The story so far

[Hubble diagram (Hubble's Law)]

→ universal expansion
  → observe with large "lookback time"
  → past was different
  → denser

→ Big Bang cosmology
  → describe past
  → predict future

assume gravity is dominant force

\[ \frac{9}{\text{r/cent}} = \Omega \]

\( \Omega > 1 \) \rightarrow "Big Crunch"

\( \Omega < 1 \) \rightarrow continued expansion

Determine density of universe

Add up mass in sufficiently large chunk of universe

Divide by volume
determining mass

1) add up light
   assume a "mass-to-light" ratio

   \[ \Rightarrow \text{mass} \]

2) measure orbit

   determine mass from Kepler's laws
   \[ \frac{V^2}{a} = \frac{GM}{a} \Rightarrow \text{calculated} \]
   \[ V \]
   \[ \Rightarrow \text{measure} \]

Galaxy at distance of 20 Mpc

opposite magnitude of 14.

\[ m - M = 5 \log \left( \frac{D}{10 \text{pc}} \right) \]

\[ = 5 \log \left( \frac{2 \times 10^9}{10} \right) = 5 \log \left( 2 \times 10^8 \right) \]

\[ = 5 \left[ \log \left( 10^8 \right) + \log \left( 2 \right) \right] \]

\[ = 5 \times 6.3 = 31.5 \]
\[ \eta - M = 31.5 \]
\[ 14 - 31.5 = M = -17.5 \]

**How many Suns?**

\[ M_1 - M_2 = \frac{5}{2} \log \left( \frac{b_1/b_2}{\alpha} \right) \]

\[ 10^{-\frac{5}{2}} (M - M_0) = b_1/b_2 \]

\[ 10^{-\frac{5}{2}} (-17.5 - 5) = b_{90}/b_{sun} \]

\[ 10^{-\frac{5}{2}} (22^\circ) = 10^{-9} \times b_{90}/b_{sun} \]

**Mass:** \[ 10^{-9} \times 2 \times 10^{20} \text{ kg} \]

(if all Sun-like stars)

**probably more massive (typically stars Rank)**

Mass should be \(10^0 M_\odot\)
\[ V^2 = \frac{GM}{a} \]

\[ V = 200 \text{ m/s} \]
\[ 2 \times 10^5 \text{ m/s} \]

\[ a = \frac{20 \text{ m/s}}{2 \times 10^4 \text{ s}} \times 3 \times 10^{10} \text{ m} \]
\[ 6 \times 10^8 \text{ m} \]

\[ M = \frac{V^2a}{G} = \frac{(2 \times 10^5)^2 \times 6 \times 10^{30}}{7 \times 10^{11}} \]
\[ = 4 \times 10^{30} \text{ kg} = 4 \times 10^{30} \text{ kg} \]

\[ \text{Sun: } \frac{2 \times 10^{30}}{2 \times 10^{30}} = 2 \times 10^0 \text{ MO} \]

\[ \text{Mass: } \frac{4 \times 10^{14}}{2 \times 10^{30}} = 2 \times 10^{-16} \text{ MO} \]
Frontiers & Controversies in 1985

"Dynamical" masses (determined by orbits around galaxies and galaxary clusters) are much bigger than you expect from light by a factor 10

\[ \text{DARK MATTER} \quad \text{What is it?} \]

Hypothesis #1: Some kind of unknown subatomic particle

- have mass
- no interaction with light

Weakly Interacting Massive Particles (WIMPs)

No direct detections
Hypothesis #2:
Chunks of ordinary matter
that don't emit light
can't be too small
"dust" would be observed by
obscur[ing light]
& glow in IR

Can't be too big
very large masses could disrupt the orbits of
stars

Could have
star-massed dark things in
holes of galaxies

Massive Astrophysical Compact
Halo Object

MACHOS
gravitational lensing
MACHOs

\( \Delta \times \)

acts like a lens
makes it brighter
alignment holds for a few weeks

lensing events observed
too few to explain
Dark Matter

No WIMPs, No MACHOs

\( \rightarrow \) most people believe
a theoretical basis
$$M_{\text{gal}} = 2 \times 10^9 M_\odot = 4 \times 10^8 u_g$$

One galaxy every $2 \ M_{\text{pc}}$

What's the density of Universe

$$\rho = \frac{M}{V} = \frac{4 \times 10^9}{(2 M_{\text{pc}})^3}$$

$$= \frac{2 \times 10^6 \times 3 \times 10^6}{(6 \times 10^{22})^3}$$

$$= \frac{200 \times 10^{66}}{2 \times 10^{68}} = 2 \times 10^{-2} \ \text{kg/m}^3$$

$$\rho = \frac{4 \times 10^9}{2 \times 10^{68}} = 2 \times 10^{-27} \ \text{kg/m}^3$$

$$s = \frac{6 \times 10^{-27}}{2 \times 10^{-2}} = \frac{1}{3}$$