Sub-GeV Dark Matter Searches: Extending the Theoretical Landscape and Performing Global Fits

CHALMERS
UNIVERSITY OF TECHNOLOGY

Knut and Alice Wallenberg Foundation

Work partly based on,
arXiv:2307.02207

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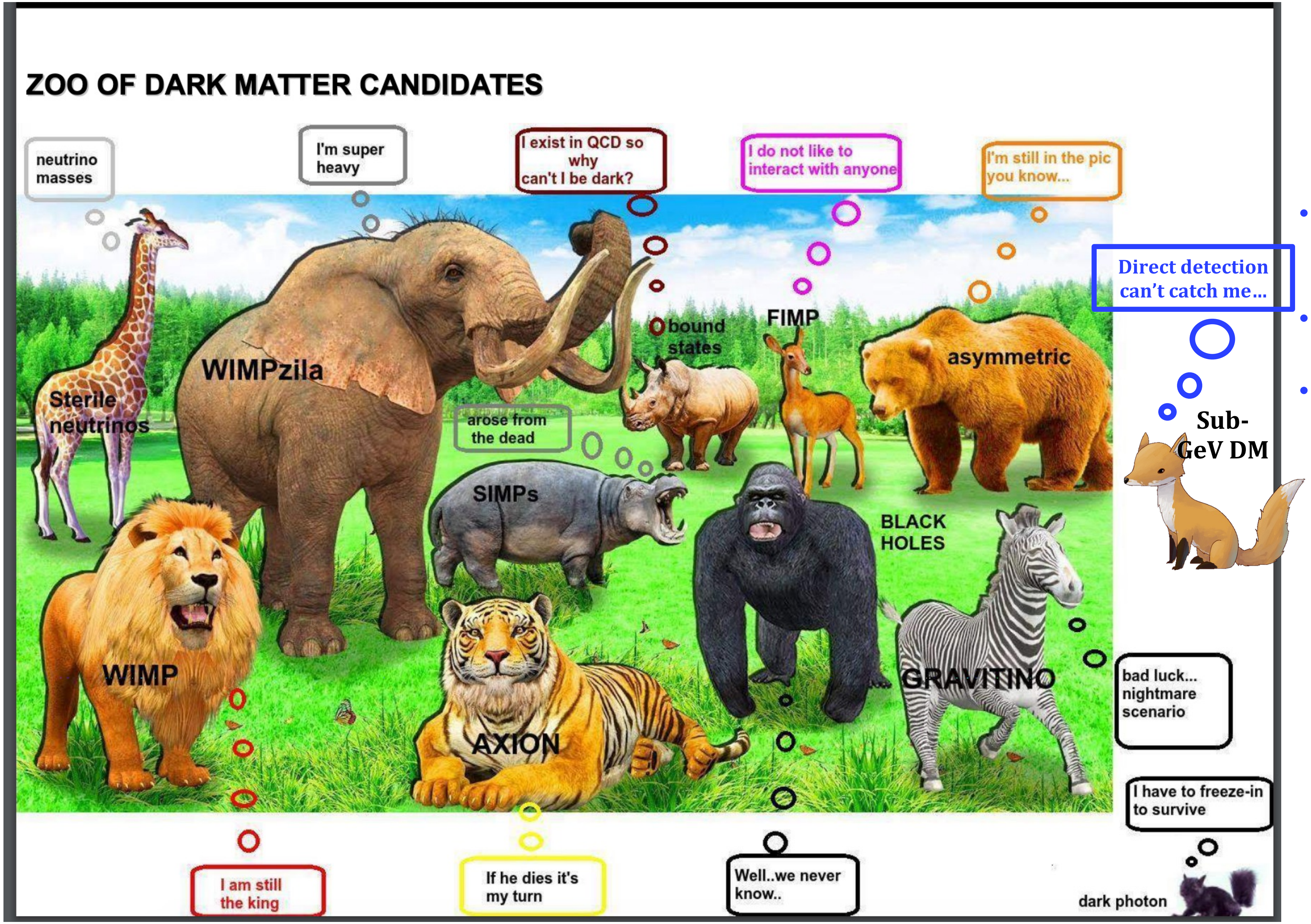
Supported by a research grant from the Wallenberg foundation



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

F. Queiroz

Dark Matter Candidates

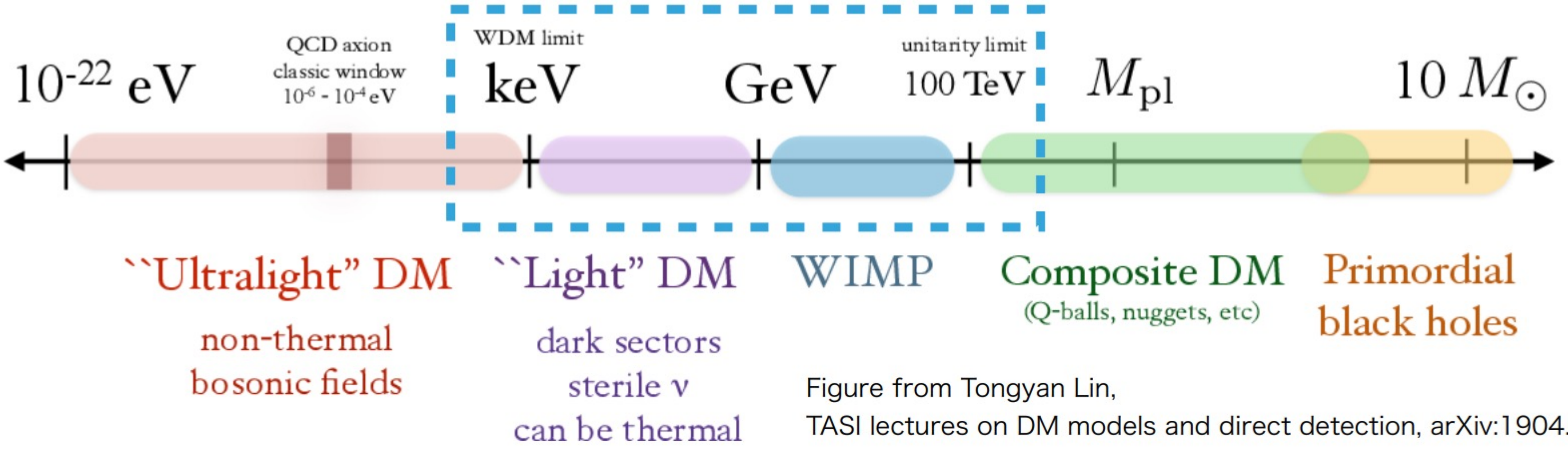
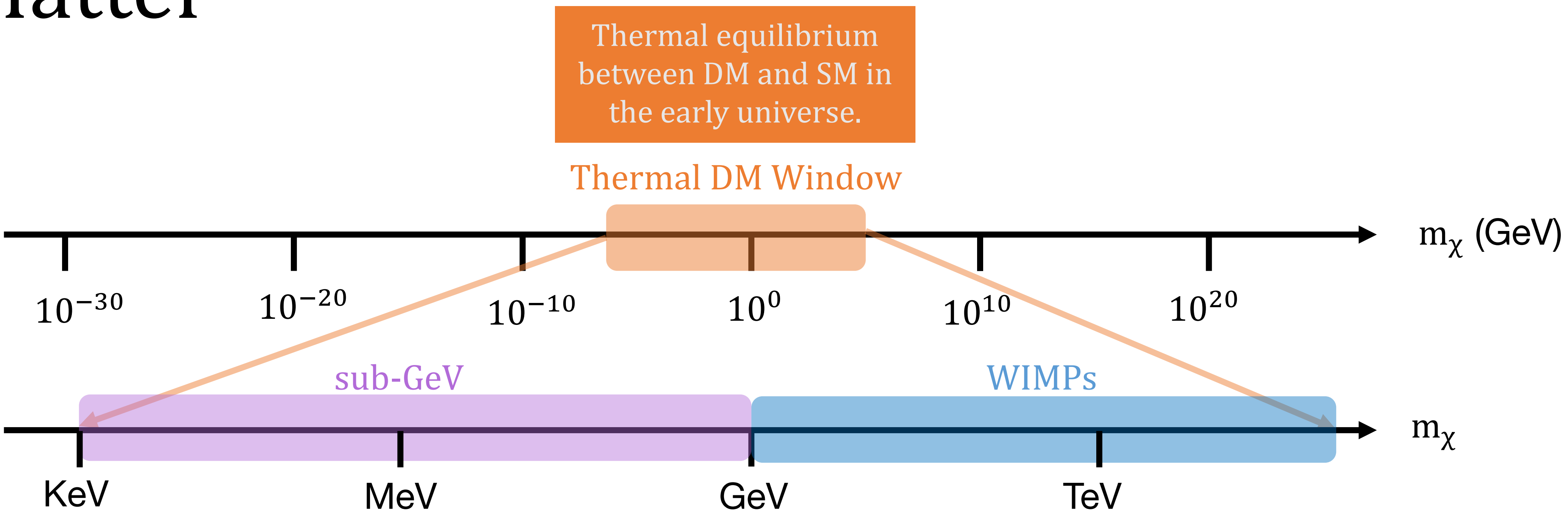


Figure from Tongyan Lin,
TASI lectures on DM models and direct detection, arXiv:1904.07915

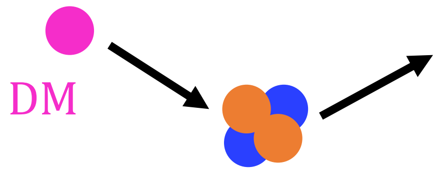
Sub-GeV Dark Matter



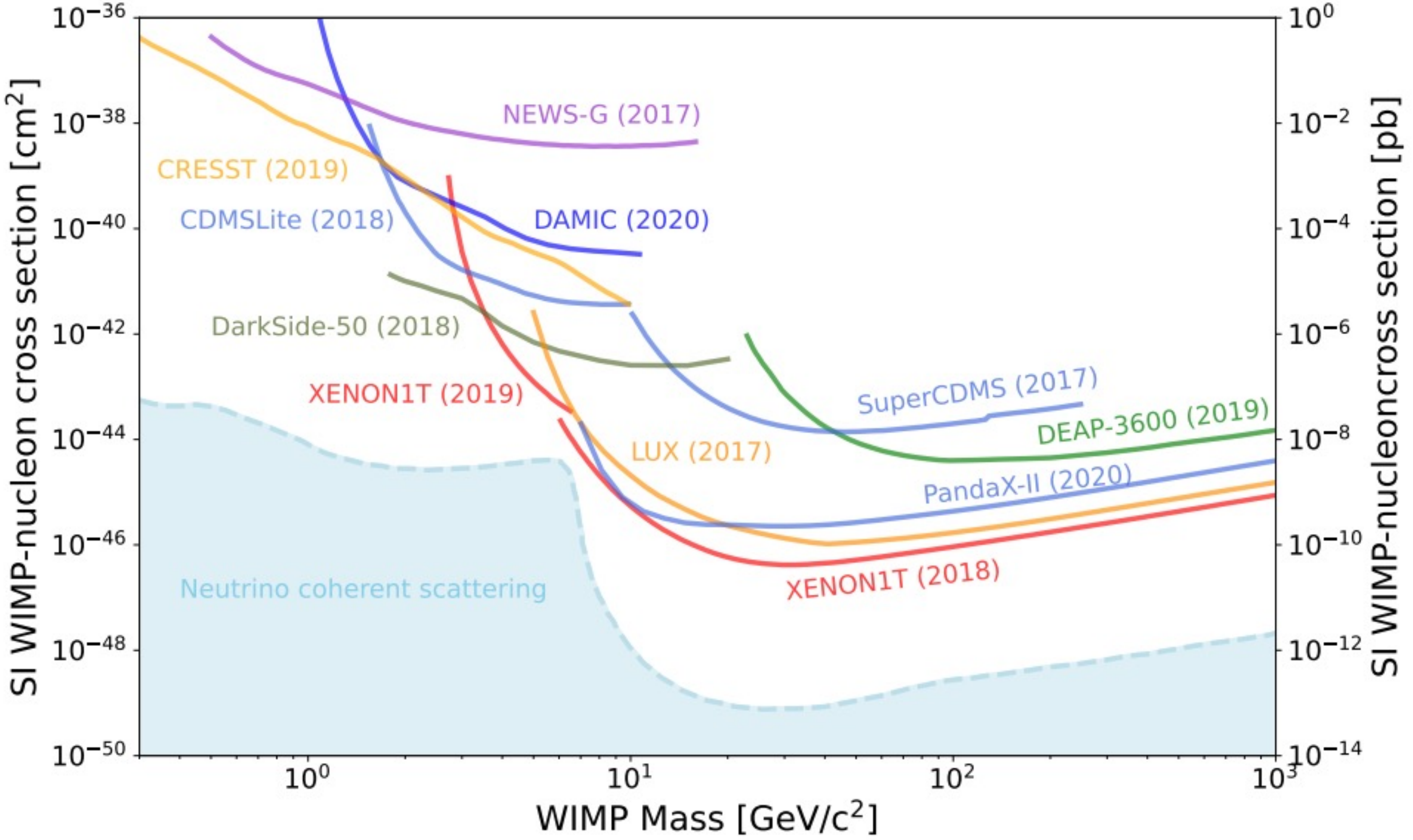
- DM produced through freeze-out near weak scale
- GeV-TeV scale thermal DM already widely tested

Nuclear Recoil Direct Detection Status

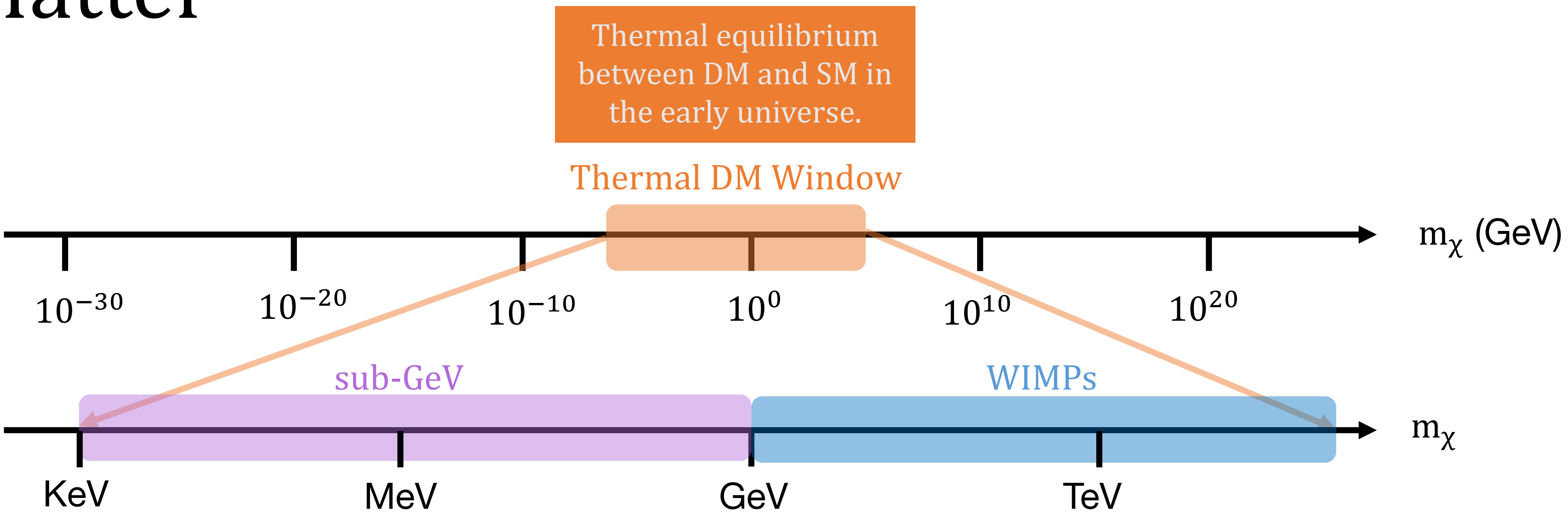
- Sensitive to GeV-TeV scale DM masses
- Approaching neutrino "fog"



PDG



Sub-GeV Dark Matter



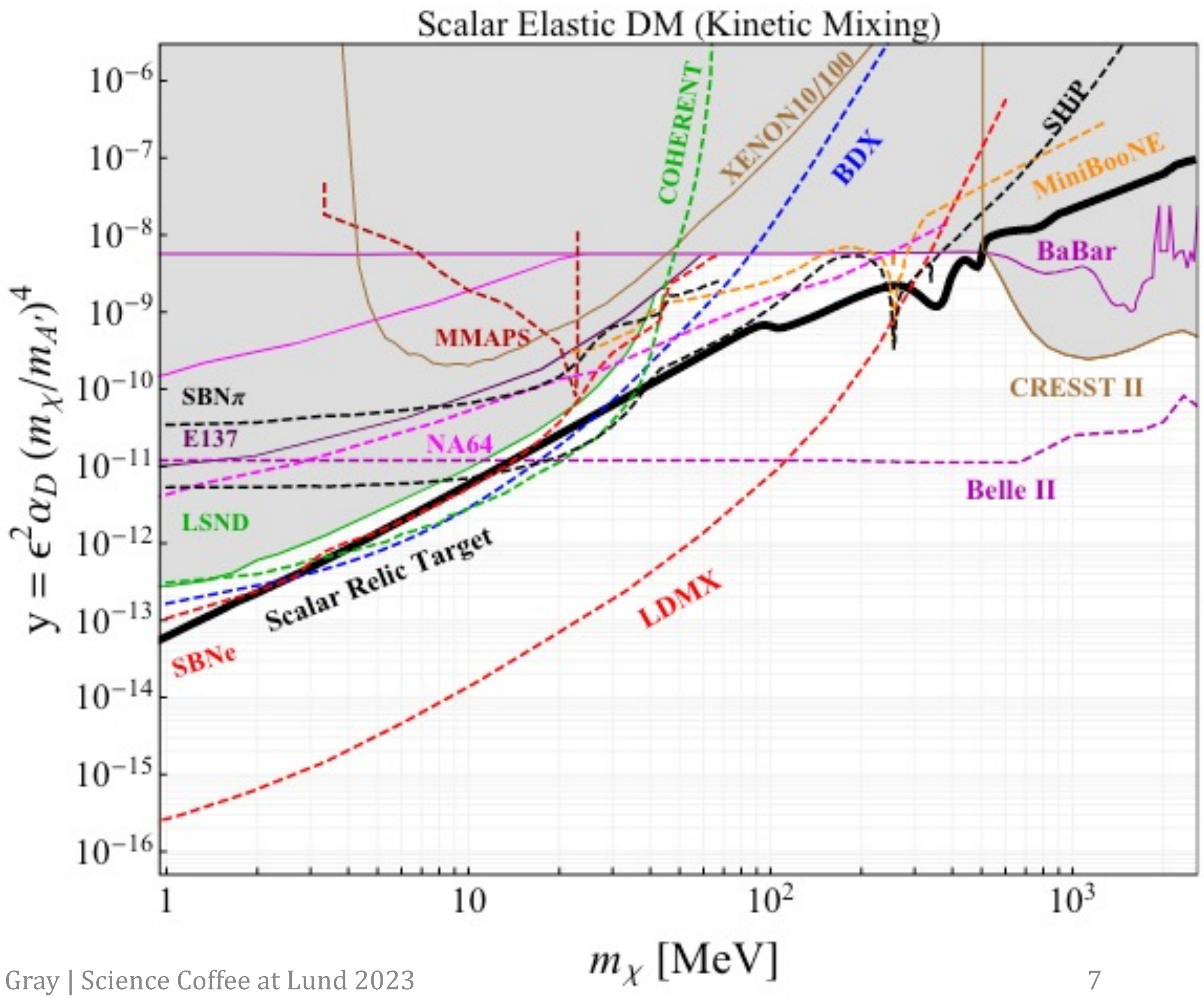
- Sub-GeV DM is largely experimentally **unexplored**..
  - Out of reach of nuclear recoil direct detection exps
  - Electron recoils and accelerator exps

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

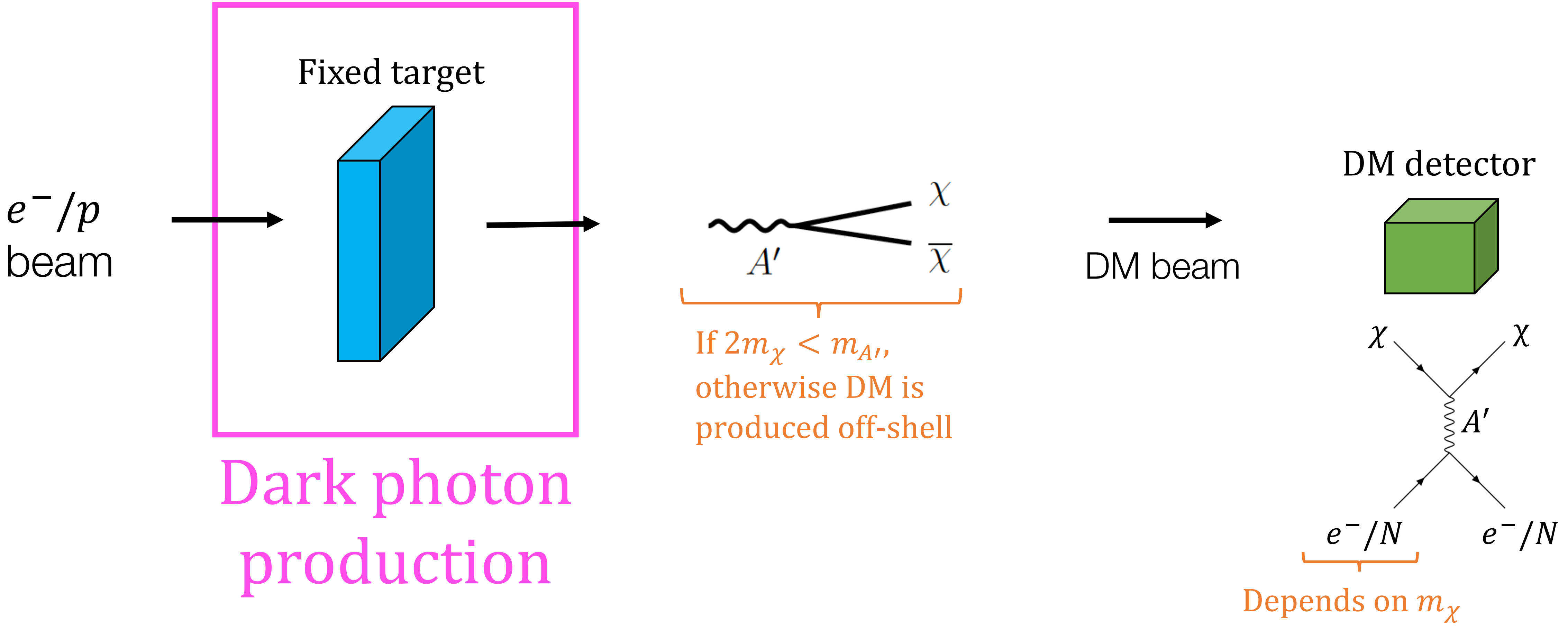
Accelerator Based DM Experiments

Complementarity with direct detection experiments

- Types
  I. beam dump
  II. missing momentum/energy
  III. missing mass
  IV. direct dark photon search
     (visible dark photon decay)



Beam Dumps (Electron and Proton)



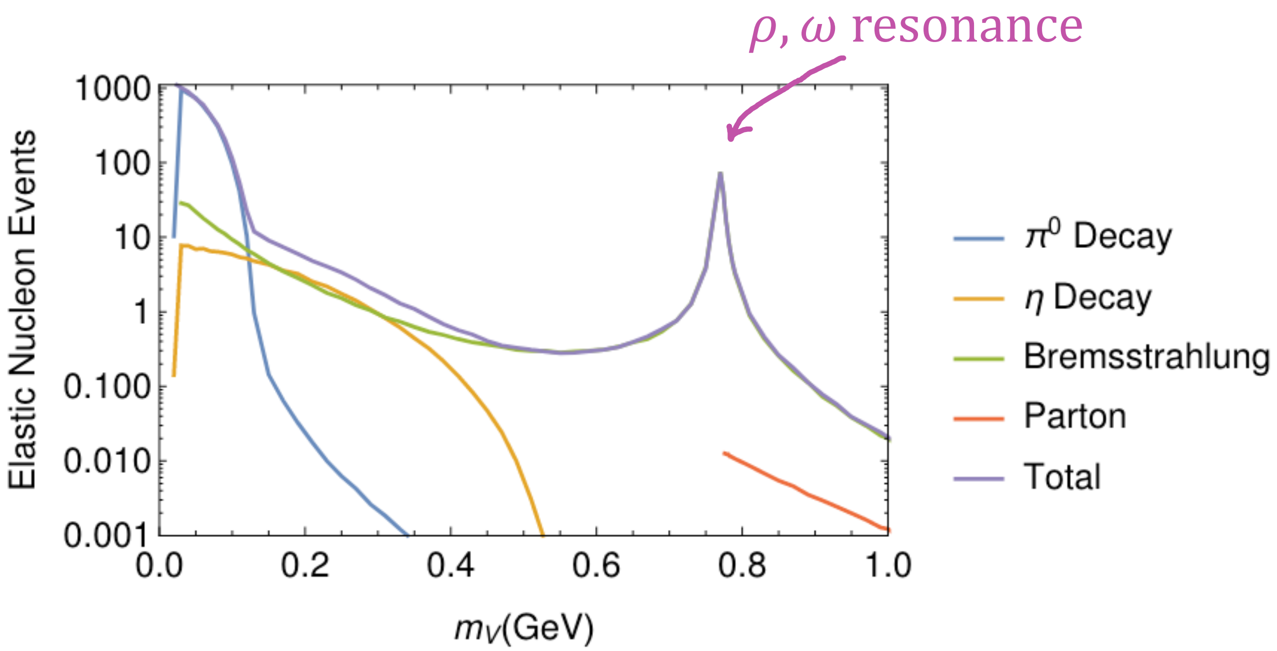
Beam Dumps (Electron and Proton)

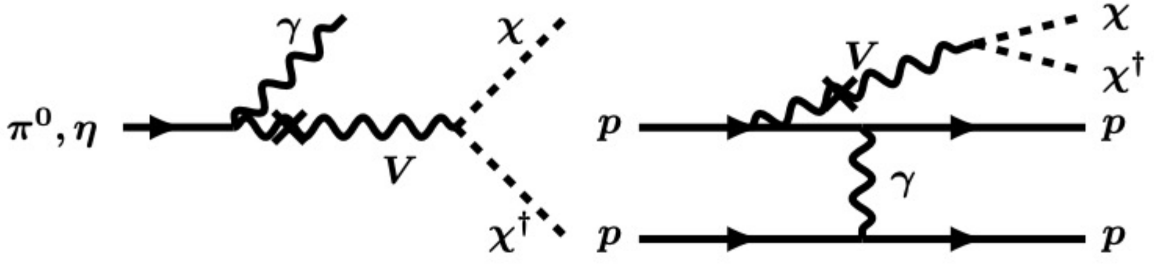
Dark Photon/DM Production

i. Mesons from proton beam – nucleon target interactions
   i. $\pi^0, \eta \rightarrow \gamma A', A' \rightarrow \chi\chi$

ii. Proton/electron dark bremsstrahlung
   i. $pN \rightarrow pNA'$
   ii. resonant vector meson mixing

iii. Direct production through parton level processes
   i. relevant for $m_{A'} > 1$ GeV





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

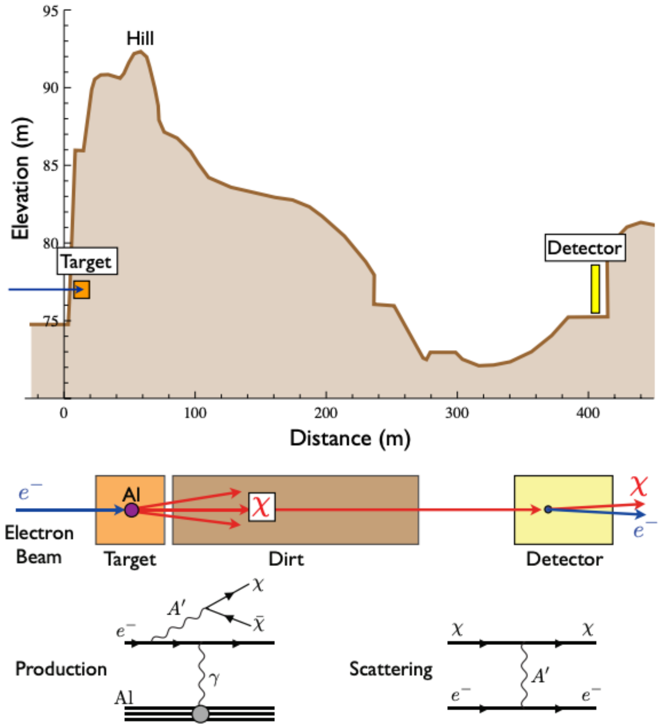
Beam Dumps (Electron and Proton)

arXiv:1107.4580

E137

arXiv:1406.2698

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



LSND

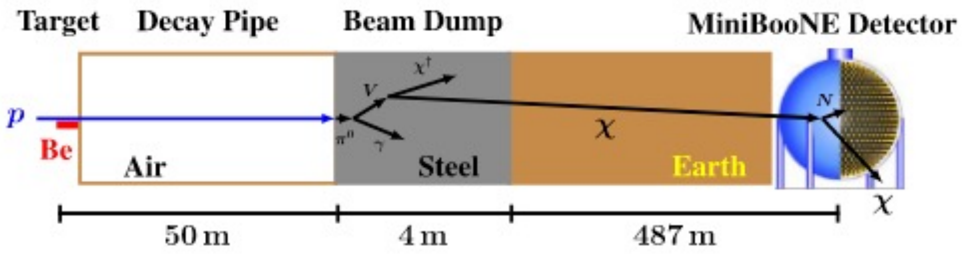
arXiv:hep-ex/0101039

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

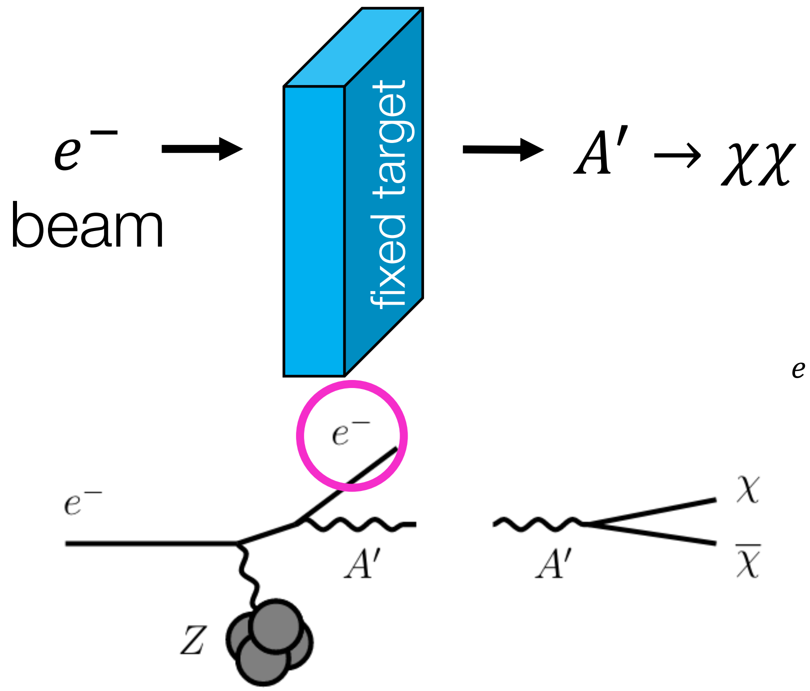
MiniBooNE

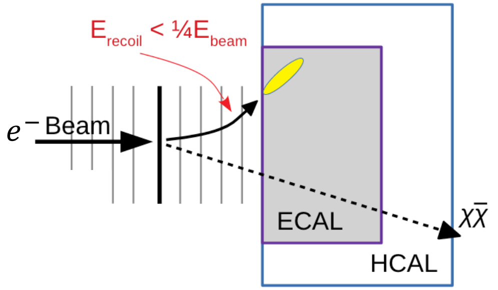
arXiv:1807.06137

- Designed to study short-baseline neutrino oscillations
- 8 GeV proton beam incident on a steel target
- Peak ~ 770 MeV (ρ mass)

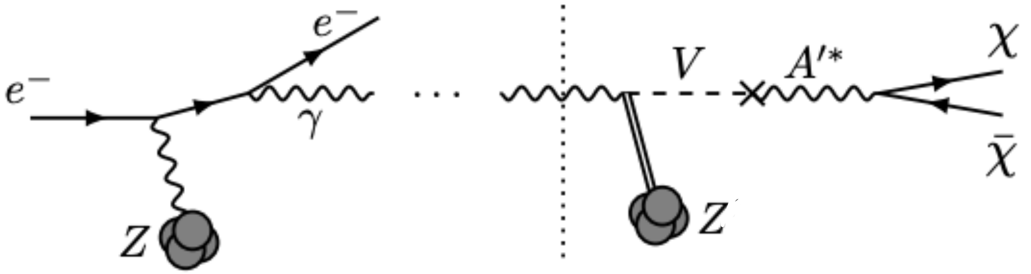


Missing Momentum/Energy Experiments





- **LDMX [Light Dark Matter eXperiment]** **(arXiv:1808.05219)**
  - In final design stage
    - Phase 1: Low-multiplicity beam at SLAC $4{\times}10^{14}$ EOT
    - Phase 2: 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



- **NA64** **(arXiv:1906.00176)**
  - **100 GeV electron beam incident on a lead target**
  - **Event: single electron produced and missing energy**

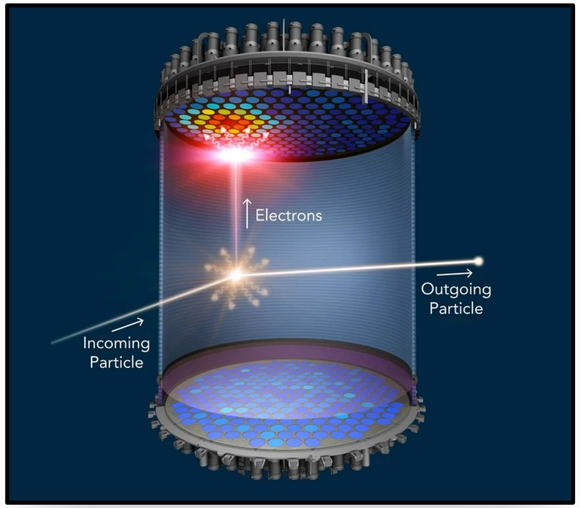
Other Experiments

Monophoton Searches

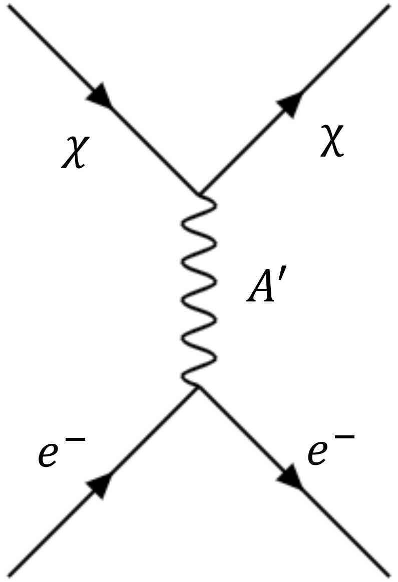
$e^+e^- \to \gamma A', A' \to XX$

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

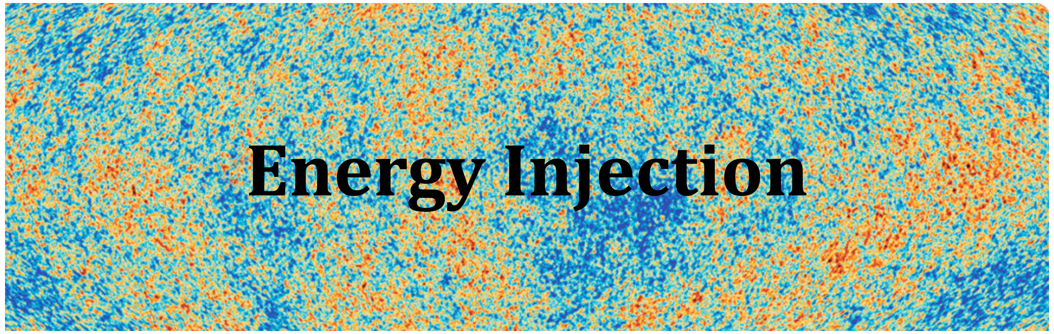
Direct Detection (arXiv:2210.07305)

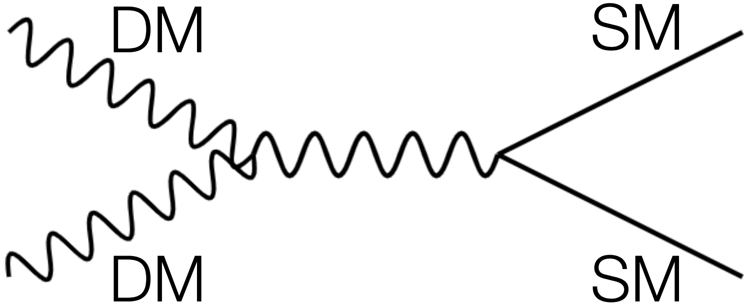


- Edelweiss
- Sensei
- Xenon1T
- Xenon10



Cosmological limits





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

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)

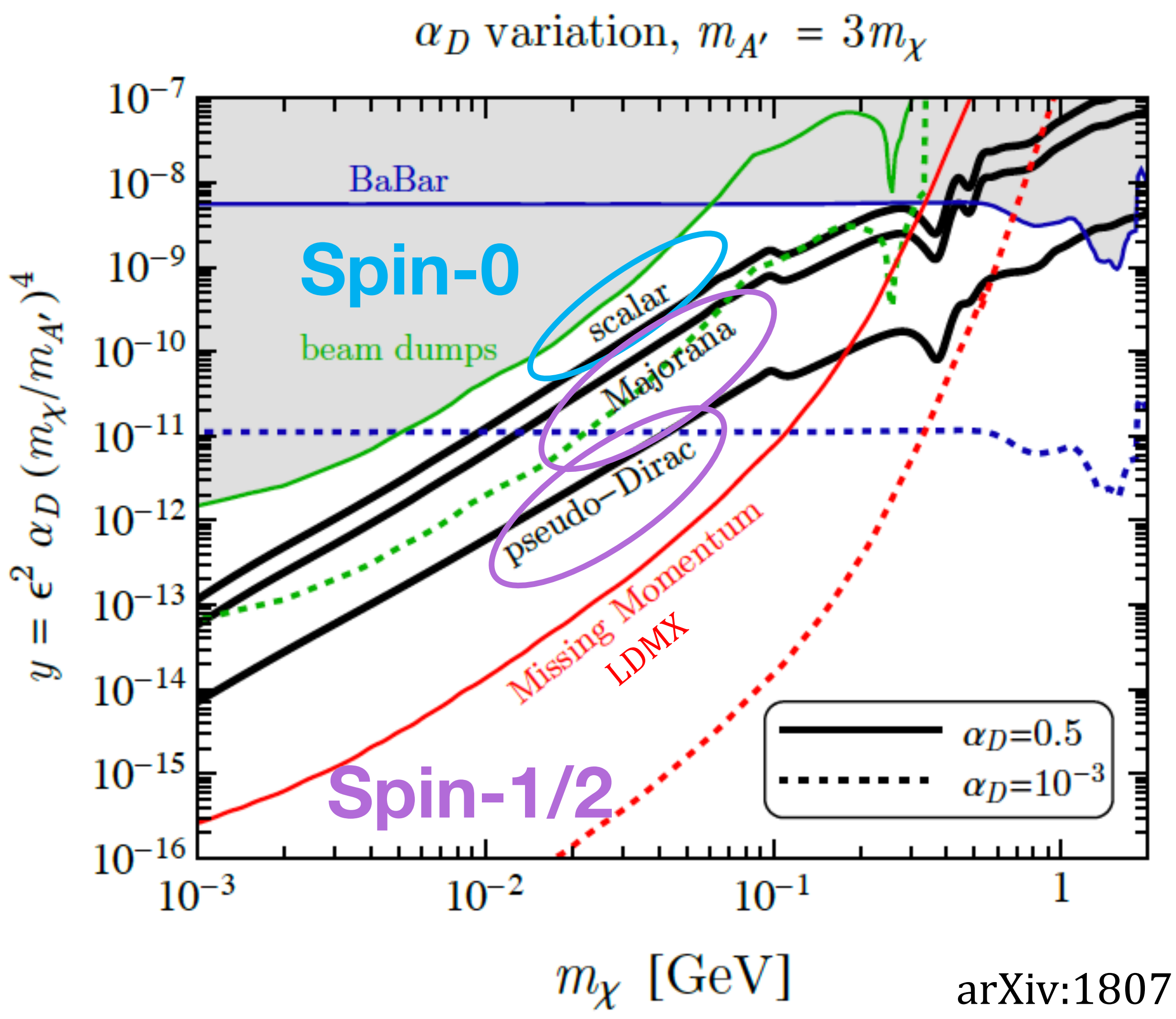
IGM temperature

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

Sub-GeV Dark Matter Landscape

- 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 of arXiv:2307.02207

- 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

  2. a renormalizable, UV complete extended Higgs sector spin-1 DM
     - Dark $SU(2) \times U(1)' \rightarrow X_3, Z'$ mediators and SIMP DM

     - Dark $SU(2) \rightarrow Z'$ mediator
       - where $m_{Z'} < 2m_X$, leading to off-shell DP production and visible signatures

ongoing work at Chalmers!

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

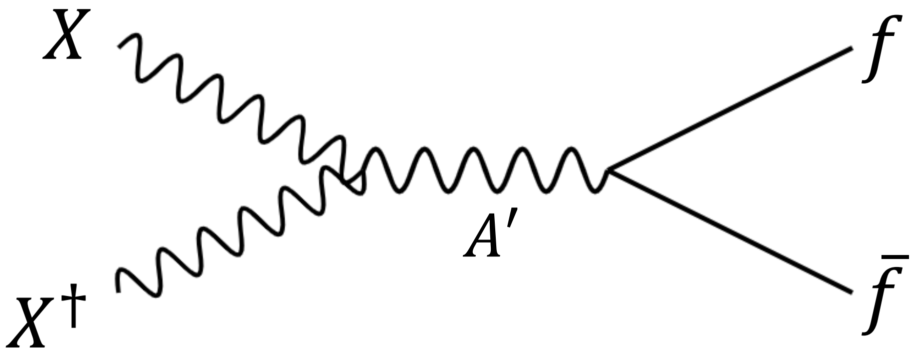
b_7: complex

h_3: real

$h_3 \equiv \epsilon e$

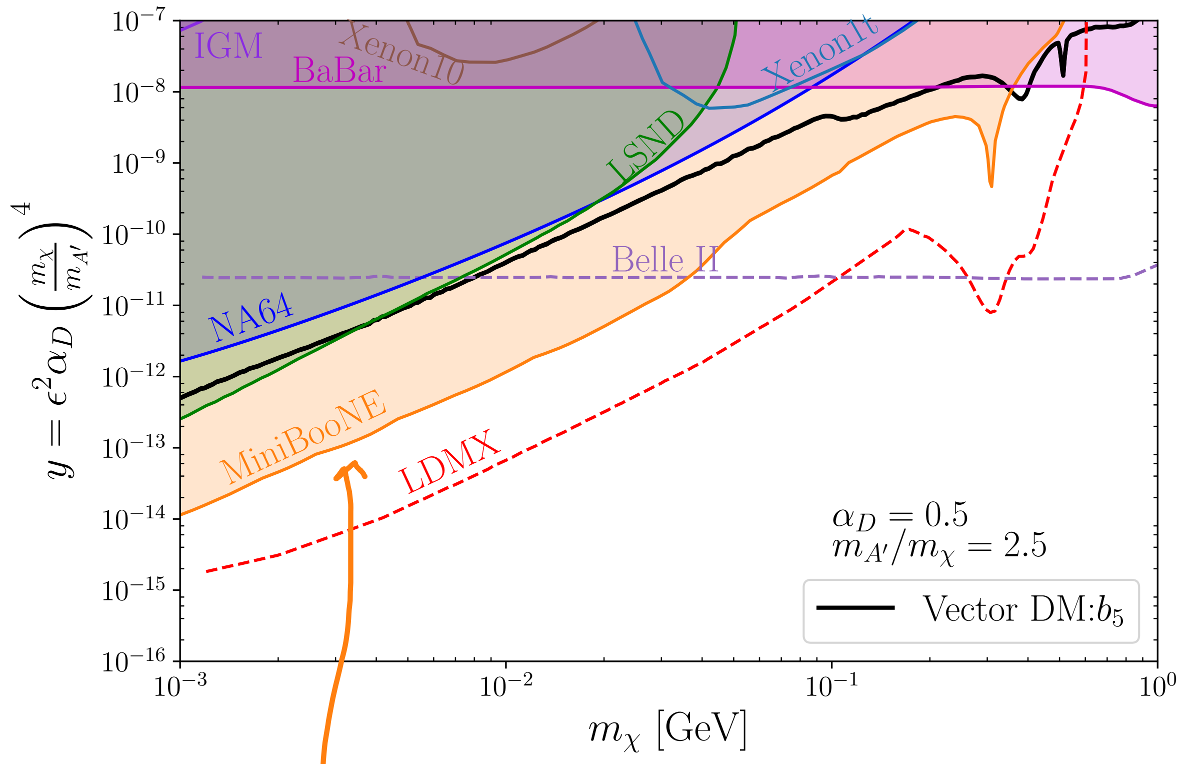
f: SM leptons and quarks

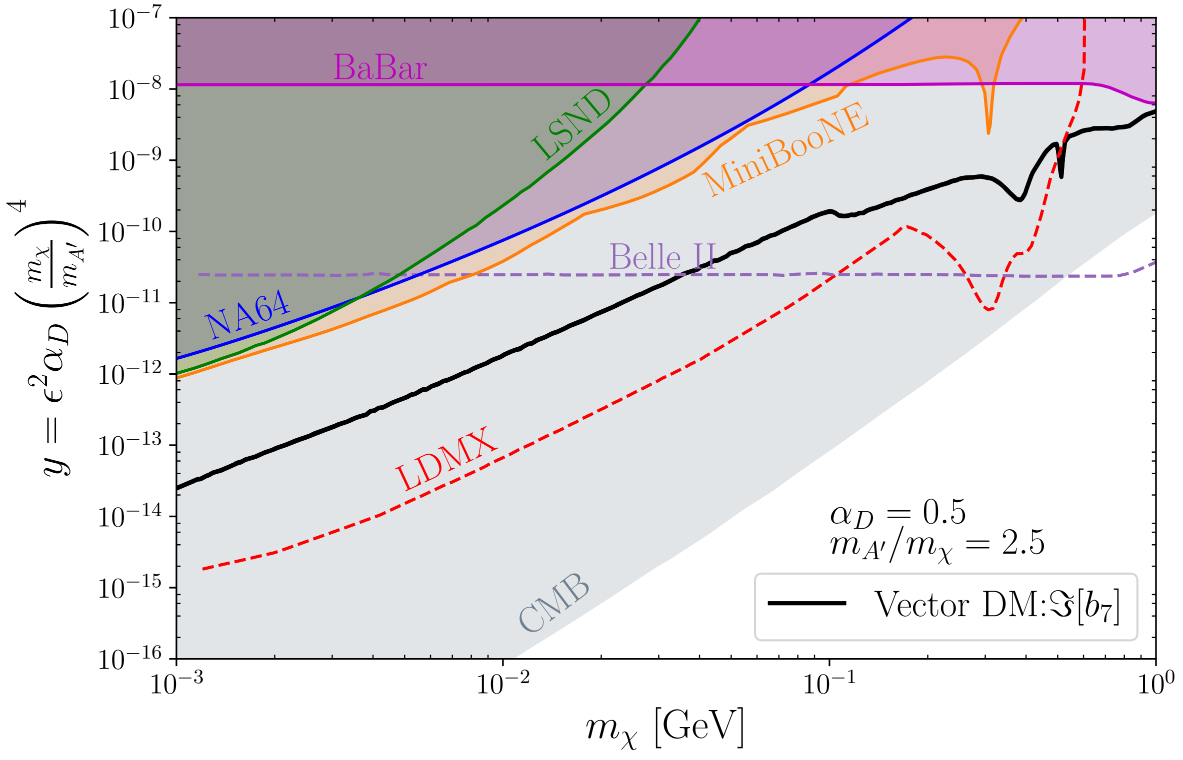
DM Freeze-Out



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

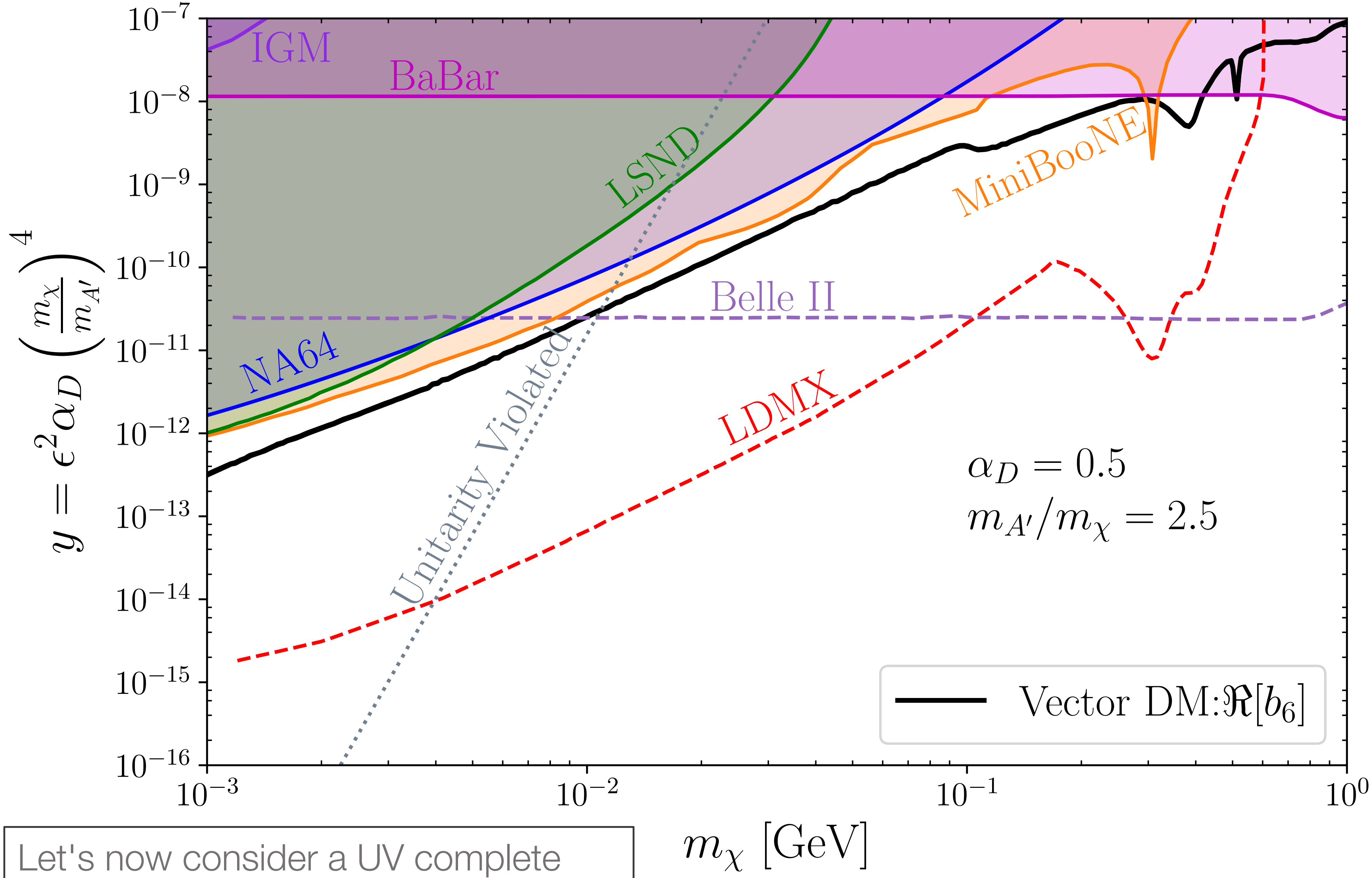
Strong Limits on Spin-1 Relic Targets





Large MiniBooNE limits due to large $\sigma_{\chi e^- \to \chi e^-}$ while m_χ is small

Ruled out by current experiments and CMB respectively..



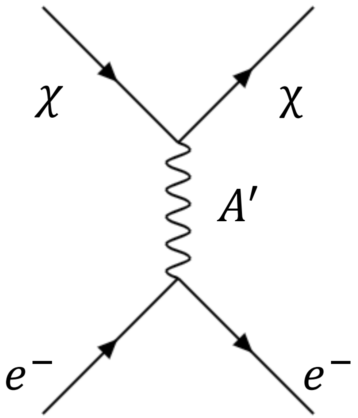
Spin-1 DM is the first to be probed by LDMX!

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

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.



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

- 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!

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

SIMP Spin-1 Dark Matter

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

with Z' and X_3 as mediators

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

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

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

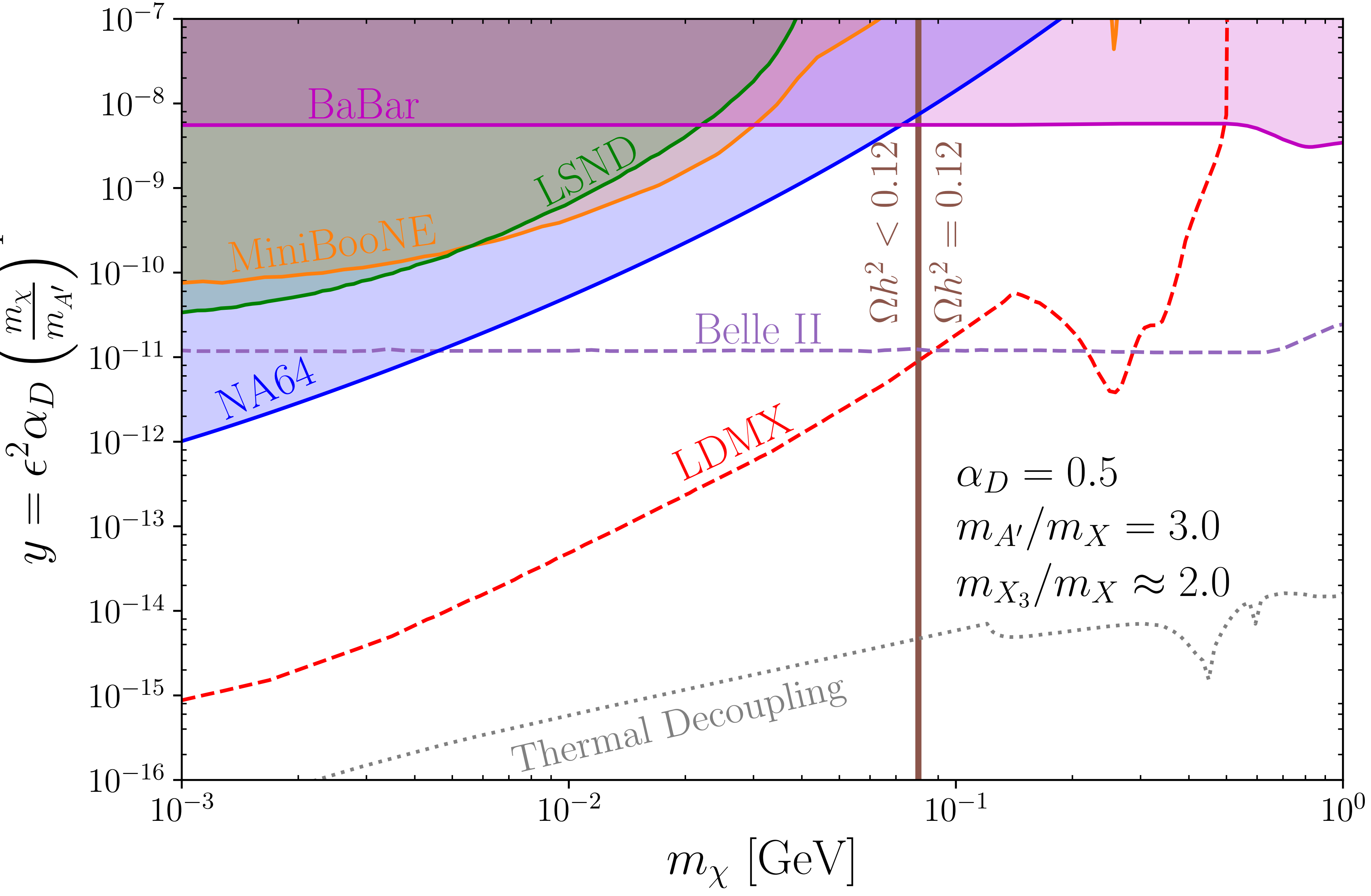
$\to$ mainly Z's are produced at fixed target experiments

processes setting the relic density $\to$

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

Dominant since $g_X \gg e\epsilon$

arXiv:1904.04109



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

Ωh^2 independent of ϵ, entire region (excluding TD region) consistent w Planck!

Global Fit of Sub-GeV Dark Matter with GAMBIT

In collaboration with: Sowmiya Balan, Csaba Balazs, Torsten Bringmann, Riccardo Catena, Timon Emken, Quan Huynh, Tomas Gonzalo, and Felix Kahlhoefer

Global Fits of sub-GeV DM

Many experiments with their own exclusion bounds.

If you approximate the combined exclusion bound as the intersection..

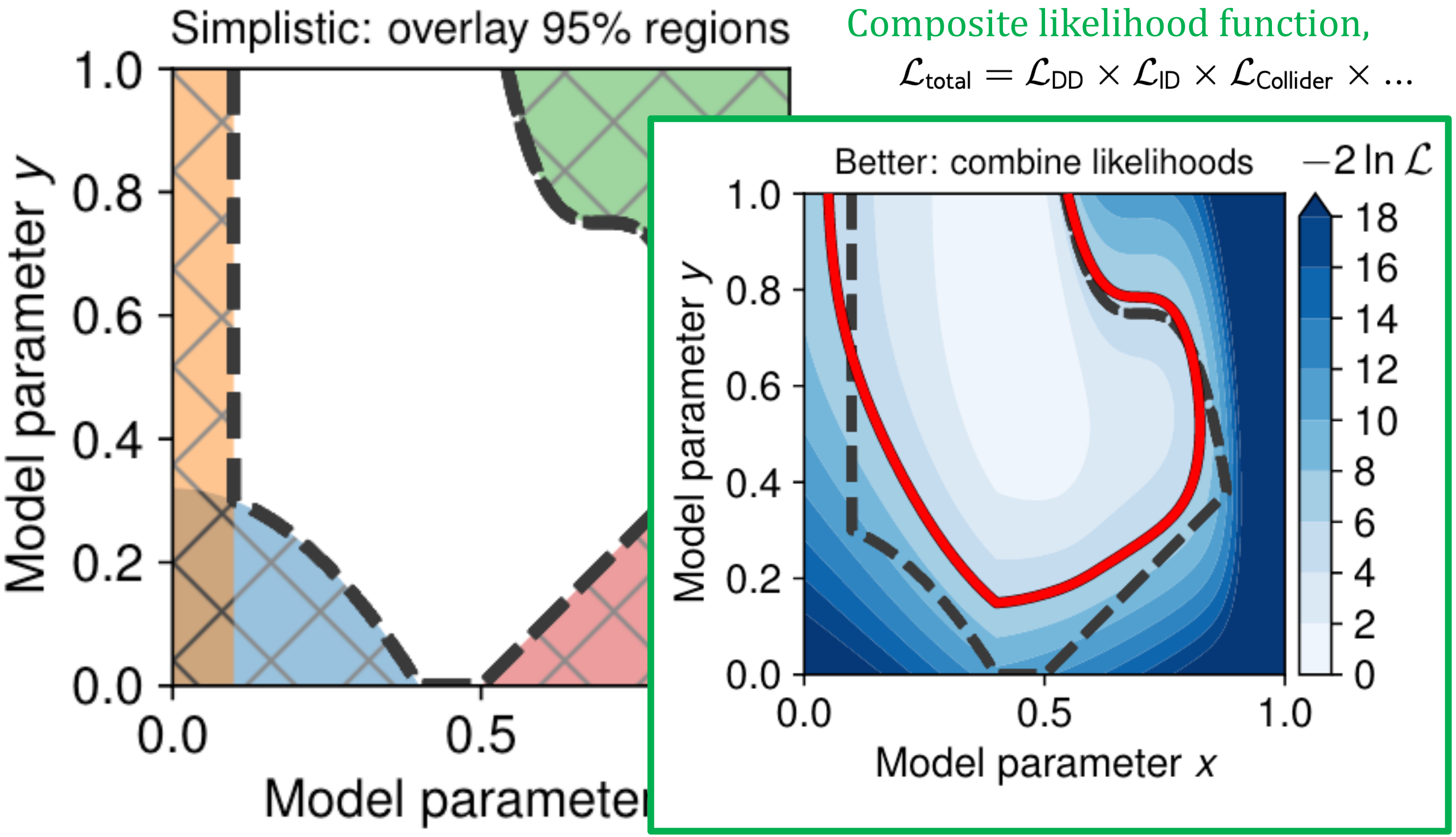
Error rate = $1 - 0.95^n$

Ex. 5 experiments,

- error rate $= 1 - 0.95^5 = 23\%$
- falsely reporting 95% C.L.

Composite likelihood function,

$$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{DD}} \times \mathcal{L}_{\text{ID}} \times \mathcal{L}_{\text{Collider}} \times \ldots$$



Global Fits of sub-GeV DM

Likelihoods we consider:

- Cosmological
  - Relic density
  - BBN
  - Exotic energy injection (CMB)
- Astrophysical
  - X-ray
  - Bullet cluster

Relic density

Gaussian likelihood centred at calculated value by **DarkSUSY**, evaluated at

$$\Omega_{\rm DM,obs}h^2 = 0.120 \pm 0.001$$

arXiv: 1705.07920

BBN

DM can give a contribution to the total energy density, altering H. **AlterBBN** package for calculating effects of DM annihilations

arXiv: 2009.03286

X-ray

X-rays from DM annihilations

$$\mathrm{DM\,DM} \to e^+e^-,$$
$$\mathrm{DM\,DM} \to \mu^+\mu^-,$$
$$\mathrm{DM\,DM} \to \pi^+\pi^-,$$

Measured by INTEGRAL telescope

arXiv: 2007.11493

Bullet cluster

$DM\ DM\ \to DM\ DM$ interactions constrainted by colliding cluster

arXiv: 1605.04307

Global Fits of sub-GeV DM

Likelihoods we consider:

- Beam dump / Fixed targets
- Direct detection
- Colliders

Poisson likelihood:

$$\mathcal{L} = \frac{e^{-(s+b)}(s+b)^n}{n!}.$$

Fixed targets

# of signal events simulated w **BdNMC** for,
- LSND
- Mini-BooNE

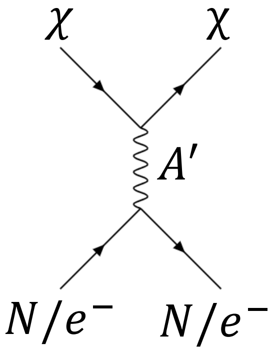
And # events calculated for,
- NA64 (from recent NA64 results)

FUTURE:
- LDMX

arXiv:1609.01770

Direct detection

obscura software for direct DM searches via nuclear and electron recoils
- XENON1T
- SENSEI
- CRESST-III
- and more..



arXiv:2112.01489

Colliders

- BaBar

FUTURE:
- Belle-II
- Visible decays

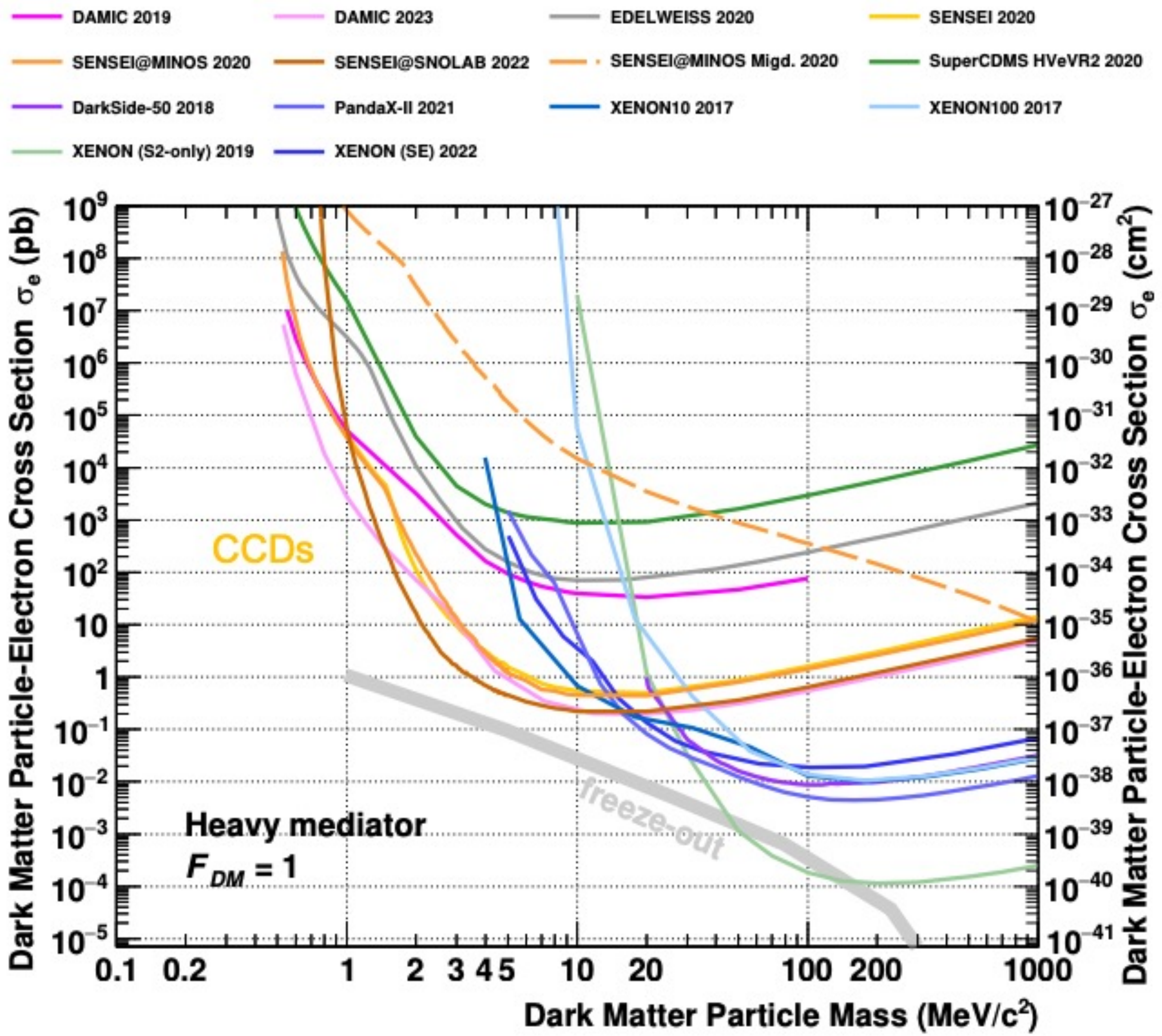
Summary

- Extending the current landscape of sub-GeV DM models considered in the context of fixed target experiments
- Spin-1 sub-GeV DM
  - where $m_{A'} > 2m_X$
- Global fits for sub-GeV DM including fixed target experiments

Future

- Ongoing work with
  - additional Vector DM models
  - sub-GeV GAMBIT scans including LDMX likelihood
- Spin-1 DM models with dark dipole dark photons

Backup Slides


DAMIC 2019
DAMIC 2023
EDELWEISS 2020
SENSEI 2020
SENSEI@MINOS 2020
SENSEI@SNOLAB 2022
SENSEI@MINOS Migd. 2020
SuperCDMS HVeVR2 2020
DarkSide-50 2018
PandaX-II 2021
XENON10 2017
XENON100 2017
XENON (S2-only) 2019
XENON (SE) 2022
Dark Matter Particle-Electron Cross Section σ_e (pb)
Dark Matter Particle-Electron Cross Section σ_e (cm^2)
Dark Matter Particle Mass (MeV/c^2)
CCDs
freeze-out
Heavy mediator
F_{DM} = 1

SIMP spin-1 DM

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

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

- 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

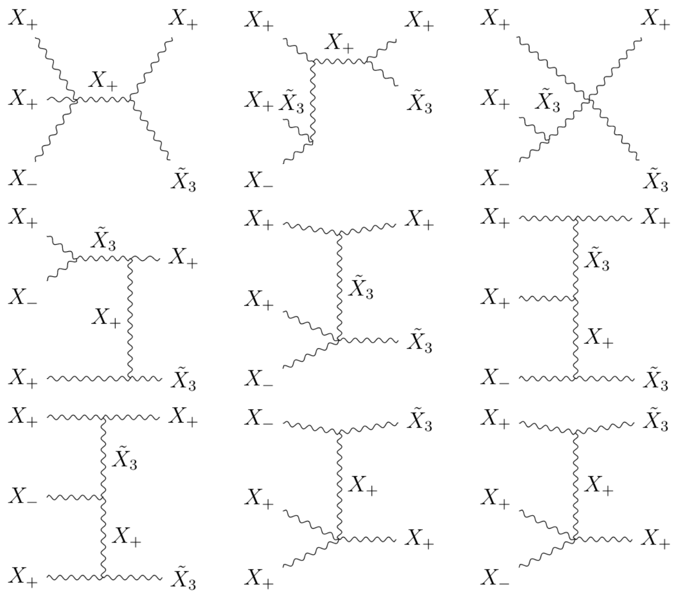


Figure 1: Feynman diagrams for $X_+X_+X_- \to X_+\tilde{X}_3$.

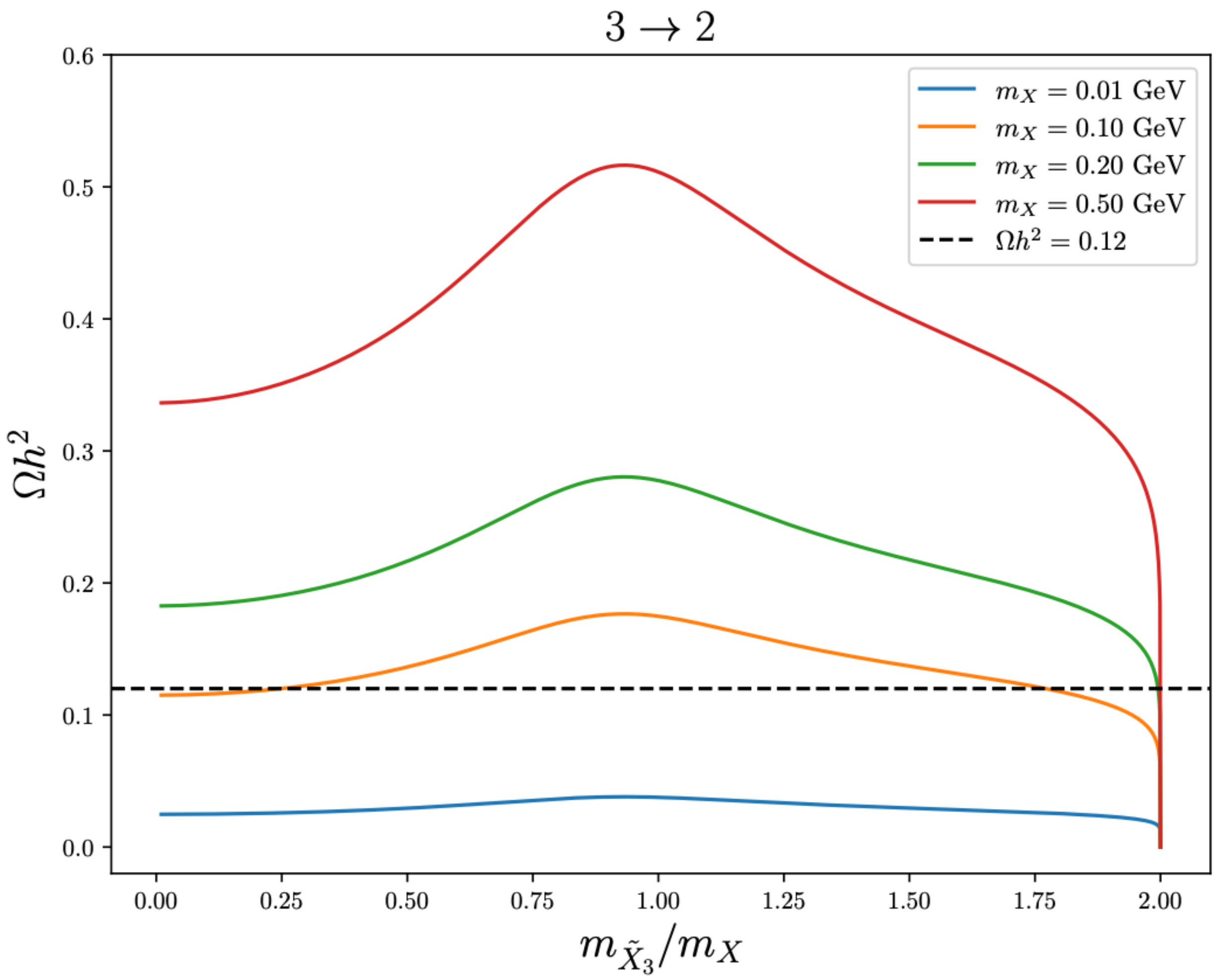
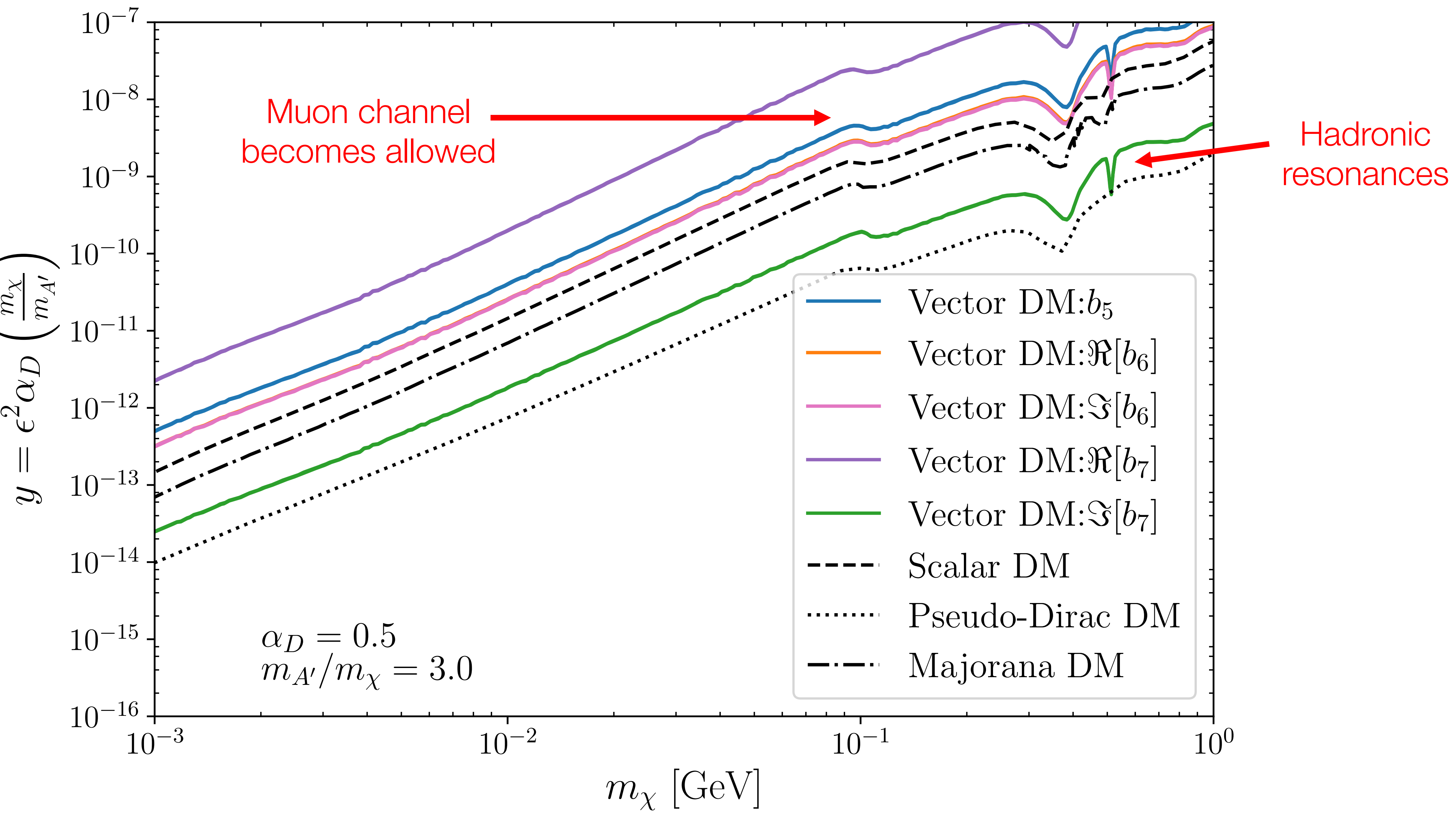


Figure 2: DM relic abundance, Ωh^2, as a function of m_X and $m_{\tilde{X}_3}/m_X$ for SIMP DM thermally produced by the freeze-out of $3 \to 2$ processes. Here we take $\alpha_D = 0.5$. The horizontal dashed line corresponds to the observed value of Ωh^2. Coloured lines have been obtained by evaluating Eq. (40) from [24].

Relic Targets of DM Models



Calculating Dark Matter Abundance

The Boltzmann Equation

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

Universe's Expansion → $3H$; Particle Physics → R

- 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
    - $Y \equiv \frac{n}{s}$, $x \equiv \frac{m}{T}$
    - s: entropy density

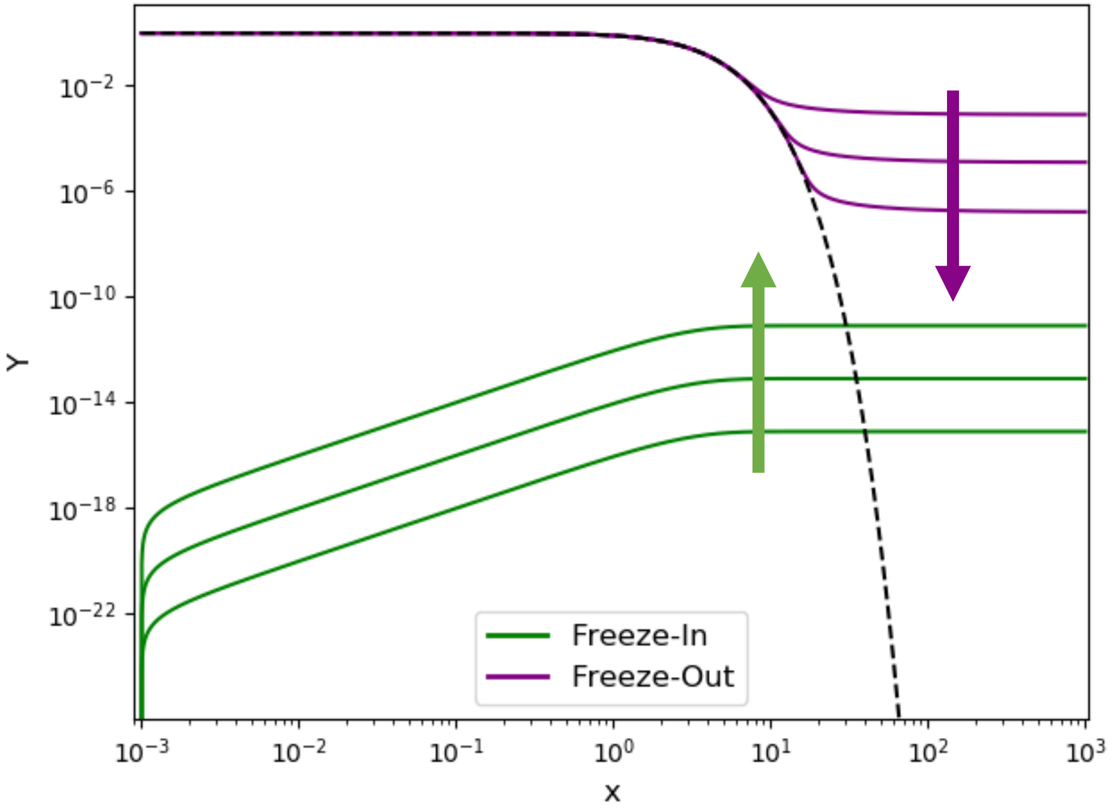
Ways of Producing Dark Matter

Γ: Interaction Rate (# interactions per time)

H: Hubble Rate (universe's expansion rate)

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

This work!



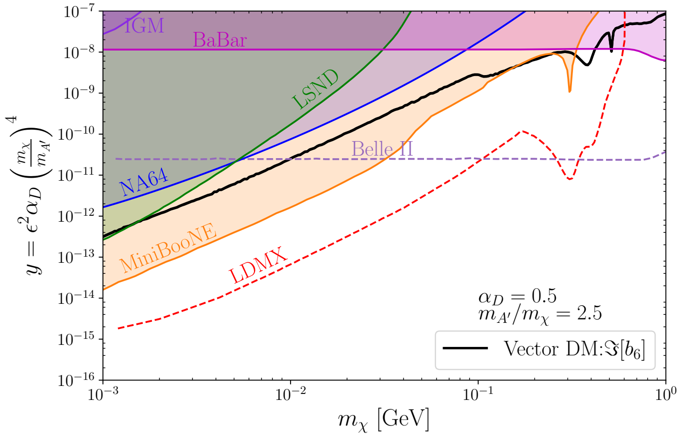
→ Increasing Coupling

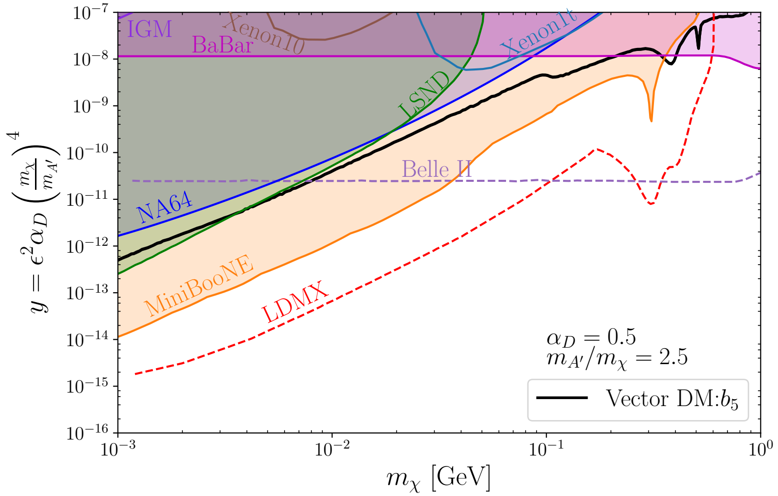
Hadronic Resonances

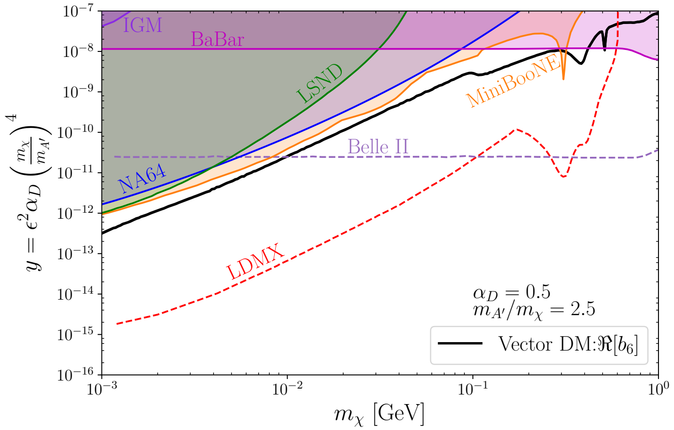
- If DM freezes-out after the QCD phase transition (~150 MeV), DM annihilates to hadronic final states rather than to quarks.
  - Must consider for $m_X \lesssim 3 GeV$

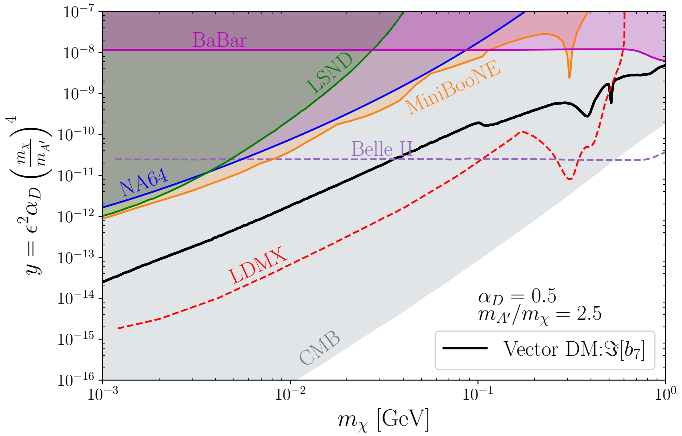
$$\sigma v_{XX \to A' \to \mathrm{hadrons}} \approx R(s) \sigma v_{XX \to A' \to \mu^- \mu^+}$$

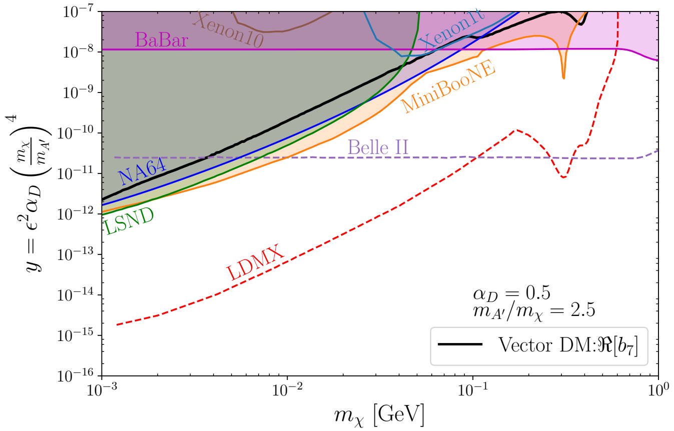
$$R(s) \equiv \sigma_{e^+ e^- \to \mathrm{hadrons}} / \sigma_{e^+ e^- \to \mu^+ \mu^-}$$


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
BaBar
Xenon10
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
BaBar
LSND
MiniBooNE
Belle II
NA64
LDMX
$\alpha_D = 0.5$
$m_{A'}/m_\chi = 2.5$
Vector DM:$\Re[b_6]$
$y = \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$
m_χ [GeV]


BaBar
LSND
MiniBooNE
Belle II
NA64
LDMX
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]


BaBar
Xenon10
Xenon1t
MiniBooNE
Belle II
NA64
LSND
LDMX
$\alpha_D = 0.5$
$m_{A'}/m_\chi = 2.5$
Vector DM:$\Re[b_7]$
$y = \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$
m_χ [GeV]

Confidence Intervals

(I'm sorry to the Bayesian statistics supporters in the audience)

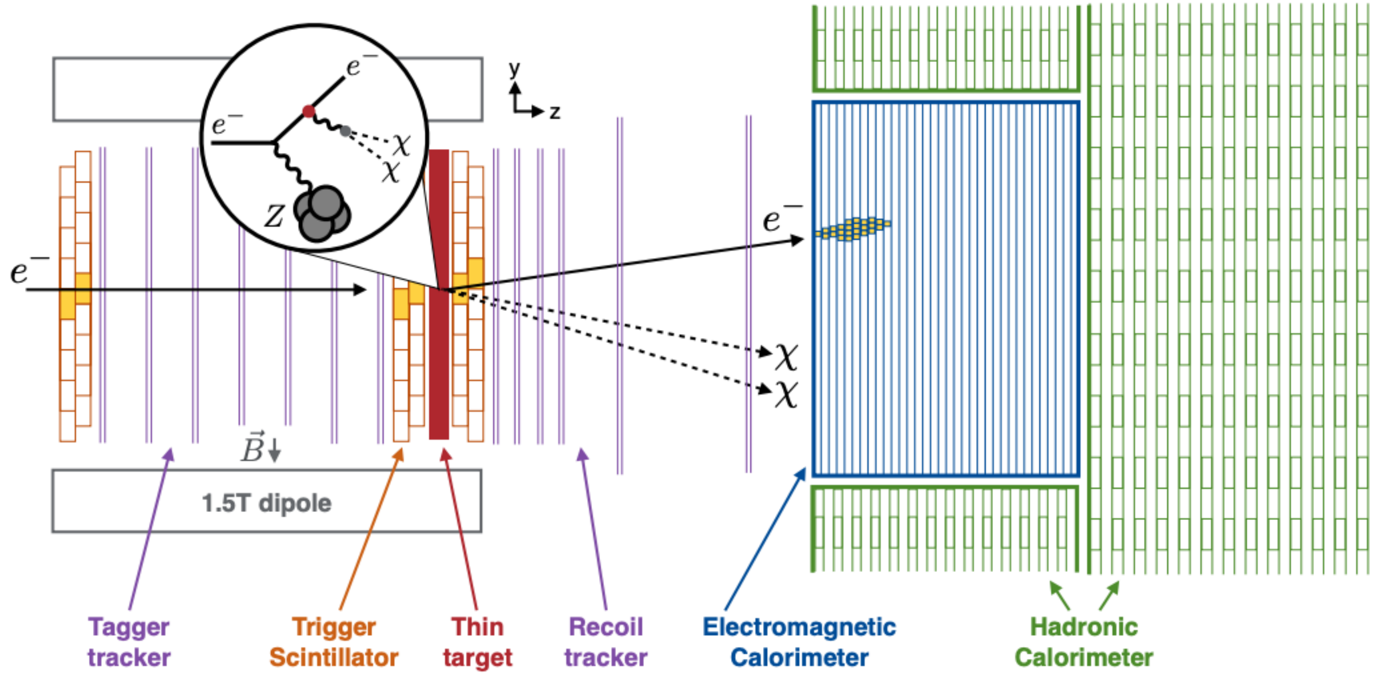
- x% CL: If experiment is repeated many times, the intervals include the true parameter x% of the time
- Counting experiment, take Poisson distribution: $f(n;\nu) = \frac{\nu^n}{n!} e^{-\nu}$

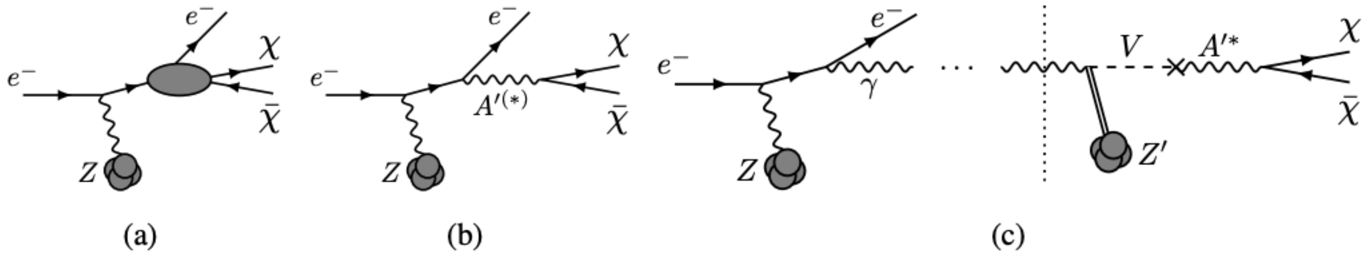
- Uncertainty on number of background events
    - Neutrino flux, NCE cross section model ($\sigma_{\nu N \to \nu N}$), detector response
    - Nuisance parameters introduced

Experiments

Light Dark Matter eXperiment (LDMX)

- Future fixed target missing momentum exp
  - 2025: LESA delivers beam to LDMX allowing $4{\times}10^{14}$ 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



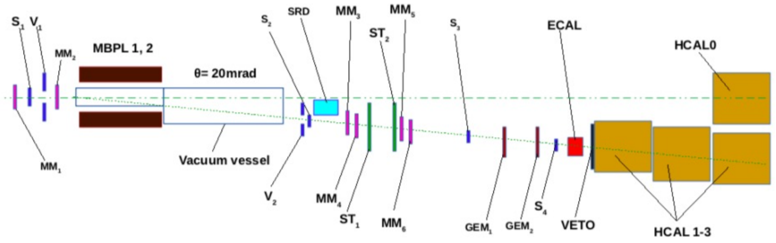


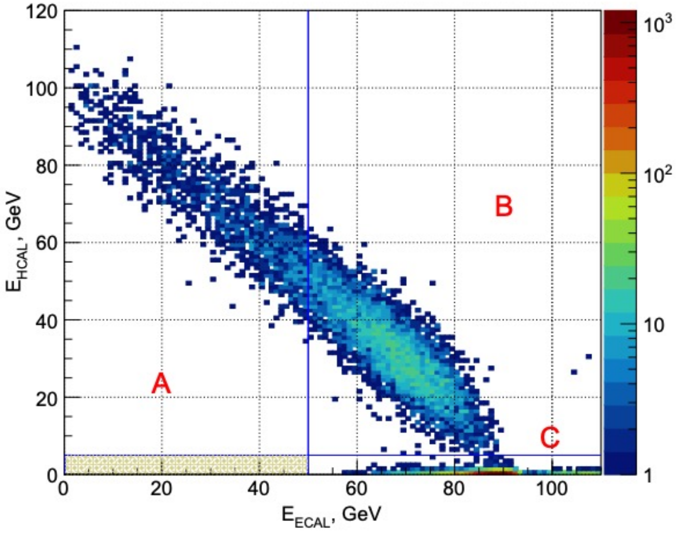
Electron Beam Dumps

NA64

arXiv:1710.00971

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

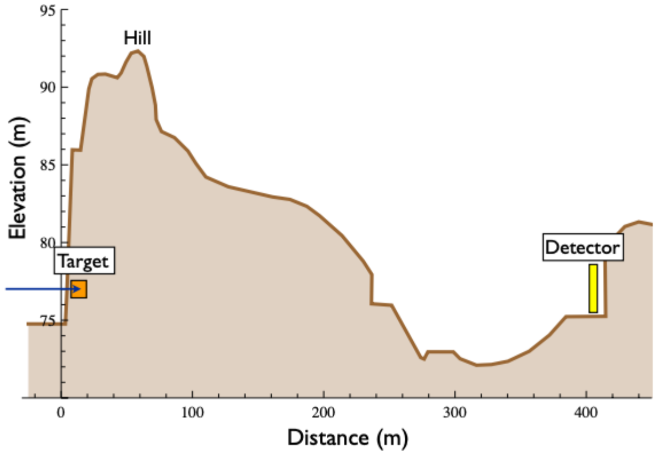


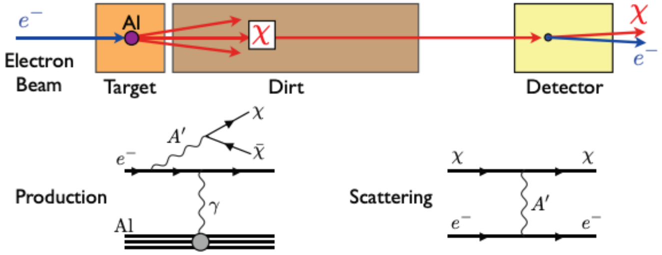


E137

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
- $\pi^0 \rightarrow A'\gamma, A' \rightarrow XX$

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)

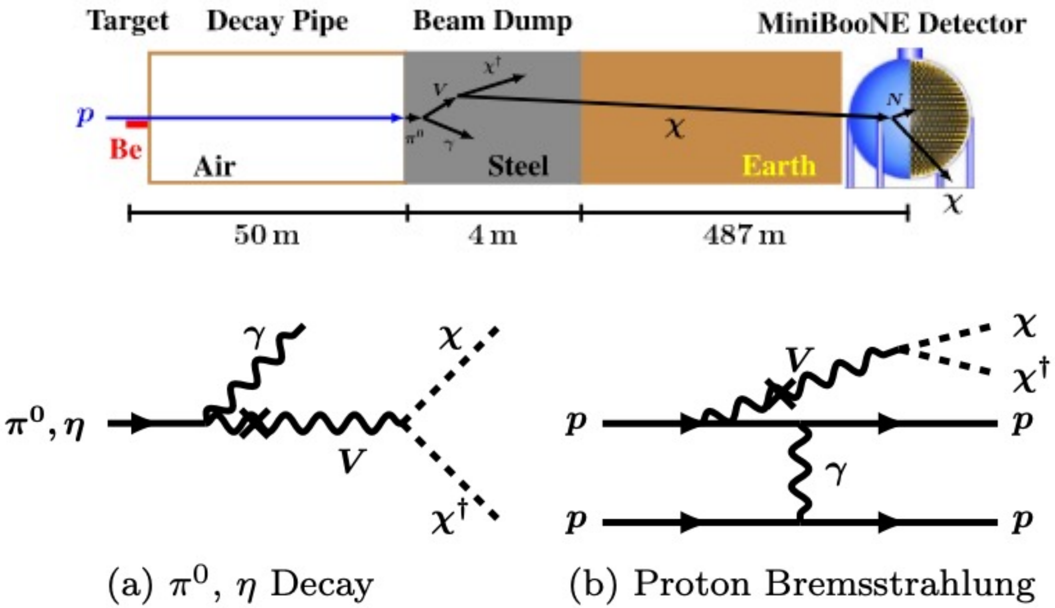


FIG. 2. DM production channels relevant for this search with an 8 GeV proton beam incident on a steel target.

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

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

BABAR

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