

# What is Dark Matter?

## History of what the universe is made of, through 2003

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October 8<sup>th</sup>, 2009

# 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.

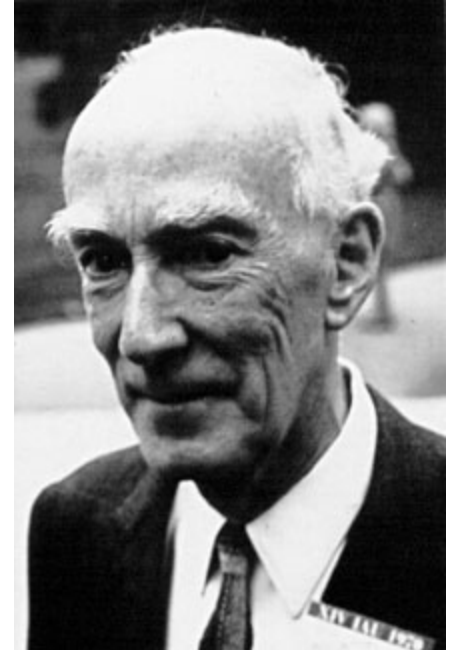
“If this is confirmed we would arrive at the astonishing conclusion that **dark matter** is present with much greater density than luminous matter.” – Zwicky, 1933



# 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

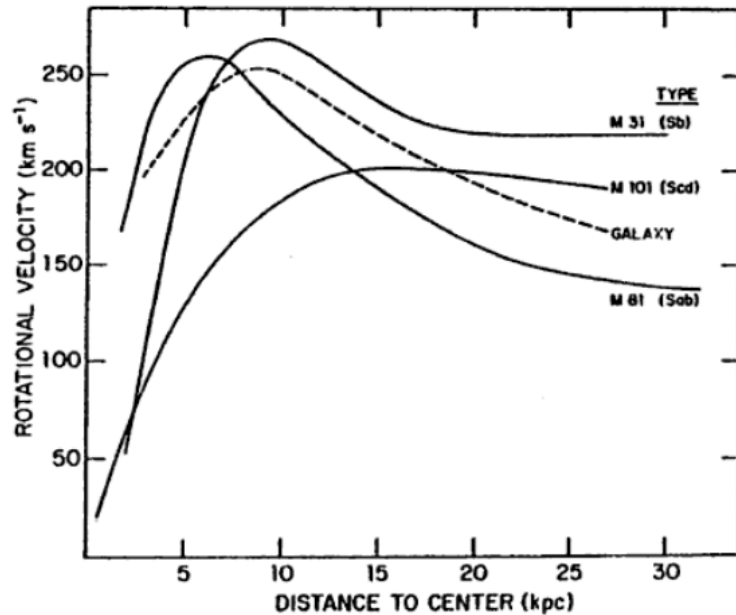
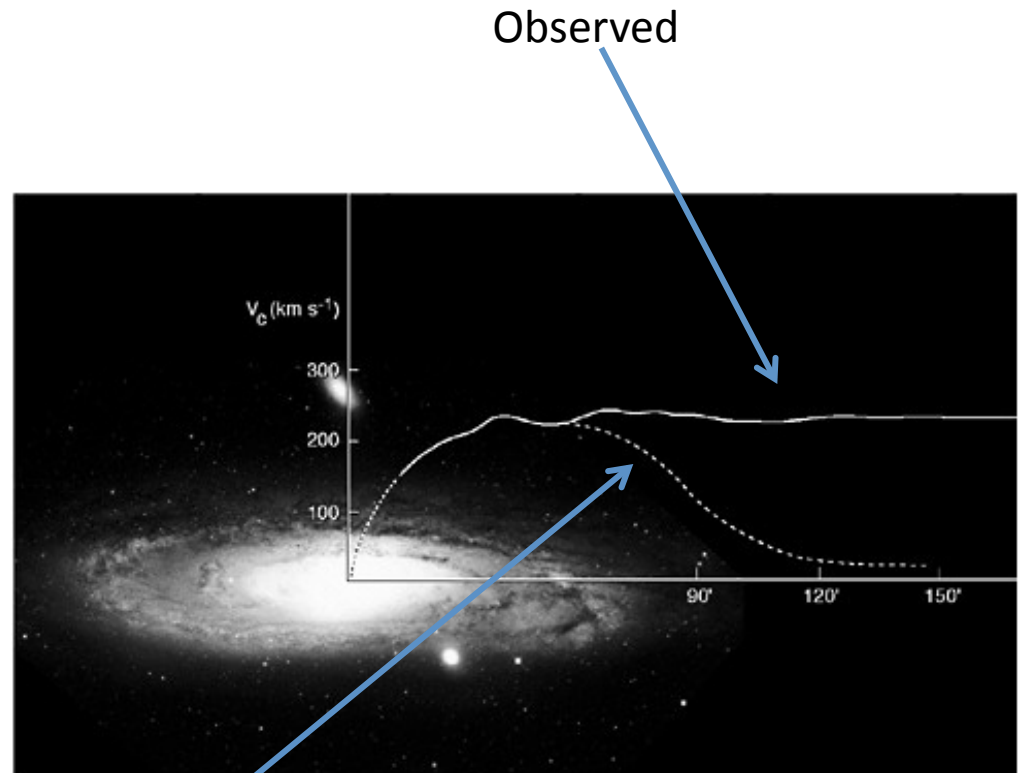


FIGURE 1. Rotation curves for the galaxies M31, M101, M81 and the rotation curve of our Galaxy, from Roberts and Rots (1973).



Theoretical



# 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  $\Omega \ll 1$  then matter would spread too thin to form galaxies.

If  $\Omega \gg 1$  then the universe would collapse immediately.

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

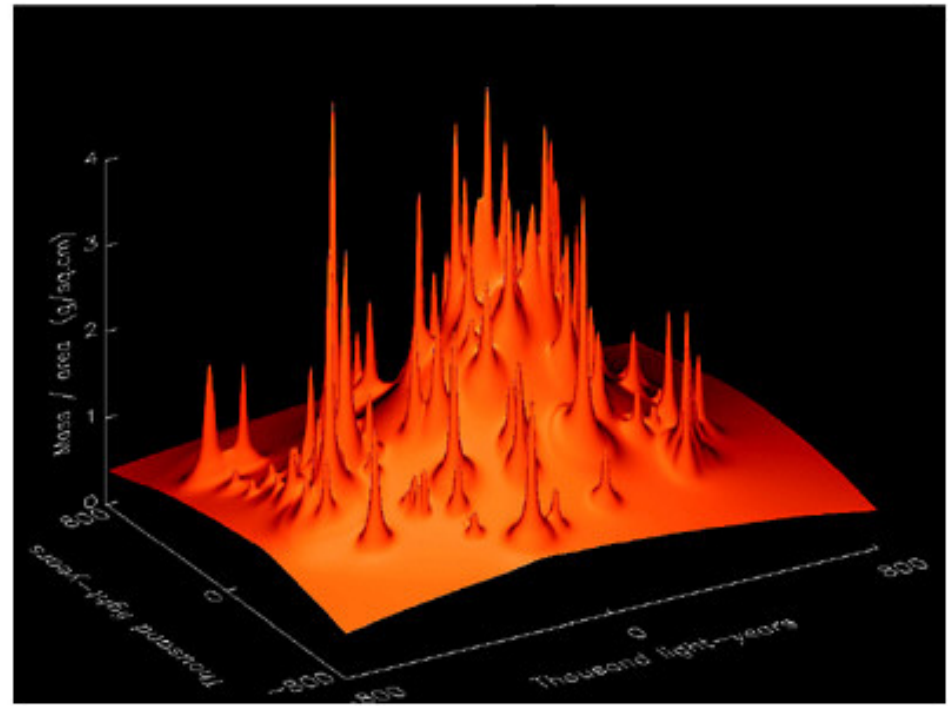
# Evidence of “missing matter”

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- In 1970's astronomers began to see evidence of gravitational lensing

# Gravitational lensing



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

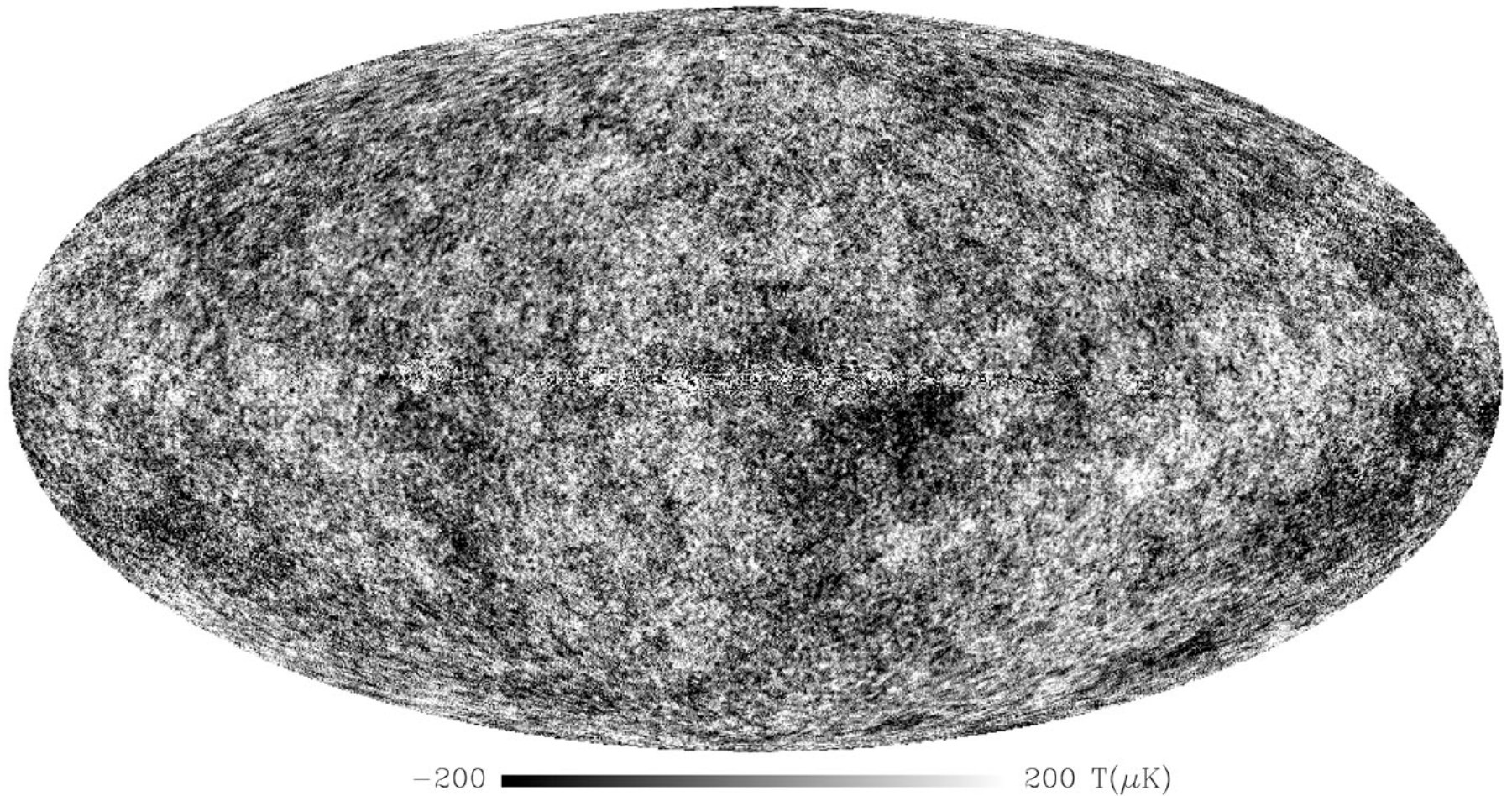


Derived map of the density of mass that is needed to produce lensing.

# Evidence of “missing matter”

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- 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 nucleosynthesis 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

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- 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