The state of the Universe

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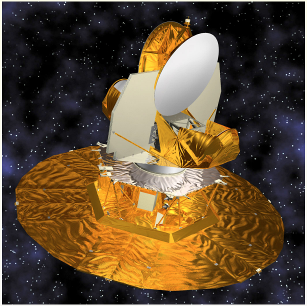
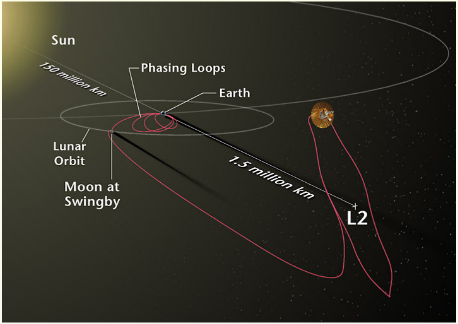
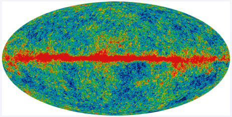
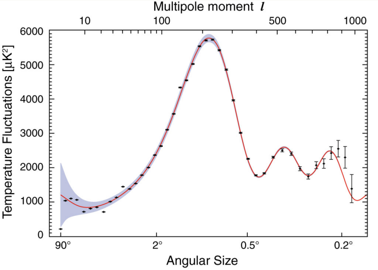
The Wilkinson Microwave Anisotropy Probe (WMAP)









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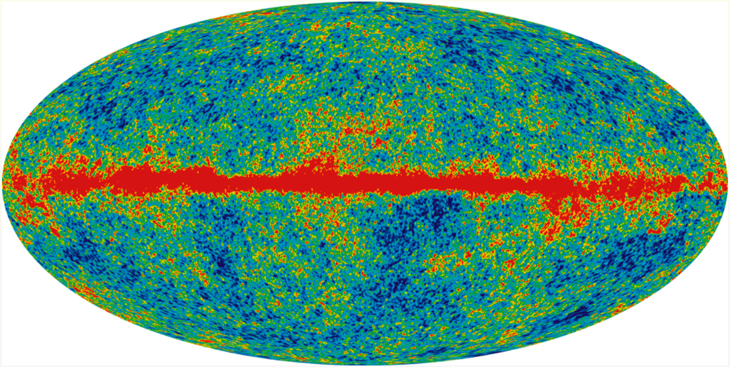

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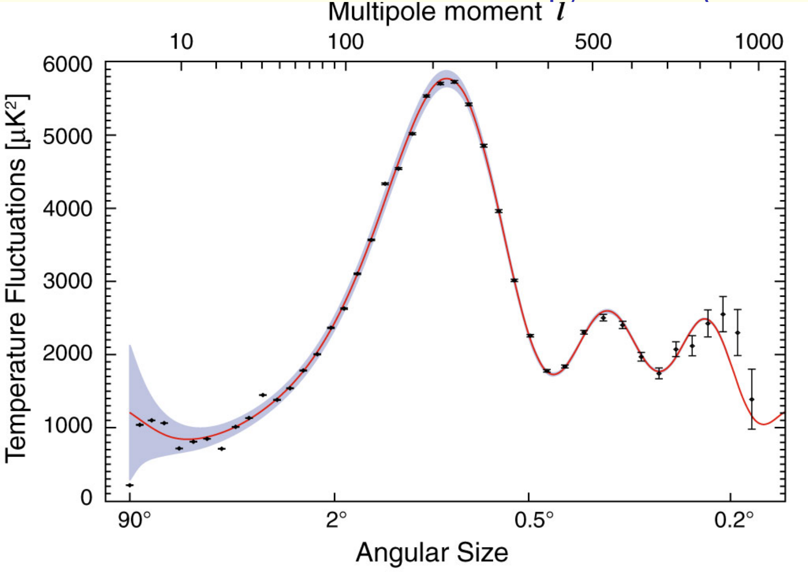
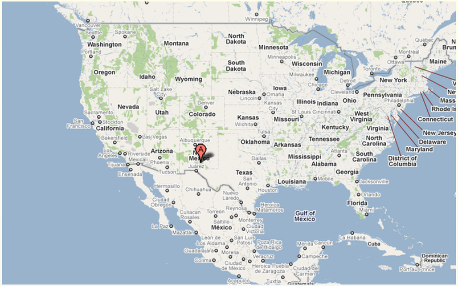
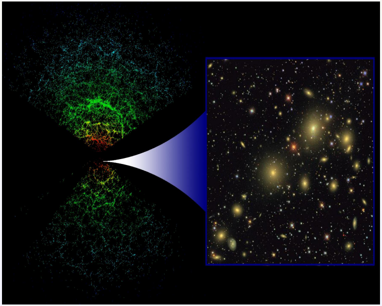
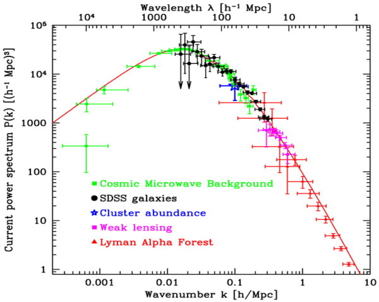


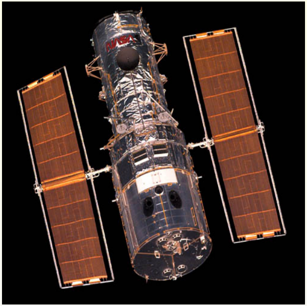
The Sloan Digital Sky Survey (SDSS)

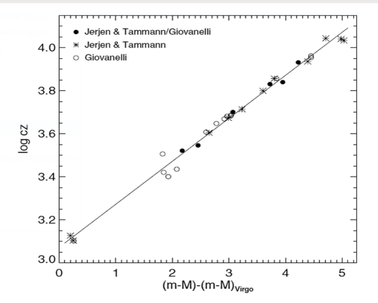




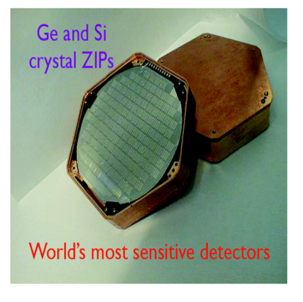


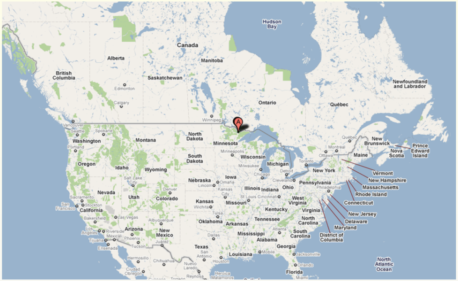
The Hubble Space Telescope (HST)

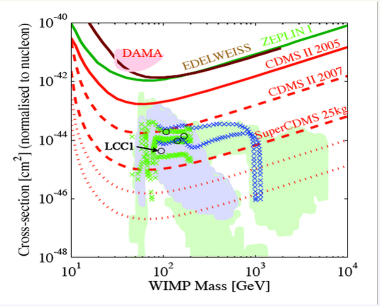


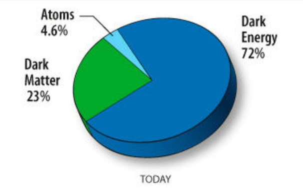


The Cryogenic Dark Matter Search (CDMS)

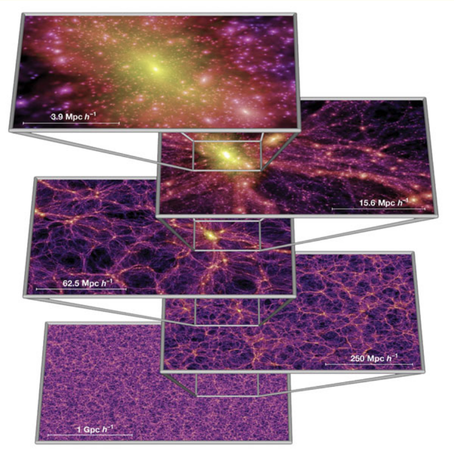








The Millennium simulation



Plan of the Talk

- Expansion of the Universe
- Dark energy and accelerated expansion
- Dark matter in the universe
- Cosmic Microwave Background Radiation
- Inflation
- Summary and conclusions

- Gravity is the weakest fundamental force in nature out of the four fundamental forces (others are electromagnetic, weak and strong). However, it dominates in the universe at very large scales.
- Gravity controls the expansion of the universe.
- Gravity leads to clustering of matter and forms galaxies, clusters of galaxies and other large scale structures in the universe.
- Einstein's general theory of relativity is the most successful theory of gravity. However,the presence of dark matter and dark energy is problematic.
- The equilibrium of a system of stationary particles under gravity is unstable which means the universe either has to expand or collapse.

- The Universe at very large scales is homogeneous and isotropic i.e., there is no special place or direction in the Universe (the cosmological principle).
- Galaxies in the universe at very large scales are moving away from one another or the Universe is expanding. The relative velocity of any pair of galaxies is proportional to their distance

$$V_{AB} \propto R_{AB} \tag{1}$$

  Here the proportionality constant is called the Hubble's constant H the value of which is of the order of 100 km/sec/Mpc[1]
- Not everything in the universe is expanding. For example our solar system and galaxy are not getting bigger with time.

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[1] $1 Mpc = 3.08568025 \times 10^{22} mt$

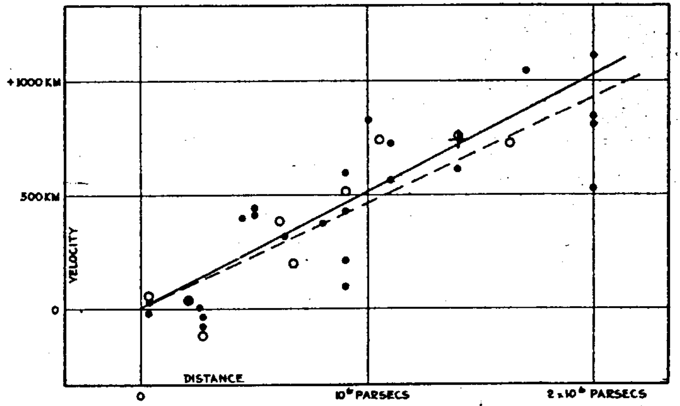


FIGURE 1

A relation between distance and radial velocity among extra galactic nebulae, Edwin Hubble (1929) PNAS Vol.15 Page 169

- scale factor

$$R_{AB}(t) = \frac{a(t)}{a(t_0)} R_{AB}(t_0) \tag{2}$$

- Redshift

$$\lambda_o = \lambda_e(1+z) \quad \text{and} \quad 1+z = \frac{1}{a(t)} \tag{3}$$

	t	a	z
Big Bang	0	0	∞
Present	13.7 Gyr	1	0

Dynamics of the Universe

- Expansion:

$$\left(\frac{da(t)}{dt}\right)^2 - \left(\frac{4\pi a^3(t)\rho(t)}{3}\right)\frac{G}{a(t)} = -Kc^2 \tag{4}$$

$$K + V = E$$

- Acceleration:

$$\frac{d^2a(t)}{dt^2} = -\frac{4\pi G}{3}\left(\rho(t) + \frac{3P(t)}{c^2}\right)a(t) \tag{5}$$

Cosmological parameters

- Hubble parameters:

$$H(t) = \frac{1}{a(t)}\frac{da(t)}{d(t)} = \frac{\dot{a}(t)}{a(t)} = 100\ h\ km\ sec^{-1}\ Mpc^{-1}$$

$$t_h = \frac{1}{H} \approx \frac{9.7}{h}\ \text{Gyr}; \quad d_h = \frac{c}{H} \approx \frac{3000}{h}\ \text{Mpc}$$

- Critical density:

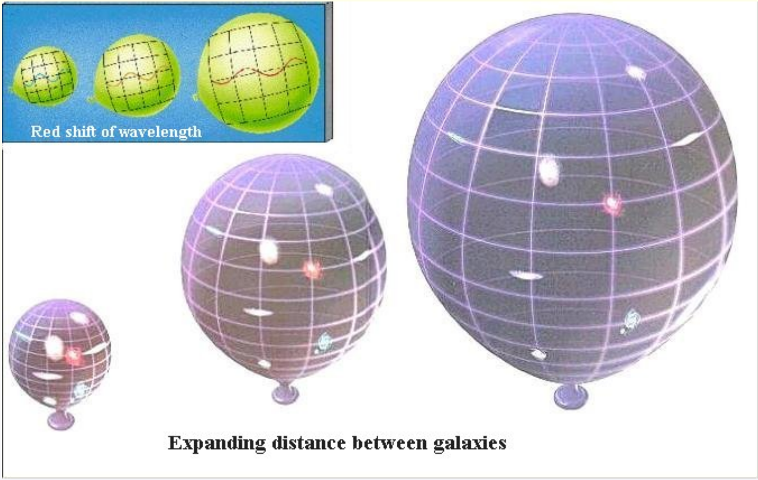
$$\rho_c = \frac{3H^2}{8\pi G}\rho_c \approx 1.87h^2\ \times 10^{-26}\ kg\ mt^{-3}$$

- Density parameter:

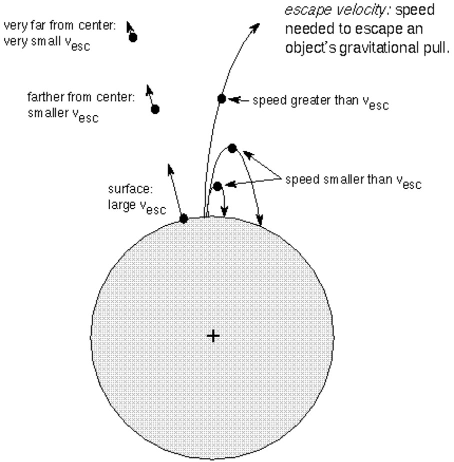
$$\Omega = \frac{\rho}{\rho_c}$$

- Deceleration parameter:

$$q = -\frac{\ddot{a}(t)}{\dot{a}^2(t)}a(t) = \frac{1}{\rho_c}\left(\rho(t) + \frac{3P(t)}{c^2}\right)$$



Expansion of the universe can be understood in terms of "opening-up" of the space between galaxies.

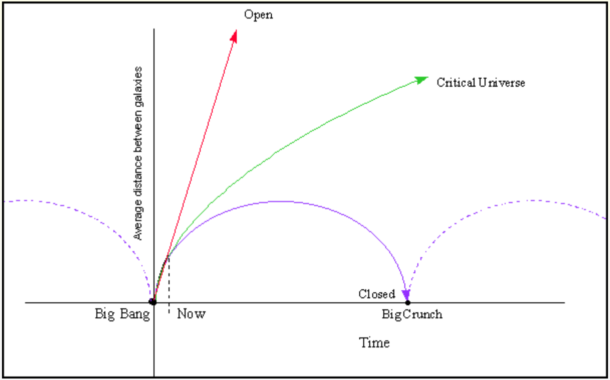


The spatial geometry of the universe depends on the total matter/energy in the universe.

Geometry of the universe

$$\frac{Kc^2}{a^2} = \frac{\rho}{\rho_c} - 1 = \Omega - 1 = \Omega_k$$

Ω	K	Geometry
> 1	$+$ve	Closed
< 1	-ve	Open
$= 1$	0	Flat



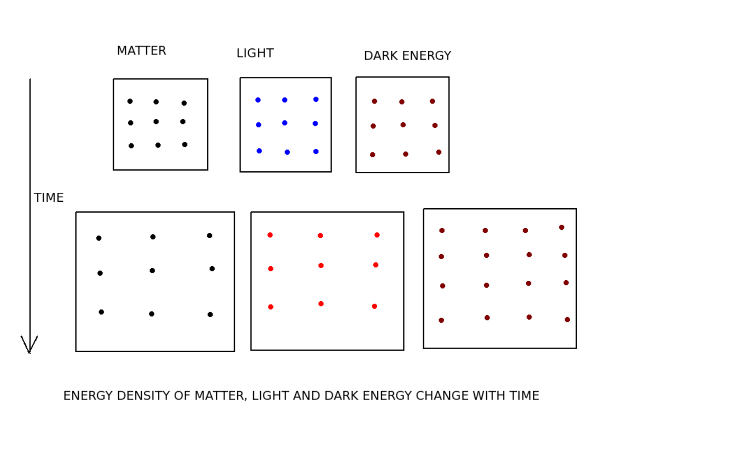
A closed universe is finite in size, flat and open are not.

Acceleration/deceleration

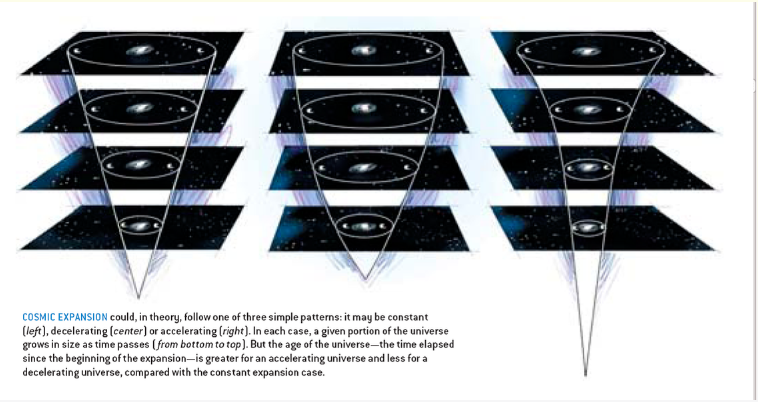
$$q \propto \left(\rho(t) + \frac{3P(t)}{c^2}\right)$$

$\left(\rho + \frac{3P}{c^2}\right)$	q	Expansion	$w = \frac{Pc^2}{\rho}$
> 0	$+$ve	Deceleration	$> -\frac{1}{3}$
< 0	-ve	Acceleration	$< -\frac{1}{3}$
$= 0$	0	Constant	$=-\frac{1}{3}$

Type of matter/energy	Equation of state parameter (w)
Non-relativistic matter (matter)	0
Relativistic matter (radiation)	$\frac{1}{3}$
Cosmological constant	-1

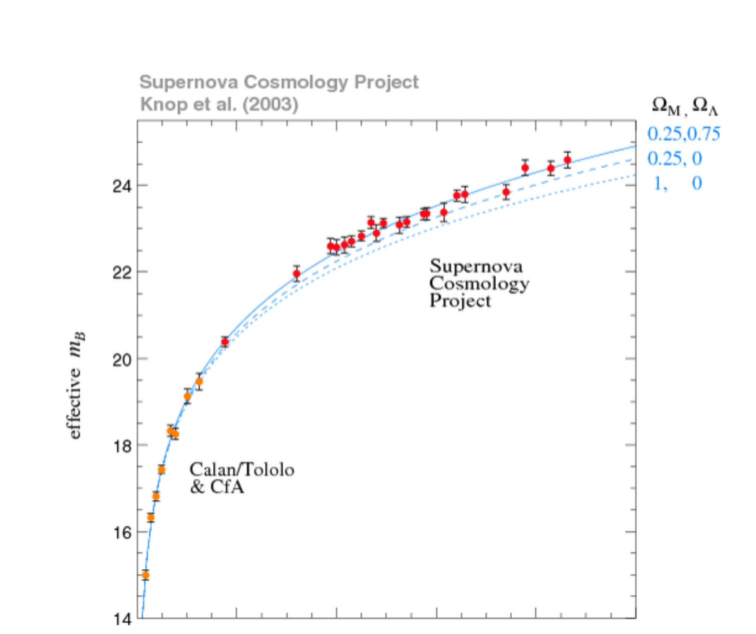


Energy densities of various species vary differently with expansion

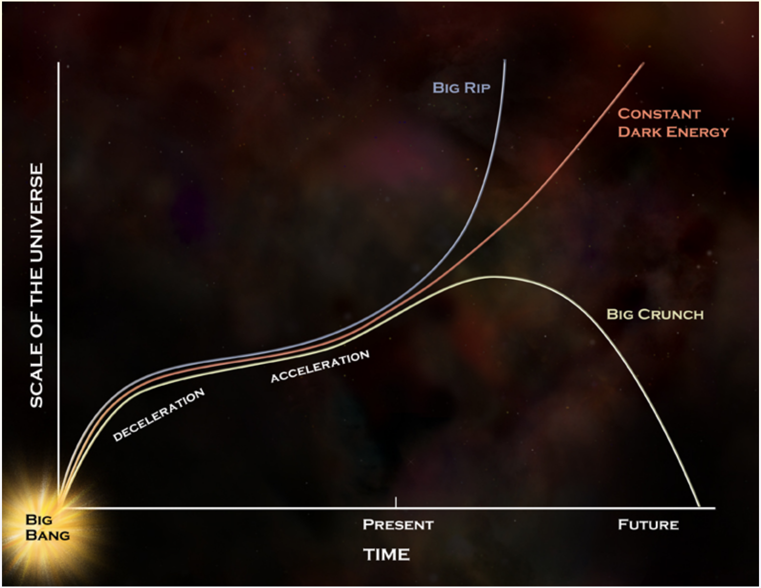


COSMIC EXPANSION could, in theory, follow one of three simple patterns: it may be constant (*left*), decelerating (*center*) or accelerating (*right*). In each case, a given portion of the universe grows in size as time passes (*from bottom to top*). But the age of the universe—the time elapsed since the beginning of the expansion—is greater for an accelerating universe and less for a decelerating universe, compared with the constant expansion case.

In an accelerating universe objects with a constant luminosity (standard candles) appear to be fainter than what they are expected to be

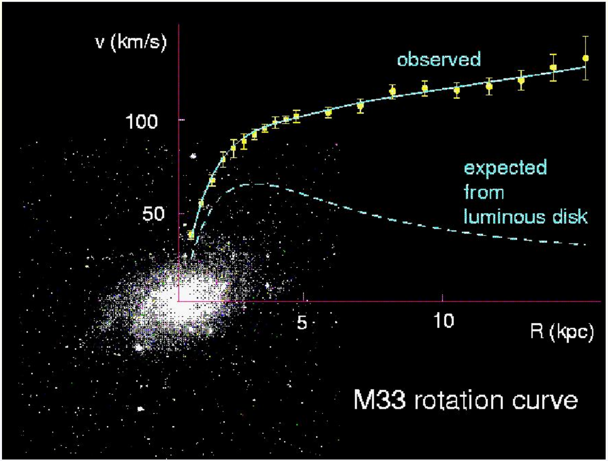


Supernovae Ia were found fainter than what they were expected to be



The universe is most likely to end in a “big-rip” rather than in a big crunch

Dark Matter



Galaxy rotation curves do not follow the Kepler's law i.e.,
$v \propto 1/\sqrt(r)$

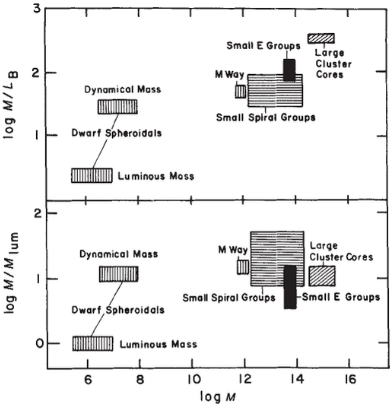


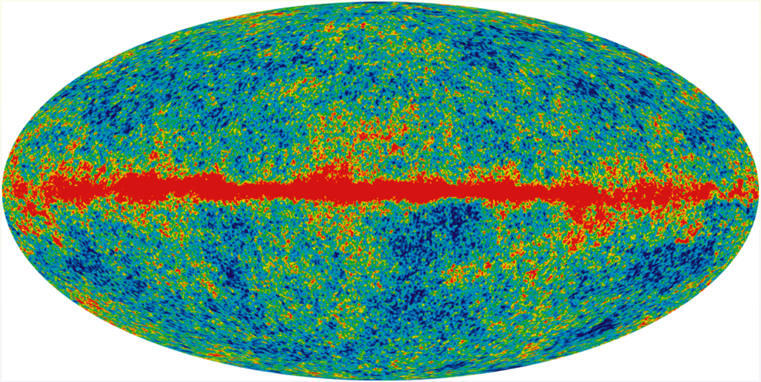
Fig. 1 Mass-to-light ratio, M/L_B, and total-to-luminous mass, M/M_{lum}, for structures of various size in the Universe. The data come from Table 1. Although M/L_B increases systematically with mass, the more physically meaningful ratio M/M_{lum} appears to be constant on all scales within the errors. If the velocity dispersion data for the dwarf spheroidal galaxies are interpreted to imply heavy haloes, the upper estimates result. The lower estimates follow from assuming that all the mass is visible. We believe the former estimate to be more realistic.

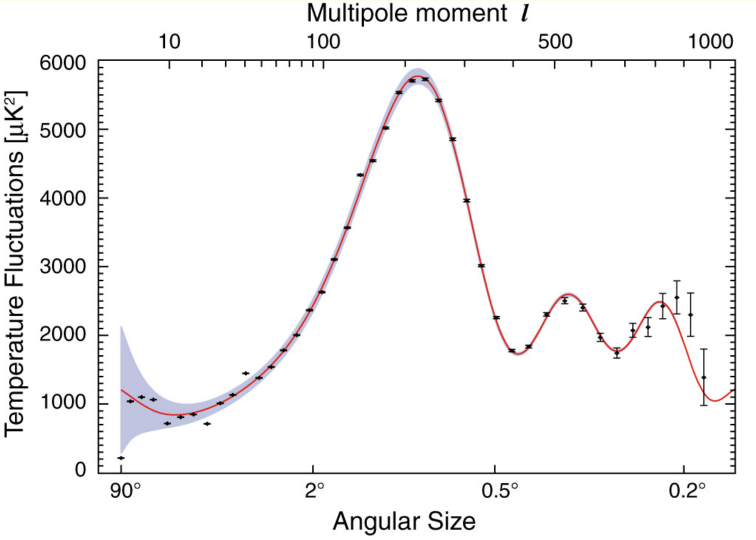
Mass to light ratio increases with scale i.e., there is more invisible matter in large scale

Dark matter

- Most of the matter (90%) in the universe is in the form of dark matter.
- Dark matter does not interact with photons in anyway therefor it does not emit any light.
- The presence of dark matter can be felt becaue of its gravitational effects on the surrounding matter.
- The clustering of dark matter can be probed by observing the clustering of galaxies if galaxy clusters in the same way as the dark matter.
- Dark matter can be in the form of Massive Astrophysical Halo Objects (MACHOS) or in the form of Weakly Interacting Massive Particles (WIMPS).
- At present it is not clear what dark matter particles consist of.

Cosmic Microwave Background Radiation




Multipole moment l
10
100
500
1000
Temperature Fluctuations [μK²]
6000
5000
4000
3000
2000
1000
0
90°
2°
0.5°
0.2°
Angular Size

Noble Prize in Physics

- The universe is filled with the Cosmic Microwave Background Radiation
  Nobel Prize in Physics 1978, Pyotr Kapitsa, Arno Penzias, Robert Woodrow Wilson
- CMBR is a back body radiation with temperature 2.7 Kelvin.
- The temperature of CMBR coming from different directions is not the same. There are anisotropies of the order of one part in 100,000 parts
  Nobel Prize in Physics 2006, John C. Mather, George F. Smoot

Cosmological Questions

- Why are the temperatures of CMBR photons coming from two widely separated points in the sky so close to one another, although they were never causally connected before ? The Horizon problem.
- Why is the spatial curvature of the universe very close to zero ? The flatness problem.
- Why are there temperature fluctuations in the CMBR temperature.

In order to solve these and many other problems in 1980s Alan Guth, Linde and others proposed a hypothesis called inflation which is as follows.
Before the big bang expansion i.e., power law expansion, the universe went through a phase of exponential expansion driven by a form of energy which has negative pressure.

Explaining the universe

When the universe expands it cools

$$t = \left(\frac{45}{16\pi^3 G}\right)^{1/2} \frac{1}{\sqrt{g_*}} \frac{1}{T^2} = \frac{2.41}{\sqrt{g_*}} \left(\frac{Gev}{T}\right)^2 \quad \mu\ sec \tag{6}$$

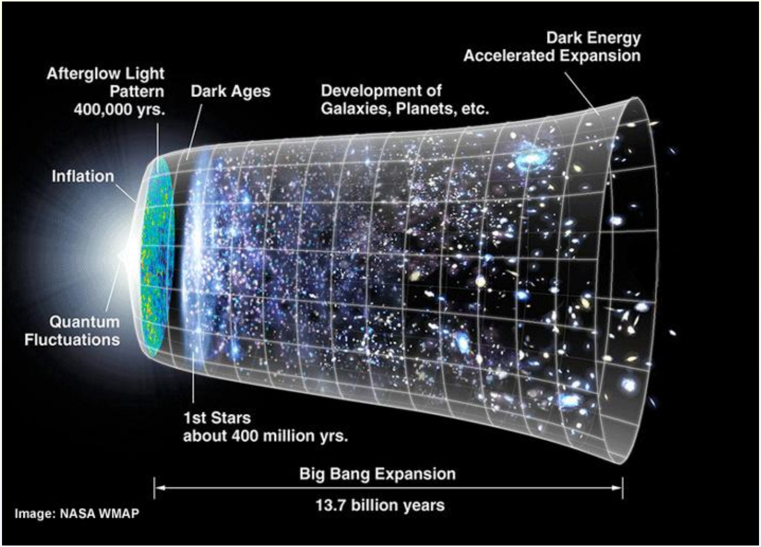
Energy	Time	Event
∞	$0\ sec$	The Big Bang
$> 10^{19} GeV$		Grand Unification
$10^{16} GeV$	$10^{-34}\ sec$	Inflation
$10^{14} Gev$		Unification
$80 Gev$		Electroweak symmetry breaking
$1 GeV$		Nucleosyntheis
$1 eV$	$10^{13}\ sec$	Recombination
$< 1 eV$		Re-ionization
$3K$	$10^{16}\ sec$	Present

A brief history of the universe

- The expansion of the universe started at the big bang and at that time the temperature and density of the universe was infinite.
- Before the big bang expansion the universe went through a very rapid phase of the expansion called inflation.
- At the end of inflation the universe was filled with a plasma of fundamental particles like photons, electrons and quarks.
- Once the temperature of the universe dropped below a certain temperature protons and neutrons (called baryons) formed from quarks.
- For the first 380,000 years of the big bang, the photons and electrons were strongly coupled to each other.
- When the temperature of the universe (photons) dropped below a certain temperature (4000 K), electrons decoupled from photons and combined with protons and formed Hydrogen. This event is called recombination.

- The photons which were decoupled from electrons at recombination are present in the universe in the form of cosmic microwave background radiation.
- At recombination the density of matter in the universe was not the same i.e., there were over-dense and under-dense regions.
- The photons which started from the over-dense region were cooler than the photons which left from the under-dense regions. This is the reason for CMBR anisotropies.
- Density fluctuations which were created during inflation got amplified due to gravity and formed structures which we see in the present universe.
- At recombination all the matter in the universe was neutral. However, when the first stars started to form (after 300,000 years after the big bang) the universe was re-ionized.

History of the Universe



Cosmological Inflation

Proc. Natl. Acad. Sci. USA 90 (1993)

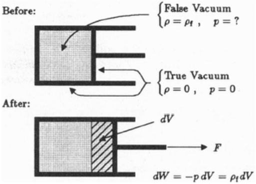
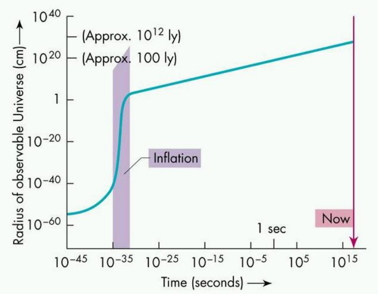


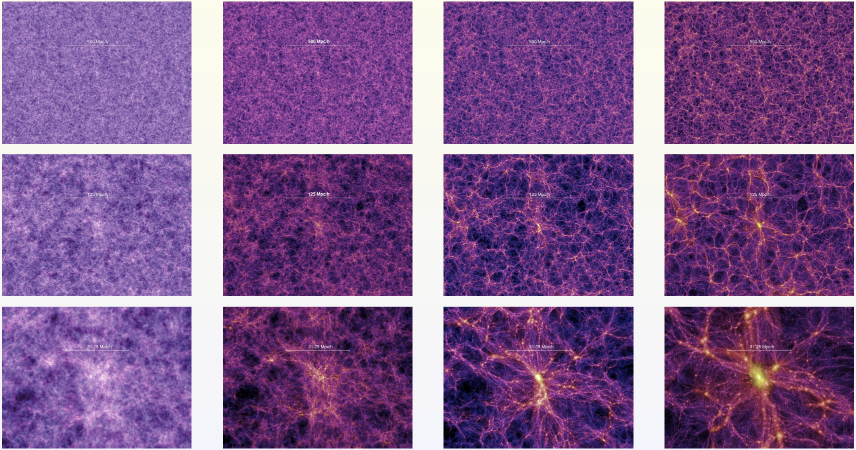
FIG. 2. A thought experiment to calculate the pressure of the false vacuum. As the piston chamber filled with false vacuum is enlarged, the energy density remains constant and the energy increases. The extra energy is supplied by the agent pulling on the piston, which must pull against the negative pressure of the false vacuum.



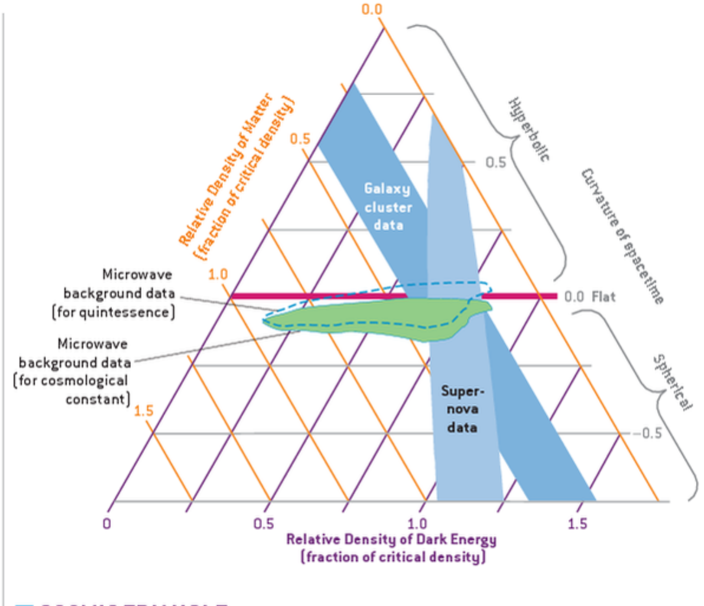
Cosmological inflation is driven by scalar field which has negative pressure

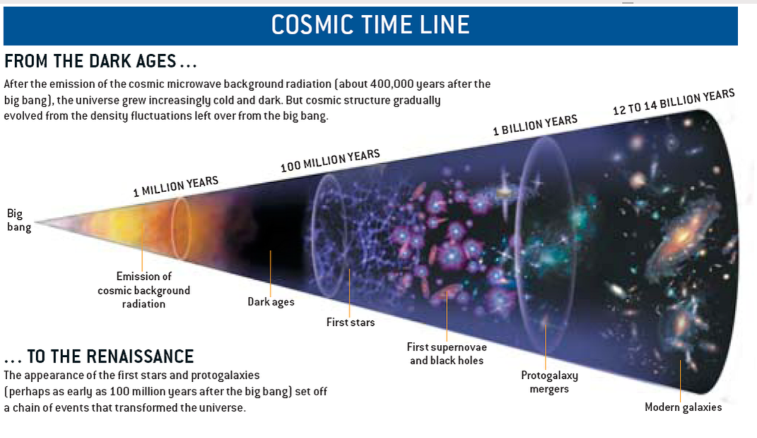
Structure formation in the universe

z= 18.3	5.7	1.4	0.0
t= 0.21	1.0	4.7	13.6 Gyr



Summary and conclusions





The history of the universe

Types of Matter

CONTENTS OF THE UNIVERSE include billions of galaxies, each one containing an equally mind-boggling number of stars. Yet the bulk of matter seems to consist of dark matter, whose identity is still uncertain. The cosmological constant, if its existence is confirmed, would act like a yet more exotic form of dark energy on cosmological scales. The quantity omega (Ω) is the ratio of the density of matter or energy to the density required for flatness. —*L.M.K.*

TYPE	LIKELY COMPOSITION	MAIN EVIDENCE	APPROXIMATE CONTRIBUTION TO Ω
VISIBLE MATTER	Ordinary matter (composed mainly of protons and neutrons) that forms stars, dust and gas	Telescope observations	0.01
BARYONIC DARK MATTER	Ordinary matter that is too dim to see, perhaps brown or black dwarfs (massive compact halo objects, or MACHOs)	Big bang nucleosynthesis calculations and observed deuterium abundance	0.05
NONBARYONIC DARK MATTER	Exotic particles such as "axions," neutrinos with mass or weakly interacting massive particles (WIMPs)	Gravity of visible matter is insufficient to account for orbital speeds of stars within galaxies and of galaxies within clusters	0.3
COSMOLOGICAL DARK ENERGY	Cosmological constant (energy of empty space)	Microwave background suggests cosmos is flat, but there is not enough baryonic or nonbaryonic matter to make it so	0.7

REPORT CARD FOR MAJOR THEORIES

Concept	Grade	Comments
The universe evolved from a hotter, denser state	A+	Compelling evidence drawn from many corners of astronomy and physics
The universe expands as the general theory of relativity predicts	A–	Passes the tests so far, but few of the tests have been tight
Dark matter made of exotic particles dominates galaxies	B+	Many lines of indirect evidence, but the particles have yet to be found and alternative theories have yet to be ruled out
Most of the mass of the universe is smoothly distributed; it acts like Einstein's cosmological constant, causing the expansion to accelerate	B–	Encouraging fit from recent measurements, but more must be done to improve the evidence and resolve the theoretical conundrums
The universe grew out of inflation	Inc	Elegant, but lacks direct evidence and requires huge extrapolation of the laws of physics

the quintessential UNIVERSE

The universe has recently been commandeered by an invisible energy field, which is causing its expansion to accelerate outward

STRUCTURE

The visible universe could lie on a membrane floating within a higher-dimensional space

the Universe's unseen DIMENSIONS

BY NIMA ARKANI-HAMED, SAVAS DIMOPOULOS AND GEORGI DVALI

ILLUSTRATIONS BY BRYAN CHRISTIE DESIGN

DESTINY

Scientists may soon glimpse the universe's beginnings by studying the subtle ripples made by gravitational waves

Echoes from the big bang

BY ROBERT R. CALDWELL AND MARC KAMIONKOWSKI

the fate of life in the universe

BILLIONS OF YEARS AGO THE UNIVERSE WAS TOO HOT FOR LIFE TO EXIST. COUNTLESS AEONS FROM NOW, IT WILL BECOME SO COLD AND EMPTY THAT LIFE, NO MATTER HOW INGENIOUS, WILL PERISH

BY LAWRENCE M. KRAUSS AND GLENN D. STARKMAN

REGORY LAUGHLIN *University of Michigan at Ann Arbor;*
AN; TIME LINE BY MARK CLEMENS

Thank You !