

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

$$\rho_{crit} = 3H^2/8\pi G$$

$$\rho/\rho_{crit} = \Omega$$

$$\Omega > 1$$

↳ "Big Crunch"

$$\Omega < 1$$

↳ 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

→ mass

2) measure orbits

determine mass

from Kepler's Laws

$$v^2 = \frac{GM}{a}$$

→ calculated

↑

measure

↑

measure

Galaxy at distance of 20 Mpc
apparent magnitude of 14.

$$m - M = 5 \log (D/10\text{pc})$$

$$= 5 \log \left(\frac{2 \times 10^7}{10} \right) = 5 \log (2 \times 10^6)$$

DO NOT
APPROXIMATE

$$= 5 [\log(10^6) + \log(2)]$$

" 6 " 0.3

$$= 5 \times 6.3 = 31.5$$

$$m - M = 31.5$$

$$14 - 31.5 = M = -17.5$$

how many stars?

$$M_1 - M_2 = \frac{5}{2} \log(b_1/b_2)$$

$$10^{-\frac{2}{5}(M_1 - M_2)} = b_1/b_2$$

$$10^{-\frac{2}{5}(-17.5 - 5)} = b_{90\%}/b_{\text{sun}}$$

1 90%
2 Sun

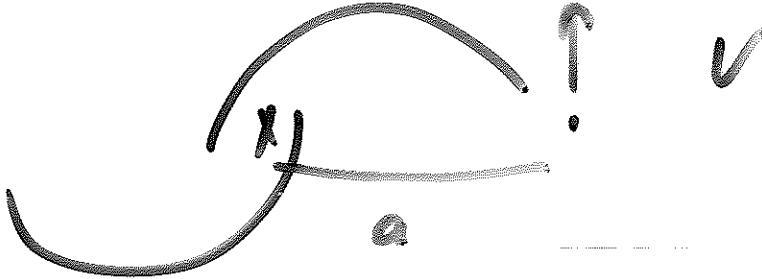
$$10^{\frac{2}{5}(22\frac{1}{2})} = 10^9 = b_{90\%}/b_{\text{sun}}$$

$$\text{mass} = 10^9 \times 2 \times 10^{30} \text{ kg}$$

(if all Sun-like stars)

probably more massive
(typically stars fainter)

mass should be $10^{10} M_{\odot}$



$$v^2 = \frac{GM}{a}$$

v

$$v = 200 \text{ km/s} \\ 2 \times 10^5 \text{ m/s}$$

$$a = 20 \text{ kpc} \\ 2 \times 10^4 \times 3 \times 10^{16} \text{ m} \\ 6 \times 10^{20} \text{ m}$$

$$M = \frac{v^2 a}{G} = \frac{(2 \times 10^5)^2 \cdot 6 \times 10^{20}}{7 \times 10^{-11}} \\ = \frac{4 \times 10^{30}}{10^{-11}} = 4 \times 10^{41} \text{ kg}$$

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$$M_{\text{sun}} = 2 \times 10^{30}$$

$$M_{\text{AES}} = \frac{4 \times 10^{41}}{2 \times 10^{30}} = 2 \times 10^{11} M_{\odot}$$

Frontiers & controversies in 1985

"dynamical" masses (determined by ~~the~~ orbits around galaxies and galaxy clusters) are much bigger than you expect from light by a factor 10

→ DARK MATTER
What is it?

hypothesis #1: some kind of unknown subatomic particle

- > have mass
- > no interaction with light

Weakly Interactive Massive Particle

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
obscuring light
& glow in IR

can't be too big

very large masses & would
disrupt the orbits of
stars

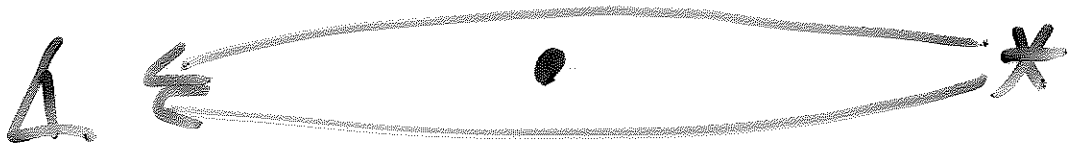
COULD HAVE

star-massed dark things in
halos of galaxies

Massive Astrophysical Compact
Halo Objects

MACHOs

gravitational lensing MACHO searches



↑
acts like a lens
makes it ^{star} brighter

alignment holds for a
few weeks

lensing events observed

TOO FEW to explain
Dark Matter

No WIMPs No MACHOs

↳ most people believe
a theoretical basis

$$M_{gal} = 2 \times 10^{11} M_{\odot} = 4 \times 10^{41} \text{ kg}$$

one galaxy every 2 Mpc

what's the dens density of Universe

$$\rho = \frac{M}{V} = \frac{4 \times 10^{41}}{(2 \text{ Mpc})^3}$$

$$2 \times 10^6 \times 3 \times 10^{16}$$

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

$$200 \times 10^{66} = 2 \times 10^{68}$$

$$\rho = \frac{4 \times 10^{41}}{2 \times 10^{68}} = 2 \times 10^{-27} \text{ kg/m}^3$$

$$\rho_{crit}$$

$$6 \times 10^{-27}$$

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$$\Omega = \rho / \rho_{crit} \sim 1/3$$