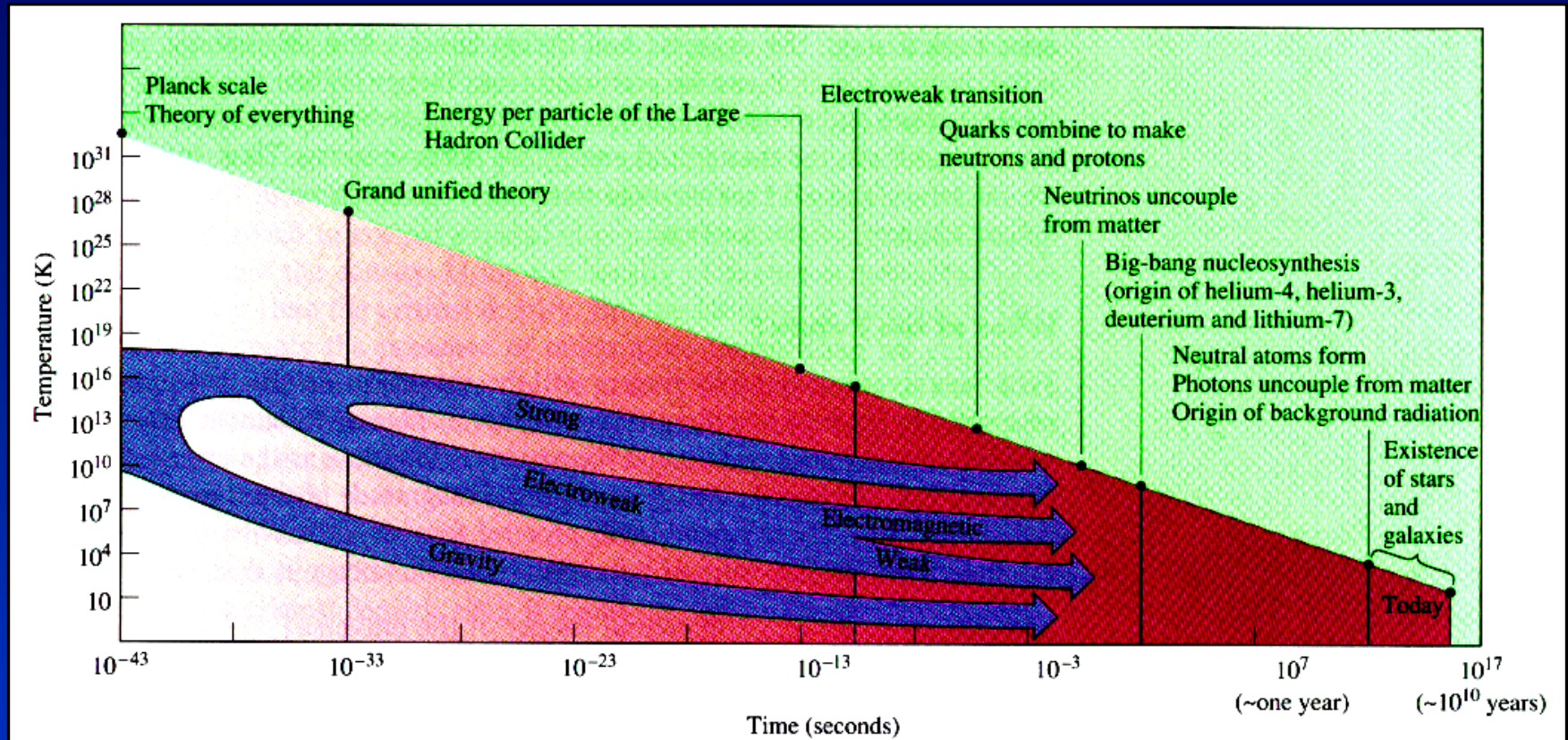


Ultralarge \leftrightarrow Ultrasmall

PARTICLE PHYSICS & COSMOLOGY



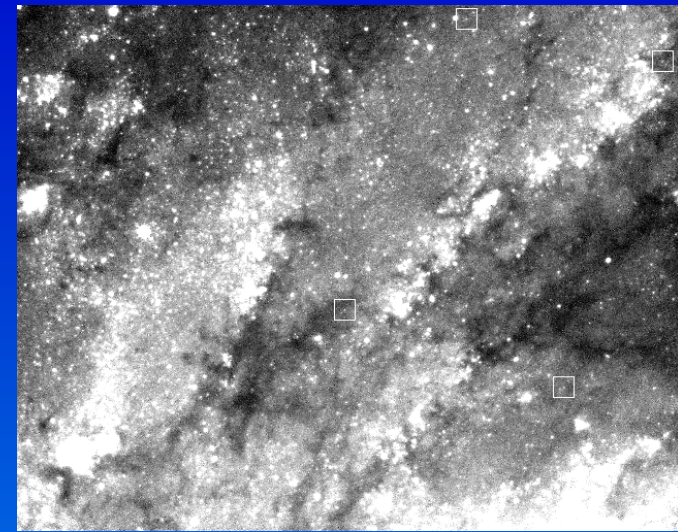
The energies needed to probe the unification of the forces are beyond our reach- at 10^{16} times higher than at CERN! They only ever existed once- right after the big bang. The physics at such energy scales (energy here in temperature units, with $1 \text{ eV} \sim 11,600 \text{ K}$) is shown along with the time when the universe was at this temperature. Note the unification of Strong & Electroweak forces at 10^{28} K , & the unification of weak & EM to make electroweak at 10^{16} K (the CERN LHC works at this energy). We believe gravity unifies Somehow with the others at $\sim 10^{33} \text{ K}$. In the very early universe can we probe this physics

Cosmic Distance & Time Scales

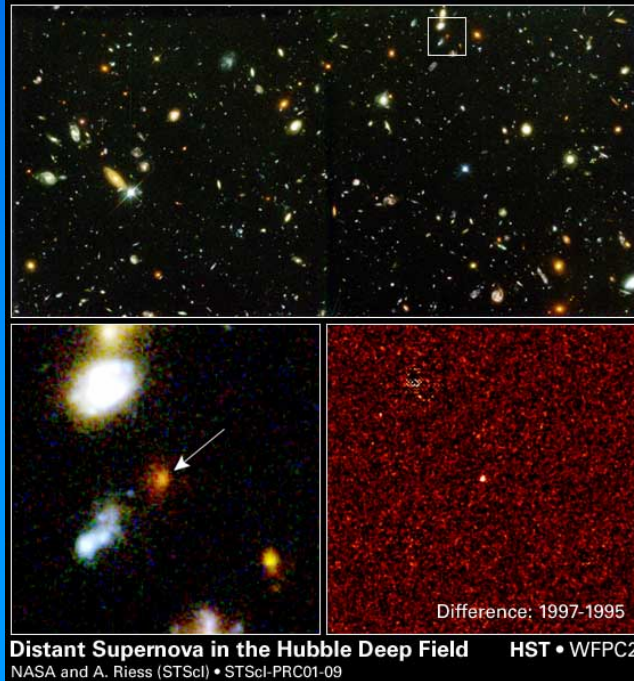


NGC 4603, @ 108 million lt. yrs

When we look out to great distances we also look back in time. So we need to measure large distances – this not easy. Cepheids play a crucial role- these giant pulsating stars have a pulsation period simply & accurately related to their luminosity. They can be seen out to $\sim 10^8$ light yrs with modern telescopes- we know their real luminosity because some Cepheids are near enough to have their distances measured in other ways (parallax, etc).



ABOVE: Close-up of NGC 4603- some Cepheids are identified in boxes



Distant Supernova in the Hubble Deep Field HST • WFPC2
NASA and A. Riess (STScI) • STScI-PRC01-09

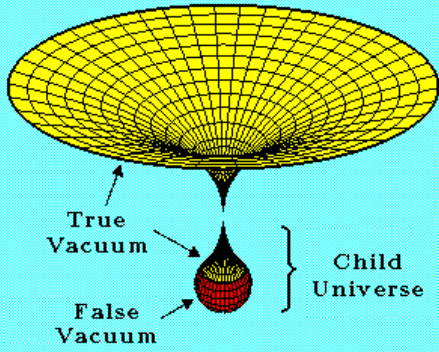
At much greater distances one relies on supernovae, whose luminosity is known fairly accurately from their spectra. These are so bright they can be seen as far as the farthest galaxies.

From all this work we find that the radius of the visible universe is ~ 14 billion (1.4×10^{10}) light years, & the age of the universe is thus $\sim 1.4 \times 10^{10}$ yrs

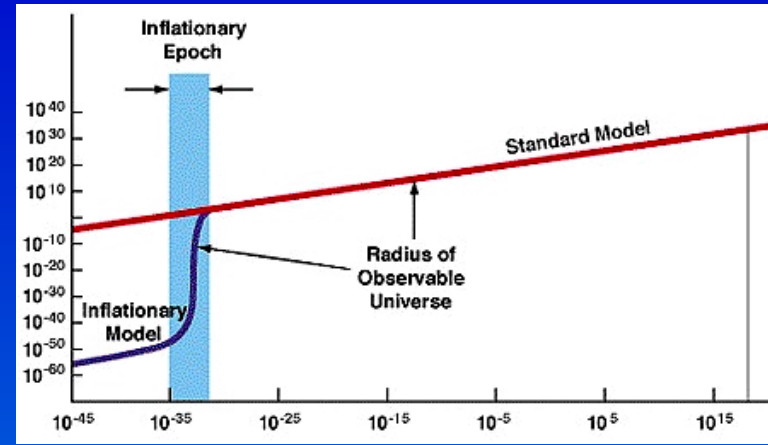
LEFT: Supernova in HST deep field- note difference between 1996-7.

Theories of the Early Universe

Creation of a Child Universe From a False Vacuum Bubble



Theories of the early universe try to combine ideas about string and/or particle physics with gravity theory. This is hard without a proper quantum theory of gravity. There are very strong theoretical reasons for a modified Big Bang which begins with the quantum tunneling of all of spacetime from a 'false vacuum'



Size of early universe plotted against time

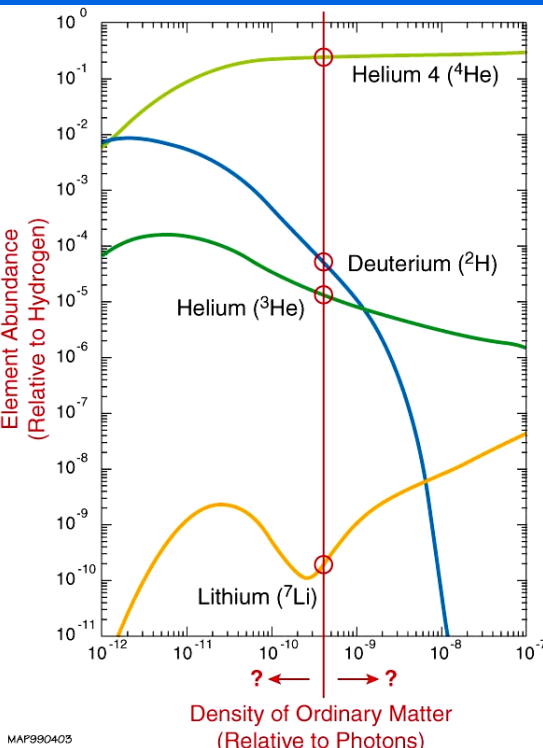
state into the present universe (in a way reminiscent of the nucleation of a new phase) followed by An extremely fast expansion, or 'inflation' (above), and finally a long period of Hubble expansion, still going on. The idea of inflation is due to Guth.



Alan Guth (1947-)

The timeline of the very early universe can only be surmised theoretically, from the standard model of high-energy physics (cf slides 5.21-5.27). On slide 5.30 the timeline of this expansion is shown – as the universe rapidly expanded it cooled, & after the various forces & particles were produced, nuclei began to be synthesized about 1 sec after the Big Bang. Initially this involved protons and electrons, but these collided to form He & Li nuclei. This stopped after 3 minutes when the thermal energy was too low, producing the initial concentrations of H, He, and Li nuclei in the primitive universe.

For a long time after this the primeval soup of photons, electrons, neutrinos, & light nuclei cooled from many billions of degrees down to a few thousand. At this Point, between 372,000 - 387,000 yrs after the Big Bang, a remarkable transformation occurred - the universe became transparent (next page)

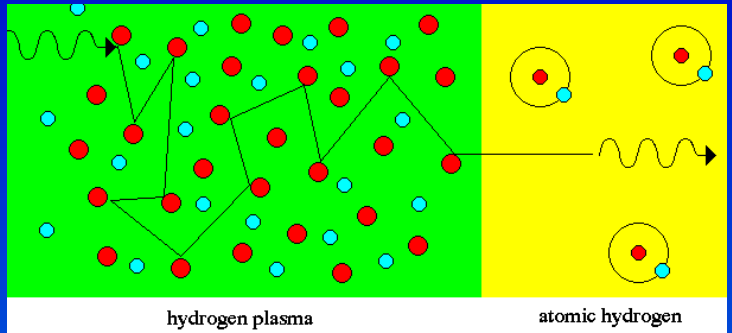


Cosmic Abundance of early nuclei

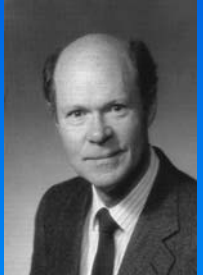
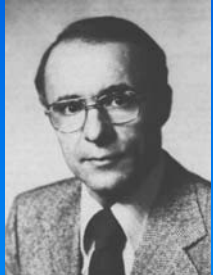
MAP980403

Radiation-Matter Decoupling: the Microwave Background

The sudden transparency of the universe after nearly 300,000 yrs came from the decoupling of matter and photons. The basic idea is shown at right. In the early hot universe, all the H, He, and Li were ionized - a 'plasma of nuclei and electrons. However as they cool they eventually bound into an expanding gas of neutral atoms. The plasma was opaque to photons - they scatter off the charged particles - but the neutral gas was almost transparent. Thus roughly 300,000 yrs after the Big Bang, the radiation decoupled from the matter, and has been traveling almost freely ever since, through and around the H, He, and Li.



Photon propagation before and after decoupling



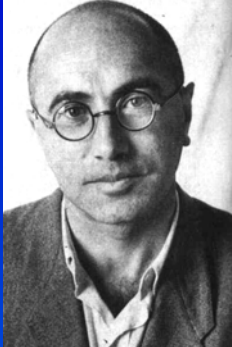
A Penzias (1933-)

R Wilson (1936-)

The expansion of the universe, since then, has cooled both these photons, & the condensed gas, down to 2.7 K - the universe is full of photons at this temperature. In the late 1940's it was realised by Gamow & Alpher that this 'microwave background' ought to exist in the universe, and that it would constitute a relic of the conditions in the early universe, at the time of decoupling. This work was mostly ignored at that time.

The discovery of the 'microwave background' by Penzias & Wilson in 1964, using a new microwave detector they had developed, thus provided dramatic evidence for the Big Bang, & stimulated a new era in cosmological research.

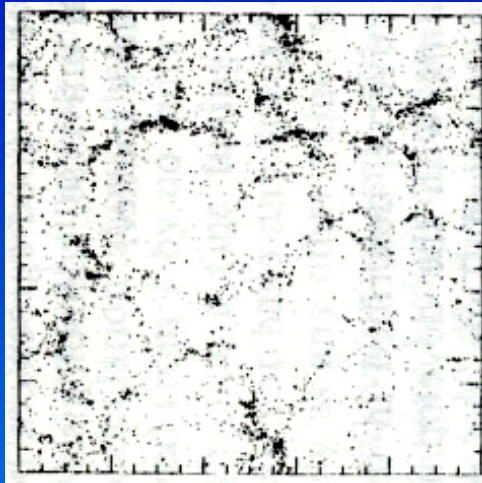
Since 1964 two important themes in 'cosmology' (the study of the properties & evolution of the universe at these cosmic scales) have been the changing constitution of all the matter in the universe (starting with nucleosynthesis in the early universe, followed by nucleosynthesis in stars - see pp. 5.11-5.17), & the changes in large-scale structure. This latter study brings together particle physics & general relativity, in the new field of relativistic astrophysics.



YB Zeldovich (1914-1984)

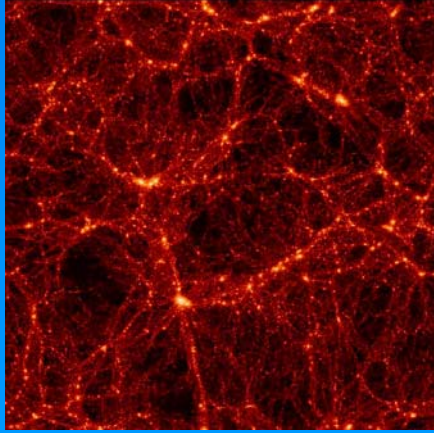
FLUCTUATIONS in the MICROWAVE BACKGROUND

Beginning in the late 1950's, the remarkable self-taught Soviet theorist Zeldovich pioneered a large part of relativistic astrophysics, exploring the role of general relativity in high-energy phenomena such as supernovae, black holes, & the early universe. Among his many contributions was the prediction that quantum fluctuations in the energy density of the early universe, around the time of radiation-matter decoupling, would determine the later distribution of matter in the universe – these small fluctuations would act as 'seeds' for the latter collapse of matter into galaxies. Remarkably, this would lead to a 'filament-like' structure for the distribution of galaxies in the universe. Moreover, one would be able to see the initial fluctuations even now, because they would be 'frozen' into the microwave background at the time of decoupling.

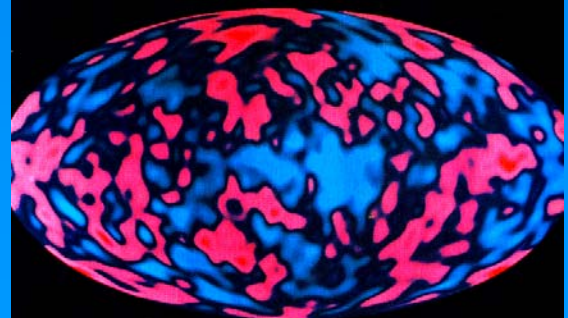


Predictions of mass distribution from Zeldovich theory

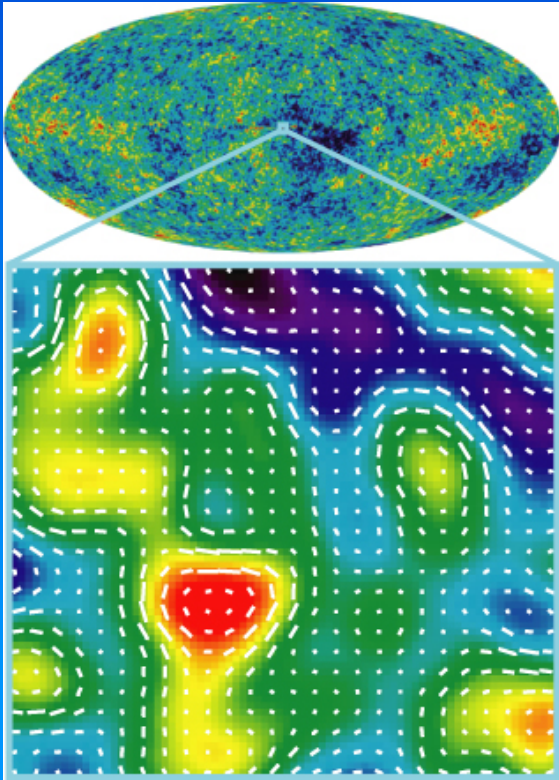
Much work since then has confirmed Zeldovich's basic ideas. Observations of the distribution of galaxies both now & in the distant past (back to when the galaxies first formed, revealed by deep space photos of supernovae & galaxies), show the predicted pattern of voids & filaments. Fluctuations in the microwave background, mapped in great detail, confirm the inflationary universe picture



Mass distribution in universe, including dark matter



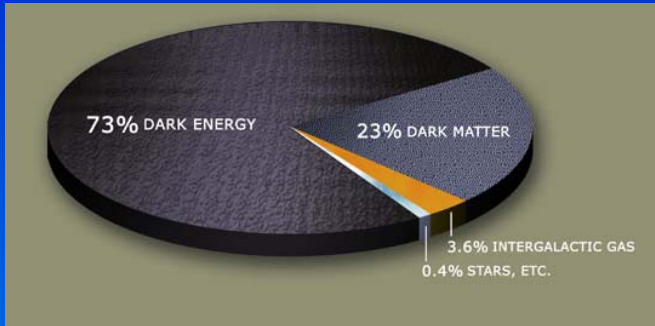
Results from the COBE observations



The WMAP observation of the microwave background – the blow-up shows the polarisation

The MYSTERY of DARK MATTER

One of the nicest things about science is the way quite unexpected phenomena turn up, flatly contradicting accepted views. The existence of a hidden component of the universe first showed itself in the peculiar dynamics of the outer parts of galaxies



Pie chart: the constituents of the universe

Less than 5 % of the universe is in the form of visible matter.



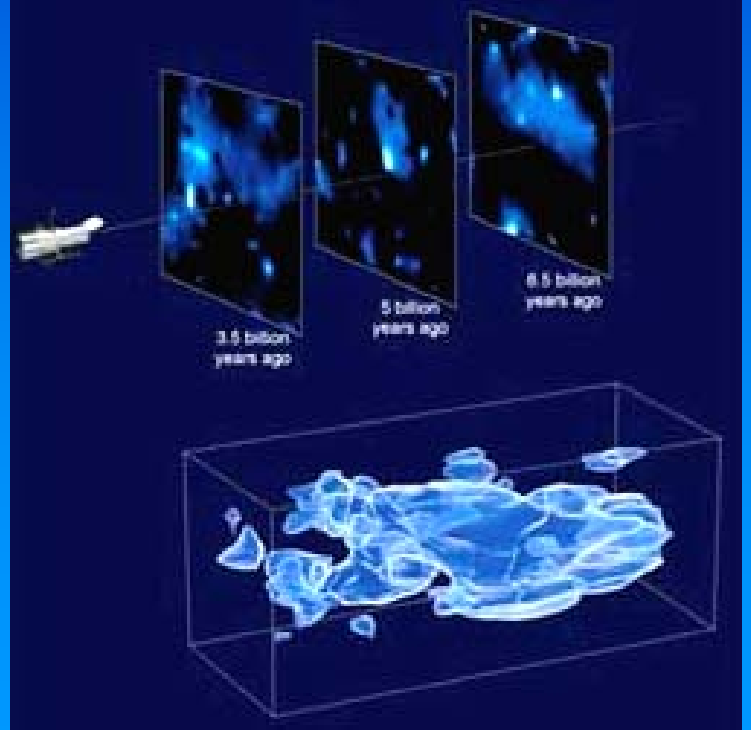
CI 0024+17 galaxy cluster: dark matter distribution

(which rotated much faster than they should). We now have v. extensive evidence for this 'dark' component (it bends light & holds clusters of galaxies together), with a fermionic part called 'dark matter' and a

bosonic part called 'dark energy'. We still do not know what dark matter is - ideas range from new particles, eg 'axions', to more traditional neutrinos, & 'junk' (brown dwarfs, planets, neutron stars). This accounts for only ~25% of the total mass. The remaining dark energy is, right now, a complete mystery. It has a crucial effect on the evolution of the universe (next slide)



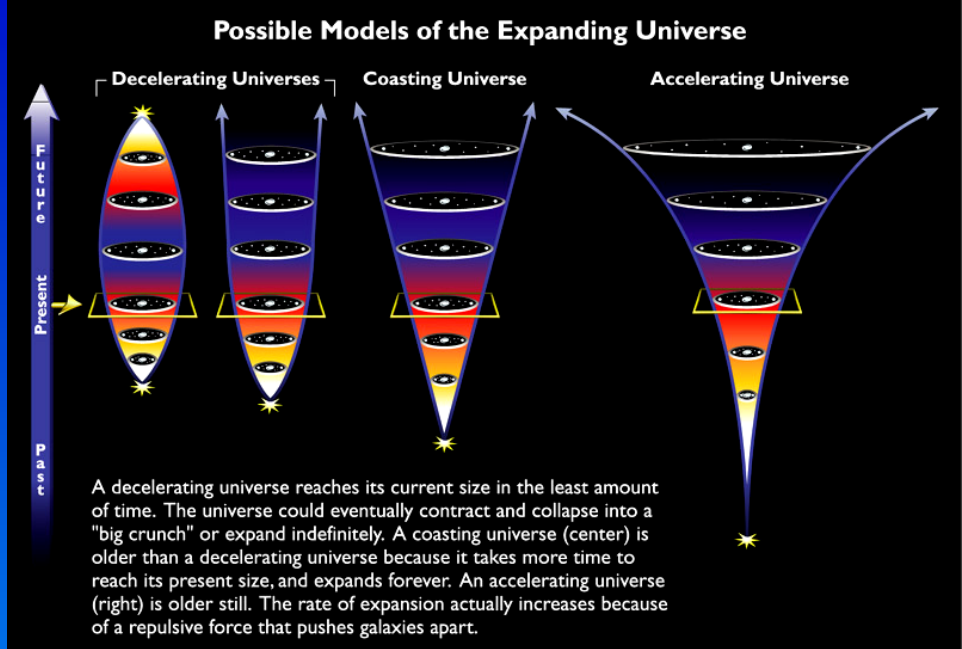
1E 0657-57 'Bullet cluster' of galaxies. Matter distribution in red, dark matter: blue.



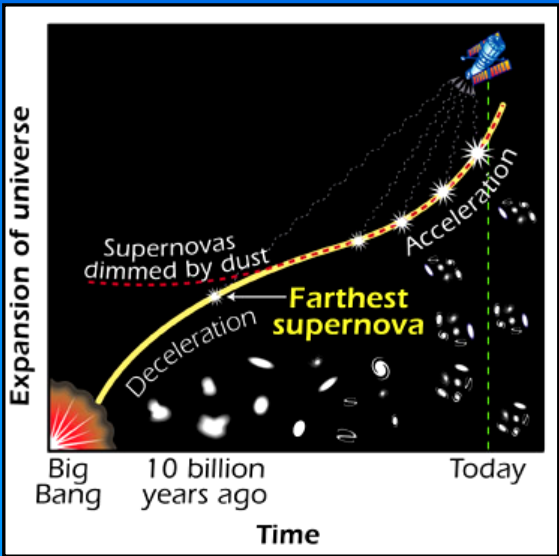
Distribution of dark matter along one direction. Nearer (more recent) matter is 'clumped'

FUTURE EVOLUTION of the UNIVERSE

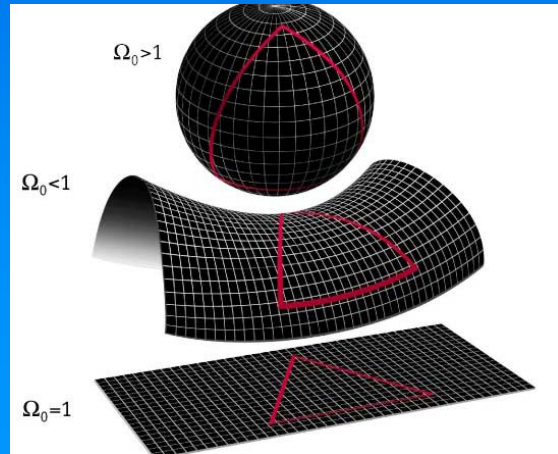
What eventually happens to universe depends on its mass/energy density. Without dark matter it Would not be self-gravitating, and would go on expanding indefinitely, and eventually die out completely. However dark matter changes this. Much effort is now being invested in measurements of the distances oand desntities of objects far in the past, including distant supernovae, and at present, to try & deduce if the universe is 'closed (ie., will fall back on itself) or open (with an accelerating expansion). The verdict on this is still not in yet.



ABOVE: different possible long-term evolutions for the universe



Recent measurements indicate the expansion of the universe may even be accelerating, due to a 5th force (quintessence)



The forn of spacetime in a closed universe (top) an open universe, & a flat universe (bottom)

This field is full of speculation, including the idea that our universe is only one of a very large number of 'multiverses' which have nucleated from false vacua (see below).

