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

$\boxed{\text{assume}}$ 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.

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

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

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

$$\log(10^6) = 6 \qquad \log(2) = 0.3$$

$$= 5 \times 6.3 = 31.5$$

DO NOT APPROXIMATE MAGS

$m - M = 31.5$

$14 - 31.5 = M = -17.5$

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how many Suns?

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

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

1 galaxy
2 Sun

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

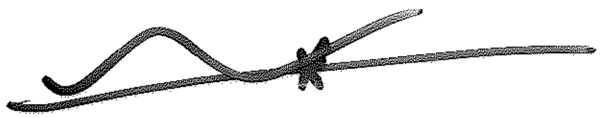
$$10^{+\frac{2}{5}(22\frac{1}{2})} = 10^{9} = b_{gal}/b_{sun}$$

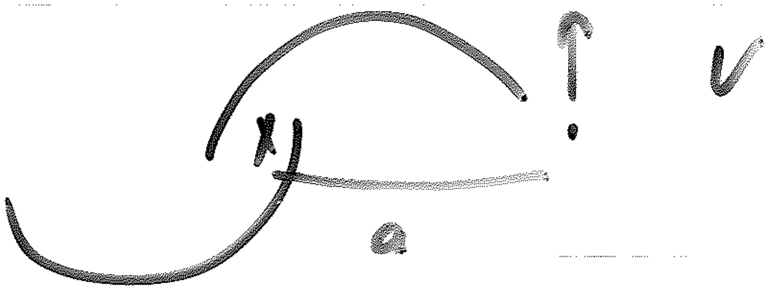
$$\text{Mass} = 10^{9} \times 2 \times 10^{30}\ \text{kg}$$

(if all Sun-like stars)

probably more massive
(typically stars fainter)

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





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

v

$v = 200$ km/s

2×10^5 m/s

$a = 20$ kpc

$2\times10^4 \times 3\times10^{16}$ m

6×10^{20} m

$$M = \frac{v^2 a}{G} = \frac{(2\times10^5)^2\,\cancel{6}\times10^{20}}{\cancel{7}\times10^{-11}}$$

$$= \frac{4\times10^{30}}{10^{-11}} = 4\times10^{41}\ \text{kg}$$

1 sun = 2×10^{30}

MASS = $\frac{4\times10^{41}}{2\times10^{30}} = 2\times10^{11}\ M_\odot$

Frontiers & controversies in 1985

"dynamical" masses (determined by orbits around galaxies and galaxy clusters) are <u>much</u> bigger than you expect from light

by ~ factor 10

→ DARK MATTER
what is it?

hypothesis #1: some kind of unknown subatomic particle

> have mass
> no interaction with light

Weakly Interactive 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
obscuring light
& glow in IR

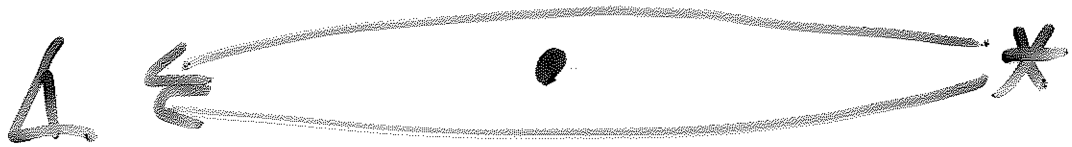
can't be too big
very large masses would
disrupt the orbits of
stars

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~~ the 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

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

one galaxy every 2 Mpc

what's the ~~dens~~ density of Universe

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

$$\frac{2 \times 10^6 \times 3 \times 10^{16}}{(6 \times 10^{22})^3}$$

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

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

ρ_{crit} $\quad 6 \times 10^{-27}$

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