Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Dark Matter Production at High Intensity Facilities

Gordan Krnjaic

Snowmass Community Planning Meeting, Session #108, Oct 6, 2020

Overview

Preliminaries

B/K-Factories

Beam Dump Production

Missing Energy/Momentum

Overview

Preliminaries

B/K-Factories

Beam Dump Production

Missing Energy/Momentum

What kind of DM can we probe?

High intensity facilities: Ecm < few GeV

Kinematically produce sub-GeV DM

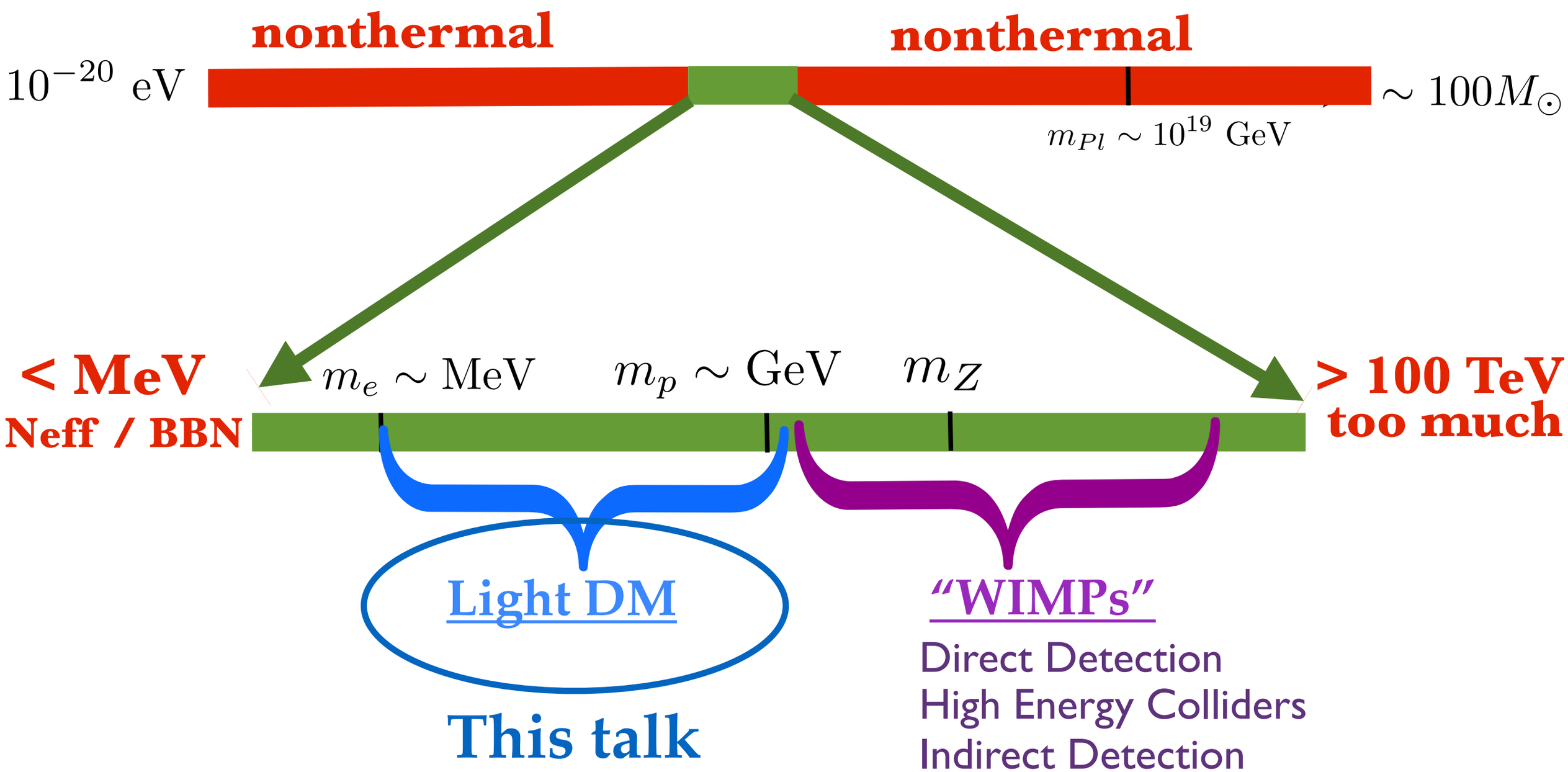
Need "large" couplings to visible matter

Accelerators sensitive to BSM couplings $g \gtrsim 10^{-4}$

Therefore { Any* DM candidate that can be made in accelerators was in equilibrium with SM in the early universe $n_\chi \sim n_\gamma \sim T^3$

Model independent consequence

Equilibrium Narrows Mass Range!



Light DM vs. WIMPs

Light DM must be SM neutral

Else would have been discovered

Light DM requires light new force carriers "mediators"

Must annihilate away huge thermal density. Weak force too weak:

$$\sigma v \sim G_F^2 m_\chi^2 \sim 10^{-29}\,\mathrm{cm}^3\,\mathrm{s}^{-1}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

need $\sigma v \sim 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ to avoid overproduction

Annihilation through renormalizable "portal" interactions

Higher dimension operators have same problem as weak force

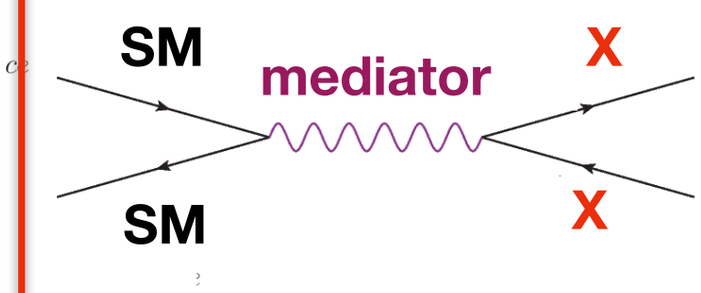
Light mediators are not optional!

Final states to look for

Invisible, non-SM

Dark Matter production

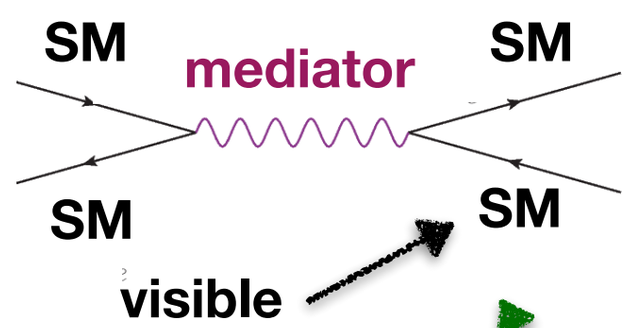
Producing stable particles that could be (all or part of) Dark Matter



Visible, SM

Production of portal-mediators that decay to SM particles

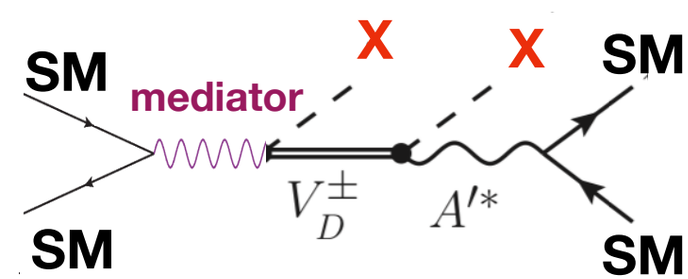
Systematically exploring the portal coupling to SM particles



Mixed visible-invisible

Production of "rich" dark sectors

Testing the structure of the dark sector



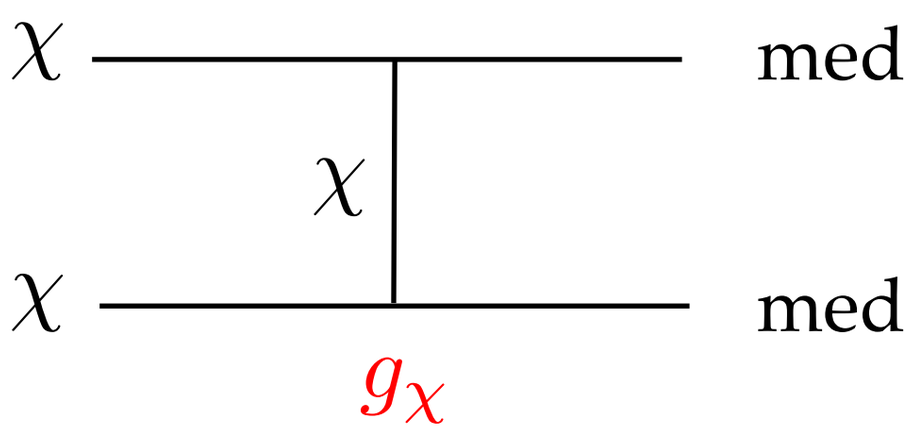
This Talk

Talk by Stefania Gori in 127

Who's Heavier: DM or Mediator?

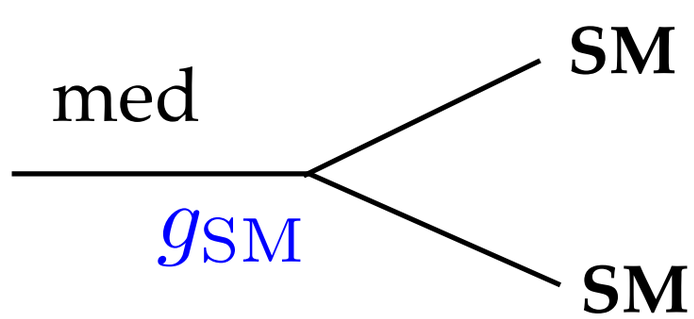
"Secluded" Annihilation

$m_\chi > m_{\rm med}$



No clear experimental target

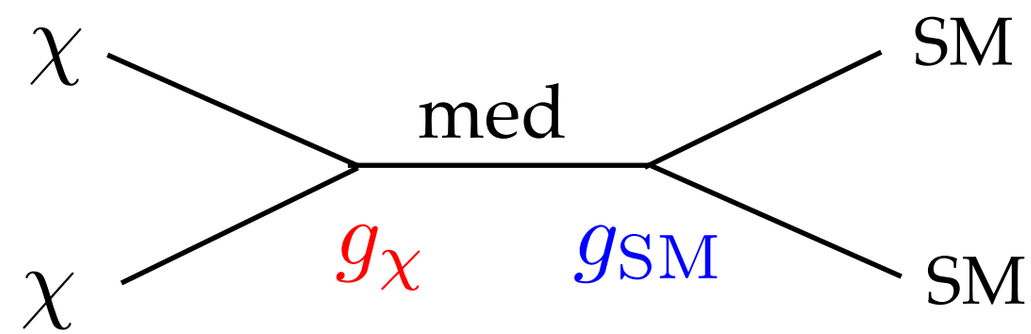
Abundance set by g_χ



Mediator decays **visibly**

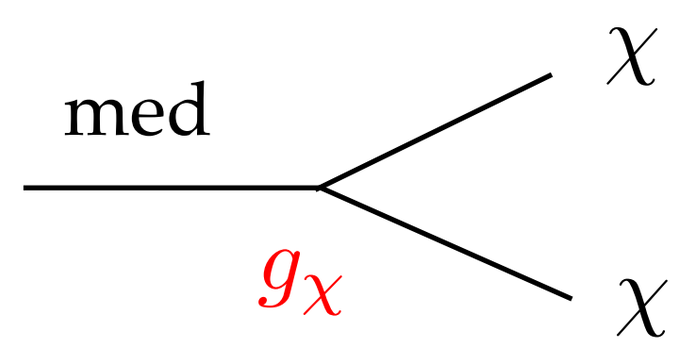
Direct Annihilation

$m_\chi < m_{\rm med}$



Predictive thermal targets

Abundance depends on $g_{\rm SM}$



Mediator decays **invisibly***

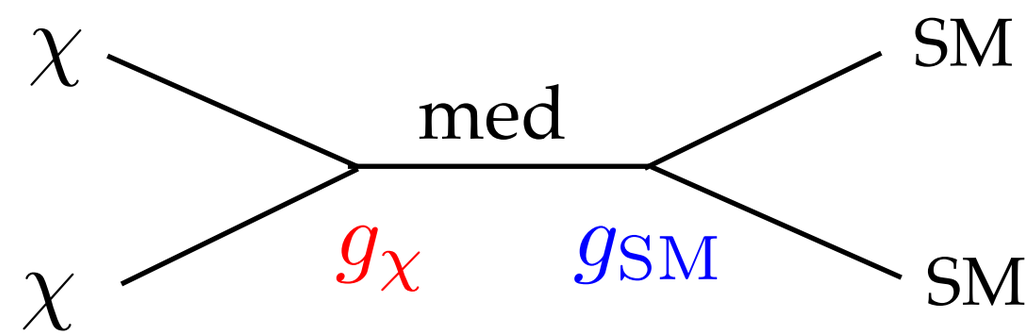
Who's Heavier: DM or Mediator?

This Talk

Same interaction produces DM
in early universe and in laboratory

Direct Annihilation

$m_\chi < m_{\rm med}$



Predictive thermal targets

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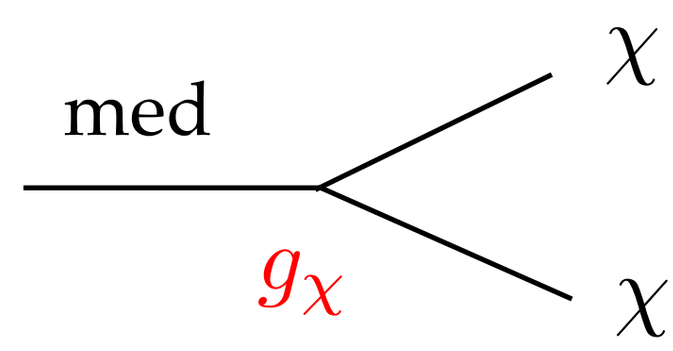


Mediator decays **invisibly***

Minimal Renormalizable Mediators

Scalar ϕ mixes with Higgs Boson

Couples to SM **masses** $\epsilon\phi\frac{m_f}{v}\bar{f}f$

Dark photon A' mixes with visible photon

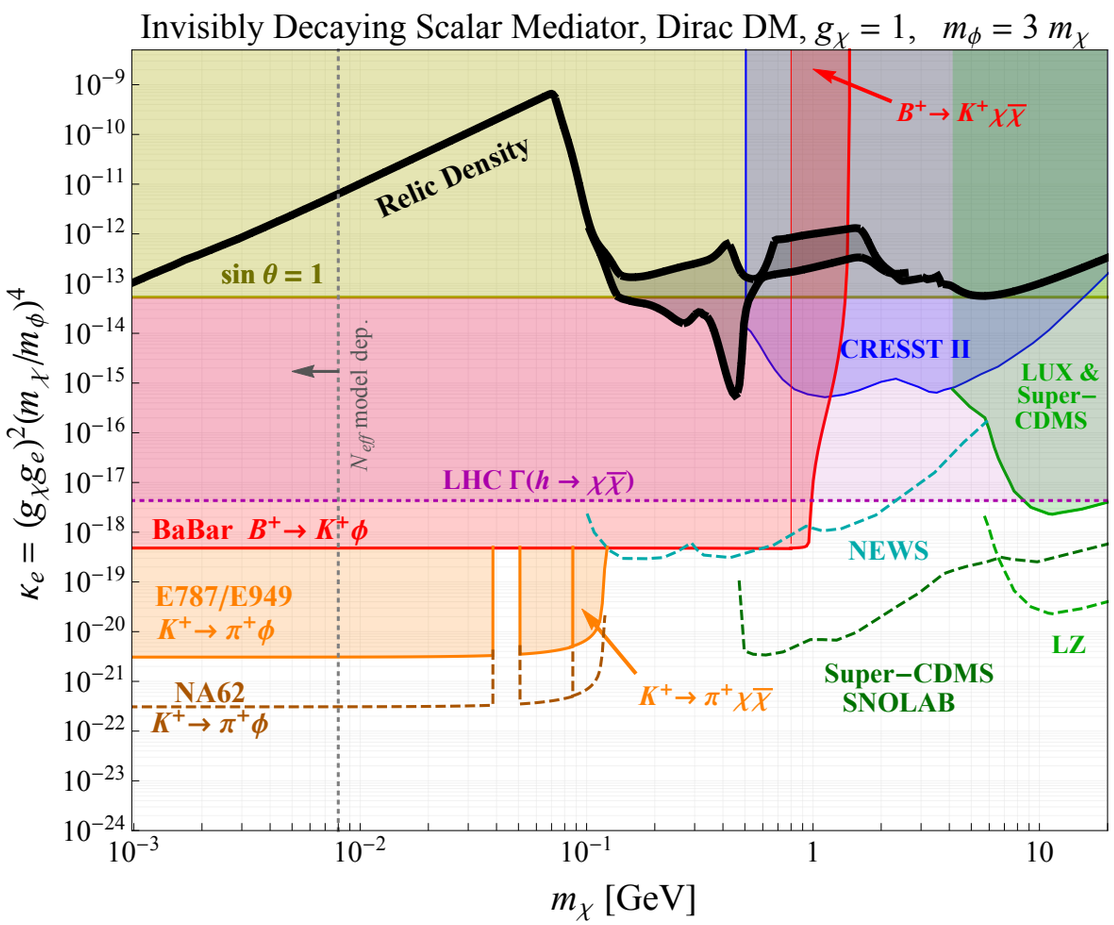
Couples to **EM** current $\epsilon A'_\mu J^\mu_{\rm EM}$

New force V directly couples to DM & SM

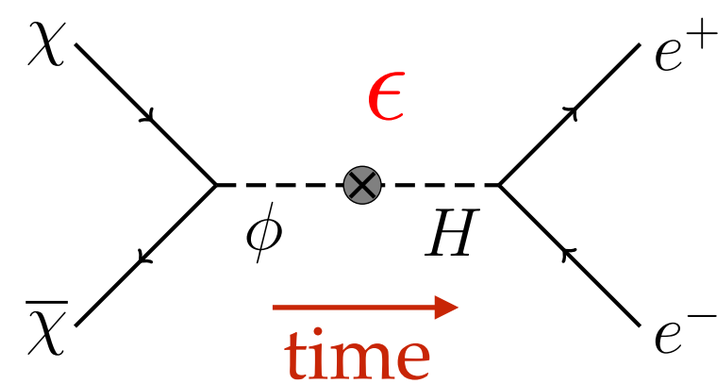
Couples to **different (non EM)** current $J^\mu_{\rm SM}$

$$B-L\ ,\ L_i-L_j\ ,\ B-3L_i$$

Scalar Force: Direct-Annihilation Ruled Out!

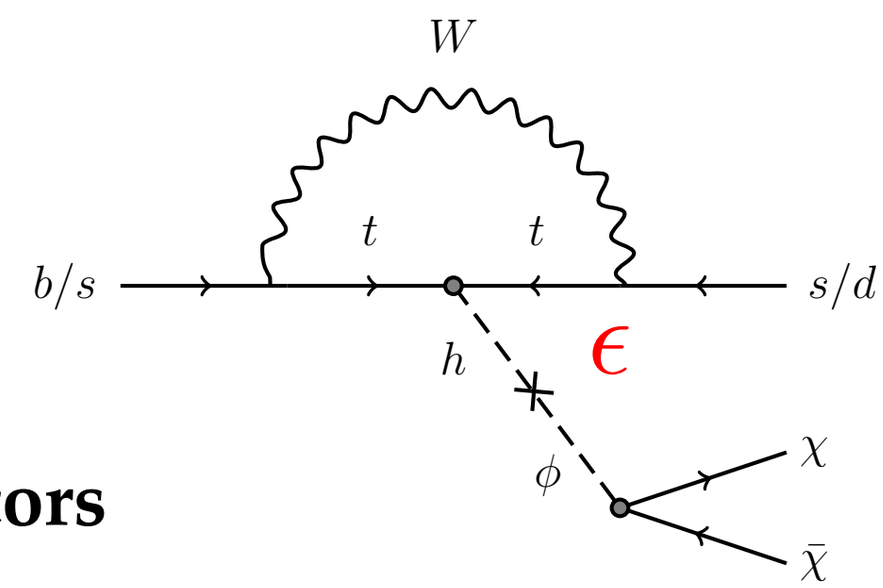


Interaction that sets the DM direct annihilation rate



enhances dangerous decays

$$K \to \pi + \text{invisible}$$



Conclusion independent of DM particle

GK arXiv:1512.04119

Can have (non-Higgs) flavored scalar mediators

Batell, Freitas, Ismail, McKeen 1712.10022

What Kind of Mediator?

Neutrality and renormalizability require "portal" interactions

~~**Scalar ϕ mixes with Higgs Boson**~~

~~Couples to SM **masses** $\epsilon\phi\frac{m_f}{v}\bar{f}f$~~

Dark photon A' mixes with visible photon

Couples to **EM** current $\epsilon A'_\mu J^\mu_{\rm EM}$

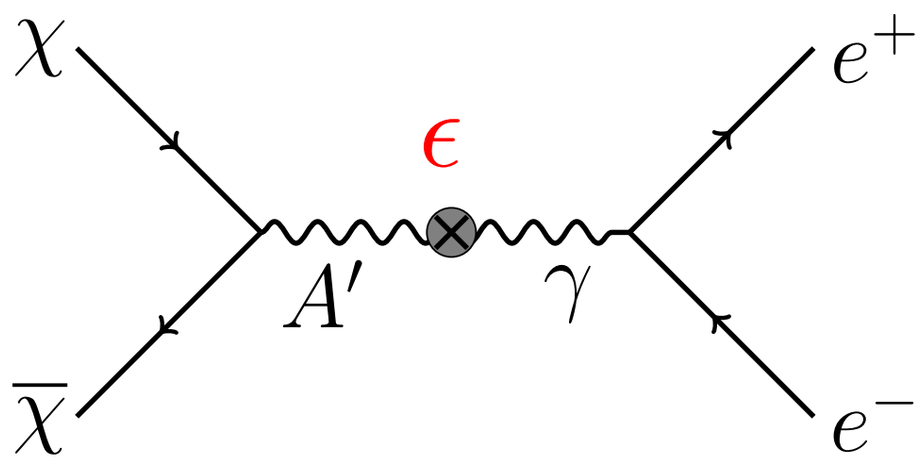
New force V directly couples to DM & SM

Couples to **different (non EM)** current $J^\mu_{\rm SM}$

$$B-L\ ,\ L_i-L_j\ ,\ B-3L_i$$

New force models all similar to A′ & also couple to neutrinos

Representative Scenario: Dark Photon Mediator A'



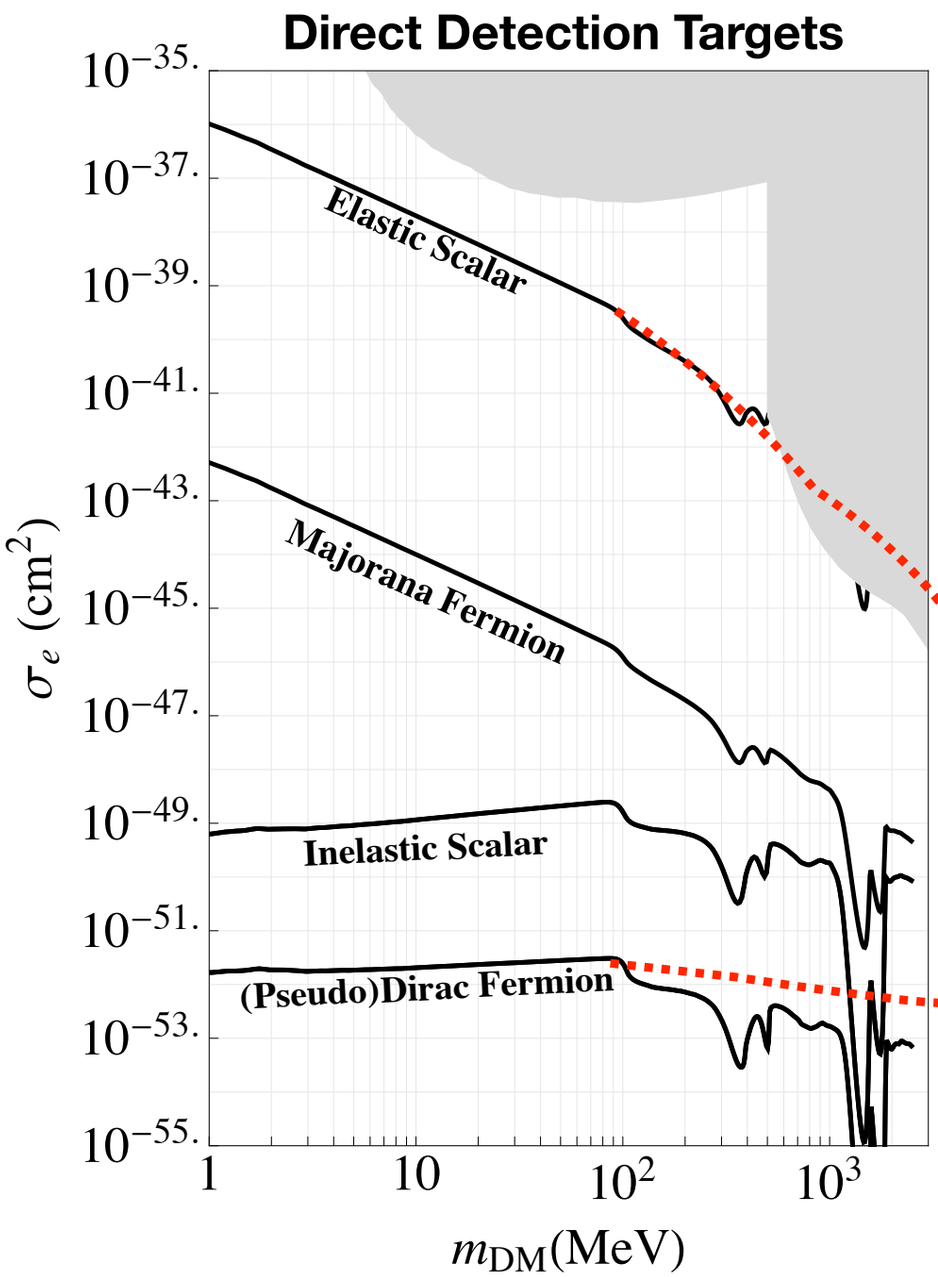
Critical freeze out value of y for each DM candidate

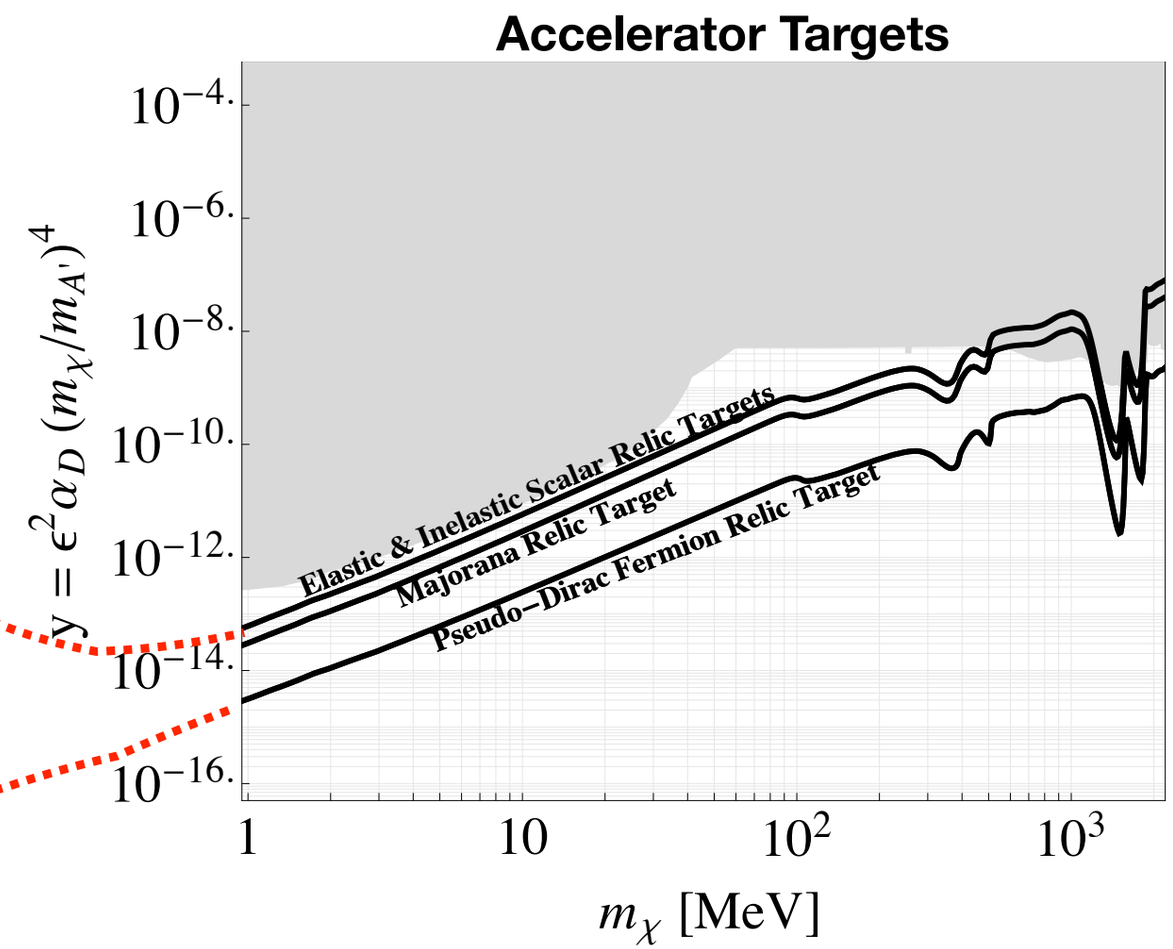
$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2} \qquad y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

Direct annihilation $m_{A'} > m_\chi$ Unitarity $\alpha_D \lesssim 1$

$\Longrightarrow$ Minimum SM coupling ϵ required for thermal freeze out

Why Accelerators? Accessible Thermal Targets





non-relativistic cross sections can be loop- or velocity- suppressed

Relativistic freeze-out kinematics

Calculable dark matter rate

No astrophysical uncertainties

All thermal targets within reach

Cosmic Visions Report https://arxiv.org/abs/1707.04591

Overview

Preliminaries

B/K-Factories

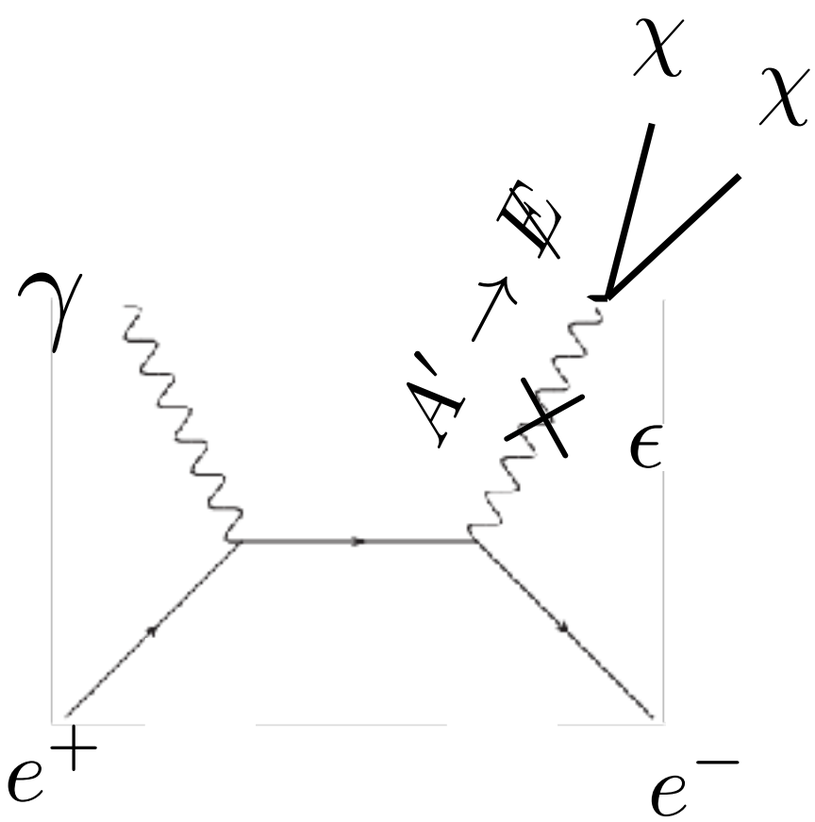
Observable: initial & final state four vectors

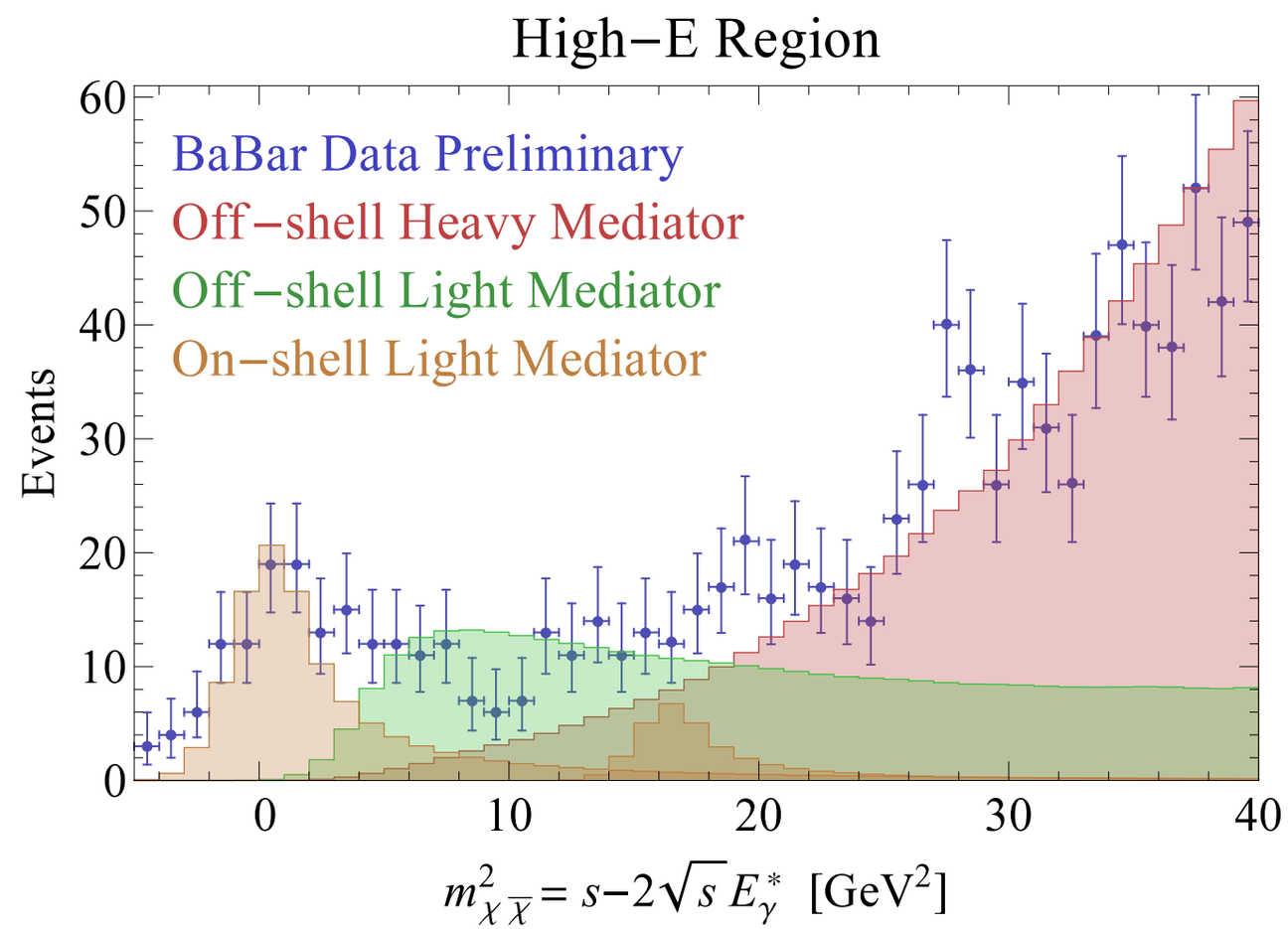
Beam Dump Production

Missing Energy/Momentum

B-Factories

"Traditional" mono-photon
+missing energy search





$$E_{\rm cm} \approx 10\,{\rm GeV}$$

$$\mathcal{L} \sim \mathcal{O}(10)\,{\rm ab}^{-1}$$

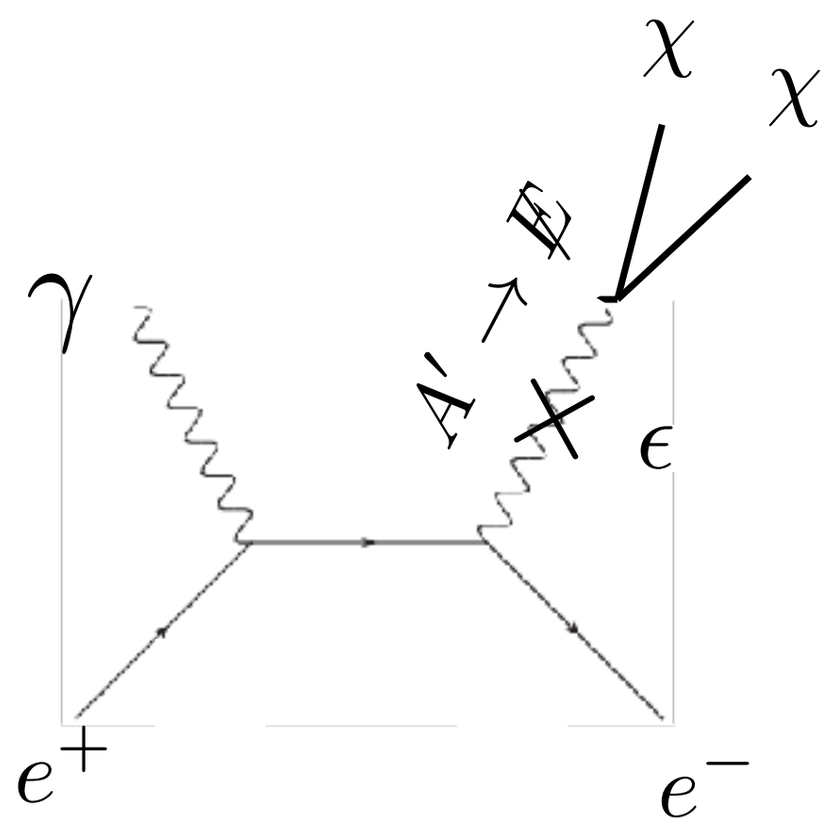
$$m^2_{\chi\chi} = (p_\gamma - p_{e^+} - p_{e^-})^2$$

BABAR, BELLE-II, BES-III

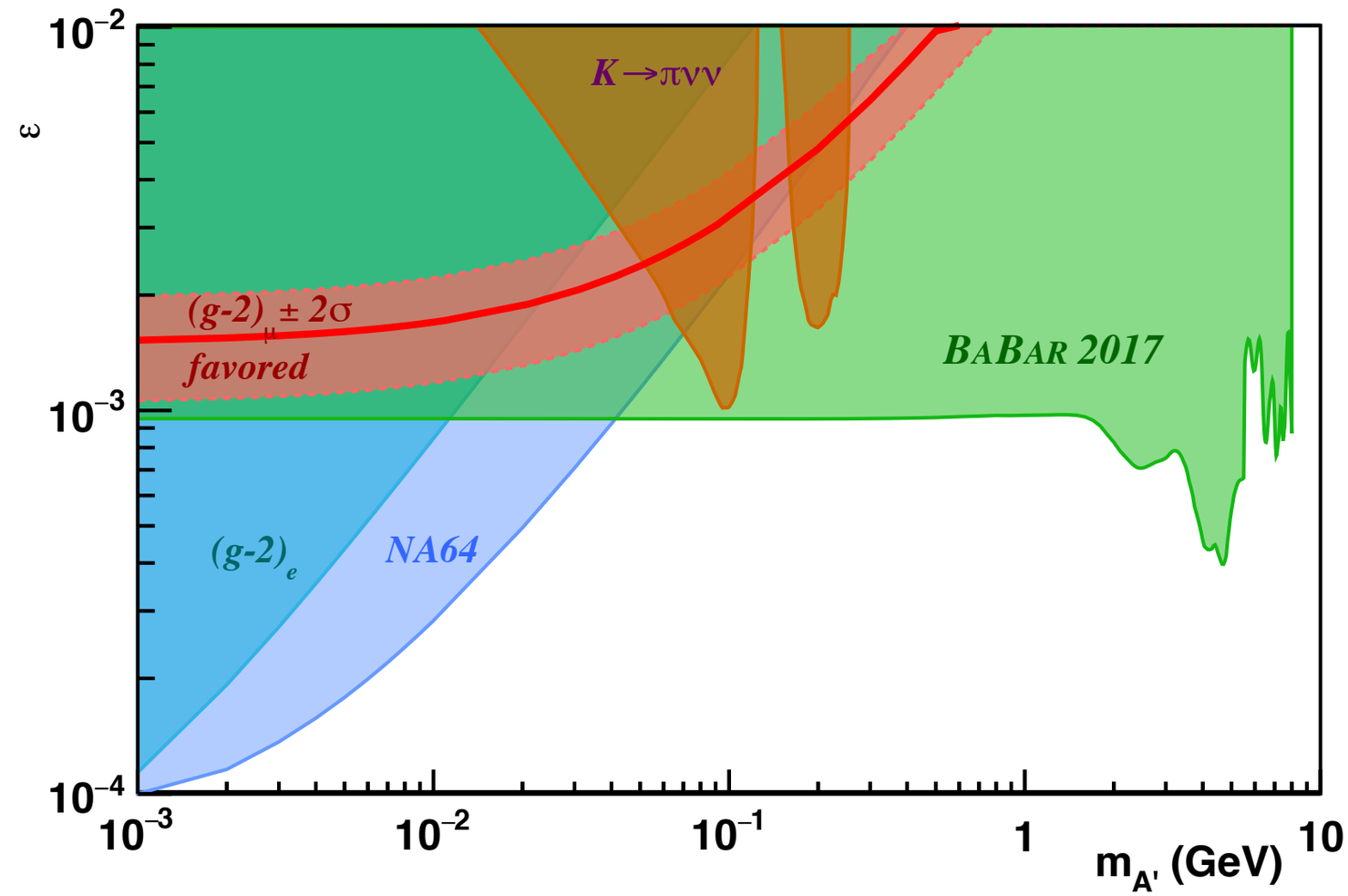
Izaguirre, GK, Schuster, Toro 1307.6554
Essig, Mardon, Papucci, Volansky Zhong 1309.5084

B-Factories

"Traditional" mono-photon
+missing energy search



signal rate $\propto \epsilon^2$



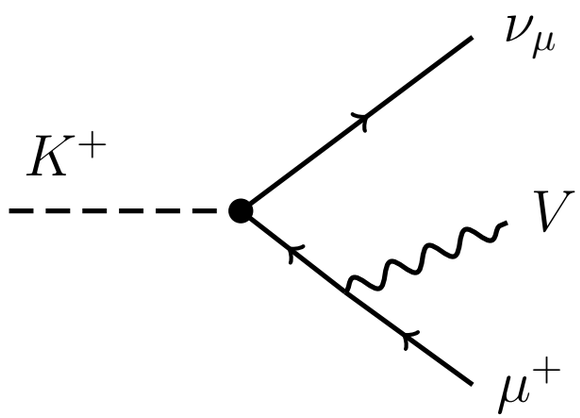
BaBar Collaboration 1702.03327

Belle-II LOI

Izaguirre, GK, Schuster, Toro 1307.6554
Essig, Mardon, Papucci, Volansky Zhong 1309.5084

Kaon Factories NA62 & KLEVER

Secondary kaon beam
Rare DM decays



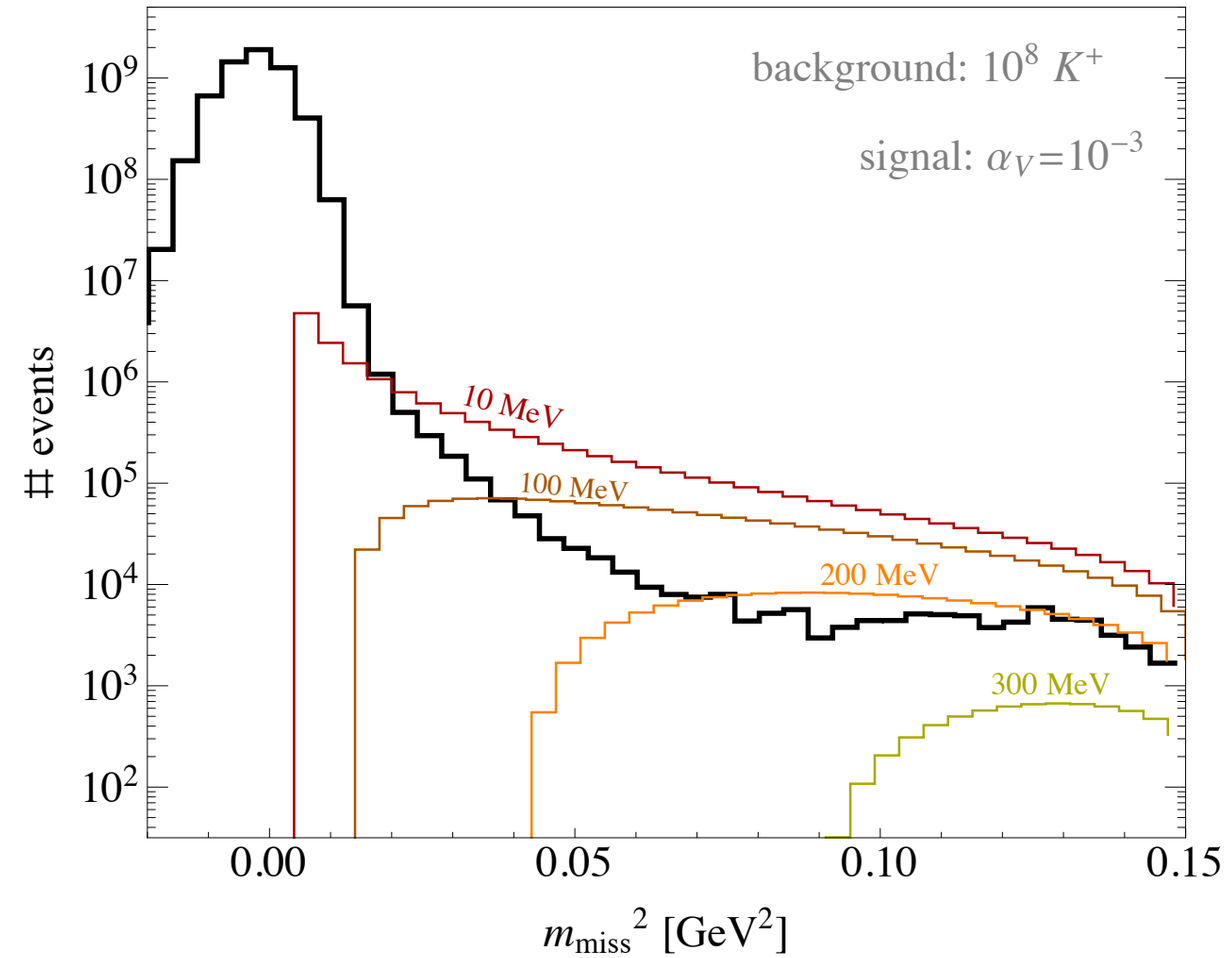
$$K^+ \to \mu^+ \nu_\mu V, \quad V \to \chi\chi$$

Kinematically distinct from main channel

Probe of muon, neutrino philic DM

Measure incident kaon, daughter muon

$$E_K \approx 75\,\mathrm{GeV}, \quad N_K \sim 10^{13} \text{ proj.}$$



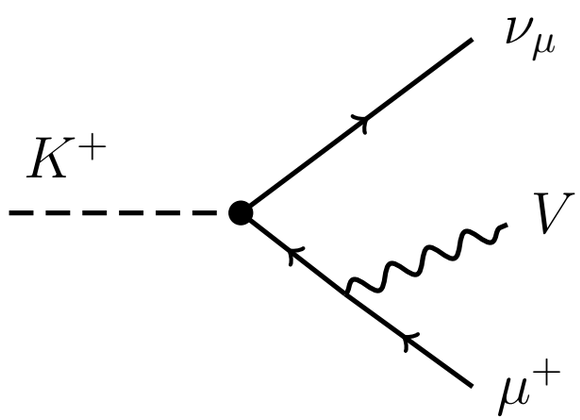
$$m_{\mathrm{miss}}^2 \equiv (p_K - p_\mu)^2$$

$$\text{signal rate} \propto \epsilon^2$$

GK, Marques-Tavares, Redigolo, Tobioka 1902.07715

Kaon Factories NA62 & KLEVER

Secondary kaon beam
Rare DM decays



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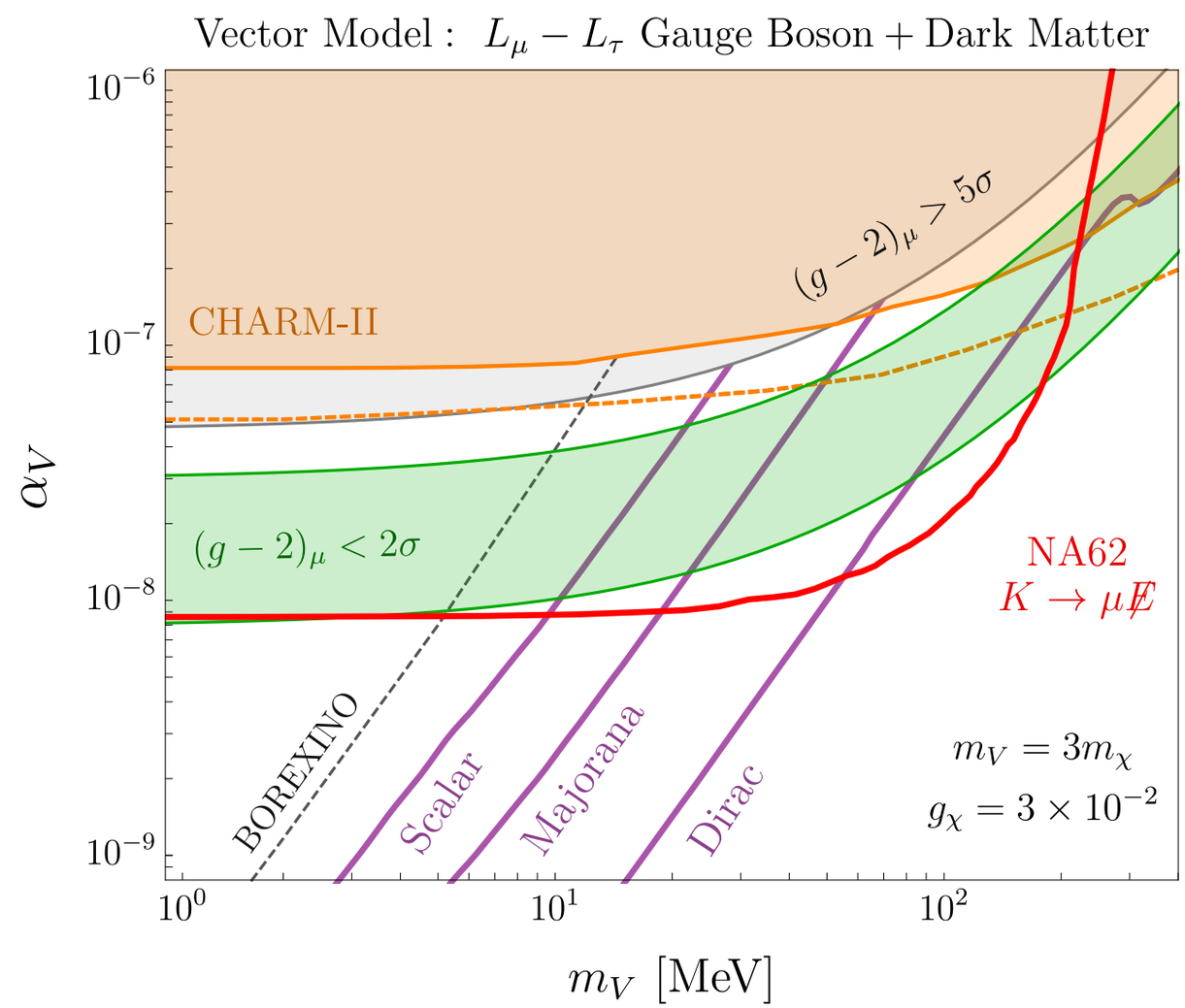


Snowmass2021 LOI:

NA62+KLEVER

Dark Sectors @ Kaon Factories

GK, Marques-Tavares, Redigolo, Tobioka 1902.07715

Overview

Preliminaries

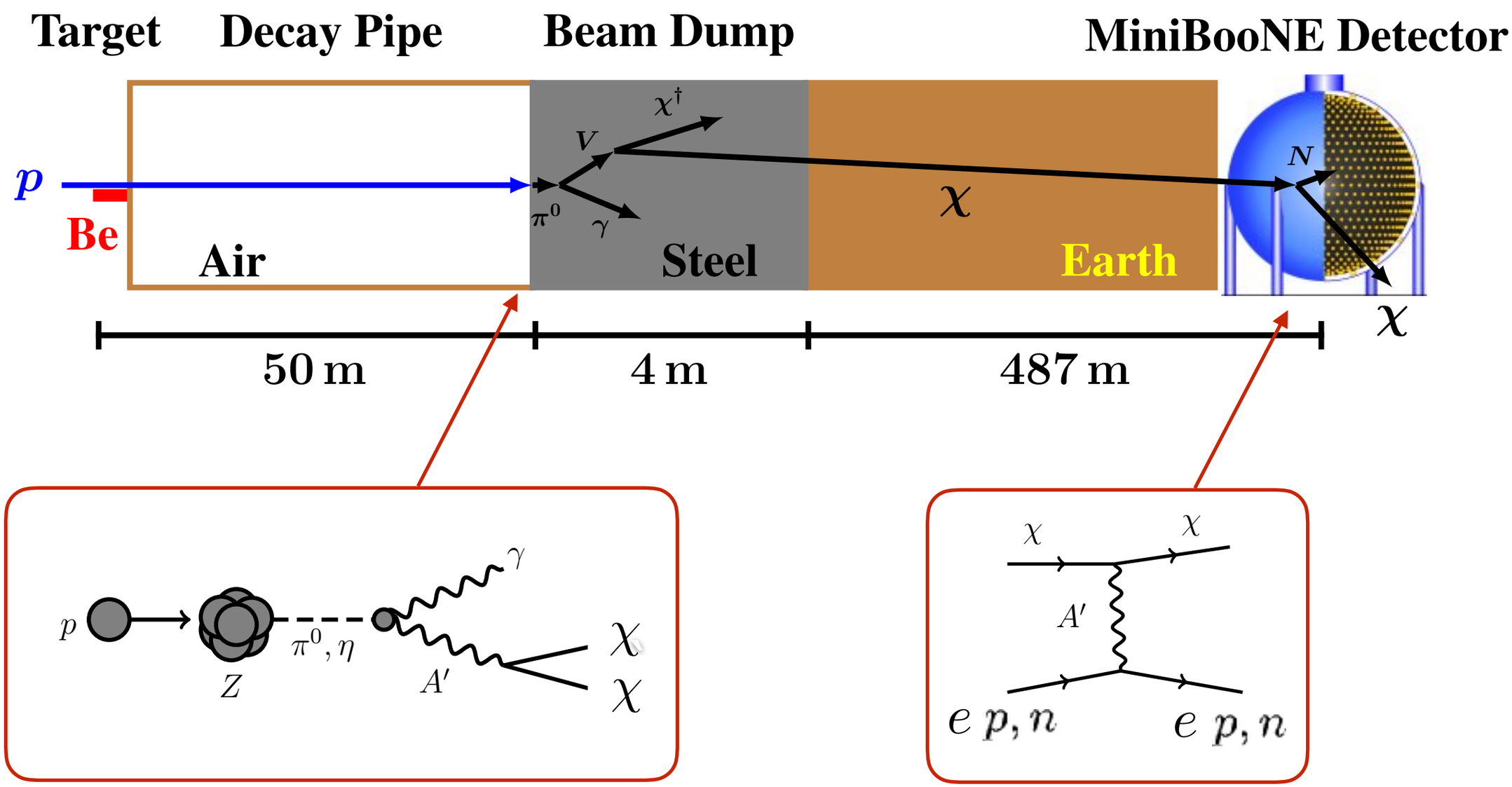
B/K-Factories

Beam Dump Production

Observable: energy deposited in downstream detector

Missing Energy/Momentum

Proton Beam Dumps



Meson decay DIS
Proton bremsstrahlung

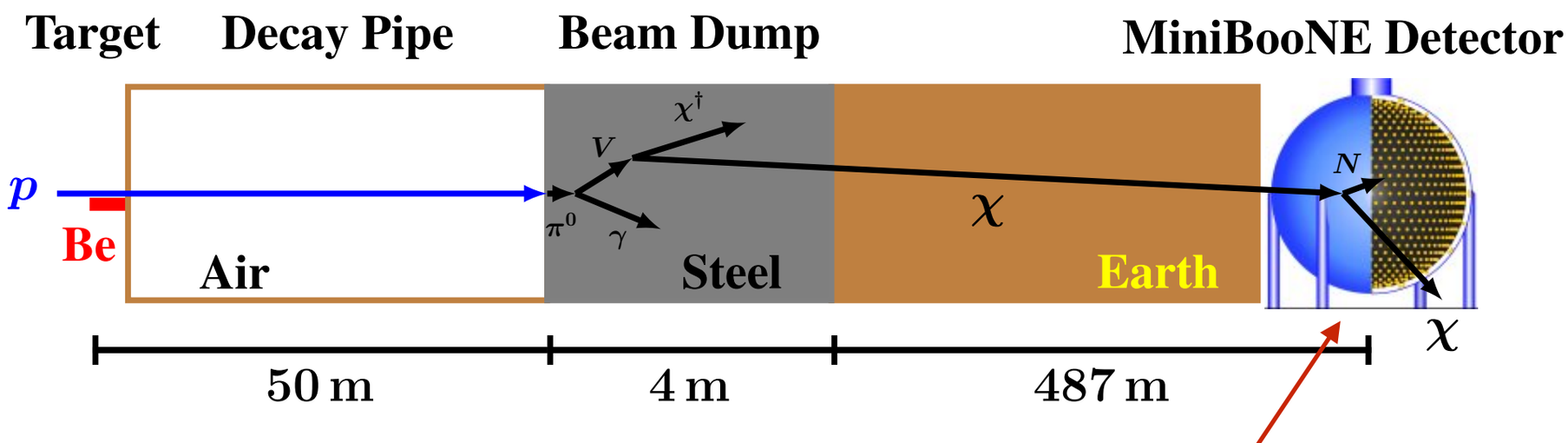
$E_p \sim 1 - 100\text{s GeV}$

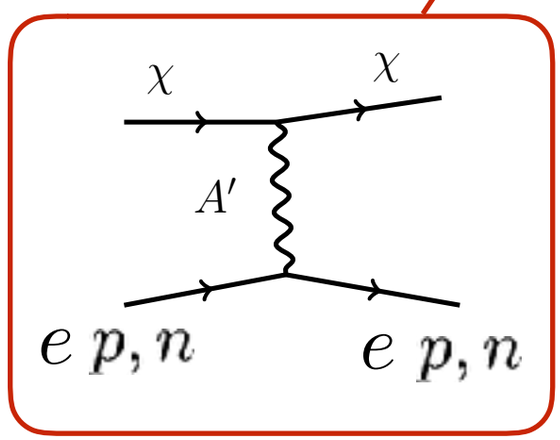
$N_{\text{POT}}\ 10^{20} - 10^{24}$

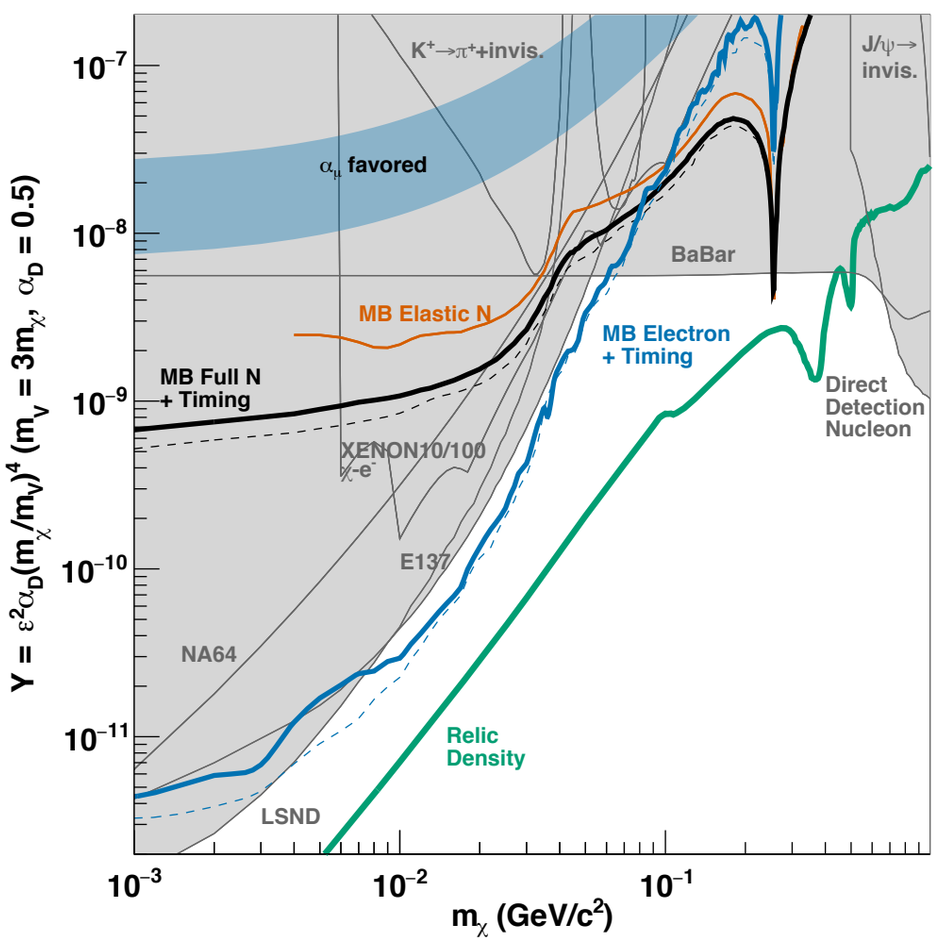
$$[\text{production}] \times [\text{detection}] \propto \epsilon^4$$

Batell, Pospelov, Ritz 0903.0363
deNiverville, Pospelov, Ritz 1107.4580
Batell, deNiverville, McKeen, Pospelov, Ritz 1405.7049
Coloma, Dobrescu, Frugiuele, Harnik 1512.03852
Frugiuele 1701.05464

Proton Beam Dumps







LSND, DUNE, SBND, CCM++

Snowmass2021 LOI:

<GeV proton beams @ FNAL

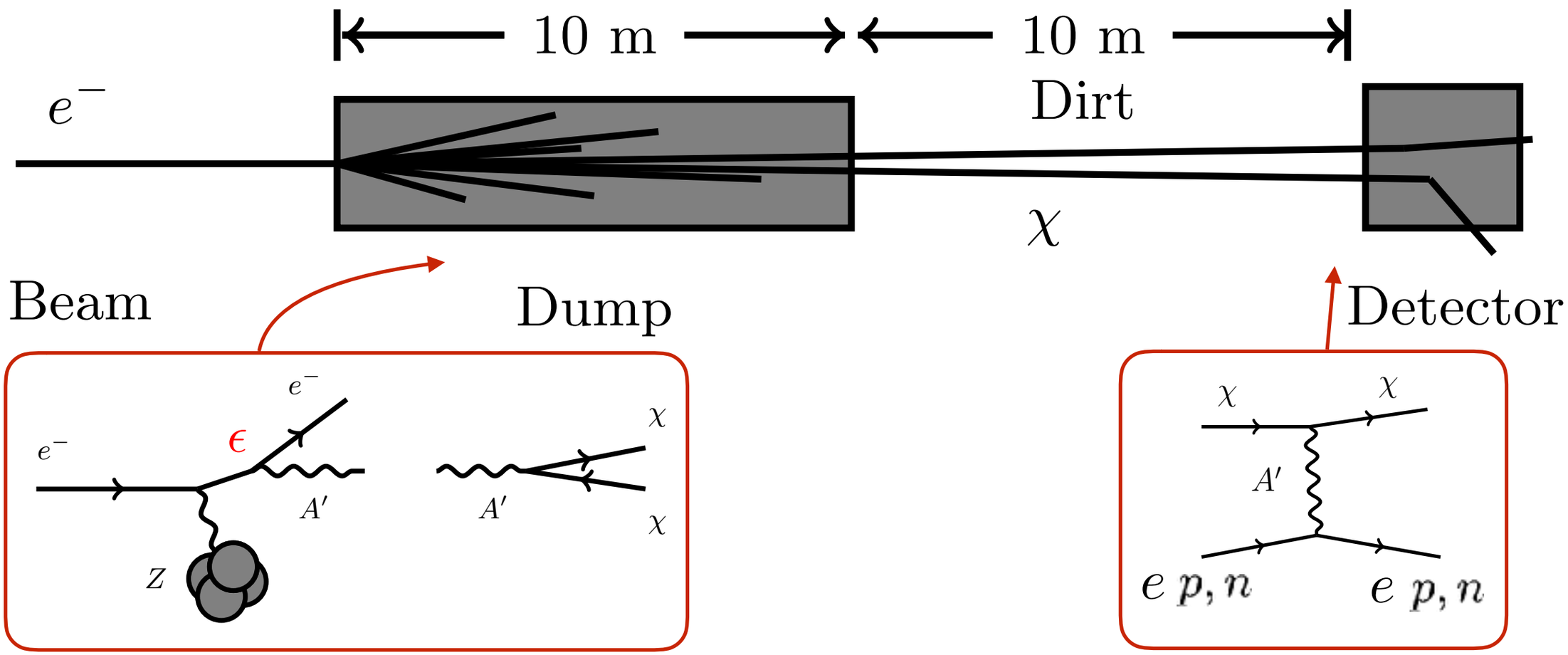
10+ GeV proton beams @ FNAL

LANSCE-PSR

MiniBooNE, Phys. Rev. Lett. 118 (2017) and 1807.06137

See Wooyoung Jong's talk

Electron Beam Dumps



$E_{\rm beam} \sim 10\,{\rm GeV}$ $\quad N_e \sim 10^{22}/{\rm yr}$ $\qquad$ [production] $\times$ [detection] $\propto \epsilon^4$

All neutrino BG EW produced, lower than p-beams

Can run "parasitically" at existing facilities. Experiments: **E137, BDX**

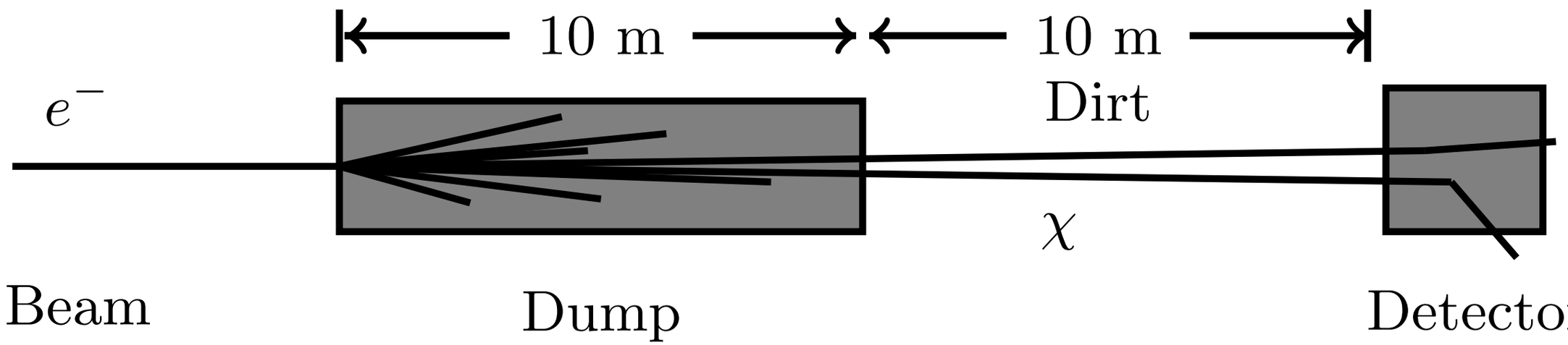
Izaguirre, GK, Schuster, Toro 1307.6554

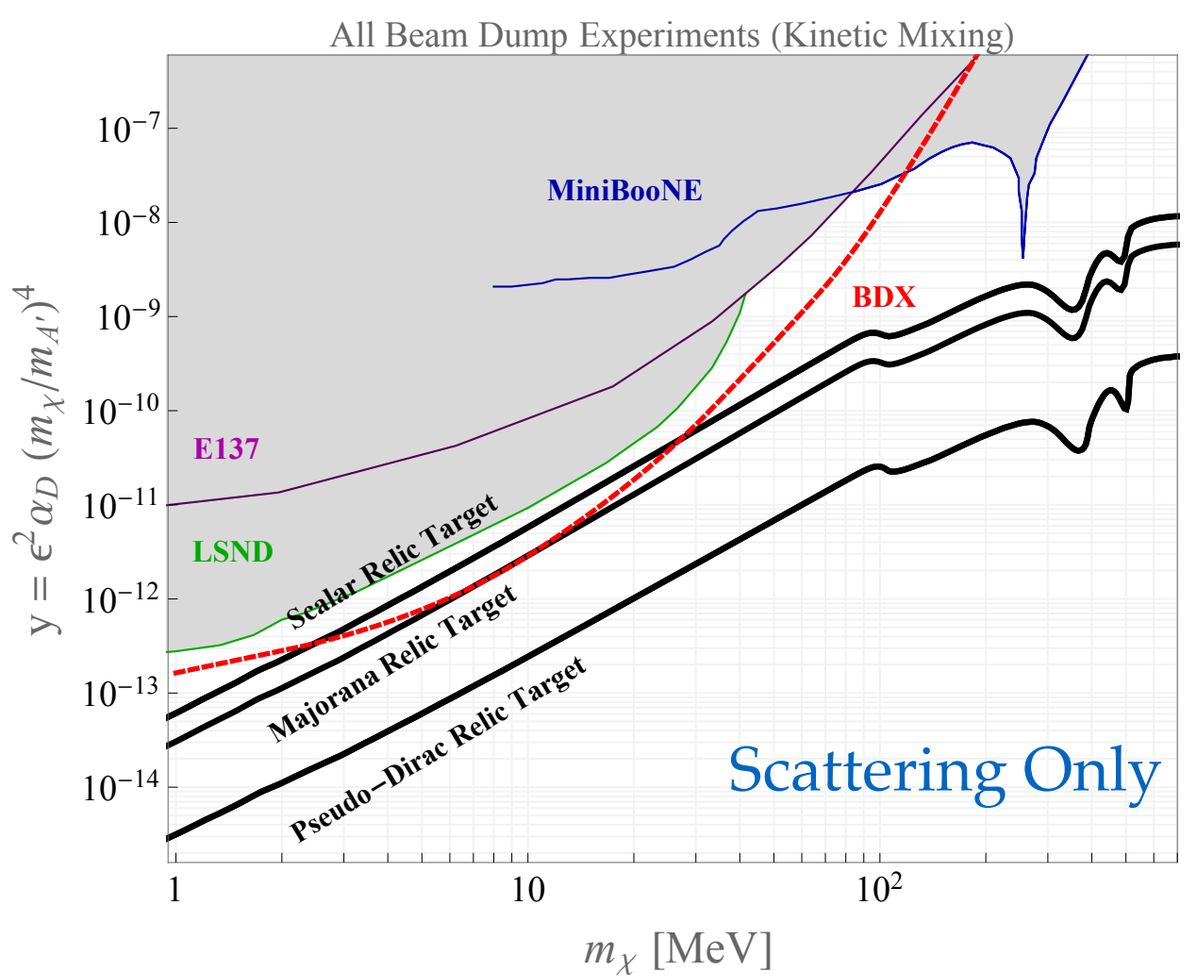
Batell, Essig, Surjuron 1406.2698

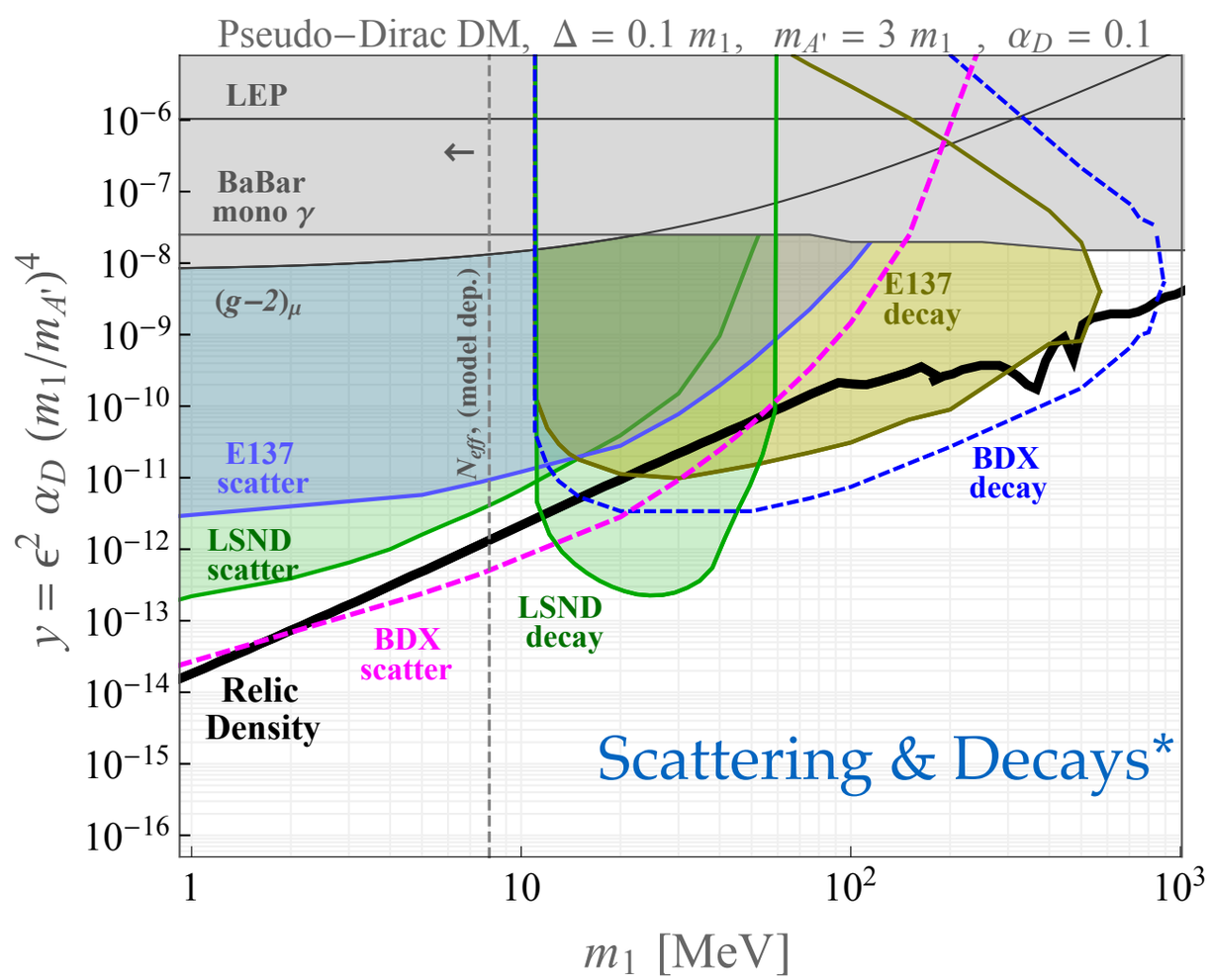
Snowmass 2021 BDX LOI

BDX Collaboration arXiv:1607.01390

Electron Beam Dumps



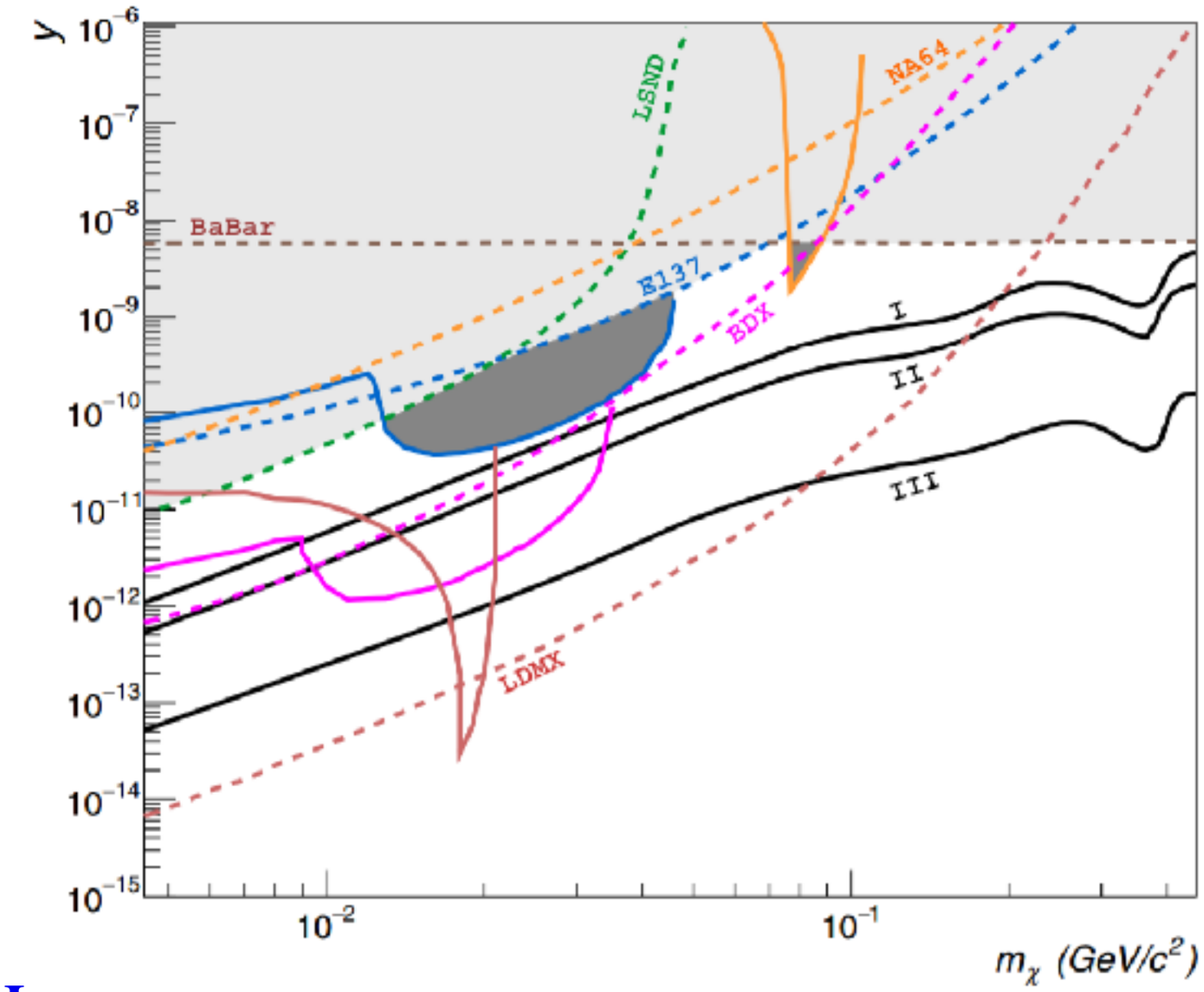




Snowmass 2021 BDX LOI

Izaguirre, Kahn, GK, Moschella 1703.06881

Electron Beam Dumps



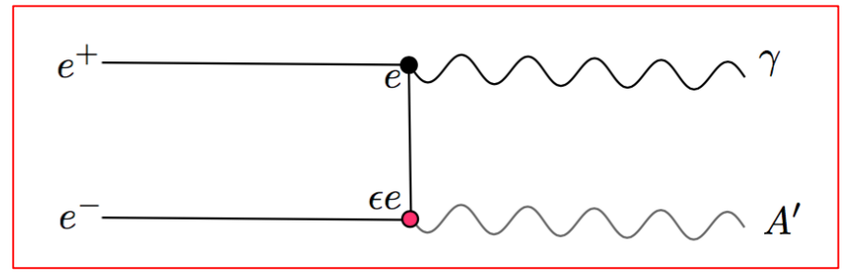
[Snowmass2021 LOI]

Also including signal from secondary positron production in beam dump

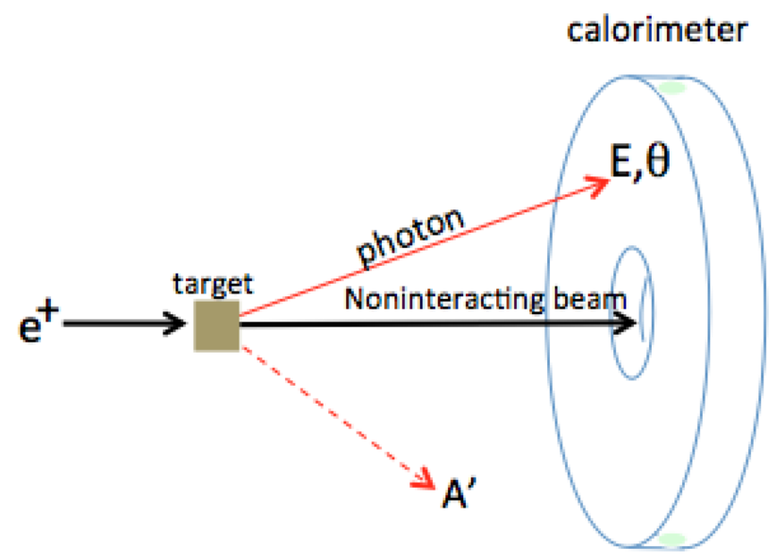
Marsicano, Battaglieri, Bondi', Carvajal, Celentano, De Napoli, De Vita, Nardi, Raggi, Valente 1802.03794

Positron Beam Dump

Process of interest:



Hardware:



- E_{beam} = 1.8 -- 5.3 GeV
- I_{beam} ~ 2.3 nA at target
- quasi-CW during ~millisecond spills @ 60H
- pulse structure: 168ns

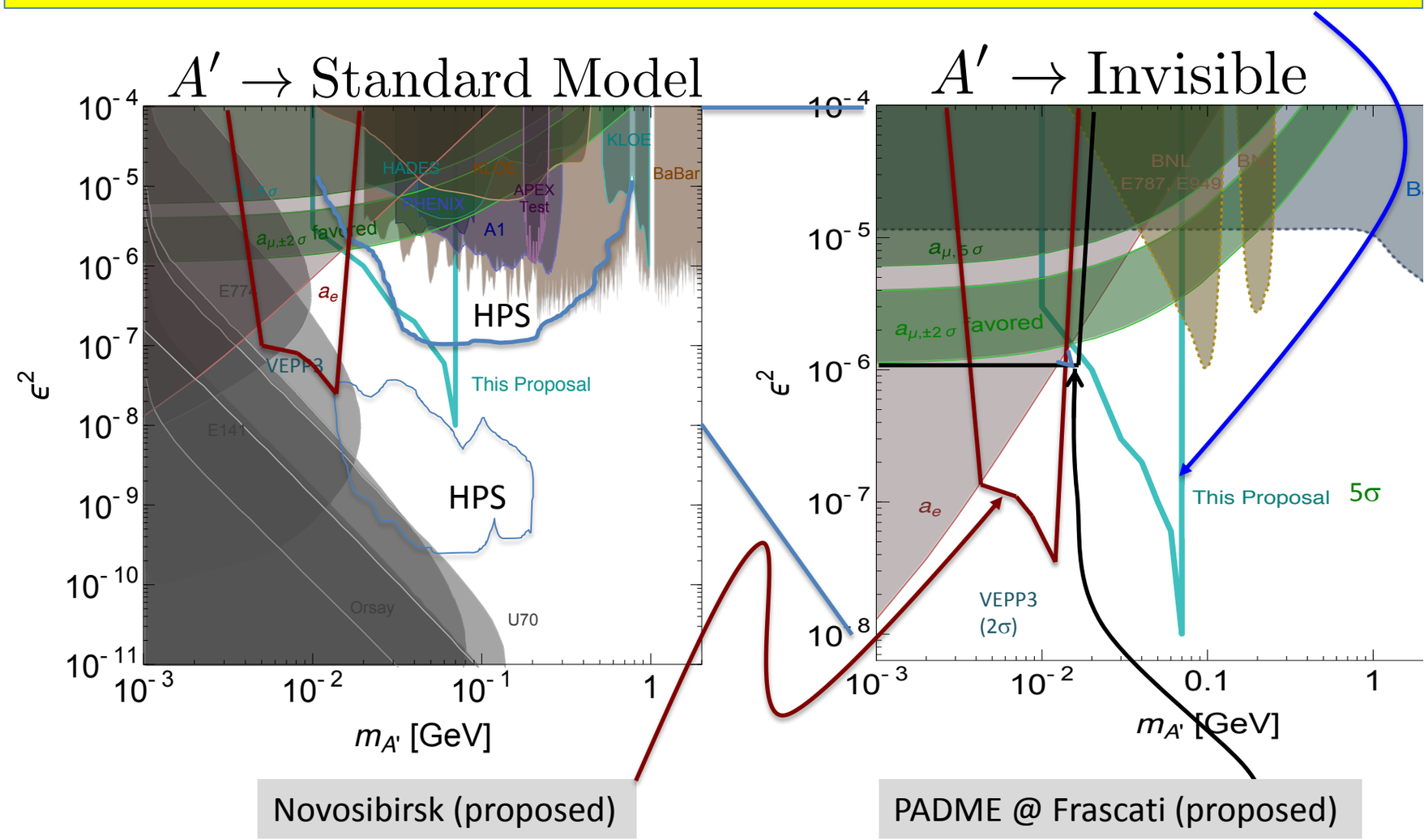
Fixed target, calorimeter 10m downstream.

Slide: Jim Alexander

Positron Beam Dump

Based on GEANT4 simulation with all bkgs and pileup included

E_{beam}=5.3GeV, I^{avg}_{beam}=2.3nA, Lumi = 1.0×10^{34}, T = 10^7sec, 5-sigma excl



[Snowmass2021 LOI]

Source: Jim Alexander

Overview

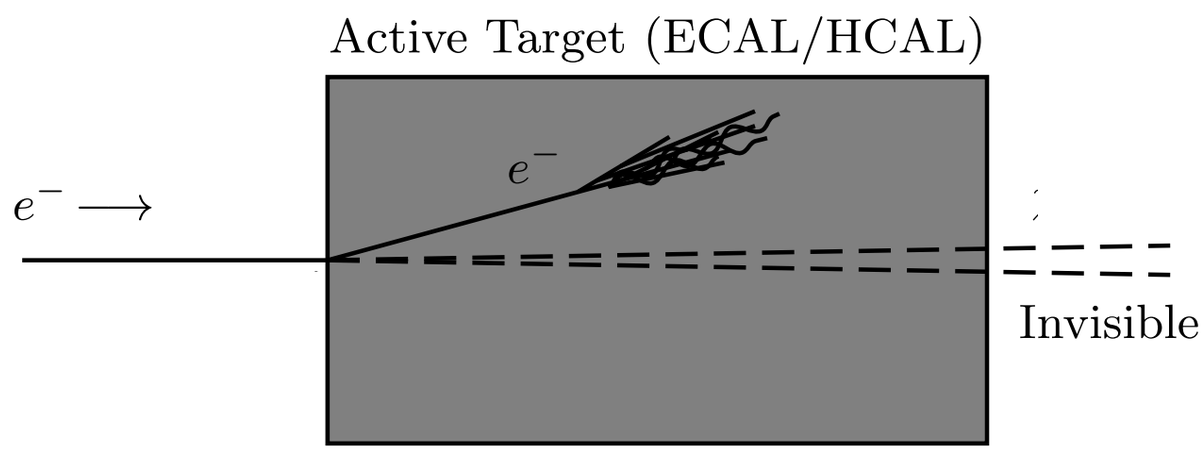
Preliminaries

B-Factories (e+e- colliders)

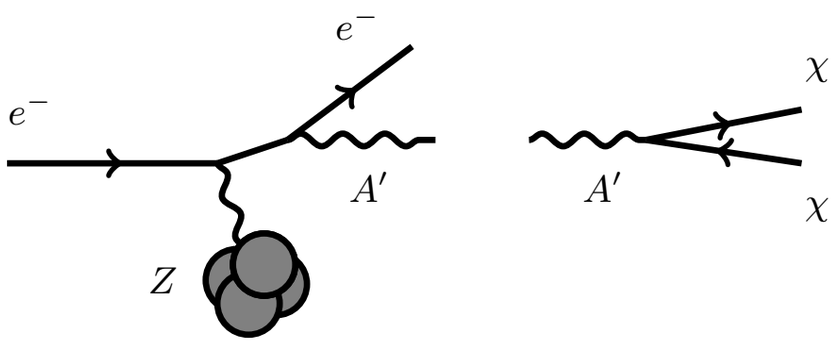
Beam Dump Production

Missing Energy/Momentum
Observable: beam energy loss + no other SM activity

Electron/Muon Missing Energy



Deliver electron beam to thick (>> X0) ECAL target



$E_e \sim 100\,\mathrm{GeV}, N_e \sim 10^{12}$

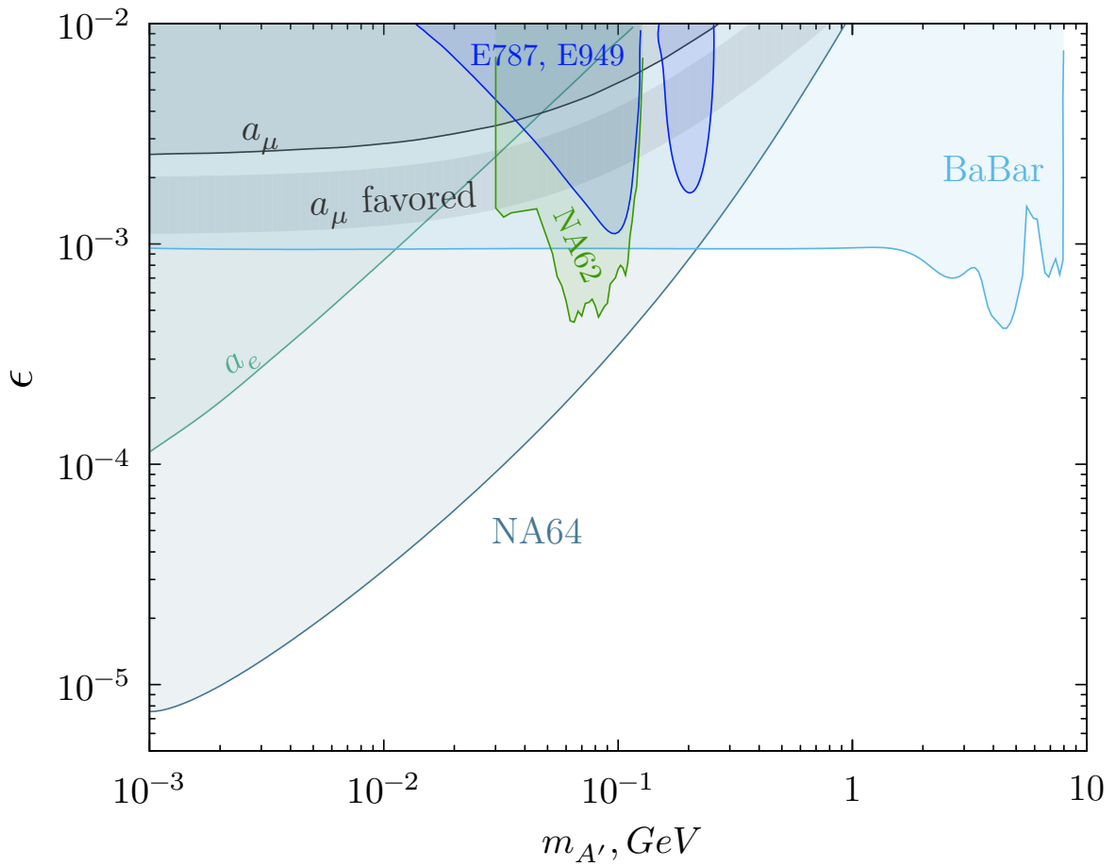
1) Measure **each** e- energy in target
2) Trigger on 50% missing energy
3) Veto additional SM activity

Only measure electron beam — don't require DM to scatter

Signal $\propto \epsilon^2$

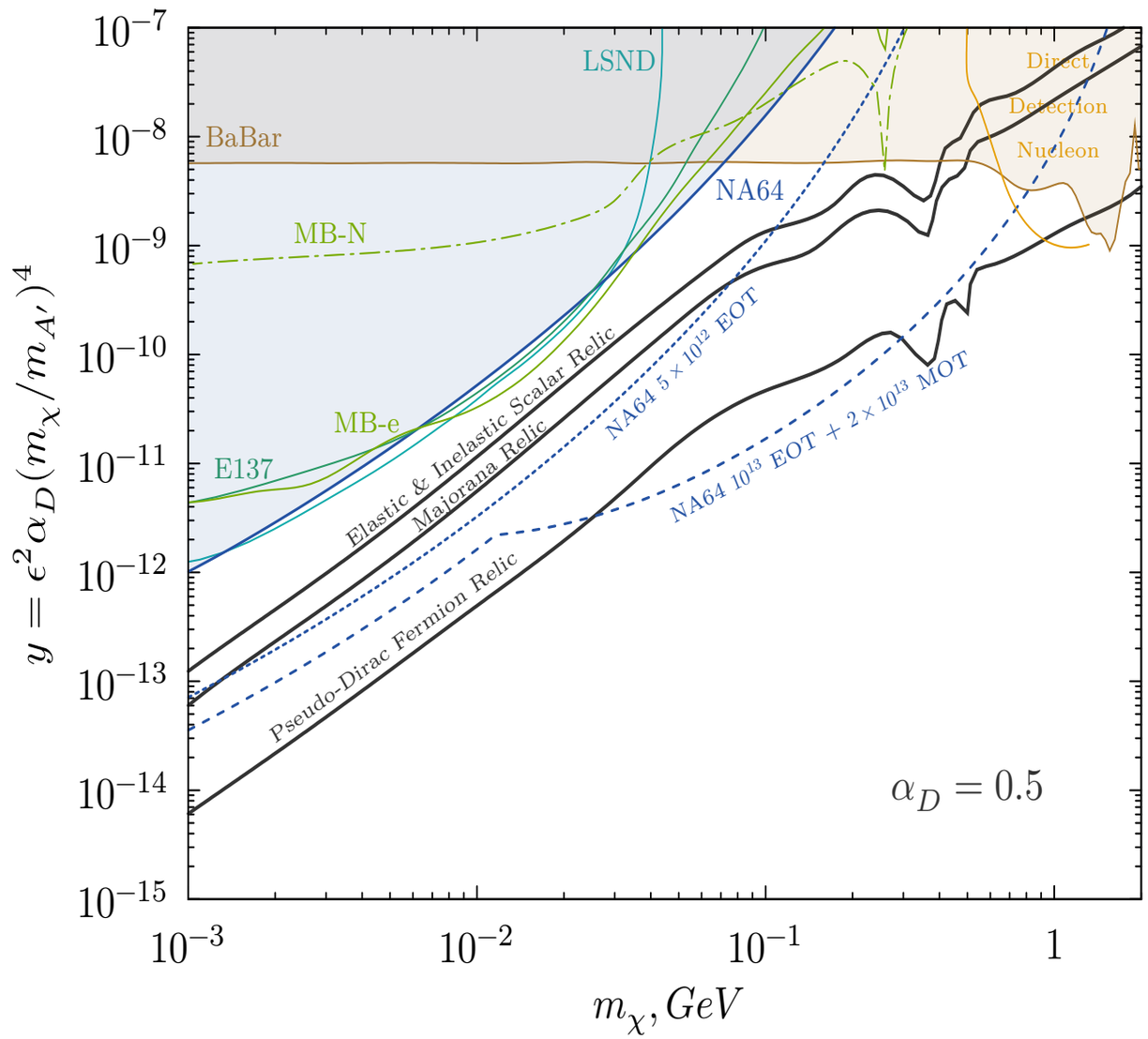
Andreas et. al. 1312.3309
NA64 Collaboration 1906.00176
Gninenko, Krasnikov, Mateev 2003.07257

Electron / Muon Missing Energy



Invisibly decaying A′

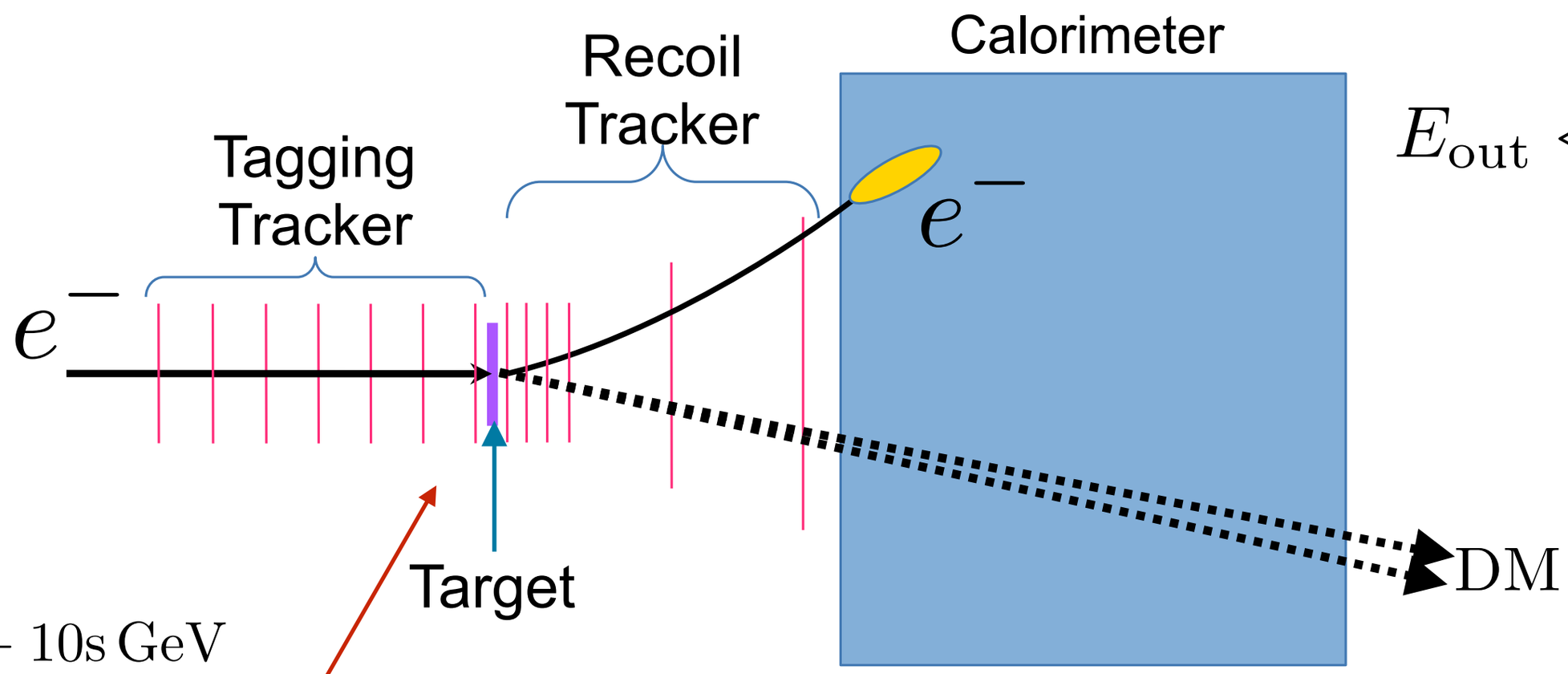
Thermal DM interpretation



NA64 currently running @ CERN

Andreas et. al. 1312.3309
NA64 Collaboration 1906.00176
Gninenko, Krasnikov, Mateev 2003.07257

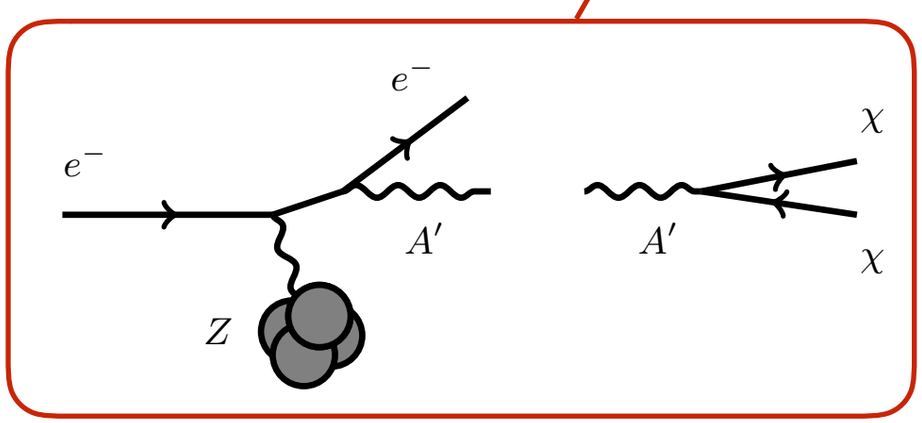
Electron Missing Momentum



$E_{\rm out} \ll E_{\rm in}$

$N_e \sim 10^{16}$

$E_e \sim \text{few} - 10\text{s GeV}$



1) Measure **each** e- energy in/out
2) Trigger on missing momentum
3) Veto additional SM activity

Only measure electron beam — don't require DM to scatter

Signal $\propto \epsilon^2$

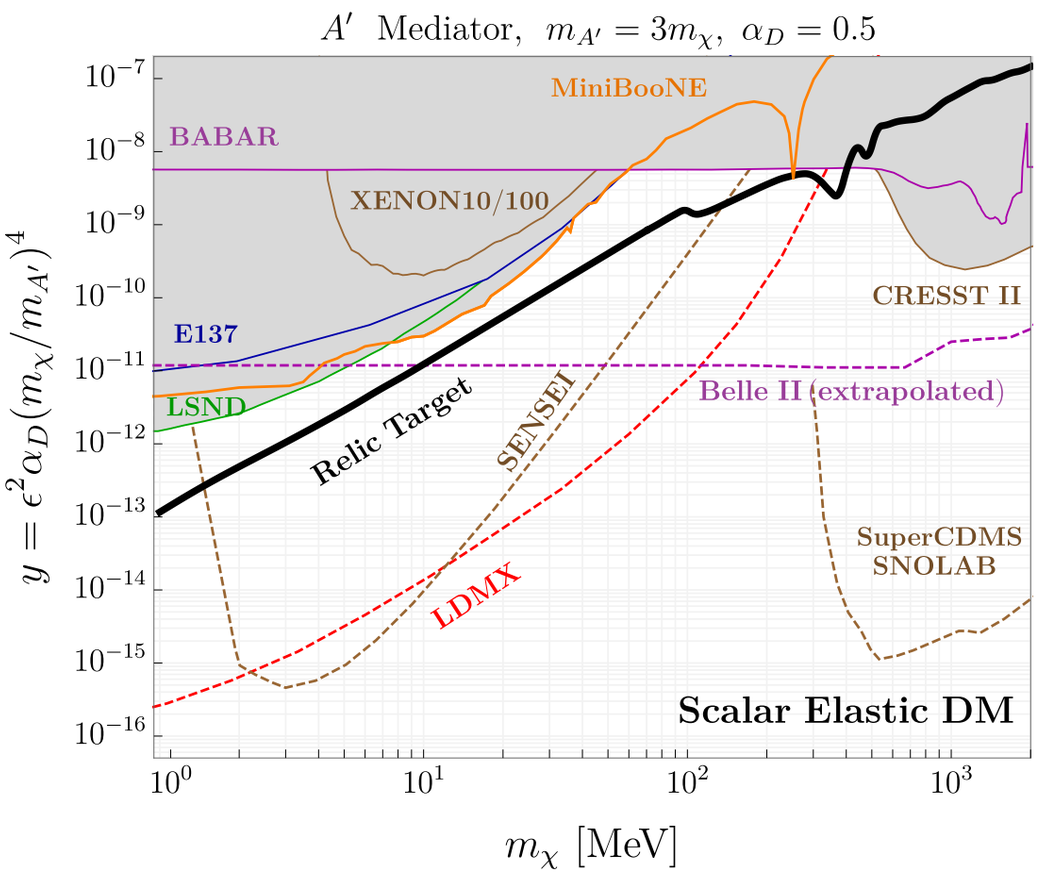
Izaguirre, GK, Schuster, Toro arXiv:1411.1404

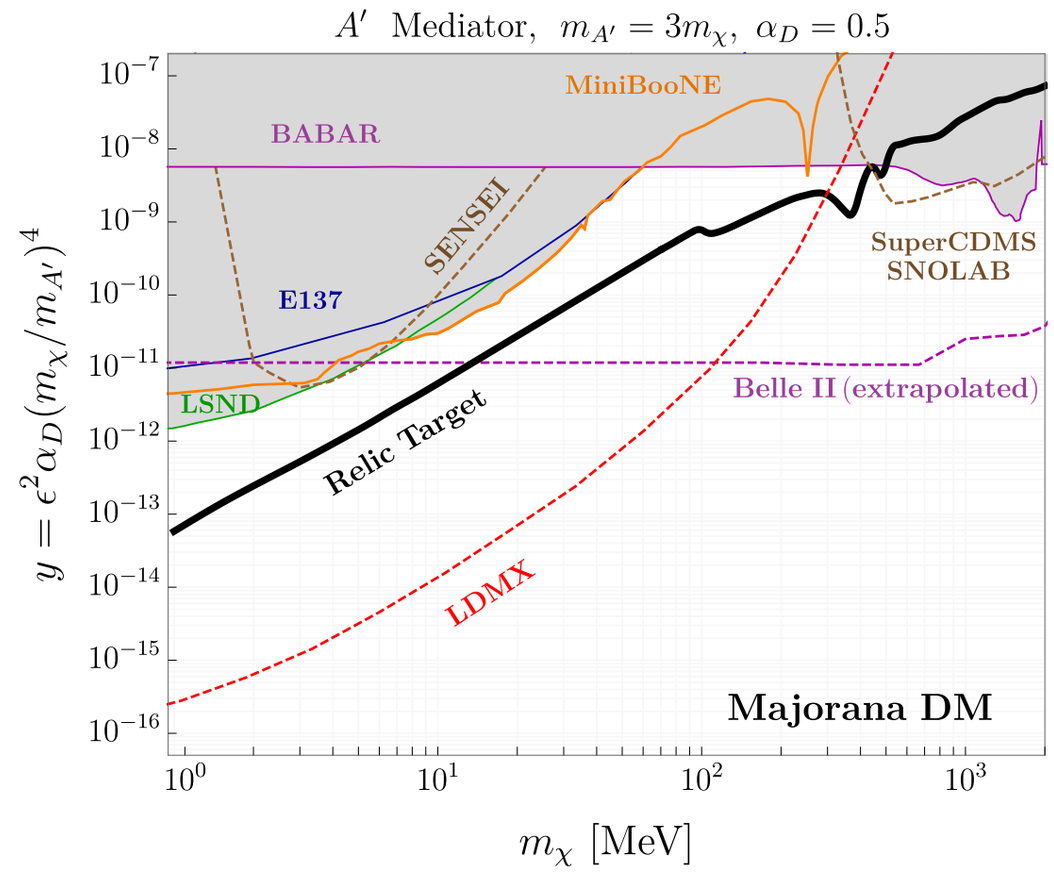
LDMX Collaboration 1808.05219

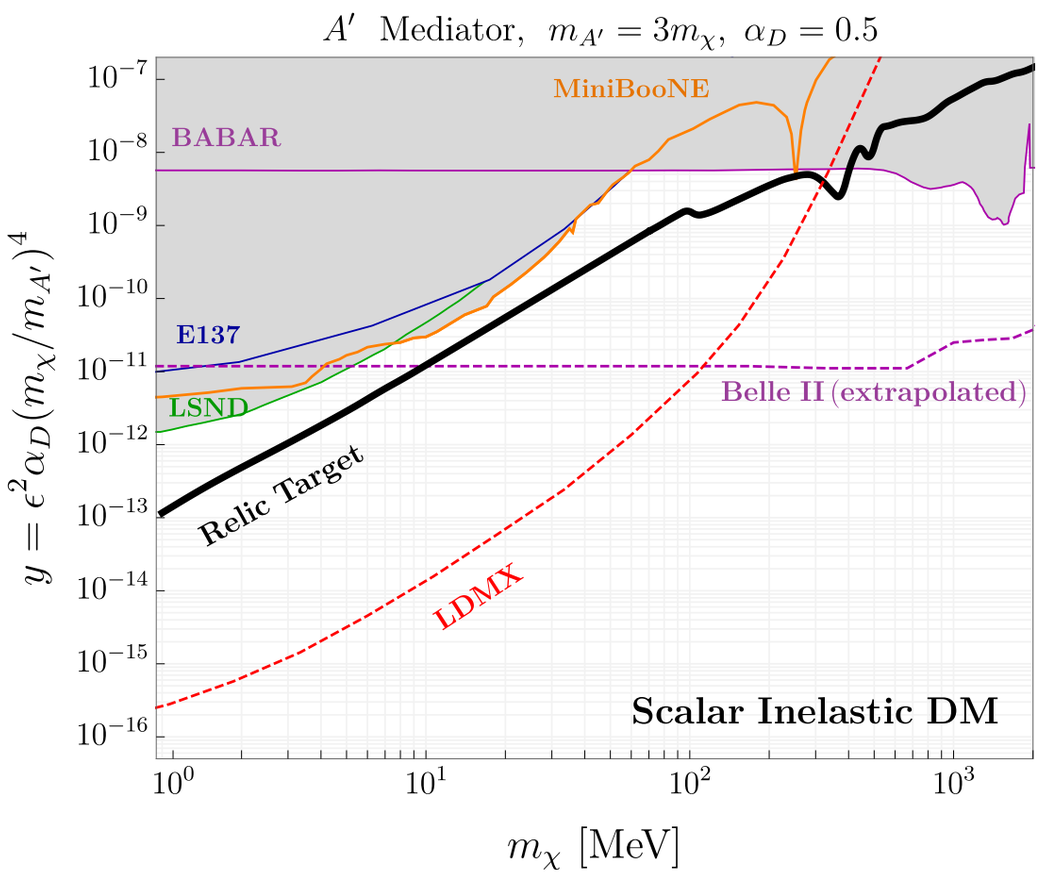
Snowmass2021 LOI: Light Dark Matter eXperiment

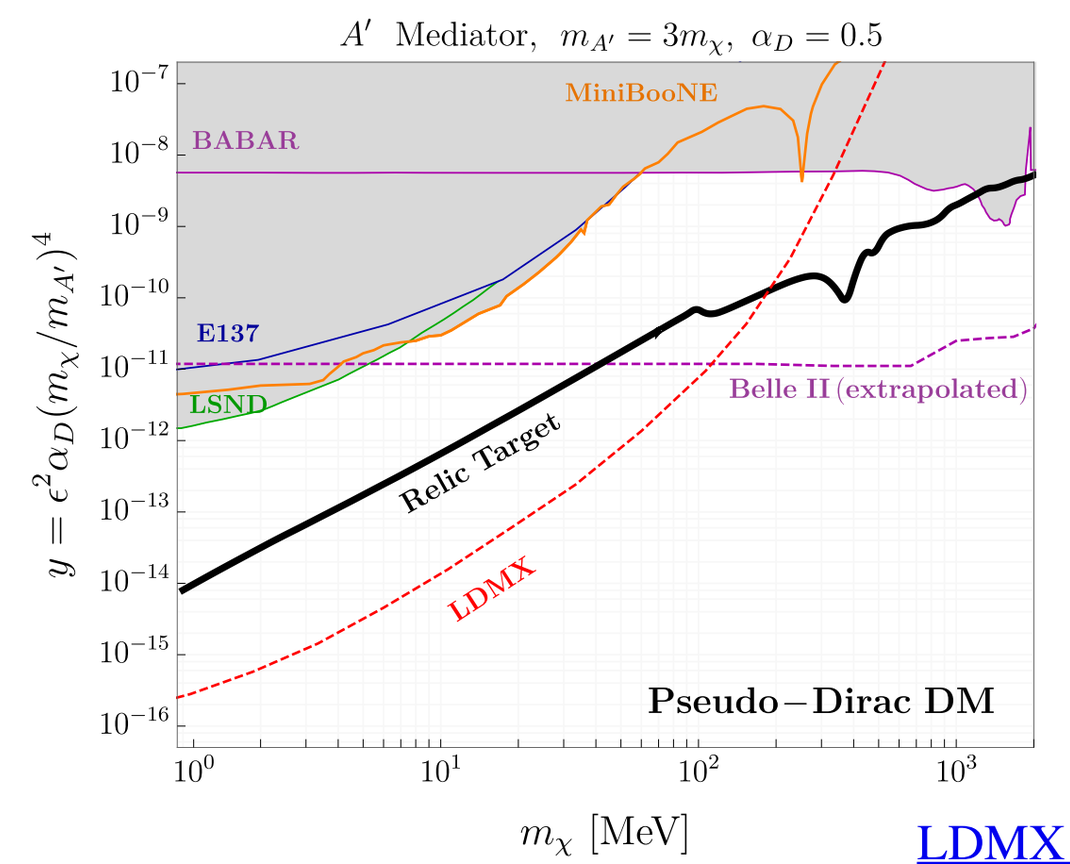
Comprehensive Coverage: A' Mediator

Berlin, Blinov GK, Schuster, Toro arXiv: 1807.01730





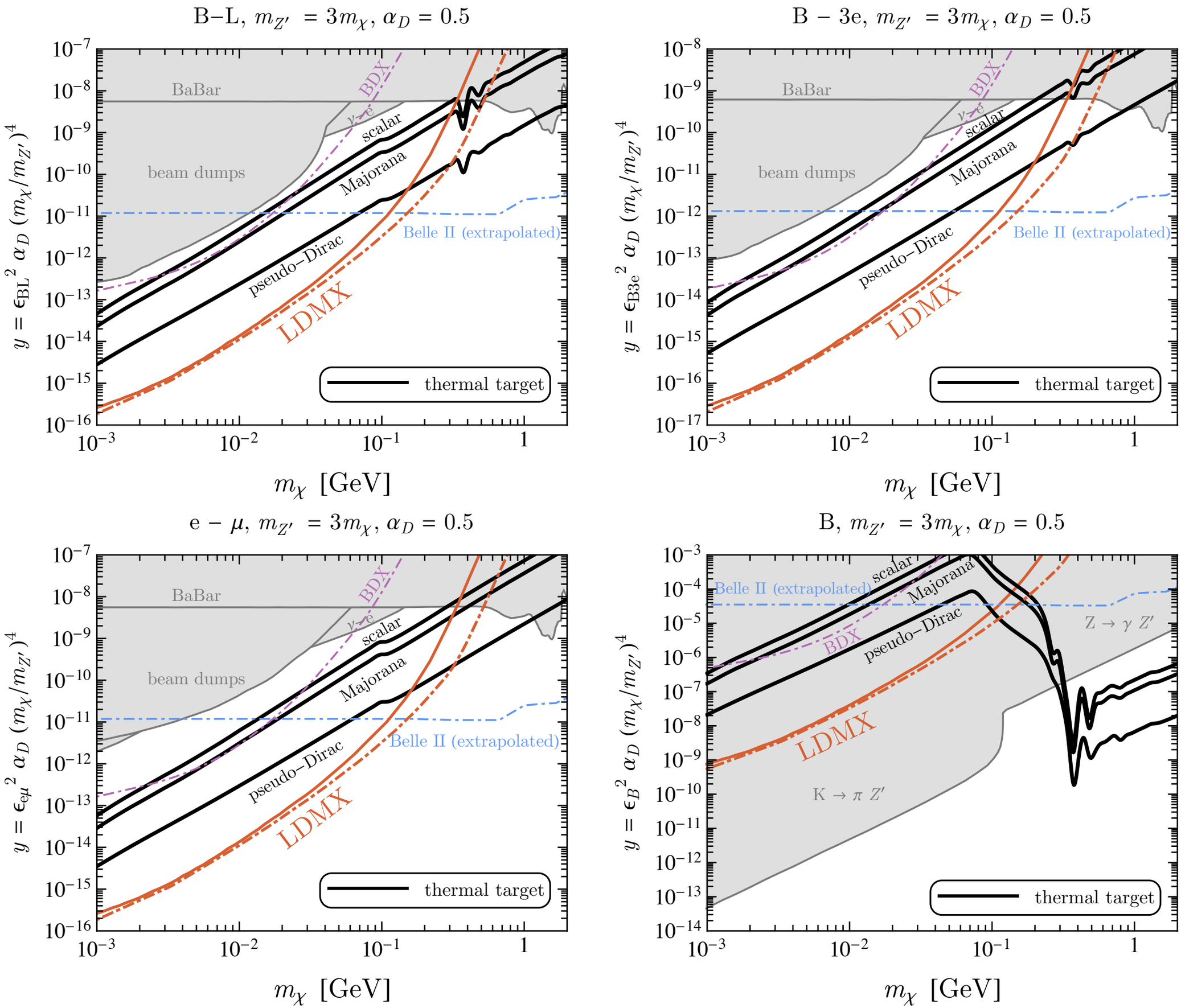




LDMX LOI

Comprehensive Coverage: other mediators

Berlin, Blinov GK, Schuster, Toro arXiv: 1807.01730

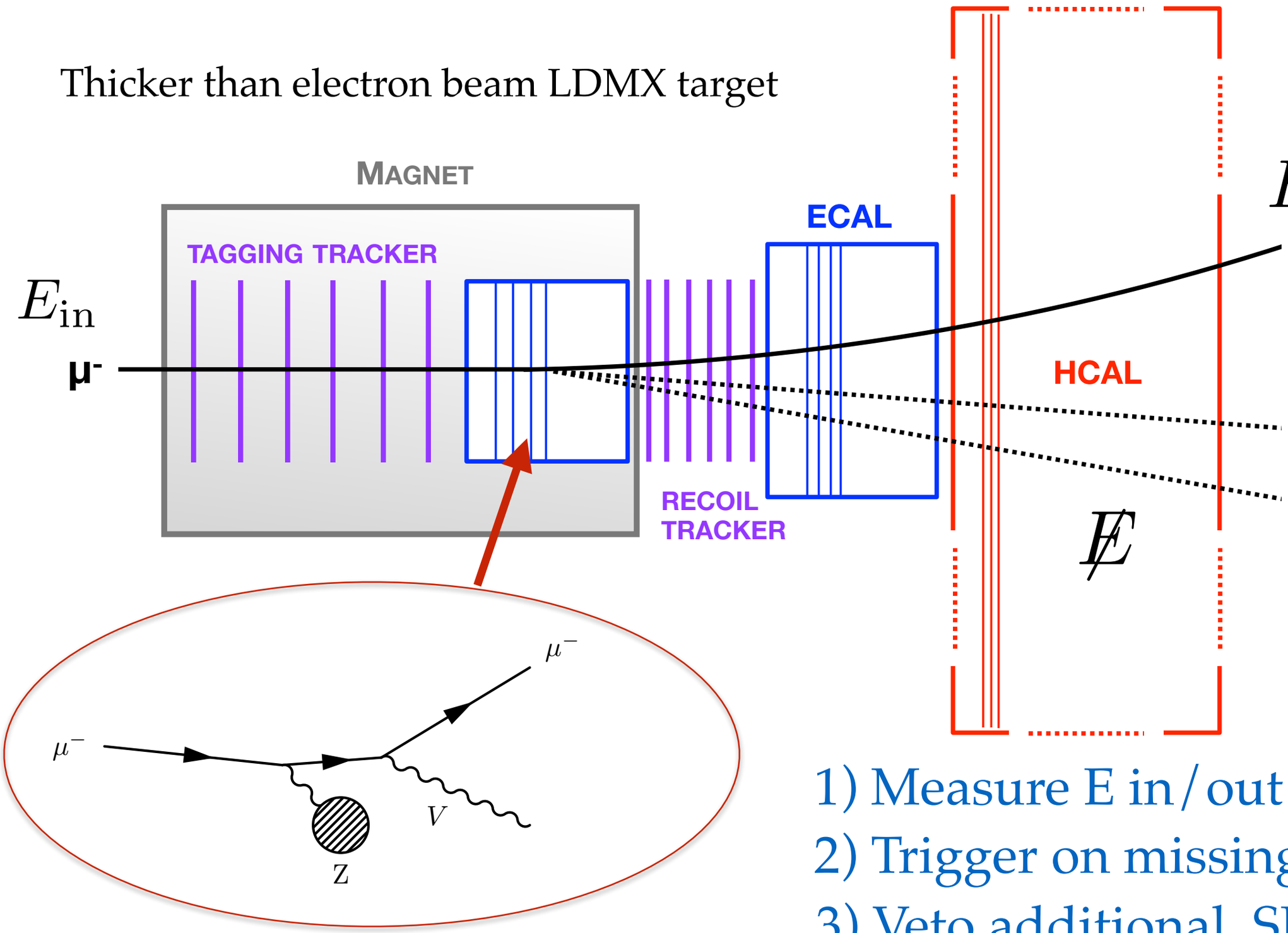


Muon Missing Momentum

Thicker than electron beam LDMX target

must measure track curvature

$E_{\text{out}} < E_{\text{in}}$

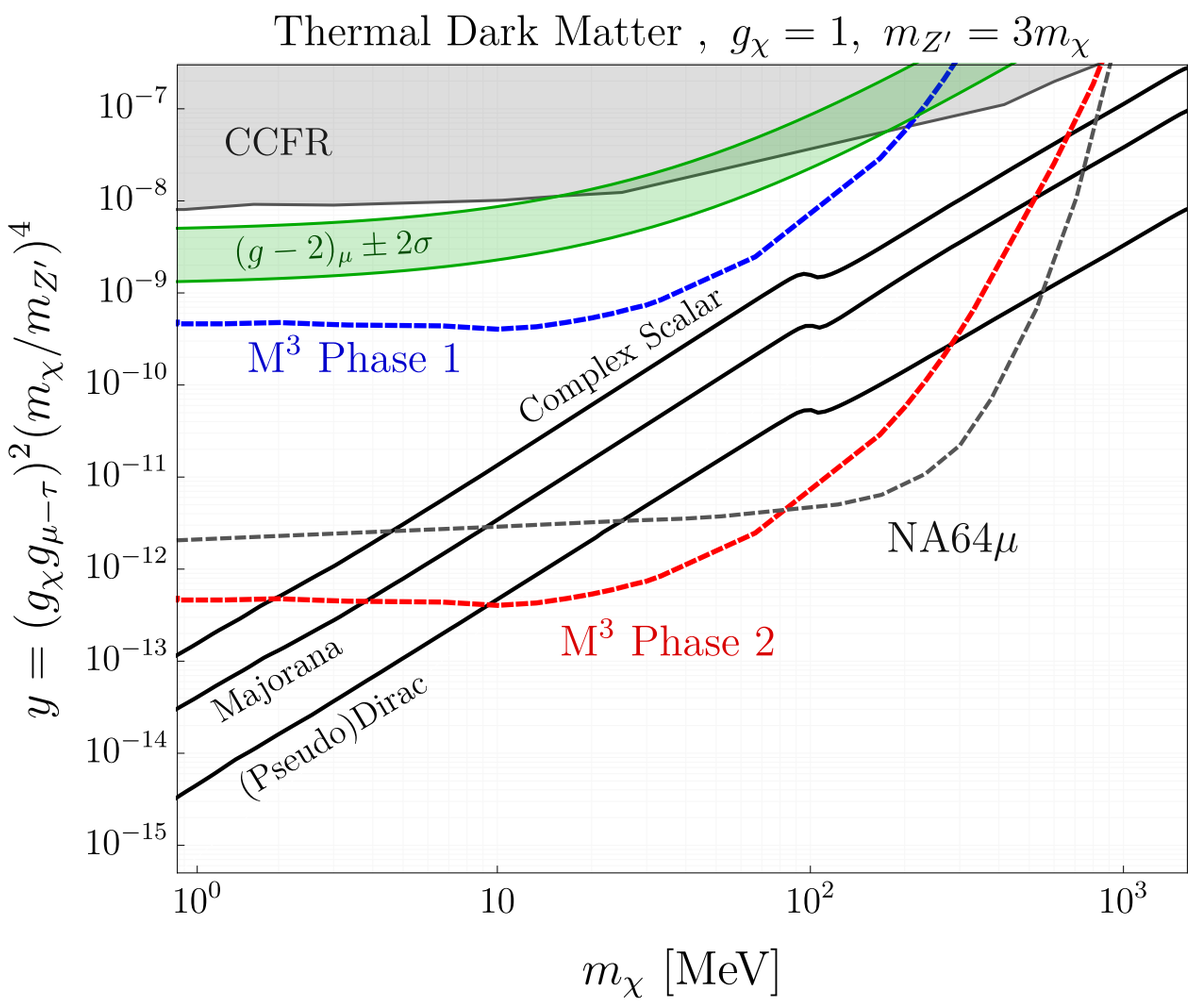


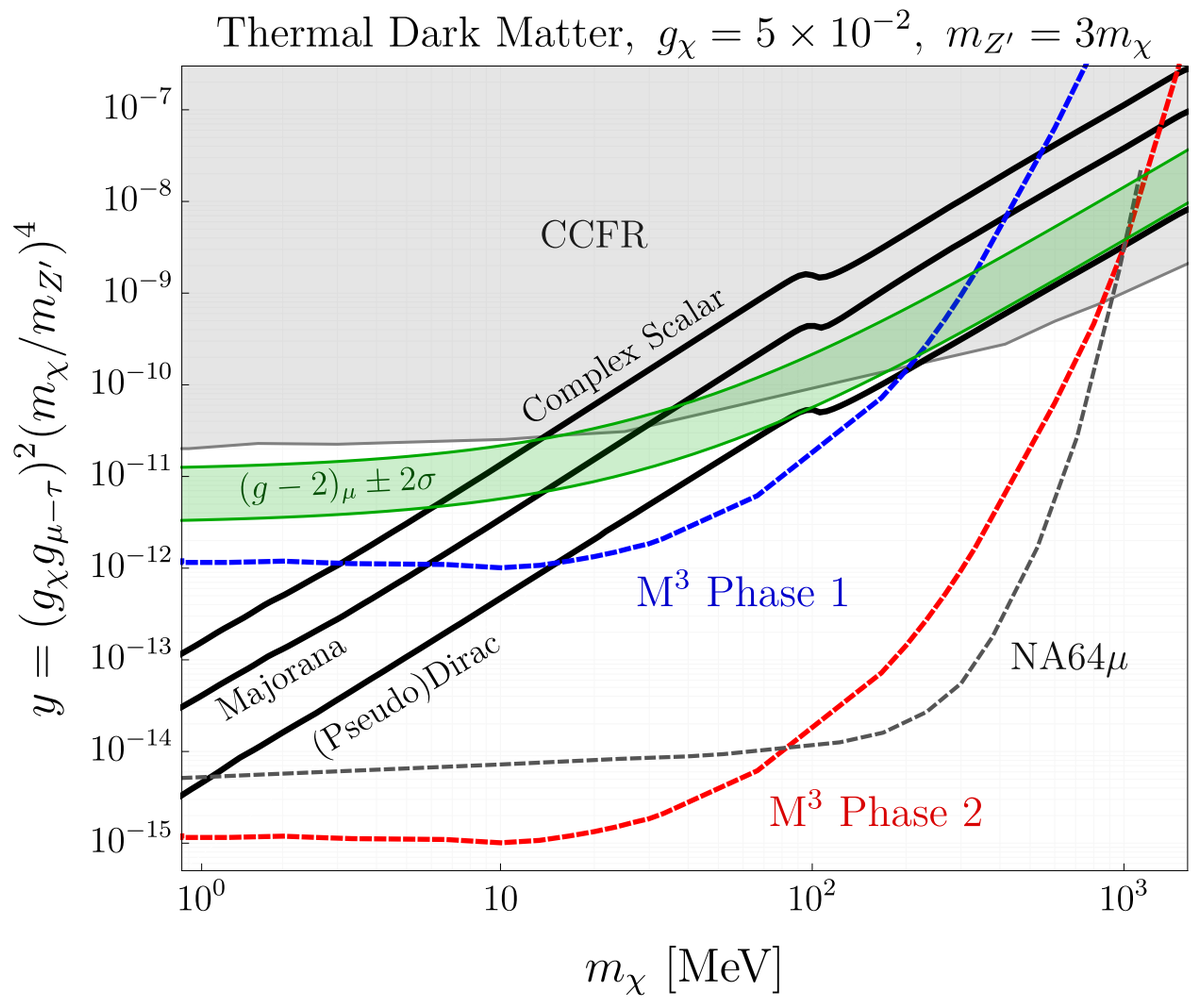
1) Measure E in/out with B field
2) Trigger on missing energy
3) Veto additional SM activity

Kahn, GK, Tran, Whitbeck 1804.03144 (JHEP 2018)

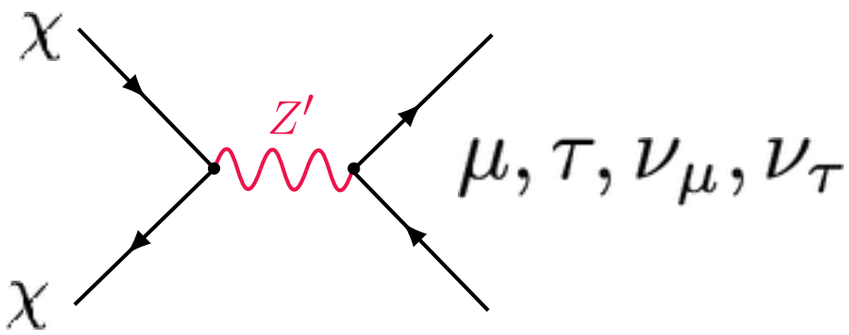
Snowmass2021 LOI

Comparing Muon Beams: NA64μ and M^3





Gauged $L_\mu - L_\tau$ Interaction

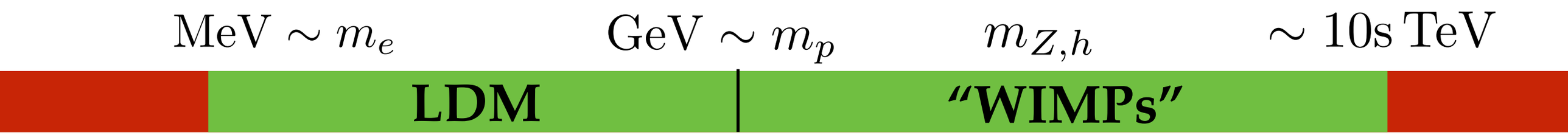


Also resolve muon g-2 with light physics

Compatible parameter space for freeze-out

Snowmass2021 LOI

New Frontier of DM Searches: Accelerators



B/K Factories

Beam Dumps

Missing Energy/Momentum

Direct Detection

Indirect Detection

Collider Production

Mature program of searches covers broad range of < GeV DM

Calculable, controllable no astro uncertainties

Replicates kinematics of hot early universe

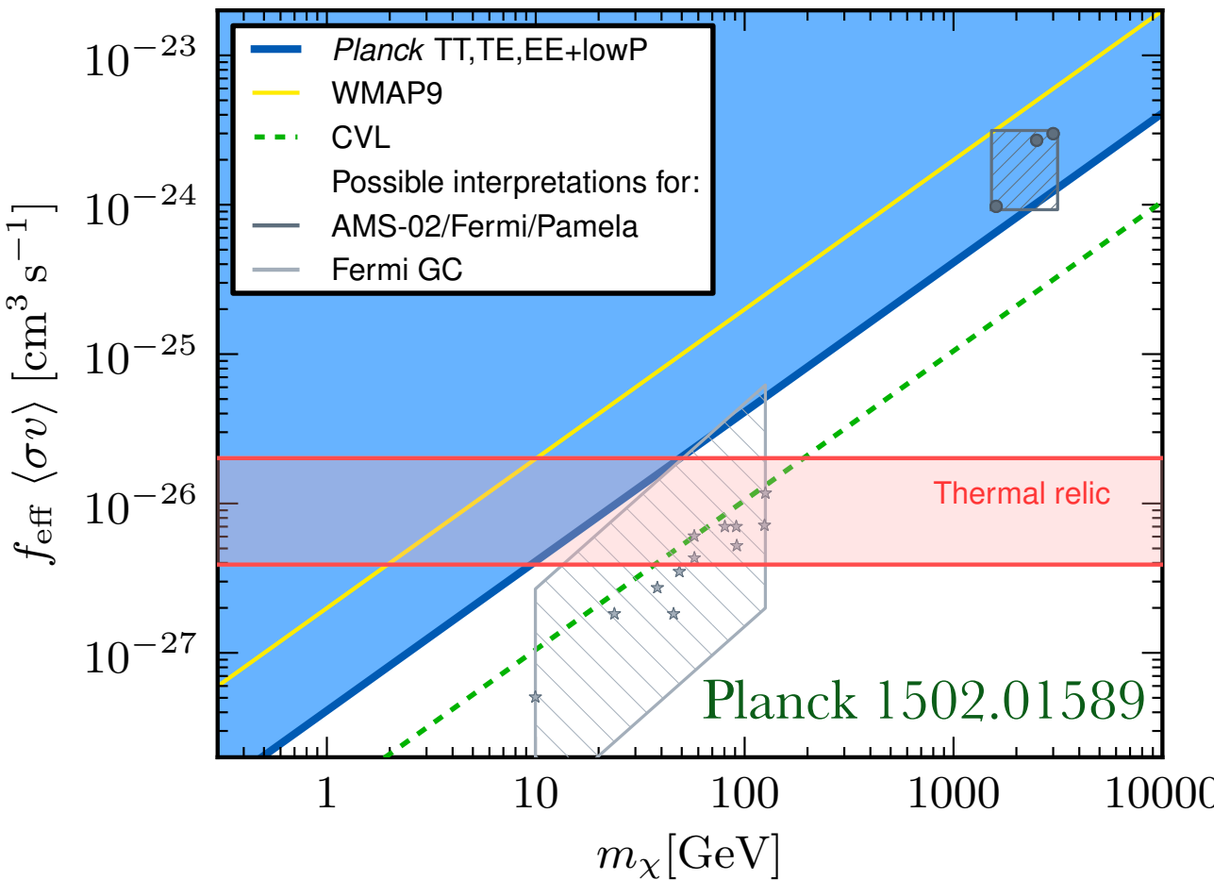
Test *nearly all* predictive DM models (density set by SM coupling)

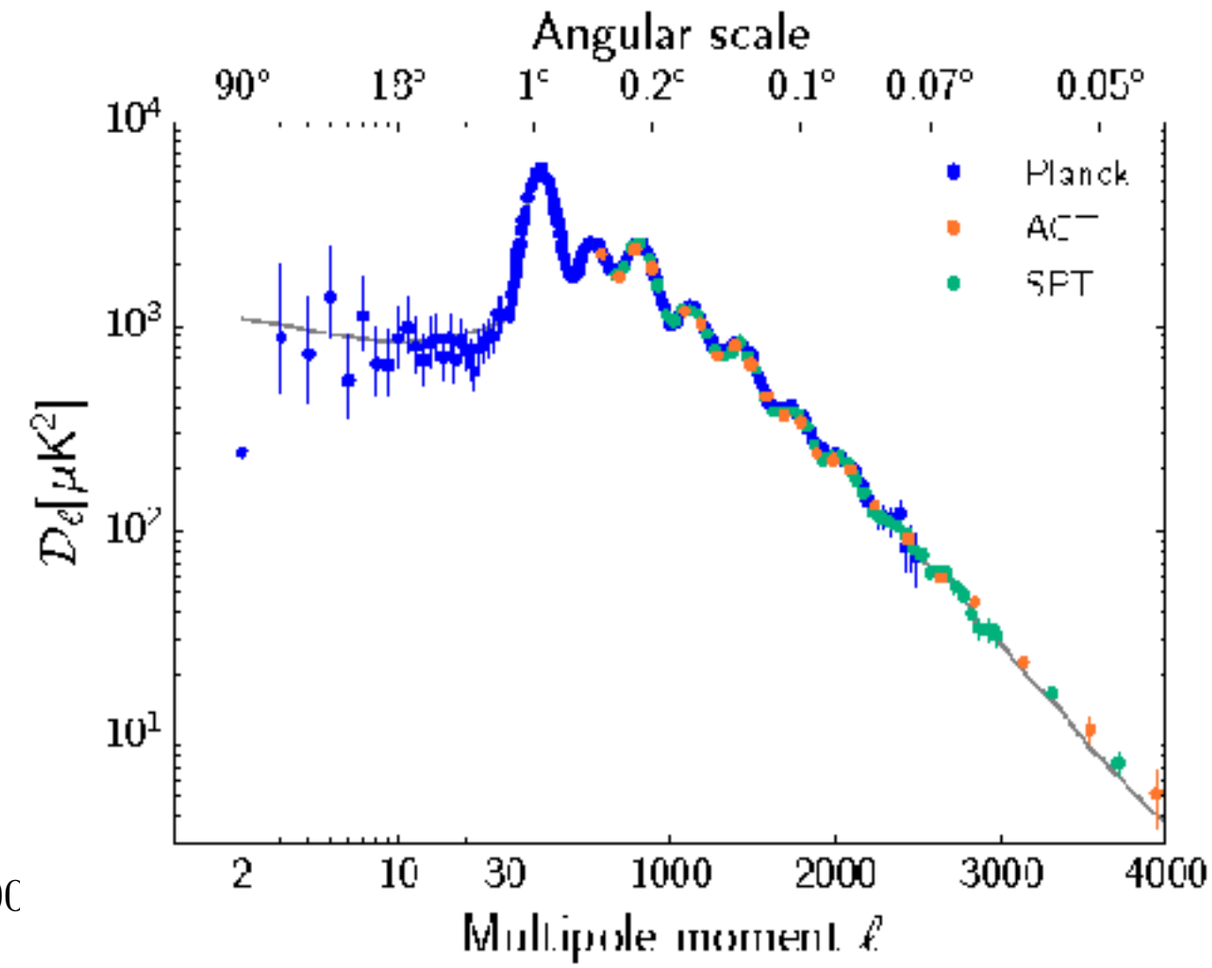
Also see 2019: DOE Basic Research Needs Report

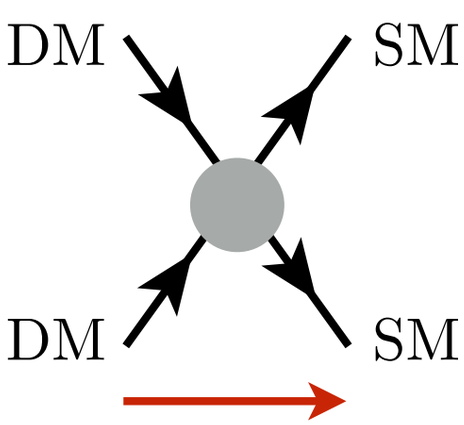
https://science.energy.gov/~/media/hep/pdf/Reports/201809_HEP-PI-BRN-Dark-Matter_New_Initiatives.pdf

Thanks!

What kind of DM? Use CMB to classify viable options







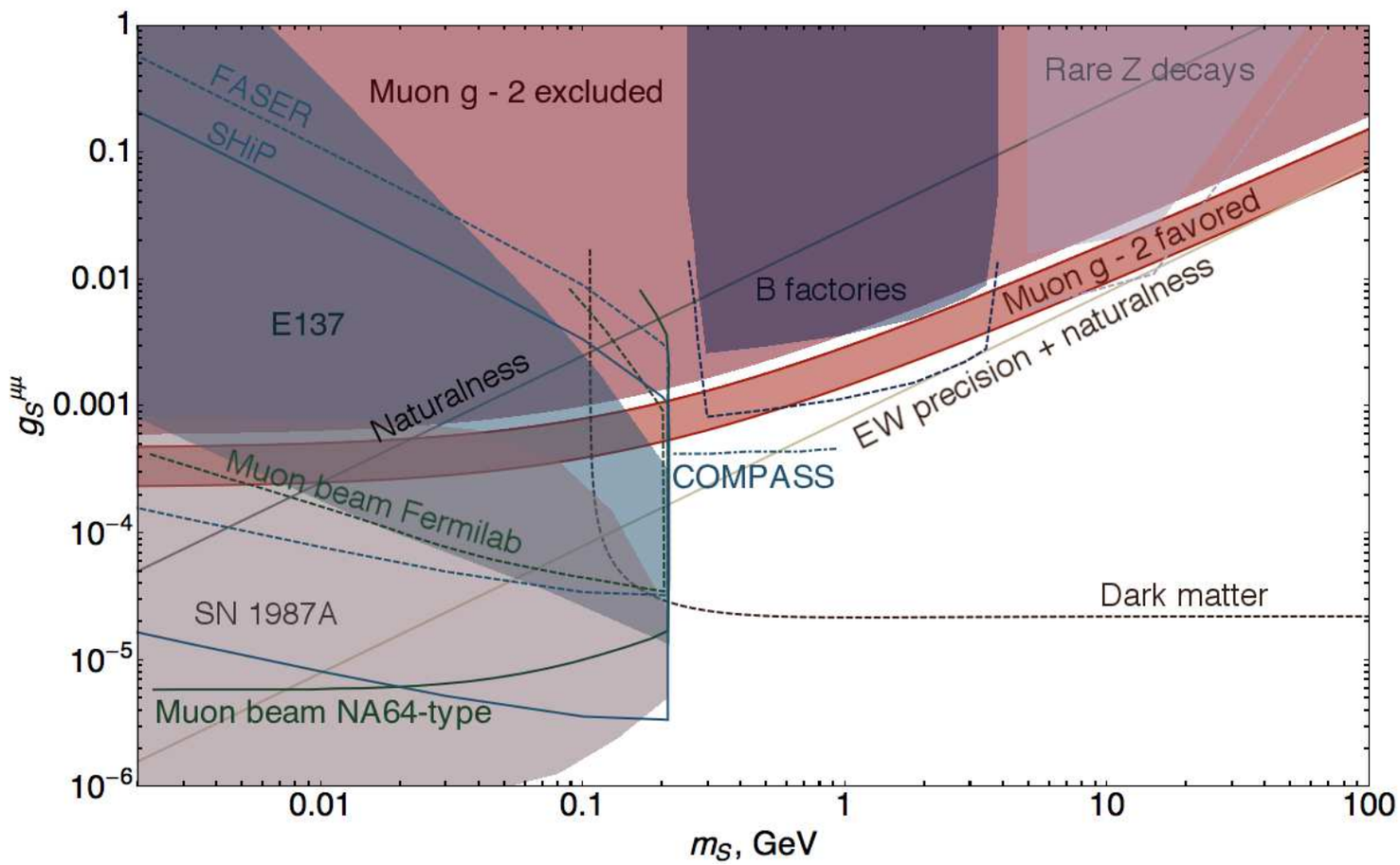
Rare out-of-equilibrium annihilation ionizes H (z=1100)

CMB photons pass through more plasma (modifies peaks)

Rules out s-wave relic cross section for DM < 10 GeV

Flavor Specific Scalar Mediators

$$\mathcal{L} \supset -\frac{1}{2}m_S^2 S^2 - \left(\bar{Q}_L Y_u U_R H_c + \frac{c_S}{M} S \bar{Q}_L U_R H_c + \text{h.c.}\right).$$



Heavy vectolrike leptons mix with muon, to generate mediator coupling

Mediator enables DM > muon annihilation

Batell, Freitas, Ismail, McKeen 1712.10022