A sub-GeV dark matter model

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Based on arXiv:1905.02692 (Dutta, Ghosh, Kumar)

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MOTIVATION FOR THE MODEL

- **Lack of evidence for WIMP miracle.**
- **Dark matter with mass $\mathcal{O}(1-100)$ MeV. Allowed by experimental data.**
- **Natural scale associated with the two lighest flavor sector is $\mathcal{O}(1-100)$ MeV.**
- **Dark matter arise from a new physics associated with the light flavor scale.**
- **New physics motivation is to solve the hierarchy problem in the Yukawa sector.**
- **Light mediator : Light scalar ϕ' and Light gauge boson A'.**

THE MODEL

Gauge symmetry : $SU(2)_L \times U(1)_Y \times U(1)_{T_{3R}}$

The electric charge, $Q = T_{3L} + Y$.

- **Only the right-handed SM fields(including ν_R) are charged under** $U(1)_{T_{3R}}$.
- **New matter fields : a scalar ϕ and two Weyl fermions, η_L and η_R. Also, a new gauge boson A'.**
- **Anomaly free if either one or two generations couple to** $U(1)_{T_{3R}}$.
- **For simplicity we consider : one up-type quark, one down-type quark, one charged lepton and one neutrino(all right-handed) couple to** $U(1)_{T_{3R}}$.

field	q_{T3R}
q_R^u	-2
q_R^d	2
ℓ_R	2
ν_R	-2
η_L	1
η_R	-1
ϕ	-2

THE MODEL

The interaction Lagrangian :

$$\mathscr{L} = -\frac{\lambda_u}{\Lambda}\tilde{H}\phi^*\bar{Q}_L q_R^u - \frac{\lambda_d}{\Lambda}H\phi\bar{Q}_L q_R^d - \frac{\lambda_\nu}{\Lambda}\tilde{H}\phi^*\bar{L}_L\nu_R - \frac{\lambda_l}{\Lambda}H\phi\bar{L}_L\ell_R$$
$$-\lambda\phi\bar{\eta}_R\eta_L - \frac{1}{2}\lambda_L\phi\bar{\eta}_L^c\eta_L - \frac{1}{2}\lambda_R\phi^*\bar{\eta}_R^c\eta_R - \mu_\phi^2\phi^*\phi - \lambda_\phi(\phi^*\phi)^2 + H.c.$$

- ϕ **gets vev** V, **breaks the** $U(1)_{T_{3R}}$ **down to** Z_2 **symmetry.** $m_{\phi'} = 2\lambda_\phi^{1/2}V$.
- **The symmetry breaking scale of** $U(1)_{T_{3R}}$ **is** $\mathcal{O}(1-10)$ **GeV**.
- **Only** $\eta_{L,R}$ **are odd under the** Z_2 **parity. They mix and give two physical Majorana fermions** $\eta_{1,2}$, **the dark matter candidates.**

The Lagrangian after symmetry breaking :

$$\mathscr{L} = -m_u\bar{q}_L^u q_R^u - m_d\bar{q}_L^d q_R^d - m_{\nu D}\bar{\nu}_L\nu_R - m_\ell\bar{\ell}_L\ell_R - \frac{1}{2}m_1\bar{\eta}_1\eta_1 - \frac{1}{2}m_2\bar{\eta}_2\eta_2$$
$$-\frac{m_u}{V}\bar{q}_L^u q_R^u\phi' - \frac{m_d}{V}\bar{q}_L^d q_R^d\phi' - \frac{m_{\nu D}}{V}\bar{\nu}_L\nu_R\phi' - \frac{m_\ell}{V}\bar{\ell}_L\ell_R\phi' - \frac{1}{2}\frac{m_1}{V}\bar{\eta}_1\eta_1\phi' - \frac{1}{2}\frac{m_2}{V}\bar{\eta}_2\eta_2\phi' + \ldots.$$

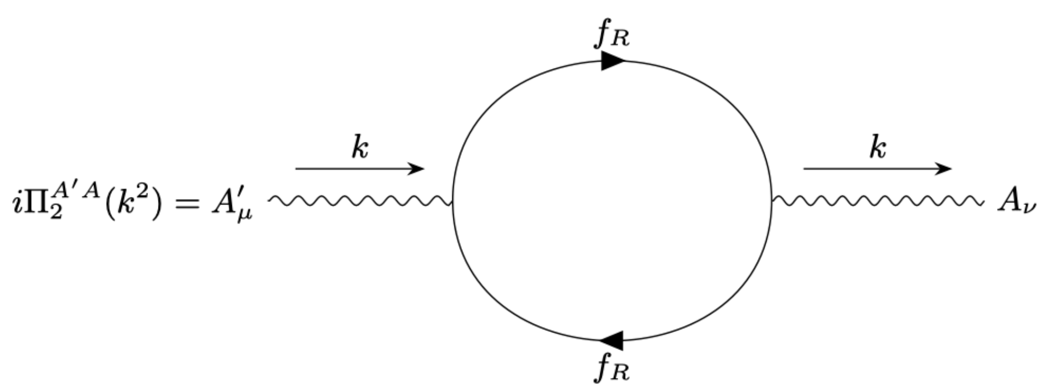
THE MODEL

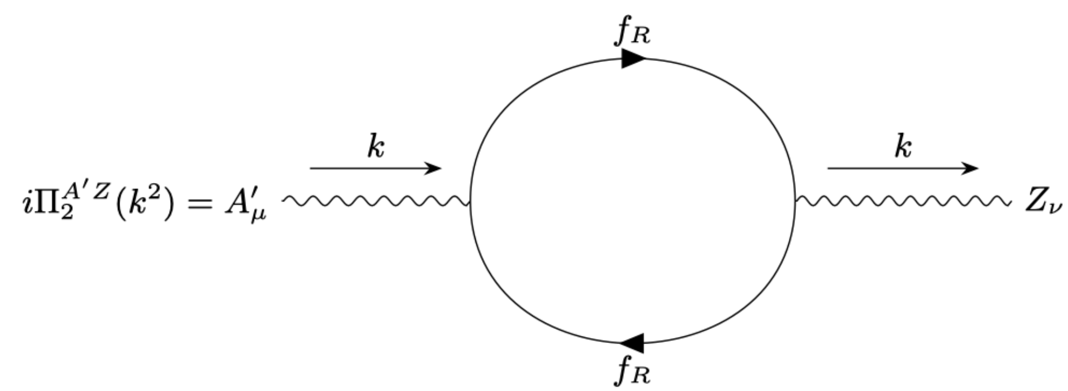
The Lagrangian for the new gauge part :

$$\mathscr{L}_{gauge} = \frac{i}{4} g_{T_{3R}} A'_\mu (\bar{\eta}_1 \gamma^\mu \eta_2 - \bar{\eta}_2 \gamma^\mu \eta_1) + \frac{m_{A'}^2}{V} \phi' A'_\mu A'^\mu + i g_{T3R} A'_\mu \left(\phi' \partial^\mu \phi'^* - \phi'^* \partial^\mu \phi \right) - \frac{1}{2} g_{T_{3R}} j^\mu_{A'} A'_\mu$$

where, $j^\mu_{A'} = \sum_f Q^f_{T_{3R}} \bar{f} \gamma^\mu f$ **and** $m^2_{A'} = 2 g^2_{T_{3R}} V^2$.

- **No tree level kinetic mixing.** A' **mix with photon and** Z **boson via loop.**





- ν_R **will mix with** ν_L **and give Majorana neutrino mass eigenstates.**

- **We assume,** ν_R **is composed of sterile neutrino mass eigenstate** ν_s **and has mixing with the active state** ν_A.

- **The lightest neutrino eigenstate can be determined by the seesaw mechanism.**

THE MODEL

- **The new particles :** ϕ', A' **and** ν_s **are not stabilized by any symmetry.**

  They will decay to SM particles.

- **The main decay channels are :**

  - $\phi' : \phi' \to \bar{\ell}\ell, \nu_s\nu_A, \pi\pi, A'A'$ **dominate, if kinematically allowed.**

    Otherwise $\phi' \to \gamma\gamma$**(mediated by a one-loop diagram) will dominate.**

  - $A' : A' \to \bar{\ell}\ell, \nu_s\nu_s, \pi\pi, \phi'\phi'$ **dominate, if kinematically allowed.**

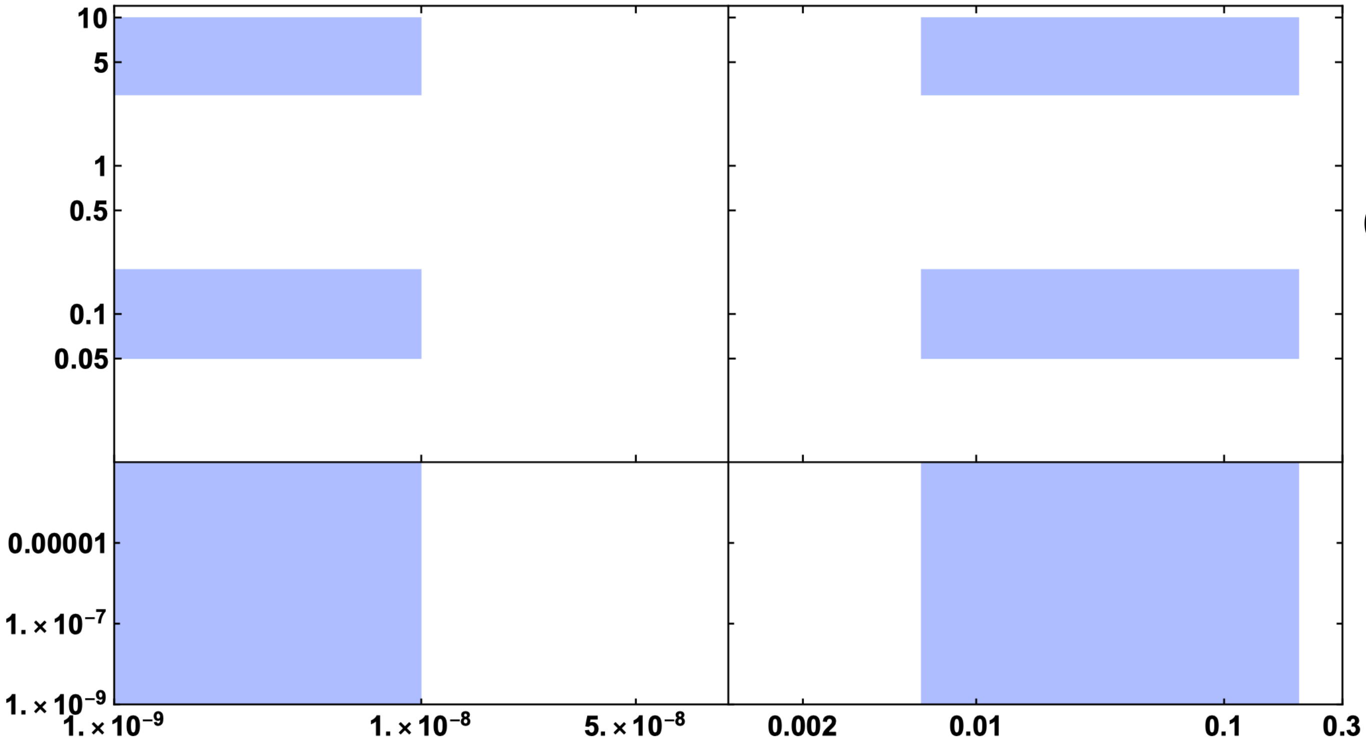
    If not allowed, $A' \to \nu_A\nu_A$ **will dominate.**

  - $\nu_s : \nu_s \to \nu_A\gamma\gamma$ **(mediated by an off-shell** ϕ') **will dominate.**

PARAMETER SPACE

- **Fermion mass set by the vev** V, $m_f \lesssim V$. **Imply** $V \sim \mathcal{O}(1-10)$ **GeV.**
- **Since** $m_{\phi'}^2 = 4\lambda_\phi V^2$ **and** $m_{A'}^2 = 2g_{T3R}^2 V^2$, **we will also get** $m_\phi', m_{A'} \lesssim \mathcal{O}$ **(GeV)**.
- **The states which couple to the dark sector are thus** $u, d,$ **a single right-handed neutrino, and either** μ **or** e.
- **We take** $V \sim 10$ **GeV and assume small neutrino mixing angle.**
- **No constraints from neutrino experiments because of the small mixing angle.**
- **No LHC constraints on** ϕ' **and** A'.
- **Two specific model :**
  - **For** $\ell = \mu : u_R, d_R, \mu_R, \nu_R, \eta_1, \eta_2, \phi', A'$
  - **For** $\ell = e : u_R, d_R, e_R, \nu_R, \eta_1, \eta_2, \phi', A'$

PARAMETER SPACE

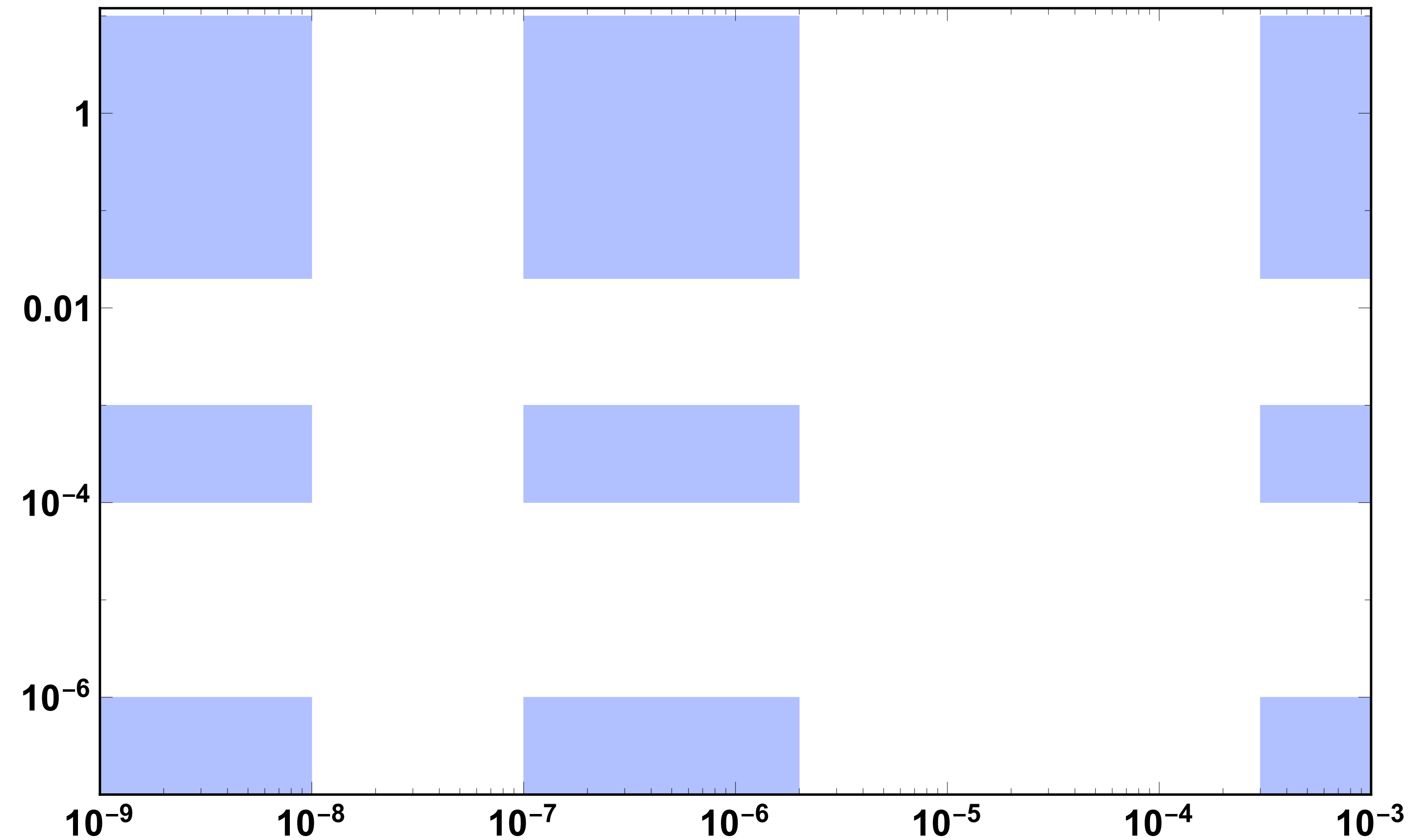


- $\ell = e$ **model :**

Constraints from Orsay, APV, E774, E141, E137 fifth force, Globular clusturs and Sun.

- $\ell = \mu$ **model :**

Constraints from BaBar, E137, fifth force, Globular cluster, Sun and supernova cooling.



DIRECT DETECTION

Nuclear recoil energy for $m \sim \mathcal{O}(1-100)$ **MeV dark matter :**

$$E_R \lesssim \frac{2\mu^2 v^2}{m_A} \sim \left(\frac{100\ \textbf{GeV}}{m_A}\right)\left(\frac{m}{100\ \textbf{MeV}}\right)^2\ \textbf{eV}$$

For XENON nucleus, $E_R \leq \mathcal{O}(1)$ **eV for dark matter of mass** $m \sim \mathcal{O}(1-100)$ **MeV**.

Thresholds from most experiments $E_{R_{th}} \geq 0.1$ **keV**

Constraints for low mass dark matter :

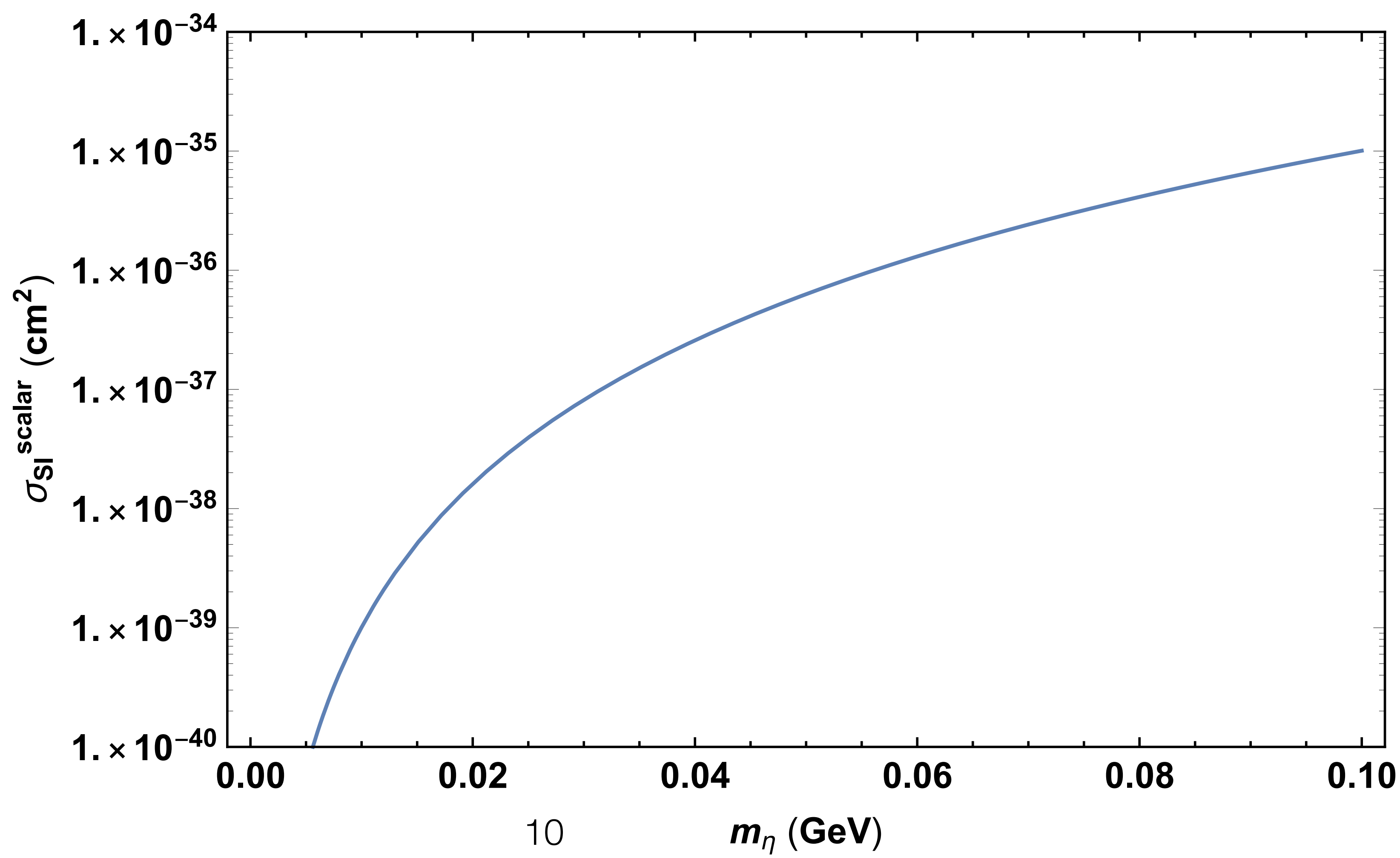
- **CRESST III** : $\sigma_{SI} \sim 10^{-35}$ **cm**^{2} **for** $m \sim 200$ **MeV**. **No bound for** $m \leq 160$ **MeV**.
  arXiv:1904.00498
- **XENON1T : For** $m \sim \mathcal{O}(1-100)$ **MeV**, $\sigma_{SI} \lesssim \mathcal{O}(10^{-30})$ **cm**^{2} **or** $\sigma_{SI} \gtrsim \mathcal{O}(10^{-28})$ **cm**^{2}.
  arXiv:1810.10543
- **CDEX-1B :** $\sigma_{SI} \lesssim (10^{-32} - 10^{-34})$ **cm**^{2} **for** $m \sim (50-180)$ **MeV**. **arXiv:1905.00354**

DIRECT DETECTION

Elastic scattering: $-\frac{1}{2}\frac{m_1}{V}\bar{\eta}_1\eta_1\phi' - \frac{1}{2}\frac{m_2}{V}\bar{\eta}_2\eta_2\phi' - \frac{m_u}{V}\bar{q}_L^u q_R^u\phi' - \frac{m_d}{V}\bar{q}_L^d q_R^d\phi'$

ϕ' mediated dark matter-nucleon scattering

$$\sigma_{SI}^{scalar(p,n)} \sim (10^{-35}\ \mathbf{cm}^2)\left(\frac{V}{10\ \mathbf{GeV}}\right)^{-4}\left(\frac{m_{\phi'}}{100\ \mathbf{MeV}}\right)^{-4}\left(\frac{\mu_{\eta N}}{100\ \mathbf{MeV}}\right)^{2}\left(\frac{m_\eta}{100\ \mathbf{MeV}}\right)^{2}$$



DIRECT DETECTION

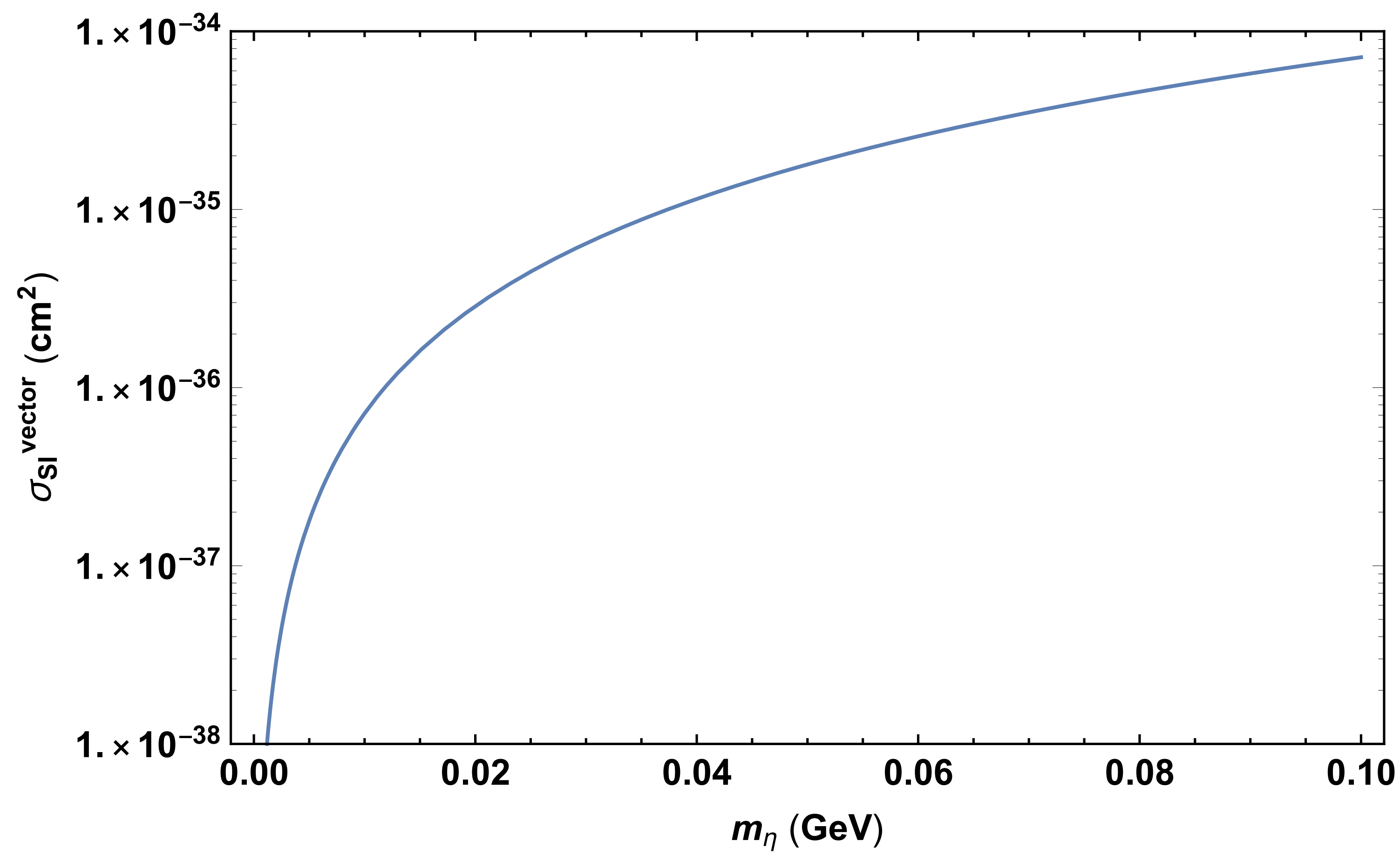
Inelastic scattering: $$\frac{i}{4\sqrt{2}}\frac{m_{A'}}{V}A'_\mu(\bar{\eta}_1\gamma^\mu\eta_2 - \bar{\eta}_2\gamma^\mu\eta_1) - \frac{1}{2\sqrt{2}}\frac{m_{A'}}{V}Q_{T_{3R}}A'_\mu(\bar{q}^u_R\gamma^\mu q^u_R + \bar{q}^d_R\gamma^\mu q^d_R)$$

A' **mediated dark matter-nucleon scattering**

$$\sigma_{SI}^{vector(p,n)} = \frac{9\mu_{\eta N}^2}{16\pi V^4}$$

$$= (7\times 10^{-35}\ cm^2)\left(\frac{V}{10\ \textbf{GeV}}\right)^{-4}\left(\frac{\mu_{\eta N}}{100\ \textbf{mev}}\right)^2$$

for small mass difference $\delta = m_j - m_i$



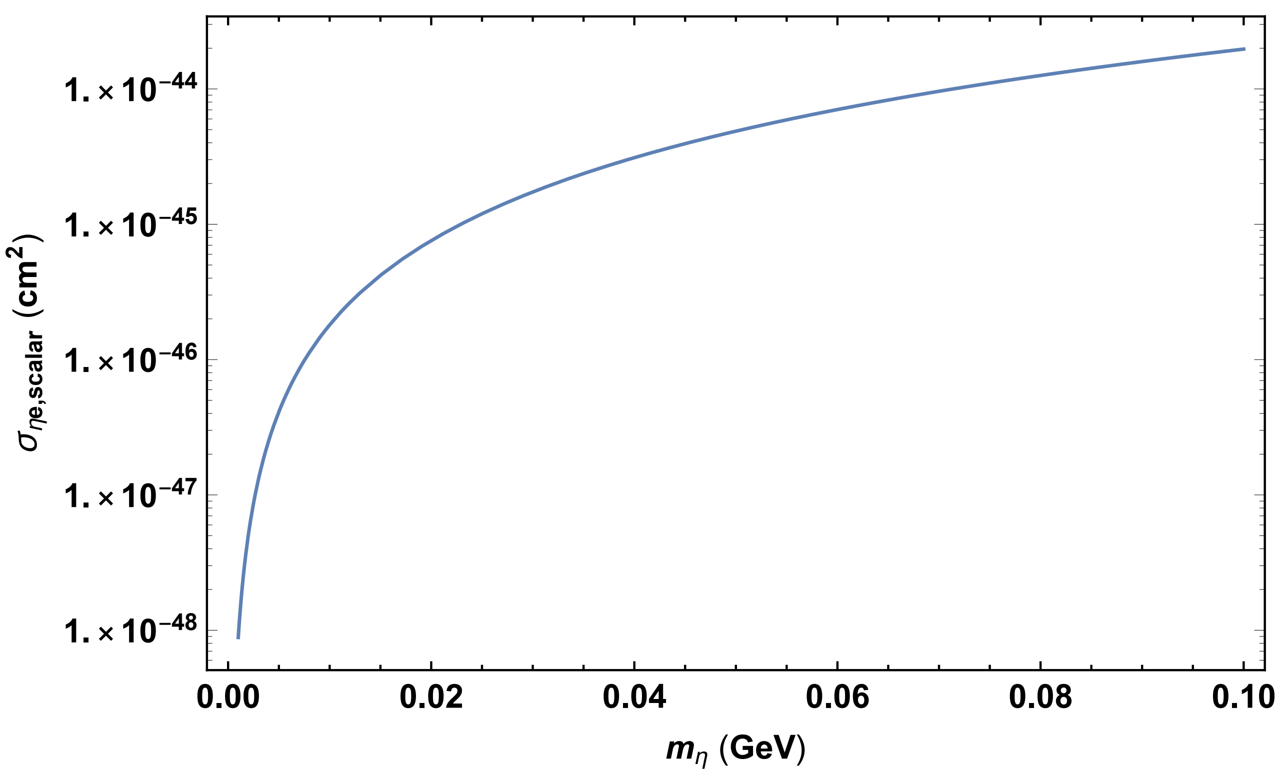
DIRECT DETECTION

Dark matter-electron scattering :

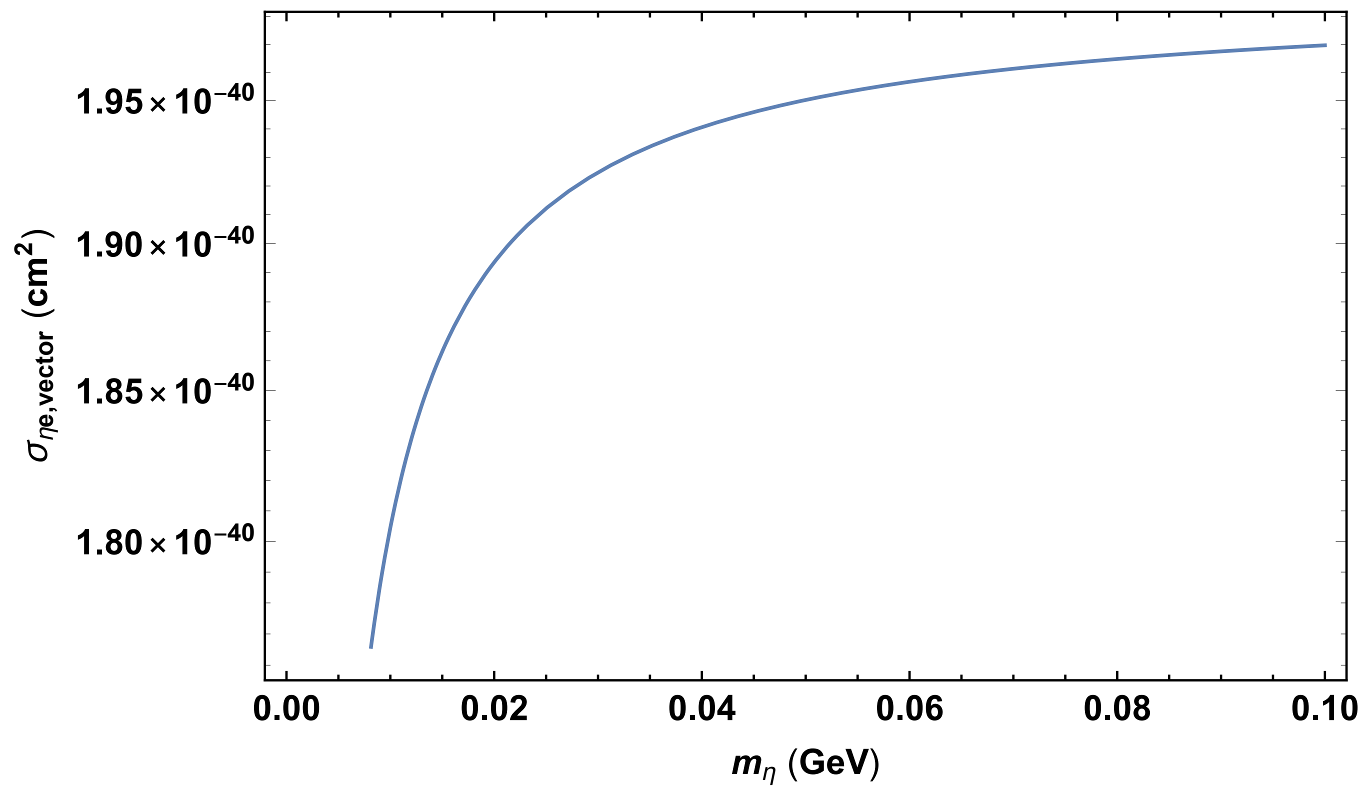
Constraints from XENON10, Super CDMS and SENSEI.

For dark matter of mass $\mathcal{O}(1-100)$ **MeV, the allowed cross section is** $\leq 10^{-38}$ **cm**^{2}.

arXiv:1811.00520.



ϕ' **mediated**

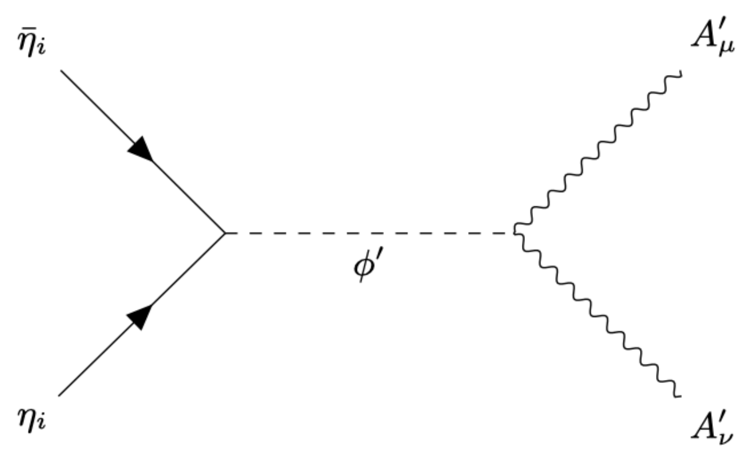


A' **mediated**

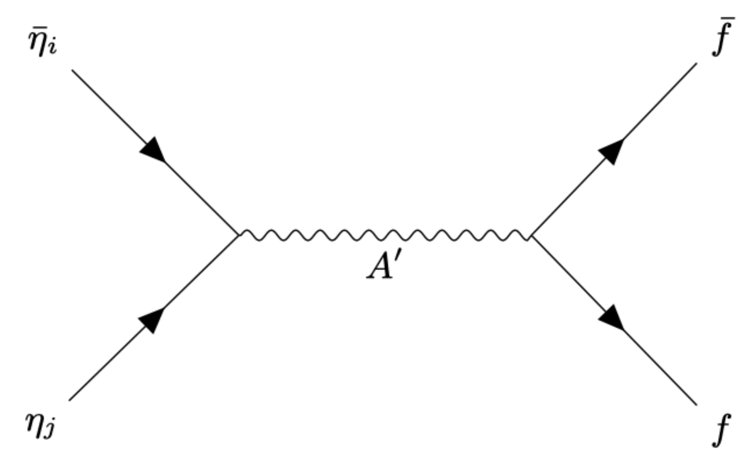
THERMAL RELIC ABUNDANCE

- **We try to get the thermal relic abundance from the (co-)annihilation to SM particles or dark sector particles.**
- **The dominant two body final states are :**

  $\bar{\ell}\ell, \bar{\nu}\nu, \pi\pi, \pi^0(\phi', A', \gamma)$ **and the purely dark sector channels** $A'A', \phi'\phi'$ **and** $\phi'A'$.
- **We consider two scenarios :** ϕ' **resonance** ($p-$**wave supressed**) **and** A' **mediated**



$p-$**wave**



$s-$**wave**

	m'_A (MeV)	m'_ϕ (MeV)	m_η (MeV)	m_{ν_s}(MeV)	$m_{\nu D}$(MeV)	$\langle\sigma v\rangle$ (cm^3/sec)	$\sigma_{\rm SI}^{scalar}$(pb)	$\sigma_{\rm SI}^{vector}$(pb)
muon case	40	102	50	10	10^{-3}	3×10^{-26}	0.56	16
	70	10^4	50	10^{13}	10^3	3×10^{-26}	5.6×10^{-9}	16
electron case	0.4	100	50	0.1	10^{-2}	3×10^{-26}	0.56	16

CONCLUSION

- **Low mass dark matter model with dark matter mass** $m \sim \mathcal{O}(1 - 100)$ **MeV.**
- **Yukawa sector hierarchy problem.**
- **Low mass mediator, mass** $\leq \mathcal{O}(10)$ **GeV. Not constrainted by LHC.**
- **Consistents with the current experiments. Can be probed in the future experiments.**
- **Gives correct thermal relic abundance.**