Sensitivity to WIMP-like Dark Matter

BULLKID-DM Meeting
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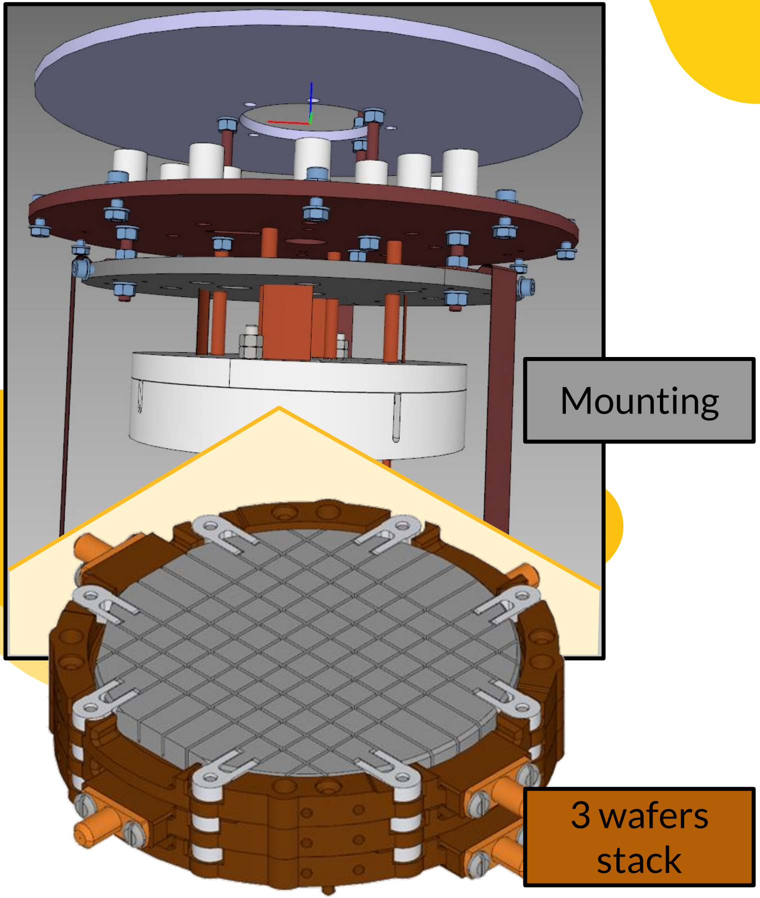
Outline of the presentation

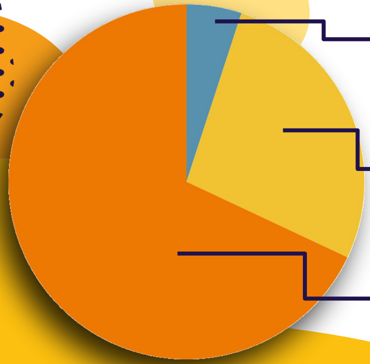
- Very brief introduction to WIMP Dark Matter
- Direct dark matter detection
- What is a dark matter exclusion plot
- State of the art in DM direct research
- Yellin method: working principle
- Yellin method: reproducing CRESST limits
- Sensitivity plots: Demonstrator & BULLKID-DM
- Toward a Bayesian credibility interval
- Conclusions

- References
- Backup slides



Introduction to dark matter

Dark matter (DM) is an elusive form of matter that doesn't interact with electromagnetic radiation



5 %
Ordinary matter

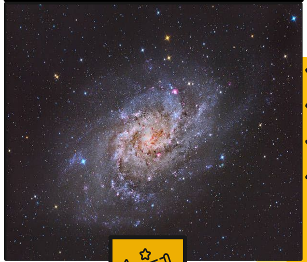
27%
Dark matter

68%
Dark energy

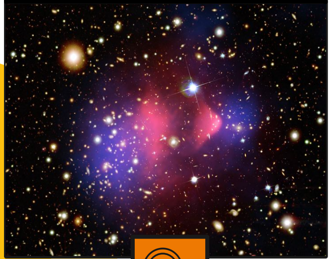
We have only gravitational hints of its existence

Larger scales

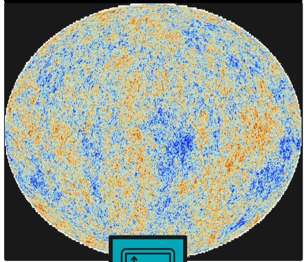
01 Galaxies



02 Galaxy clusters

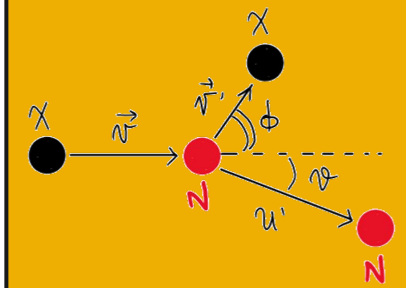


03 CMB



Cold Weakly interacting massive particles (WIMPs) in the GeV-TeV mass range could explain the DM abundance, and also they fit well in theories for physics beyond the Standard Model.

Dark matter direct detection

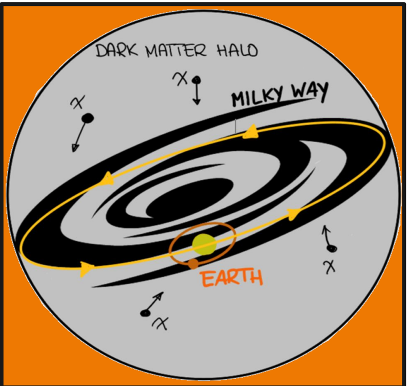


Direct detection aims to observe the transferred energy-momentum of WIMP particles scattering with **ordinary matter nuclei.**

$$E = 2\frac{\mu^2}{m_N} v^2 \cos^2(\theta)$$

E <~ 1 keV

We assume a DM distribution surrounding our Milky Way. The solar system is traveling in this halo hitting a DM wind coming from the Cygnus constellation.

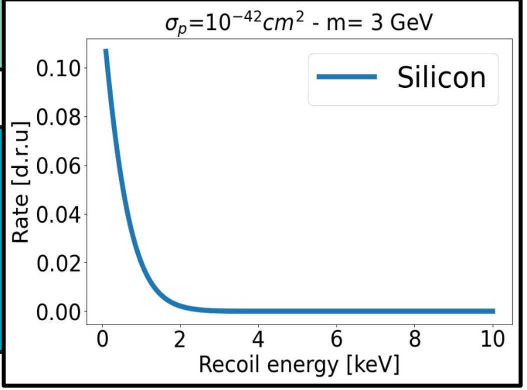


$$\rho(\mathcal{R}_o) = 0.3\,\mathrm{GeV/cm^3} \quad v_C(\mathcal{R}_o) = 220\,\mathrm{km/s}$$

$$\frac{dR}{dE} \sim \frac{R_0}{E_0} \exp\left(-\frac{E}{E_0}\right)$$

Order of (1 evn/kg/yr)

Expected a low rate of interactions with a exponentially decreasing energy spectrum

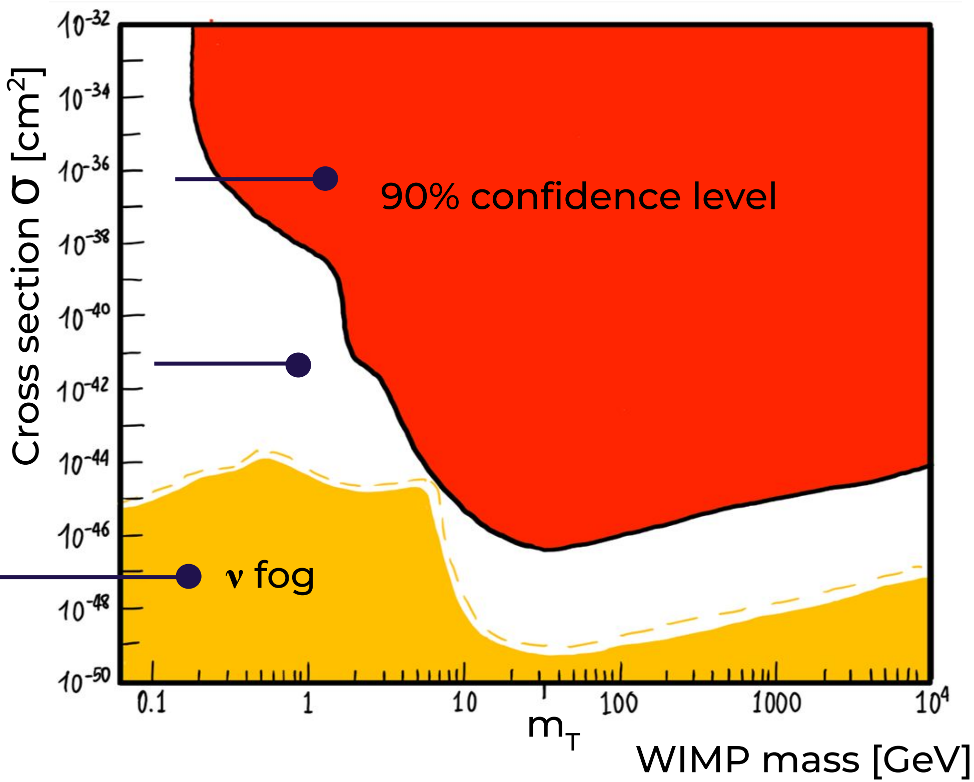


Exclusion bounds

Even nothing means something

Until we find evidences of DM, we can set exclusion limits

- Excluded region
- Still motivated region
- Atmospheric and solar neutrinos constitute irreducible background with a rate comparable to WIMP-DM



Going down requires more exposure

Going left requires lower energy threshold

Exclusion bounds

State of the art

Until we find evidences of DM, we can set exclusion limits

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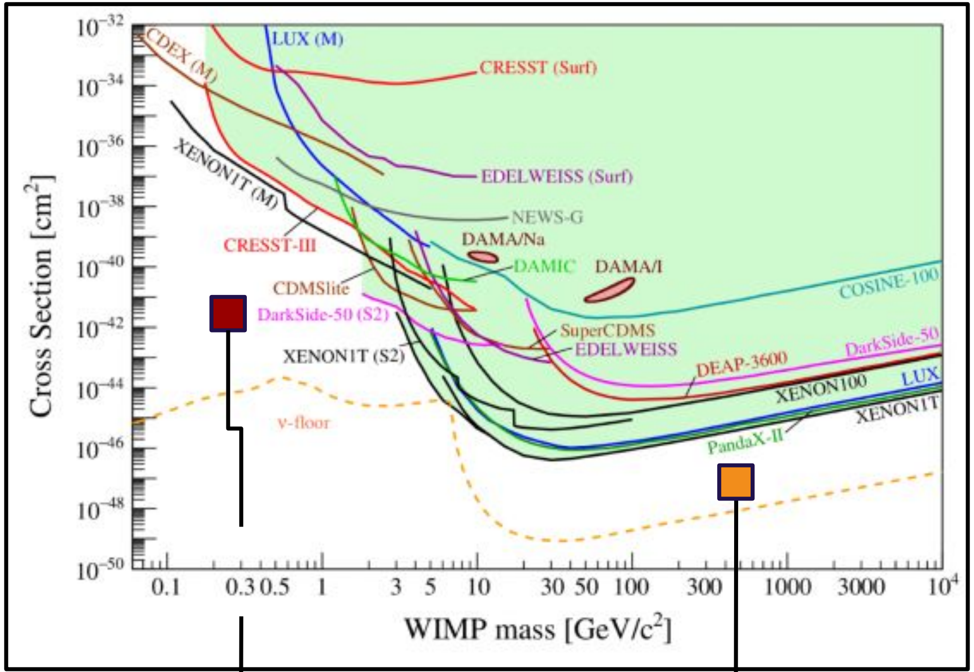


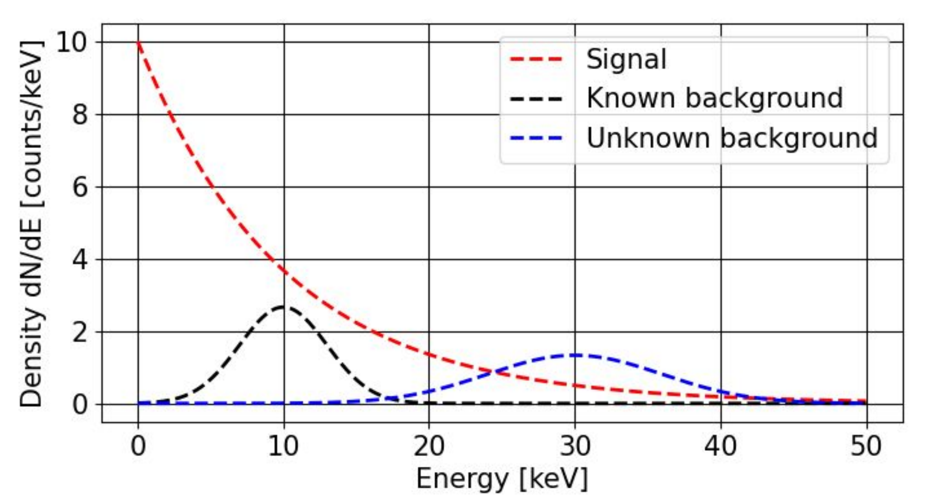
Sub-GeV range still mostly unexplored even if still theoretically valuable

High WIMP masses largely excluded by multi-ton liquid scintillators

Yellin’s optimum interval method

“The optimum interval method produces a true, though possibly conservative, classical (frequentist) confidence interval” [1]

It works even in presence of a too poorly understood background contaminating the data, putting a stronger limit than would be possible if it were ignored”

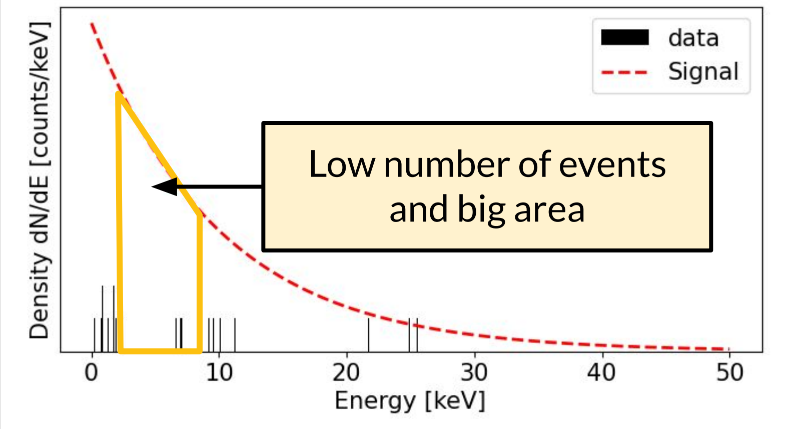


Working principle

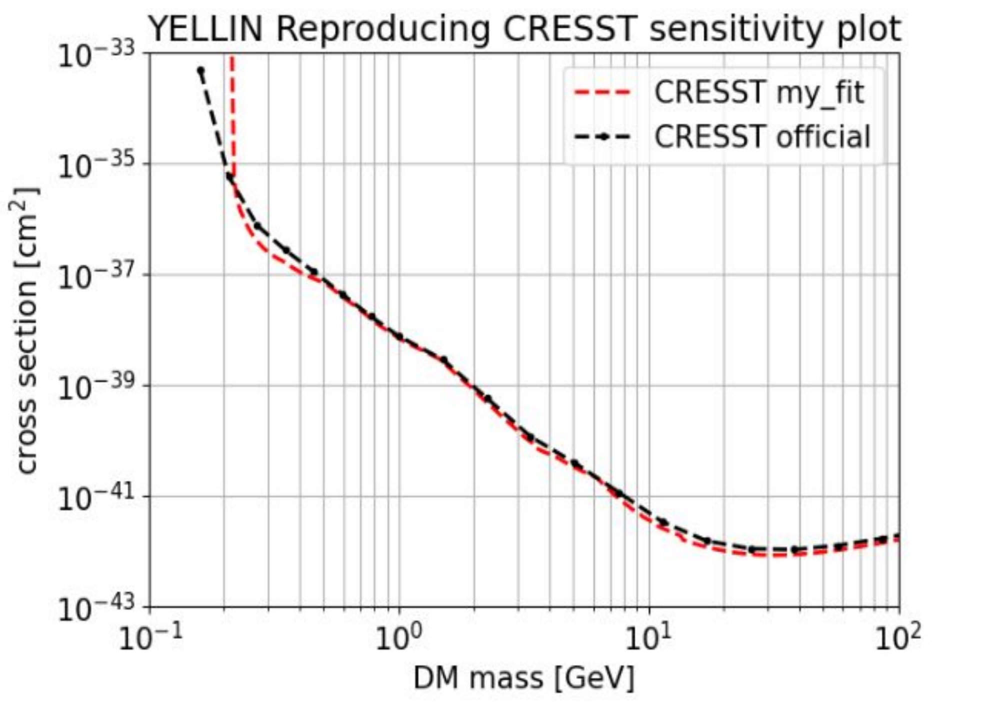
The energy ranges with **less recorded events** should also be the ranges **less affected** by the unknown background.

Hence I put the limit in one of such ranges where, on the other hand, **I expect to see more signal.**

The limit can be estimated through the use of a **MC toy.**

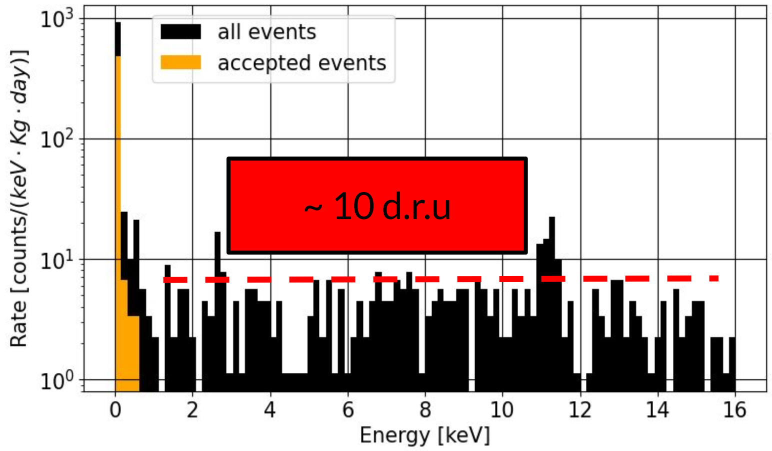


Reproducing CRESST results



The differences between the two curves are believed to be due to a different algorithm for evaluating the WIMP rate

One of the main reasons we adopt Yellin's method is the fact that the CRESST experiment adopts it for its limits



CRESST experimental settings [2]

ROI: [0.0301, 16] keV Resolution: ~ 46 eV

Exposure: 0.015 kg Y

Efficiency: ~50% + efficiency of the cuts

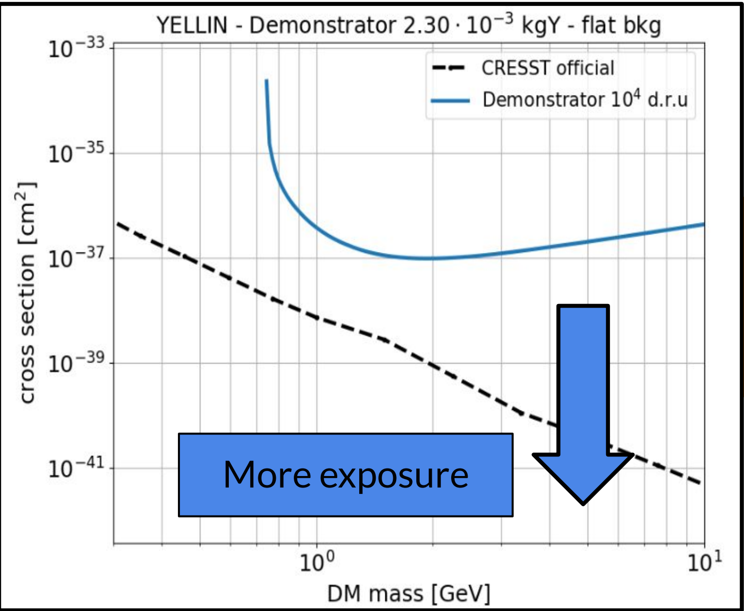
Target material: $CaWO_4$

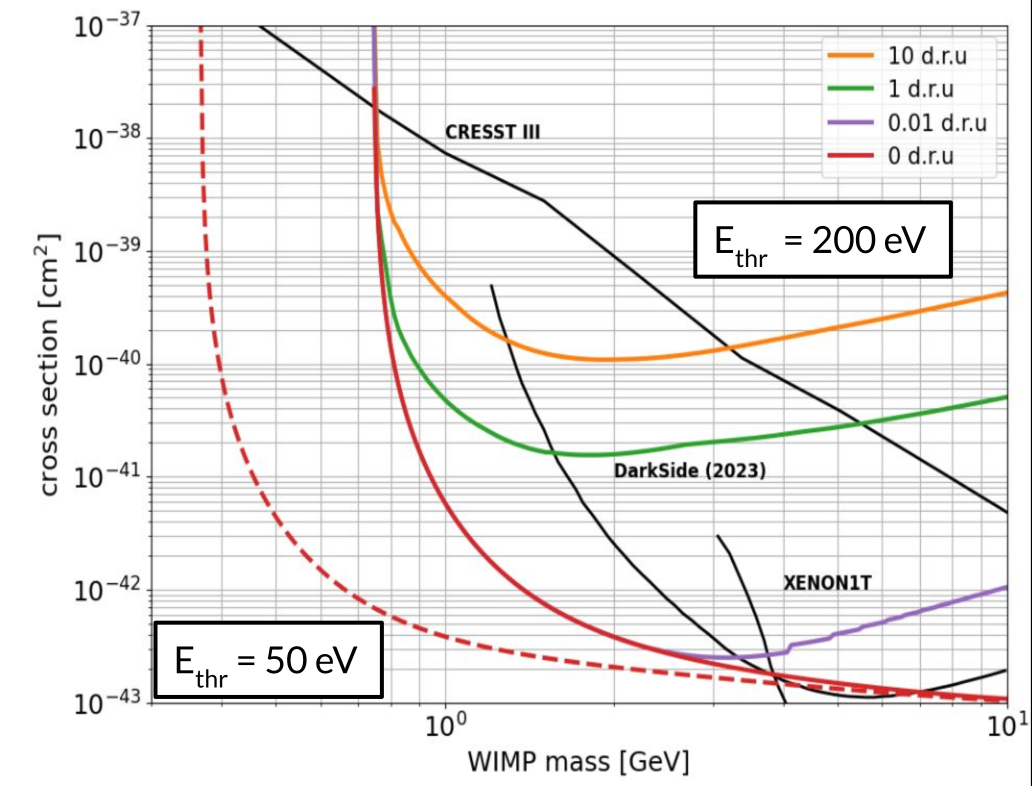
Rate: ~ 10 d.r.u

BULLKID sensitivity plots

Demonstrator - Flat background
ROI : [0.2, 16] keV — Target material: Silicon
Time: 2 weeks — Target mass: 0.06 Kg

BULLKID-DM - Flat background at different rates
ROI : [E_{thr}, 16] keV — Target material: Silicon
Time: 1 year — Target mass: 0.6 Kg





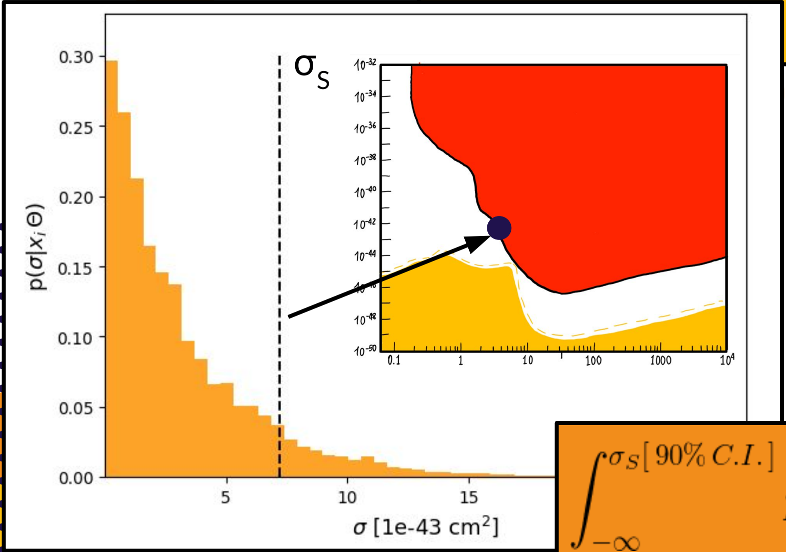
Notes
0 d.r.u means we expect less than 1 event @ 90% C.L

Toward a Bayesian credibility interval

The next goal is to adopt a Bayesian approach to infer the upper bound and to estimate the expected experimental sensitivities to the interaction of DM candidates with ordinary matter.

posterior

$$p(r_s, \vec{\theta} \,|x_i) = \frac{p(x_i\,|r_s, \vec{\theta})\pi(r_s, \vec{\theta})}{\int_\Omega \int_0^\infty p(x_i\,|r_s, \vec{\theta})\pi(r_s, \vec{\theta})}$$



likelihood
(my model)

prior

normalization (0 < P < 1)

$$\int_{-\infty}^{\sigma_S[90\%\,C.I.]} p(\sigma|x_i;\vec{\theta})\,d\sigma = 0.90$$

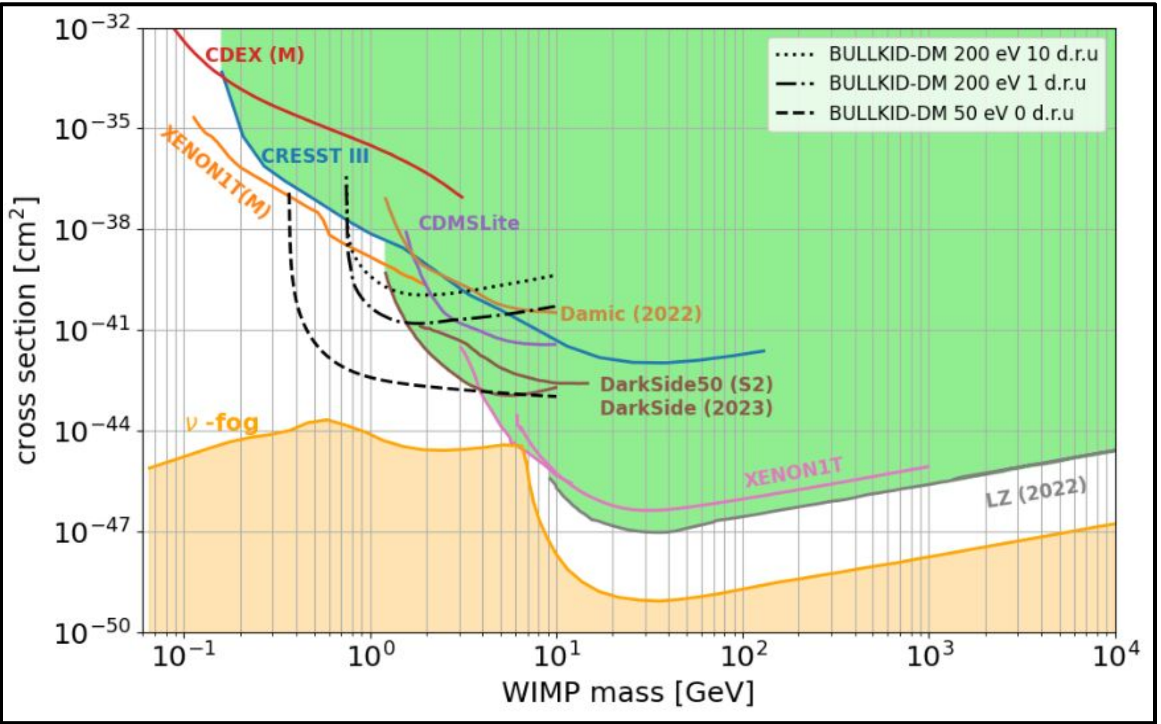
Analysis implemented through the Bayesian Analysis Toolkit (BAT)

Conclusions

BULLKID-DM - Flat background at different rates

ROI : [E_{thr}, 16] keV Target material: Silicon

Time: 1 year Target mass: 0.6 Kg



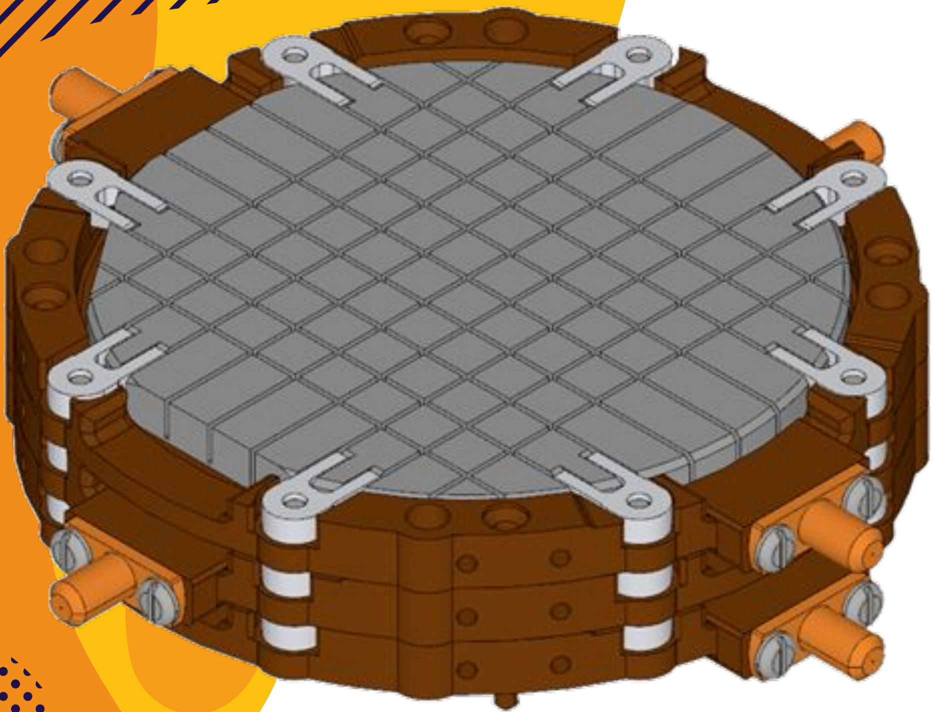
References for the plot [5]-[8]

The BULLKID-DM sensitivity limits have been presented for **a wide range of scenarios**.

In all these cases, a future limit in an **unexplored range** of the WIMP's parameter space has been estimated.

We are developing a **Bayesian algorithm** for the evaluation of the future credibility limits.

It would represents a more robust **probabilistic approach** and would also allow a validation of our background model, **as done in DarkSide** [4].



Thank you for the attention!

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References

[1] Finding an upper limit in presence of an unknown background, S. Yellin (2002), arXiv:physics/0203002

[2] Description of CRESST-III Data, CRESST collaboration (2019), arXiv:1905.07335

[3] A synthetic summary about the probabilistic concepts, used in this presentation, can be found in the following review from the Particle data Group https://pdg.lbl.gov/2020/reviews/rpp2020-rev-statistics.pdf

[4] DarkSide Bayesian network approach: https://arxiv.org/pdf/2302.01830.pdf

[5] Direct Detection of Dark Matter -- APPEC Committee Report arXiv:2104.07634

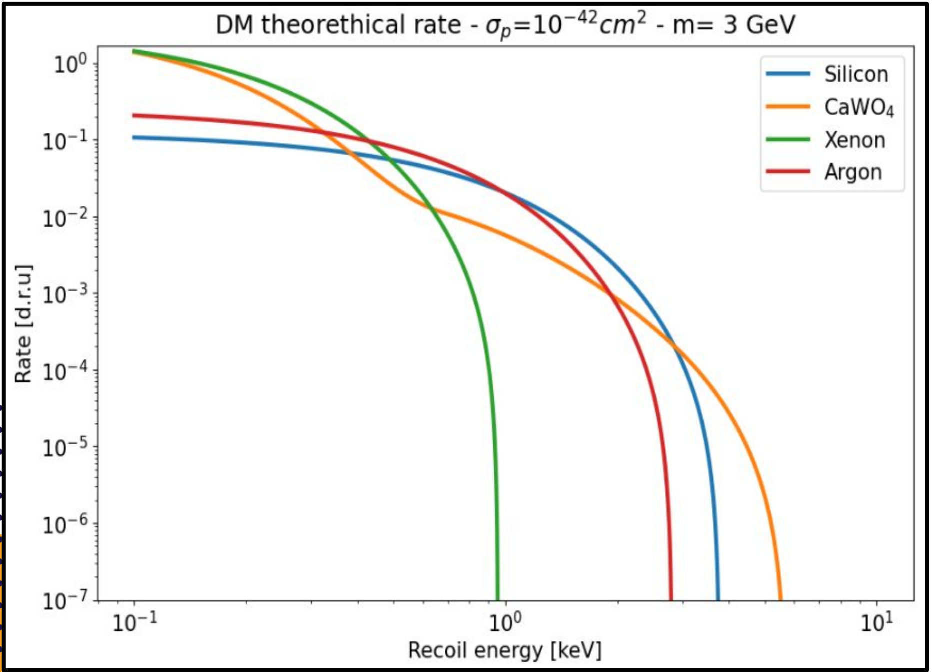
[6] LUX-ZEPLIN (LZ) Experiment: https://arxiv.org/pdf/2207.03764.pdf

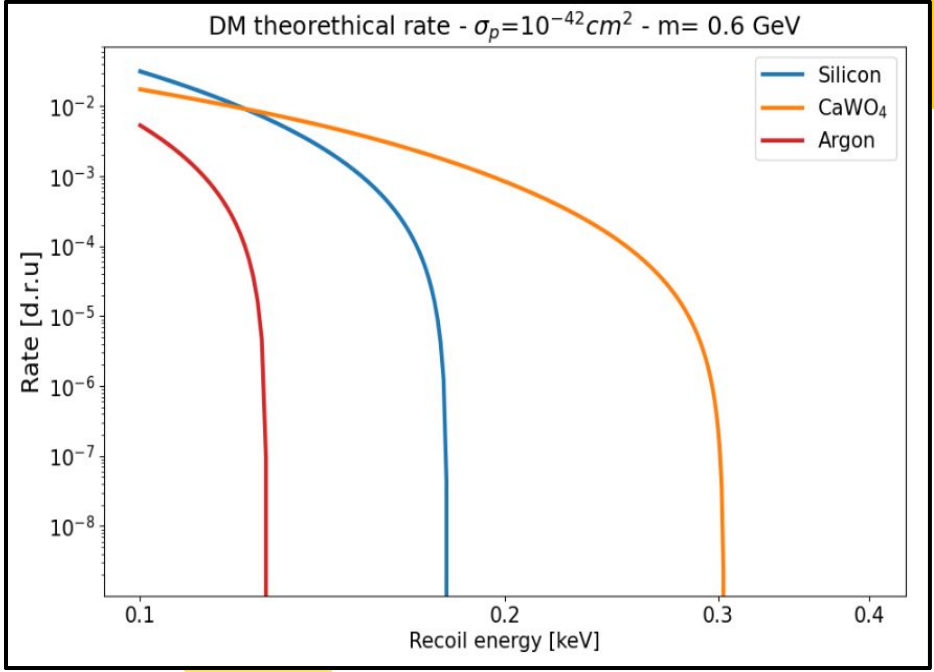
[7] Damic at SNOLAB: https://arxiv.org/pdf/2007.15622.pdf

[8] DarkSide 50 (2023): https://journals.aps.org/prd/pdf/10.1103/PhysRevD.107.063001

BACKUP

WIMP-DM rate





[9] Rates evaluated with the WIMpy package

[10] A wonderful manual on theory of direct dark matter detection can be found at arXiv:2104.12785

v_0 = 220 km/s

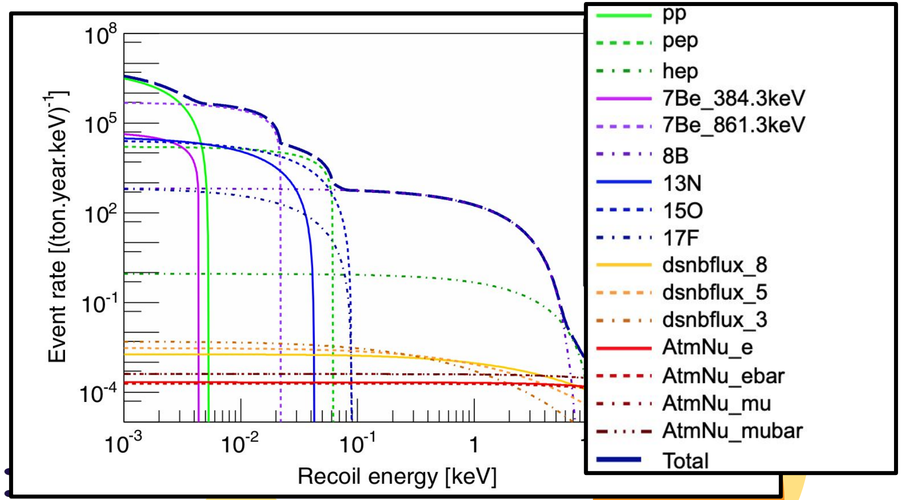
v_{esc} = 544 km/s

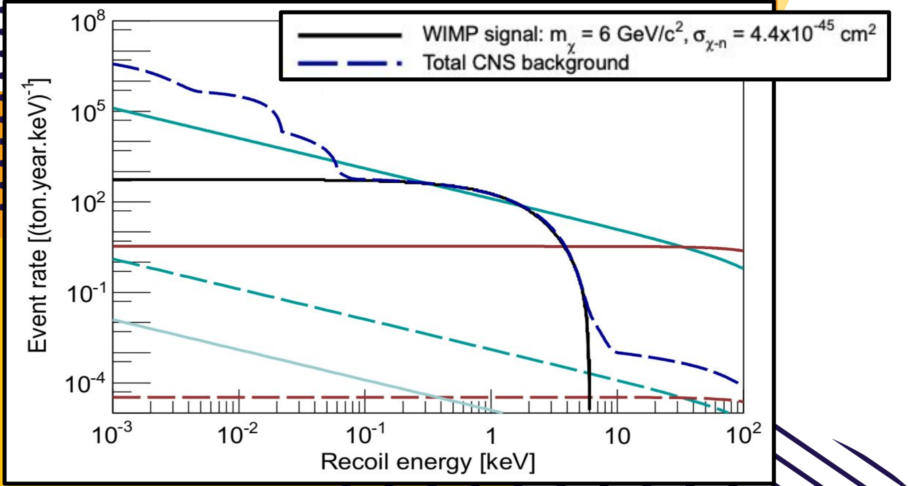
ρ = 0.3 GeV/cm^3

v_{lab} = 238 km/s

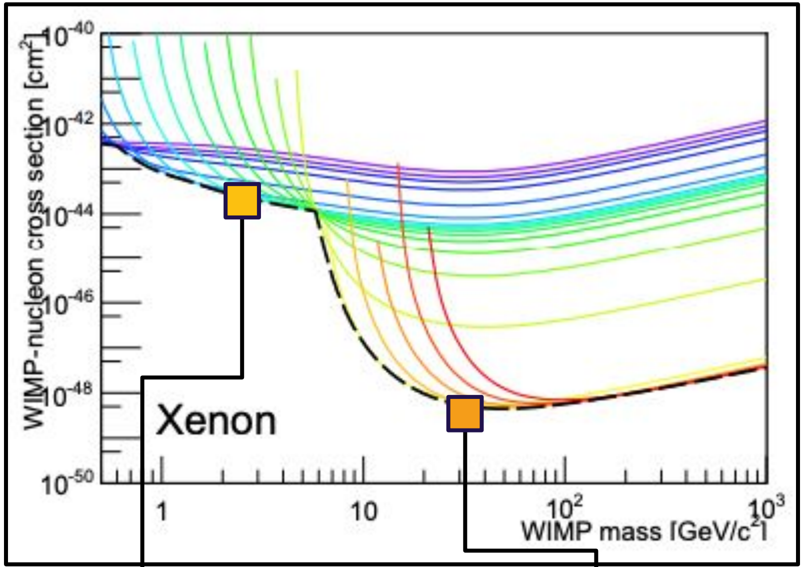
[11] arXiv:1307.5458

Neutrino Fog





The **Neutrino Fog** is identified, for a certain target element, as the convolution of all background-free exclusion limits with varying threshold. The exposure of such curves is adjusted such that a single neutrino event is expected.

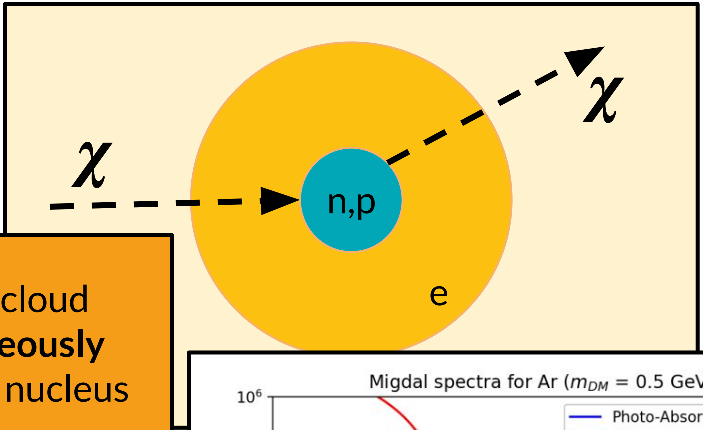


hep and ^8B neutrinos dominant

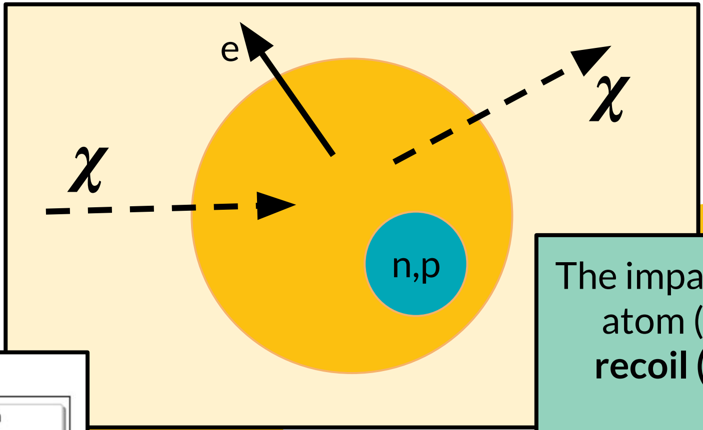
atmospheric neutrinos dominant

Migdal effect

Standard Nuclear recoil (NR)

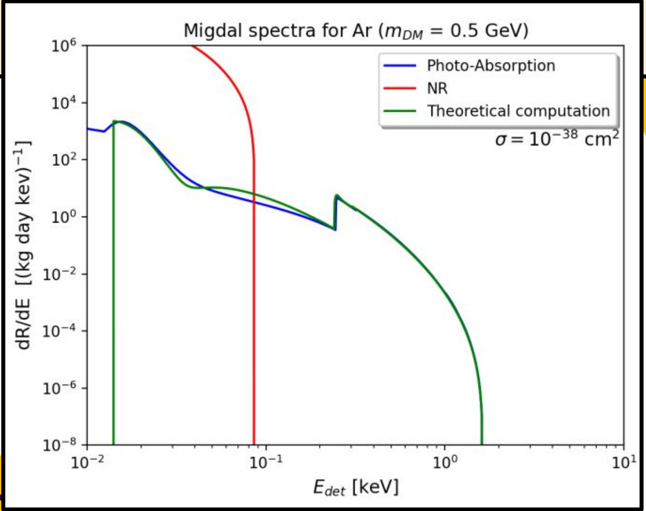


Migdal effect



Electron cloud **instantaneously follows** the nucleus

The impact ionizes the atom (**electronic recoil (ER) signal)**



Plot from [12] https://hdl.handle.net/11573/1641306

The Migdal effect allows an indirect detection of sub-threshold NR interactions through ERs

Migdal effect observed?

✓ α decay: https://doi.org/10.1103/PhysRevC.11.1740

✓ β decay: https://doi.org/10.1103/PhysRevA.97.023402

✗ **NR: not yet observed**

Yellin method

Fix the cross-section of the signal

$n = 0$ — $C_0(x_0,\mu)$

$n = 1$ — $C_1(x_1,\mu)$

$n = 2$ — $C_2(x_2,\mu)$

$n = N$ — $C_N(x_N,\mu)$

Choose the biggest of all the evaluated probabilities

Modify the cross-section until the probability becomes of 90%

n = number of events in the chosen interval

N = total number of detected events

$x_n(\sigma)$ = greater number of expected events in the interval

$\mu(\sigma)$ = total number of expected events

Probabilities evaluated through a MC Toy

"The optimum gap method includes automatic selection of which n to use"

"The optimum interval is the interval that mostly indicates that the proposed cross-section is too high"

Bayesian network approach

Eur. Phys. J. C (2023) 83:322
https://doi.org/10.1140/epjc/s10052-023-11410-4
THE EUROPEAN PHYSICAL JOURNAL C
Check for updates
Regular Article - Experimental Physics

Search for low mass dark matter in DarkSide-50: the bayesian network approach

DarkSide-50 Collaboration

Improved iterative Bayesian unfolding

G. D'Agostini
Università "La Sapienza" and INFN, Rome, Italy
(giulio.dagostini@roma1.infn.it, http://www.roma1.infn.it/~dagos)

Two fundamental papers regarding the application of Bayesian Networks in physics and in direct dark matter research

[13] arXiv:2302.01830
[14] arXiv:1010.0632

This technique has the advantage, over the widely used profiling methods, to be **exact in terms of uncertainty propagation, to not rely on template morphing, and to properly take into account cross correlations between parameters and phase space regions**. In addition, if the physical parameters describing the detector response model and constrained by calibrations are retained as parameters inside the likelihood function, this method gives the possibility **of verifying the goodness of the calibrations and, a posteriori, further constrains the detector response model.**