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

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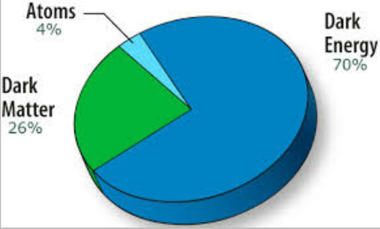
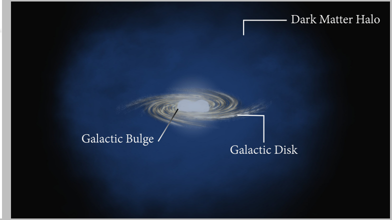
Overview

Present Understanding

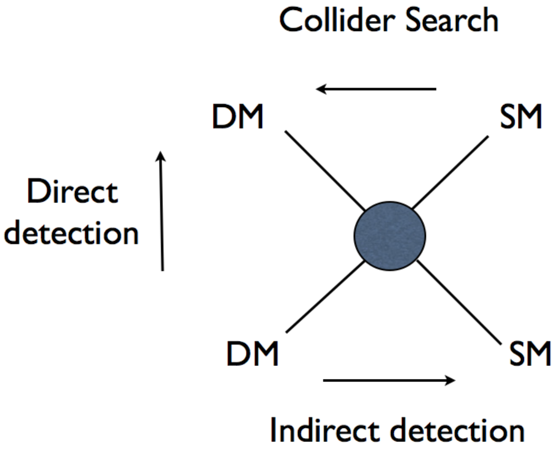
- Structure formation of the universe: Luminous matter ($\sim 4\%$) is not sufficient, non-luminous matter (dubbed as dark matter $\sim 26\%$) is required (Cannoni M., 2016, Eur. Phys. J. C, 76, 137).





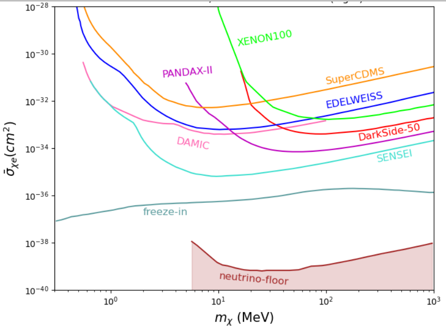
- They are dark as they can't absorb, emit, reflect light! They does not interact with the electromagnetic force like SM particles.
- Their interaction with the SM particles is very weak whereas they are highly massive (WIMPs).
- Primary evidences are anomaly in galaxy rotation curve, gravitational lensing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

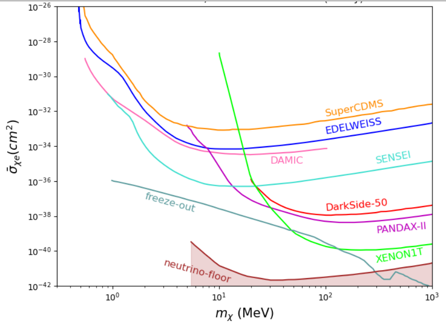
Detection Strategies



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

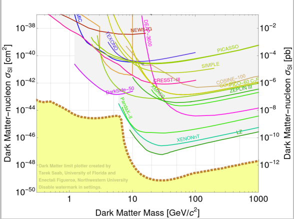
Courtesy : Dark matter limit plotter v5.18

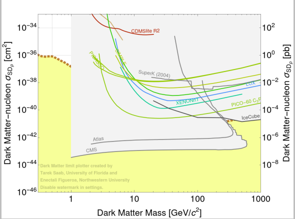
Limitation of Direct detection experiments

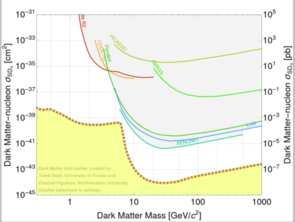
Direct Detection experiments lose sensitivity for low mass DM.

- 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.

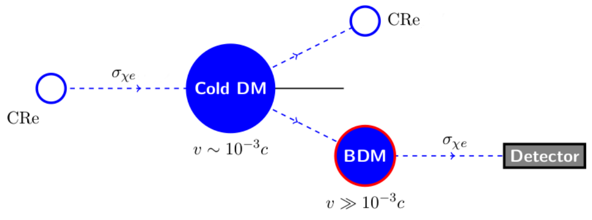






Courtesy : Dark matter limit plotter v5.18

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.

Cosmic-ray Boosted Dark Matter

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

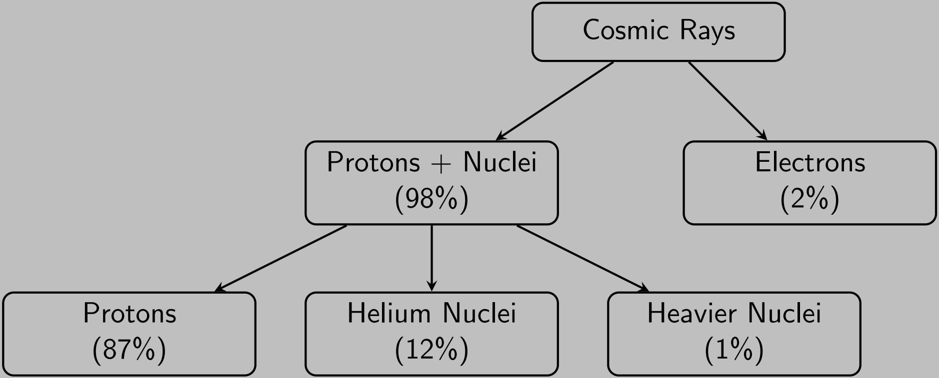
$$\left(\frac{d\Phi_\chi}{dT_\chi}\right)_i = D_{eff} \times \frac{\rho_\chi^{\rm local}}{m_\chi} \int_{T_i^{min}}^{\infty} dT_i \, \frac{d\Phi_i}{dT_i} \, \frac{1}{T_\chi^{max}(T_i)}$$

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

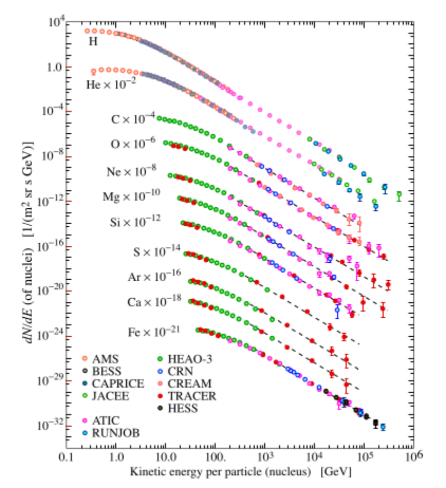
Components of Cosmic Ray



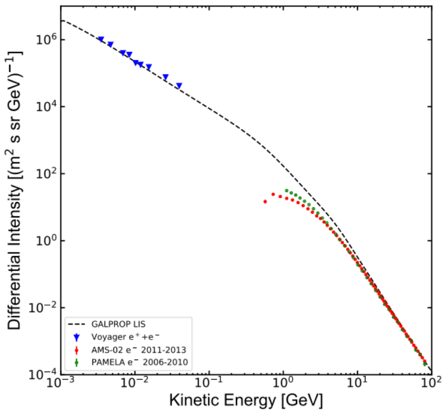
Longair, M. S. , "High Energy Astrophysics", Cambridge University Press (2011).

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)

Models for our analysis

- Secluded dark sector (Dark photon):

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

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

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

- $L_e - L_\mu$:

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

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

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

Flux of Boosted Dark Matter

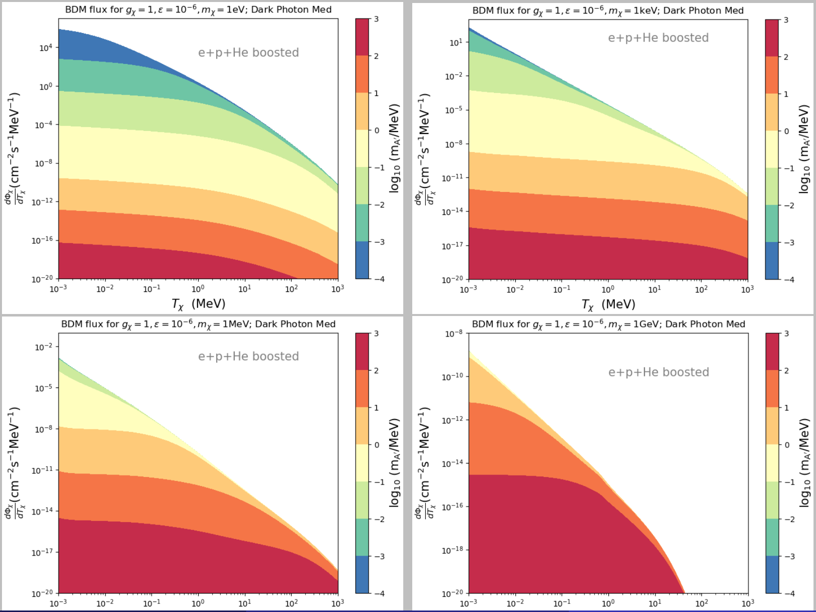
$$\frac{d\Phi_\chi}{dT_\chi} = D_{eff} \times \frac{\rho_\chi^{\rm local}}{m_\chi} \left[\int_{T_e^{min}}^{\infty} dT_e \, \frac{d\Phi_e}{dT_e} \, \frac{d\sigma_{\chi e}}{dT_\chi} + \int_{T_p^{min}}^{\infty} dT_p \, \frac{d\Phi_p}{dT_p} \, \frac{d\sigma_{\chi p}}{dT_\chi} G_p^2(2m_\chi T_\chi) + \int_{T_{He}^{min}}^{\infty}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

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

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

where, $\Lambda_p = 770$ MeV, $\Lambda_{He} = 410$ 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.

Exclusion Limit

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

$$\chi^2 = \sum_i \frac{(O_i - E_i)^2}{E_i + \left(\sigma_i^2\right)_{\rm data}} \tag{1}$$

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

- O_i are the observed number of events
- E_i are the expected number of events
- $(\sigma_i)_{\rm data}$ is uncertainity 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.)

Exclusion Limit on the kinetic mixing parameter

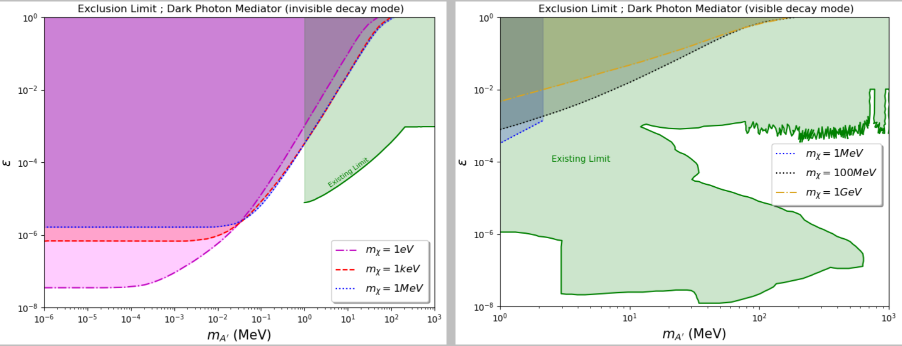


Figure: Shaded regions are excluded at 95% confidence level for $g_\chi = 1$, in the ε vs $m_{A'}$ plane, for the invisible decay scenario (Left) and for the visible decay scenario (Right).

Exclusion Limit on the kinetic mixing parameter

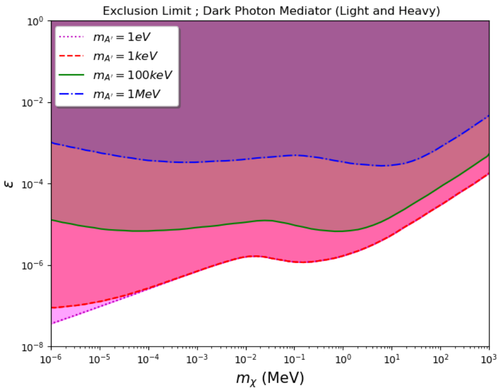
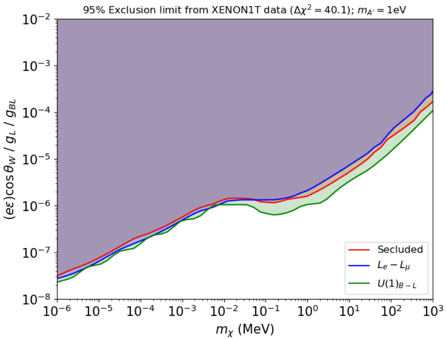


Figure: Shaded regions are excluded at 95% confidence level for $g_\chi = 1$, in the ε vs m_χ plane, both for the light and the heavy mediator scenario. For $m_{A'} = 1$ GeV, there is no valid kinetic mixing parameter ($\varepsilon \leq 1$) which can produce enough recoil at the detector.

Exclusion Limit on the couplings



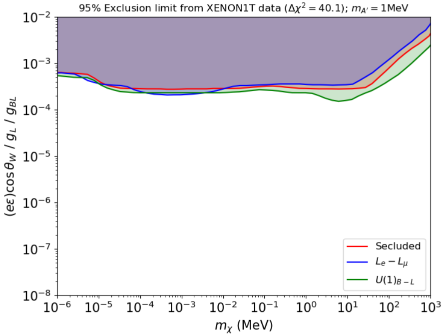


Figure: Shaded regions are excluded at 95% confidence level for $g_\chi = 1$, in the coupling vs m_χ plane, for light mediator (Left) and heavy mediator scenario (Right).

Exclusion Limit on the DM-electron crosssection

Conventionally normalized form of DM-electron scattering crossection :

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

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

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 $E_R, T_\chi \ll m_e$

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

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

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 $g_\chi = 1$

$$\overline{\left|\mathcal{M}_{free}(\alpha m_e)\right|^2} = \frac{16\; {g_{e\chi}^{A'}}^2\;\; m_e^2 m_\chi^2}{(\alpha^2 m_e^2 + m_{A'}^2)^2}$$

$$\bar{\sigma}_{\chi e} = \frac{{g_{e\chi}^{A'}}^2\;\; \mu_{\chi e}^2}{\pi(\alpha^2 m_e^2 + m_{A'}^2)^2}$$

$$\implies \bar{\sigma}_{\chi e} = \begin{cases} \frac{{g_{e\chi}^{A'}}^2\;\; \mu_{\chi e}^2}{\pi(\alpha^2 m_e^2)^2} & \text{for light mediator,} \\ \frac{{g_{e\chi}^{A'}}^2\;\; \mu_{\chi e}^2}{\pi(m_{A'}^2)^2} & \text{for heavy mediator.} \end{cases}$$

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

Exclusion Limit on the DM-electron crosssection

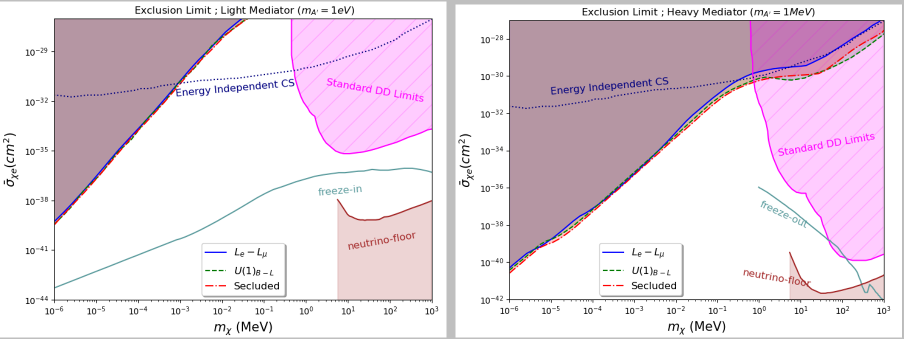


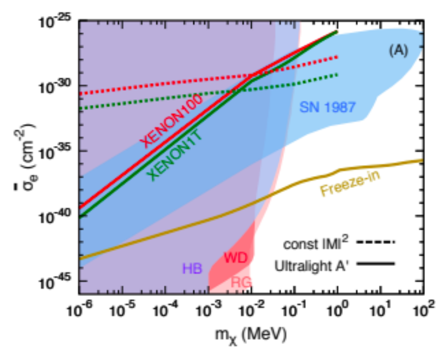
Figure: Shaded regions are excluded at 95% confidence level for $g_\chi = 1$, in the $\sigma_{\chi e}$ vs m_χ plane, for light mediator (Left) and for heavy mediator scenario (Right).

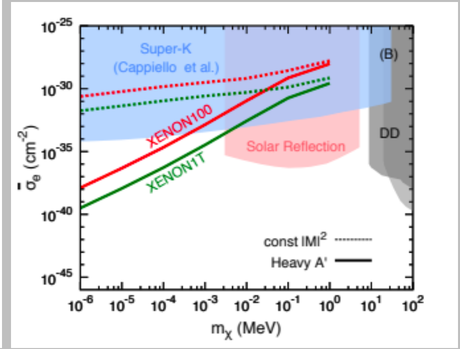
Conclusions

- For low mass dark matter, exclusion limits becomes stronger if we invoke energy dependence of the crosssection by considering exact model of interaction between DM and SM particles.
- Cosmic ray boosted dark matter could be an alternative to probe low mass dark matter compared to the cold dark matter searches in standard direct detection experiments.

The End

Existing Bound





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

Flux of CR electron, proton and nuclei

$$\frac{d\Phi_e}{dT_e}(T_e) = \begin{cases} \dfrac{1.799\times10^{44}\ \ T_e^{-12.061}}{1+2.762\times10^{36}\ \ T_e^{-9.269}+3.853\times10^{40}\ \ T_e^{-10.697}} & \text{if } T_e < 6880 \text{ MeV} \\ 3.259\times10^{10}\ \ T_e^{-3.505} + 3.204\times10^{5}\ \ T_e^{-2.620} & \text{if } T_e \geqslant 6880 \text{ MeV} \end{cases}$$

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].

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

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