

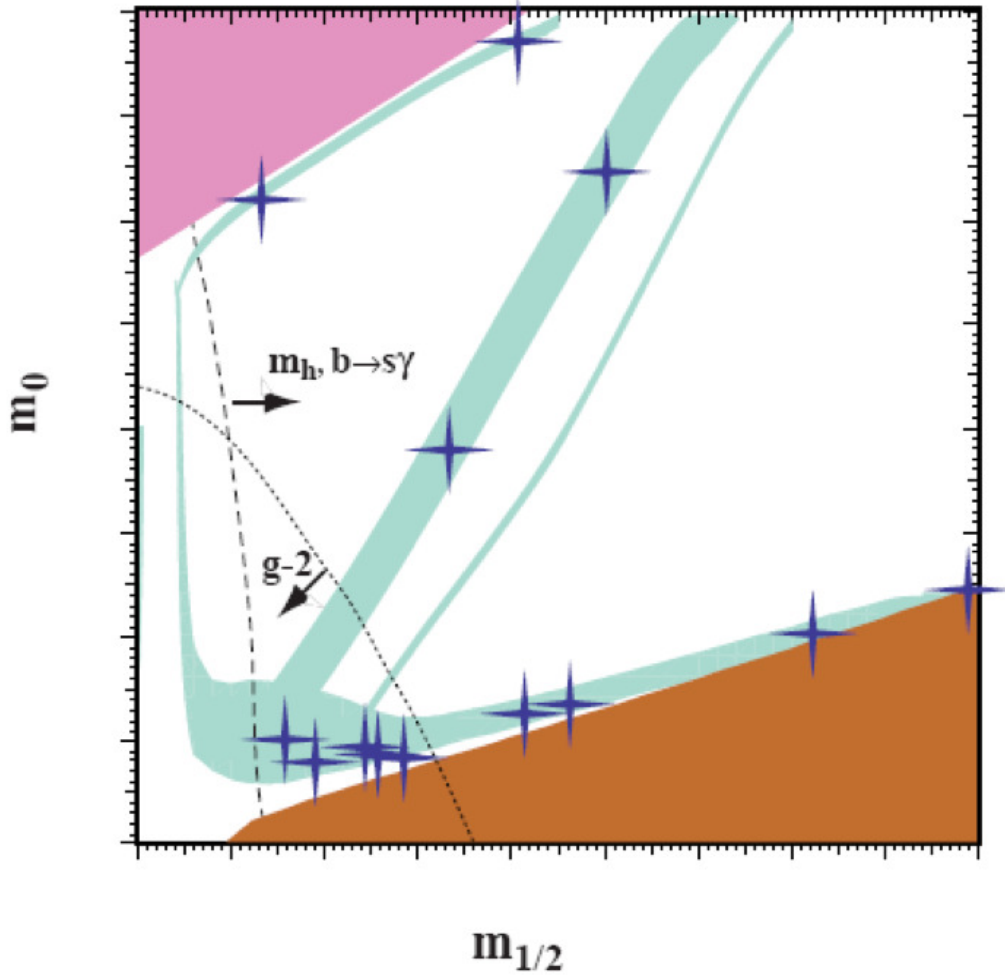


Figure 8.3: Generic illustration of the allowed neutralino dark matter regions (puke green) in the $(m_0, m_{1/2})$ -plane for mSUGRA. Except for the low m_0 and $m_{1/2}$ regions the area outside of the allowed green region gives too much dark matter. The dashed line shows the Higgs mass limit which pushes towards larger values of $m_{1/2}$, while the dotted line represents the limit from the anomalous magnetic moment of the muon.

8.3.2 Sneutrinos

The left handed sneutrino $\tilde{\nu}_L$ is happily excluded as a potential dark matter candidate due to the large cross section for $\tilde{\nu}_L q \rightarrow \tilde{\nu}_L q$ via Z -exchange.⁴ The large cross means that it should already have been seen by direct detection experiments, see Sec 8.4. It is also problematic to get $m_{\tilde{\nu}_L} < m_{\tilde{l}_L}$ due to hyperfine-splitting. However, the right-handed sneutrino $\tilde{\nu}_R$ couples very weakly and is still a viable candidate. This would necessitate adding right-handed

⁴For the neutralinos this problem only exists for a higgsino $\tilde{\chi}_1^0$ LSP, as the wino and bino do not couple to the Z .

neutrinos and sneutrino superfields to the MSSM.

8.3.3 Gravitino

The **gravitino** is the massive spin-3/2 supersymmetric partner of the graviton in models with supergravity. With only gravitational strength interactions, the gravitino is *not* a WIMP as it is never in chemical equilibrium. If it is the LSP it can be created from the decays of the next-to-lightest supersymmetric particle (NLSP), giving, in R-parity conserving scenarios,

$$\Omega_{\tilde{G}} = \frac{m_{\tilde{G}}}{m_{\text{NLSP}}} \Omega_{\text{NLSP}}.$$

However, these scenarios are problematic because the NLSP is long-lived due to the extremely weak interaction and creates potential trouble in BBN by injecting energy that changes the production of light elements.

Alternatively, the gravitino can be created in non-thermal production processes in the period of reheating after inflation. One potential process $gg \rightarrow \tilde{g}\tilde{G}$ is shown in Fig. 8.4. The reverse process $\tilde{g}\tilde{G} \rightarrow gg$ is not efficient as the density of gravitinos is never high enough given the small cross section. This type of dark matter creation process is often called **freeze-in**. For the gravitino this gives a new magic formula:

$$\Omega_{\tilde{G}} h^2 \approx 0.5 \cdot \left(\frac{T_R}{10^{10} \text{ GeV}} \right) \left(\frac{100 \text{ GeV}}{m_{\tilde{G}}} \right) \left(\frac{m_{\tilde{g}}}{1 \text{ TeV}} \right)^2, \quad (8.3)$$

where T_R is the unknown and very weakly constrained reheating temperature. This production mechanism is also valid for models with R-parity violation. There the small gravitino coupling $\propto \frac{1}{M_P}$ makes the gravitinos very long-lived, with lifetimes longer than the age of the Universe, but not absolutely stable because of the R-parity violating operators.

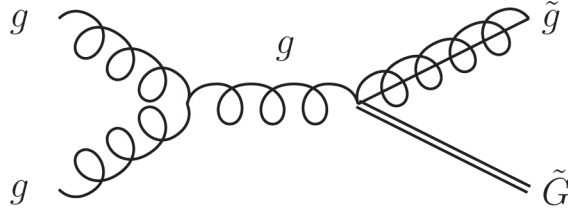


Figure 8.4: One possible diagram for the non-thermal production of gravitinos from the scattering of gluons.

8.3.4 Others

One could even imagine colour charged supersymmetric particles as dark matter, in particular the gluino, which, if stable, after hadronisation with Standard Model quarks and/or gluons would form so-called **R-hadrons**. These have very strict limits from searches, but these limits are somewhat obfuscated by complications in modelling R-hadron scattering.

8.4 Direct detection

In addition to the direct production of dark matter at colliders and the corresponding searches for missing energy, there are two other main ways to search for dark matter, direct and indirect detection. Here we briefly discuss **direct detection**.

Direct detection seeks to make weak and thus rare dark matter interactions with standard model matter visible by very low background searches in large volumes, using local galactic halo dark matter interacting with ordinary matter on Earth. The feasibility of direct detection is very dependent on the χ scattering cross section on nucleons (quarks), which can in principle be calculated in a given model⁵ but also on the dark matter halo density distribution and velocity distribution, which have large uncertainties.

The rate of interaction between dark matter and a particular type of nucleons in a sample can be expressed in the differential scattering rate with respect to the recoil energy E_r of a scattered nucleon with mass M as

$$\frac{dN}{dE_r} = \frac{\sigma \rho_{DM}}{2\mu^2 m_\chi} |F(q)|^2 \int_{v_{min}}^{v_{esc}} \frac{f(\vec{v})}{v} d^3v, \quad (8.4)$$

where σ is the dark matter scattering cross section off the nucleus in question, ρ_{DM} is the dark matter halo density at Earth, $\mu = m_\chi M/(m_\chi + M)$ is the dark matter and nucleus reduced mass, $F(q)$ is a nuclear form factor dependent on the scattering momentum transfer $q = \sqrt{2ME_r}$ and the nucleon type, $f(\vec{v})$ is the velocity distribution of the dark matter in the halo, $v_{min} = \sqrt{ME_r/2\mu^2}$ is the minimal velocity that gives a recoil energy E_r and v_{esc} is the escape velocity from the halo.

In general direct detection relies heavily on suppressing Standard Model backgrounds which would be the overwhelmingly dominant cause of observed recoils. This is done by moving the experiments deep under ground where they are shielded from cosmic rays, and by specifically shielding the detector samples against local radioactivity. Beyond this, there are two main tactics followed in order to try to directly detect dark matter:

- Suppress (almost) all backgrounds and monitor as large a volume as possible. This used in experiments such as XENON, PANDAS and CDMS.
- Look for an annular modulation in the event rate – due to the Earth’s movement in the galactic rest frame and thus in the dark matter halo, changing the velocity integral in Eq. (8.4) – to observe a small dark matter signal on top of a constant background, such as used in the DAMA and CoGeNT experiments.

Figure 8.5 shows results from the current most important direct detection experiments as limits on the dark matter–nucleon cross section as a function of dark matter mass. Observe that while DAMA claims a detection (closed regions), these are already excluded by many other experiments. For reference, a neutralino WIMP could reasonably be expected to have a scattering cross section in the range $10^{-45} - 10^{-50} \text{ cm}^2$ for masses in the range 100–1000 GeV [52]. The dashed yellow line shows what is called the **neutrino floor**. This is the cross section that can be reached before the experiments would be saturated with recoils due to neutrinos scattering off the experiment sample. Going below the neutrino floor would need

⁵However, while the quark–dark matter cross section is relatively easy to calculate, the fact that the quark is bound in a nucleon, and the nucleon bound to a nucleus makes this more difficult in practice, involving also estimates from nuclear physics.

new experimental techniques, fundamentally, the direction of the particle creating the recoil would need to be reconstructed.

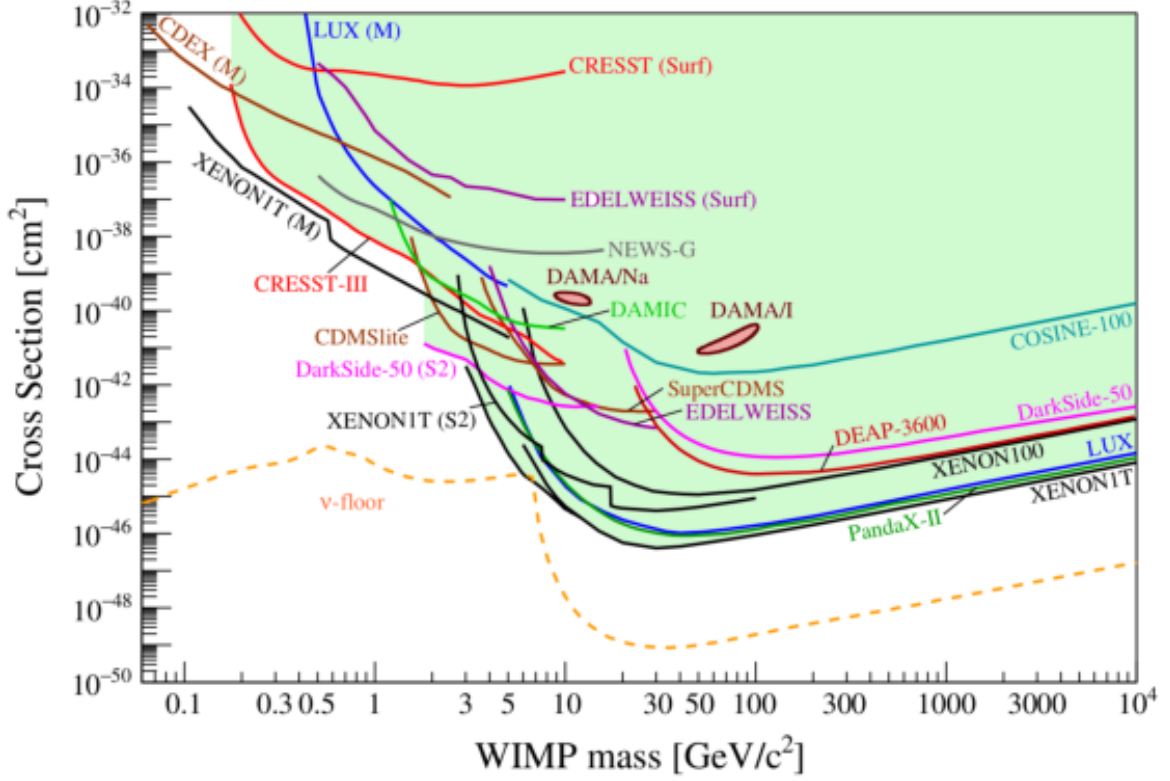


Figure 8.5: Plot of different exclusion and detection results for direct detection of dark matter in the WIMP mass versus WIMP–nucleon cross section plane [53]. The dashed yellow line shows the neutrino floor.

8.5 Indirect detection

In **indirect detection** we look for the annihilation, $\chi\chi \rightarrow SM SM$, or decay products of dark matter in multiple final (messenger) states in cosmic rays. The viable search channels must be stable Standard Model particles, so that they can reach the Earth (or satellites in orbit). The messengers should also have as low backgrounds from ordinary astrophysical processes as possible, this makes searches with electrons and protons extra challenging. The remaining candidates are photons, neutrinos, positrons, antiprotons and antideuterons.^[6] We now discuss the properties of each of these in a little more detail.

Photons

These can either come from direct production processes such as the annihilation channels $\chi\chi \rightarrow \gamma\gamma, Z\gamma$, which is relatively easy to detect because the spectrum is a sharp line at

^[6]Potentially, even heavier antinuclei than antideuterons could be used, but they would be even rarer.

exactly the mass of the dark matter, or they could be γ from bremsstrahlung or pion decays in the annihilation decay products, which creates a broad spectrum. This is harder to detect because of the large background of bog-standard astrophysical photons, but is expected to make up the majority of photons from dark matter. Photons from dark matter have the advantage that they point to the source, so we can focus our searches on areas in our galaxy or nearby galaxies with large ρ_{DM} , where annihilation or decay is more probable, and thus reducing potential backgrounds relative to the signal. We can also look for photons that are extragalactic in origin, but then we have to account for the red-shifting of the spectrum.

Dark matter annihilating in our own galaxy into photons should result in a differential flux at Earth in terms of energy E and solid angle Ω given by

$$\frac{d\Phi}{dEd\Omega} = \frac{1}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \langle\sigma v\rangle \int_{\text{l.o.s.}} \rho_{DM}^2(l) dl, \quad (8.5)$$

where $N_\gamma(E)$ gives the number of photons with energy E in a single annihilation event and the integral is over the dark matter density in the line of sight. We see that the flux depends on the square of the dark matter density since annihilation requires two particles to be present. For decaying dark matter the corresponding expression is proportional to ρ_{DM} .

There have been some indications of an excess of photons above expected backgrounds from the galactic centre (a.k.a. the Hooperon [54]), however, no unambiguous dark matter signal has been confirmed. Current limits from the Fermi-LAT experiment seems to rule out most possible models for a dark matter explanation for this excess, and, more importantly, sets a cross section limit for dark matter annihilation close, and for some masses beyond, to the canonical limit of

$$\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1},$$

which would give the correct dark matter density, see Fig. 8.6.⁷ This limit is some of the strongest evidence today against WIMP dark glitter.

Neutrinos

These also point to their source since since they are electrically neutral, and can be extragalactic in origin just like the photons, still reaching the Earth. The same flux calculation can be used, starting from the neutrino spectrum from dark matter annihilation. While the astrophysical background is much smaller, the neutrino signal is difficult to detect due to the weak matter interaction. The current leading experiment in detecting neutrinos from dark matter annihilation or decay is the IceCube experiment at the South Pole that has instrumented a cubic kilometre of the South Pole ice with photodetectors a kilometre below the surface.⁸

One interesting alternative possibility is that dark matter scatters on ordinary matter sufficiently strongly that the dark matter accumulates at the centre of the Sun (or possibly the Earth), because it scatters off the Sun's atoms, loses energy and becomes gravitationally bound, ultimately being further downscattered in energy in multiple interactions, settling at the Sun's centre. When these DM particles annihilate the only decay products that can escape the Sun's interior are neutrinos. These could then potentially be detected, and the fact that

⁷Keep in mind though, that the velocity distribution of any dark matter today would not be the same as during freeze-out at a much higher temperature, so the cross section numbers are not exactly translatable.

⁸This should, on galactic scales, get some sort of prize for the geniusly nutscase idea.

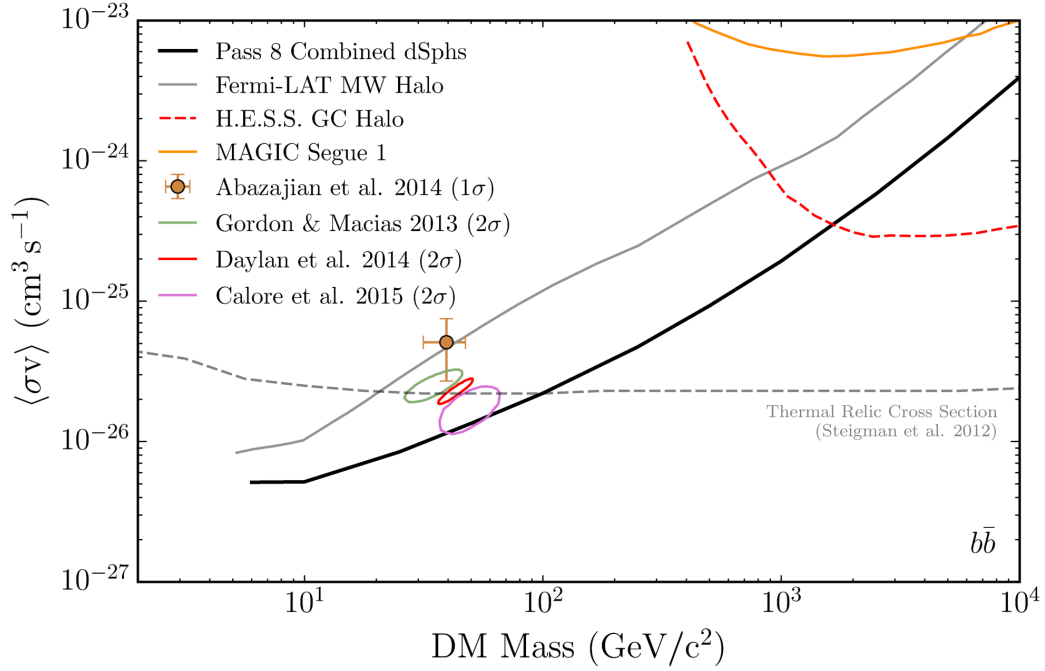


Figure 8.6: Results from Fermi-LAT indirect gamma-ray searches in the $\chi\chi \rightarrow b\bar{b}$ channel. Grey line shows limit from Milky Way halo search, black line from Milky Way dwarf spheroidal galaxy search with six years of data [55].

high energy neutrinos would be coming directly from the Sun would reduce astrophysical backgrounds significantly.

Positrons

Charged particles propagate in a complicated way through the galactic magnetic field, and they are therefore impossible to track back to the source. At the same time sources outside of our own Galaxy cannot contribute significantly to the flux at Earth. Positrons also have relatively large astrophysical backgrounds, for example pulsars are expected to produce a significant amount of lower energy positrons, so experiments search for small excesses on large backgrounds, mostly at high energies. Some potential excess has been seen in the past by Fermi-LAT and PAMELA, but this has not been conclusive.

Antiprotons

Just as the positrons these propagate in a complicated manner, but the backgrounds are under better control due to the lack of significant astrophysical antiproton production, except from the scattering of very high energy cosmic rays on the interstellar medium. The current best limits here come from the AMS-02 experiment.

Antideuterons

These have very low backgrounds because the production of antideuterons in astrophysical processes is extremely rare, in particular at low energies, due to the conservation of baryon number and the required high energy of cosmic rays to produce two antibaryons (at least two baryons must be produced in the same interaction). This means that the detection of an antideuteron should be a smoking duck signal of dark matter annihilation or decay. However, the physics of the formation of antideuterons from dark matter is quite complicated and hard to reliably calculate, bringing in extra uncertainty. Current searches set upper bounds on the flux of antideuterons at the Earth. It is hoped that AMS-02 will provide new better data on antideuterons soon.⁹

8.6 Exercises

Exercise 8.1

Show that $\chi\chi \rightarrow Z \rightarrow f\bar{f}$ gives

$$\sigma v \approx \frac{g^4 E_\chi^2}{128\pi m_Z^2}, \quad (8.6)$$

which in the low-velocity limit can be shown to be

$$\langle\sigma v\rangle_0 \approx 10^{-25} \text{ cm}^3\text{s}^{-1}.$$

⁹This has been hoped for a very long time.