e^- Beam Dump eXperiment(s) to Search for Light Dark Matter

Gordan Krnjaic

& **Eder Izaguirre, Philip Schuster, Natalia Toro**

1307.6554 & 1403.6836

& **The BDX Collaboration**

1406.3028

Intense Electron Beam Workshop

Cornell University, June 18, 2015

Light (Thermal) DM $\Longrightarrow$ Light Mediator

Otherwise DM is overproduced in early universe

Higgs Portal $(H^\dagger H)\hat{\mathcal{O}}_{D=2}$

Axion Portal $\tilde{F}_{\mu\nu}F_{\mu\nu}\hat{\mathcal{O}}_{D=1}$

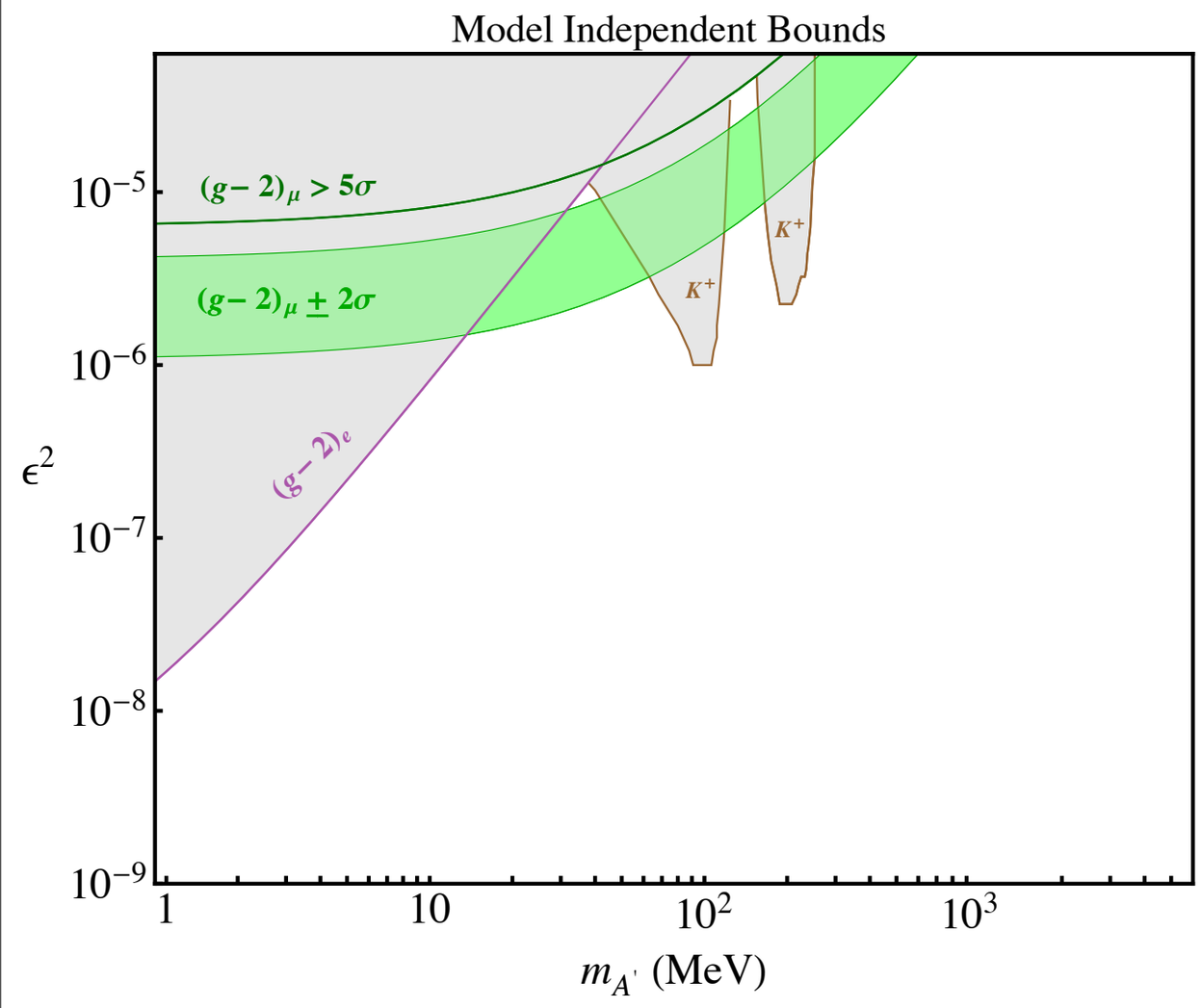
Vector Portal (kinetic mixing) $F_{\mu\nu}\hat{\mathcal{O}}^{\mu\nu}_{D=2}$

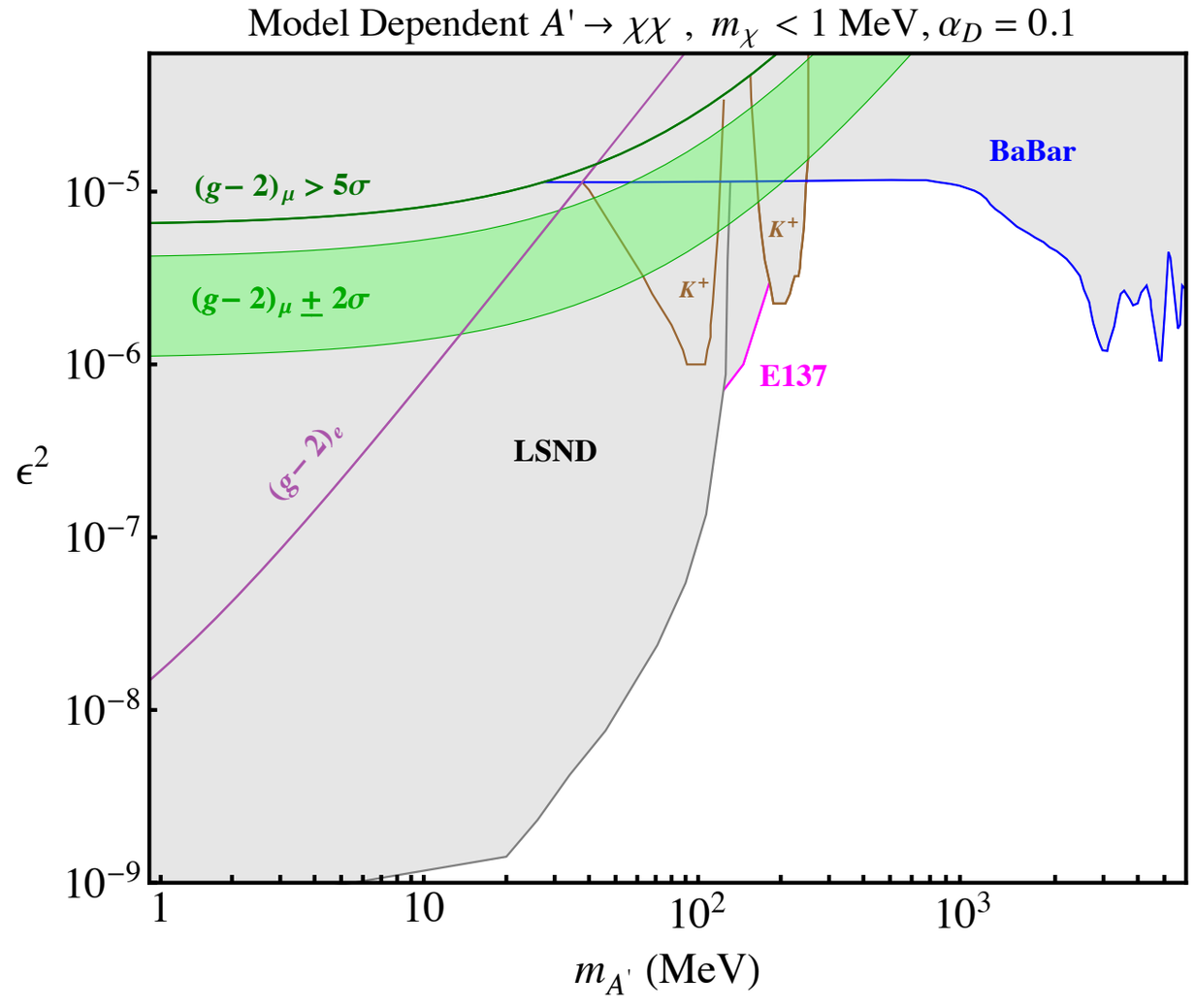
Only remaining viable option DM (see overview talk)

If *A'* Decays *Invisibly* to DM

4+ dimension parameter space

$$Br(A' \to \bar{\chi}\chi) \simeq 1$$





Lots of room left to cover (including GUT motivated)

Opportunity to discover DM

Simplified Model

Familiar starting point

$$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{m^2_{A'}}{2} A'^{\mu} A'_{\mu} + \bar{\chi}(i\not{D} + m_\chi) + \cdots$$

Most of this talk

$$m_\chi, m_{A'} \sim \mathrm{MeV} - \mathrm{GeV}$$

$$\epsilon \sim 10^{-5} - 10^{-2}$$

$$\alpha_D \sim 10^{-2} - 1$$

Relevant for thermal DM & fixed targets

Simplified Model

Familiar starting point

$$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{m^2_{A'}}{2} A'^{\mu} A'_{\mu} + \bar{\chi}(i\not{D} + m_\chi) \quad + \cdots$$

Most of this talk

$$m_\chi, m_{A'} \sim \mathrm{MeV} - \mathrm{GeV}$$

$$\epsilon \sim 10^{-5} - 10^{-2}$$

$$\alpha_D \sim 10^{-2} - 1$$

Relevant for thermal DM & fixed targets

Symmetry breaking sector always there!

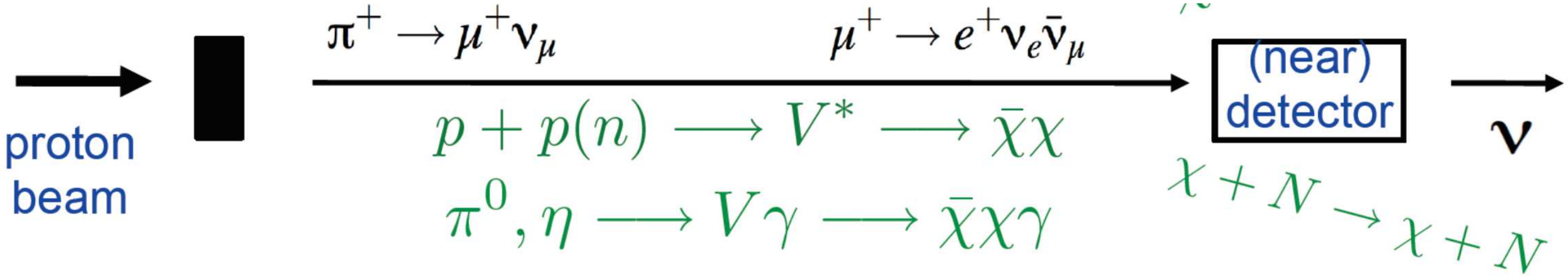
Generic DM mass splitting

$$H_D \overline{\chi^c} \chi \to v_D \overline{\chi^c} \chi$$

$$\Delta \equiv m_{\mathrm{ex.}} - m_{\mathrm{gd.}} \sim m_\chi$$

Identical model, Rich pheno, CMB 100% OK!

Low mass: best limits from neutrino factories



Pioneering searches: MiniBooNE, LBNE, MINOS NOvA…

DM produced via nuclear physics, scatters downstream

(Batell, Pospelov, de Niverville, McKeen, Ritz, Dharmapalan...)

However:

Designed to make neutrinos: large CC/NC backgrounds

Large (100 m+) baseline degrades geometric acceptance

Proper search expensive, requires dedicated beam time

Why Prefer Electron Beams?

Beam backgrounds: small $\Longrightarrow$ real discovery potential

High acceptance: nearby detector & forward kinematics

"Parasitic" (symbiotic): existing beams, detectors, & facilities

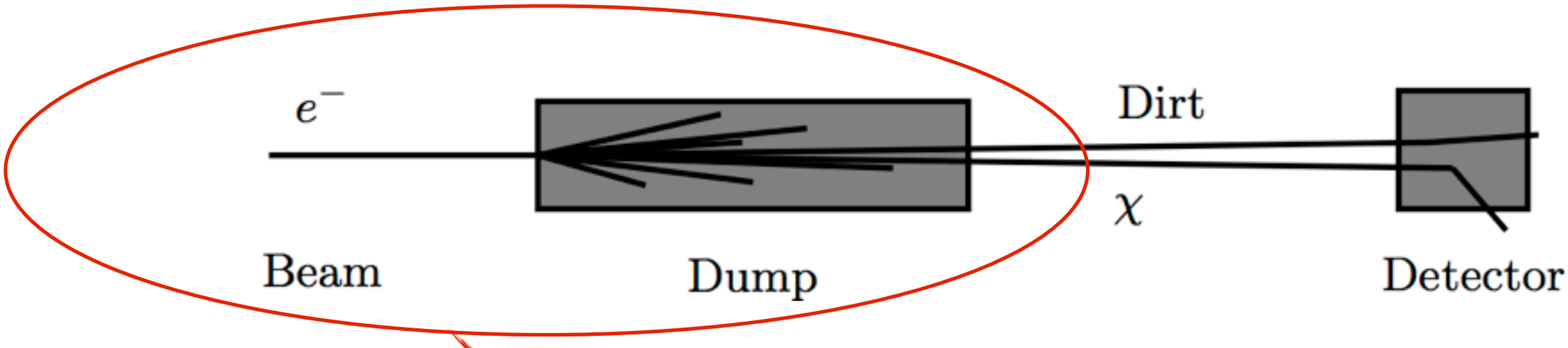
Discount physics: small, relatively cheap

Cosmic backgrounds: beatable, reducible, or zero

Complementary physics: neutrino factories & visible searches

How to Search

Ingredients



Already exist

Electron beam (few-100) GeV, continuous or pulsed

Beam dump & dirt ~ 10 m, range out beam BG

Just need

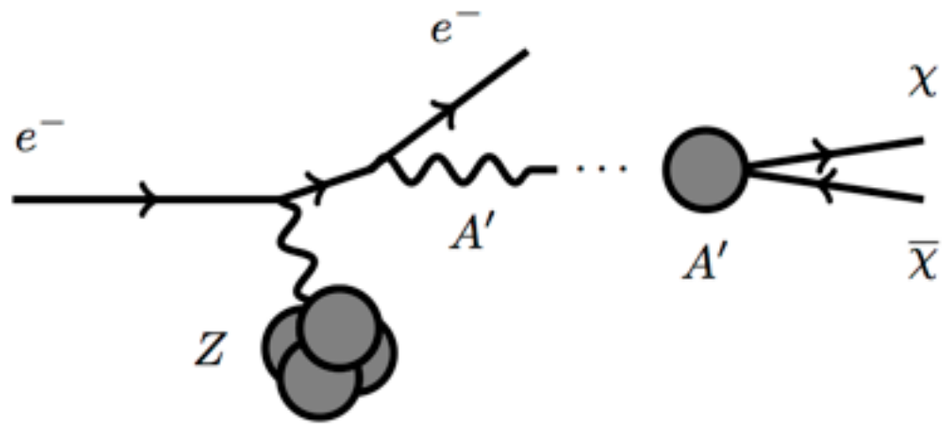
Detector for NC scattering: plastic-scintillator, LAr-TPC...

Can exploit existing technology

How to Search

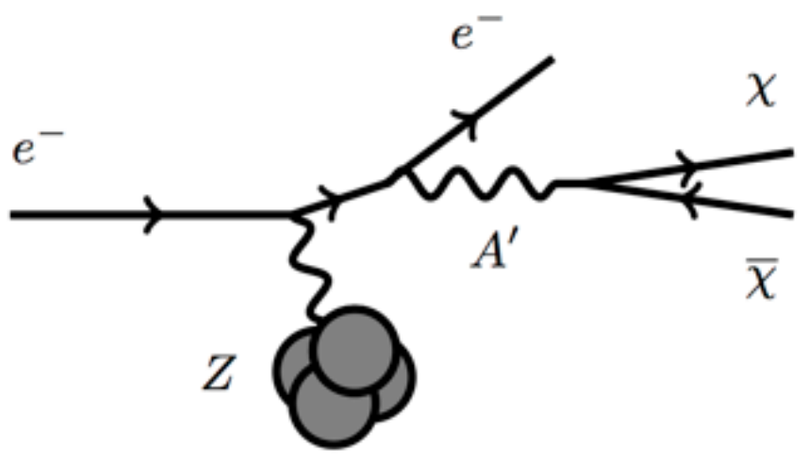
Production

$m_{A'} > 2m_\chi \implies$ **on-shell A'-strahlung**



$$\sigma \sim \frac{\epsilon^2}{m_{A'}^2}$$

$m_{A'} < 2m_\chi \implies$ **off-shell radiative**



$$\sigma \sim \frac{\alpha_D \epsilon^2}{m_\chi^2}$$

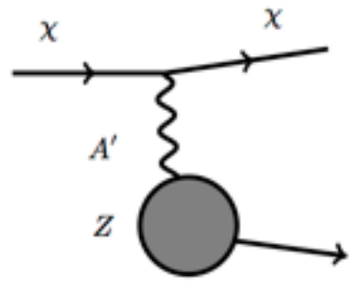
A' gets large fraction of beam energy

How to Search

Elastic Detection $\Delta = 0$

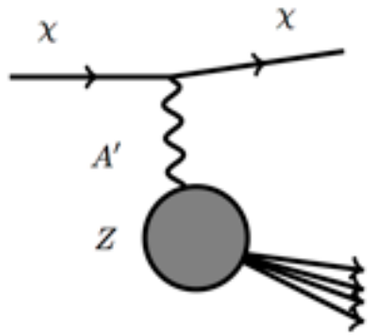
Coherent Nuclear

Low recoil energies, light mediator
Z^2 enhancement, form factor



Inelastic hadro-production

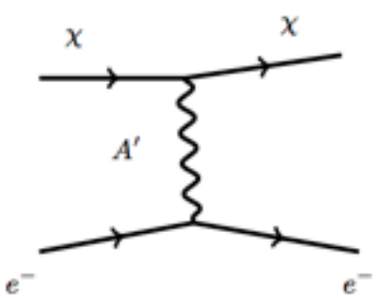
High Q transfer



$\pi, K \cdots$

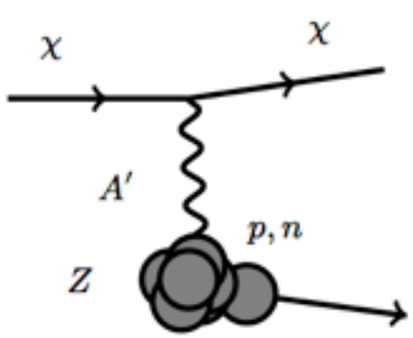
Electron Scattering

Low recoil energies, light mediator



Quasi-elastic Nucleon

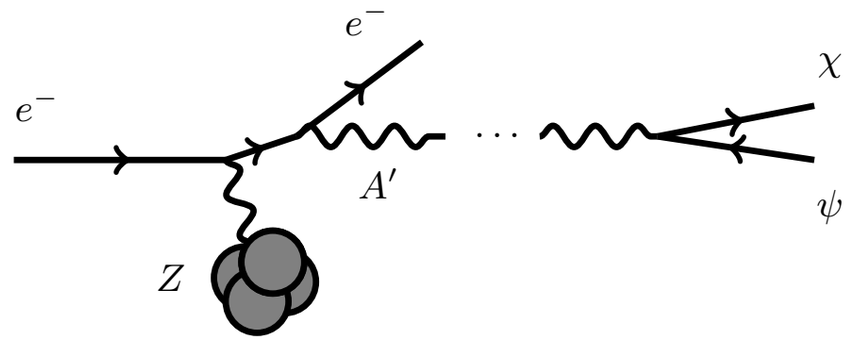
Higher recoil energies > 10s MeV,



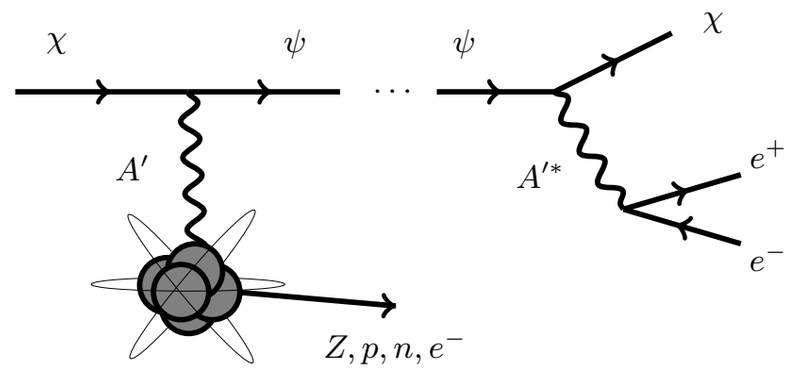
How to Search

Inelastic Detection $\Delta > 0$

1. *A'* decays to ground & excited state (beam dump)



2. DM upscatters into excited state (detector)



3. Excited state decays promptly (detector)

$$\Gamma(\psi \to \chi\, e^+e^-) = \frac{8\epsilon^2\alpha\alpha_D\Delta^5}{15\pi m_{A'}^4} + \mathcal{O}(\Delta^6)$$

$$\ell = c\tau \simeq 0.01\text{cm}\left(\frac{\gamma}{2}\right)\left(\frac{10^{-3}}{\epsilon}\right)^2\left(\frac{0.1}{\alpha_D}\right)\left(\frac{50\text{ MeV}}{\Delta}\right)^5\left(\frac{m_{A'}}{50\text{ MeV}}\right)^4$$

V1.8
June 2, 2014

Letter of Intent to PAC 42

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

The BDX Collaboration

M. Battaglieri*†, A. Bersani, A. Celentano†, R. De Vita†, E. Fanchini, S. Fegan, P. Musico, M. Osipenko, M. Ripani, E. Santopinto, M. Taiuti
Istituto Nazionale di Fisica Nucleare, Sezione di Genova e Dipartimento di Fisica dell'Università, 16146 Genova, Italy

E. Izaguirre†, G. Krnjaic†, P. Schuster, N. Toro
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada, N2L 2Y5

M. Dalton, A. Freyberger, F.-X. Girod, V. Kubarovsky, E. Smith†, S. Stepanyan†, M. Ungaro
Jefferson Lab, Newport News, VA 23606, USA

G. De Cataldo, R. De Leo, D. Di Bari, L. Lagamba, E. Nappi, R. Perrino
Istituto Nazionale di Fisica Nucleare, Sezione di Bari e Dipartimento di Fisica dell'Università, Bari, Italy

M. Carpinelli, V. Sipala
Università di Sassari e Istituto Nazionale di Fisica Nucleare, 07100 Sassari, Italy

S. Aiello, V. Bellini, M. De Napoli, A. Giusa, F. Mammoliti, E. Leonora, F. Noto, N. Randazzo, G. Russo, M. Sperduto, C. Sutera, C. Ventura
Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Catania, Italy

L. Barion, G. Ciullo, M. Contalbrigo, P. Lenisa, A. Movsisyan, F. Spizzo, M. Turisini
Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara e Dipartimento di Fisica dell'Università, Ferrara, Italy

F. De Persio, E. Cisbani, C. Fanelli, F. Garibaldi, F. Meddi, G. M. Urciuoli
Istituto Nazionale di Fisica Nucleare, Sezione di Roma e Gruppo Collegato Sanità, e Università La Sapienza, Italy

S. Anefalos Pereira, E. De Sanctis, D. Hasch, V. Lucherini, M. Mirazita, R. Montgomery, S. Pisano
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, P.O. 13, 00044 Frascati, Italy

G. Simi
Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Padova, Italy

A. D'Angelo, L. Colaneri L. Lanza, A. Rizzo, C. Schaerf, I. Zonta
Istituto Nazionale di Fisica Nucleare, Sezione di Roma-TorVergata e Dipartimento di Fisica dell'Università, Roma, Italy

D. Calvo, A. Filippi
Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Torino, Italy

M.Holtrop, R. Peremuzyan
University of New Hampshire, Durham NH 03824, USA

D. Glazier, D. Ireland, B. McKinnon, D. Sokhan
University of Glasgow, Glasgow G12 8QQ, United Kingdom

A. Afanasev, B. Briscoe
The George Washington University, Washington, D.C., 20052

N. Kalantarians
Department of Physics, Hampton University, Hampton VA 23668, USA

L. Weinstein
Old Dominion University, Department of Physics, Norfolk VA 23529, USA

P. Beltrame, A. Marphy, D. Watts, L. Zana
Edinburgh University, Edinburgh EH9 3JZ, United Kingdom

K. Hicks
Ohio University, Department of Physics, Athens, OH 45701, USA

*Contact Person, email: Marco.Battaglieri@ge.infn.it
†Spokesperson

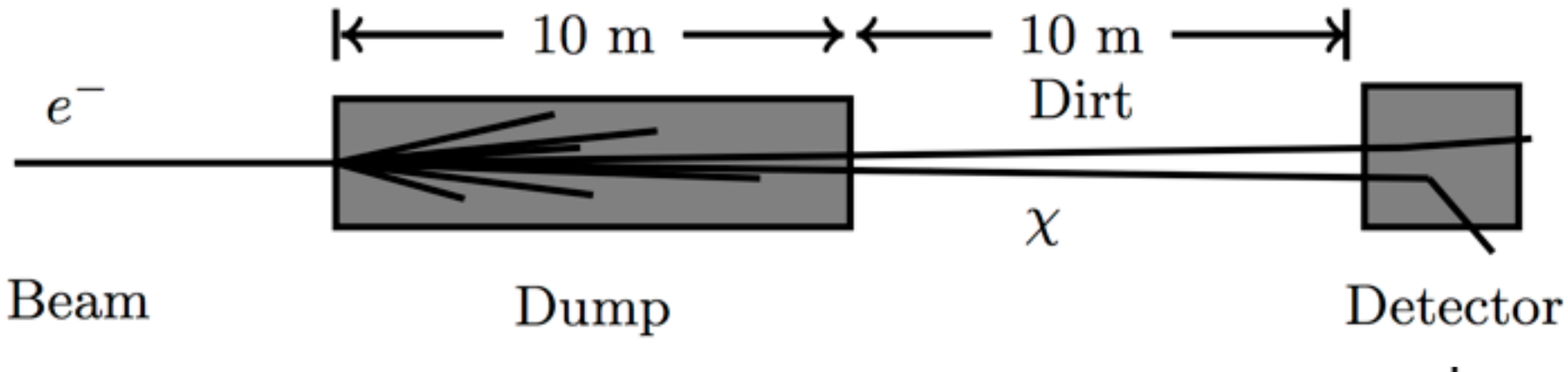
80+ members (Canada, US, UK, Italy)

Spokespeople:

Marco Battaglieri
Rafaella De Vita
Andrea Celentano
Eder Izaguirre
GK

Basic Concept

Jefferson Lab Setup

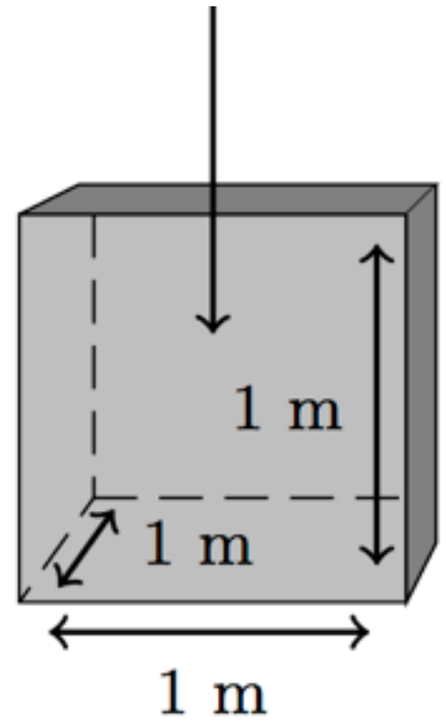


12 GeV beam energy

Average current ~ $100\mu A$

10^{22} EOT (~ 1 yr.)

Fiducial volume $= 1\text{m}^3$



Plastic Scintillator
@ 15 m.w.e. depth

Basic Concept

Beam Correlated Backgrounds

Neutrinos from beam π/μ

Nuclear recoil cut $E_{recoil} > 10$ MeV

$(0.1 - 1)$ BG event per $10^{22}\, e^-$

Consistent with SLAC mQ rates

Ejected Neutrons

$E_n < 10\,\mathrm{MeV}$, below cuts

$\Longrightarrow$ **Beam backgrounds very small**

GEANT validation in progress

Basic Concept

Beam Uncorrelated Backgrounds

Cosmic muons

Decays in flight ~ 0.005 Hz (veto)

Stopped decays ~ 100 μs cut (veto)

Cosmogenic neutrons

$$\Phi(E > 10\ \mathrm{MeV}) \approx 2 \times 10^{-2}\mathrm{m}^{-2}\mathrm{s}^{-1}$$

Consistent with CDMS-SUF (~ 10 m.w.e)

Pulsed beam : livetime 10^3 s , $\mathcal{O}(10)$ cosmic BG events

$\Longrightarrow$ ***Small, Measurable***

Sensitivity ~ 10 events signal yield

Basic Concept

Signal Yield

$$N_{\rm sig} = n_T \int_{E_{\rm cut}}^{E_B} dE_R \int_{E_\chi^{\rm min}(E_R)} dE_\chi \int_{\rm Det} d\Omega\, \ell(\Omega) \frac{d^2 N_\chi}{d\Omega\, dE_\chi} \frac{d\sigma}{dE_R}$$

Target Density

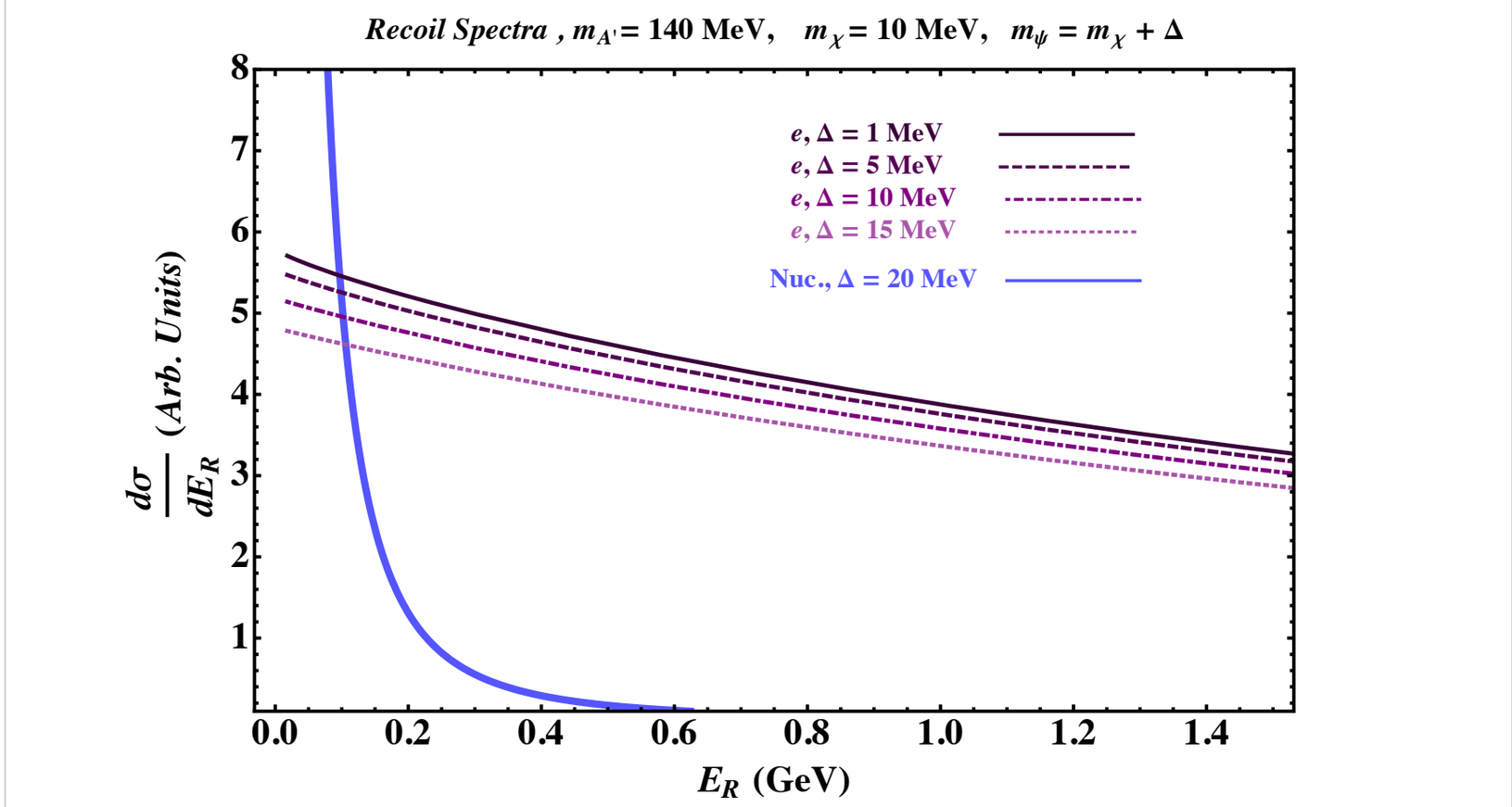
Detector Threshold

Acceptance & DM path

Production Distribution $\sim \epsilon^2$

Recoil Profile $\sim \epsilon^2 \alpha_D$

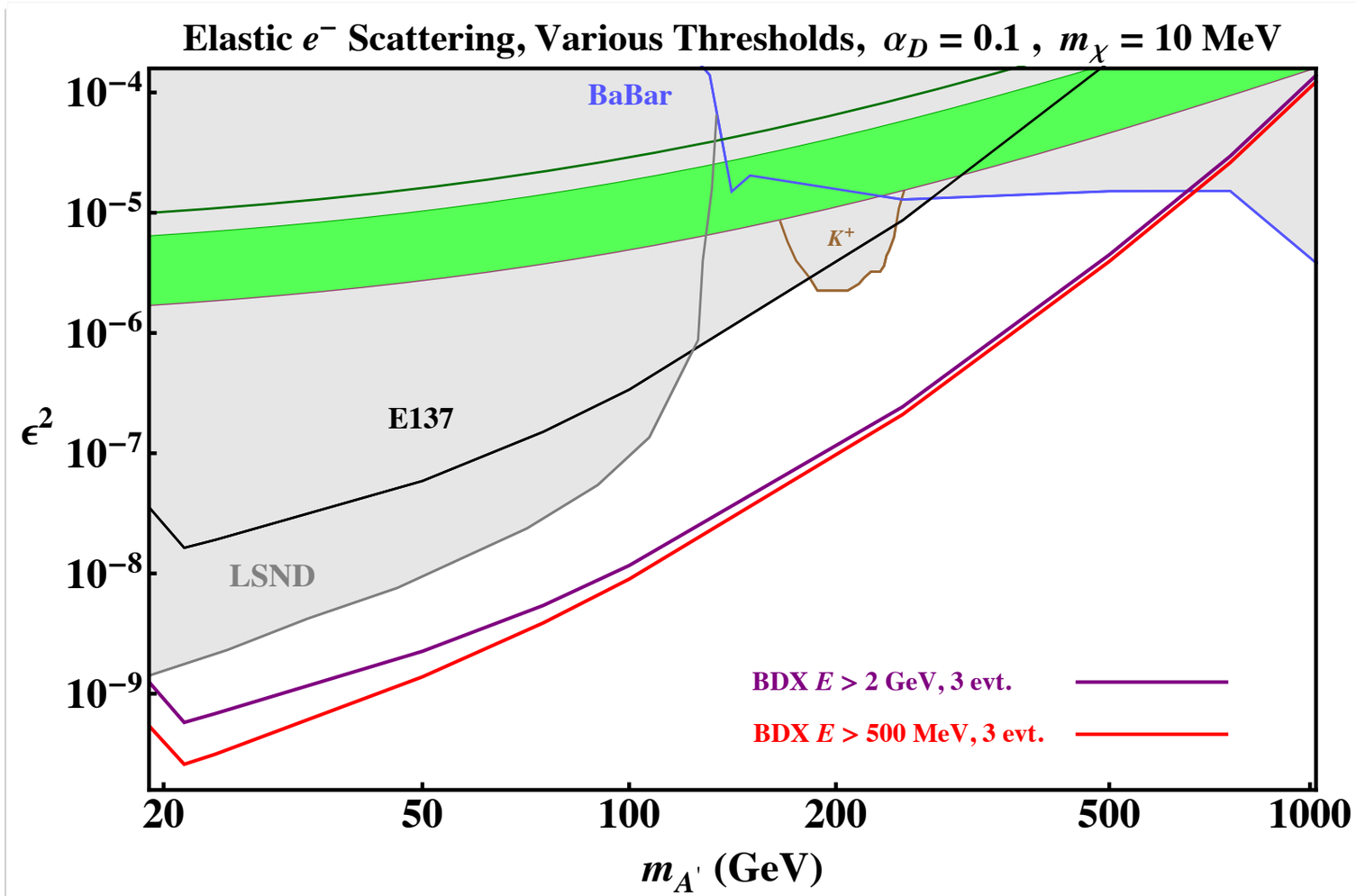
For electron-recoils or inelastic signals:

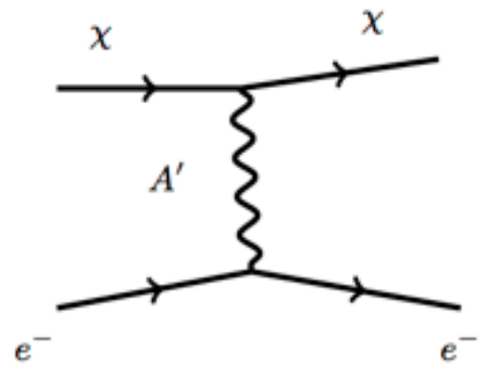


but, for quasi-elastic nucleon scattering:

Will need some background reduction strategies

BDX Elastic Electron Channel
Sensitivity Projection JLab

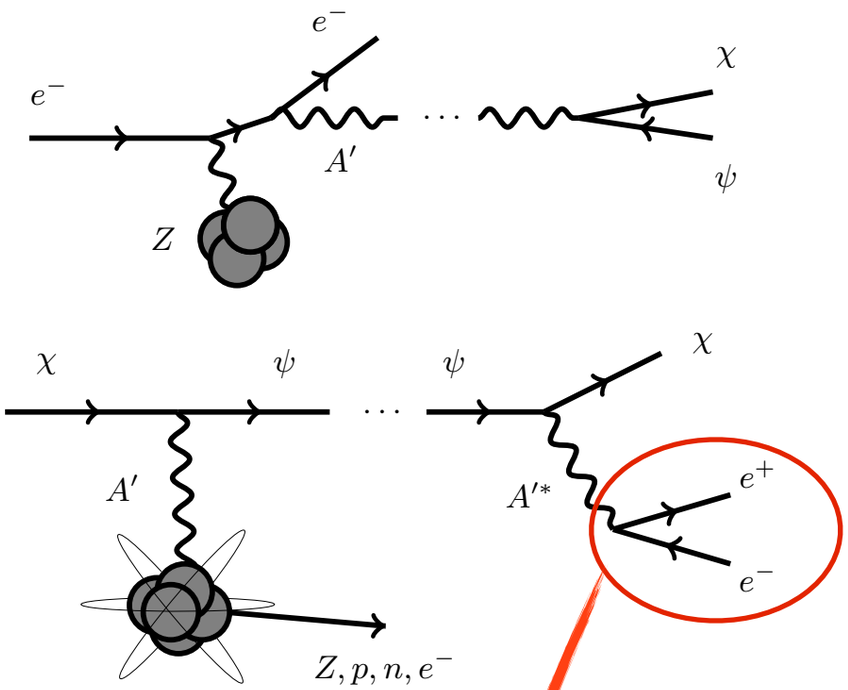


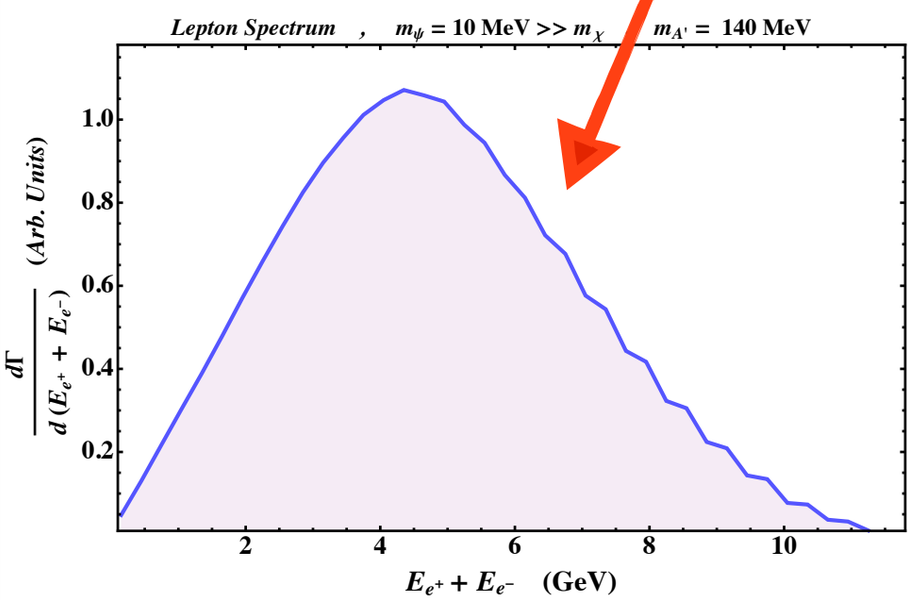


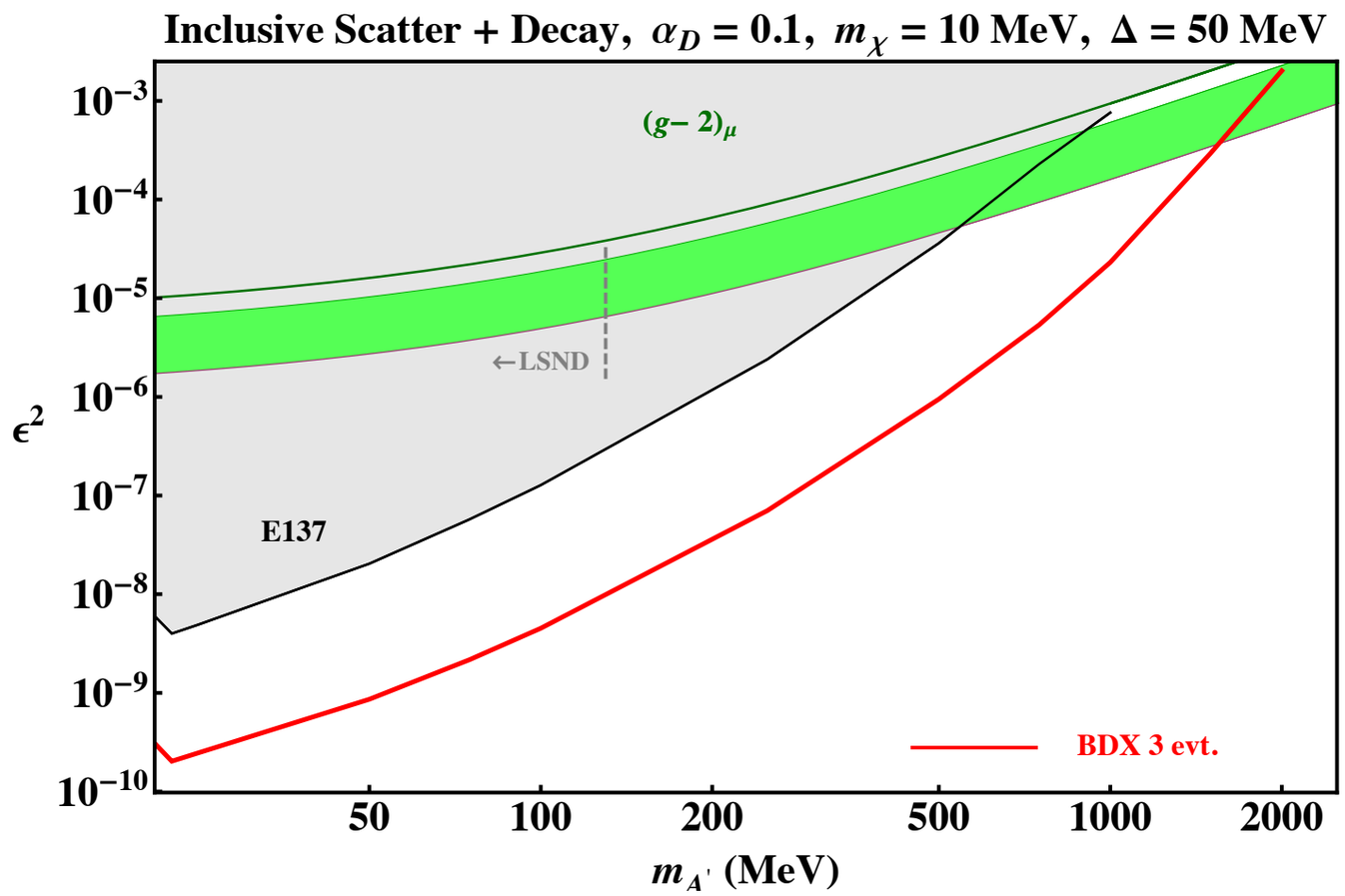
10^{22} EOT $\quad$ $1\,\mathrm{m}^3$ detector

Inelastic Scattering

Sensitivity Projection, inclusive of all targets (*e*,*p*,*Z*)



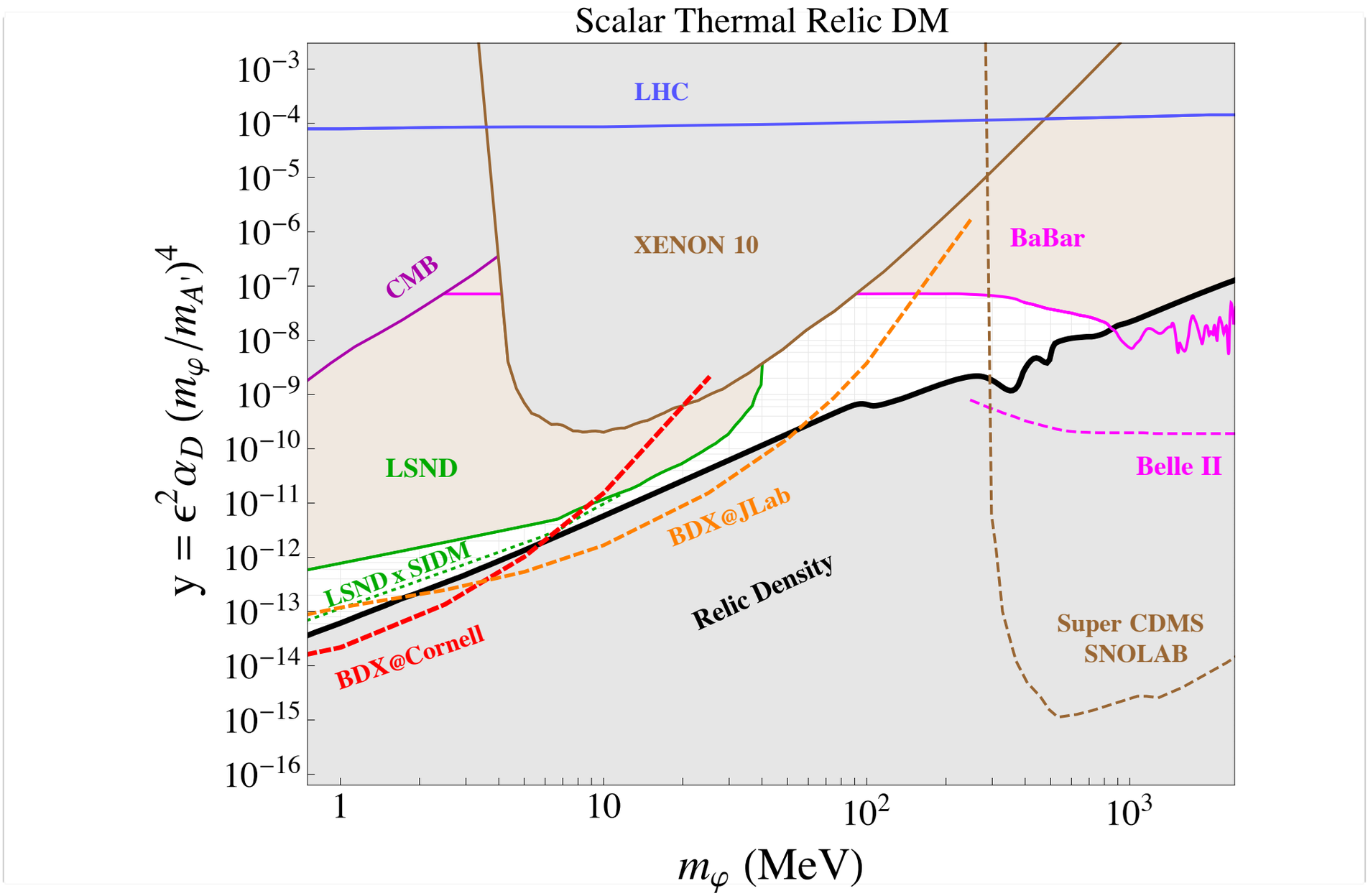




10^{22} EOT $1\,\mathrm{m}^3$ detector

Comparable reach w/ Cornell Synchrotron @ 12 GeV

Thermal Target Reach

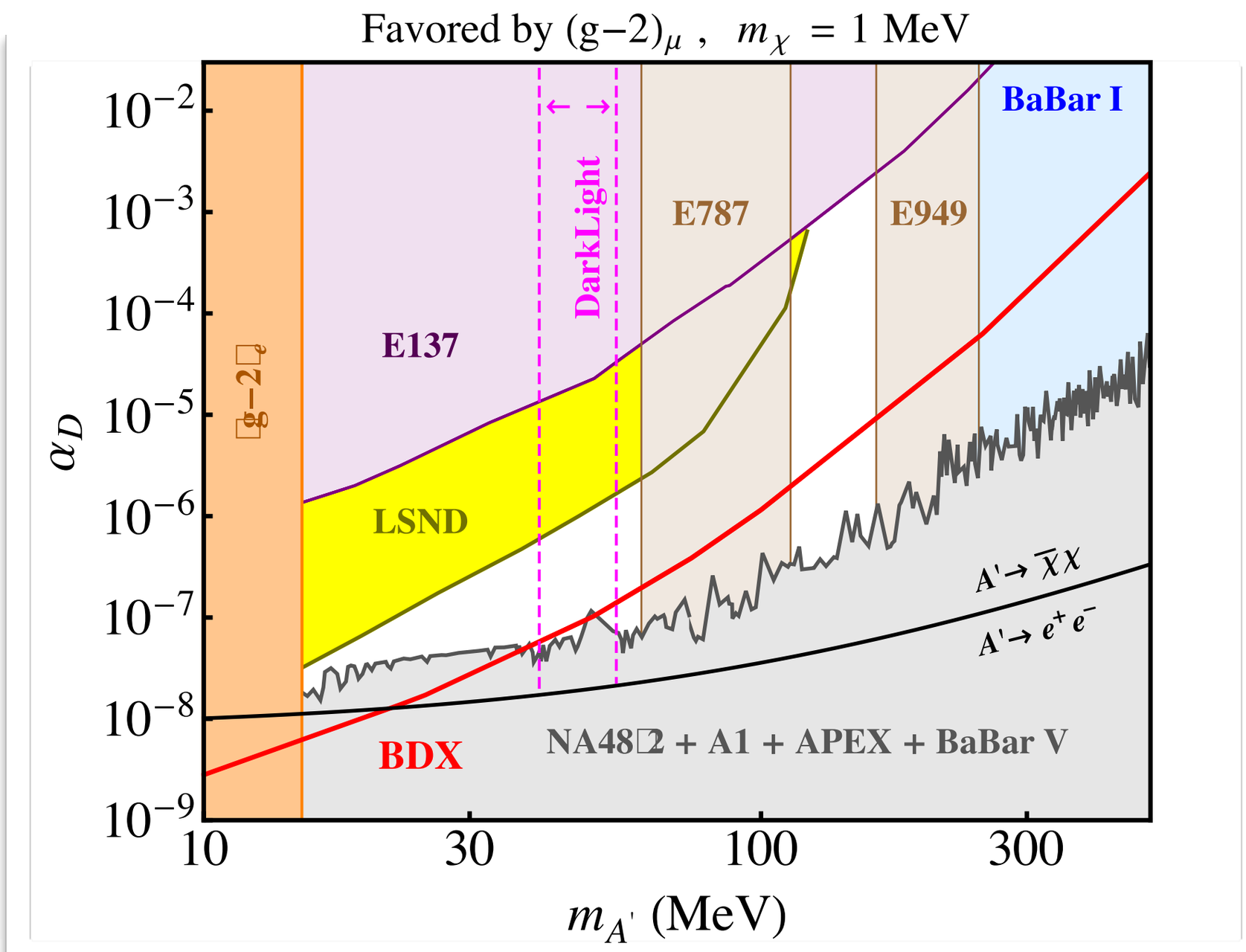


10^{22} EOT

BaBar, LSND, LHC, E137,BDX: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$

Cornell e-linac, 400 MeV beam

Model Independent $(g-2)_\mu$ Coverage



Fix : $\epsilon \rightarrow \epsilon_{(g-2)_\mu}$

Summary

Electron beam-dump searches are powerful

Convincing discovery potential

Negligible beam BG, reducible cosmic BG

High luminosity & low cost

Can probe light thermal DM

Cover scenarios other methods can't

Complement visible *A'* searches

Cover nearly all remaining $(g-2)_\mu$ territory

Run parasitically at existing facilities

Jefferson Lab, Cornell, SLAC, Mainz, Fermilab (?)

Stay tuned

BDX positive review from JLAB PAC-42