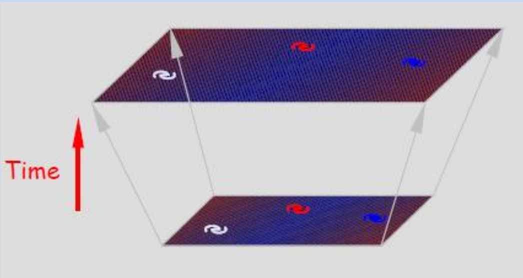


Very wide-angle view of almost the entire night sky, by NASA's WMAP satellite.

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.

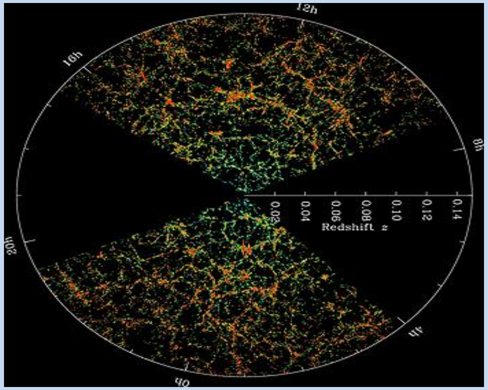
CMB, the remnant heat from the Big Bang, has a temperature which is highly uniform over the entire sky. This fact strongly supports the notion that the gas which emitted this radiation long ago was very uniformly distributed.

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 200 Mpc the Universe begin to appear smooth.

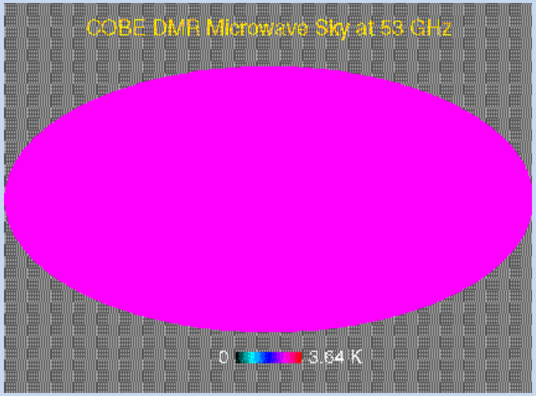
✓CMB observations:

RELIKT, COBE, WMAP, Planck and other CMB explorers

have found extremely high isotropy,

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

Universe 380 000 y old



CP is confirmed by observations.

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.

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 HI 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

cosmological redshift of light

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

Cosmology is easy
because the Universe looks the same everywhere.

The smooth Universe is described by finite number of parameters like:

$$H(t),\ \ k,\ \ \rho(t),\ \ \Lambda,\ T(t),$$

Friedman Robertson-Walker Universe

Universe Dynamics

Theoretical Milestones

Dynamics is provided by General Relativity

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

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.

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

Solutions in case of special symmetries:

- 1917 Einstein solution

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

Einstein cosmological model:

static Universe, GTR modified with a "cosmological constant"

- 1917 de Sitter model of empty (vacuum) Universe
- 1922-1924 Friedmann mathematical models of nonstationary Universe (closed, open)

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 $T_{\mu\ ;\nu}^{\ \nu} = 0$ ⇒ $\dot\rho = -3H(\rho + p)$

⇒ $\rho \propto R^{-3(1+w)}$

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

The expansion of the perfect fluid is isoentropic dS=0.

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

- Contemporary Physics, Astrophysics, Thermodynamics, Quantum Field Theory

Gamow, Lemaitre, Piebles, Zeldovich, Novikov, Dolgov, Linde, Turner, Kolb ....

Theoretical Basis

- Friedman equations   Non-stationary Universe

rate of expansion

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

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

Space curvature k depends on the energy density.

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

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

NB: not only energy, but also pressure contributes to the gravitational force.

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

$\Omega < 1$	$\kappa < 0.$
$\Omega = 1$	$\kappa = 0.$
$\Omega > 1$	$\kappa > 0.$

The density defines the geometry.

$p < -1/3\rho$ leads to anti-gravity and accelerated expansion.

6 atoms H/ m^{-3}

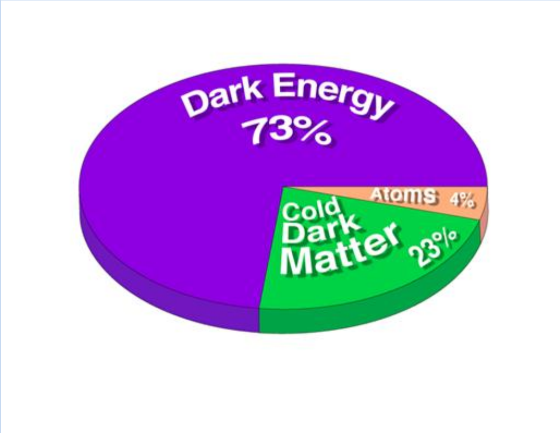
$$\rho_C \equiv 3H_0^2 / 8\pi G = 1.88 \times 10^{-26} h^2 \text{ kg m}^{-3}$$

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

Theoretical Basis

Universe Matter Content:

Current observations point to at least four components: radiation, baryonic matter dark matter, dark energy.



$p_R = \rho_R/3$	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	$w = -1$	$\rho_V \sim R^{0}$

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

Universe Matter Content

Current observations point to at least four components:

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

Radiation (relativistic degrees of freedom) ~0.002%

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

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% $\Omega_b h^2 = 0.022 \pm 0.001$

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

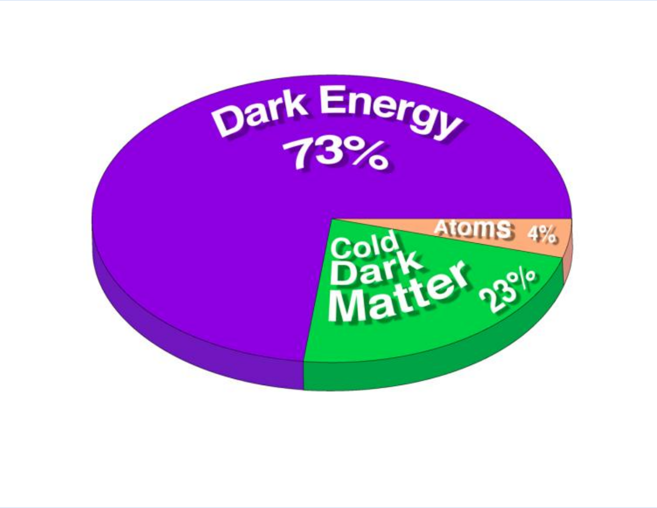
Was not directly detected yet, but should be there.

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)

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

Theoretical Basis

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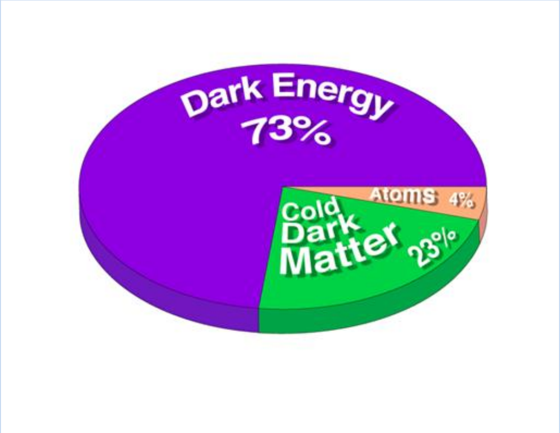

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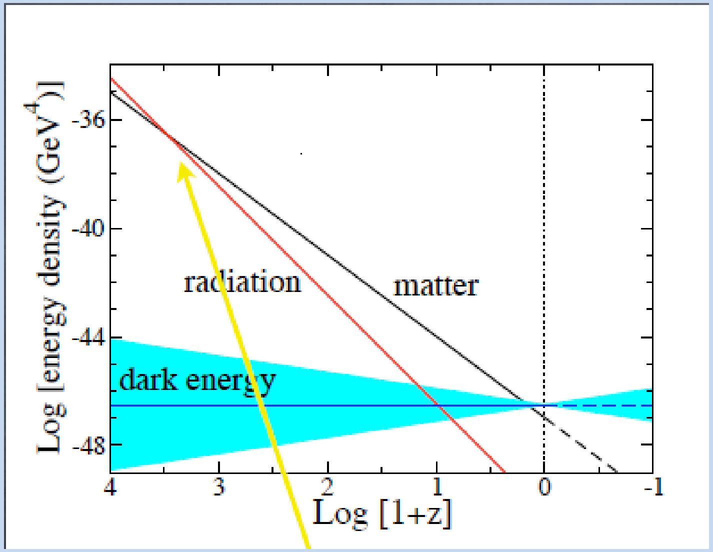
$w = -0.967^{+0.073}_{-0.072}$



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 .

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

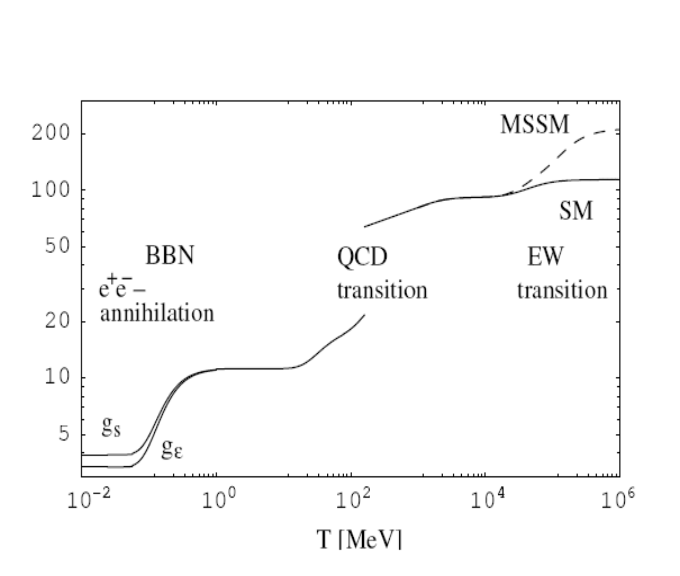
Relation between the scale factor and temperature in an expanding Universe : R(t)~1/T

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

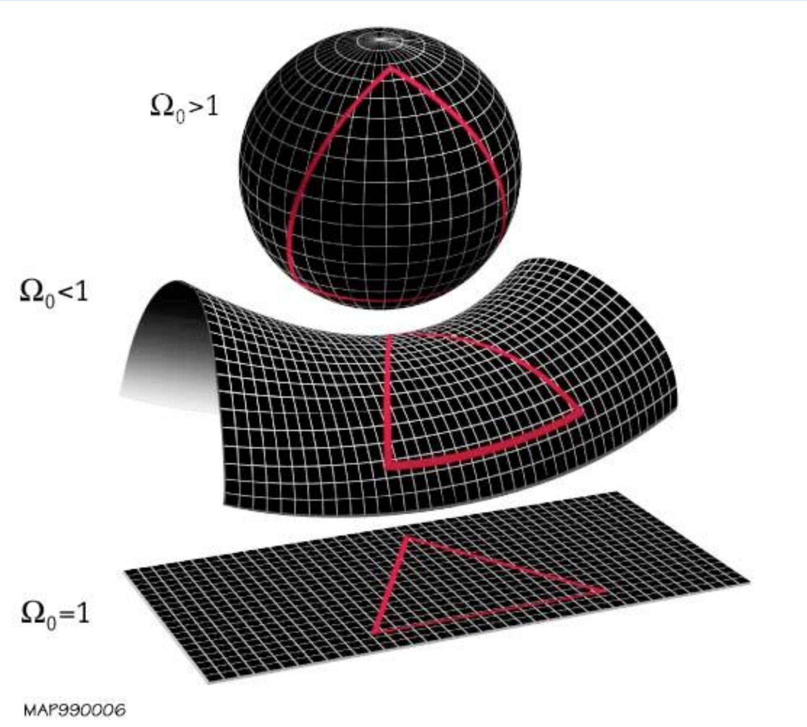
The Friedmann equation can be interpreted within Newtonian mechanics. It takes the form of energy conservation for test particles bounded in the gravitational potential created by mass

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

k=1 corresponds to negative binding energy, recollaps 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.

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

Possible scenarios:

Λ is zero: the geometry and Universe fate are connected:

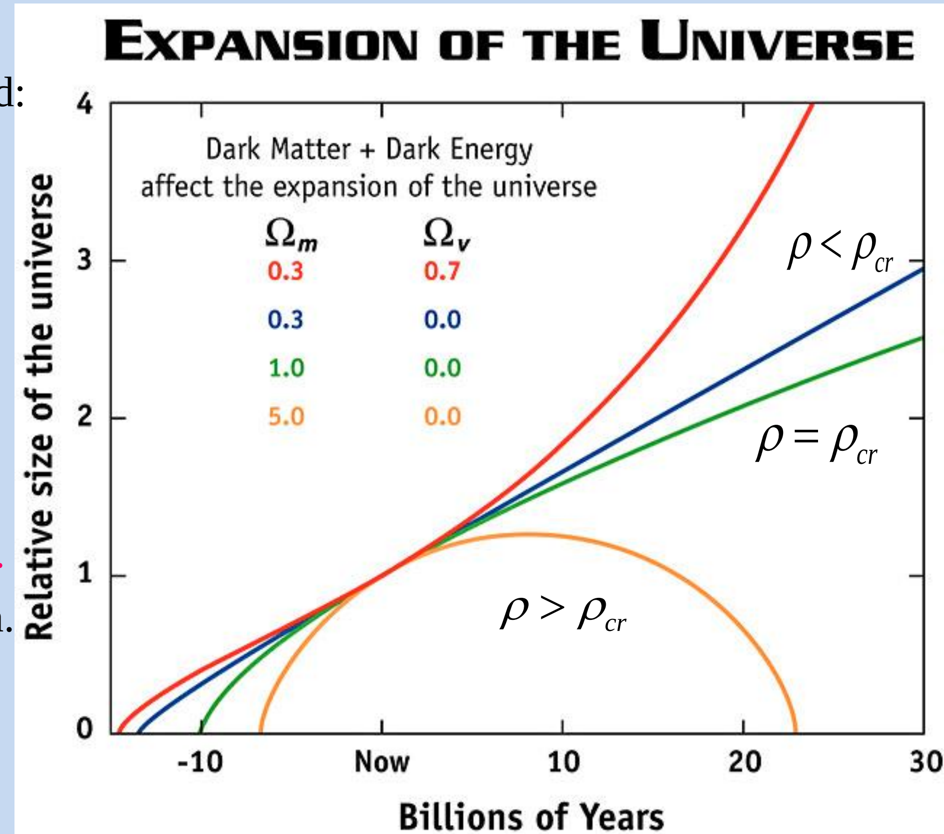
Orange – closed, overcritical density, will collapse

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.

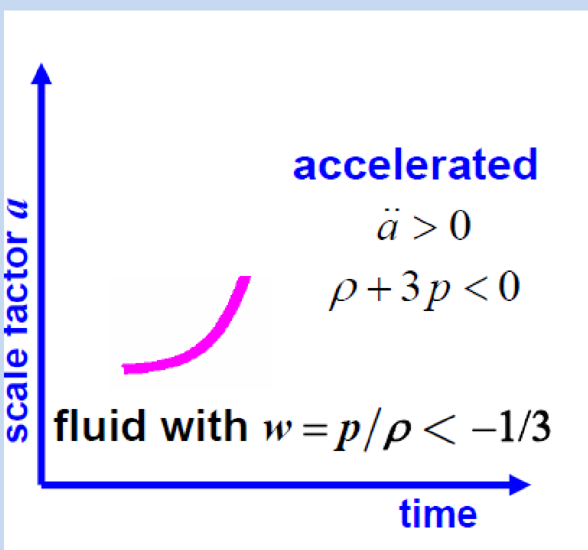
Λ is non zero:

red - a universe with a large fraction of matter in a form of dark energy, causing an accelerated expansion .



If Λ<0 the Universe will collapse independent of k sign.

For Λ> Λs even a closed Universe will expand forever.



Observations: accelerated expansion.

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

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→∞

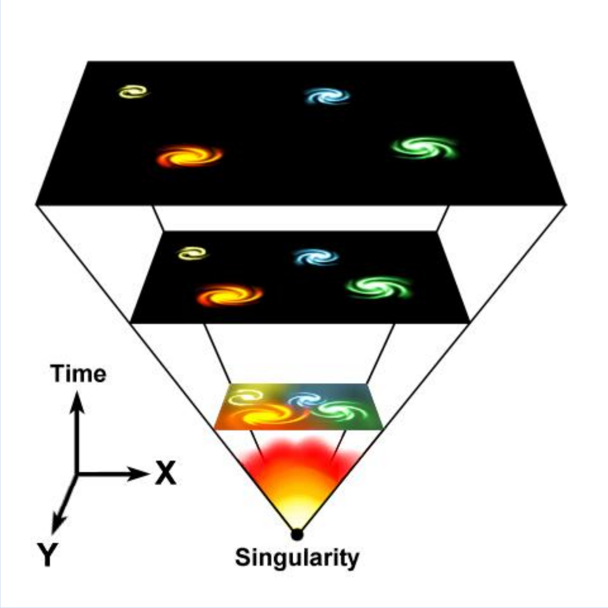
SCM predicts relic microwave background

from the early hot stage – CMB detected !

The future fate of the Universe depends on Λ:

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

The Universe now shows accelerating expansion.



The Big Bang

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.

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

Expansion of the Universe

Observations:

Today’s Universe has accelerated expansion.

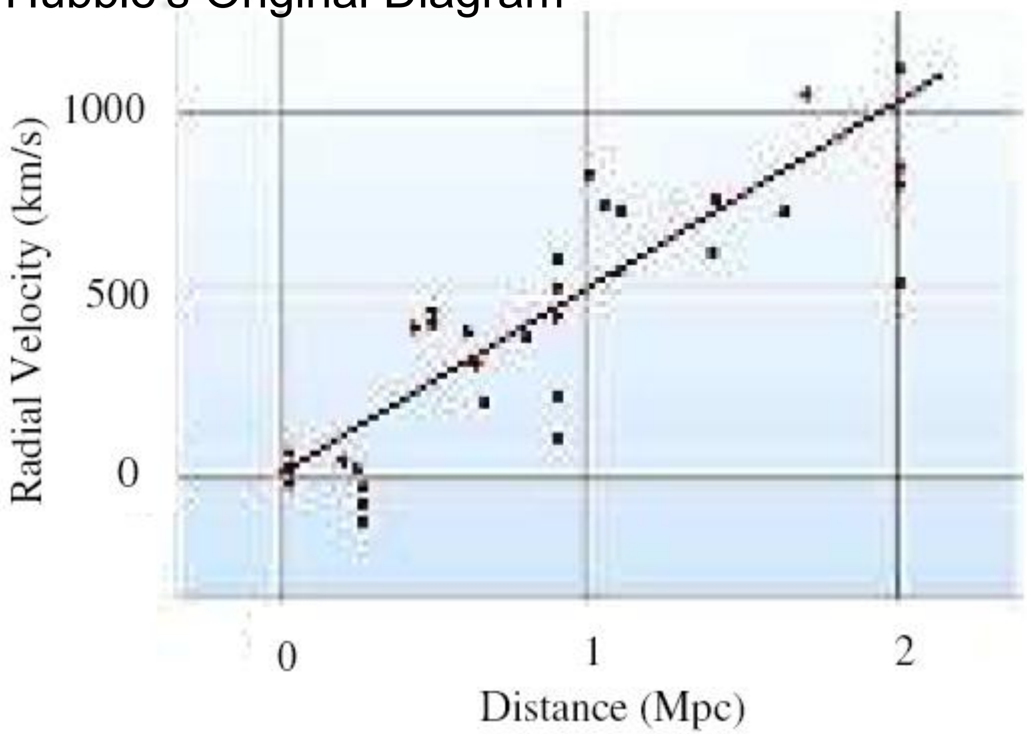
The Expanding Universe - Observations

1912-1917 Slipher: spiral nebula are receding

1920's- Hubble: velocity-distance proportionality

Distance-Velocity Relationship

Hubble's Original Diagram



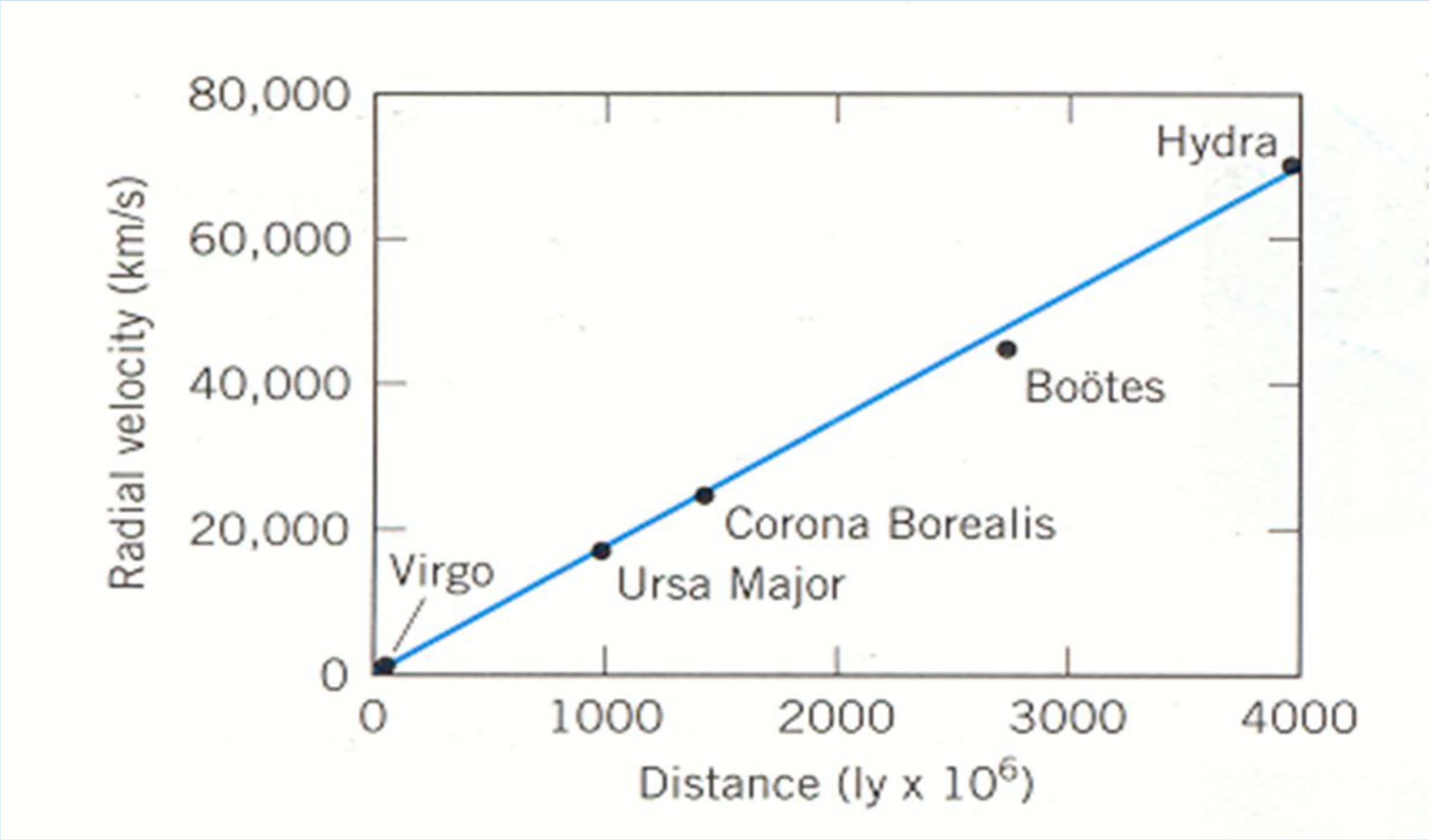
Hubble's Law

v~cz = H d

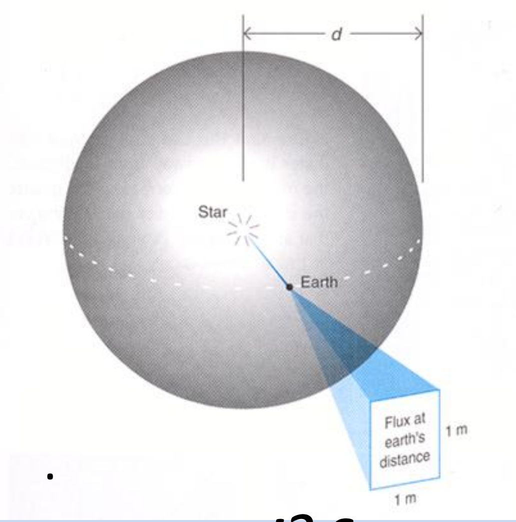
The receding velocity increases with the distance.

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

Modern version of the Hubble's diagram



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

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

$$L = 4\pi d^2 f$$

Step by step approach (the distance ladder):

based on the assumption that cepheids, RR Lyrae stars, SN explosions have the same properties in other galaxies. 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);

brightest Sc I spirals, which have about the same luminosity

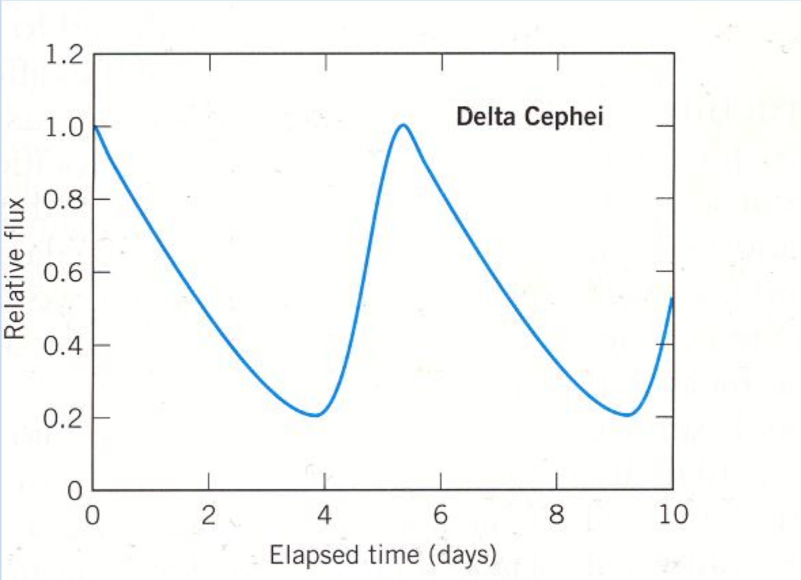
Tully-Fisher relation, between the rotational velocity of a spiral galaxy and its luminosity - 400 – 600 Mpc.

Cepheid variables:

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

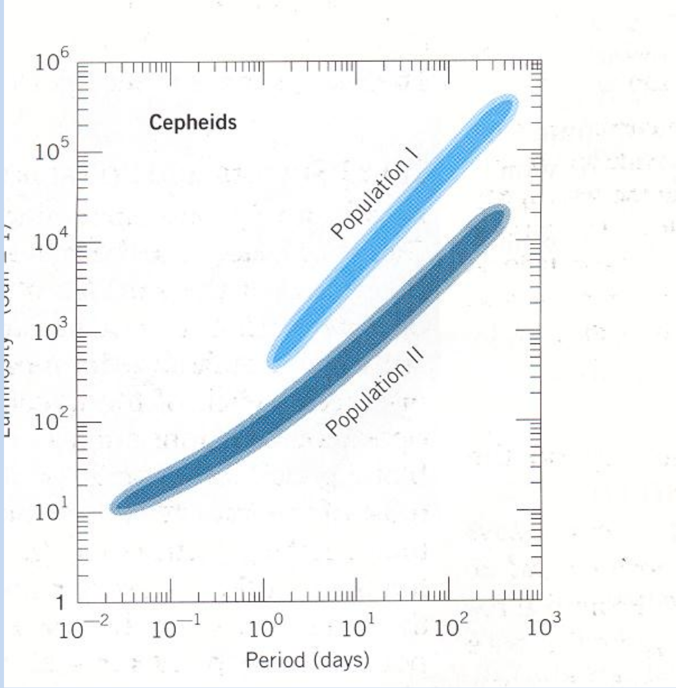
Classical cepheids (Population I): period of typically 5 to 10 days.

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.

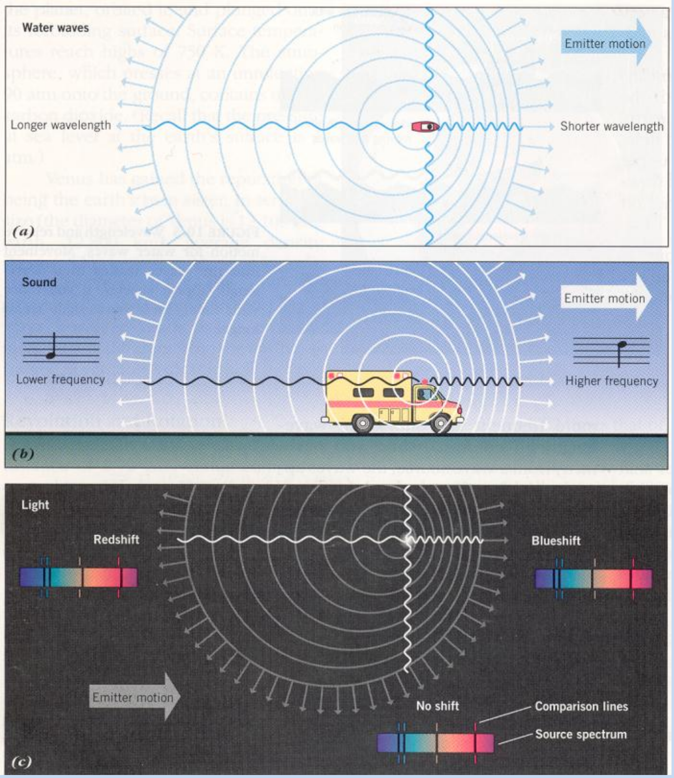
The shift of emission lines with respect to the frequency measurements by the local observer is related to velocity, and is used as an observable instead of the velocity. Note that cosmological redshift is not entirely due to Doppler effect, but, rather, can be interpreted as a mixture of Doppler effect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

for z<0.2,

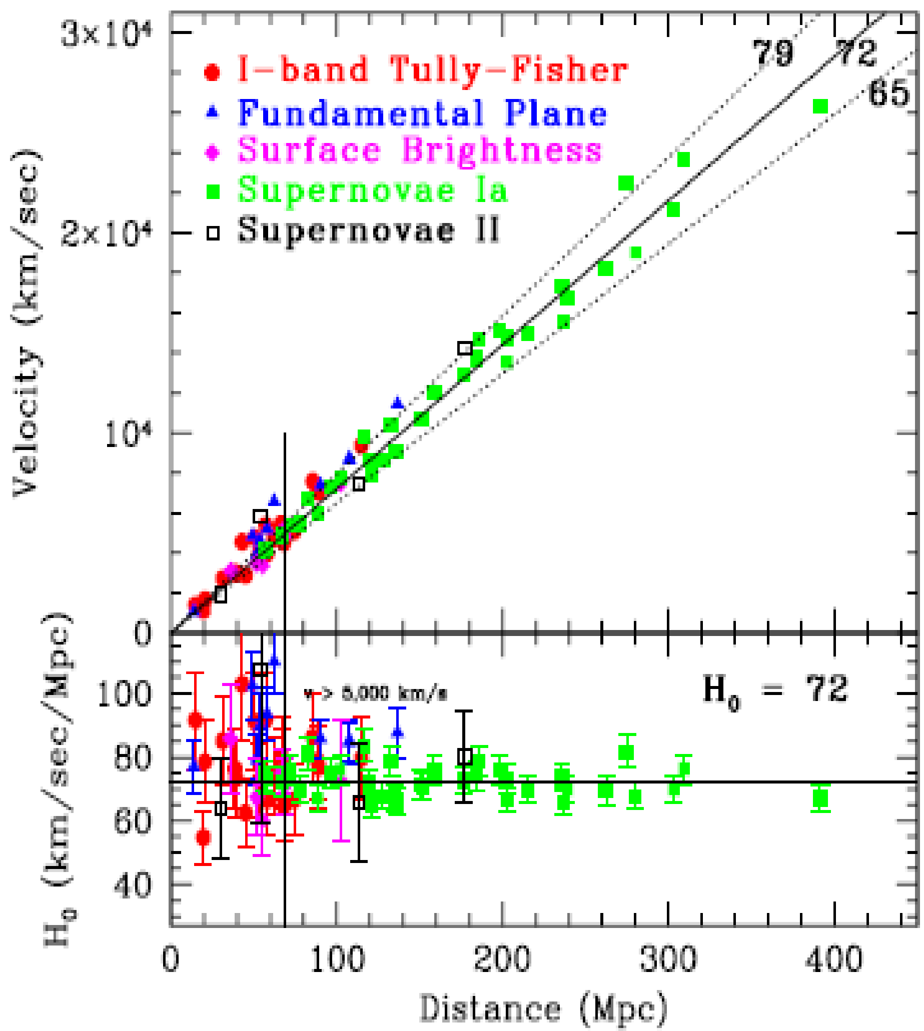
$$z \equiv \frac{\lambda_d - \lambda_e}{\lambda_e} \approx \frac{v}{c}$$

otherwise

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



Contemporary Hubble Diagrams



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, $0.4 < h < 1.0$

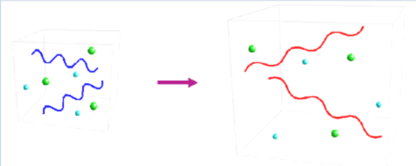
Corresponds to a *homogeneous* expanding universe (r, T decrease)

- Not applicable for gravitationally bound systems.
  Space itself expands

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

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

- Matter density decreases with volume increase,
  radiation – faster due to the decrease of photons energy
  while vacuum energy $\rho_{vac} \propto a^0 = constant$



- Applicable for distances higher than those
  corresponding to peculiar velocities.

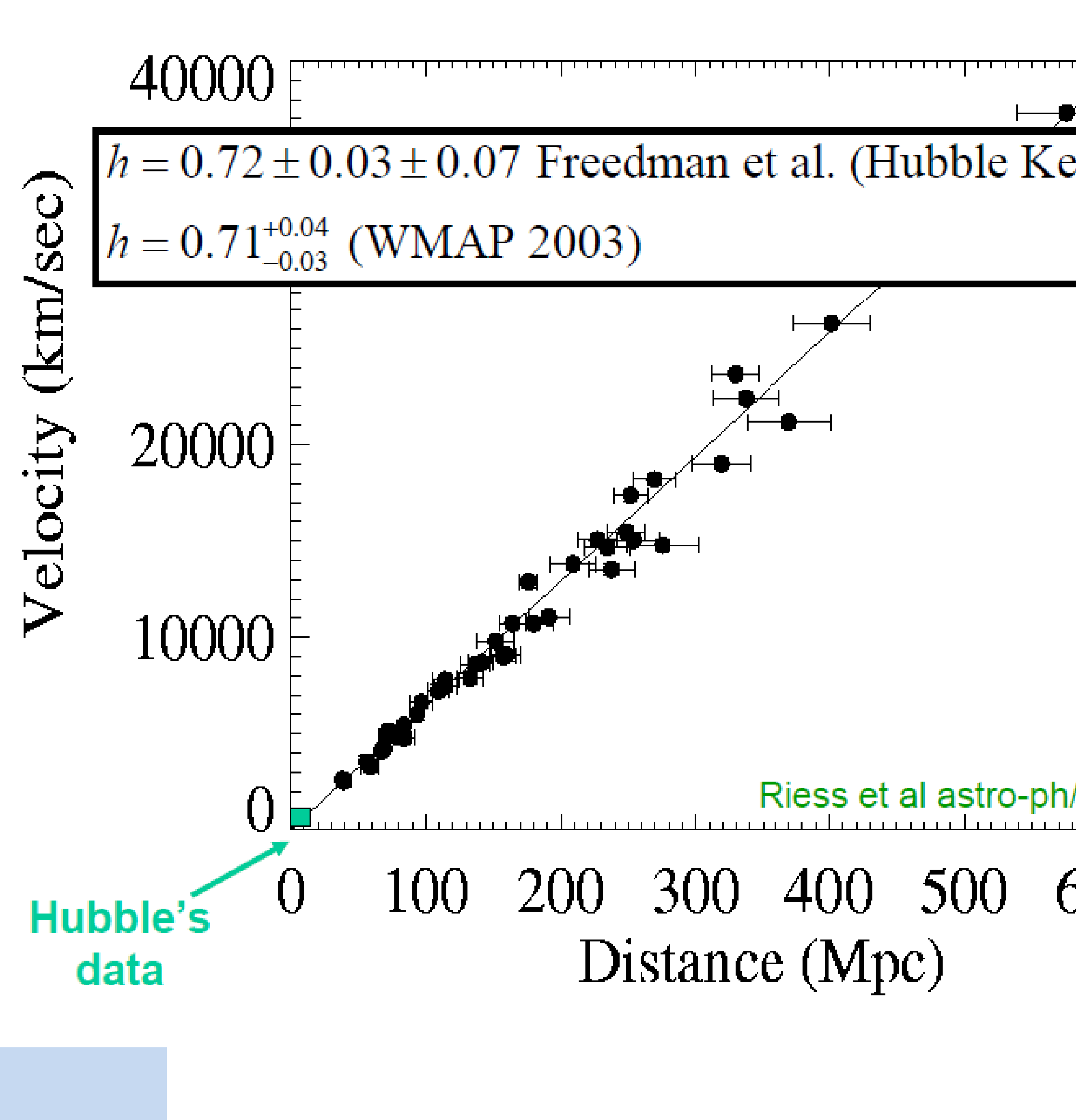
$$H \equiv 100\,h \text{ km s}^{-1}\text{ Mpc}^{-1}$$
$$\Rightarrow H^{-1} = 9.78\,h^{-1}\text{ Gyr}$$
$$= 2998\,h^{-1}\text{ Mpc}\,.$$

- $d = 3000h^{-1}$ 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.

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
≈ $(10^{10}$ years$)^{-1}$
≈ $(10^{18}$ sec$)^{-1}$
≈ $(10^{28}$ cm$)^{-1}$ (c = 1)
≈ 10^{-33} eV



WMAP7: H=71 +/-2.5 (km/sec)/Mpc

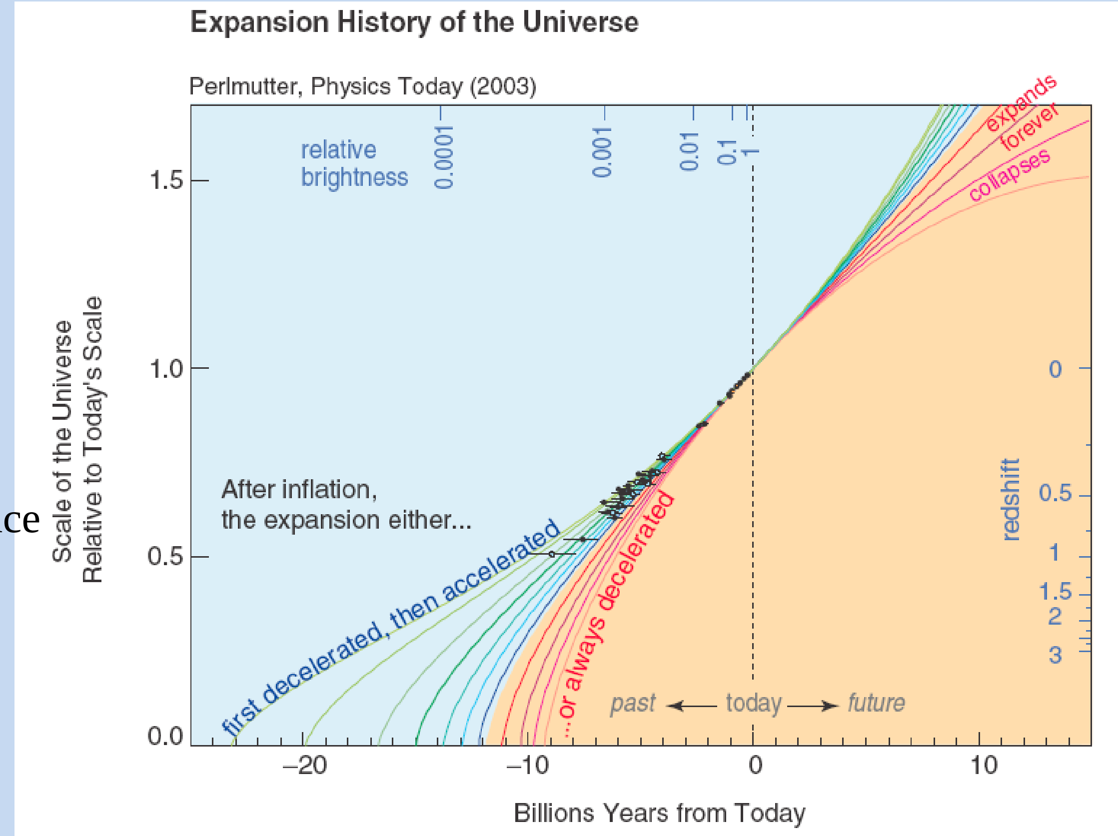
HST 240 Cepheids:

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

WMAP7 +BAO+SN+ …= 70.4 +1.3/- 1.4 (km/sec)/Mpc

Universe Expansion

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



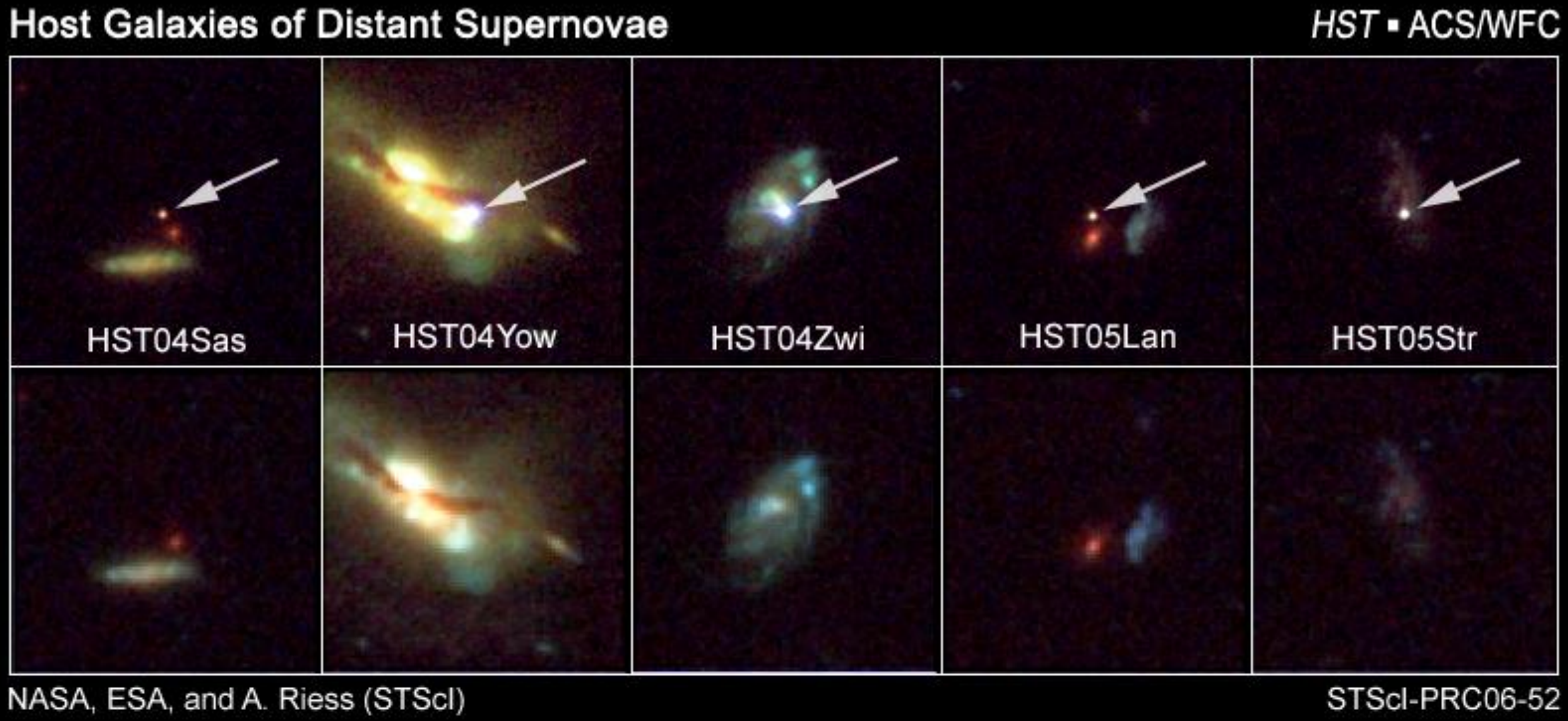
2 studies "SN cosmology project"
" High z SN search team"
lead by Adam Riess (Space Telescope Science Inst.) & Brian Schmidt (Mount Stromlo Observatory)

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 833 SN Ia is available "Union sample"

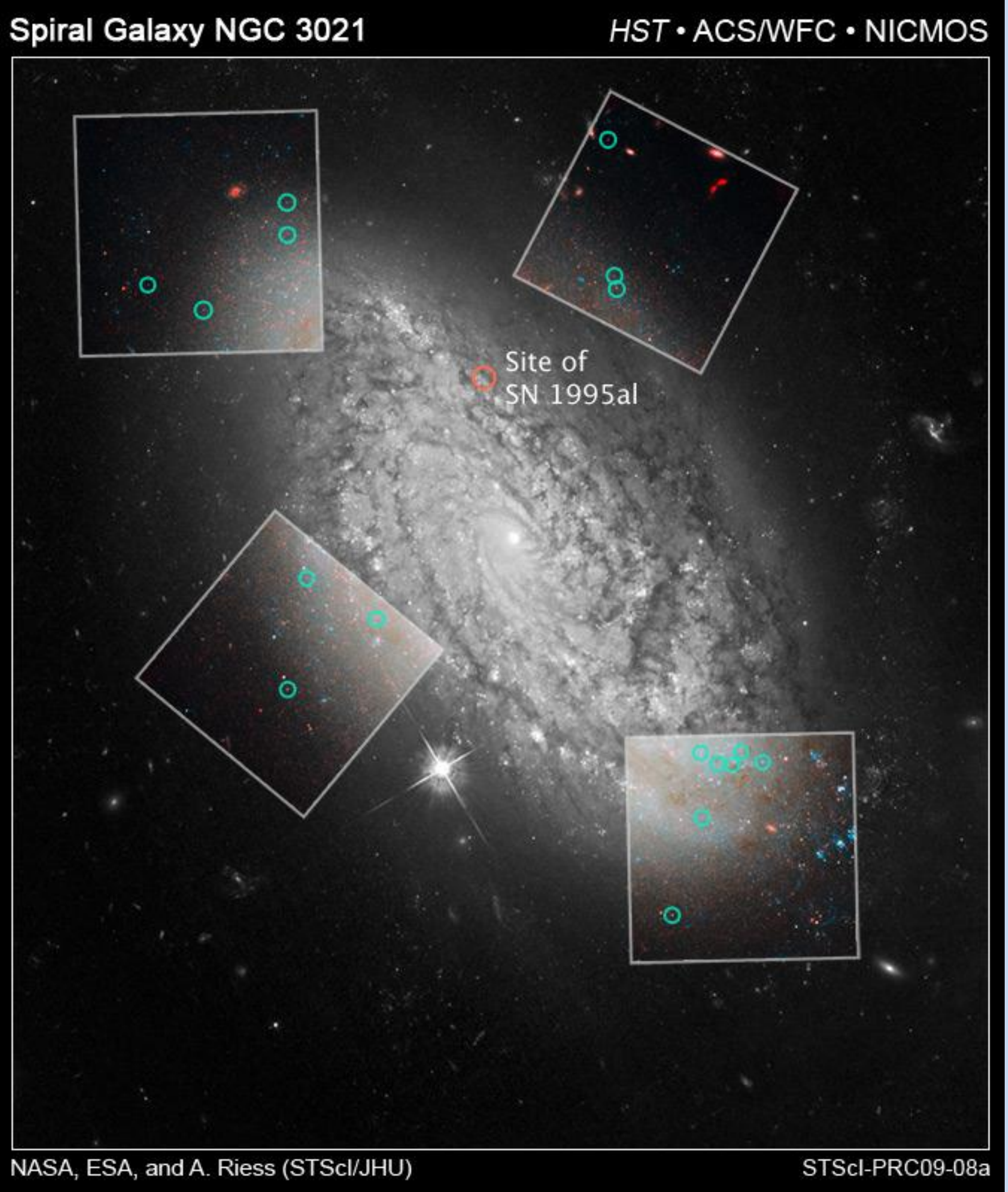
HST, SN and DE

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



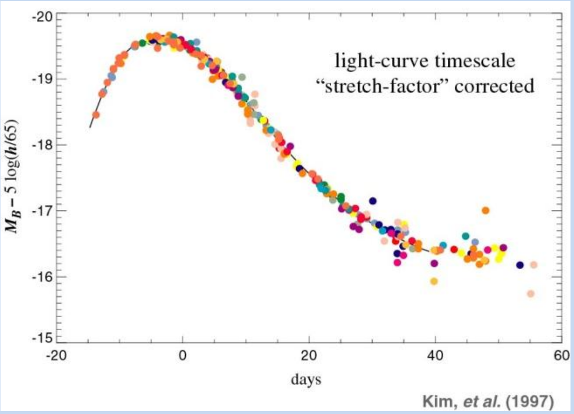
Snapshots, taken by NASA's Hubble Space Telescope, reveal five supernovae and their host galaxies. The supernovae exploded between 3.5 and 10 billion years ago. Only Hubble can measure these supernovae because they are too distant, and therefore too faint, to be studied by the largest ground-based telescopes.

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.



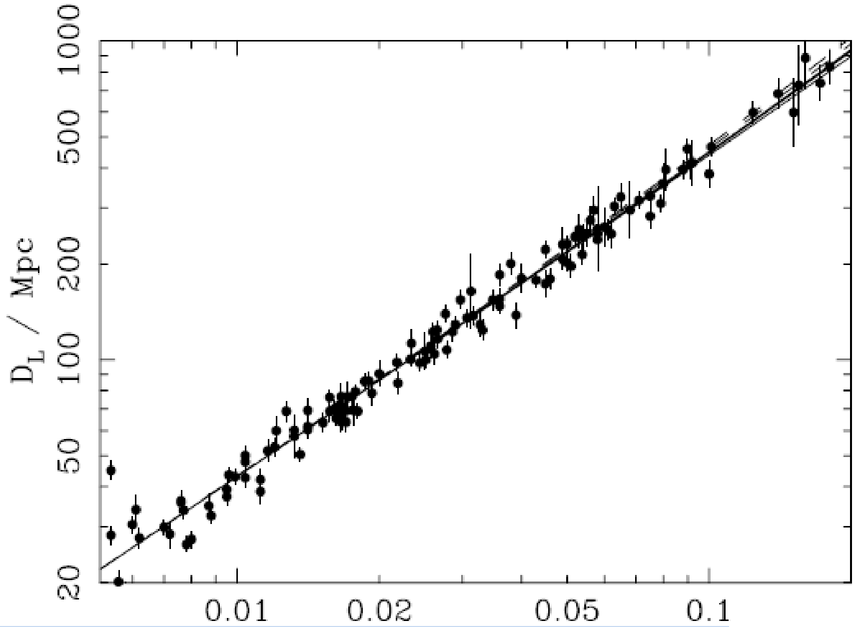
Hubble Space Telescope photo of the spiral galaxy NGC 3021.

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).



- SNIa allow to measure distance with high accuracy.

SN + Cepheid data from HST determine Ho.

- Analysis of SN data at great distances allowed first serious tests of the geometry of the Universe.

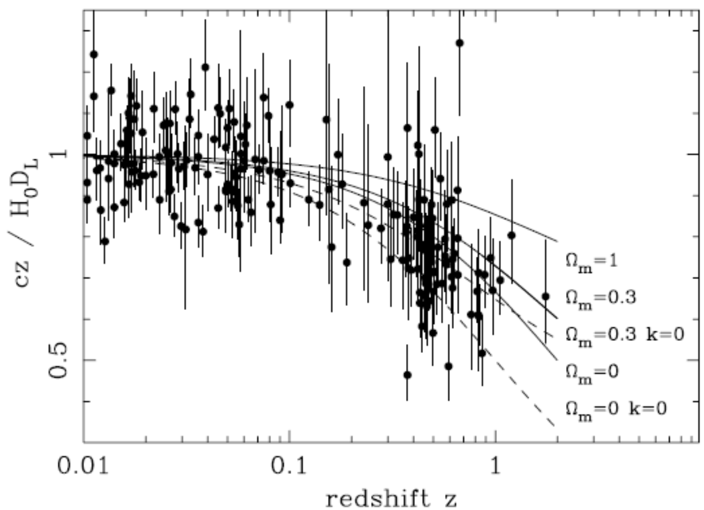
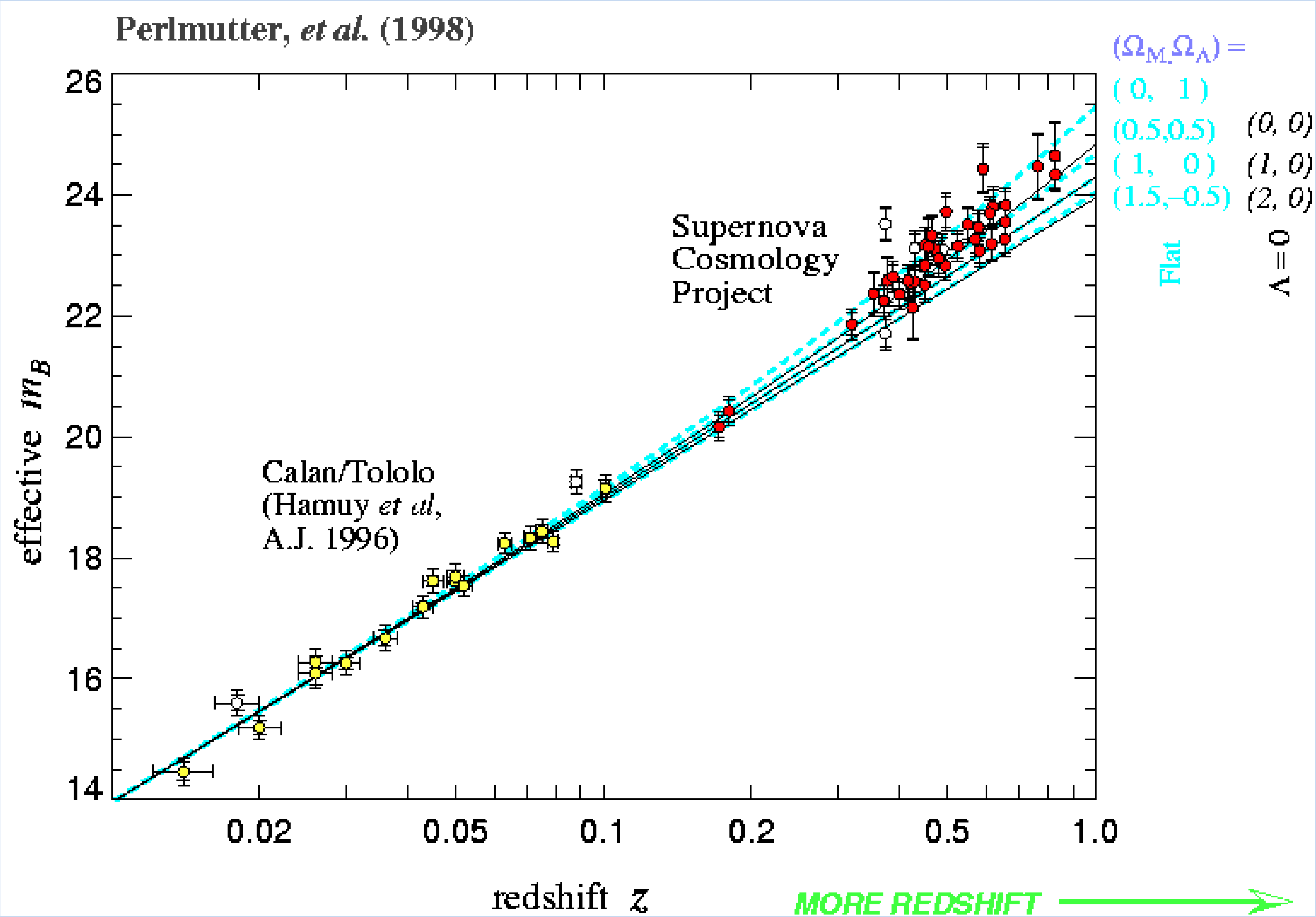


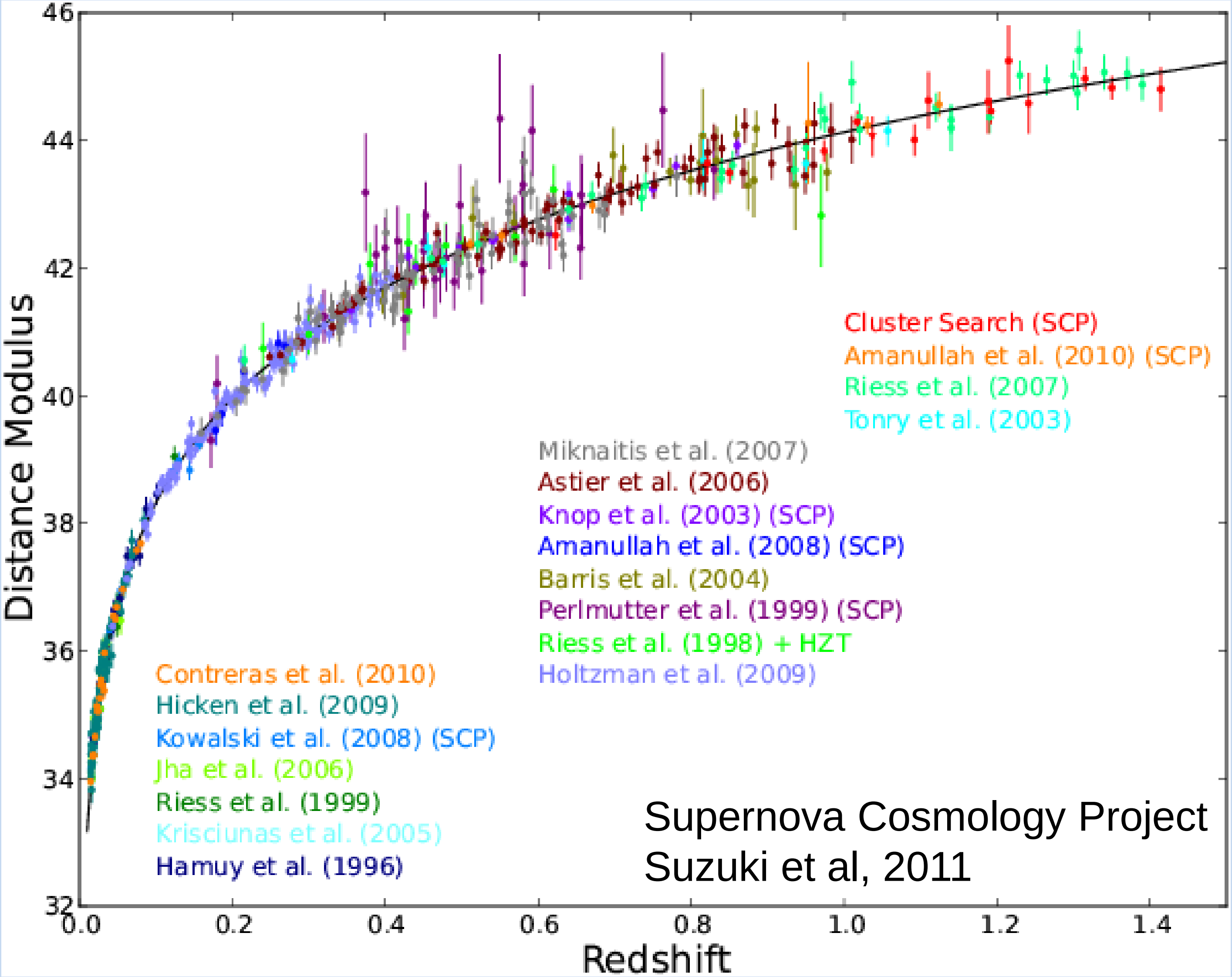
Figure 19.1: The type Ia supernova Hubble diagram [20–22]. The first panel shows that for $z \ll 1$ the large-scale Hubble flow is indeed linear and uniform; the second panel shows an expanded scale, with the linear trend divided out, and with the redshift range extended to show how the Hubble law becomes nonlinear. ($\Omega_r = 0$ is assumed.) Comparison with the prediction of Friedmann-Lemaître models appears to favor a vacuum-dominated Universe.

Hubble Diagram SNIa

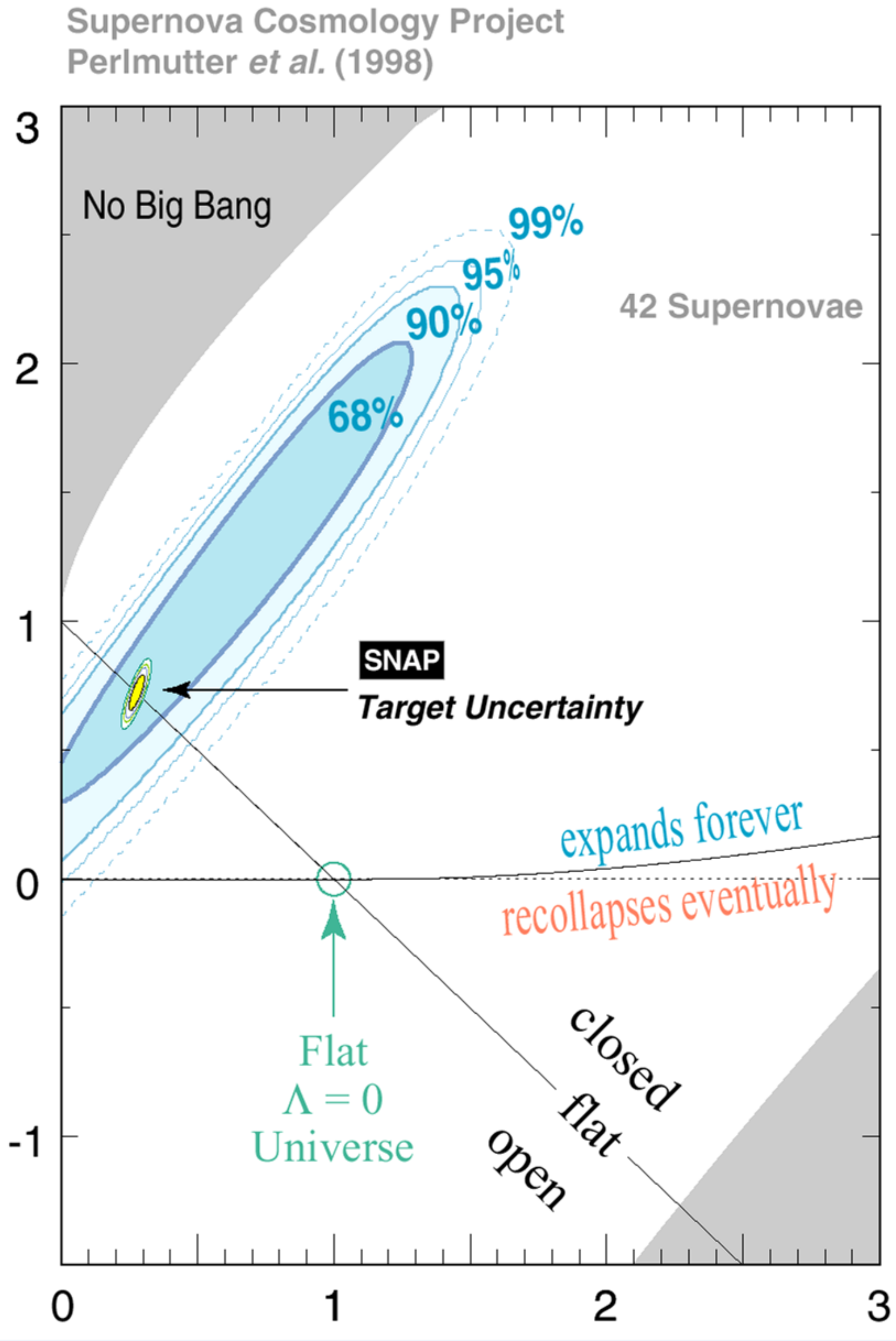


Sometime around 5 billion years ago, the universe began accelerating - its expansion getting faster and faster, rather than gradually slowing down.

Hubble Diagram



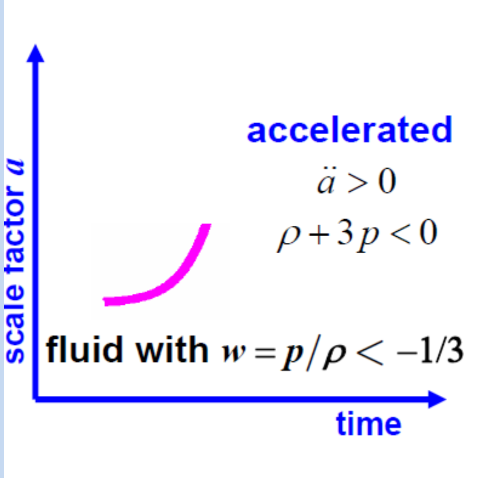
Hubble Diagrams of Union Sample (> 500 SN) constructed with selection cuts and outlier rejection. Each sample is independently binned in redshift bins of 0.01. The x-axis is sqrt(redshift).



Ordinary matter gravitates.

Antigravity requires unusual medium with

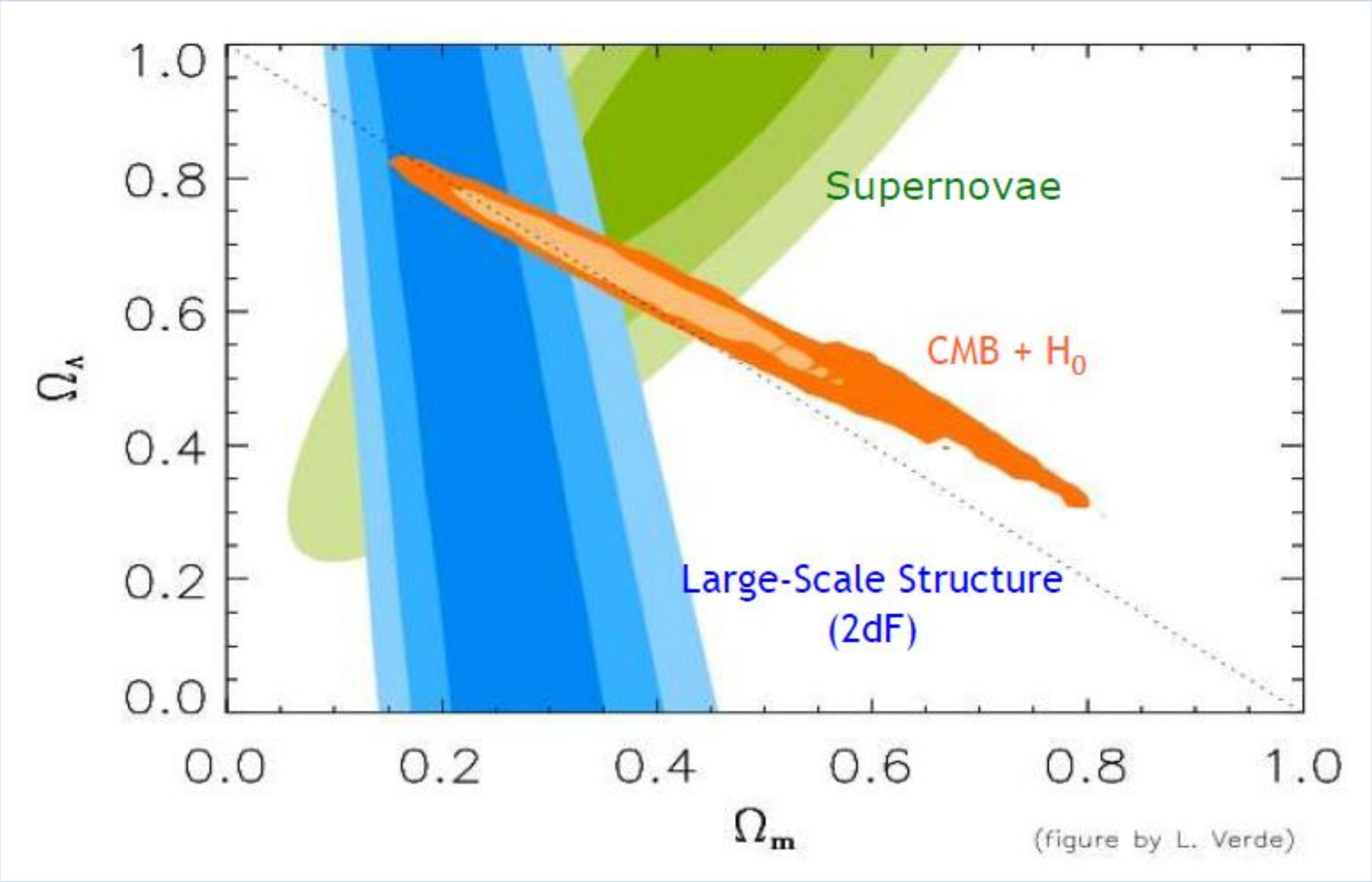
P < 0 and $p/\rho = \omega < -1/3$



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

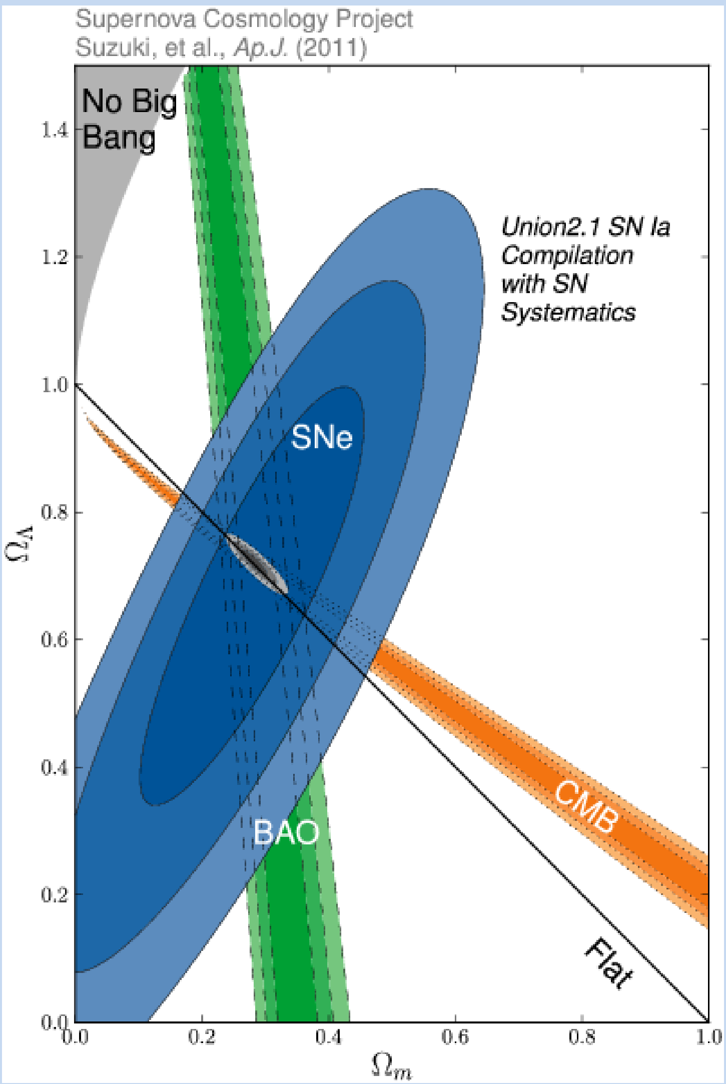
Concordance of independent data points:

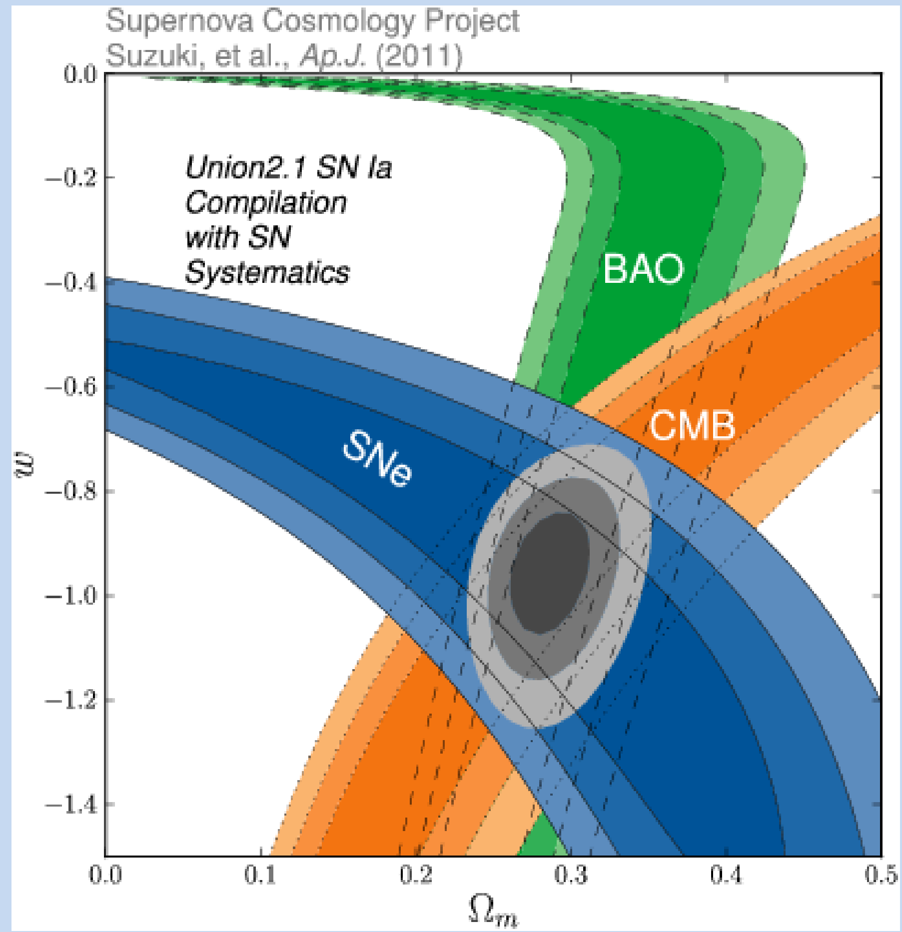
$\Omega_M \sim 0.3, \;\; \Omega_\Lambda \sim 0.7$



Комбинираните резултати от свръхнови (Hubble ST), КМФ (WMAP) и галактични купове указват на съществуването на ТВ и ТЕ:

Union 300 SN Ia
&
КМФ
&
БАО





Ω_m-Ω_Λ and Ω_m-*w* With and Without Systematics
68%, 95%, and 99.7% constraints from the Union Compilation. The filled contours show statistical constraints only; the dotted contours include systematic errors.

Universe Age

Hubble age:

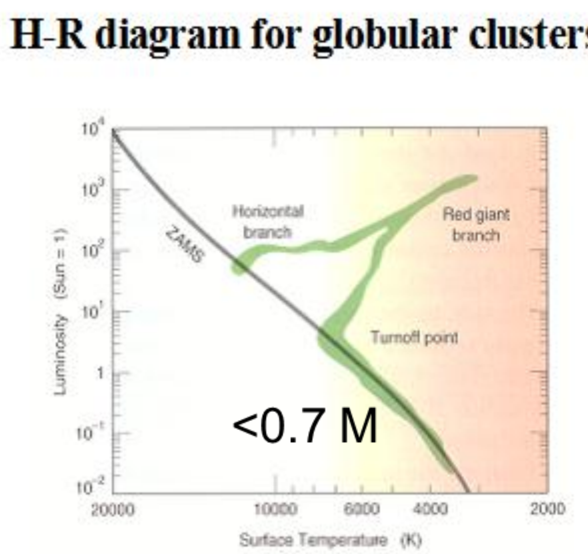
If v=const, then for the distance b/n galaxies d:

$d = v.t \Rightarrow \quad t = d/v = d/Hd \qquad t = \mathbf{1/H_o}$

Flat MD Universe: $\mathbf{2/(3\,H_o)}$

Universe with very low density: $\mathbf{1/H_o}$

Universe with DE, the age may be much larger.



$L \propto M^4$

11-13 billions years

In case of total density <1:

$$H_0 t_0 \simeq \tfrac{2}{3}\left(0.7\Omega_m + 0.3 - 0.3\Omega_v\right)^{-0.3}$$

In case of total density =1:

$$H_0 t_0 = \frac{2}{3\sqrt{\Omega_v}} \ln \frac{1+\sqrt{\Omega_v}}{\sqrt{1-\Omega_v}} \quad (\Omega_m < 1)$$

WMAP +CMB (ACBAR и CBI) measure with 1% accuracy: 13.73 bly (0.12 bly)

The Universe is

Homogeneous and isotropic at large scales

Flat, negligible curvature

Expands with acceleration the last 5 bln years

Dominated by DE with characteristics of Λ