Dark Sectors at Electron Fixed-Target Facilities

Eder Izaguirre

BROOKHAVEN NATIONAL LABORATORY

BNL, Dark Interactions Workshop, October 4th, 2016

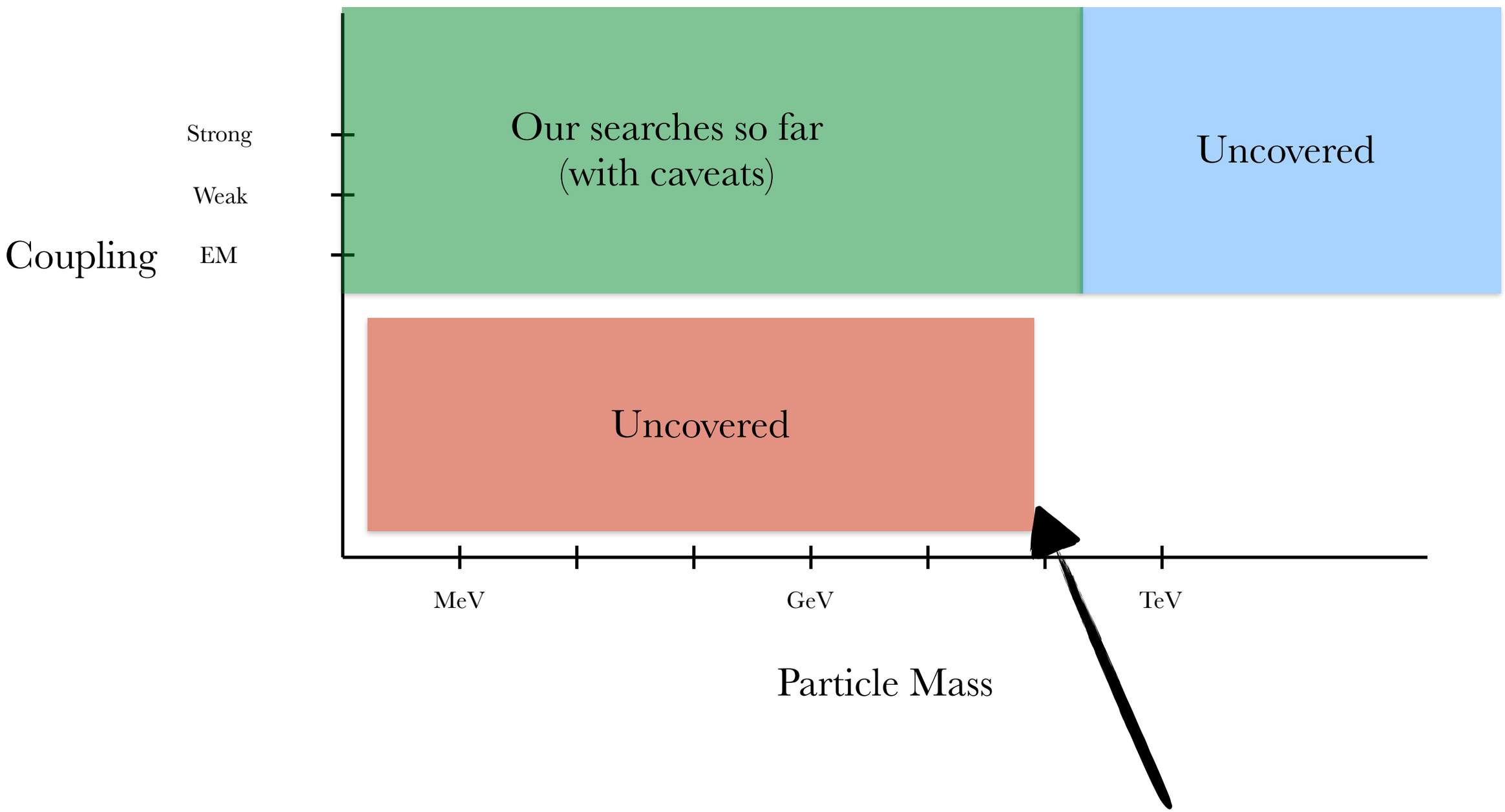
Outline

Introduction ★

Why Fixed-Target Beam-Dump Experiments?

Outlook

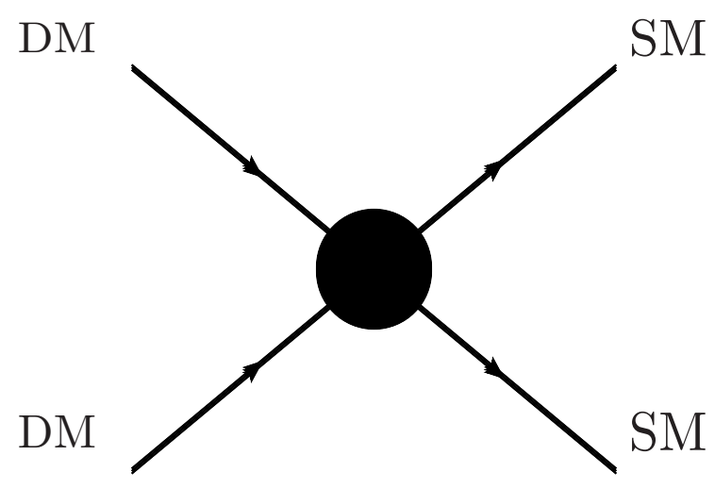
The Search for New Particles and Forces



This morning: Reasons why we should look her

A Thermal Origin For Dark Matter

Suppose DM was in thermal equilibrium with SM



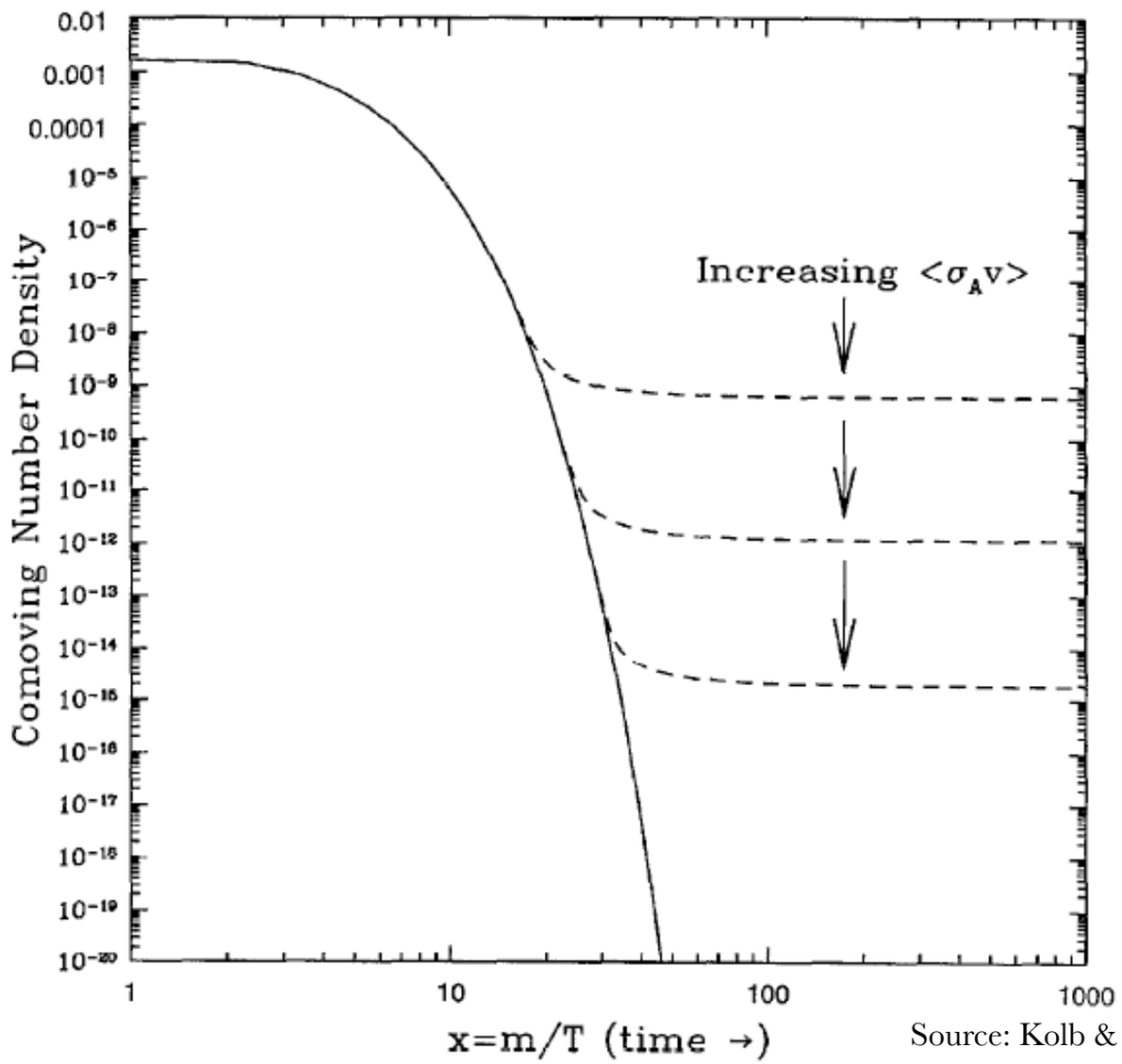
$$\Gamma = n\sigma v$$

Thermal equilibrium will cease when

$$\Gamma < \Gamma_H$$

After this point, DM is “frozen out”

A Thermal Origin



Source: Kolb & Turner

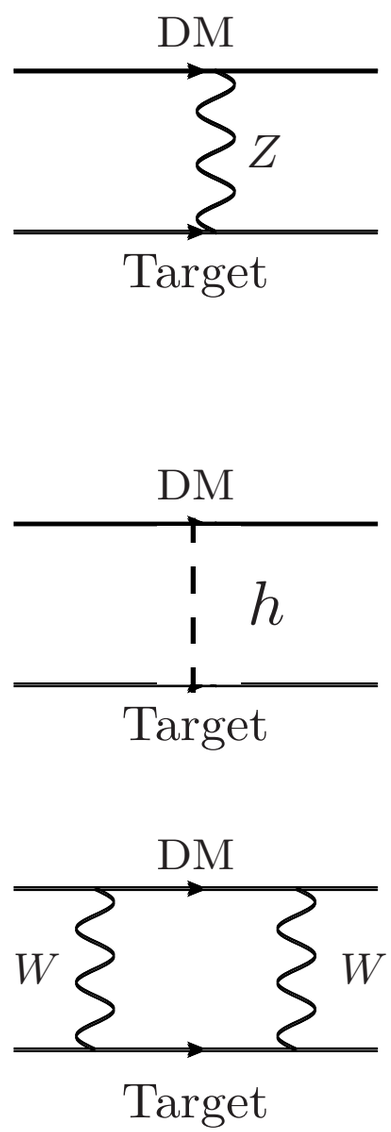
To get today's observed DM abundance we only need

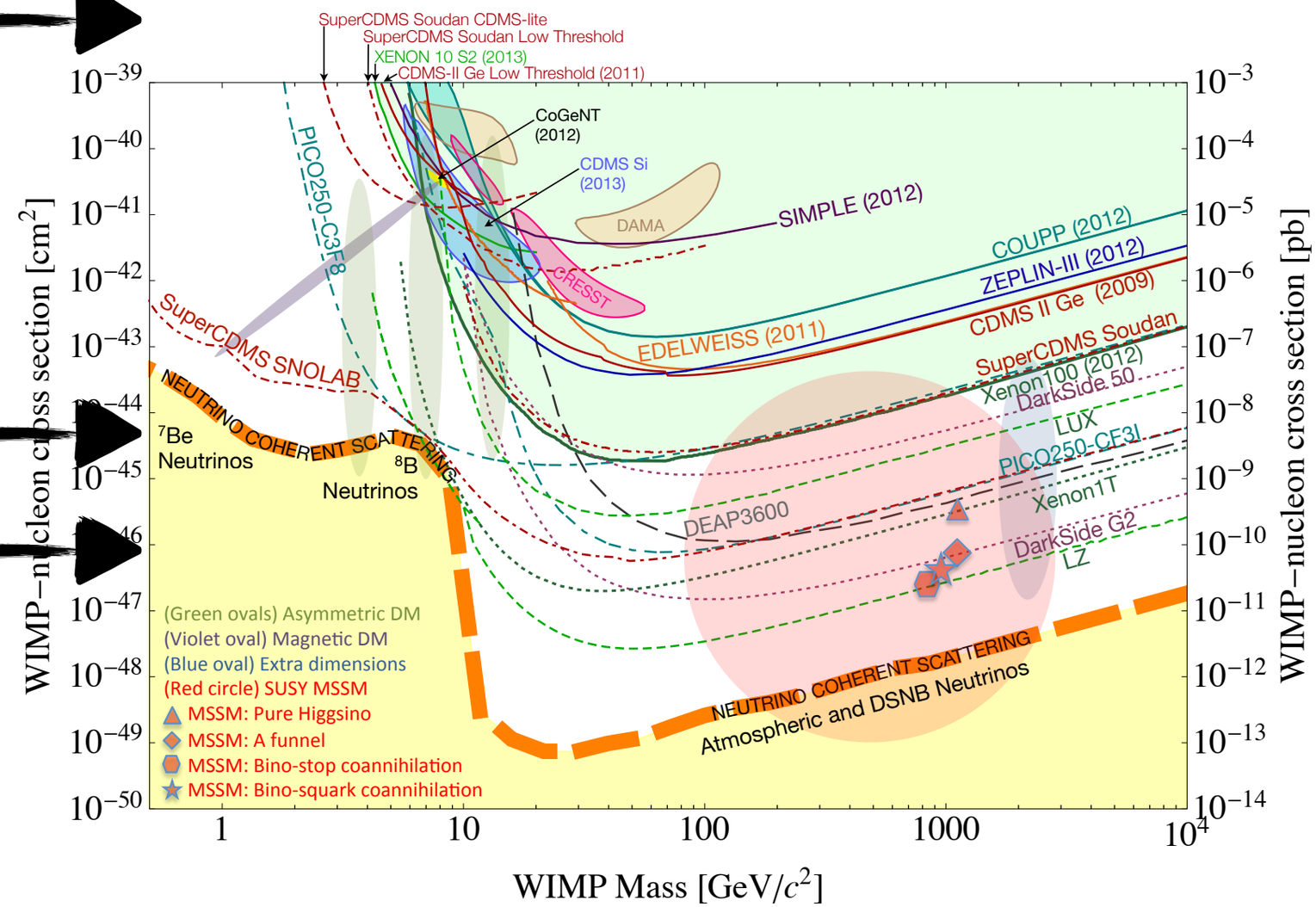
$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \frac{\mathrm{cm}^3}{\mathrm{s}}$$

A particle with Weak-scale mass that interacts with SM through Z gives rate close to this number

Thermal origin is a broad paradigm
Suggests non-gravitational interactions between DM and SM

Status of Dark Matter Searches

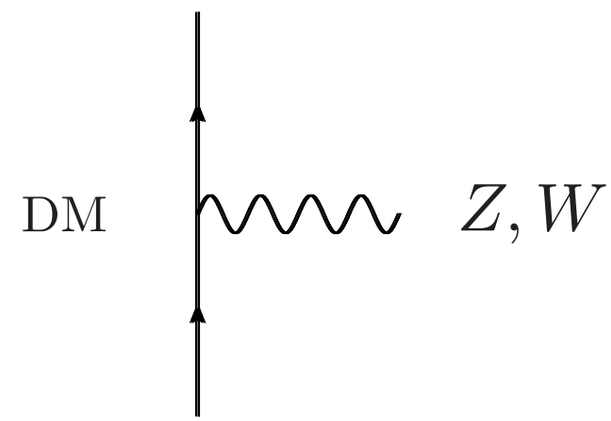




Light DM that communicates with the SM through a new force remains largely unexplored!
Two parts: Mediator-SM and DS dynamics

Two Simple Possibilities

Primarily looked for DM charged under **known** forces



Two Simple Possibilities

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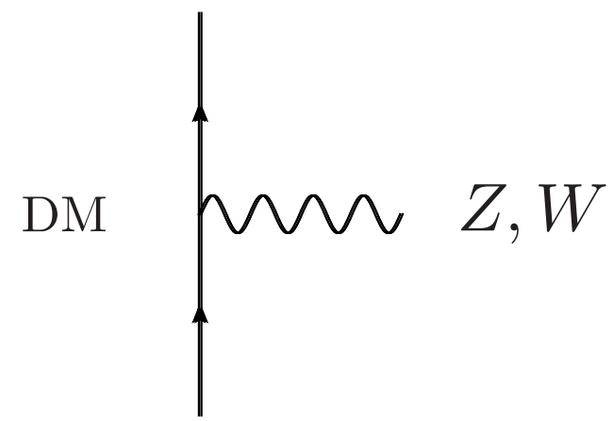
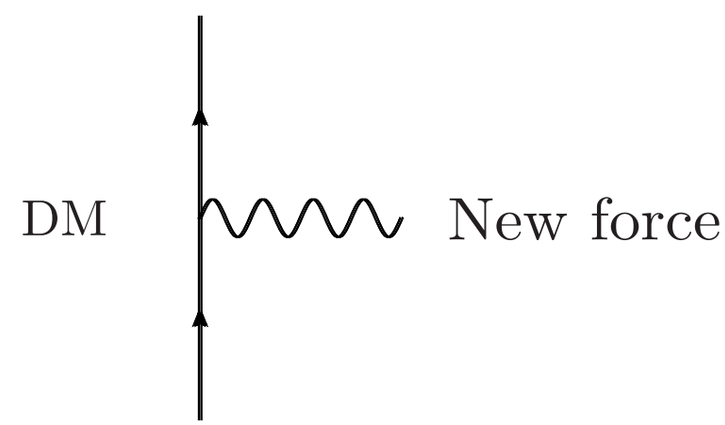


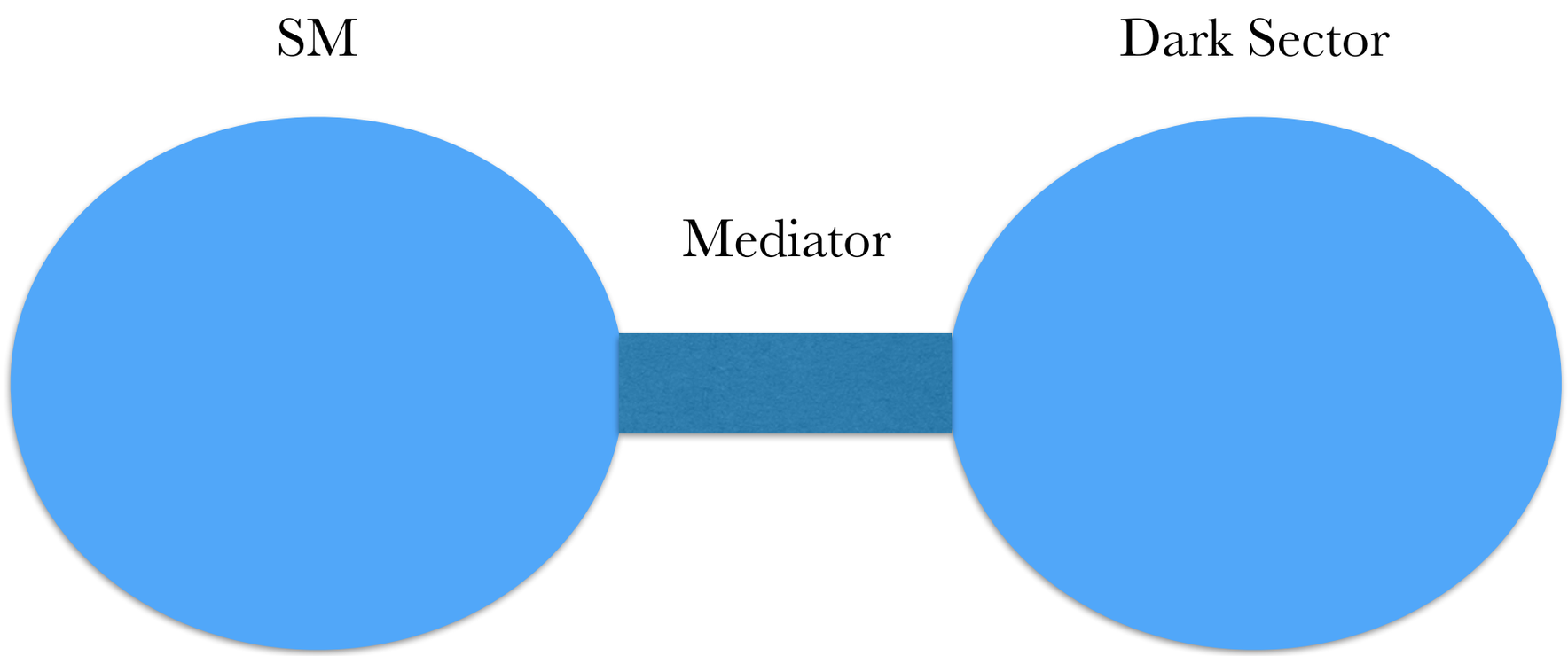
What about the other possibility?
DM charged under **new** force



A Broader Hidden Sector Paradigm

Beyond the SM physics that lives in a "dark sector"

A new force/interaction connects the SM to a Dark Sector (DS)



DM is just one example of new physics that might reside in its own sector

What are the "simplest" (renormalizable) allowed interactions between the SM and the DS?

The Most Minimal Interactions

The symmetries of the SM greatly restrict the number of "minimal" interactions that can mediate an interaction with a DS

Vector Portal (spin 1) $\epsilon_Y B^{\mu\nu} F'_{\mu\nu}$

Scalar Portal (spin 0) $\epsilon_h |h|^2 |\phi|^2$

Fermion Portal (spin 1/2) $\epsilon_\nu L h \psi$

Note: higher-dimensional portals worthy of study
e.g. dipole, axion, neutron portal,…

The Portals

Vector Portal (spin 1) $\epsilon_Y B^{\mu\nu} F'_{\mu\nu}$

Scalar Portal (spin 0) $\epsilon_h |h|^2 |\phi|^2$

Fermion Portal (spin 1/2) $\epsilon_\nu L h \psi$

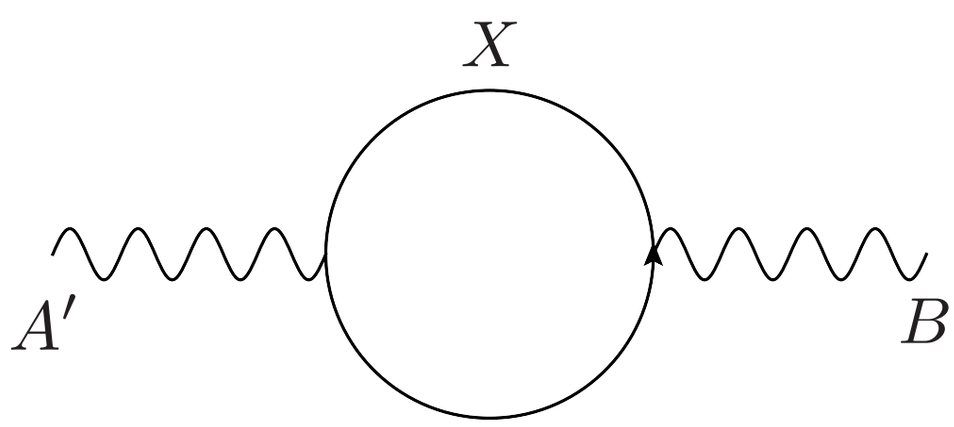
The Vector Portal

Holdom - 1985

Minimal Lagrangian = SM Lagrangian + Dark QED + "Kinetic Mixing"

$$\mathcal{L} \supset -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\kappa}{2}B^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^{\mu}A'_{\mu}$$

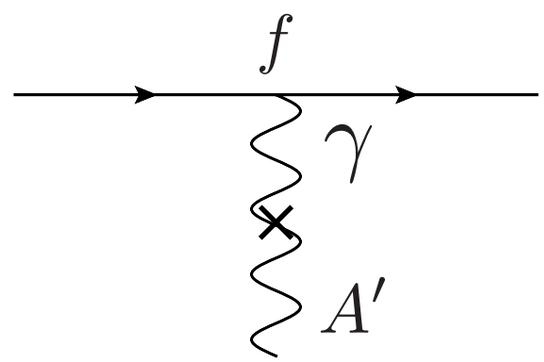
Even if absent from fundamental theory
the "kinetic mixing term" can be generated
through virtual effects of massive particles



Induce $\kappa \sim \frac{g_D g_Y}{16\pi^2} \sim 10^{-3}$

The Vector Portal

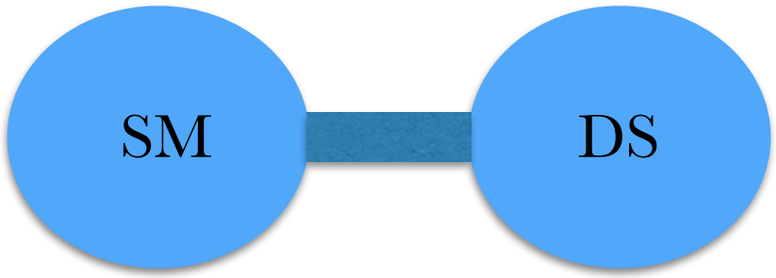
SM fermions acquire a small charge
under a short-range force
mediated by the "dark photon"!



$$Q_D \approx \kappa \cos\theta_W e$$

While dark fermions remain neutral under EM

Matter in the Dark Sector



Fermion

$$\mathcal{L} \supset i\bar{\psi}(\partial + ig_D \not{A}' + im_\psi)\psi \quad \text{could also allow} \quad -\frac{y_D}{2}\langle v_D \rangle \bar{\psi}^c \psi$$

Scalar

$$\mathcal{L} \supset |D_\mu \varphi|^2 - m_\varphi^2 |\varphi|^2$$

Outline

Introduction

Why Fixed-Target Beam-Dump Experiments?

Outlook

Maximizing Our Knowledge

Through a robust experimental program

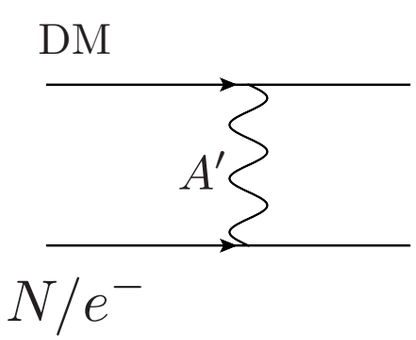
Two broad categories

Direct detection

Accelerators

Maximizing Our Knowledge

An aside: Direct detection



Could teach us

$\epsilon^2 \alpha_D / m_{A'}^4 \quad (\alpha_D \equiv \frac{g_D^2}{4\pi})$

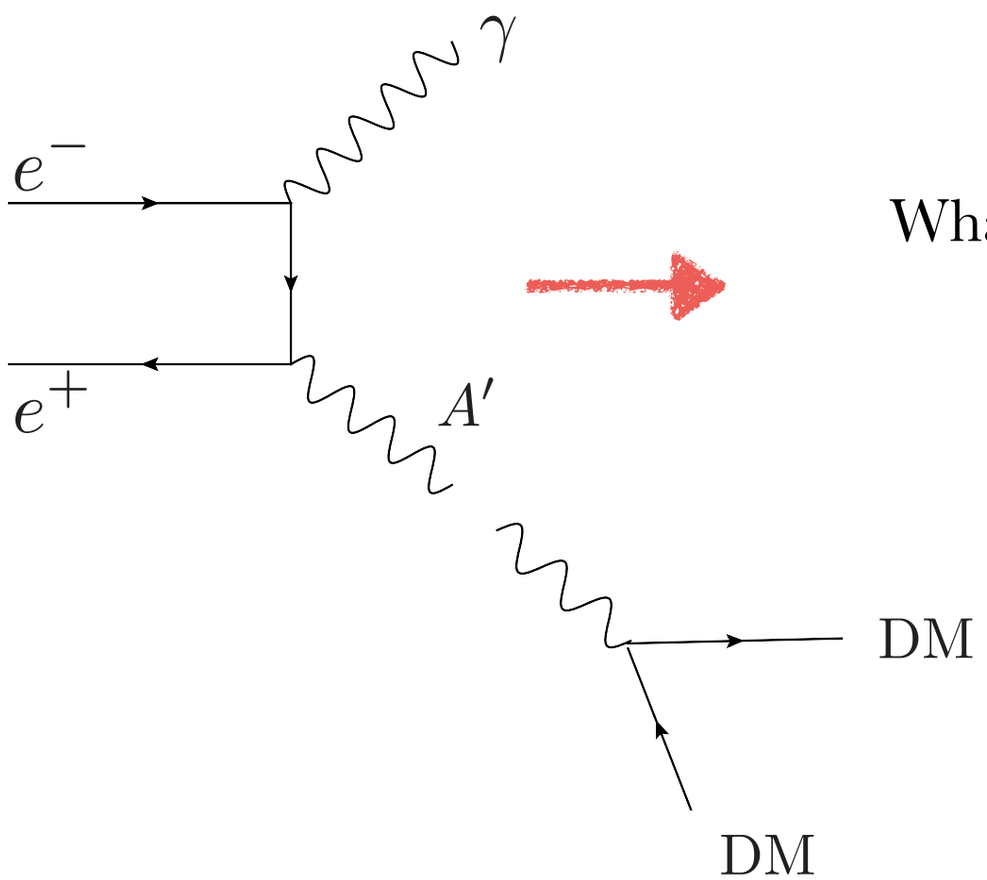
$\sim m_{\rm DM}$

Also can cover unique model space
e.g. ultralight vector DM

Maximizing Our Knowledge

Accelerators

Collider



What can we learn?
Assuming

$$\alpha_D \gtrsim \epsilon^2$$

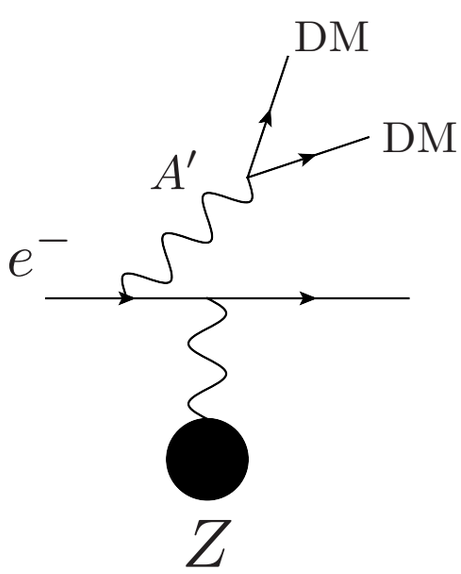
ϵ^2

$m_{A'}$

Maximizing Our Knowledge

Accelerators

Fixed-Target Missing Momentum



What can we learn?
Assuming

$$\alpha_D \gtrsim \epsilon^2$$

$$\epsilon^2$$

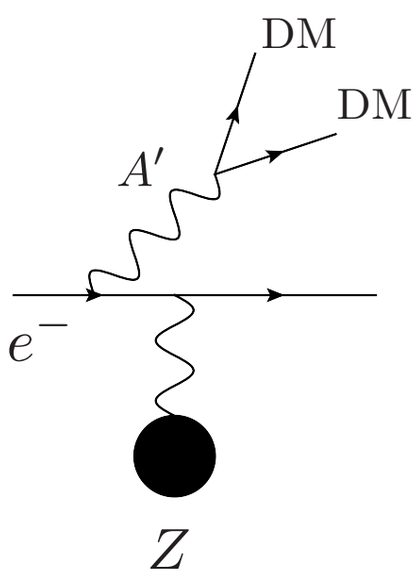
$$\sim m_{A'}$$

Maximizing Our Knowledge

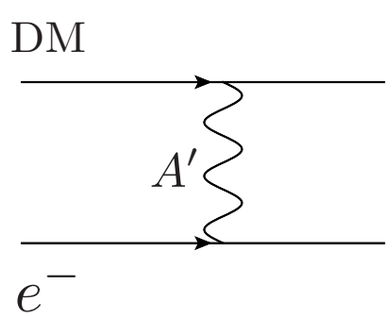
Accelerators

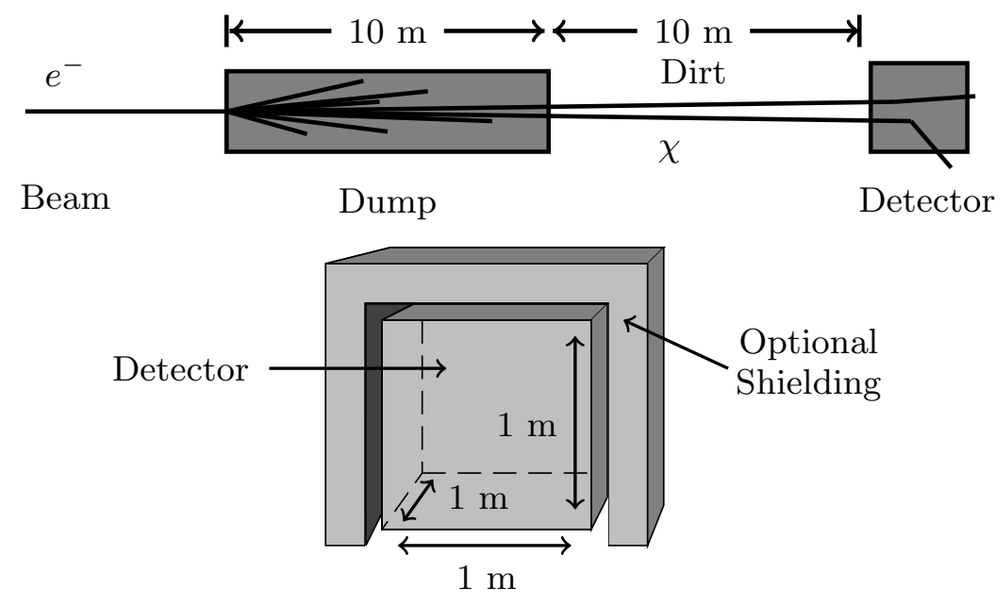
Fixed-Target Beam-Dump

Production



Detection



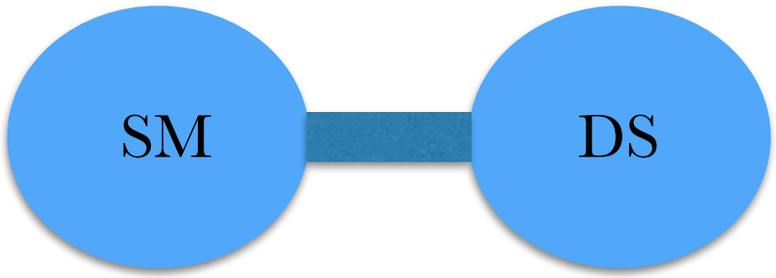


What can we learn?

$\epsilon^4 \alpha_D$

maybe $\sim m_{A'}$

Recall



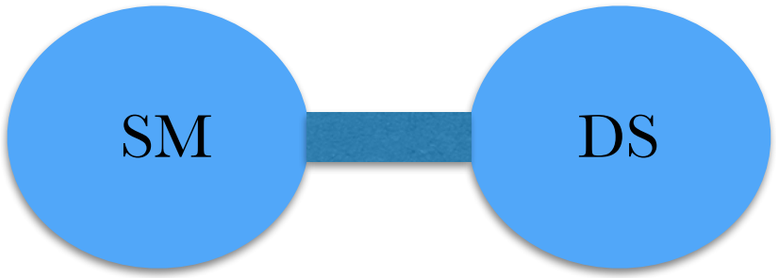
Fermion

$$\mathcal{L} \supset i\bar{\psi}(\partial + ig_D \not{A}' + im_\psi)\psi$$ could also allow $$-\frac{y_D}{2}\langle v_D \rangle \bar{\psi}^c \psi$$

Scalar

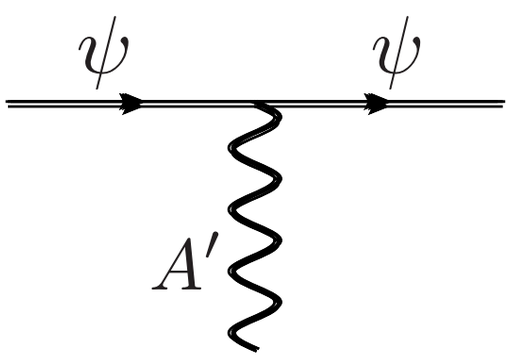
$$\mathcal{L} \supset |D_\mu \varphi|^2 - m_\varphi^2 |\varphi|^2$$

Vector Portal: Majorana-Like DM

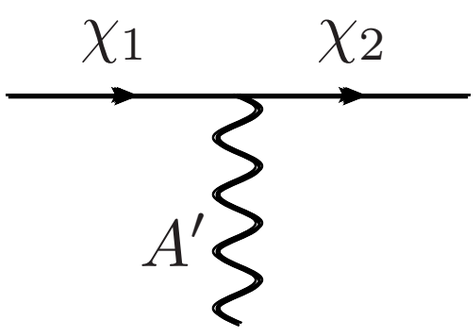


Let's assume DS matter is a fermion (lesson applicable to spin 0)

Dirac-like matter



Majorana-like matter: $m_M \bar{\psi}^c \psi \neq 0$



$m_1 < m_2$

χ_2 is unstable

Signature may be absent in direct detection

Kinetic Mixing Portal Model

Fermionic iDM (analogous case for scalar iDM)

Start with a Dirac fermion $\psi = \begin{pmatrix} \eta & \xi^\dagger \end{pmatrix}$ charged under a $U(1)_D$ symmetry

The vector current is diagonal

$$\mathcal{J}^\mu = \overline{\psi}\gamma^\mu\psi = \eta^\dagger\overline{\sigma}^\mu\eta - \xi^\dagger\overline{\sigma}^\mu\xi$$

Gauge invariance only allows a Dirac mass
But when symmetry is spontaneously broken can also write Majorana mass

$$-\mathcal{L} \supset m_D\eta\xi + \frac{m_\eta}{2}\eta\eta + \frac{m_\xi}{2}\xi\xi + \text{h.c.}$$

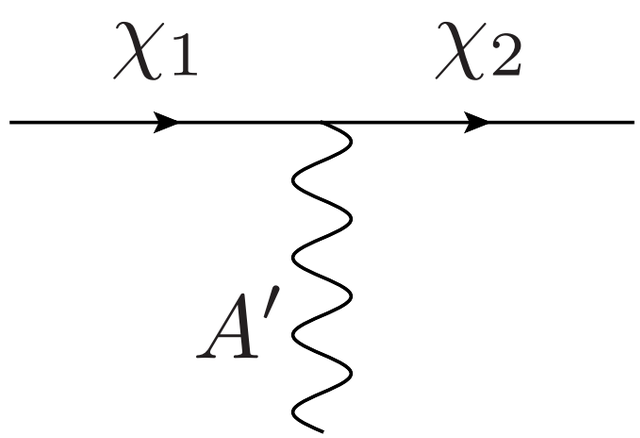
Kinetic Mixing Portal Model

The mass eigenstates

$$\chi_1 = i(\eta - \xi)/\sqrt{2}\ ,\ \ \chi_2 = (\eta + \xi)/\sqrt{2}$$

now have (dominantly) off-diagonal interactions

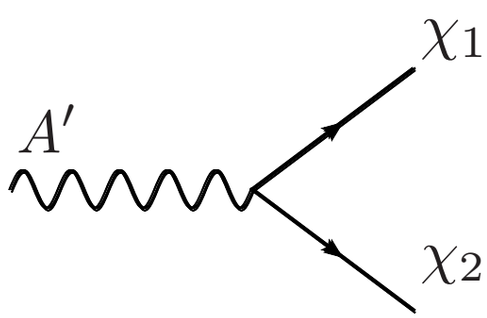
$$\mathcal{J}^\mu = i(\chi_1^\dagger \overline{\sigma}^\mu \chi_2 - \chi_2^\dagger \overline{\sigma}^\mu \chi_1)$$



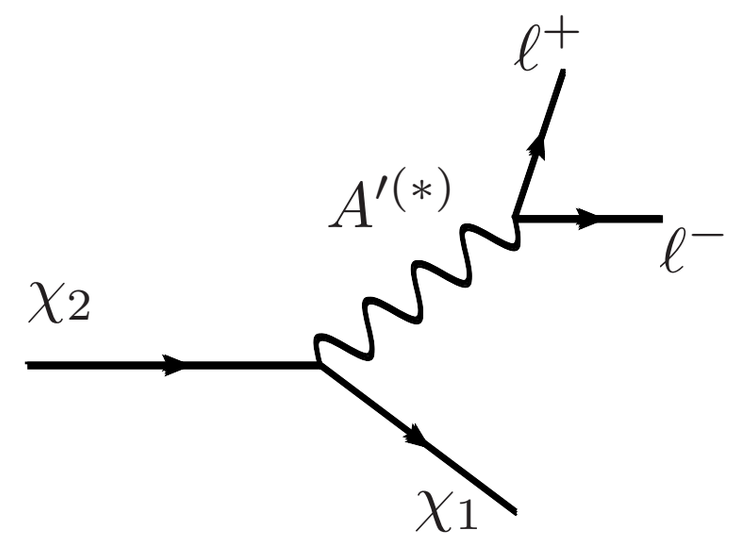
Vector Portal: Majorana-Like DM in Massive Phase

Phenomenology can be drastically altered

Decay of A'



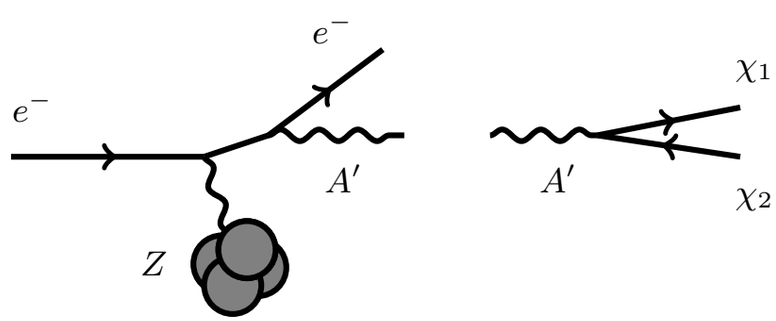
Decay of excited state



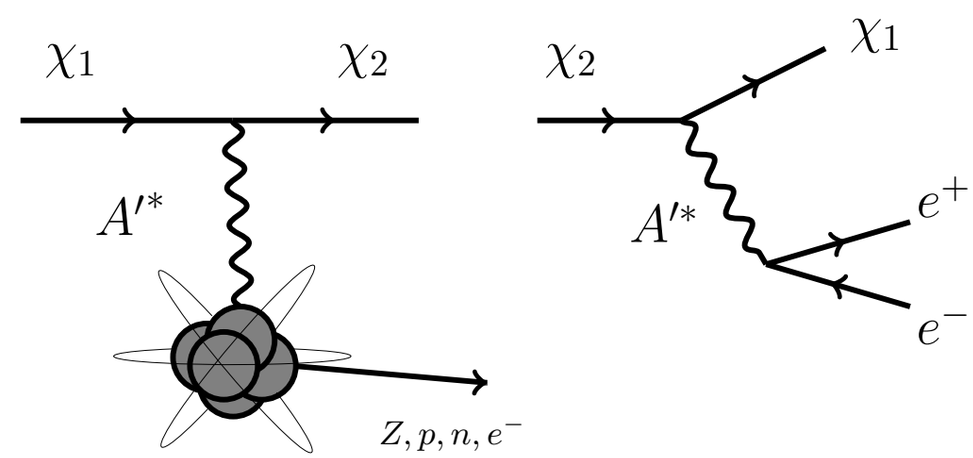
Vector Portal: Majorana-Like DM in Massive Phase

At Beam-Dump Experiments

Production



Detection



May be challenging for missing momentum fixed-target
i.e. DM system is no longer fully invisible

A New Beam-Dump Experiment

EI, Krnjaic, Schuster, Toro, PRD (1307.6554),PRD (1403.6826)
BDX Collaboration arXiv:1406.3028, arXiv:1607.01390

JLab CBAF capable of delivering 10^{22} 11 GeV EOT/year (!)

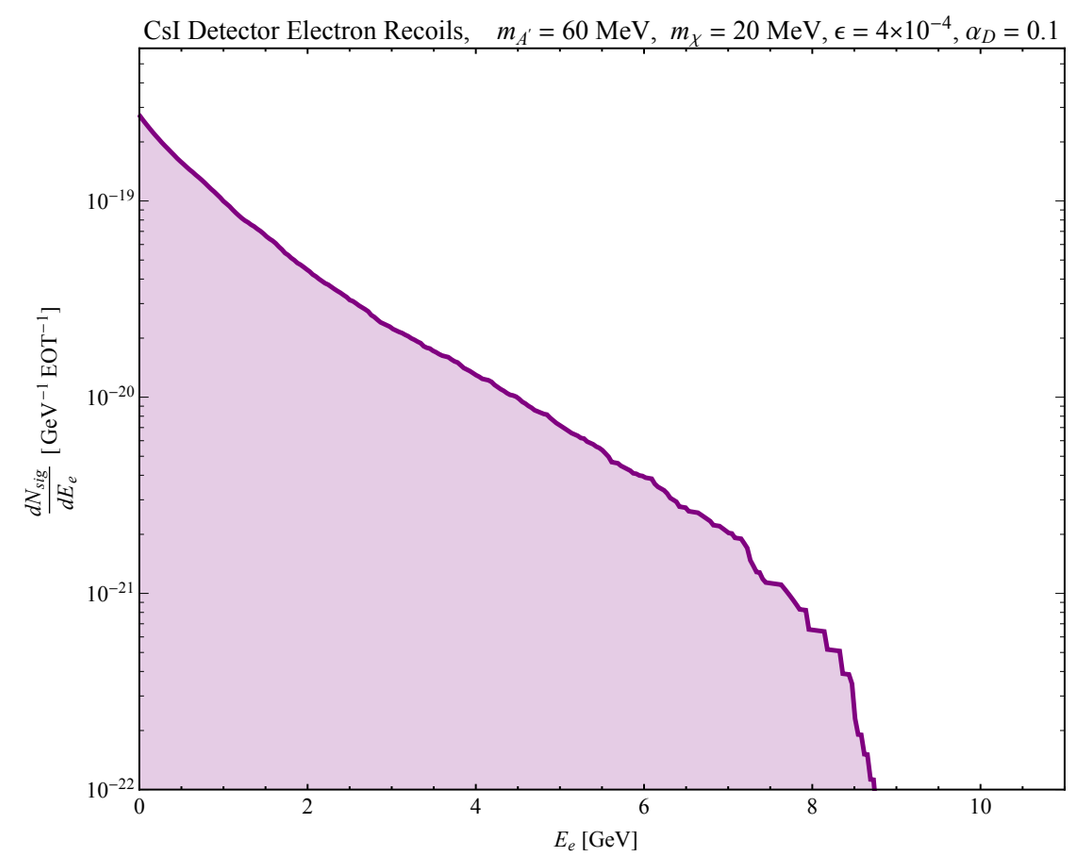
Lum up to ~ ab^{-1}/day

$$\sigma_{\rm prod} \sim \frac{\alpha^3 \epsilon^2 Z^2}{m_{A'}^2}$$

$$\sigma_{\rm det} \propto \epsilon^2 \alpha_D$$

Signal carries O(1) of beam energy!
DM with diagonal (or off-diagonal couplings)

Signal also collimated $\theta \sim (\frac{m_{A'}}{E_{\rm beam}})^{5/4}$



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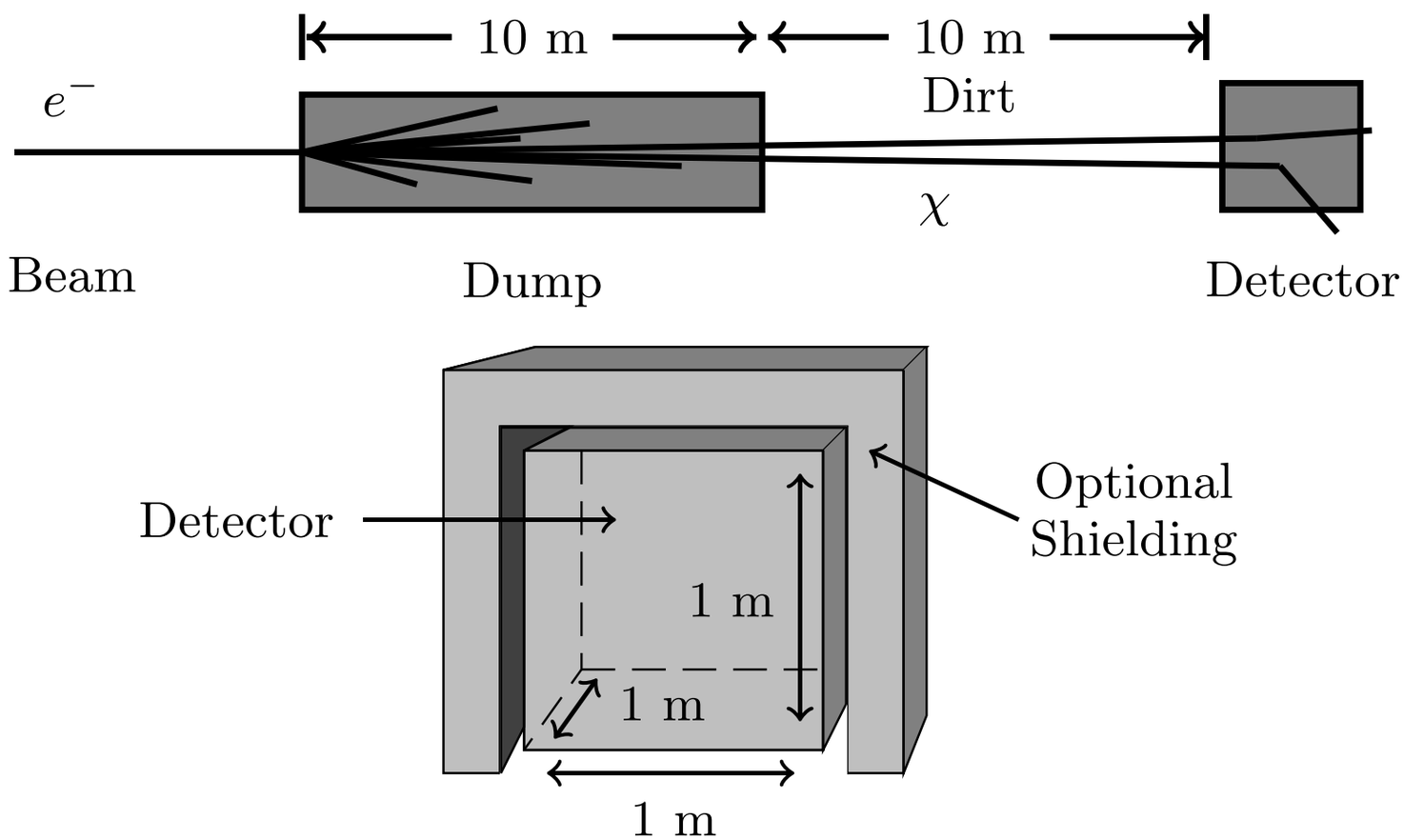


BDX

BDX Collaboration, arXiv:1607.01390

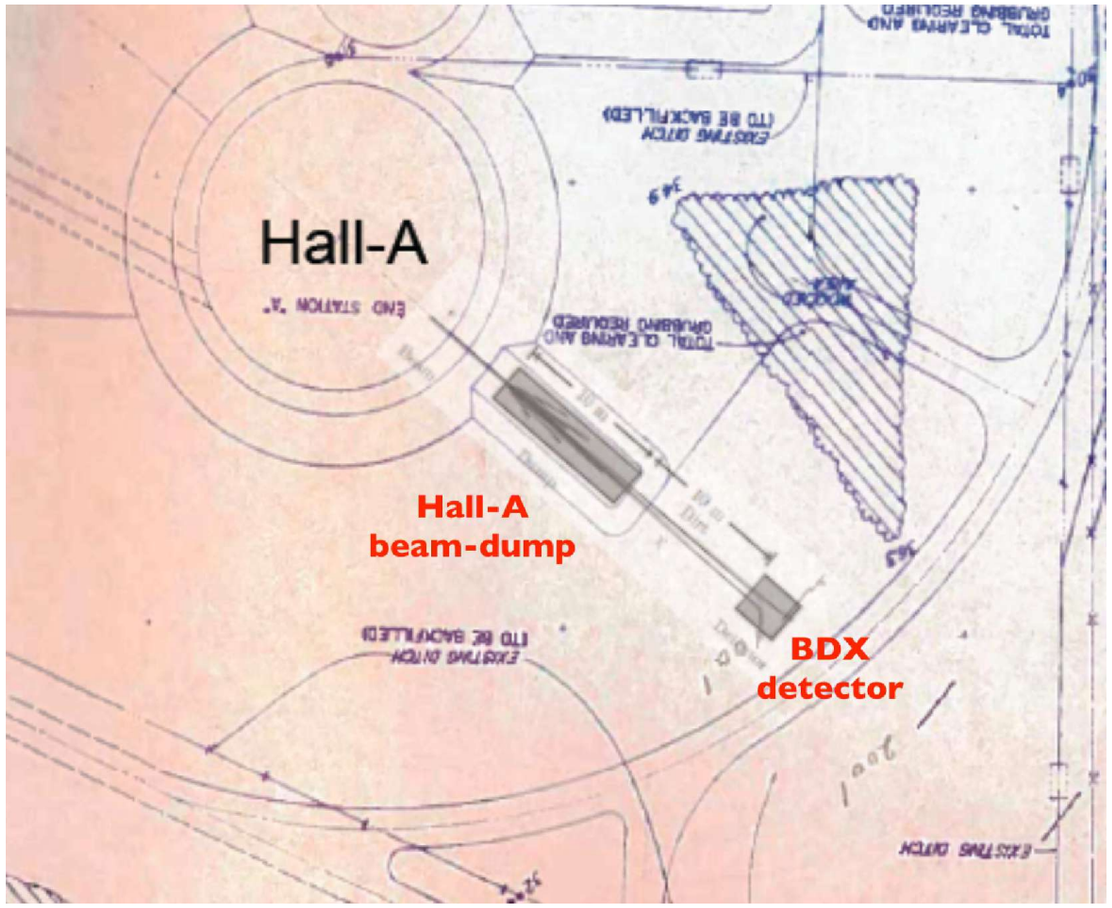
V2.0
July 7, 2016

Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab

The BDX Collaboration

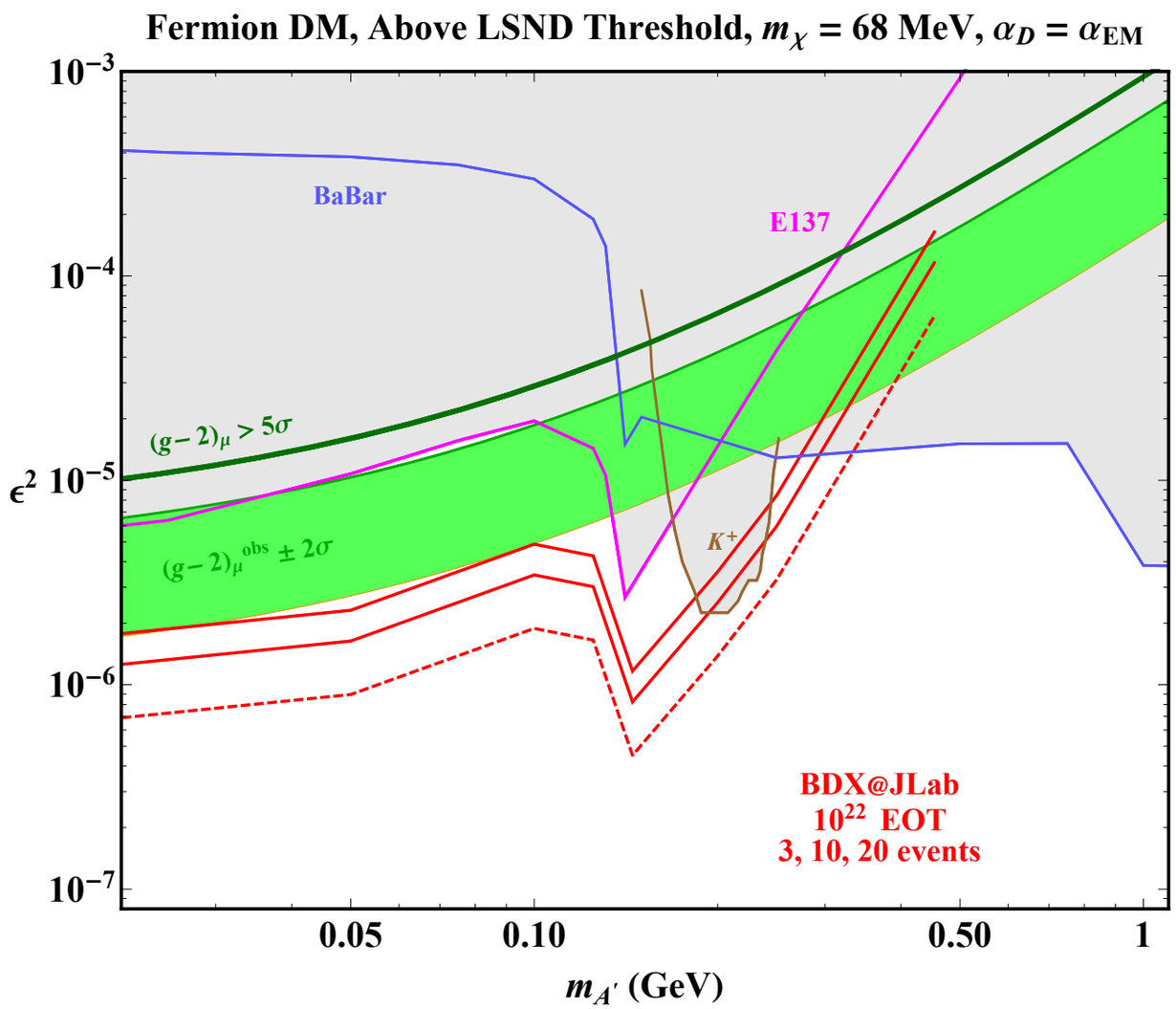
Abstract

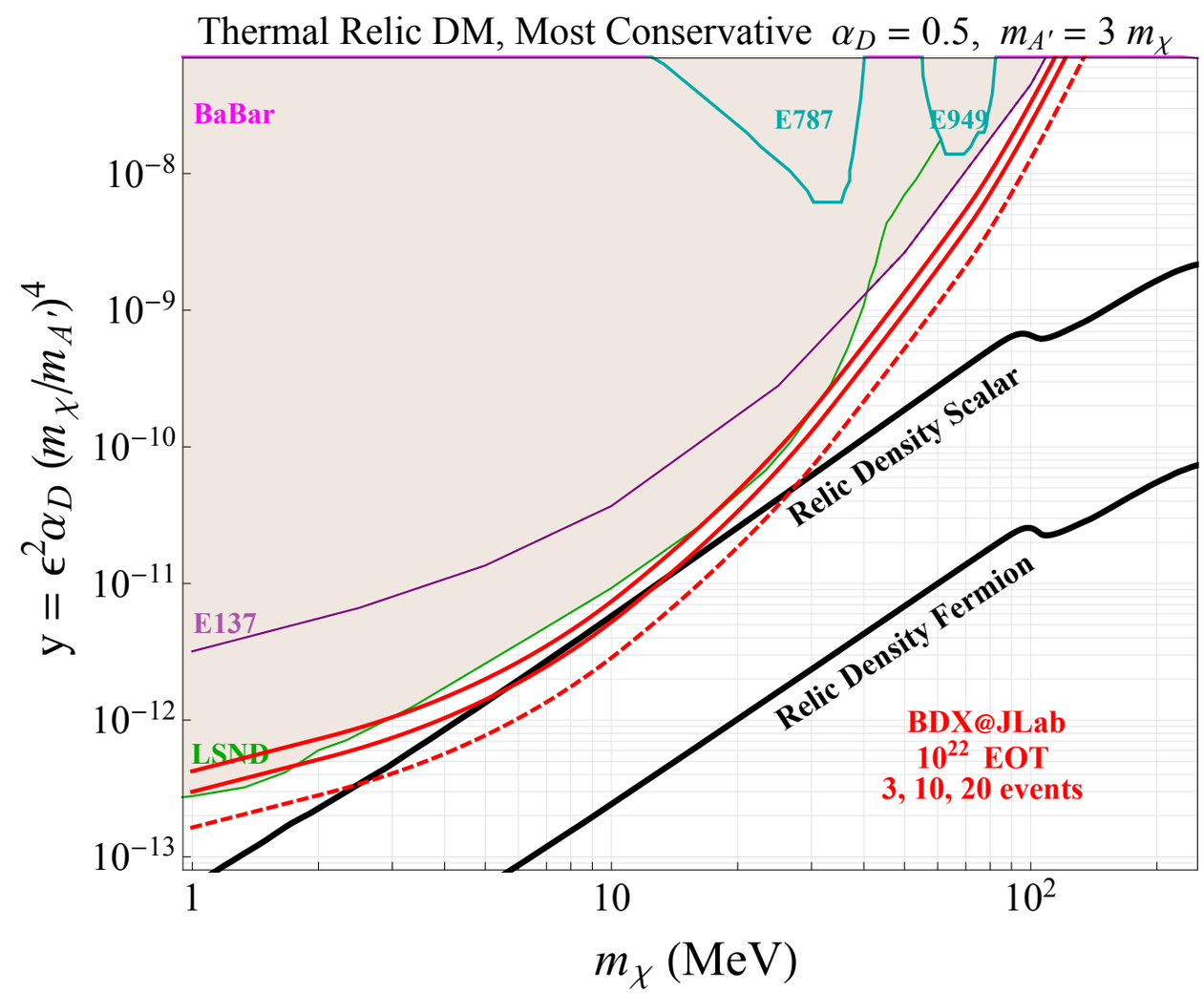
MeV-GeV dark matter (DM) is theoretically well motivated but remarkably unexplored. This proposal presents the MeV-GeV DM discovery potential for a $\sim$1 m^3 segmented CsI(Tl) scintillator detector placed downstream of the Hall A beam-dump at Jefferson Lab, receiving up to 10^{22} electrons-on-target (EOT) in 285 days. This experiment (Beam-Dump eXperiment or BDX) would be sensitive to elastic DM-electron and to inelastic DM scattering at the level of 10 counts per year, reaching the limit of the neutrino irreducible background. The distinct signature of a DM interaction will be an electromagnetic shower of few hundreds of MeV, together with a reduced activity in the surrounding active veto counters. A detailed description of the DM particle χ production in the dump and subsequent interaction in the detector has been performed by means of Monte Carlo simulations. Different approaches have been used to evaluate the expected backgrounds: the cosmogenic background has been extrapolated from the results obtained with a prototype detector running at INFN-LNS (Italy), while the beam-related background has been evaluated by GEANT4 Monte Carlo simulations. The proposed experiment will be sensitive to large regions of DM parameter space, exceeding the discovery potential of existing and planned experiments in the MeV-GeV DM mass range by up to two orders of magnitude.



Potential Sensitivity

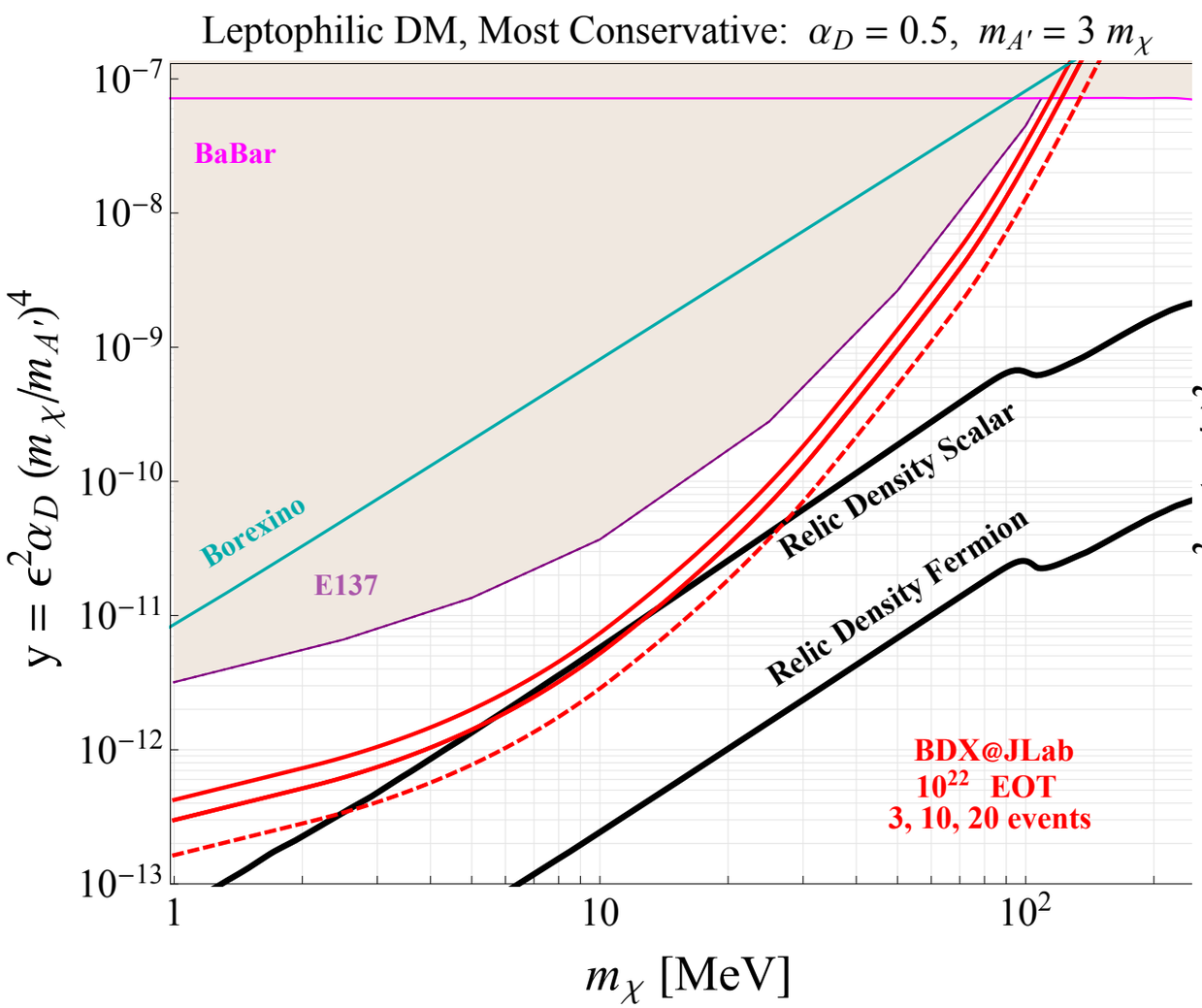
Assuming ~ 300 days of running, requiring $E_e > 300$ MeV

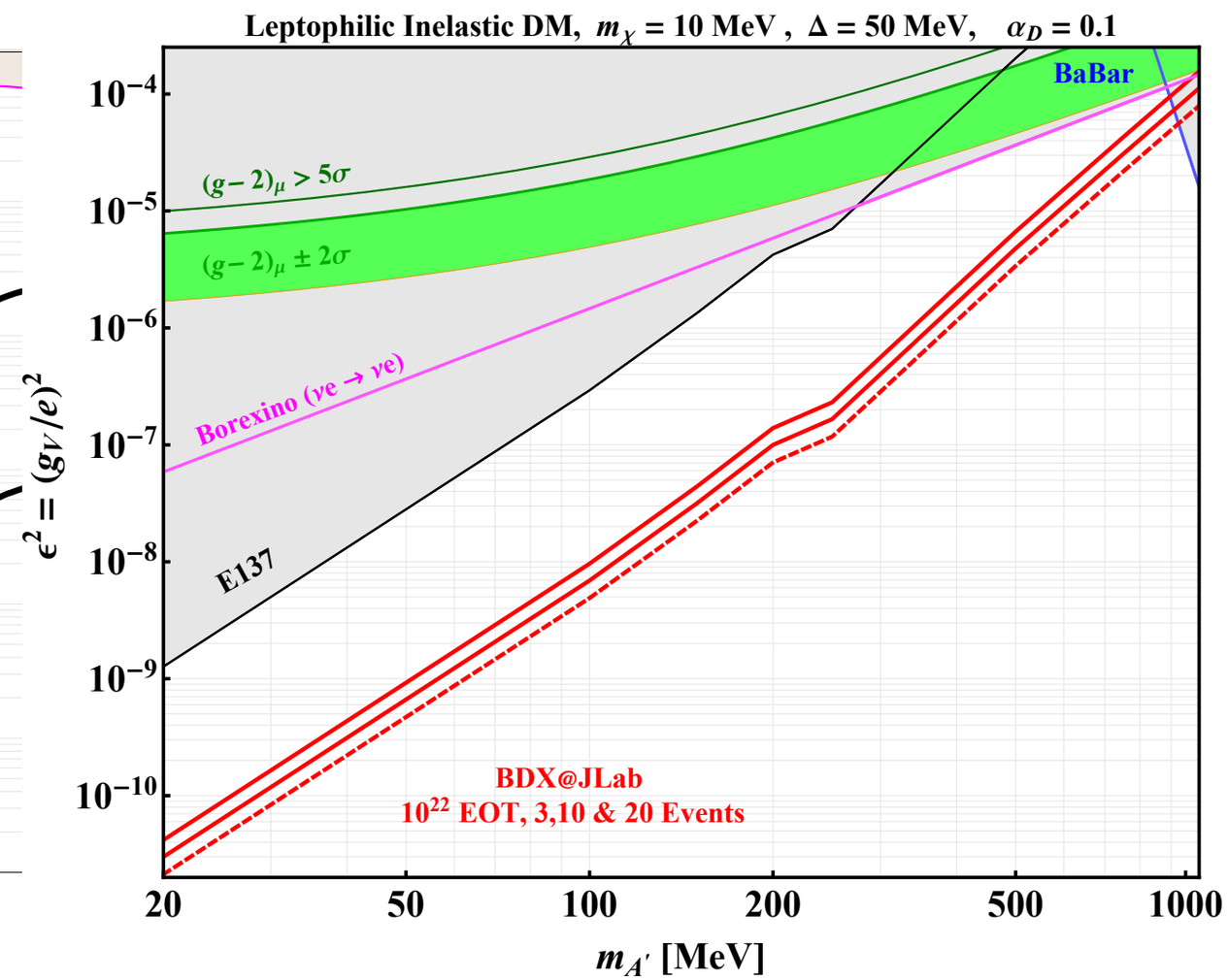




Potential Sensitivity

Beyond dark photons





Conclusions

Kinetic Mixing portal prime for study
Important theoretical benchmark within reach in next 5-10 years

Various experimental techniques proposed

I've tried to highlight the uniqueness of each (there's some overlap too)
focusing on the the strengths of beam-dump experiments

Discussed the outlook for BDX: a proposal for a beam-dump experiment at JLab