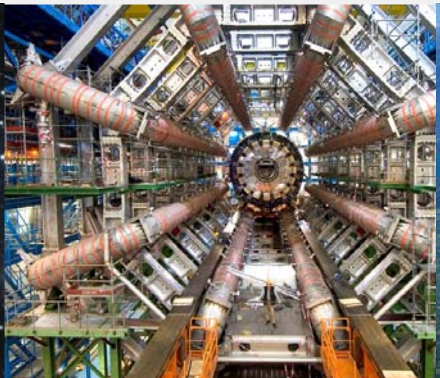
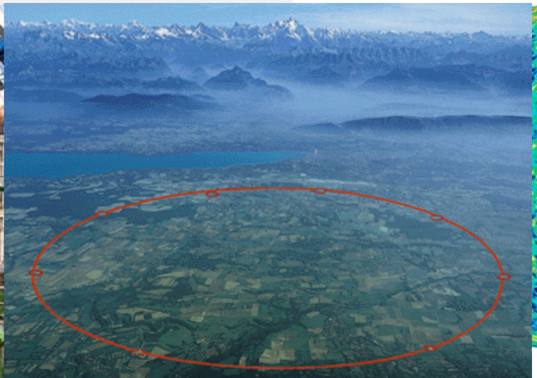
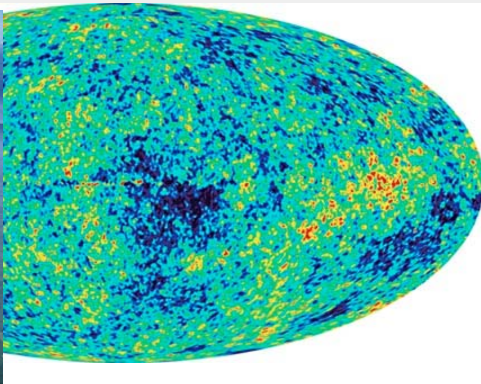
Dark Matter, Dark Energy, and all that stuff

From cosmology to particle physics

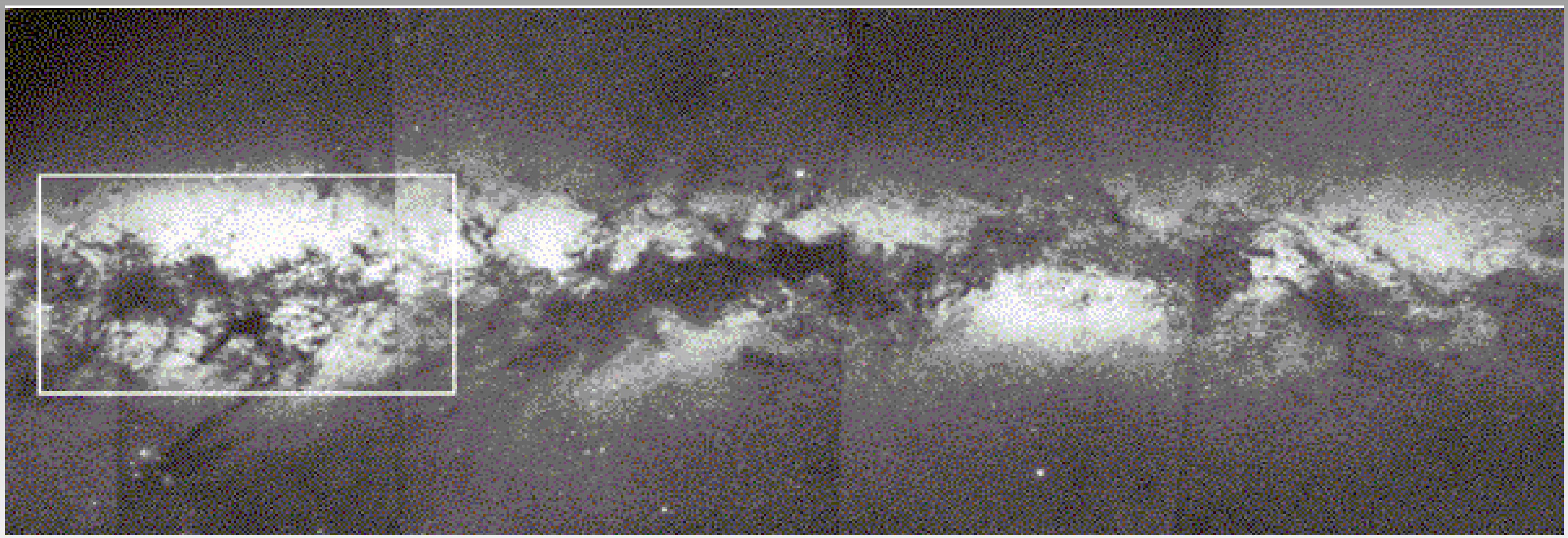
K. Ragan/McGill







Let’s start close to home: The Milky Way



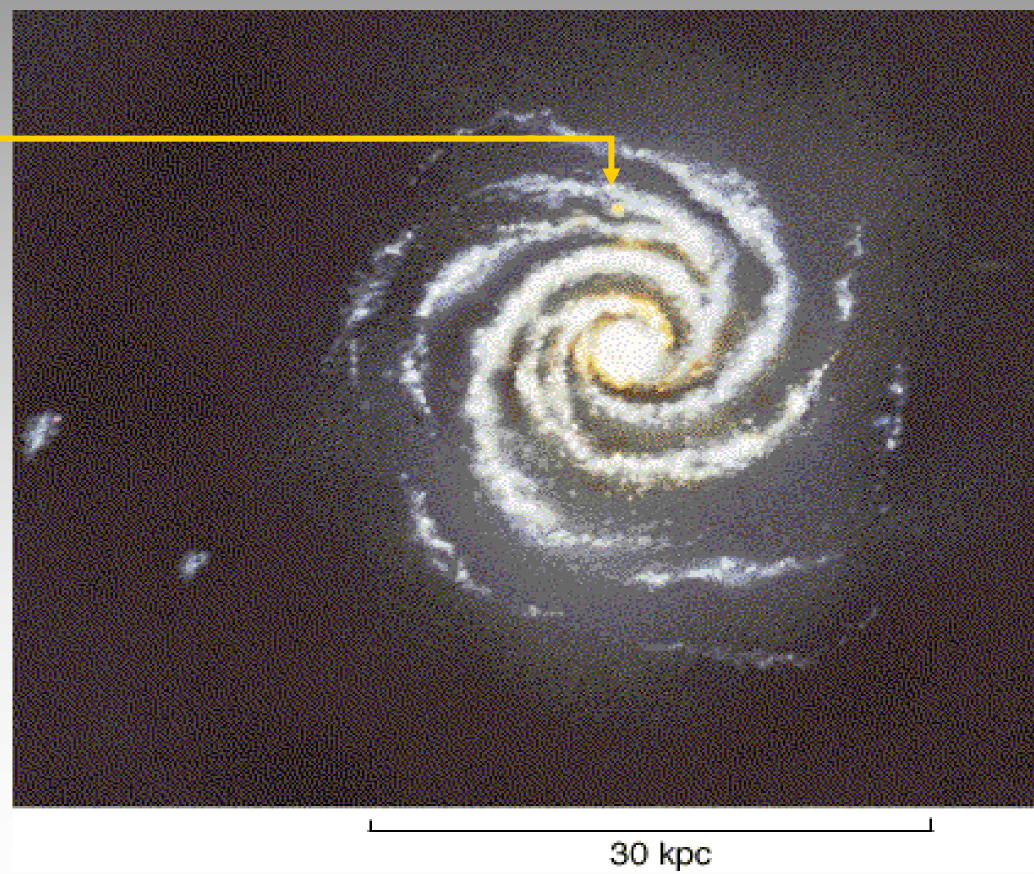
A faintly brighter band of light is visible across the sky on dark nights away from city lights, called the ‘Milky Way’.

The Milky Way in Infrared

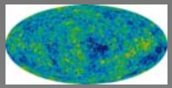
This Milky Way is now understood to arise because our Sun sits inside an enormous disc of stars, with a bulge at its centre.

Map of the Milky Way

You are here.

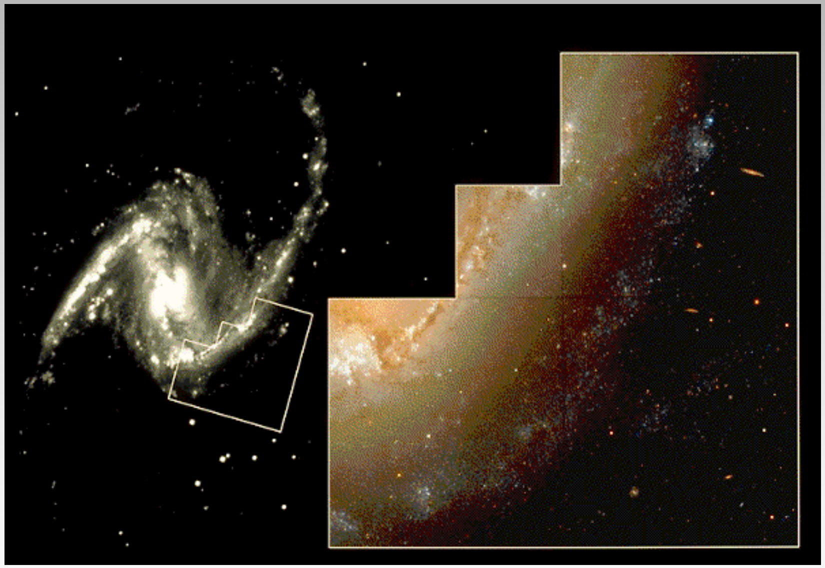


1 parsec = 3.2 light years

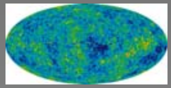


Other Galaxies

- All *individual* stars visible by eye are in *our* Galaxy: the Milky Way.
- Essentially all stars live in galaxies of their own, most of which are extremely distant from the Milky Way.
  - Stars are light years apart
  - Galaxies can be 10,000 light years across and millions of light years apart.
- An enormous number of galaxies are known, with a variety of shapes and sizes.

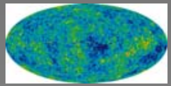


Galaxies are diverse



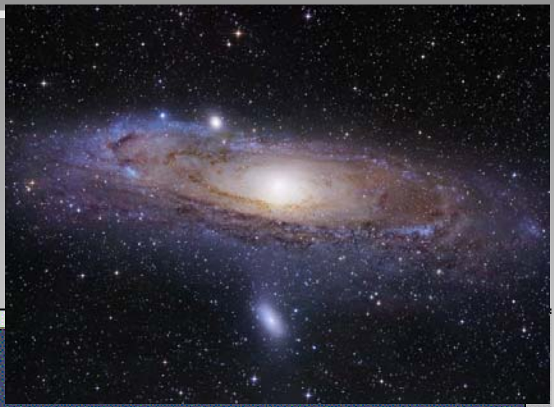
Galactic Distances

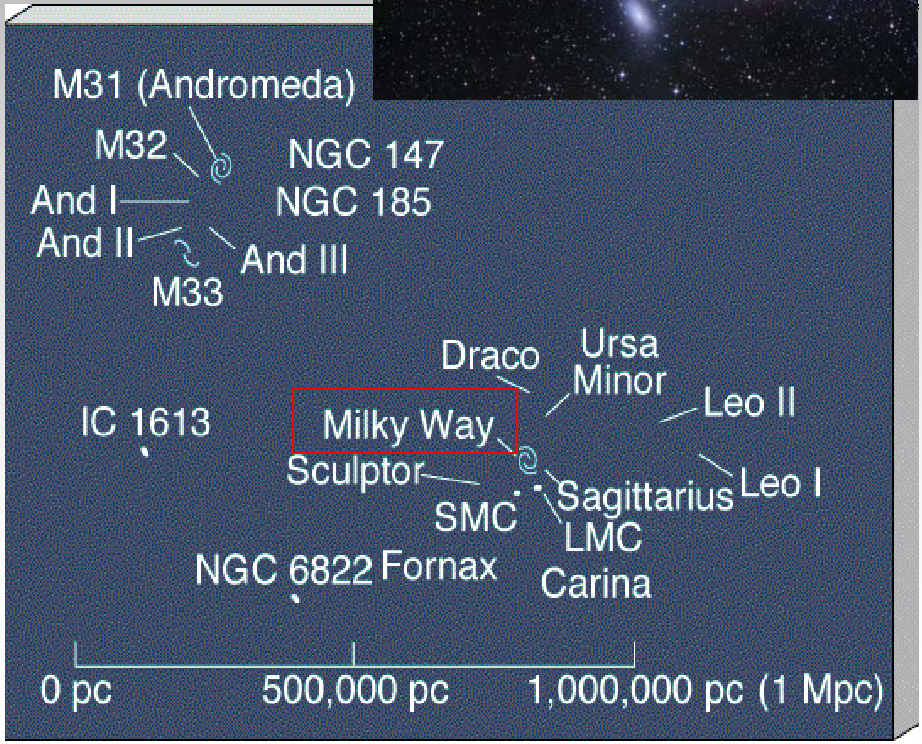
- Distances to galaxies can be found if you can see objects (called ‘standard candles’) in the galaxy whose luminosity is known.
- Measuring distances to galaxies means we can start to map the cosmos that surrounds us

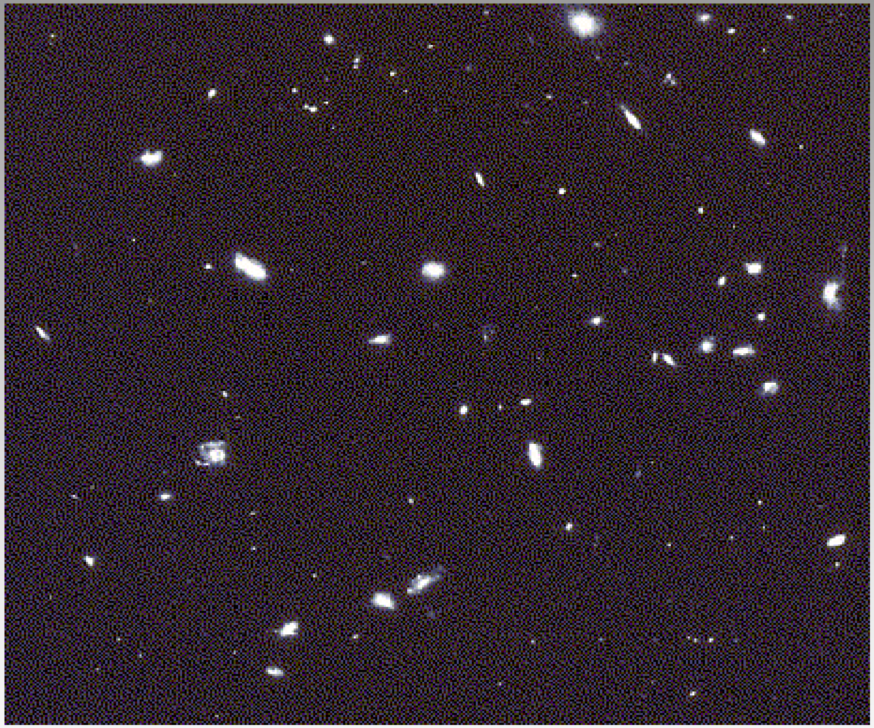
The Local Group

- Our galaxy is in a cluster of galaxies called the *Local Group*, which consists of about 20 galaxies and is about ***1 Mpc*** across.
  - Galaxies within a cluster are **gravitationally bound** together (and not just ‘passing through’).



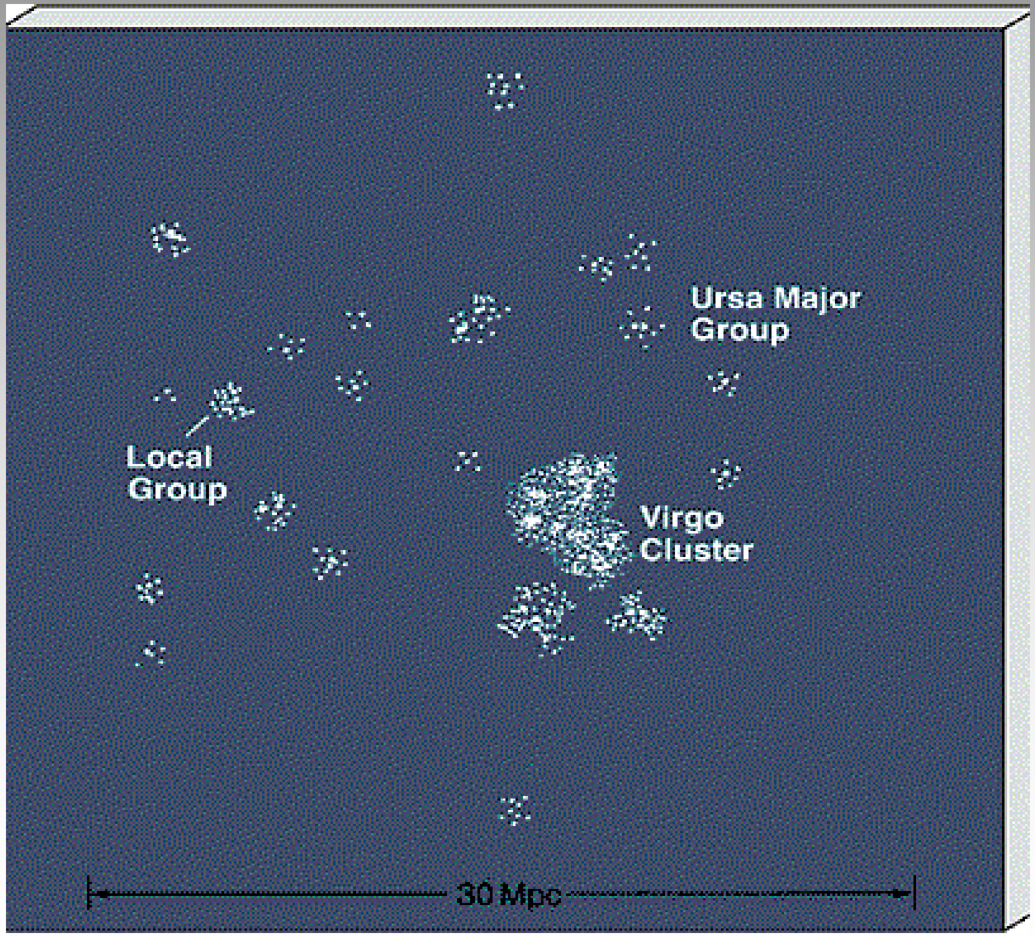


Galaxies Tend to Cluster



- Most galaxies are found in *clusters*.
  - Galaxies within a cluster are gravitationally bound together (and not just ‘passing through’).

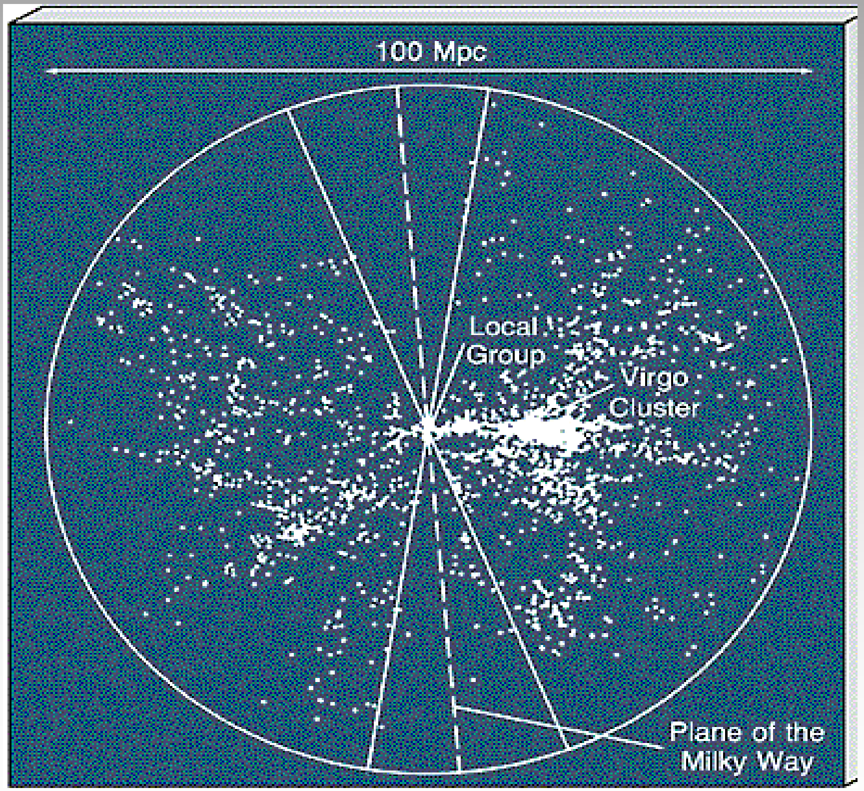
Some Local Clusters



Virgo: 2500 galaxies in ~3 Mpc!

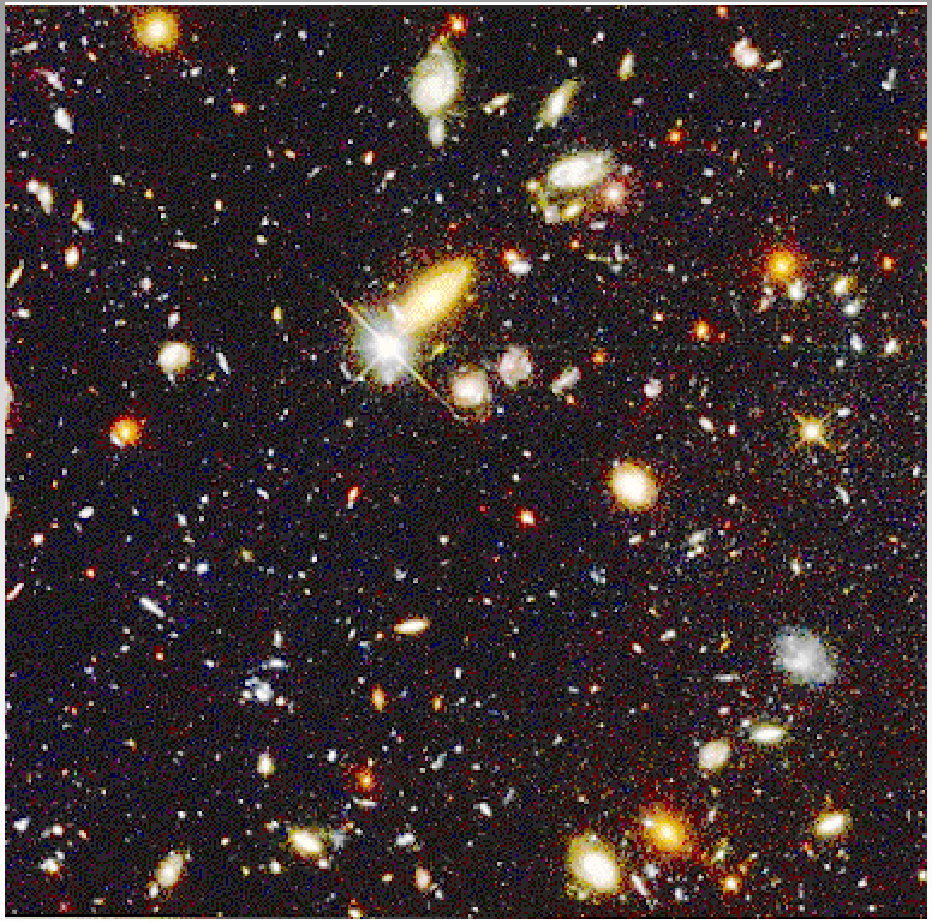
Galaxy Superclusters

- Galaxy clusters tend to group together into bound superclusters.
  - Our *Local Supercluster* (containing tens of thousands of galaxies) is ***~100 Mpc*** across.



The Hubble 'Deep Field'

Galaxies, galaxies, everywhere!



Measuring Galaxy Masses

- The mass in a galaxy can be inferred using Kepler's and Newton's Laws from the speed of objects which orbit it.
  - If the rotation speed is measured as a function of distance from the galaxy centre, its mass distribution can also be measured as a function of this distance.
  - The orbit of an object at a radius *r* turns out to be sensitive mostly to the mass which is ***closer*** to the galactic centre than *r*.

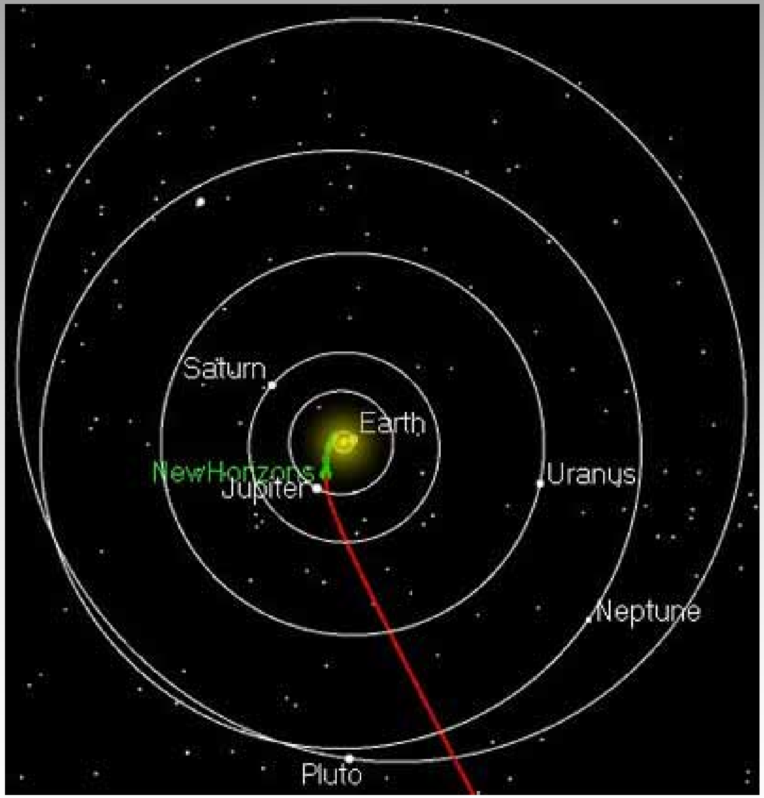
Keplerian Orbits

- If mass M is at the center of the system and provides centripetal force, then:

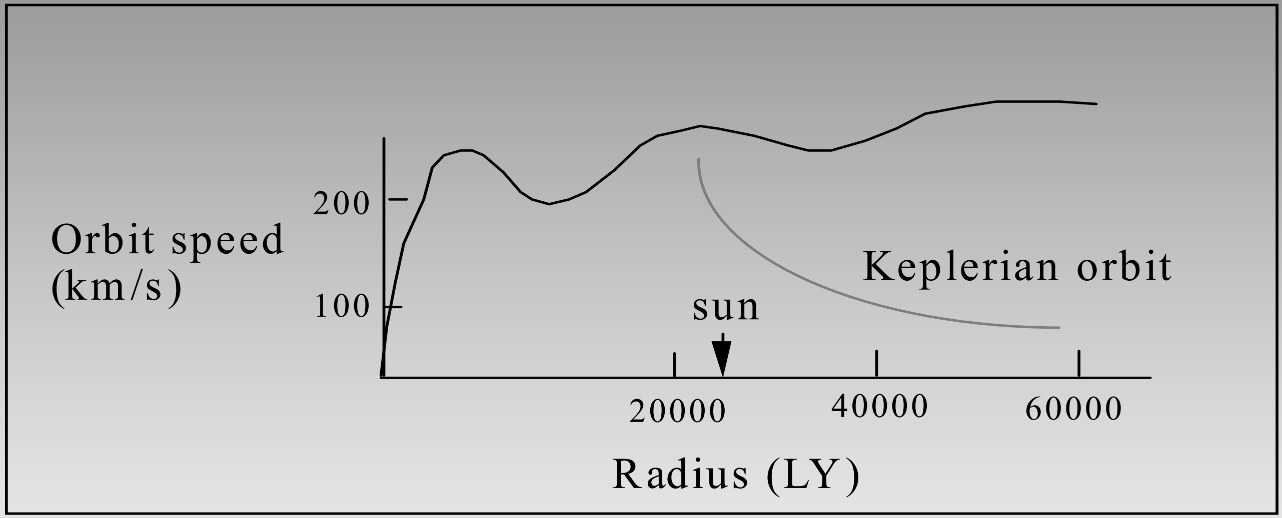
$$GMm/r^2 = mv^2/r$$

$$v = \sqrt{(GM/r)}$$

- Orbital speed depends only on distance r and central mass M
- So: measure speed, infer mass…

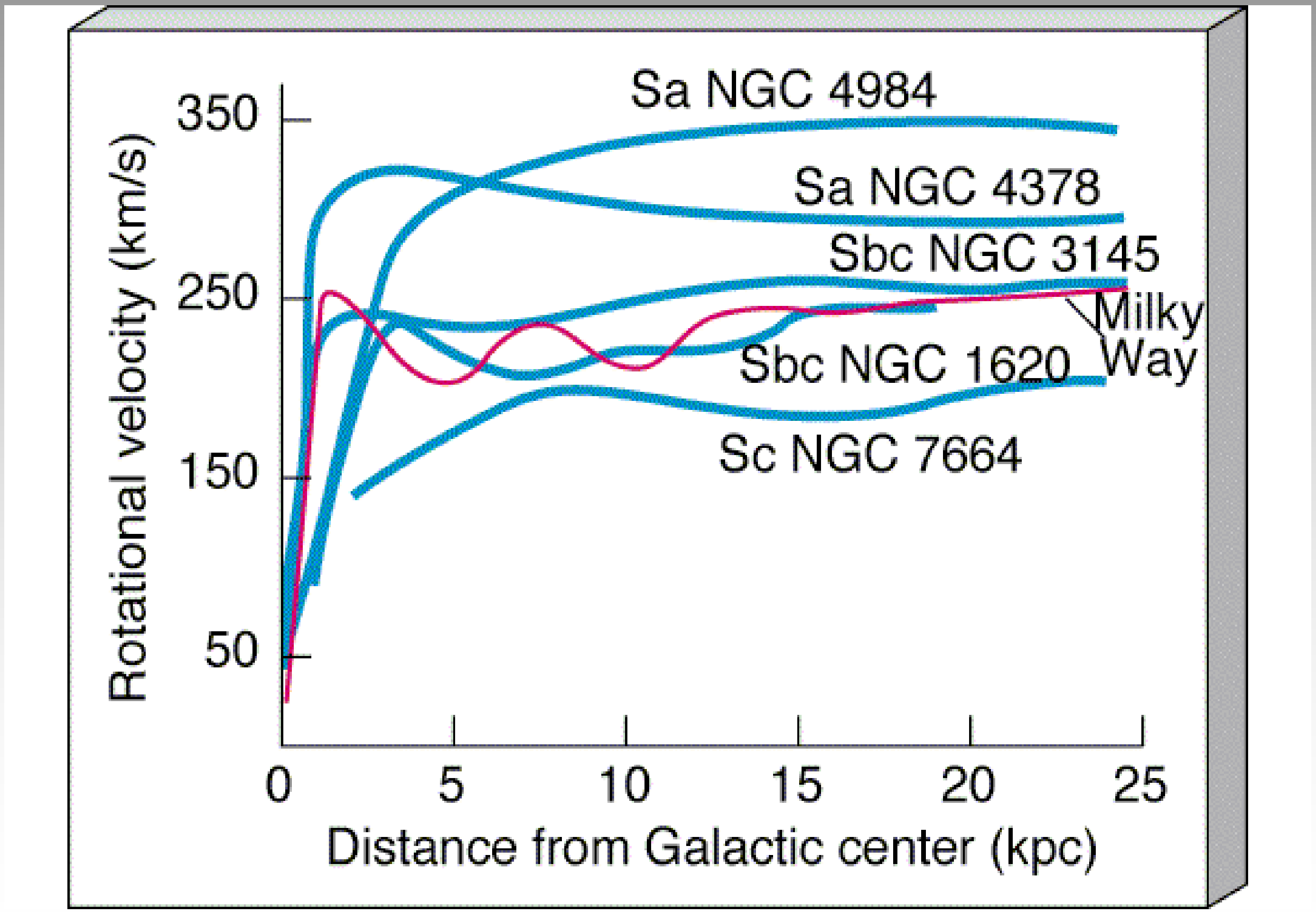


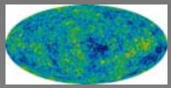
Interpreting Rotation Curves



- Hydrogen clouds orbit galaxies up to 15 kpc *beyond* the outermost visible stars, and so their motion gives the total mass inside their orbits.
- From *Kepler's Law* orbital speeds should fall with increasing radius according to like $v \propto 1/\sqrt{r}$.
- *Surprise!!* Rotational speeds instead *rise* slowly at large radii!

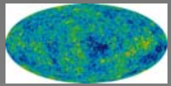
Some Galactic Rotation Curves



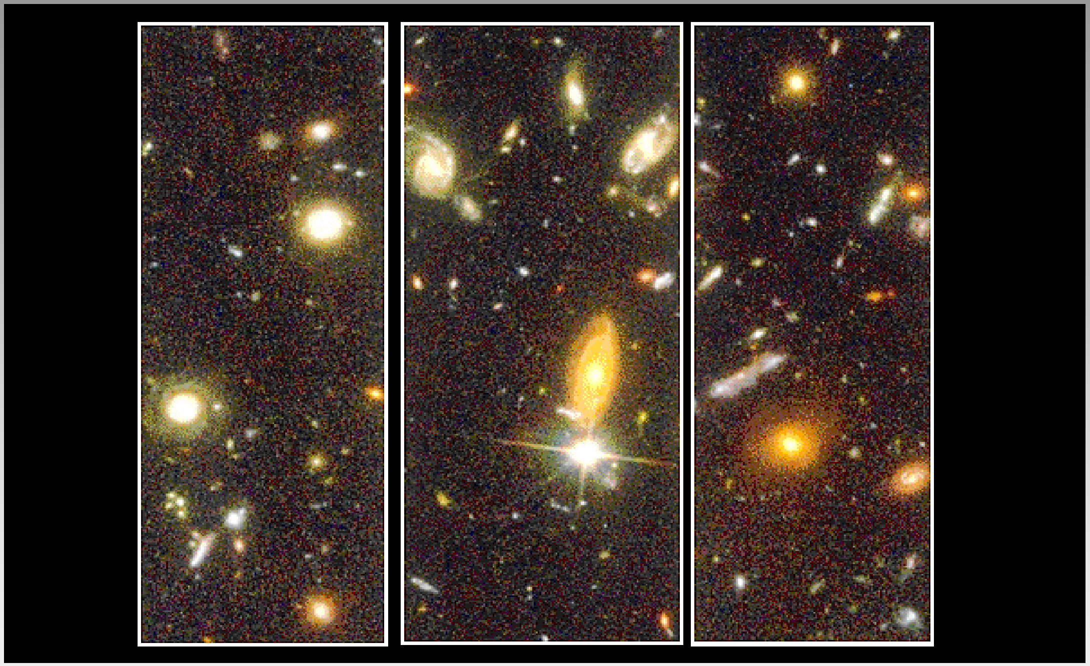


Rotation Curves imply Dark Matter!

- Galactic rotation curves imply mass is NOT concentrated at centers of galaxies
- Worse still, the total implied mass is much larger than one would infer from the brightness of galactic cores.
- This implies *dark matter*: gravitationally interacting (“normal”) but not visible through light emission (hence “dark”).

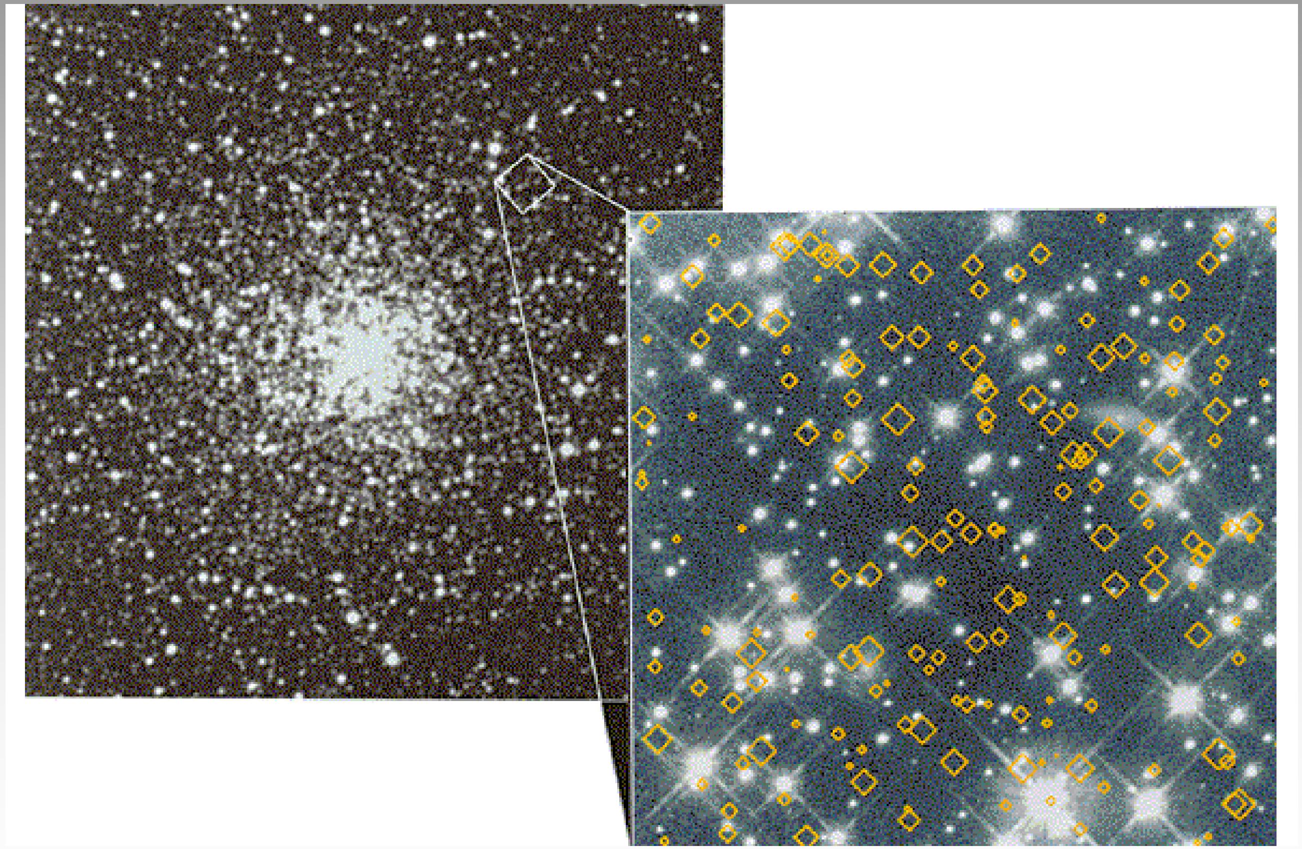


What is the Dark Matter?

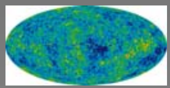


- There are two classes of theories:
  - Dirt: **MACHOS** (Massive Compact Halo Objects)?
  - New Elementary Particles: **WIMPS** (Weakly Interacting Massive Particles)?

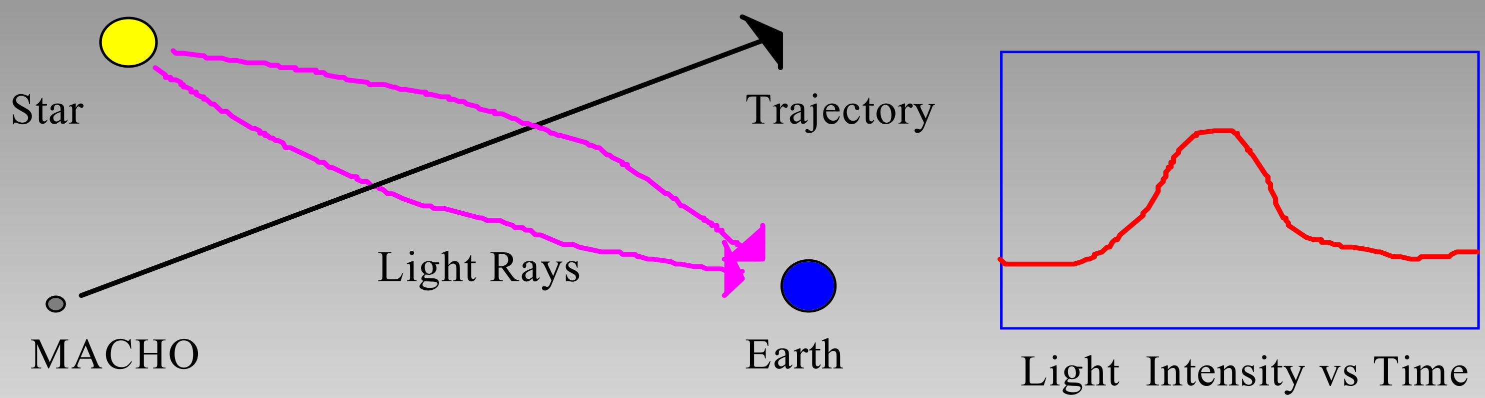
It’s Not Just Faint Stars



Faint stars in globular cluster



It’s Not Jupiters

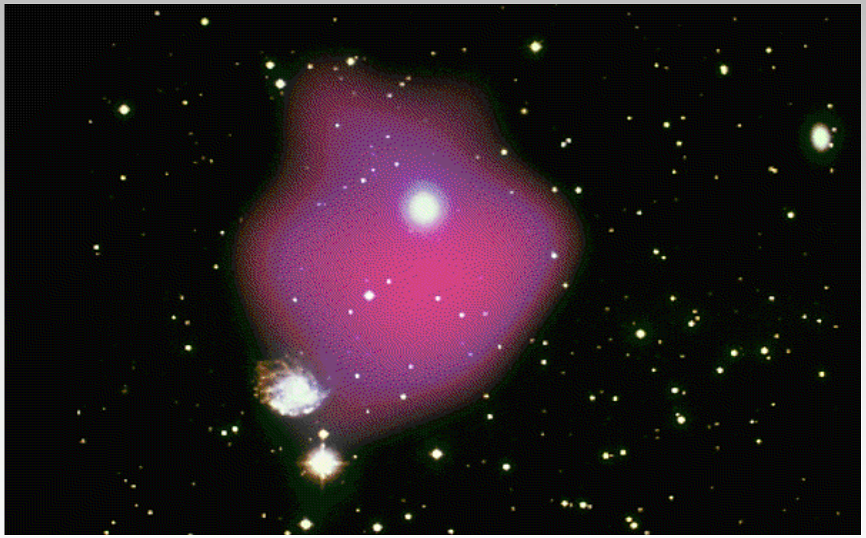


Gravitational Microlensing

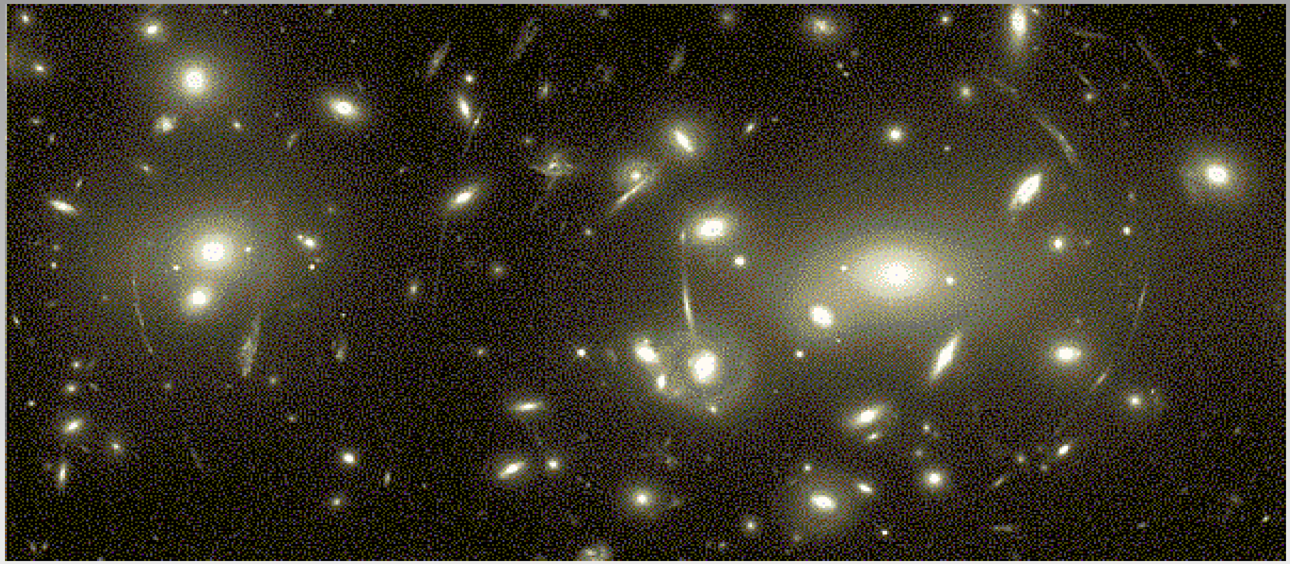
- Dark objects (like planets) occasionally pass in front of distant stars, and their gravity would magnify the light of the background star.
  - This effect is called ***gravitational microlensing.***
  - The dark objects are called **MACHOS** (Massive Compact Halo Objects).
- Millions of stars have been watched, and a handful of these microlensing events have been observed.
  - Not near enough to account for the dark matter.

Masses of Galaxy Clusters

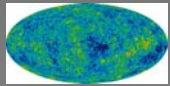
- The mass of galaxy clusters can also be measured, in two different ways.
  - By measuring the orbital speeds of the galaxies within the cluster.
  - By asking how much mass would be required to trap the hot gas which is found there.
- Typical clusters turn out to contain *10^{13} - 10^{14} M(Sun).*
  - This is ***10-100 times*** more mass than is found by adding up the mass in the stars and gas!!



An Independent Measure

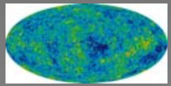


- The amount of gravitational lensing gives an independent measure of how much mass is contained in the foreground galaxy cluster.
  - This measurement confirms the conclusion that there is 10 - 100 times as much mass as can be accounted for from the visible galaxies and hot gas seen to be in the cluster.

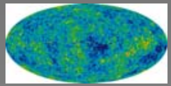
So, amazing but true:

- Galaxies all contain around *3 – 10 times* more dark matter than can be accounted for by the visible stars, gas and dust they contain!!
  - The dark matter seems to be distributed spherically and extends out as far as can be seen !
  - It is **Really Dark**: Not just invisible at visible wavelengths.
- Galaxy clusters contain *10-100 times* as much mass as can be accounted for from the galaxies and gas they contain.
- *Nobody knows what this dark matter is!*
  - *There is evidence that it is NOT just unlit ordinary matter.*



Galactic Velocities

- Within clusters galaxies orbit randomly.
- The clusters themselves are all receding from ours.
  - Light from all other clusters is *redshifted*, indicating they are moving away from us.
  - Since all but the nearest clusters recede with a higher speed than the speed of the galaxies within them, all but two galaxies within the Local Group (including Andromeda) and a few in the Virgo Cluster are receding!



Hubble's Law

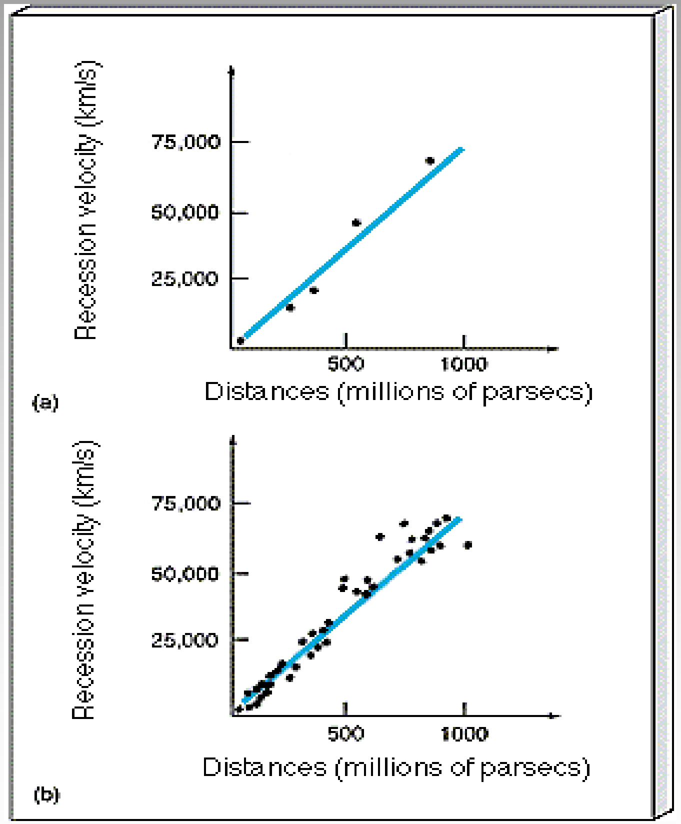
- Hubble discovered that a distant galaxy's speed, *v*, away from us is proportional to its distance, *d*, from us.

- The *Hubble Law* is:

$$v = H_0\, d$$

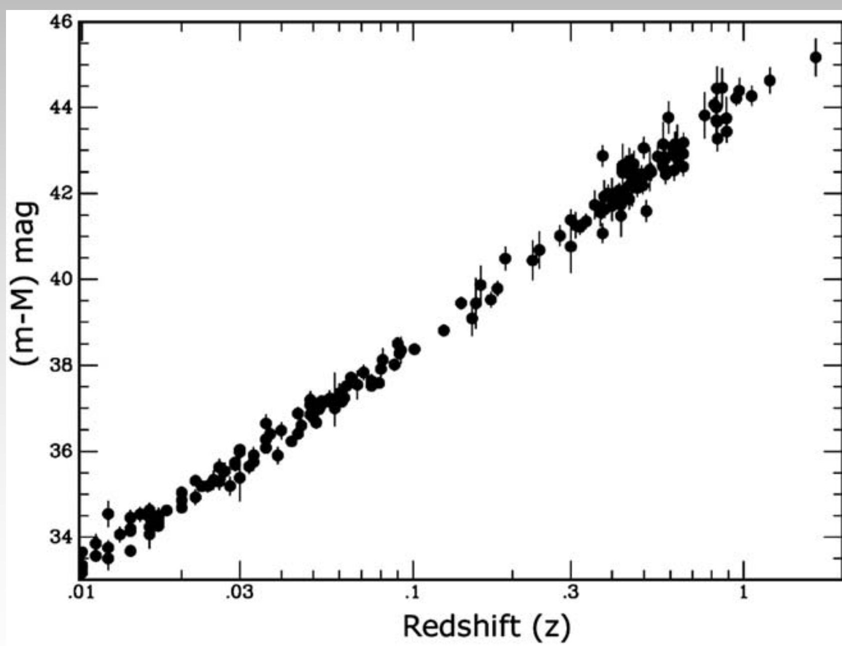
where ***Hubble's constant*** is:

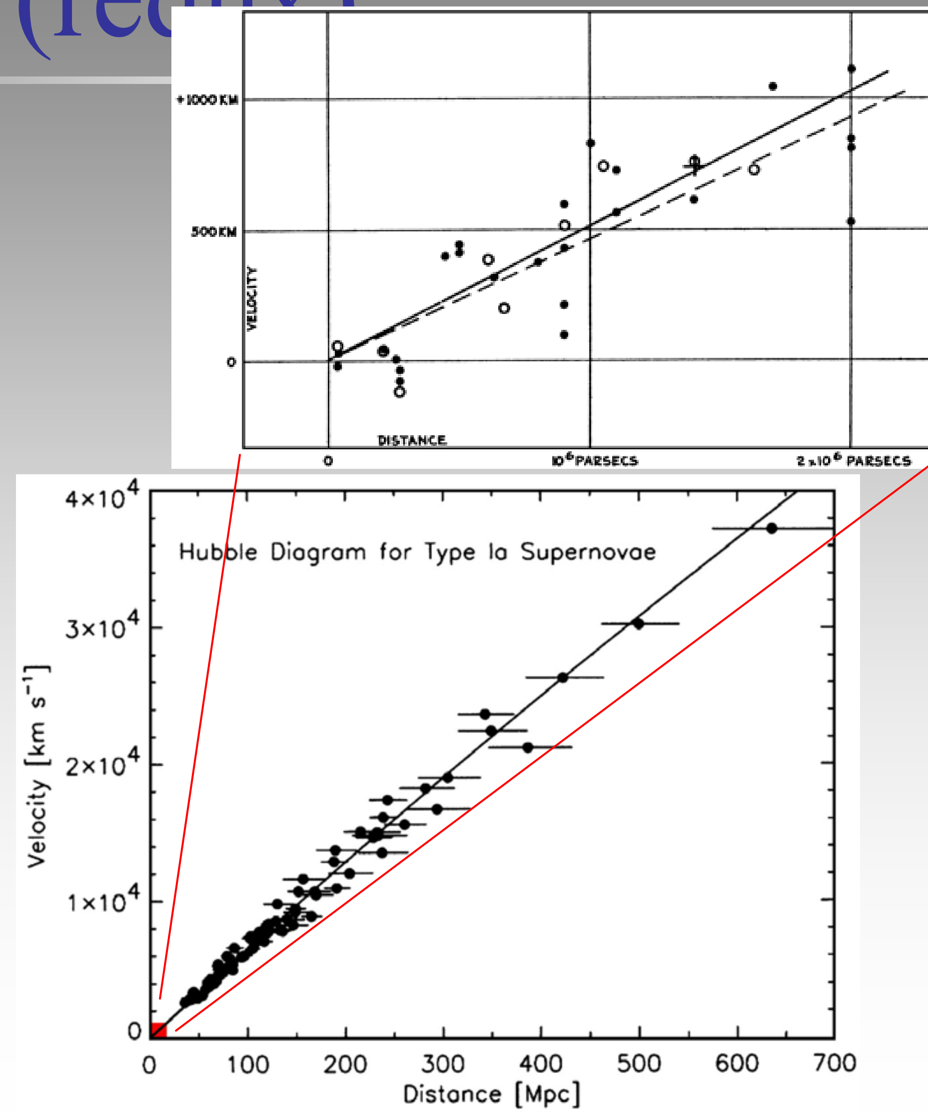
$$H_0 = 65 \pm 15\ \text{km/sec/Mpc}$$



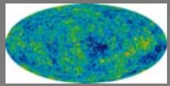
Hubble's Law (redux)

Original data vs. modern data from SN Ia:



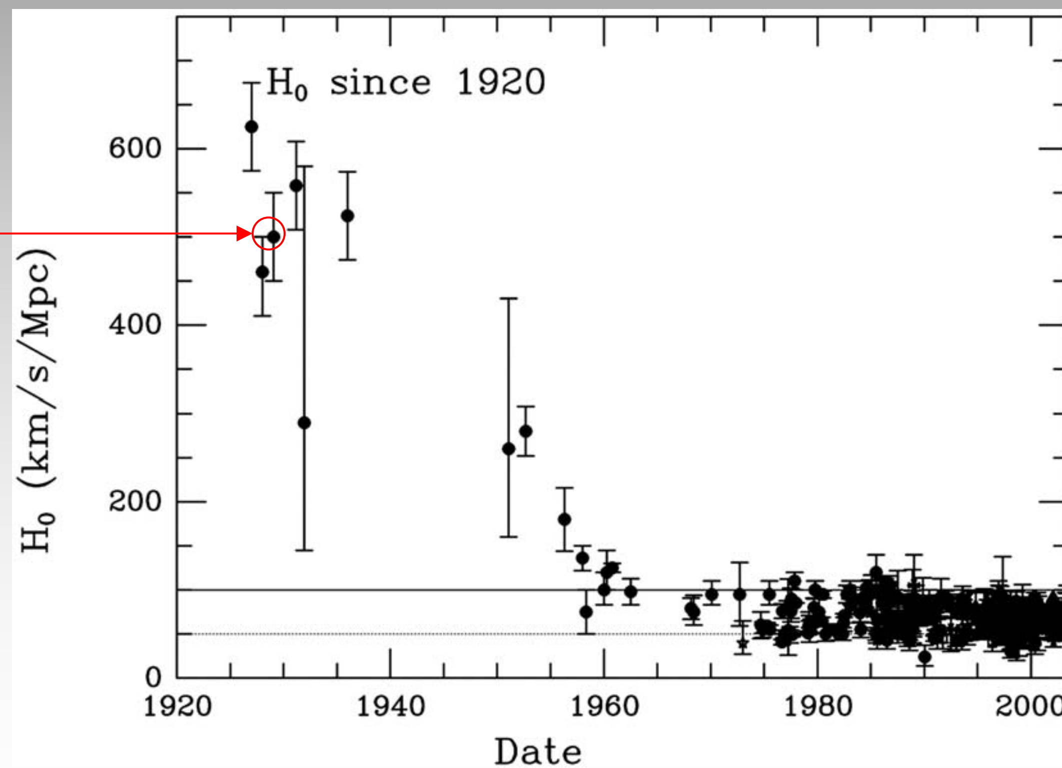


Hubble constant: 72 +/- 7 km/sec/Mpc

Hubble's Constant

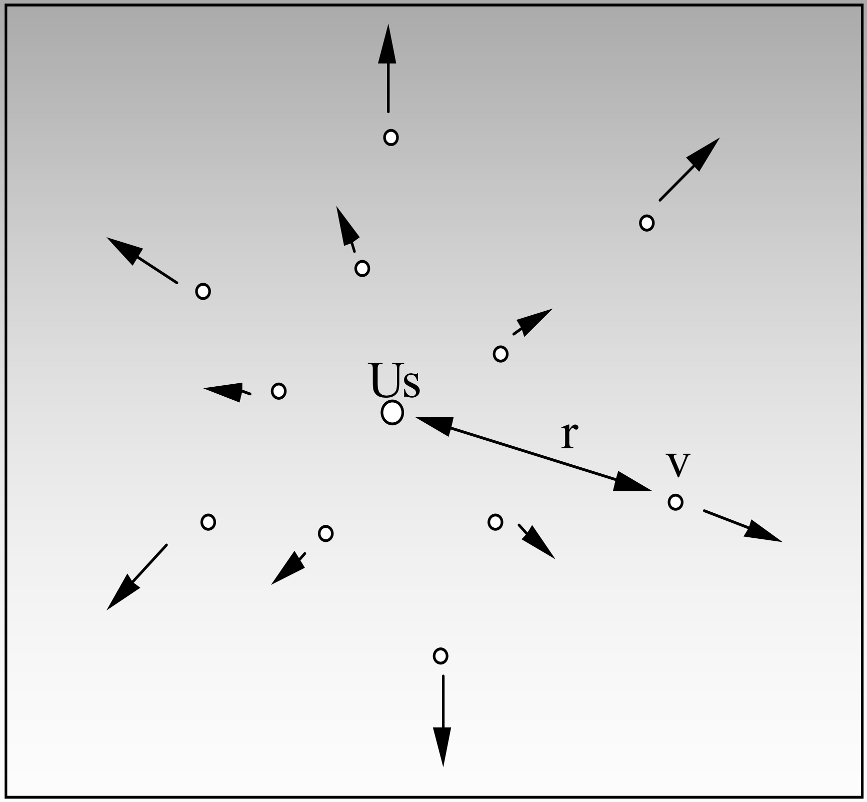
Hubble, 1929

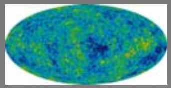


Hubble constant: 72 +/- 7 km/sec/Mpc

The Hubble Flow

- The Hubble Law implies an overall flow of galaxies away from one another.
  - The view is precisely the same from any galaxy!
  - Hubble motion dominates intracluster motion for d > 100 Mpc.
- Hubble's Law can be used to find distances > 200 Mpc!





The Expanding Universe

Us $\bullet \longleftarrow$ r = 1 Mpc = 3 x 10^{19} km $\longrightarrow \bullet$ It $\longrightarrow$

v = 75 km/s

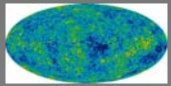
- If distant galaxies recede according to *Hubble's Law*...

  $$\mathbf{v = H_0\, d}$$

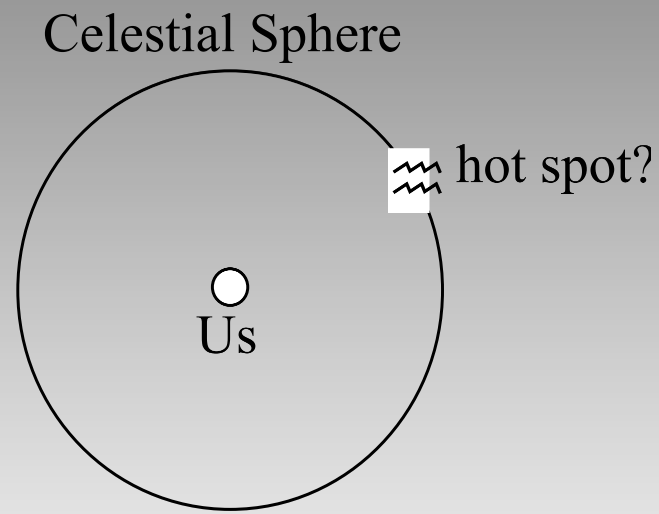
  then they would all have been *at the same place* when

  $$\mathbf{t = d / v = 1 / H_0 \approx 15 \pm 2 \text{ billion years.}}$$

- The universe appears to be expanding as it would after a cosmic explosion: *the Big Bang*.

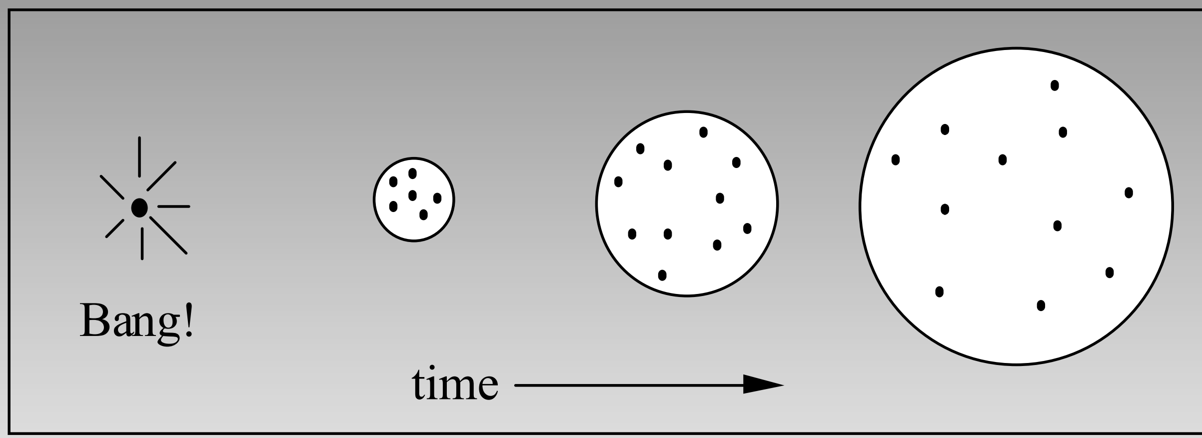


Where Was the Big Bang?



- If galaxies are rushing from some earlier explosion, where did this explosion take place?
  - Is there a *cosmic hotspot* in a particular direction of the sky?
- Photons coming from the Big Bang have been seen and they come *uniformly from all directions* of the sky.

It’s Everywhere! It’s Everywhere!



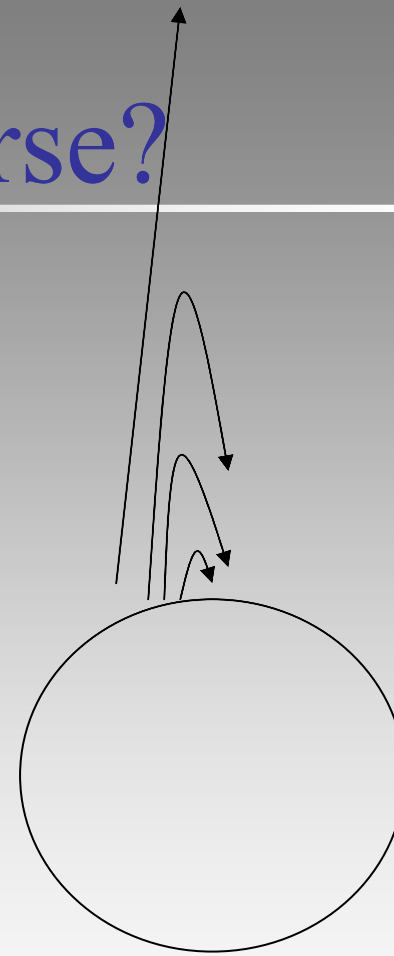
- The Big Bang didn’t occur at a point in the Universe:

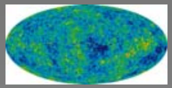
  It is the Entire Universe Itself Which is Expanding!

  - Galaxies are like points painted on an inflating balloon. They move away from one another ***just because the balloon inflates***.

How Old is the Universe?

- Imagine launching a bit o'mass upwards in a gravitational field
- Distance the object goes depends on initial velocity *and* on gravitational field
- Gravitation acts to *decelerate* the bit o'mass





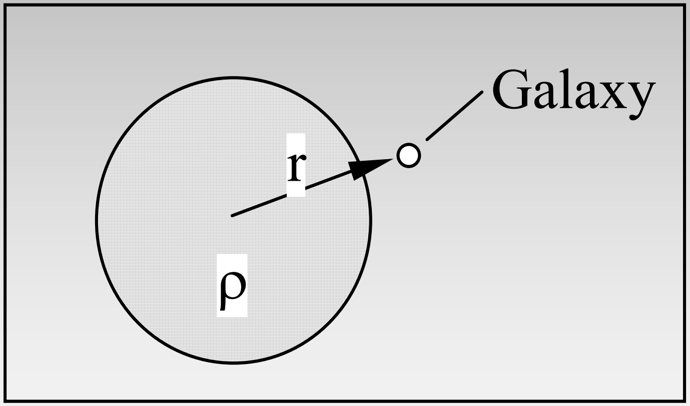
How Old is the Universe?

- Mutual gravitation of matter acts to *decelerate* the rate of universal expansion.
  - Precise age can be calculated given the **current matter density**.
  - Our previous reasoning:

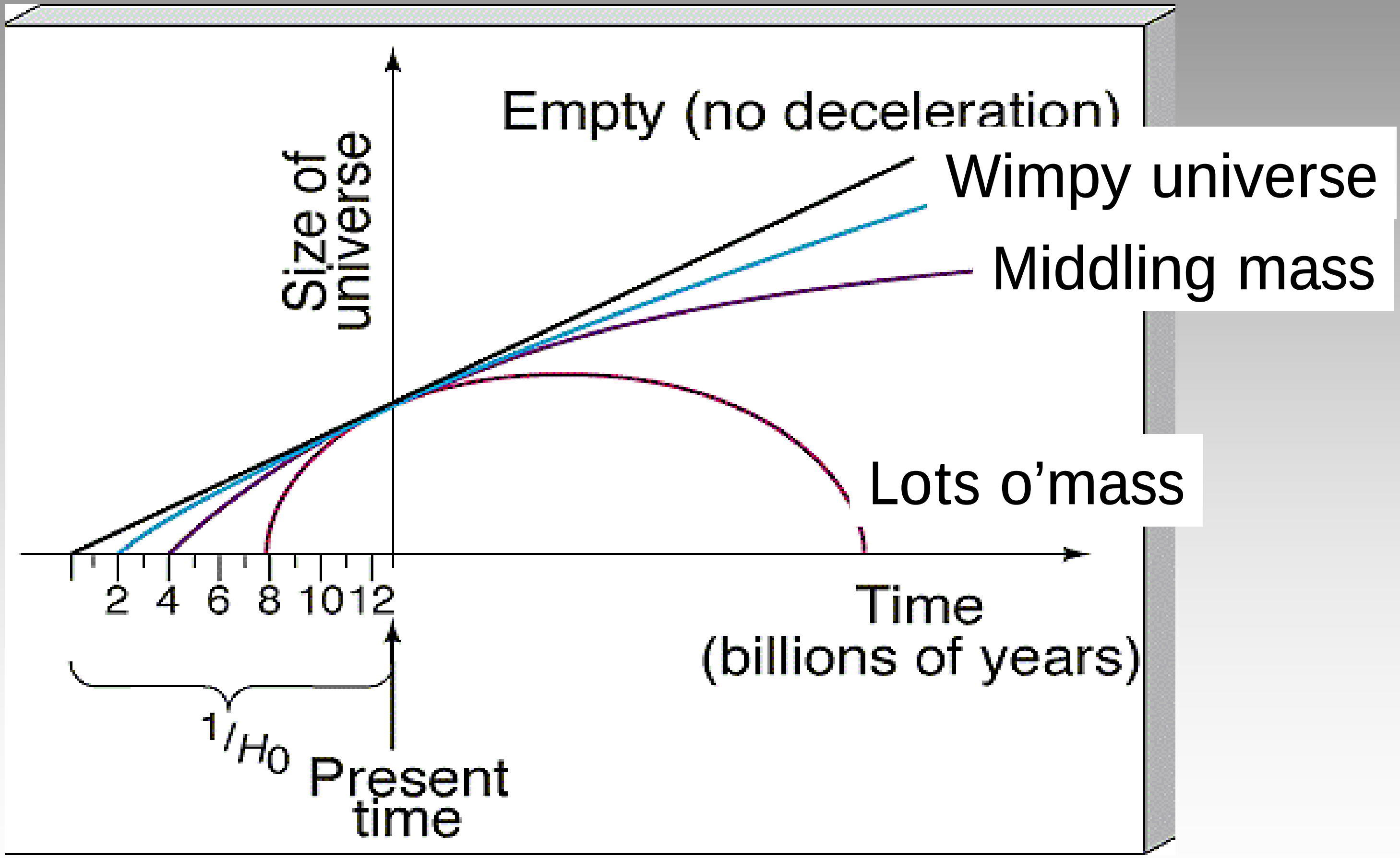
    Universe's Age = 1 / H_0

    = 15 ± 2 billion

    years probably overestimates its real age.

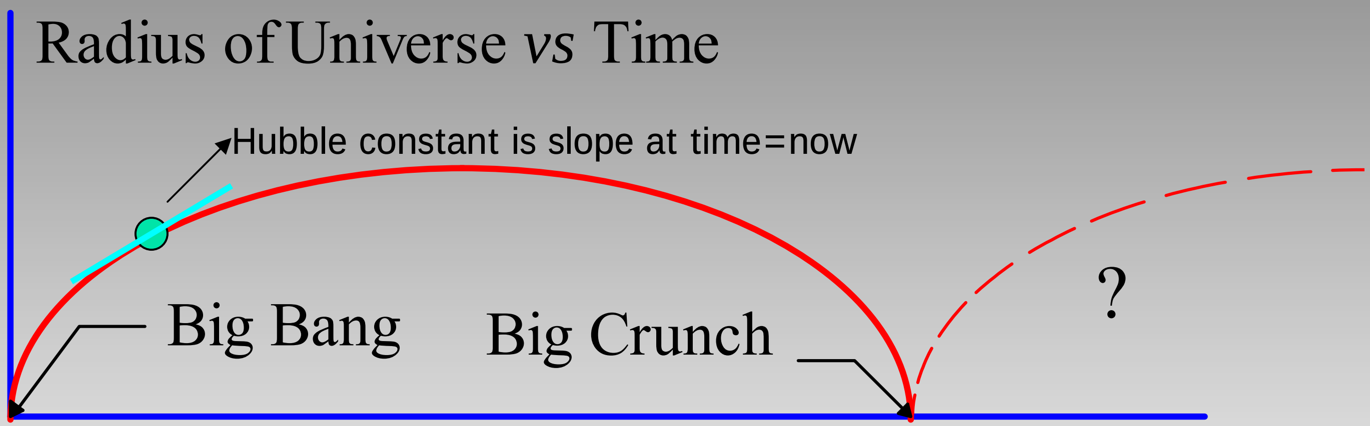


How Old is the Universe?



Answer will depend on the amount of mass *(density)* in the Universe

A Big Crunch?

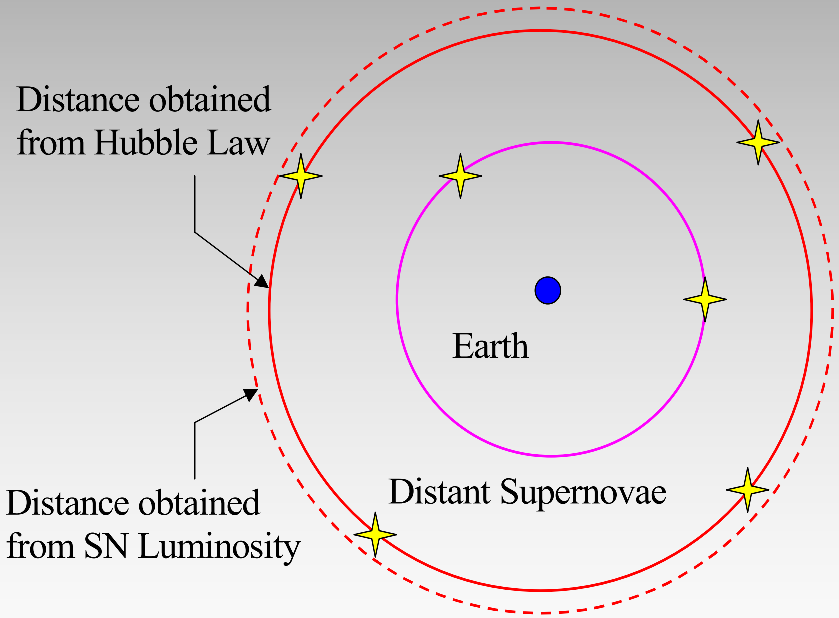


- If the density of matter is higher than a critical density, ρ_c, the mutual pull of gravity can cause Universe to recontract to a Big Crunch. Otherwise it expands forever.
  - Critical density: ρ_c **= 10^{-29} g/cc = 6 H** atoms per cubic metre.

    (Assuming $H_0 = 65$ km / sec / Mpc.)
  - ***Luminous matter is only a few % of this critical density.***
  - ***The Key Question: How much dark matter is there?***

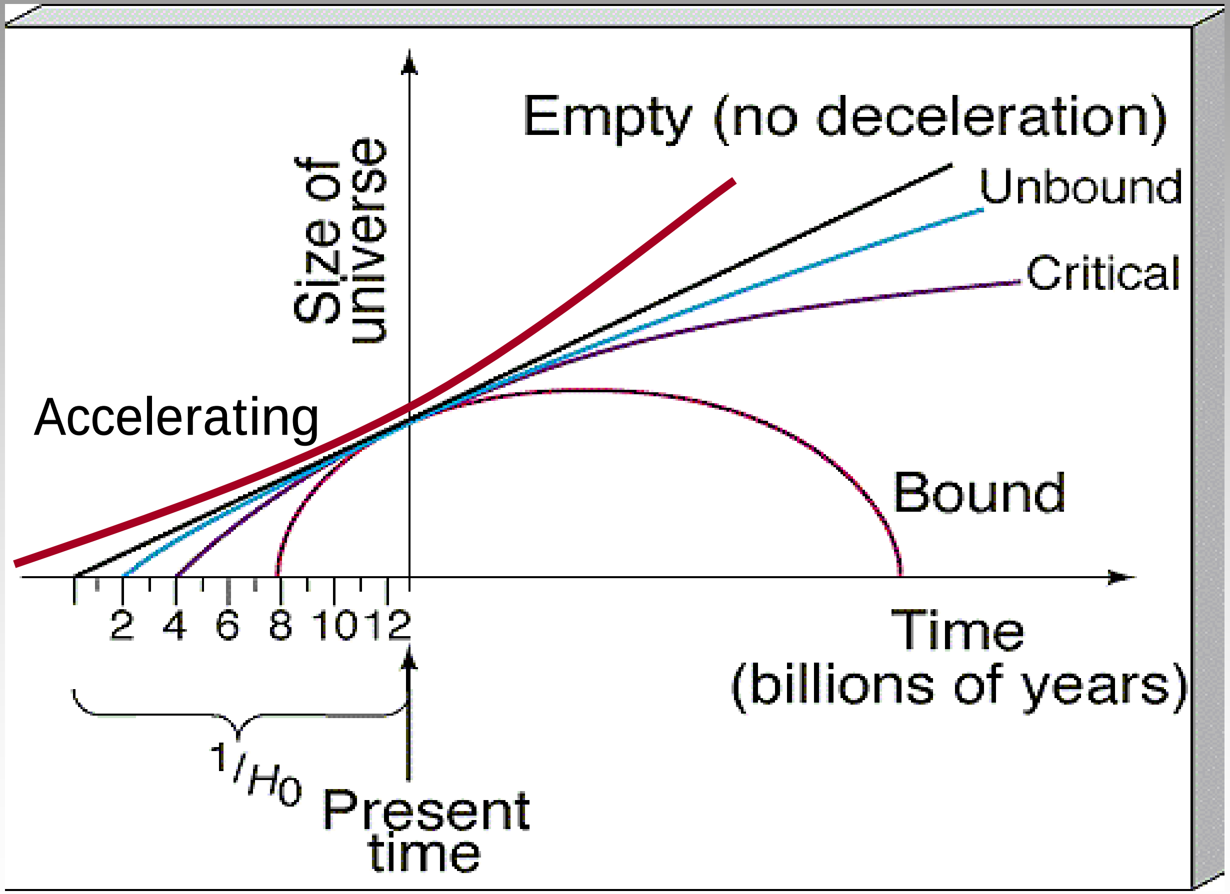
But the Universe is *Accelerating!*

- In the late 1990's two experiments surveyed Type I Supernovae out to redshift $z = 1$ with surprising results:
  - Supernovae appear to be dimmer ***(and so more distant)*** then they should be if their distances were properly given by the Hubble Law!!
- *Very high stakes:*
  - Such cosmic ***acceleration*** cannot be obtained using ordinary or dark matter, because gravity ***always*** causes deceleration.

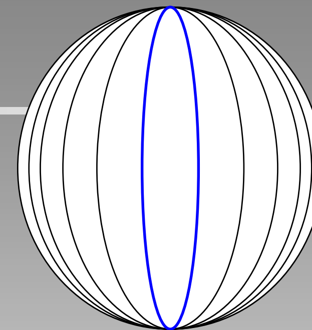


Requires a new type of unknown matter: Dark Energy!

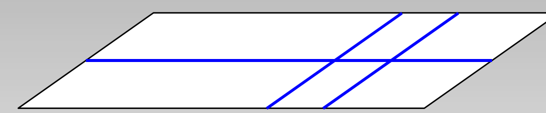
The Universe's Age and Its Future

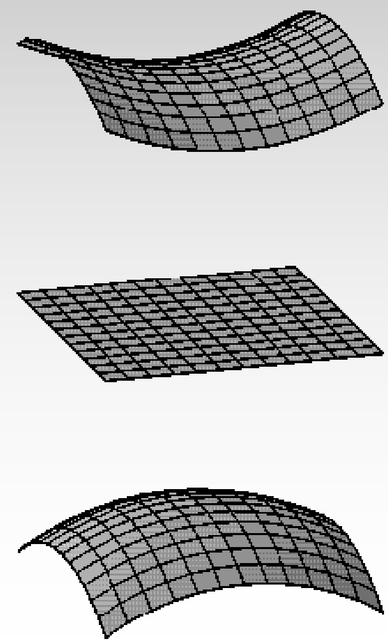


Homogeneous Isotropic Geometry

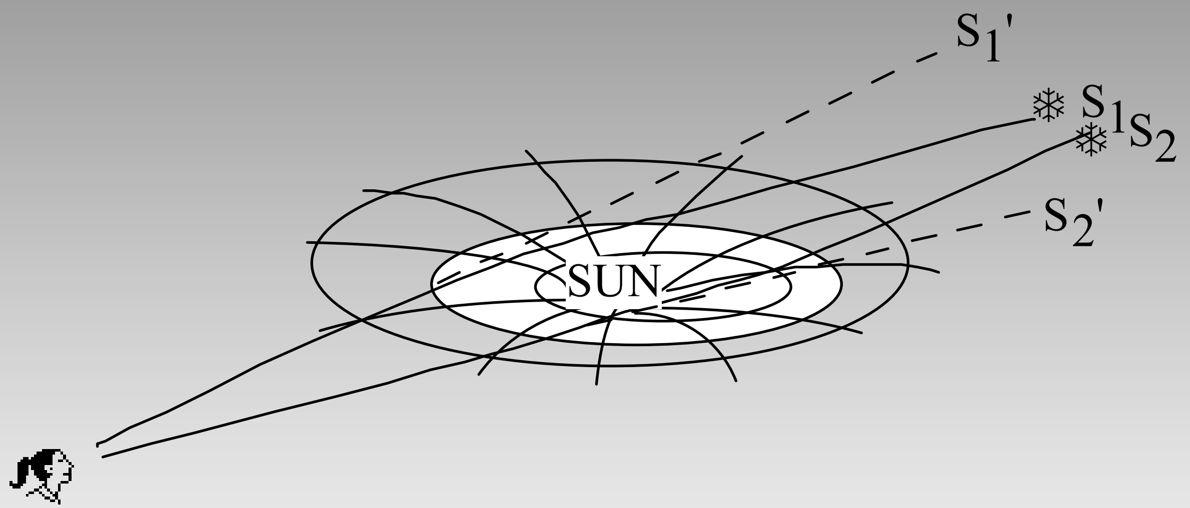


- There are three kinds of geometry which are consistent with the observed homogeneity and isotropy of the Universe.
  - **Spherical Geometry:** Space has the geometry of a three-dimensional sphere.
  - **Flat Geometry:** Space has the usual Euclidean geometry.
  - **Hyperbolic Geometry:** Space has the geometry of a three-dimensional **saddle**.

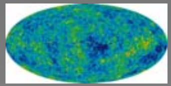




Gravity and the Geometry of Space



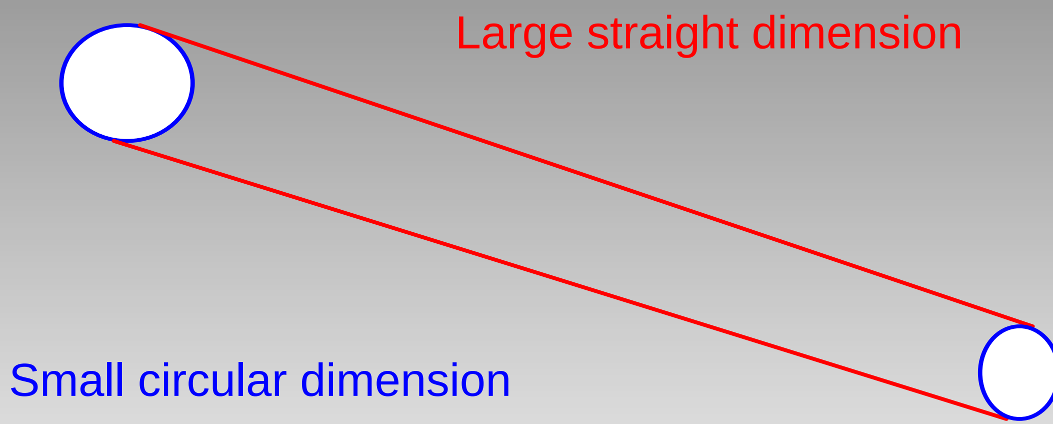
- Einstein's theory of gravity states that gravity can be understood as the bending of space and time by matter.
- When applied to the Universe at large, the matter distribution determines the overall geometry of space.



The Geometry of Space

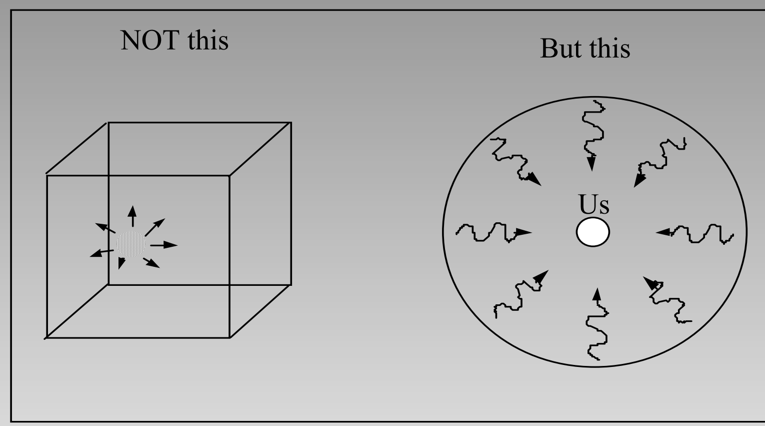
- The *geometry of space* depends on whether the matter density is larger or smaller than ρ_c:
  - If $\rho > \rho_c$ then space has a *spherical* geometry and is called a *'closed'* Universe.
    - A diverging pencil of light rays can traverse the universe and reconverge at their starting point.
  - **If** $\rho = \rho_c$ then space is *flat*.
    - Initially parallel light rays remain parallel forever.
  - **If** $\rho < \rho_c$ then space has a *hyperbolic* geometry and is called an *'open'* Universe.
    - Initially parallel light rays diverge and never return to their starting point.

How Many Dimensions?

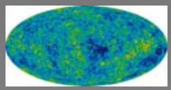


- If gravity is geometry, the *dimension of spacetime* is an experimental question.
  - Usually suppose there are **4** dimensions: **3 space** dimensions (length, width, height) plus **time**.
  - *What if there are more space dimensions, but these are too small to have been detected??*

Which brings us to: The Hot Big Bang

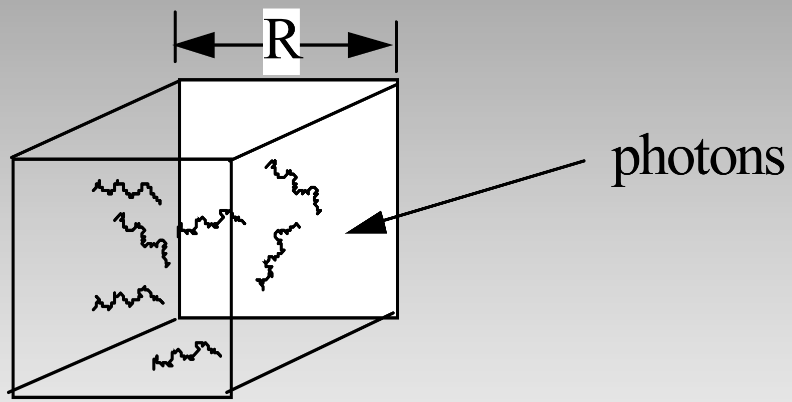


- Matter in an expanding container cools.
  - Extrapolating the observed expansion backwards should imply the Universe was once very small and very hot.
- The *Hot Big Bang* theory assumes the Universe was initially much smaller than now, and was hot enough that atoms and nuclei cannot hold together.
  - At these temperatures matter is a soup of elementary particles (protons, neutrons, electrons, neutrinos, dark matter, *etc*)



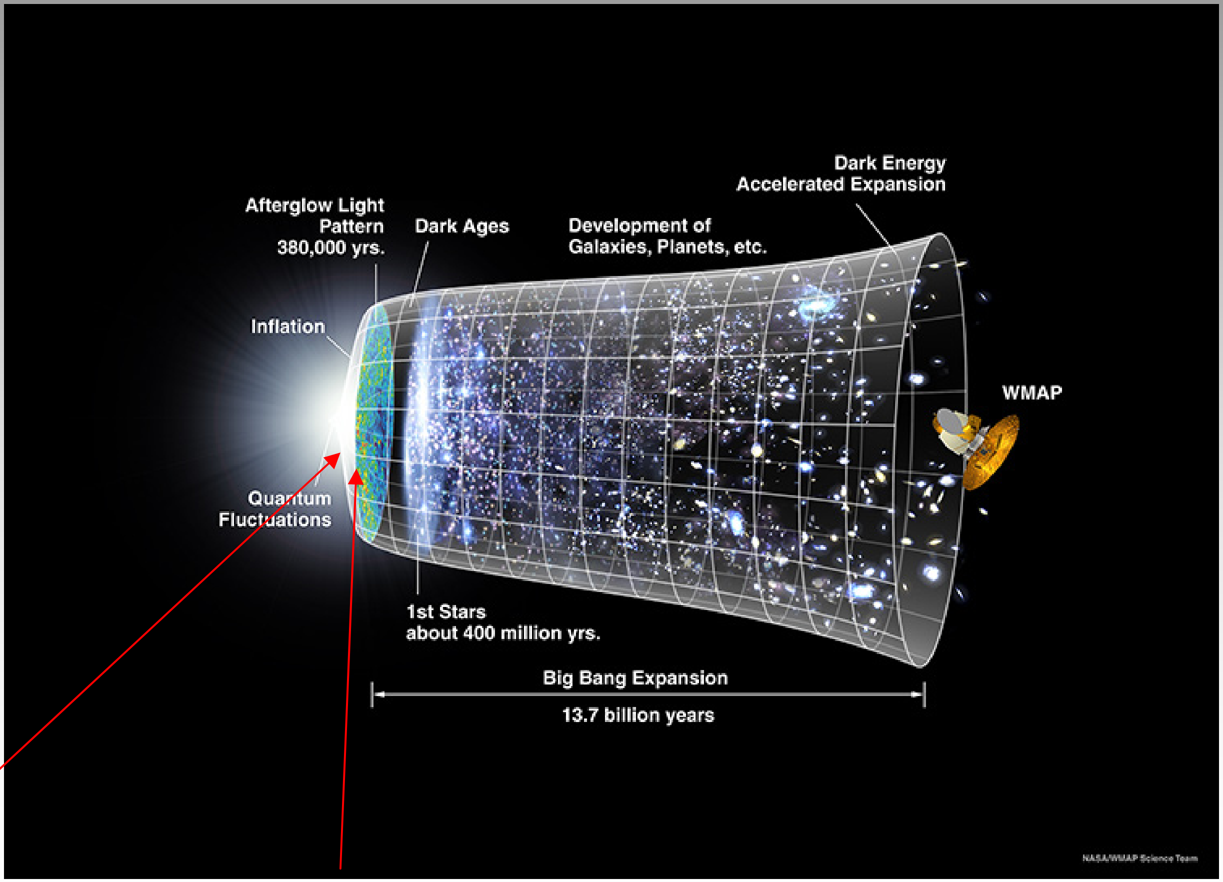
An Expanding, Cooling Universe

- As the Universe expands it cools like an expanding box whose sides don't admit any heat.
  - Red-shifting of cosmic background photons implies they ***cool*** as the universe expands.
  - The temperature is inversely proportional to the size of the universe.

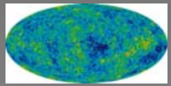


$$\frac{T}{T_{now}} = \frac{R_{now}}{R} = z + 1$$

An Expanding, Cooling Universe

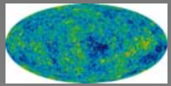


nucleosynthesis Reionization & the CMB



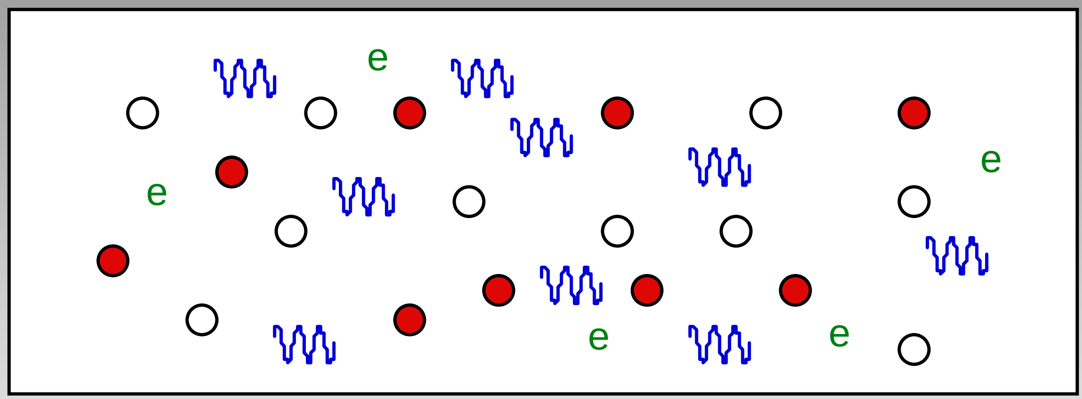
Important Events

- By running the Hot Big Bang forwards we can see if it reproduces the properties of the Universe which we presently see.
  - *Temperature = 10^{10} K:* ***Nuclei form*** like Helium, Deuterium and a few others.
  - *Temperature = 10^{4} K:* ***Neutral Atoms form*** and the Universe becomes transparent.
  - *Temperature = 10^{4} K:* The energy density of photons falls below the energy density of ordinary matter.
    - It is only ***after*** this that gravity can cluster matter together.
  - ***Formation of galaxies*** by the amplification by gravity of small initial density inhomogeneities.



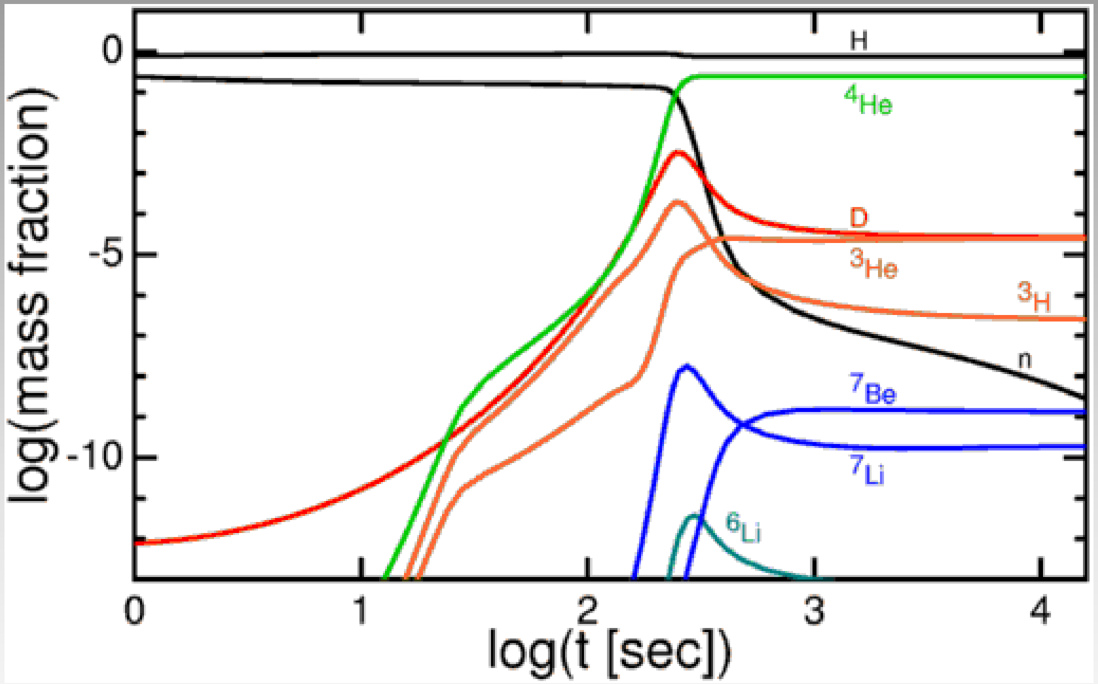
Big Bang Nucleosynthesis

P N photons, neutrinos e - electrons, positrons

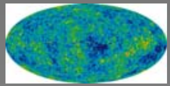


- When the Universe is hotter than around 10^{10} K (ie, younger than a few minutes old) it is hot enough that nuclei cannot survive.
  - Ordinary matter is a soup of protons, neutrons and electrons.
- Once cooled below this temperature – ***the epoch of primordial nucleosynthesis*** - light elements *(mostly Helium)* are formed.

Primordial Abundances



- The predicted abundances of the light elements agree with the observed abundances, providing an explanation for the abundance of Deuterium, Helium, Berilium and Lithium.



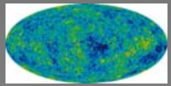
The Deuterium Bottleneck

- In order to form Helium (2 protons + 2 neutrons), you first make *Deuterium* (1 proton + 1 neutron).
  - Deuterium turns out to be easy to break and so does not survive long enough to make Helium until the temperature falls from 10^{10} K to about 10^{9} K.
- *BUT:* neutrons also decay into protons, and only those which have not done so when deuterium forms can be cooked into Helium.
- *How much Helium you get depends on how fast the Universe cools from 10^{10} to 10^{9} K.*

$$p + n \longleftrightarrow d + \gamma$$

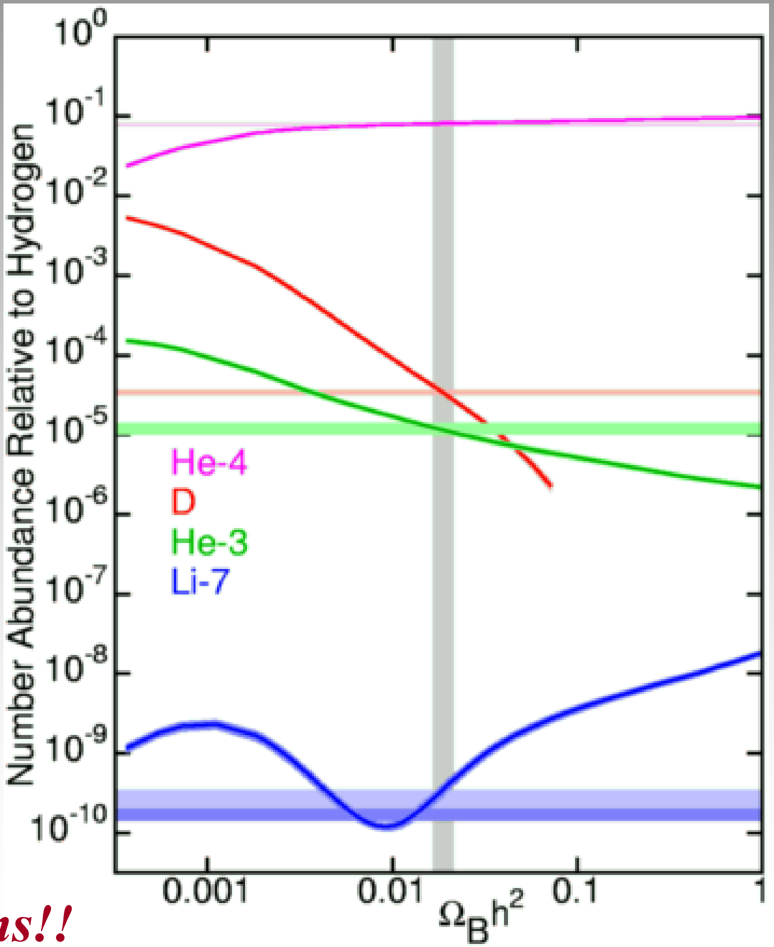
$$d + d \longrightarrow He^{4} + \gamma$$

$$n \longrightarrow p + e^{-} + \bar{\nu}$$

Dark Matter is NOT Atoms!

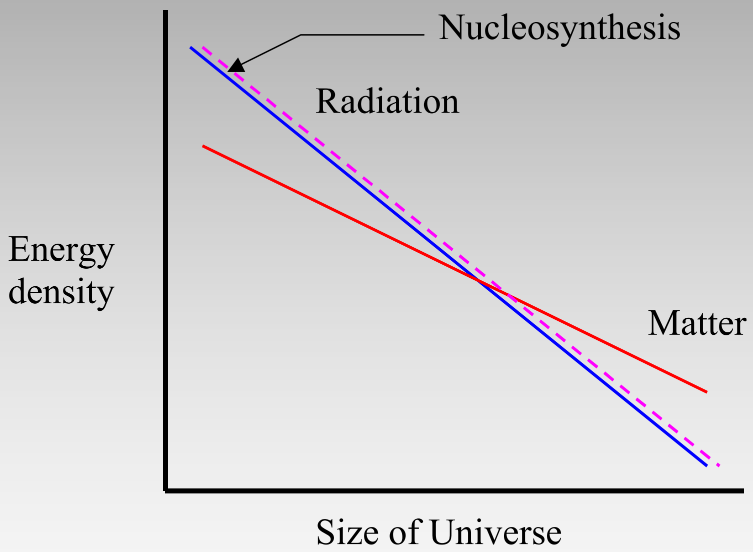
- The relative abundance of ^{4}He, ^{3}He, D and ^{7}Li is sensitive to the total number of protons and neutrons present in the universe.
  - If there are fewer protons and neutrons, they have more difficulty finding one another to react.
- Agreement with observations requires there be *at most* a few times more protons and neutrons than are visible.



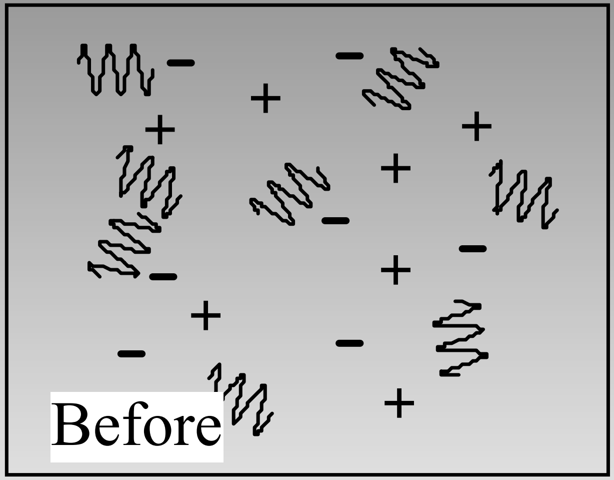
Dark matter cannot all be protons and neutrons!!

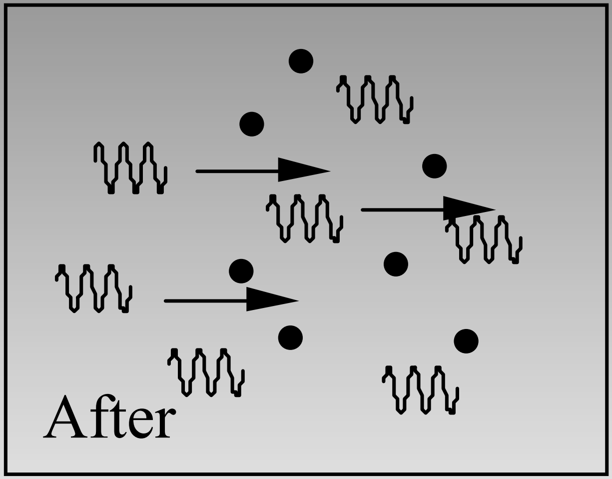
Nucleosynthesis Constraints

- The Helium abundance depends on how quickly the Universe cools during the nucleosynthesis epoch.
- The cooling rate depends on the Universe's expansion rate, which depends on the amount of matter present during the nucleosynthesis epoch.
- Success of predictions for He abundance shows that any exotic forms of matter make up at most 10% of the universal energy density during nucleosynthesis.



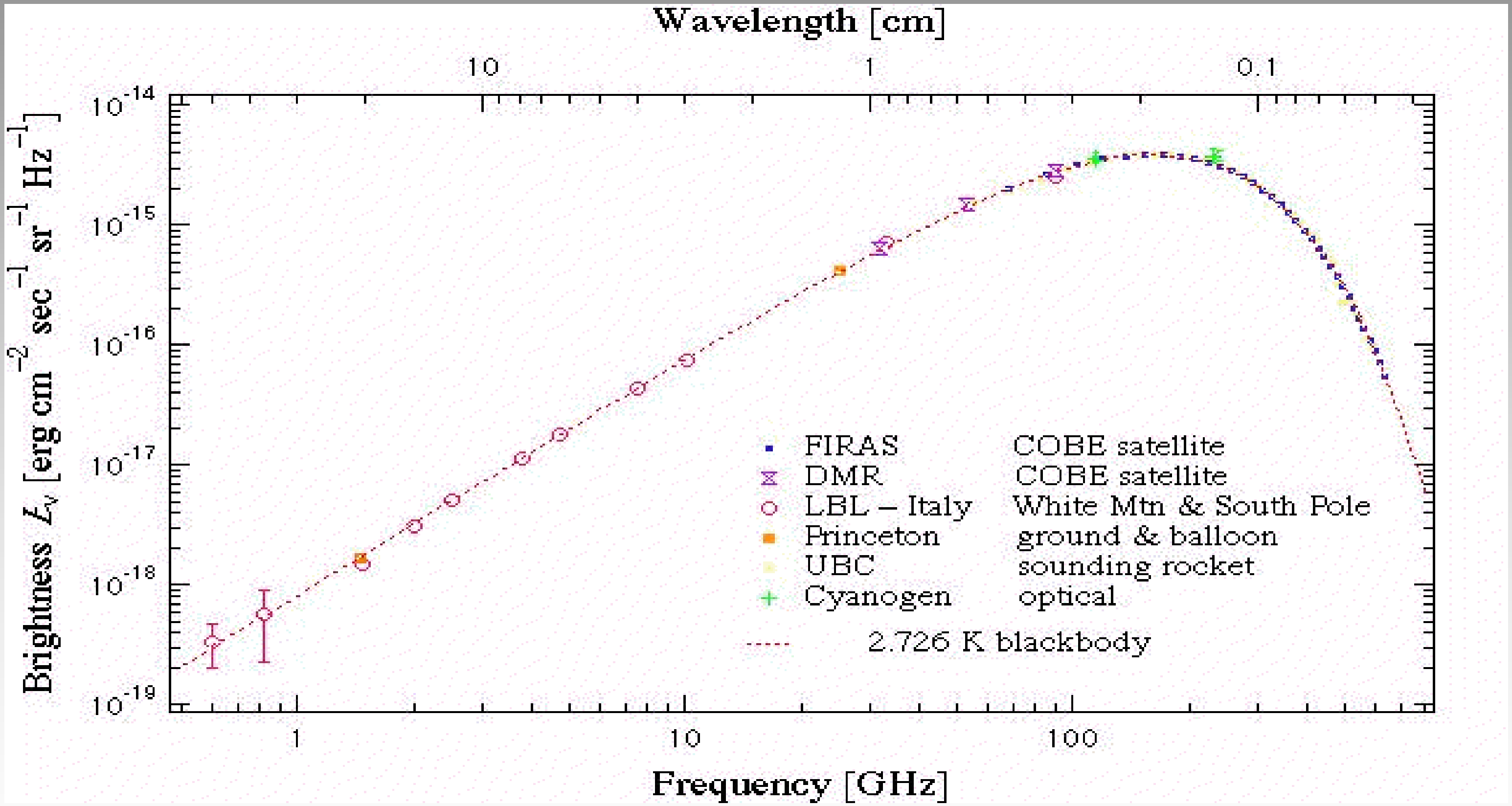
Recombination





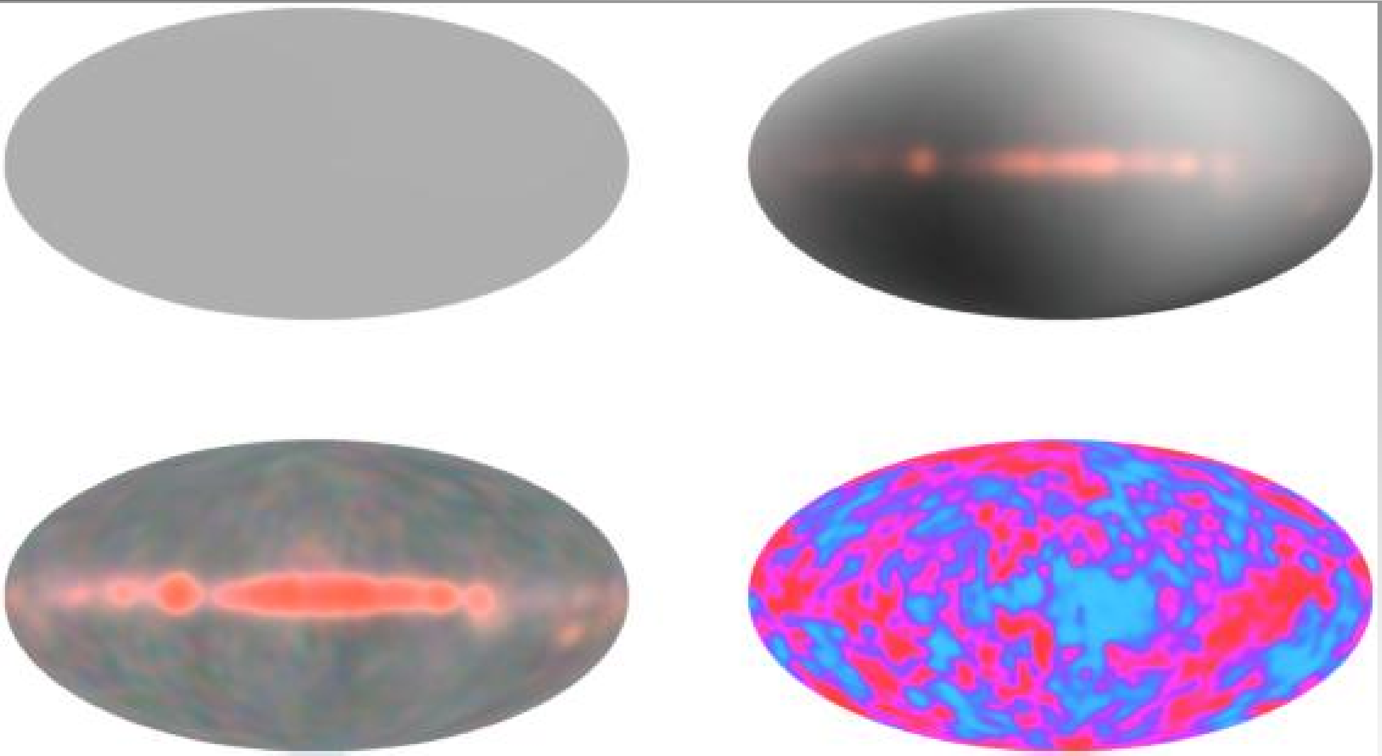
- Before around 100,000 years after the Big Bang the Universe was hot enough to ionize atoms.
  - Above these temperatures the Universe is opaque to light.
  - When the Universe cools below 3000 degrees nuclei and electrons combine into neutral atoms, and the Universe becomes transparent.
  - This is the Universe we 'see' when looking at the cosmic microwave background radiation (CMB).

The CMB Temperature

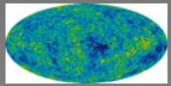


Cosmic photons were discovered by **Penzias** and **Wilson**, but as microwave photons since the temperature has been red-shifted down to ***2.73 K***.

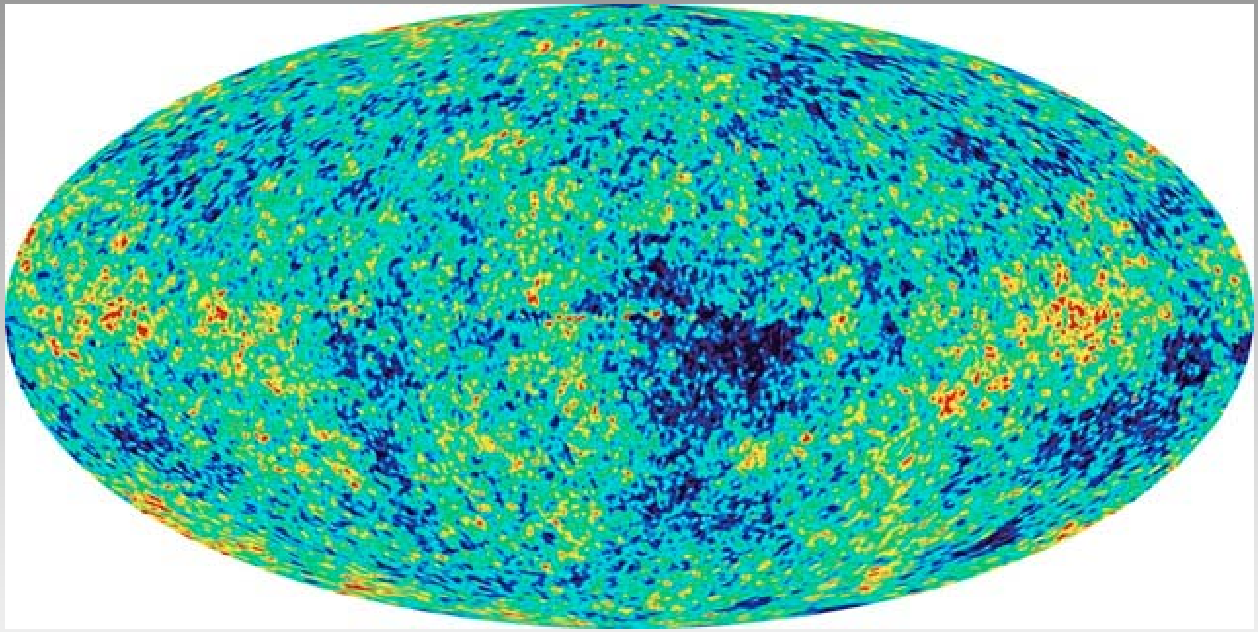
Primordial Inhomogeneities



- CMB looks uniform (to one part in 10^3) but has imprinted on its smaller fluctations our motion through space, our galaxy's mass distribution, and (ultimately) remnants from the moments of recombination.

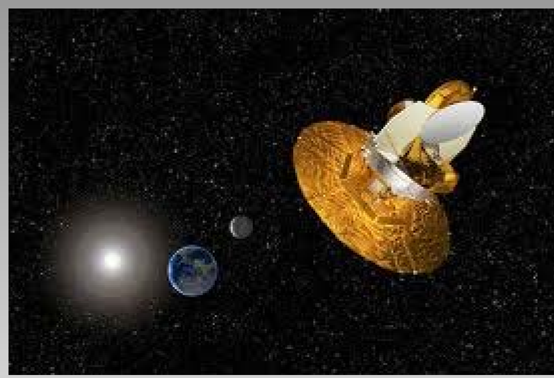


Primordial Inhomogeneities

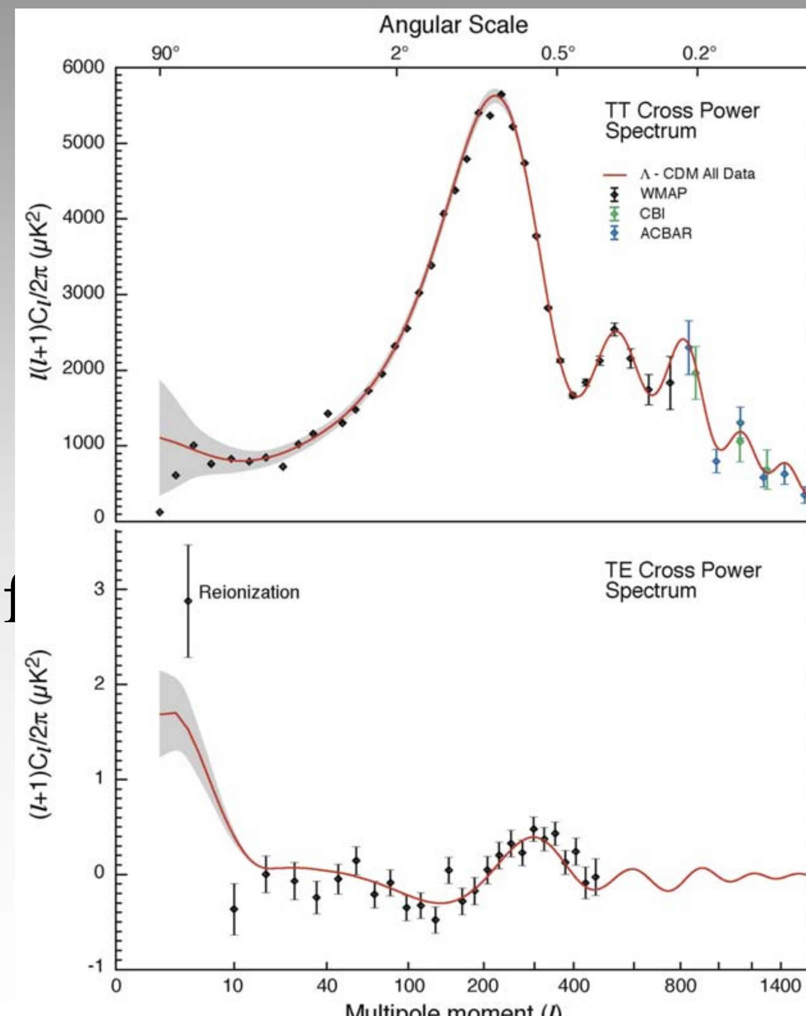


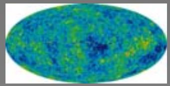
- Once the motion of the Earth is compensated for, the CMB temperature is uniform to 1 part in 10^5 in all directions.
  - This implies the early Universe was ***extremely*** homogeneous.
- Current precision measurements of the small CMB temperature fluctuations *redundantly* test the Big Bang Model.

WMAP CMB Measurements



Measuring the CMB fluctuations allow precision measurements of parameters of the hot big bang model





Remarkable convergence!

Recent cosmological parameters:

H_o = 71 ± 4 km/s/Mpc (Hubble const)

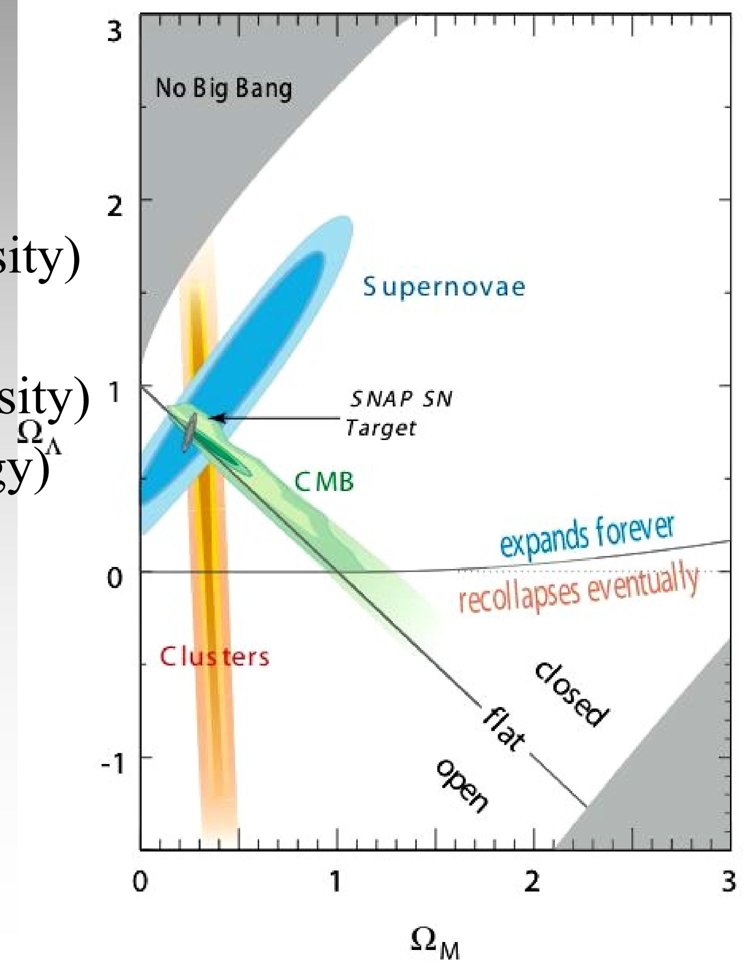
t_o = 13.7 ± 0.2 Gyr (Universe age)

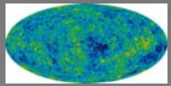
Ω_m = 0.27 ± 0.04 (Dark matter density)

Ω_{baryon} = 0.044 ± 0.004 (Regular stuff)

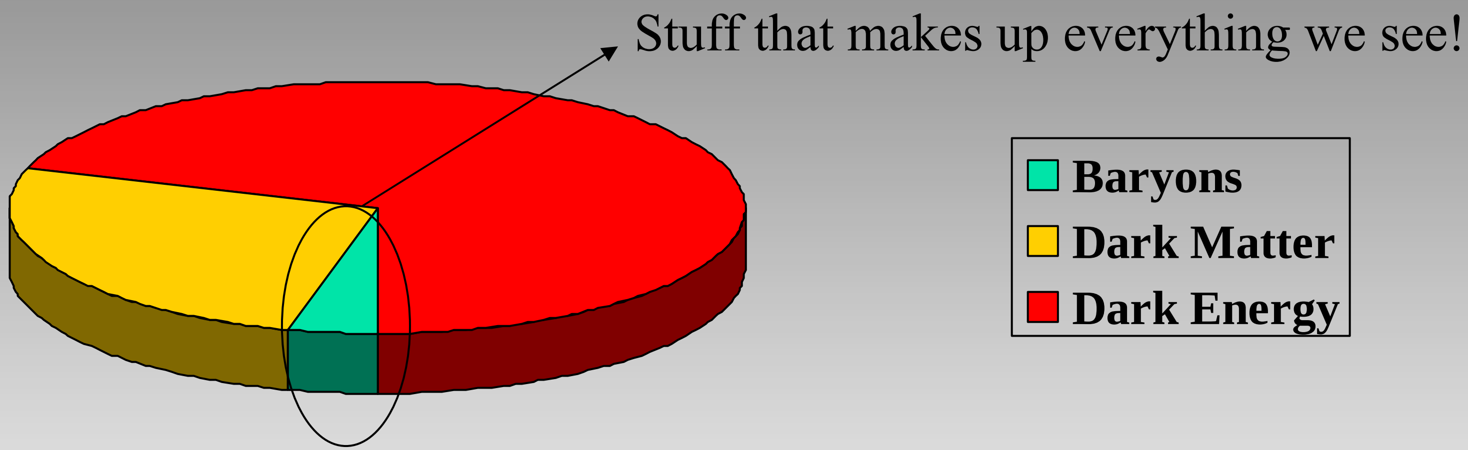
Ω_Λ = 0.73 ± 0.04 (Dark energy density)

Ω_T = 1.02 ± 0.02 (Total mass/energy)





The Universal Energy Budget

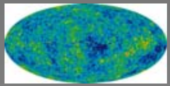


- The total energy density is critical: $\rho = \rho_c$
- The fraction of energy density is written: $\Omega_i = \rho_i/\rho_c$

Ω*(Dark Energy)* = *70%*

Ω*(Dark Matter)* = *26%*

Ω*(Protons/neutrons)* = *4%*

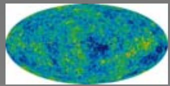


The Hot Big Bang is a compelling model…

…but it has some issues:

- What is the dark matter?
- What is the dark energy?
- Do we really understand the full evolution to the world we see today?

- Observationally, we can study the remants (the CMB, galaxies) or we can try to *reproduce* the big bang conditions



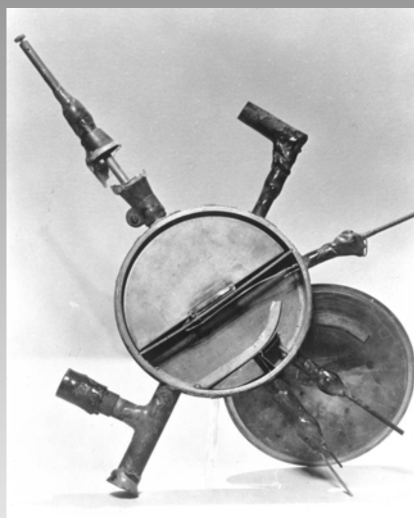
Particle physics

Particle physics seeks to understand how the subatomic world works – higher energies help explore a more complex world than our everyday one.

High energy particle collisions mimic the conditions of an earlier, hotter (ie, more energetic) Universe.

The history of particle physics is the history of producing ever-more energetic collisions!

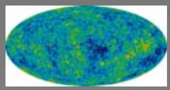
The Growth of Accelerators



Cyclotron, Lawrence, 1930's

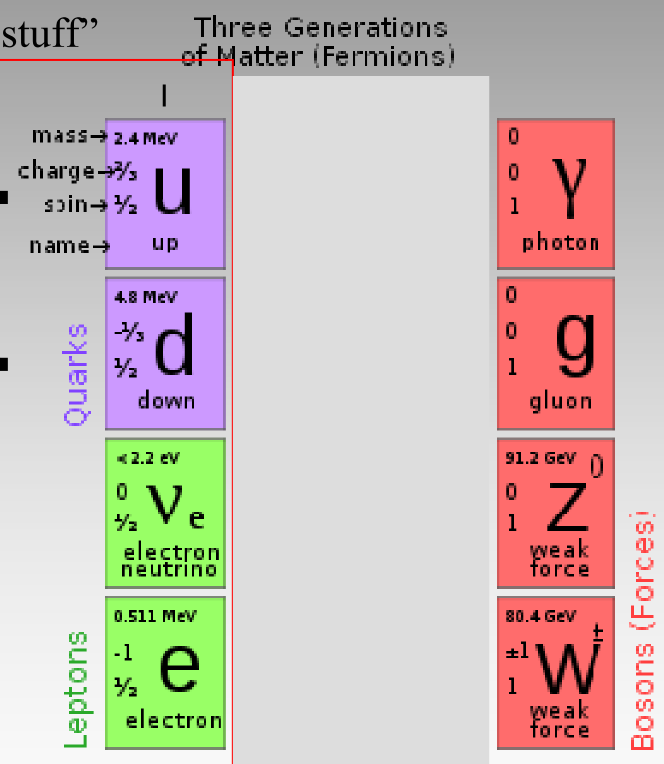
Fermilab, 1980's

Berkeley 184-inch cyclotron, 1940's



The Standard Model

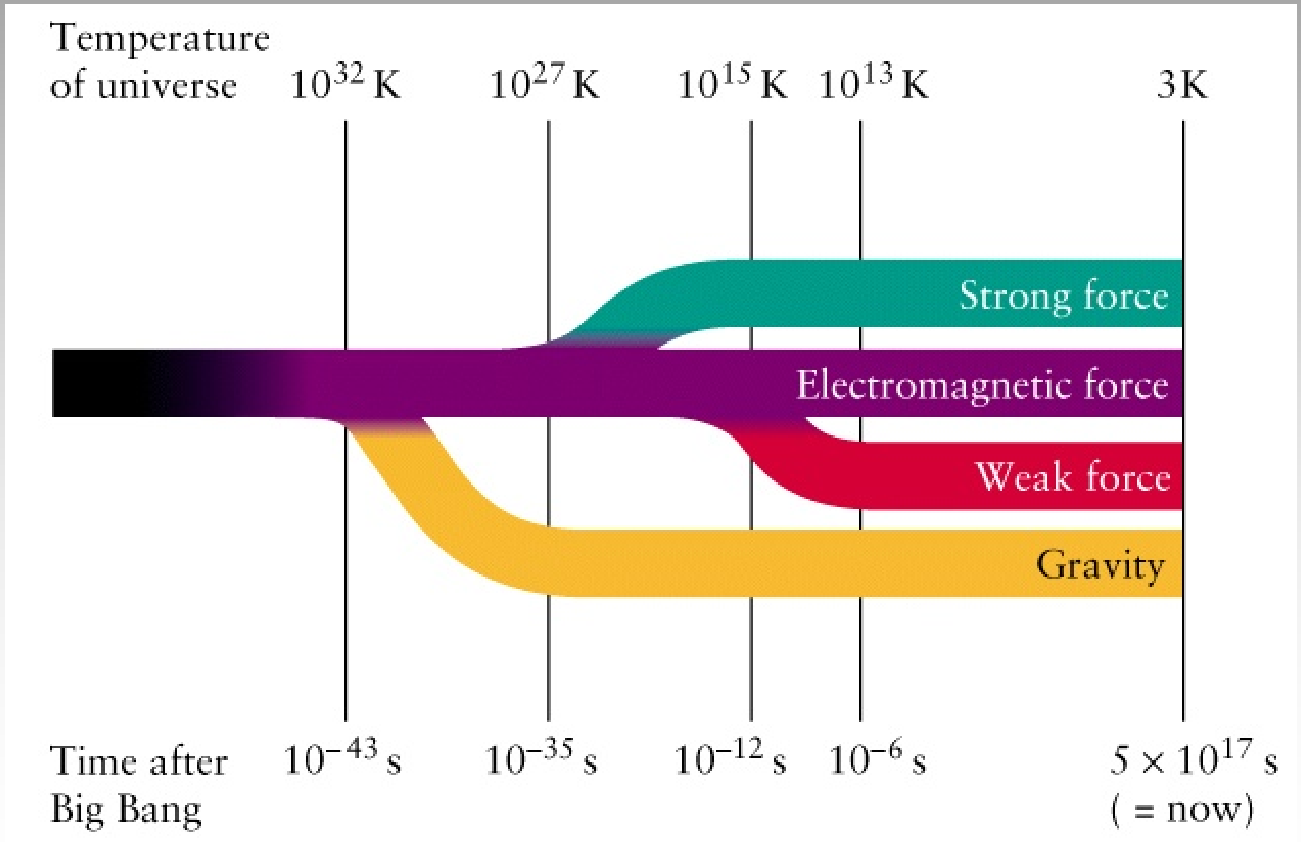
Regular “stuff”

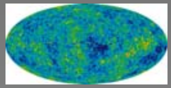


Protons, neutrons, nuclei

Atoms

Why higher energies?



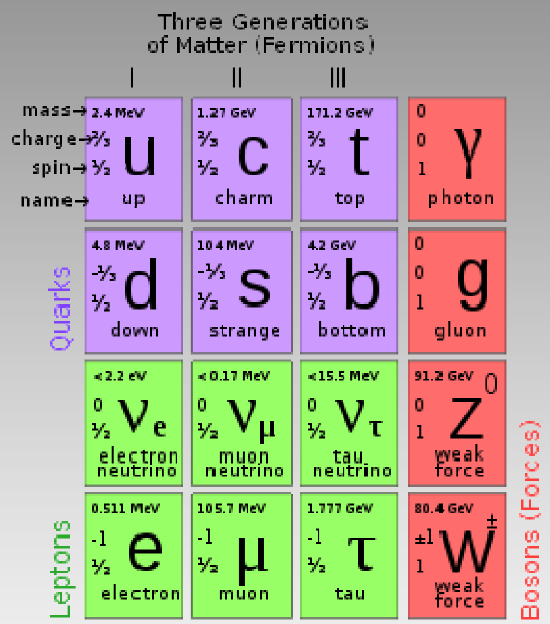


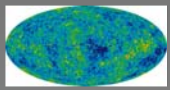
The Standard Model isn’t the whole answer!

Phenomenally successful…

but incomplete!

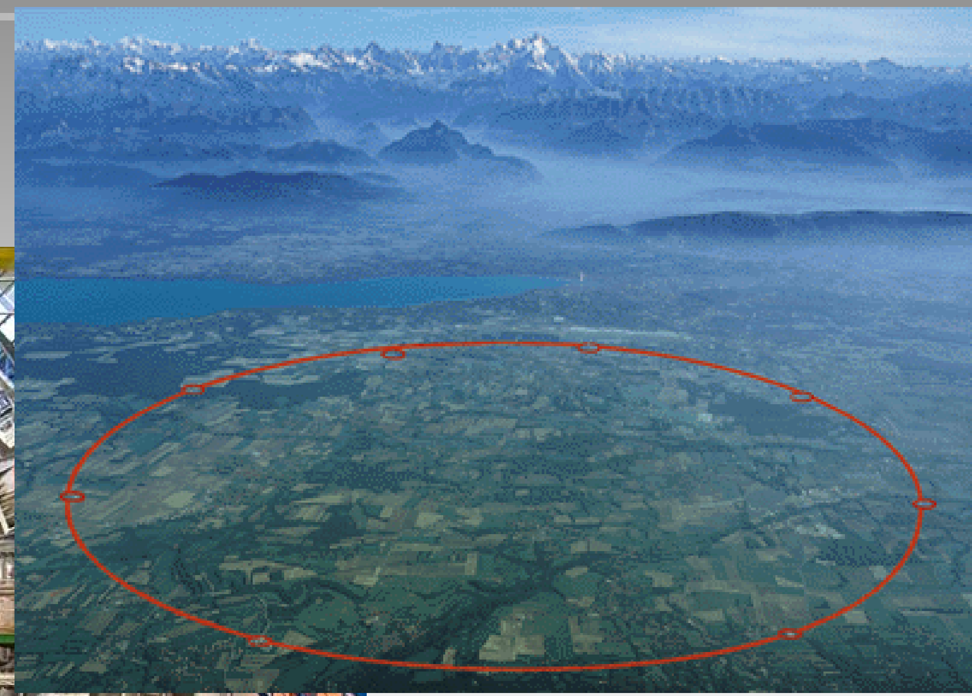
- Why so many particles?
- What gives them mass?
- Where did all the anti-matter go?

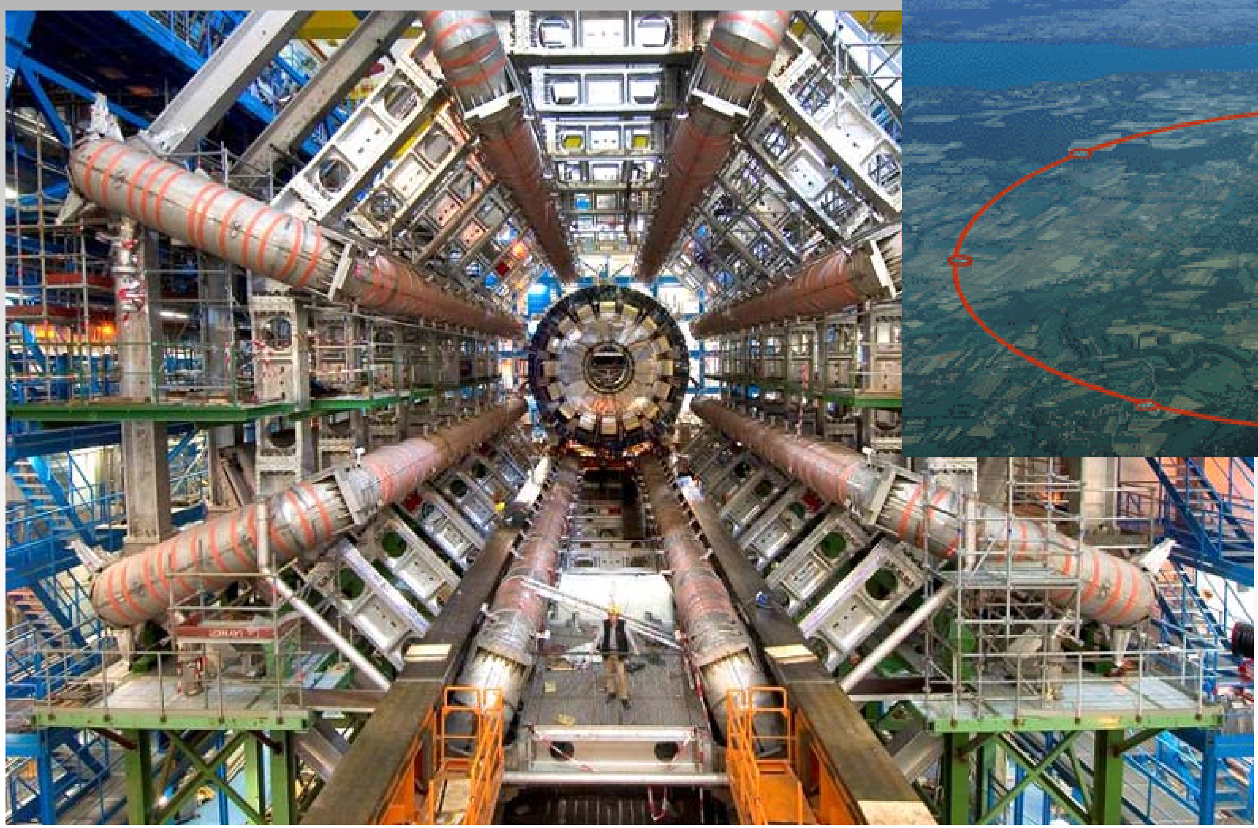


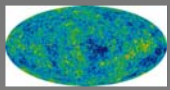
  

The answer may lie at higher energies!

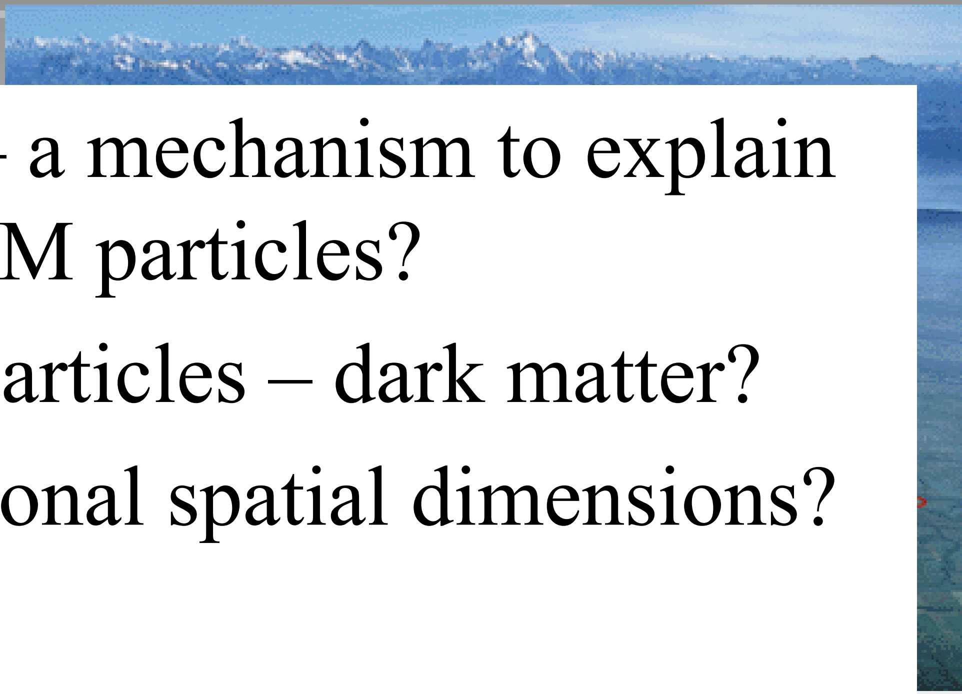
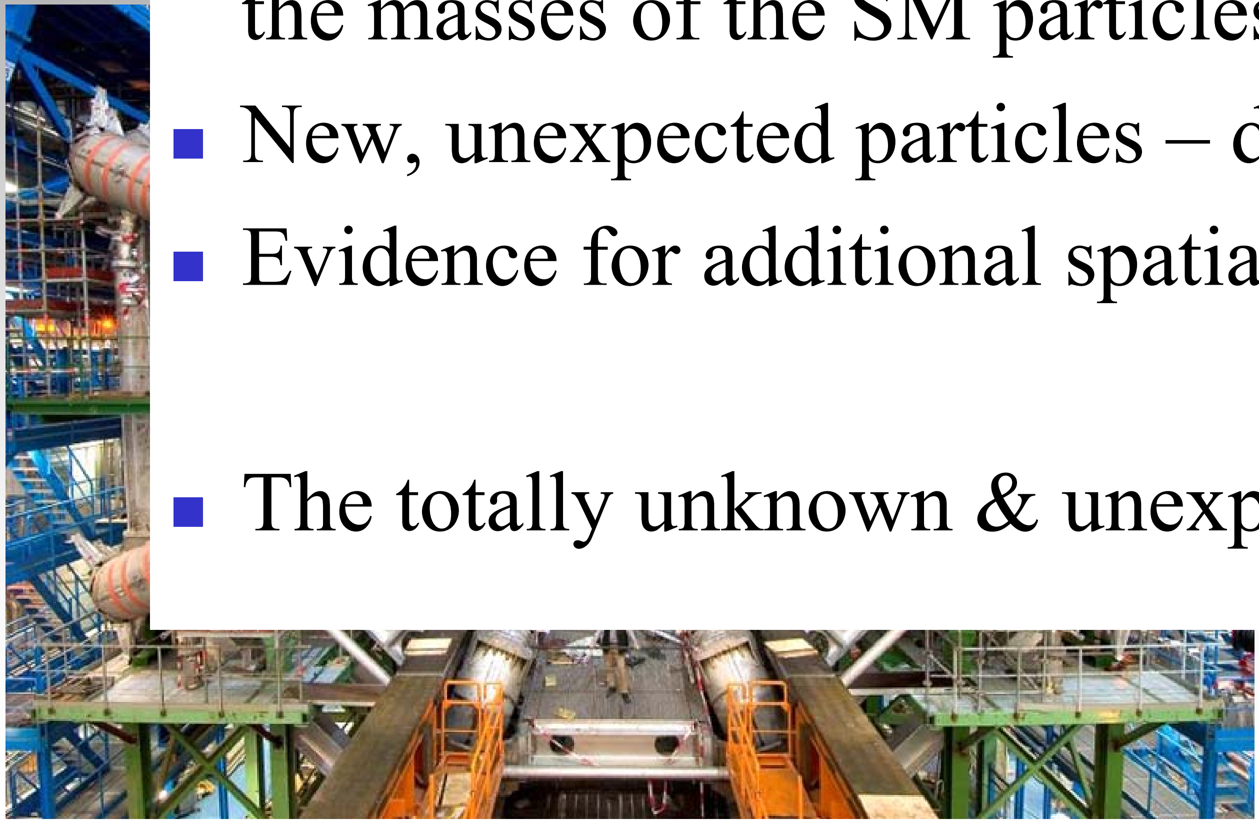
The LHC:



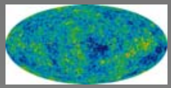




What would we love to see at the LHC?

- The Higgs Boson – a mechanism to explain the masses of the SM particles?
- New, unexpected particles – dark matter?
- Evidence for additional spatial dimensions?
- The totally unknown & unexpected!



The take-home message

- Cosmology and Particle Physics are deeply inter-twined
- The Hot Big Bang model, together with the Standard Model of particle physics, provides a compelling *quantitative* description of the Universe's evolution
- Neither description is entirely complete, and our hopes are pinned on the LHC to show the way forward!