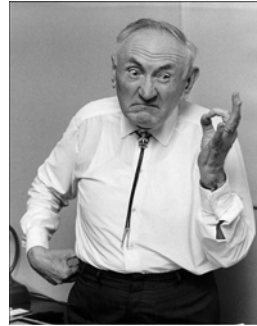


Dark Matter actually discovered in 1933

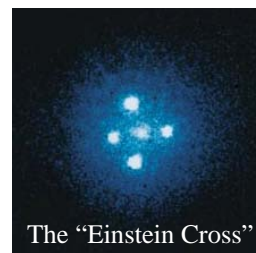
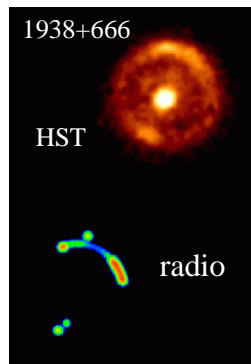
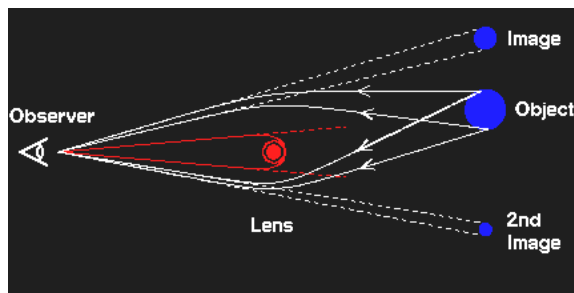


Fritz Zwicky

- Motions of galaxies within large clusters.
 $P^2 = a^3/(M_1+M_2)$
- Rapid motions → larger cluster mass than suggested by luminosity of galaxies.

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

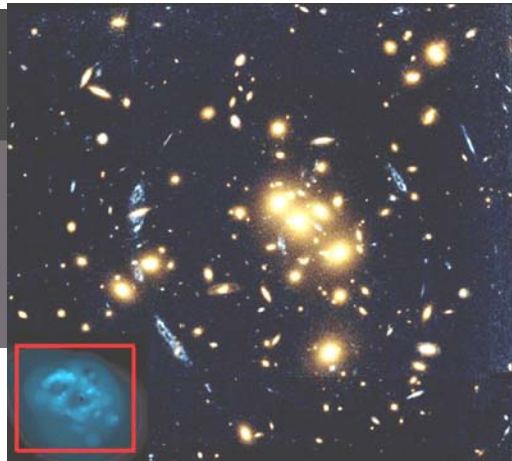
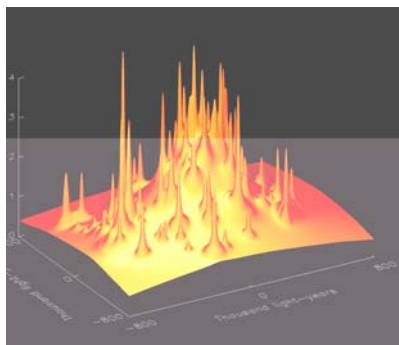


- Foreground cluster distorts images of numerous background galaxies.
- Use to determine total mass of foreground cluster.
- Shows that 85% of mass is Dark Matter.

[Fig. 16.10]

The Remarkable Case of CL0024+1654

Mass per unit area on sky →



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

[see Fig 16.8]

Existence of Dark Matter:

Collision between 2 galaxy clusters.
Normal matter (gas) loses energy in collisions.
Dark Matter particles do not.

Blue = Total Mass Distribution (deduced from gravitational lensing).

Red = Hot Gas Distribution (deduced from X-ray emission).

[movie1](#)
[movie2](#)

What is the Universe Made Of ?

15% Normal Matter

- protons, neutrons, electrons.
- arranged into *atoms*

85% Dark Matter

This is the only part we see.

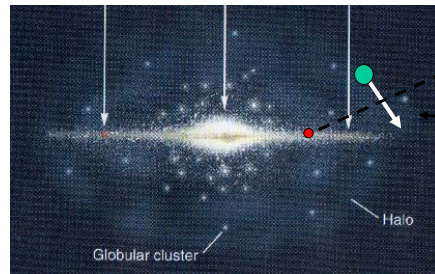
We infer it is there, but we don't know what it is.

What *is* Dark Matter?

- Normal matter that doesn't emit light?

Massive Compact Halo Objects (MACHOs)

- Ruled out by gravitational lensing test.



Orbiting MACHO crosses our line-of-sight. Gravitational lensing causes brightening.

What *is* Dark Matter?

- ~~• Normal matter that doesn't emit light?~~

~~Massive Compact Halo Objects (MACHOs)~~

- ~~• Ruled out by gravitational lensing test.~~

- Hot Dark Matter?

Light, fast-moving particles

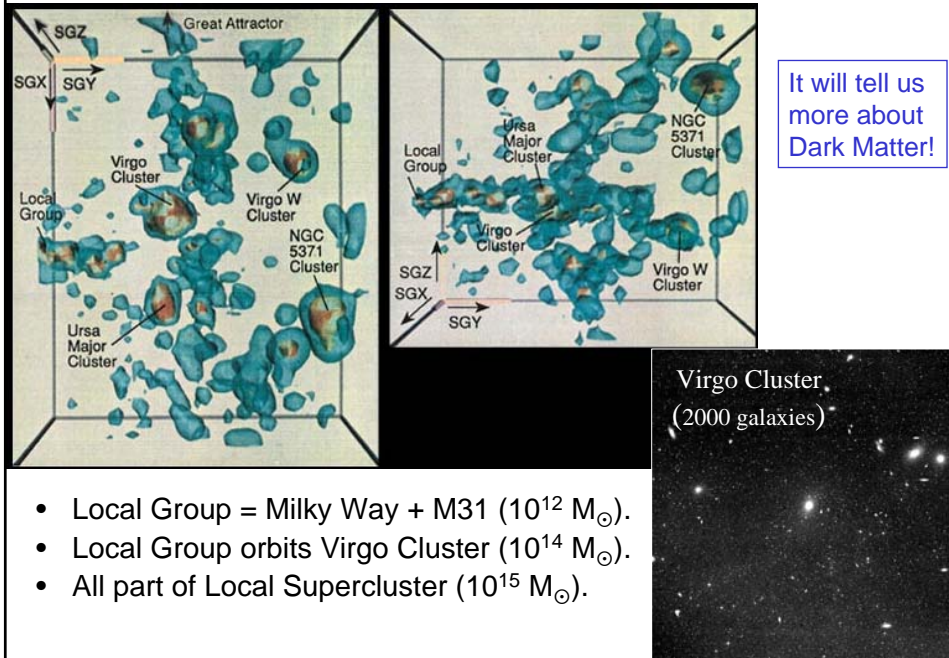
- Neutrinos recently discovered to have mass.
- But only 1% of total mass.

- Cold Dark Matter?

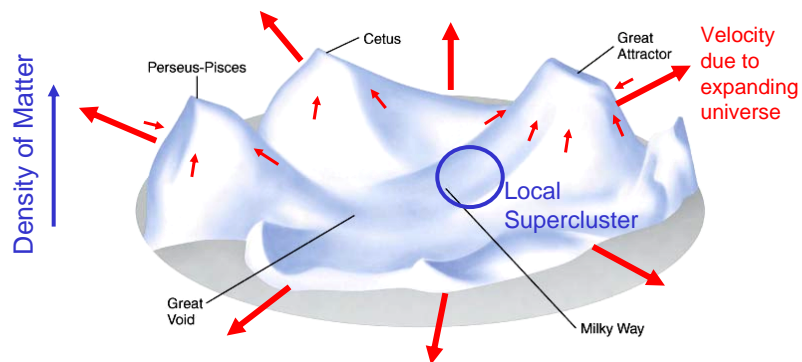
Weakly-Interacting Massive Particles (WIMPs)?

- Left over from earlier, hotter phase of Universe

“Structure” within the Universe



Structure upon structure



- Local Supercluster is part of streaming motion towards “Great Attractor”
 - $10^{16-17} M_{\odot}$
 - located 100 million LY away.
- Detected by extra motions superimposed on “Hubble Flow”.

Large-Scale Structures: A Slice of the Sky

[see Fig 16.13]

