Recasting Direct Detection Limits Within MicrOMEGAs And Implication For Non-Standard DarkMatter Scenarios

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based on G. Belanger, A. Mjallal, A. Pukhov in preparation

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JRJC Centre Moulin Mer in Finistere, November 25, 2019

- Provide a tool that allows to reinterpret the 90% direct detection limits obtained by the experimental collaborations within their specific framework.
- Apply them to a wider set of Dark Matter (DM) models and DM velocity distributions.

Outline

- Introduction
- Direct Detection Framework.
- Recasting DD Limits With micrOMEGAs
- Applications
- Conclusion

Direct DM Detection
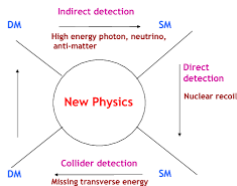
- It is based on the search of the scattering between DM particles and nuclei in an underground detector.
- This process is observable through the recoiling nucleus, with an energy:

$$E_R = \frac{1}{2} m_\chi v^2 \frac{4 m_\chi m_N}{(m_\chi + m_N)^2} \frac{1 + \cos\theta}{2}$$

- No "confirmed" signal for DM have been found.
- For DM masses above roughly 6 GeV, the best limits are currently obtained by XENON-1T.

Direct Detection Framework

Assumptions:

- Point-Like interaction (e.g: $\mathcal{L}_{eff} = \lambda_N \bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N$)

- Equal proton and neutron spin-independent (SI) cross sections.

- Specific choice of DM density ($\rho_{DM} = 0.3 \frac{GeV}{cm^3}$)

- Maxwell velocity distribution of DM with these parameters $v_{Rot} = 220 \frac{Km}{s}$, $v_{Esc} = 544 \frac{Km}{s}$ and $V_{Earth} = 232 \frac{km}{s}$.

Direct Detection Framework

- The spectrum of nuclei recoils from DM interaction

$$\frac{dN^{SI}}{dE} = T M_{det} \frac{\rho_{DM}}{2 M_\chi \mu_{\chi A}^2} \sigma^{SI} F^2(E) \int_{v_{min}} \frac{f(\vec{v})}{v} d\vec{v}$$

where $f(\vec{v})$ is the velocity distribution function of DM, $v_{min} = \sqrt{\frac{E M_A}{(2\mu_{\chi A}^2)}}$ and $F(E)$ is nucleus form factor.

- SI DM-nucleons cross sections for heavy mediator:

$$\sigma_{\chi N}^{SI} = \frac{4}{\pi} \mu_{\chi N}^2 \lambda_N^2 \ , \ \ N = n, p$$

- Multiplying $\frac{dN^{SI}}{dE}$ by detector 's acceptance $p(E)$ (say Xenon) and then computing the likelihood, one can get the SI exclusion limits on DM-nucleon cross sections.

Note that $\mu_{\chi N} = \frac{M_\chi M_N}{M_\chi + M_N}$.

SI Xenon1T Reconstruction

- To repeat exactly Xenon1T analysis, we need detailed information on events distribution, background estimation and the used of nuisance parameters for all points of event space.
- Since we have incomplete information, we assume that there is some effective subspace of the total space of events where no events were detected.
- In this region, the probability to register DM event after applying all cuts is $p_{eff}(E)$.
- Our goal is to recover $p_{eff}(E)$ using Xenon1T data, in order to recast exclusion for different condition.

Recovering p_{eff}

- The likelihood function reads

$$L = e^{-\mathcal{L} \int_0^{E_{max}} \left(p_{eff}(E) \frac{dN}{dE} + \frac{dB}{dE} \right) dE}$$
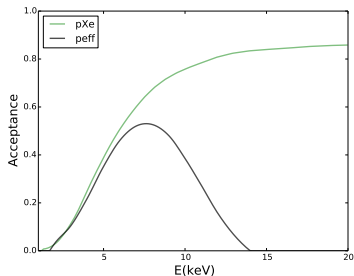
  $\mathcal{L}$ is the exposure.

- Maximal likelihood is reached for zero DM signal event. We introduce

$$p_{val} = \frac{L}{L_{max}} = e^{-\mathcal{L} \int_0^{E_{max}} p_{eff}(E) \frac{dN}{dE} dE}$$

- We exploit the exclusion provided by Xenon to derive an integral equation for the acceptance $p_{eff}(E)$.

$$\mathcal{L} \int p_{eff}(E) \frac{dN^{90}(M_\chi)}{dE} dE = \log\left(1/p_{val}\right) = 2.3$$
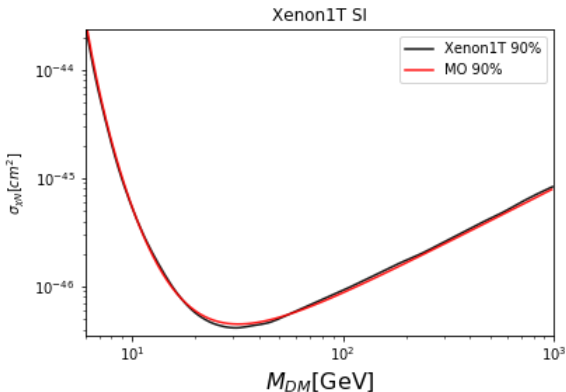
- Solving this equation, we reconstruct $p_{eff}(E)$.

Our acceptance match very well the Xenon one near threshold, i.e. for $E < 6KeV$ and so we reproduce very well the exclusion at low masses since this is the only relevant region for DM masses below $10GeV$.
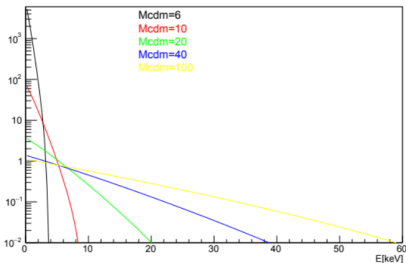
Predicted energy recoil distribution of Xenon1T for $\mathcal{L} = 279 * 900 days.Kg$, where σ^{90}: the 90% excluded cross section for each mass in the figure.
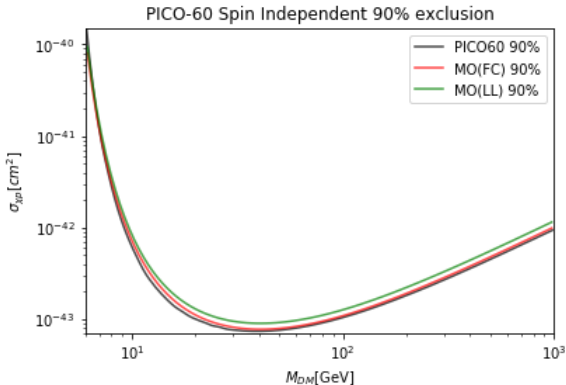
Xenon1T SI

- We observe an excellent agreement between the Xenon1T excluded cross sections and our reconstruction.
- Maximal difference is roughly 10% and is reached for $M_{DM} = 20 GeV$.

SI PICO-60 Reconstruction

- PICO is an F_8 detector that provides the best sensitivity to SD interactions on proton.
- To reconstruct the PICO-60 exclusion curve for SI interactions, we assume an acceptance described by a step function starting from zero and rising to 100% at a certain threshold energy.
- The value of the threshold is optimized to 1.6 KeV in order to match the PICO-60 exclusion curve.

90% SI exclusion limits on $\sigma_{\chi p}$ by PICO-60 experiment.
The likelihood method leads to difference of at most 20% level for
large masses, $M_{DM} > 100\,GeV$ while the Feldman-Cousins method
gives an excellent agreement for all masses.

SD and SI interactions have very similar recoil energy spectra, therefore we use the recasting done for SI interactions and apply it directly to SD ones for both PICO-60 and Xenon1T.

PICO-60 SDp 90% exclusion

Xenon1T SDn 90% exclusion
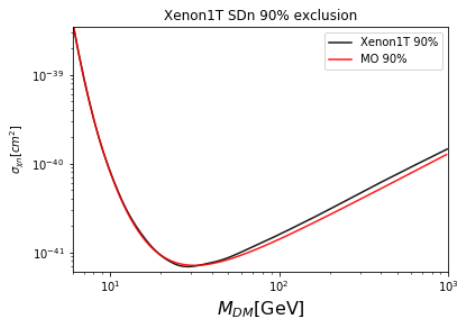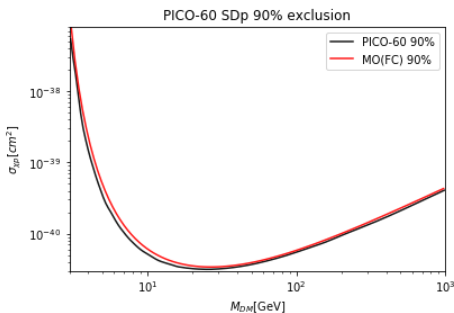
We can use our reconstruction of DD experimental limits to study these cases:

- Case of a light mediator.
- Dependence of exclusion cross section on cosmological parameters.
- Millicharged Dark matter.

ZpPortal Model

- We consider the case of a Z' portal with pure-vector couplings to the SM and a Dirac fermion DM. The Lagrangian is given by:

$$\mathcal{L}_{int} = -g_\chi Z'_\mu \bar{\chi} \gamma^\mu \chi - \sum_f g_f Z'_\mu \bar{f} \gamma^\mu f$$

Light Mediator

Motivations:

- Possibility to provide strong DM self-interactions and explain anomalies in galaxy clusters.
- Possibility to enhance the direct detection signal in models with feebly coupled particles.
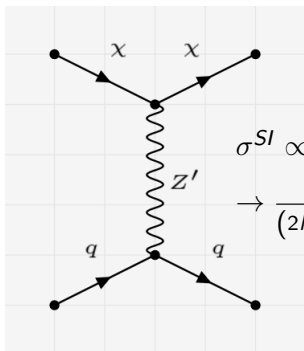
$\sigma^{SI} \propto \dfrac{g_f^2 g_\chi^2}{\left(2M_A E_R + M_{Z'}^2\right)^2} \to \dfrac{1}{M_{Z'}^4}$ for heavy mediator

$\to \dfrac{1}{\left(2M_A E_R + M_{Z'}^2\right)^2}$ for light mediator.

Light Mediator

- We consider a long-range interaction between a DM particle and a nucleus A, with t-channel light propagator

$$\frac{1}{t - M_{med}^2} = \frac{-1}{2M_A E_R + M_{med}^2}$$

(see also Hambye et al., arXiv:1807.05022)

- For the typical minimal recoil energy in Xenon1T $E_R \sim 2KeV$, $M_{Xe} \sim 130GeV$ we can have $2M_A E_R \sim (22MeV)^2$.

- The recoil spectrum $\frac{dN_A^{std}}{dE_R}$ generally computed from the amplitudes for CDM-nucleon elastic scattering at zero momentum needs to be improved, it becomes

$$\frac{dN_A}{dE_R} = \frac{M_{med}^4}{\left(M_{med}^2 + 2M_A E_R\right)^2} \frac{dN_A^{std}(\sigma_0)}{dE_R}$$

- DD routines in micrOMEGAs check automatically the presence of a light mediator and make this improvement.

Results For Zp Model
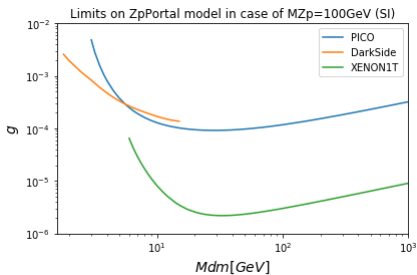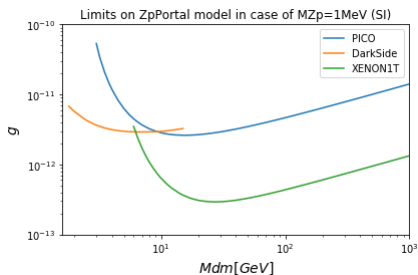
where $g = g_f g_\chi$.

- We always have the best exclusion from Xenon1T for high DM mass.
- In case of light mediator, we can probe smaller couplings and so testing Feebly Interacting Massive Particle (FIMP) DM model is possible.
- FIMP $\rightarrow$ couplings of order 10^{-12}.

Velocity Distribution

Maxwell

- It is the Standard isotropic isothermal spherical DM halo (SHM), in which velocities are isotropic and follow Gaussian law.

$$f(v) = \frac{1}{(2\pi\sigma^2)^{3/2}} \exp\left[-\frac{(\vec{v} + \vec{v}_{Earth})^2}{2\sigma^2}\right]$$

where $\sigma = \frac{v_{Rot}}{\sqrt{2}}$.

SHMpp

- Proposed in ref: Evans, O'Hare, McCabe, arXiv:1810.11468 .
- New data suggest that our stellar halo lies in a strongly radially anisotropic population, the 'Gaia Sausage'.
- It is described as:

$$f(v) = (1 - \eta)f_{Maxwell}(v) + \eta f_S(v)$$

Velocity Distribution

where η is the DM density in the Sausage and f_S is the velocity distribution of the Gaia Sausage. It is a function of the anisotropy β.

These parameter are fit to Gaia data.
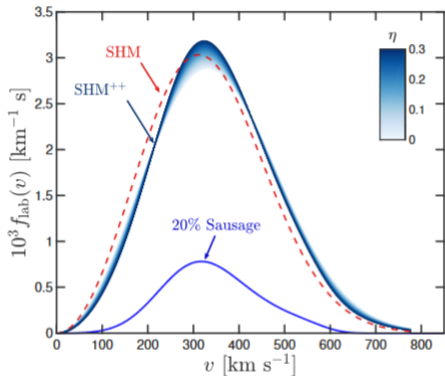
SHMpp parameters:

$$\rho_{DM} = 0.55 \pm 0.17 \, GeV/cm^3$$

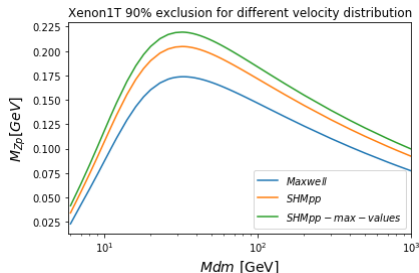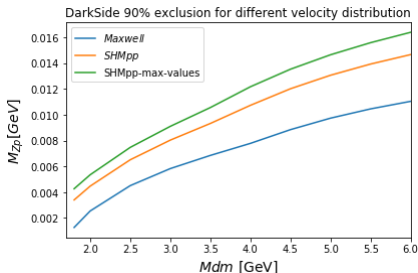$$v_{Rot} = 233 \pm 3 km/s$$

$$v_{Esc} = 580 \pm 63 km/s$$

$$\beta = 0.9 \pm 0.05$$

$$\eta = 0.2 \pm 0.1$$

Results For Different Velocity Distribution

Fixing the couplings, we get:

The strongest dependence on the velocity distribution is observed for small DM mass. For Xenon1T, we get the largest increasing on the value of MZp excluded for $Mdm \simeq 6\,GeV$ (80%). While for DarkSide, the largest increasing is for $Mdm \simeq 1.8\,GeV$ (238%). For larger values of ρ_{DM} we can test smaller cross sections (higher cuts on MZp).

Millicharged DM

- It is the SM plus an extra abelian gauge field that couples to a massive Dirac fermion ("Dark QED") and that mixes with SM 's hypercharge through the kinetic term:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\slashed{\partial} + ie'\slashed{A}' + iM_{mcp}\right)\psi - \frac{k}{2}A'_{\mu\nu}B^{\mu\nu}$$

Where $k << 1$ and $B_{\mu\nu} = \cos(\theta_\omega)A_\mu - \sin(\theta_\omega)Z_\mu$
$A'_\mu \to A'_\mu - kB_\mu$, we get:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\slashed{\partial} + ie'\slashed{A}' - ike'\slashed{B} + iM_{mcp}\right)\psi \ .$$

So DM couples to the photon and it has a millicharge $q = ke'\cos(\theta_\omega)$.

Photon can be treated as light mediator with a very small mass, thus allowing to write the energy distribution as:

$$\frac{dN_A^{ph}}{dE_R} = \frac{m_{ph}^4}{(2M_A E_R)^2} \frac{dN_A^{std}(\sigma_{\chi P})}{dE_R}$$

where $\sigma_{\chi P} = 16\pi\alpha_{EM}^2 q^2 \frac{\mu_{\chi P}^2}{m_{ph}^4}$

(see also Hambye et al., arXiv:1807.05022).

Note however that the parameter m_{ph} cancels out.

Preliminary Results For Milicharged DM

- Milicharged DM loose energy before it reaches the detector through scattering with nucleus or electrons and so it may not produce a recoiling energy above threshold.
- There is an upper limit on DM charge 'q'.
- The main process of energy lost is elastic scattering of DM with atomic nucleus.

Conclusion
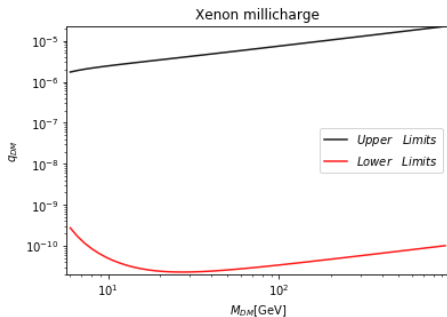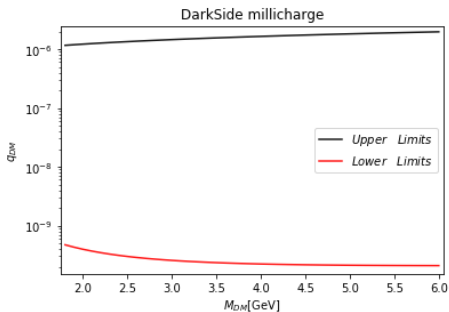
MicrOMEGAs has a new module that allows:

- Impose DD limits on a variety of DM models (WIMP, FIMP, light mediator, millicharged DM, 2 DM model).
- take into account different velocity distributions, nuclear form factors
- Currently included : Xenon1T, Pico60, DarkSide50, CRESST3.

We are planning to include other experiments when they improve on these results.

Future plan: constraints on Inert Doublet + Singlet model with Z4 symmetry and two DM candidates.