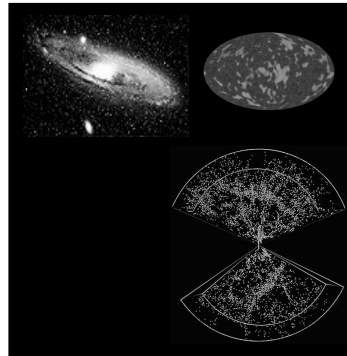


Vital Statistics of the Universe

Today...

- Observational evidence for the Big Bang
- Vital statistics of the Universe
 - ◆ Hubble's Constant (H_0)
 - ◆ Curvature (k)
 - ◆ Density (Ω)
- How will it all end?
(Expand forever - or collapse?)

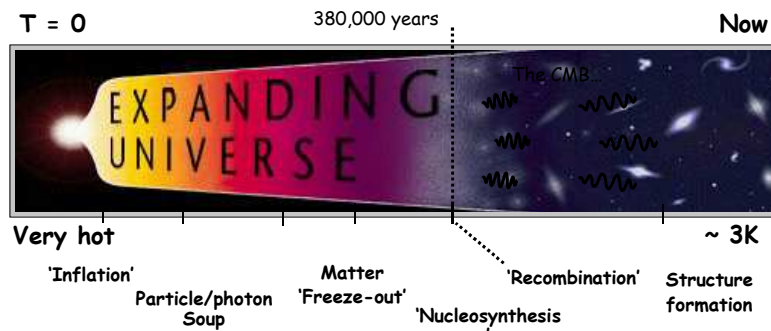


Our Evolving Universe

1

The Big Bang so far...

The universe is expanding & cooling after an initial 'explosion' ~14 billion years ago.



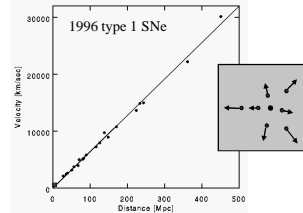
Our Evolving Universe

2

Evidence for the Big Bang

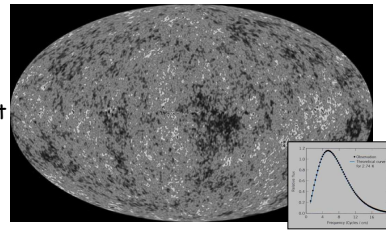
■ Hubble's Law

- $V = H_0 \times D$ (H_0 =Hubble's Constant)
- Evidence for expanding universe (not specifically for Big Bang)



■ The Cosmic Microwave Background

- Photons from 'recombination' at $T = 380,000$ yrs
- Evidence for a HOT beginning



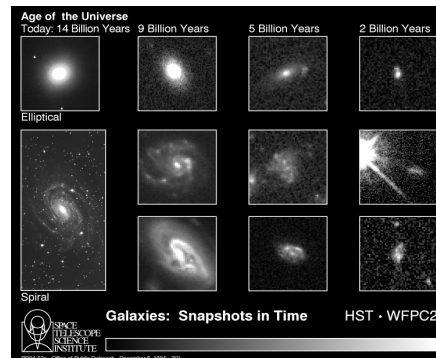
Our Evolving Universe

3

Evidence for the Big Bang

■ The evolution of galaxies

- Distant (older) galaxies look different from those nearby.
 - ◆ Older galaxies generally smaller, more irregular & more interacting
 - ◆ More active galaxies
- Evidence for changing, non-eternal universe.



Earlier lecture 'Evolution of Galaxies'

Our Evolving Universe

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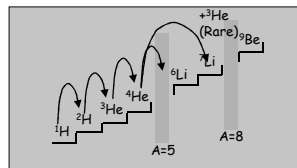
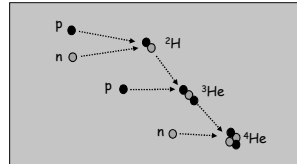
Evidence for the Big Bang...

The abundance of elements

Big Bang Nucleosynthesis predicts:

- Mostly Hydrogen & ^4He formed - with much smaller quantities of heavier elements.
- Relative abundance of ^4He to Hydrogen predicted to be **25%** (by mass) of total.
 - ◆ Dependent on ratio of proton to neutrons at the time of nucleosynthesis (~7:1)
- Levels of ^2H , ^3He and ^7Li also predicted.

Theory makes clear predictions based on 'well understood physics



Our Evolving Universe

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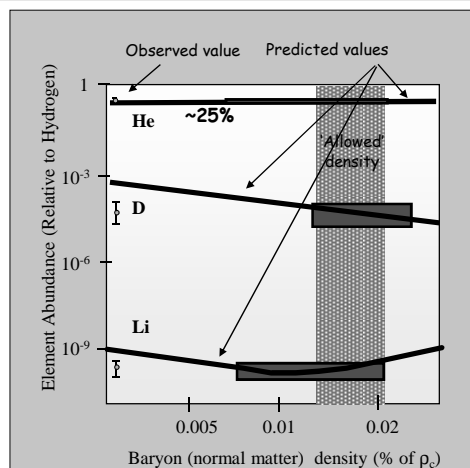
Evidence for the Big Bang...

The abundance of elements

Observations...

- (Current abundances dependent on density of ordinary matter at nucleosynthesis - & therefore density now).
- Observations agree **VERY WELL** with predictions
- More **STRONG** evidence for Hot Big Bang

(Allowed 'baryon' density also of great interest for later studies of 'Dark Matter')



Our Evolving Universe

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Evidence for the Big Bang...

Summary...

Overall...
Plenty of evidence FOR the Big Bang...
Nothing directly AGAINST.

Our Evolving Universe

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Vital statistics of the universe

- Parameters needed to describe the state (& predict the fate) of the Universe :

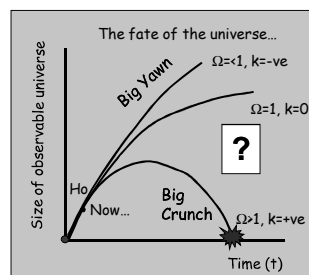
Hubble's constant (H_0)

Density (ρ or Ω)

- $\Omega = \text{density/critical density} = \rho/\rho_c$

Curvature (k)

- (For 'flat' universe $k = 0$).



$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{R^2} + \frac{\Lambda}{3}$$

Hubble's Constant Density term Curvature term Cosmological Constant

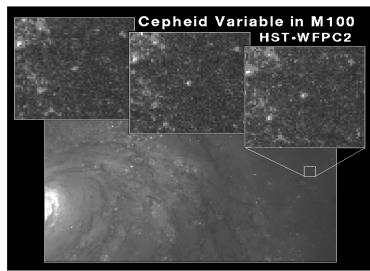
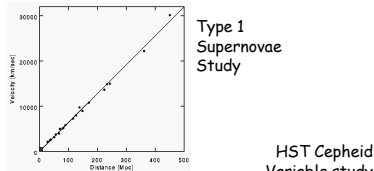
Einstein's General Relativity says how it all fits together.

Our Evolving Universe

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Vital statistics of the universe...

Measurement of Hubble's constant



- Many ways to do this
 - redshift easy: distance challenging
 - need long distances (>300 Mlyr or so)
- Recent results:
 - $73 \pm 2 \pm 4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (compilation, 2010)
 - $69.8 \pm 1.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (WMAP + galaxy surveys)

Our Evolving Universe

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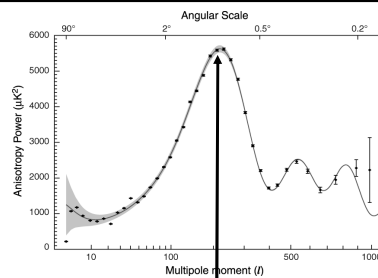
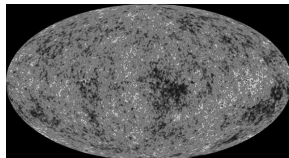
Vital statistics of the universe...

Measurements of curvature

Curvature (k)

- Is dependent on total density Ω .
- Inflation predicts universe is FLAT! (i.e. $k = 0$).

Curvature can be determined through analysis of the ripples in the CMB



Position gives:
 $k = 0$ (Flat!)
(Also $H = 70 \pm 2 \text{ km/s/Mpc}$)

Our Evolving Universe

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Vital statistics of the universe...

Measurements of density (1)

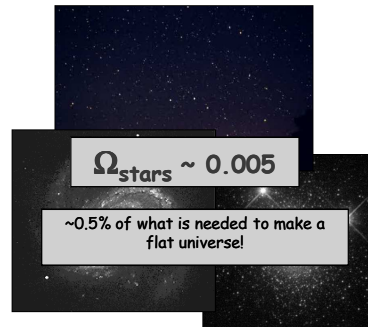
Density (Ω)

- Ω = density/critical density
= ρ/ρ_c
- $\rho_c \sim 10^{-26} \text{ kg}\cdot\text{m}^{-3}$
 $\sim 6 \text{ H atoms per m}^3$

There are many different ways of determining the density of the universe...

1) Contribution of stars

- Add up the masses of all stars...



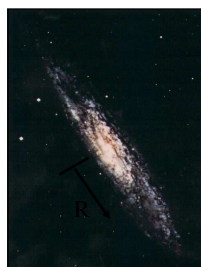
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Vital statistics of the universe...

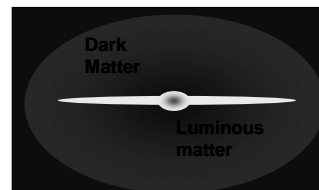
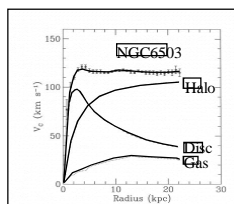
Measurements of density (2)

2) Contribution of galaxies



'Rotation curves' tell us about distribution & amount of mass in galaxies

Over 90% of the total mass of galaxies is in the form of a 'Dark Matter' Halo



$$\Omega_{\text{galaxies}} \sim 0.1$$

$< 10\%$ of what is needed to make a flat universe!

Our Evolving Universe

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Vital statistics of the universe...

Measurements of density (3)

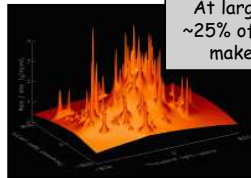
3) Contribution of clusters

A) Gravitational lensing study...



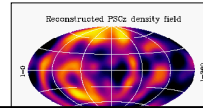
$$\Omega_{\text{clusters}} \sim 0.25$$

Mass distribution implied by warping



B) 'Bulk flow' study...

- Using redshift to look at motion of large scale structures...

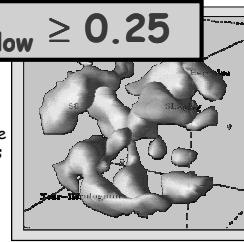


'PSCz' Infrared Experiment

$$\Omega_{\text{bulkflow}} \geq 0.25$$

At largest scales we see ~25% of what is needed to make a flat universe.

Large scale structures

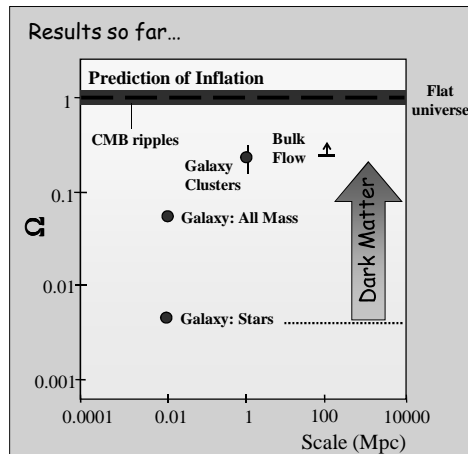


Our Evolving Universe

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Vital statistics of the universe...

Ω - how it all adds up...



Results so far...

- Inflation theory and CMB observations indicate:
 - The universe is FLAT (ie. $\Omega_{\text{total}} = 1$)
- ~25% of the mass needed is seen in observations of largest structures
- BUT - the majority (>90%) of the mass in the universe is some form(s) of non-luminous and unknown **DARK MATTER**...

Is this enough to understand the fate of the universe?

Our Evolving Universe

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Vital statistics of the universe...

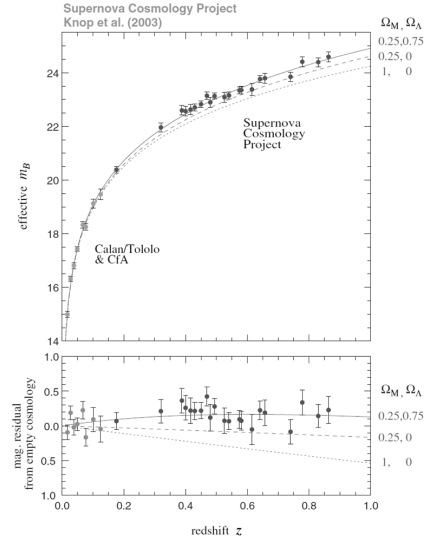
A new twist?

- 1999 - Type 1a supernovae studies of Hubble's law at large distances...

Expected: The expansion rate to have decreased due to pull of gravity.

Found: The expansion rate has increased!

The expansion of the Universe is accelerating!



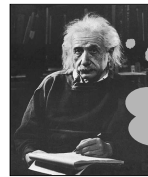
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Vital statistics of the universe...

A new twist?

- What is causing this accelerating expansion?
 - Some kind of 'Vacuum energy' that OPPOSES pull of gravity?



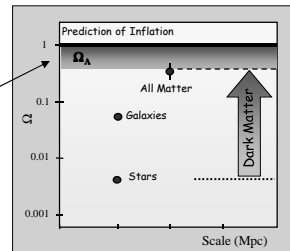
The Cosmological Constant is back!

$$H^2 = \frac{8\pi G}{3}\rho - \frac{\kappa}{R^2} + \frac{\Lambda}{3}$$

- Also known as: 'DARK ENERGY'
 - Because it is energy it also contributes to the universe's total mass (or density)

$$\Omega_{\text{total}} = \Omega_{\text{matter}} + \Omega_\Lambda$$

1 / 0.3 / 0.7



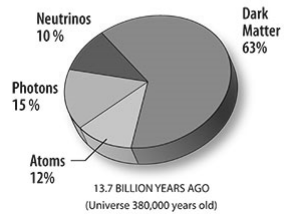
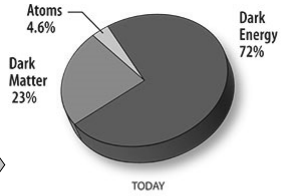
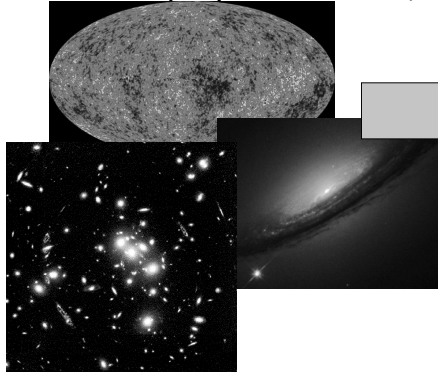
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Recipe for the Universe

of which only 1/10 stars!

- From WMAP data + galaxy clusters, supernovae etc.

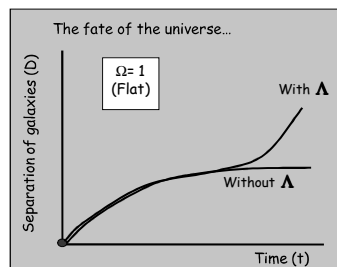


Our Evolving Universe

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How will it all end?

- How does Λ affect the fate of the universe?
 - Even though universe is nearly flat - it will continue to EXPAND FOREVER...
 - ...at an EVER-INCREASING rate



- But... **What is DARK ENERGY (Λ)?**

And... **What is DARK MATTER?**

Our Evolving Universe

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Summary

Evidence for the Big Bang (as against alternative models) includes:

- The Cosmic Microwave Background.
- The evolution of galaxies.
- The abundance of elements.

Vital statistics of the universe:

- $H_0 = 73 \pm 5 \text{ km.s}^{-1}\text{Mpc}^{-1}$
- Curvature = 0 (FLAT)
- Matter Density = $0.3 \times \rho_c$
- ~98% of the mass of the universe is dark
- ~85% is exotic 'Dark Matter'

Recent evidence indicates:

- A positive cosmological constant (Λ) is causing the expansion of the universe to increase.
- The fate of the universe is to continue to expand and cool forever.....