What is the Dark Matter?

Standard Model Particles and Hot Dark Matter

Could It Be Standard Model Particles?

$$\Omega_b = 0.0490 \pm 0.0010$$
$$\Omega_d = 0.2607 \pm 0.0053$$
$$\Omega_\Lambda = 0.6889 \pm 0.0056$$

- Our best fit for all our parameters:
- What is all that dark matter?
- If it is standard model particles, it must be stable
- Only stable particles are:
  - Protons and neutrons (and their anti-particles)
  - Electrons (and their anti-particles)
  - Photons
  - All three neutrinos
- Photons are easy to detect – we can see them
- Because universe is charge neutral, every electron is associated with a proton
  - Which makes their mass irrelevant
- We therefore narrow it down to baryons or neutrinos

Could the Dark Matter Be Baryons?

Arguments against dark matter being baryons:

- Counting baryons indicate that the estimate for identified baryons is, if anything, *smaller* than what we need
- The numbers at right are based mostly on studying the CMBR
- The CMBR was generated at recombination
- You can't stuff baryons in white dwarfs, etc., made later
- Also, we can get an estimate by studying primordial nucleosynthesis
- And this yields the same baryon density

$$\Omega_b = 0.0490 \pm 0.0010$$
$$\Omega_d = 0.2607 \pm 0.0053$$
$$\Omega_\Lambda = 0.6889 \pm 0.0056$$

- Bottom line: It's very difficult to imagine it's all baryons

What Do We Know About Neutrinos?

- We have clear evidence that there are three neutrinos
  - Predicted by theory
  - Indirectly measured by primordial nucleosynthesis
  - Directly measured by studying decay of *Z*-boson

$$\Omega_b = 0.0490 \pm 0.0010$$
$$\Omega_d = 0.2607 \pm 0.0053$$
$$\Omega_\Lambda = 0.6889 \pm 0.0056$$

- *Direct* measurements for neutrinos masses give only negative results

$$m_{\nu e} < 2\ \text{eV}/c^2$$

- We can best measure the neutrino corresponding to the electron

- *Indirect* observations can only measure some *differences* between neutrino masses

$$m_2^2 - m_1^2 \approx (7.4 \pm 0.1) \times 10^{-5}\ \text{eV}^2/c^4\ ,$$
$$\left| m_3^2 - m_1^2 \right| \approx (2.48 \pm 0.04) \times 10^{-3}\ \text{eV}^2/c^4$$

- The smallest the masses could be:

$$m_1 \approx 0, \quad m_2 \approx 0.009\ \text{eV}/c^2\ , \quad m_3 \approx 0.050\ \text{eV}/c^2$$

- The largest the masses could be:

$$m_1 \approx m_2 \approx m_3 \approx 1.1\ \text{eV}/c^2$$

- Sum of masses

$$0.06\ \text{eV} < \sum_{i=1}^{3} m_i c^2 < 3.3\ \text{eV}\ .$$

So Could It Be Neutrinos?

$$0.06 \text{ eV} < \sum_{i=1}^{3} m_i c^2 < 3.3 \text{ eV}.$$

$$\Omega_b = 0.0490 \pm 0.0010$$
$$\Omega_d = 0.2607 \pm 0.0053$$
$$\Omega_\Lambda = 0.6889 \pm 0.0056$$

- The number density of neutrinos was computed previously

$$T_{\nu 0} = 1.945 \text{ K} \qquad n_{\nu i} = \frac{\zeta(3)}{\pi^2}\left(\frac{k_B T_\nu}{\hbar c}\right)^3 \frac{3}{4}\cdot 2 = 1.12\times 10^8 \text{ m}^{-3}$$

- In a homework, we then calculated the contribution to Ω

$$\Omega_\nu = \frac{8\pi G\rho_\nu}{3H_0^2} = \frac{8\pi G n_\nu}{3H_0^2 c^2}\sum_{i=1}^{3} m_{\nu i}c^2 = \frac{1}{43.3 \text{ eV}}\sum_{i=1}^{3} m_{\nu i}c^2 = 0.0014 - 0.076$$

- To get it to be *all* of the dark matter, we would need neutrinos of mass 3.7 eV each
- This makes it clear that neutrinos are apparently not *all* of the dark matter
- But it could still be *much* of the dark matter
- We also have to be nervous that the neutrinos might work

Hot and Cold Dark Matter

- Two generic categories of dark matter:
  - Cold dark matter is anything that froze out when it was non-relativistic
  - Hot dark matter is anything that froze out when it was relativistic

- Neutrinos are the classic example of hot dark matter

- Typically, hot dark matter will have a number density comparable to the density of photons

- They will become non-relativistic right at the time of matter-radiation equality

- No matter what they are, we will need a mass ~ few eV, depending on several details

- For definiteness, we will work out what happens if we have three neutrinos with mass 3.7 eV each

So What's Wrong With Hot Dark Matter? (1)

The list is long

- We will focus on one aspect: structure formation
- Consider the momentum of neutrinos of mass 3.7 eV/c^2
- At freeze out, their energy is roughly $3k_BT_\nu$, and momentum is $p = E/c = 3k_BT_\nu/c$
- At the time of matter-radiation equality, this formula still works

$$p = \frac{3k_BT_\nu}{c} = \frac{3\cdot 0.714 k_BT}{c} = 1.63 \text{ eV}/c$$

- These are now non-relativistic, so their velocity will be

$$v = \frac{p}{m} = c\frac{pc}{mc^2} = c\frac{1.63 \text{ eV}}{3.7 \text{ eV}} = 0.44c$$

- They will therefore move a distance

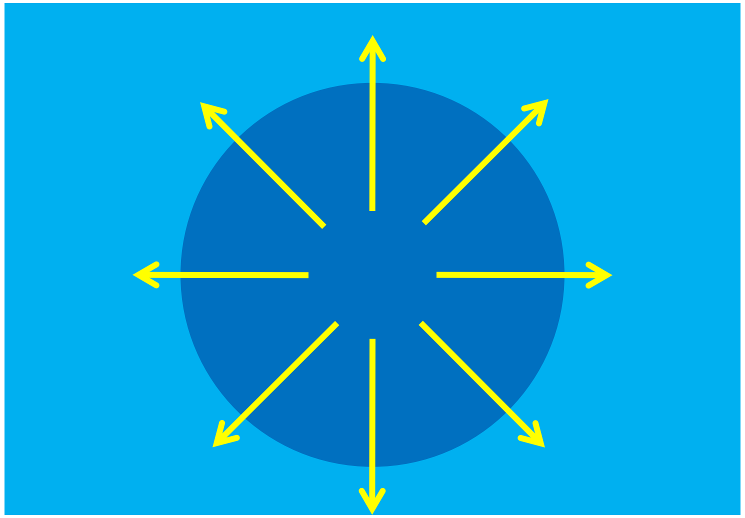
$$d = vt = 0.44\left(3.00\times10^8 \text{ m/s}\right)\left(57,000 \text{ y}\right)\left(3.156\times10^7 \text{ s/y}\right) = 2.4\times10^{20} \text{ m}$$

$$\boxed{d = 7.7 \text{ kpc}}$$

So What's Wrong With Hot Dark Matter? (2)

- Suppose at this time, there were a region smaller than this that had high density
- Neutrinos would simply run from high density region to low density
- Any scales smaller than this are wiped out
- Matter-radiation equality came at roughly $z = 3400$
- So fluctuations on this scale would have grown by a factor of 3401, and now would be of size

$$d = 7.7 \text{ kpc}$$



$$d_0 = (1+z)d = 3401(7.7 \text{ kpc}) = 26 \text{ Mpc}$$

- This is size of the Laniekea Supercluster
- Suggests superclusters formed before clusters, galaxies, or globular clusters
- But observations suggest smaller objects were probably first

Learning About Neutrinos from Cosmology

$$0.06\text{ eV} < \sum_{i=1}^{3} m_i c^2 < 3.3\text{ eV}.$$

$$\Omega_\nu = \frac{1}{43.3\text{ eV}} \sum_{i=1}^{3} m_{\nu i} c^2$$

$$\Omega_b = 0.0486$$
$$\Omega_d = 0.2589$$
$$\Omega_\Lambda = 0.6911$$
$$\Omega_\nu = 0.0014$$

- If mass sum is 11 eV/c^2, all dark matter would be neutrinos
  - But it doesn't lead to a universe that looks like ours
- If mass sum is 3.3 eV/c^2, a significant fraction of dark matter would be neutrinos

- How low can we make the neutrino masses and lead to a universe that looks like ours?
- Assume a specific neutrino mass sum
- Predict large scale structure and small angular CMBR variations
- Match to experiment
- We find

$$\sum_{i=1}^{3} m_{\nu i} c^2 < 0.13\text{ eV}$$

- This gives us limits on Ω_ν

$$0.0014 < \Omega_\nu < 0.0030$$

- Normally assumed to be near the lower end of this limit

Cold Dark Matter

Annihilation of Cold Dark Matter

- We have ruled out hot dark matter
  - Matter which fell out of equilibrium before it became non-relativistic

- Now consider cold dark matter
  - Matter which was non-relativistic when it fell out of equilibrium

- It must be stable (or very long-lived) particles that are not in the standard model
- Call the particle *X* and its mass m_X
- Like all particles, it must have an anti-particle *X*-bar
  - Though the anti-particle could be the same particle
- Generally, when particles combine with anti-particles, they can annihilate:

$$X\bar{X} \to e^+e^- \quad \text{if not its own anti-particle}$$

$$XX \to e^+e^- \quad \text{if it is its own anti-particle}$$

- So why didn't they all annihilate when $3k_BT$ drops below m_X?

What Stops the Annihilation Process?

$$X\bar{X} \to e^+e^- \quad \text{if not its own anti-particle}$$

$$XX \to e^+e^- \quad \text{if it is its own anti-particle}$$

- There are two reasons this process could stop:

- There is an excess of *X*'s over anti-*X*'s
  - This only makes sense if *X*'s and anti-*X*'s are distinct

- The *X*'s and anti-*X*'s become so low in density that they have trouble finding each other
  - Makes sense in either case

- If it's the former, we can't really figure out how many there should be left

- If it's the latter, then the process should stop when the average *X* collides only once in the age of the universe with its anti-particles

- We'll assume this second case

$$\boxed{\Gamma t \approx 1}$$

When Does the Annihilation Happen?

$$X\bar{X} \to e^+e^- \quad \text{or} \quad XX \to e^+e^-$$

$$\boxed{\Gamma t \approx 1}$$

- X particles will begin disappearing as soon as $k_B T < m_X c^2/3$
- At this point, any remaining X's will be non-relativistic
- And so long as they remain in thermal equilibrium, their density will be proportional to

$$E = m_X c^2$$

$$n \propto \exp\left(-\frac{E}{k_B T}\right) = \exp\left(-\frac{m_X c^2}{k_B T}\right)$$

- Because we need to get rid of most, but not all of them, we need to have $k_B T$ well below $m_X c^2/3$
- We need about
  - Almost independent of mass

$$\boxed{k_B T_F \approx \tfrac{1}{30} m_X c^2}$$

- The average kinetic energy at this time is about
- Match this to the non-relativistic formula for kinetic energy
- And we have the velocity

$$E_{kin} = \tfrac{3}{2} k_B T_F = \tfrac{1}{2} m_X v^2$$

$$\boxed{v = \sqrt{\frac{3k_B T_F}{m_X}}}$$

Density of Dark Matter at Freezeout

$$X\bar{X} \to e^+e^- \quad \text{or} \quad XX \to e^+e^-$$

$$\boxed{\Gamma t \approx 1}$$

$$\boxed{v = \sqrt{\frac{3k_B T_F}{m_X}}}$$

- The rate at which any collision occurs is
  - n is number density
  - σ is cross-section
  - Δv is relative velocity

$$\Gamma = n_X \sigma (\Delta v)$$

- We also know the time-temperature relationship

$$t = \frac{2.42\ \text{s}}{\sqrt{g_{\text{eff}}}} \left(\frac{\text{MeV}}{k_B T_F} \right)^2$$

- Freezeout occurs when density has dropped to the point where

$$1 = \Gamma t = n_F \sigma (\Delta v) t = n_F \sigma \sqrt{\frac{3k_B T_F}{m_X}} \frac{2.42\ \text{s}}{\sqrt{g_{\text{eff}}}} \left(\frac{\text{MeV}}{k_B T_F} \right)^2 = n_F \sigma \frac{4.19\ \text{s} \cdot \text{MeV}^2}{\sqrt{g_{\text{eff}} m_X} (k_B T_F)^{3/2}}$$

- Solve for n_F:

$$n_F = \frac{\sqrt{g_{\text{eff}} m_X} (k_B T_F)^{3/2}}{\sigma (4.19\ \text{s} \cdot \text{MeV}^2)}$$

- Multiply n_F by m_X to get the density:

$$\rho_d = n_F m_X = \frac{\sqrt{g_{\text{eff}}} (k_B T_F m_X)^{3/2}}{\sigma (4.19\ \text{s} \cdot \text{MeV}^2)}$$

The Current Dark Matter Density

- We have the density at this time

$$\rho_d = \frac{\sqrt{g_{\text{eff}}}\left(k_B T_F m_X\right)^{3/2}}{\sigma\left(4.19\ \text{s}\cdot\text{MeV}^2\right)}$$

$$k_B T_F \approx \tfrac{1}{30} m_X c^2$$

- But the universe has continued to expand
  - Roughly $a \sim T^{-1}$
  - So density $\rho \sim T^3$

$$\rho_{d0} = \rho_d \left(\frac{T_0}{T_F}\right)^3 \cdot \frac{3.36}{g_{\text{eff}}} = \frac{0.802\left(k_B T_0\right)^3}{\sigma\sqrt{g_{\text{eff}}}\left(\text{s}\cdot\text{MeV}^2\right)}\left(\frac{m_X}{k_B T_F}\right)^{3/2}$$

- So we have roughly

$$\frac{m_X}{k_B T_F} \approx \frac{30}{c^2}$$

- Small correction because of reheating as various particles annihilated
- Substitute the various quantities in:

$$\rho_{d0} = \frac{0.802\left[\left(8.617\times10^{-5}\ \text{eV/K}\right)\left(2.725\ \text{K}\right)\right]^3 30^{3/2}}{\sigma\sqrt{g_{\text{eff}}}\left(\text{s}\cdot10^{12}\text{eV}^2\right)\left(3.00\times10^8\ \text{m/s}\right)^3}\cdot 1.602\times10^{-19}\ \text{J/eV}$$

- Note that the mass has cancelled out
  - The only real unknown here is g_{eff}

$$\rho_{d0} = \frac{1.102\times10^{-65}\ \text{kg/m}}{\sigma\sqrt{g_{\text{eff}}}}$$

The Annihilation Cross Section

- If we knew the cross-section, we could predict the current density

$$\rho_{d0} = \frac{1.102\times 10^{-65}\ \text{kg/m}}{\sigma\sqrt{g_{\text{eff}}}}$$

- But we know the current density

$$\rho_{d0} = 2.235\times 10^{-27}\ \text{kg/m}^3$$

- Turn this around and get the current cross-section

$$\sigma = \frac{1.102\times 10^{-65}\ \text{kg/m}}{\rho_d\sqrt{g_{\text{eff}}}}$$

- Exact value will depend g_{eff}
  - Which depends on number of particles at these unknown high energy
- For definiteness, let's pick $g_{\text{eff}} = 100$

$$\sigma = \frac{1.102\times 10^{-65}\ \text{kg/m}}{\left(2.235\times 10^{-27}\ \text{kg/m}^3\right)\sqrt{100}}$$

- This value is probably accurate to about a factor of two

$$\sigma \approx 4.5\times 10^{-40}\ \text{m}^2$$

What is the Mass of the Dark Matter Particle?

$\sigma \approx 4.5\times 10^{-40}\ \text{m}^2$ $\quad$ $X\bar{X} \to e^+e^-$ or $XX \to e^+e^-$

- We have a pretty good idea of the cross-section
  - And we know it isn't any standard model particle
- Typical cross-sections depend on particle physics model, but …
- Usually such cross sections look something like:

$$\sigma \approx \frac{\alpha_X^2 \hbar^2}{M^2 c^2}$$

- The factor α_X is a dimensionless *coupling constant*
- Typical values in most theories have $\alpha_X \sim 10^{-2} - 1$
  - Electromagnetism, for example, has $\alpha = 1/137$

$$\sigma \le 4\pi \left(\frac{\hbar}{p}\right)^2$$

- There is also an approximate upper limit on the cross section
- Put this all together and you can get a range on the mass of the *X*:

$$10^2\ \text{GeV} < m_X c^2 < 10^5\ \text{GeV}$$

So What Is the Dark Matter?

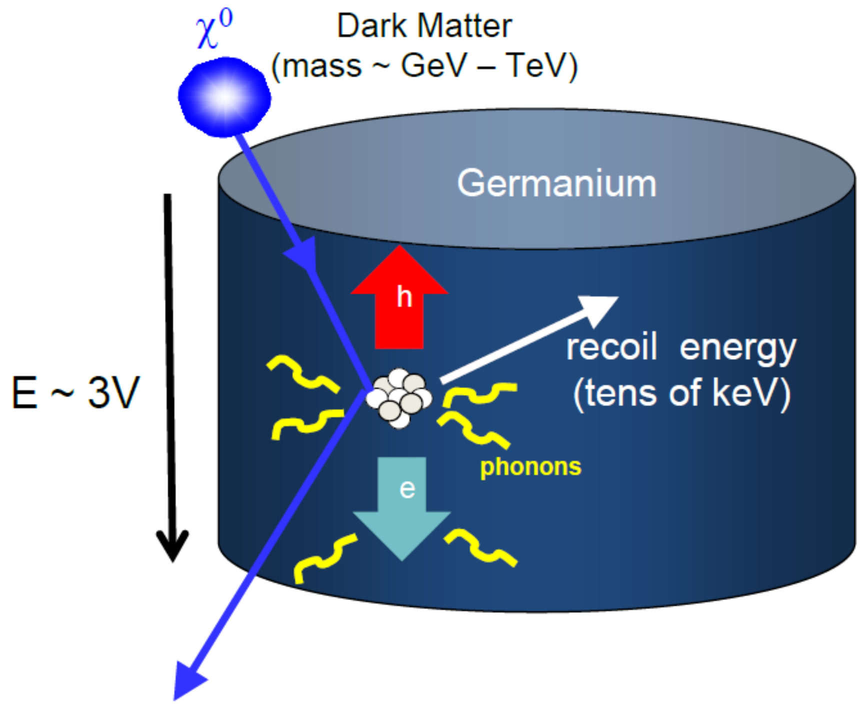
$\sigma \approx 4.5\times10^{-40}\ \mathrm{m}^2$ $\quad 10^2\ \text{GeV} < m_X c^2 < 10^5\ \text{GeV}$

- Supersymmetry is supposed to have particle called the *Lightest Superpartner* that is both stable and can annihilate to ordinary particles
- It is predicted to be probably around $10^2 - 10^4$ GeV
- It should be *perfect* for the dark matter
- But thus far, all such searches have been unsuccessful
  - So probably it is somewhat above 10^3 GeV
- Other theories contain massive particles that have only weak interactions
  - WIMPs = Weakly Interacting Massive Particles
- There are countless other candidate theories for the dark matter

Can We Detect the Dark Matter?

$$\boxed{\sigma \approx 4.5\times10^{-40}\ \text{m}^2} \qquad 10^2\ \text{GeV} < m_X c^2 < 10^5\ \text{GeV}$$

- If it is lighter than a few TeV, we should find it soon
  - LHC operates at 7 TeV + 7 TeV
- But not sure how to discover it
- We can also look for collisions of the dark matter with ordinary nuclei
  - Should happen for WIMPs
  - Thus far, no detection
- It is also possible we will some day discover annihilation products from the remaining dark matter particles



$$X\bar{X} \to \gamma\gamma$$

Other Dark Matter Candidates

Is it Necessarily Cold Dark Matter?

- We discussed hot and cold dark matter
- We ruled out hot dark matter and therefore concluded it must be cold dark
  - But there may be other, even better alternatives
- How well does cold dark matter work?
- So well that the standard cosmological model is called the ΛCDM model
- But not perfectly!
- Many aspects of galaxy formation are fudged – they include factors that are poorly understood
- Also, most simulations indicate that dark matter should cluster more strongly towards the center of galaxies
- May indicate that we have some important details wrong

Random Examples of Crazy Dark Matter Ideas

- Countless alternatives have been proposed over the years
- Many of them have been tested and found wanting

- When you eliminate those, the list gets shorter

- One idea that is currently popular is warm dark matter
  - Particles were slightly non-relativistic when they froze out
- An example would be sterile neutrinos with mass ~ few keV/c^2 or so
  - Neutrinos with little or no weak interactions

- Bottom line – we don't really know what the dark matter is

- ~~Eric D. Carlson, Marie E. Machacek, and Lawrence J. Hall, "Self Interacting Dark Matter," Astrophys. J. 398, 43 (1992).~~
- ~~Eric D. Carlson, Rahim Esmailzadeh, Lawrence J. Hall, and Stephen D. H. Hsu, "Black Hole Nucelosynthesis and $\Omega_B = 1$," Phys. Rev. Lett. 65, 2225 (1990).~~
- ~~Eric D. Carlson and L.J. Hall, "ν_μ and ν_τ as dark matter," Phys. Rev. D40, 3187 (1989).~~