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6 Dark matter

6.1 Observational evidence for dark matter

The term *dark matter* was coined by Jacobus Kapteyn in 1922 in his studies of the motions of stars in our galaxy to refer to matter that interacts gravitationally, but is not seen via electromagnetic radiation [1]. He found that no dark matter is needed in the galactic Solar neighbourhood. In 1932, Jan Oort made the contrary claim that there is twice as much dark matter as visible matter in the Solar vicinity. This is the first claimed evidence for dark matter. However, later observations have shown it to be wrong, and the discovery of dark matter is usually credited to Fritz Zwicky who made the first correct argument for the existence of dark matter in 1933. Zwicky concluded from measurements of the redshifts of galaxies in the Coma cluster that their velocities are much larger than expected based on the visible mass of the cluster.

There are nowadays large amounts of evidence for dark matter, including from BBN, gravitational lensing, expansion rate of the universe, CMB, and other observations. One of the earliest, and easiest to understand, pieces of evidence comes from *rotation curves* of galaxies, which have been studied extensively since the 1970s, notably by Vera Rubin. According to Newtonian gravity, the velocity $v(r)$ of a body on a circular orbit in an axially symmetric mass distribution is

$$\frac{v(r)^2}{r} = G_\mathrm{N}\frac{M(r)}{r^2} \ , \tag{6.1}$$

where $M(r)$ is the mass inside radius r, and the function $v(r)$ is called the *rotation curve*. For an orbit around a compact central mass, for example planets in the Solar system, we get $v \propto r^{-1/2}$, in agreement with Kepler's third law. For stars orbiting the centre of a galaxy the situation is different, since the mass inside the orbit increases with the distance. Suppose that the energy density of a galaxy decreases as a power-law,

$$\rho \propto r^{-n} \tag{6.2}$$

with some constant n. Then the mass inside radius r is

$$M(r) \propto \int \mathrm{d}r r^2 r^{-n} \propto r^{3-n} \qquad \text{for} \quad n < 3 \ . \tag{6.3}$$

Thus the rotation velocity depends on the distance from the centre as

$$v(r) \propto r^{1-n/2} . \tag{6.4}$$

Observed rotation curves increase with r for small r, i.e. , near the centre of the galaxy, but then typically flatten out, so that $v(r) \approx$ const.. According to (6.4), this would correspond to the density profile

$$\rho \propto r^{-2} . \tag{6.5}$$

However, the density of stars and gas falls more rapidly away from the core of a galaxy, and goes down exponentially at the edge. Also, the total mass from visible matter is too small to account for the rotation velocity at large distances.

This seems to indicate the presence of another mass component to galaxies. This mass component should have a different density profile than the visible matter, such that it is subdominant in the inner parts of the galaxy, but dominates in the outer parts. The dark component appears to extend well beyond the visible parts of galaxies, forming a dark *halo* around the galaxy.

More detailed observations indicate that instead of of $1/r^2$, the distribution of dark matter in galaxies is well fit by the *Navarro-Frenk-White (NFW) profile*,

$$\rho = \frac{\rho_0}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2} , \tag{6.6}$$

where ρ_0 and r_s are constants. The profile obviously does not hold all the way to the centre (the physical density is finite everywhere). Near the centres of galaxies, the densities are typically dominated by baryonic matter, and the dark matter profile rises less steeply than in the NFW case.

Estimates for the total matter density based on the gravitational effects of matter in the universe via many different methods show that $\Omega_{\rm m0} \approx 0.3$. The precise number and the error bars depend on the adopted cosmological model and datasets. One of the most precise determinations comes from the CMB, which gives $\Omega_{\rm m0} = 0.315 \pm 0.007$ for the ΛCDM model [2] and $\omega_{\rm m} = \Omega_{\rm m0}h^2 = 0.14 \pm 0.01$ model-independently [3, 4][1].

In the previous chapter we found that BBN gives $100\Omega_{\rm b0}h^2 = 2.205 \pm 0.043$ at 95% C.L. (and the CMB gives a similar range), so for $h = 0.7$ we get $\Omega_{\rm b0} = 0.04 \ldots 0.05$. This is much less than even conservative model-independent estimates of $\Omega_{\rm m0}$. Determining the nature of the no-baryonic dark matter is one of the most important problems in cosmology today. In earlier decades the expression "baryonic dark matter" was used to refer to luminous matter that we have not seen (for example, collapsed objects in interstellar space whose mass was not sufficient for nuclear reactions to ignite, i.e. less than about $0.07 M_\odot$). However, now the strongest evidence comes from BBN and the CMB, not direct measurement of baryonic objects on the sky, so its luminosity is not important. However, one possibility for dark matter is *primordial black holes*, which have collapsed from ordinary matter before BBN and recombination. They would therefore not be included in the BBN and CMB baryon budget. The mass range that is not excluded by observations is around

[1] The CMB anisotropy pattern looks qualitatively different than in the case with only baryonic matter, so the CMB provides a strong case for dark matter even without any other observations.

asteroid mass, $10^{-15} \ldots 10^{-11} M_\odot$, or possibly relics of primordial black holes that were created in the early universe and have evaporated via Hawking radiation down to Planck mass ($\sim 10^{-6}$ g). We will consider only particle candidates of dark matter.

6.2 Hot, warm and cold dark matter

A simple possibility for dark matter is that it is a thermal relic, i.e. that at early times it was in chemical equilibrium with Standard Model particles but decoupled when the interactions became too weak, like neutrinos. Such dark matter is called hot dark matter (HDM), warm dark matter (WDM), or cold dark matter (CDM), based on whether it is ultrarelativistic, in-between or non-relativistic when its interactions freeze out, respectively.[2]. The terminology of hot, warm and cold dark matter has also become adopted for particles that have not been in thermal equilibrium and are not in kinetic equilibrium, if the phase space distribution is mostly populated by modes with large, intermediate or small momenta at early times, even if it does have the thermal shape.

HDM, WDM and CDM all have a different effect on structure formation in the universe. Structure formation refers to the process in which the originally nearly homogeneously distributed matter forms bound structures such galaxies and galaxy clusters under the pull of gravity. We can differentiate between HDM, WDM and CDM through observations of *large-scale structure* in the universe. Observations show that HDM is definitely ruled out, WDM remains a possibility, and CDM fits observations well. We show in figure 1 the results of a simulation of the halo of dark matter around the Milky Way and two other galaxies. For CDM, there is more substructure and satellites around the galaxy, while their formation is suppressed for WDM.

6.3 Hot dark matter

The archetypal HDM candidates are neutrinos. They were one of the first particles to be considered as dark matter, because they are definitely known to exist. The cosmic neutrino background would make a significant contribution to the total density parameter today if the neutrinos had a mass of the order of 1 eV or above.

For massive neutrinos, the number density today is the same as for massless neutrinos, but their energy density today is dominated by their rest masses, giving (there is a factor of 3/4 since neutrinos are fermions and and 4/11 due to e^+e^--annihilation)

$$\rho_\nu = \sum_i m_{\nu_i} n_{\nu_i} = \frac{3}{11} n_\gamma \sum_i m_{\nu_i} \ , \tag{6.7}$$

where the sum is over the neutrino mass eigenstates (which are not the same as the weak interaction eigenstates, for whom the names electron neutrino, muon neutrino and tau neutrino are properly reserved). For $T_0 = 2.725$ K, this gives the neutrino density parameter

$$\Omega_{\nu 0} h^2 = \frac{\sum_i m_{\nu_i}}{94.14 \text{ eV}} \ , \tag{6.8}$$

[2]Today, the HDM particles must be nonrelativistic to count as matter.

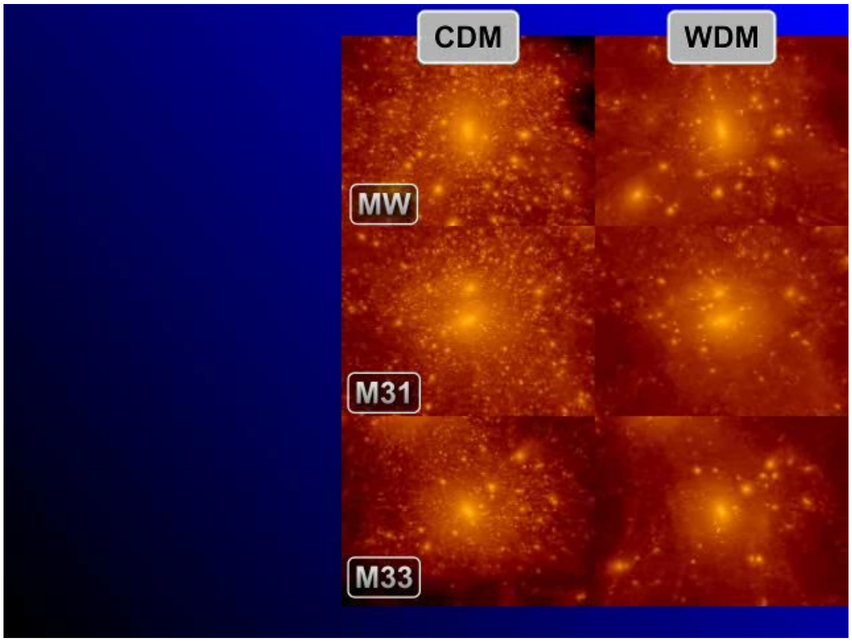

Figure 1: Comparison of the expected halo of the Milky Way and the galaxies M31 and M33 in CDM and WDM models. From http://www.clues-project.org/images/darkmatter.html.

which applies if the neutrino masses are less than the neutrino decoupling temperature (1 MeV), but greater than the present temperature of massless neutrinos ($T_{\nu 0} = 0.168$ meV), which is true for at least two our of three neutrino species. They then contribute to $\Omega_{\mathrm{m}0}$ today, but to radiation during BBN. Note that the mass has to be small, because the number density is high as the neutrinos decouple with relativistic. The same applies to other forms of HDM as well. CMB observations give the upper bound [2]

$$\sum_i m_{\nu_i} \lesssim 0.12 \text{ eV} \ . \tag{6.9}$$

Therefore the maximum contribution of neutrinos is $100\Omega_{\nu 0}h^2 < 0.13$, i.e. (taking $h = 0.7$) $\Omega_{\nu 0} < 0.3 \times 10^{-2}$, an order of magnitude below baryonic matter. So neutrinos can give a small contribution to dark matter today, although usually the term dark matter refers only to the particles other than neutrinos.

Even if the limit on neutrino mass were relaxed, neutrinos could not be the dominant form of dark matter, since they wipe away density perturbations efficiently on small scales. Data on large scale structure combined with structure formation theory requires that a majority of the matter in the universe has to be CDM – in a universe dominated by neutrinos, we would not have galaxies. The same applies to other forms of HDM – because the mass is small, the velocity remains large until late, erasing structure.

If neutrinos were the dominant form of matter, there would be a lower limit on their mass from constraints on the phase space density, called the *Tremaine–Gunn limit*. Essentially, in order to achieve a certain rotation velocity for galaxies, you need a certain amount of mass inside a given volume, and the Pauli exclusion principle constrains the number number of particles you can pack inside a given volume. Even though we know that neutrinos are a subdominant component of dark matter, the

Tremaine-Gunn limit applies to any fermionic dark matter candidate, even if its distribution is not thermal. There is no such lower limit on the mass of a bosonic dark matter particle.

Exercise. Suppose neutrinos dominate the mass of galaxies (to the extent we can ignore all other forms of matter). We know the mass of a galaxy (within a certain radius) from its rotation velocity. The mass could come from a smaller number of heavier neutrinos or a larger number of lighter neutrinos, but the available phase space (you don't have to assume a thermal distribution) limits the total number of neutrinos whose velocity is below the escape velocity. This leads to a lower limit of the neutrino mass m_ν. Assume for simplicity that either **a**) all neutrinos have the same mass, or **b**) only ν_τ is massive. Let r be the radius of the galaxy, and v its rotation velocity at this distance. Find the minimum m_ν needed for neutrinos to dominate the galaxy mass. (Assume that the neutrino distribution is spherically symmetric, and that the escape velocity within radius r equals the escape velocity at r.) Give the numerical value for the case $v = 200$ km/s and $r = 10$ kpc.

6.4 Cold dark matter

Observations of large-scale structure together with the theory of structure formation require that dark matter is dominated by CDM or WDM, with CDM being the currently preferred option. There is no particle in the Standard Model of particle physics that is suitable as CDM. Cosmological observations of dark matter are thus one of the most important pieces of evidence for physics beyond the Standard Model. (The possibility of primordial black holes, mentioned earlier, aside. They would behave like CDM.)

A major class of CDM particle candidates is *WIMPs* (Weakly Interacting Massive Particles). For a HDM candidate, the mass must be small so that the total contribution to the energy density today would not be huge; from (6.8) we see that a neutrino mass larger than about a dozen eV would give more energy density than observed. In contrast, if the mass of a weakly interacting particle species is much larger than the decoupling temperature of weak interactions, these particles are largely annihilated before the decoupling. This suppression of the number density makes it possible to achieve a suitable energy density starting from a thermal distribution at very high temperatures, despite the large mass. The interactions of some CDM candidates are stronger or weaker than those of WIMPs. For example, *gravitinos* have only gravitational-strength interactions, while TIMPs (Technicolour Interacting Massive Particles) can interact strongly.

A favourite WIMP candidate comes from supersymmetric extensions of the Standard Model. In the simplest version, the Minimal Supersymmetric Standard Model (MSSM), every Standard Model particle has a partner with the same quantum numbers[3] but a spin which is different by 1/2. The MSSM has a symmetry called R-parity as a result of which superpartners can only be created or destroyed in pairs, so the lightest supersymmetric partner (LSP) is stable. The parameters of the MSSM can be chosen such that the LSP is electrically neutral and a color singlet, so that it has only weak interactions. If it exists, it is possible that the LSP would be created

[3] If supersymmetry were unbroken, the mass would also be the same. In that case superpartners would have been observed already, so supersymmetry has to be broken. The partners retain the same quantum numbers, but their masses become different.

and detected at the LHC (Large Hadron Collider) at CERN. A measurement of its properties would allow a calculation of its expected number and energy density in the universe. Thus far, there has been no evidence for (or even suggestions of) MSSM, or any other physics beyond the Standard Model, at the LHC.

If a CDM particle was in thermal equilibrium in the early universe, its number density is suppressed, as noted above. Its mass then has to be large to have a significant energy density today. (We will soon look at this in detail!) In the MSSM, the LSP is expected to have a mass somewhere in the range between 100 GeV to a few TeV or so. However, if the particle was not in thermal equilibrium when it decoupled, the number density is not thus constrained.

For the particle not to be in thermal equilibrium, its interactions need to be very weak, and typically it should not even feel the weak interaction (which, despite the name, is not actually weak at large energies; recall that the weak interaction cross section is $\propto E^2$). One such candidate is called the *axion*. Axion particles are born with small velocities and have never been in thermal equilibrium. They are related to the *strong CP problem* in particle physics. We will not go into the details, but it is related to the question why the neutron electric dipole moment so small. (The electric dipole moment is zero to the accuracy of measurement, the upper limit being $d_n < 0.18 \times 10^{-25} e\text{cm}$ [5].) A proposed solution involves an additional symmetry of particle physics, the Peccei–Quinn symmetry. The axion would is the *Goldstone boson* of the breaking of this symmetry. The important point for us is that these axions would be created in the early universe when the temperature falls below the QCD transition scale, with negligible kinetic energy. Thus axions would have tiny velocities, and act like CDM. (Though calling axions "cold" is bit of a misnomer, as their phase space distribution is not thermal.) Another dark matter candidate of this type is the *gravitino*, the supersymmetric partner of the graviton.

6.5 WIMP decoupling

WIMPs and many other dark matter candidates are in thermal equilibrium at early times and decouple once their interactions become too weak to keep them in equilibrium. Such particles are called *thermal relics*, since their density today is determined by thermal equilibrium of the early universe, like neutrinos. If the candidate is stable (or has a lifetime much longer than the age of the universe) and there are no particles decaying or annihilating to it, the number of particles is conserved after decoupling, so the number density falls like a^{-3}. If we assume that the main interaction is the annihilation of dark matter particles and antiparticles, we can write

$$\dot{n}_{\rm dm} + 3Hn_{\rm dm} = -\langle\sigma v\rangle\bar{n}_{\rm dm}n_{\rm dm} + \psi_{\rm dm} \ , \tag{6.10}$$

where $n_{\rm dm}$ is the number density of the dark matter particles, $\bar{n}_{\rm dm}$ is the antiparticle number density, $\psi_{\rm dm}$ is the rate of creation of the dark matter particles, and $\langle\rangle$ indicates average over the phase space distribution. Let us first consider the case when there is no particle-antiparticle asymmetry, so the chemical potential is zero, $\mu_{\rm dm} = 0$. We will later see what happens if there is a conserved quantum number which enforces a particle-antiparticle asymmetry. (Sometimes the term "thermal relic" is used to refer only to the case when asymmetry between particles and antiparticles is not important.) In equilibrium, equal numbers of particles are annihilated and created, so $\psi_{\rm dm} = \langle\sigma v\rangle n_{\rm dm}^2 \equiv \langle\sigma v\rangle n_{\rm eq}^2 \equiv \Gamma n_{\rm eq}$, where $n_{\rm eq}$ is the number density in equilibrium. Denoting the number of dark matter particles by $N_{\rm dm} \propto a^3 n_{\rm dm}$ (and the equilibrium number by $N_{\rm eq}$), we have

$$\frac{1}{N_{\rm eq}} \frac{{\rm d}N_{\rm dm}}{{\rm d}(\ln a)} = -\frac{\Gamma}{H} \left[\left(\frac{N_{\rm dm}}{N_{\rm eq}} \right)^2 - 1 \right] . \tag{6.11}$$

In the limit $\Gamma \gg H$, interactions rapidly restore any deviations from the equilibrium distribution. If $N_{\rm dm} > N_{\rm eq}$, the right-hand side of (6.11) is negative, so the numbers will decrease, and the opposite for $N_{\rm dm} < N_{\rm eq}$. In the limit of weak coupling, $\Gamma \ll H$, we get $N_{\rm dm} \approx$ constant. The time when the number of particles reaches this constant value is called decoupling (a term we already used with photons and neutrinos) or *freeze-out*. As before, we make the approximation that decoupling happens at exactly the temperature $T_{\rm d}$ where $H = \Gamma$, and that the number of particles follows the equilibrium behaviour before and is conserved afterwards, like we did for the neutrinos.

If a particle decouples while it is relativistic, its number density is of the order $T_{\rm d}^3$. We calculated this starting from the phase space distribution, but it is fairly obvious, because $T_{\rm d}$ is the only relevant dimensional quantity. As we discussed above, such hot dark matter would have a large energy density today unless the mass is small. However, as a particle species becomes non-relativistic, the number density falls exponentially (assuming that the chemical potential can be neglected), so the mass of the dark matter particle can be large while keeping the number density small.

The number density of a non-relativistic particle in thermal equilibrium (with zero chemical potential) at decoupling time $t_{\rm d}$ and temperature $T_{\rm d}$ is

$$n_{\rm eq}(t_{\rm d}) = g_{\rm dm} \left(\frac{m T_{\rm d}}{2\pi} \right)^{3/2} e^{-m/T_{\rm d}} , \tag{6.12}$$

where m is the mass of the dark matter particle. From this we get the density today as (assuming negligible decay)

$$n_{\rm dm}(t_0) = \frac{a(t_{\rm d})^3}{a(t_0)^3} n_{\rm eq}(t_{\rm d}) = \frac{g_{*S}(T_0)}{g_{*S}(T_{\rm d})} \left(\frac{T_0}{T_{\rm d}} \right)^3 n_{\rm eq}(t_{\rm d}) , \tag{6.13}$$

where we have used the relation $g_{*S}(T) T^3 a^3 =$ constant, which follows from conservation of entropy. Their energy density is $\rho_{\rm dm} = m n_{\rm dm}$.

In order to determine the number density of a thermal relic, we need to know the mass, the decoupling temperature and the number of degrees of freedom at decoupling. At decoupling, we have $\Gamma = n_{\rm eq}(t_{\rm d}) \langle \sigma v \rangle$, so we need to know the mean of the cross section times the velocity. The cross-section depends on the details of the particle physics, but we can roughly parametrise the annihilation cross-section as $\sigma v \propto v^{2q}$, where $q = 0$ for annihilation in the ground state (*s-wave*), and $q = 1$ for annihilation in the *p-wave* state. This can be understood as an expansion in the square of the velocity, and since $v \ll 1$, only the leading term is relevant. (The p-wave term is only important if annihilation in the ground state is forbidden or strongly suppressed for some reason.) For a non-relativistic particle, $\langle v \rangle = \sqrt{8/\pi} \sqrt{T/m}$, so we write $\langle \sigma v \rangle = \sigma_0 (T/m)^q$. We therefore have

$$\Gamma(t_{\rm d}) = \sigma_0 m^3 \frac{g_{\rm dm}}{(2\pi)^{3/2}} y^{-q-3/2} e^{-y} , \tag{6.14}$$

where we have defined $y \equiv m/T_\mathrm{d}$; we have $y \gg 1$ since the dark matter particle is non-relativistic.

According to the Friedmann equation, the Hubble parameter is given by

$$3H^2 = \frac{\pi^2}{30M_{Pl}^2} g_*(T)T^4 \ , \tag{6.15}$$

so

$$H(t_\mathrm{d}) = \pi\sqrt{\frac{g_*(T_\mathrm{d})}{90}}\frac{m^2}{M_{Pl}}y^{-2} \ . \tag{6.16}$$

Equating $\Gamma(t_\mathrm{d}) = H(t_\mathrm{d})$, we get an equation from which we can solve the decoupling temperature in units of the dark matter mass, y,

$$N y^{1/2-q} e^{-y} = 1 \ , \tag{6.17}$$

where $N \equiv \sqrt{45/(4\pi^5 g_*(T_\mathrm{d}))} g_\mathrm{dm} M_{Pl} m\sigma_0$. For a given value of $g_\mathrm{dm} m\sigma_0/\sqrt{g_*(T_\mathrm{d})}$, we can straightforwardly solve y numerically from (6.17). However, we can also do an analytical approximation, writing (6.17) as

$$y = \ln N + \left(\frac{1}{2} - q\right)\ln y \ . \tag{6.18}$$

It is now transparent that for $y \gg 1$ we can drop the second term on the right-hand side, so $y \approx \ln N$. From (6.12) and (6.13), the relic abundance is then

$$\begin{aligned} n_\mathrm{dm0} &= \frac{g_{*S}(T_0)}{g_{*S}(T_\mathrm{d})}\frac{g_\mathrm{dm}}{(2\pi)^{3/2}} y^{3/2} e^{-y} T_0^3 \\ &= \frac{g_{*S}(T_0)}{g_{*S}(T_\mathrm{d})}\frac{g_\mathrm{dm}}{(2\pi)^{3/2}} N^{-1} y^{1+q} T_0^3 \\ &= \frac{\pi^3}{\sqrt{360}}\frac{g_{*S}(T_0)}{\zeta(3)}\frac{y^{1+q}}{\sqrt{g_*(T_\mathrm{d})}M_{Pl}m\sigma_0} n_{\gamma 0} \\ &\approx 5.31 \frac{y^{1+q}}{\sqrt{g_*(T_\mathrm{d})}M_{Pl}m\sigma_0} n_{\gamma 0} \ , \end{aligned} \tag{6.19}$$

where we have used (6.17), put $g_{*S}(T_\mathrm{d}) = g_*(T_\mathrm{d})$ (we assume that no particles are becoming non-relativistic as the dark matter decouples) and $g_{*s}(T_0) \approx 3.91$, and traded the temperature today for the photon number density via the relation $n_\gamma = 2\zeta(3)T^3/\pi^2$. The relic energy density $\rho_\mathrm{dm0} = m n_\mathrm{dm0}$ depends on the mass only logarithmically via y, apart from the possible mass dependence of σ_0.

6.6 The WIMP miracle

Let us consider a particle with with $g_\mathrm{dm} = 4$ (for example, a spin $\frac{1}{2}$ fermion with both left- and right-handed components), mass m not too different from GeV, weak-scale annihilation cross section $\sigma_0 \sim G_F^2 E^2 \sim G_F^2 m^2$, where the Fermi constant is $G_F \approx 1.17 \times 10^{-5}$ GeV^{-2}. Let us also assume that the particle annihilates via the s-wave process, $q = 0$. Then we have $n_\mathrm{dm0} \propto m^{-3}, \rho_\mathrm{dm0} \propto m^{-2}$. In the Standard Model, $g_*(T_\mathrm{d}) = 75.75$ for 4 GeV $> T >$ 1 GeV, and let us adopt that value. We then have $N \approx 2.9 \times 10^7 (m/\text{GeV})^3$, or $\ln N \approx 17 + 3\ln(m/\text{ GeV})$, which is also the approximate the value of y. We thus get $T_\text{d} \approx m/[17 + 3\ln(m/\text{ GeV})]$. This is consistent with the adopted value of $g_*(T_\text{d})$ only for roughly 40 GeV $\gtrsim m \gtrsim$ 10 GeV, but since $g_*(T_\text{d})$ enters only logarithmically, the value of T_d is not sensitive to the precise number of degrees of freedom. These numbers give

$$\begin{aligned} n_\text{dm0} &\approx 3 \times 10^{-8} \left(1 + 0.2 \ln \frac{m}{\text{GeV}}\right) \left(\frac{m}{\text{GeV}}\right)^{-3} n_{\gamma 0} \\ &= 3 \times 10^{-8} \eta^{-1} \left(1 + 0.2 \ln \frac{m}{\text{GeV}}\right) \left(\frac{m}{\text{GeV}}\right)^{-3} n_\text{b0} \\ &\approx 50 \left(1 + 0.2 \ln \frac{m}{\text{GeV}}\right) \left(\frac{m}{\text{GeV}}\right)^{-3} n_\text{b0} \ , \end{aligned} \tag{6.20}$$

where we have used the value $\eta = 6 \times 10^{-10}$. Since $m_\text{N} \approx 1$ GeV, we have

$$\rho_\text{dm0} \approx 50 \left(1 + 0.2 \ln \frac{m}{\text{GeV}}\right) \left(\frac{m}{\text{GeV}}\right)^{-2} \rho_\text{b0} \ . \tag{6.21}$$

For $m = 1$ GeV, we have $\rho_\text{dm0}/\rho_\text{b0} \approx 50$, whereas $m = 100$ GeV gives $\rho_\text{dm0}/\rho_\text{b0} \approx 10^{-2}$. As $\rho_\text{b0} \approx 0.05\rho_{c0}$, we get the bound $m \gtrsim 2$ GeV on the mass of the dark matter particle in order for its present density not to exceed the critical density. This is called the *Lee–Weinberg* bound. We get the observed ratio $\rho_\text{dm0}/\rho_\text{b0} \approx 5$ for $m \approx 3$ GeV. Note the assumptions in the derivation of the bound: the particle is assumed to be a thermal relic (i.e. the number density is determined by the thermal equilibrium distribution at decoupling) and the annihilation occurs via the s-wave process.

The fact that a thermal relic with weak interaction cross section and mass not too different (in logarithmic terms) from the weak scale gives the right relic abundance is called the *WIMP miracle*. However, in the MSSM, a weakly interacting dark matter particle with a mass of a few GeV would already have been detected in collider experiments. The lower mass limit from collider experiments for fermionic SUSY partners in the MSSM is around 94 GeV [5], but lighter particles can be viable in more complicated models. The preferred range for dark matter masses is of the order 100 GeV or so in the usually studied models. One can still get the right relic abundance by making the self-annihilation cross section smaller so that more particles remain, and extensions of the Standard Model such as MSSM contain enough free parameters to adjust the cross sections and masses. However, they can be independently tested in colliders and via direct and indirect detection of the dark matter particles, which we will shortly discuss.

6.7 Asymmetric dark matter

It is noteworthy that the observed dark matter abundance is so close to the baryon abundance, given that in the scenario discussed above the two are determined by completely different physics. The baryon number density is determined by the conservation of baryon number after *baryogenesis* in the primordial universe, while for a WIMP thermal relic the dark matter number density is determined by the balance between weak interactions and gravity via the freeze-out temperature.

There are also models where the dark matter abundance is determined by a conserved quantum number, as is the case for baryons. It is illustrative to first consider what would happen if there were no baryon-antibaryon asymmetry. Then the baryon abundance would be determined by the freeze-out of nucleon annihilations just as in the case for WIMP dark matter. We have $g = 4$ (protons and neutrons both have 2 spin states) and $m_N = 0.94$ GeV. The nucleon-antinucleon annihilation cross section is $\langle\sigma v\rangle = \sigma_0 \sim m_{\pi^0}^{-2}$, where the neutral pion mass is $m_{\pi^0} = 135$ MeV. We take $g_*(T_\mathrm{d}) = 10.75$, which is the value for T_d between 100 MeV and 0.5 MeV. These numbers give $N \approx 6 \times 10^{19}$, or $\ln N \approx 46$, which gives $y \approx 50$. For the freeze-out temperature we get $T_\mathrm{d} \approx 19$ MeV. The resulting nucleon abundance is $n_{N0} \approx 7 \times 10^{-19} n_{\gamma 0}$, about 10^{-9} times smaller than the observed nucleon density $n_{N0} = n_{\mathrm{b}0} = 6 \times 10^{-10} n_{\gamma 0}$.

This failure of the reasoning based on the naive freeze-out argument which does not account for the presence of a conserved quantum number can be light-heartedly called the *"baryon catastrophe"*. The lesson is that primordial baryon asymmetry and the conservation of baryon number are essential in determining the baryon density.

We don't know what is the correct theory of particle physics that determines the dark matter density. In many models, such as MSSM, there is no dark matter-antimatter asymmetry. However, there are also models where the dark matter carries a conserved quantum number which has an asymmetry generated at early times. In particular, this is the case in some *technicolour* models.

In the Standard Model colour interaction, quarks are the relevant degrees of freedom at high energies, but at low energies they are bound into mesons and baryons. Technicolour is a higher energy version of the same idea. In technicolour, the Higgs is not an elementary particle, but a bound state of some elementary fields which become visible when probing sufficiently high energies. Technicolour models also contain other bound states, just like QCD, and one of those bound states could be the dark matter particle. In correspondence to the baryon number B of the Standard Model, there is the *technibaryon number* T_B, carried by elementary technicolour particles and their bound states. If there is a conserved asymmetry in the technibaryon number, the abundance of dark matter particles may be determined by this asymmetry, and it can be very different from the freeze-out abundance we calculated above, as is the case for baryons.

If the process which generates the asymmetry in the dark matter is related to the process that generates the asymmetry in the baryons (*baryogenesis*), then the baryon and dark matter number densities are naturally related to each other. This possibility is called *cogenesis*. Alternatively, the quantum numbers could be related because they are mixed by some later process, a possibility called *sharing*. The details depend on the particle physics models, and as in the case of WIMP thermal relics, we keep the discussion at a general level.

If the dark matter particle carries one unit of the conserved quantum number Q (which could for example be the technibaryon number) and the symmetry-violating interactions produce N units of Q for every unit of B, and there is no mixing afterwards, the dark matter abundance today is simply

$$n_{\mathrm{dm}0} = N n_{\mathrm{b}0} \ , \tag{6.22}$$

so

$$\frac{\rho_{\mathrm{dm}0}}{\rho_{\mathrm{b}0}} = N \frac{m_{\mathrm{dm}}}{m_N} \ , \tag{6.23}$$

which agrees with the observed ratio ≈ 5 for $m_{\rm dm} = 5/N$ GeV.

One constraint on such models is that the phase space distribution of the dark matter particles has to correspond to CDM (or WDM). So the dark matter particle cannot have decoupled at the electroweak crossover with a thermal distribution function if its mass is smaller than 100 GeV. However, a model where the distribution function is not thermal would be possible – the essential thing is that the high momentum states of the dark matter particles are not occupied. From the point of view of technicolour models, $m_{\rm dm} \lesssim 10$ GeV is also an unnaturally low mass unless $N \ll 1$, since the technicolour scale has to be $\gtrsim 1$ TeV to be consistent with collider experiments (no technicolour bound states –or any other signatures of technicolour for that matter– have been observed). Naively, one would expect the mass of the stable technicolour dark matter particle to be of this order, or at least of the order of the Higgs mass, $m_H = 125$ GeV, since they have the same origin as bound states. But there could be a reason why the lightest stable fermionic bound state is much lighter than a bosonic unstable state. (In QCD, the lightest bosonic bound states, the pions with $m_{\pi^0} = 135$ MeV and $m_{\pi^\pm} = 140$ MeV, are about an order of magnitude lighter than the lightest stable bound state, the proton with $m_p = 938$ MeV, because of *chiral symmetry*.)

Alternatively, we can have reactions that mix particles carrying baryon number and particles carrying Q together, so that their relative abundance depends on the freeze-out temperature T_f of these interactions. Let's say that we have reactions which interconvert baryons and dark matter particles,

$$\mathrm{dm} + X \leftrightarrow q + Y \ , \tag{6.24}$$

where q stands for a quark, which carries $B = 1/3$, dm stands for the dark matter particle that carries $Q = 1$ (or any other particle carrying the same quantum number), and X and Y are particles which carry neither B nor Q, and we assume we can neglect their chemical potentials. We then have, as long as these reactions are in equilibrium, $\mu_{\rm dm} = \mu_q$. Let us assume that these reactions freeze out at the electroweak crossover, and take the particle carrying the quantum number to be massless. (Since the top quark receives a mass of the order of the electroweak scale at the crossover, this assumption may seem questionable. However, at least in some technicolour models, the mass of the top quark does not make a difference [6].)

We assume that the technicolour particles are in thermal equilibrium. In order for them to count as CDM, we then need $m_{\rm dm} \gg T_f$. We thus have

$$\begin{aligned} n_B - \bar{n}_B &= g_B T^3 \frac{\mu_B}{T} \\ n_{Q_{\rm dm}} - \bar{n}_{Q_{\rm dm}} &= g_{\rm dm} \left(\frac{m_{\rm dm} T}{2\pi} \right)^{3/2} e^{-\frac{m_{\rm dm}}{T}} \left(e^{\frac{\mu_{\rm dm}}{T}} - e^{-\frac{\mu_{\rm dm}}{T}} \right) \\ &\simeq 2 \frac{\mu_{\rm dm}}{T} g_{\rm dm} \left(\frac{m_{\rm dm} T}{2\pi} \right)^{3/2} e^{-\frac{m_{\rm dm}}{T}} \ , \end{aligned} \tag{6.25}$$

where we have taken into account that the asymmetries and thus the chemical potentials are small, and $g_B = 24$ (the number of degrees of freedom in the quarks is 72, and each quark has $B = 1/3$). Note that just as g_B is the number of degrees of freedom which carry the conserved quantum number B which ends up in baryons, $g_{\rm dm}$ is the number of degrees of freedom which carry $Q_{\rm dm}$, which in the late universe is carried by the dark matter particles only. Equating the chemical potentials and noting that today $\rho_{b0} = m_N n_{b0}$, we obtain

$$\frac{\rho_{dm0}}{\rho_{b0}} = \frac{g_{dm}}{12(2\pi)^{3/2}} \frac{m_{dm}}{m_N} \left(\frac{m_{dm}}{T_f} \right)^{3/2} e^{-\frac{m_{dm}}{T_f}} . \tag{6.26}$$

Taking $g_{dm} = 100$ and $T_f = 160$ GeV, we get the observed abundance for $m_{dm} \approx 1200$ GeV ~ 1 TeV. (The temperature at which the electroweak crossover happens may change from the Standard Model value 160 GeV due to the new particles and interactions present in technicolour.)

The technicolour models share the same weakness as the MSSM: because their scale is close to the Standard Model scale of 100 GeV, we would have expected to have seen technicolour particles or supersymmetric partners at the LHC. No physics beyond the Standard Model have been seen at the LHC.

6.8 Dark matter vs. modified gravity

Since all evidence for dark matter comes from its gravitational effects, it could in principle be possible to explain the observations by instead changing the law of gravity. Until the dark matter particle is detected, there is room for reasonable doubt. The problem for such *modified gravity* proposals is that there are many different observations explained by dark matter, in different physical systems: motions of stars in galaxies, motions of galaxies in clusters, gravitational lensing, large-scale structure, CMB anisotropies, and so on. Gravity has to be adjusted in a different manner for these different observations, and the resulting models are rather contrived. Expressed another way, the dark matter scenario is very predictive: the simple hypothesis of a massive particle with weak couplings to itself and to the Standard Model particles explains a number of disparate observations and has made several successful predictions.

One example that has received a lot of attention is the *Bullet cluster* [7]. It a collision between two clusters of galaxies, shown in figure 2. In the dark matter scenario the mass of a galaxy cluster has three main components: 1) visible galaxies, 2) intergalactic gas and 3) dark matter. The last component is expected have the largest mass, and the first one the smallest. When two clusters of galaxies collide, it is unlikely for individual galaxies to crash, and the intergalactic gas is too thin to noticeably slow down the relatively compact galaxies. On the other hand, the intergalactic gas components do not travel through each other freely, but are slowed down and heated up by the collision. Thus after the clusters have passed through each other, much of the intergalactic gas is left behind between the receding clusters. Dark matter should be weakly interacting, and thus practically collisionless. So the dark matter components of both clusters should also travel through each other unimpeded.

In the Bullet cluster the intergalactic gas has indeed been left behind the galaxies in the collision. The mass distribution of the system has been estimated from the gravitational lensing effect on the shapes of galaxies behind the cluster. If there were no CDM, most of the mass would be in the intergalactic gas, whose mass is estimated to be about five times that of the visible galaxies. Even in a modified gravity theory, we would expect most of the lensing effect to be where most of the mass is. However, expectation is not proof, so the observation cannot be said to rule

Figure 2: A composite image of galaxy cluster 1E 0657-56, also called the Bullet Cluster. It consists of two subclusters, a larger one on the left, and a smaller one on the right. They have recently collided and travelled through each other. One component of the image is an optical image which shows the visible galaxies. Superposed on it, in red, is an X-ray image, which shows the heated intergalactic gas, that has been slowed down by the collision and left behind the galaxy components of the clusters. The blue colour is another superposed image, which represent an estimate of the total mass distribution of the cluster, based on gravitational lensing. NASA Astronomy Picture of the Day 2006 August 24. Composite Credit: X-Ray: NASA/CXC/CfA/M. Markevitch et al. Lensing map: NASA/STScI; ESO WFI; Magellan/U. Arizona/D. Clowe et al. Optical: NASA/STScI; Magellan/U. Arizona/D. Clowe et al..

out all possible models of modified gravity. Nevertheless, it does provide an example of a successful prediction of the dark matter hypothesis.

6.9 Direct detection

As we have seen, there are different plausible mechanisms for producing the observed dark matter abundance. (There also mechanisms that we did not discuss, involving neither a conserved quantum number nor a thermal relic, such as those relevant for axions and gravitinos.) These mechanisms are in turn realised in many different models. In order to distinguish between the models and confirm the identity of the dark matter particle, and to be sure that the correct interpretation of observations is really dark matter and not modified gravity, we have to observe dark matter via non-gravitational interactions.

Usually, detection of dark matter is divided into three different categories: producing the dark matter particle at colliders (*collider detection*), measuring the interactions dark matter with baryonic matter in the laboratory (*direct detection*) and measuring the end products of astrophysical dark matter annihilation or decay (*indirect detection*). A fourth category could be added, *astrophysical detection*, detecting the influence of dark matter on stars and the intergalactic medium. For example, dark matter annihilation in the early universe can heat up the gas that forms stars and thus have an impact on the formation of early stars and reionisation. It has also been suggested that the first stars would be powered mainly by dark matter annihilation instead of fusion reactions: these have been dubbed *dark stars* [8] (something of a misnomer, as they are in fact brighter than normal stars). The Bullet Cluster and similar observations have put a constraint on the self-interactions of dark matter, as well as the nong-gravitational interactions between dark matter and baryonic matter, but they could also yield a detection of such interactions via the displacement of dark and baryonic matter due to non-gravitational friction. Another novel possible signature is the suppression of small-scale structure due to the large de Broglie wavelength for extremely light dark matter candidates, with mass $\sim 10^{-21}$ eV, called *fuzzy dark matter*. Detailed collider signals are also properly the topic of a specialised particle physics course, we simply note that if dark matter physics is related to the electroweak scale, whether via supersymmetry, technicolour or some other theory, then it is expected to be accessible in experiments at the LHC. On the other hand, axions or light warm dark matter particles would not necessarily have any signature in high-energy colliders.

Let us first consider direct detection. Since dark matter is everywhere, including on (and in) the Earth, we may be able to detect its interactions with baryonic matter if we look carefully enough. As dark matter interactions with ordinary matter have to be weak in order to agree with cosmological observations, sensitive dedicated experiments are required. Mostly WIMPs, like neutrinos, pass through the Earth without interacting, but sometimes they interact with ordinary matter. A typical WIMP direct detection setup is a well isolated crystal or liquid sample, which is being observed to find the energy and momentum deposited inside it by a collision of a nucleus with a dark matter particle.[4] The problem is that many background events

[4]For dark matter particles that do not feel the weak interaction, different detection methods are needed. For axions, one kind of a detector is a low noise microwave cavity with a large magnetic field. An axion may interact with the magnetic field and convert into a microwave photon. No

can cause a similar signal: WIMP detectors see spurious signals all the time. One way to eliminate them is to combine different detection channels, like light signals from and vibration of the target. Another way is to look for an annual modulation in the signal. WIMPs, if they exist, have a particular velocity distribution related to the gravitational well of our galaxy. They are expected to be, on average, at rest with respect to the Galactic rest frame. The Earth is moving with respect to this frame, because the Sun orbits the center of the Galaxy and the Earth orbits the sun. The annual change in the direction of Earth's motion should result in a corresponding variation in the detection rate.

Let us estimate the expected energy deposition from the elastic collision of a dark matter particle and a nucleus. Dark matter velocities are non-relativistic (by definition), so in the laboratory frame we have from conservation of energy and momentum

$$\begin{aligned} \frac{1}{2}mv^2 &= \frac{1}{2}mv_{\rm dm}^2 + \frac{1}{2}m_{\rm t}v_{\rm t}^2 \\ mv &= mv_{\rm dm} + m_{\rm t}v_{\rm t} \ , \end{aligned} \tag{6.27}$$

where $m_{\rm t}$ is the mass of the target nucleus, and m is still the dark matter mass. For the kinetic energy $E = \frac{1}{2}m_{\rm t}v_{\rm t}^2$ given to the nucleus, we get

$$\begin{aligned} E &= \frac{2m_{\rm t}}{(1+m_{\rm t}/m)^2}v^2 \\ &\approx \frac{2A}{(1+Am_N/m)^2}\left(\frac{v}{300\ \rm km/s}\right)^2 \ \rm keV \ , \end{aligned} \tag{6.28}$$

where A is the mass number of the target nucleus and $m_{\rm t} \approx Am_N$.

The velocity distribution of the dark matter particles is often taken to be Maxwellian (with a cut-off at the Galactic escape velocity), with a dispersion of $220/\sqrt{2}$ km/s, the velocity of the Solar system with respect to the Galaxy is 230 km/s, and the velocity of the Earth relative to the Sun is 30 km/s. A rough estimate of the typical root mean square velocity is thus $v \approx 200\ldots300$ km/s. Note that the interaction strength is irrelevant for the energy exchange, it only affects the probability of the interaction (i.e. the rate of events observed in the detector). The expected annual modulation is roughly 30 (km/s)/v, which in our approximation is about 10%. There are uncertainties in the dark matter distribution and the rotation of the Solar system in the Galaxy, and the real annual modulation rate can be between 1% and 10% [9].

The event rate depends on the dark matter-nucleus cross-section, $\sigma_{\rm dm-nucleus} \approx A^2\sigma_{{\rm dm}-p}$, where $\sigma_{{\rm dm}-p}$ is the dark matter-proton cross section. The dark matter-proton cross section can be completely different from the dark matter-dark matter annihilation cross section. The total number of events per unit time is given by the interaction rate of a single nucleus the number of nuclei in the target with mass M, which we denote by $N = M/(Am_N)$:

$$\begin{aligned} \Gamma N &= \langle\sigma_{\rm dm-nucleus}v\rangle n_{\rm dm}N \\ &\approx \frac{2\times10^4 A}{\rm yr}\frac{M}{\rm ton}\frac{\langle\sigma_{{\rm dm}-p}v\rangle}{10^{-40}\ {\rm cm}^2\times300\ {\rm km/s}}\frac{\rho_{\rm dm}}{0.3\ {\rm GeV/cm}^3}\left(\frac{m}{\rm GeV}\right)^{-1} \ , \end{aligned} \tag{6.29}$$

axions have been detected.

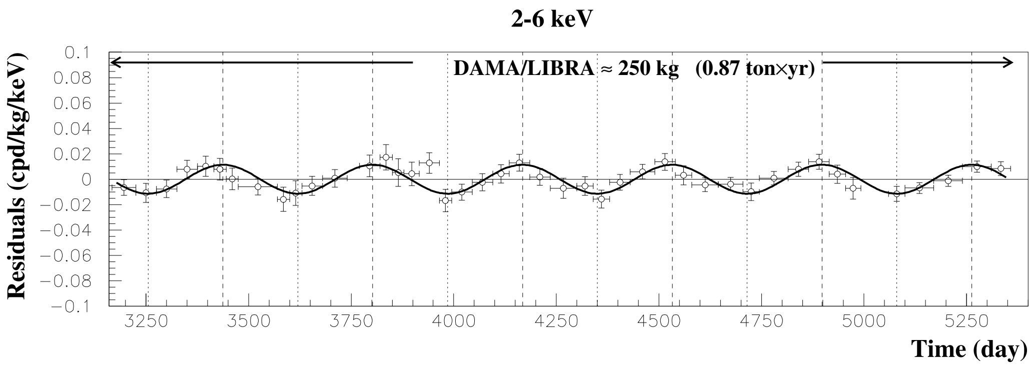

Figure 3: Modulation of the detection rate of the DAMA/LIBRA experiment in the 2-6 keV energy range, in units of counts per day/kg/keV. From [10].

where we have inserted typical values for the cross section, velocity and dark matter density. The latter two are determined by taking a given density profile for the dark matter as a function of radius and using the observed rotation curves, and they also agree with typical values obtained from galactic simulations of dark matter.[5] For comparison, the weak interaction annihilation cross section for 1 GeV mass is $\sigma \sim G_F^2\ \mathrm{GeV}^2 \sim 10^{-10}\ \mathrm{GeV}^{-2} \approx 4 \times 10^{-38}\ \mathrm{cm}^2 \approx 10^{-27}\ \mathrm{cm}^3/\mathrm{s}$, using the relation 197 MeV $\approx$ 1/fm.

One direct detection experiment, DAMA/LIBRA[6] has claimed to have detected dark matter. They see an annual modulation in the event rate with the maximum on June 2 and minimum around 2 December, as expected based on the direction of the Solar system's velocity with respect to the galaxy and the Earth's velocity with respect to the Sun. They use a sodium-iodine crystal, which has a mixture of $A = 23$ and $A = 127$. The modulation of the rate is shown in figure 3. The peak of the energy is at 3 keV, corresponding to a dark matter particle mass around 10 GeV. They had a total of about 1.17 ton×year of exposure in the beginning of 2010 (when figure 4 was released), so we would expect about $4 \times 10^5 \sigma_{\mathrm{dm}-p}/(10^{-40}\ \mathrm{cm}^2)$ events. With a modulation rate of 10%, this roughly agrees with the number 0.02 in figure 3 for $\sigma_{\mathrm{dm}-p} \approx 10^{-40}\ \mathrm{cm}^2$. (Note that the y-axis for counts per day/kg/keV. We should integrate that number over the energy-dependent count rate over the range 2–6 keV to compare to our estimate; this will give a factor of order unity.) DAMA/LIBRA has taken much more data since 2010, all of which according to their analysis is consistent with dark matter, and no one has found any systematic effect that could account for it.

However, other direct detection experiments have ruled out ordinary WIMPs scattering elastically as an explanation for DAMA/LIBRA, as shown in figure 4. Non-elastic collisions involving an excited state of the dark matter particle and other physics that makes the collisions different for different target nuclei have been

[5] The energy density one gets in detailed analyses typically does not vary from $\rho_{\mathrm{dm}} = 0.3\ \mathrm{GeV/cm}^3$ by more than a factor of a few. However, strictly speaking, observations are consistent with no dark matter in the Solar system. The direct upper limit on the density of dark matter in the Solar system comes from the fact that no disruption of planetary orbits in has been observed, and it is about 10^6 times this value. As far as the galactic rotation curves is concerned, dark matter is needed more in the outer parts of the Milky Way than at our location.

[6] https://www.lngs.infn.it/en/dama

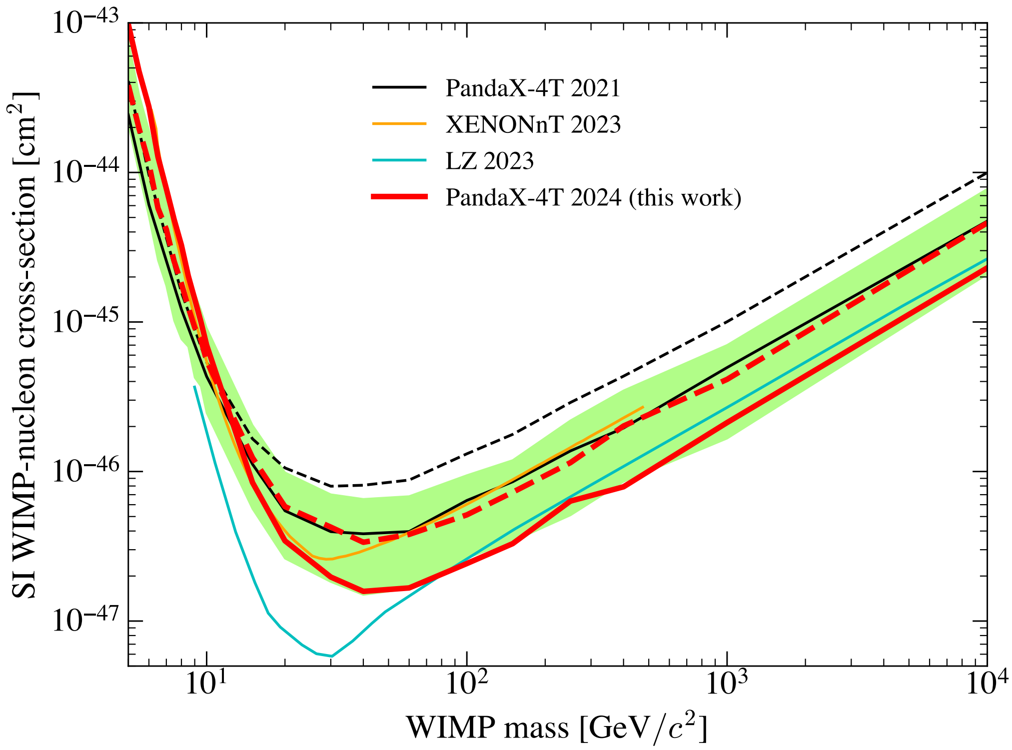

Figure 4: Allowed regions of parameter space for a WIMP scattering elastically with protons and neutrons from the PandaX experiment and other direct detection experiments. The parameter values of the WIMP interpretation of the DAMA result lie deep inside the excluded region (above the lines). From [12].

proposes as a way to reconcile the signal in DAMA/LIBRA and the absence of a signal in other experiments. However, other experiments have then used the same nuclei and the same type of crystals as DAMA/LIBRA, most notably the ANAIS experiment, which sees no signal and has almost ruled out any new physics origin of the DAMA/LIBRA modulation [11]. The experiments COSINE-100[7] and COSINUS[8] are also using sodium iodine crystals, and are expected to close remaining loopholes in the comparison of the experimental results.

The DAMA/LIBRA results highlight the importance of having multiple experiments, and the results that exclude also show how the allowed interaction cross sections between nucleons and WIMPs are now far below the electroweak cross-section. The original WIMP miracle therefore seems less attractive, although it is important to bear in mind that the cross-section relevant for the relic abundance is the WIMP self-interaction cross-section, whereas direct detection probes the WIMP-nucleon cross-section, and they can be very different. In contrast, indirect detection can probe the self-interaction cross-section.

[7] https://cosine.yale.edu/about-us/cosine-100-experiment

[8] https://www.lngs.infn.it/en/cosinus-eng

6.10 Indirect detection

Indirect detection refers to the case when the dark matter particle is identified through its annihilation or decay products. If there are no dark matter antiparticles around, as is the case for asymmetric dark matter, there is no annihilation signal. If the particle is stable or has a lifetime much longer than the age of the universe, there is no detectable signal from decays. We consider only annihilation.

The relic density of a thermal relic WIMP is determined by when the annihilation reactions freeze out, related to the density getting so low that particles and antiparticles don't meet. However, the density in local clumps grows during structure formation, and this can lead to observable amounts of annihilation. (Note the similarity to nuclear reactions: they freeze out in the early universe, but light up again in regions where the density of baryonic matter rises sufficiently due to gravitational collapse.)

The amount of annihilation is proportional to the square of the dark matter density, so the largest signal is expected from regions with high dark matter density, such as dwarf galaxies or the centre of our own galaxy. Dark matter can also accumulate in the Sun and at the centre of the Earth, and though the numbers are much smaller, these locations are much nearer to us, so detection is easier. However, only neutrinos can escape from the Sun or the centre of the Earth, whereas in the case of other astrophysical objects we can observe several kinds of annihilation products – though there too the propagation of charged particles is a bit complicated. From the direction where we measure a positron or an antiproton we cannot deduce where the source is, since the paths of charged particles are twisted by magnetic fields on the way. Therefore, only the detected number of charged particles carries useful information, not their direction (and to calculate the expected numbers we have to make some assumptions about propagation). In contrast, neutrinos, and photons at the relevant energies, travel basically unimpeded through the galaxy, so we can immediately determine where they have come from. (Scattering of light due to dust is negligible at high energies.)

As noted, indirect detection has the virtue that it probes the same process that determines, for thermal relics, the relic abundance. This means that for a given dark matter particle mass the cross-section is fixed. The drawback is that the observational signal is very dependent on the decay channel. There is also uncertainty from lack of knowledge of the small-scale structure of the dark matter density distribution. Foregrounds, i.e. radiation from astrophysical processes, are also a significant complication for the interpretation of the signals. There have been several observations that people have rushed to interpret as being due to dark matter annihilation, but nothing definite has emerged, as astrophysical foregrounds have not been ruled out. Existing bounds for WIMPs are model-dependent, but for masses $\lesssim 10$ GeV already exclude WIMPs, under assumptions about the decay channels. As with direct detection, the reach of indirect detection experiments is increasing, and many avenues are being investigated.

Whether dark matter will be detected (via its non-gravitational interactions) depends on which model of dark matter is correct. It is worth bearing in mind that there are some candidates, such as gravitinos and Planck-scale primordial black hole relics, whose non-gravitational interactions are too weak to detect in the foreseeable future.

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