AS 4022: Cosmology

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Online notes:
star-www.st-and.ac.uk/~hz4/cos/cos.html

take your own notes (including blackboard lectures

Look forward

Malcolm S. Longair's "Galaxy Formation" 2nd edition [Library]

Chpt 1-2,5-8: expanding metrics, energy density, curvature, distances

Chpt 4,11,15,20: DM, Structure growth, inflation

Chpt 9-10,13: Thermal History of Particle Reaction, Neutrinos, WIMPs

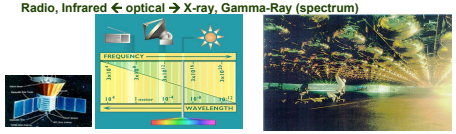
Text (intro): Andrew Liddle: Intro to Modern Cosmology
(advanced): John Peacock: Cosmological Physics
Web Lecture Notes: John Peacock, Ned Wright

Why Study Cosmology?

- **Fascinating questions:**
  - Birth, life, destiny of our Universe
  - Hot Big Bang --> (75% H, 25% He) observed in stars!
  - Formation of structure (galaxies …)
- **Technology -> much recent progress:**
  - Precision cosmology: uncertainties of 50% --> 2%
- **Deep mysteries remain:**
  - Dark Matter? Dark Energy? General Relativity wrong?
- **Stretches your mind:**
  - Curved expanding spaces, looking back in time, …

Observable Space-Time and Bands

See What is out there? In all Energy bands
Pupil → Galileo's Lens → 8m telescopes → square km arrays
Radio, Infrared ← optical → X-ray, Gamma-Ray (spectrum)

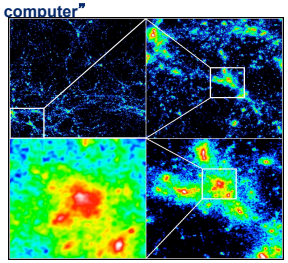


COBE satellites ← Ground → Underground DM detector

Know How were we created? XYZ & T ?
Us, CNO in Life, Sun, Milky Way, … further and further
→ first galaxy → first star → first Helium → first quark
Now → Billion years ago → first second → quantum origin

The Visible Cosmos: a hierarchy of structure and motion

"Cosmos in a computer"



Observe A Hierarchical Universe

Planets
moving around stars;
Stars grouped together,
moving in a slow dance around the center of galaxies.

Cosmic Village

The Milky Way and Andromeda galaxies,
- along with about fifteen or sixteen smaller galaxies,
- form what's known as the Local Group of galaxies.

The Local Group
- sits near the outer edge of a supercluster, the Virgo cluster.
- the Milky Way and Andromeda are moving toward each other,
- the Local [illegible] of the Virgo cluster, and

the entire Virgo cluster itself,
- is speeding toward a mass
- known only as "The Great Attractor."

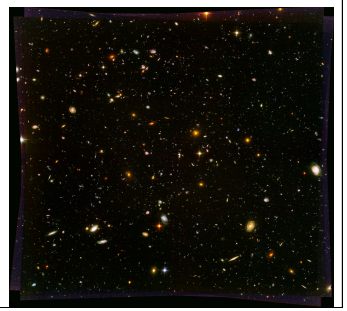
Hubble Deep Field:

At faint magnitudes, we see **thousands of Galaxies for every star** !

$\sim 10^{10}$ galaxies in the visible Universe

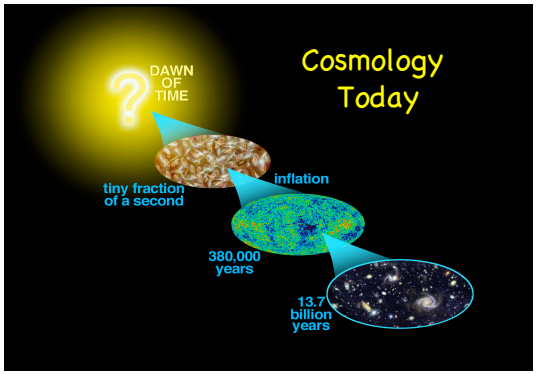
$\sim 10^{10}$ stars per galaxy

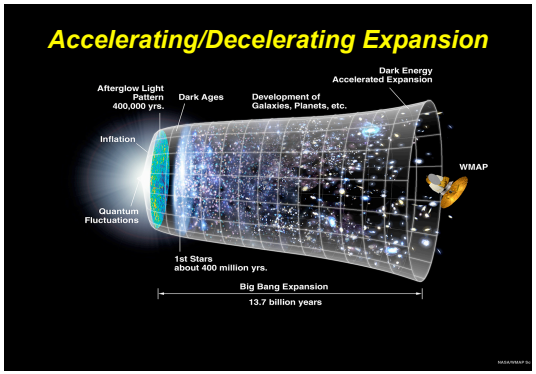
$\sim 10^{20}$ stars in the visible Universe



Galaxies themselves
- some 100 billion of them in the observable universe—
- form galaxy clusters bound by gravity as they journey through the void.

But the largest structures of all are superclusters,
- each containing thousands of galaxies
- and stretching many hundreds of millions of light years.
- are arranged in filament or sheet-like structures,
- between which are gigantic voids of seemingly empty space.





Introducing Gravity and DM (Key players)

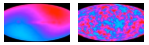
These structures and their movements
- can't be explained purely by the expansion of the universe

must be guided by the gravitational pull of matter.

Visible matter is not enough

one more player into our hierarchical scenario:
dark matter.

Cosmologists hope to answer these questions:

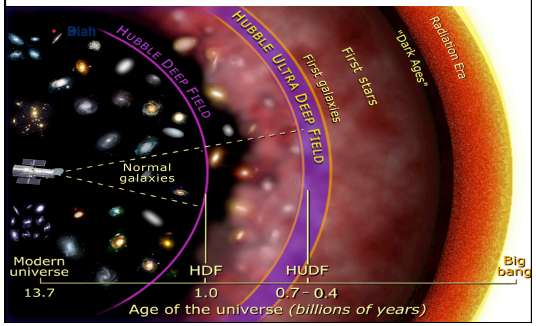


How old is the universe? H_0
Why was it so smooth? P(k), inflation

How did structures emerge from smooth? N-body
How did galaxies form? Hydro

Will the universe expand forever? Omega, Lamda
Or will it collapse upon itself like a bubble?

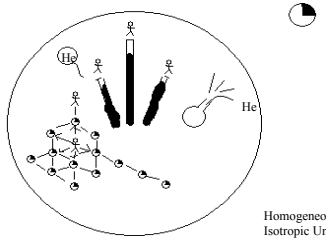
Looking Back in Time



main concepts in cosmology

Expansion & Metric
Cosmological Redshift
Energy density

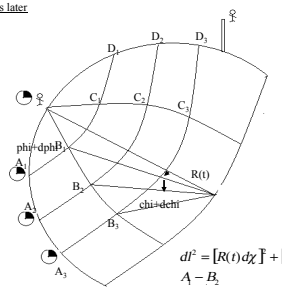
A few mins after New Year
Celebration at Trafalgar Square



Homogeneous
Isotropic Universe

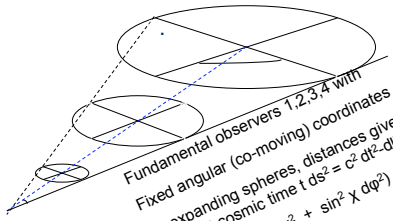
Walking ↔ Elevating ↔ Earth Radius Stretching $R(t)$

Feb 14 t=45 days later



$$dl^2 = [R(t)d\chi]^2 + [R(t)\sin\chi d\phi]^2$$
$$A_1 - B_2$$

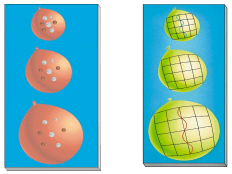
1st concept Metric: ant network on expanding sphere



Fundamental observers 1,2,3,4 with
Fixed angular (co-moving) coordinates (χ,φ)
on expanding spheres, distances given by
Metric at cosmic time t $ds^2 = c^2 dt^2 - dl^2$,
$dl^2 = R^2(t)\,(d\chi^2 + \sin^2\chi\, d\varphi^2)$

Stretch of photon wavelength in expanding space

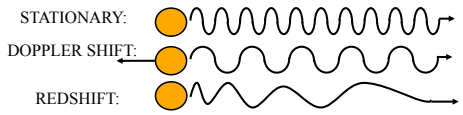
Emitted with intrinsic wavelength λ_0 from Galaxy A at time $t<t_{now}$ in smaller universe $R(t) < R_{now}$



→ Received at Galaxy B now (t_{now}) with λ
$\lambda / \lambda_0 = R_{now} / R(t) = 1+z(t) > 1$

Redshift

- Expansion is a stretching of space.
- The more space there is between you and a galaxy, the faster it appears to be moving away.
- Expansion **stretches the wavelength of light**, causing a galaxy's spectrum to be REDSHIFTED:



REDSHIFT IS NOT THE SAME AS DOPPLER SHIFT

2nd main concept: Cosmological Redshift

The space/universe is expanding,
Galaxies (pegs on grid points) are receding from each other

As a photon travels through space, its wavelength becomes stretched gradually with time.
Photons wave-packets are like links between grid points

This redshift is defined by:

$$z \equiv \frac{\lambda - \lambda_o}{\lambda_o}$$

$$\frac{\lambda}{\lambda_o} = 1 + z$$

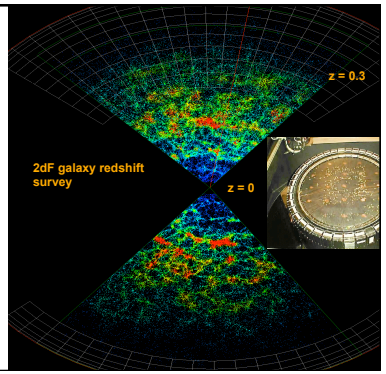
Galaxy Redshift Surveys

Large Scale Structure:

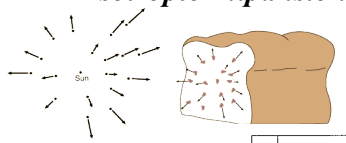
Empty **voids**
~50Mpc.

Galaxies are in
1. **Walls** between voids.
2. **Filaments** where walls intersect.
3. **Clusters** where filaments intersect.

Like Soap Bubbles !



Isotropic Expansion

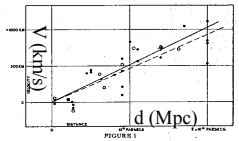


Hubble law :

$$V = H_0 \, d$$

Hubble "constant":

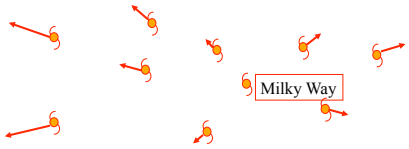
$H_0 \approx 500 \text{ km s}^{-1}\text{Mpc}^{-1}$



Why WRONG? Extinction by interstellar dust was not then known, giving incorrect distances.

Universal Expansion

Hubble's law appears to violate Copernican Principle. The Are we at a special location?



Is everything moving away from us?

Universal Expansion

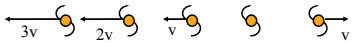
Q : What is so special about our location ?

A : Nothing !

According to Hubble's Law:

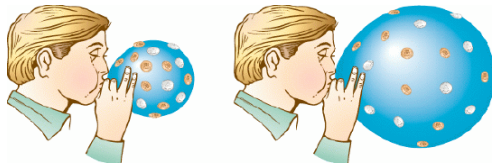
I see:

You see:



The Universal Expansion

- An observer in any galaxy sees all other galaxies moving away, with the same Hubble law.
- Expansion (or contraction) produces a centre-less but dynamic Universe.



E.g. Consider a quasar with redshift z=2. Since the time the light left the quasar the universe has expanded by a factor of 1+z=3. At the epoch when the light left the quasar,

the distance between us and Virgo (presently 15Mpc) was 5Mpc.

the CMB temperature then (presently 3K) was 9K.

the quasar appears receding with Doppler speed V=2c.

The quasar appears at a look-back "distance" d = [t(0)-t(z)] c, where the look-back time [t(0)-t(z)] ~ z/H_0 at small z<<1, H_0^{-1}=Taylor expansion coeff.

$$1+z=\frac{\lambda_{now}}{\lambda(t)} \quad \text{(wavelength)}$$

$$=\frac{R_{now}}{R(t)} \quad \text{(expansion factor)}$$

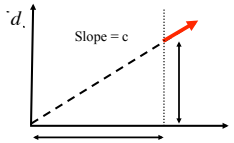
$$=\frac{T(t)}{T_{now}} \quad \text{(Photon Blackbody T } \propto 1/\lambda, \textit{why?)}$$

Hubble Law → typical age (at z=1)

$$V = H_0\, d$$

$$t_0 \approx \frac{d}{V} = \frac{1}{H_0} = \left(\frac{1\,\text{Mpc}}{72\ \text{km/s}}\right)\left(\frac{3\times10^{19}\,\text{km}}{\text{Mpc}}\right)\left(\frac{1\ \text{yr}}{3\times10^{7}\,\text{s}}\right)$$

$$\approx 13\times10^{9}\,\text{yr} = 13\ \text{Gyr}.$$



Convert H as a frequency Hertz, find an integer close to log10(H)? Multiple choices -30, -10, 0, 10, 30.

3rd concept: The changing rate of expansion

Newtonian Analogy:

Consider a sphere of radius R(t) ,

→ effective mass inside M = 4πρ R^3/3

if energy density inside is e=ρ(t) c^2.

On this expanding sphere, a test m

Kin.E. + Pot.E. = const Energy

→ m $(dR/dt)^2$/2 – G m M/R = (-k/2)m c^2

→ $(dR/dt)^2/(2c^2) - (4\pi G/3)\rho R^2/c^2 = -k/2$

Unitless k <0, =0, >0 → open-flat-close

Newtonian expansion satisfies

$H^2 = (dR/dt/R)^2 = (\rho + \rho_{cur})\,(8\pi G/3)$

the cst k absorbed in "density"

$\rho_{cur}(t) = -k(cH_0^{-1}/R)^2\,(3H_0^2/8\pi G)$

$\sim -k\,R^{-2} * \text{cst}$

Now $H = H_0$