AS 4022 Cosmology

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Lecture Slides will be on this web page:
http://star-www.st-and.ac.uk/~kdh1/cos/cos.html

Text (intro): Andrew Liddle: Intro to Modern Cosmology
(intermediate): Barbara Ryden: Introduction to Cosmology
Dan Maoz: Astrophysics in a Nutshell
(advanced): John Peacock: Cosmological Physics

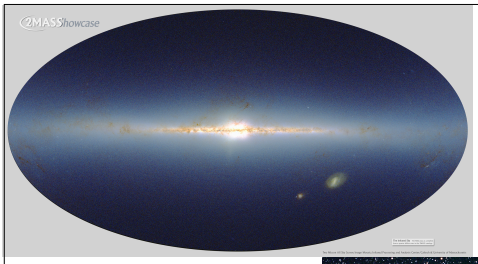
Web Lecture Notes: John Peacock, Ned Wright

Lecture 1

Review / Overview

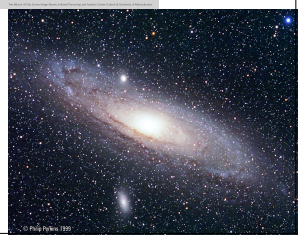
Why Study Cosmology?

- **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, …



Milky Way

Andromeda



~10^{10} stars per Galaxy:

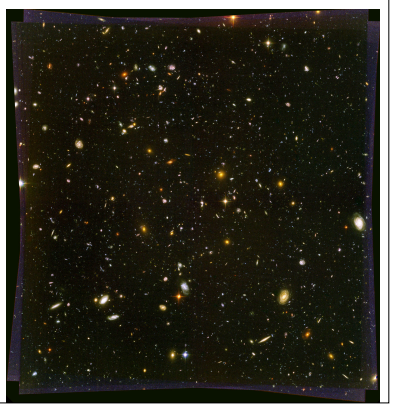
Hubble Deep Field:

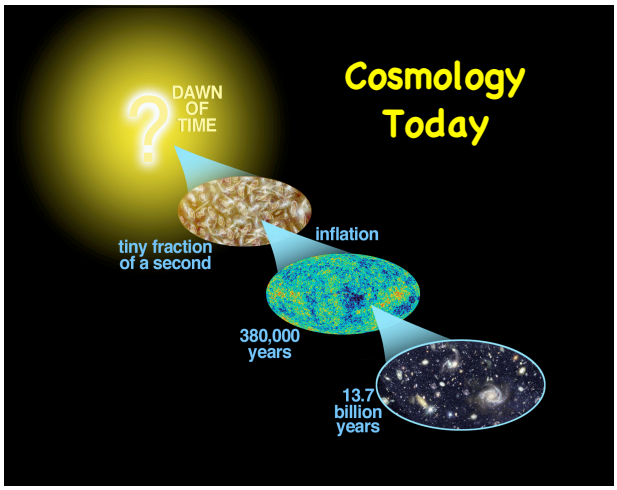
At faint magnitudes, we see **thousands of Galaxies for every star** !

~10^{10} galaxies in the visible Universe

~10^{10} stars per galaxy

~10^{20} stars in the visible Universe

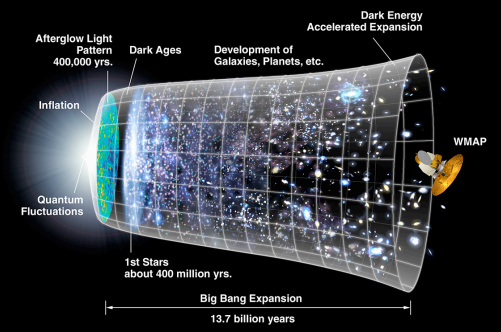




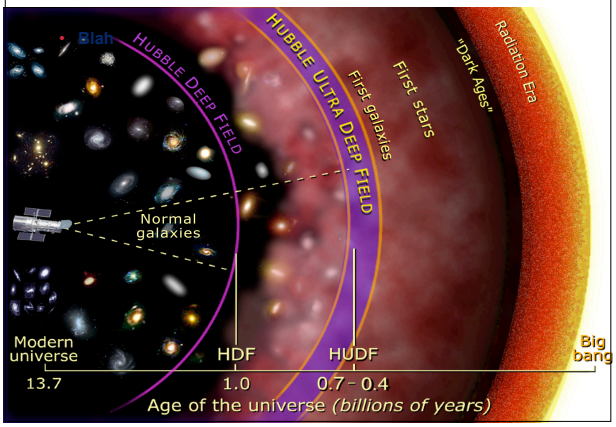
1980: Inflation (Alan Guth)

- Universe born from "**nothing**" ?
- A **quantum fluctuation** produces a tiny bubble of "**False Vacuum**".
- High vacuum energy drives **exponential expansion**, also known as **"inflation."**
- Universe expands by huge factor in tiny fraction of second, as false vacuum returns to true vacuum.
- Expansion so fast that **virtual particle-antiparticle pairs** get separated to become **real particles and anti-particles**.
- Stretches out all structures, giving a **flat geometry** and uniform T and ρ, with **tiny ripples**.
- Inflation launches the **Hot Big Bang**!

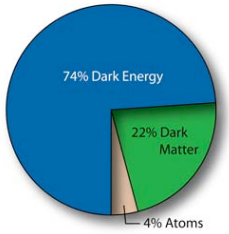
Accelerating/Decelerating Expansion



Looking Back in Time



Current Mysteries



Dark Matter ?
Holds Galaxies together
Triggers Galaxy formation

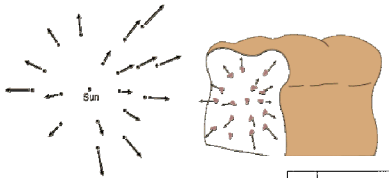
Dark Energy ?
Drives Cosmic Acceleration.

Modified Gravity ?
General Relativity wrong ?

Cosmology Milestones

- 1925 Galaxy redshifts $\lambda = \lambda_0 (1+z)$ $V = c\,z$
  - Isotropic expansion. (Hubble law $V = H_0 d$)
  - Finite age. ($t_0 = 13 \times 10^9$ yr)
- 1965 Cosmic Microwave Background (CMB)
  - Isotropic blackbody. $T_0 = 2.7$ K
  - Hot Big Bang $T = T_0 (1+z)$
- 1925 General Relativity Cosmology Models :
  - Radiation era: $R \sim t^{1/2}$ $T \sim t^{-1/2}$
  - Matter era: $R \sim t^{2/3}$ $T \sim t^{-2/3}$
- 1975 Big Bang Nucleosynthesis (BBN)
  - light elements (^{1}H … ^{7}Li) $t \sim 3$ min $T \sim 10^9$ K
  - primordial abundances (75% H, 25% He) as observed!

Isotropic Expansion

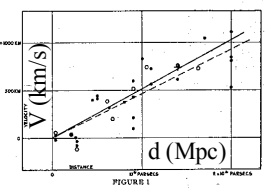


Hubble law :

$V = H_0\, d$

Hubble "constant":

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

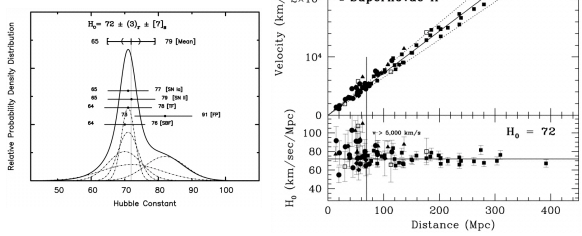


WRONG ! Extinction by interstellar dust was not then known, giving incorrect distances.

H_0 from the HST Key Project

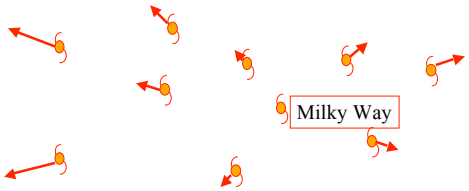
$$H_0 \approx 72 \pm 3 \pm 7 \quad \text{km s}^{-1}\ \text{Mpc}^{-1}$$

Freedman, et al.
2001 ApJ 553, 47.



Universal Expansion

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

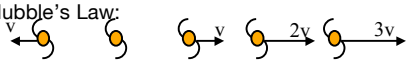


Is everything moving away from us?

Universal Expansion

Q : What is so special about our location ?
A : Nothing !

According to Hubble's Law:
I see:

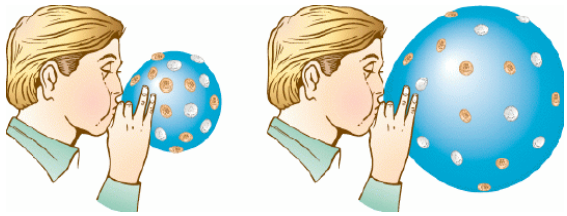


You see:

We all see the same Hubble law expansion.

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.**

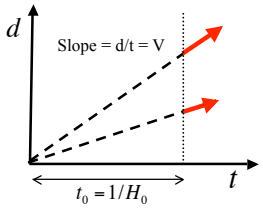


Hubble Law --> Finite age.

$$V = H_0\, d$$

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

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



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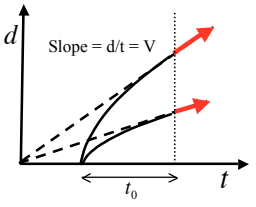
Gravity decelerates :

$$t_0 \approx \frac{2}{3}\frac{1}{H_0}.$$



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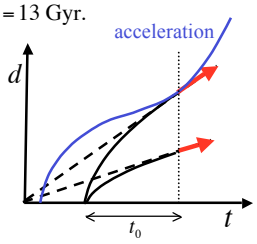
$$\approx 13\times10^{9}\,\text{yr} = 13\,\text{Gyr}.$$

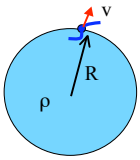
Gravity decelerates:

Dark Energy accelerates

$t_0 > \frac{2}{3}\frac{1}{H_0}$.



Critical Density



- Newtonian analogy:

escape velocity:

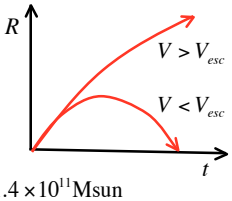
$$V_{esc}^{\,2} = \frac{2GM}{R} = \frac{2G}{R}\left(\frac{4\pi R^3\rho}{3}\right) = \frac{8\pi G R^2\rho}{3}$$

Hubble expansion:

$V = H_0 R$

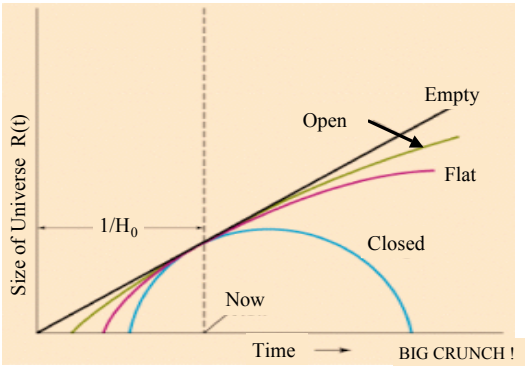
critical density:

$$\left(\frac{V_{esc}}{V}\right)^2 = \frac{8\pi G\rho}{3H_0^{\,2}} = \frac{\rho}{\rho_c}$$



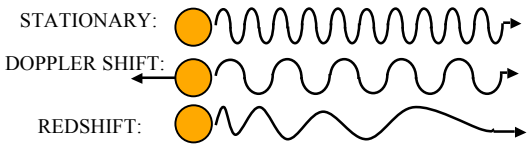
$$\rho_c \equiv \frac{3H_0^{\,2}}{8\pi G} \approx 10^{-26}\,\text{kg m}^{-3} \approx \frac{1.4\times10^{11}\,\text{Msun}}{(\text{Mpc})^3}$$

Re-collapse or Eternal Expansion ?



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:



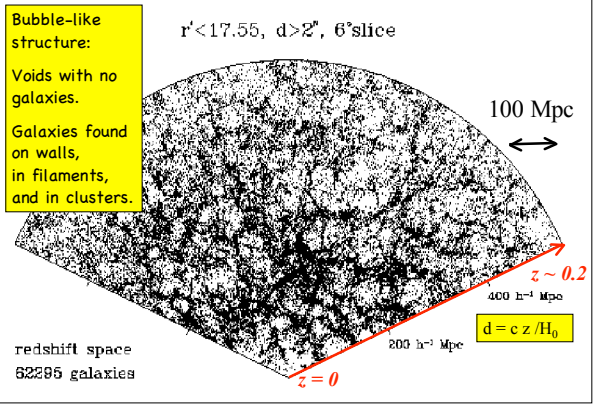
REDSHIFT IS NOT THE SAME AS DOPPLER SHIFT

Galaxy Redshift Surveys

Bubble-like structure:

Voids with no galaxies.

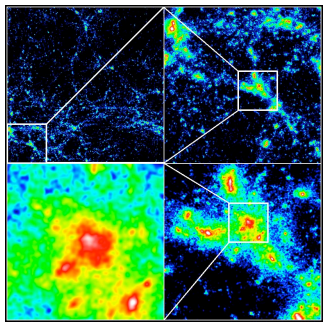
Galaxies found on walls, in filaments, and in clusters.



The Visible Cosmos:

a hierarchy of structure and motion

- Computer simulations of structure formation:



Cosmological Models

Einstein's gravity theory (General Relativity)
Assume Universe filled with uniform density fluid.
[OK on large scales > 100 Mpc]

Density: $\rho = \Omega\, \rho_c$ Energy density: $\varepsilon = \rho\, c^2$

Critical density: $\rho_c \equiv \frac{3 H_0^2}{8\pi G} \approx 10^{-26}\text{kg m}^{-3} \approx \frac{1.4\times10^{11}\text{Msun}}{(\text{Mpc})^3}$

3 components:

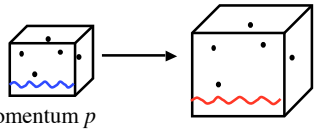
1. ***Radiation*** $\Omega_R \approx 5\times10^{-5}$
2. ***Matter*** $\Omega_M \sim 0.3$ { "Dark Matter" $\Omega_D \sim 0.26$; baryons $\Omega_B \sim 0.04$
3. "***Dark Energy***" $\Omega_\Lambda \sim 0.7$

Total $\Omega = \Omega_R + \Omega_M + \Omega_\Lambda = 1$

Only ~4% is matter as we know it!

Energy Density of expanding box

volume R^3
N particles
particle mass m momentum p



energy $E = h\nu = \sqrt{m^2c^4 + p^2c^2} = m\,c^2 + \frac{p^2}{2m} + \ldots$

Cold Matter: ($m > 0$, $p << mc$)

$E \approx m\,c^2 = \text{const}$

$\varepsilon_M \approx \frac{N\,m\,c^2}{R^3} \propto R^{-3}$

Radiation: ($m = 0$)
Hot Matter: ($m > 0$, $p >> mc$)
$\lambda \propto R$ (wavelengths stretch):

$E = h\,\nu = \frac{h\,c}{\lambda} \propto R^{-1}$

$\varepsilon_R = \frac{N\,h\,\nu}{R^3} \propto R^{-4}$

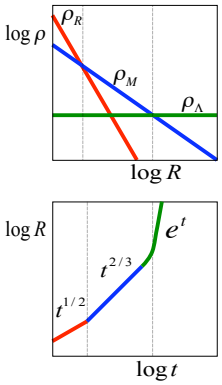
3 Eras: radiation…matter…vacuum

radiation: $\rho_R \propto R^{-4}$
matter: $\rho_M \propto R^{-3}$
vacuum: $\rho_\Lambda = \text{const}$

$a \equiv \frac{R}{R_0} = \frac{1}{1+z}$

$\rho = \frac{\rho_{R,0}}{a^4} + \frac{\rho_{M,0}}{a^3} + \rho_\Lambda$

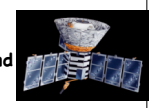
$\rho_R = \rho_M$ at $a \sim 10^{-4}$ $t \sim 10^4$ yr
$\rho_M = \rho_\Lambda$ at $a \sim 0.7$ $t \sim 10^{10}$ yr



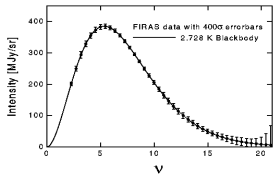
Cosmic Microwave Background

- CMB predicted by Gamov in 1948. Discovered by Penzias and Wilson in 1965.

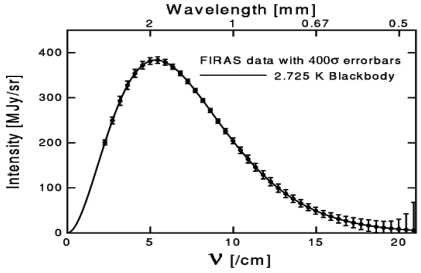
1992 NASA - COBE COsmic Background Explorer



A perfect Blackbody!



COBE spectrum of CMB

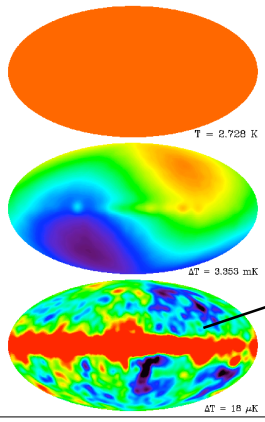


A perfect Blackbody !

No spectral lines -- strong test of Big Bang.
Expansion preserves the blackbody spectrum.

T(z) = T_0 (1+z) ***T_0 ~ 3000 K*** ***z ~ 1100***

Cosmic Microwave Background



Almost isotropic

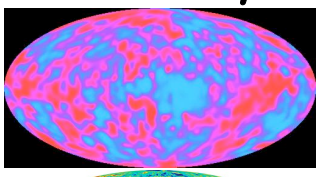
$T = 2.728$ K

Dipole anisotropy
$\frac{V}{c} = \frac{\Delta\lambda}{\lambda} = \frac{\Delta T}{T} \approx 10^{-3}$
Our velocity:
$V \approx 600$ km/s

Milky Way sources
+ anisotropies $\frac{\Delta T}{T} \sim 10^{-5}$

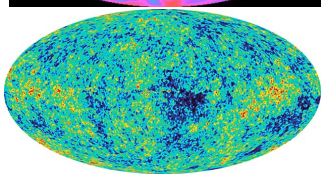
CMB Anisotropies

COBE 1994



$\frac{\Delta T}{T} \sim 10^{-5}$

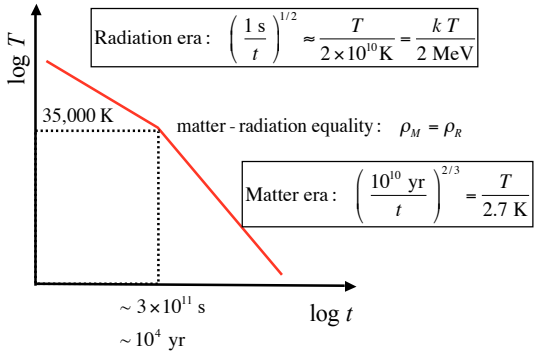
WMAP 2004



$\Delta\theta \sim 1^{\circ}$

Snapshot of Universe at z = 1100
Seeds that later form galaxies.

Cooling History: T(t)

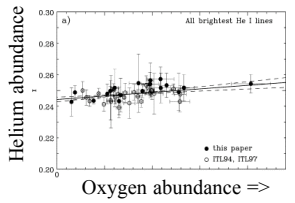


1975: Big Bang Nuclear Fusion

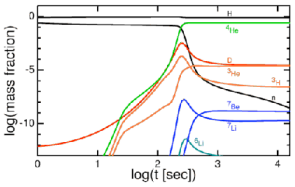
Big Bang + 3 minutes
T ~ 10^9 K
First atomic nuclei forged.
Calculations predict:
75% H and 25% He
AS OBSERVED !

+ traces of light elements
D, ^{3}H, ^{3}He, ^{7}Be, ^{7}Li

=> normal matter only 4% of critical density.



Oxygen abundance =>



1998: Supernova Cosmology

- Do galaxies at VERY large distances have the same distance/velocity relationship as the Hubble Law?
- Has the rate of expansion changed?

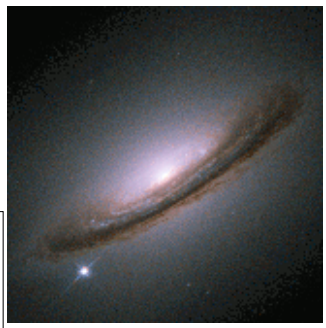
- SN Ia as "standard candles": same maximum *L*
- Search lots of galaxies for SN Ia: very bright

SN Type Ia in Virgo Galaxy NGC 4526

Supernova outshines the entire galaxy, but only for a month or so.

Type II -- massive stars (M > 8 M_{SUN}) explode at end of life.

Type Ia -- white dwarf in a binary system accretes mass, collapses when M_{WD} = 1.4 M_{SUN}.
Good "standard bombs".



Calibrate SN distances using HST to see Cepheids in Virgo galaxies.

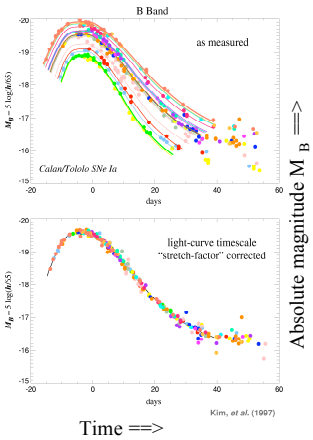
Calibrating "Standard Bombs"

1. Brighter ones decline more slowly.

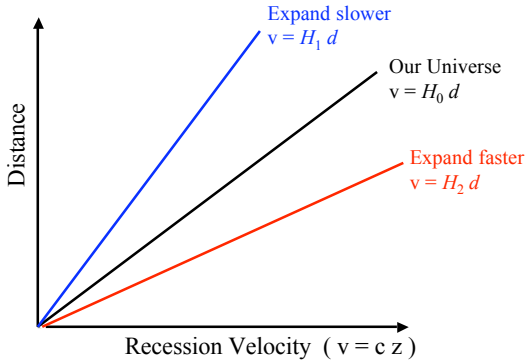
2. Time runs slower by factor (1+z).

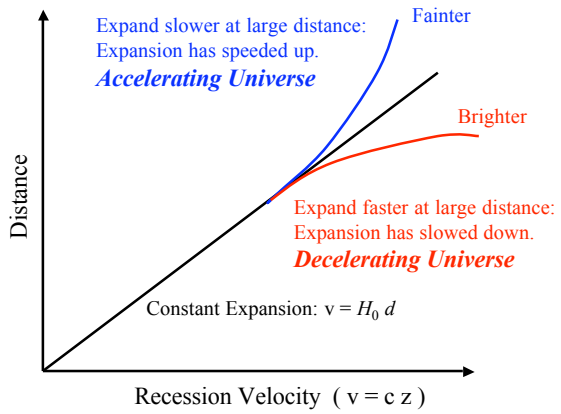
AFTER correcting:
Constant peak brightness
M_B = -19.7

Observed peak magnitude: m = M + 5 log (d/Mpc) + 25 gives the distance!

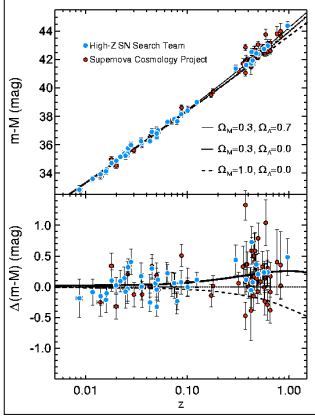


Varying Hubble Laws





1998: Accelerating Universe !?



Distant SNe (z ~ 0.8) are **25% fainter** than the Hubble Law.
=> **ACCELERATING!**

Need cosmological constant Λ or DARK ENERGY.

Proposed satellite: ***SNAP*** ***S****uper****N****ova* ***A****cceleration* ***P****robe* to find even more distant SNe …

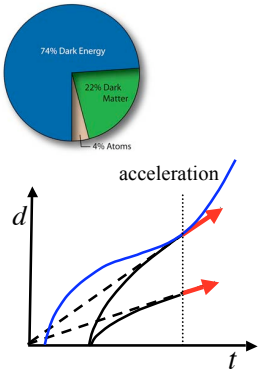
Acceleration by DARK ENERGY

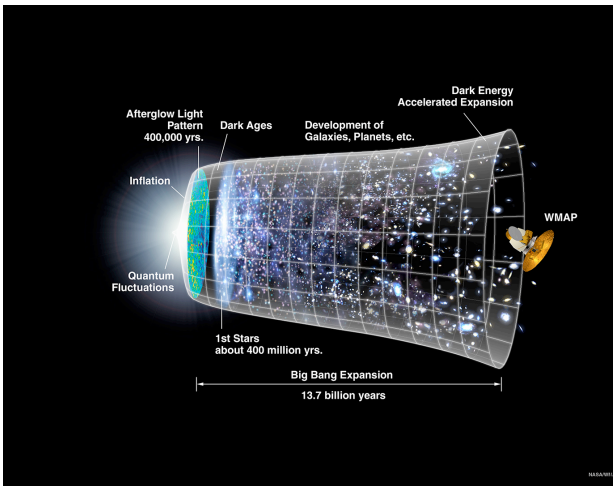
First, gravity from high matter density decelerates the expansion.

Expansion reduces matter density, deceleration slows.

Then, **DARK ENERGY** accelerates.

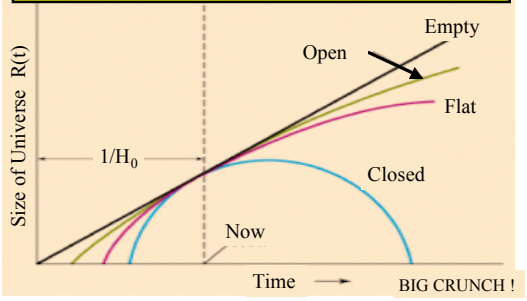
Slight Problem:
Quantum vacuum predicts Dark Energy density
$\rho_\Lambda = 10^{120}\ \rho_{CRIT}$
Observed:
$\rho_\Lambda = 0.7\ \rho_{CRIT}$





Re-collapse or Eternal Expansion ?

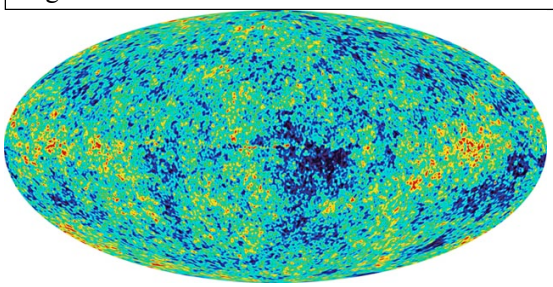
Inflation => expect FLAT GEOMETRY CRITICAL DENSITY



2004: WMAP all-sky CMB temperature map.

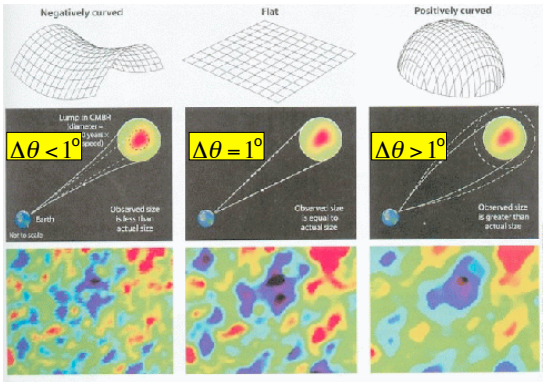
Tiny ripples (at z=1100, T=3000K, t=3x10^5 yr) are the seeds of galaxy formation!

Angular size $\Delta\theta = 1^o$ => FLAT GEOMETRY

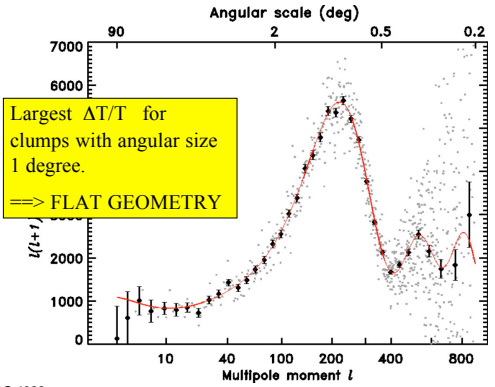


Curvature of the Universe

Negative FLAT Positive



2004: WMAP - Power Spectrum



Largest $\Delta T/T$ for clumps with angular size 1 degree.

==> FLAT GEOMETRY

Possible Universes

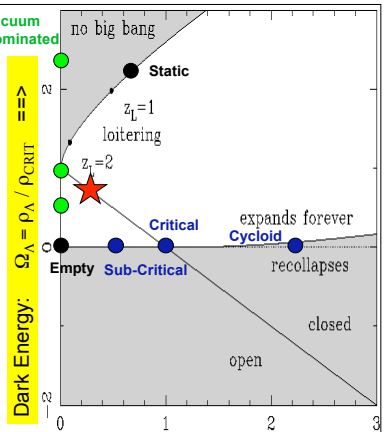
$$H_0 \approx 72 \frac{\text{km/s}}{\text{Mpc}}$$

$$\Omega_M \sim 0.3$$

$$\Omega_\Lambda \sim 0.7$$

$$\Omega_R \sim 8 \times 10^{-5}$$

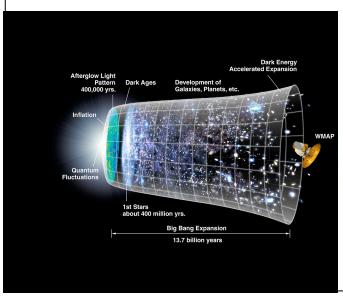
$$\Omega = 1.0$$

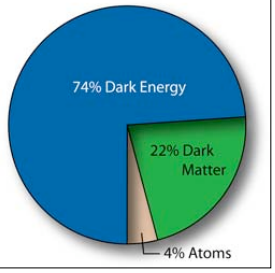


Matter: $\Omega_M = \rho_M / \rho_{CRIT}$ --

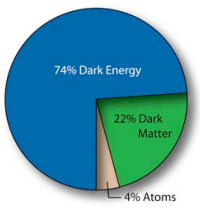
Our "Crazy" Universe

~4% Normal Matter
~22% "Dark Matter"
~74% "Dark Energy"





Or …. Has General Relativity Failed ?



Can an *Alternative Gravity* Model fit all the data without Dark Matter and Dark Energy ?

No luck yet, but people are trying.