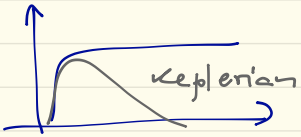
Dark matter

$$\rho(r) = \frac{\rho_0}{(r/a)(1 + r/a)^2}$$

- x Evidence for dark matter
- x Hot & Cold dark matter
- ↑ WIMPS & Machos
  - Too few machos in the halo.

WD's no more than 10% of halo mass.

x Galaxy rotation curve



x Self-gravity of the gas disk

Exponential decay.

Flat rotation curve:

$$\Omega = \frac{V}{R} \qquad \frac{mV^2}{2} = \frac{GM_r m}{r^2}$$

Solve for M_r : $M_r = \frac{V^2 r}{G}$ $\therefore$ $\frac{dM_r}{dr} = \frac{V^2}{G}$

Mass conservation:

$$\frac{dM_r}{dr} = 4\pi r^2 \rho \quad \therefore \quad 4\pi r^2 \rho = \frac{V^2}{G} \quad \therefore \quad \boxed{\rho = \frac{V^2}{4\pi G} \cdot \frac{1}{r^2}}$$

The luminous disk falls as $\rho \propto \rho^{-2.5}$

To avoid divergences and account for rigid body rotation

$$\rho(r) = \frac{\rho_0}{1+(r/a)^2}$$; ρ_0 and a vary from galaxy to galaxy

if $r \gg a$; r^{-2}; if $r \ll a$; $\rho \sim$ const.

Also, must cope off somewhere since if $\rho \propto r^{-2}$, then $M \propto r$

Simulations of galaxy formation show

$$\rho(r) = \frac{\rho_0}{(r/a)(1+r/a)^2}$$

Behaves like $1/r^2$ over much of halo, but shallower $1/r$ near center and steeper $1/r^3$ near edge.

Still the mass is not bound. Dark matter halos may overlap.

Baryonic or non-baryonic dark matter?

Microlensing events in MW: only up to 15% of the dark matter halo can be explained by MACHOs (baryonic DM).

BBN: Why is the Universe 1/4 He? Temperature at time t in radiation era:

at $t \sim 10^{-4}$s, $T \sim 10^{12}$ K: mix of photons, electron-positron pairs, neutrinos, some protons and neutrons. (1 per 10^{10} photons)

$$n \rightleftharpoons p + e^- + \bar{\nu}_e$$
$$n + e^+ \rightleftharpoons p + \bar{\nu}_e$$
$$n + \nu_e \rightleftharpoons p + e^-$$

Mass difference $(m_p - m_n)c^2 \approx 1.3$ MeV, while at 10^{12} K, $KT \simeq 86$ MeV

At 10^{10} K, Temperature dropped below the 1.022 MeV threshold for positron–electron creations. They now annihilate without being replaced.

Ratio of protons to neutrons, which was close to 1:

$$\frac{n_n}{n_p} = e^{-(m_p - m_n)c^2/KT}$$ given by this as long as the reactions are in equilibrium.

(0.985 close to 10^{12} K), decreased, and became locked at the present value of ≈0.223

No more neutrons being produced, but β-decay continues turning neutrons into protons. Neutrons can be locked in deuterium, but not at 10^{10} K because at these temperatures the bond is easily dissociated. So from $T = 10^{10}$ to $T = 10^9$ K protons and neutrons were out of equilibrium and decoupled.

$R \propto T$

$R \propto t^{1/2} \therefore T \propto t^{1/2}$ (100 seconds)

Given the half-life of the neutron, the ratio went to 0.17 → 170 for 1000 protons. Or, 360 neutrons for 2000 protons.

Forms 180 $^4_2$He with 1640 $^1_1$H left over

The mass fraction is thus $\frac{4(180)}{1640-4(180)} \approx 0.3$

All neutrons locked into He^4, so abundance of He^4 independent of density.

However, amounts of D, He_3, Li_7 depend sensitively on the density of baryonic matter at that time.

Precludes lots of baryonic dark matter at present day.

Cold / Warm / Hot dark matter

Hot dark matter: Neutrino (only dark matter particle identified so far. Dark radiation).

Ruled out because of CMB anisotropy. Cannot explain galaxy formation CMB is smooth. Fast particles cannot clump together on small scales from this initial smoothness.

Sterile neutrino: only interacts through gravity (no weak force)

ΛCMD: Dark energy and cold dark matter

Problems: Missing satellites. Simulations predict much more small dwarf galaxies than seen.

Satellites seem to be in a disk: sims show a random distribution

Self-interacting dark matter?

LSB galaxies:

baryonic mass in form of neutral gas, not-stars.

95% non-baryonic dark matter.

No supernovae.

Extremely high mass-to-light ratio.

No bulges. DM-dominated even in center.

Mass-to-light ratio:

$$\frac{\text{Mass (in solar masses)}}{\text{Light (Luminosity, in } L_\odot)}$$

For a galaxy composed only of ⋆ like the Sun, mass-to-light ratio is 1.

Visible light → ranges 1-30

If $M/L \gg 30$, evidence for DM.