Revised slide from last lecture.

The Expanding Universe

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

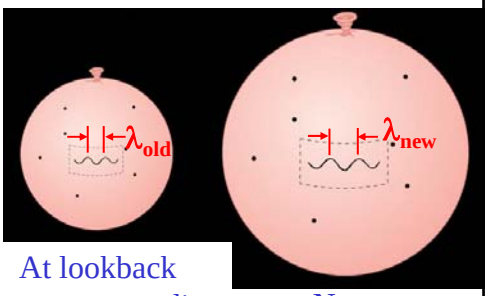
Doppler shift measures velocity v:

Redshift $z = \Delta\lambda/\lambda = v/c$

But in cosmology:

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

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



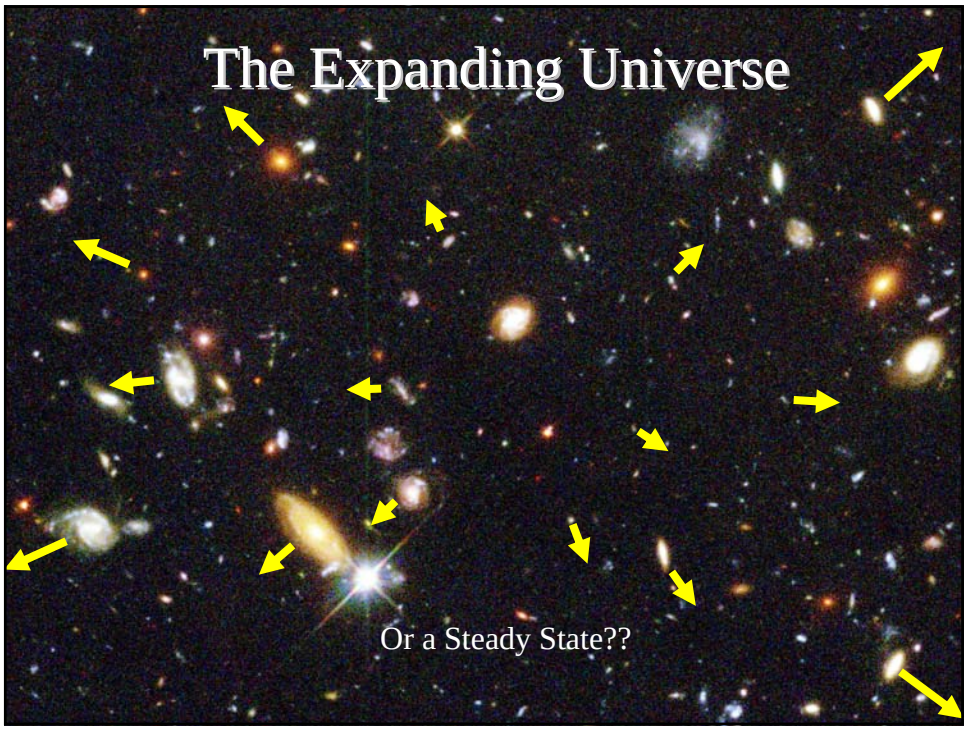
At lookback time corresponding to redshift z

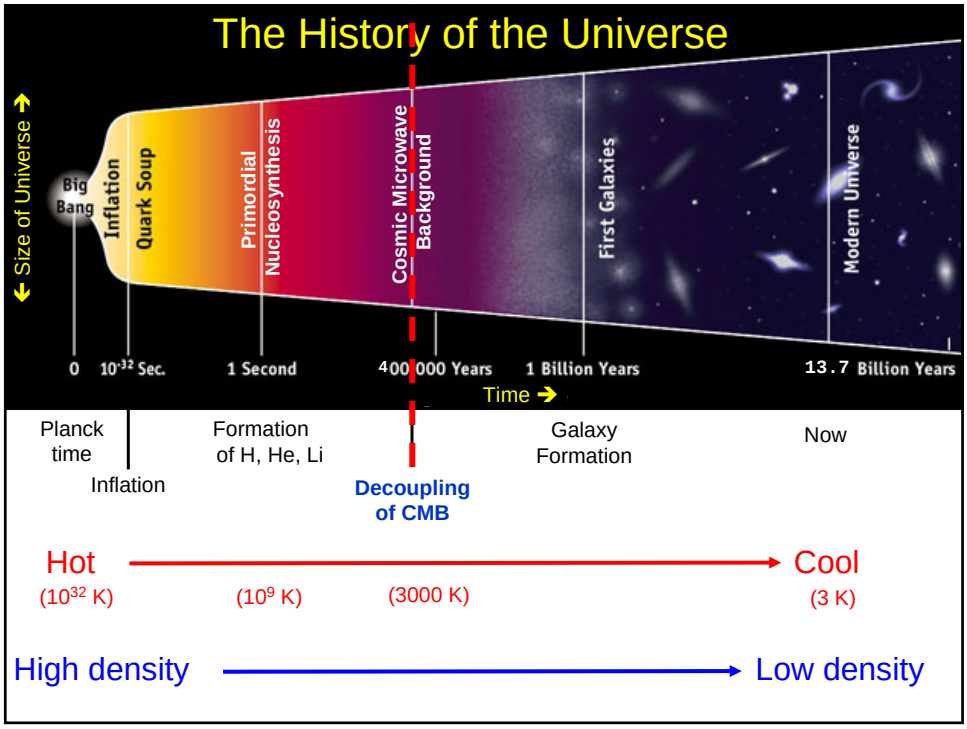
Now

doppler demo applet

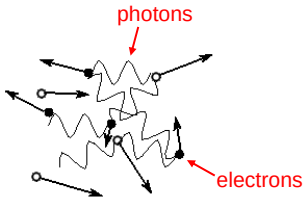
Redshift ➔ scale factor R(t) at time light was emitted.

Analogy having 1 less dimension





Cosmic Microwave Background



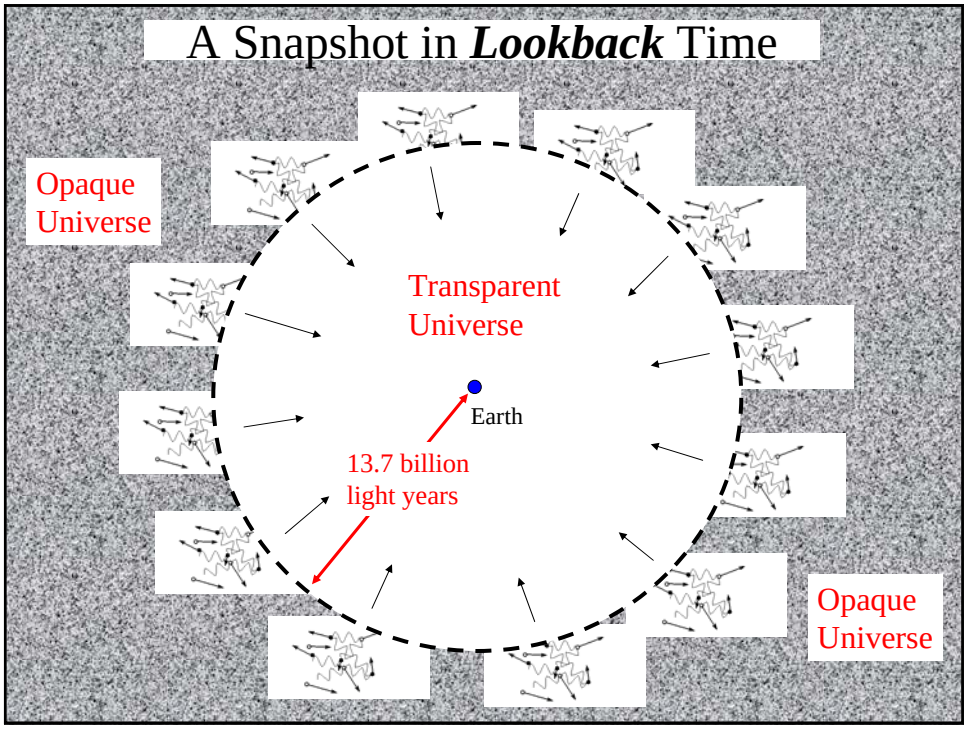
Hotter

- Hydrogen ionized.
  - Universe opaque.
    - Photons travel only short distances.
    - Absorbed, re-emitted by free electrons.

Decoupling { T = 3000°K; 13.7 billion yrs ago; Universe 380,000 yrs old.

- Hydrogen becomes neutral ($p + e^- \rightarrow H$).
  - Universe becomes transparent.
  - Photons decouple from matter, continue in whatever direction they were moving.

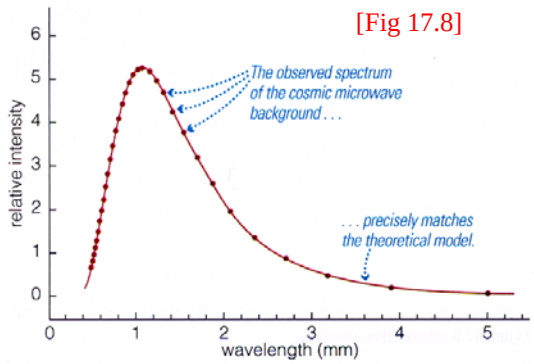
Cooler



Expansion of universe ➔ redshift

- Photons formed in thermal emitter with T ~ 3000^o K
- Redshifting ➔ lower energy per photon
  - $E_{photon} = h\nu = hc/\lambda$
  - So we see T = 3^o K thermal spectrum

[Fig 17.8]



Discovered in 1965

Penzias, Wilson, and their radio telescope.

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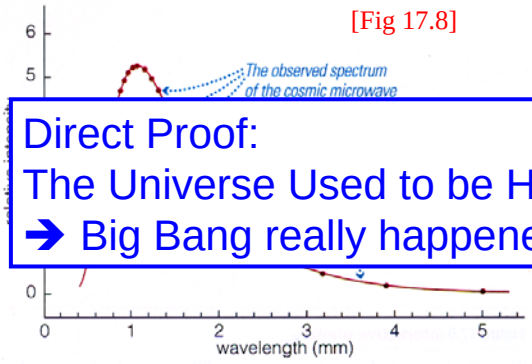
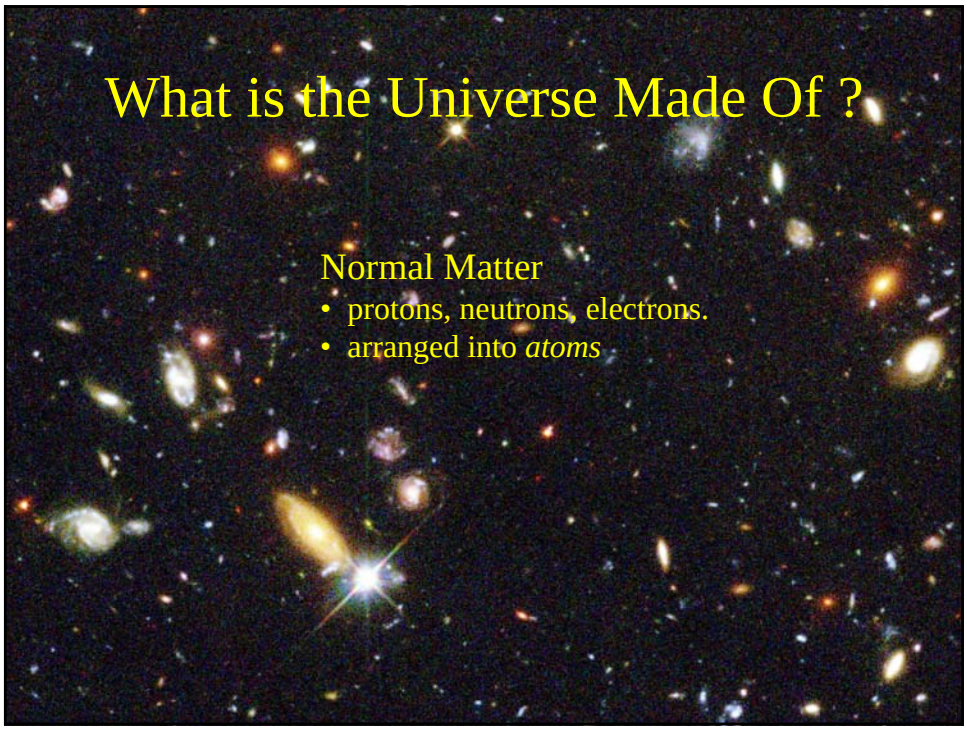
[Fig 17.8]



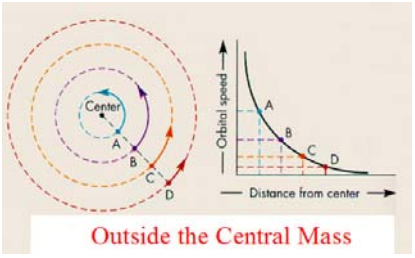
Direct Proof:
The Universe Used to be Hotter.
➔ Big Bang really happened!

Discovered in 1965

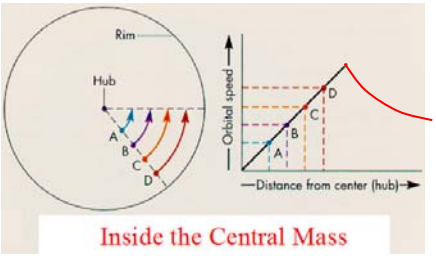
Penzias, Wilson, and their radio telescope.



The masses of galaxies

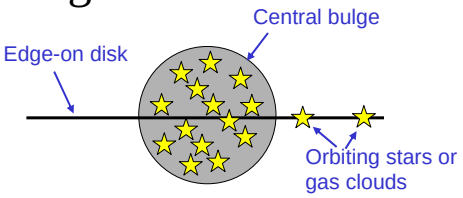


Outside the Central Mass

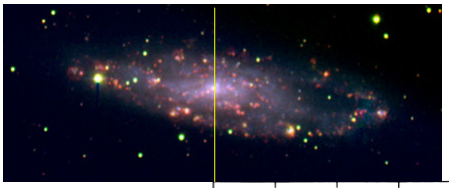


Inside the Central Mass

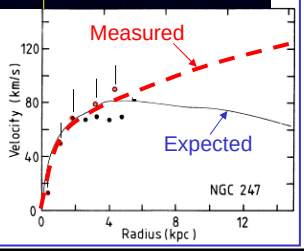
See [Fig. 16.1]



A slightly idealized spiral galaxy

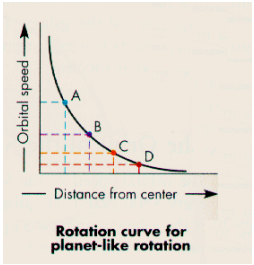


What was actually seen

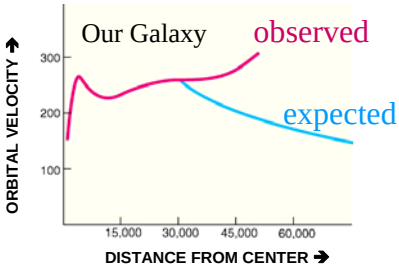


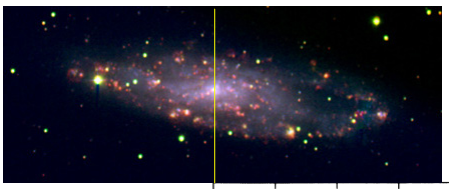
DARK MATTER

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



- Faster orbital motions found in outer parts of galaxies
  - ➔ large amounts of additional "dark matter" in outer parts of spiral galaxies.





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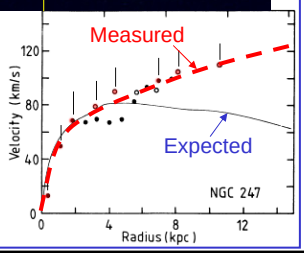
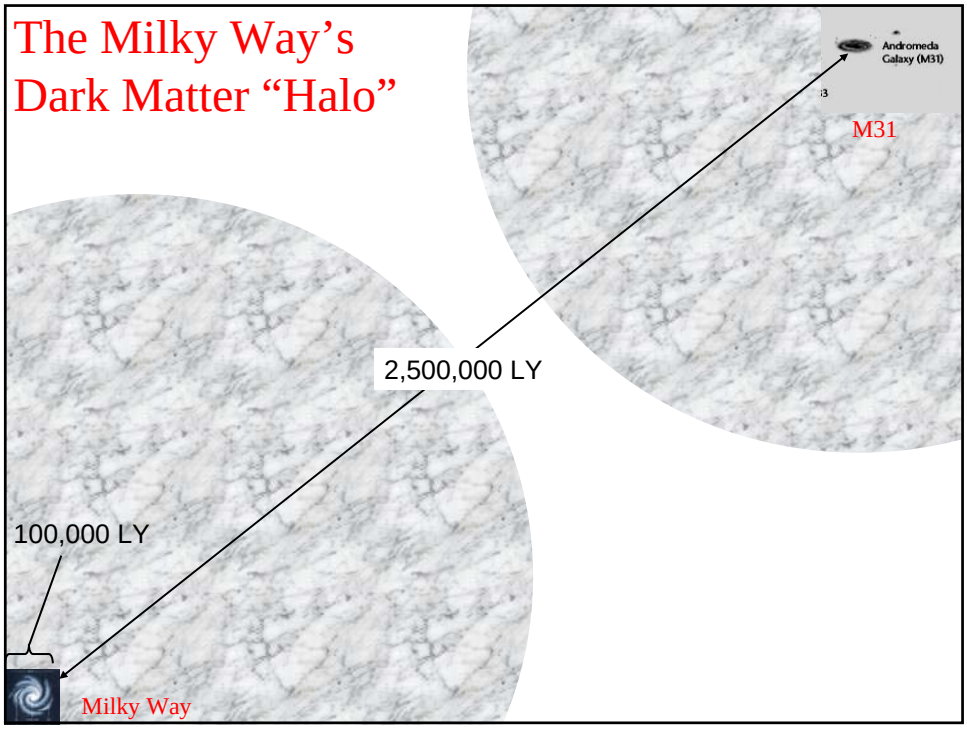
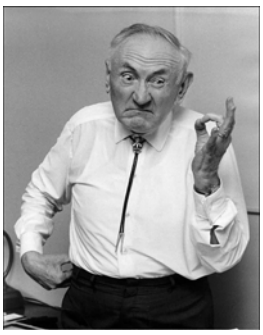


The Milky Way's Dark Matter "Halo"



"Missing 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.