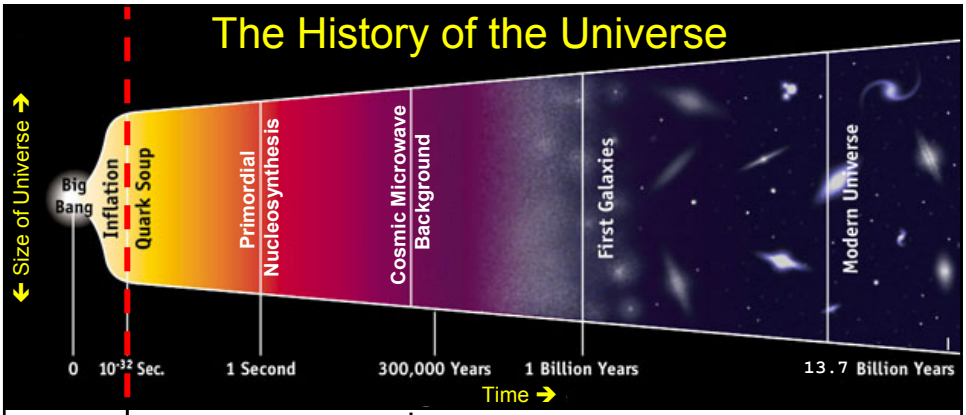
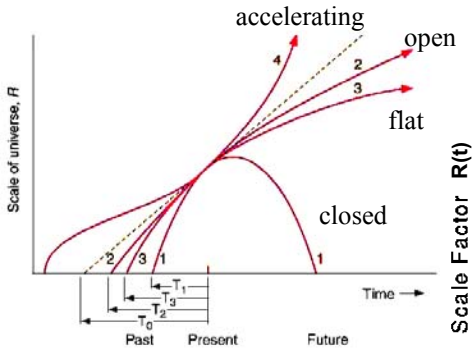


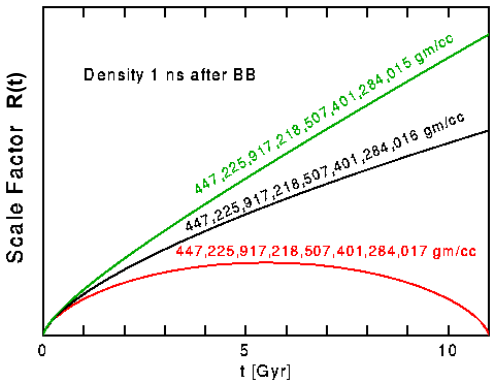
Planck time | Inflation | Formation of H, He, Li | Decoupling of CMB | Galaxy Formation | Now

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

High density → Low density

What happened back at the Big Bang?





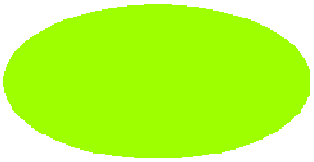
- The Flatness Problem:

  NOW: Kinetic energy ~ Gravitational energy
  - But this requires incredible precision at start (t = 0).
  - kinetic *exactly* = gravitational energy ← Critical Density

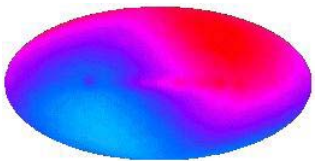
Isotropy of the Cosmic Microwave Background

Whole-Earth Map

- COBE satellite.



Blue = 0°K
Red = 4°K

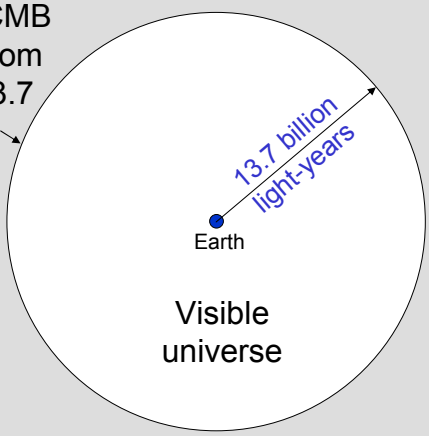


Blue = 2.724°K
Red = 2.732°K
Dipole Anistropy
➔motion of Sun through Universe.

Whole-Sky Maps

The Horizon

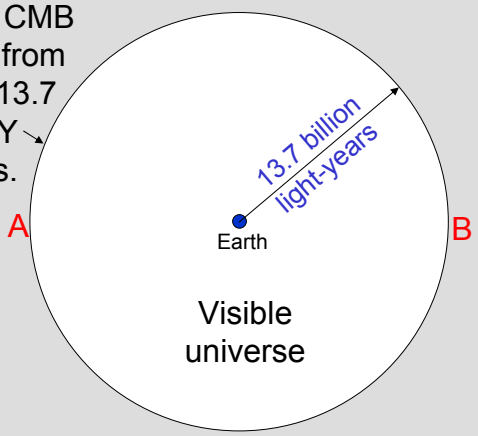
Current CMB emitted from sphere 13.7 billion LY in radius.



We will only see this part of universe sometime in future.

The Horizon

Current CMB emitted from sphere 13.7 billion LY in radius.



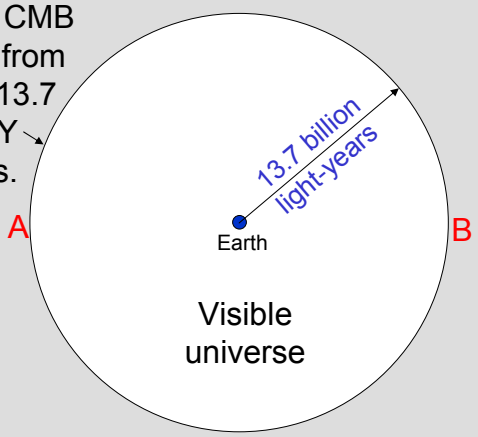
We will only see this part of universe sometime in future.

Clicker Question. Has Point A *ever* communicated with Point B?

A. Yes
B. No
C. Maybe

The Horizon

Current CMB emitted from sphere 13.7 billion LY in radius.



We will only see this part of universe sometime in future.

The Horizon Problem: Causality

- Points A and B have *never* communicated.
- How do they know how to have almost *exactly* the same conditions?

The solution: Inflation

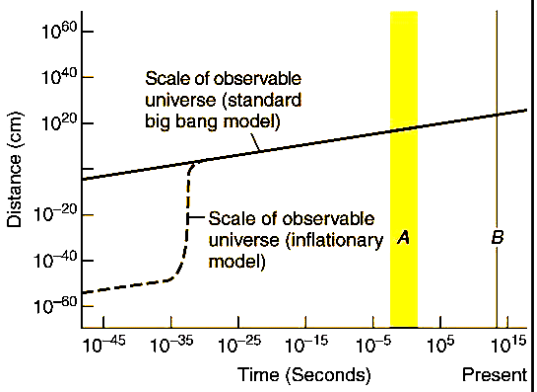
(probably)

(maybe)

Extremely rapid expansion of universe

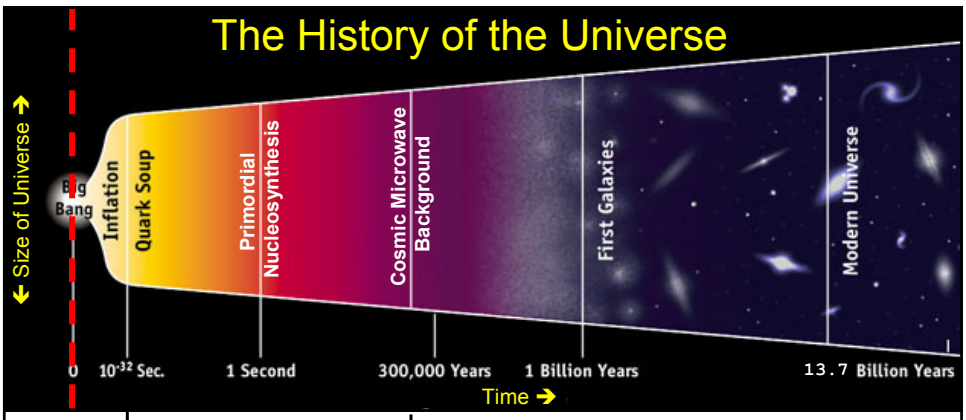
- due to release of energy in "phase change" .
- like ice to water.

Universe became 10^{43} times larger within 10^{-32} seconds.



[See Section 17.3]

10,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000



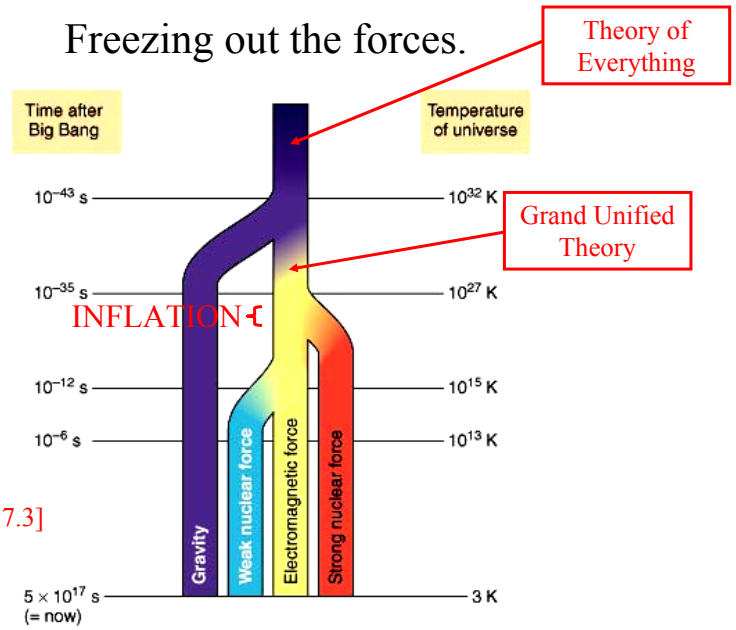
Planck time | Formation of H, He, Li | Galaxy Formation | Now

Inflation | Decoupling of CMB

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

High density → Low density

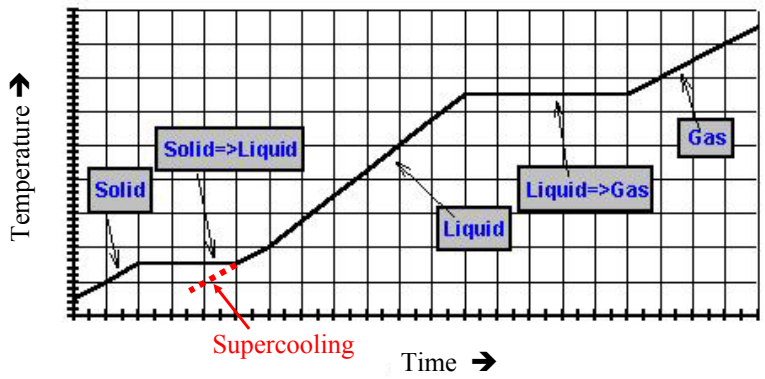
Freezing out the forces.



[See Fig 17.4/17.3]

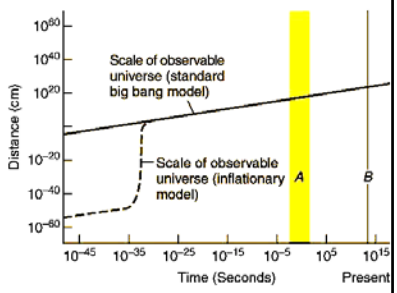
Phase changes and latent heat

- Apply heat energy at a steady rate to a fixed quantity of H_2O
- How does the temperature change?

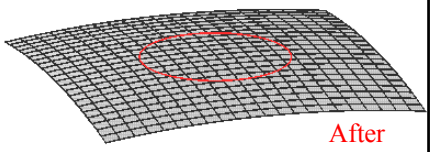


What does inflation predict for geometry of present universe?

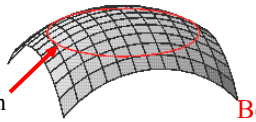
Universe became 10^{43} times larger within 10^{-32} seconds.



- Predicts a flat universe
- Solves horizon problem.

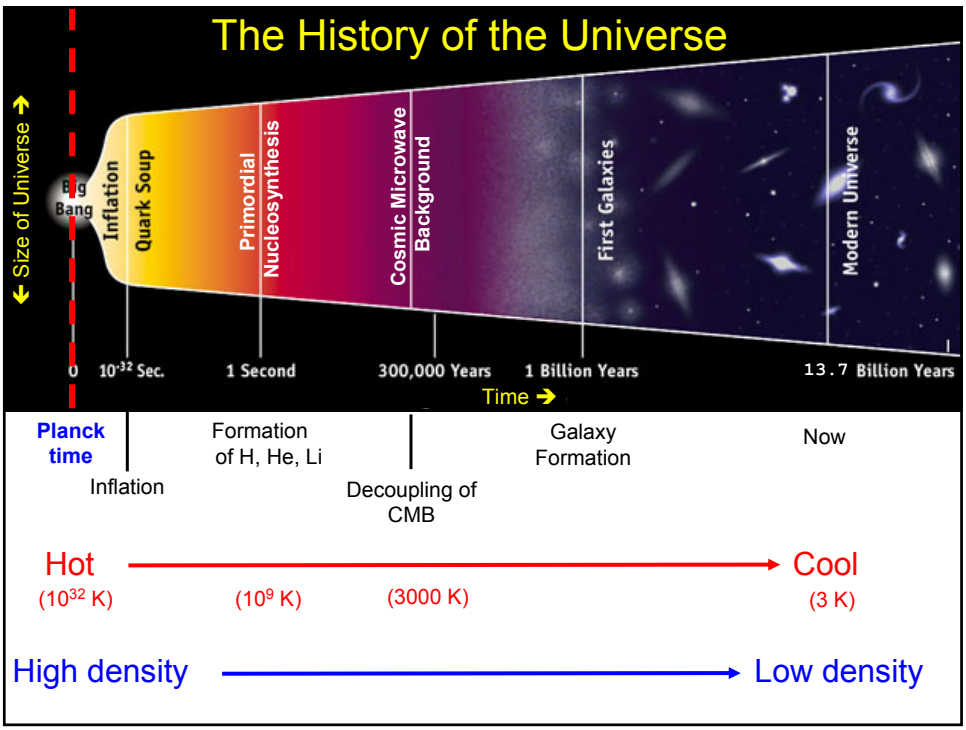


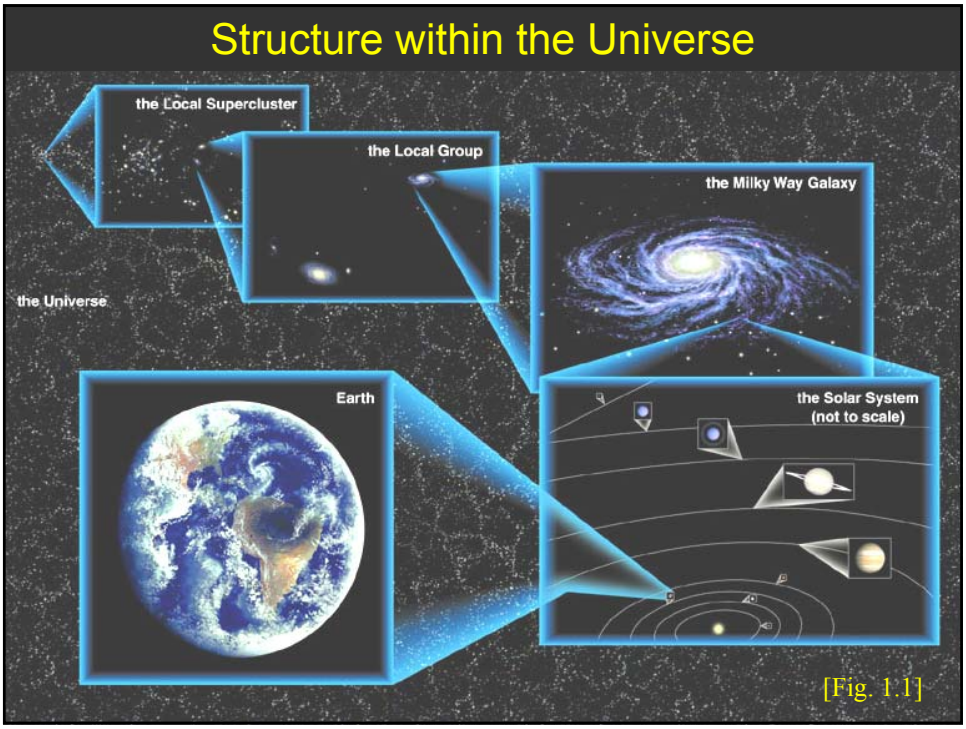
After Inflation



Red circle = horizon

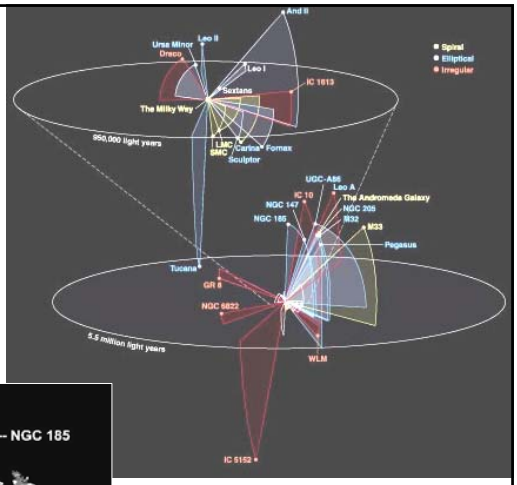
Before Inflation

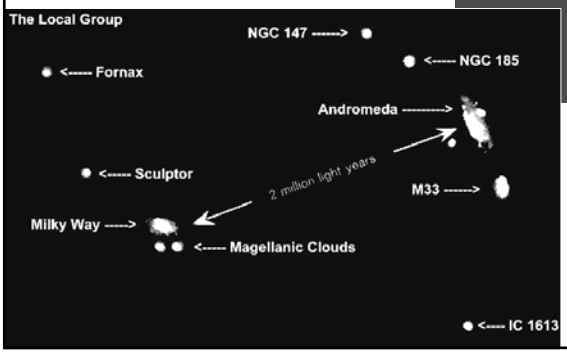




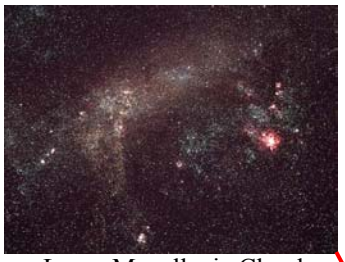
The Local Group

- Our Galaxy and its satellites.
- Andromeda galaxy (M31) and its satellites.





Satellite Galaxies



Large Magellanic Cloud

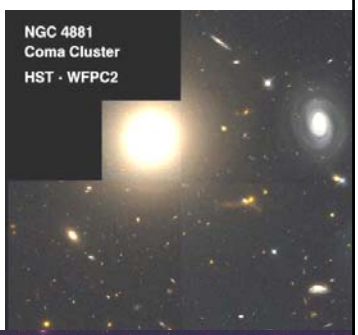
Small Magellanic Cloud

Milky Way

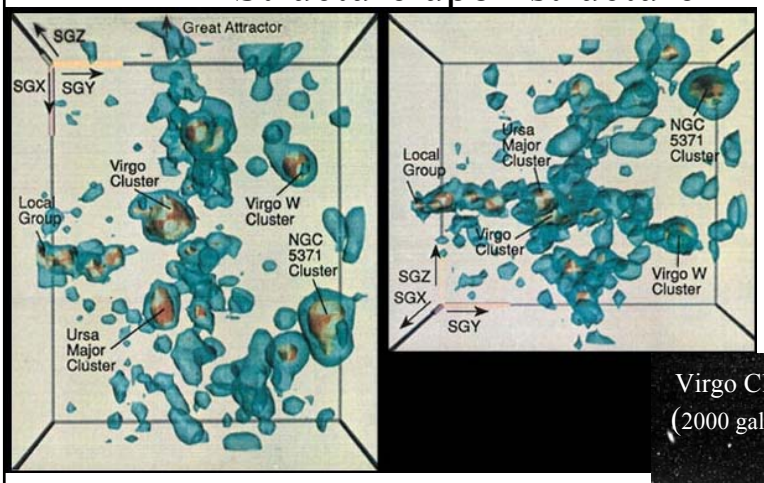
M31, M32,
NGC 205

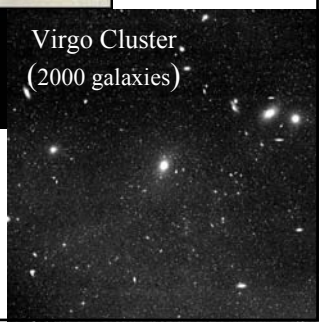
Galaxy Clusters

1000's of galaxies



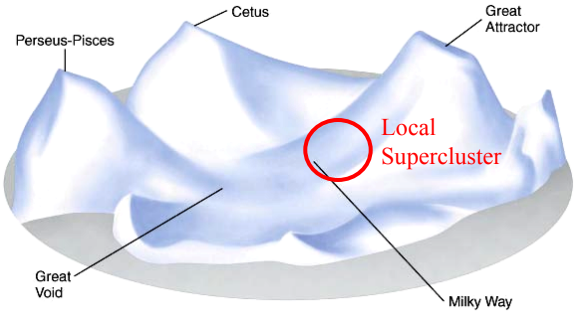
Structure upon structure





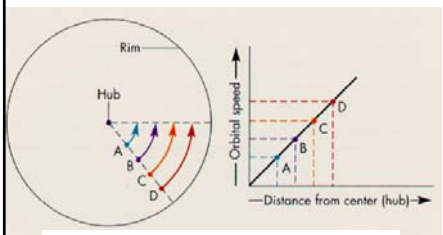
- Local Group is in orbit about Virgo Cluster (10^{14} $M_\odot$).
- All part of Local Supercluster (10^{15} $M_\odot$)

Structure upon structure

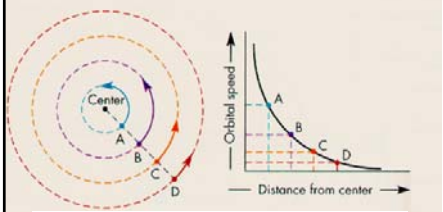


- Local Group is in orbit about Virgo Cluster (10^{14} $M_\odot$).
- All part of Local Supercluster (10^{15} $M_\odot$)
- Local Supercluster is part of streaming motion towards "Great Attractor"
  - $10^{16\text{-}17}$ $M_\odot$
  - located 100 million LY away.
- Detected by extra motions superimposed on "Hubble Flow".

The masses of galaxies



Inside the Central Mass

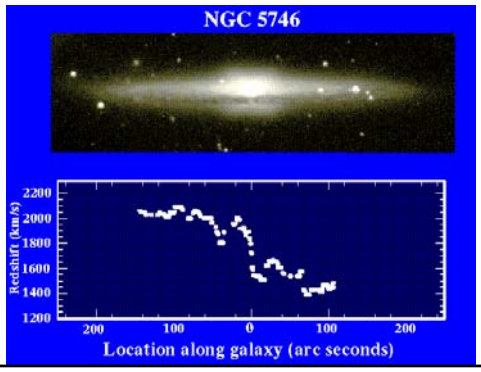


Outside the Central Mass

See [Fig. 16.1]

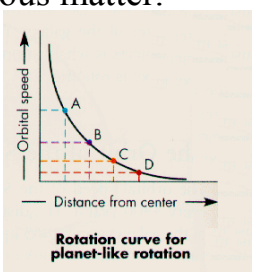
For orbits outside central mass:

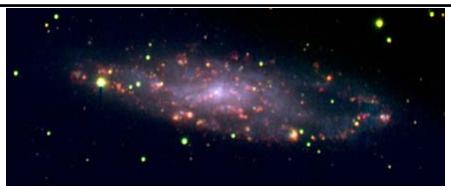
- $P^2 (M_1 + m_{star}) = a^3$
- Velocity = $(2\pi a)/P \propto \sqrt{1/a}$
- Measure Doppler shift of absorption lines & emission lines at different points in galaxy.

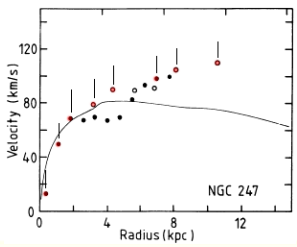


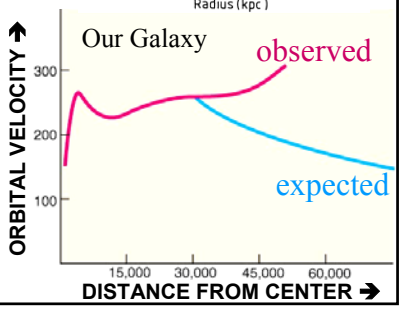
Dark matter

- We expected falling "Keplerian" curve out beyond outermost luminous matter.



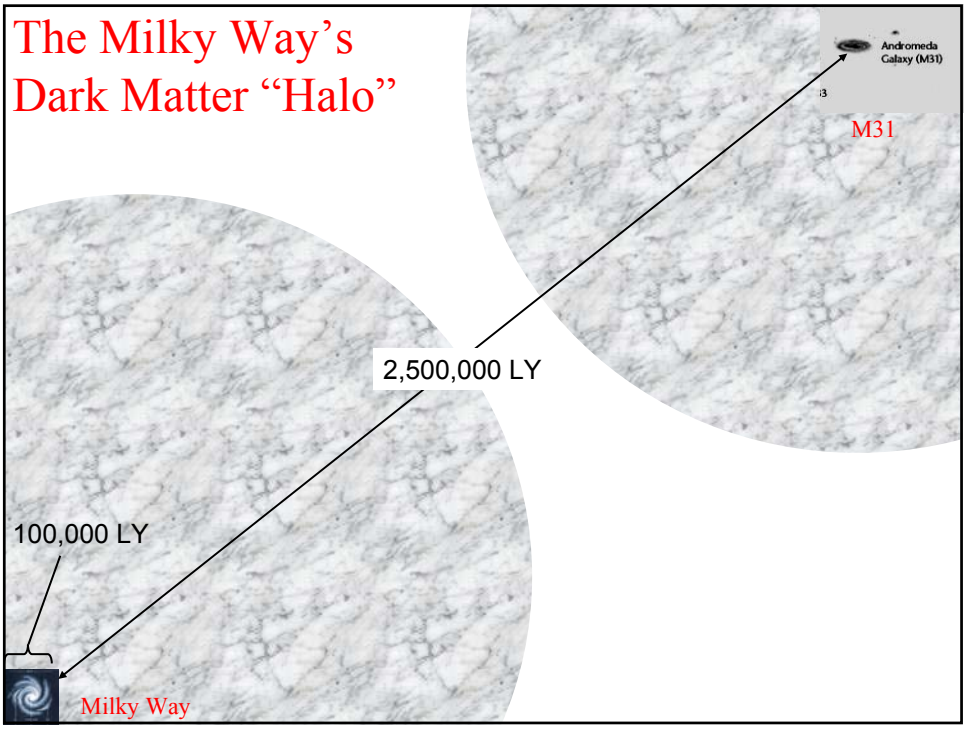






- But curves do not drop off
  - ➔ large amounts of additional "dark matter" in outer parts of spiral galaxies.

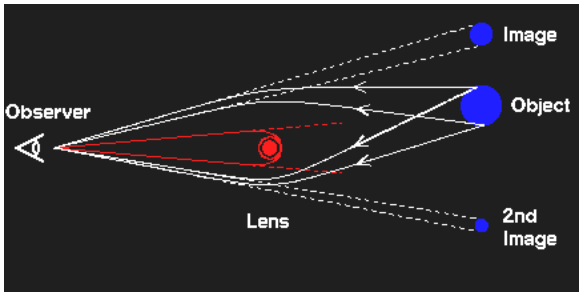
The Milky Way's Dark Matter "Halo"

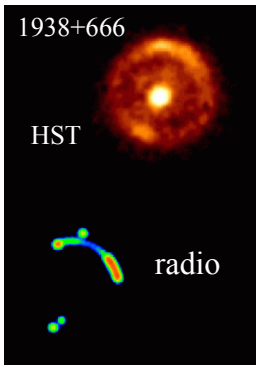


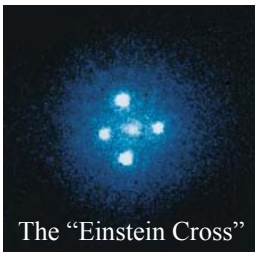
Gravitational Lenses

Another way to measure *total* mass in clusters

(see Fig [16.9])

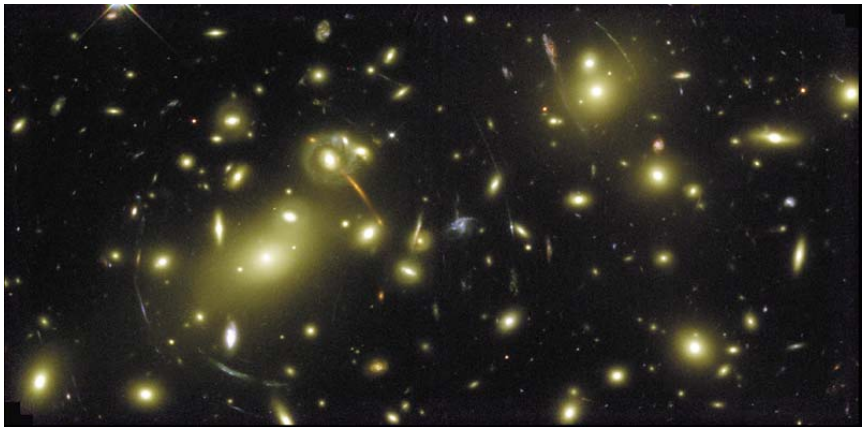






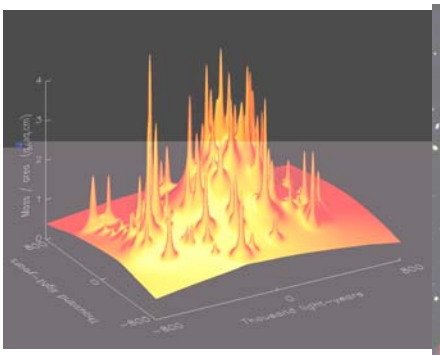
Galaxy at center causes 4 images of same quasar.

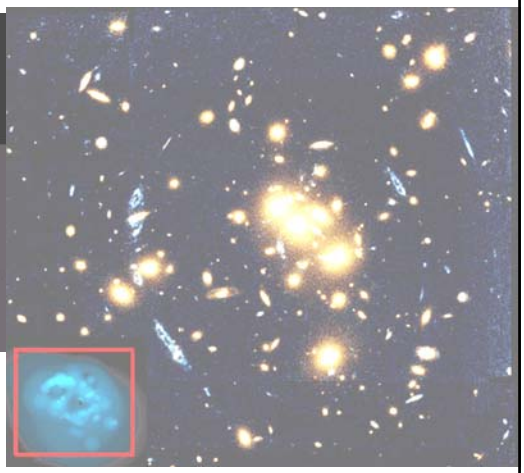
Gravitational Lens in Galaxy Cluster Abell 2218



- Foreground cluster distorts images of numerous background galaxies. [Fig. 16.10]
- Use to determine total mass of foreground cluster.
- Shows that 85% of mass is Dark Matter.

The Remarkable Case of CL0024+1654





- Single distant blue galaxy.
- Lensed by foreground cluster.
- 8 different images. [see Fig 16.8]
- Allows detailed analysis of mass distribution in cluster.
- 83% of mass is non-luminous Dark Matter.

What *is* Dark Matter?

- Weakly-Interacting Massive Particles (WIMPs)?
  - Current best bet.
  - Being searched for here on Earth.