Nuclear Physics and Astrophysics

PHY-302

Dr. E. Rizvi

Lecture 23
Cosmology

Queen Mary
University of London

Material For This Lecture

Big bang cosmology

- 4 epochs of the universe
- light nucleosynthesis
- heavy nucleosynthesis
- the fate of the universe

Warning: fast moving field - Krane is out of date in some cases!

Big Bang Cosmology

Standard Model of hot big bang cosmology tells us about evolution of universe

- general relativity
- nuclear physics
- Standard Model of particle physics
- 'reasonable' extrapolations

Basic primary observations used to constrain model

- relative abundances of light nuclei
- formation of heavy nuclei is more difficult to understand
  (reactions harder to reproduce / thermodynamics less understood)

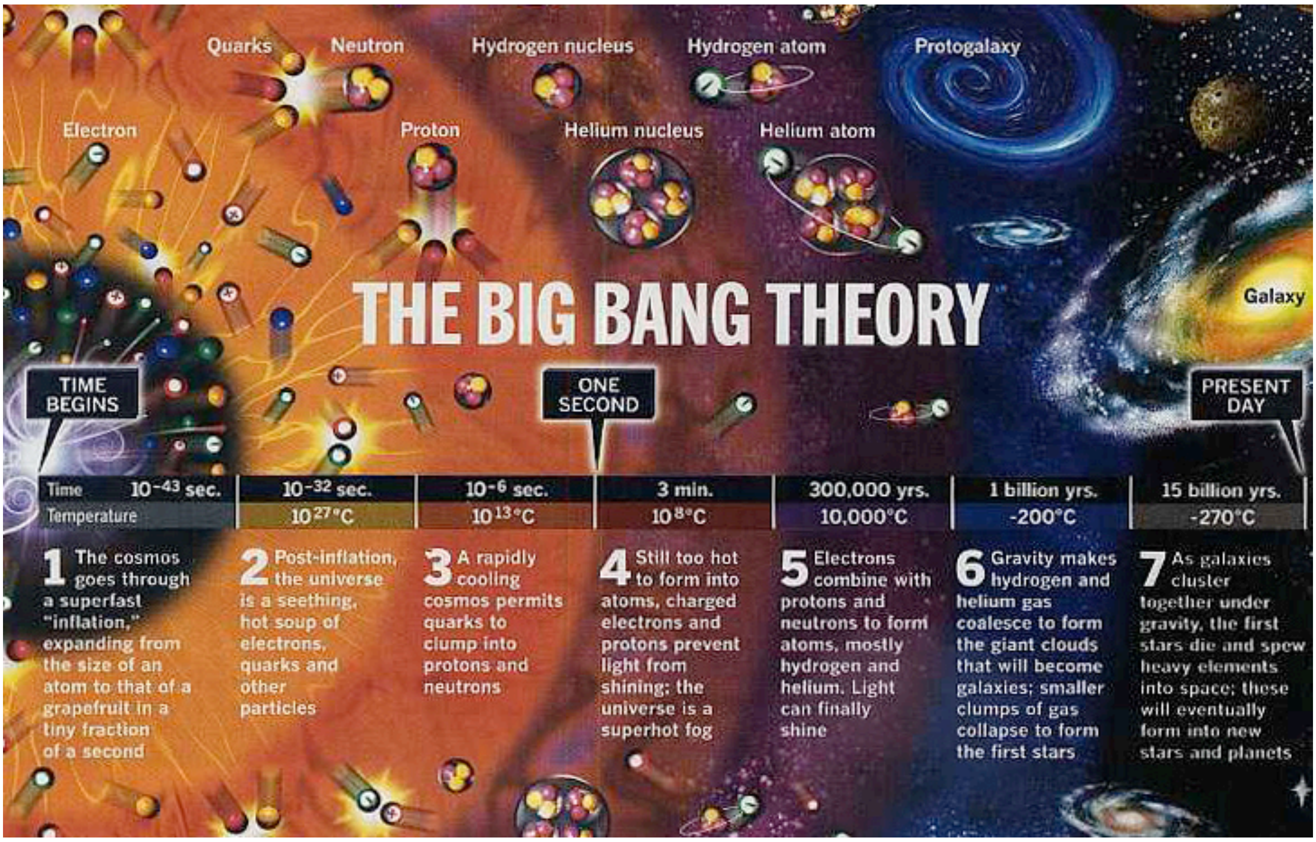
Model used to explain further astronomical observations

Evolution Of Universe

Evolution of universe divided into 4 epochs:

- primordial nucleosynthesis - atomic formation (duration~10^6 years)
- galactic condensation (duration ~ 1-2 x 10^9 years)
- stellar nucleosynthesis (large uncertainty)
- solar system evolution (know accurately from lunar / meteorite data)

Total age of universe 13.7 x 10^9 y



How Do We Know This?

Early last century universe believed to be static

General Relativity showed gravity = curvature of space-time from matter/energy

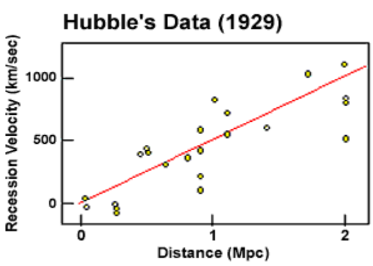
GR has one arbitrary parameter

Einstein believed in static universe: introduced constant to force static universe solution

purely attractive masses would yield no static solution

1929: Hubble found galaxies in recession

- measured red-shifts of spectral lines - determines recession velocity
- used independent methods to determine distance to galaxy



Hubbles Law

$$v = H_0 \, d$$

v is velocity   d is distance

H_0 is Hubble parameter

Assuming constant relative velocities: d = v t

$\Rightarrow 1/H_0$ = age of universe

At this point Einstein dropped the cosmological constant from GR equations

Note: galaxies are not actually moving - rather space between galaxies is expanding

Evidence For Big Bang

If universe is expanding (and getting cooler now) - must have been hotter smaller earlier

Should be seen in remnant radiation: cosmic microwave background (CMB)

In 1940s afterglow of big bang was predicted by Ahler, Gamov & Hermann

1964: Penzias & Wilson accidentally discovered CMB - initially thought to be noise in experiment

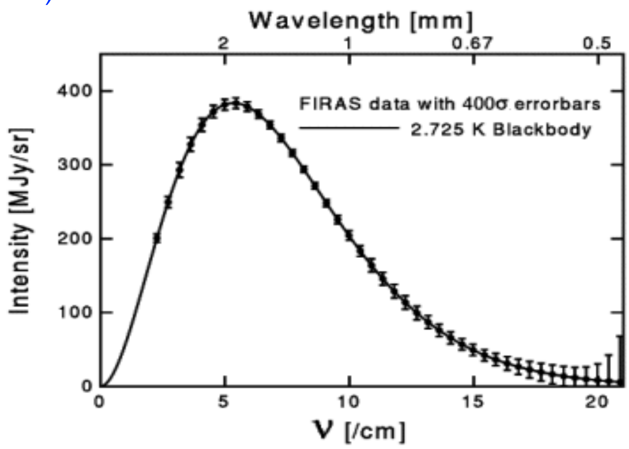
detractors claimed scattered starlight from distant galaxies...

...but, CMB isotropic - too smooth

Spectrum almost perfect black-body spectrum (2.725 K)

recent experiments have extended precision
anisotropies discovered at level of $1:10^5$

Where is the CMB coming from?



How Do We Know This?

Current measurements use type Ia supernovae

Standard candles

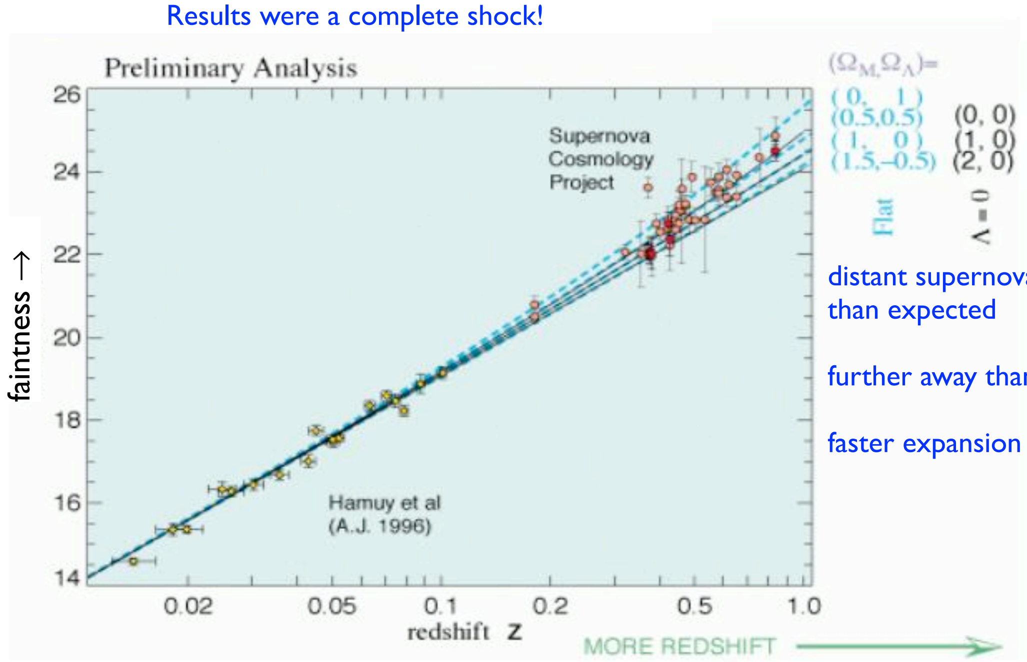
Type Ia:

- white dwarf: unable to burn C & O in fusion - not hot enough
- no source of energy within star...
- star cools - supported by 'degeneracy pressure' - Pauli exclusion principle
- Chandrasekhar limit: largest mass supported (~1.4 solar masses)
- in binary system star can accrete mass from companion up to the limit
- if accretion continues - star collapses till C & O fusion re-ignites it
- supernova explosion
- <u>thus type Ia all very similar in mass & luminosity</u>
- Brightness gives direct measurement of distance

More accurate data allow better determination of H_0

2005: H_0=71 ± 0.04 km s^{-1} / Mpc (WMAP survey)

Published in 1998
Results were a complete shock!



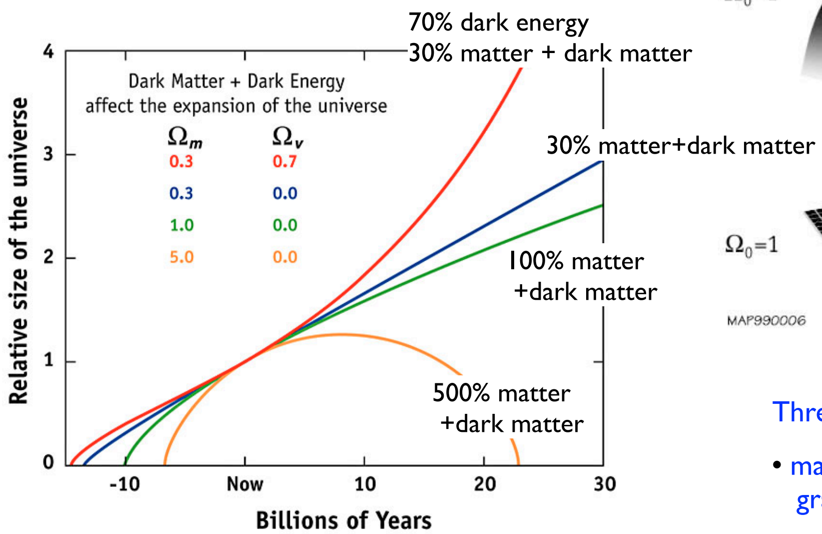
distant supernovae dimmer than expected

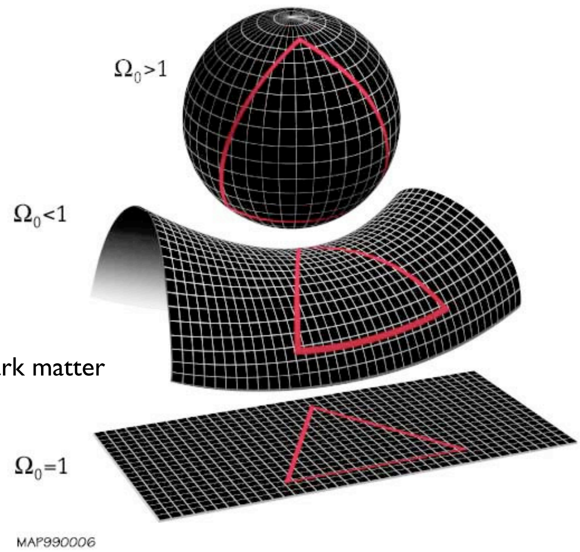
further away than expected!

faster expansion than expected!

What Does This Mean?

This tells us about the shape of space-time and fate of universe



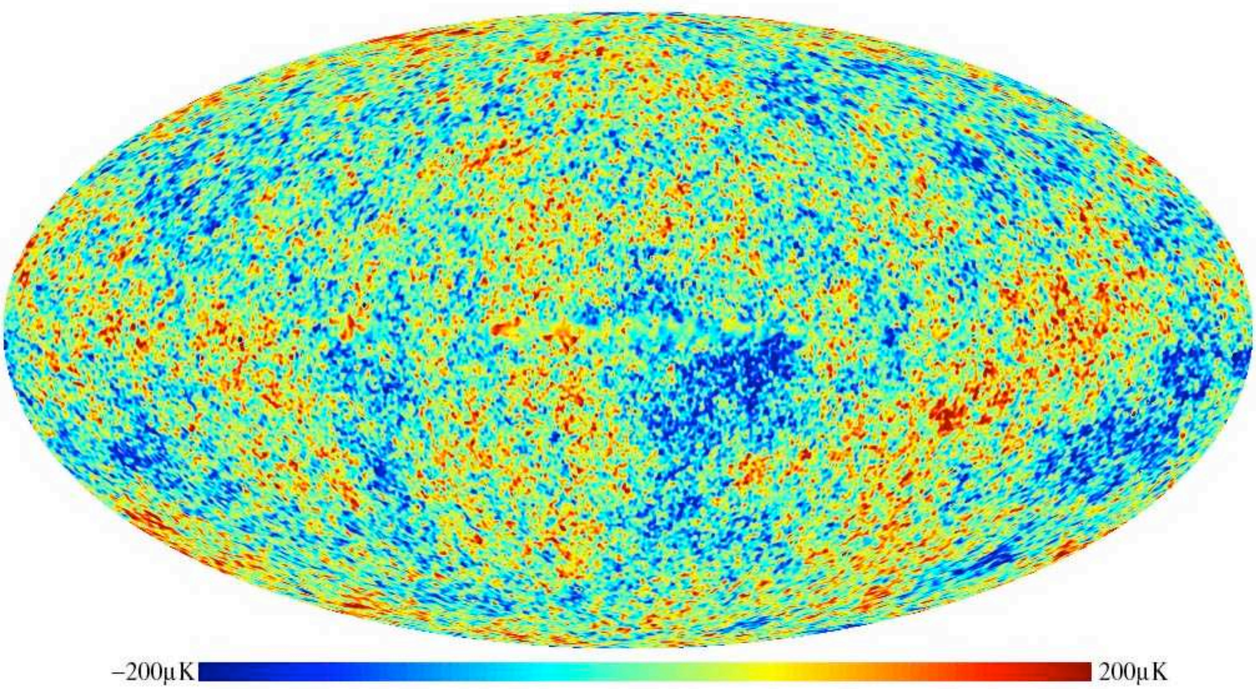


Ω= mass-energy density as fraction of critical mass-energy density

Three future scenarios possible:

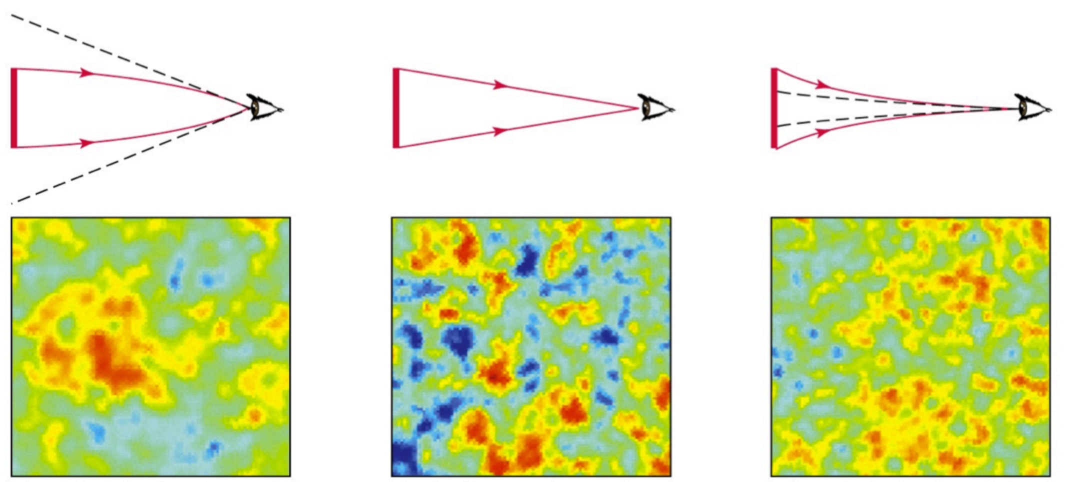
- mass-energy density reverses expansion gravity wins
- gravity too weak to halt expansion
- gravity exactly balances expansion critical mass-energy density

Previous data show universal expansion is accelerating!



CMB anisotropy - fluctuations ~ 1:10^5
Exquisite precision!

Looking at angular size of 'blobs' tells us about space-time curvature



a If universe is closed, “hot spots” appear larger than actual size

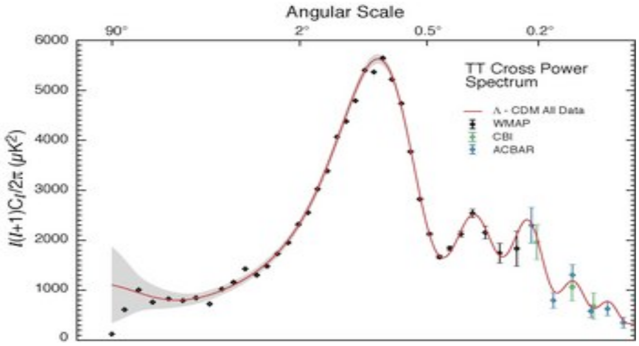
b If universe is flat, “hot spots” appear actual size

c If universe is open, “hot spots” appear smaller than actual size

CMB Power Spectrum

CMB power spectrum is very important
statistical frequency of 'blob' size in CMB anisotropy
tells us about:

- composition of universe
- neutrinos / dark matter / baryonic
- dark energy
- Hubble parameter
- geometry of universe



Model based on:
- current theory of galaxy formation and
- primordial nucleosynthesis
- (non-stellar formation of elements)

shown as red curve

Prediction: main peak at angular size ~1°
$\Rightarrow$ Flat universe

data agree within ±2% !!!

relative peak heights provide information about contributions to mass-energy density of universe: e.g. baryonic matter (p^+ & n^0)

Where is the Matter-Energy Density?

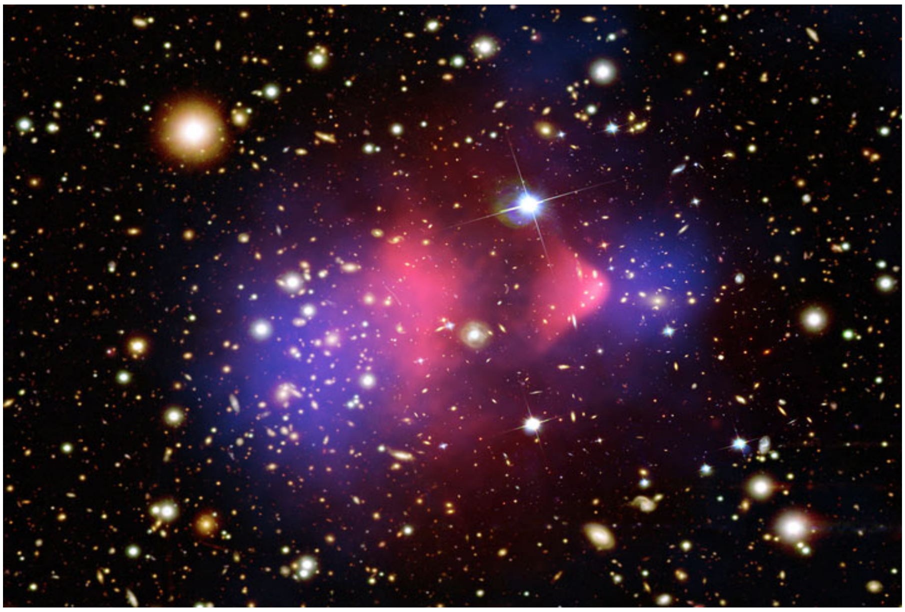
CMB power spectrum tells us universe is flat:
- critical mass-energy density in universe $\Omega = 1$
- equivalent to 9.9×10^{-30} g/cm^3 i.e. 6 protons/m^3

Look at universe and add up all contributions to Ω:
- 4% ordinary atoms observation of stars / dust clouds
- 23% dark matter galactic rotation curves / gravitational lensing
- 73% dark energy CMB power spectrum

96% of matter-energy density of universe is unknown!

<u>Dark Matter:</u>

measurement of orbital velocity of star in galaxy - infer gravitational mass of galaxy
use gravitational lensing to infer mass of lensing galaxy
both show more mass than is visible in stars / dust clouds - majority of galactic mass!
Can be MACHOs (Massive Active Compact Halo Objects) super black-holes / brown dwarfs
Can be WIMPs (Weakly Interacting Massive Particles) new particles



August 2006

Collision of two galactic clusters

Red:
Luminous x-ray emitting matter

Blue:
Dark matter inferred from gravitational lensing

In this collision of 2 galaxies the hot luminous matter is slowed in the collision

Dark matter is undisturbed

Dark Energy:

Prediction of theory of primordial nucleosynthesis + galaxy formation models

Mass-energy density is critical, 27% is dark matter + ordinary matter ⇒ 73% is dark energy

Postulated to have negative gravitational pressure (cause of accelerated universal expansion)

WMAP measurements indicate: homogenous, not very dense, only interacts via gravity

Two possible forms:

- cosmological constant (vacuum energy)
- quintessence

cosmological constant Λ is one free parameter of general relativity

same at all points in universe

property of the vacuum

currently most favoured explanation

The Higgs field

Particle physics predicts existence of a uniform field at all points in the universe

- has a constant non-zero energy everywhere: its a property of the quantum vacuum
- particles interacting with this field acquire mass

Cosmological constant calculated from Higgs field is 10^{120} times larger than measured!!!

“the worst theoretical prediction in the history of physics!”