7 Dark Matter

- We know that the Universe contains matter, and as $\varepsilon_M \propto a^{-3}$, matter must have been the dominant energy density component in the not so distant past. We also know that the supernova results are consistent with a range of $\Omega_{m,0}$ and $\Omega_{\Lambda,0}$, so if we can measure one we know the other. We don't see Λ, or have a good way of estimating $\Omega_{\Lambda 0}$, but we can add up the matter that we see or infer to exist.

In doing so, the density to bear in mind is that required to make the Universe flat, the critical density

$$\rho_{c,0} = 1.3 \times 10^{11} M_\odot \, Mpc^{-3} \qquad (7.1)$$

Visible Matter

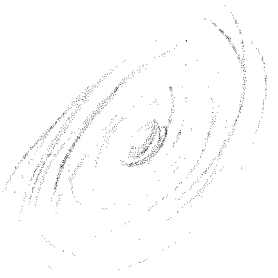
- The obvious place to start a census of matter is with what we can see; stars. Their luminosity is what makes galaxies visible at optical wavelengths. Adding up the light from galaxies in the local Universe finds a luminosity density (here 'v' means visible wavelengths).

$$\Psi_v \sim 10^8 L_{\odot,v} \, Mpc^{-3} \qquad (7.2)$$

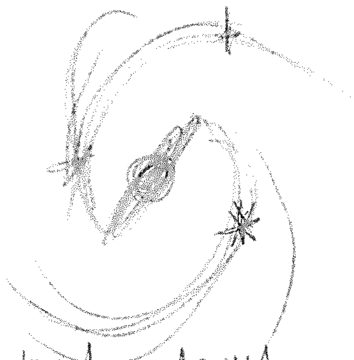
this measurement is useless unless we can convert it to a mass density. If all stars wese like the Sun, then we could us a "mass to light ratio" of $1 M_\odot / L_{\odot,v}$, and get

$$\Omega_{stars,0} = \frac{\rho_{stars,0}}{\rho_{c,0}} \sim 10^{-3} \qquad (7.3)$$

of course, not all stars are like the Sun. In fact, low-mass stars, which are faint, are the most common. However, a high-mass star is far more luminous than hundreds of low-mass stars, but high mass stars are very short-lived. The mass to light ratio of a galaxy thus depends on whether star-formation is ongoing.



elliptical galaxy
old, little star formation
high M/L ratio ~ 8 $M_\odot / L_{\odot,V}$



spiral galaxy
young, lots of star formation
low M/L ratio ~ 0.3 $M_\odot / L_{\odot,V}$

these mass to light ratios are not much larger, and including other ~stars such as neutron stars, black holes, and brown dwarfs still only finds $\Omega_{stars,0} \sim 0.005$.

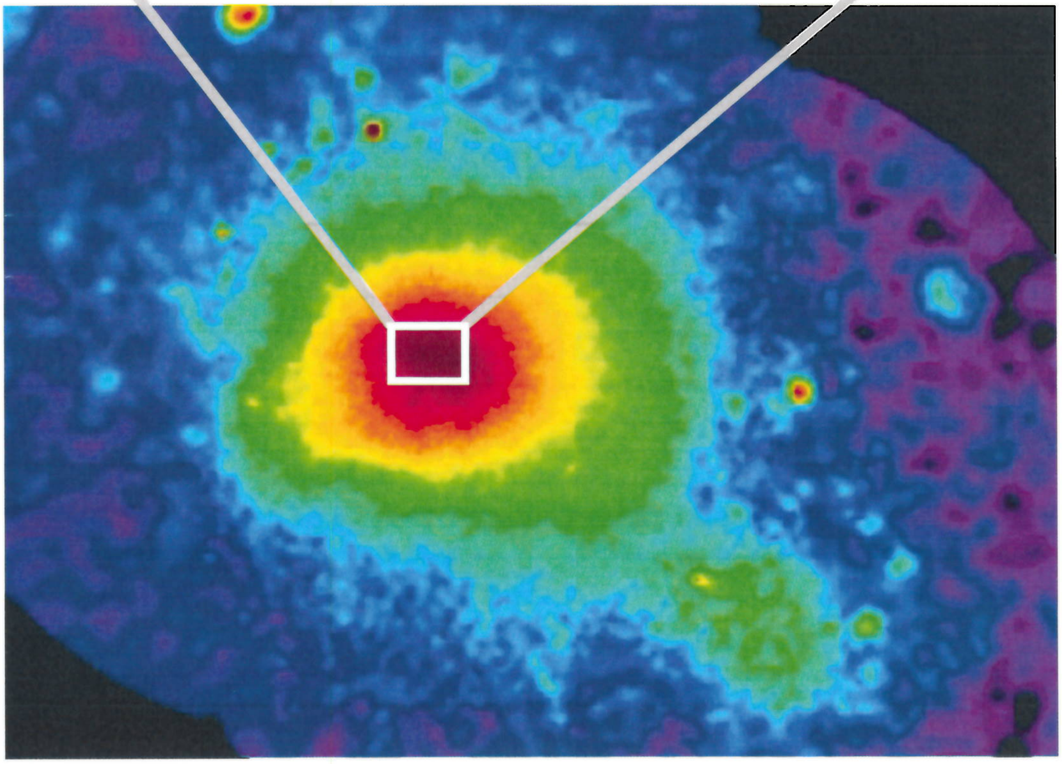
- stars turn out to be a minor component of "visible matter" because most of the baryonic matter isn't bright at optical (humanly visible) wavelengths. Most is actually in gas that lies between galaxies, and only ~10% of the matter density is in stars, hence $\Omega_{bary,0} \sim 0.05$

- the most precise measurement of baryonic matter comes from CMB temperature fluctuations (chapter 8):

$$\Omega_{bary,0} = 0.048 \pm 0.003 \qquad (7.4)$$

far too little energy density to make the Universe flat.

Coma cluster of galaxies at visible wavelengths, NASA / JPL-Caltech / L. Jenkins (GSFC)



Coma cluster of galaxies in x-rays, S. L. Snowden USRA, NASA/GSFC

Evidence for Dark Matter

- We have known for a long time that evidence for "nonbaryonic dark matter" exists. The reason it must be non-baryonic comes from measurements of light elements and the theory of nucleosynthesis. Dark matter doesn't interact with light directly (asorption, emission, saltering), but does exert a gravitation influence, and this is how we find it.

- Evidence for dark matter comes in three forms:

  - galaxy rotation curves, 1970s
  - galaxy cluster velocities, 1930s
  - gravitational lensing, 1980s

- Dark matter in galaxies

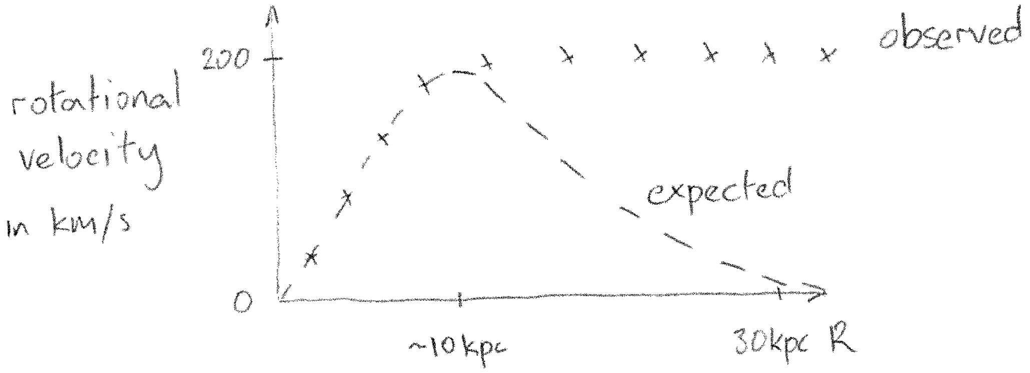
  Newtonian dynamics tells us that the orbital velocity (for circular orbits) is

$$v^2 = \frac{GM(R)}{R} \tag{7.5}$$

  where M(R) is the mass within a sphere of radius R. Most of a galaxy's mass lies within some scale length, which is typically 5kpc for a galaxy like the Milky Way.

  - beyond a few scale lengths, the tangential velocity of material in a galaxy should fall as $v \propto 1/\sqrt{R}$

- what we see tends to have $V = \text{constant}$, implying that the mass is increasing with radius beyond where it is visible as stars.



- constant velocity implies $M(R) \propto R$ to at least tens of kpc. If we assume this is true for the Milky Way then we can write a scaling relation:

$$M(R) = \frac{v^2 R}{G} = 10^{11} M_\odot \left(\frac{V}{235\ \text{km/s}}\right)^2 \left(\frac{R}{8.2\ \text{kpc}}\right) \qquad (7.6)$$

The measured luminosity is $L_{MW,V} \sim 2\times10^{10} L_{\odot,V}$, so if the dark matter "halo" extends to some distance R_{halo} the mass to light ratio is (using $M(100\text{kpc}) = 1.2\times10^{12} M_\odot$ from 7.6)

$$\left.\frac{M}{L_V}\right|_{MW} \sim 60\ M_\odot/L_{\odot,V} \left(\frac{R_{halo}}{100\ \text{kpc}}\right) \qquad (7.7)$$

- thus, $\Omega_{m,0}$ is considerably higher than we obtain by adding up what we see directly in galaxies.

Dark matter in clusters

- The evidence for dark matter in clusters of galaxies is essentially the same as in individual galaxies, but relies on measurements of the velocities of many galaxies. It was found that the velocities observed are too high, and unless there exists unseen gravitating material, the cluster would fly apart.

- We can again formulate a relation between mass, velocity, and a size scale, this time using the "virial theorem". For a population of gravitationally bound objects (that aren't expanding with $a(t)$) in a cluster of "size" R_{cl}

$$W + 2K = 0 \tag{7.8}$$

where W is the gravitational potential energy and K the kinetic energy. This gives (ignoring some ~1 factors)

$$m\langle v^2\rangle \approx \frac{GM^2}{R_{cl}} \quad \text{or} \quad M \approx \frac{\langle v^2\rangle R_{cl}}{G} \tag{7.9}$$

where $M = \sum m_i$, the summed mass of all material in the cluster. This is just the same as equation (7.6), but now we must measure the average square velocity of the galaxies, and R_{cl} is an estimated size (e.g. half light radius).

- in the Coma cluster $\langle v^2\rangle \sim 10^{12}\ \mathrm{m^2/s^2}$, $R_{cl} \sim 1.5$ Mpc so $M_{coma} \sim 10^{15} M_\odot$, and the mass to light ratio is about $400\ M_\odot/L_{\odot,V}$. This conversion includes the mass in gas between the galaxies, but not between clusters. Typically,

$$\Omega_{clus,0} \approx 0.2 \tag{7.10}$$

Gravitational lensing

- Just as dark matter affects how matter moves, it also bends the trajectory of photons. We see this effect in <u>images</u> of some clusters, such as Abell 2218. Masses calculated using this method agree with those from appying the virial theorem to clusters.

- Background objects are magnified by this "lensing", making the detection of very distant (old) objects possible.
- Weak lensing distorts background galaxies, stong lensing can create multiple images

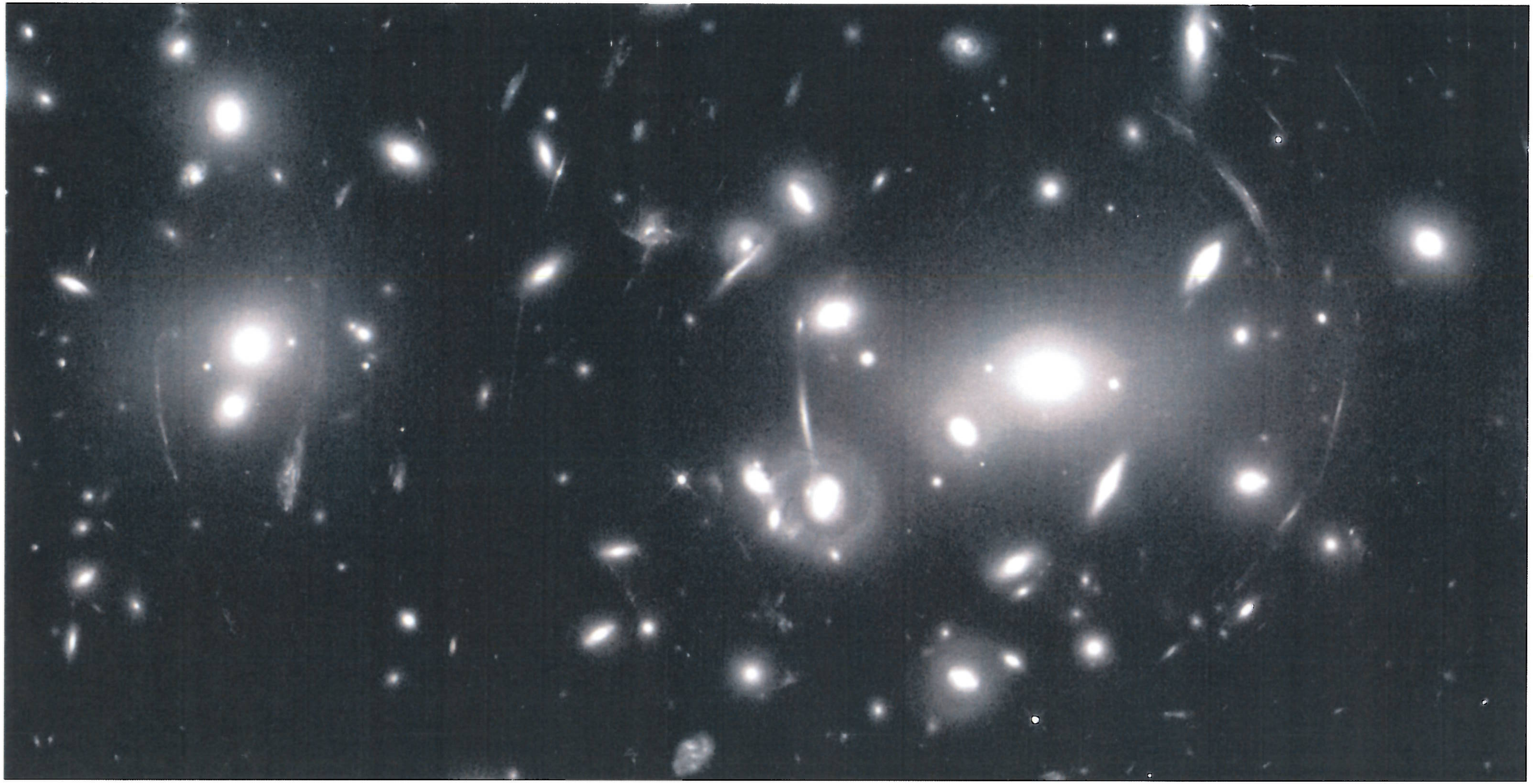
What is dark matter?

- In short, the answer is that we don't know. We can however rule some things out, and deduce some of the basic properties dark matter must have.

- Dark matter might be "hot" (relativistic) or "cold" ($v \ll c$). We can rule out hot dark matter because it would be moving too fast to get caught into baryonic structure, and wouldn't be a significant component of galaxies or clusters. An example of hot dark matter is a massive neutrino, but this is ruled out; the required mass is $m_\nu c^2 \approx 3.8$ eV but the average mass is in the range 0.02 to 0.1 eV.

  - dark matter is "cold", sometimes called CDM.

- Two main classes of dark matter candidates are "Weakly Interacting Massive Particles" (WIMPs), and "Massive Compact Halo Objects" (MACHOs).



The galaxy cluster A bell 2218, background galaxies are “lensed” and appear as long arcs

W.Couch (University of New South Wales), R. Ellis (Cambridge University), and NASA/ESA

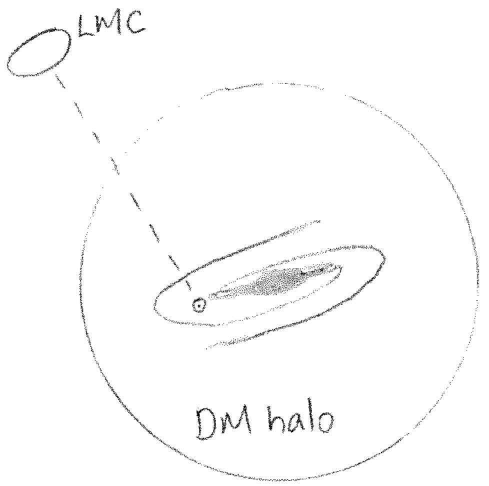
- MACHOs are generally things that we know exist but that are too faint to detect directly, such as

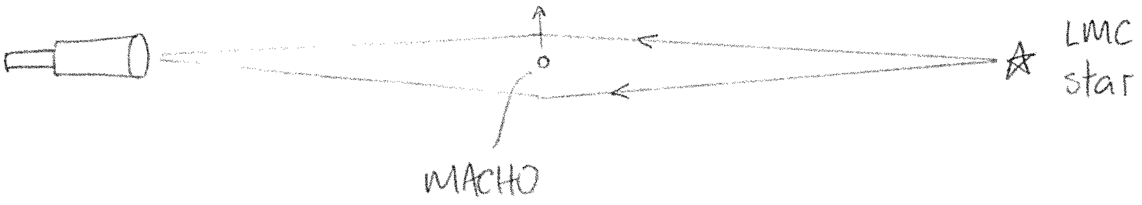
- white dwarfs	~ $0.6 M_\odot$
- brown dwarfs	~ $0.1 M_\odot$
- neutron stars	~ $1.4 M_\odot$
- black holes	~ $10 M_\odot$

we can search for them via gravitational lensing on a small scale, called "microlensing". The idea is that the dark matter halo of the Milky Way could be made up wholly or partly of MACHOs, and they will bend light coming in to our Galaxy from elsewhere. This bending causes <u>magnification</u> because the light takes more than one path around the MACHO.

- the experimental setup is →

our line of sight to the Large Magellanic Cloud passes through our dark matter halo, so MACHOs in the halo will lense LMC stars





relative to a background star, the MACHO is moving, so the brightness of the background star rises and falls as the MACHO goes past (wheras the images of galaxy clusters are static).

7-8

- the rate of microlensing rates was expected to be very low, even if the Milky Way's dark matter halo was entirely MACHOs, thus millions of stars were monitored.

- MACHOs were detected, making them unique among dark matter candidates, but the detection rate is only enough to explain about 10% of the Milky Way's halo mass. Dark matter is more evenly distributed, not in MACHOs.

· WIMPs are various fundamental particles, which are predicted to exist by variations or extensions of the standard model of particle physics. There exist various ongoing attempts to detect WIMPs, such as underground detectors. Nothing found, yet, but WIMPs remain a possible candidate.