Constraints on cosmic-ray boosted dark matter from the XENONnT experiment : An analysis based on energy dependent crosssection

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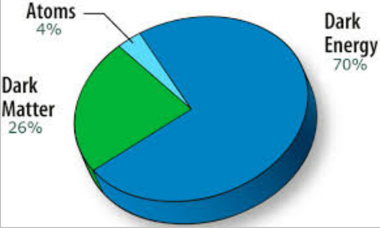
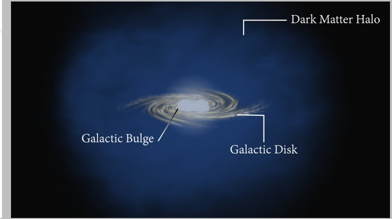
Overview

1. Present Understanding About the structure of the Universe
2. Dark Matter Detection Strategies
3. Limitation of Direct detection experiments
4. Cosmic-ray Boosted Dark Matter
5. Conclusions

Present Understanding

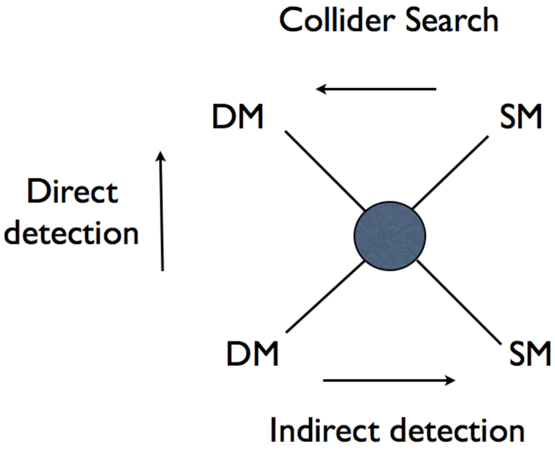
- Structure formation of the universe: Luminous matter ($\sim 4\%$) is not sufficient, non-luminous matter (dubbed as dark matter $\sim 26\%$) is required (Cannoni M., 2016, Eur. Phys. J. C, 76, 137).





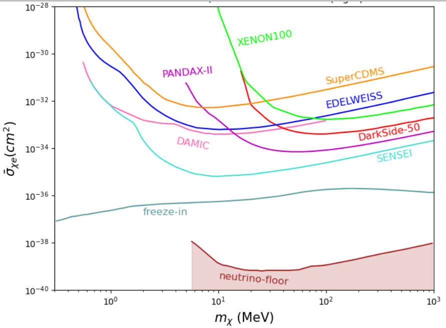
- They are dark as they can't absorb, emit, reflect light! They does not interact with the electromagnetic force like SM particles.
- Their interaction with the SM particles is very weak whereas they are highly massive (WIMPs).
- Primary evidences are anomaly in galaxy rotation curve, gravitational lensing and bullet cluster.

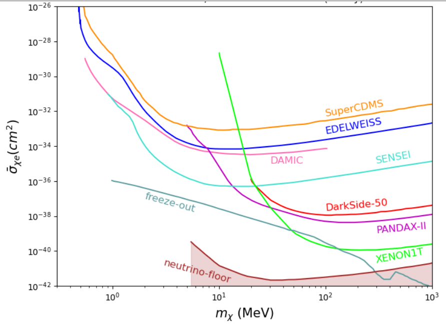
Detection Strategies



Direct detection experiments

Experiments : XENON, SENSEI, DarkSide
Basic working principle : To measure the recoil energy of electron/nucleus assuming that the DM particles scatter off the target.





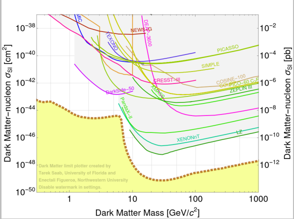
Light mediator Heavy mediator

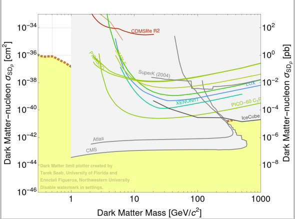
Courtesy : Dark matter limit plotter v5.18

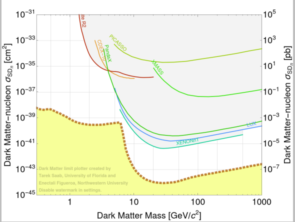
Direct Detection experiments lose sensitivity for low mass DM.

- Below DM mass of ~ 0.3 GeV for DM-nucleon cross-section.
- Below DM mass of ~ 0.3 MeV for DM-electron crosssection

Very light DM particles cannot produce enough recoil to be detected.

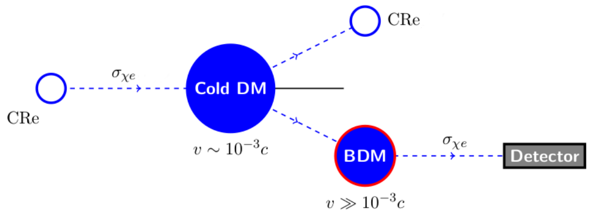






Courtesy : Dark matter limit plotter v5.18

Cosmic-ray Boosted Dark Matter



The energy transfer to the cold DM by the CR particle:

$$T_\chi = T_\chi^{max}\left(\frac{1-\cos\theta}{2}\right)$$

$$T_\chi^{max} = \frac{(T_i)^2 + 2T_i m_i}{T_i + (m_i + m_\chi)^2/(2m_\chi)}$$

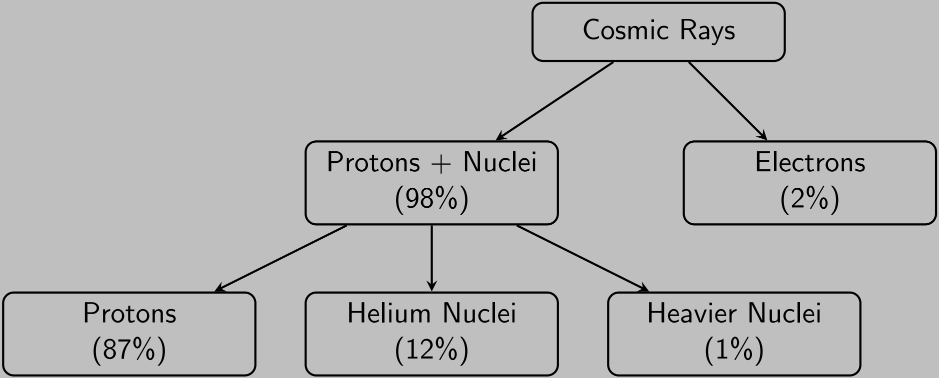
θ is the scattering angle at the centre of momentum frame.

$$T_i^{min} = \left(\frac{T_\chi}{2} - m_i\right)\left[1 \pm \sqrt{1 + \frac{2T_\chi}{m_\chi}\frac{(m_i + m_\chi)^2}{(2m_i - T_\chi)^2}}\right]$$

$$\left(\frac{d\Phi_\chi}{dT_\chi}\right)_i = D_{eff} \times \frac{\rho_\chi^{\rm local}}{m_\chi} \int_{T_i^{min}}^{\infty} dT_i \, \frac{d\Phi_i}{dT_i} \, \frac{1}{T_\chi^{max}(T_i)}$$

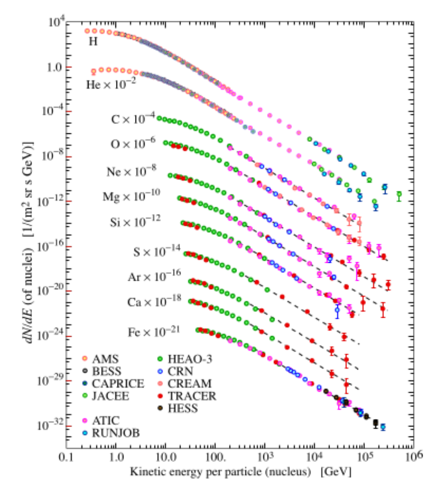
D_{eff} = Effective distance out to which we take into account CRs as the source of a possible high-velocity tail in the DM velocity distribution
ρ_χ, m_χ = Density and mass of DM particles
T_i = Kinetic energy of the CR particle i

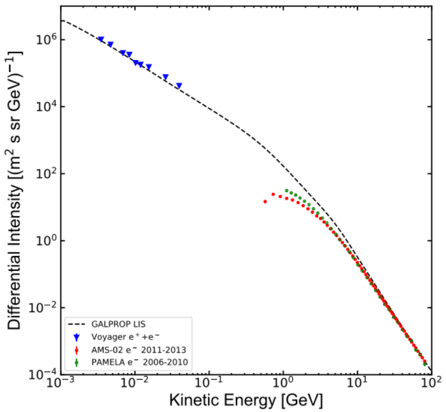
Components of Cosmic Ray



Longair, M. S. , "High Energy Astrophysics", Cambridge University Press (2011).
Cosmic Rays, Particle Data Group, PDG-2022.

Flux of CR electron, proton and nuclei





Phys. Rev. D 98, 030001 (2018)

Astrophys. J. 854, 94 (2018)

Flux of CR electron, proton and nuclei

$$\frac{d\Phi_e}{dT_e}(T_e) = \begin{cases} \dfrac{1.799\times 10^{44}\ \ T_e^{-12.061}}{1+2.762\times 10^{36}\ \ T_e^{-9.269}+3.853\times 10^{40}\ \ T_e^{-10.697}} & \text{if } T_e < 6880 \text{ MeV} \\ 3.259 \times 10^{10}\ \ T_e^{-3.505} + 3.204 \times 10^{5}\ \ T_e^{-2.620} & \text{if } T_e \geqslant 6880 \text{ MeV} \end{cases}$$

where the unit of $\frac{d\Phi_e}{dT_e}(T_e)$ is given in $\left(\mathrm{m}^2\ \mathrm{s}\ \mathrm{sr}\ \mathrm{MeV}\right)^{-1}$ and the kinetic energy (T_e) of the CR electrons is in MeV.

Astrophys. J. 854, 94 (2018), arXiv:1801.04059 [astro-ph.HE].

Flux of CR electron, proton and nuclei

$$\frac{dI}{dR} \times R^{2.7} = \begin{cases} \sum_{i=0}^{5} a_i R^i, & \text{if } R \leqslant 1 \text{ GV} \\ b + \frac{c}{R} + \frac{d_1}{d_2+R} + \frac{e_1}{e_2+R} + \frac{f_1}{f_2+R} + gR, & \text{if } R > 1 \text{ GV} \end{cases}$$

with the following parameter set

	a_0	a_1	a_2	a_3	a_4	a_5
p	94.1	−831	0	16700	−10200	0
He	1.14	0	−118	578	0	−87

	b	c	d_1	d_2	e_1	e_2	f_1	f_2	g
p	10800	8590	−4230000	3190	274000	17.4	−39400	0.464	0
He	3120	−5530	3370	1.29	134000	88.5	−1170000	861	0.03

Cosmic ray proton and Helium flux is then obtain by the following relations

$$\frac{d\Phi_p}{dT_p}(T_p) = 4\pi \frac{dR}{dT_p}\frac{dI}{dR}$$

$$\frac{d\Phi_{He}}{dT_{He}}(T_{He}) = 4\pi \frac{dR}{dT_{He}}\frac{dI}{dR}$$

Astrophys. J. 840, 115 (2017), arXiv:1704.06337 [astro-ph.HE].

Models for our analysis

- Secluded dark sector (Dark photon):

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{SM} + \bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi - g_\chi \bar{\chi}\gamma_\mu \chi \hat{A'}^\mu \\
&+ \frac{1}{2} m^2_{\hat{A}'} \hat{A'}_\mu \hat{A'}^\mu - \frac{1}{4}\hat{A'}_{\mu\nu}\hat{A'}^{\mu\nu} - \frac{\sin\varepsilon}{2}\hat{B}_{\mu\nu}\hat{A'}^{\mu\nu}
\end{aligned}
$$

- $U(1)_{B-L}$:

$$
\mathcal{L}_{B-L} \supset g_{B-L}\left[-\bar{l}\gamma^\mu A'_\mu l - \bar{\nu}_R \gamma^\mu A'_\mu \nu_R + \frac{1}{3}\bar{q}\gamma^\mu A'_\mu q\right] - g_\chi \bar{\chi}\gamma_\mu \chi \hat{A'}^\mu
$$

- $L_e - L_\mu$:

$$
\mathcal{L}_{L_e - L_\mu} \supset g_L\left[\bar{l}_e \gamma^\mu A'_\mu l_e - \bar{l}_\mu \gamma^\mu A'_\mu l_\mu\right] - g_\chi \bar{\chi}\gamma_\mu \chi \hat{A'}^\mu
$$

Dark Photon Model

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{SM} + \bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi - g_\chi \bar{\chi}\gamma_\mu \chi \hat{A}'^{\mu} \\ &+ \frac{1}{2} m_{\hat{A}'}^2 \hat{A}'_\mu \hat{A}'^{\mu} - \frac{1}{4}\hat{A}'_{\mu\nu}\hat{A}'^{\mu\nu} - \frac{\sin\varepsilon}{2}\hat{B}_{\mu\nu}\hat{A}'^{\mu\nu}\end{aligned}$$

We use the transformations

$$\begin{aligned}\hat{B} &= c_{\hat{W}} A - \left(t_\varepsilon s_\xi + s_{\hat{W}} c_\xi\right) Z + \left(s_{\hat{W}} s_\xi - t_\varepsilon c_\xi\right) A' \\ \hat{W}_3 &= s_{\hat{W}} A + c_{\hat{W}} c_\xi Z - c_{\hat{W}} s_\xi A' \\ \hat{A}' &= \frac{s_\xi}{c_\varepsilon} Z + \frac{c_\xi}{c_\varepsilon} A' \quad ; \quad \tan 2\xi = -\frac{m_{\hat{Z}}^2 s_{\hat{W}} \sin 2\varepsilon}{m_{\hat{A}'}^2 - m_{\hat{Z}}^2\left(c_\varepsilon^2 - s_\varepsilon^2 s_{\hat{W}}^2\right)}\end{aligned}$$

to diagonalize away the kinetic mixing term

$$\begin{aligned}\mathcal{L} \supset\ & A'_\mu \left[g_{fL}^{A'}\ \bar{f}\gamma^\mu P_L f + g_{fR}^{A'}\ \bar{f}\gamma^\mu P_R f + g_\chi^{A'}\ \bar{\chi}\gamma^\mu \chi\right] \\ +\ & Z_\mu \left[g_{fL}^{Z}\ \bar{f}\gamma^\mu P_L f + g_{fR}^{Z}\ \bar{f}\gamma^\mu P_R f + g_\chi^{Z}\ \bar{\chi}\gamma^\mu \chi\right]\end{aligned}$$

Dark Photon Model

Relevant couplings are : (JHEP 1102:100,2011)

$$\begin{aligned}
g_{fL}^{A'} &= -\frac{e}{c_W s_W} c_\xi \left\{ T_3 \left[s_W t_\varepsilon - t_\xi + \frac{1}{2}\omega \left(t_\xi + \frac{s_W t_W^2 t_\varepsilon}{1 - t_W^2} \right) \right] \right. \\
&+ \left. Q \left[s_W^2 t_\xi - s_W t_\varepsilon + \frac{1}{2} t_W^2 \omega \left(\frac{t_\xi - s_W t_\varepsilon}{1 - t_W^2} \right) \right] \right\} \\
g_{fR}^{A'} &= -\frac{e}{c_W s_W} c_\xi Q \left[s_W^2 t_\xi - s_W t_\varepsilon + \frac{1}{2} t_W^2 \omega \left(\frac{t_\xi - s_W t_\varepsilon}{1 - t_W^2} \right) \right] \\
g_\chi^{A'} &= -g_\chi \frac{c_\xi}{c_\varepsilon} \; ; \quad g_\chi^Z = -g_\chi \frac{s_\xi}{c_\varepsilon} \\
g_{fL}^{Z} &= -\frac{e}{c_W s_W} c_\xi \left\{ T_3 \left[1 + \frac{\omega}{2} \right] - Q \left[s_W^2 + \omega \left(\frac{2 - t_W^2}{2\left(1 - t_W^2\right)} \right) \right] \right\} \\
g_{fR}^{Z} &= \frac{e}{c_W s_W} c_\xi Q \left[s_W^2 + \omega \left(\frac{2 - t_W^2}{2\left(1 - t_W^2\right)} \right) \right]
\end{aligned}$$

with $\omega = s_W t_\xi t_\varepsilon$ and t_ξ can be found by

$$1 + s_{\hat{W}} t_\xi t_\varepsilon = \frac{c_{\hat{W}}^2 s_{\hat{W}}^2}{c_W^2 s_W^2}; \quad \rho = \frac{s_W^2}{s_{\hat{W}}^2}; \quad \rho - 1 = 4_{-4}^{+8} \times 10^{-4}$$

Flux of Boosted Dark Matter

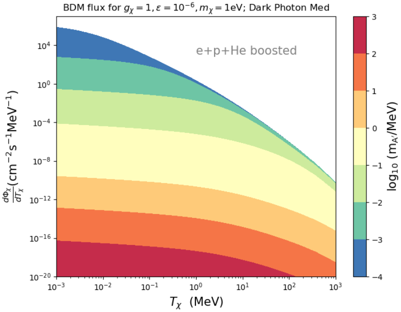
$$\begin{aligned}\frac{d\Phi_\chi}{dT_\chi} &= D_{eff} \times \frac{\rho_\chi^{\rm local}}{m_\chi} \left[\int_{T_e^{min}}^{\infty} dT_e \, \frac{d\Phi_e}{dT_e} \, \frac{d\sigma_{\chi e}}{dT_\chi} \right. \\ &+ \int_{T_p^{min}}^{\infty} dT_p \, \frac{d\Phi_p}{dT_p} \, \frac{d\sigma_{\chi p}}{dT_\chi} G_p^2(2m_\chi T_\chi) \\ &+ \left. \int_{T_{He}^{min}}^{\infty} dT_{He} \, \frac{d\Phi_{He}}{dT_{He}} \, \frac{d\sigma_{\chi He}}{dT_\chi} G_{He}^2(2m_\chi T_\chi) \right]\end{aligned}$$

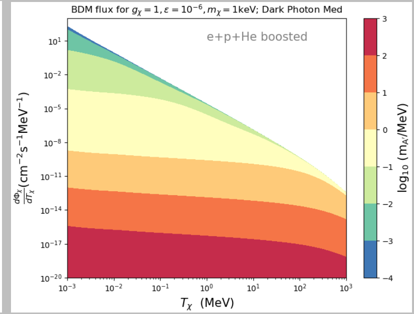
$$\frac{d\sigma_{\chi i}}{dT_\chi} = {g_{i\chi}^{A'}}^2 \, \frac{2m_\chi (m_i + T_i)^2 - T_\chi \left\{ \left(m_i + m_\chi\right)^2 + 2m_\chi T_i \right\} + m_\chi T_\chi^2}{8\pi \left(2m_i T_i + T_i^2\right) \left(2m_\chi T_\chi + m_{A'}^2\right)^2}$$

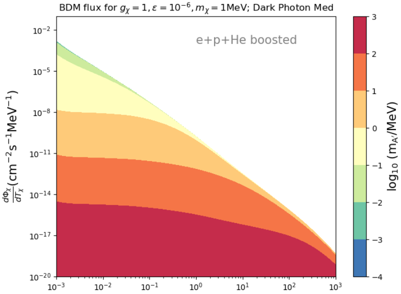
$$i = e, p, He; \quad G_i\left(q^2\right) = \left(1 + \frac{q^2}{\Lambda_i^2}\right)^{-2} \quad \rightarrow \text{ nucleon electromagnetic form factor}$$

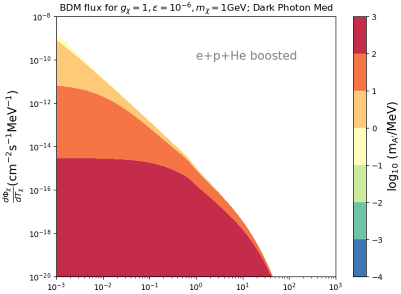
where, $\Lambda_p = 770 \text{ MeV}$, $\Lambda_{He} = 410 \text{ MeV}$, $g_{i\chi}^{A'} = g_i^{A'} g_\chi^{A'}$

Flux of Boosted Dark Matter









Rate equation

Predicted differential rate at the detector

$$\frac{dR}{dE_R} = \aleph \int_{T_\chi^{min}(E_R)}^{\infty} dT_\chi \sum_{i=e,p,He} \left(\frac{d\Phi_\chi}{dT_\chi}\right)_i \frac{d\sigma_{\chi e}}{dE_R}$$

with

$$\frac{d\sigma_{\chi i}}{dE_R} = {g_{e\chi}^{A'}}^2 \frac{2m_e\left(m_\chi + T_\chi\right)^2 - E_R\left\{\left(m_e + m_\chi\right)^2 + 2m_e T_\chi\right\} + m_e E_R^2}{8\pi\left(2m_\chi T_\chi + T_\chi^2\right)\left(2m_e E_R + m_{A'}^2\right)^2}$$

- Recoil spectrum for XENON1T is obtained by taking $\aleph = Z_{Xe}/m_{Xe}$, where Z_{Xe} is atomic number of Xenon and m_{Xe} is the mass of a single Xenon atom.

To find the exclusion region, we perform a χ^2 analysis

$$\chi^2 = \sum_i \frac{(O_i - E_i)^2}{E_i + (\sigma_i^2)_{\mathrm{data}}} \quad (1)$$

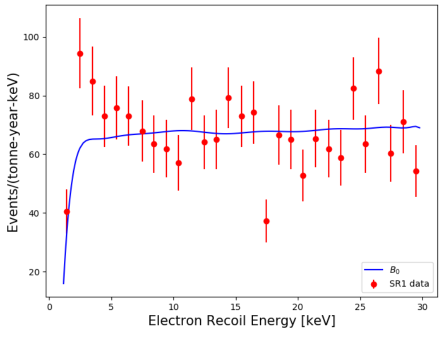
$$\Delta\chi^2 = \chi^2(BDM + B_0) - \chi^2(B_0 \text{ only}) \quad (2)$$

- O_i are the observed number of events
- E_i are the expected number of events
- $(\sigma_i)_{\mathrm{data}}$ is uncertainty in the measured data

(For the $(BDM + B_0)$ case, to calculate the E_i values, we sum the BDM signal and the background B_0 for each energy bin.)

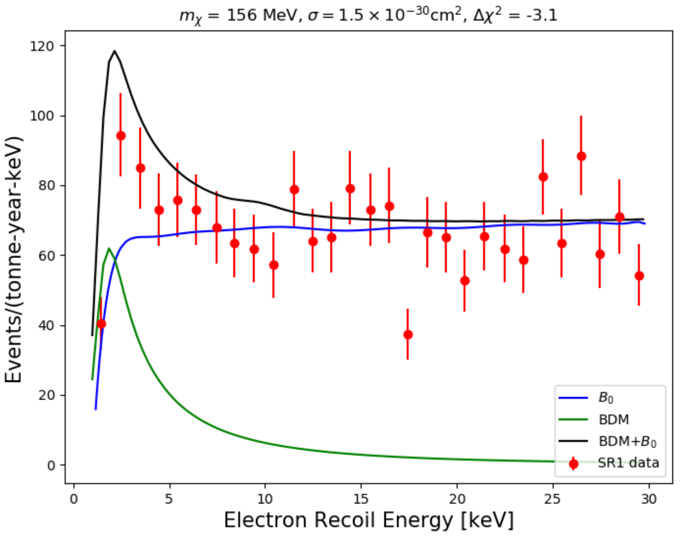
XENON1T excess

No.	Component	Expected Events	Fitted Events
i	^{214}Pb	(3450, 8530)	7480 ± 160
ii	^{85}Kr	890 ± 150	773 ± 80
iii	Materials	323 (fixed)	323 (fixed)
iv	^{136}Xe	2120 ± 210	2150 ± 120
v	Solar neutrino	220.7 ± 6.6	220.8 ± 4.7
vi	^{133}Xe	3900 ± 410	4009 ± 85
vii	^{131m}Xe	23760 ± 640	24270 ± 150
	^{125}I (K)	79 ± 33	67 ± 12
viii	^{125}I (L)	15.3 ± 6.5	13.1 ± 2.3
	^{125}I (M)	3.4 ± 1.5	2.94 ± 0.50
ix	^{83m}Kr	2500 ± 250	2671 ± 53
	^{124}Xe (KK)	125 ± 50	113 ± 24
x	^{124}Xe (KL)	38 ± 15	34.0 ± 7.3
	^{124}Xe (LL)	2.8 ± 1.1	2.56 ± 0.55

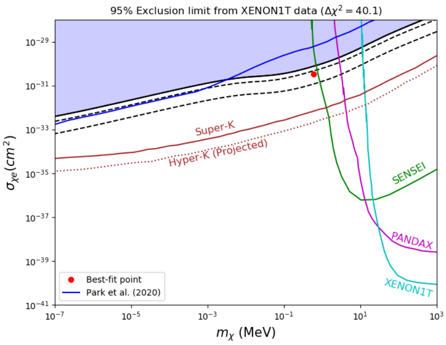


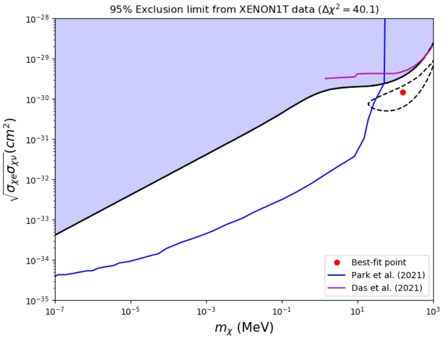
Excess events (electron recoil energy 1 - 7 keV) have been reported by E. Aprile et al. (XENON), Phys. Rev. D 102, 072004 (2020).

Best Fit Recoil Spectrum for XENON1T data

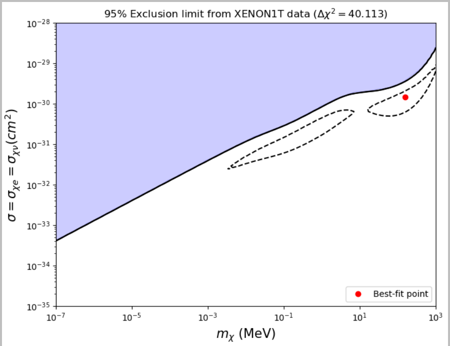


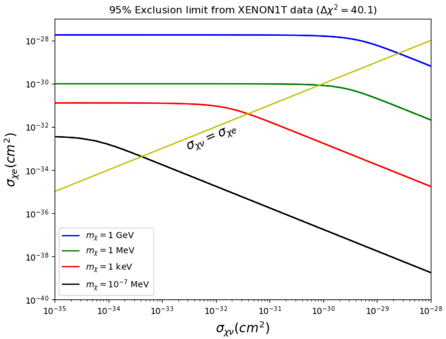
Exclusion Limit





Exclusion Limit

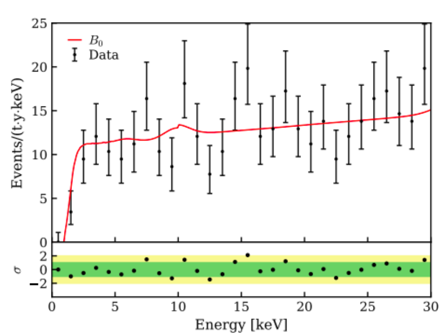




XENONnT Results 2022

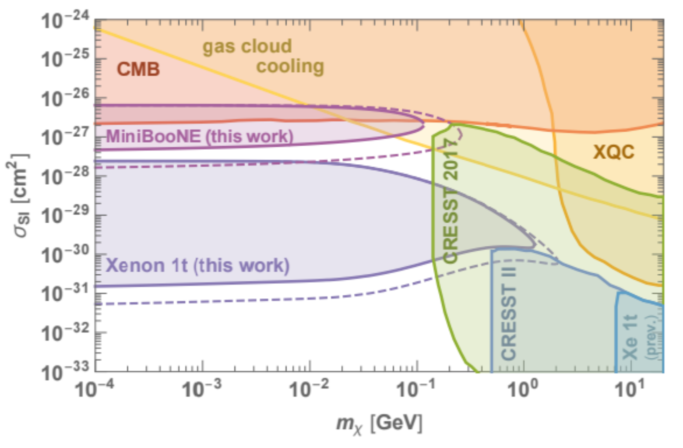
TABLE I. The background model B_0 with fit constraints and best-fit number of events for each component in (1, 140) keV.

Component	Constraint	Fit
^{214}Pb	(570, 1200)	960 $\pm$ 120
^{85}Kr	90 $\pm$ 60	90 $\pm$ 60
Materials	270 $\pm$ 50	270 $\pm$ 50
^{136}Xe	1560 $\pm$ 60	1550 $\pm$ 50
Solar neutrino	300 $\pm$ 30	300 $\pm$ 30
^{124}Xe	-	250 $\pm$ 30
AC	0.70 $\pm$ 0.04	0.71 $\pm$ 0.03
^{133}Xe	-	150 $\pm$ 60
^{83m}Kr	-	80 $\pm$ 16

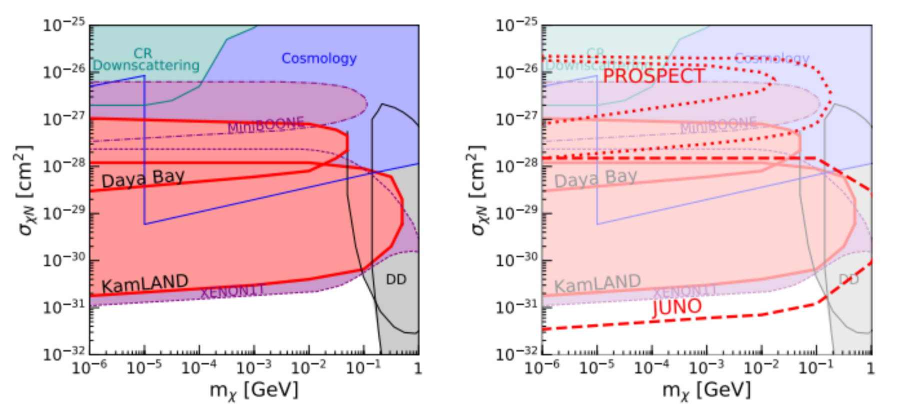


Phys. Rev. Lett. 129, 161805 (2022)

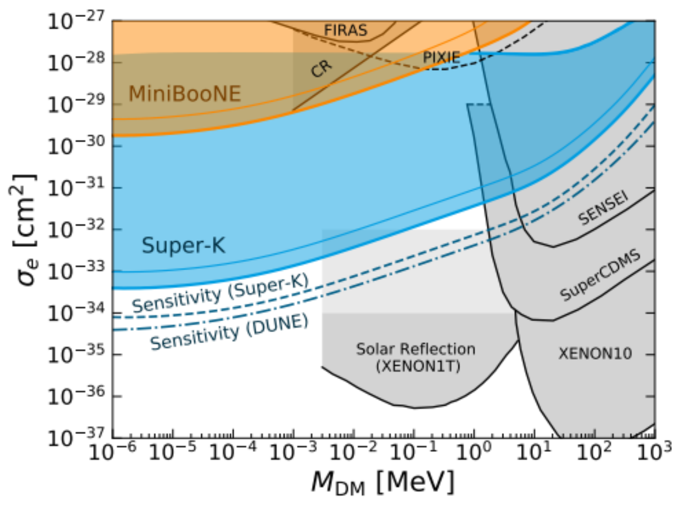
Constraining WIMP-Nucleon Crosssection from BDM



Constraining WIMP-Nucleon Crosssection from BDM

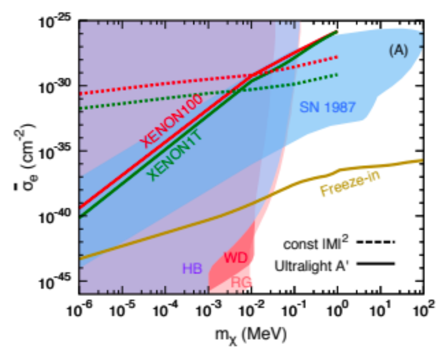


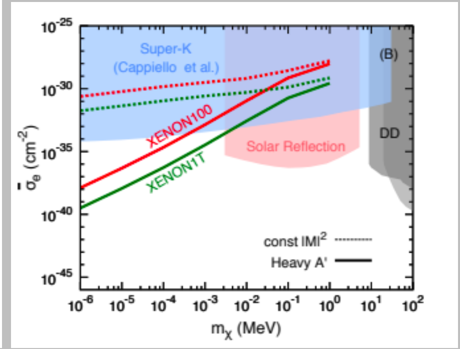
Constraining WIMP-Electron Crosssection from BDM



©Y. Ema, F. Sala, and R. Sato, Phys. Rev. Lett. 122, 181802 (2019)

Constraining WIMP-Electron Crosssection from BDM





Cao et al, Chin. Phys. C 45, 045002 (2021), arXiv:2006.12767 [hep-ph].

Exclusion Limit on the kinetic mixing parameter

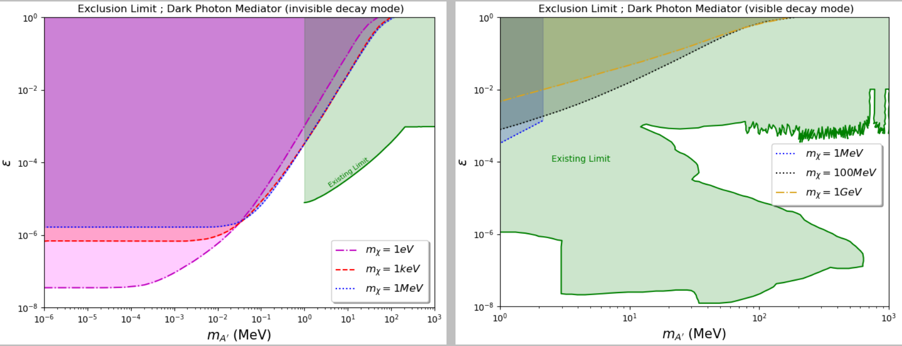


Figure: Shaded regions are excluded at 95% confidence level for $g_\chi = 1$, in the ε vs $m_{A'}$ plane, for the invisible decay scenario (Left) and for the visible decay scenario (Right).

Exclusion Limit on the kinetic mixing parameter

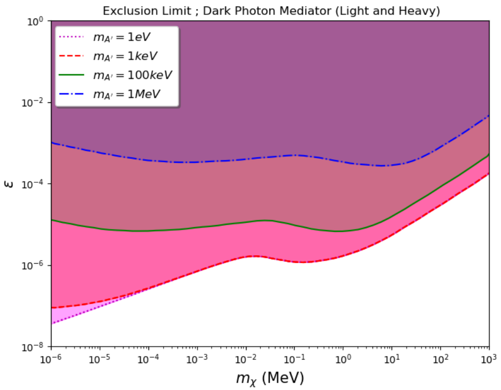


Figure: Shaded regions are excluded at 95% confidence level for $g_\chi = 1$, in the ε vs m_χ plane, both for the light and the heavy mediator scenario. For $m_{A'} = 1$ GeV, there is no valid kinetic mixing parameter ($\varepsilon \leq 1$) which can produce enough recoil at the detector.

Exclusion Limit on the couplings

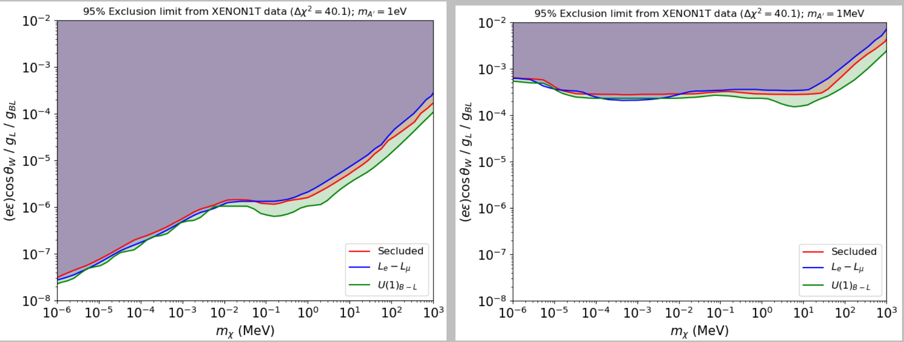


Figure: Shaded regions are excluded at 95% confidence level for $g_\chi = 1$, in the coupling vs m_χ plane, for light mediator (Left) and heavy mediator scenario (Right).

Exclusion Limit on the DM-electron crosssection

Conventionally normalized form of DM-electron scattering crossection :

$$\overline{\left|\mathcal{M}_{free}\right|^2} = \overline{\left|\mathcal{M}_{free}(\alpha m_e)\right|^2} \times \left|F_{DM}(q)\right|^2$$

$$\bar{\sigma}_{\chi e} = \frac{\mu_{\chi e}^2 \overline{\left|\mathcal{M}_{free}(\alpha m_e)\right|^2}}{16\pi m_\chi^2 m_e^2}$$

For our case, the form factor at the detector

$$\left|F_{DM}(q = \sqrt{2m_e E_R})\right|^2 = \frac{(\alpha^2 m_e^2 + m_{A'}^2)^2}{(2m_e E_R + m_{A'}^2)^2} \times \frac{2m_e(m_\chi + T_\chi)^2 - E_R\left[(m_\chi + m_e)^2 + 2m_e T_\chi\right] + m_e E_R^2}{2m_e m_\chi^2}$$

In the non-relativistic limit $E_R, T_\chi \ll m_e$

$$\left|F_{DM}(q)\right|^2 = \frac{(\alpha^2 m_e^2 + m_{A'}^2)^2}{(q^2 + m_{A'}^2)^2}$$

For heavy-mediator limit $\left|F_{DM}(q)\right| = 1$
For light-mediator limit $\left|F_{DM}(q)\right| \sim \frac{1}{q^2}$

Exclusion Limit on the DM-electron crosssection

With these definitions and $g_{i\chi}^{A'} = e\varepsilon \cos\theta_W \ / \ g_L \ / \ g_{B-L}$ for $g_\chi = 1$

$$
\begin{aligned}
\overline{\left|\mathcal{M}_{free}(\alpha m_e)\right|^2} &= \frac{16 \ {g_{e\chi}^{A'}}^2 \ m_e^2 m_\chi^2}{(\alpha^2 m_e^2 + m_{A'}^2)^2} \\
\bar{\sigma}_{\chi e} &= \frac{{g_{e\chi}^{A'}}^2 \ \mu_{\chi e}^2}{\pi(\alpha^2 m_e^2 + m_{A'}^2)^2} \\
\implies \bar{\sigma}_{\chi e} &= \begin{cases} \frac{{g_{e\chi}^{A'}}^2 \ \mu_{\chi e}^2}{\pi(\alpha^2 m_e^2)^2} & \text{for light mediator,} \\ \frac{{g_{e\chi}^{A'}}^2 \ \mu_{\chi e}^2}{\pi(m_{A'}^2)^2} & \text{for heavy mediator.} \end{cases}
\end{aligned}
$$

Using these relations we translate our exclusion limit on the kinetic mixing parameter to the crosssection.

Exclusion Limit on the DM-electron crosssection

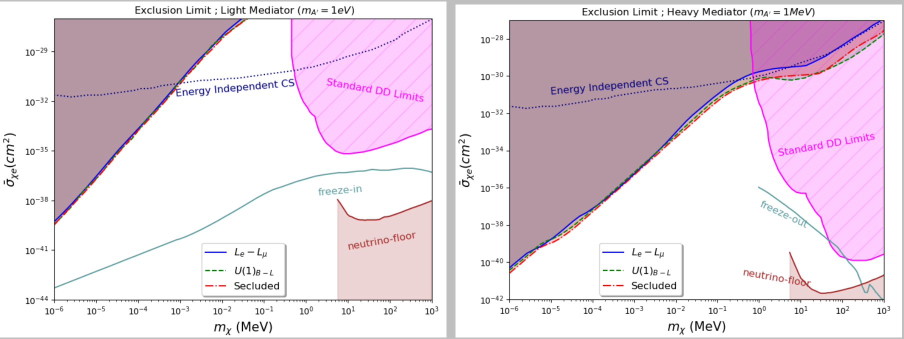


Figure: Shaded regions are excluded at 95% confidence level for $g_\chi = 1$, in the $\sigma_{\chi e}$ vs m_χ plane, for light mediator (Left) and for heavy mediator scenario (Right).

Conclusions

- Direct detection experiments lose sensitivity for low mass of DM.
- Boosting mechanism from Cosmic ray is useful to look for lower mass dark matter at direct detection compared to cold dark matter search.
- Energy dependent cross-section can represent more realistic phenomena in comparison with the constant cross-section case.
- For low mass dark matter, exclusion limits become stronger if we invoke energy dependence of the cross-section by considering exact model of interaction between DM and SM particles.

The End