Early evidence for dark matter

Zwicky, 1933: estimate the mass of Coma galaxy cluster in two ways

Method 1

- Count galaxies
- Convert galaxy luminosities to masses using mass-to-light ratio of $\frac{M}{L} \sim 3 \frac{M_\odot}{L_\odot}$, calibrated from local Kapteyn stellar system
- Zwicky's numbers: ~ 800 galaxies, each $\sim 10^9$ solar masses

$$\Rightarrow M_{tot} \simeq 800 \times 10^9 \times \underbrace{2 \times 10^{33} g}_{M_\odot} \simeq 1.6 \times 10^{45} g$$

Ratio of inferred masses: ~ 200 or mass-to-light ratio of $\sim 600 \frac{M_\odot}{L_\odot}$ vs $3 \frac{M_\odot}{L_\odot}$ expected from Kapteyn. (Zwicky found 500 for this ratio).

Modern values (w/ better value of H_0, & hence of distance to Coma), find $M/L \sim 160\ M_\odot/L_\odot$, discrepancy of $O(50)$.

Method 2

- Observe velocities of (eight) galaxies in cluster, via Doppler shifts

Velocity dispersion $\sigma \simeq 1019 \pm 360$ km/s

(Modern value $\sigma = 1082$ km/s, Colless & Dunn 1996)

Virial theorem for equilibrium system:

$$KE = -\frac{1}{2} PE$$

$$\text{Total } PE \simeq -\frac{3}{5} \frac{GM^2}{R} \simeq -2KE = -M\langle v^2 \rangle$$

$$\Rightarrow M \simeq \frac{5}{3} \frac{\langle v^2 \rangle R}{G}$$

Zwicky took $R \sim 10^6$ lyr $\sim 10^{24}$ cm

$$\Rightarrow M \sim \frac{5}{3} \frac{(10^8 \text{ cm/s})^2 \times 10^{24} \text{ cm}}{6.67 \times 10^{-8} \text{ cm}^3/g/s^2}$$

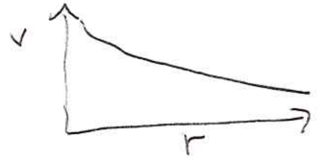
$$\sim 3 \times 10^{47} g$$

(Modern value: $\sim$ few $\times 10^{48} g$)

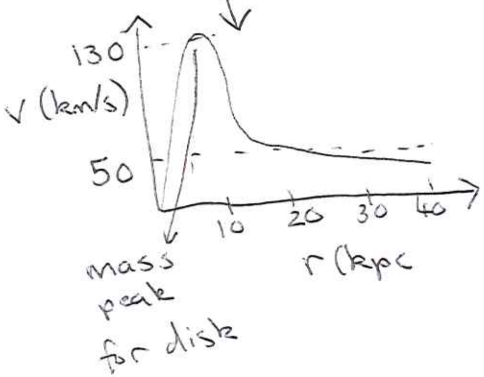
Rotation curves:

- Consider orbital velocity of objects in our Galaxy
- If mass is concentrated in a central region w/ total mass M, then outside that region,

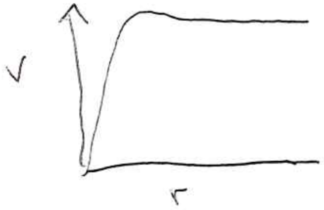
$$\frac{v^2}{r} \approx \frac{GM}{r^2} \Rightarrow v \propto \frac{1}{\sqrt{r}}$$



- Example: actual modeling based on observed disk of galaxy NGC 3198 (van Albada et al 1985)



But observations (by Vera Rubin, collaborators Ford & Thonnard, others), over a wide range of systems, found instead v(r) became near-flat at lage r.



If $\frac{v^2}{r} = \frac{GM(r)}{r^2}$, v constant $\Rightarrow M(r) \propto r$. If $M(r) = 4\pi \int_0^r r'^2 dr' \overset{\text{mass density}}{\rho(r')}$, $\Rightarrow \rho(r) \propto \frac{1}{r^2}$

Most mass lies out beyond the visible disk - extended dark halo

Suggests different physical behavior from luminous matter (collapsed into disk).

Modern version: simulations of cold, collisionless dark matter predict that visible galaxies are embedded in extended dark matter halos, with densities approximately described by NFW or Einasto profiles.

NFW (Navarro-Frenk-White) profile:

DM mass density

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

r_s = scale radius where $\frac{d\ln\rho}{d\ln r} = -2$

For MW-sized galaxies, $r_s \sim 20$ kpc

At small r, $\rho \propto \frac{1}{r}$; at large r, $\rho \propto \frac{1}{r^3}$. Region around $r \sim r_s$ corresponds to flat part of rotation curve.

Einasto profile:

$$\rho(r) = \rho_{-2} \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right)\right]$$

steeply rising density "cusps" at small r

r_{-2} = radius where $\frac{d\ln\rho}{d\ln r} = -2$, analogous to r_s for NFW

Parameter α estimated to be $\alpha \approx 0.17$ for Milky-Way-sized halos, in simulations

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Observations ~~of~~ show some disagreement with these simulation-based predictions - but there is ongoing debate as to whether all such discrepancies can be consistently explained by simply including visible/baryonic matter

In general, CDM-only simulations seem to systematically over-predict the density of DM on small ($\lesssim 10$ kpc) scales, see Bullock & Boylan-Kolchin 1707.04256

* "Too big to fail" & "cusp-core" problems - dwarf galaxies with stellar mass $\sim 10^{7-9} M_\odot$ appear less concentrated than predicted

- Fewer massive + dense DM subhalos than predicted, among satellites and in the field (Boylan-Kolchin et al '12, Garrison-Kimmel et al '14)
- Flattened cores, 0.1-1 kpc in size (e.g THINGS & LITTLE THINGS surveys) Oh et al '12, '15

Also some claimed evidence of cores in:
- Galaxy clusters (Newman et al '12)
- Low surface brightness spiral galaxies (de Blok et al '01, '02; Simon et al '05)
- High surface brightness spiral galaxies (Gentile et al '04)

Some of these may be due to systematic effects - e.g resolution issues, assumptions of sphericity / isotropicity biasing reconstructed orbits of stars

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- Once we include baryonic/ordinary matter in simulations, picture can change from cold + collisionless DM only
- Primarily an issue at small scales - EM interactions allow ordinary matter to dissipate energy & angular momentum, form dense disks, so baryons typically dominate over DM in centers of halos & control the gravitational potential there
- Outflows of baryonic matter can remove low-angular-momentum material from the centers of halos, converting cusps → cores
- Size of effect depends strongly on whether star formation history is "bursty" or smooth - bursts of star formation → fluctuations in grav potential, disrupting cusps & spurring outflows
- See review by Alyson Brooks, 1407.7544.

- DM self-interactions could also significantly affect small-scale structure (e.g Spergel & Steinhardt 2000, simulations by Vogelsberger et al, Robertson et al 1711.09096)

Let us understand what kind of cross-sections are needed for a large effect.

What kind of self-interaction xsec do you need?

$\underbrace{\text{Core number density} \times \text{cross section} \times v}_{\text{scattering rate for a DM particle}} \gtrsim$ once per dynamical time

$$\frac{\rho}{m_\chi} \langle \sigma v \rangle \sim \frac{1}{\tau}$$

$\tau \to \sim 10^9\ \text{yr} \sim \pi \times 10^{16}\ \text{s} \sim 10^{27}\ \text{m} \sim 10^{29}\ \text{cm}$

take $\rho \sim 1\ \text{GeV/cm}^3$, close to local measured density

$v \sim 10^{-4}$–$10^{-5}\, c$ in dwarf galaxies

$$\Rightarrow \frac{\sigma}{m_\chi} \sim \frac{1}{\rho v \tau} \sim \frac{1}{\frac{1\ \text{GeV}}{\text{cm}^3} \times 10^{29}\ \text{cm} \times 10^{-4}} \sim \frac{10^{-25}\ \text{cm}^2}{\text{GeV}} \sim 0.1-1\ \frac{\text{cm}^2}{\text{g}}$$

$(1\ \text{GeV} = 2 \times 10^{-24}\ \text{g})$

$$\sim \frac{10^{-25}(2 \times 10^{14}\ \text{GeV}^{-1})^2}{\text{GeV}} \sim \frac{1}{(100\ \text{MeV})^3}$$

For ~ 1 GeV DM,

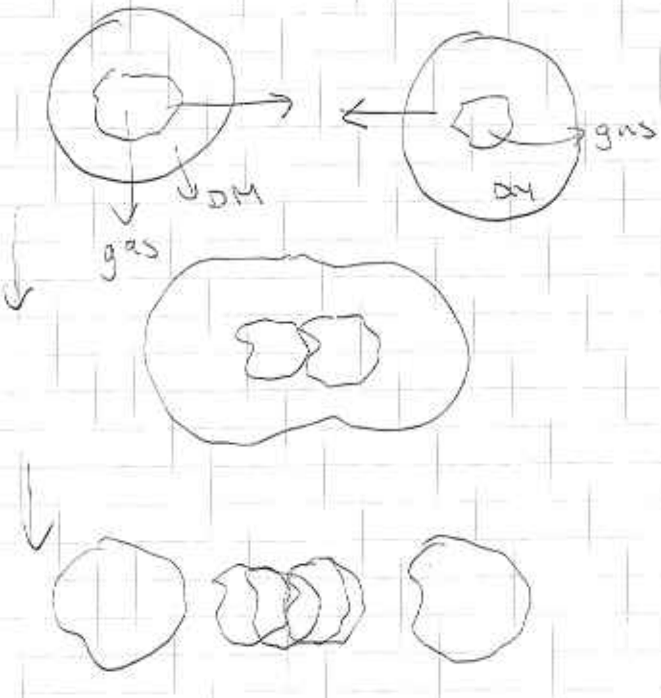
$O(1\ \text{b})$ xsec – QCD-scale cross-section

Natural mass scale $O(100\ \text{MeV})$

Larger xsecs than this constrained by measurements of colliding clusters, halo ellipticities.

The Bullet Cluster

Clowe et al 2006: observed non-equilibrium system of two colliding clusters



Measure position of hot gas using X-rays
↳ bulk of visible mass

Measure concentration of gravitating mass using weak lensing of background objects

Find that the latter is displaced from the former
→ difficult to explain w/ modified gravity only & no DM

Also sets upper bound on DM SI xsec
- e.g can study offset between mass peaks & distribution of galaxies within cluster as measure of collisionality. But must be done with caution!
e.g 1605.04307 Robertson et al
- Bullet cluster allows $2\,cm^2/g$ xsec/mass, in contrast w/ prior claimed constraints.

Cluster density profiles ← prefer SI xsections $\sim 0.01 - 0.1\ cm^2/g$ or smaller

Possible probes of SI x-sections from displacement between DM halo & central galaxy in relaxed merger remnant, shapes of cluster-scale halos, etc
(see review Buckley & Peter 0712.06615)