Spin-1 Thermal Targets for Dark Matter Searches at Fixed Target Experiments

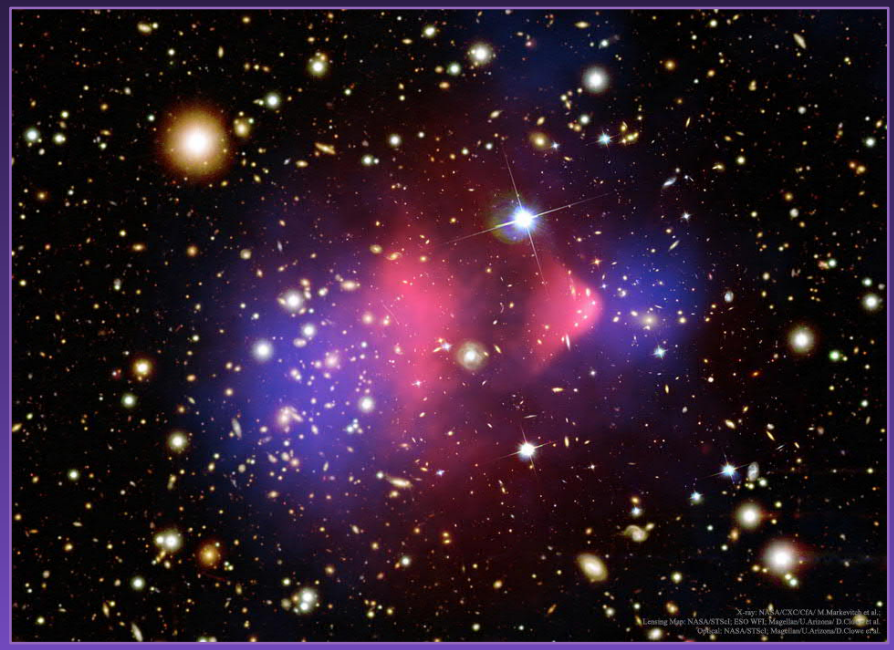
arXiv:2307.02207

Taylor R. Gray[a]

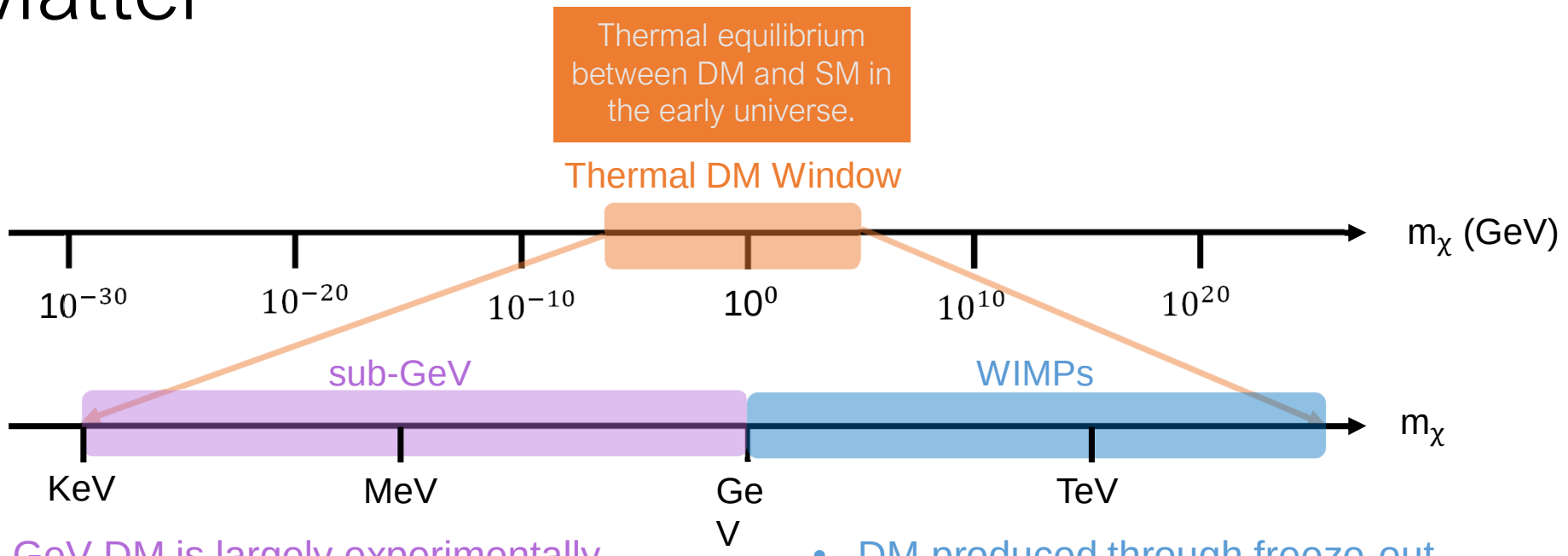
In collaboration with Riccardo Catena[a]

[a]Chalmers University of Technology

Supported by a research grant from the Wallenberg foundation



Sub-GeV Dark Matter

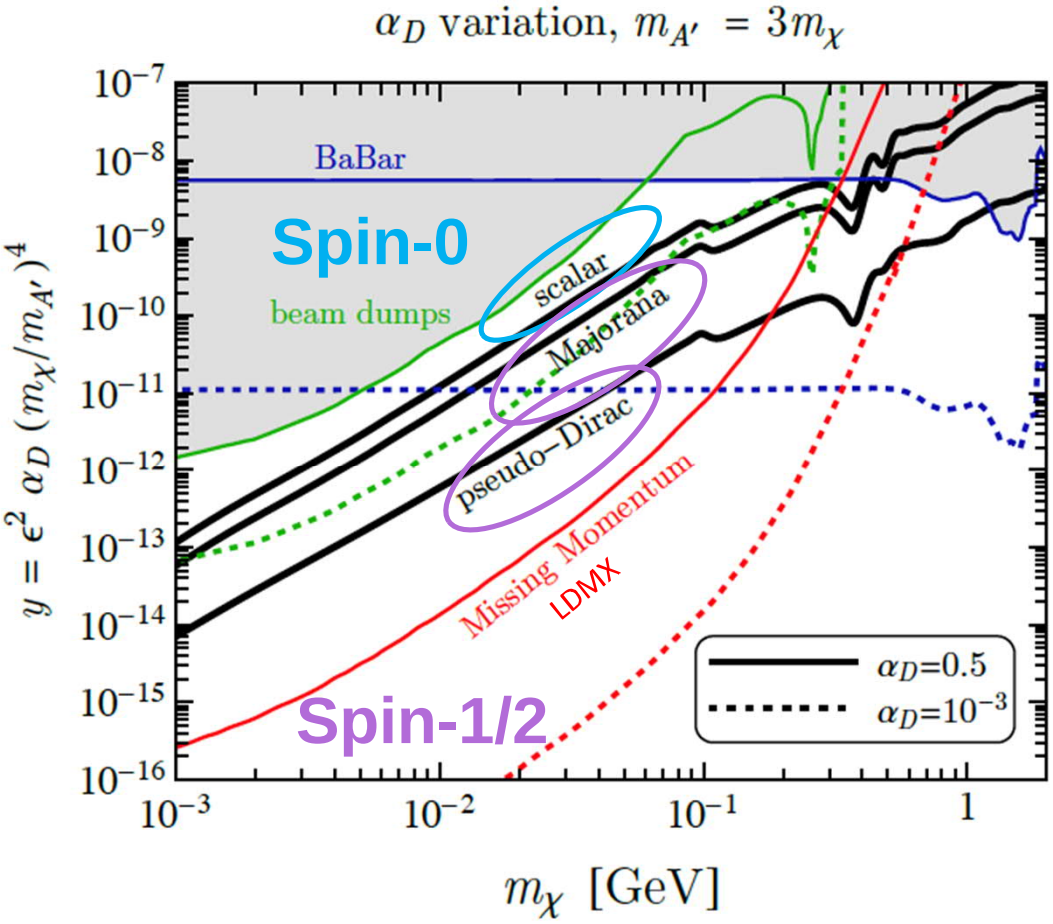


- Sub-GeV DM is largely experimentally **unexplored**..
  - Out of reach of nuclear recoil direct detection exps

- DM produced through freeze-out near weak scale
- GeV-TeV scale thermal DM already widely tested

Sub-GeV Dark Matter

- Fixed target experiments can probe sub-GeV DM
- Future fixed target experiments such as **LDMX** will reach new sensitivities in the sub-GeV mass range.
- How about **spin-1** DM?



arXiv:1807.0170

The Goal

- Broaden the existing studies on sub-GeV DM at LDMX

1. Set of simplified spin-1 DM candidates which have a dark photon mediator

2. Renormalizable, UV complete extended Higgs sector spin-1 DM
   - Dark SU(2) x U(1)' -> X_3, Z' mediators and SIMP DM
   - Dark SU(2) -> Z' mediator and millicharged DM
     - where $m_{Z'} < 2m_X$, leading to off-shell DP production and visible signatures

Ongoing work!

Simplified Spin-1 Dark Matter Models

with a Dark Photon Mediator

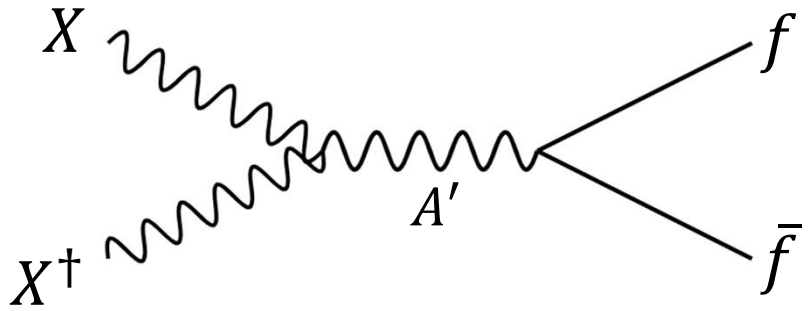
$$-\mathcal{L} \supset \left(ib_5 X_\nu^\dagger \partial_\mu X^\nu A'^\mu + b_6 X_\mu^\dagger \partial^\mu X_\nu A'^\nu + b_7 \epsilon_{\mu\nu\rho\sigma} \left(X^{\dagger\mu} \partial^\nu X^\rho\right) A'^\sigma + h.c.\right) + h_3 A'_\mu \bar{f} \gamma^\mu f$$

b_5: real
b_6: complex
b_7: complex
h_3: real

$h_3 \equiv \epsilon e$

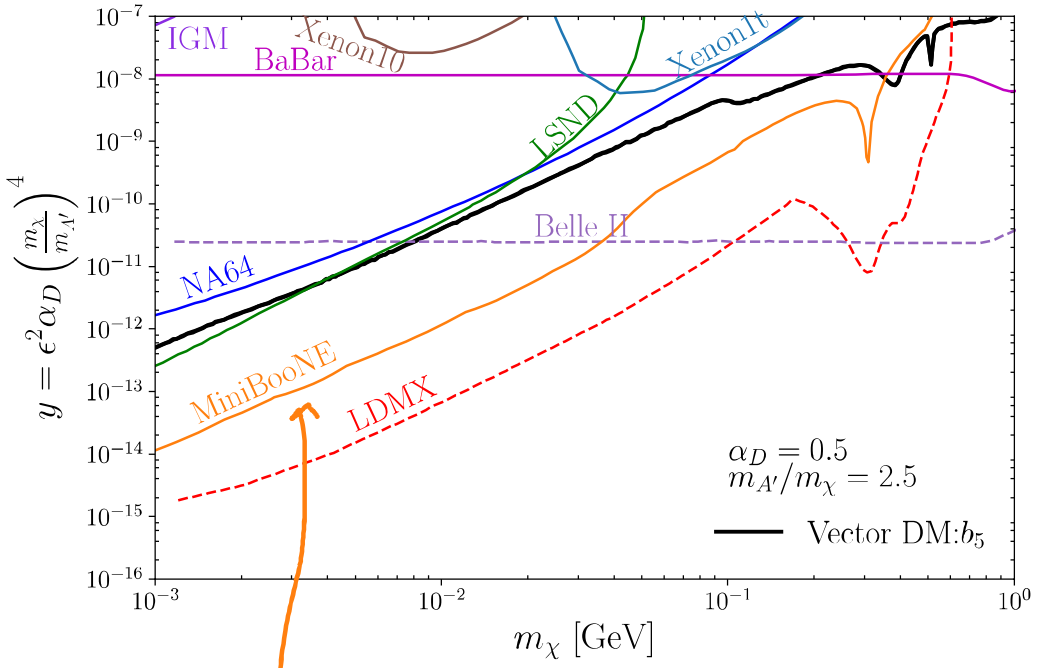
f: SM leptons and quarks (excluding neutrinos)

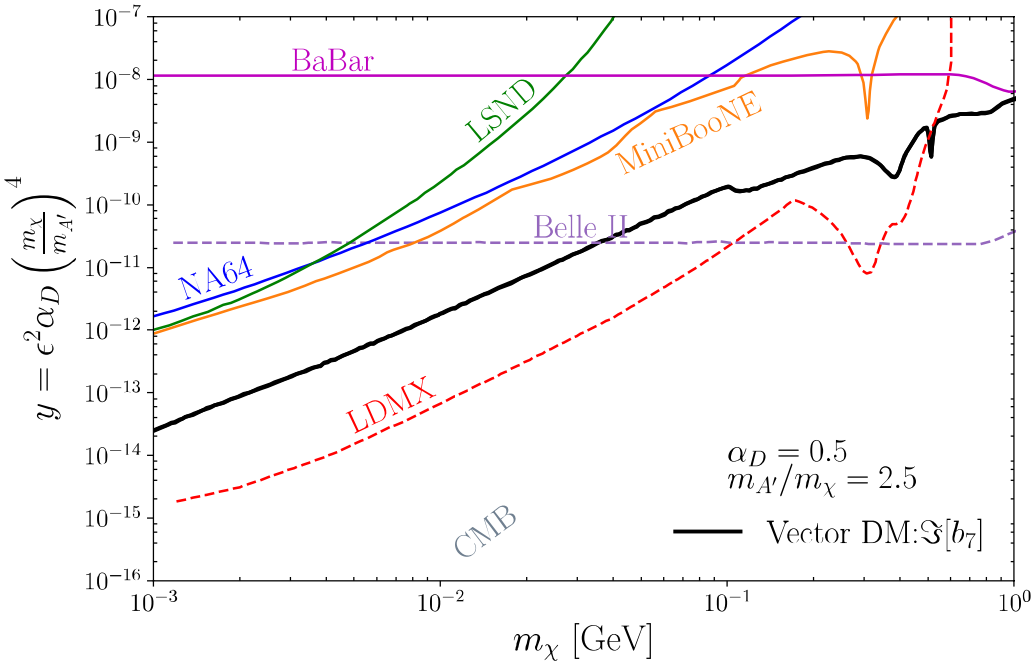
DM Freeze-Out



If $2m_X < m_{A'}$, s-channel dominates DM annihilations.

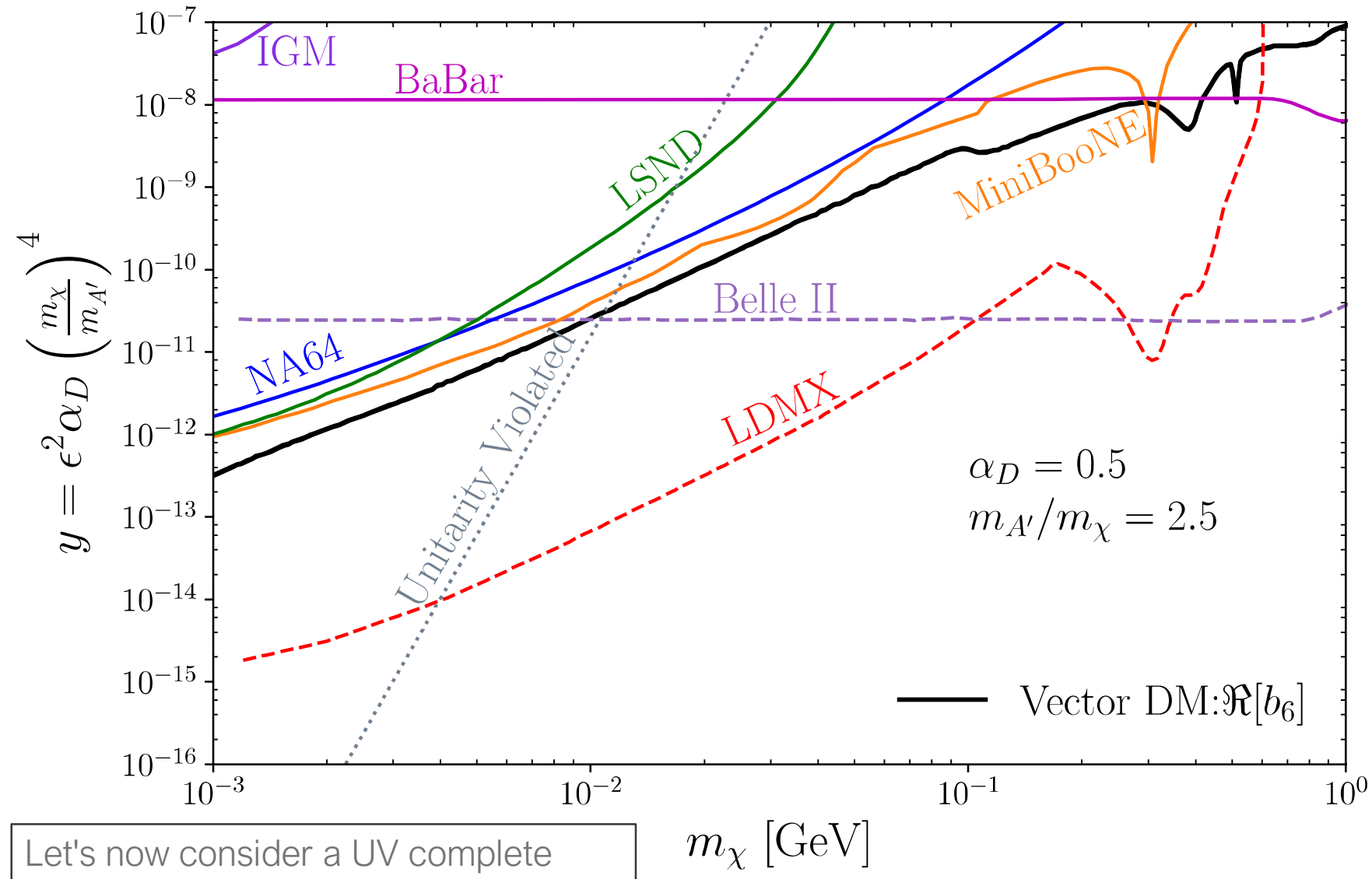
Strong Limits on Spin-1 Relic Targets





Large MiniBooNE limits due to $\boldsymbol{\sigma_{\chi e^- \to \chi e^-}}$ being large when $\boldsymbol{m_\chi}$ is small

Ruled out by current experiments and CMB



Spin-1 DM is the first to be probed by LDMX!

Let's now consider a UV complete model where unitarity is not violated!

$b_5 \to g_X$
$\Im[b_6] \to -g_X/2$

SIMP Spin-1 Dark Matter

$SU_X(2) \times U_{Z'}(1)$

with Z' and X_3 as mediators

$$
\begin{aligned}
-\mathcal{L} \supset & -ig_X \cos\theta'_X \left[\left(\partial^\mu X^\nu - \partial^\nu X^\mu\right) X^\dagger_\mu \tilde{X}_{3,\nu} - \left(\partial^\mu X^{\nu\dagger} - \partial^\nu X^{\mu\dagger}\right) X_\mu \tilde{X}_{3,\nu} + X_\mu X^\dagger_\nu \left(\partial^\mu \tilde{X}_3^\nu - \partial^\nu \tilde{X}_3^\mu\right) \right] \\
& -ig_X \sin\theta'_X \left[\left(\partial^\mu X^\nu - \partial^\nu X^\mu\right) X^\dagger_\mu \tilde{Z}'_\nu - \left(\partial^\mu X^{\nu\dagger} - \partial^\nu X^{\mu\dagger}\right) X_\mu \tilde{Z}'_\nu + X_\mu X^\dagger_\nu \left(\partial^\mu \tilde{Z}'^\nu - \partial^\nu \tilde{Z}'^\mu\right) \right] \\
& -e\varepsilon \cos(\theta'_X)\, \tilde{Z}'_\mu\, \bar{f}\gamma^\mu f + e\varepsilon \sin(\theta'_X)\, \tilde{X}_{3\mu}\, \bar{f}\gamma^\mu f \qquad (1)
\end{aligned}
$$

$$\sin(\theta'_X) \ll \cos(\theta'_X)$$

→ mainly Z's are produced at fixed target experiments

processes setting the relic density →

$$X_+X_- \to f\bar{f}$$

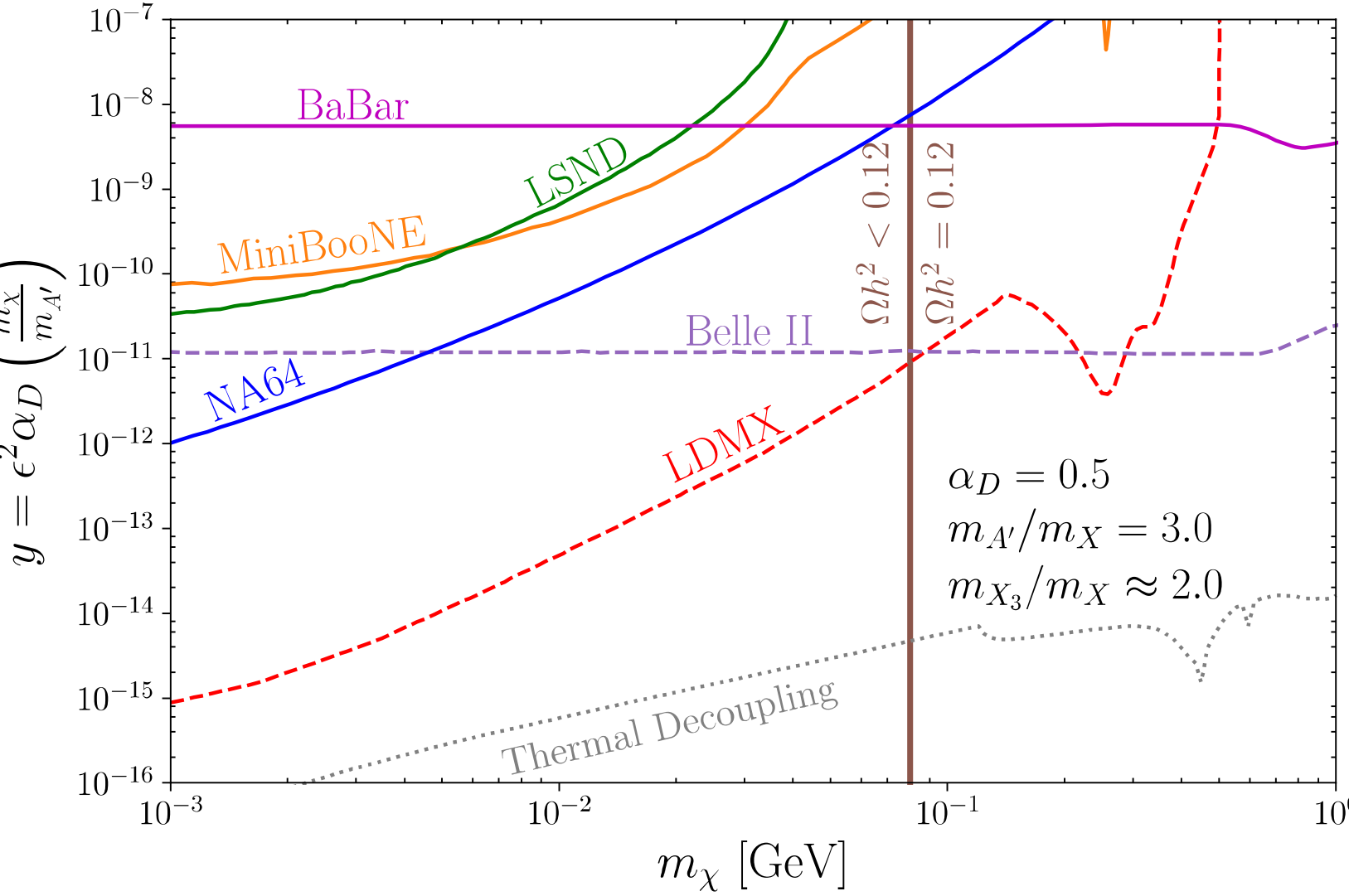
$$X_+X_+X_- \to X_+\tilde{X}_3$$

$$X_+X_- \to \tilde{X}_3\,\tilde{X}_3$$

Dominant since $g_X \gg e\epsilon$

arXiv:1904.04109

$$m_X^2 < m_{\tilde{X}_3}^2 < m_{\tilde{Z}'}^2$$



Weaker beam dump limits since DM – e^- scattering cross section is suppressed

Relic density is independent of ϵ, entire region consistent w Planck!

Summary

- Extending the current landscape of sub-GeV DM models considered in the context of fixed target experiments
- Spin-1 sub-GeV DM
  - where $m_A, > 2m_X$
- First model to be probed at upcoming LDMX!!

Future

- Ongoing work with dark SU(2)xU(1)' Vector DM
- Ongoing work with GAMBIT
- Vector DM models with dark dipole dark photons

Backup Slides

SIMP spin-1 DM

$$SU_X(2) \times U_{Z'}(1)$$

$$
\begin{aligned}
-\mathcal{L} \supset & -ig_X \cos\theta'_X \left[\left(\partial^\mu X^\nu - \partial^\nu X^\mu\right) X^\dagger_\mu \tilde{X}_{3,\nu} - \left(\partial^\mu X^{\nu\dagger} - \partial^\nu X^{\mu\dagger}\right) X_\mu \tilde{X}_{3,\nu} + X_\mu X^\dagger_\nu \left(\partial^\mu \tilde{X}^\nu_3 - \partial^\nu \tilde{X}^\mu_3\right) \right] \\
& -ig_X \sin\theta'_X \left[\left(\partial^\mu X^\nu - \partial^\nu X^\mu\right) X^\dagger_\mu \tilde{Z}'_\nu - \left(\partial^\mu X^{\nu\dagger} - \partial^\nu X^{\mu\dagger}\right) X_\mu \tilde{Z}'_\nu + X_\mu X^\dagger_\nu \left(\partial^\mu \tilde{Z}'^\nu - \partial^\nu \tilde{Z}'^\mu\right) \right] \\
& -e\varepsilon \cos(\theta'_X)\, \tilde{Z}'_\mu\, \bar{f}\gamma^\mu f + e\varepsilon \sin(\theta'_X)\, \tilde{X}_{3\mu}\, \bar{f}\gamma^\mu f
\end{aligned}
\tag{1}
$$

- Dark spontaneous symmetry breaking by the VEVs of dark Higgs fields
- Dark Higgs Sector
  - Singlet scalar S
  - H_X
  - Kinetic mixing between Z' and hypercharge gauge bosons

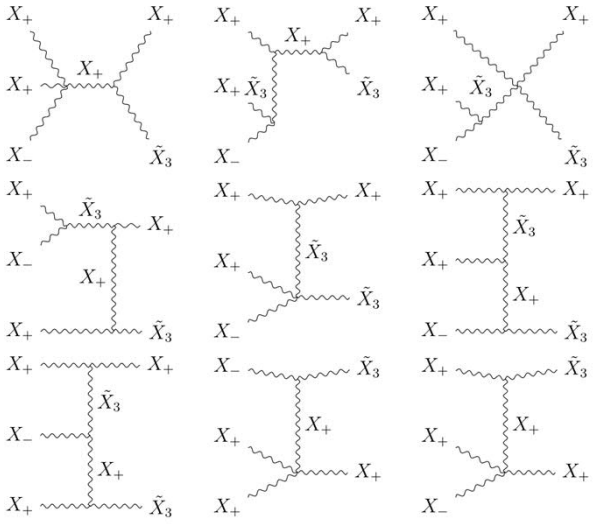
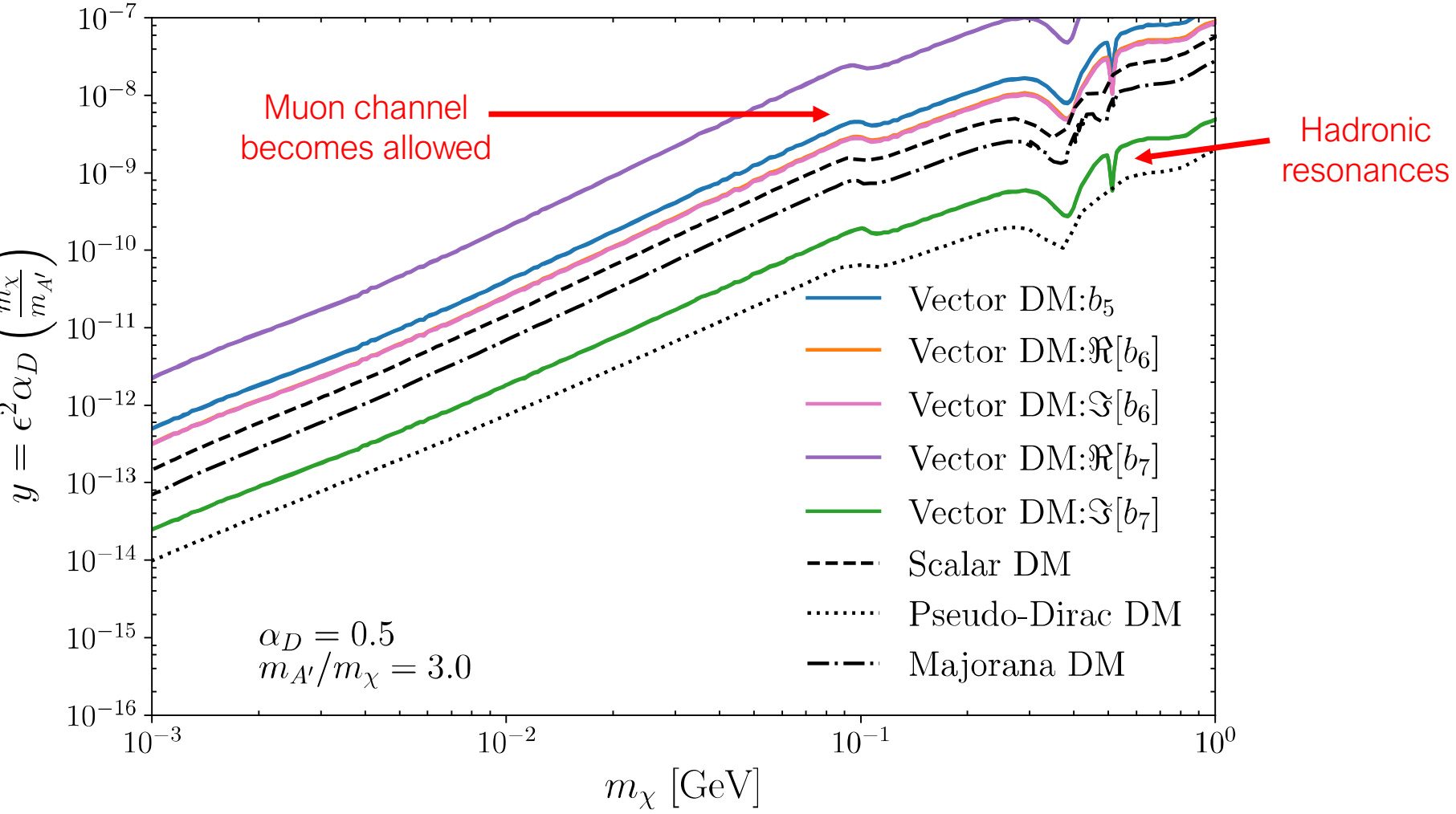
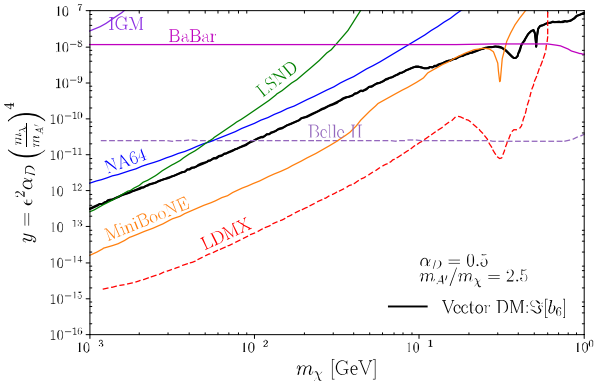
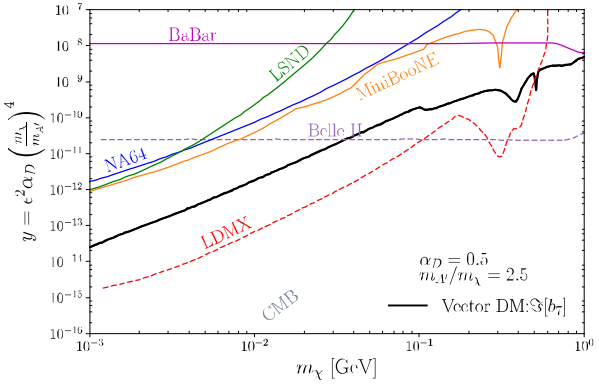


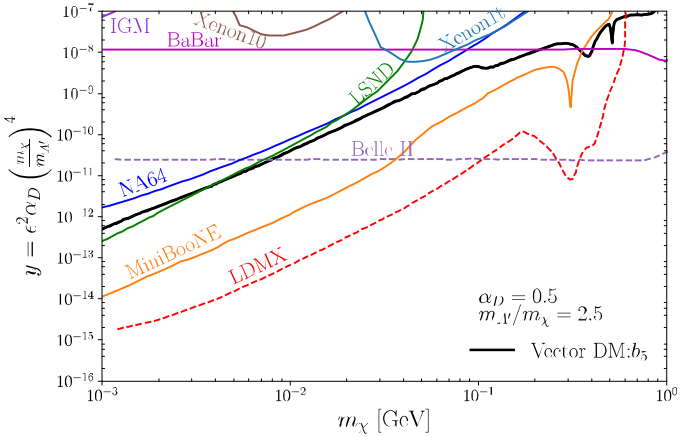
Figure 1: Feynman diagrams for $X_+X_+X_- \to X_+\tilde{X}_3$.

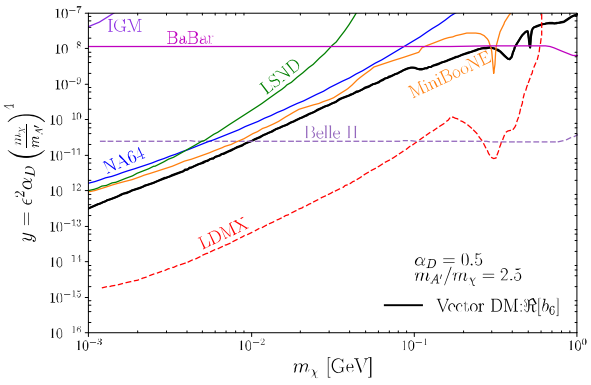
Relic Targets of DM Models

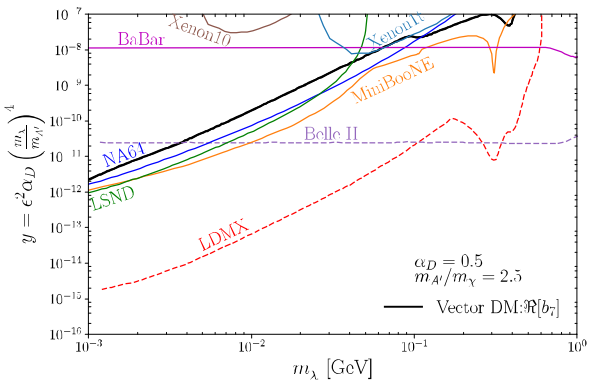



IGM
BaBar
LSND
NA64
Belle II
MiniBooNE
LDMX
$\alpha_D = 0.5$
$m_{A'}/m_\chi = 2.5$
Vector DM:$\Im[b_6]$
m_χ [GeV]
$y = \epsilon^2\alpha_D\left(\frac{m_\chi}{m_{A'}}\right)^4$


BaBar
LSND
MiniBooNE
Belle II
NA64
LDMX
CMB
$\alpha_D = 0.5$
$m_{A'}/m_\chi = 2.5$
Vector DM:$\Im[b_7]$
m_χ [GeV]
$y = \epsilon^2\alpha_D\left(\frac{m_\chi}{m_{A'}}\right)^4$


IGM
BaBar
Xenon1t
LSND
Xenon1t
Belle II
NA64
MiniBooNE
LDMX
$\alpha_D = 0.5$
$m_{A'}/m_\chi = 2.5$
Vector DM:b_5
m_χ [GeV]
$y = \epsilon^2\alpha_D\left(\frac{m_\chi}{m_{A'}}\right)^4$


IGM
BaBar
LSND
MiniBooNE
Belle II
NA64
LDMX
$\alpha_D = 0.5$
$m_{A'}/m_\chi = 2.5$
Vector DM:$\Re[b_6]$
m_χ [GeV]
$y = \epsilon^2\alpha_D\left(\frac{m_\chi}{m_{A'}}\right)^4$


BaBar
Xenon1t
Xenon1t
MiniBooNE
Belle II
NA64
LSND
LDMX
$\alpha_D = 0.5$
$m_{A'}/m_\chi = 2.5$
Vector DM:$\Re[b_7]$
m_χ [GeV]
$y = \epsilon^2\alpha_D\left(\frac{m_\chi}{m_{A'}}\right)^4$