

Cosmology: The evidence for dark matter and dark energy

Sarah Bridle (UCL)

Cosmology: The evidence for dark matter and dark energy

- Dark matter
 - Not everything emits light
 - It's not normal (baryonic)
- Dark energy
 - The Universe is accelerating
- Prospects for the future

Cosmology: The evidence for dark matter and dark energy

- Dark matter
 - Not everything emits light
 - It's not normal (baryonic)
- Dark energy
 - The Universe is accelerating
- Prospects for the future

The COMA cluster of galaxies



Fritz Zwicky 1937



Observations of COMA

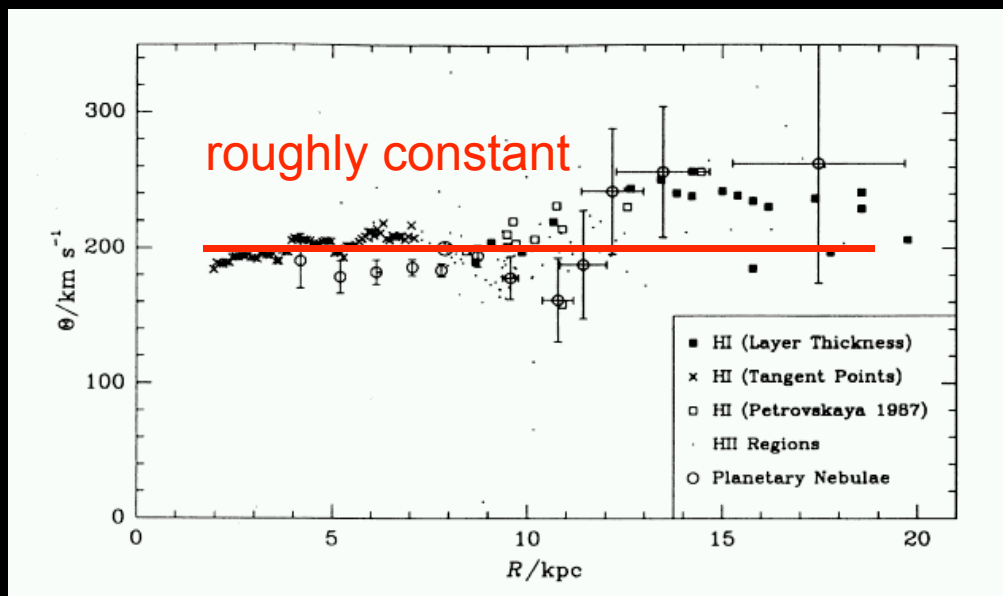
- Measured speeds of galaxies
 - ~ 1200 km/s
 - Law of gravity gives $F_g = GMm/r^2$
 - Centrifugal force gives $F_c = mv^2/r$
 - Must have $F_g \sim F_c$ or galaxies fly out!
 - Gives $M \sim 5 \times 10^{14} M_\odot$
 - Observed amount of starlight
 - $\sim 10^{13} M_\odot$
- $\Rightarrow$ Fifty times more mass than seen!



Galaxy rotation curves

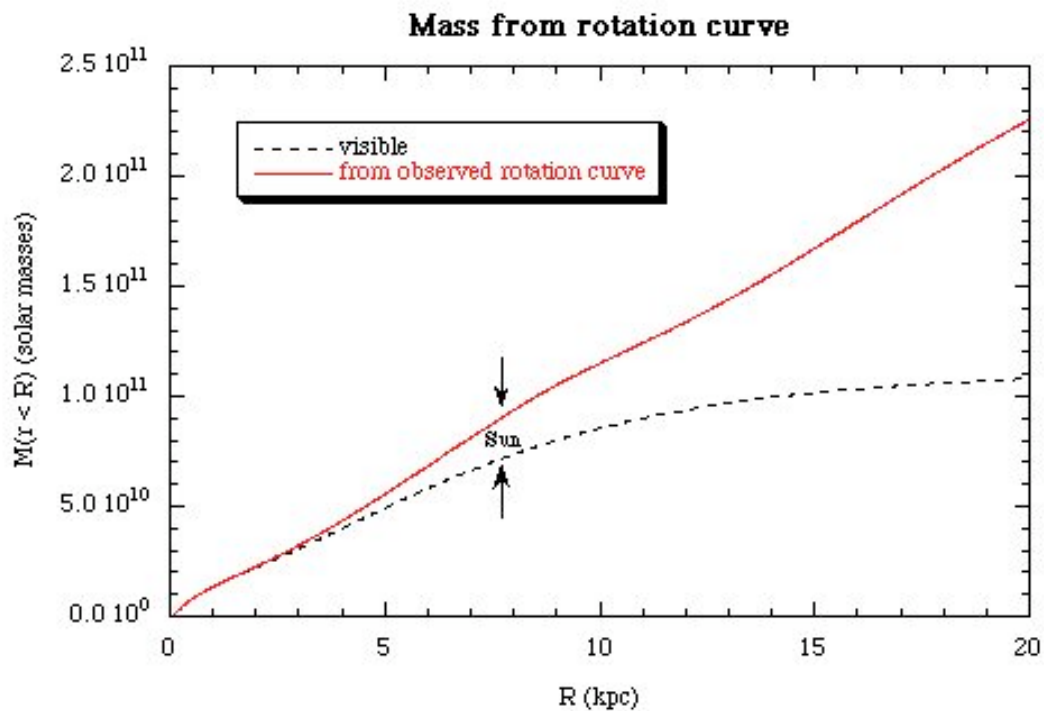
- Measure rotation speed of galaxies
- $v^2 / r = G M(r) / r^2$
- $M(r) = v^2 r / G$

Rotation of our galaxy



Galaxy rotation curves

- Measure rotation speed of galaxies
- $v^2 / r = G M(r) / r^2$
- $M(r) = v^2 r / G$
- $v \sim \text{constant} \Rightarrow M(r) / r !$

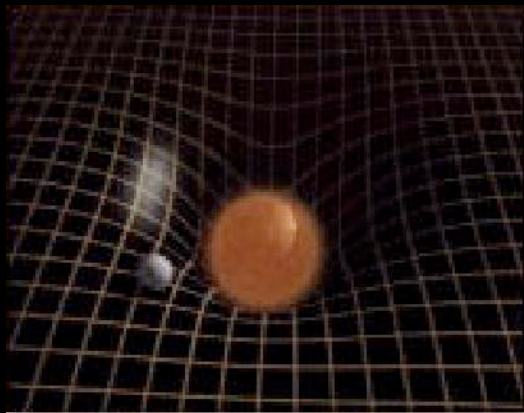


http://hepwww.rl.ac.uk/ukdmc/dark_matter/rotation_curves.html

Galaxy rotation curves

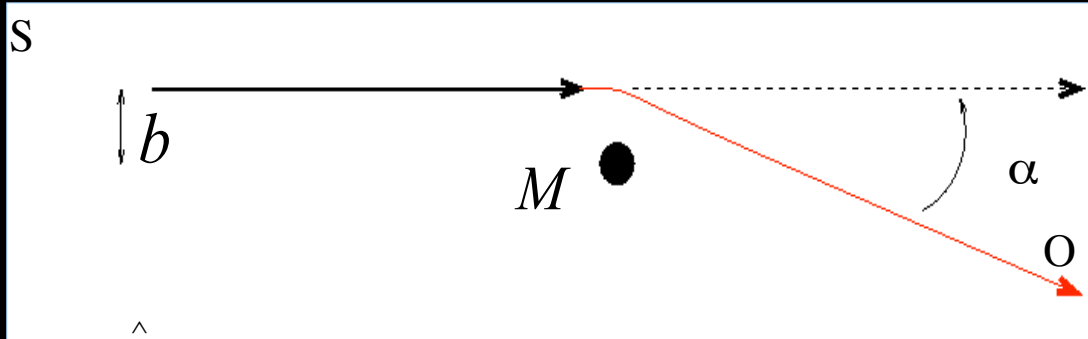
- Measure rotation speed of galaxies
- $v^2 / r = G M(r) / r^2$
- $M(r) = v^2 r / G$
- $v \sim \text{constant } M(r) / r$!
- Whereas light is nearly constant
⇒ Dark matter!

Space-time is bent by mass

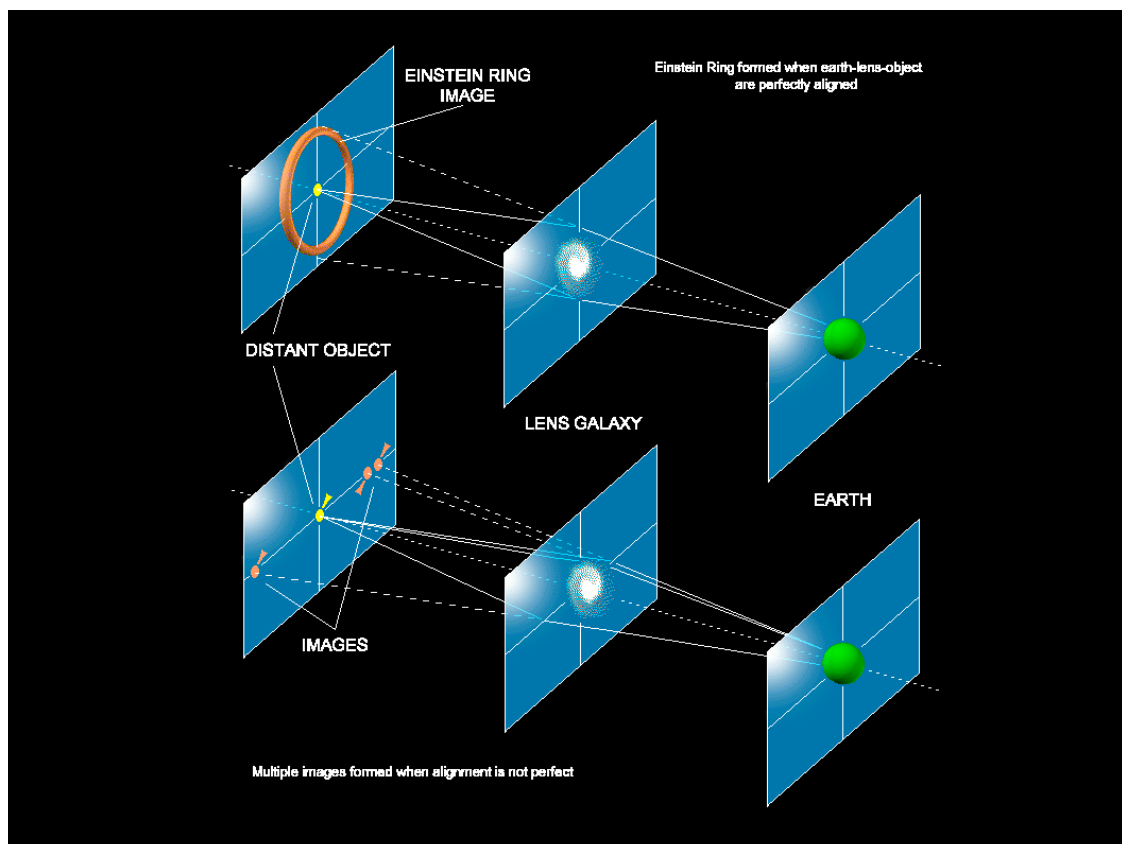


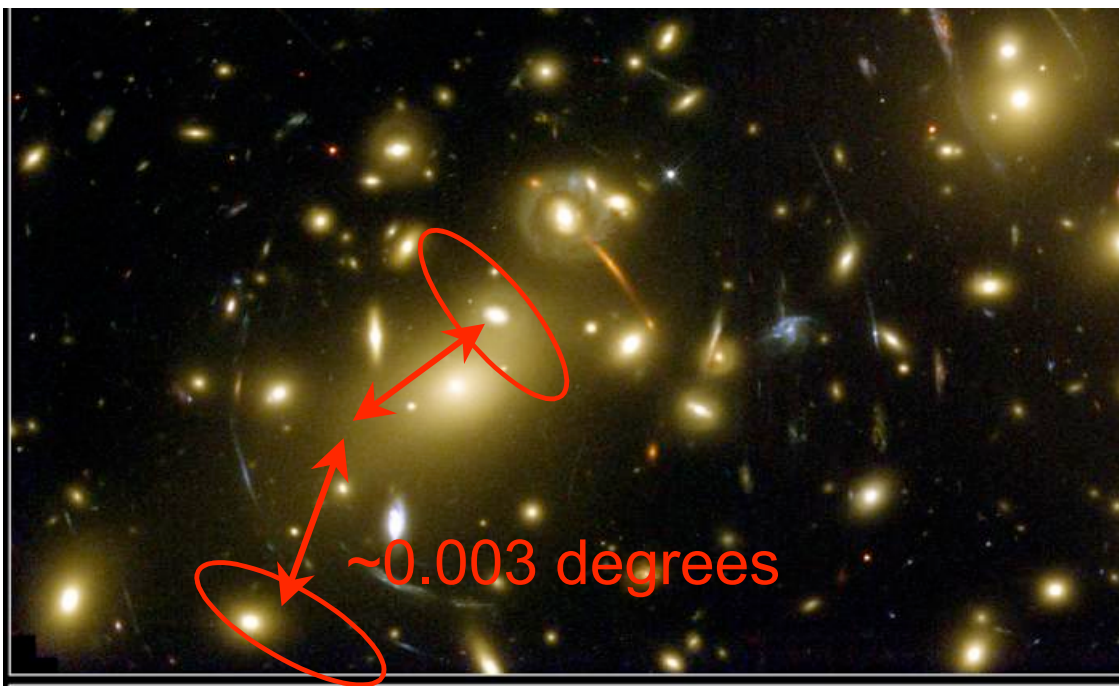
Gravitational lensing

- Light follows straight lines in space-time



- $\alpha = 4 G M / (c^2 b)$
- Independent of light wavelength





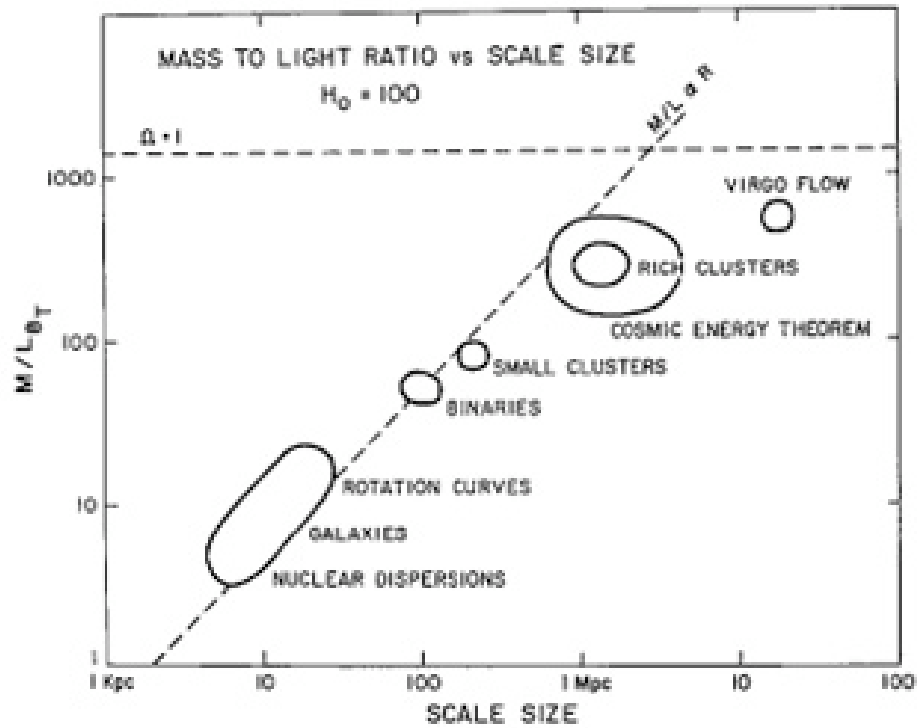
Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

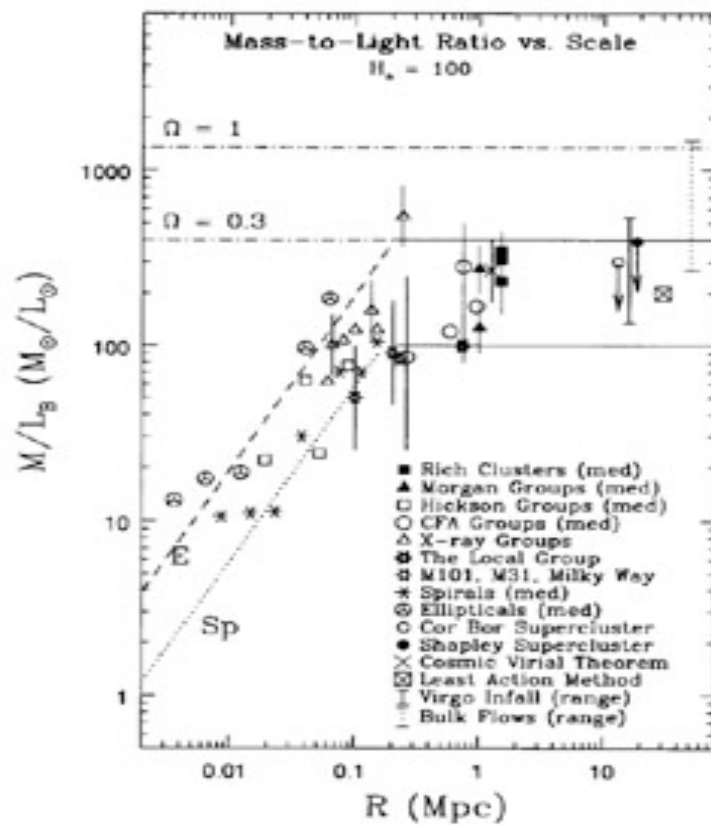
Arc radius _ Mass enclosed

$$\theta_E^2 = 4GM/c^2 D_{ds} / (D_d D_s)$$

- $\theta \sim 0.003$ degrees
- Mass expected from starlight $\sim 10^{13} M_\odot$
- Mass measured from gravitational lensing
 $\sim 10^{15} M_\odot$
- Factor of ~ 100 different!
- Mass-to-light ratio = $M/L \sim 100$



<http://gladstone.uoregon.edu/~cturner/p405/step3.html>



Bahcall et al

Dark matter density

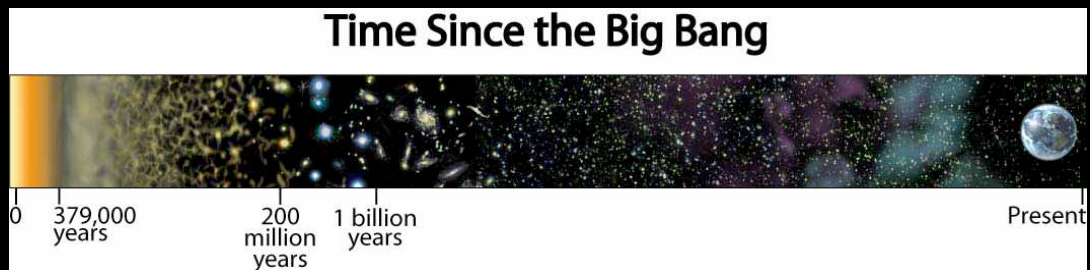
- Calculate density of light emitting matter
- Multiply by M/L

⇒ Density of dark matter $\rho_m \sim 0.6 \text{ } m_p / \text{m}^3$

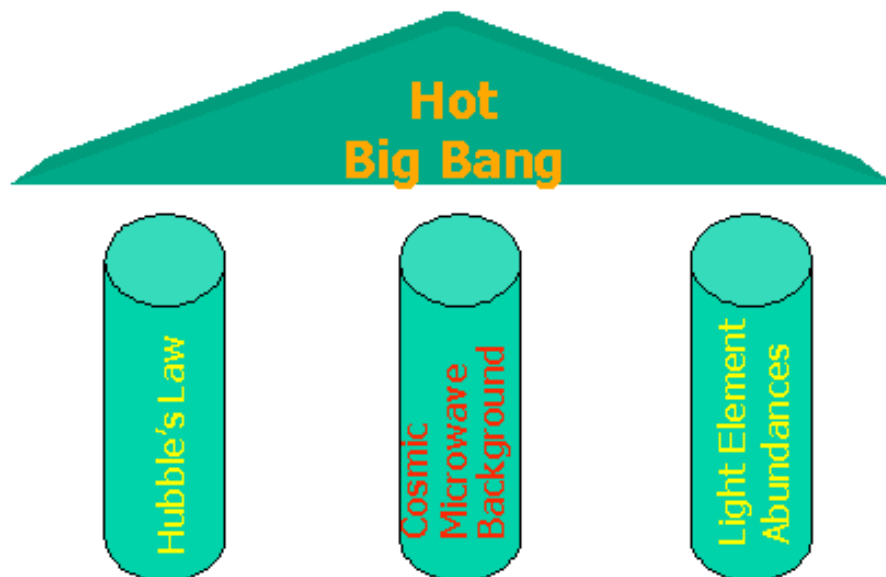
Cosmology: The evidence for dark matter and dark energy

- Dark matter
 - Not everything emits light
 - Its not normal (baryonic)
- Dark energy
 - There must be something else
- Prospects for the future

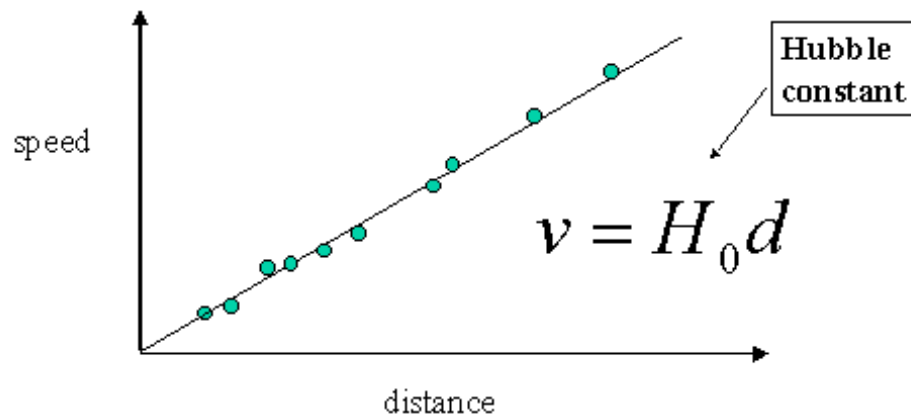
A brief history of the Universe



Three Pillars of Evidence for the Hot Big Bang Model

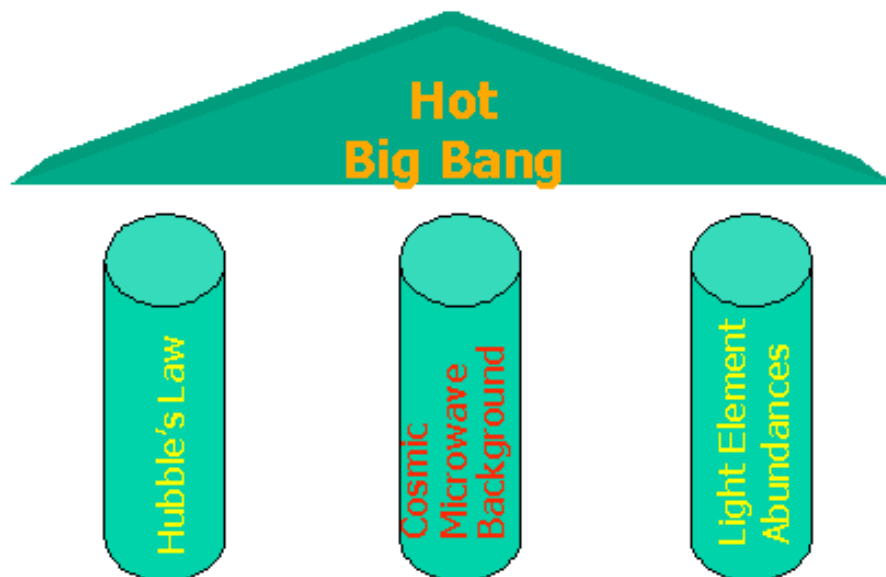


The Hubble Law



<http://physics.ucsd.edu/students/courses/fall2001/physics5/notes/ch17/sld004.htm>

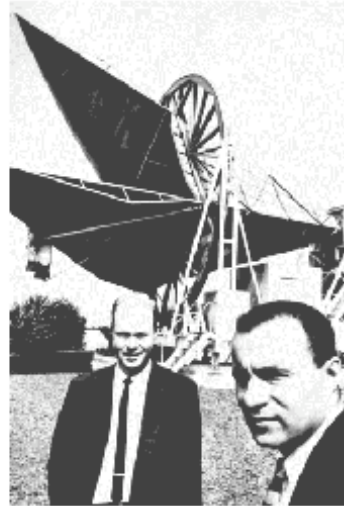
Three Pillars of Evidence for the Hot Big Bang Model



<http://physics.ucsd.edu/students/courses/fall2001/physics5/notes/ch17/sld026.htm>

Cosmic Microwave Background (CMB)

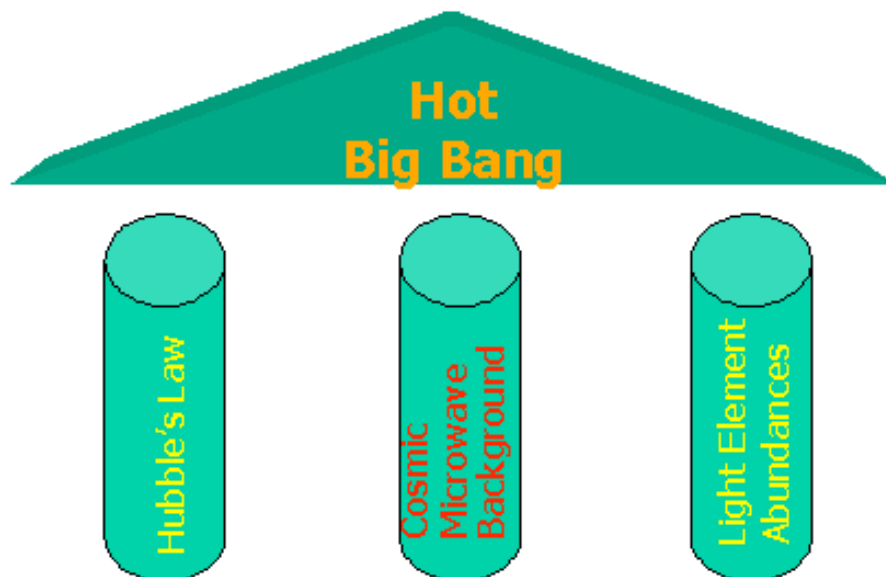
- Discovered serendipitously in 1964 by Arno Penzias and Robert Wilson at AT&T Bell Labs
- Microwave noise
- Isotropic



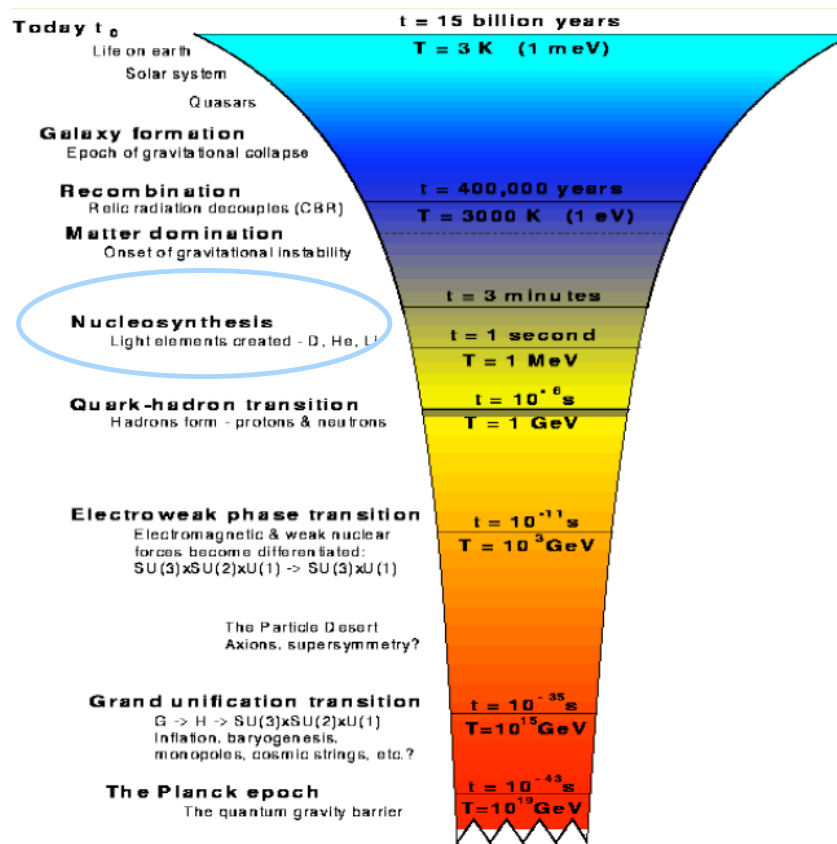
Penzias and Wilson with horn antenna (Lucent)

<http://physics.ucsd.edu/students/courses/fall2001/physics5/notes/ch17/sld027.htm>

Three Pillars of Evidence for the Hot Big Bang Model



<http://physics.ucsd.edu/students/courses/fall2001/physics5/notes/ch17/sld026.htm>

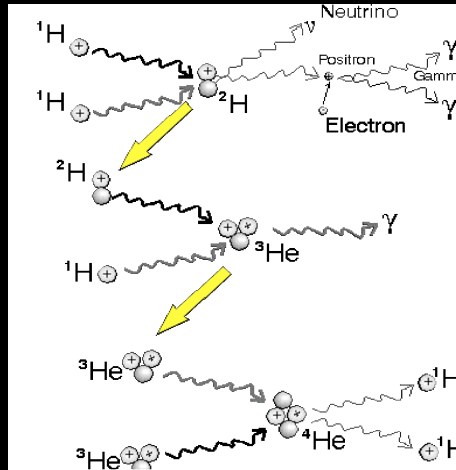


Baryons

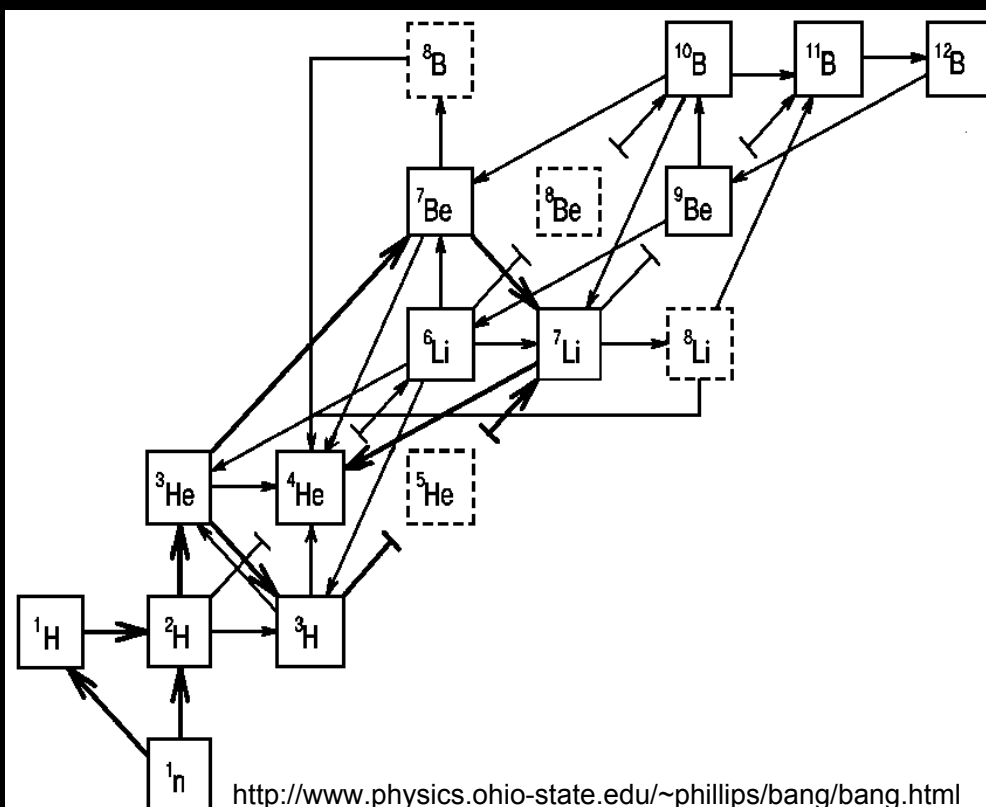
- Made up of 3 quarks
 - Protons, neutrons
- Nuclei of atoms are made of p, n
 - therefore are baryonic
- Non-baryonic:
 - e.g. photons (light), electrons, neutrinos ...

Nucleosynthesis

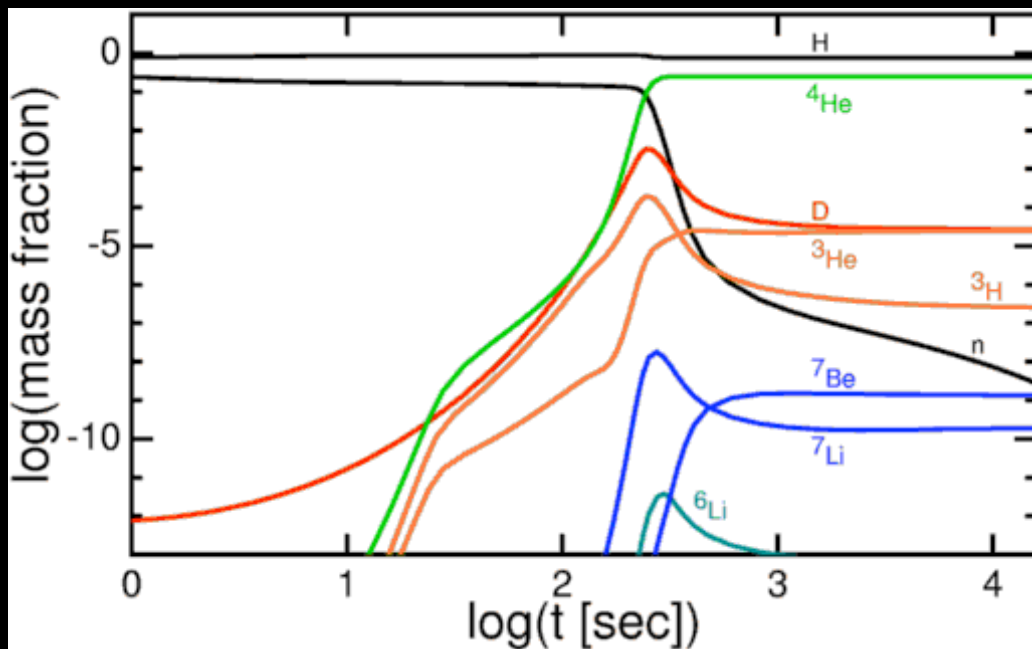
- ~3 minutes after the Big Bang
- Universe cools enough for nuclei to form



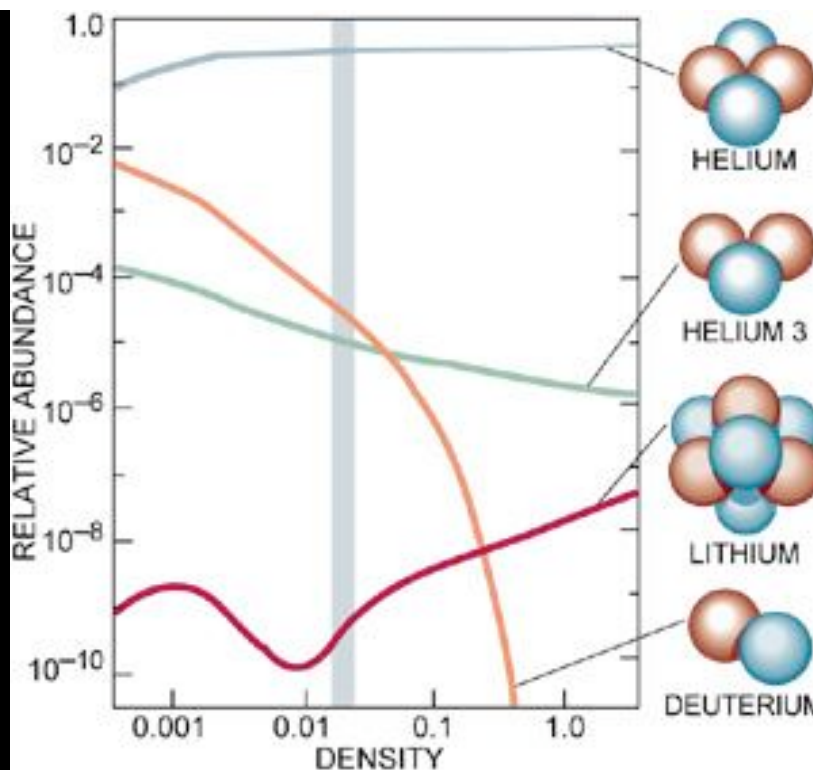
http://www.mhhe.com/physsci/astronomy/army/student/webtutor/solar_energy/



<http://www.physics.ohio-state.edu/~phillips/bang/bang.html>

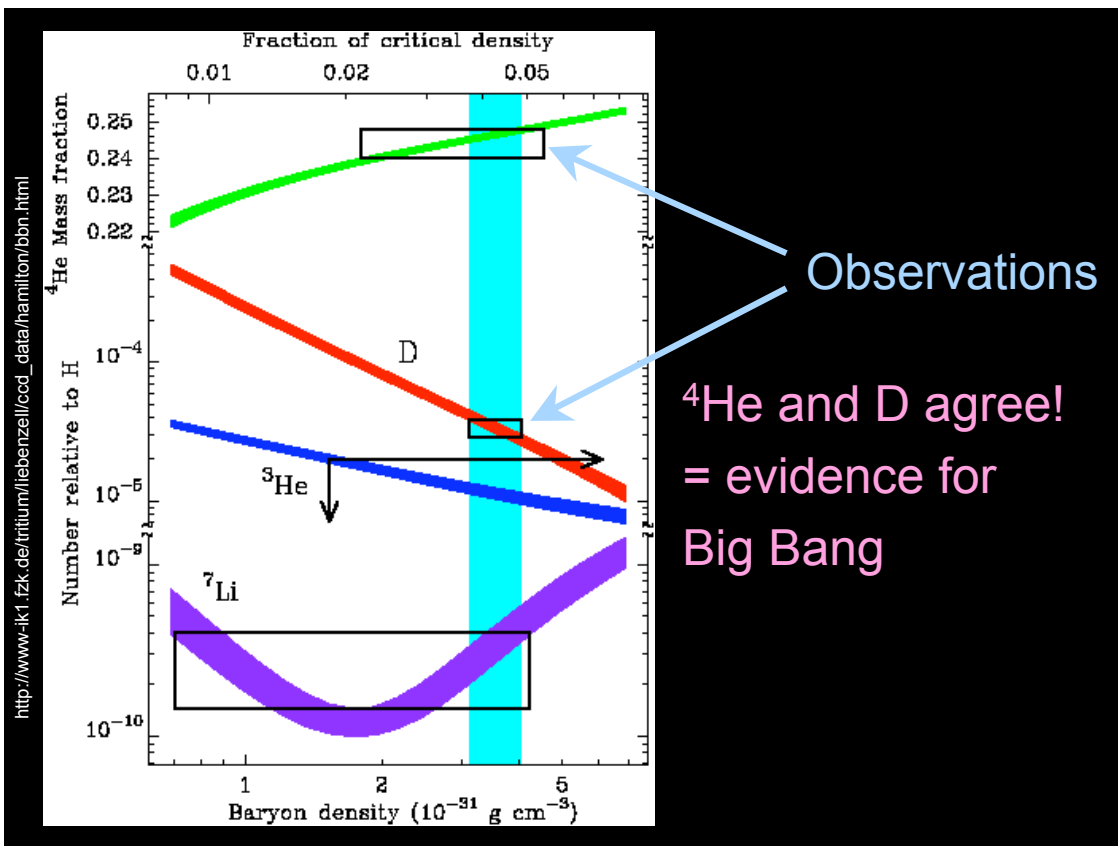


<http://www.astro.ucla.edu/~wright/BBNS.html>

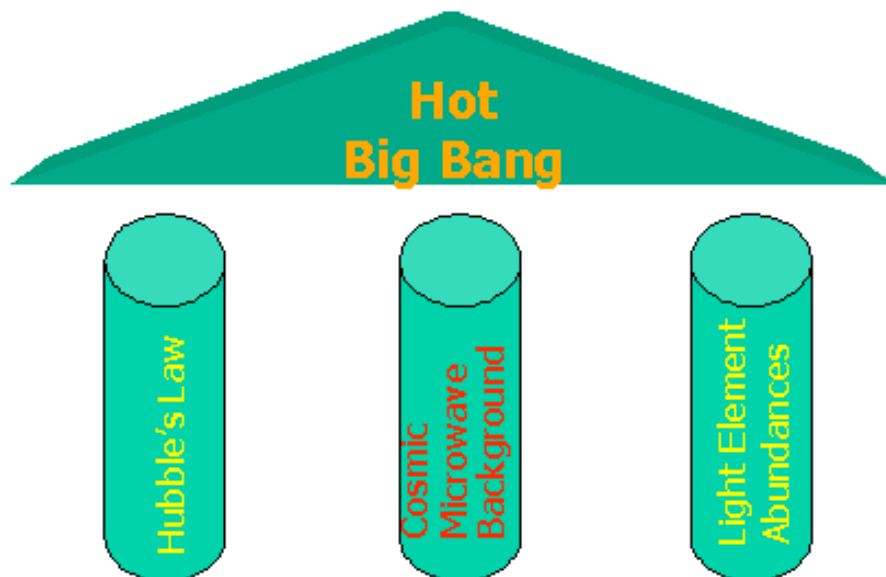


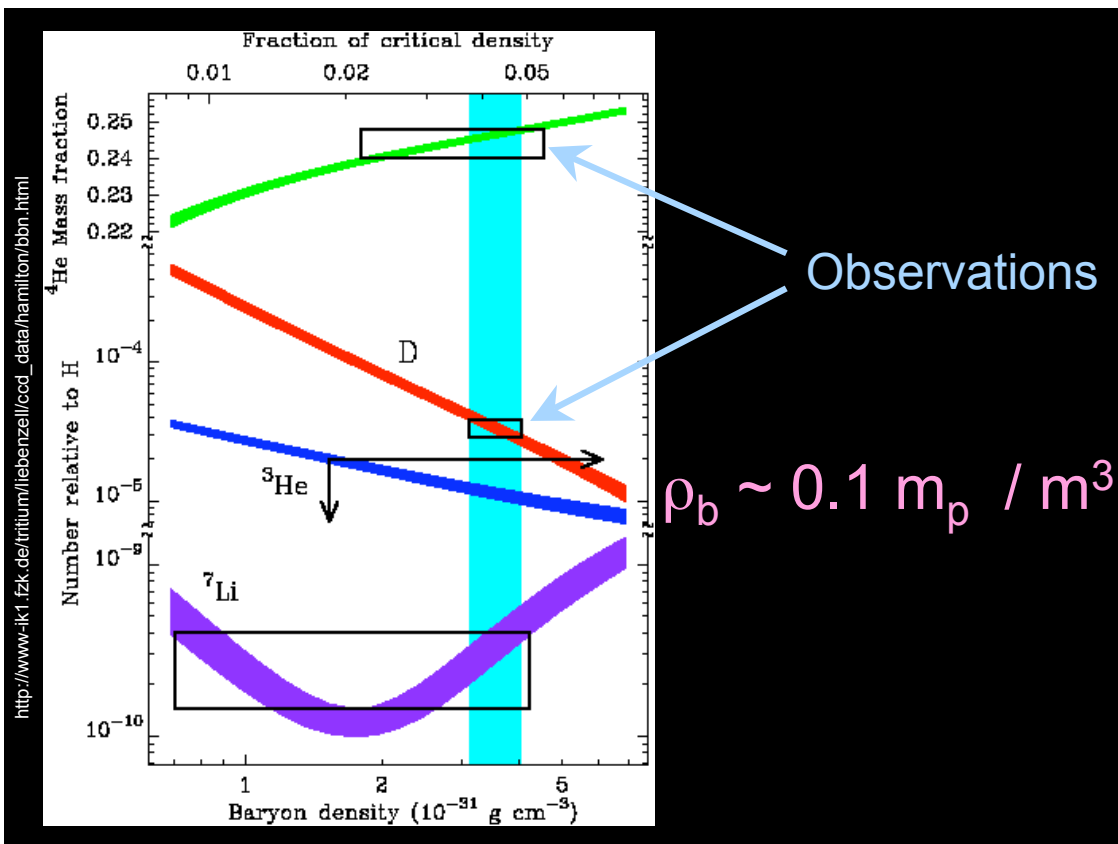
Baryon density controls relative abundances

http://departments.weber.edu/physics/carroll/Wonder/big_bang_nucleosynthesis.htm



Three Pillars of Evidence for the Hot Big Bang Model



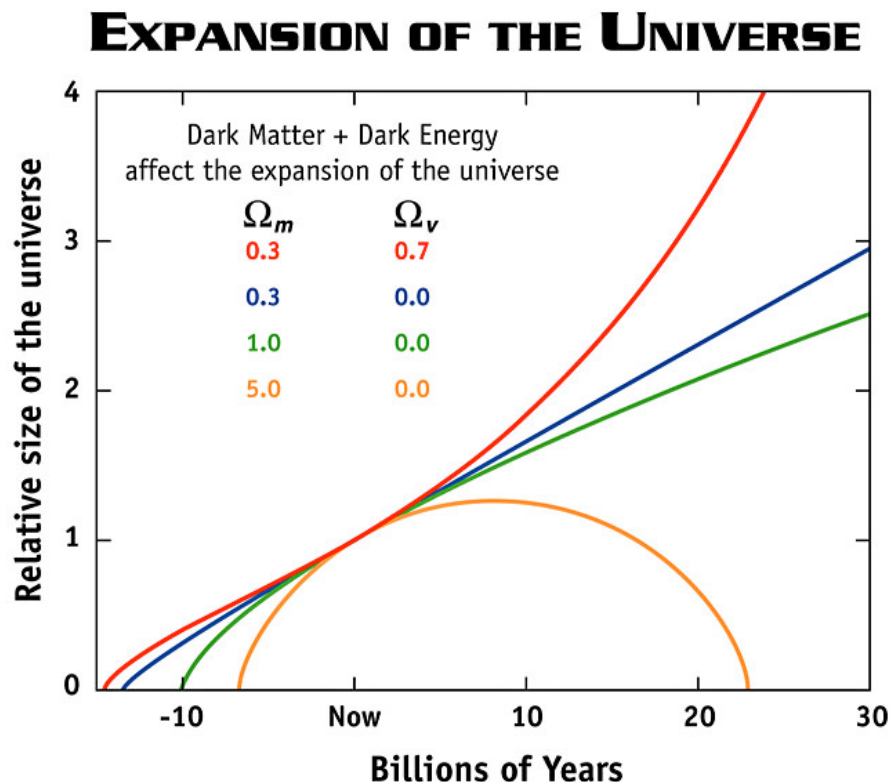


Dark matter is not normal (baryonic)

- From M/L ratio:
- Density of dark matter $\rho_m \sim 0.6 m_p / m^3$
- From nucleosynthesis
- Baryon density $\rho_b \sim 0.1 m_p / m^3$
- What is the non-baryonic dark matter?

Jargon: The “critical density”

- The critical density ρ_{crit}
- $\rho_m < \rho_{\text{crit}}$ (and no dark energy) $\Omega_m < 1$
 - Universe expands forever
- $\rho_m > \rho_{\text{crit}}$ $\Omega_m > 1$
 - Big Crunch
- $\rho_m = \rho_{\text{crit}}$ $\Omega_m = 1$
 - Universe eventually stops expanding (at $t=1$)
- Define matter density $\Omega_m = \rho_m / \rho_{\text{crit}}$

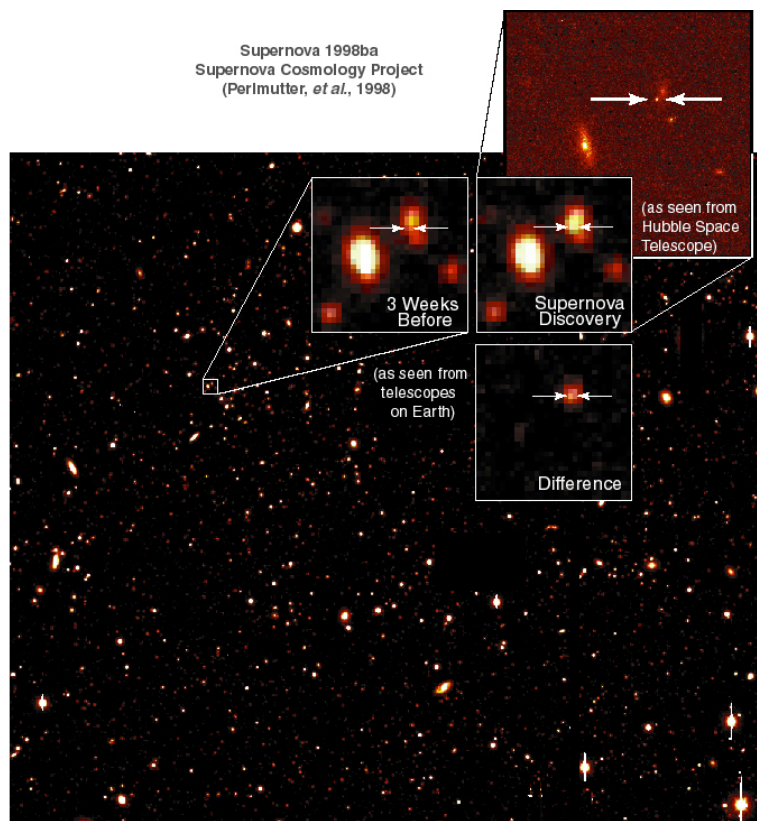


Dark Matter: Summary

- Mass compared to starlight: $M/L \sim 100$
- Extrapolate M/L to give $\Omega_m \sim 0.3$
- Nucleosynthesis: $\Omega_b \sim 0.05$
- Galaxy clustering gives $\Omega_v < 0.05$
- Mass is dominated by “dark matter”
- We don't know what it is!

Cosmology: The evidence for dark matter and dark energy

- Dark matter
 - Not everything emits light
 - Its not normal (baryonic)
- Dark energy
 - The Universe is accelerating
- Prospects for the future

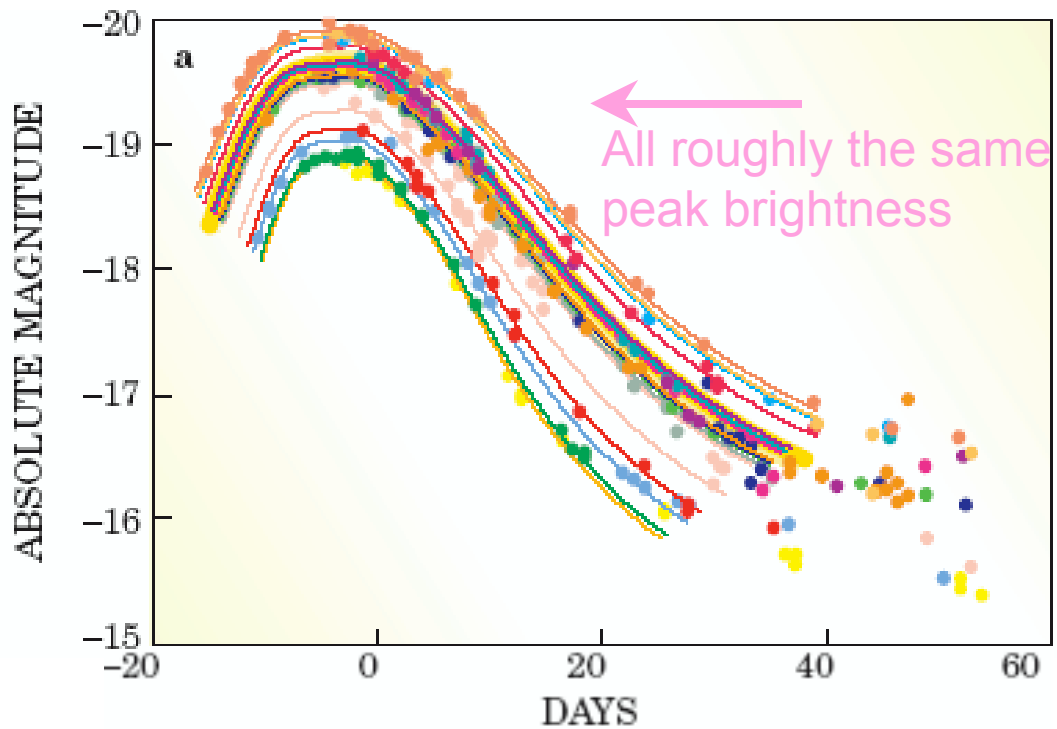


<http://panisse.lbl.gov/>

Standard Candles

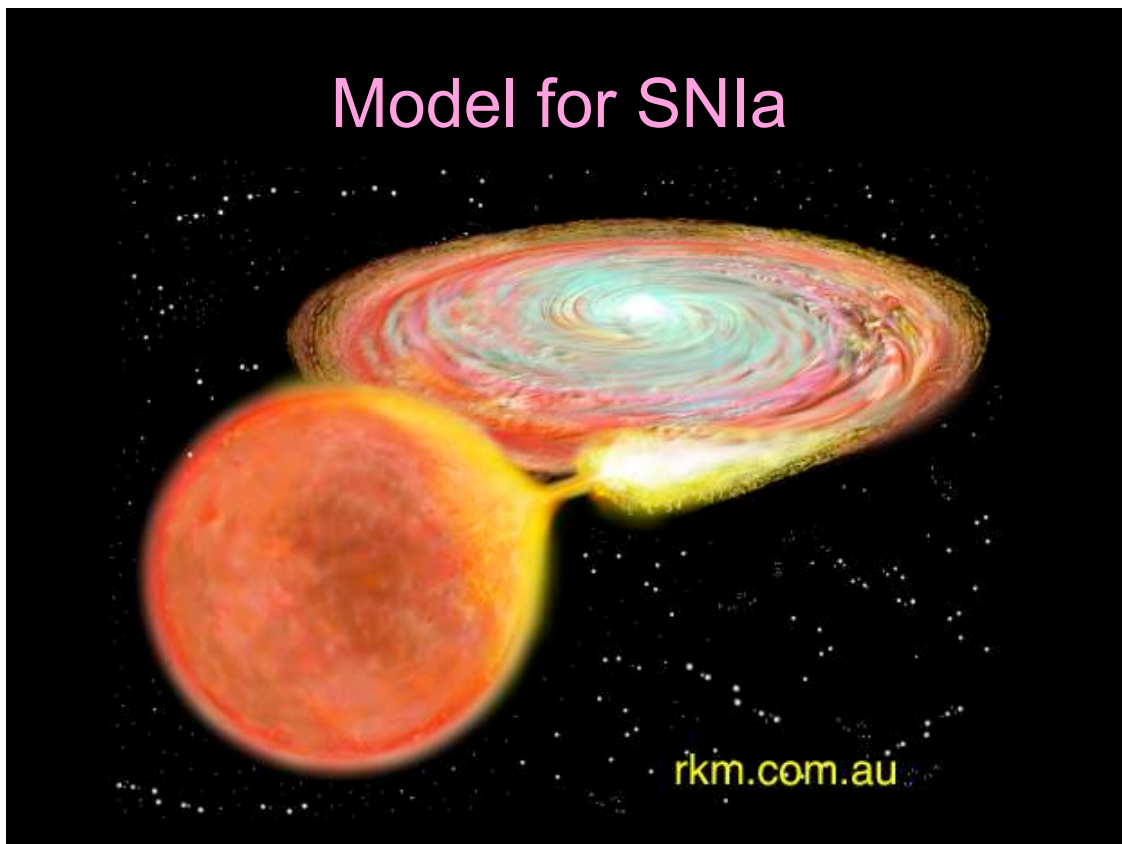
- **Definition:**
 - Anything that is intrinsically the same brightness wherever it is placed
- **e.g.**
 - Could estimate distance to nearby farmhouse by looking at apparent brightness of lightbulb
- **Historical examples**
 - e.g. Hubble used galaxies for discovering expansion

Observations of Supernova type Ia



S. Perlmutter, Physics Today, April 2003 <http://panisse.lbl.gov/PhysicsTodayArticle.pdf>

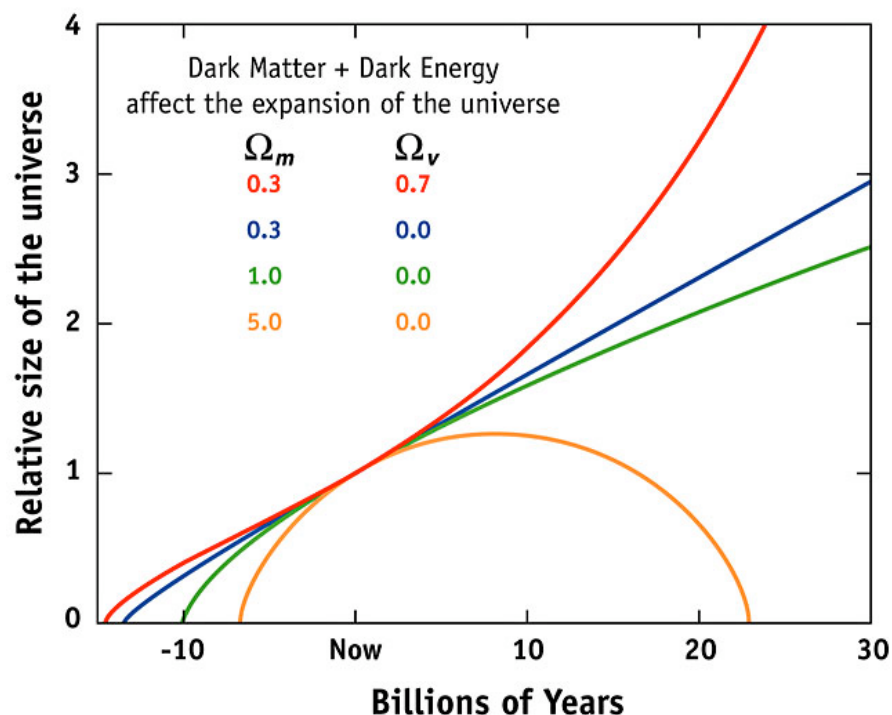
Model for SNIa



Why might SNIa be standard candles?

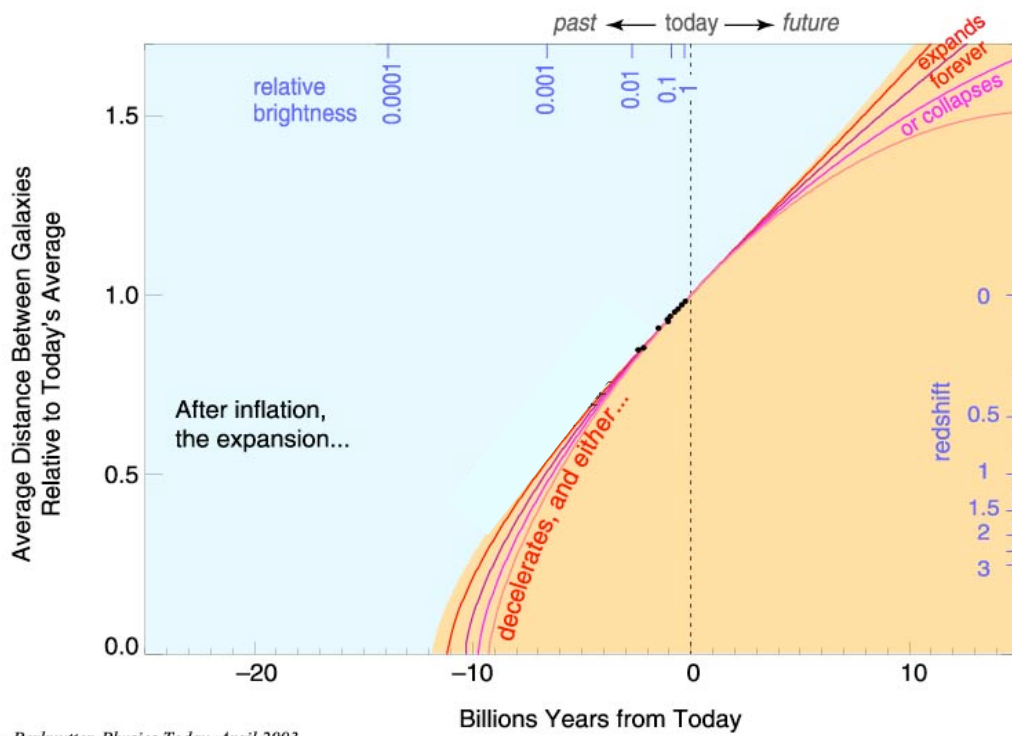
- Accreting white dwarf reaches Chandrasekhar mass and explodes
- Chandrasekhar mass well defined
- White dwarfs might be very simple
- Problems:
 - explosion v hard to model (esp in 3d)
 - composition varies from WD to WD

EXPANSION OF THE UNIVERSE



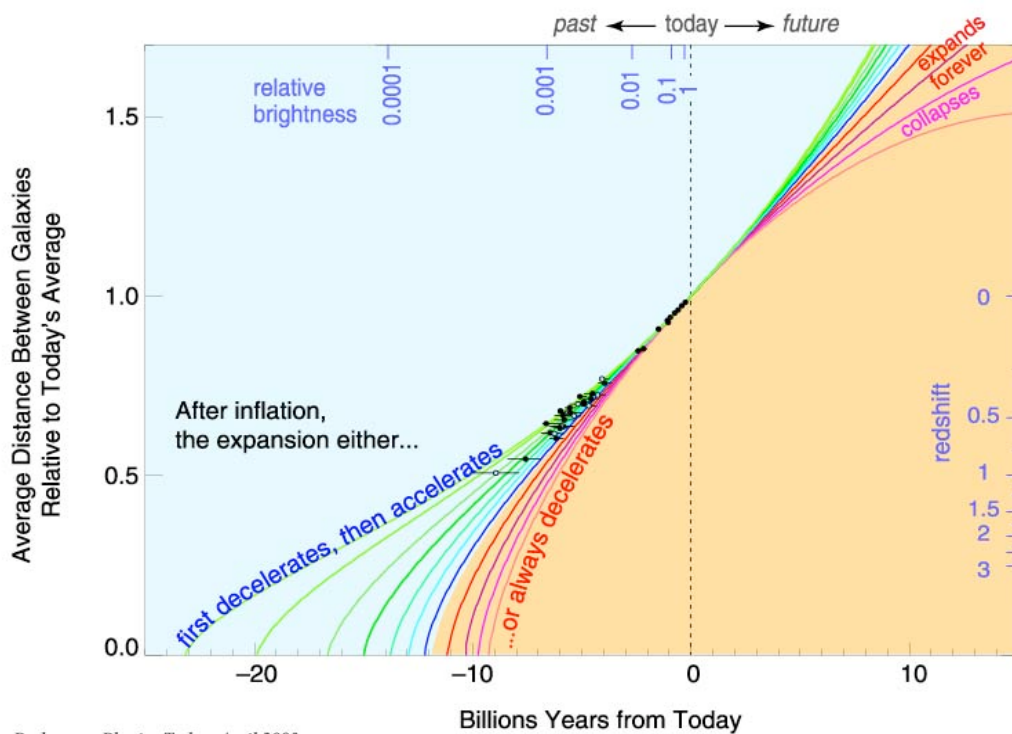
map.gsfc.nasa.gov/m_uni/101bb2_1.html

Expansion History of the Universe

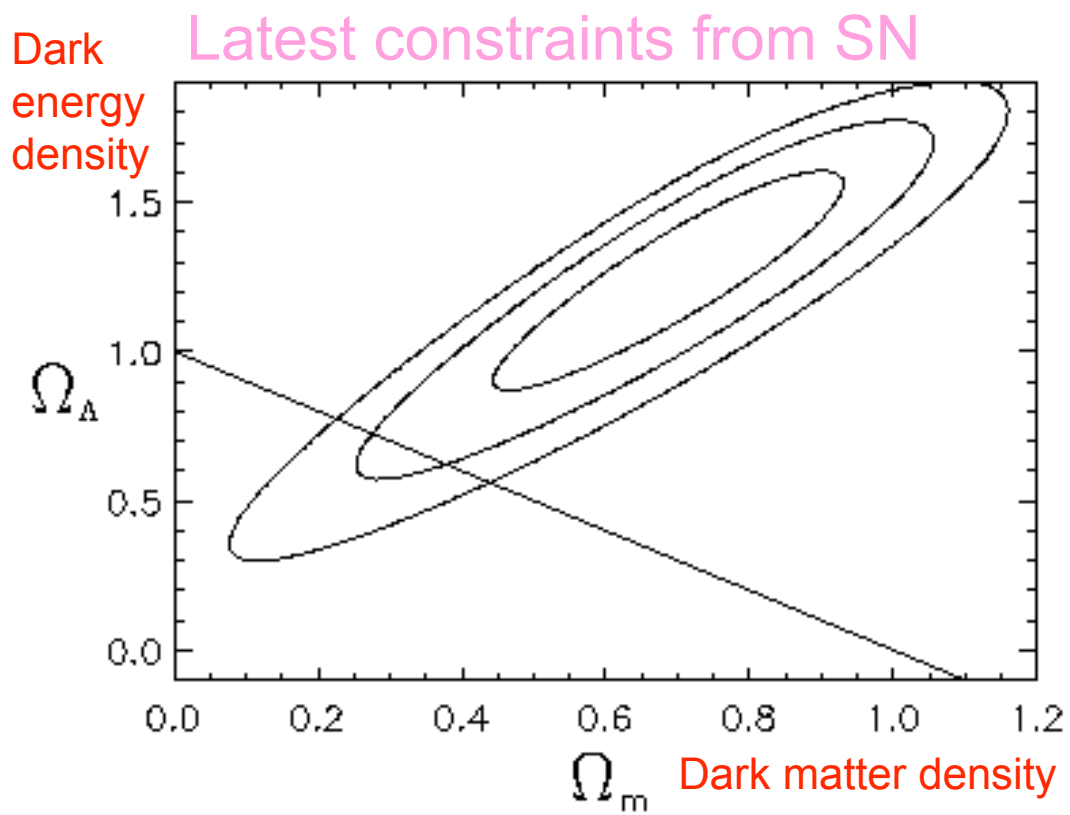
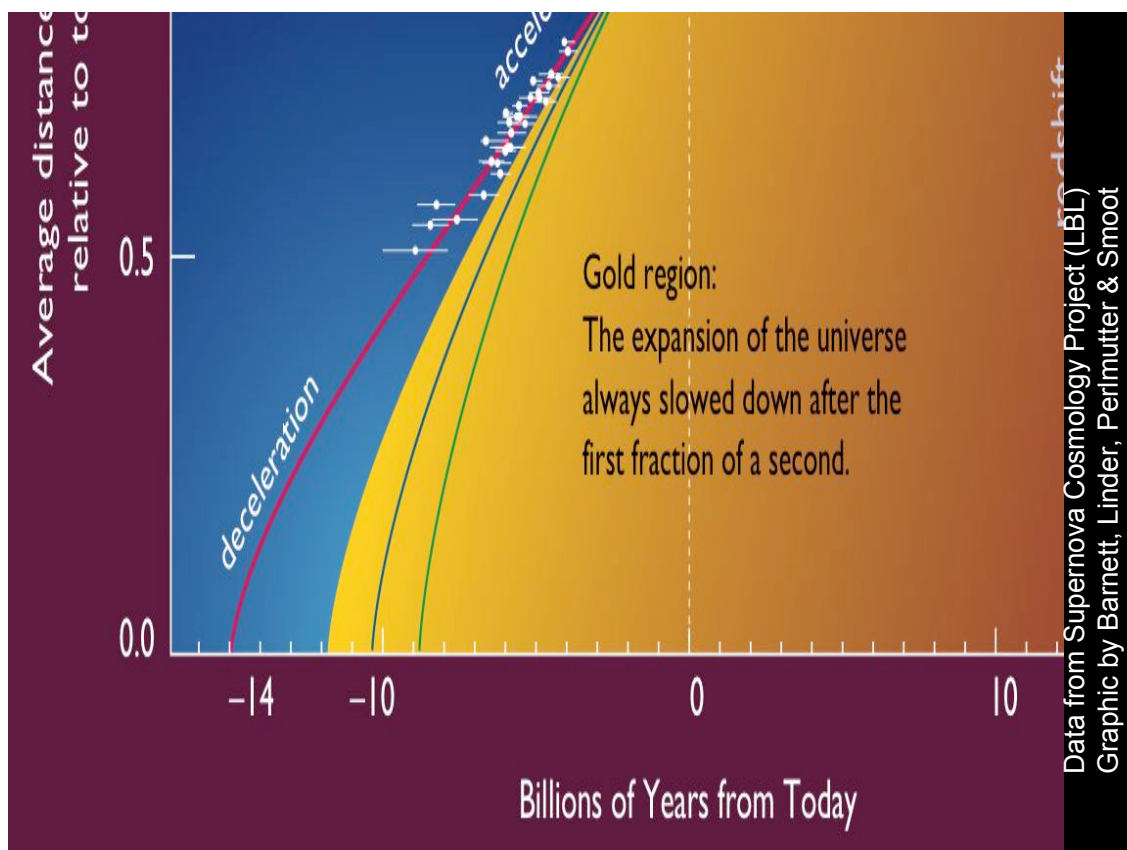


Perlmutter, *Physics Today*, April 2003

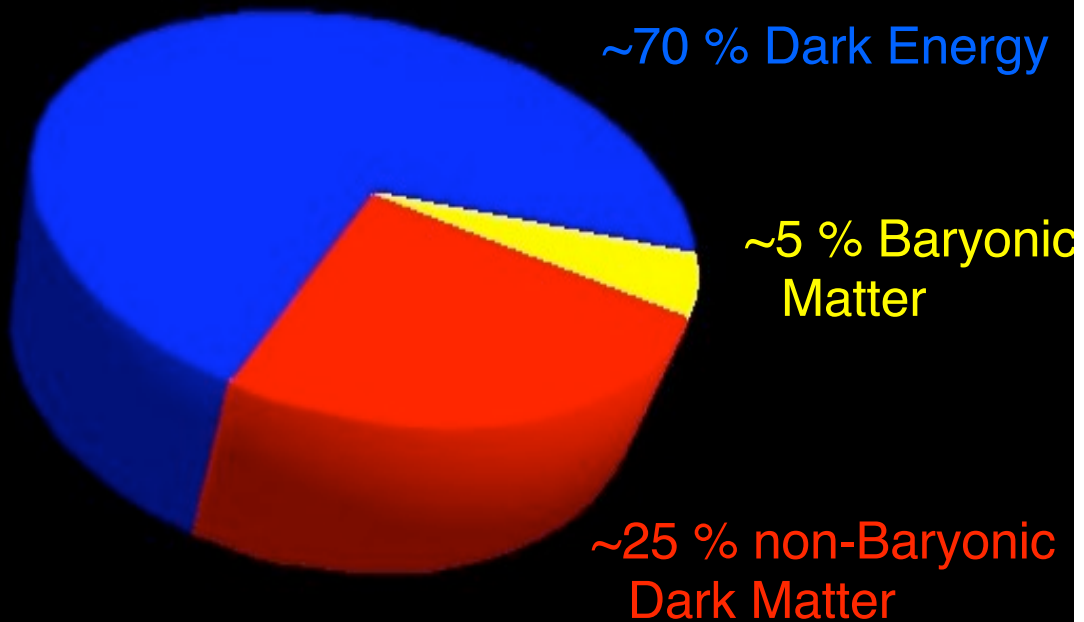
Expansion History of the Universe



Perlmutter, *Physics Today*, April 2003



Current Cosmological Model



Cosmic Coincidence?

Graphic from <http://supernova.lbl.gov/~evlinder/linderdoegeneral.ppt>

