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

arXiv:2307.02207

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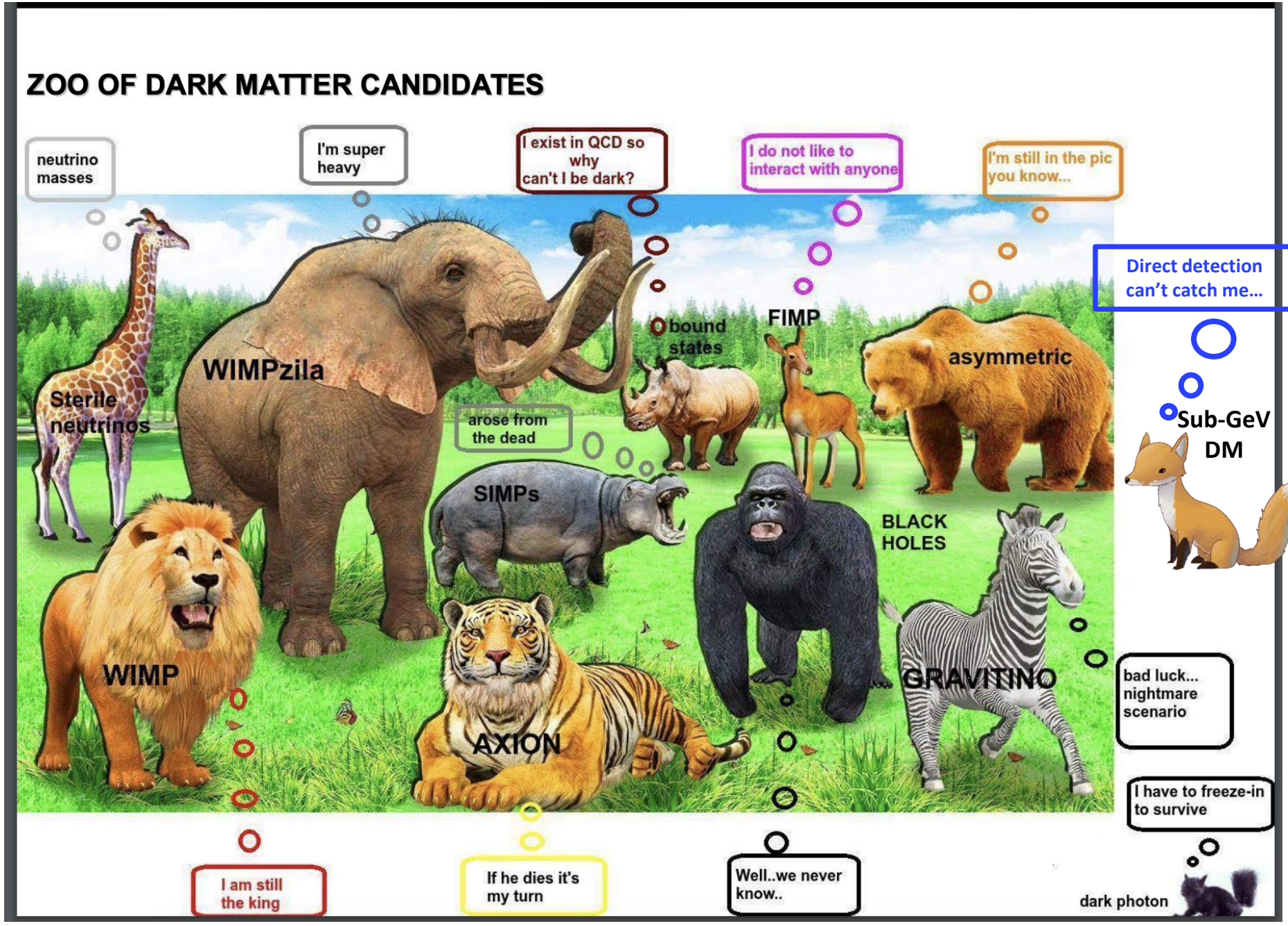
Supported by a research grant from the Wallenberg foundation

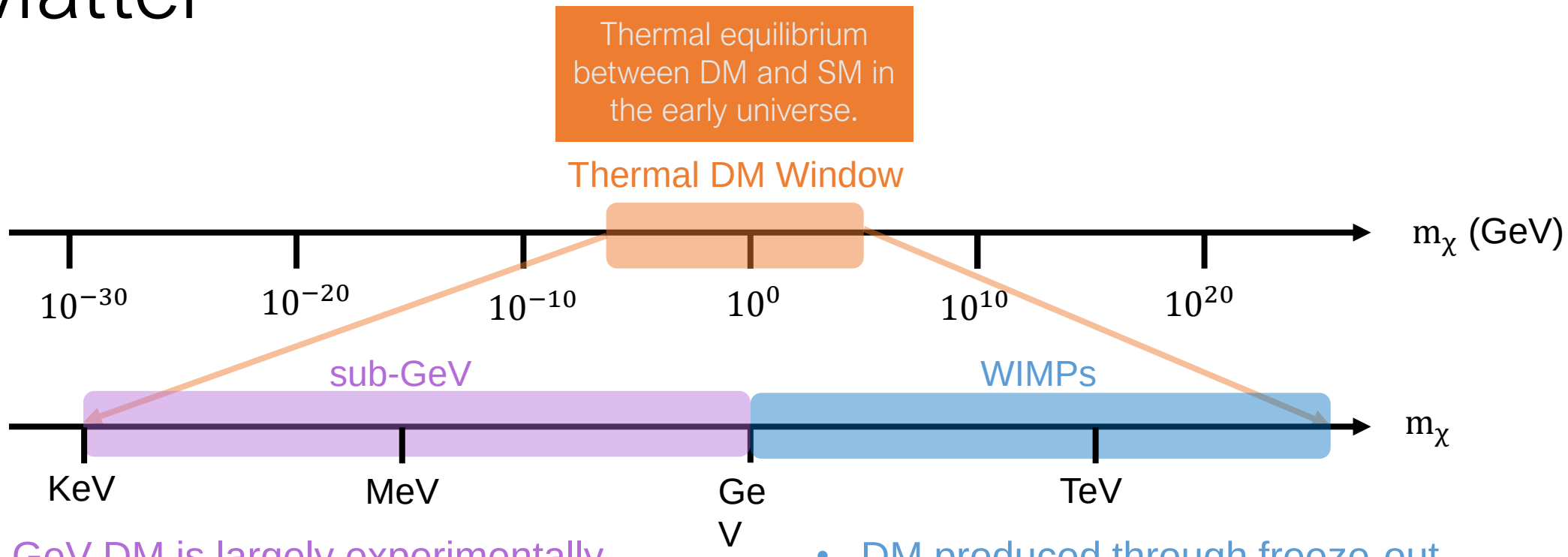
TAUP Vienna 2023



- Was once in thermal equilibrium w SM
- mass: ~ MeV – GeV
- interacts w SM via a new hypothetical dark mediator particle

F. Queiroz

Sub-GeV Dark Matter



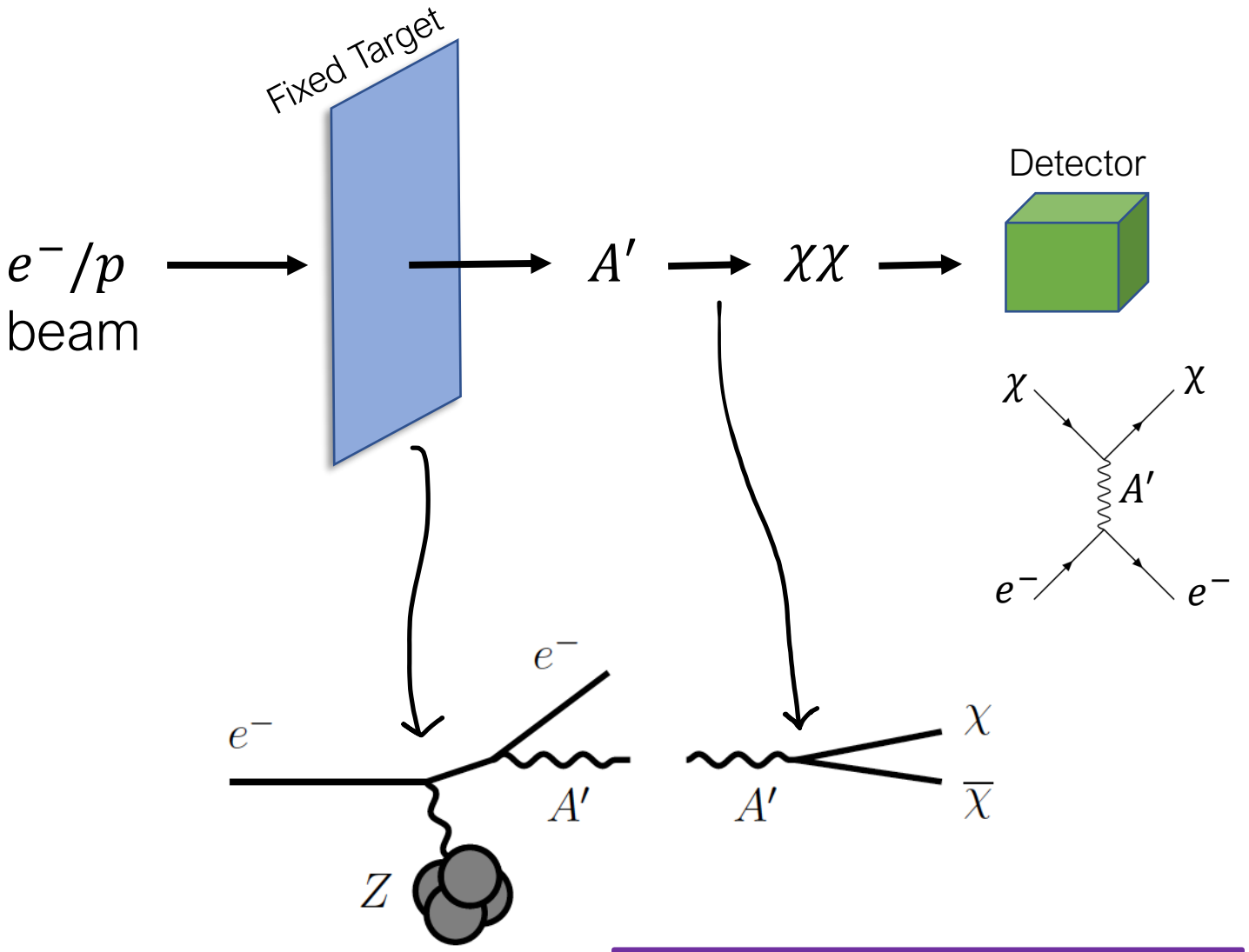
- Sub-GeV DM is largely experimentally **unexplored**..
  - Out of reach of nuclear recoil direct detection exps

- 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

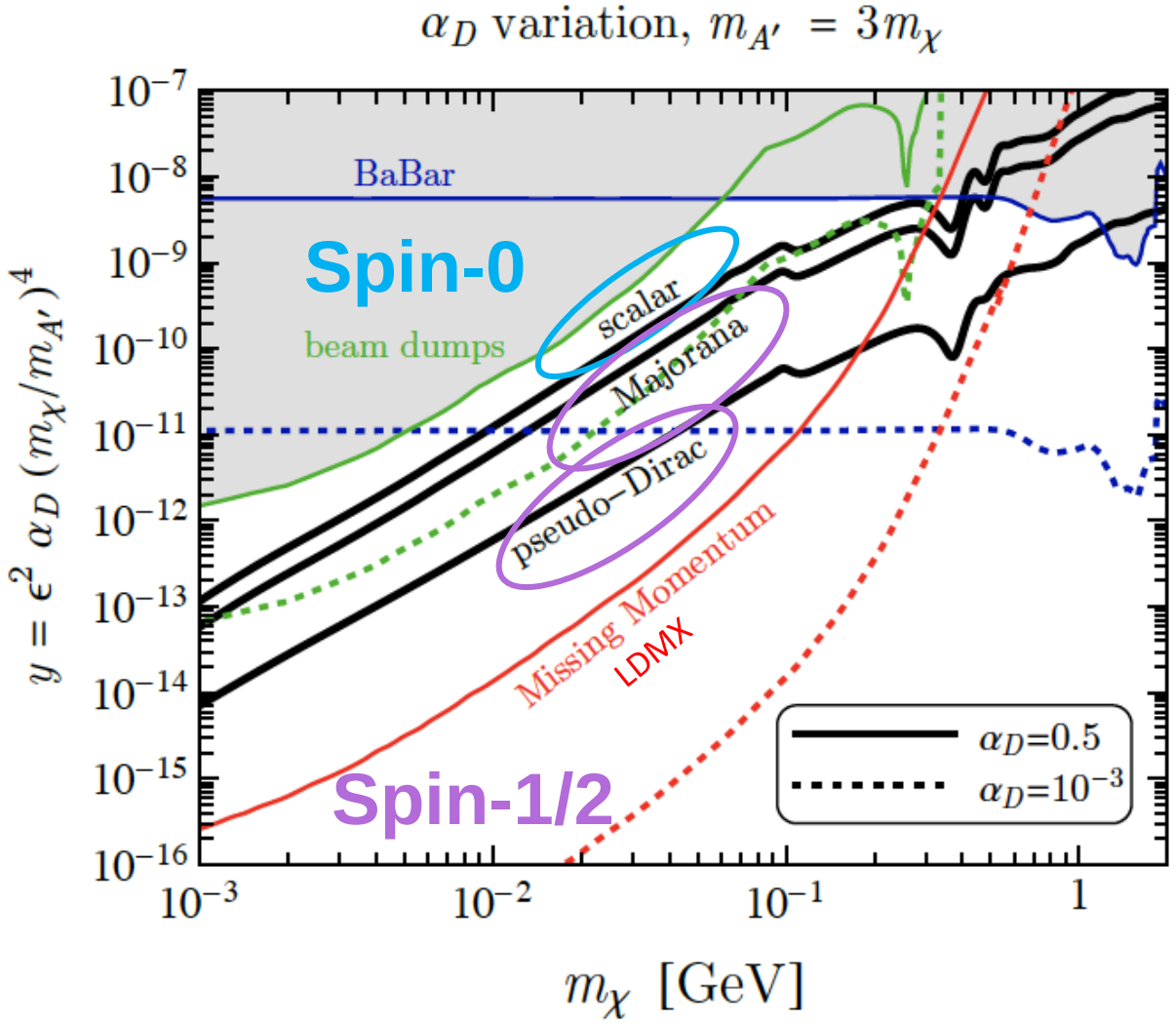
- Future fixed target experiments such as **LDMX** will reach new sensitivities in the sub-GeV mass range.



See Lene Kristian's talk next on LDMX!

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

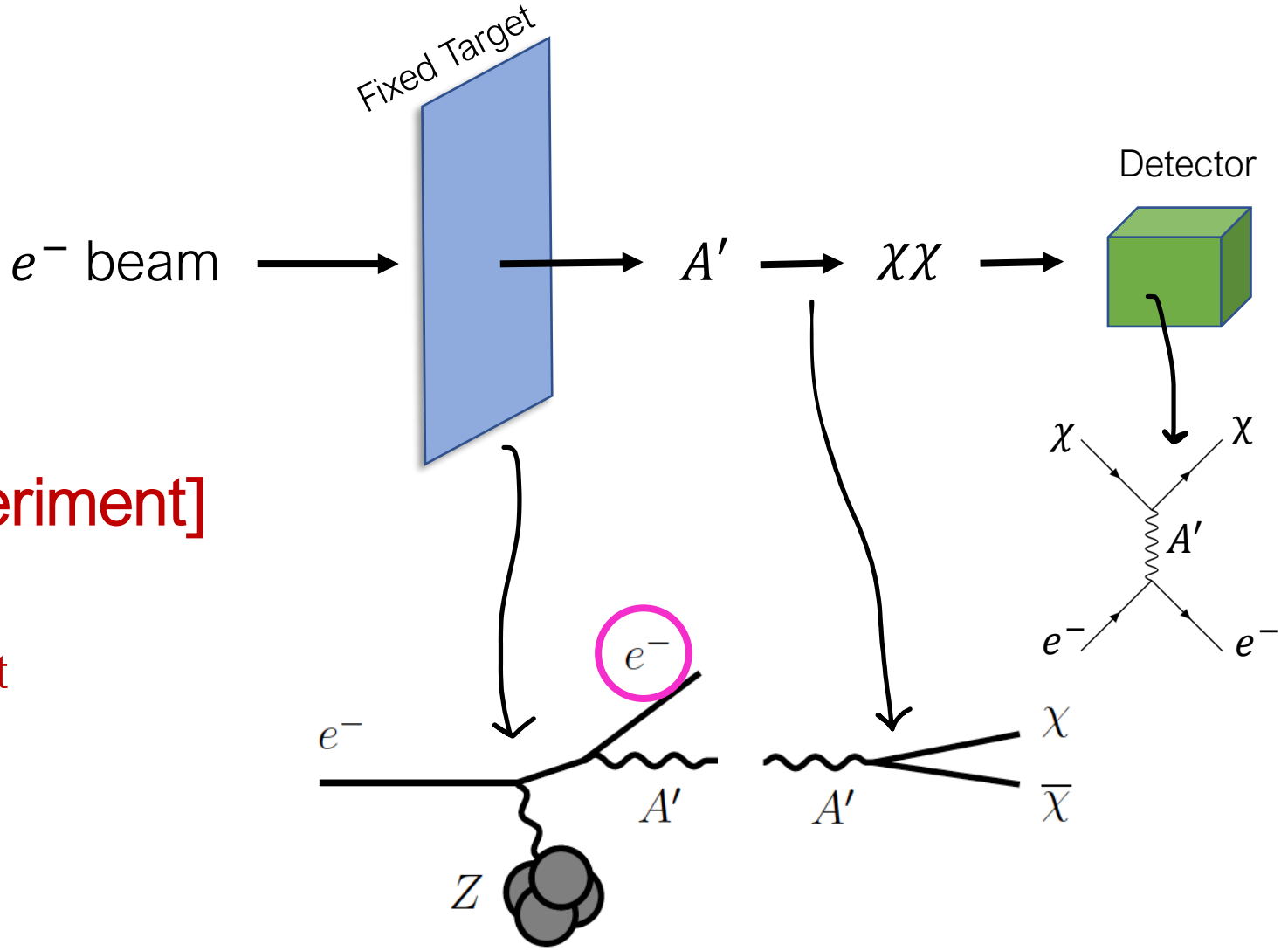
- Broaden the existing studies on sub-GeV DM at fixed target experiments

- We consider,
  1. a set of simplified spin-1 DM candidates which have a dark photon mediator X, A'

  2. a renormalizable, UV complete SIMP spin-1 DM model with two mediators X, A', X_3

Limits/Projections

Electron Dark-Bremsstrahlung + (In)Visible Decay

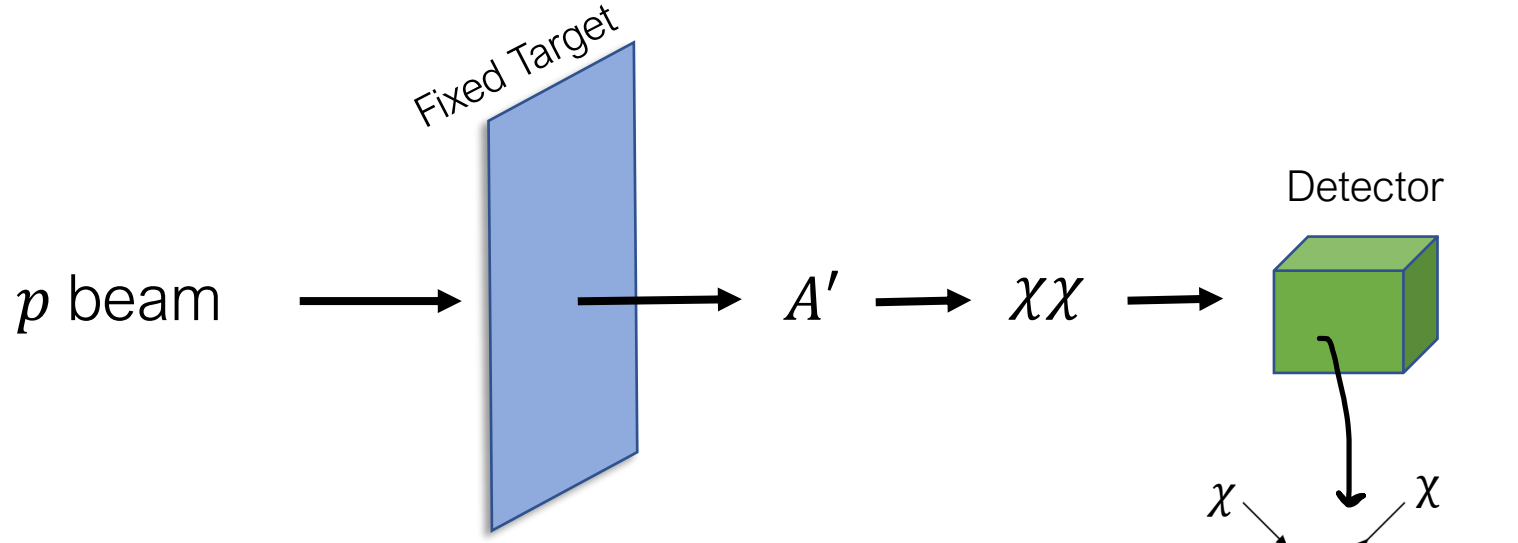


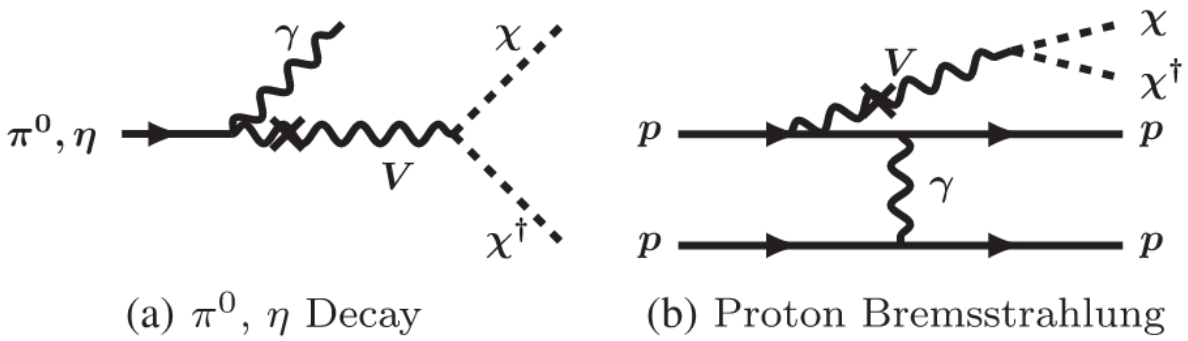
- **LDMX [Light Dark Matter eXperiment]** (arXiv:1808.05219)
  - Future Experiment
  - Missing Energy/Momentum experiment
  - pT and E distributions of recoil e^-
- **NA64** (arXiv:1906.00176)
  - Missing Energy
  - E distributions of recoil e^-
- SLAC E137 (arXiv:1406.2698)

Limits/Projections

Proton Beam Dumps with Downstream DM Detector

BdNMC software





(a) π^0, η Decay (b) Proton Bremsstrahlung

LSND (arXiv:1107.4580)

- DM-electron scattering

MiniBooNE (arXiv:1702.02688)

- DM-electron/nucleon scattering

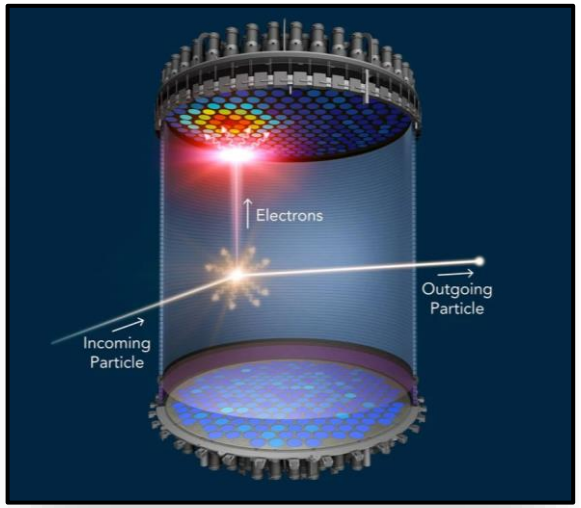
Limits/Projections

Monophoton Searches

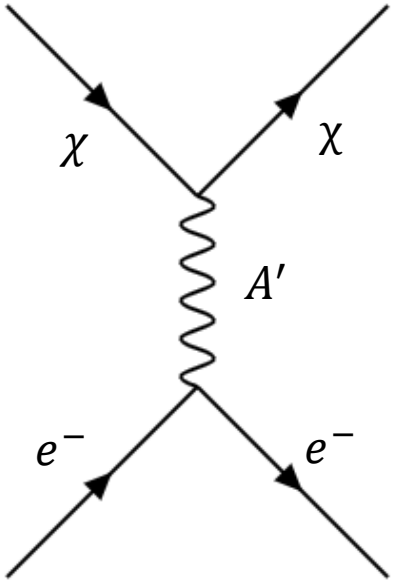
$e^+e^- \rightarrow \gamma A', A' \rightarrow XX$

- BaBar (arXiv:1702.03327)
- Belle II
  - Future experiment

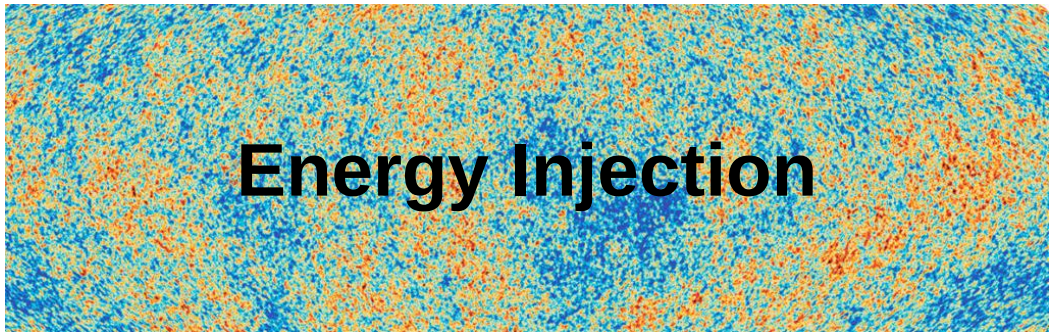
Direct Detection (arXiv:2210.07305)

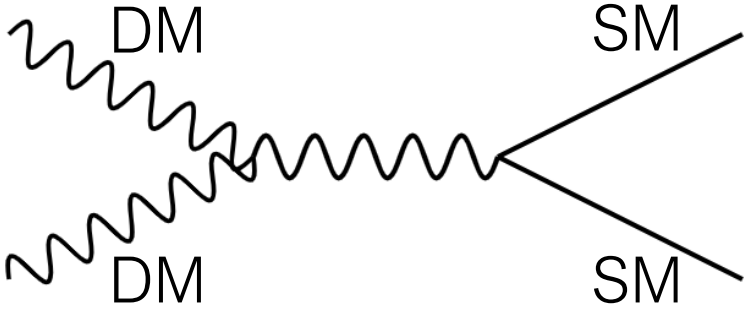


- Edelweiss
- Sensei
- Xenon1T
- Xenon10



Limits/Projections





$$\langle \sigma v \rangle = \underbrace{a}_{\langle \sigma v \rangle_s} + \underbrace{bv^2}_{\langle \sigma v \rangle_p} + \dots$$

CMB

- anisotropies measurements by Planck constrain the annihilation parameter, P_{ann}

$$P_{ann} \equiv f(z) \frac{< \sigma v >_{\chi\chi \to f\bar{f}}}{m_\chi}$$

$$P_{ann} \lessapprox 3.2 \times 10^{-28} cm^3 s^{-1} GeV^{-1}$$

(Planck 2018)

IGM temperature

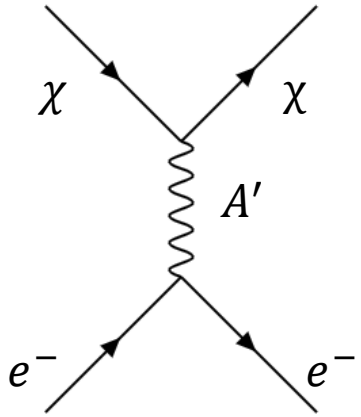
- Lyman-α forest measurements, we require that the energy injected into the IGM does not overheat it at late times

Limits/Projections

Unitarity Violation

$$|\mathrm{Im}(M_{ii}^{J})|, 2|\mathrm{Re}(M_{ii}^{J})| \leq 1$$

If the matrix elements in the theory are too large at tree level, additional fields or higher order diagrams are needed to restore unitarity of the S matrix.



- Need to be careful of this for the simplified spin-1 DM models…
- But, the renormalizable and UV complete SIMP spin-1 DM model by construction does not violate unitarity!

arXiv:1510.02110: simplified DM
arXiv:2303.08351: spin-1 DM self scattering

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

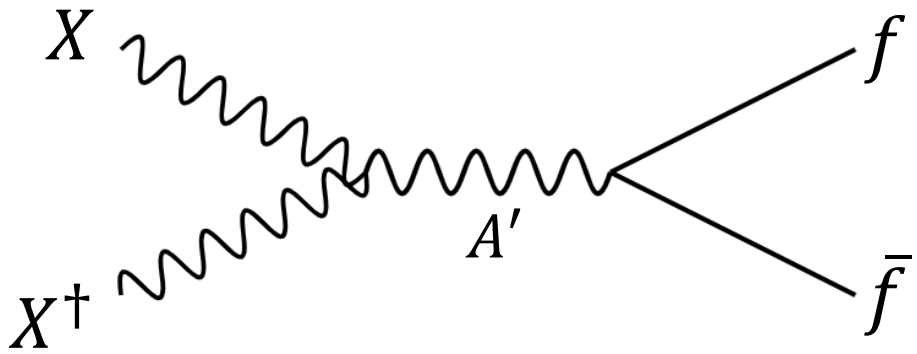
b_7: complex

h_3: real

$h_3 \equiv \epsilon e$

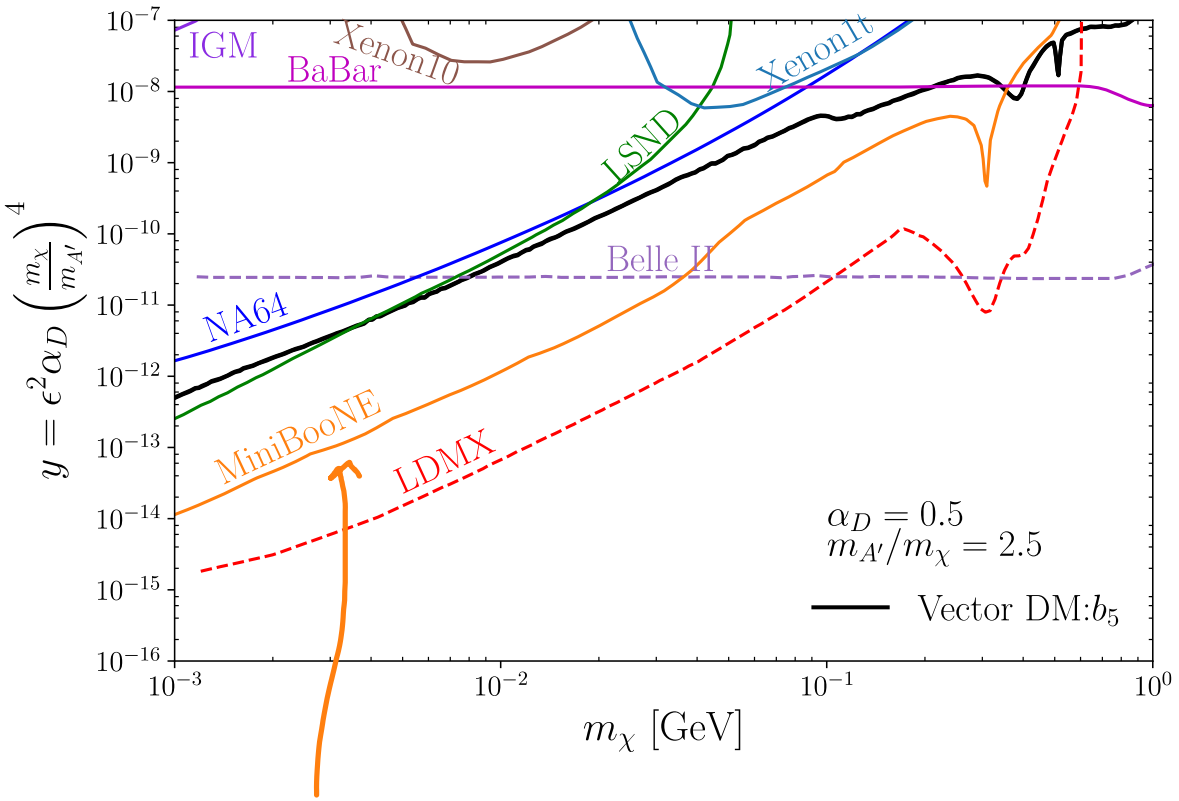
f: SM leptons and quarks (excluding neutrinos)

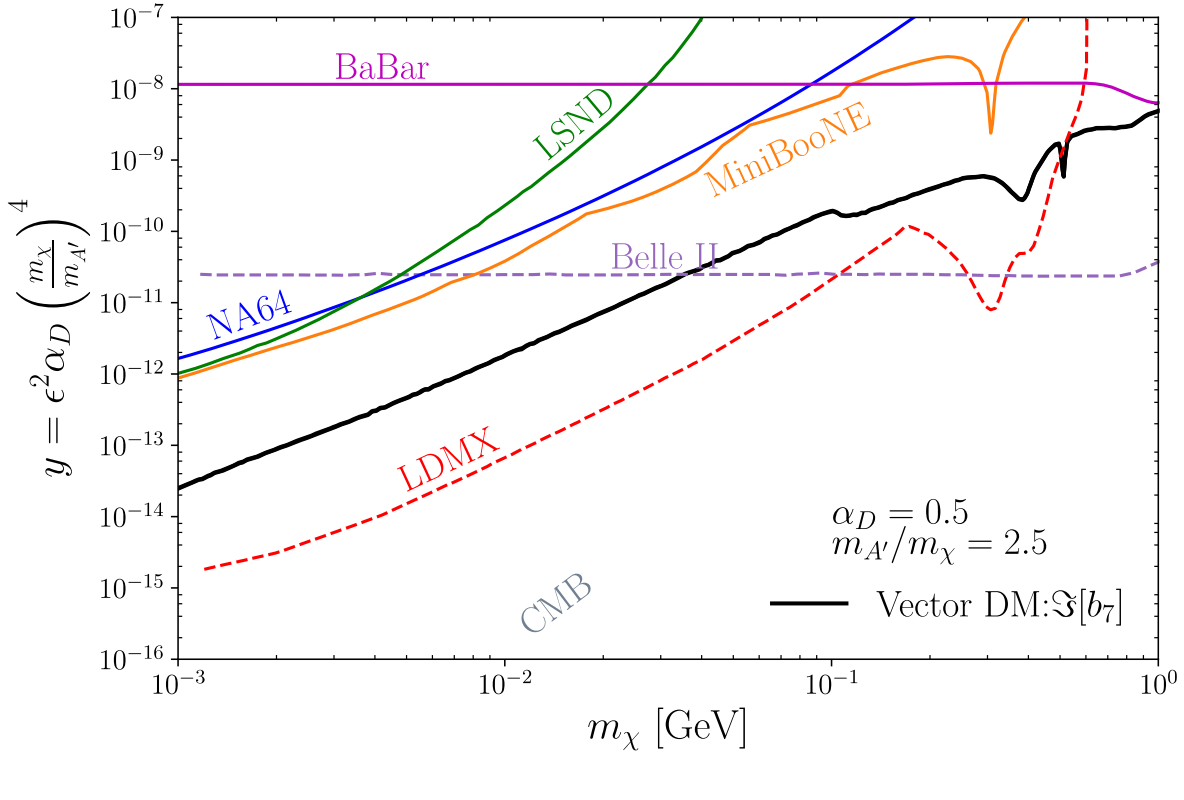
DM Freeze-Out



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

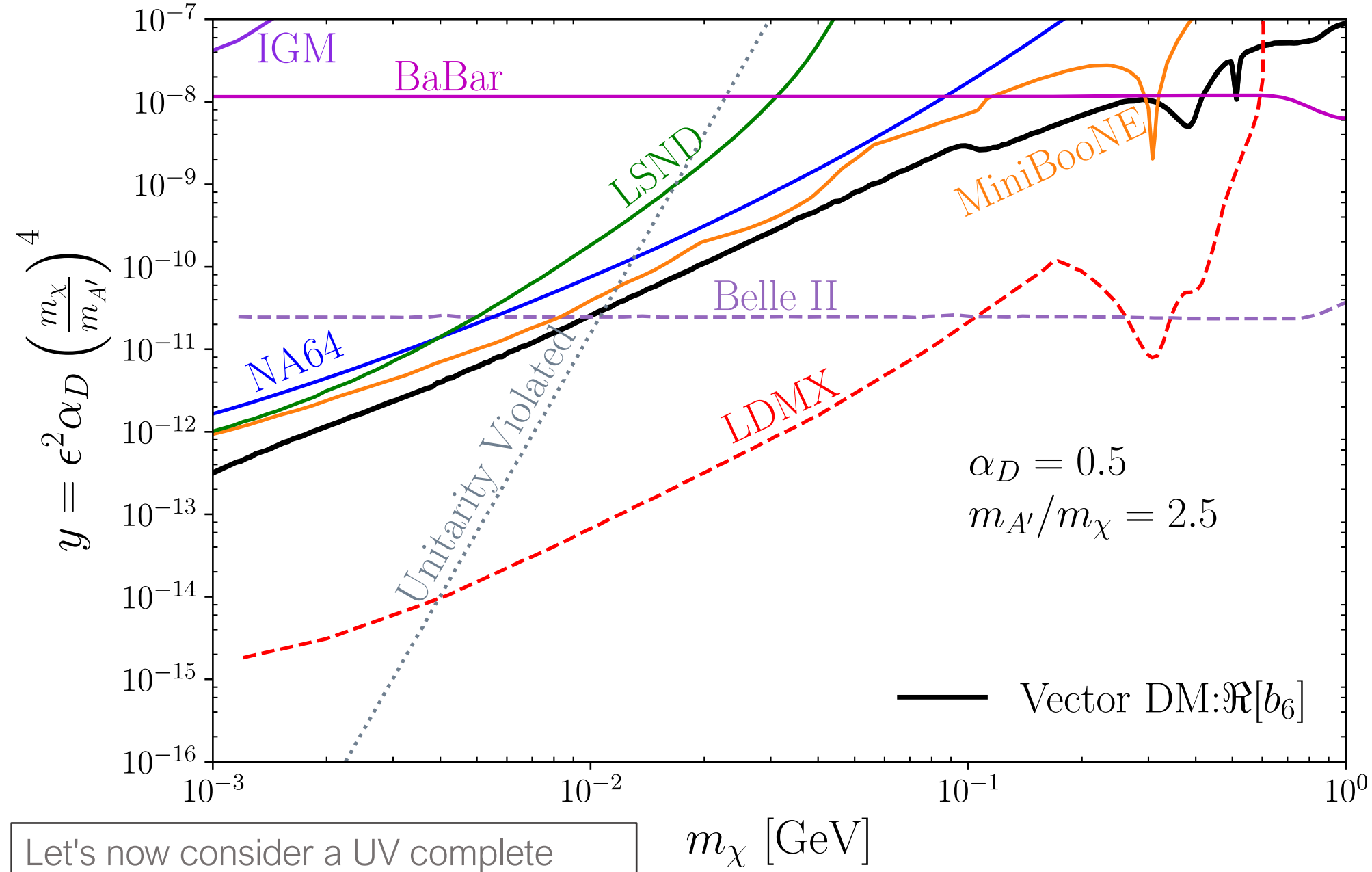
Strong Limits on Spin-1 Relic Targets





Large MiniBooNE limits due to $\sigma_{\chi e^- \to \chi e^-}$ being large when m_χ 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

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

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

→ mainly Z's are produced at fixed target experiments

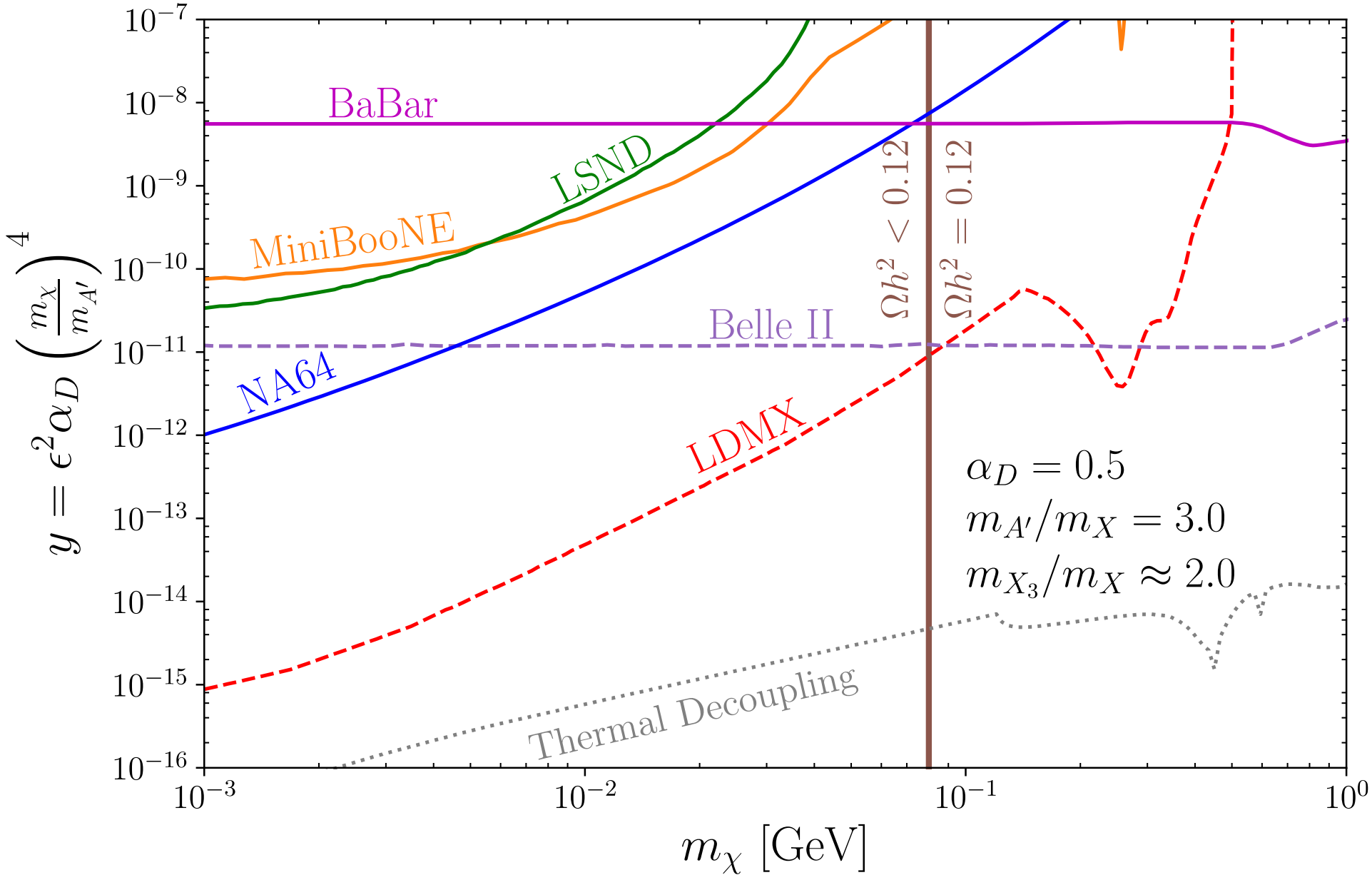
processes setting the relic density →

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

Dominant since $g_X \gg e\epsilon$

arXiv:1904.04109

$$m^2_X < m^2_{\tilde{X}_3} < m^2_{\tilde{Z}'}$$



Weaker beam dump limits since $\mathbf{DM - e^-}$ 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 $m_{A'} > 2m_{\chi}$
- First model to be probed at upcoming LDMX!!

Future

- Consider $m_{A'} < 2m_{\chi}$
  - visible decays
- Additional UV complete spin-1 DM scenarios

Danke!

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

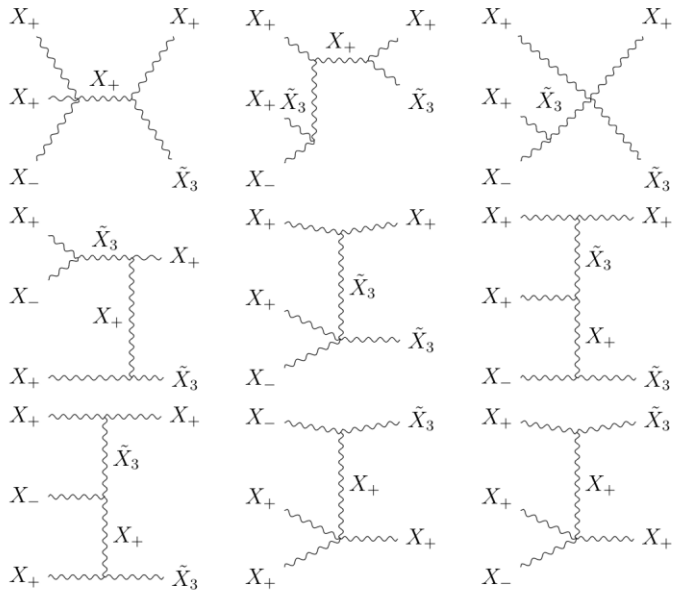
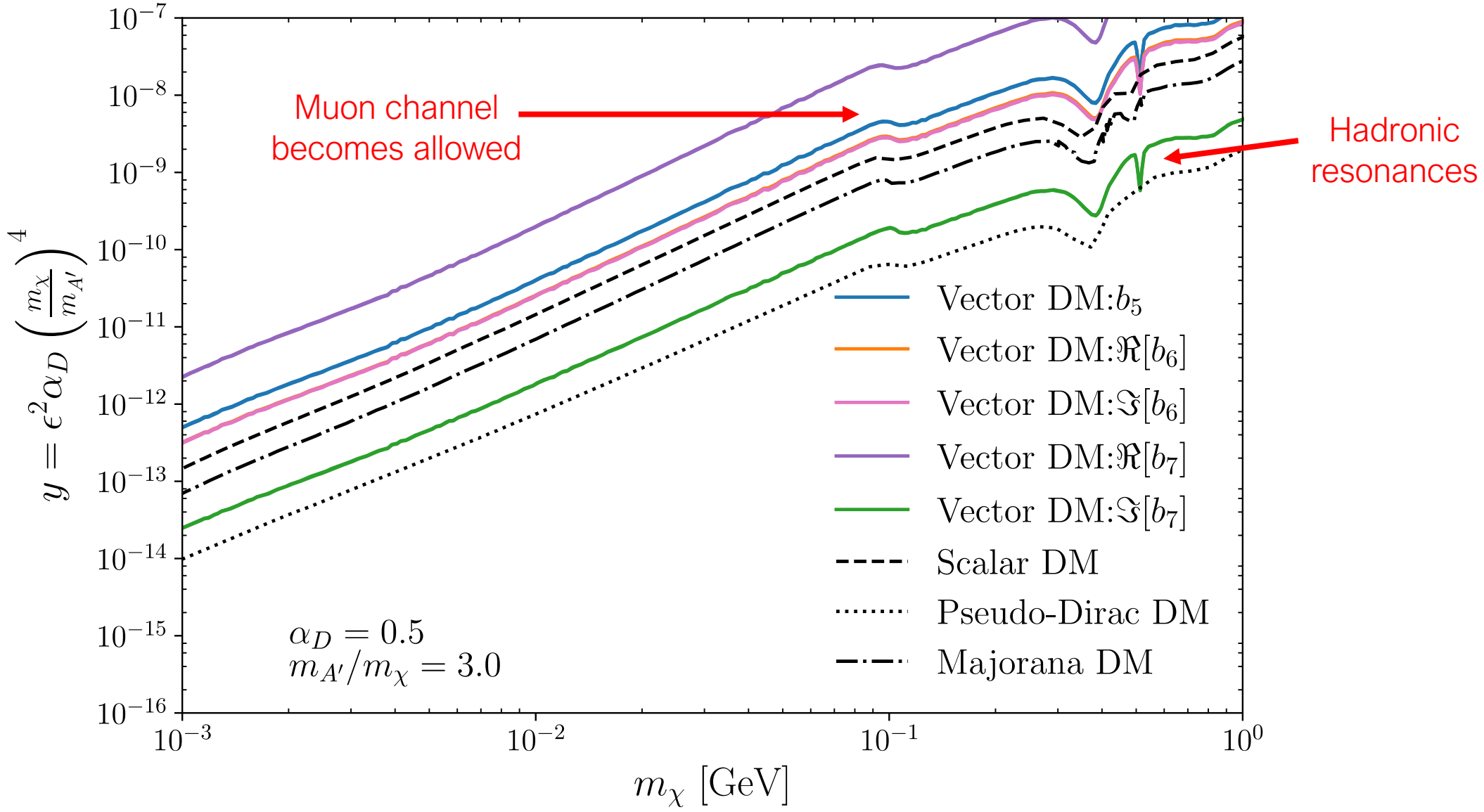


Figure 1: Feynman diagrams for $X_+X_+X_- \to X_+\tilde{X}_3$.

Relic Targets of DM Models



Calculating Dark Matter Abundance

The Boltzmann Equation

$$\dot{n} + 3Hn = R$$

Universe's Expansion

Particle Physics

- n: number density
- H: Hubble Rate (Universe's Expansion)
- R: Interaction Rate Density (# interactions per time and volume)
  - Includes all annihilations and productions

- More convenient to define Y and x
  - $\mathrm{Y} \equiv \frac{\mathrm{n}}{\mathrm{s}}$, $\mathrm{x} \equiv \frac{\mathrm{m}}{\mathrm{T}}$
  - s: entropy density

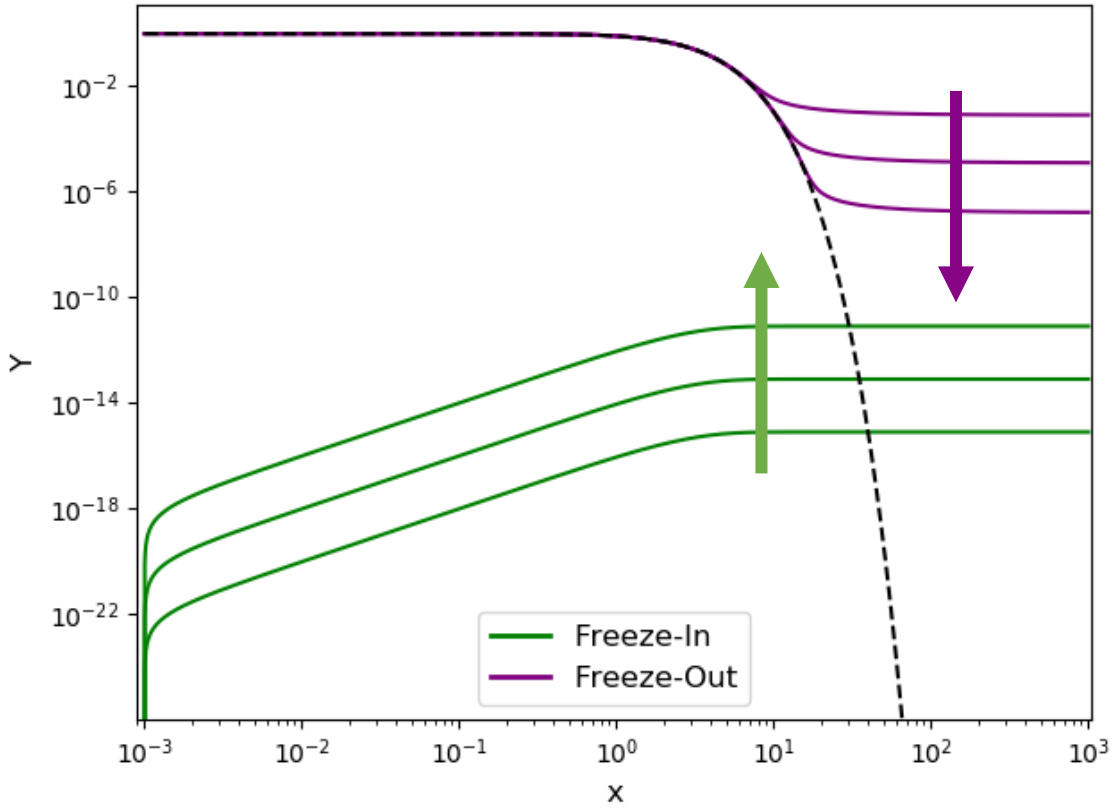
Ways of Producing Dark Matter

Γ: Interaction Rate (# interactions per time)

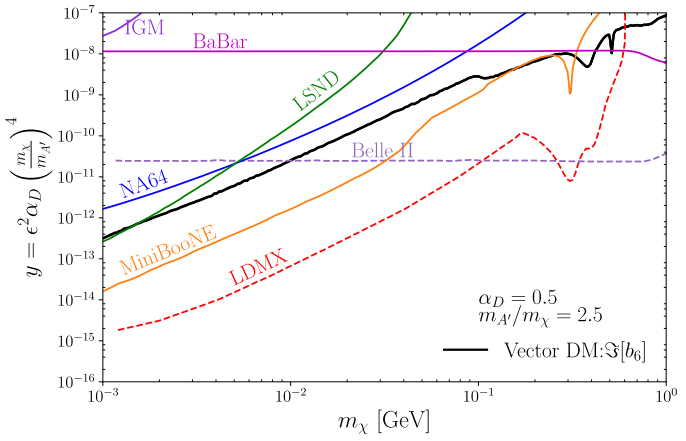
H: Hubble Rate (universe's expansion rate)

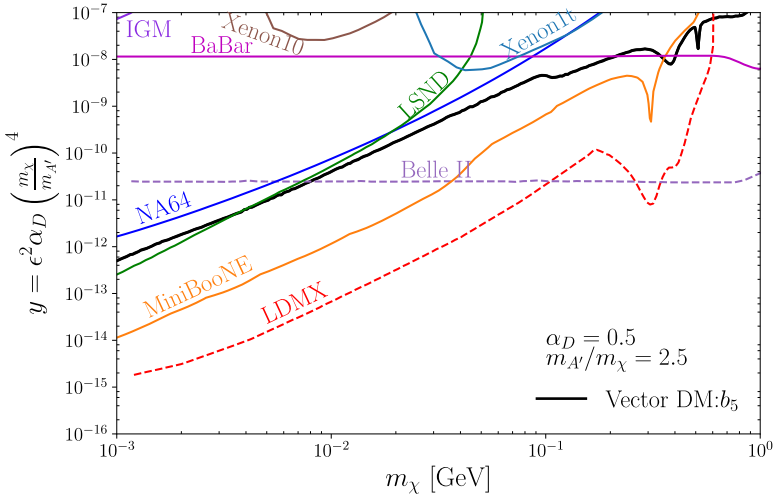
- Freeze-In
  - $\Gamma < H$ (decoupled)
  - small interaction rates
  - **never** thermalizes with bath
- Freeze-Out
  - $\Gamma > H$ (coupled)
  - large interaction rates
  - ~~thermalizes with bath~~

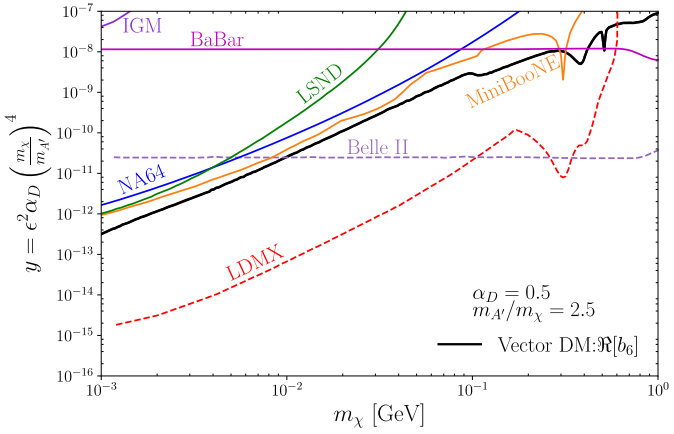
This work!



→ Increasing Coupling


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


IGM
Xenon10
BaBar
Xenon1T
LSND
Belle II
NA64
MiniBooNE
LDMX
$\alpha_D = 0.5$
$m_{A'}/m_\chi = 2.5$
Vector DM:b_5
$y = \epsilon^2\alpha_D\left(\frac{m_\chi}{m_{A'}}\right)^4$
m_χ [GeV]


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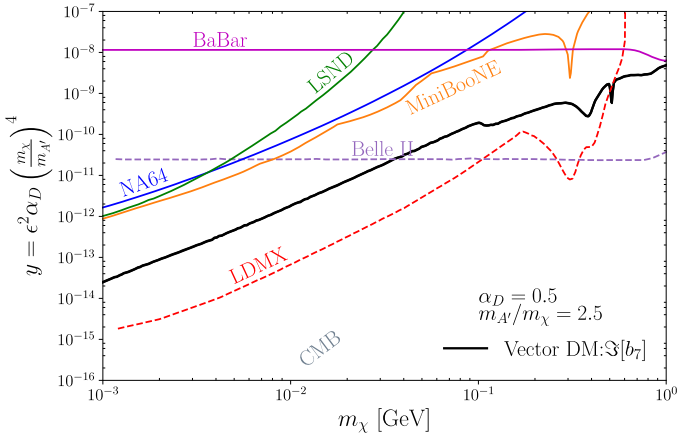
$\alpha_D = 0.5$
$m_{A'}/m_\chi = 2.5$
Vector DM:$\Re[b_6]$
$y = \epsilon^2\alpha_D\left(\frac{m_\chi}{m_{A'}}\right)^4$
m_χ [GeV]


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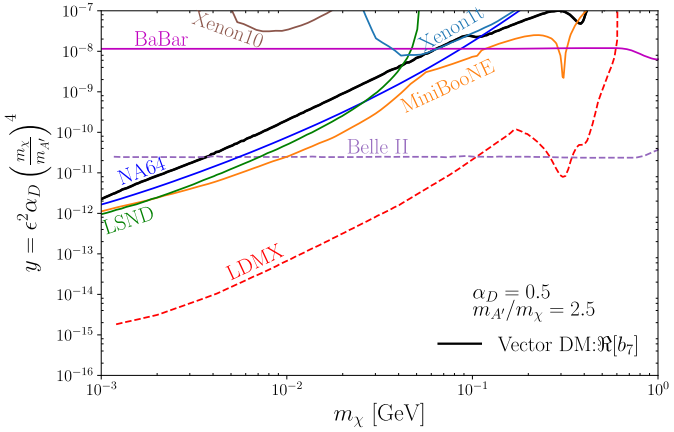
CMB
$\alpha_D = 0.5$
$m_{A'}/m_\chi = 2.5$
Vector DM:$\Im[b_7]$
$y = \epsilon^2\alpha_D\left(\frac{m_\chi}{m_{A'}}\right)^4$
m_χ [GeV]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$\alpha_D = 0.5$
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Vector DM:$\Re[b_7]$
$y = \epsilon^2\alpha_D\left(\frac{m_\chi}{m_{A'}}\right)^4$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

Confidence Intervals

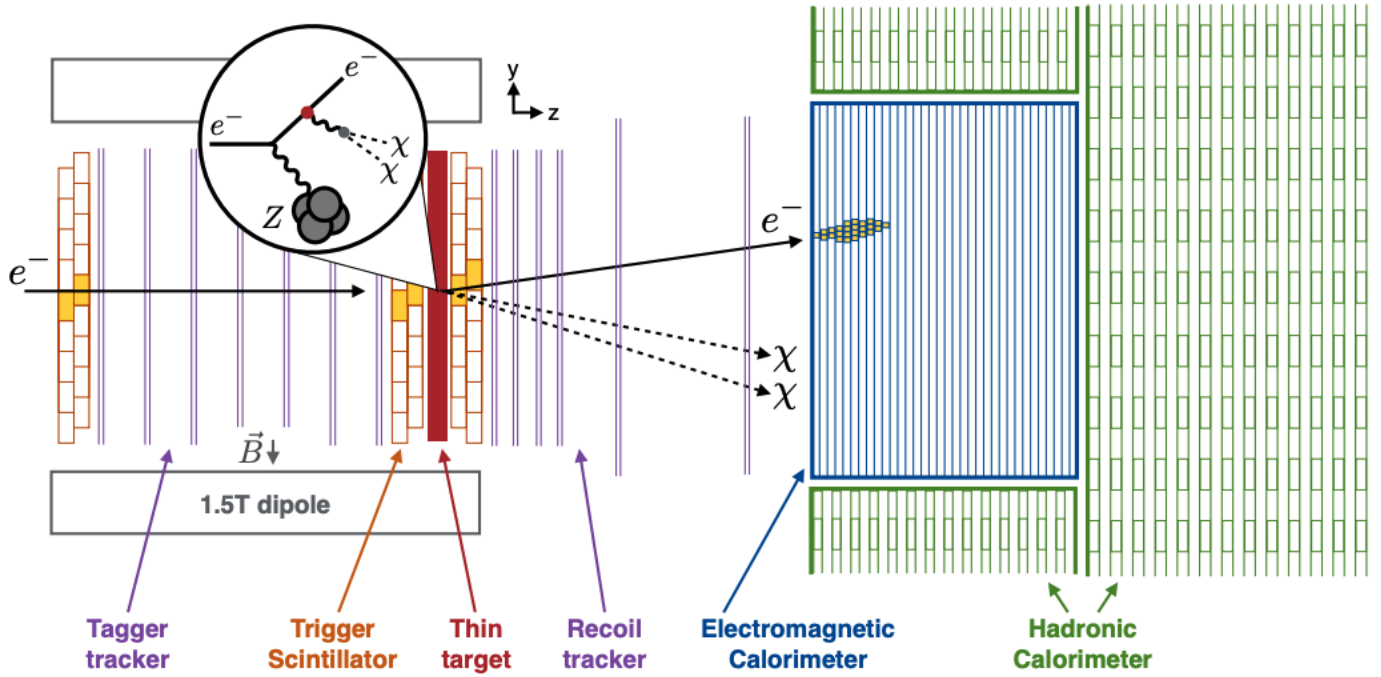
- x% CL: If experiment is repeated many times, the intervals include the true parameter x% of the time
- Counting experiment, take Poisson distribution: $f(n;\nu) = \frac{\nu^n}{n!} e^{-\nu}$

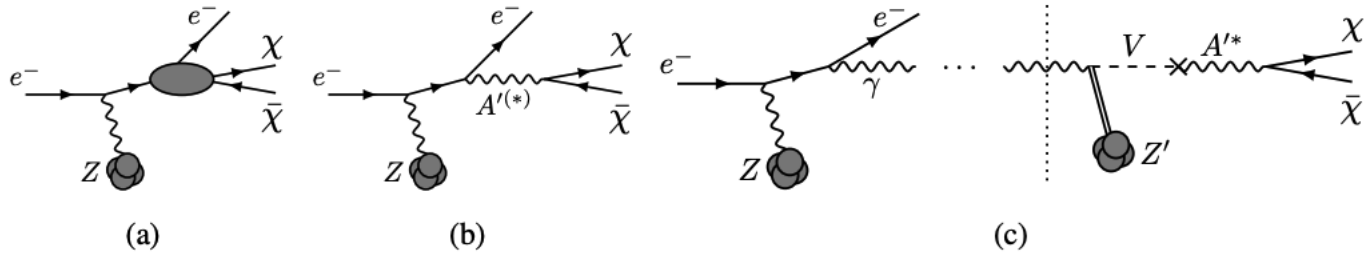
- Uncertainty on number of background events
  - Neutrino flux, NCE cross section model ($\sigma_{\nu N \to \nu N}$), detector response
  - Nuisance parameters introduced

Experiments

Light Dark Matter eXperiment (LDMX)

- Future fixed target missing momentum exp
  - 2025: LESA delivers beam to LDMX allowing 4×10^{14} EOT
  - 2027: 10^{16} EOT
- e^- incident on a thin tungsten target
- Charged particle tracker and calorimeters to measure DM signature
  - Recoil electron pT accompanied by absence of other particle activity



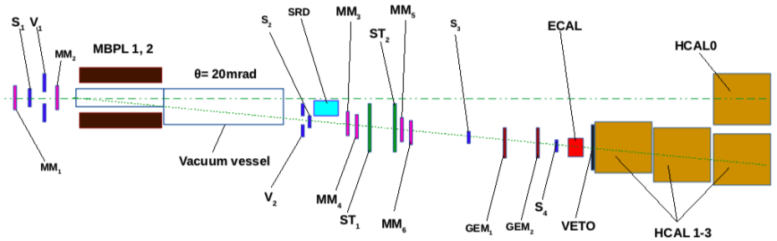


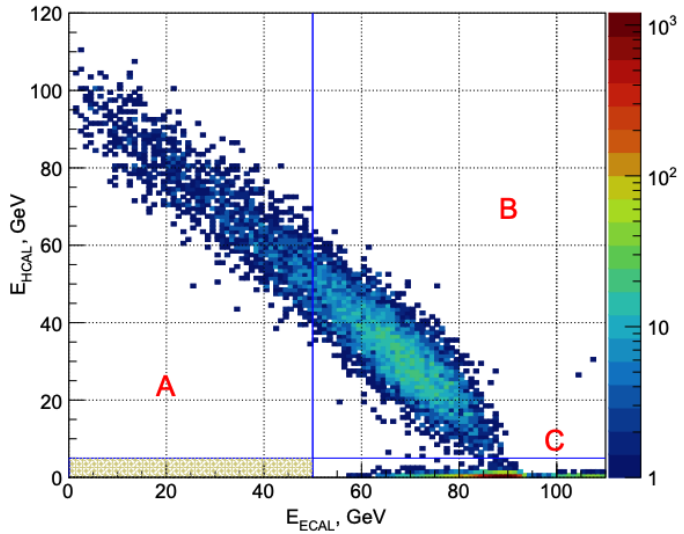
Electron Beam Dumps

NA64

arXiv:1710.00971

- 100 GeV electron beam incident on a lead target
- Event: single electron produced and missing energy

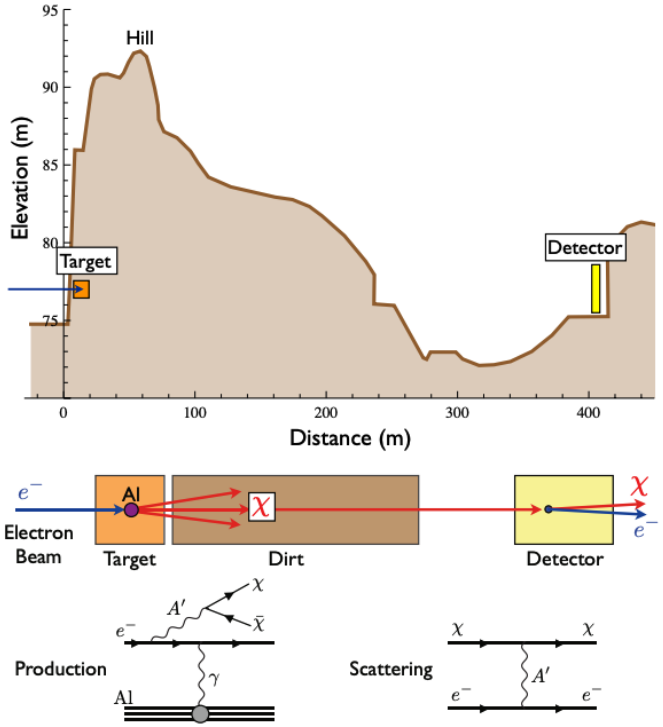




E137

arXiv:1406.2698

- DM produced from electron-target collisions
- 20 GeV beam incident on a set of aluminum plates interlaced with cooling water.
- Downstream detector



Proton Beam Dumps

arXiv:1107.4580

DM scatterings mimic neutrino scatterings!
(Neutral current-like scatterings)

LSND

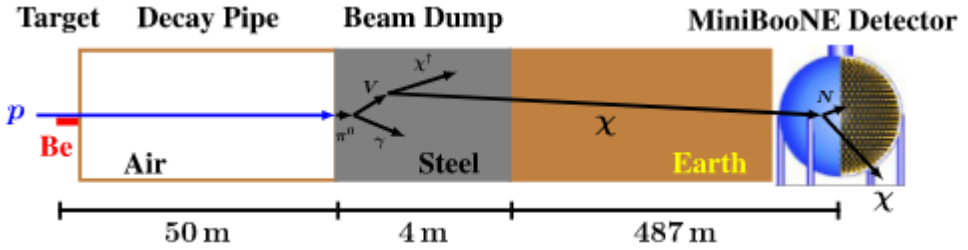
arXiv:hep-ex/0101039

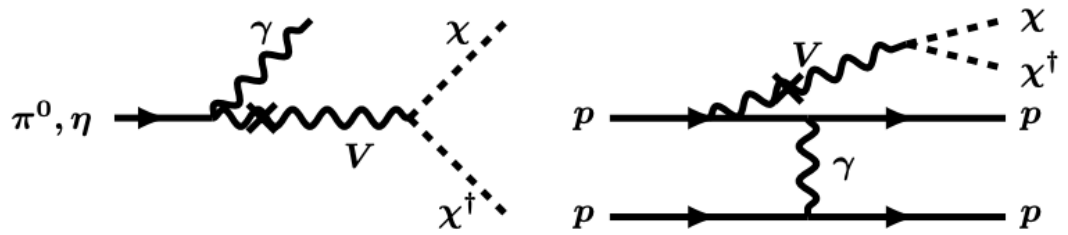
- pions produced by impacting an 800 MeV proton beam onto a water or metal target
- $\pi^0 \to A'\gamma, A' \to XX$

Mini-Boone

arXiv:1807.06137

- Designed to study short-baseline neutrino oscillations
  - 8 GeV proton beam incident on a steel target
- Peak ~ 800 MeV (ρ mass)





(a) π^0, η Decay (b) Proton Bremsstrahlung

FIG. 2. DM production channels relevant for this search with an 8 GeV proton beam incident on a steel target.

Monophoton Searches $e^+e^- \to \gamma A', A' \to XX$

Search for single photon events in e^+e^- collision data

arXiv:1702.03327

- BABAR detector at PEP-II B-factory
- Large missing energy/momentum
- Exclusions for $m_{A'} \leq 8$ GeV

Belle-II

arXiv:1808.10567

- Experiment operated at SuperKEKB
- First data taken in 2019, more to come..
- 7 GeV electrons with 4 GeV positrons

Hadronic Resonances

- If DM freezes-out after the QCD phase transition (~150 MeV), DM annihilates to hadronic final states rather than to quarks.
  - Must consider for $m_X \lesssim 3\,GeV$

$$\sigma v_{X\,X \to A' \to \mathrm{hadrons}} \approx R(s) \sigma v_{X\,X \to A' \to \mu^- \mu^+}$$

$$R(s) \equiv \sigma_{e^+ e^- \to \mathrm{hadrons}} / \sigma_{e^+ e^- \to \mu^+ \mu^-}$$