Exp. Methods in Astroparticle Physics (SS 2020) - Problem sheet 5

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Direct detection of dark matter, part II

5.1 Liquid xenon (LXe) time projection chambers (TPCs) *5 Points*

As an example of a liquid noble gas direct detection experiment, we will look at the XENON1T experiment. Read `https://arxiv.org/pdf/1708.07051.pdf` and answer the following questions (do not get lost in the technical parts of the paper):

a) Which kinds of interaction with the xenon target can incoming particles have? Which one of these are WIMPs expected to typically undergo?

b) What are S1/S2 signals, and how are they generated? Is all of the energy deposited by a particle accessible for read out using these signals? Name possible processes that lead to losses of the signal strength.

c) Which information can one extract from the S1 signal of an interaction in conjunction with the S2 signal to which it belongs? What is this information used for? State three examples.

d) Name three different background mitigation techniques employed in XENON1T and explain shortly which background sources are suppressed using these techniques.

5.2 Displaying results of dark matter searches *5 Points*

In Fig. 1 you can find a recent summary plot of direct dark matter detection bounds, showing the results of various experiments.

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) Select four of the experiments indicated in the plot and indicate for each of them the target element and the used technology. Explain why for different experiments the exclusion curves can be so different (w.r.t. shape, sensitivity, mass region, ...). How can closed shaded regions in this parameter space be obtained? Try to give an explanation on the two red shaded regions 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.

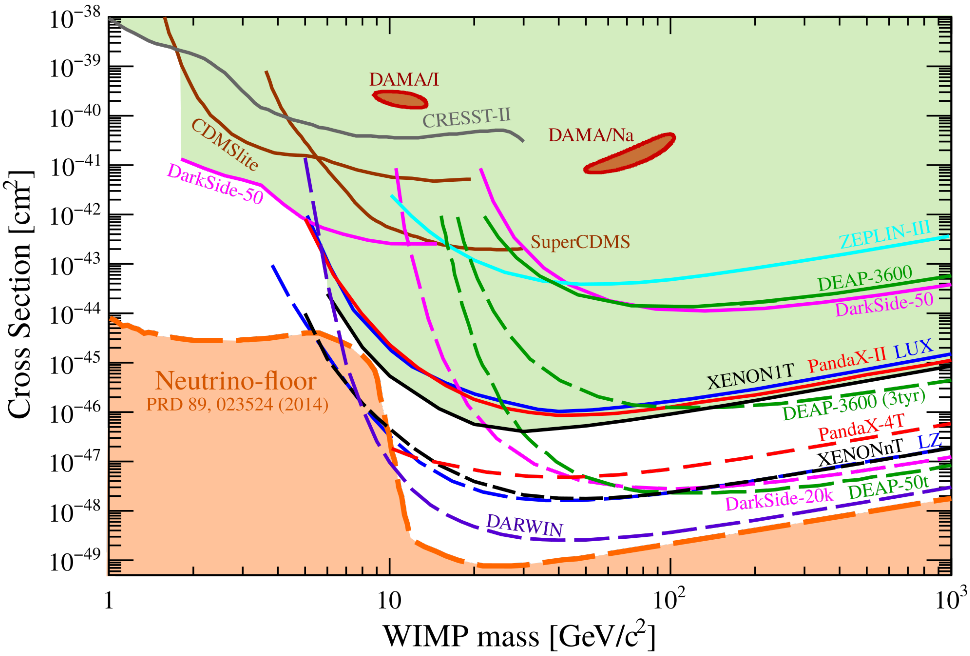

Figure 1: Direct detection bounds from various experiments.

d) The dashed orange line in Fig. 1 indicates the so-called neutrino floor. Describe why this can be a limiting background for direct detection experiments. What expected halo dark matter feature would an experiment need to exploit in order to be sensitive to regions below this floor?

5.3 Calculating a limit on the WIMP-interaction rate *2 Bonus Points*

Let us come back to the hypothetical direct detection collaboration from last week's exercise sheet (exercise 4.1). Imagine you have chosen to go for the xenon detector with an active target mass of $M = 35\,\mathrm{kg}$. Assume that over the whole run time of $T = 100\,\mathrm{days}$, you observed a total of $n_0 = 3$ events, from which $b = 1$ event is expected to be induced by the detector background (e.g. from radioactive trace elements in the target). Use the table in the figure below to derive a 90% confidence interval on the WIMP interaction rate R for this case.

(Hint: Remember that the number of WIMP scattering events N is connected to the interaction rate R by $N = R \cdot M \cdot T$)

$n_0 \backslash b$	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
0	0.00, 2.44	0.00, 1.94	0.00, 1.61	0.00, 1.33	0.00, 1.26	0.00, 1.18	0.00, 1.08	0.00, 1.06	0.00, 1.01	*0.00, 0.98*
1	0.11, 4.36	0.00, 3.86	0.00, 3.36	0.00, 2.91	0.00, 2.53	0.00, 2.19	0.00, 1.88	0.00, 1.59	0.00, 1.39	0.00, 1.22
2	0.53, 5.91	0.03, 5.41	0.00, 4.91	0.00, 4.41	0.00, 3.91	0.00, 3.45	0.00, 3.04	0.00, 2.67	0.00, 2.33	0.00, 1.73
3	1.10, 7.42	0.60, 6.92	0.10, 6.42	0.00, 5.92	0.00, 5.42	0.00, 4.92	0.00, 4.42	0.00, 3.95	0.00, 3.53	0.00, 2.78
4	1.47, 8.60	1.17, 8.10	0.74, 7.60	0.24, 7.10	0.00, 6.60	0.00, 6.10	0.00, 5.60	0.00, 5.10	0.00, 4.60	0.00, 3.60
5	1.84, 9.99	1.53, 9.49	1.25, 8.99	0.93, 8.49	0.43, 7.99	0.00, 7.49	0.00, 6.99	0.00, 6.49	0.00, 5.99	0.00, 4.99
6	2.21,11.47	1.90,10.97	1.61,10.47	1.33, 9.97	1.08, 9.47	0.65, 8.97	0.15, 8.47	0.00, 7.97	0.00, 7.47	0.00, 6.47
7	3.56,12.53	3.06,12.03	2.56,11.53	2.09,11.03	1.59,10.53	1.18,10.03	0.89, 9.53	0.39, 9.03	0.00, 8.53	0.00, 7.53
8	3.96,13.99	3.46,13.49	2.96,12.99	2.51,12.49	2.14,11.99	1.81,11.49	1.51,10.99	1.06,10.49	0.66, 9.99	0.00, 8.99
9	4.36,15.30	3.86,14.80	3.36,14.30	2.91,13.80	2.53,13.30	2.19,12.80	1.88,12.30	1.59,11.80	1.33,11.30	0.43,10.30
10	5.50,16.50	5.00,16.00	4.50,15.50	4.00,15.00	3.50,14.50	3.04,14.00	2.63,13.50	2.27,13.00	1.94,12.50	1.19,11.50
11	5.91,17.81	5.41,17.31	4.91,16.81	4.41,16.31	3.91,15.81	3.45,15.31	3.04,14.81	2.67,14.31	2.33,13.81	1.73,12.81
12	7.01,19.00	6.51,18.50	6.01,18.00	5.51,17.50	5.01,17.00	4.51,16.50	4.01,16.00	3.54,15.50	3.12,15.00	2.38,14.00
13	7.42,20.05	6.92,19.55	6.42,19.05	5.92,18.55	5.42,18.05	4.92,17.55	4.42,17.05	3.95,16.55	3.53,16.05	2.78,15.05
14	8.50,21.50	8.00,21.00	7.50,20.50	7.00,20.00	6.50,19.50	6.00,19.00	5.50,18.50	5.00,18.00	4.50,17.50	3.59,16.50
15	9.48,22.52	8.98,22.02	8.48,21.52	7.98,21.02	7.48,20.52	6.98,20.02	6.48,19.52	5.98,19.02	5.48,18.52	4.48,17.52
16	9.99,23.99	9.49,23.49	8.99,22.99	8.49,22.49	7.99,21.99	7.49,21.49	6.99,20.99	6.49,20.49	5.99,19.99	4.99,18.99
17	11.04,25.02	10.54,24.52	10.04,24.02	9.54,23.52	9.04,23.02	8.54,22.52	8.04,22.02	7.54,21.52	7.04,21.02	6.04,20.02
18	11.47,26.16	10.97,25.66	10.47,25.16	9.97,24.66	9.47,24.16	8.97,23.66	8.47,23.16	7.97,22.66	7.47,22.16	6.47,21.16
19	12.51,27.51	12.01,27.01	11.51,26.51	11.01,26.01	10.51,25.51	10.01,25.01	9.51,24.51	9.01,24.01	8.51,23.51	7.51,22.51
20	13.55,28.52	13.05,28.02	12.55,27.52	12.05,27.02	11.55,26.52	11.05,26.02	10.55,25.52	10.05,25.02	9.55,24.52	8.55,23.52

Figure 2: 90 % confidence level intervals for Poisson signal mean μ, for total events observed n_0, for known background b (Feldman and Cousins 1999).