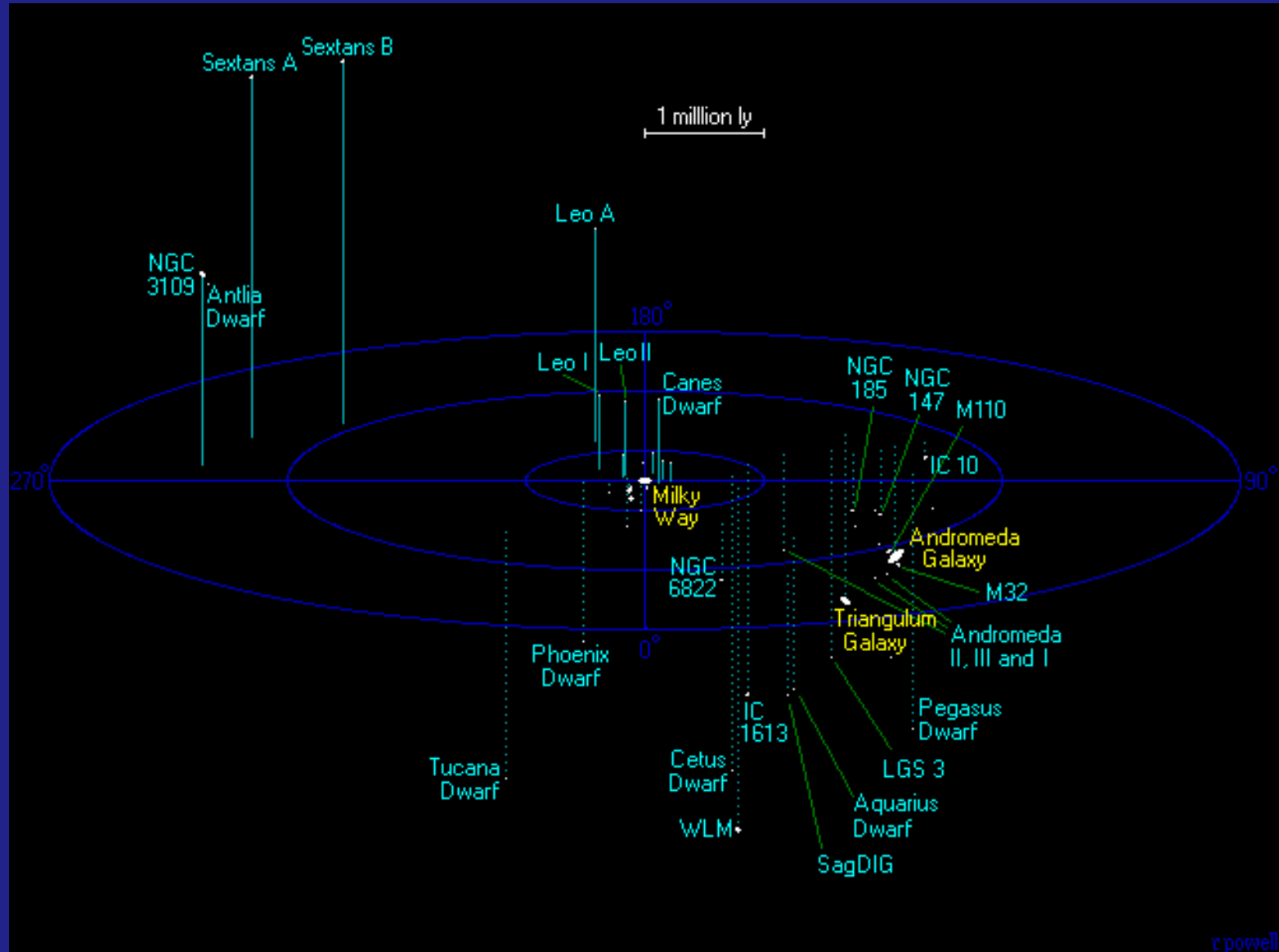


Map of the Local Group

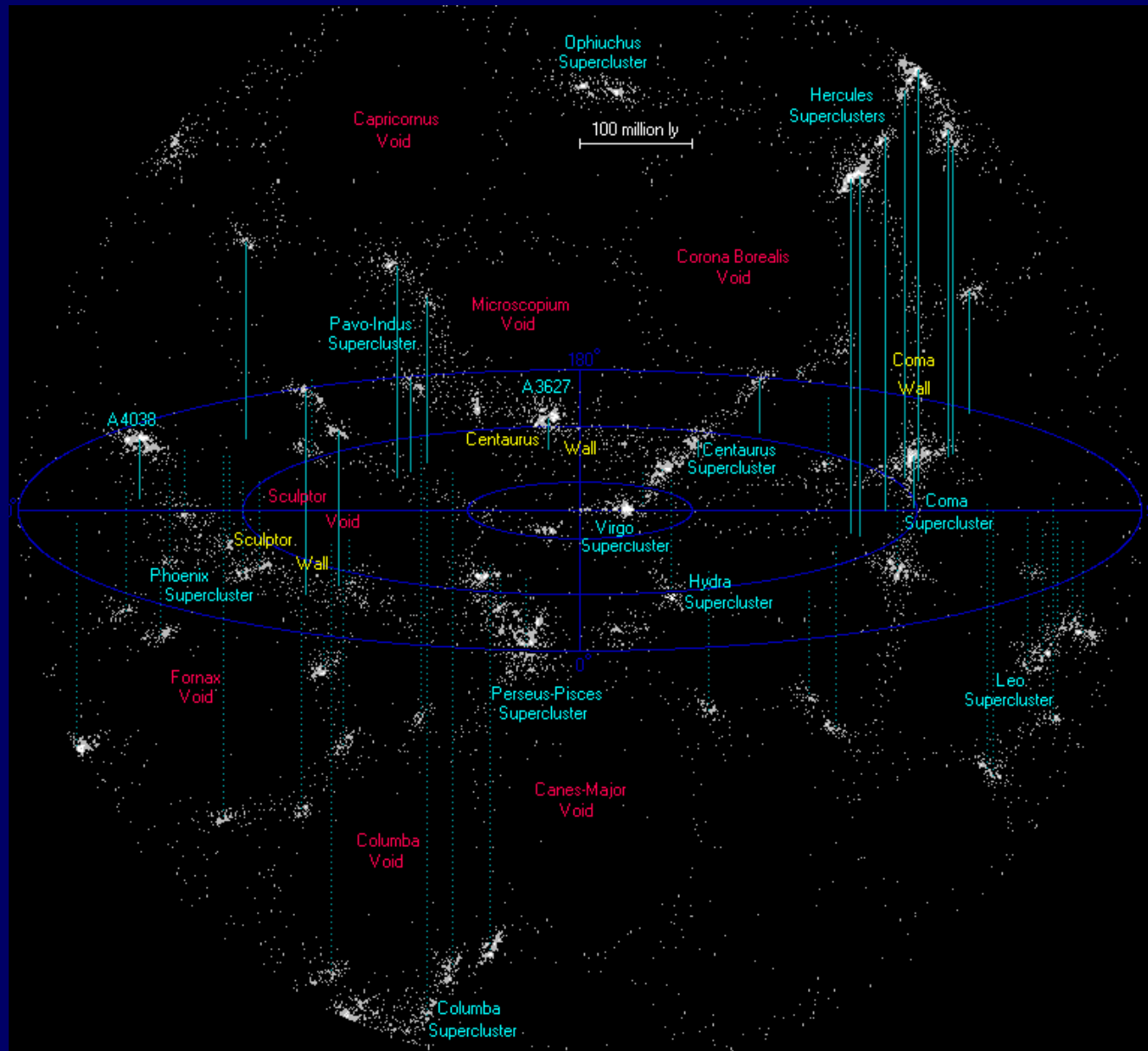
The Earth orbits the Sun - a star - one of 10^{11} in our milky way galaxy.



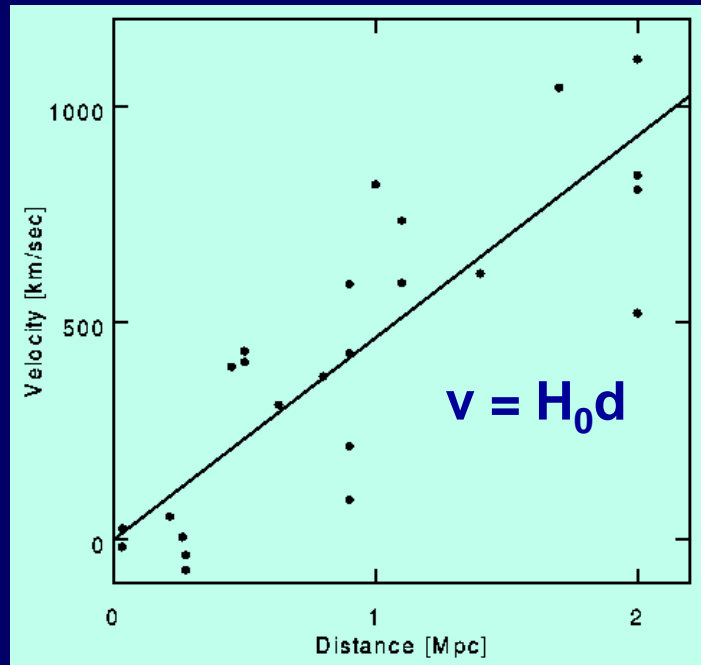
The Large Scale Structure of the Universe

Scale $1:4 \times 10^{24}$

An
expanding
foam of
galaxies
and clusters
of galaxies.



Hubble's original diagram showing velocity \propto distance



Implication - the universe is

expanding

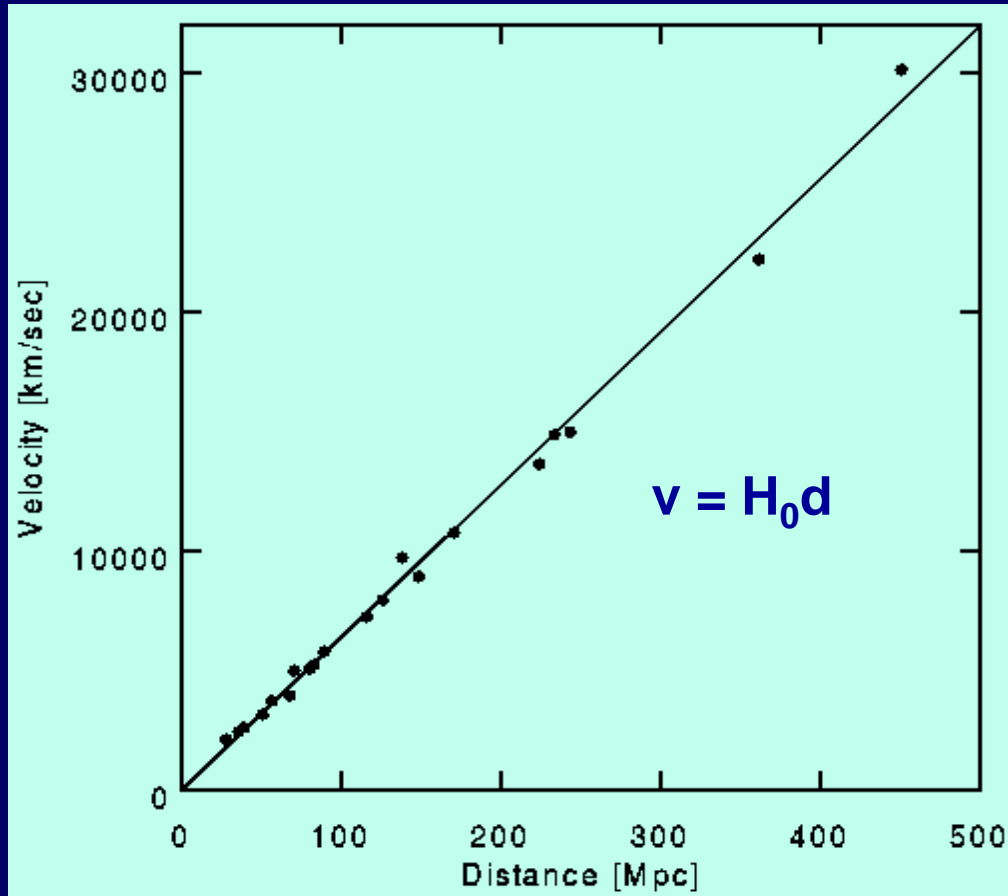
(See the 'elastic' universe model – we don't have to be at the centre)

The gradient or slope of this graph tells us the expansion rate of the universe, H_0 .

Here, $H_0 = 500 \text{ km/sec} / \text{Mpc}$

i.e. speeds increase by 500 km/s for every Mpc in distance.

A more accurate recent diagram, here, $H_0 = 67 \text{ km/s/Mpc}$



In the past galaxies were closer together - the universe was then **denser**.

The inverse of the slope of the graph (distance/velocity) shows that the time since **the beginning** of the expansion - **The 'Big-Bang'** - was about **14 billion years ago**.

The previous diagram gave 'only' 2 billion years – younger than the Earth!!

We can use General Relativity theory to predict the evolution of the universe with time.

The predictions depend on the density of matter and energy in the universe.

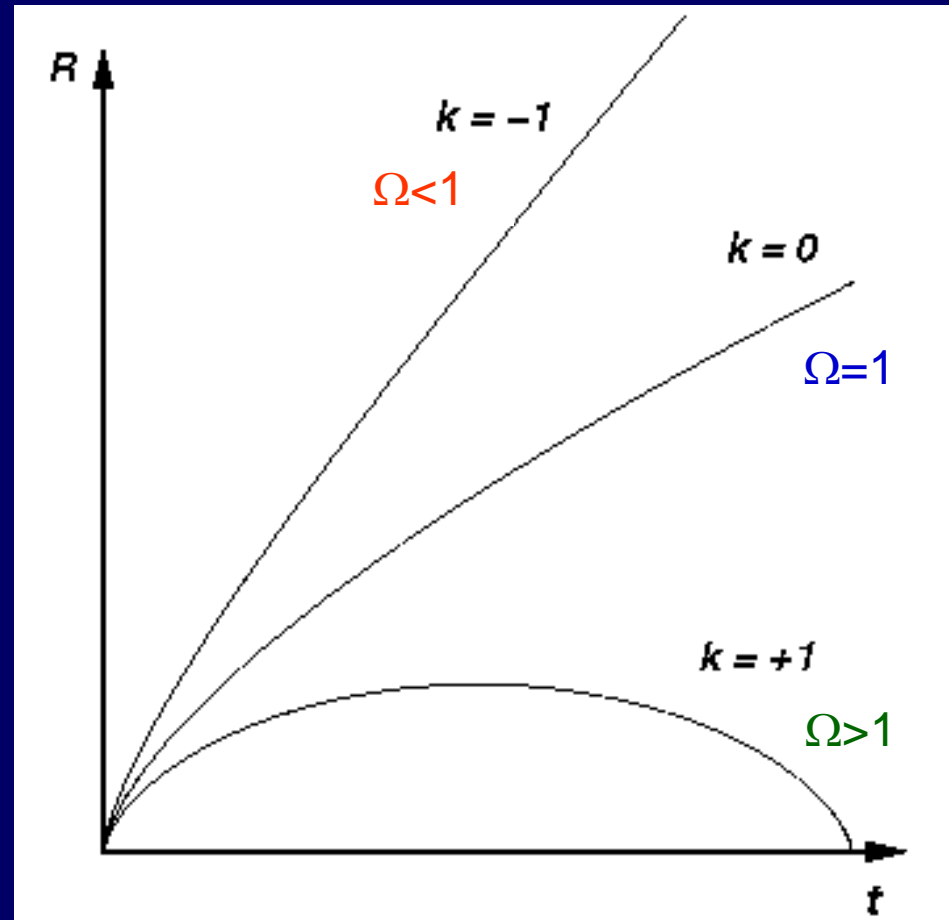
Parameterised by the Omega factor, Ω

Standard Models - gravitating matter causes the expansion to decelerate.

open = low density $\Omega < 1$

critical = critical density, 'flat' geometry $\Omega = 1$

closed = high density $\Omega > 1$



But which universe do we inhabit?

Do we know the density of the universe?

The Omega Factor

For a universe containing only gravitating mass:

If $\Omega < 1$ the universe is open ('saddle' type geometry)

If $\Omega > 1$ the universe is closed (spherical geometry)

If $\Omega = 1$ the universe has critical density and 'flat' geometry

What we find:

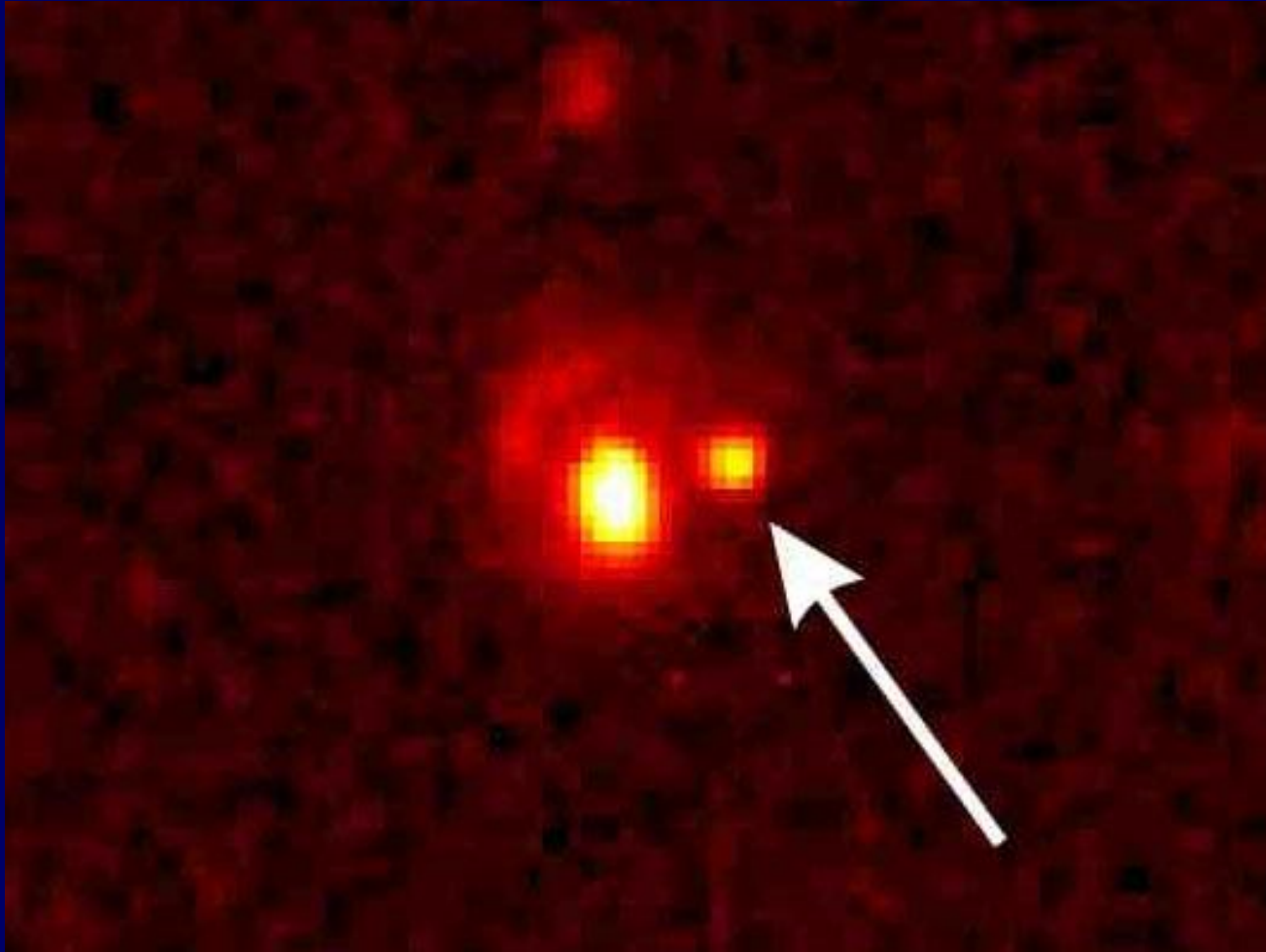
Visible matter in galaxies $\Omega_{\text{vis}} = 0.01$

Galaxy dynamics $\Omega_{\text{gal}} = 0.02 \text{ to } 0.04$ (rotation curves)

Dynamics of galaxy clusters $\Omega_{\text{m}} = 0.3$ (motions within clusters)

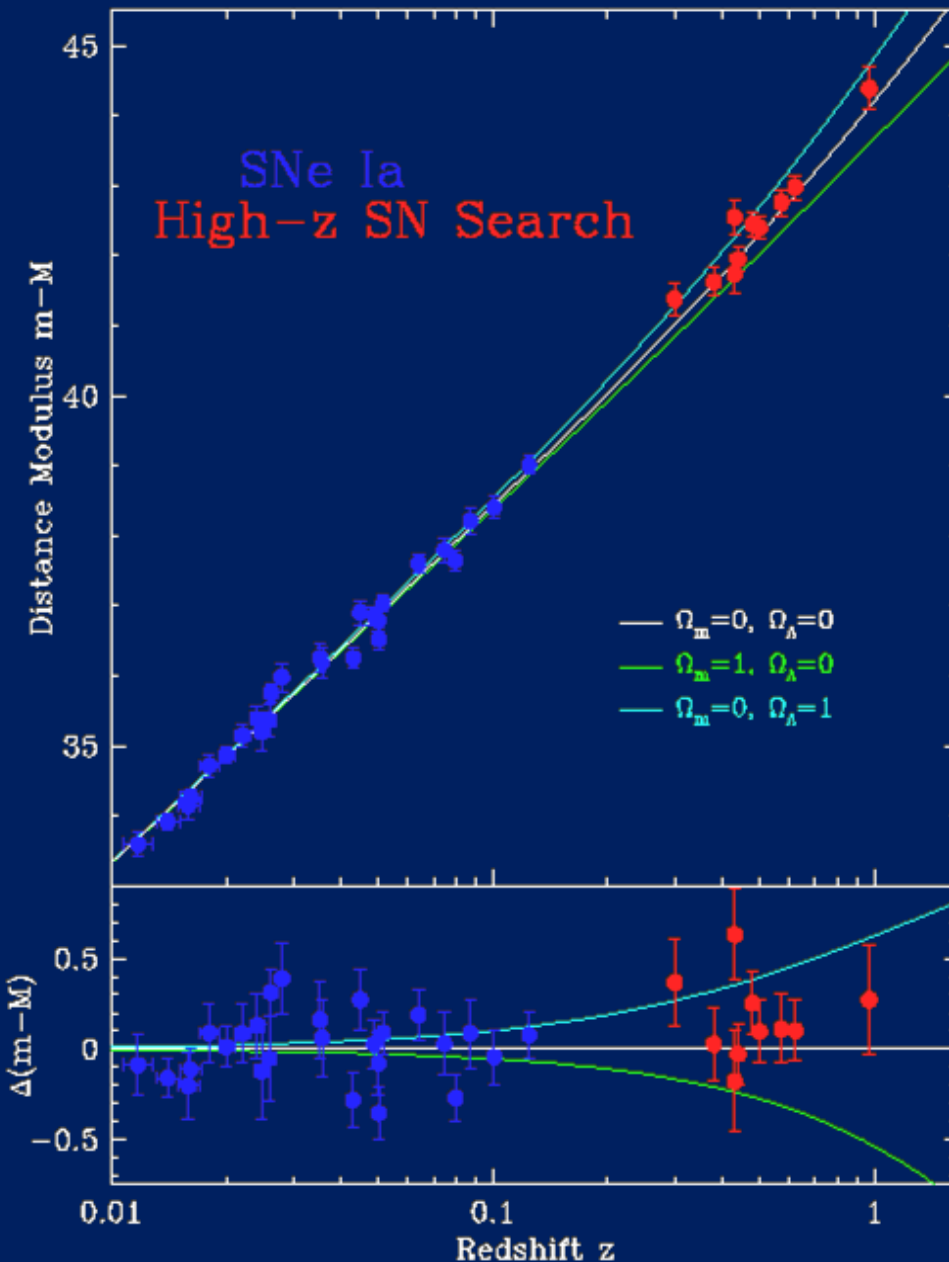
There is a lot of Dark Matter out there!! — we will see later that there is convincing evidence to suggest that most of this is in some form of 'exotic' i.e. non-atomic mass.

Extending the Hubble diagram to high redshifts – distances become difficult to determine....need 'standard candles'



A distant supernova ~ 10 billion light years away

Recent Hubble diagrams using high redshift supernovae

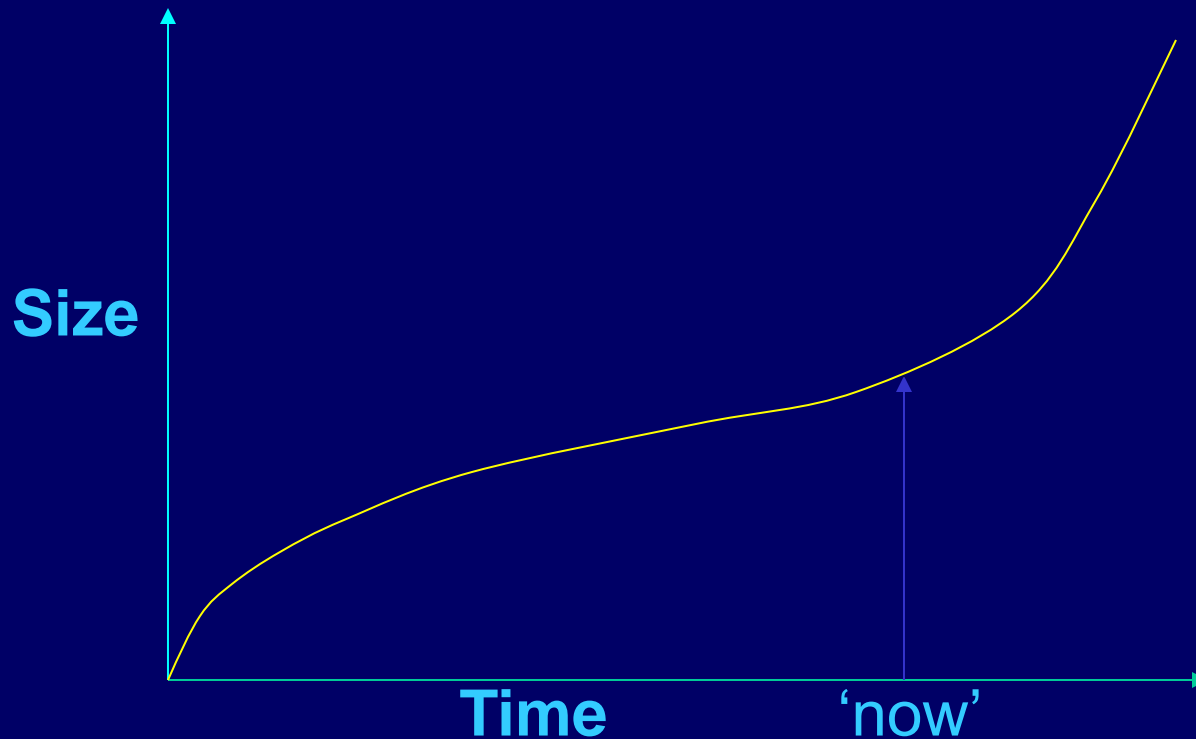


We know that Ω_m is at least 0.3 so to fit data we need a vacuum energy component about twice as great to 'lift' predicted curve back to data.

The best fit is $\Omega_T = 1$ (flat geometry) with gravitating mass $\Omega_m = 0.3$ and dark/vacuum energy $\Omega_\Lambda = 0.7$.

This particular model has a current age of 14 Gyr - consistent with all age constraints.

A recent model – the accelerating universe



A geometrically 'flat' universe - total $\Omega = 1$.

Made up of $\Omega_m = 0.3$ – gravitating matter (both 'ordinary' and 'dark matter') - plus $\Omega_v = 0.7$ - vacuum energy or 'dark energy'. Vacuum energy has the strange property of negative pressure which leads to an anti-gravitational effect and causes the expansion to eventually accelerate.

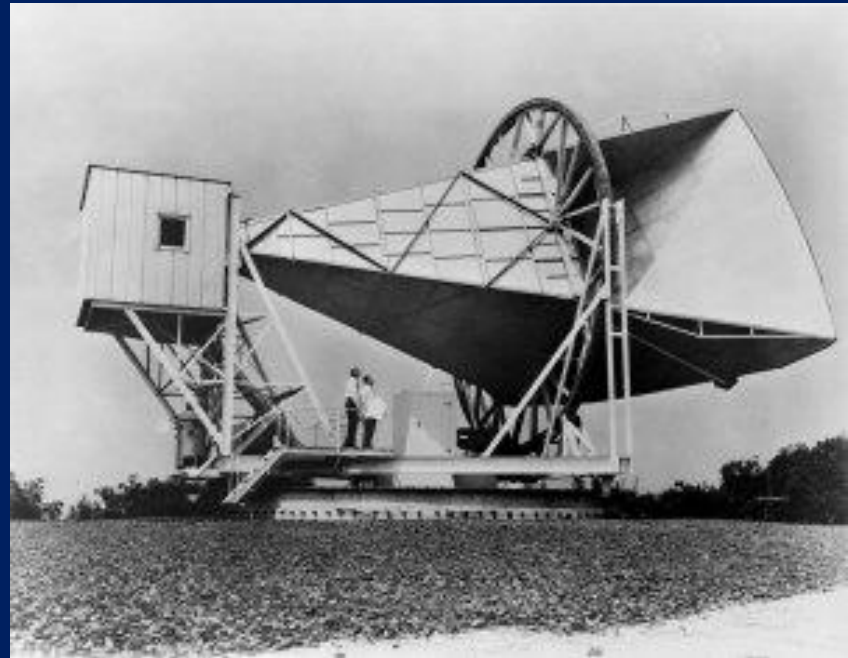
Other Evidence for a Big-Bang:

The Microwave Background

Reversing time the universe gets smaller - eventually galaxies cannot exist because the universe is too small - before this time we expect the universe to be full of radiation because it would be so hot. This radiation field still fills the universe and hence we should still be able to detect it. Because of expansion the temperature of this relic of the fireball phase of the universe is now only 2.7K - it was 3000K at the time.

Predicted first by Alpher, Gamow and Herman in 1948, later by Dicke , Peebles, Roll and Wilkinson in early 1960s.

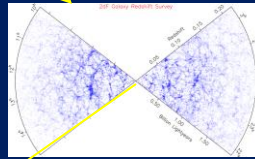
In 1965 the microwave radiation was discovered accidentally by Penzias and Wilson at the Bell labs – they received a Nobel prize (1978).



Map of the Observable Universe

Scale $1:10^{26}$

The 2dF galaxy redshift survey



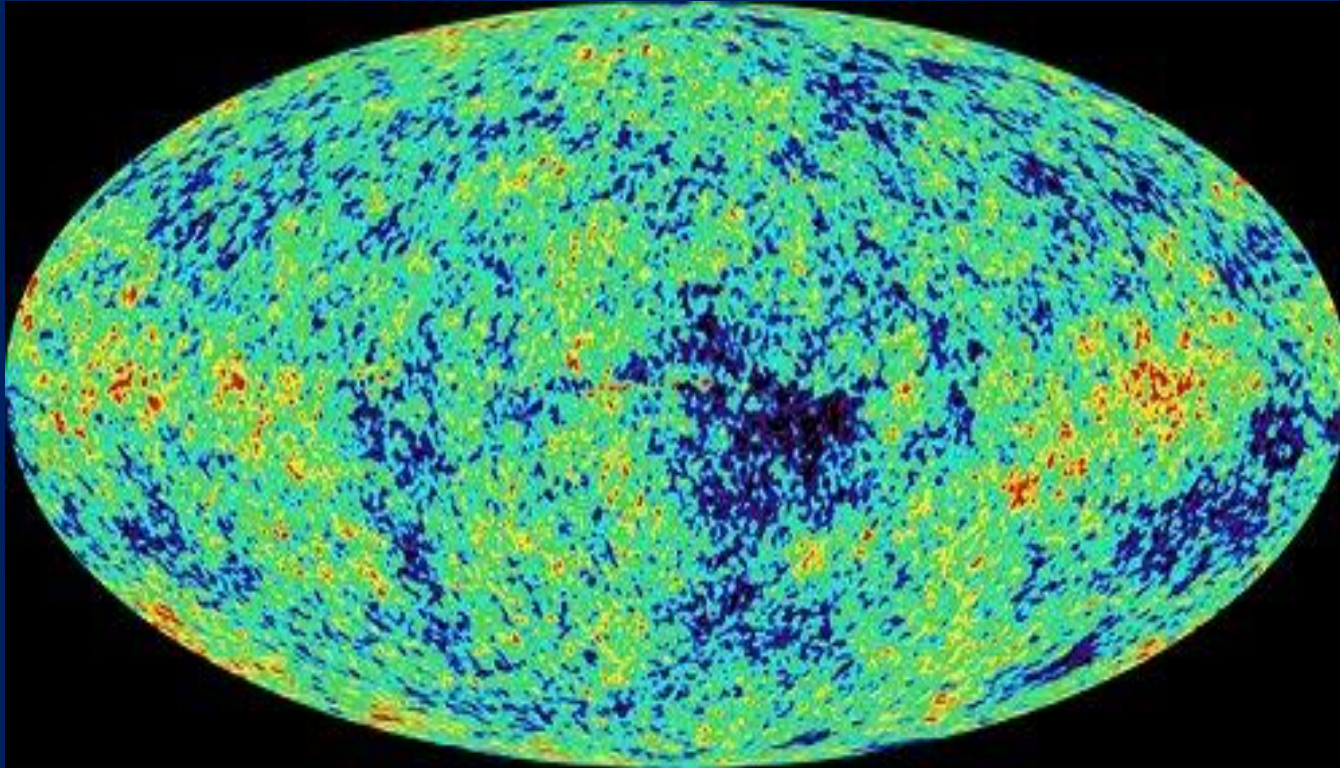
galaxies formed in here

14 billion light years

The microwave background

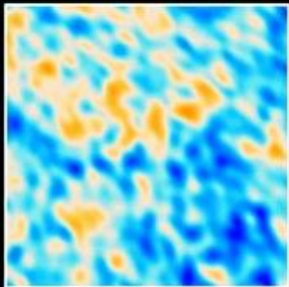
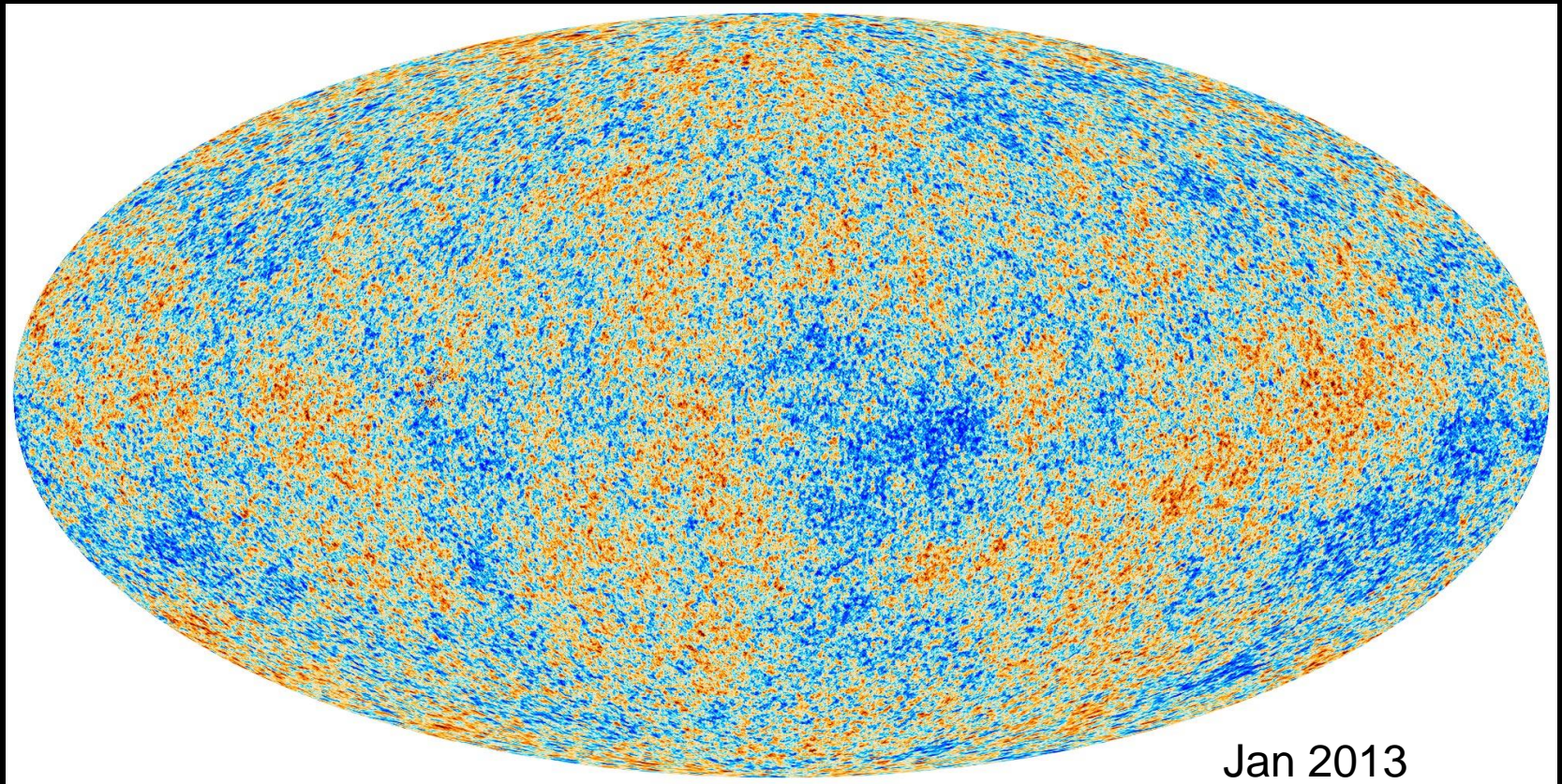
The horizon of the observable universe

Latest results from the WMAP satellite (NASA)

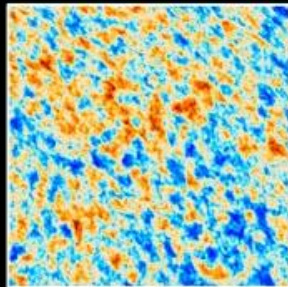


The Planck (ESA) satellite is currently building an even more detailed map.

Planck satellite – microwave background whole sky map - 2013.

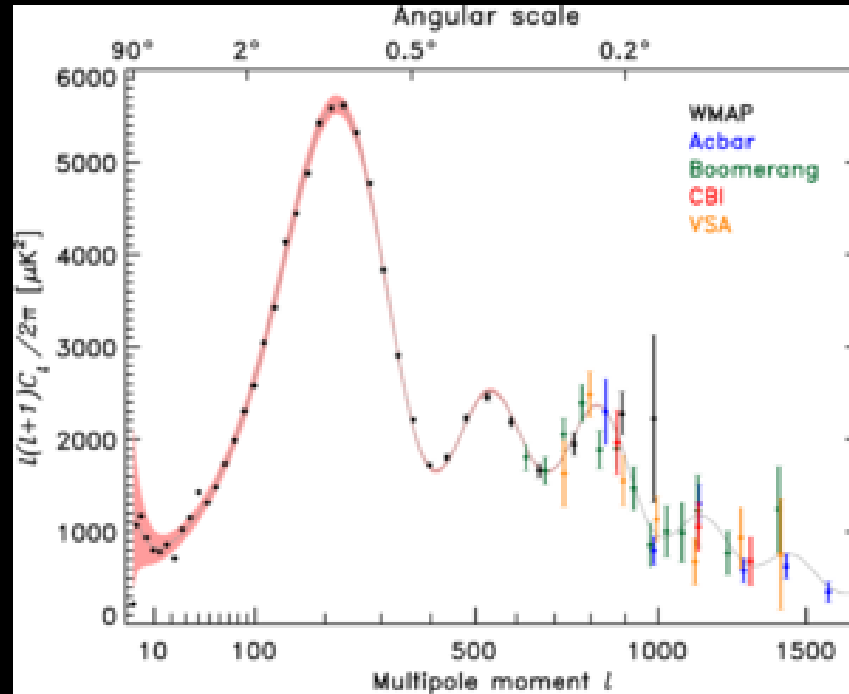
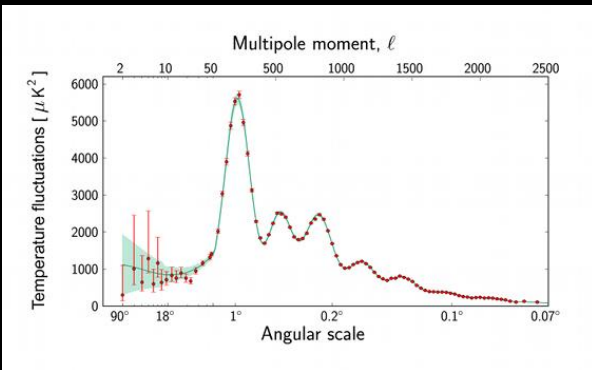


WMAP



Planck

Recent results from WMAP and other projects



‘Acoustic oscillations’ caused by matter within the horizon scale oscillating and changing density, hence temp.

The best fit is $\Omega_T = 1$ (flat geometry) with $\Omega_m = 0.32$ (normal $\Omega_b = 0.05$ + exotic mass $\Omega_{dm} = 0.27$), $\Omega_\Lambda = 0.68$ (dark/vacuum energy).

Consistent with the SN Hubble diagrams – too good to be true??

Studies of the clustering of very distant galaxies are trying to identify similar features in the galaxy distribution.

Before the microwave background:

The Radiation Era

Time	1sec	→	10^5 years
Temp	10^{10}K	→	10^4K
Density	10^8 kg/m^3	→	10^{-16} kg/m^3

Light Element Synthesis

During the first three minutes $T \sim 10^9\text{K}$

At this time there were 2 neutrons for every 14 protons

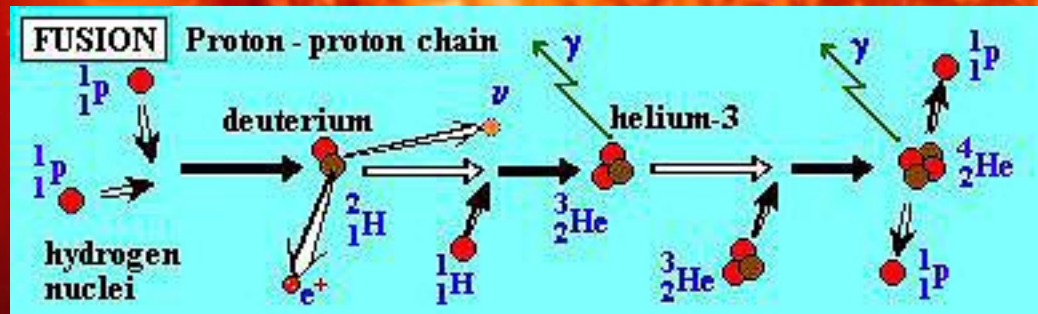
Helium nucleus = $2n+2p$ leaving 12p's

We end up with 1 He for 12p's (H)

Hence fraction of He $\sim 4/16 \sim 25\%$ by mass

This is what we actually observe as the Helium fraction of the universe! - the big-bang theory solved the long standing 'helium problem'.

Reactions occurring in the universe in the first few minutes are the same as those going on inside the sun now. The universe was like the inside of a star - everywhere!

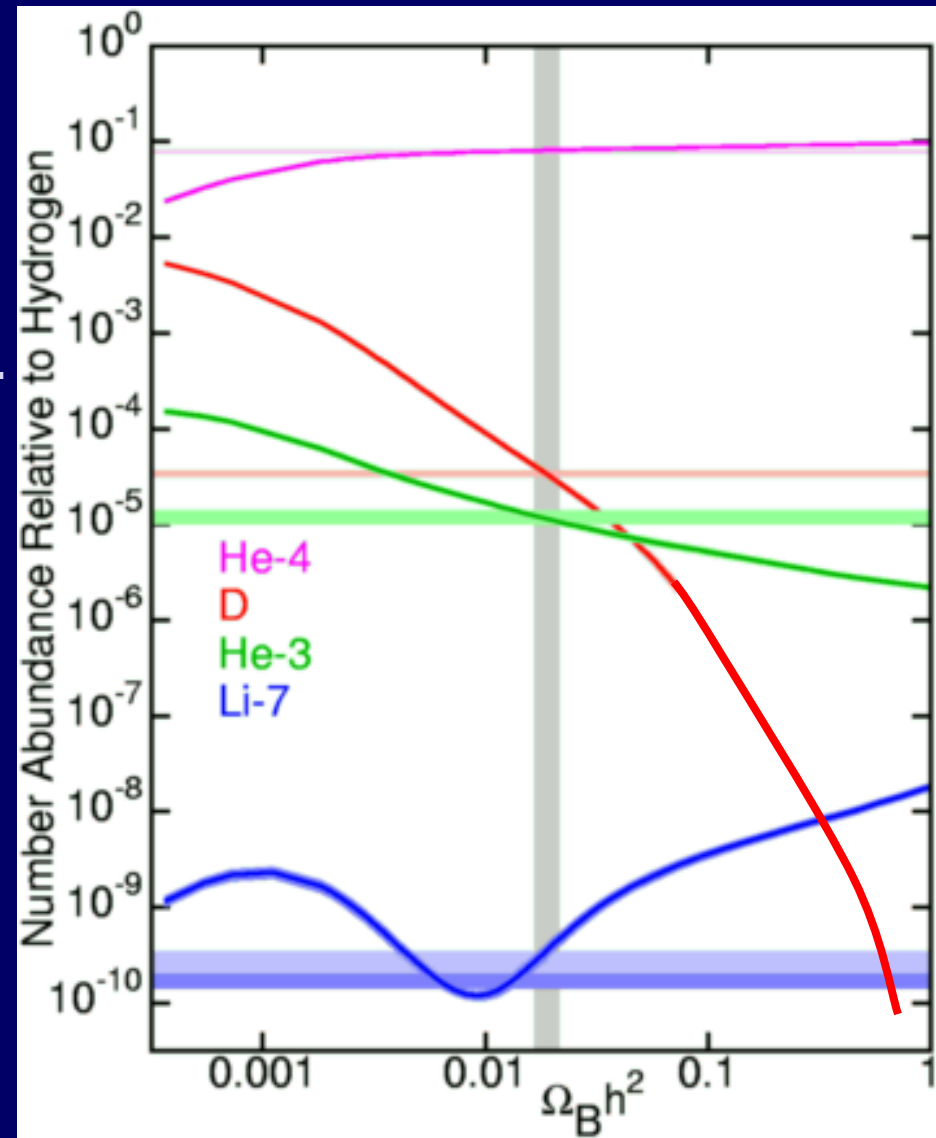


Nucleosynthesis of the light elements in the 'first three minutes' of the big-bang.

The abundance of Deuterium is very sensitive to the density of the universe.

Implies that the density of 'normal' matter $\Omega_b = 0.05$.

The difference between the above and $\Omega_m = 0.3$ from the cluster observations implies the existence of a large amount of 'exotic' dark matter.



WIMPs are being searched for at Boulby mine (Cleveland UK) as well as other places - Gran Sasso tunnel Italy, Soudan mine US, Sudbury Canada.

No conclusive detection yet.....

Some tantalising results from Fermi (gamma ray telescope in orbit) and PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) satellite and the AMS on the ISS.....excesses of positrons *maybe* from the decay of DM particles.

Anomalous X ray signals from the Sun *could* be evidence of Axions. X-ray data from M31 and Perseus Cluster *could* be evidence for sterile neutrinos.....

Hopes for the LHC continue.....

No conclusive detection yet – the nature of the dark matter is one of the biggest current cosmological mysteries.....

We are now going to talk about **The First Second**

You may think that this would not take long but the shorter the time period you look at in the early universe the longer it takes to explain what's going on!

The Leptonic Era

Time	10^{-4} sec	→	1second
Temp	10^{12} K	→	10^{10} K
Density	10^{16} kg/m ³	→	10^8 kg/m ³

Temperature is high enough for most of the radiation in the universe to be in the form of gamma rays - these can undergo e^- , e^+ pair production: $\gamma \rightarrow e^- + e^+ \rightarrow \gamma$ (since $hf > 2m_e c^2$)



Weak interactions in the leptonic era:

$$n + e^+ \rightarrow p^+ + \bar{\nu}$$

$$p^+ + e^- \rightarrow n + \nu$$

At $t = 1\text{s}$, the temperature T has fallen so $e^- + e^+ \rightarrow \gamma$ but not the reverse - the n/p ratio is 'frozen' (at $1/7$ as discussed earlier) and neutrinos 'decouple'

Leads to the possibility of a **cosmic neutrino background** from this era - a future branch of observational cosmology.

Because of their higher mass the other Leptons will annihilate each other at earlier times as do the baryons (e.g. protons/anti-protons at $t = 10^{-6}\text{ s}$ in the Hadronic Era - see later)

So why is the universe today not just radiation?

The Antimatter Problem

Possible solution - in the even earlier universe there was a slight imbalance or **asymmetry in the particle reactions** leading to 10^9+1 matter particles for every 10^9 anti-particles. After annihilation we therefore get $\sim 10^9$ photons for every matter particle - we observe $\sim 10^9$ photons/m³ in the microwave background and ~ 1 p⁺/m³ in particles.

Such asymmetries are seen in certain particle decays - K mesons - and are predicted by certain Grand Unified Theories (see later) - this is currently an area of very active research e.g. BaBar at SLAC.

The same asymmetry applies to the e⁻/e⁺ annihilation discussed above.

If it wasn't for this slight imbalance of 1 part in a billion not much would happen after $t = 1$ s - the universe would now consist of just the microwave background - galaxies, stars, planets and certainly humans wouldn't be here!!

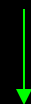
FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c ²	Electric charge
ν_e electron neutrino	$<1 \times 10^{-8}$	0
e electron	0.000511	-1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	-1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	-1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c ²	Electric charge
u up	0.003	2/3
d down	0.006	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	175	2/3
b bottom	4.3	-1/3

Quarks



Hadrons

3q = **Baryons**

2q = **Mesons**

e.g.

proton = 2u + 1d

neutron = 2d + 1u

BOSONS

force carriers
spin = 0, 1, 2, ...

Higgs Boson

Gives particles mass via their interaction with the Higgs field

Unified Electroweak spin = 1		
Name	Mass GeV/c ²	Electric charge
γ photon	0	0
W^-	80.4	-1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge
g gluon	0	0

Gravity (mass) ??

Graviton, massless, spin 2

Electromagnetism -
affects all charged
particles

Weak Force - changes
quark flavour and affects
lepton interactions

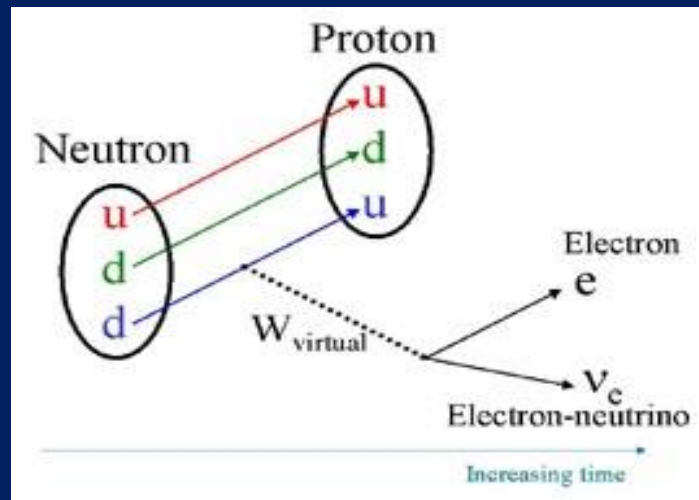
Strong Force - via
colour charge - binds
quarks into hadrons and
nuclei

The Hadronic Era

Time	10^{-11} sec	→	10^{-4} second
Temp	10^{15} K	→	10^{12} K
Density	10^{28} kg/m ³	→	10^{16} kg/m ³

Because of their larger mass the hadrons require more energy for their production - this is possible during the hadronic era until their final annihilation at the end of this era leaving a small excess of hadronic matter particles - as was the case for electrons and positrons in the leptonic era.

The start of the hadronic era (10^{-11} s) is at a critical point in the history of the universe - at higher energies (earlier times) two of the fundamental forces of nature - electromagnetic and weak were united in a single **electro-weak force**. There were then only three fundamental interactions.



The theory of the electro-weak force led to the prediction and discovery of the W,Z particles and so is well founded physics.

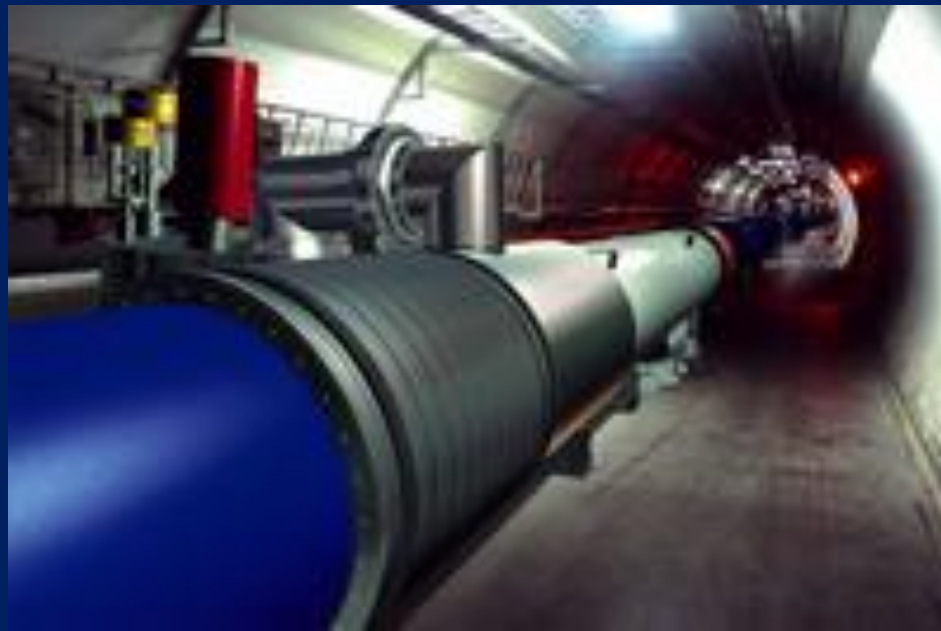
Studies of Z production are consistent with the idea that there are three species of neutrino and hence three families of fundamental particles.

The Electro-Weak or Quark Era

Time	10^{-35} sec	→	10^{-11} second
Temp	10^{28} K	→	10^{15} K
Density	10^{78} kg/m ³	→	10^{28} kg/m ³

The universe (all of it!) was in the state of a quark-lepton plasma.

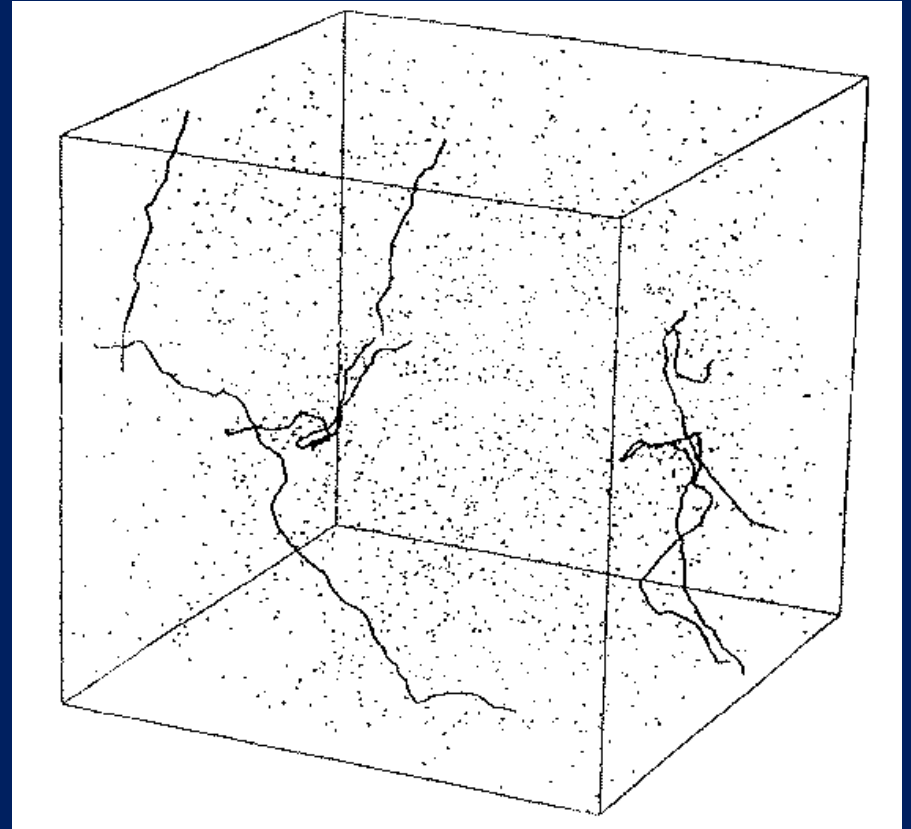
The highest energy particle accelerators can attain these energies ($\sim 10^4$ GeV) - we are therefore confident that we understand the particle interactions that occur after $\sim 10^{-14}$ s that's 0.00000000000001s! - before this time we rely more on theory.



At the start of this era (10^{-35} s) the strong force separates from the grand-unified or hyper-weak force (H-W). At earlier times there were only two forces, H-W and G.

The phase transition brought about by the strong force separation could have caused an **inflationary period** of expansion - if the phase transition was imperfect it could have left behind **topological defects** - **cosmic strings** - 10^{21} kg/m.

Their effects may be detectable in the microwave background

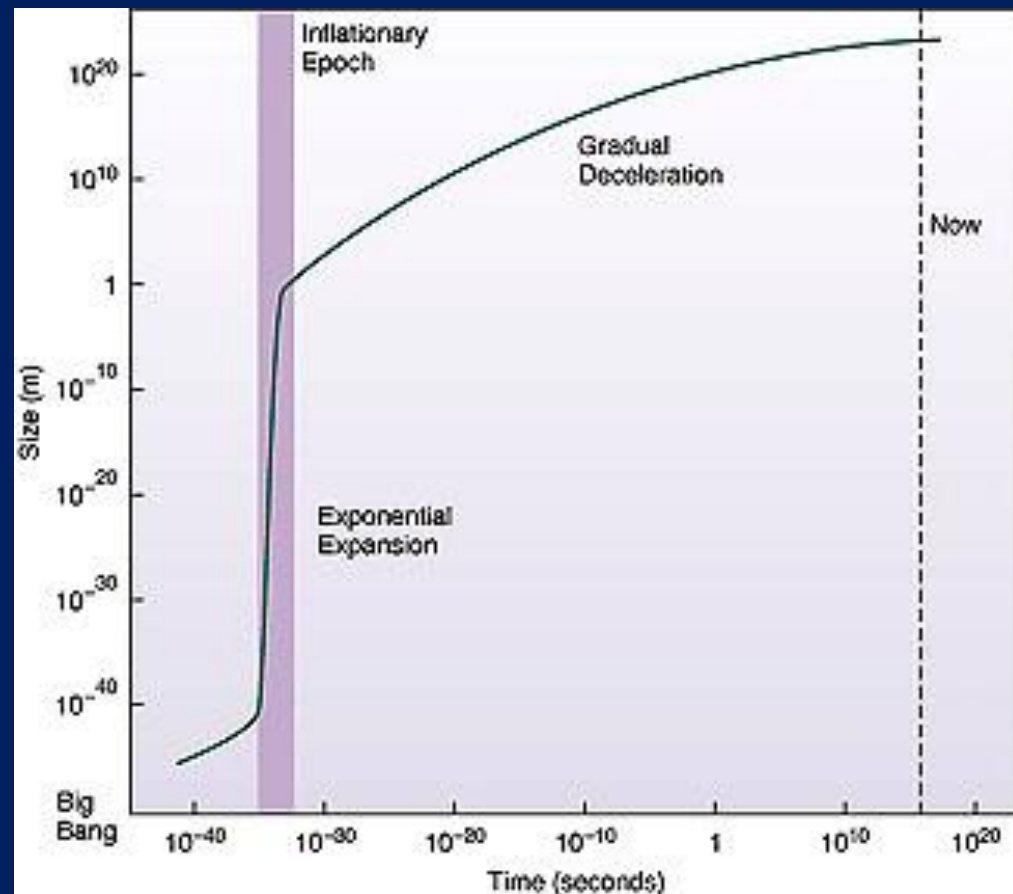


Inflation

May have only lasted $\sim 2.5 \times 10^{-32}$ s, however the universe doubled in size every 10^{-34} s giving 250 doublings - the size of the universe would have grown by a factor of 10^{75} !

The phase transition involves energy fields with very peculiar properties - **negative pressure** which according to Einsteins theory of general relativity will produce an **anti-gravitational effect** - this is what produces the inflation.

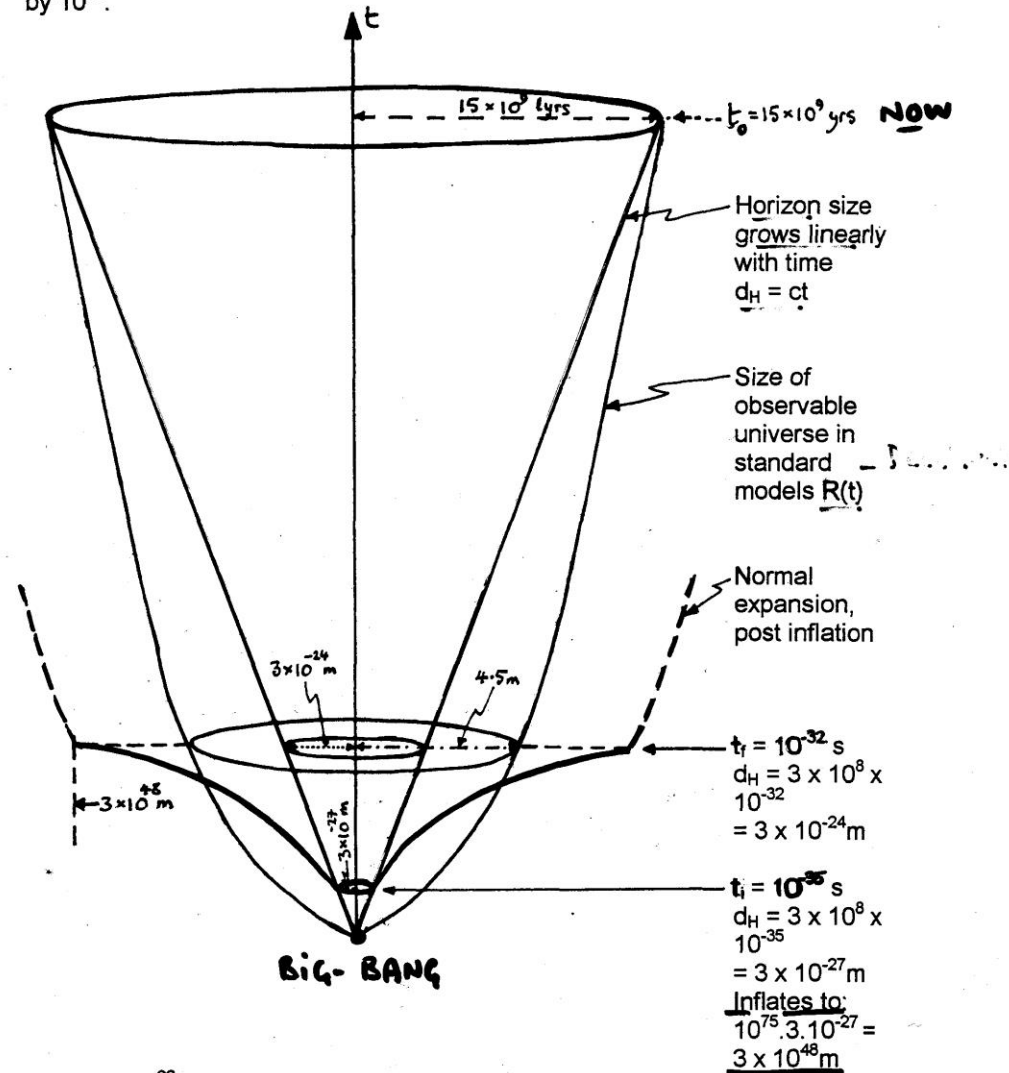
The vacuum may still be left with a remnant energy density of this form which could give rise to the observed *acceleration of the current expansion* of the universe - thus explaining the origin of the vacuum/dark energy.



Inflation can also help to explain some of the other problems with the standard cosmological model - the horizon problem, flatness problem, monopole problem and galaxy formation / primordial fluctuations.

How Inflation Solves the Horizon Problem

Inflation from $t_i = 10^{-35}\text{s} \rightarrow t_f = 10^{-32}\text{s}$ during which time the scale factor grows by 10^{75} .



At t_f , $T = 10^{26} \text{ K}$ and now, t_0 , $T_0 = 3 \text{ K}$

In standard models $T \propto 1/R$

So what is now the observable universe had a size at t_f given by $15 \times 10^9 \times 9.5 \times 10^{15} / (10^{26}/3) \text{ m} = 4.5 \text{ m}$

However, the horizon size - which is the largest scale on which the universe might be expected to be homogeneous - at $t_f = 10^{-24} \text{ m}$ - so why is the observable universe homogeneous? Inflation takes the small homogeneous regions at t_i and expands them by 10^{75} to $3 \times 10^{48} \text{ m}$ which is vastly greater than 4.5 m !

The Grand-Unified Era

Time	10^{-43} sec	→	10^{-35} second
Temp	10^{32} K	→	10^{28} K
Density	10^{94} kg/m ³	→	10^{78} kg/m ³

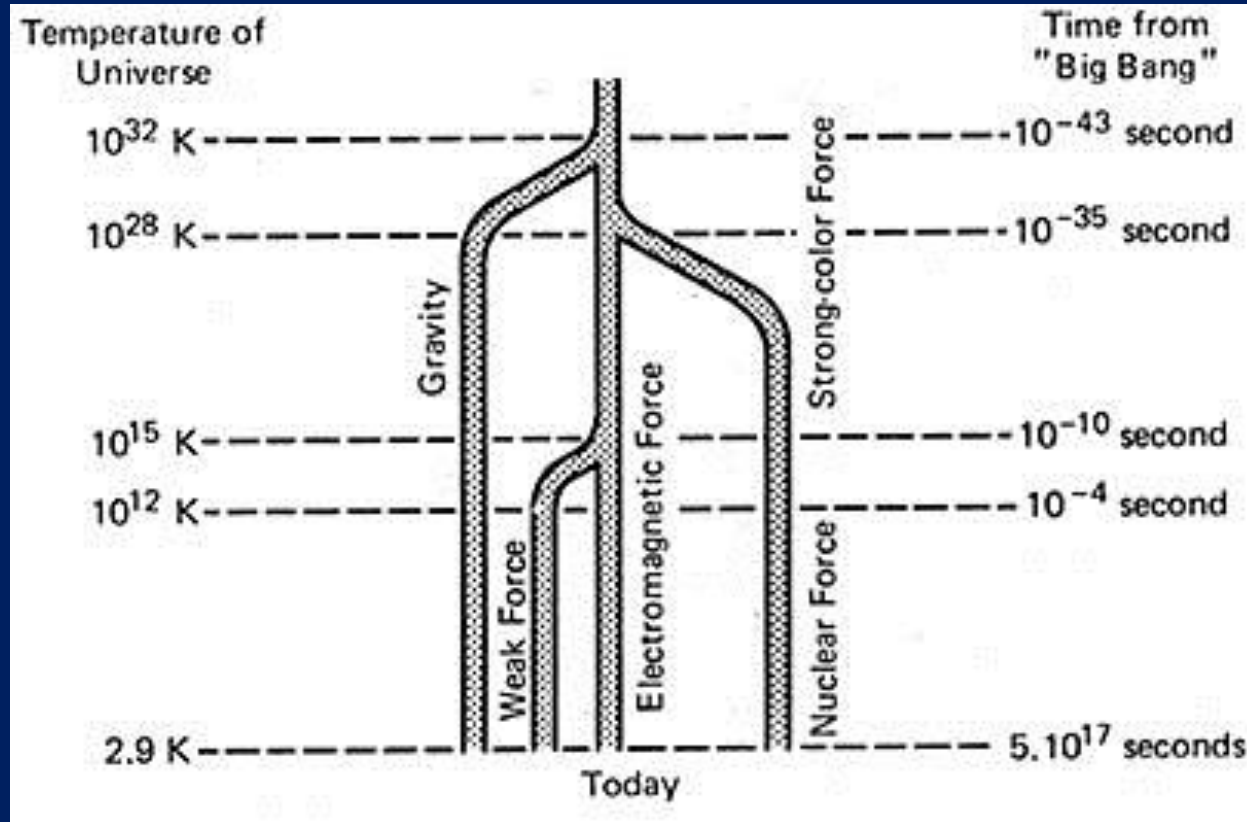
Quarks  Leptons via the exchange of X Bosons

It is the slight asymmetries in these reactions that ultimately give rise to the slight excess of matter over anti-matter.

Theories that describe these reactions are called **Grand Unified Theories** or **GUTs**.

Proton decay may be an observational consequence - there is no evidence so far - the lower limit being $>10^{32}$ years - that's 10^{22} times the current best estimate for the age of the universe!

At the beginning of this era gravity separates from the 'super-force'. At earlier times all of the fundamental interactions become indistinguishable.



At $t = 10^{-43}$ s - the Planck time - the 'standard model' breaks down - the quantum mechanical (deBroglie) wavelength of the universe is the same size as the universe itself.

The Quantum Gravity or Super-Symmetry Era

$t < 10^{-43}$ s, $T > 10^{32}$ K, $\rho > 10^{96}$ kg/m³

These extreme conditions require a 'theory of everything' or TOE in order to explain what's happening - **all fundamental interactions are unified.**

Current favorites are **super-symmetry** (SUSY) and **string theory**.

Matter and Radiation can interchange:

Fermions \Leftrightarrow Bosons

Every particle we know will have a higher energy 'super partner':

electron \Leftrightarrow selectron

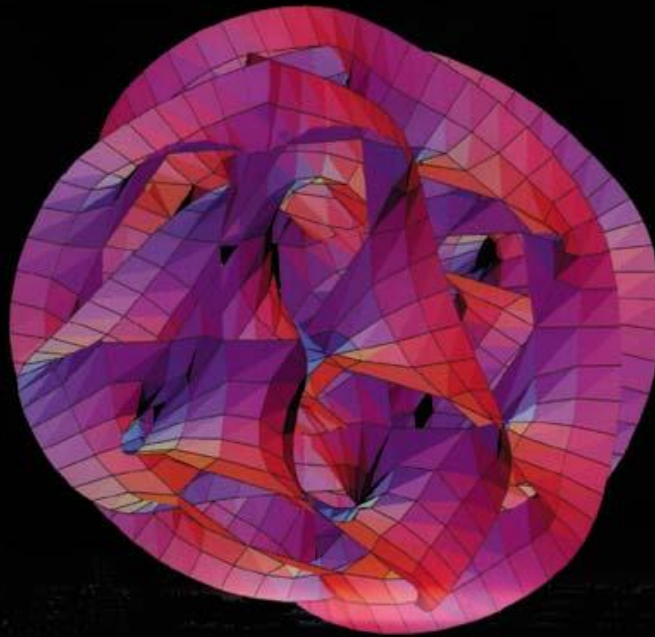
quark \Leftrightarrow squark

photino \Leftrightarrow photon

gravitino \Leftrightarrow graviton

The lightest super-particle will be stable and ***could comprise the 'exotic' dark matter*** (not the dark energy – see earlier).

According to string theory fundamental particles are no longer points but consist of tiny vibrating **strings or membranes in a multi-dimensional space** - current theories require 10 space and 1 time - 7 being curled up on such a small scale that we do not experience them.



This is as far as we can go.....

What We Know

1. We live in an evolving universe
it started off ~15 Gyrs ago in a hot
dense state.
2. It has been expanding and cooling
and forming more complex structures
ever since.

What We Would Like to Know

1. The far future - endless expansion or re-contraction?

Current observations suggest the former but future observations of the microwave background and galaxies at the edge of the observable universe will refine the fit of the observations with potential models. These will depend on the resolution of 2-3 below.

2. What is the nature of the exotic dark matter?

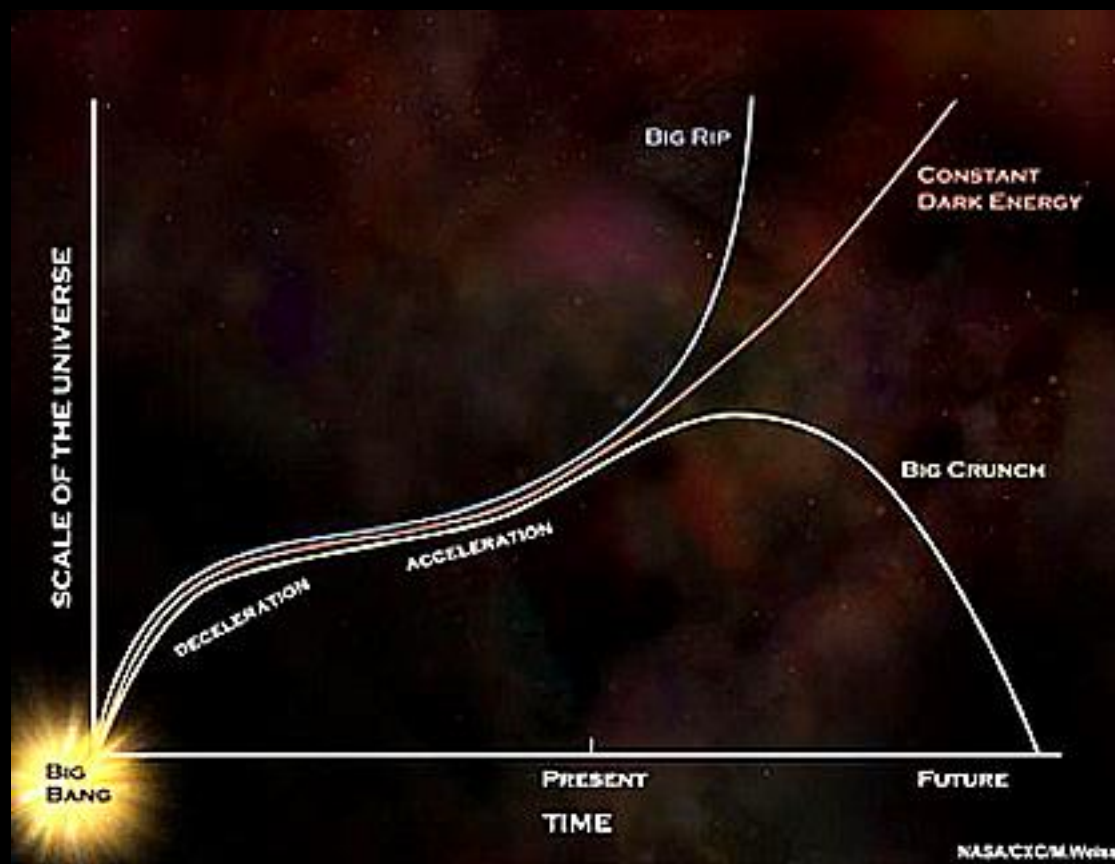
Particle physics experiments - Boulby mine etc - may detect the elusive dark matter that astronomical observations convince us exists. Particle theories will help to narrow down the list of possible candidates – WIMPs? Particle accelerators may discover new candidates for the dark matter – one of the hopes for the LHC.

If all else fails maybe we need a new theory of gravity – MOND?

3. What is the nature of the vacuum energy?

Even less is known about vacuum or dark energy than dark matter!

Is it likely to be constant with time like Einstein's original Λ term? If it is then the universe continues to accelerate. If it varies with cosmic time (quintessence) then this leads to many different possibilities for the eventual fate of the universe – from big-rip to big-crunch!



Is it just coincidence that $\Omega_v \sim \Omega_m$?

QM calculations suggest a vacuum energy of $\sim 10^{97} \text{kg/m}^3$ – (only differences in density cause measurable effects so we don't normally notice this huge density) – this is about 10^{123} times the measured value!! A unified theory of QM and GR may be able to explain this huge discrepancy. New ideas in quantum theory may allow us to understand the vacuum better – do all types of virtual particle affect it in the same way?? We may eventually have to resort to radical theories such as variable speed of light (faster in the early universe) – for which there is no evidence so far. Or the ekpyrotic universe – see later.

Or use the anthropic principle – maybe only universes with a low vacuum energy are suitable for the evolution of life??

SNAP – supernova acceleration probe - may help – launch? hopes to detect 2000sn per year! It will refine the distant Hubble diagrams.

Many other ground based and space based projects are being planned.

5. Avoiding the big-bang

Always a hope ever since the steady state theory.

A variation on the inflationary model – eternal inflation – has no $t=0$. Our universe grew from a bubble within a much larger inflating space full of ‘false vacuum’. This larger space has no beginning – it is one type of multi-verse (see later).

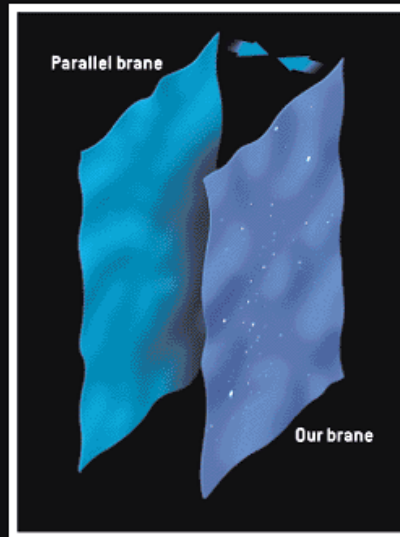
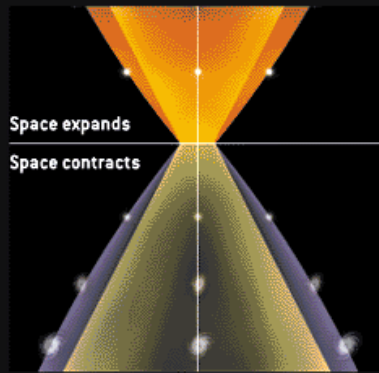
Other possibilities now hinge on unifying quantum theory and general relativity – string theory and others.

Loop quantum gravity – Lee Smolin – predicts a type of oscillating universe that turns itself inside out at the big-bang/crunch. Loops are the quanta of space-time on the Planck scale – 10^{-35} m . This is one of the few alternatives to string theory.

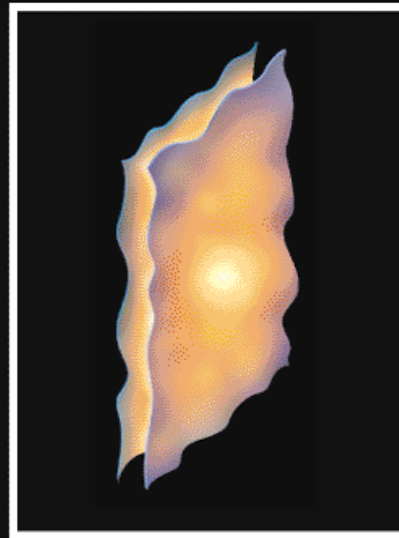
Using the possible extra dimensions of string theory the ekpyrotic universe of Steinhardt and Turok envisages our three dimensions of space as a ‘brane’ floating in a higher dimensional space – every trillion years or so it collides with a similar brane separated from us along a short 4th space dimension.

EKPYROTIC SCENARIO

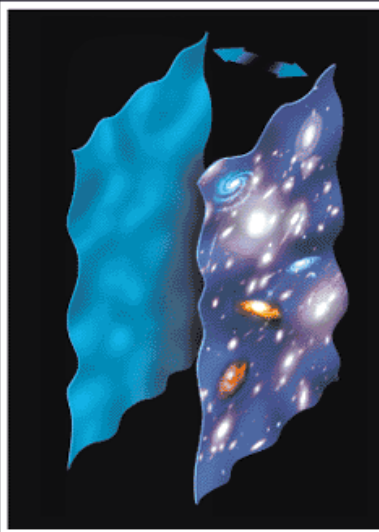
If our universe is a multidimensional membrane, or simply a "brane," cruising through a higher-dimensional space, the big bang may have been the collision of our brane with a parallel one. The collisions might recur cyclically. Each galaxy follows an hourglass-shaped path through spacetime (*below*).



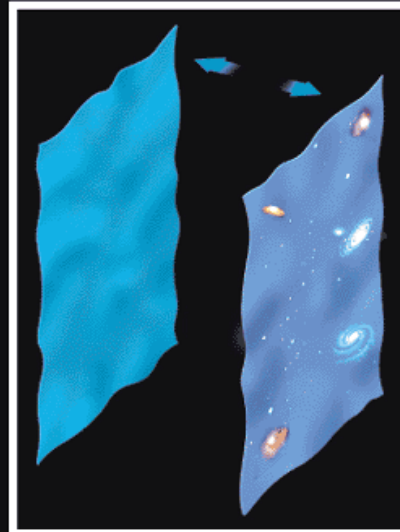
Two nearly empty branes pull each other together. Each is contracting in a direction perpendicular to its motion.



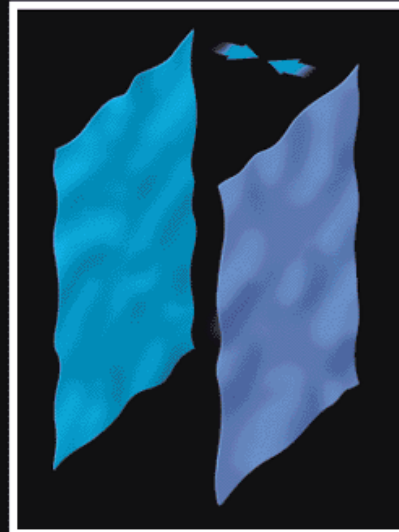
The branes collide, converting their kinetic energy into matter and radiation. This collision is the big bang.



The branes rebound. They start expanding at a decelerating rate. Matter clumps into structures such as galaxy clusters.



In the cyclic model, as the branes move apart, the attractive force between them slows them down. Matter thins out.

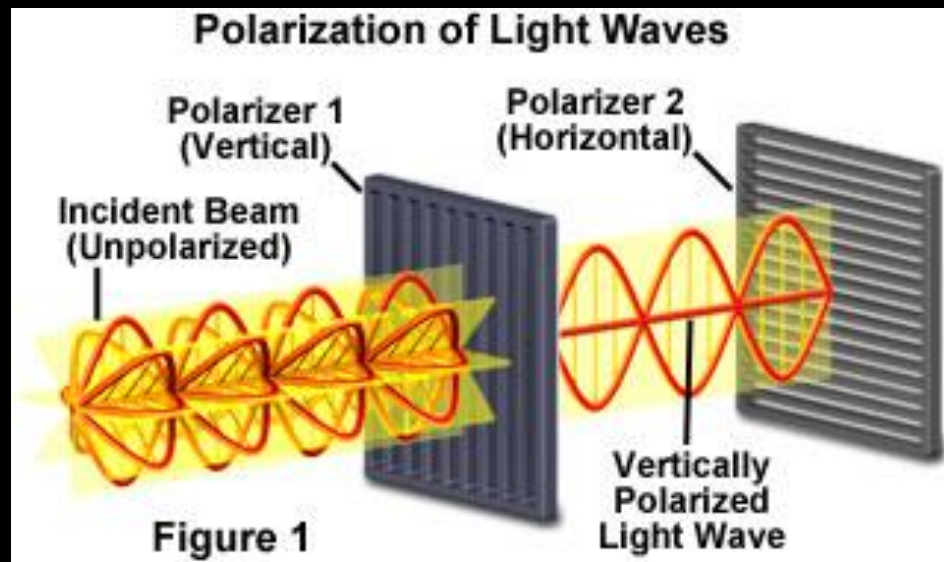


The branes stop moving apart and start approaching each other. During the reversal, each brane expands at an accelerated rate.

The model agrees with all of the standard model predictions after the initial bounce – and seems to give all the advantages of inflation - the only observational way to discriminate between this and the inflationary model is in the form of primordial G waves produced – these will affect the polarisation of the microwave background patterns in a particular way

Polarisation

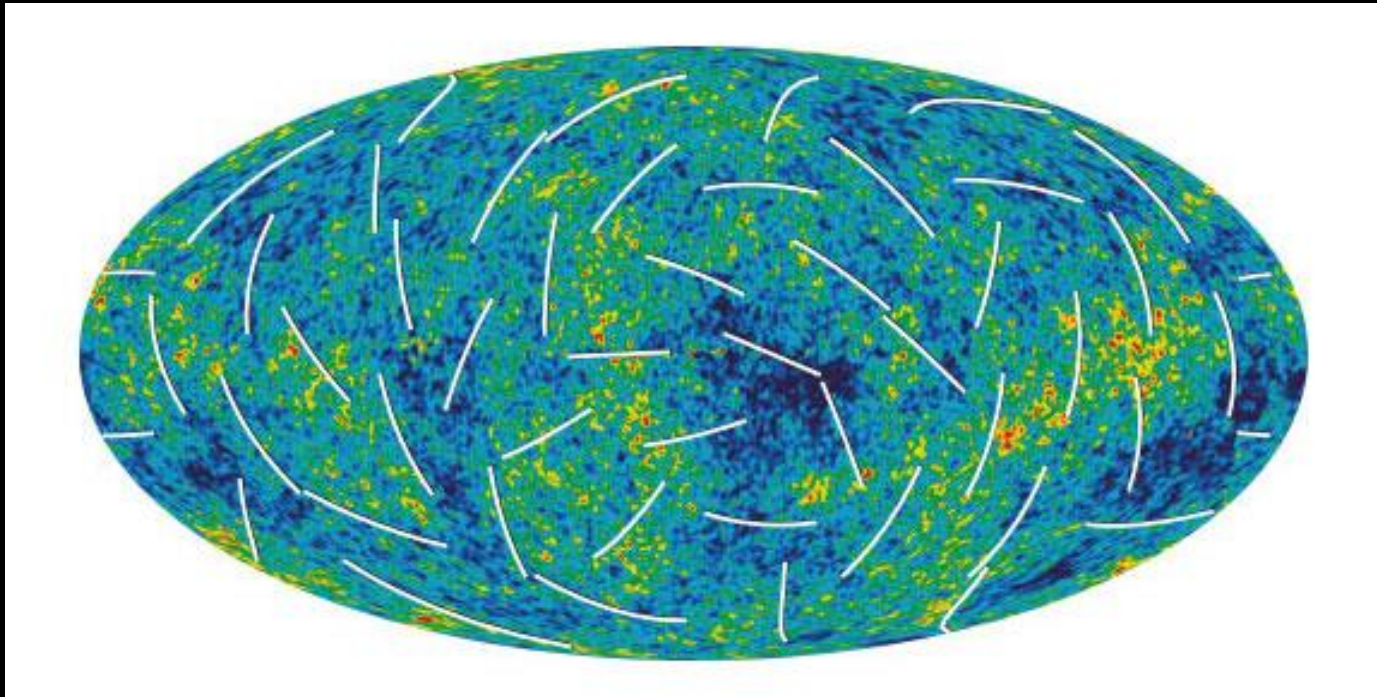
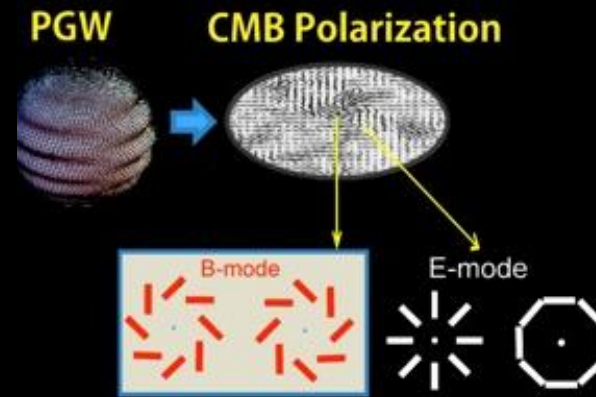
Electro-magnetic theory of light - light is comprised of varying electric and magnetic fields travelling at 300,000km/s as a transverse wave motion (like those in a shaken rope). Vibrations occur in planes perpendicular the direction of travel.



Polarising sunglasses work in an analogous way. The molecular structure of the material selectively absorbs and scatters light of different polarisations.

Light is also polarised by reflection.

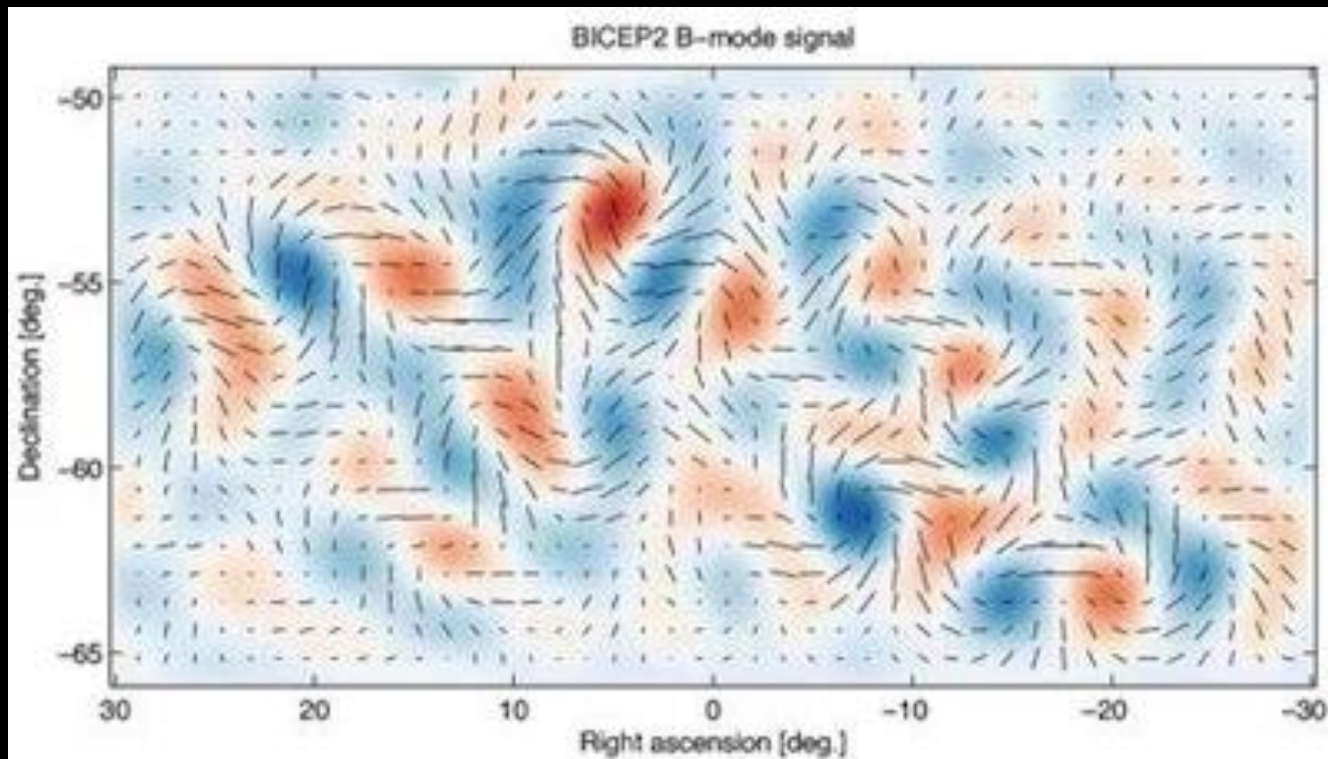
Inflation predicts E
and B modes –
ekpyrotic only E



Observed polarisation in the WMAP map – consistent with
E modes (lines look curved because of projection) – need
higher sensitivity for B? e.g. Planck satellite

Pattern of microwave background polarisation obtained by the Bicep2 project in Antarctica.

Evidence for inflationary expansion in the early universe 'B modes' – or maybe just an effect of foreground dust - most likely explanation after more recent data obtained.



5. Is our universe unique - or is it just part of a 'multi-verse'?

Type 1 – if space is infinite in extent but finite in age then we are confined within our cosmic horizon.

There are potentially an infinite number of similar isolated universes out there. You are likely to have a twin in a galaxy 10^{118} m from here!

They will experience the same laws but may have differing initial conditions.

If space is accelerating as we currently think we gradually see less of the whole as time goes on.

Type 2 – Eternal chaotic inflation

Possibly an infinite number of Type 1 universes separated by expanding vacuum moving faster than the speed of light.

Each inflationary bubble will have different initial conditions and maybe different numbers of dimensions and values of physical constants – because of quantum effects. This is one way of avoiding the problem of why our universe seems to be fine tuned for life – the anthropic principle.

Each ekpyrotic bounce may produce a different type 1 universe?

Type 3 – Quantum many worlds theory

Each quantum choice splits into two universes where each is realised.

Parallel universes embody different ways that events could have unfolded.

Maybe time is an illusion related to how we are moving through a sequence of static ordered universes?!

Type 4 – Other Mathematical Structures

Universes that differ not just in location, cosmic properties or quantum state but have different laws of physics.

May help to solve conundrums such as – did the laws come into existence with the universe? If they did it's difficult to explain the origin of a universe using them - but if every possibility is actuated (complete mathematical symmetry) we will exist in one of them.....

BUT -WHAT IS THE UNIVERSE?

Cosmologists study universes = 'models' constructed within a particular physical framework - the 'laws of physics'.

Cosmology was originally based on magic and myths - we now (supposedly) live in the age of scientific cosmology.

We still do not know the Universe - compare Victorian and Einsteinian universes - what next?

The Universe may be unknowable.

But we are in the (probably) unique situation of being able to try and understand it.

'Human Beings...represent the Universe perceiving and thinking about itself'

Ed Harrison