Dark Matter (WS 2018/19) - Problem sheet 6

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Deadline for this sheet: 05.12.2018

Direct detection of dark matter

Direct searches for dark matter are shielded detectors placed underground, which try to measure interactions of dark matter with targets made from different elements. A recent summary plot of direct detection bounds is shown in Fig. 1.

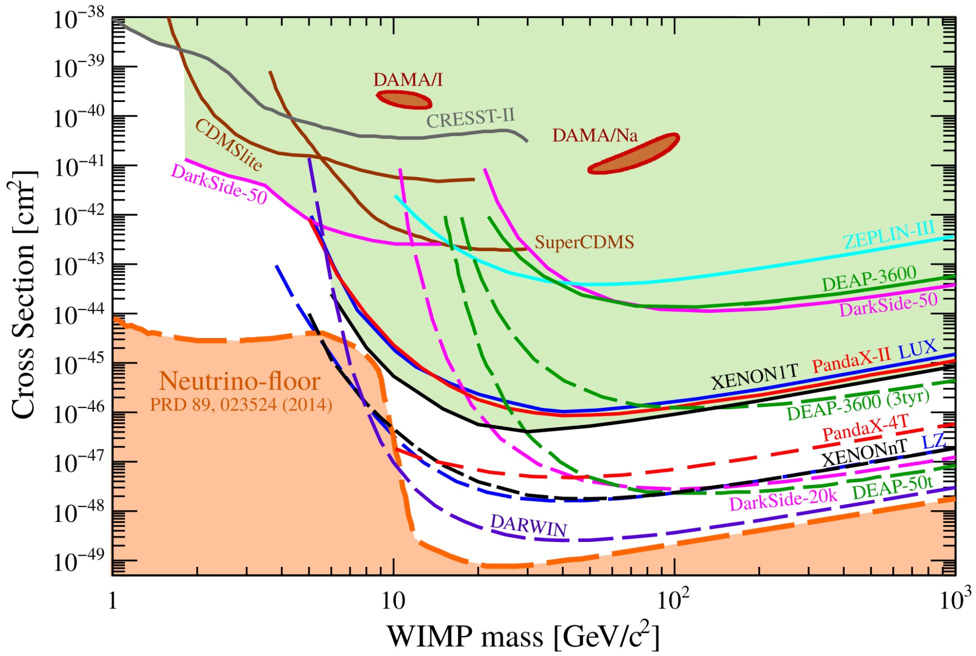

Figure 1: Direct detection bounds from various experiments.

6.1 Displaying results of dark matter searches *3 Points*

a) Explain the general shape of the exclusion limits (the sharp drop at $m_{DM} \approx 10\,\mathrm{GeV/c^2}$ and the linear slope for higher masses)!

b) Research the target element and the technology used in five of the above experiments. Can you explain the differences in the excluded regions (shape, sensitivity, mass region, ...)? What is the difference between the open curves and the shaded areas in the upper part of the plot?

c) How does the sensitivity scale with the mass and the runtime of these experiments? Describe the influence of the experimental background on the sensitivity of the experiment.

6.2 Expected rate *7 Points*

You are now an experimentalist working in a direct detection collaboration considering two detectors. The first is based on a germanium target and the second has a xenon target:

		Germanium	**Xenon**
Energy Threshold	E_t	$1\,\mathrm{keV/c^2}$	$5\,\mathrm{keV/c^2}$
Energy Interval	ΔE	$(1-40)\,\mathrm{keV/c^2}$	$(5-40)\,\mathrm{keV/c^2}$
Target Mass	M	$1\,\mathrm{kg}$	$35\,\mathrm{kg}$
Target Element Mass	m_A	$65\,\mathrm{GeV/c^2}$	$122\,\mathrm{GeV/c^2}$
Mass Number	A	73	131

The goal is to provide the best possible limit on a theory predicting a

- light dark matter candidate $M_\chi = 5\,\mathrm{GeV/c^2}$,
- heavy dark matter candidate $M_\chi = 500\,\mathrm{GeV/c^2}$,

In both cases the commissioned runtime is $T = 100\,\mathrm{days}$.

a) Since the WIMP-nucleon relative speed is of order $100\,\mathrm{km/s}$, elastic scattering occurs in the extreme non-relativistic limit. Direct detection experiments are limited by the nuclear recoil energy threshold of the target material E_t . Show that in terms of the velocity v of the dark matter particle and the scattering angle θ, the recoil energy E is given by

$$E = v^2 \frac{\mu_N^2}{m_A}(1-\cos\theta), \tag{1}$$

in which the reduced mass is given by $\mu_N = \frac{m_A M_\chi}{m_A + M_\chi}$. Using equation 1, compute the minimal velocity v_{min} for the germanium and xenon detector and the two dark matter masses given above.

b) Assume that the dark matter velocity distribution is isotropic, spherical symmetric and follows a Maxwell-Boltzmann distribution

$$f(\mathbf{v}) = N e^{-\mathbf{v}^2/v_0^2}, \tag{2}$$

with $v_0 = 220\,\mathrm{km/s}$ being the circular velocity of the dark matter halo and $N = 1/(\sqrt{\pi} v_0)^3$. Integrate out the angular dependencies so that you can sketch the function with respect to v. Indicate the values which you have derived in part a). Does it even make sense to consider very fast dark matter particles or should the velocity distribution be truncated at a certain speed v_{max}?

c) The expected rate for WIMP interactions can be expressed as

$$R \approx \frac{A^2}{2\mu_P^2\, M_\chi}\, \sigma_0\, \rho_\chi \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv \cdot \Delta E, \tag{3}$$

in which $\mu_P = \frac{m_N M_\chi}{m_N + M_\chi}$ is the reduced mass of the dark matter and a nucleon (either proton or neutron) $m_N \approx 1\,\mathrm{GeV/c^2}$. The local dark matter density $\rho_\chi = 0.3\,\mathrm{GeV/cm^3}$ and the velocity distribution given above are astrophysical inputs. The mass of the dark matter candidate and the cross section $\sigma_0 = 1 \cdot 10^{-45}\,\mathrm{cm^2}$ are quantities provided by your particle physics colleague. Compute the expected number of events $N = R \cdot T \cdot M$ for the two detectors and both the heavy and light dark matter candidate. (Make sure you are using consistent units!)

d) Explain the limiting features of the two detectors that were considered.

6.3 The neutrino floor *2 Bonus Points*

The dashed orange line in figure 1, indicates the so called neutrino floor. Describe, why this can be a limiting background for direct detection experiments. Is its shape the same for different target elements? What feature would an experiment need to exploit in order to be sensitive to regions below this floor?

6.4 Save the date!

There will be the opportunity for you to visit our group and our laboratories at the Max-Planck-Institut für Kernphysik. The visit will take place during the time of the exercise group on 13th December 2018. Instead of the usual venue we would meet at Bismarckplatz. From there we will take the 39 bus (Königstuhl) leaving at 9.30 am.