What is Dark Matter?
History of what the universe is made of, through 2003

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Early astronomy methods

- Measuring distances to galaxies
  - "Standard candle" Type Ia Supernova used to measure distance to galaxies (1-100 Mps)
- Measuring velocities of galaxies
  - Speed is proportional to amount of Doppler shift in emission and absorption lines

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

Early astronomy methods

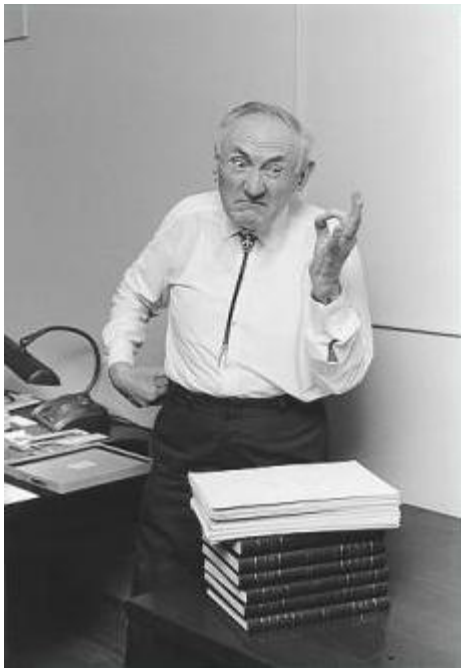
- Estimating masses of galaxies
  - From mass to luminosity ratio (M/L)
    - Based on the sun (Sun's M/L = 1)
    - Our galaxy has M/L is 6
  - From rotational velocity of gas clouds and stars
    - Kepler's laws of motion say that faster stellar motions are caused by larger mass concentration

$$M = \frac{r \cdot v^2}{G}$$

First mention of “dark matter”

- In 1933 Fritz Zwicky analyzed velocities of galaxies in Coma cluster
- Calculated mass was 50 times larger than mass estimated from luminosity.

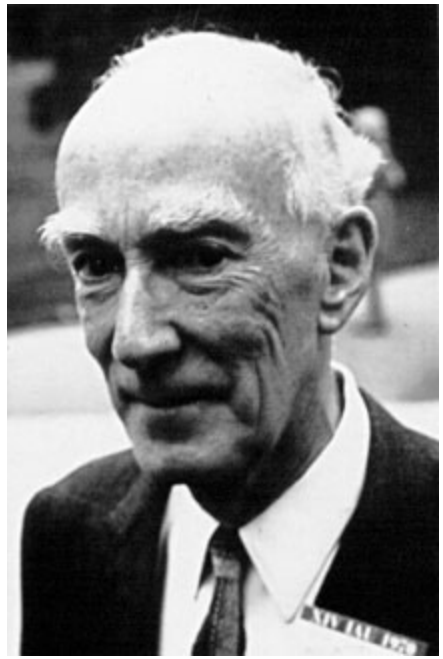
“If this is confirmed we would arrive at the astonishing conclusion that **dark matter** is present with much greater density than luminous matter.” – Zwicky, 1933



More missing mass…

- In 1936 Sinclair Smith concluded Virgo galaxy has 10 times the mass estimated from luminosity.
- In 1940 Jan Oort concluded NGC 3115 has 25 times mass estimated from luminosity.

"[T]he distribution of mass in this system appears to bear almost no relation to that of light." – Oort 1940



Better astronomy methods

- In 1950's astronomers started using radio telescopes
- In 1960's astronomers started using X-ray telescopes
- Astronomers began investigating dynamics of galaxies
- Evidence accumulated for idea of missing mass

Evidence of “missing matter”

- In 1960’s astronomers began to see puzzling rotational curves

Rotational curves

- "We saw that the rotation curve flattened out toward the edge…we didn't make a big deal about it, since this was only one galaxy…" – Vera Rubin, 1970

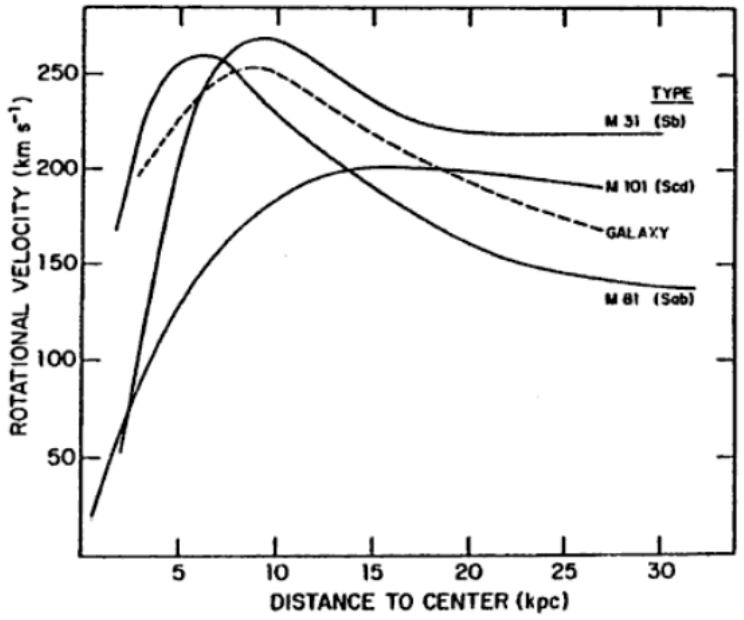
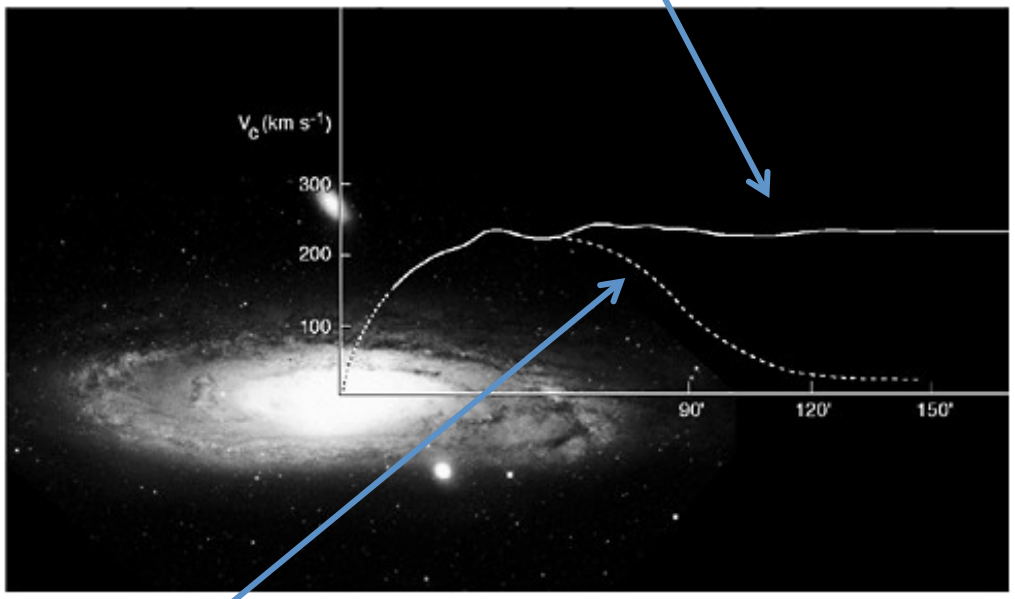


FIGURE 1. Rotation curves for the galaxies M31, M101, M81 and the rotation curve of our Galaxy, from Roberts and Rots (1973).



Evidence of “missing matter”

- In 1960’s astronomers began to see puzzling rotational curves
- Late 1960’s Robert Dicke introduced idea of flat universe

Omega

$$\Omega = \frac{\text{actual density of universe}}{\text{density required to slow expansion of universe indefinitely}}$$

Robert Dicke proposed $\Omega \approx 1$.

If $\Omega << 1$ then matter would spread too thin to form galaxies.

If $\Omega >> 1$ then the universe would collapse immedietly.

Estimates say that $\Omega \approx 0.01 - 0.1$. 90 - 99% of the mass is missing.

Evidence of “missing matter”

- In 1960’s astronomers began to see puzzling rotational curves
- Late 1960’s Robert Drake introduced idea of flat universe
- In 1970’s astronomers began to see evidence of gravitational lensing

Gravitational lensing

Gravitational lensing from Hubble Space Telescope photo (1990's)

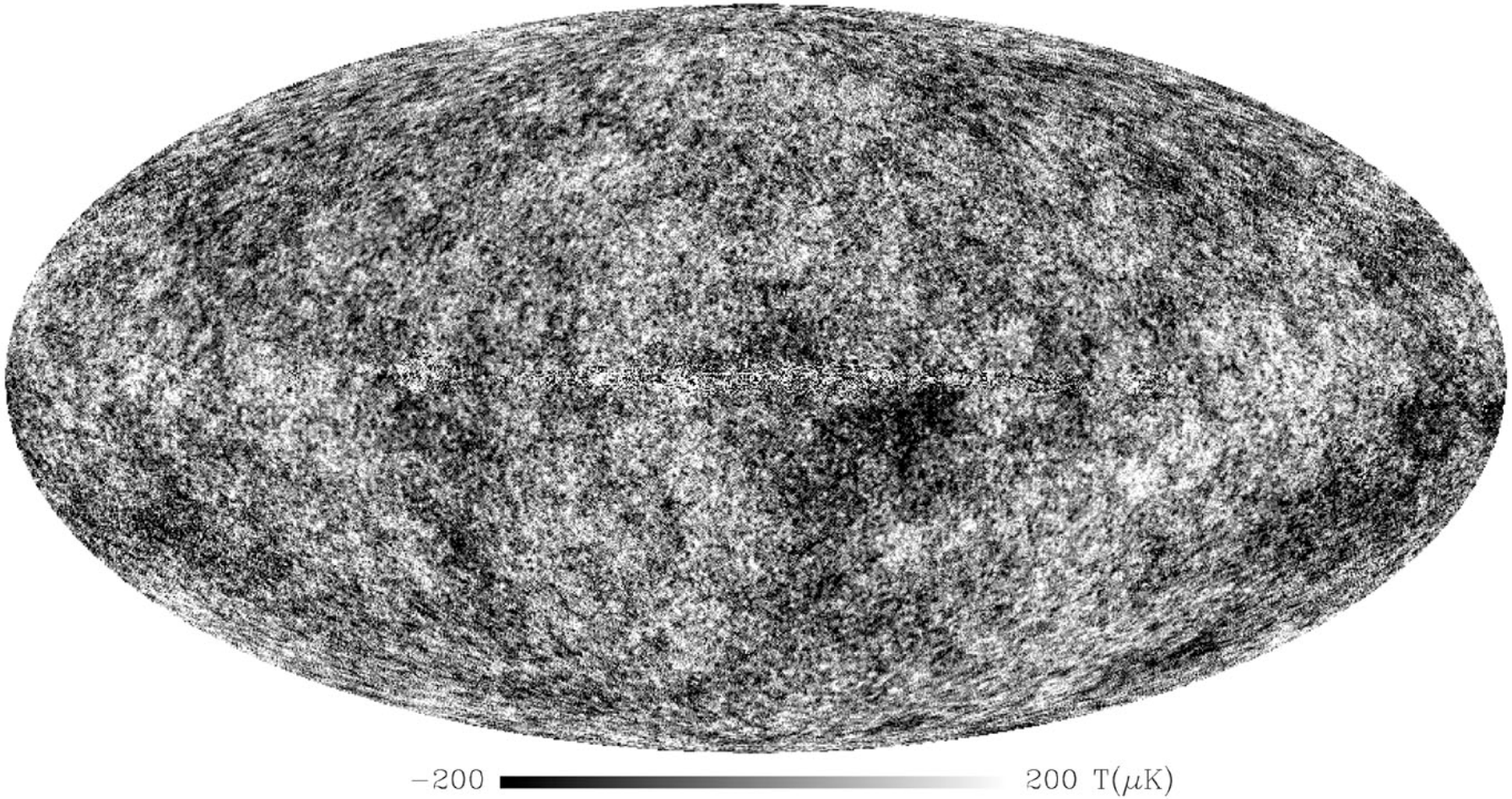
Derived map of the density of mass that is needed to produce lensing.

Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century (2003)

Evidence of “missing matter”

- In 1960’s astronomers began to see puzzling rotational curves
- Late 1960’s Robert Drake introduced idea of flat universe
- In 1970’s astronomers began to see evidence of gravitational lensing
- In 1993 the COBE satellite verified cosmic background theories
- All ideas need dark matter to explain extra mass

Cosmic microwave background



Full sky temperature map of the cosmic microwave background derived from the WMAP satellite (Bennett et al 2003, Tegmark et al 2003)

Search for Dark matter begins

- In 1975 astronomers were convinced that the missing mass is cosmologically significant
- Searched for explanations of “dark matter”

Explanations from standard model

- Black holes
  - √ Extremely high velocity dispersion especially high near nucleus indicates extremely dense mass
  - √ Black holes around edge of luminous matter could explain flat rotational curves
  - ? Under investigation

Explanations from standard model

- Very hot gas
  - √ Hotter gas requires more baryonic particles, more mass
  - x X-ray telescopes found hot gas in galaxies, but the mass is too insignificant to account for dark matter
- Brown dwarf
  - √ Too small and dim to be a star, too massive and hot to be a planet
  - √ Detectable by a few light years
  - x Big bang nucelosynthesis says that not enough baryons in universe

Search for Dark matter continues

- Neutrinos (nonbaryonic)
  - √ Discovered in 1950's and verified by CERN in 1990
  - √ Weakly interact with matter and radiation
  - x Neutrinos travel near speed of light during big bang (denoted "hot" dark matter)
- Start search for cold dark matter

Beyond the standard model

- In 1987 Milgrom & Bekenstein proposed modification for Newton's laws
  - √ Explains flat rotational curves
  - x Doesn't explain much else

Beyond the standard model

- Axion
  - √ theoretical particle proposed as a solution to problem in theory of quantum chromodynamics
  - √ Cold dark matter
  - √ Enough mass to account for missing
  - ? Not detected yet

Beyond the standard model

- Neutralino
  - √ particle proposed from supersymmetry theory
  - √ Cold dark matter
  - √ Enough mass to account for missing mass
  - ? Not detected yet

The future of Dark matter

- Experiments becoming more sensitive
- Soon we may have the technology to see why matter is missing from the universe