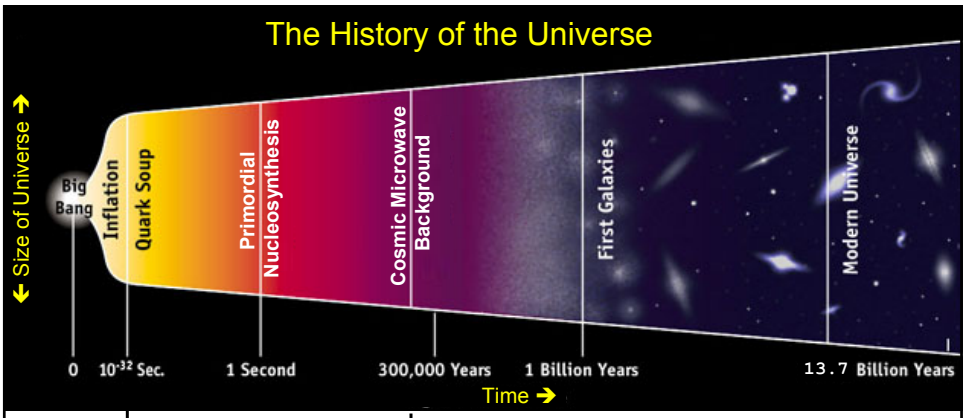
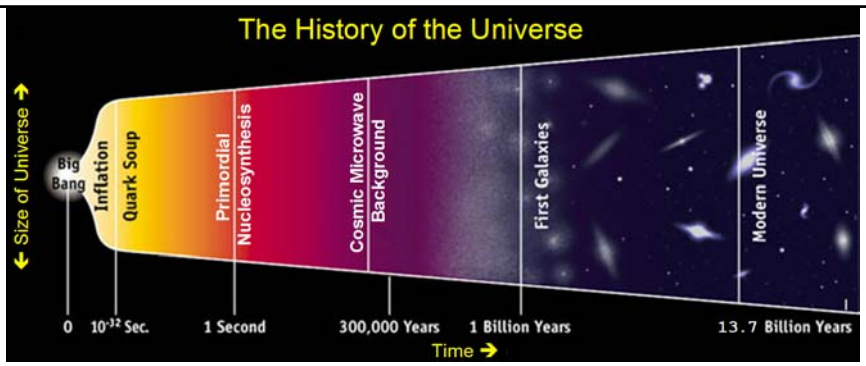


Planck time | Inflation | Formation of H, He, Li | Decoupling of CMB | Galaxy Formation | Now

Hot (10^{32} K) → (10^{9} K) → (3000 K) → Cool (3 K)

High density → Low density



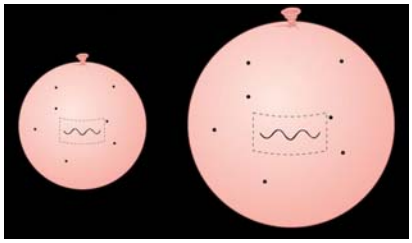
Event	Age of U.	Redshift	°K
Planck time; Gravity separated out	10^{-43} sec	10^{74}	10^{32}
Strong nuclear force separated out	10^{-38} sec	10^{71}	10^{29}
Inflation	10^{-36} sec	---	---
Electromagentic, Weak nuclear forces	10^{-12} sec	10^{14}	10^{15}
Nucleosynthesis of H, He, Li	1 sec - 3 min	10^{8}	10^{9}
Decoupling of CMB	300,000 yrs	1100	3000
Galaxy Formation	950 million yrs	6	19
Now	13.7 billion yrs	0	2.73

hot ↓ cool

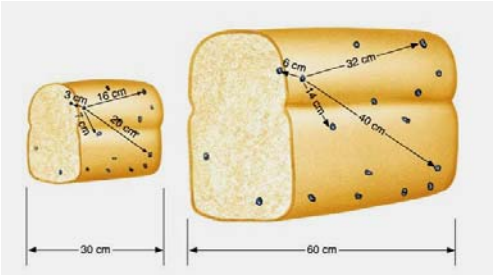
high density ↓ low density

The scale factor R(t)

sometimes called a(t)



2D version



3D

- Co-moving coordinates
- Proper distance

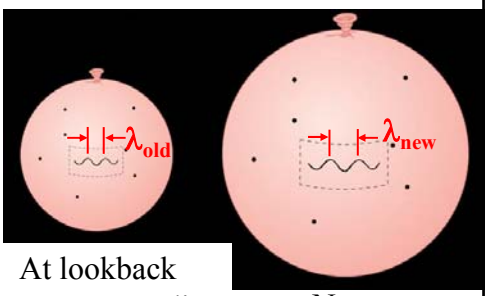
The Expanding Universe

- Individual galaxies do not get stretched.
- Light waves *do* get stretched ➔ redshift.

Redshift

$$z = \frac{\lambda_{new} - \lambda_{old}}{\lambda_{old}} = \frac{\lambda_{new}}{\lambda_{old}} - 1$$

$$R(t) = \frac{\lambda_{old}}{\lambda_{new}} = \frac{1}{1+z}$$

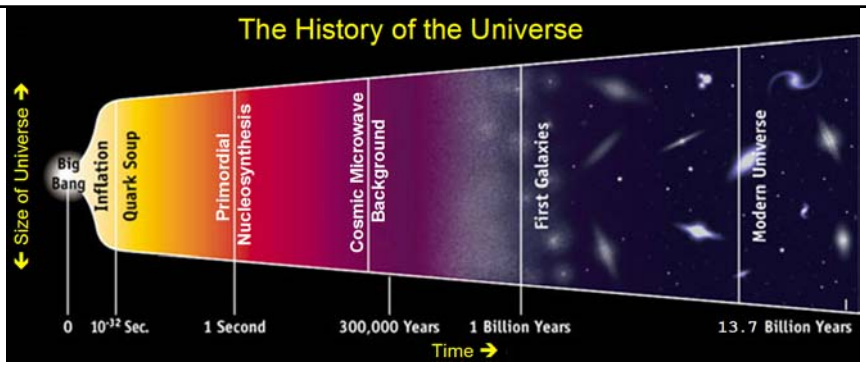


At lookback time corresponding to redshift z

Now

doppler demo applet

Redshift ➔ scale factor R(t) at time light was emitted.



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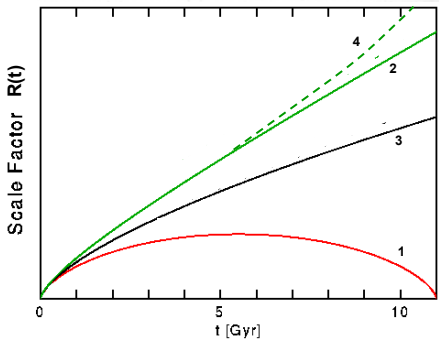
R(t) vs. t

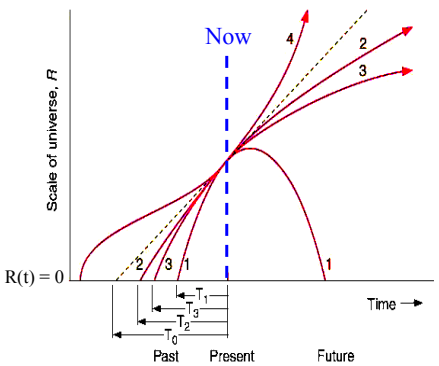
Solutions to the Friedmann Eqn. [29.108]

Matter density, Dark energy, Curvature

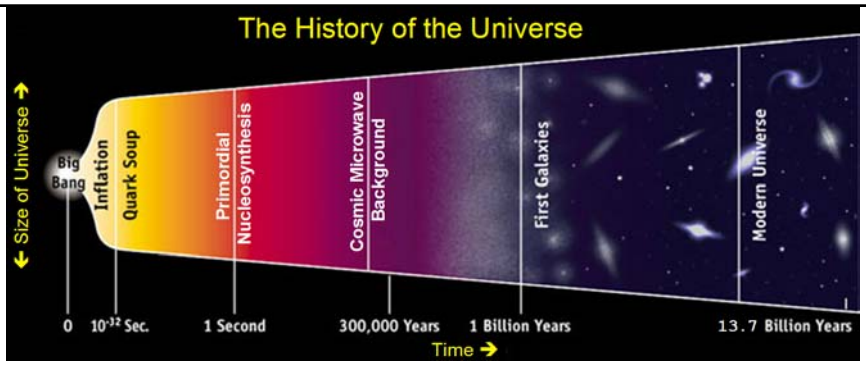
$$\left[\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho - \frac{1}{3}\Lambda c^2\right]R^2 = -kc^2$$



Component	% of mass-energy density
Normal Matter	4%
Dark Matter	23%
Dark Energy	73%



- As t → 0, R(t) ∝ $t^{1/2}$ in all 4 models.
- But current age of U. very different in different models.



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The Great Debate: *The Size of the Universe* (1920)

Heber Curtis

- Our Galaxy is rather small, with Sun near the center.
  - 30,000 LY diameter.
  - Kapteyn's result.
- Universe composed of many separate galaxies
  - Spiral nebulae = "island universes"

The Judges?

Harlow Shapley

- Our Galaxy is very large, with Sun far from center.
  - 300,000 LY diameter.
  - Sun 60,000 LY from center.
  - Based on distribution of globular clusters,
    - Pulsating variables.
- Spiral Nebulae are inside our galaxy.
  - "nova" magnitudes
  - "Proper motion" ➔ rapid rotation.

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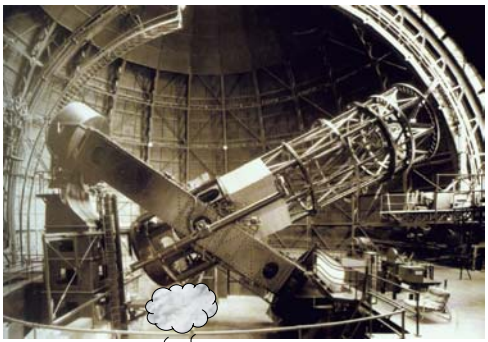
Astronomy in 1926

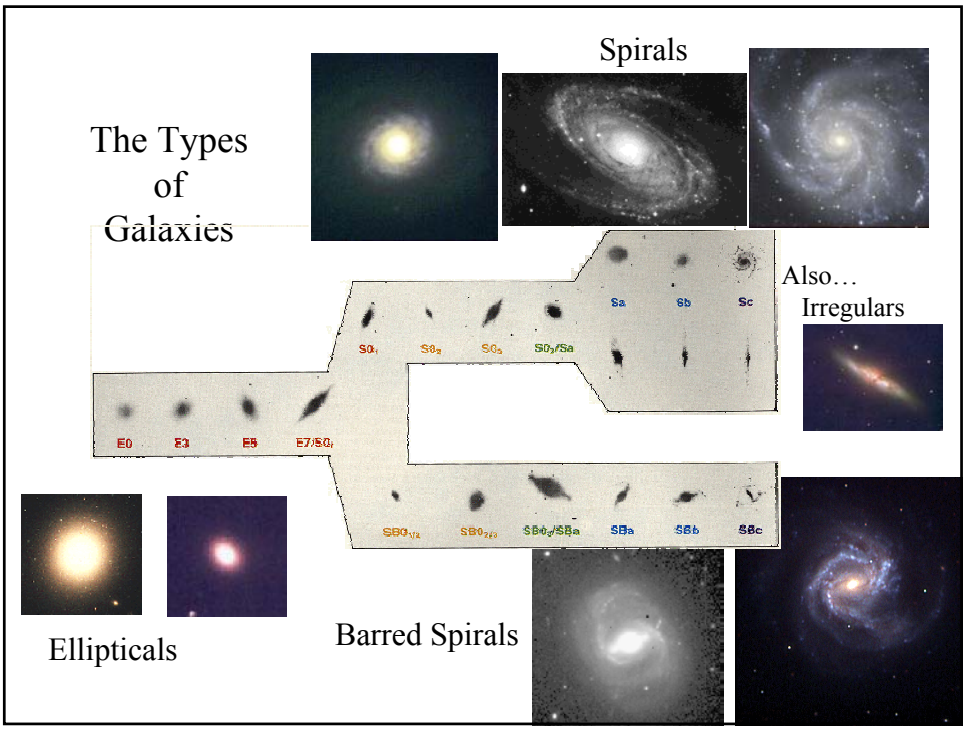


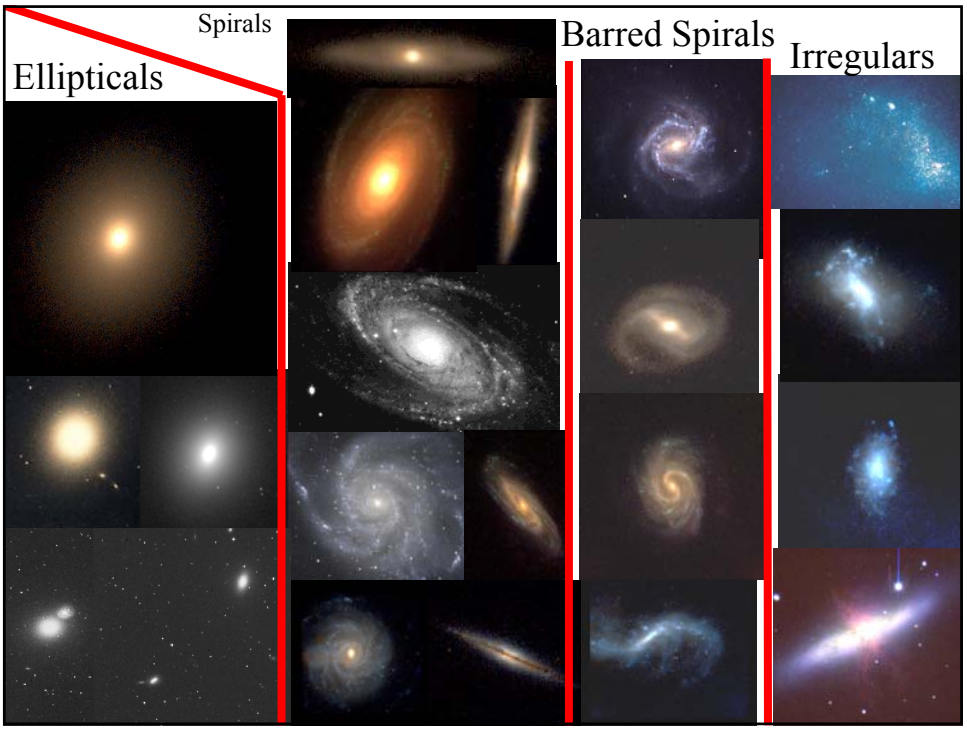
100 inch telescope
Completed 1918

Edwin Hubble

- ~1770: Messier catalogue
- 1888: NGC, IC catalogues
- Van Maanen's "contribution"
- 1920: Curtis-Shapley debate
- 1923: Hubble measured distance to M31
- 1926: Hubble's E, S, I galaxy classification scheme.

- 1929 Expanding Universe
- 1936: *Realm of the Nebulae* described Hubble classification system.


The Types of Galaxies
Spirals
Also…
Irregulars
Ellipticals
Barred Spirals
E0
E1
E5
E7/S0
S0₁
S0₂
S0₃
S0₂/Sa
Sa
Sb
Sc
SB0
SB0/SBa
SBa
SBb
SBc


Spirals
Ellipticals
Barred Spirals
Irregulars

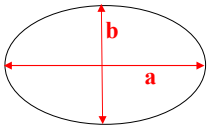
Usual classes used at current time:

- E0-E7
- S0, Sa, Sab, Sb, Sbc, Sc, Scd, Sd, Sdm, Sm, Im, Ir (or amorphous)
- SB0, SBa, SBab, SBb, SBbc, SBc, SBcd, SBd, SBdm, SBm

General Properties of Galaxy Types

- **E**
  - M_B = -8 to less than –23
  - Mass = 10^7 – 10^{13} $M_\odot$
  - diameters <1 kpc – hundreds of kpc
- **S**
  - M_B = -16 to –23
  - Mass = 10^9 – 10^{12} $M_\odot$
  - luminous diameters 5-100 kpc
- **Irr**
  - M_B = -13 to –20
  - Mass = 10^8 – 10^{10} $M_\odot$
  - luminous diameters 1–10 kpc

E0➔E7
10*(1-b/a)



Sa➔Sc
- Bulge:disk ratio
- Tightness of winding
- Resolution of arms into star clusters & H II regions.

Morphological Types of Local Galaxies

(images taken from Frei, Guhathakurta, Gunn & Tyson 1996)