Searching for Vector Dark Matter at Fixed Target Experiments

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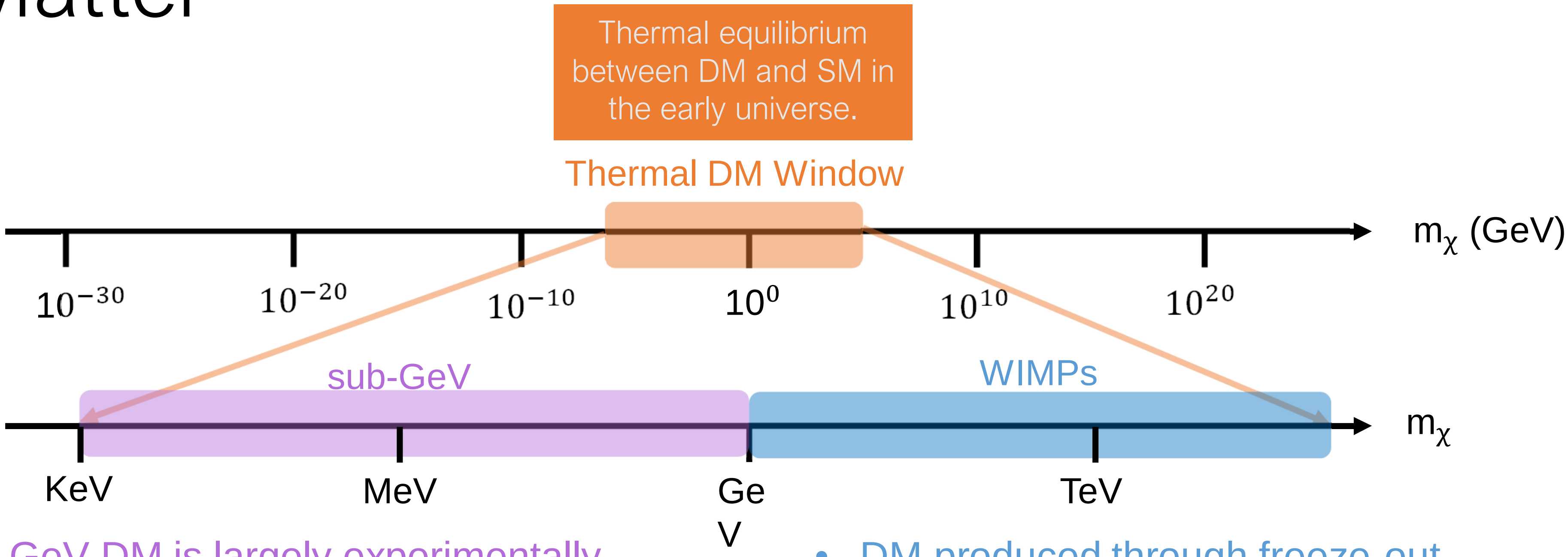
X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

Sub-GeV Dark Matter


Thermal equilibrium between DM and SM in the early universe.

Thermal DM Window

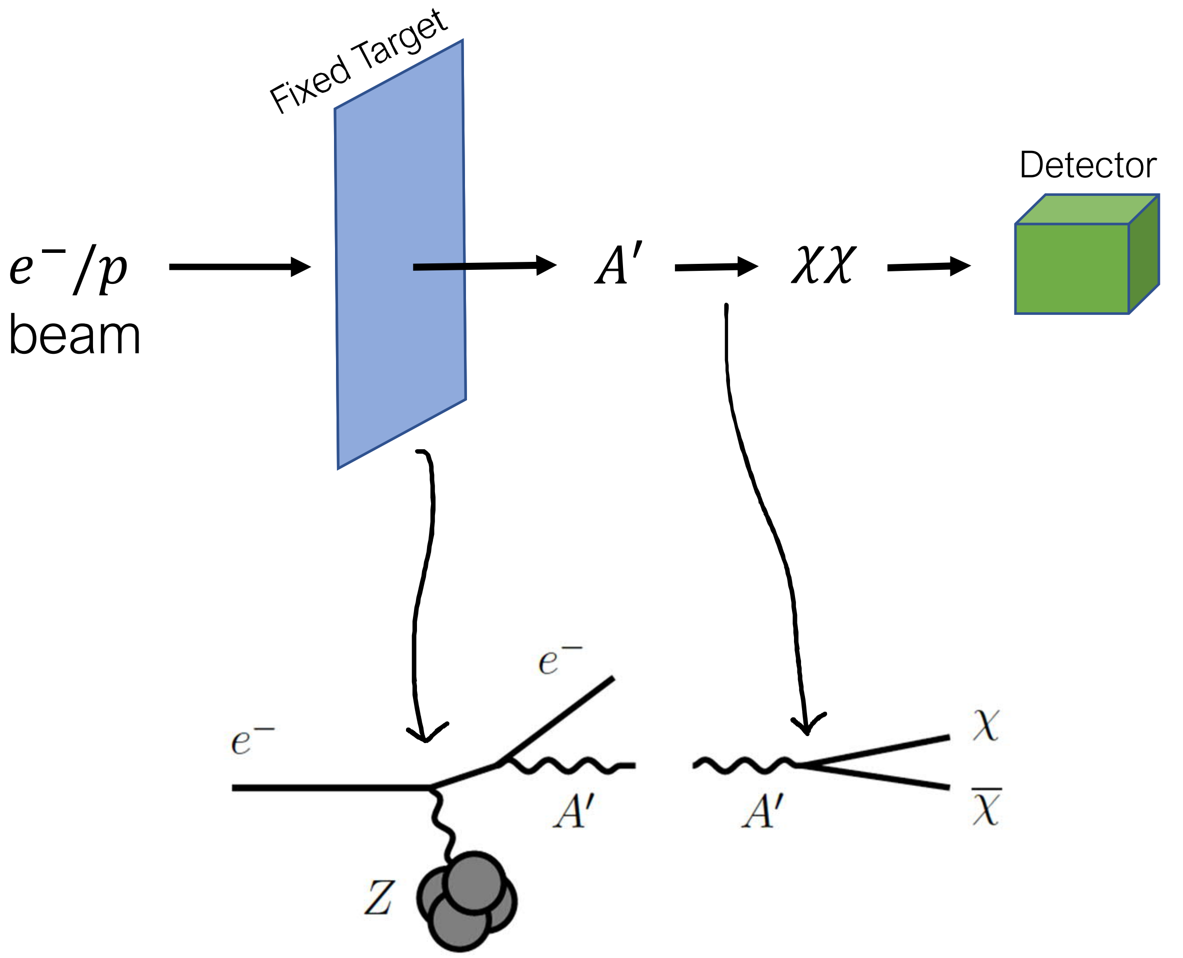
- Sub-GeV DM is largely experimentally **unexplored**..
  - Out of reach of nuclear recoil direct detection exps

- DM produced through freeze-out near weak scale

- GeV-TeV scale thermal DM already widely tested

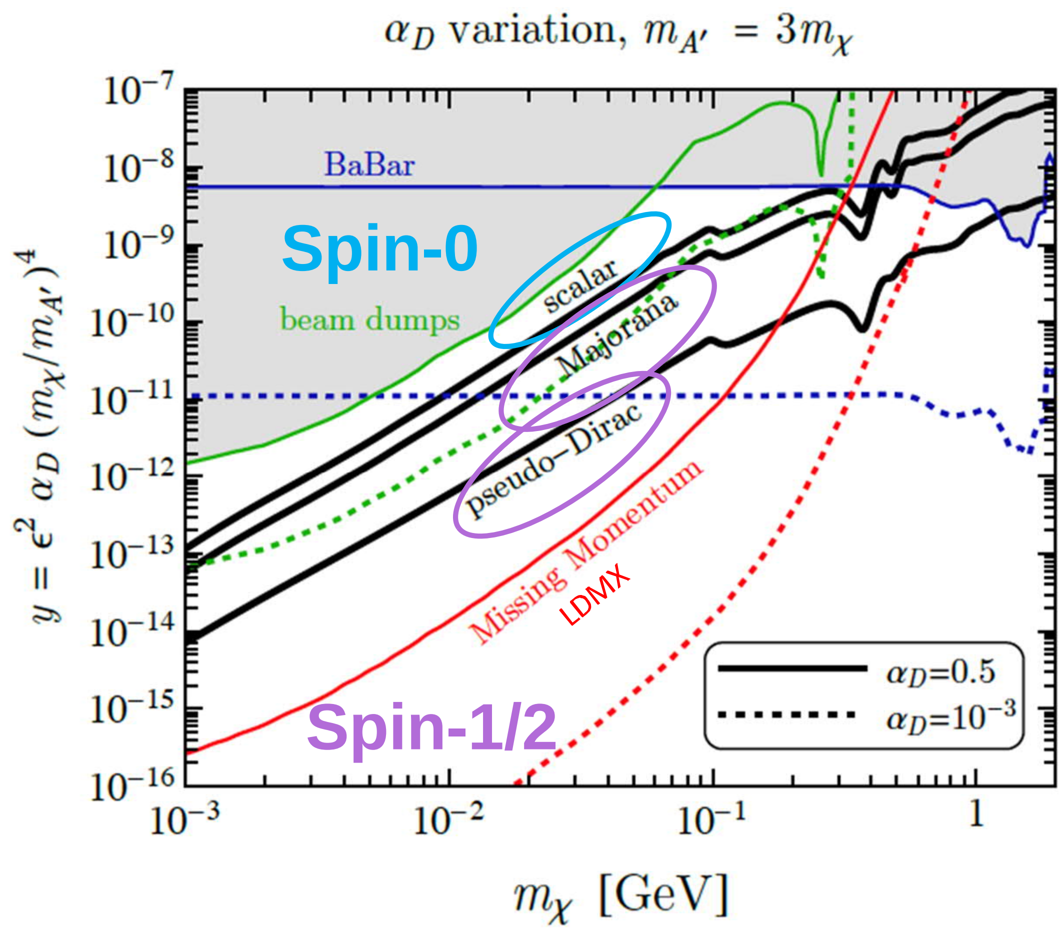
Sub-GeV Dark Matter

- 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.



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

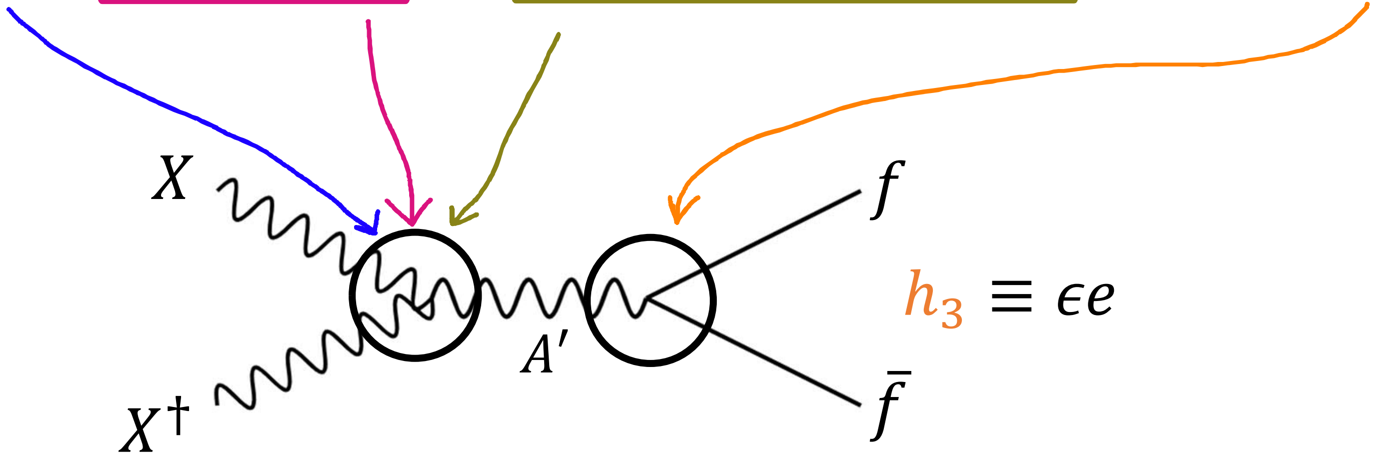
The Goal

- Broaden the already existing studies on sub-GeV DM at fixed target experiments.
- Extend the SM with the most general renormalizable spin-1 DM model compatible with Lorenz and Gauge symmetry.

Spin-1 Dark Matter

with a Dark Photon Mediator

$$-\mathcal{L} \supset \Big(\underbrace{i b_5 X^\dagger_\nu \partial_\mu X^\nu A'^\mu} + \underbrace{b_6 X^\dagger_\mu \partial^\mu X_\nu A'^\nu} + \underbrace{b_7 \epsilon_{\mu\nu\rho\sigma} \left(X^{\dagger\mu} \partial^\nu X^\rho \right) A'^\sigma} + h.c. \Big) + \underbrace{h_3 A'_\mu \bar{f} \gamma^\mu f}$$



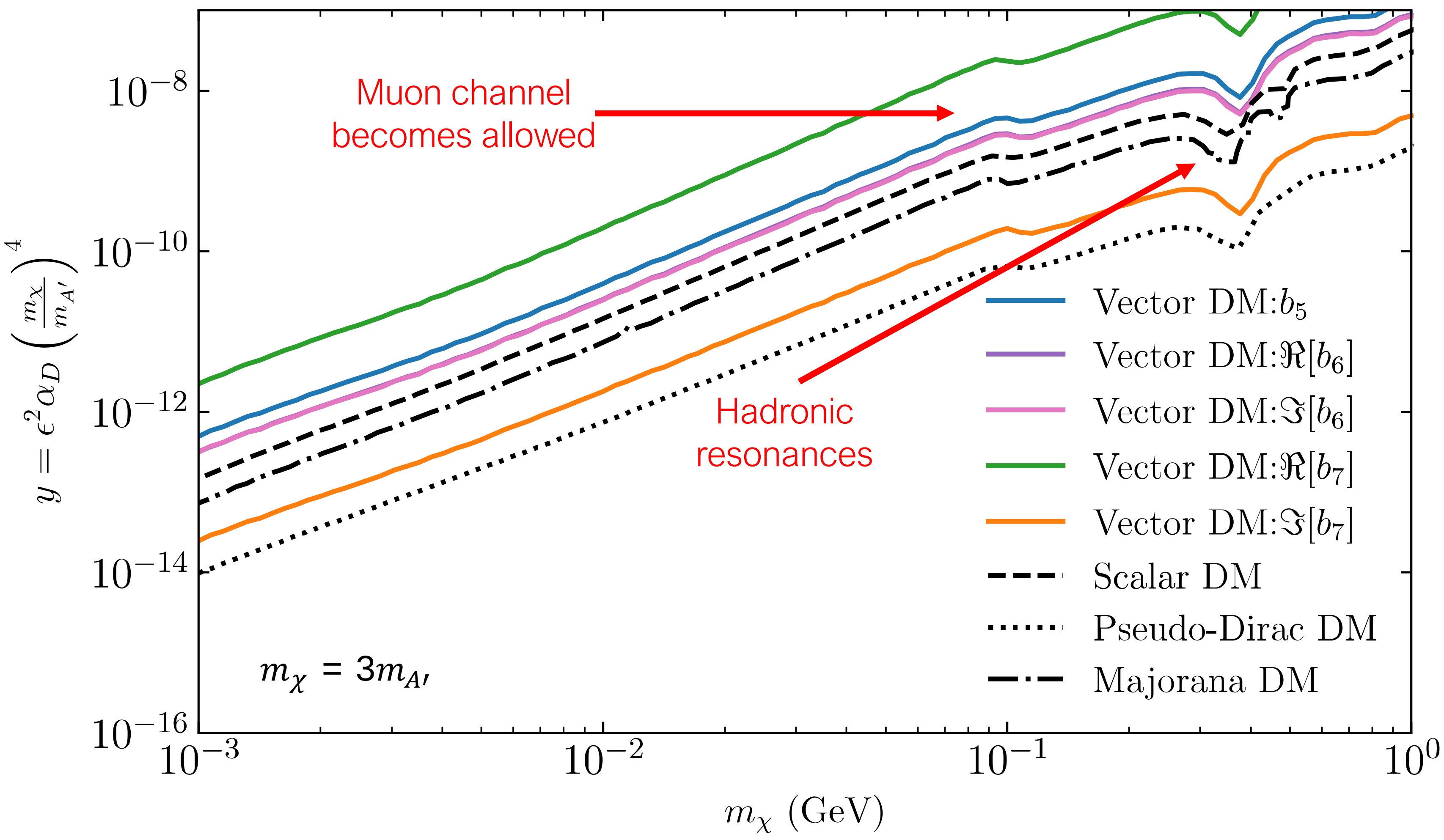
b_5: real
b_6: complex
b_7: complex
h_3: real

$h_3 \equiv \epsilon e$

f: SM leptons and quarks
(excluding neutrinos)

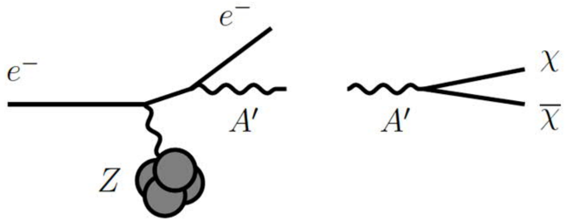
If $2m_X < m_A$, s-channel dominates DM annihilations.

Relic Targets of DM Models



Limits/Projections

Electron Bremsstrahlung + (In)Visible Decay



LDMX

- Missing Energy/Momentum
- arXiv:1808.05219

SLAC E137

arXiv:1406.2698

NA64

arXiv:1906.00176

Proton Beam Dumps with Downstream DM Detector

LSND

arXiv:1107.4580

Mini-Boone

arXiv:1702.02688

BaBar

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

arXiv:1702.03327

Energy Injection

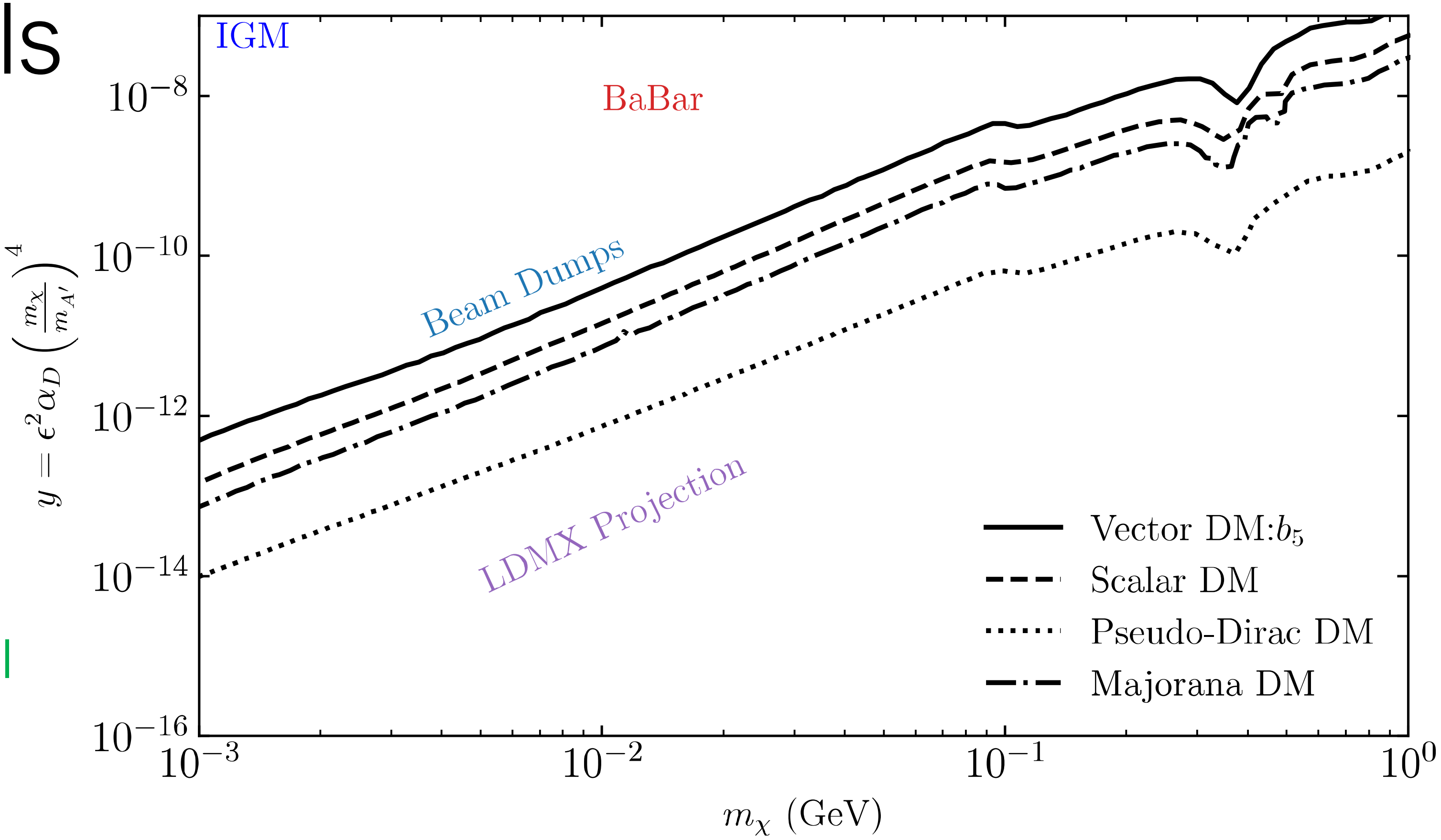
- Injection of EM particles into the universe during its early history leads to changes in CMB anisotropies and the IGM.

Direct Detection

- $Xe^- \rightarrow Xe^-$
- SENSEI, XENON, CRESST II
- In progress

Experimental Limits/Projections on DM Models

only b_5 non-zero



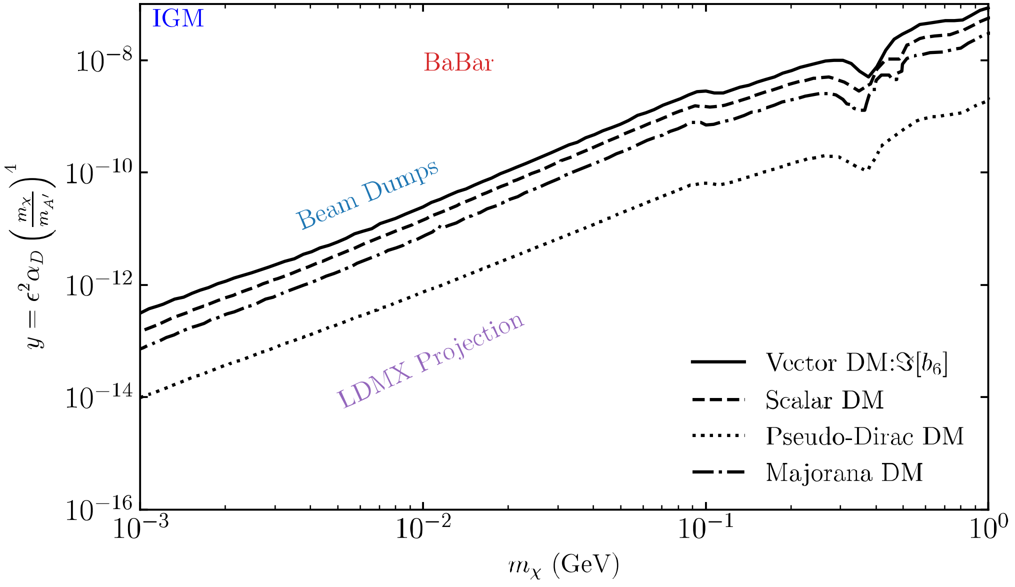
LDMX projection

- 10% radiation length tungsten target
- 8 GeV electron beam
- 10^{16} EOT

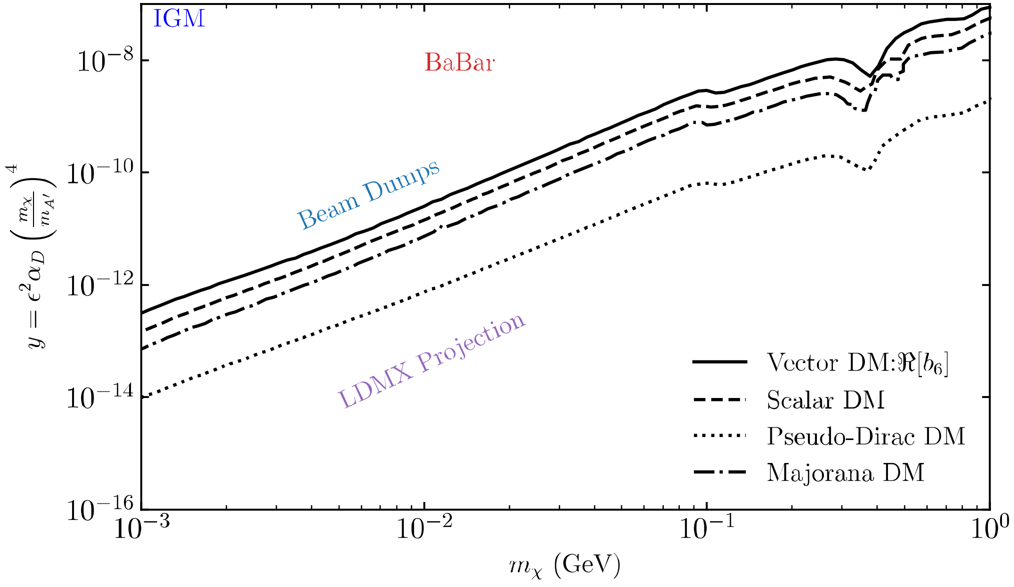
Vector DM is the first model to be probed by LDMX!

Experimental Limits/Projections on DM Models

only $\Im[b_6]$ non-zero



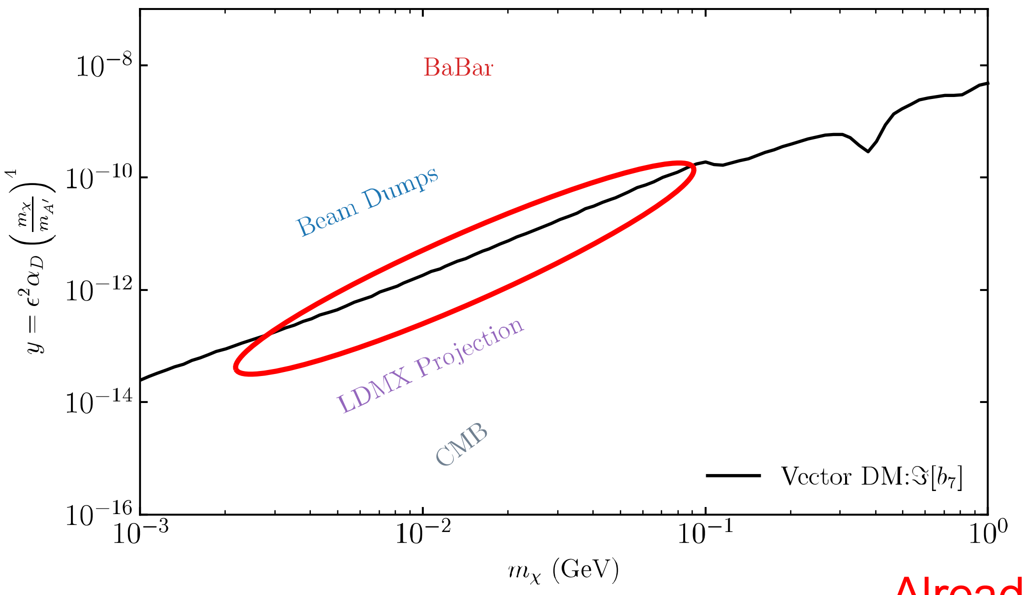
only $\Re[b_6]$ non-zero



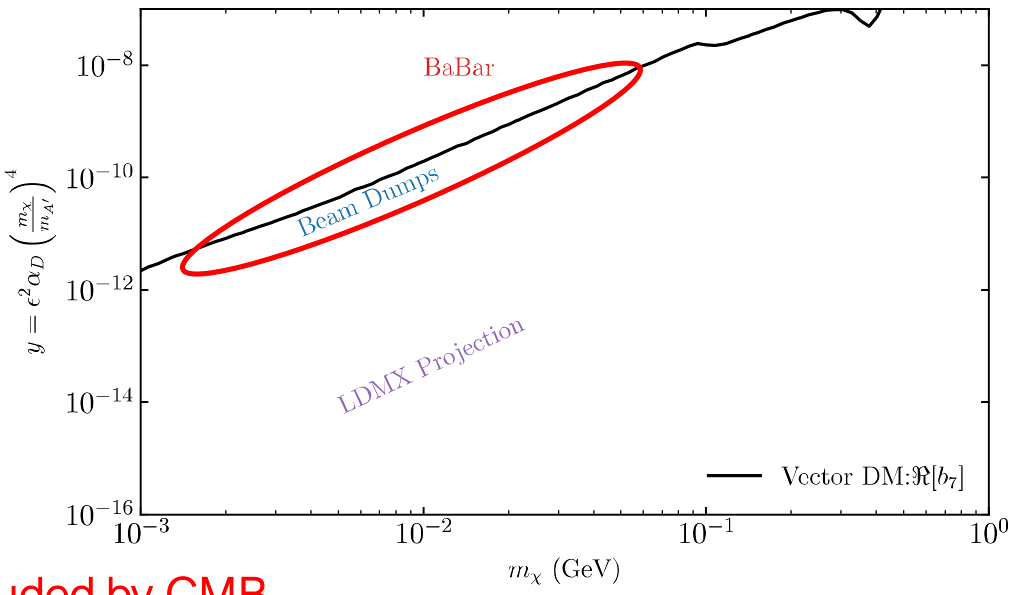
First models to be probed by LDMX!

Experimental Limits/Projections on DM Models

only $\Im[b_7]$ non-zero



only $\Re[b_7]$ non-zero



Already Excluded by CMB
and current beam dumps!

Summary and Future Work

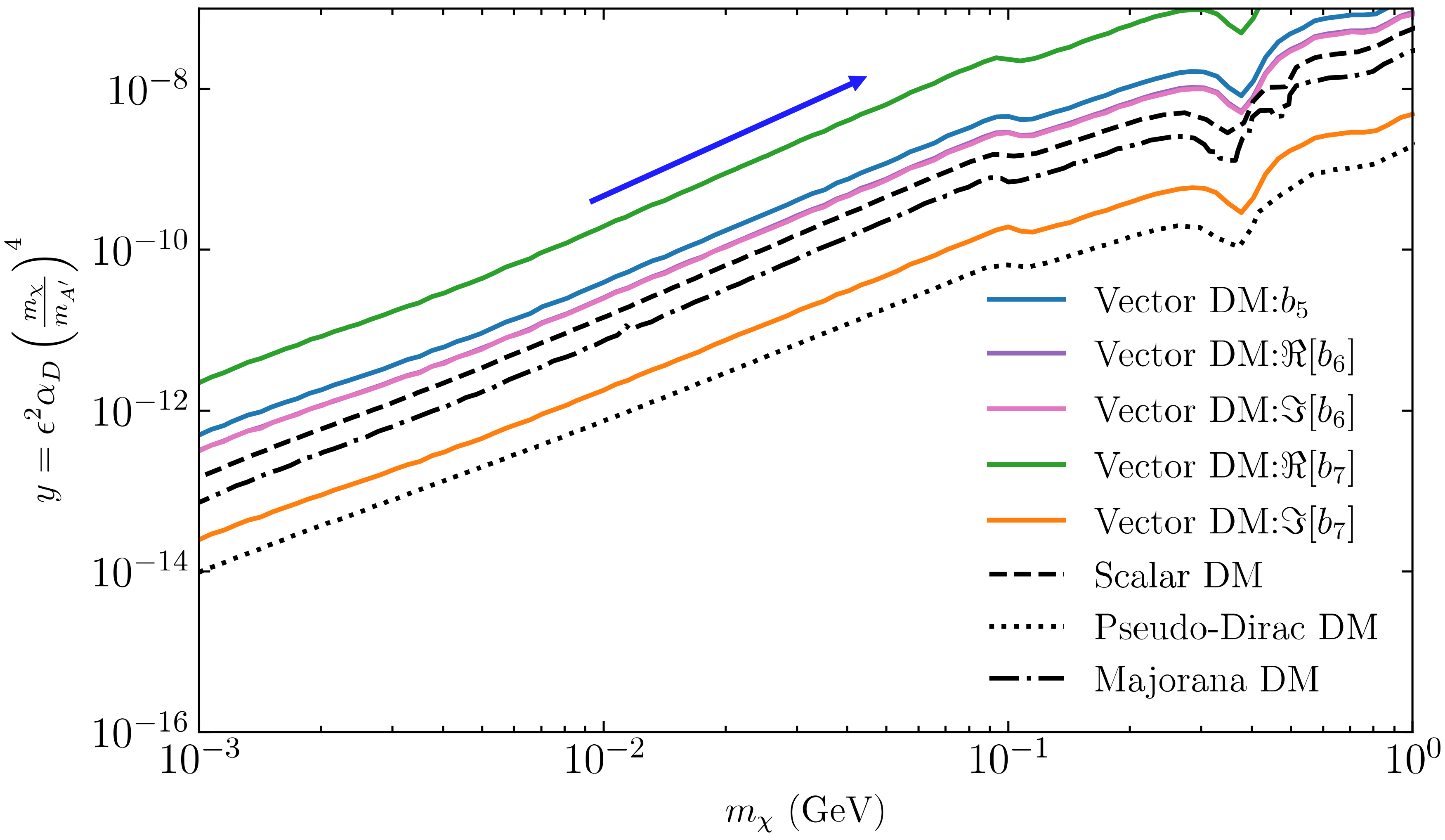
- **Extending** the current landscape of **sub-GeV DM models** considered in the context of **fixed target experiments** (such as **LDMX**) and more
- Focused on **spin-1 sub-GeV DM** where $m_{A'} = 3m_X$
- Complementarity between experimental limits

- Off-shell dark photon ($m_{A'} < 2m_X$)
  - Visible decay limits
- Spin-1 DM w axial + vector boson mediator
- Freeze-in spin-1 DM

Thank You!

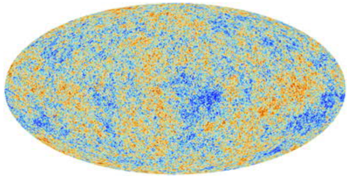
Backup Slides

- Larger DM mass → Larger relic abundance → Larger couplings



Relic Target Calculation

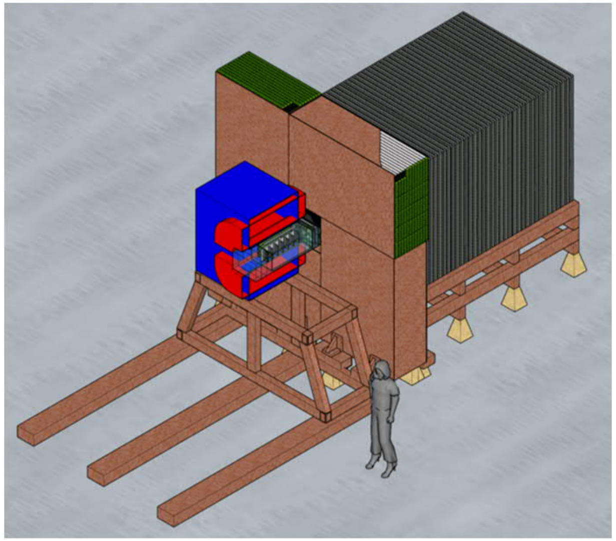
- DM relic abundance consistent with Planck
  - $\Omega h^2 \approx 0.12$



- Assume DM is produced through freeze-out.
- $3m_X = m_{A'}$
- DM relic density dominantly set by on-shell s-channel A′ exchange:
  - $XX \rightarrow A' \rightarrow f\bar{f}$

Experimental Reach

- Place exclusion/projection bounds on parameter space.
  - Current + future experiments
  - Cosmological bounds



(LDMX)

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 $m_X \lesssim 3GeV$

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

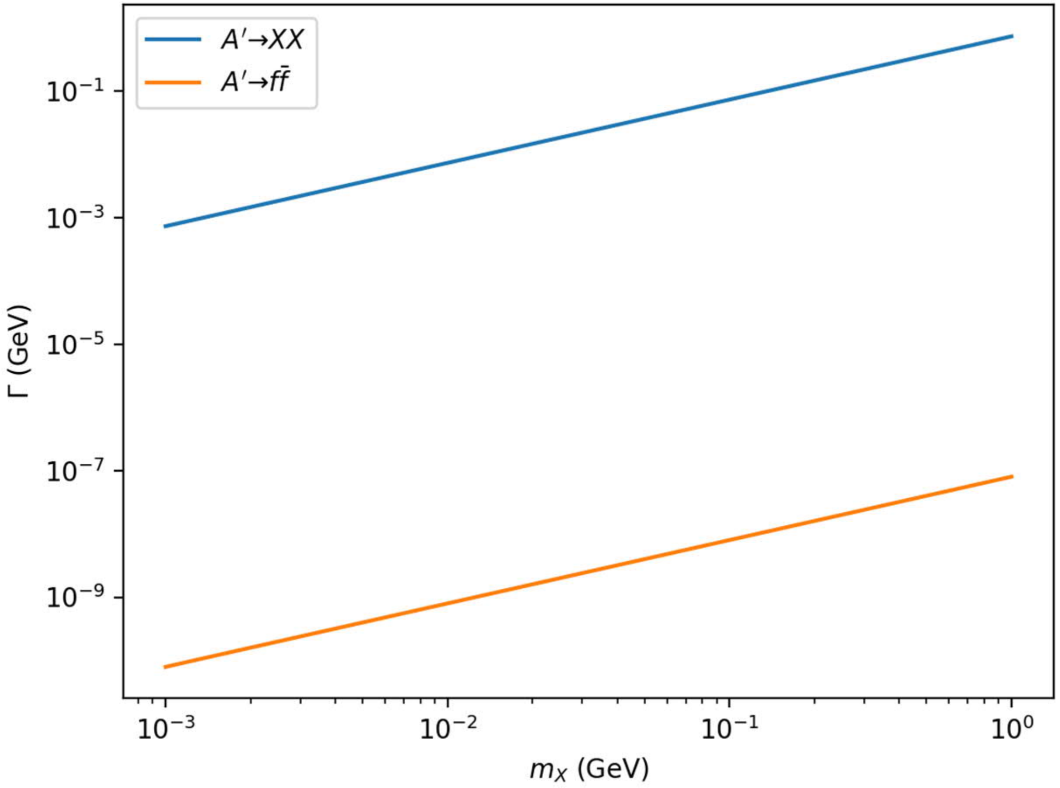
$$R(s) \equiv \sigma_{e^+e^-\to \mathrm{hadrons}}/\sigma_{e^+e^-\to \mu^+\mu^-}$$

Why $\mathrm{BR}_{\mathrm{A}'\to\mathrm{XX}} > \mathrm{BR}_{\mathrm{A}'\to\bar{\mathrm{f}}\mathrm{f}}$ is a good assumption

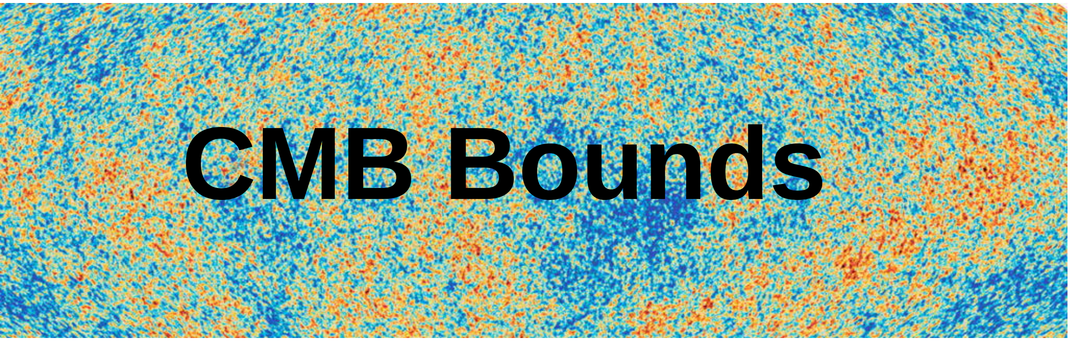
For $\alpha_D = 0.5, \frac{m_{A'}}{m_x} = 3, h_3 = 0.001$:

$BR_{A'\to XX} \approx 0.9999999$

$BR_{A'\to ff} \approx 1.1 \times 10^{-7}$



CMB Bounds

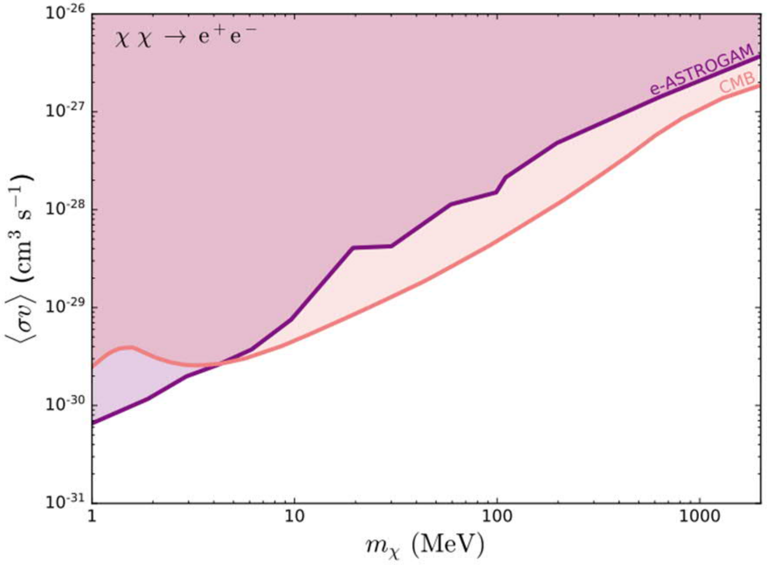


p-wave: arXiv:1308.2578
s-wave: arXiv:1506.03811

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

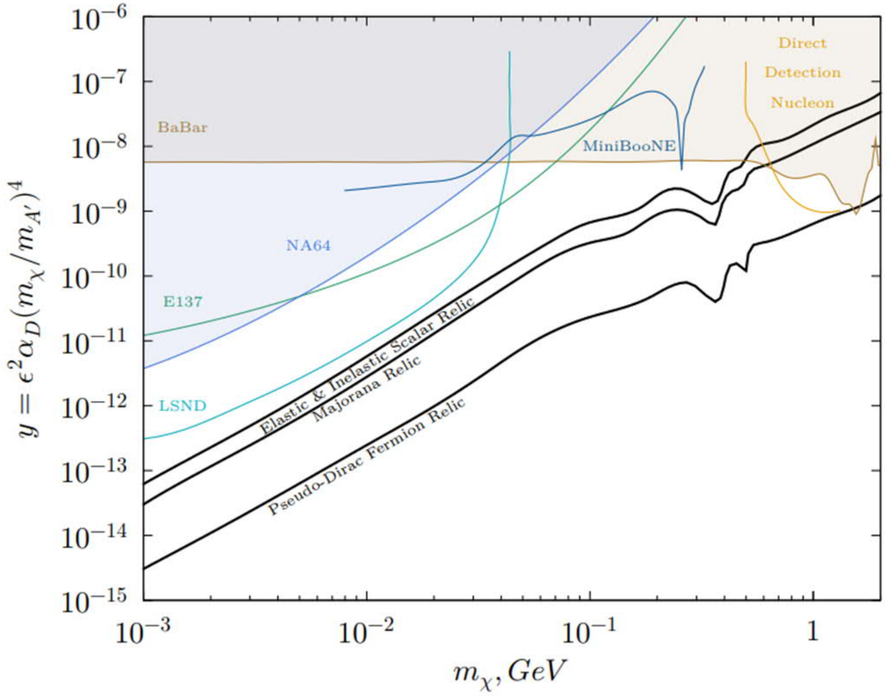
$$P_{ann} \lesssim 3.2 \times 10^{-28} cm^3 s^{-1} GeV^{-1}$$ (Planck 2018)

- CMB anisotropies measurements by Planck constrain the annihilation parameter, P_{ann}
- Limits are placed on DM annihilation under the assumption that the power deposited is directly proportional to that injected at the same redshift/energy.
  - with efficiency $f(z)$



arXiv:1801.05447

Electron Beam Dumps



E137

arXiv:1406.2698

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

NA64

arXiv:1710.00971

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

Proton Beam Dumps arXiv:1107.4580

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

Mini-Boone

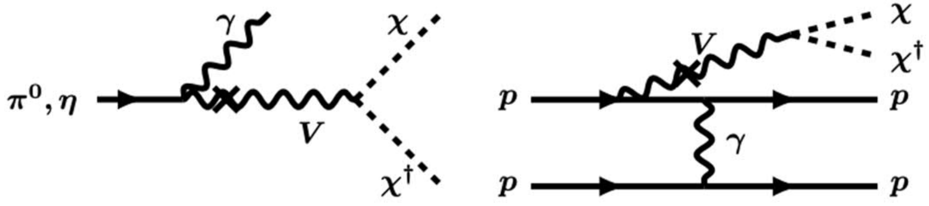
arXiv:1807.06137

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

LSND

arXiv:hep-ex/0101039

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



(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.

BaBar arXiv:1702.03327

- Search for single photon events in e^+e^- collision data
- BABAR detector at PEP-II B-factory
- Large missing energy/momentum
- Exclusions for $m_{A'} \leq 8$ GeV
- $e^+e^- \rightarrow \gamma A', A' \rightarrow XX$

Calculating Dark Matter Abundance: The Boltzmann Equation

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

Universe's Expansion → $3H$

Particle Physics → R

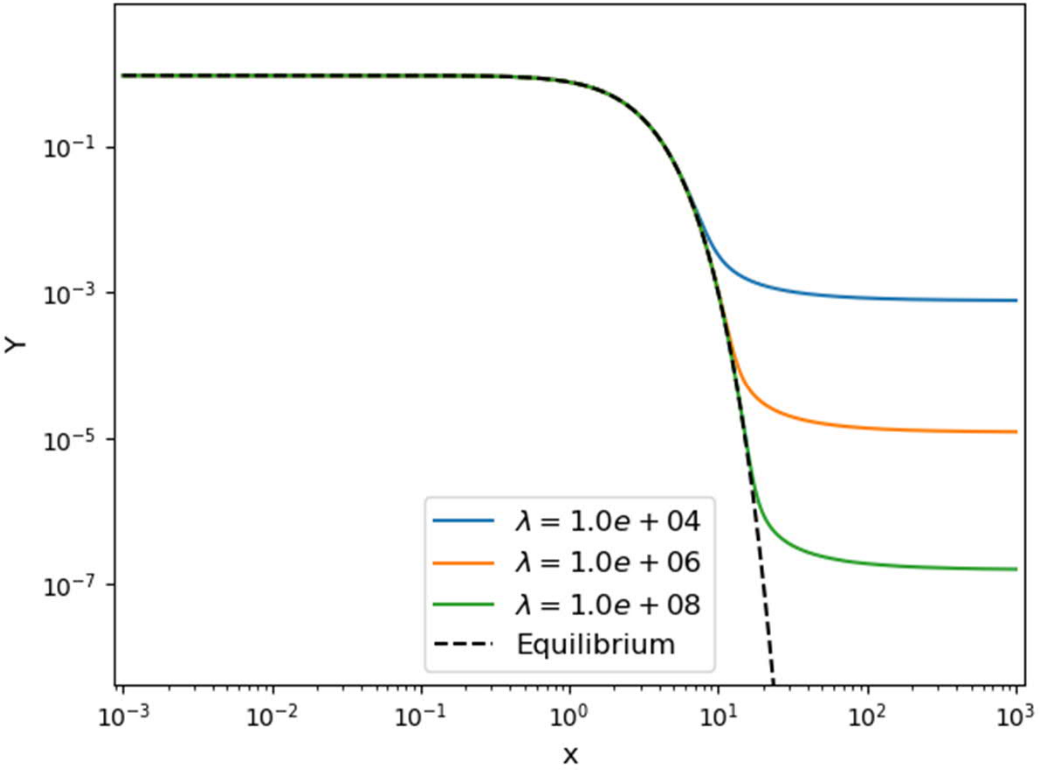
- n: number density
- H: Hubble Rate (Universe's Expansion)
- R: Interaction Rate Density (# interactions per time and volume)
  - Includes all annihilations and productions

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

Freeze-Out Calculation

For the process $12 \leftrightarrow \chi\chi$

- The Boltzmann equation:
  - $\frac{dY}{dx} = \frac{\lambda(x)}{x^2} < \sigma v >_{\chi\chi\to 12} [(Y_\chi^{eq})^2 - Y^2]$
- Calculate freeze-out temperature T_f
- After T_f, $Y_\chi \gg Y_\chi^{eq}$:
  - $Y_\infty^{-1} = Y_f^{-1} + \int_0^{T_f} \lambda < \sigma v >_{\chi\chi\to 12} dT$



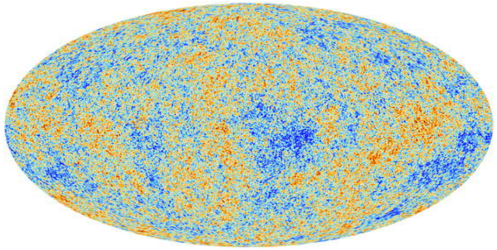
Dark Matter Evidence and Overview

Evidence:


NASA, ESA, J. Mack (STScI) and J. Madrid (Australian Telescope National Facility)

- Galaxy clusters
- Rotation curves of galaxies
- Large scale structure
- Cosmic Microwave Background (CMB)

Overview:



- Abundance $\Omega h^2 \approx 0.12$ (Planck)
- Interacts gravitationally with ordinary matter
- If it interacts non-gravitationally with ordinary matter it does very weakly