# New Accelerator Searches for Light Dark Matter and Other New Physics


Natalia Toro
SLAC


KITP "New Probes for Physics Beyond the Standard Model"
April 9, 2018

recent & ongoing work with **A. Berlin, N. Blinov,** S. Gori, P. Schuster

# WIMPs: Confluence of Motivations

**Simple, familiar Particle Content:**

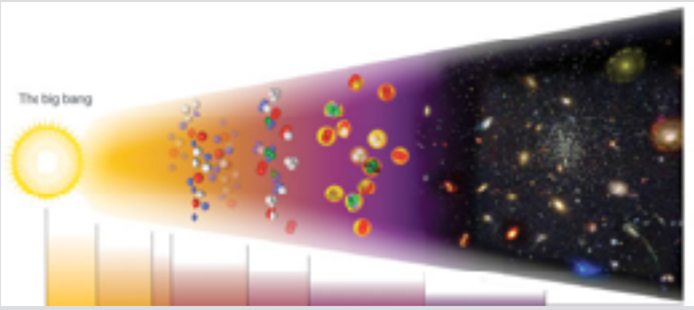
**New Standard-Model-like matter at Standard-Model-like scales**

in particular, weak-scale matter with weak interactions

particularly motivated by hierarchy problem

**A simple, predictive explanation for origin of dark matter:**

Dark matter was once in thermal equilibrium with familiar matter



Measured abundance ⇒ annihilation cross-section

$$\sigma_{\mathrm{ann}} \approx \left(\frac{\alpha}{\alpha_2}\right)^2 \left(\frac{m_{\mathrm{DM}}}{m_W}\right)^2 \left(\frac{m_{\mathrm{Med}}}{m_W}\right)^{-4}$$

# WIMPs: Confluence of Motivations

**Simple, familiar Particle Content:**

**New Standard-Model-like matter at Standard-Model-like scales**

in p
mat

part
hier

**A simple, predictive explanation for <u>origin</u> of dark matter:**

Dark matter was once in thermal equilibrium with familiar matter

Constraints on WIMPs and TeV-scale physics more generally motivate a modest generalization of this picture

$$\sigma_{\rm ann} \approx \left(\frac{\alpha}{\alpha_2}\right)^2 \left(\frac{m_{\rm DM}}{m_W}\right)^2 \left(\frac{m_{\rm Med}}{m_W}\right)^{-4}$$

Dark Sectors

# Confluence of Motivations

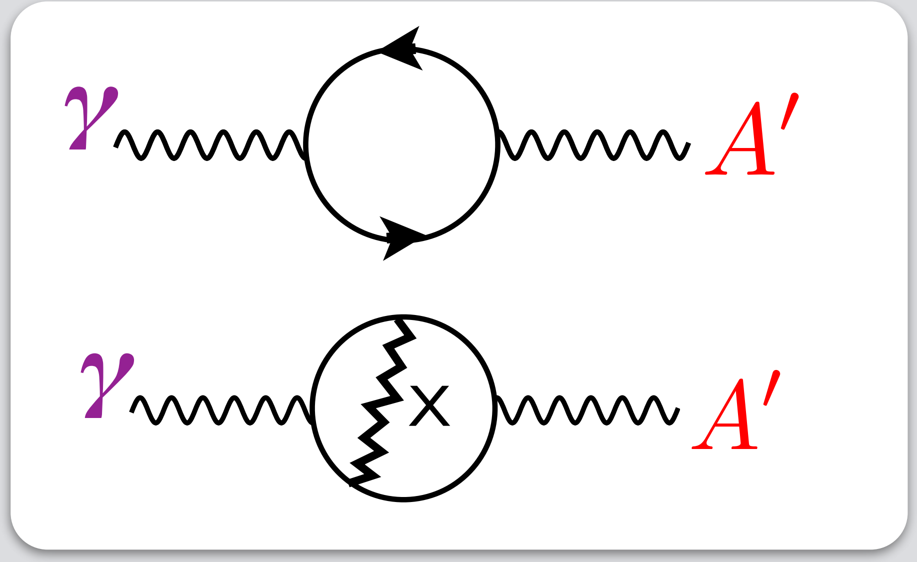
**Simple, familiar particle content:**

**New Standard-Model-like matter**
**and forces**
**at Standard-Model-like scales**

many solutions to hierarchy problem involve such new **sectors** – may be at different mass scale

Familiar matter must be neutral under these forces – so how would we test it?

Residual interactions from quantum corrections:




$$g_{\rm eff} \sim (10^{-6} - 10^{-2})e$$

Weak enough to be missed experimentally so far

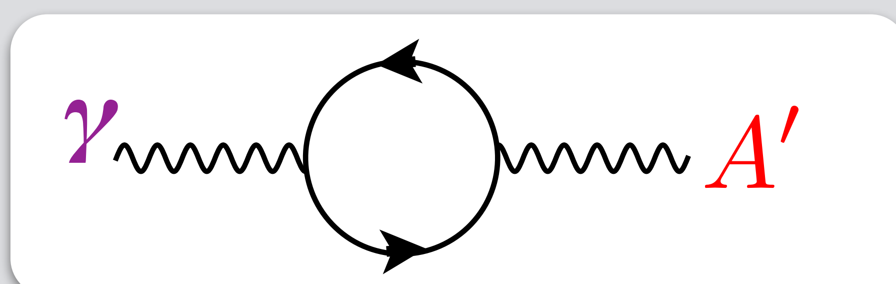
## Dark Sectors

# Confluence of Motivations

**Simple, familiar particle content:**

**New Standard-Model-like matter**
and forces
**at Standard-Model-like scales**

many solutions to hierarchy problem involve such new **sectors** – may be at different mass scale

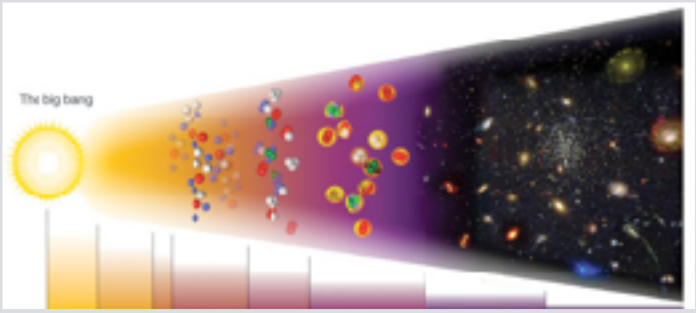



$$g_{\rm eff} \sim (10^{-6} - 10^{-2})e$$

Weak enough to be missed experimentally so far

**A simple, predictive explanation for <u>origin</u> of dark matter:**

Dark matter was once in thermal equilibrium with familiar matter



Measured abundance ⇒ annihilation cross-section:

$$\sigma_{\rm ann} \approx \left(\frac{\alpha}{\alpha_2}\right)^2 \left(\frac{m_{\rm DM}}{m_W}\right)^2 \left(\frac{m_{\rm Med}}{m_W}\right)^{-4}$$

Very weak coupling
$\longleftrightarrow$
Lower (MeV–GeV) mass

Dark Sectors

# Confluence of Motivations

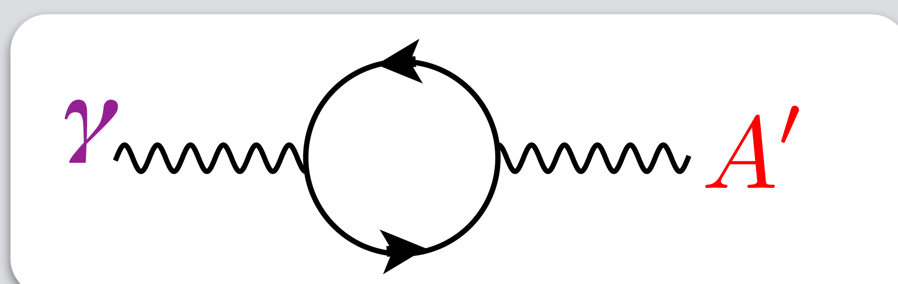
**Simple, familiar particle content:**

**New Standard-Model-like matter**

**and forces**

**at Standard-Model-like scales**

many
probl
**secto**
mass scale




$$g_{\rm eff} \sim (10^{-6} - 10^{-2})e$$

Weak enough to be missed experimentally so far

**A simple, predictive explanation for <u>origin</u> of dark matter:**

Dark matter was once in thermal equilibrium with familiar matter

A simple & motivated extension of WIMP paradigm

Measured abundance ⇒ annihilation cross-section:

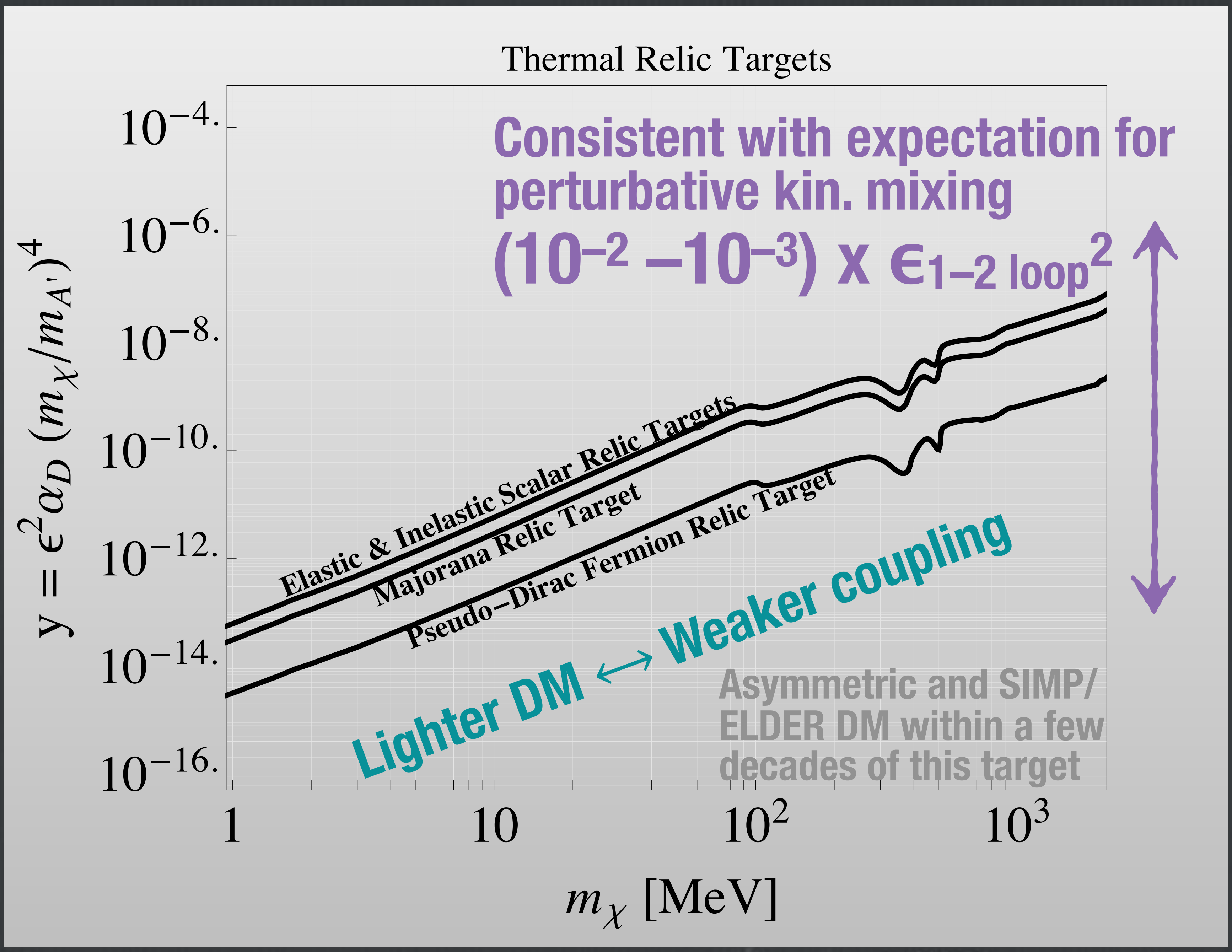
$$\sigma_{\rm ann} \approx \left(\frac{\alpha}{\alpha_2}\right)^2 \left(\frac{m_{\rm DM}}{m_W}\right)^2 \left(\frac{m_{\rm Med}}{m_W}\right)^{-4}$$

Very weak coupling

$\longleftrightarrow$

Lower (MeV–GeV) mass

# Light Thermal Dark Matter





$$\sigma v \sim \frac{\epsilon \alpha \alpha_D m_{DM}^2}{m_W^4}$$

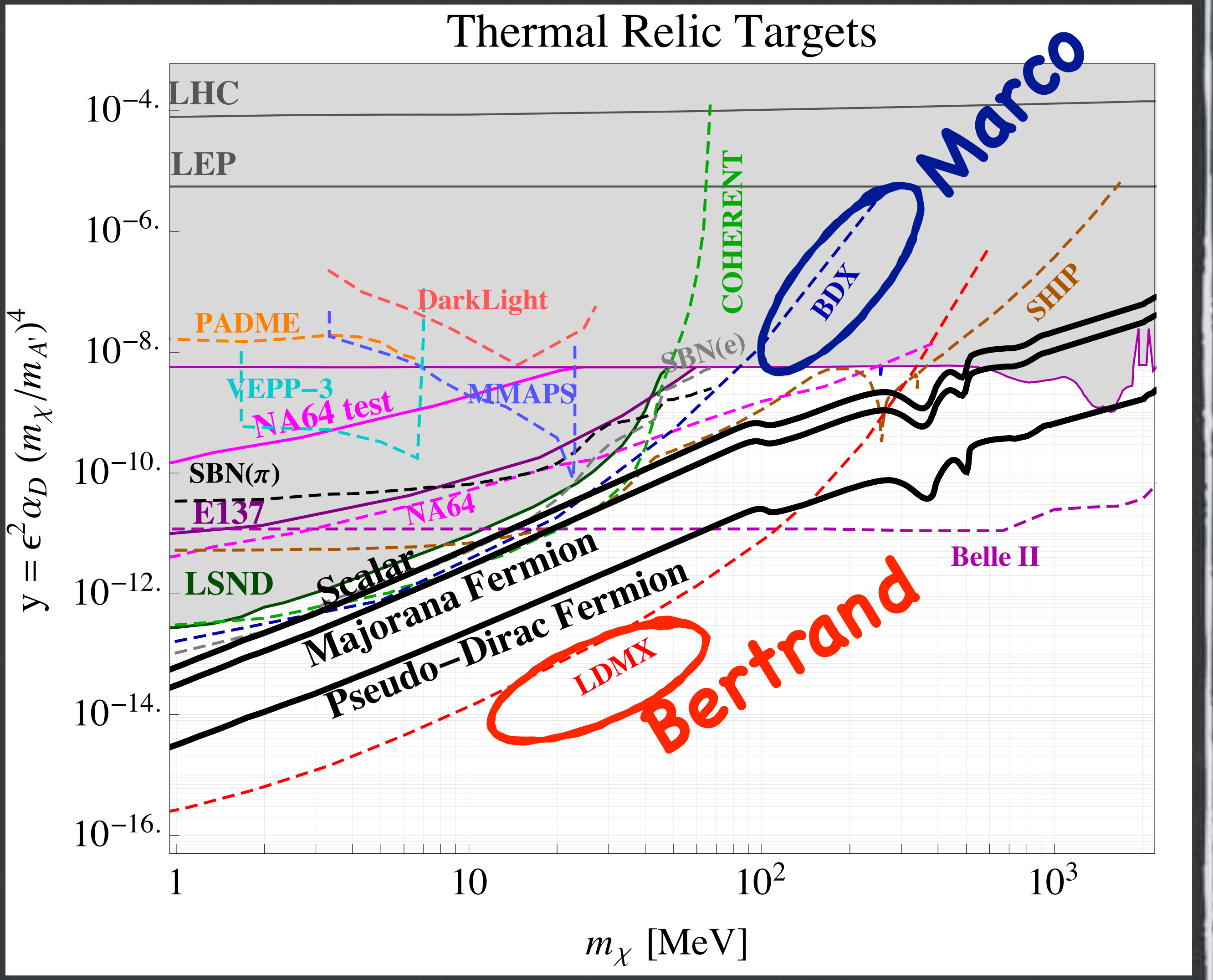
X (velocity-factors)

⇓

precise coupling depends on DM spin

# Thermal Relic Targets

- Canonical assumptions about the interactions and thermal origin of sub-GeV DM imply sharp parameter-space milestones!
  - They are allowed by current data!
  - And they can be tested by upcoming experiments!

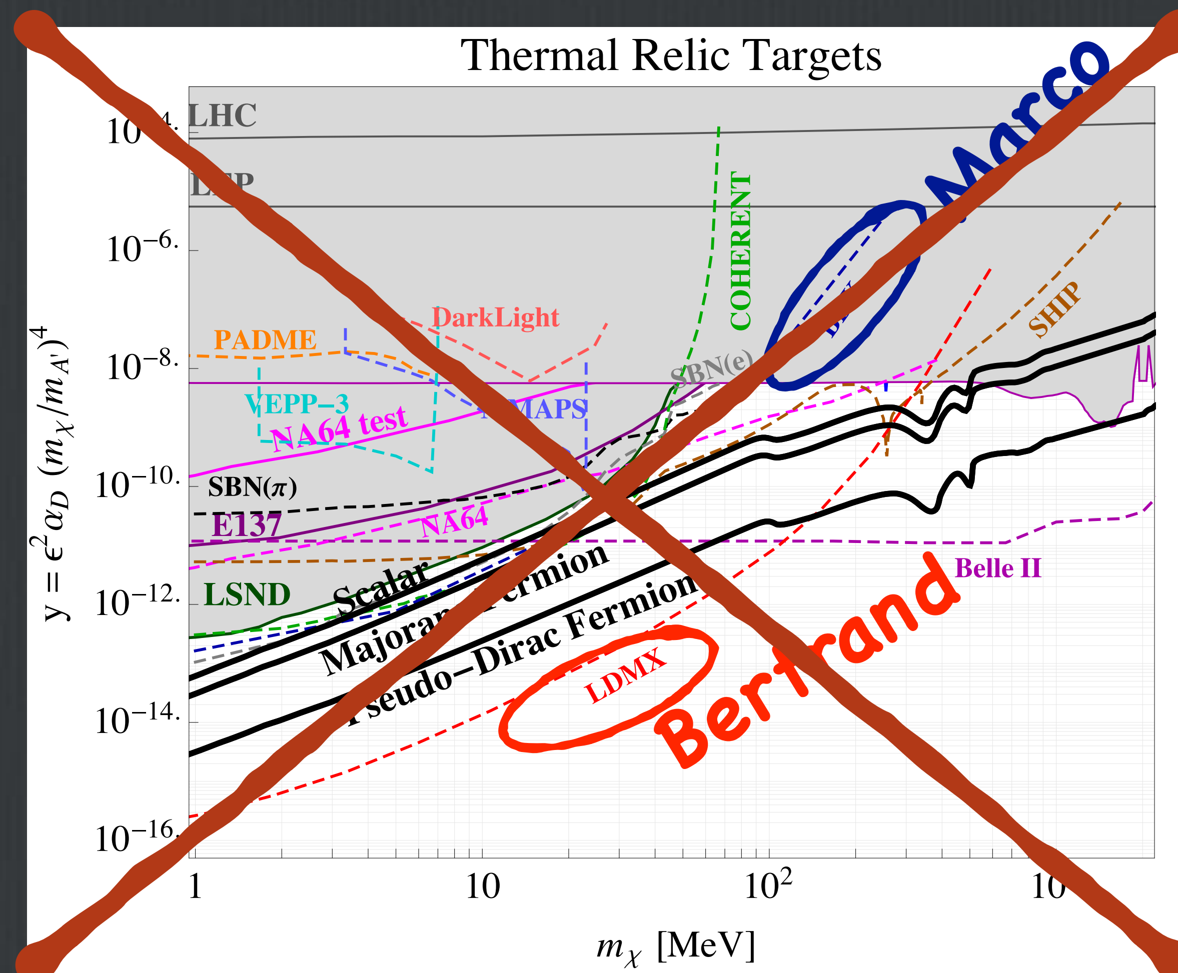



- This is strong motivation for new experiments…but it's just the tip of the iceberg

# Beyond the Thermal Targets

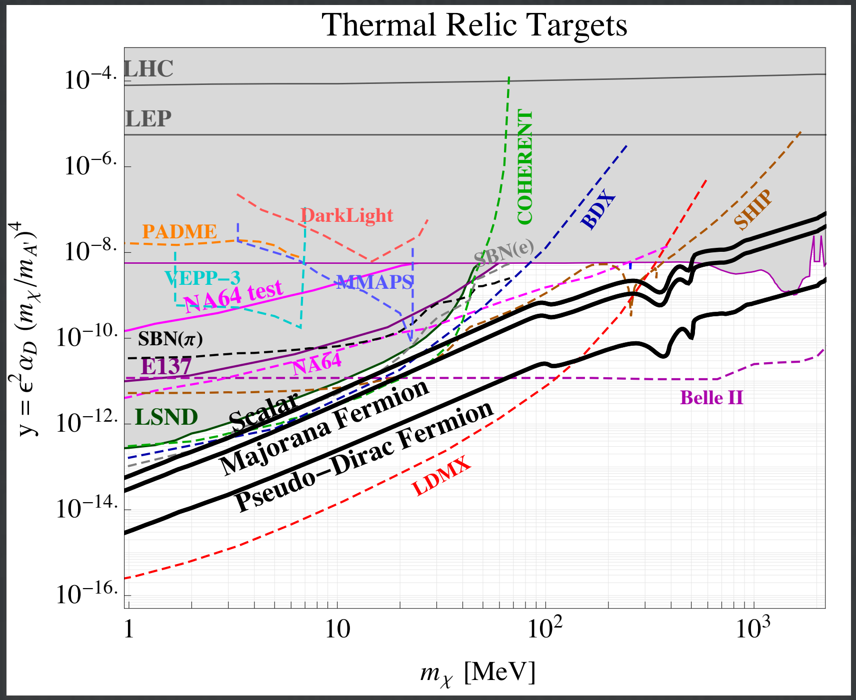
- Let's think about experiments like LDMX & BDX in broader contexts
  - Embracing the paradigm shift


    - Look for weakly coupled "portals" irrespective of direct connection to dark matter
  - Shaking up thermal origin story
    - New signals from non-minimal structure within the dark sector (CF Asher's talk)



# Significance of the Thermal Targets

## "High value milestones"




## vs.

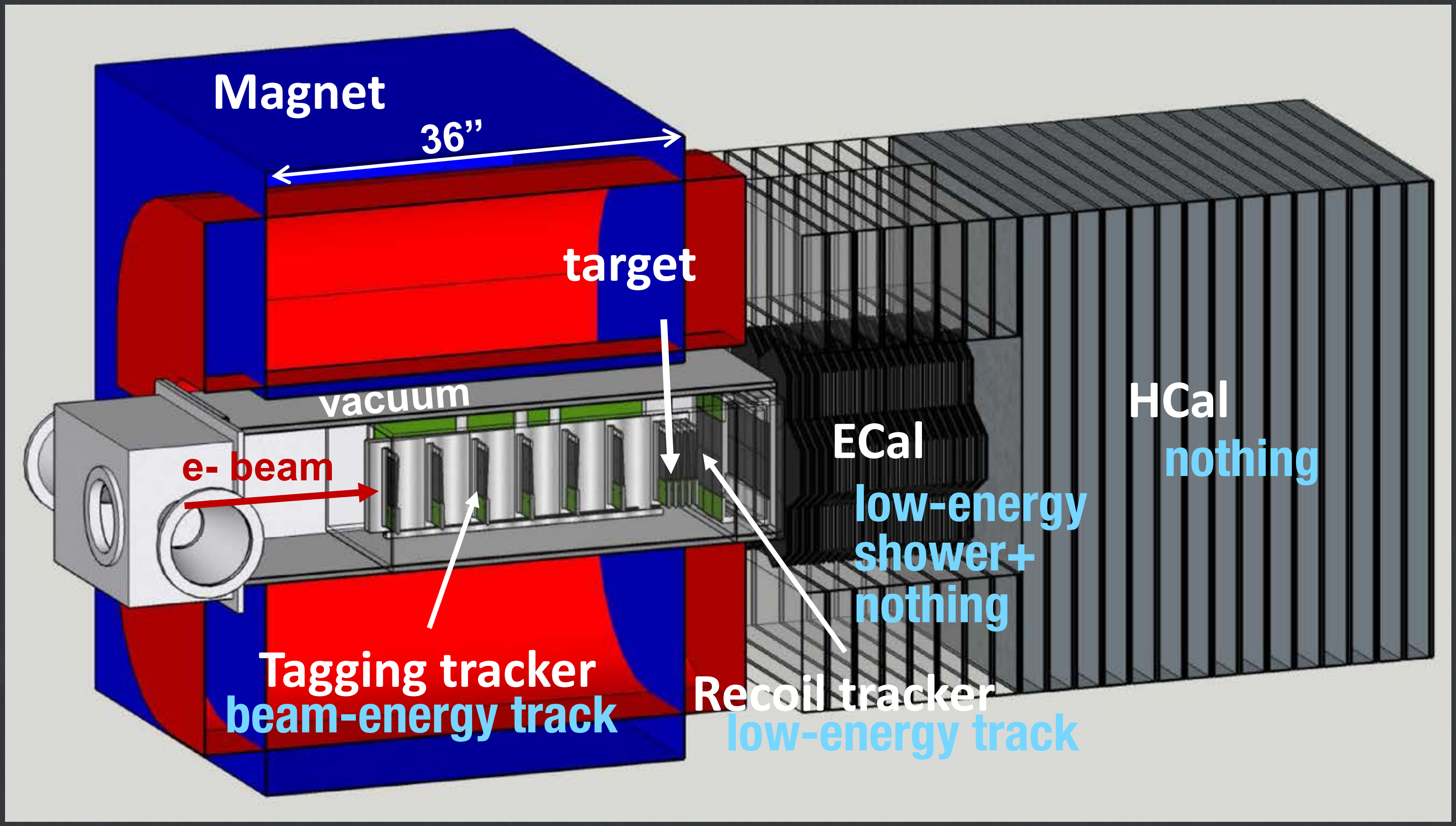
## "The dark sector could be anything"

# Outline

- ☐ Beyond Thermal Dark Matter
  - New forces and millicharges at LDMX
  - Non-minimal DM signals at BDX
- ☐ Light Thermal Dark Matter
  - Why do thermal targets stand out?
  - How do we get there?
  - What are we still missing?

# Case Study: LDMX

designed to precisely measure $e_{hard} \rightarrow e_{soft}$ + nothing

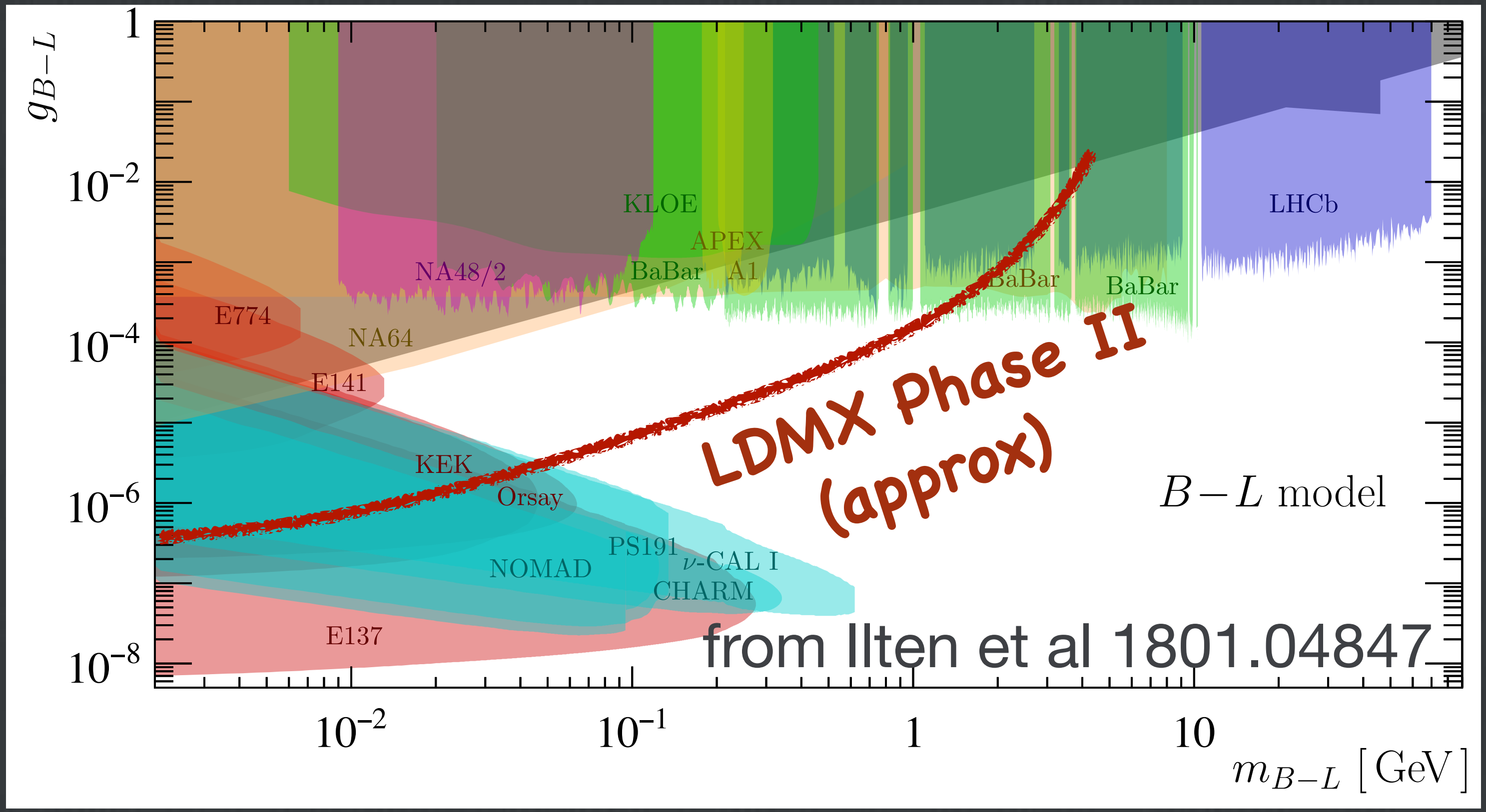



the following are ROUGH estimates of LDMX “Phase II” sensitivity to a variety of different models

# Applications of Missing Momentum

In addition to light DM, explore new parameter space for

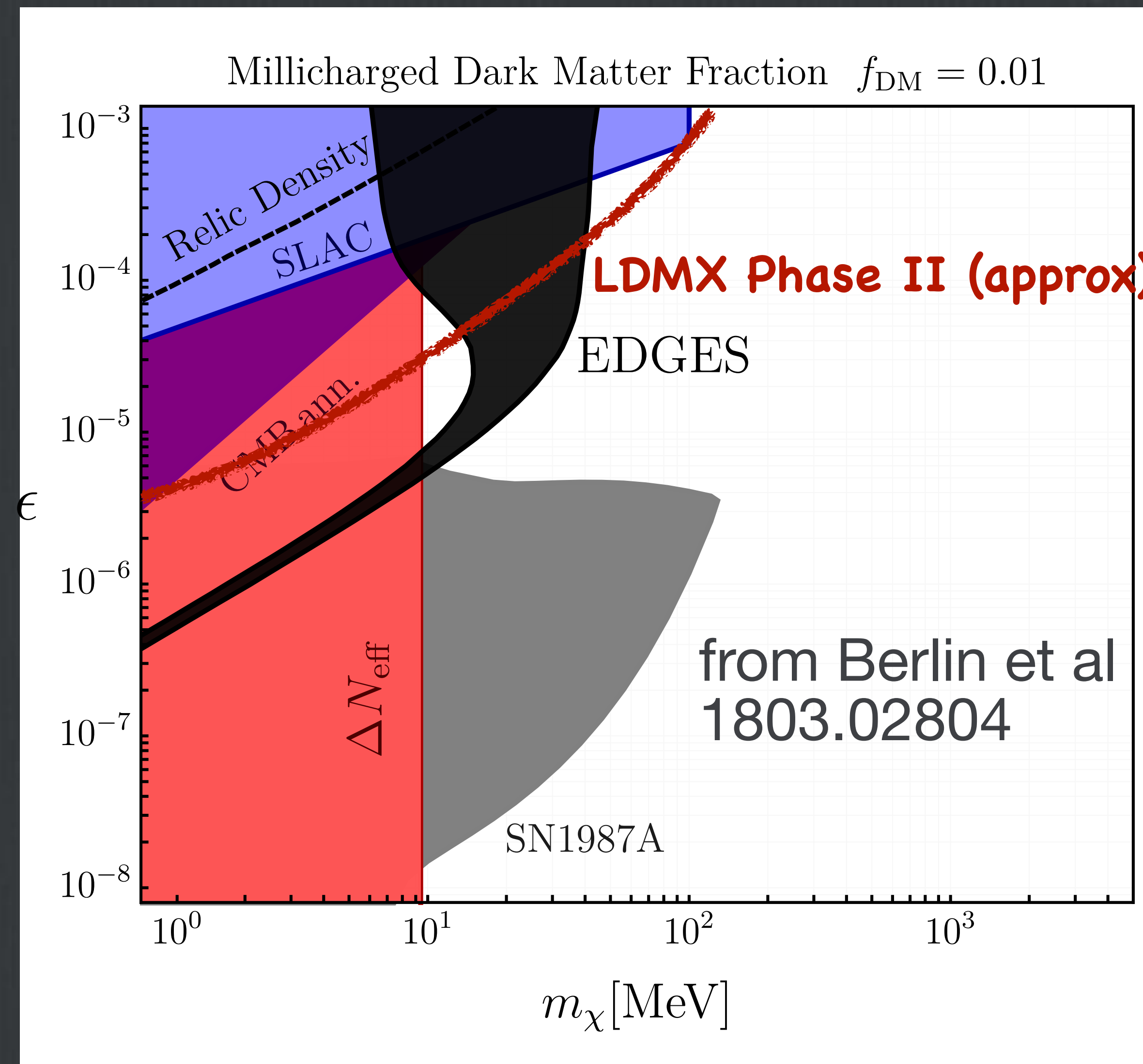
- light mediator decays to $\nu\bar{\nu}$ (e.g. gauged B-L)



# Applications of Missing Momentum

In addition to light DM, explore new parameter space for

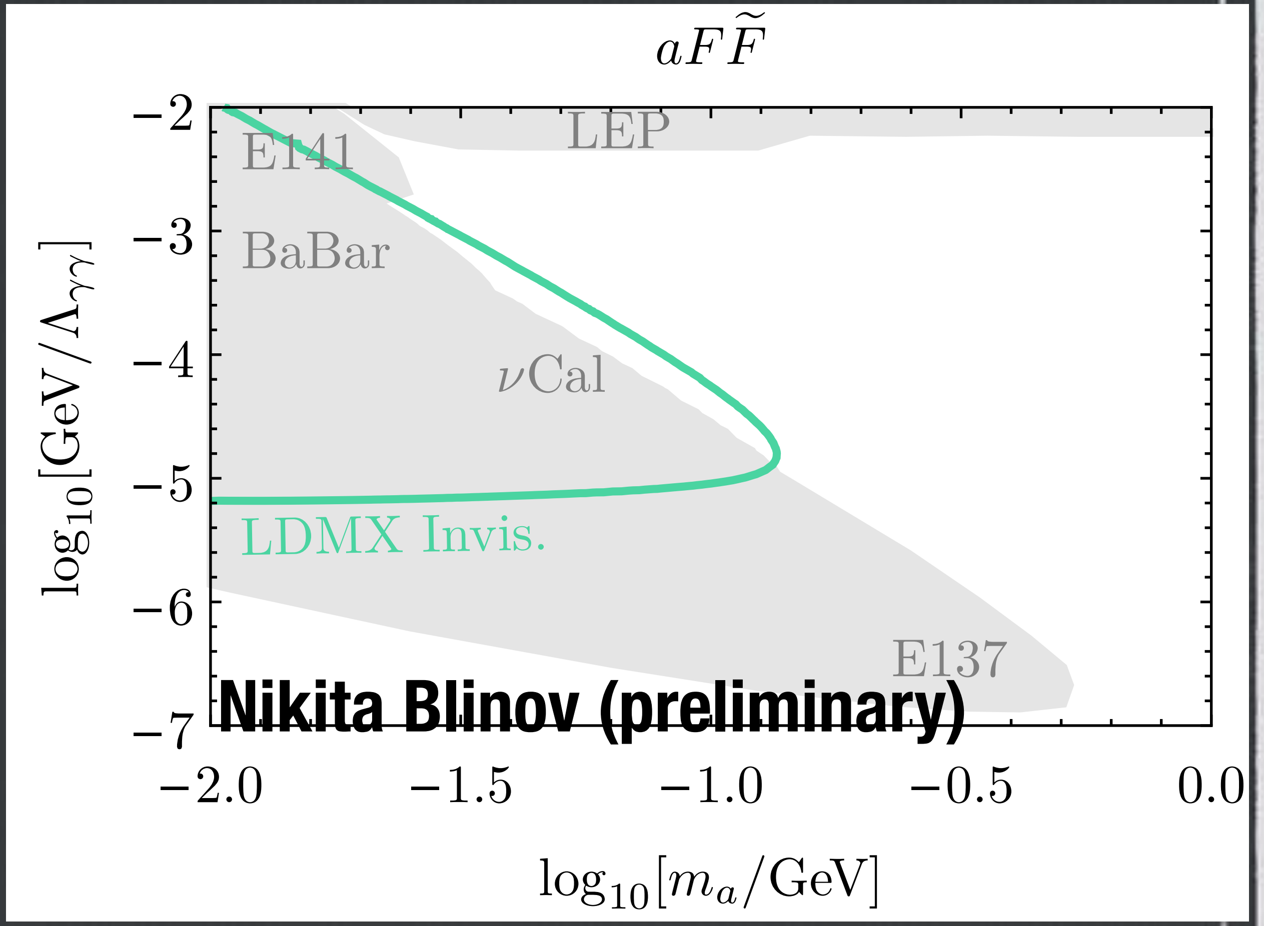
- ☐ light mediator decays to $\nu\bar{\nu}$ (e.g. gauged B-L)
- ☐ Milli-charged particles (including parameter space motivated by EDGES anomaly)



# Applications of Missing Momentum

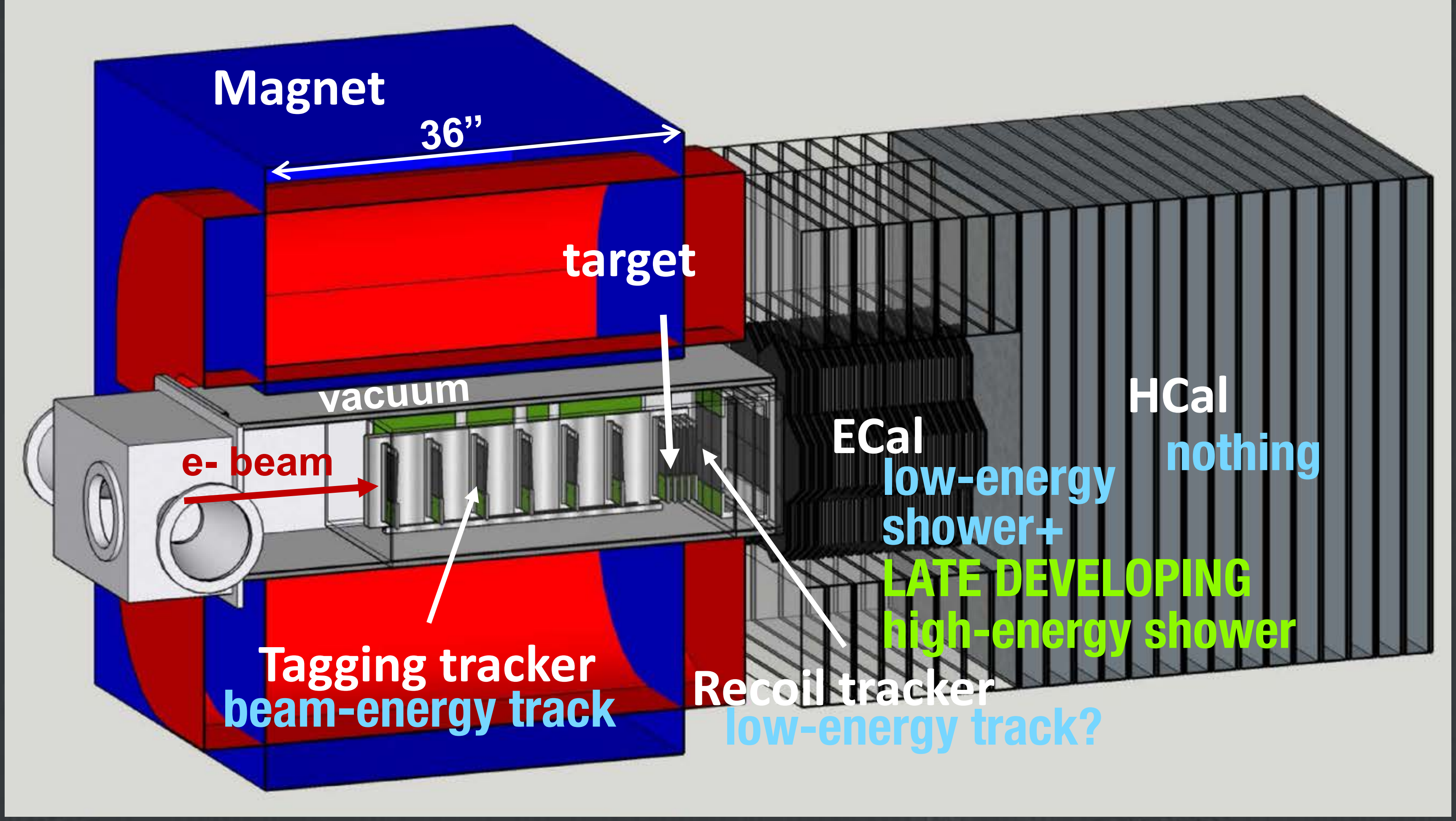
In addition to light DM, explore new parameter space for

- light mediator decays to $\nu\bar{\nu}$ (e.g. gauged B-L)
- Milli-charged particles (including parameter space motivated by EDGES anomaly)
- Long-lived particles produced by eN or γN collisions & decaying behind the LDMX HCAL (e.g. ALPs and minimal dark photons)



# Other Signatures at LDMX

**LDMX is also well suited to search for long-lived particles carrying most of the beam energy and decaying deep in the ECAL (or in the HCAL)**
*analogous to LHC searches for LLPs in HCAL or muon chambers

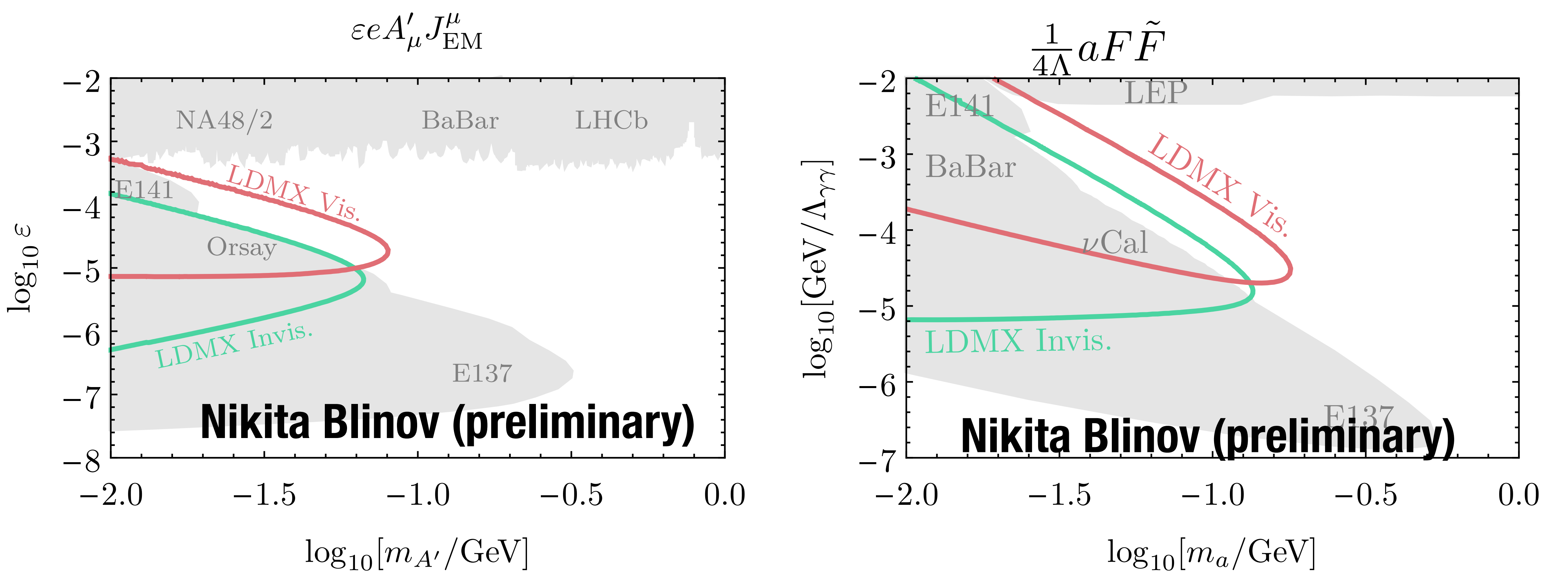



- ECAL designed to fully contain irreducible bkg from late photon conversions
- Use energy resolution to reject γ-nuclear final states

# Late Decays

## in last ~10 $X_0$ of ECAL or back HCAL

## Yield-Limited Sensitivity Estimates

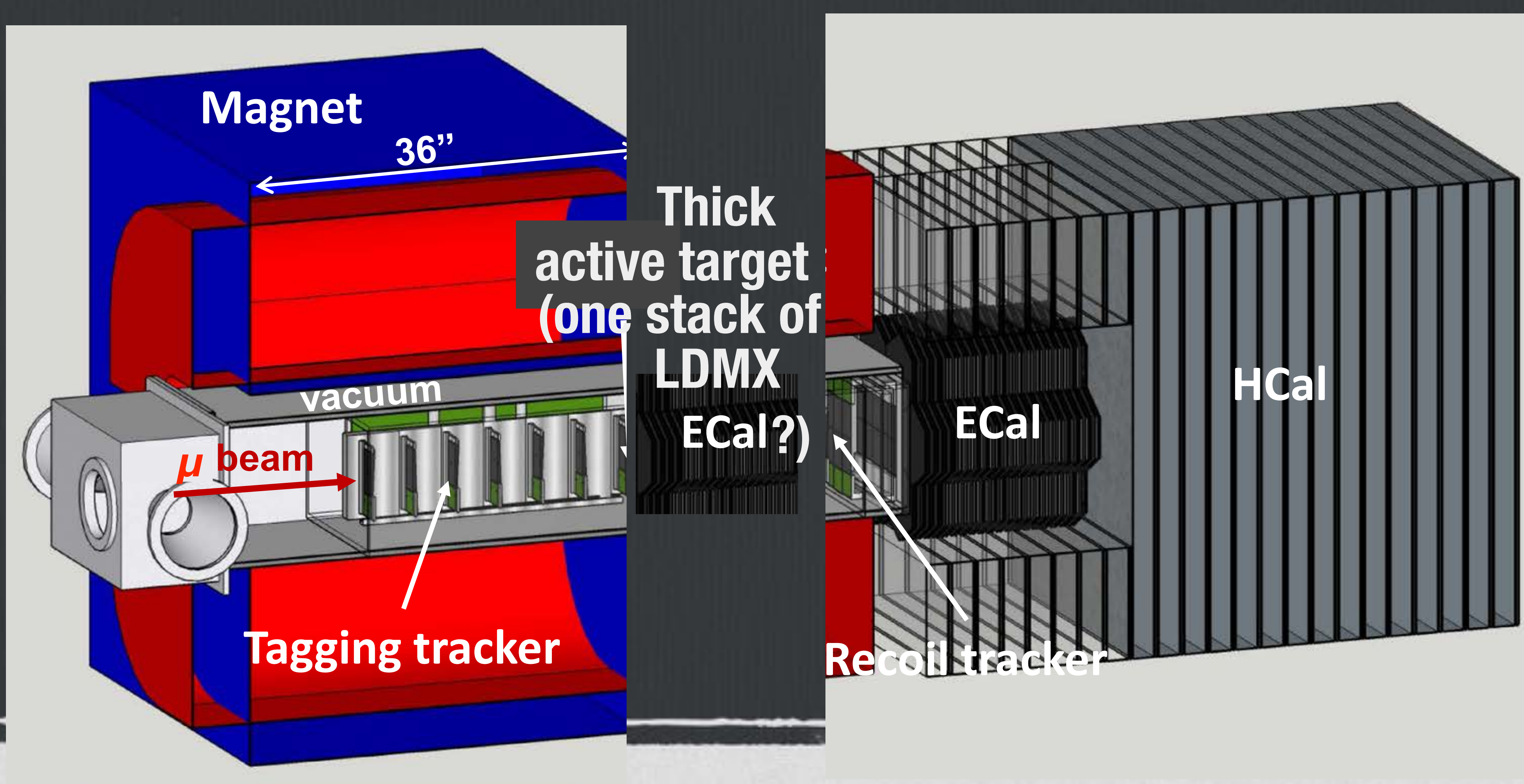



**Red curves correspond to 9 events beyond z=28 cm (i.e. in LDMX HCAL)
More studies needed to define realistic sensitivity for ECAL events, which should give access to larger couplings.**

# Missing Momentum in Muon Beams

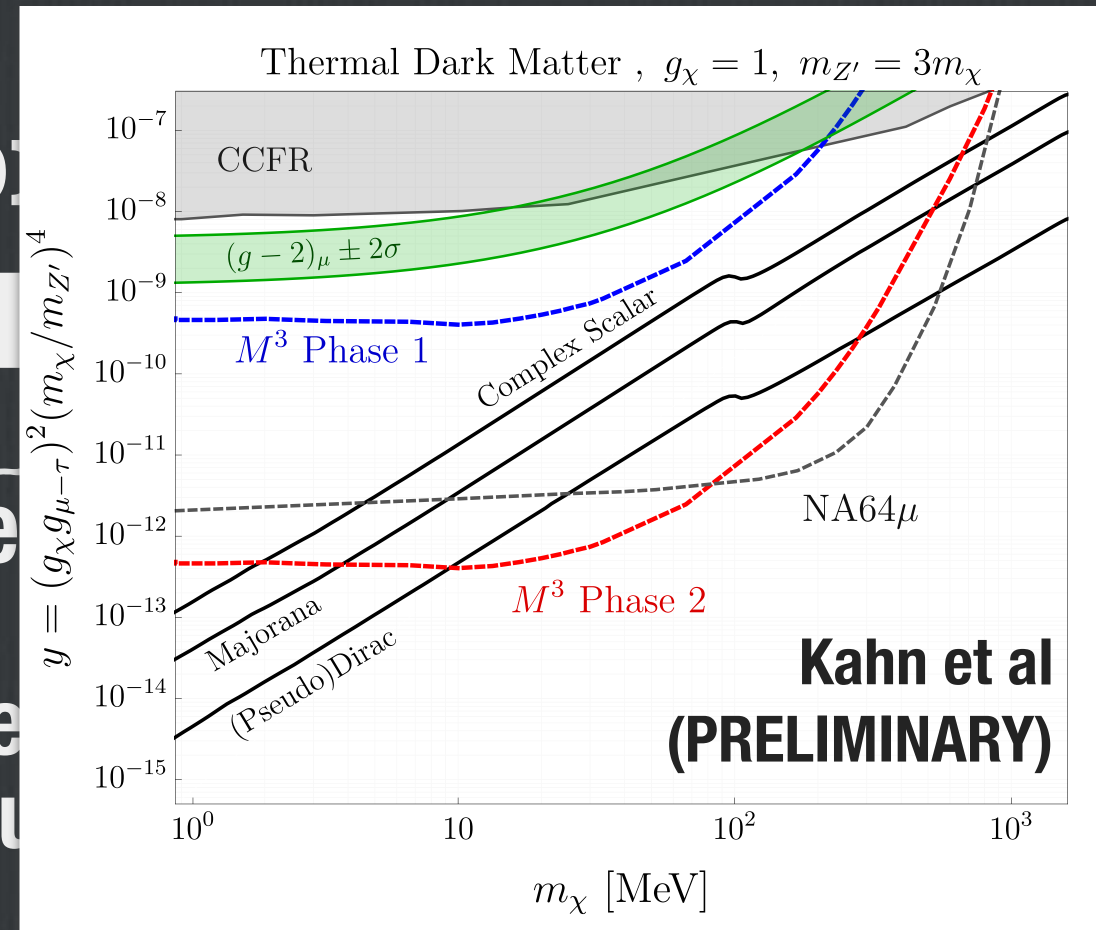
## What about new physics that doesn't couple to electrons or photons?

- Most anomaly-free vectors couple to muons (also motivated by g-2)
- Scalars mixed with SM Higgs should also couple to muons.



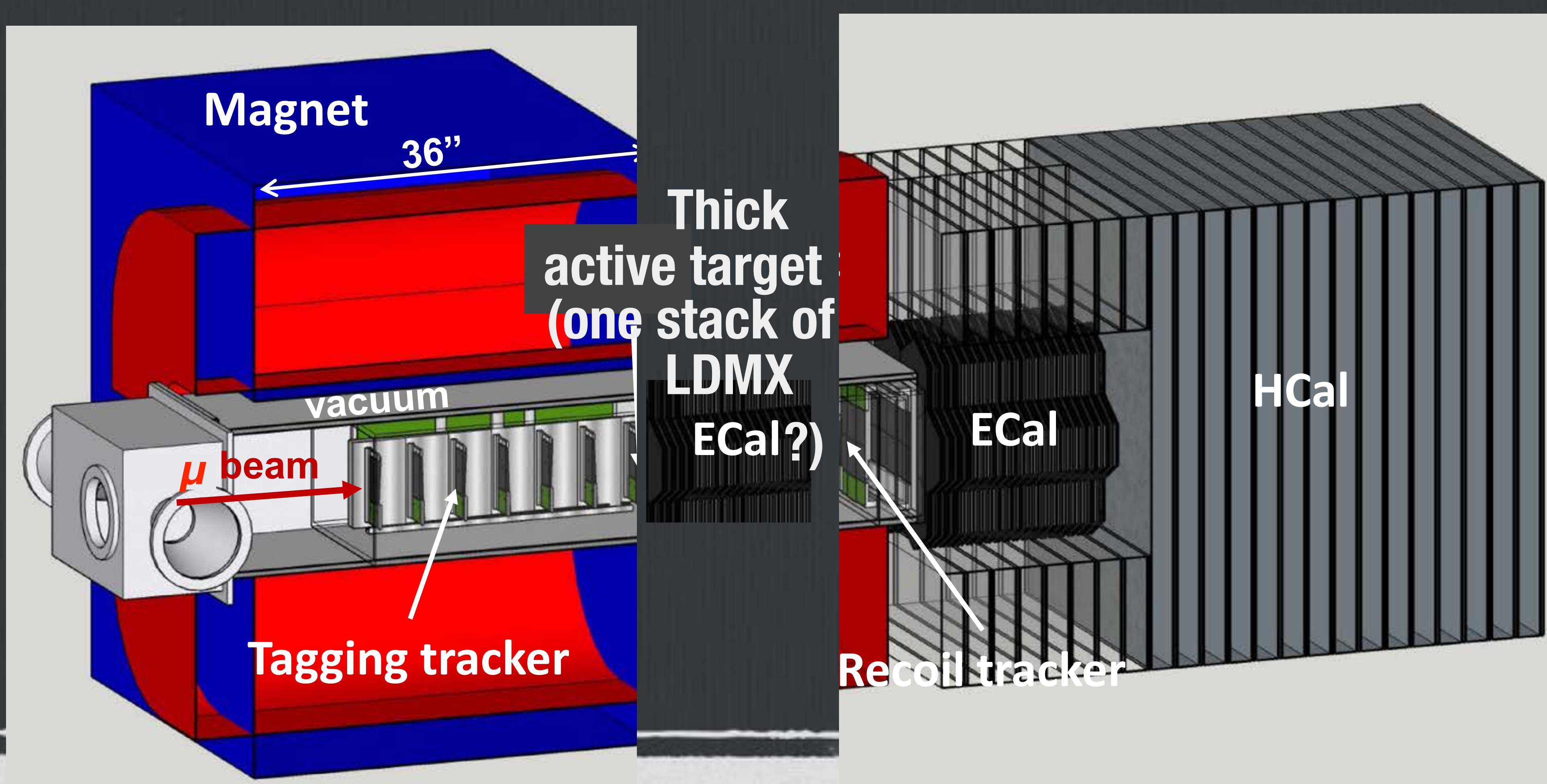

**Work to appear shortly by Kahn, Krnjaic, Tran, Whitbeck**

# Missing Mo
# in Muon 



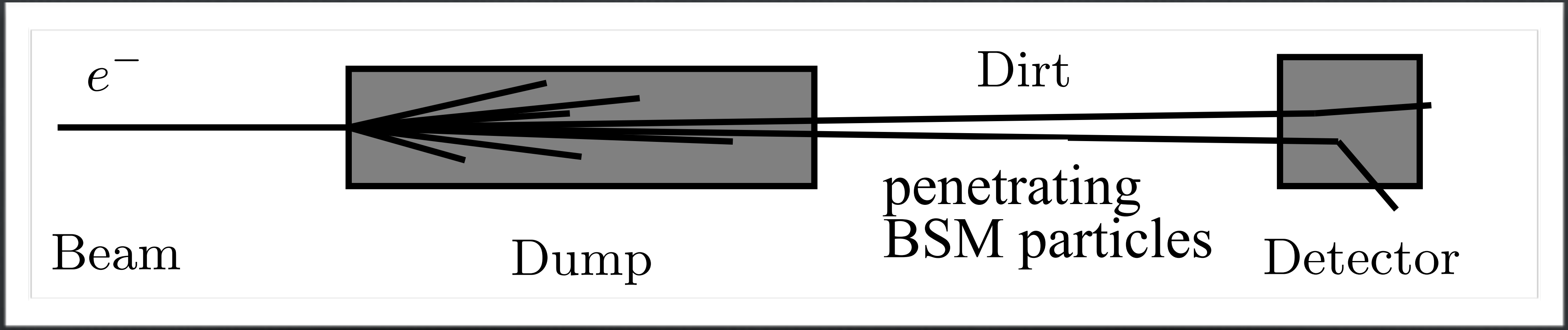

What about new physics that doe
photons?

- Most anomaly-free vectors couple 2)
- Scalars mixed with SM Higgs shou



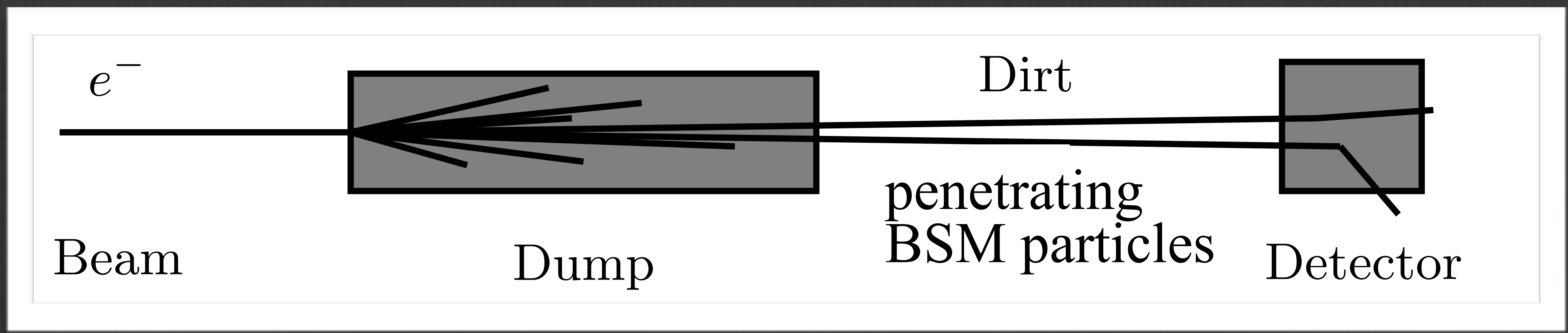

Work to appear shortly by Kahn, Krnjaic, Tran, Whitbeck

# Beam Dump Experiments

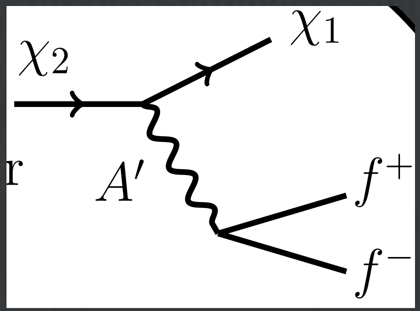



- Look for unexpected energy deposition behind intense beam dump (~$10^{22}$ $e^-$ at BDX, $10^{21}$ p at SBN)
  - High, but comparable to E137, Orsay beam dump
  - Better acceptances
  - Much lower energy thresholds
  - Timing-based rejection of ν background (proton beams)

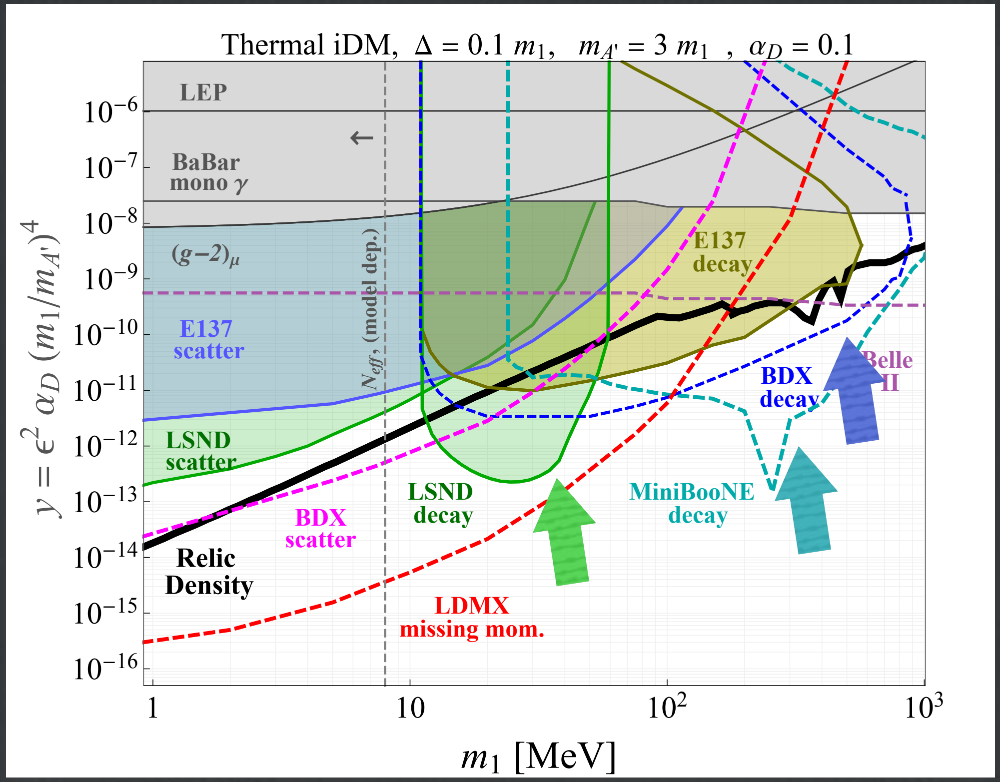
# Beam Dump Experiments




In addition to the "canonical" DM scattering signal, search for decays of DM excited states (inelastic DM)




Izaguirre, Kahn, Krnjaic, Moschella 1703.06881




Similar signals possible in SIMP models

# Summary

- It makes sense to optimize new experiments for minimal models of light thermal dark matter…
- But these experiments are broader “dark sector explorers” with powerful reach for other physics
  - New force & millicharge searches
  - Explore signals of non-minimal dark sectors
- In some cases (e.g. late decays at LDMX), understanding this sensitivity may motivate minor modifications to detector geometry
  - Important to explore these now!

# Outline

- Beyond Thermal Dark Matter
  - New forces and millicharges at LDMX
  - Non-minimal DM signals at BDX
- Light Thermal Dark Matter
  - Why do thermal targets stand out?
  - How do we get there?
  - What are we still missing?

# Build Your Own Dark Sector
# 1. Choose your Mediator

**Standard Model symmetries admit four renormalizable interactions of SM particles with new, SM-neutral particles:**

*Bosonic mediators*

$$\epsilon_Y B^{\mu\nu} F'_{\mu\nu}$$

→ induces kinetic mixing with photon at low energies

$$g_X Z'_\mu J^\mu_X$$

→ coupling to SM global conserved charge (e.g. B-L, $L_\mu$-$L_e$, etc)

$$A|h|^2\phi + \lambda|h|^2\phi^2$$

→ mixing with SM Higgs ⇒ couplings proportional to fermion masses

*Fermionic mediator*

$$\kappa H L N$$

→ Sterile neutrino mediator …I won't discuss it, but see Battel et al arXiv:1709.07001

Adding more TeV-scale matter content to SM allows for more general couplings (e.g. vector coupled to non-conserved currents– but see Dror, Lasenby, and Pospelov 2017– or scalar with non-Higgs-like Yukawas )

# Build Your Own Dark Sector
# 2. Choose your Dark Matter

- Is Dark Matter a scalar or fermion?
(For scalar mediator, this is all we need to ask.)
- For vector mediator, do DM masses preserve or violate the U(1) gauged by the dark force?
  - Since mediator mass breaks symmetry, reasonable for DM mass to break it too

**We should stay agnostic about DM physics, but details alter physics of both annihilation and scattering at low temperatures**

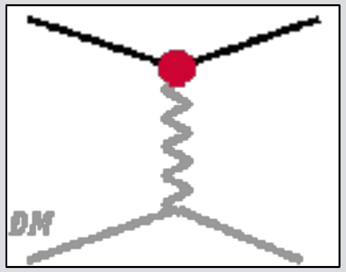
# Build Your Own Dark Sector
# 2. Choose your Dark Matter

- Is Dark Matter a scalar or fermion?
  (For scalar mediator, this is all we need to ask.)
- For vector mediator, do DM masses preserve or violate the U(1) gauged by the dark force?

  Since mediator mass breaks symmetry, reasonable for DM mass to break it too

**We should stay agnostic about DM physics, but details alter physics of both annihilation and scattering at low temperatures**

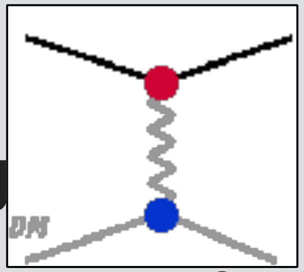
U(1)-preserving mass




$\sigma \sim g_{SM}^2$

U(1)-breaking mass only (Majorana)

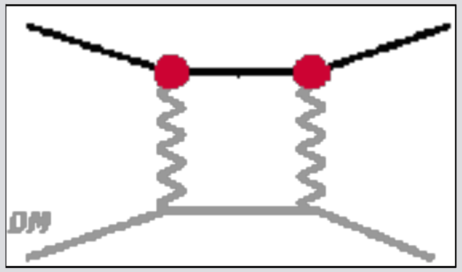
⇒ axial coupling




$\sigma \sim g_{SM}^2\, v^2$

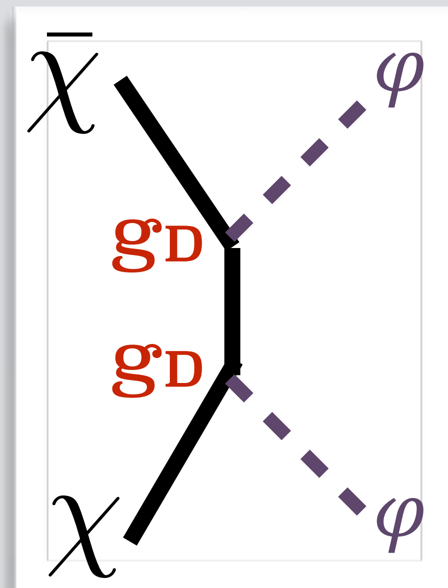
U(1)-breaking & preserving

⇒ mass-off -diagonal coupling

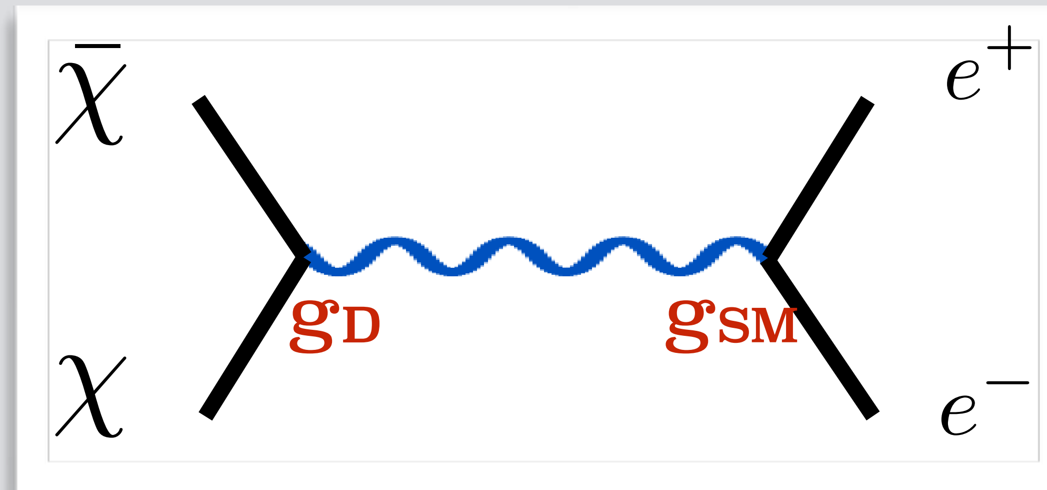



$\sigma \sim g_{SM}^4$

# Build Your Own Dark Sector
# 3. Choose your Annihilation Mode




Abundance set by small $g_D$ – independent of $\varphi$-SM coupling




Abundance set by $g_D g_{SM}/m_{Med}^2$
$\Rightarrow$ sharp target for production & scattering!

$m_\chi$ $2\,m_\chi$ $m_{Med}$

Visibly decaying mediator
+ DM production
via off-shell mediator

Invisible mediator

DM scattering

# Build Your Own Dark Sector

1. Choose your Mediator
   - ☐ Vector coupled to…
     - ☐ Charge (via kinetic mixing)
     - ☐ Non-anomalous global symmetry
       - ☐ B-L, e-μ, e-τ,
       - ☐ B-μ, μ-τ, B-τ
     - ☐ Anomalous global symmetry (+1*)
     - ☐ Effective Z′ coupling (+3*)
   - ☐ Scalar coupled to…
     - ☐ Fermion masses via Higgs mixing
     - ☐ General EFT (+3*)

*extra charge for new TeV-scale physics needed to make theory consistent

Let's assumes dark sector was once in thermal contact with familiar matter

2. Choose your Dark Matter
   - ☐ Complex Scalar
   - ☐ Pseudo-Complex Scalar
   - ☐ Majorana Fermion
   - ☐ Dirac Fermion
   - ☐ Pseudo-Dirac Fermion
3. Choose your Mass Hierarchy
   - ☐ $m_{Med} < m_{DM}$: "Secluded" annihilation into two mediators [least predictive]
   - ☐ $m_{Med} > m_{DM}$: "Direct" annihilation via mediator into SM final states [most predictive]
4. Extras (+3)
   - ☐ Depletion via dark-sector self-interaction (SIMP)
   - ☐ Forbidden annihilation ($m_{Med} \simeq m_{DM}$)
   - ☐ Resonant annihilation ($m_{Med} \simeq 2m_{DM}$)

# Build Your Own Dark Sector

1. Choose your Mediator
   - ☐ Vector coupled to…
     - ☐ Charge (via kinetic mixing)
     - ☐ Non-anomalous global symmetry
       - ☐ B-L, e-μ, e-τ,
       - ☐ B-μ, μ-τ, B-τ
     - ☐ Anomalous global symmetry (+1*)
     - ☐ Effective Z′ coupling (+3*)
   - ☐ Scalar coupled to…
     - ☐ Fermion masses via Higgs mixing

2. Choose your Dark Matter
   - ☐ Complex Scalar
   - ☐ Pseudo-Complex Scalar
   - ☐ Majorana Fermion
   - ☐ Dirac Fermion
   - ☐ Pseudo-Dirac Fermion
3. Choose your Mass Hierarchy
   - ☐ $m_{Med} < m_{DM}$: “Secluded” annihilation into two mediators [less predictive]
   - ☐ $m_{Med} > m_{DM}$: ”Direct” annihilation via mediator into SM final states [most predictive]

elf-

*

r

ed≃$m_{DM}$)

- ☐ Resonant annihilation ($m_{Med}$≃$2m_{DM}$)

**Even ignoring the “premium” options, this seems like an intractably long menu…but many combinations are phenomenologically similar, and not all are allowed.**

## s

1. Choose your Mediator
   - ☐ Vector coupled to…
     - ☐ Charge (via kinetic mixing)
     - ☐ Non-anomalous global symmetry
       - ☐ B-L, e-τ, e-μ
       - ☐ μ-τ, B-μ, B-τ
     - ☐ Anomalous global symmetry (+1*)
     - ☐ Effective Z′ coupling (+3*)
   - ☐ Scalar coupled to…
     - ☐ Fermion masses via Higgs mixing
     - ☐ General EFT (+3*)

*extra charge for new TeV-scale physics needed to make theory consistent

2. Choose your Dark Matter
   - ☐ Complex Scalar
   - ☐ Pseudo-Complex Scalar
   - ☐ Majorana Fermion
   - ☐ Dirac Fermion
   - ☐ Pseudo-Dirac Fermion
3. Choose your Mass Hierarchy
   - ☑ $m_{Med} < m_{DM}$: "Secluded" annihilation into two mediators [least predictive]
   - ☐ $m_{Med} > m_{DM}$: "Direct" annihilation via mediator into SM final states [most predictive]
4. Extras
   - ☐ Depletion via dark-sector self-interaction (SIMP)
   - ☐ Forbidden annihilation ($m_{Med} \simeq m_{DM}$)
   - ☐ Resonant annihilation ($m_{Med} \simeq 2m_{DM}$)

s

1. Choose your Mediator
   - ☐ Vector coupled to…
     - ☐ Charge (via kinetic mixing)
     - ☐ Non-anomalous global symmetry
       - ☐ B-L, e-τ, e-μ
       - ☐ μ-τ, B-μ, B-τ
     - ☐ Anomalous global symmetry (+1*)
     - ☐ Effective Z′ coupling (+3*)
   - ☐ Scalar coupled to…
     - ☐ Fermion masses via Higgs mixing
     - ☐ General EFT (+3*)

*extra charge for new TeV-scale physics needed to make theory consistent

2. Choose your Dark Matter
   - ☐ Complex Scalar

CMB power spectrum bounds
$\sigma v_{ann}(T\sim eV) \ll \sigma v_{ann}(T_{fo}\sim mDM/20)$
for DM below ~10 GeV

⇒ Focus on models with
$\sigma v_{ann}\sim v^2$ or
inelastic DM co-annihilation

[least predictive]

   - ☐ $m_{Med} > m_{DM}$: "Direct" annihilation via mediator into SM final states [most predictive]

4. Extras
   - ☐ Depletion via dark-sector self-interaction (SIMP)
   - ☐ Forbidden annihilation ($m_{Med} \simeq m_{DM}$)
   - ☐ Resonant annihilation ($m_{Med} \simeq 2m_{DM}$)

s

1. Choose your Mediator
   - ☐ ~~Vector coupled~~ to…
     - ☐ ~~Charge (via kinetic mixing)~~
     - ☐ ~~Non-anomalous global symmetry~~
       - ☐ ~~B-L, e-τ, e-μ~~
       - ☐ ~~μ-τ, B-μ, B-τ~~

excluded by C
bound on late-
time annihilati

     - ☐ Anomalous global symmetry (+1*)
     - ☐ Effective Z′ coupling (+3*)
   - ☐ Scalar coupled to…
     - ☐ Fermion masses via Higgs mixing
     - ☐ General EFT (+3*)

*extra charge for new TeV-scale physics needed to make theory consistent

2. Choose your Dark Matter
   - ☐ Complex Scalar

CMB power spectrum bounds
$\sigma v_{ann}(T\sim eV) \ll \sigma v_{ann}(T_{fo}\sim mDM/20)$
for DM below ~10 GeV

⟹ Focus on models with
$\sigma v_{ann} \sim v^2$ or
inelastic DM co-annihilation

[least predictive]

   - ☐ $m_{Med} > m_{DM}$: "Direct" annihilation via mediator into SM final states [most predictive]

4. Extras
   - ☐ Depletion via dark-sector self-interaction (SIMP)
   - ☐ Forbidden annihilation ($m_{Med} \simeq m_{DM}$)
   - ☐ Resonant annihilation ($m_{Med} \simeq 2m_{DM}$)

s

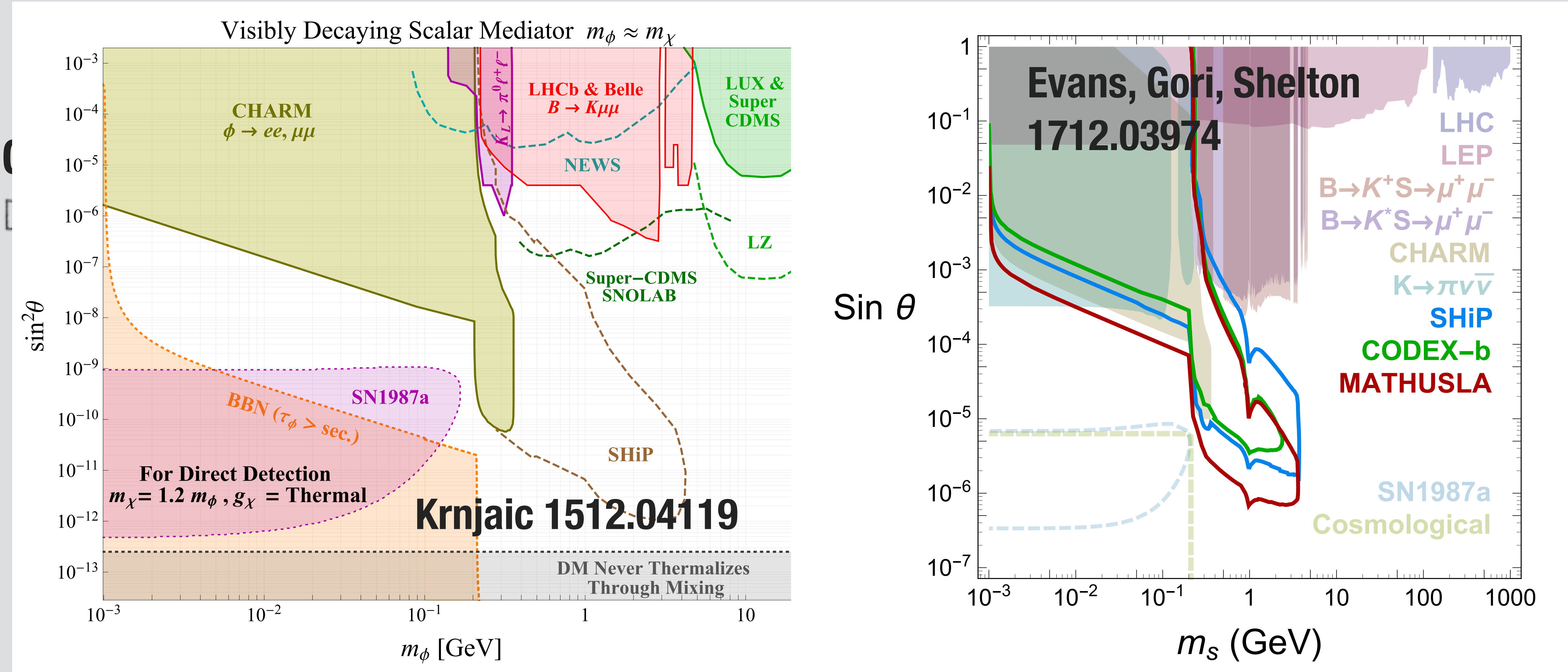
1. Choose your Mediator
   - ☐ ~~Vector coupled~~ to…
     - ☐ ~~Charge (via kinetic mixing)~~
     - ☐ ~~Non-anomalous global symmetry~~
       - ☐ ~~B-L, e-τ, e-μ~~
       - ☐ ~~μ-τ, B-μ, B-τ~~
     - ☐ Anomalous global symmetry (+1*)
     - ☐ Effective Z′ coupling (+3*)
   - ✓ Scalar coupled to…
     - ✓ Fermion masses via Higgs mixing
     - ☐ General EFT (+3*)

excluded by CMB bound on late-time annihilation

2. Choose your Dark Matter
   - ☐ Complex Scalar
   - ☐ Pseudo-Complex Scalar
   - ☐ Majorana Fermion
   - ☐ Dirac Fermion
   - ☐ Pseudo-Dirac Fermion
3. Choose your Mass Hierarchy
   - ✓ $m_{Med} < m_{DM}$: “Secluded” annihilation into two mediators [least predictive]
   - ☐ $m_{Med} > m_{DM}$: ”Direct” annihilation via mediator into SM final states [most predictive]
4. Extras
   - ☐ Depletion via dark-sector self-interaction (SIMP)
   - ☐ Forbidden annihilation ($m_{Med} \simeq m_{DM}$)
   - ☐ Resonant annihilation ($m_{Med} \simeq 2m_{DM}$)

*extra charge for new TeV-scale physics needed to make theory consistent

1. C




☐ Effective Z' coupling (+3')

[least predictive]

✓ Scalar coupled to…

✓ Fermion masses via Higgs mixing

☐ $m_{Med} > m_{DM}$: "Direct" annihilation via mediator into SM final states [most predictive]

Below ~200 MeV, $g_{\chi\phi}$~$10^{-6}$–$10^{-4}$ (fixed by secluded freeze-out) and small window of allowed Higgs mixing (from consistency with CHARM, SN1987a, and BBN) **define a parameter-space target.** But tiny couplings make these models difficult to explore further with accelerators or direct detection ($\sigma_{\chi e} \lesssim 10^{-44}$ cm$^2$). At higher masses, some new parameter space can be explored by proton beams (eg. SHIP) and direct detection (eg SuperCDMS) with significant complementarity.

# Build Your Own Dark Sector

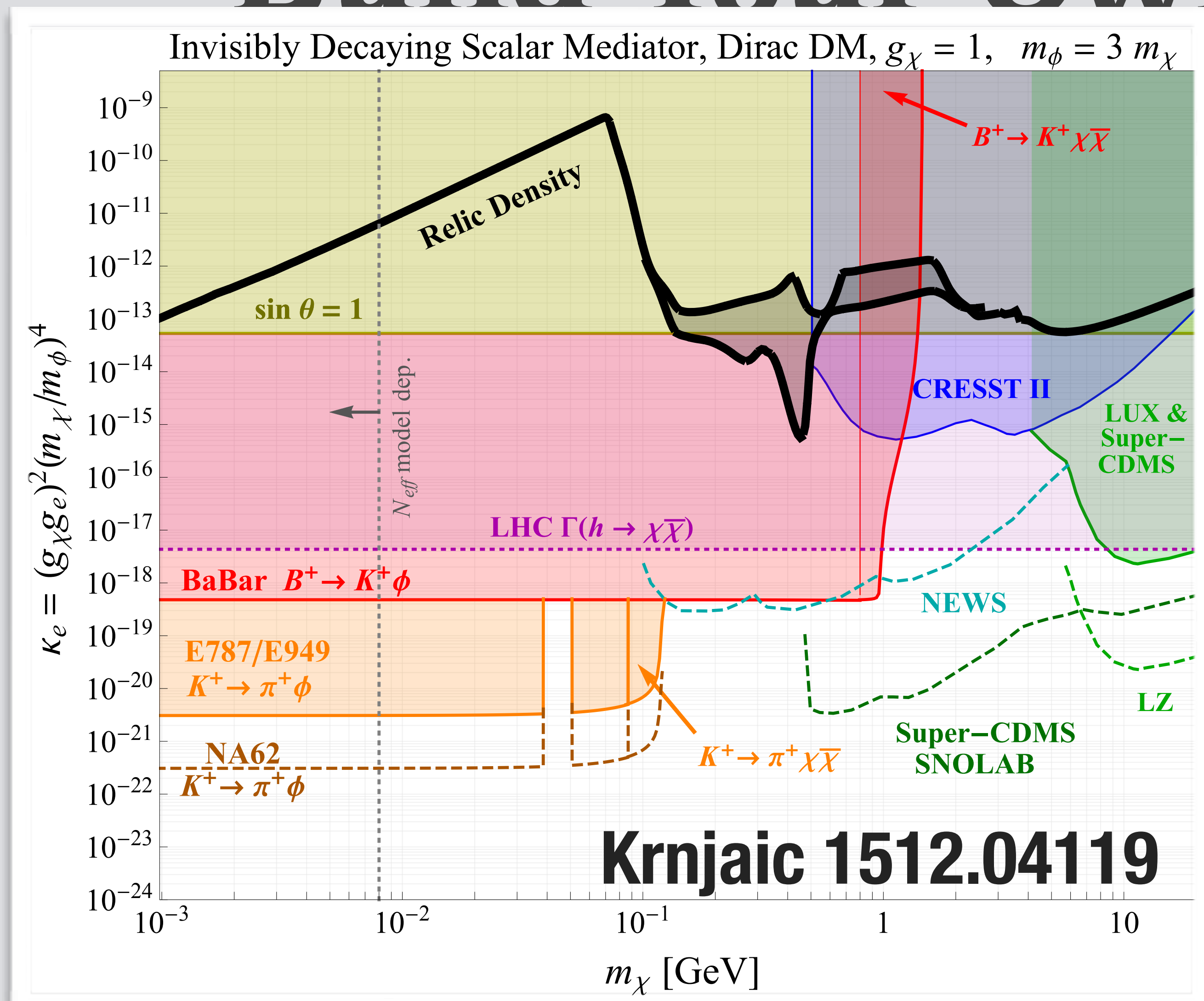
1. Choose your Mediator
   - ☐ Vector coupled to…
     - ☐ Charge (via kinetic mixing)
     - ☐ Non-anomalous global symmetry
       - ☐ B-L, e-τ, e-μ
       - ☐ μ-τ, B-μ, B-τ
     - ☐ Anomalous global symmetry (+1*)
     - ☐ Effective Z′ coupling (+3*)
   - ☐ Scalar coupled to…
     - ☐ Fermion masses via Higgs mixing
     - ☐ General EFT (+3*)

*extra charge for new TeV-scale physics needed to make theory consistent

2. Choose your Dark Matter
   - ☐ Complex Scalar
   - ☐ Pseudo-Complex Scalar
   - ☐ Majorana Fermion
   - ☐ Dirac Fermion
   - ☐ Pseudo-Dirac Fermion
3. Choose your Mass Hierarchy
   - ☐ $m_{Med} < m_{DM}$: “Secluded” annihilation into two mediators [least predictive]
   - ✓ $m_{Med} > m_{DM}$: ”Direct” annihilation via mediator into SM final states [most predictive]
4. Extras
   - ☐ Depletion via dark-sector self-interaction (SIMP)
   - ☐ Forbidden annihilation ($m_{Med} \simeq m_{DM}$)
   - ☐ Resonant annihilation ($m_{Med} \simeq 2m_{DM}$)

# Build Your Own Dark Sector

1.




☐ ~~Fermion masses via Higgs mixing~~ excluded by meson & Higgs invisible decays

☐ General E

2. Choose your Dark Matter
- ☐ Complex Scalar
- ☐ Pseudo-Complex Scalar
- ☐ Majorana Fermion
- ☐ Dirac Fermion
- ☐ Pseudo-Dirac Fermion

3. Choose your Mass Hierarchy
- ☐ $m_{Med} < m_{DM}$: "Secluded" annihilation into two mediators [least predictive]
- ☑ $m_{Med} > m_{DM}$: "Direct" annihilation via mediator into SM final states [most predictive]

Extras
- ☐ Depletion via dark-sector self-interaction (SIMP)
- ☐ Forbidden annihilation ($m_{Med} \simeq m_{DM}$)
- ☐ Resonant annihilation ($m_{Med} \simeq 2m_{DM}$)

*extra charge for new TeV-scale physics needed to make theory consistent

# Build Your Own Dark Sector

1. Choose your Mediator
   - ☑ Vector coupled to…
     - ☐ Charge (via kinetic mixing)
     - ☐ Non-anomalous global symmetry
       - ☐ B-L, e-τ, e-μ
       - ☐ μ-τ, B-μ, B-τ
     - ☐ Anomalous global symmetry (+1*)
     - ☐ Effective Z′ coupling (+3*)
   - ☐ Scalar coupled to…
     - ☐ ~~Fermion masses via Higgs mixing~~
     - ☐ General E

excluded by meson & Higgs invisible decays

2. Choose your Dark Matter
   - ☐ Complex Scalar
   - ☐ Pseudo-Complex Scalar
   - ☐ Majorana Fermion
   - ☐ Dirac Fermion
   - ☐ Pseudo-Dirac Fermion
3. Choose your Mass Hierarchy
   - ☐ $m_{Med} < m_{DM}$: "Secluded" annihilation into two mediators [least predictive]
   - ☑ $m_{Med} > m_{DM}$: "Direct" annihilation via mediator into SM final states [most predictive]

Extras
- ☐ Depletion via dark-sector self-interaction (SIMP)
- ☐ Forbidden annihilation ($m_{Med} \simeq m_{DM}$)
- ☐ Resonant annihilation ($m_{Med} \simeq 2m_{DM}$)

*extra charge for new TeV-scale physics needed to make theory consistent

# Build Your Own Dark Sector

1. Choose your Mediator
   - ☑ Vector coupled to…
     - ☐ Charge (via kinetic mixing)
     - ☐ Non-anomalous global symmetry
       - ☐ B-L, e-τ, e-μ
       - ☐ μ-τ, B-μ, B-τ

     look very similar for e- beam/ scattering
     - ☐ Anomalous global symmetry (+1*)
     - ☐ Effective Z′ coupling (+3*)
   - ☐ Scalar coupled to…
     - ☐ ~~Fermion masses via Higgs mixing~~
     - ☐ General E

     excluded by meson & Higgs invisible decays

*extra charge for new TeV-scale physics needed to make theory consistent

2. Choose your Dark Matter
   - ☐ Complex Scalar
   - ☐ Pseudo-Complex Scalar
   - ☐ Majorana Fermion
   - ☐ Dirac Fermion
   - ☐ Pseudo-Dirac Fermion
3. Choose your Mass Hierarchy
   - ☐ $m_{Med} < m_{DM}$: "Secluded" annihilation into two mediators [least predictive]
   - ☑ $m_{Med} > m_{DM}$: "Direct" annihilation via mediator into SM final states [most predictive]

Extras
- ☐ Depletion via dark-sector self-interaction (SIMP)
- ☐ Forbidden annihilation ($m_{Med} \simeq m_{DM}$)
- ☐ Resonant annihilation ($m_{Med} \simeq 2m_{DM}$)

# Build Your Own Dark Sector

1. Choose your Mediator
   - ☑ Vector coupled to…
     - ☐ Charge (via kinetic mixing)
     - ☐ Non-anomalous global symmetry
       - ☐ B-L, e-τ, e-μ
       - ☐ μ-τ, B-μ, B-τ

     look very similar for e- beam/ scattering
     - ☐ Anomalous global symmetry (+1*)
     - ☐ Effective Z′ coupling (+3*)
   - ☐ Scalar coupled to…
     - ☐ ~~Fermion masses via Higgs mixing~~
     - ☐ General E

     excluded by meson & Higgs invisible decays

2. Choose your Dark Matter
   - ☐ Complex Scalar
   - ☐ Pseudo-Complex Scalar
   - ☐ Majorana Fermion
   - ☐ Dirac Fermion
   - ☐ Pseudo-Dirac Fermion
3. Choose your Mass Hierarchy
   - ☐ $m_{Med} < m_{DM}$: "Secluded" annihilation into two mediators [least predictive]
   - ☑ $m_{Med} > m_{DM}$: "Direct" annihilation via mediator into SM final states [most predictive]

Extras
- ☐ Depletion via dark-sector self-interaction (SIMP)
- ☐ Forbidden annihilation ($m_{Med} \simeq m_{DM}$)
- ☐ Resonant annihilation ($m_{Med} \simeq 2m_{DM}$)

*extra charge for new TeV-scale physics needed to make theory consistent

# Build Your Own Dark Sector

1. Choose your Mediator
   - ☑ Vector coupled to…
     - ➡ Charge (via kinetic mixing)
     - ☐ Non-anomalous global symmetry
       - ☐ B-L, e-τ, e-μ
       - ➡ μ-τ, B-μ, B-τ
     - ☐ Anomalous global symmetry (+1*)
     - ☐ Effective Z′ coupling (+3*)
   - ☐ Scalar coupled to…
     - ☐ ~~Fermion masses via Higgs mixing~~
     - ☐ General E

look very similar for e- beam/ scattering

excluded by meson & Higgs invisible decays

2. Choose your Dark Matter
   - ☐ Complex Scalar
   - ☐ Pseudo-Complex Scalar
   - ☐ Majorana Fermion
   - ☐ ~~Dirac Fermion~~
   - ☐ Pseudo-Dirac Fermion

excluded by CMB bound on late-time annihilation

3. Choose your Mass Hierarchy
   - ☐ $m_{Med} < m_{DM}$: "Secluded" annihilation into two mediators [least predictive]
   - ☑ $m_{Med} > m_{DM}$: "Direct" annihilation via mediator into SM final states [most predictive]

Extras
   - ☐ Depletion via dark-sector self-interaction (SIMP)
   - ☐ Forbidden annihilation ($m_{Med} \simeq m_{DM}$)
   - ☐ Resonant annihilation ($m_{Med} \simeq 2m_{DM}$)

*extra charge for new TeV-scale physics needed to make theory consistent

# Build Your Own Dark Sector

1. Choose your Mediator
   - ☑ Vector coupled to…
     - ☐ Charge (via kinetic mixing)
     - ☐ Non-anomalous global symmetry
       - ☐ B-L, e-τ, e-μ
       - ☐ μ-τ, B-μ, B-τ
     - ☐ Anomalous global symmetry (+1*)
     - ☐ Effective Z′ coupling (+3*)
   - ☐ Scalar coupled to…
     - ☐ ~~Fermion masses via Higgs mixing~~
     - ☐ General E…

look very similar for e- beam/ scattering

excluded by meson & Higgs invisible decays

*extra charge for new TeV-scale physics needed to make theory consistent

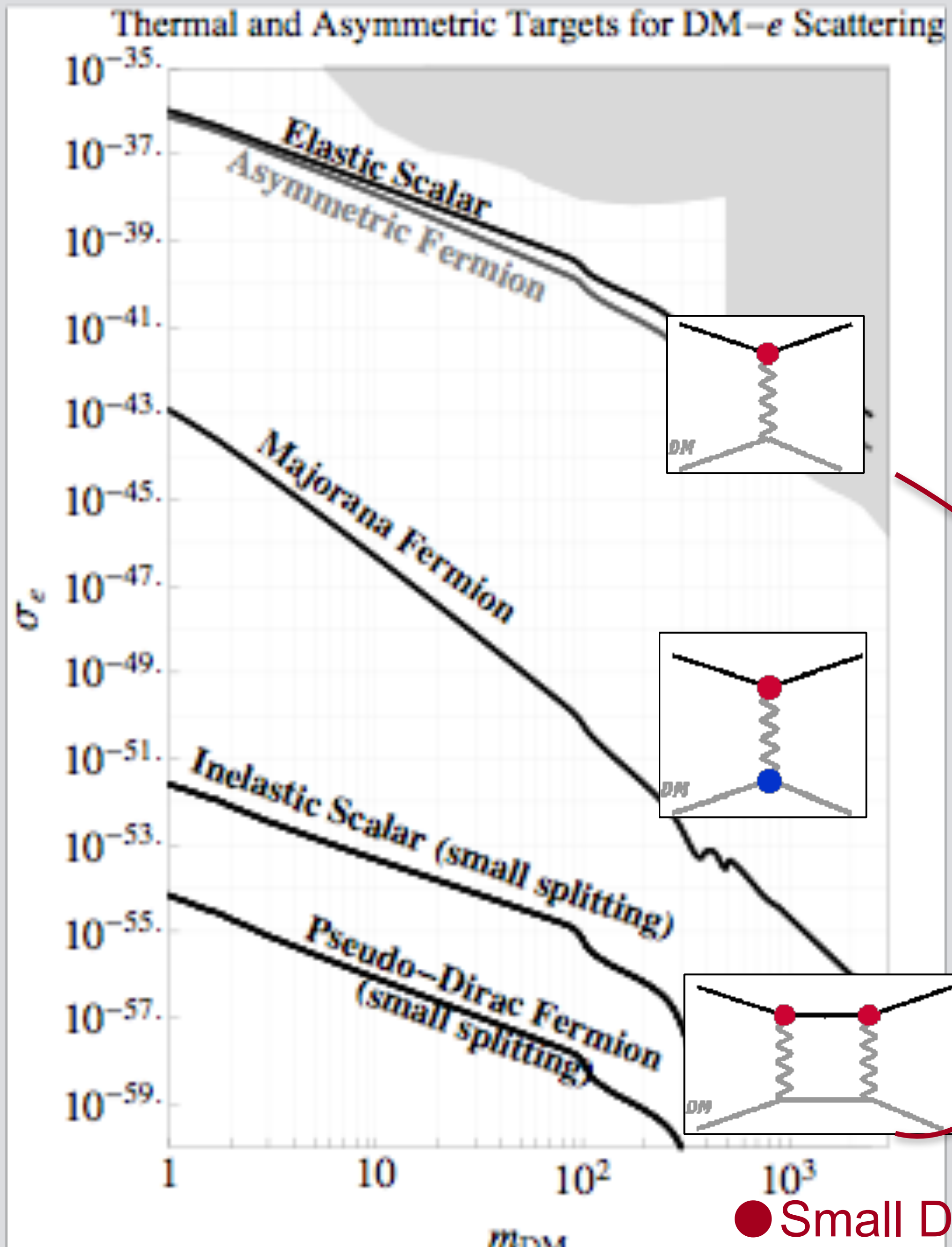
2. Choose your Dark Matter
   - ☐ Complex Scalar
   - ☐ Pseudo-Complex Scalar
   - ☐ Majorana Fermion
   - ☐ ~~Dirac Fermion~~
   - ☐ Pseudo-Dirac Fermion

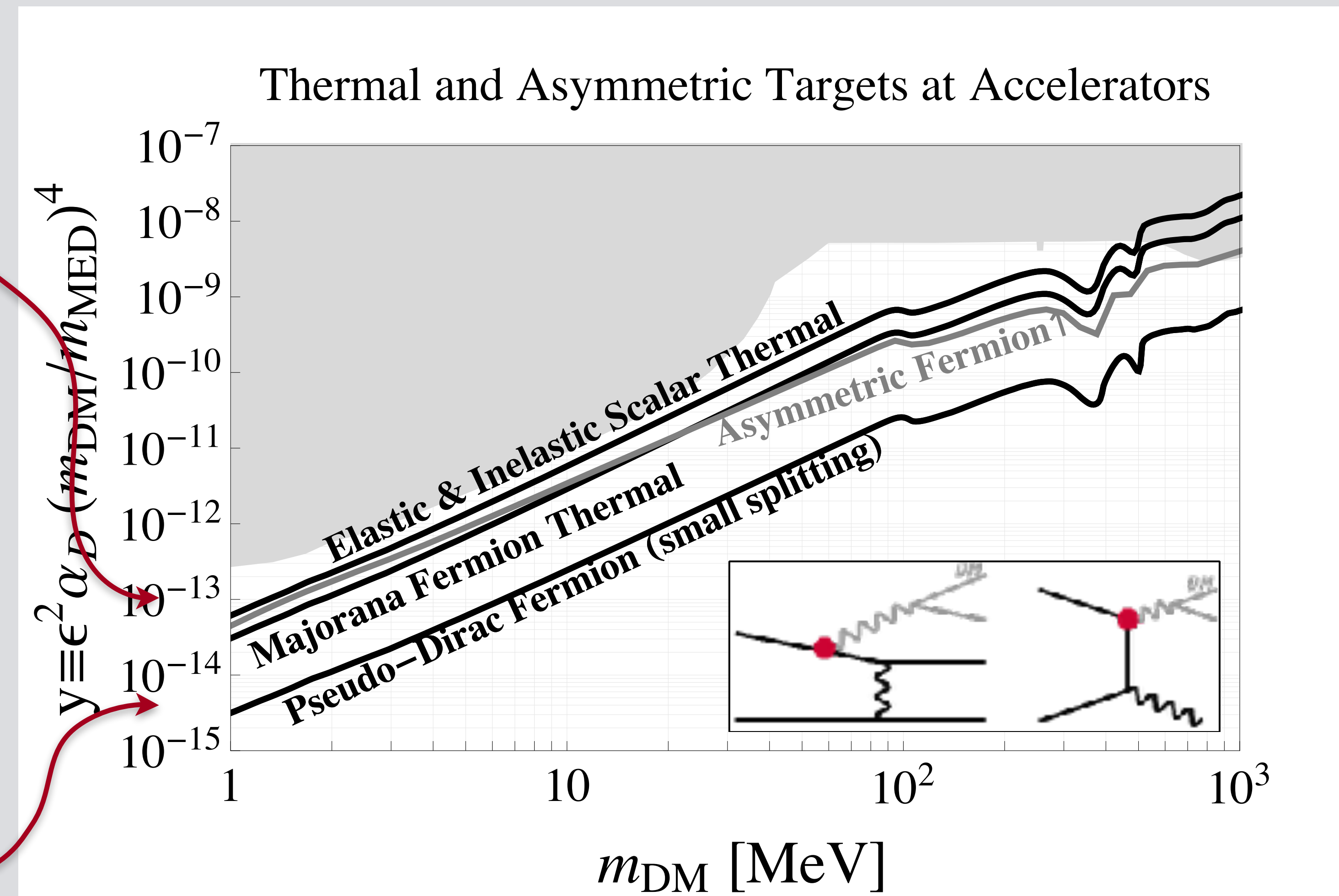
at accelerators, only differ by factor of 30 in yield

3. Choose your Mass Hierarchy
   - ☐ $m_{Med} < m_{DM}$: "Secluded" annihilation into two mediators [least predictive]
   - ☑ $m_{Med} > m_{DM}$: "Direct" annihilation via mediator into SM final states [most predictive]

Extras
   - ☐ Depletion via dark-sector self-interaction (SIMP)
   - ☐ Forbidden annihilation ($m_{Med} \simeq m_{DM}$)
   - ☐ Resonant annihilation ($m_{Med} \simeq 2m_{DM}$)

# Accelerator-Based Searches and Thermal Targets




● Small DM-SM coupling
● Velocity-suppression

**The <u>full</u> set of direct annihilation targets are robustly accessible at accelerators!**

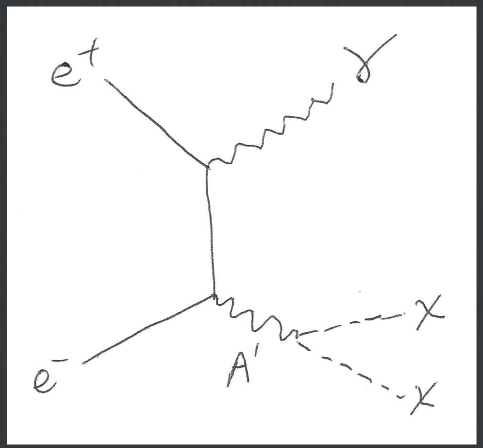
# Detection Strategies

| | Colliding Beams | Fixed Target |
|---|---|---|
| **Detect DM scattering** | | beam dump (p or e beam) |
| **Infer from kinematics** | Missing $E_T$ (pp)<br>Missing Mass ($e^+e^-$) | Missing Mass ($e^\pm$ beam)<br>Missing E/p ($e^-$ beam) |
| **Dark-force searches** | Lepton jets & exotic Z/h decays (pp)<br>Displaced vtx & resonance ($e^+e^-$) | Displaced vtx & resonance ($e^-$ beam, meson decays) |

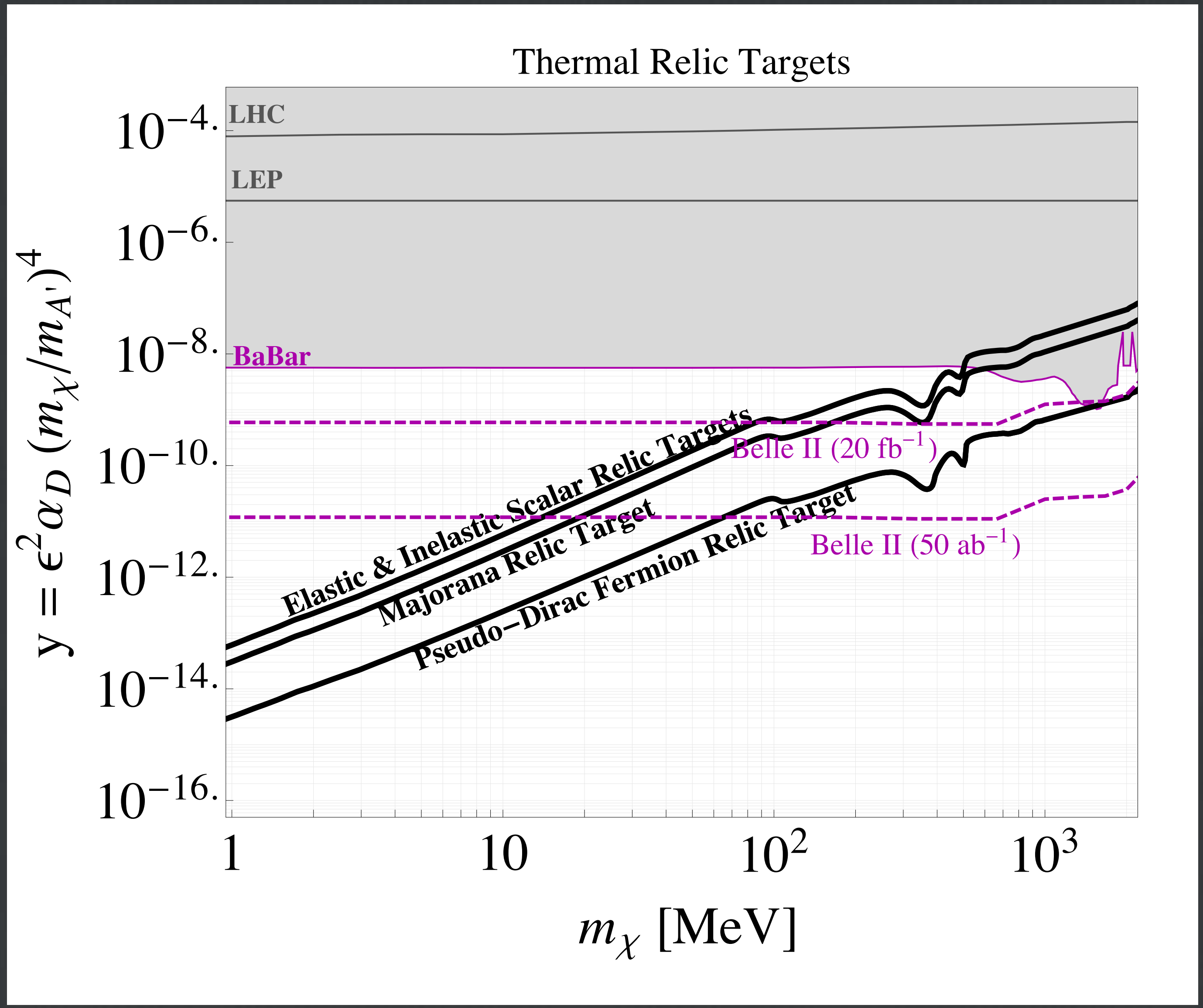
Different strategies for multi-GeV → O(GeV) → sub-GeV detection
–Trade energy [kinematic reach] for luminosity [coupling reach] –

# Missing Mass at Colliders

## Motivating process

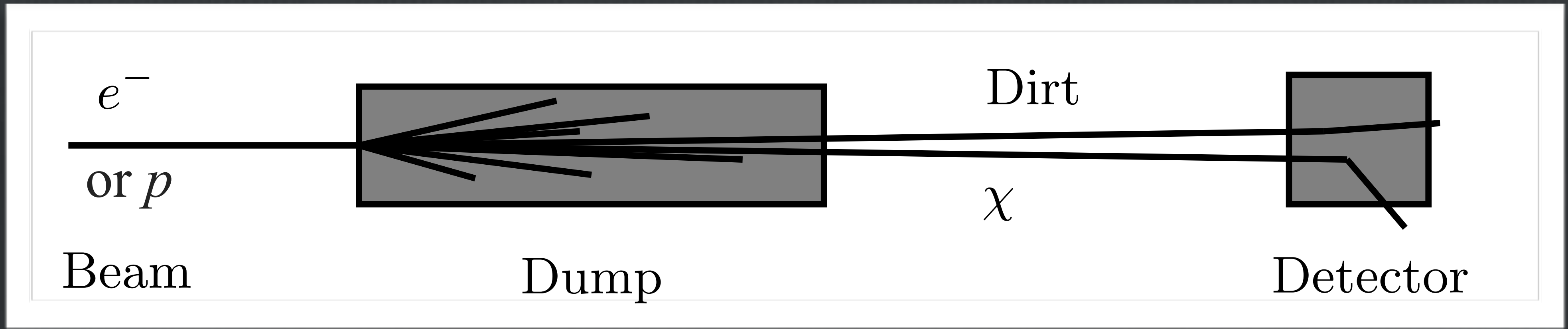



- Look for single γ recoiling against "nothing"
- Reconstruct invisible mass from $(p_{e-}+p_{e+}-p_{\gamma})^2$
- Bump signal if A′ on-shell




**Belle II luminosity explores thermal DM above ~100 MeV**

# Beam Dump Experiments



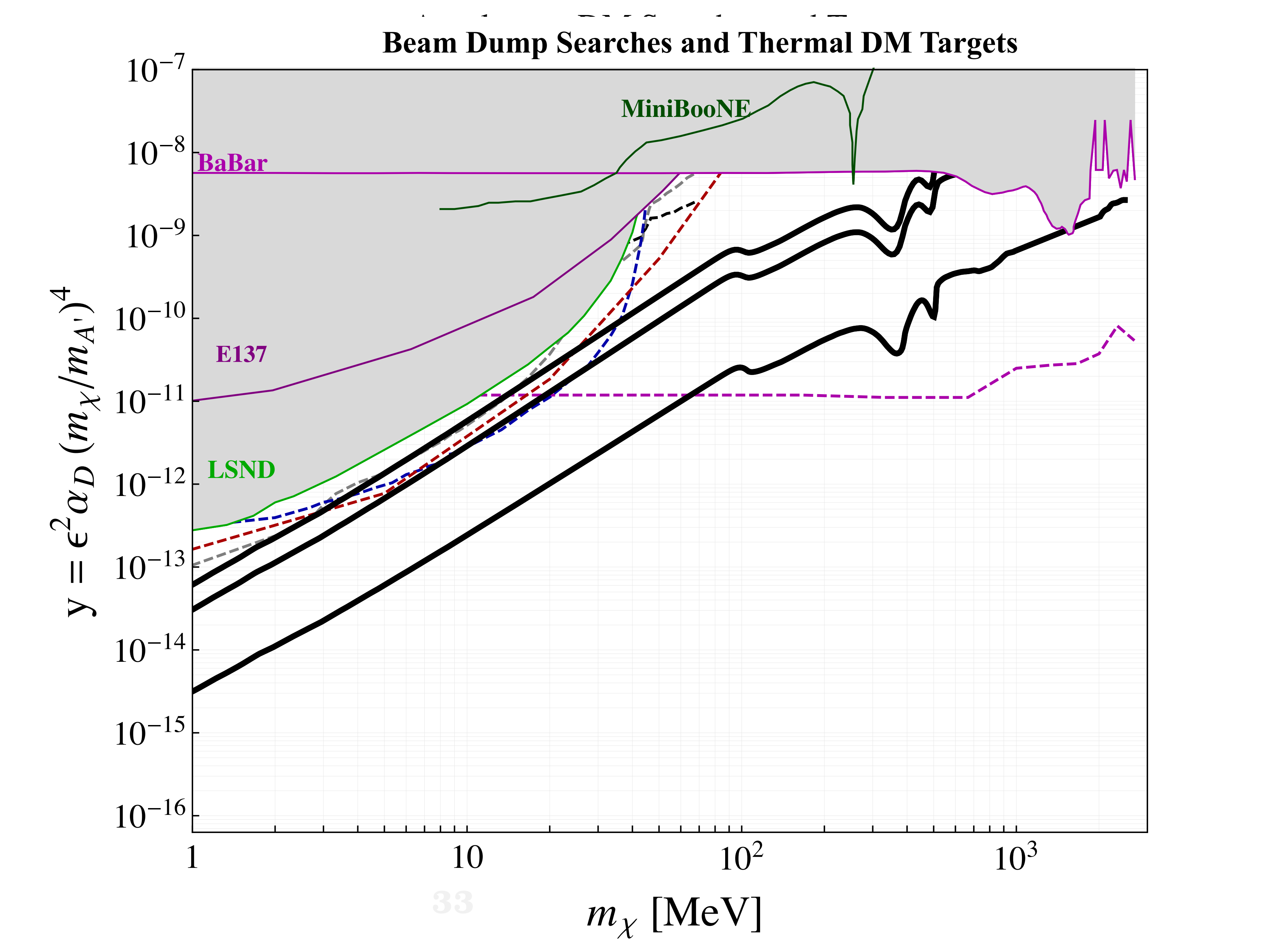

- Uniquely achievable at fixed target experiments – collimated forward DM production needed for efficient detection
- Combine high luminosity (e.g. LSND: $10^{23}$ protons on target, 1 barn$^{-1}$ per proton → $10^5$ ab$^{-1}$) with low detection threshold
- Many experiments can be done (mostly) parasitically
  - dedicated analysis/run at accelerator neutrino experiment [already done @ LSND, MiniBooNE]
  - downstream of beam-dump for other e– beam experiments [several proposals]
- On-shell mediator not essential to signal definition (but enhances yield)

# Beam Dump Sensitivity

Bounds from mining 1980s data [both p (LSND) and e⁻ (E137) beam] already world-leading below 100 MeV!

Recent dedicated MiniBoone run sets best limit on hadronic couplings at higher masses

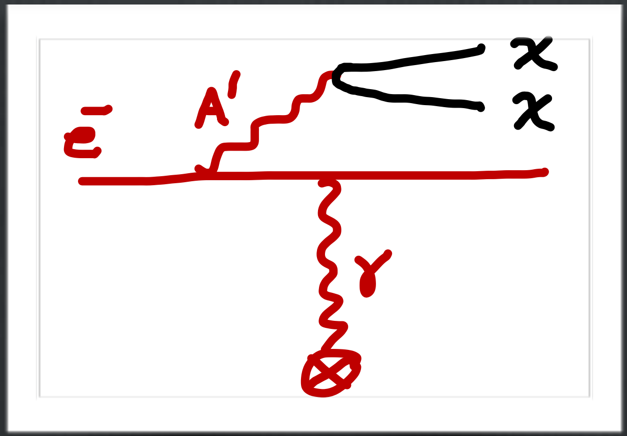
Several ideas to go further…but scales slowly (yield ~ $\epsilon^4$!)

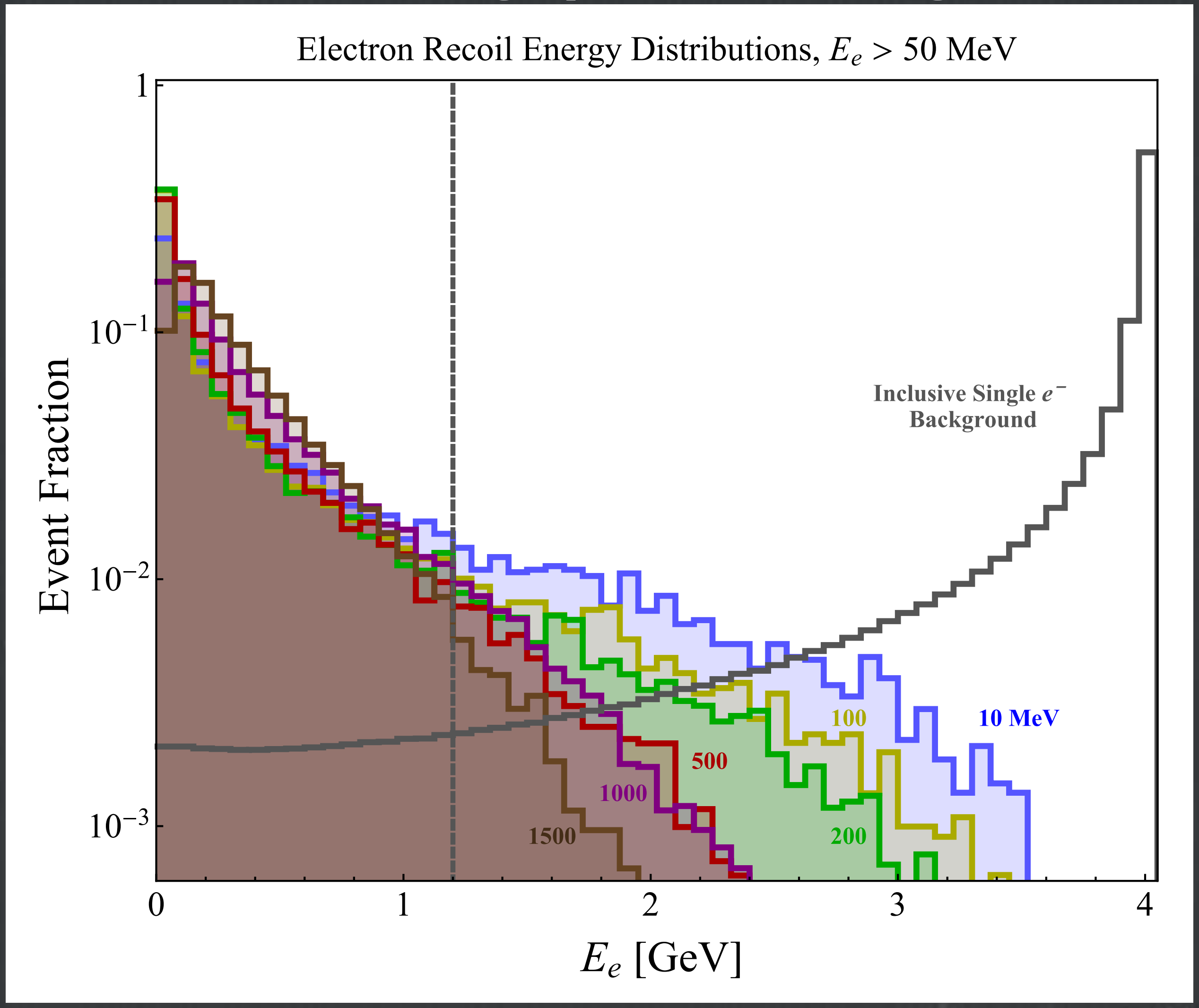


# Missing Energy/Momentum

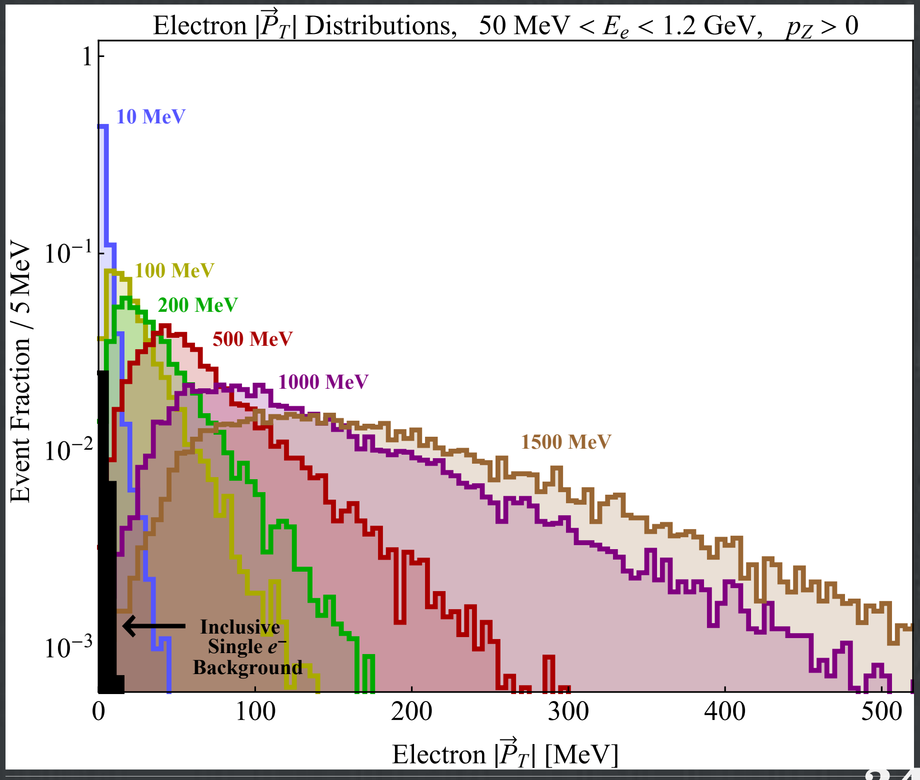
Use distinctive kinematics of A′ / DM pair production in e⁻ beam, without trying to reconstruct its mass

- When DM pair is produced, it carries away most of the incident e– energy
- Look for low energy deposition (no hadronic energy) from a high-energy e–




A detector with tracking can measure e⁻ $p_T$ for a second hint of heavy-particle production



# Missing Energy/Momentum

Use distinctive kinematics of A′ / DM pair production in e⁻ beam, without trying to reconstruct its mass

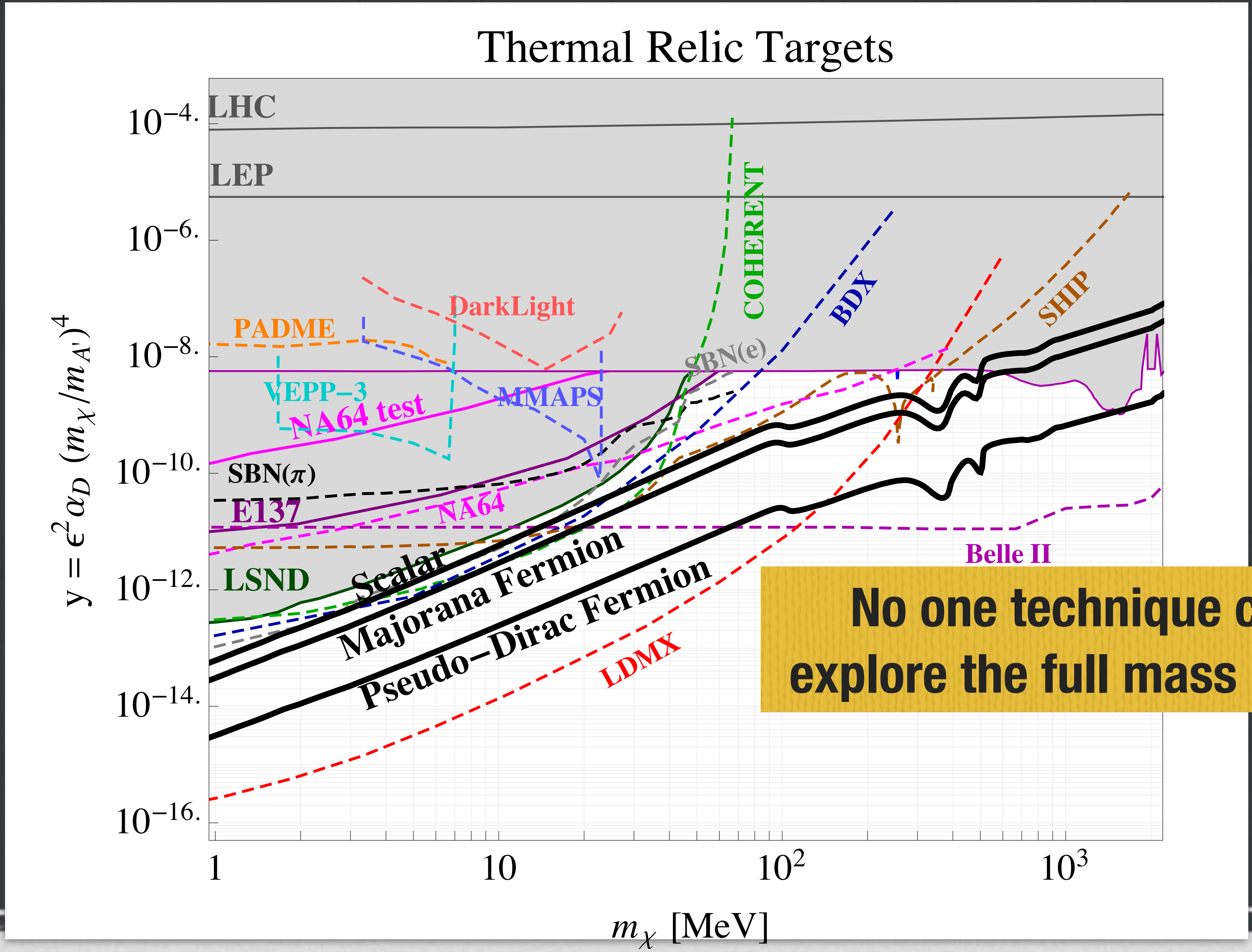
- When DM pair is produced, it carries away most of the incident e– energy
- Look for low energy deposition (no hadronic energy) from a high-energy e–

Such a search requires firing one electron at a time, measuring detector response, and vetoing other final state particles with exquisite efficiency.

A relatively new technique, but the only one capable of scaling well below current beam-dump sensitivity

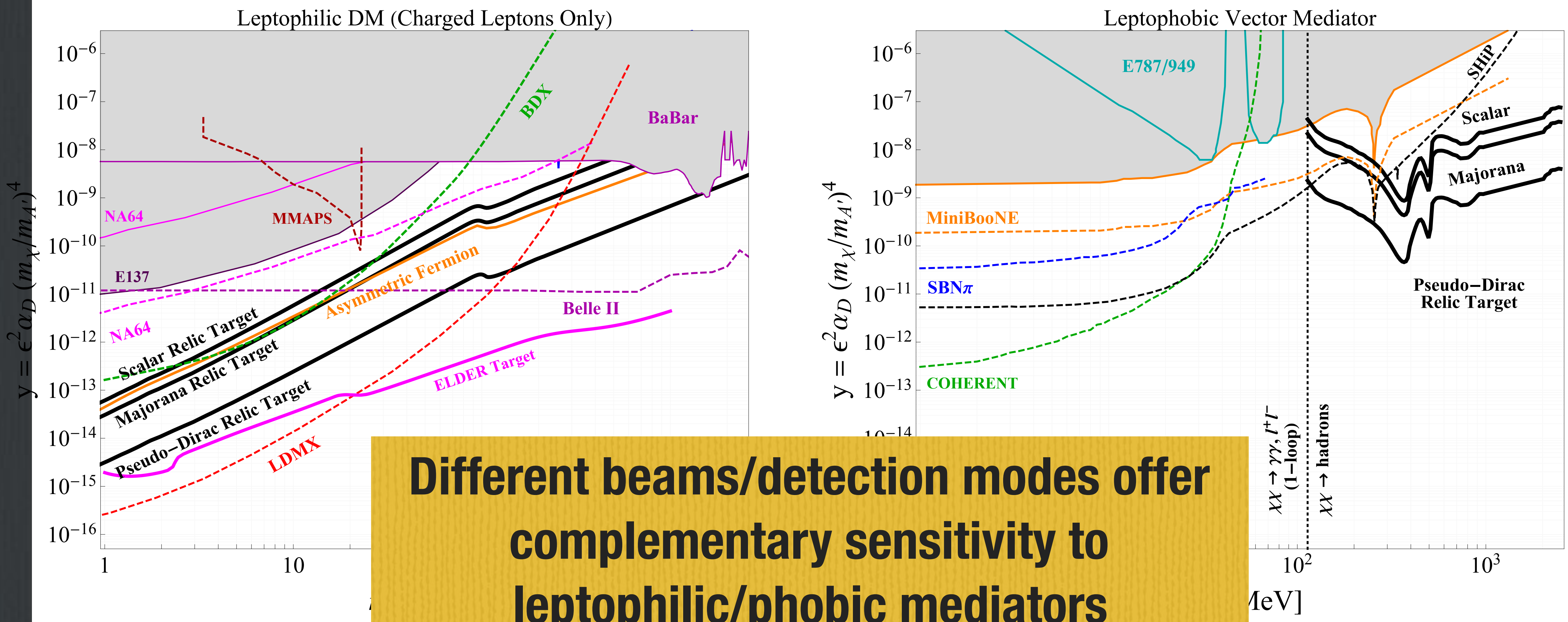
Demonstrated by NA64, pursued at high statistics by LDMX

# Need Multiple Experiments!




No one technique can explore the full mass range

# Need Multiple Experiments!



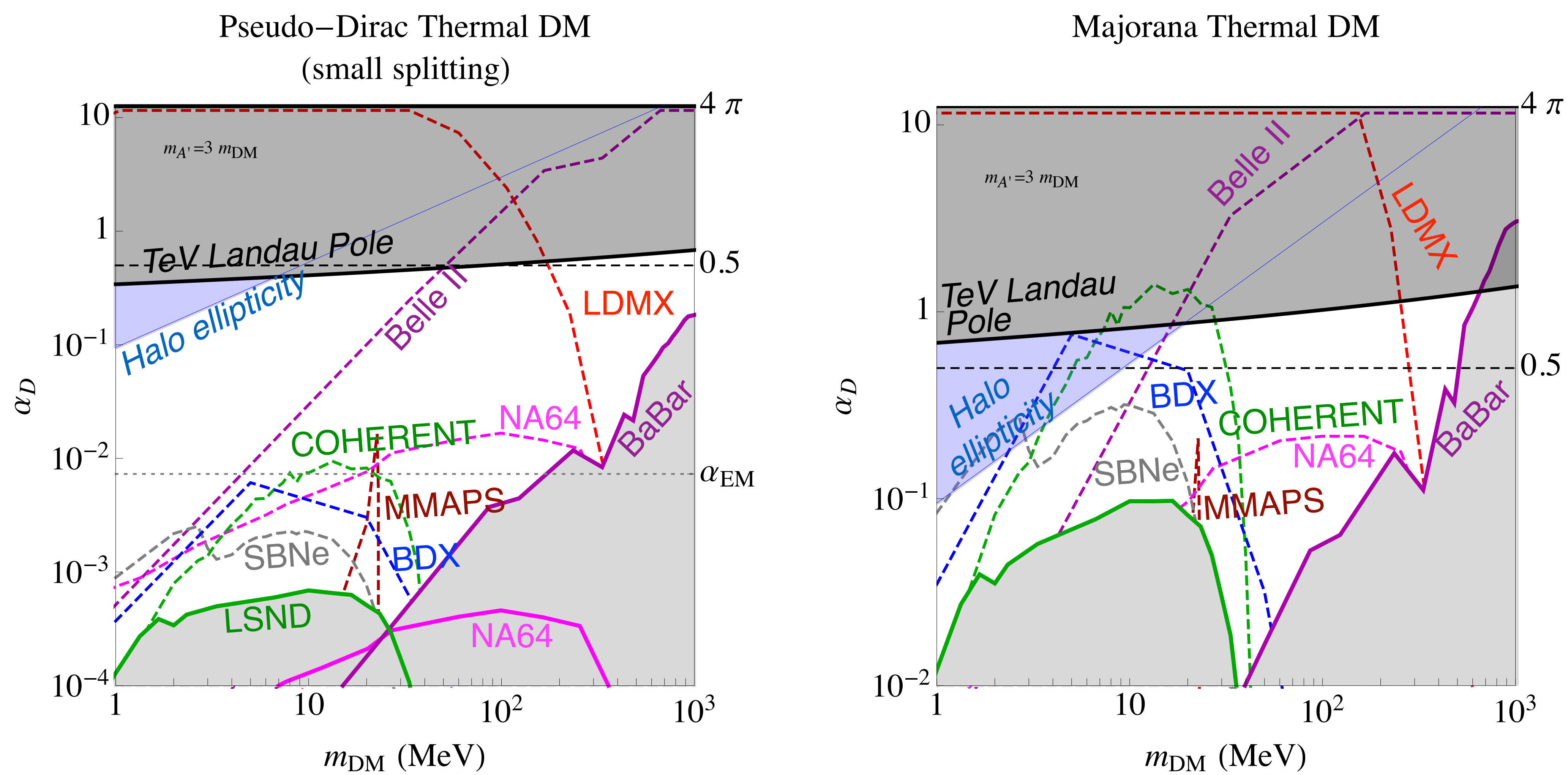

**Different beams/detection modes offer complementary sensitivity to leptophilic/phobic mediators**

**Cosmic Visions Dark Matter 1707.04591**

# Different Slicings

**The above plots make conservative choices of other parameters to show pessimistic sensitivity of experiments. e.g. use $\alpha_D$~0.5 as reference, since smaller DM-mediator coupling implies larger signal for thermal relic.**

**Here, assume thermal relic & vary DM-mediator coupling (with fixed mass ratio)**

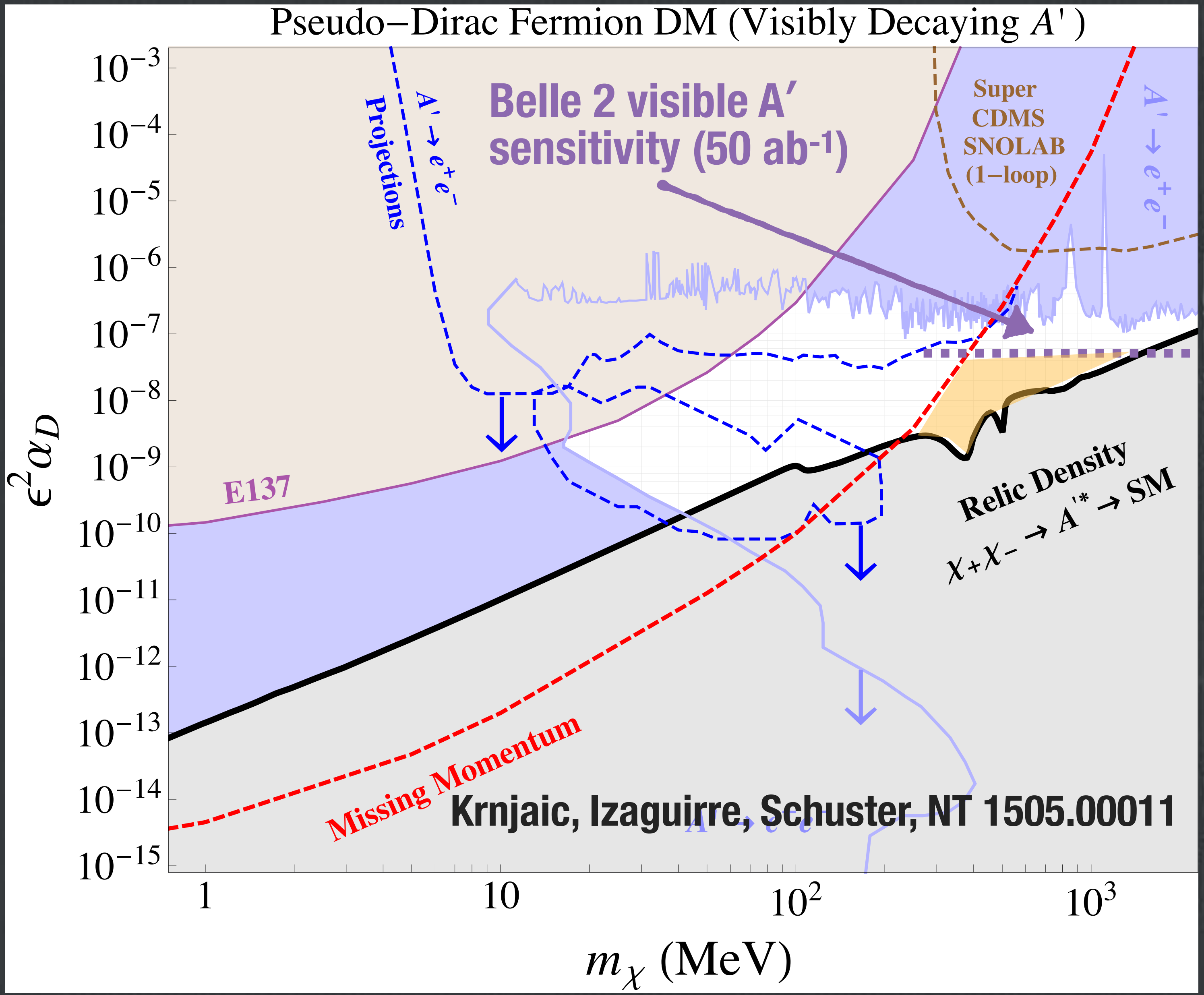



**Cosmic Visions Dark Matter 1707.04591**

# Off-Shell Dark Matter

For $m_\chi < m_{Med} < 2\,m_\chi$, can search for **visible mediator decays** and/or non-resonant DM signals (e.g. **missing momentum**)

Can cover most thermal parameter space (except for **stubborn corner**?)



# Conclusions

- Sub-GeV dark matter is an attractive alternative to WIMPs
  - Within this framework, direct annihilation of sub-GeV DM defines a compelling target in parameter space
- The concepts needed to reach it are in place! And they also open a much wider window on light, weakly coupled physics!
  - Excellent prospects for discovery of DM and new physics in the next several years
- Important windows that remain quite challenging, e.g
  - Weak couplings needed for secluded DM
    - even weaker couplings for freeze-in with generic mediator masses
  - Parts of directly annihilating DM parameter space, for off-shell or electrophobically coupled mediators
  - The lower couplings allowed for strongly-interacting DM –complementary signals are available (see Asher's talk) but not yet thoroughly explored