Light Dark Matter & Accelerators

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Fermilab

DOE Cosmic Visions Meeting

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Overview

- **Historical Perspective**
  Thermal DM & WIMPs

- **Light DM (<GeV)**
  Models & Milestones

- **Accelerator Searches**
  Proton & Electron Beams

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Understanding the Electroweak Sector

Discovery of Radioactivity	(1890s)
Fermi Scale Identified	(1930s)
Non-Abelian Gauge Theory	(1950s)
Higgs Mechanism	(1960s)
W/Z Bosons Discovered	(1970s)
Higgs Discovered	(2010s)

Each step required revolutionary theoretical/experimental leaps

$$t \sim 100 \text{ years}$$

Understanding the Electroweak Sector

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Understanding the Dark Sector?

Discovery of missing mass	**(1930s)**
Rotation curves	**(1970s)**
Precision CMB measurements	**(1990s)**
Relevant scale?	**> 2017**

No clear target for non-gravitational contact

Discovery time frame? $t > 80$ yrs

DM Prognosis?

Bad news: DM-SM interactions are not obligatory

If nature is unkind, we may never know the right scale

DM Prognosis?

Bad news: DM-SM interactions are not obligatory

If nature is unkind, we may never know the right scale

Good news: most *discoverable* DM candidates are in thermal equilibrium with us in the early universe

Why is this good news?

Thermal Equilibrium
Advantage #0: Easily Realized

If interaction rate exceeds Hubble expansion

$$\mathcal{L}_{\text{eff}} = \frac{g^2}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)(\bar{f}\gamma_\mu f)$$

$$H \sim n\sigma v \quad \Longrightarrow \quad \frac{T^2}{m_{Pl}} \sim \frac{g^2 T^5}{\Lambda^4}\bigg|_{T=m_\chi}$$

Equilibrium is easily achieved in the early universe if

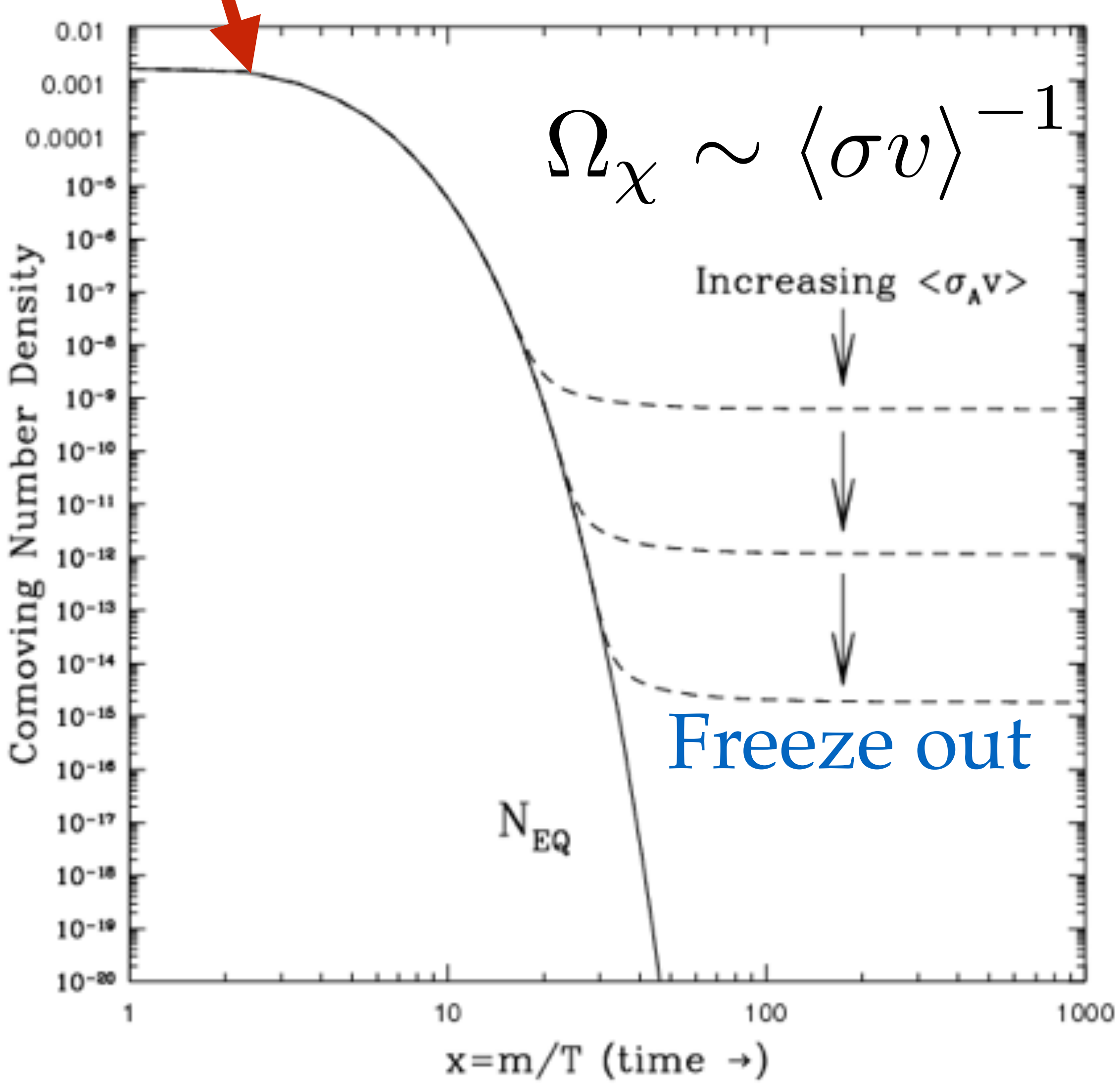
$$g \gtrsim 10^{-8}\left(\frac{\Lambda}{10\,\text{GeV}}\right)^2\left(\frac{\text{GeV}}{m_\chi}\right)^{3/2}$$

Applies to nearly all models with couplings large enough for detection (rare counterexample: QCD axion DM)

Thermal Equilibrium
Advantage #1: Minimum Annihilation Rate

DM is overproduced, need to annihilate away the excess!

$$n_{\rm DM}^{\rm (eq.)} = \int \frac{d^3p}{(2\pi)^3}\frac{g_i}{e^{E/T}\pm 1} \sim T^3$$



$$\Omega_\chi \sim \langle \sigma v \rangle^{-1}$$

Freeze out

Griest et. al. 1992

Symmetric Thermal DM

Observed density requires

$$\sigma v_{\rm sym} \sim 3 \times 10^{-26} {\rm cm}^3{\rm s}^{-1}$$

Asymmetric Thermal DM:

Just need to deplete antiparticles

$$\sigma v_{\rm asym} > 3 \times 10^{-26} {\rm cm}^3{\rm s}^{-1}$$

Rate can be bigger, but not smaller

Either way, there's a target!

Thermal Equilibrium
Advantage #2: UV Insensitive

Initial condition known

Calculable & compatible with nearly all UV scenarios
(contrast e.g. w/ axion/ALP DM)

Mass & couplings set abundance

Can learn a lot from a discovery!

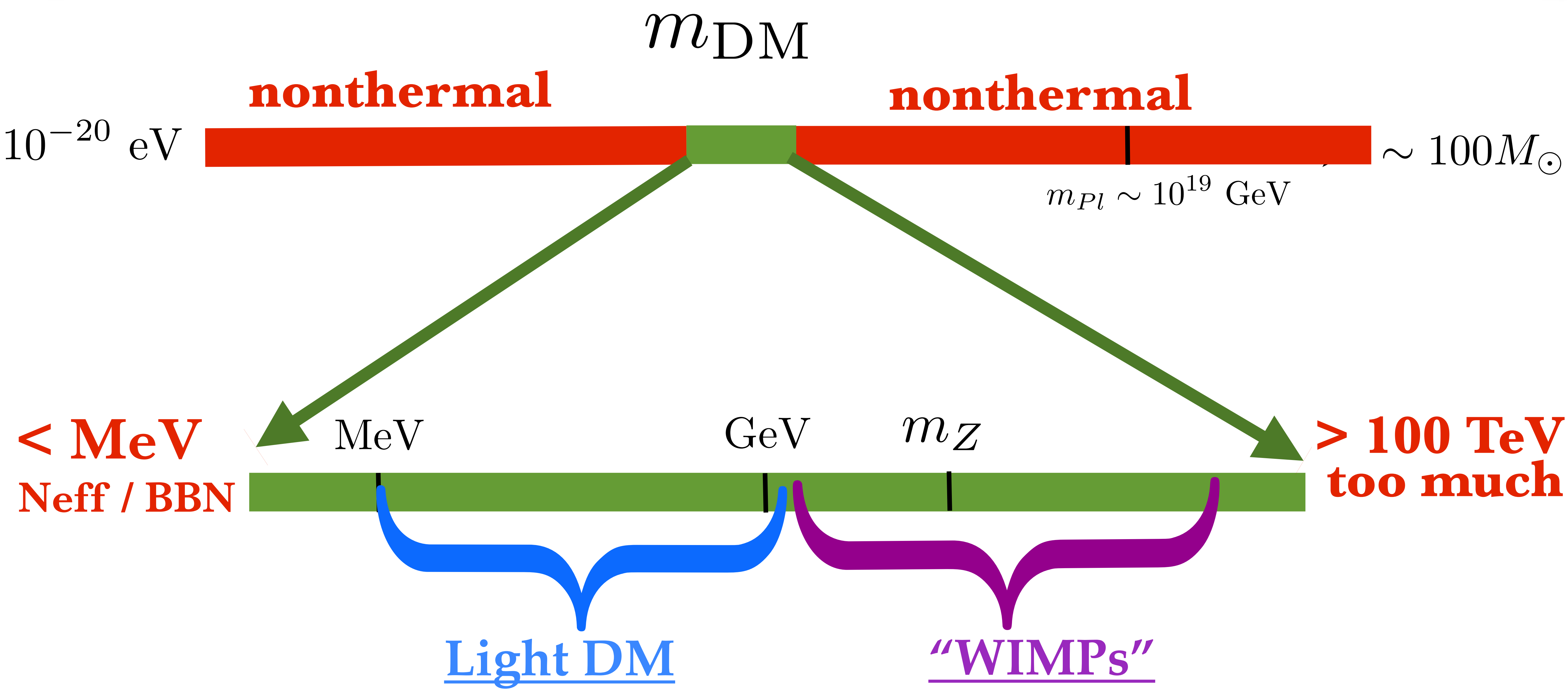
Only *other* UV insensitive mechanism is "freeze-in"

Wide viable range $\mathrm{keV} \lesssim m_{\mathrm{DM}} \lesssim m_{Pl}$

DM produced through feeble couplings, very hard to test

But, certain models can be explored with direct detection

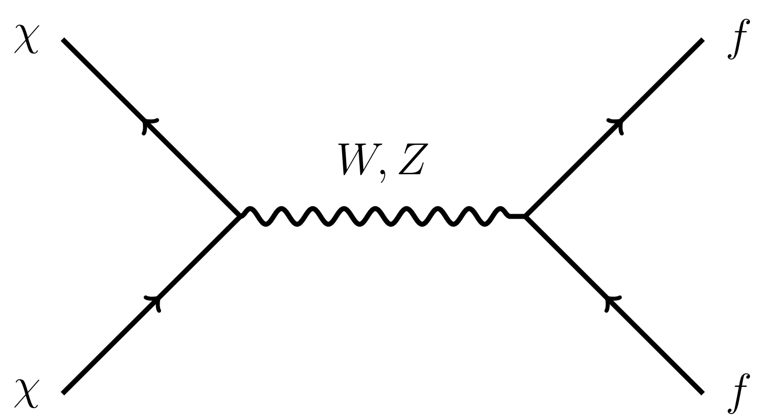
Thermal Equilibrium
Advantage #3: Narrows Viable Mass Range



~ 1985, natural starting point
right after *W&Z* discoveries

The WIMP Miracle

WIMP DM charged under SM gauge group



$$\langle \sigma v \rangle_{\rm WIMP} \sim 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1} \left(\frac{\rm TeV}{m_\chi} \right)^2$$

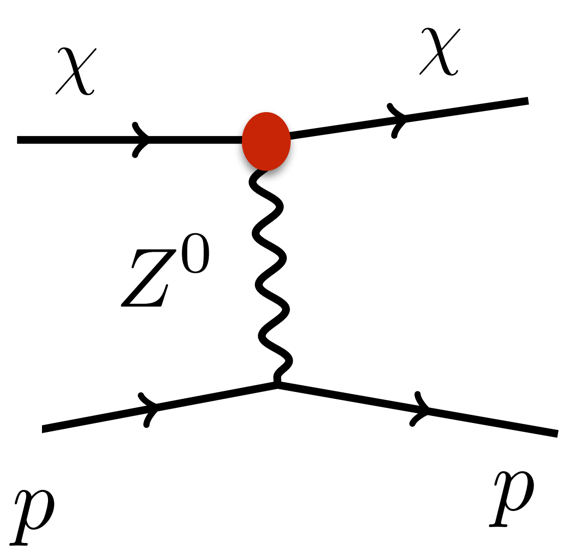
Successful thermal freeze-out for weak scale masses

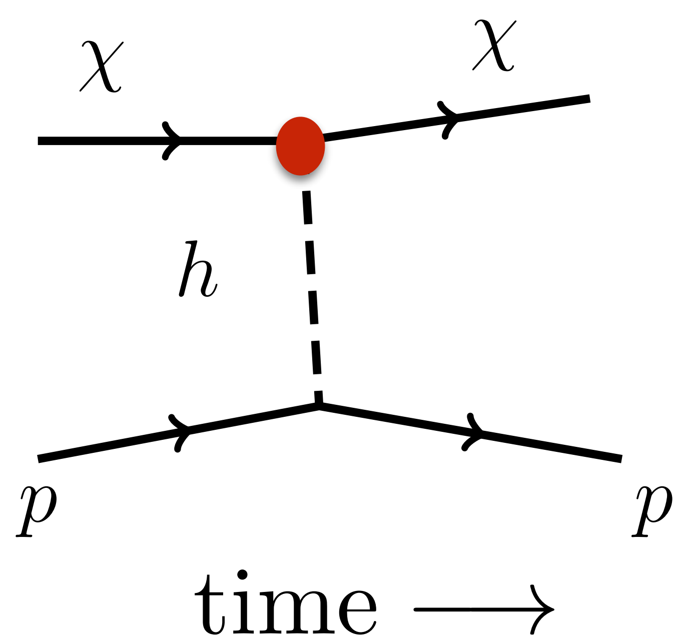
Naturally realized in SUSY models (w/ R-parity)

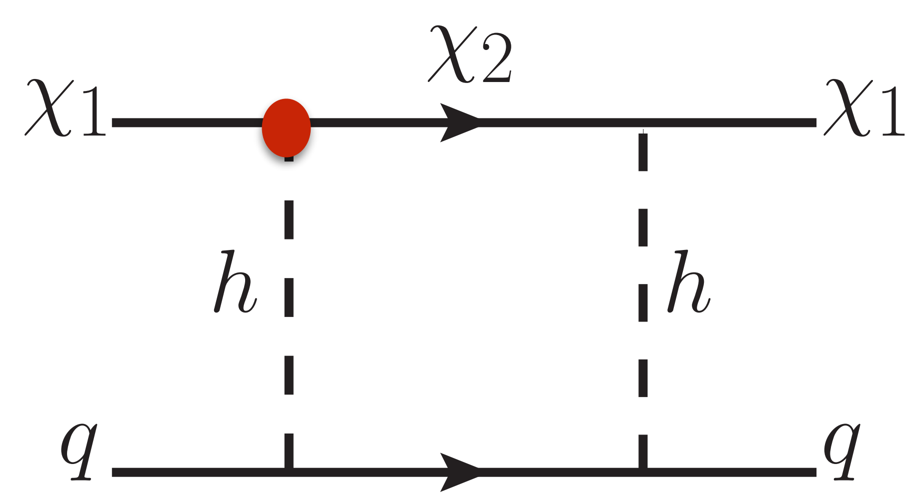
Predicts direct detection cross section

Driven experimental effort for ~ 30 years

Classifying Typical WIMP Interactions







Z Exchange

$$\sigma_p \sim 10^{-39}\,\text{cm}^2$$

Higgs Exchange

$$\sigma_p \sim 10^{-45}\text{cm}^2$$

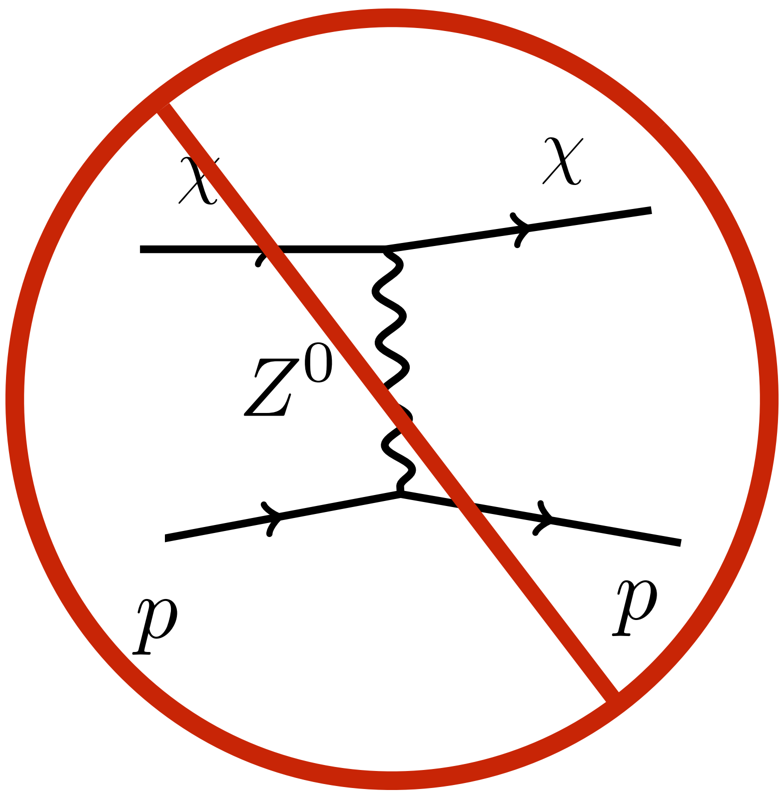
Inelastic coupling
EW loop

$$\sigma_p \sim 10^{-47}\text{cm}^2$$

Very different at low energy, despite high energy similarities

Each ● interaction can realize thermal annihilation at *T ~ M*

Classifying Typical WIMP Interactions



Z Exchange

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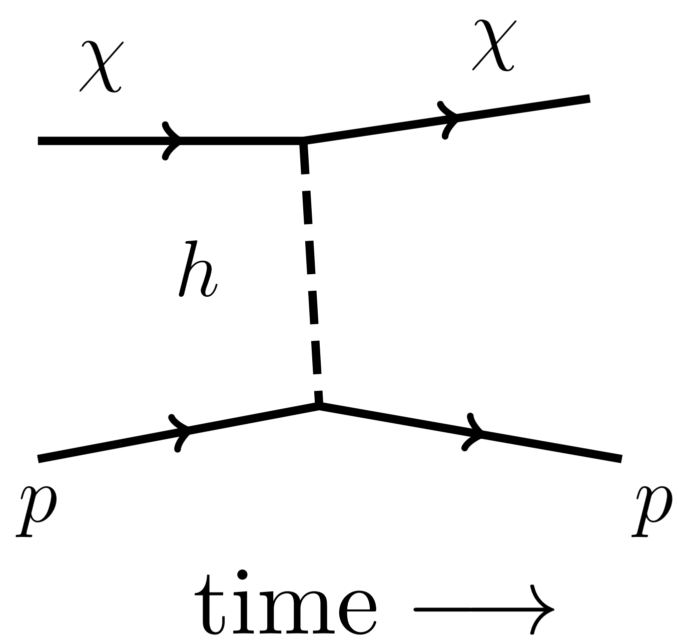
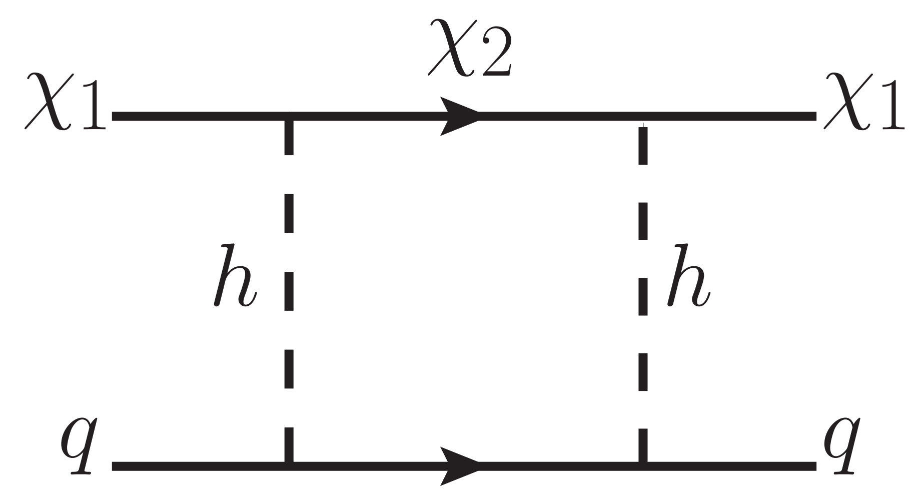


Higgs Exchange

$$\sigma_p \sim 10^{-45}\mathrm{cm}^2$$



Inelastic coupling EW loop

$$\sigma_p \sim 10^{-47}\mathrm{cm}^2$$

Ruled out with first generation direct detection experiments

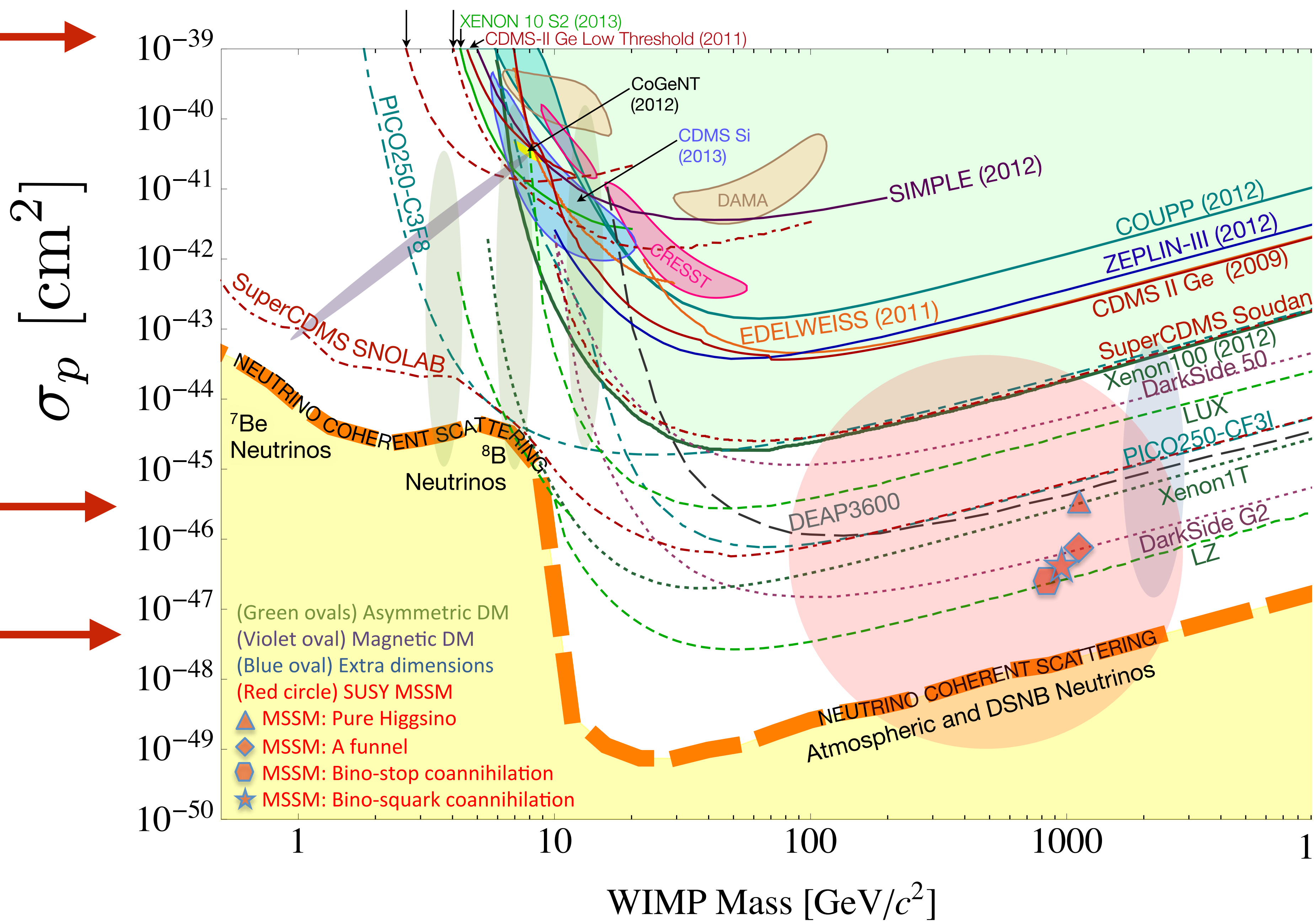
But still a long way to go to fully test others …

WIMP Milestones

Elastic Z exchange

Higgs exchange

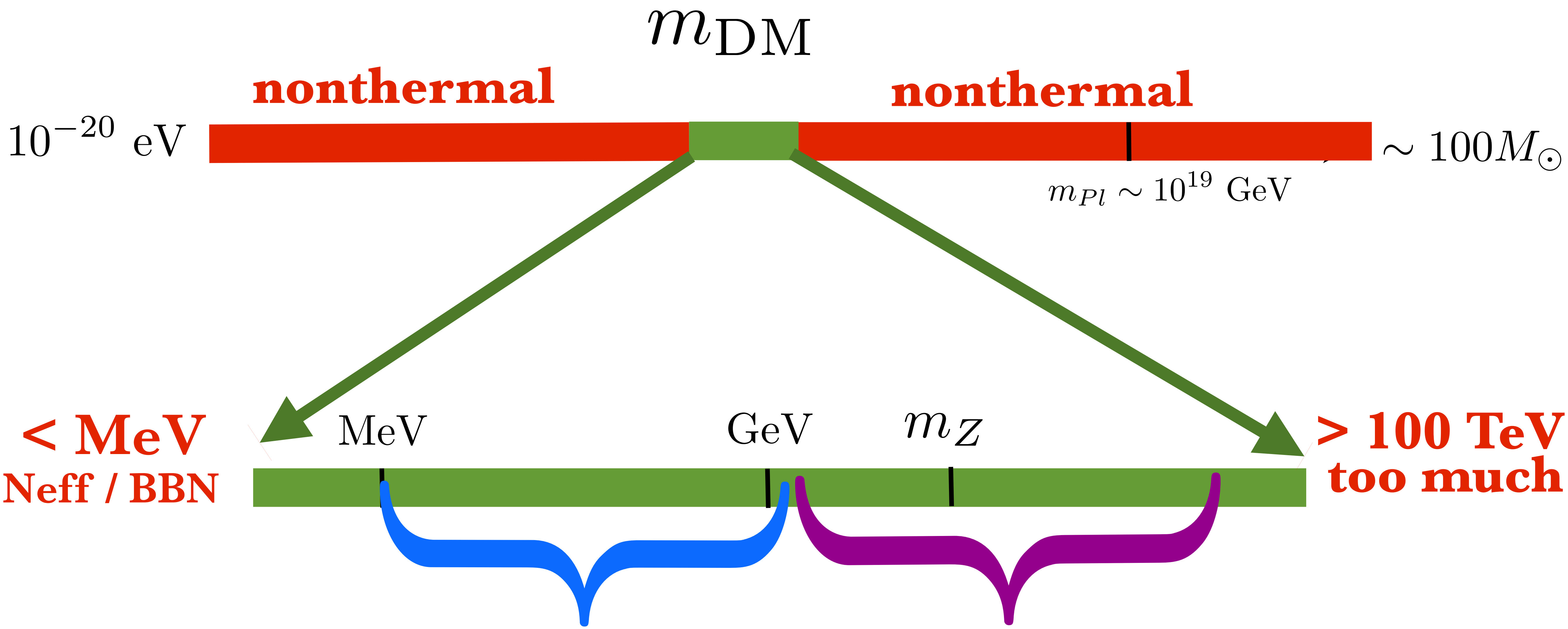
1-Loop EW box



Rough targets due to WIMP model dependence

Cushman et al. arXiv:1310.8327

Logical Next Step?



Light DM

?

“WIMPs”

Mature search program will test most WIMP milestones (but LHC + neutrino floor…)

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  B-factories & Fixed Targets

Why the MeV-GeV range?

Weak scale is still mysterious (Hierarchy problem…)

WIMPs are natural if DM has ~ O(1) coupling to EWSB

< GeV scale arises if coupling is << O(1)

Look both above and below!

Why the MeV-GeV range?

Weak scale is still mysterious (Hierarchy problem…)

WIMPs are natural if DM has ~ O(1) coupling to EWSB

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Look both above and below!

Especially since lighter scales can be derived from v

via loops or mixings $$\mathrm{GeV}^2 \sim \frac{\alpha v^2}{16\pi^2}$$

e.g. hidden sector only feels SUSY breaking through mixing with MSSM (**Morrissey, Poland, Zurek arXiv:0904.2567**)

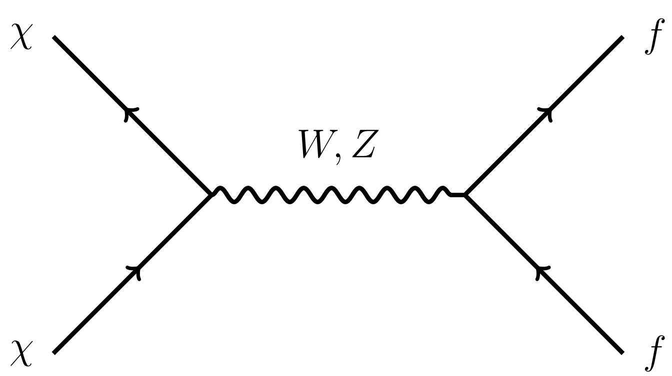
< GeV Model Building

DM must be a SM singlet

Else would have been discovered (LEP…)

Even if it weren't, freeze out still needs new forces

DM overproduced unless there are light new "mediators"



$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

Lee/Weinberg '79

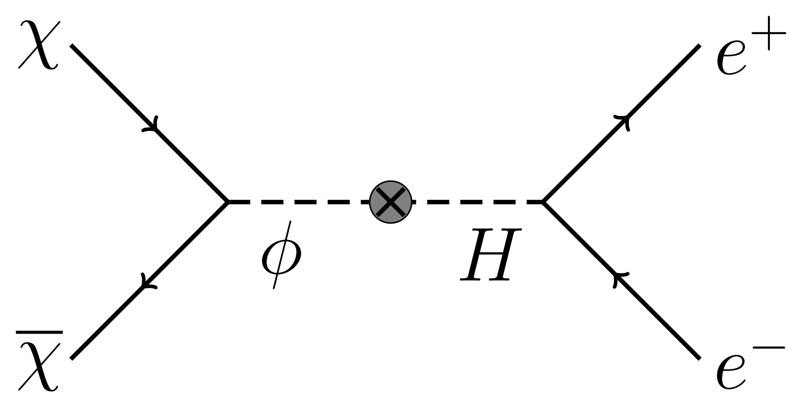
Simplicty: can't use higher dimension operators

Requires renormalizable interactions

What Kind of Mediator?

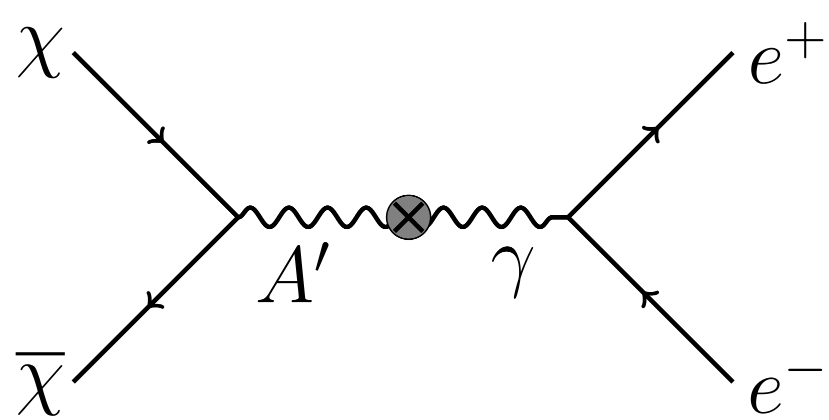
Must also be neutral under SM

New scalar mediator mixing w/ Higgs



$\epsilon\,\phi H^\dagger H$

New vector mediator A' mixing w/ photon



$\epsilon F'_{\mu\nu} F^{\mu\nu}$

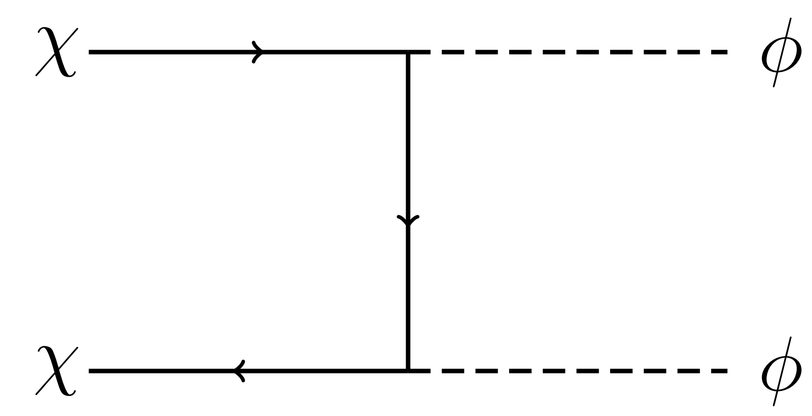
Can also charge both DM & SM under new gauge group (very similar pheno, typically needs more particles)

Who's Heavier? DM or Mediator?

"Secluded" Annihilation

No target: independent of mixing
Mediator decays to SM, not DM

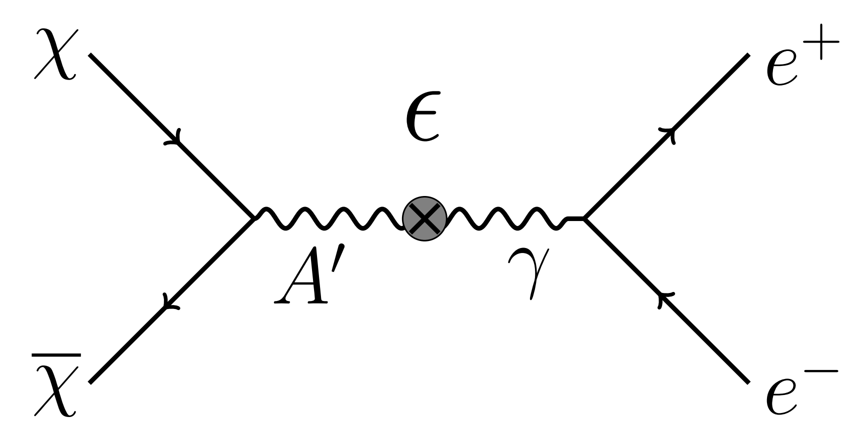
$$m_\chi > m_\phi$$



Direct Annihilation

Predictive: minimum SM coupling
Ruled out for scalar mediators

arXiv:1512.04119, GK



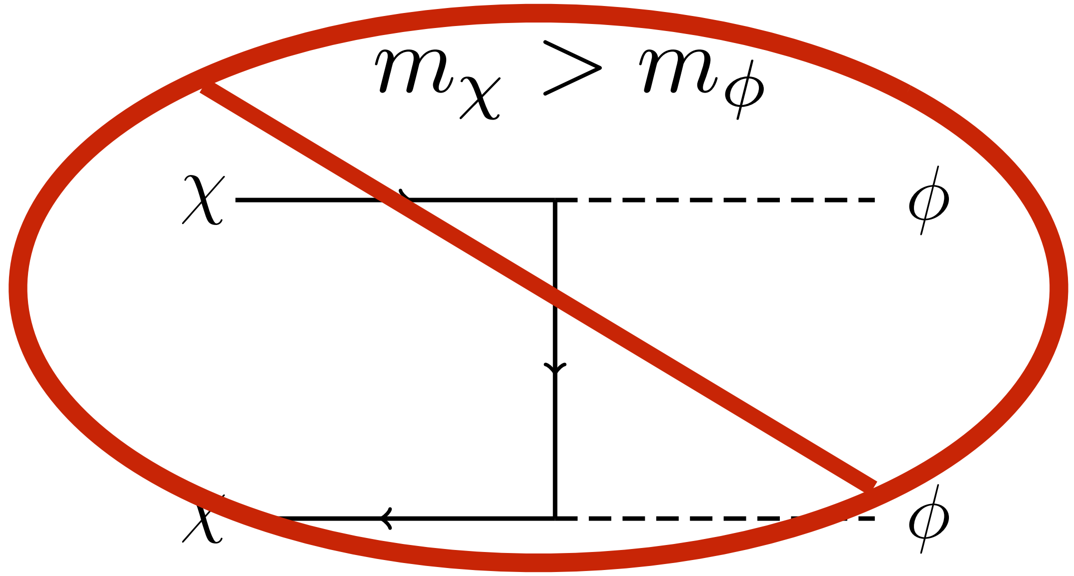
$$m_\chi < m_{A'}$$

Natural starting point, motivates vector mediators

Who's Heavier? DM or Mediator?

"Secluded" Annihilation

No target: independent of mixing
Mediator decays to SM, not DM



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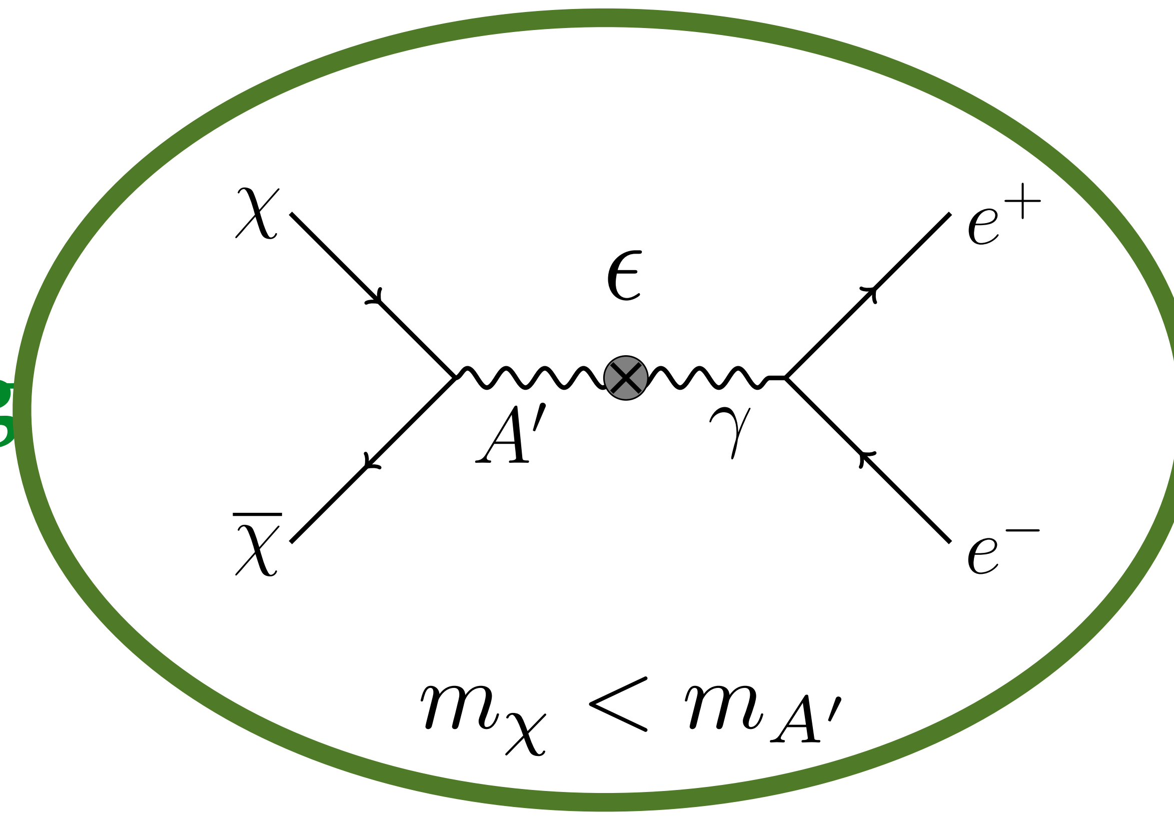
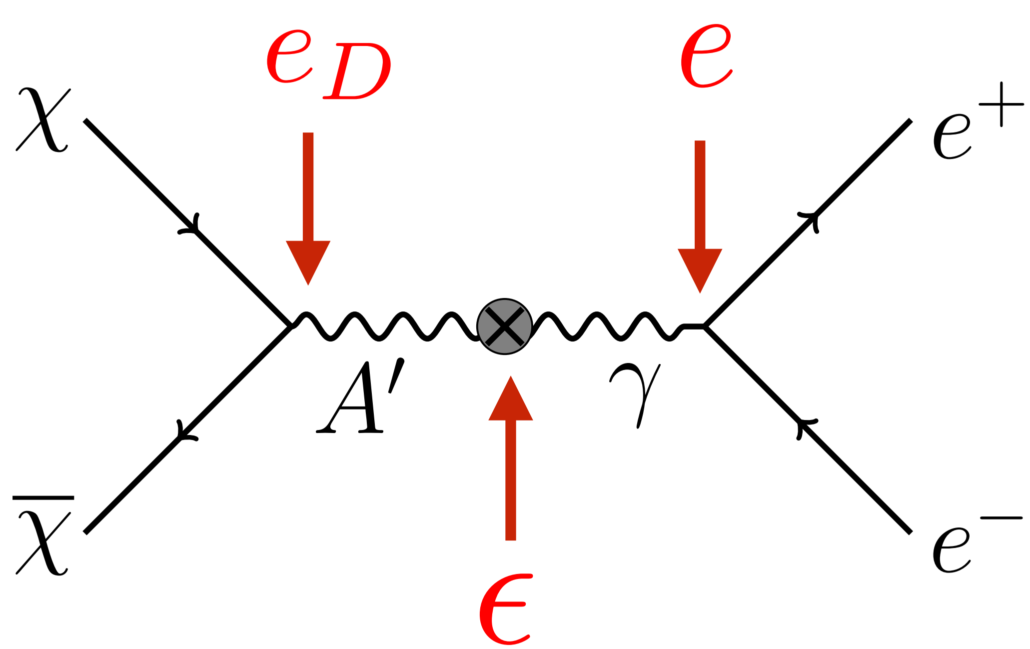


Natural starting point, motivates vector mediators

Representative Model: Dark QED

$$\alpha_D \equiv \frac{e_D^2}{4\pi}$$

DM



SM

$$\alpha \equiv \frac{e^2}{4\pi}$$

DM charged under new force: $e_D \sim e$

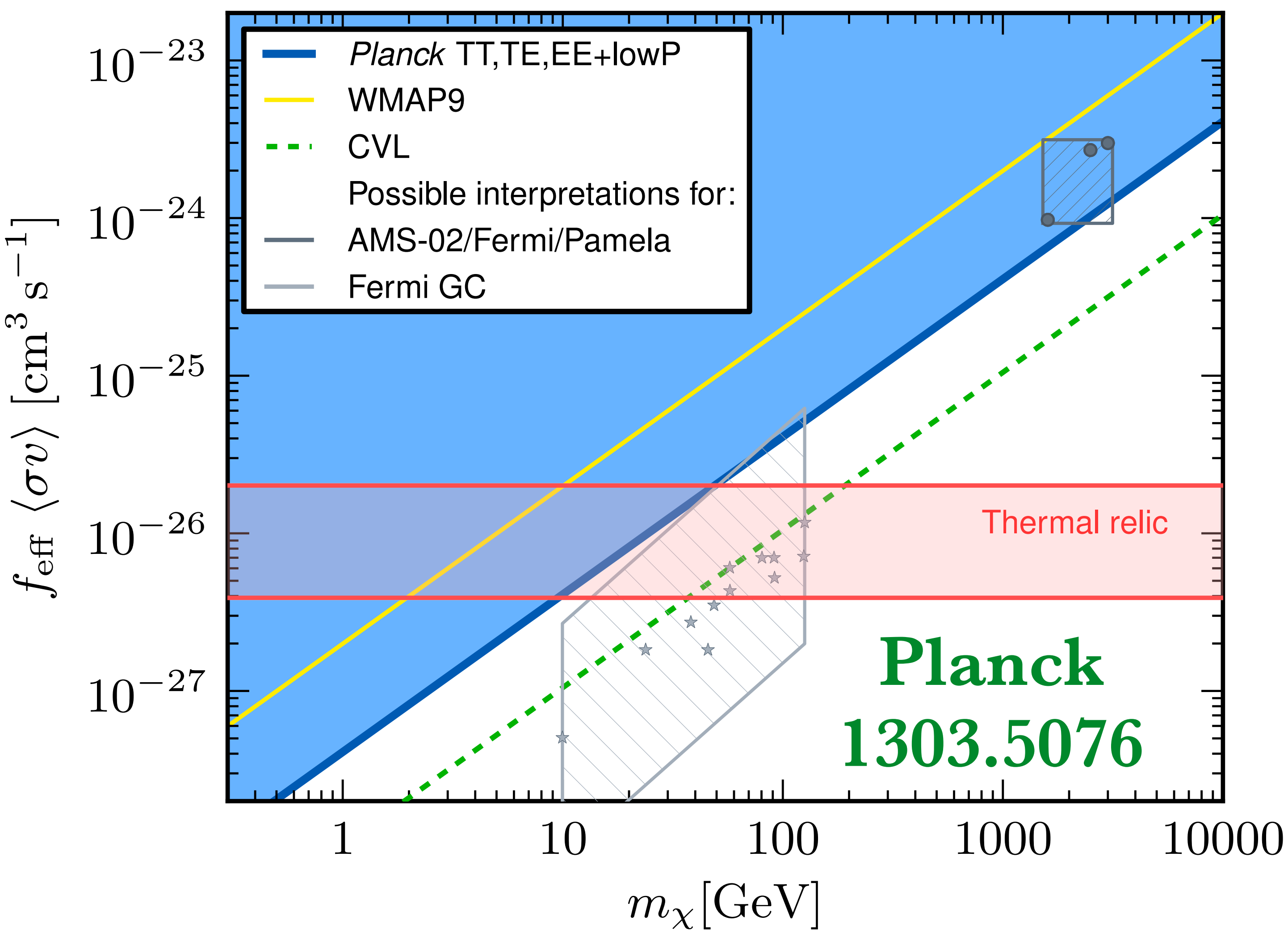
Allowed small *A′*-photon mixing: $\epsilon \ll 1$

SM acquires small charge under *A′*: $e\epsilon$

Not the only model, but qualitatively similar to all viable choices

Simplest DM Candidate?

Particle/antiparticle symmetric Dirac fermion



Annihilation is *s*-wave
Ruled out by CMB

Viable models:

(1) p-wave annihilation

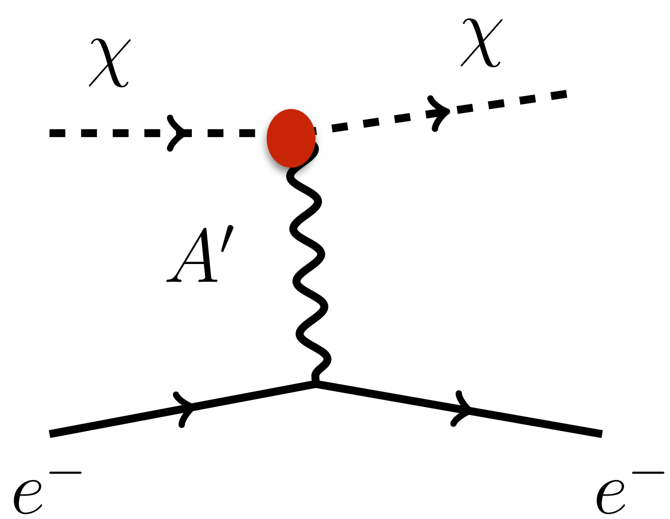
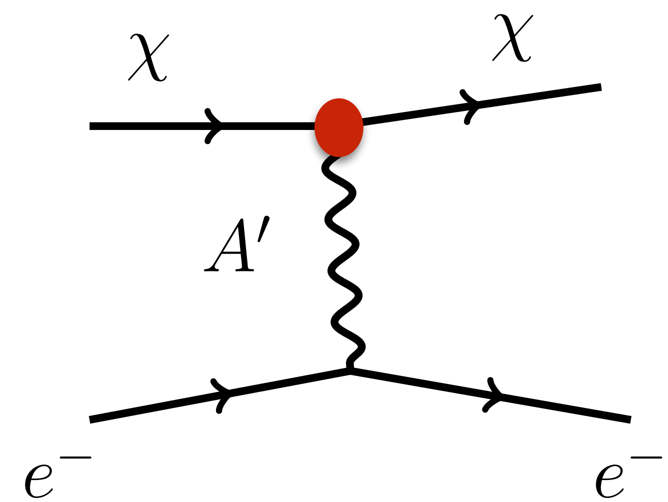
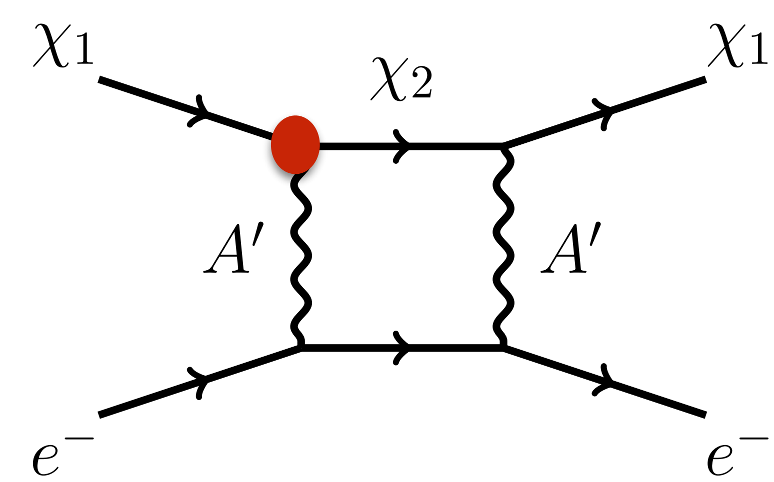
OR

(2) annihilation shuts off before CMB

(no indirect detection!)

Like *Z*-exchange for WIMPs, simplest model excluded first

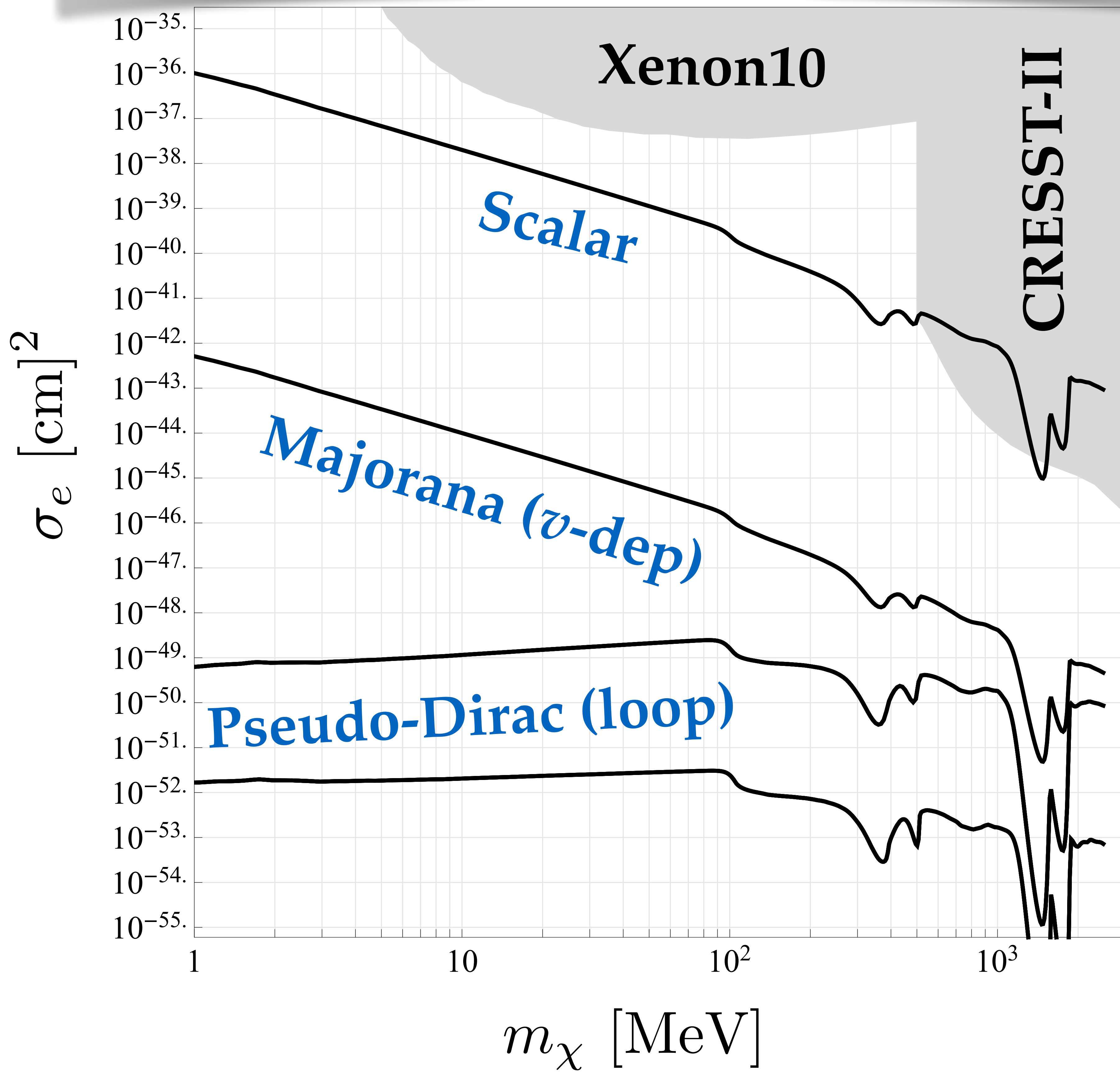
Classify Viable Models by DD Scattering?

Scalar DM	**Majorana DM**	**Pseudo-Dirac DM inelastic**
		
$A'_\mu \chi^* \partial_\mu \chi$	$A'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$	$A'_\mu \bar{\chi}_1 \gamma^\mu \chi_2$
$\sigma_e \sim 10^{-39} \text{cm}^2$	$\sigma_e \sim 10^{-39}\, v^2\, \text{cm}^2 \sim 10^{-45}\, \text{cm}^2$	$\sigma_e \sim 10^{-48}\, \text{cm}^2$

Very different cross sections despite similarity @ high energy

Each ● interaction can realize thermal annihilation at *T* ~ *M*

< GeV Thermal Relic Milestones



Q: Can we put these on the same footing?

A: Yes, produce DM relativistically!

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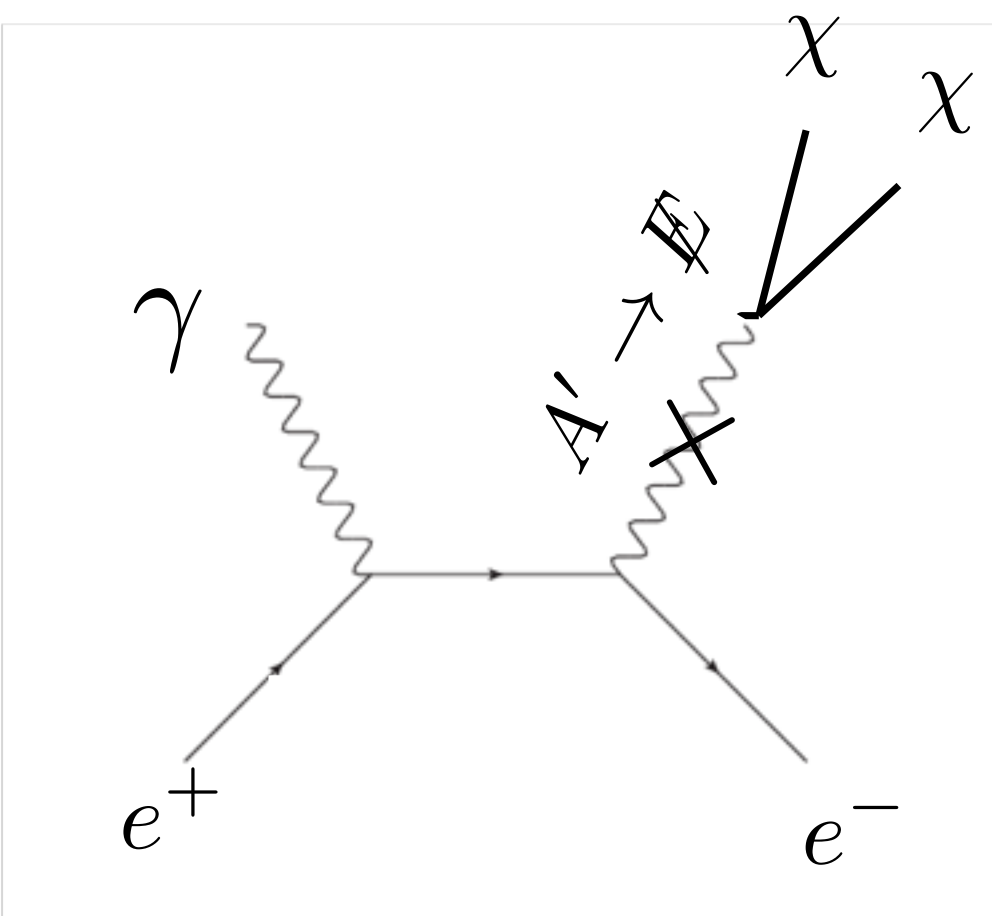
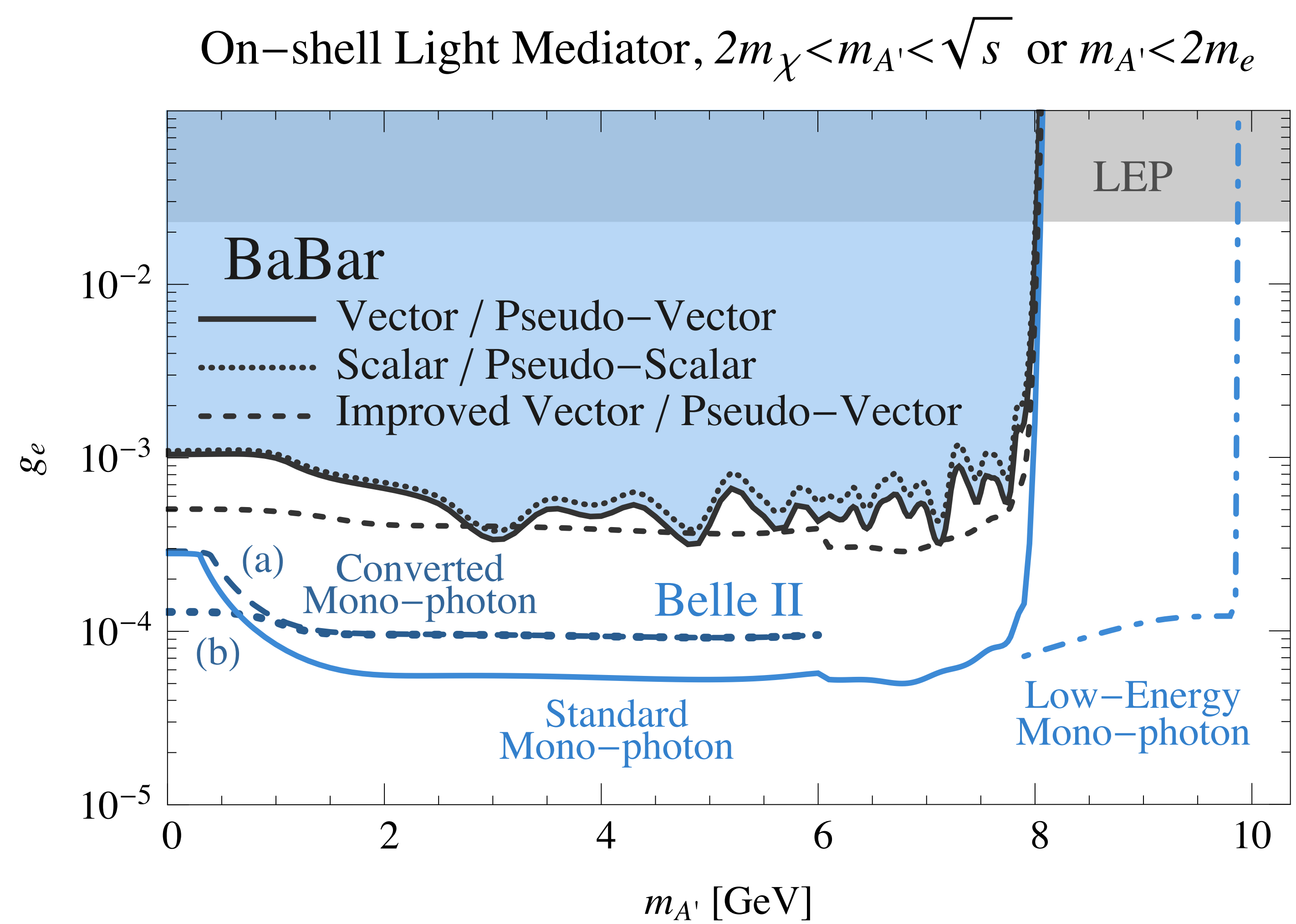
Signatures @ B-Factories

mono photon + missing energy



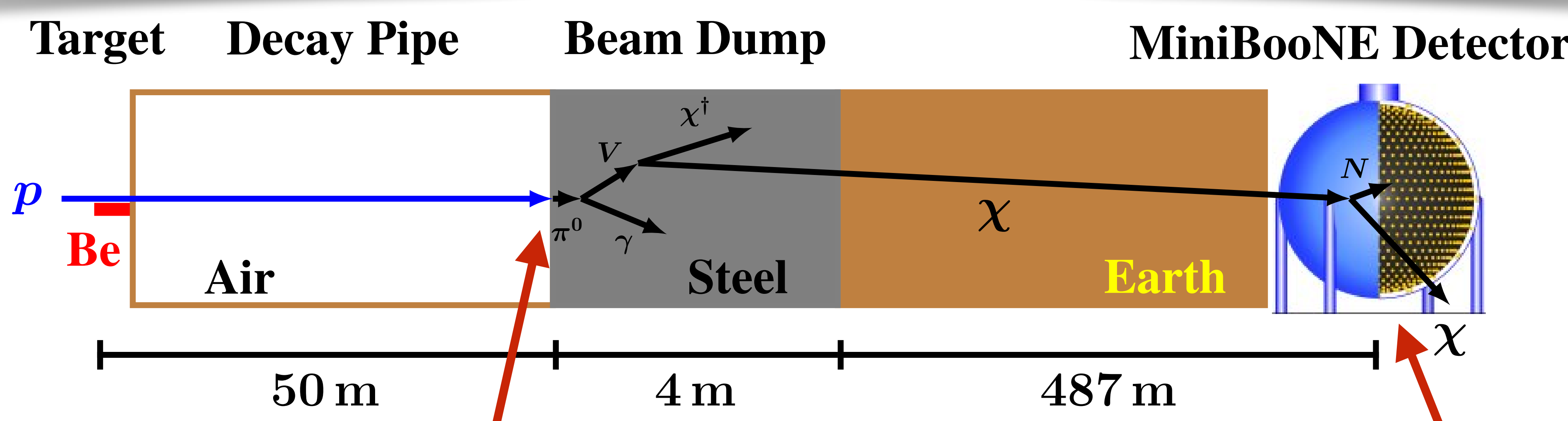


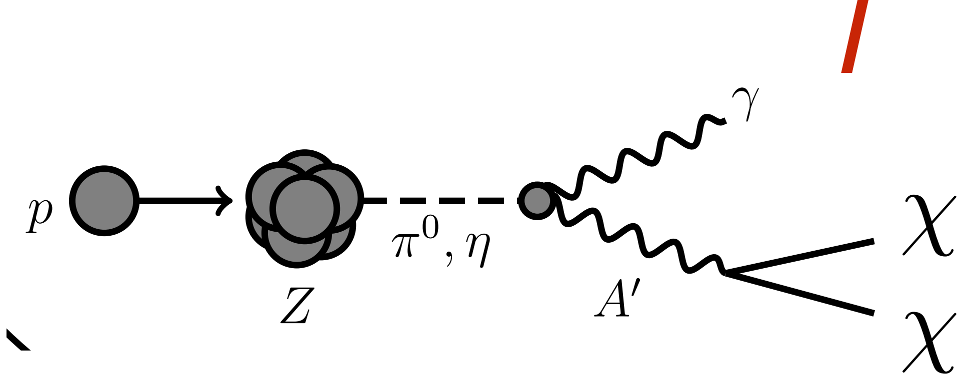
Can explore/test Scalar, Majorana, & pseudo-Dirac DM

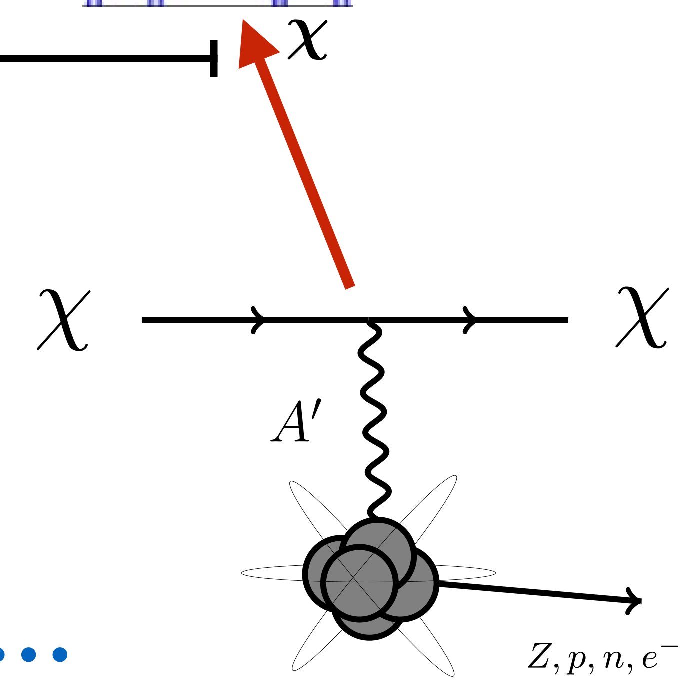
Izaguirre, GK, Schuster, Toro 1307.6554
Essig, Mardon, Papucci, Volansky Zhong 1309.5084

Signatures @ Proton Beam Dumps

1. (quasi)elastic scattering







@ LSND,MiniBooNE, T2K, NOvA, DUNE…

Can explore/test

Scalar

Majorana

pseudo-Dirac DM

Batell, Pospelov, Ritz 0903.0363

deNiverville, Pospelov, Ritz 1107.4580

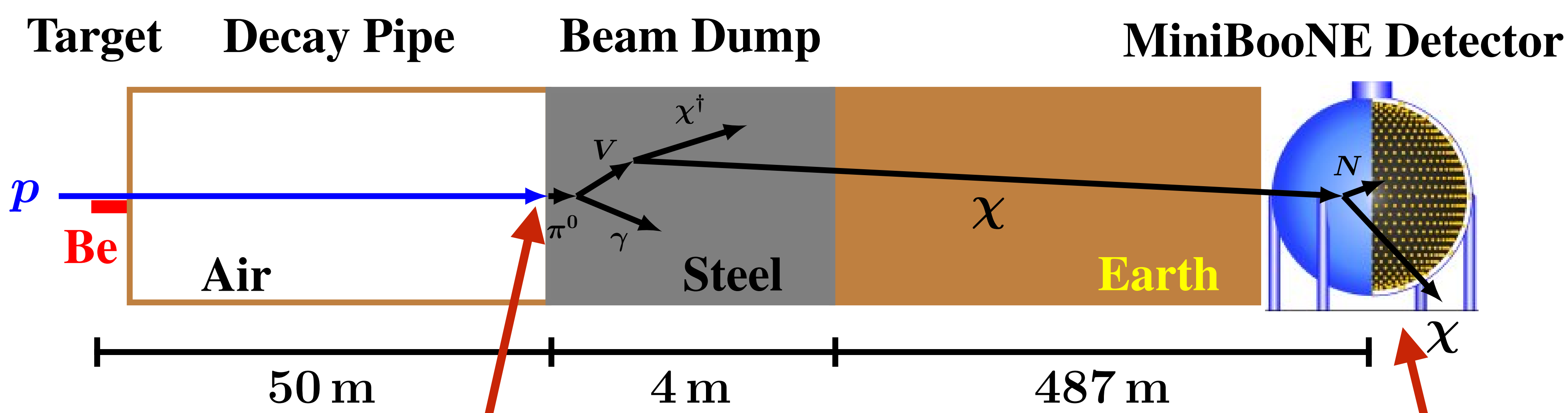
Batell, deNiverville, McKeen, Pospelov, Ritz 1405.7049

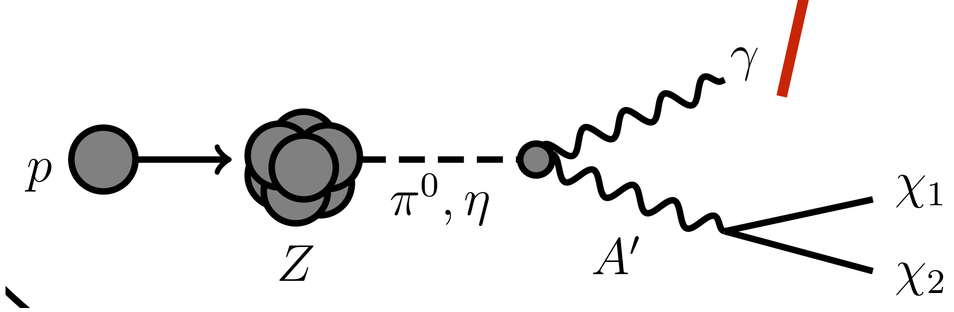
Coloma, Dobrescu, Frugiuele, Harnik 1512.03852

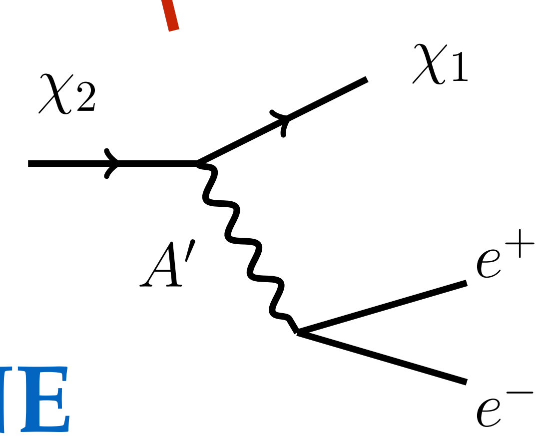
Frugiuele 1701.05464

Signatures @ Proton Beam Dumps

2. inelastic scattering & decays







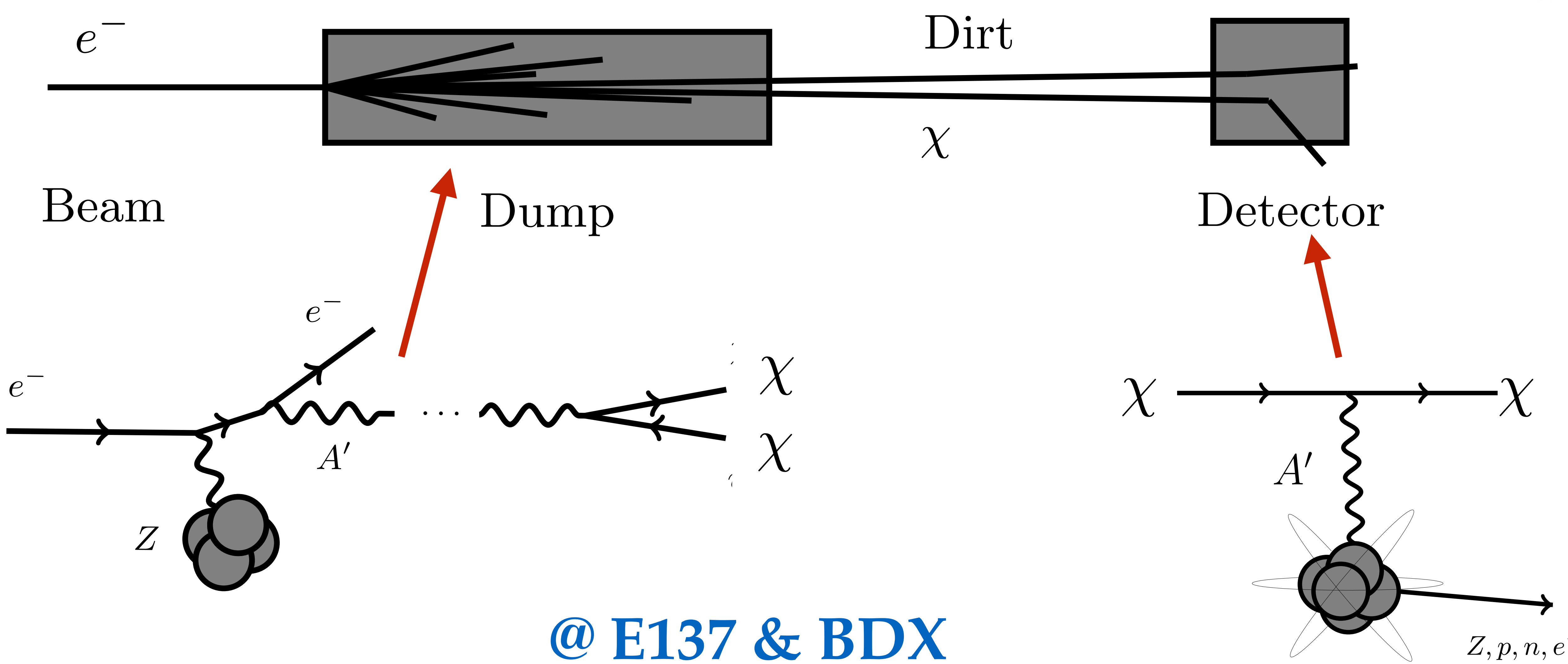
@ LSND,MiniBooNE, SeaQuest, NOvA, DUNE

Can explore/test pseudo-Dirac DM

Morrissey, Spray 1402.4817
Izaguirre, Kahn, GK, Moschella 1703.06881
Berlin, Gori, Schuster, Toro 1703.XXXX

Signatures @ Electron Beam Dumps

1. (quasi) elastic scattering



@ E137 & BDX

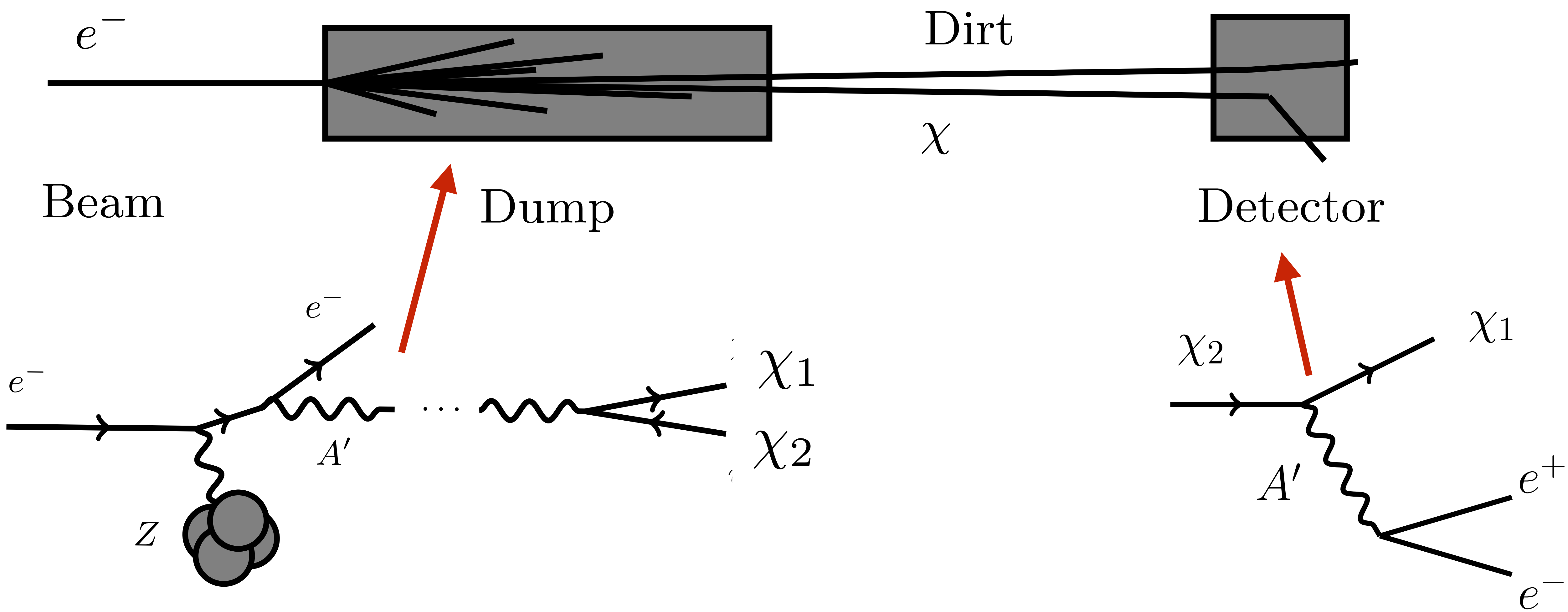
Can explore/test

Scalar
Majorana
pseudo-Dirac DM

Batell, Essig, Zurjuron 1406.2698
Izaguirre, GK, Schuster, Toro 1307.6554

Signatures @ Electron Beam Dumps

2. inelastic scattering & decay



@ E137 & BDX

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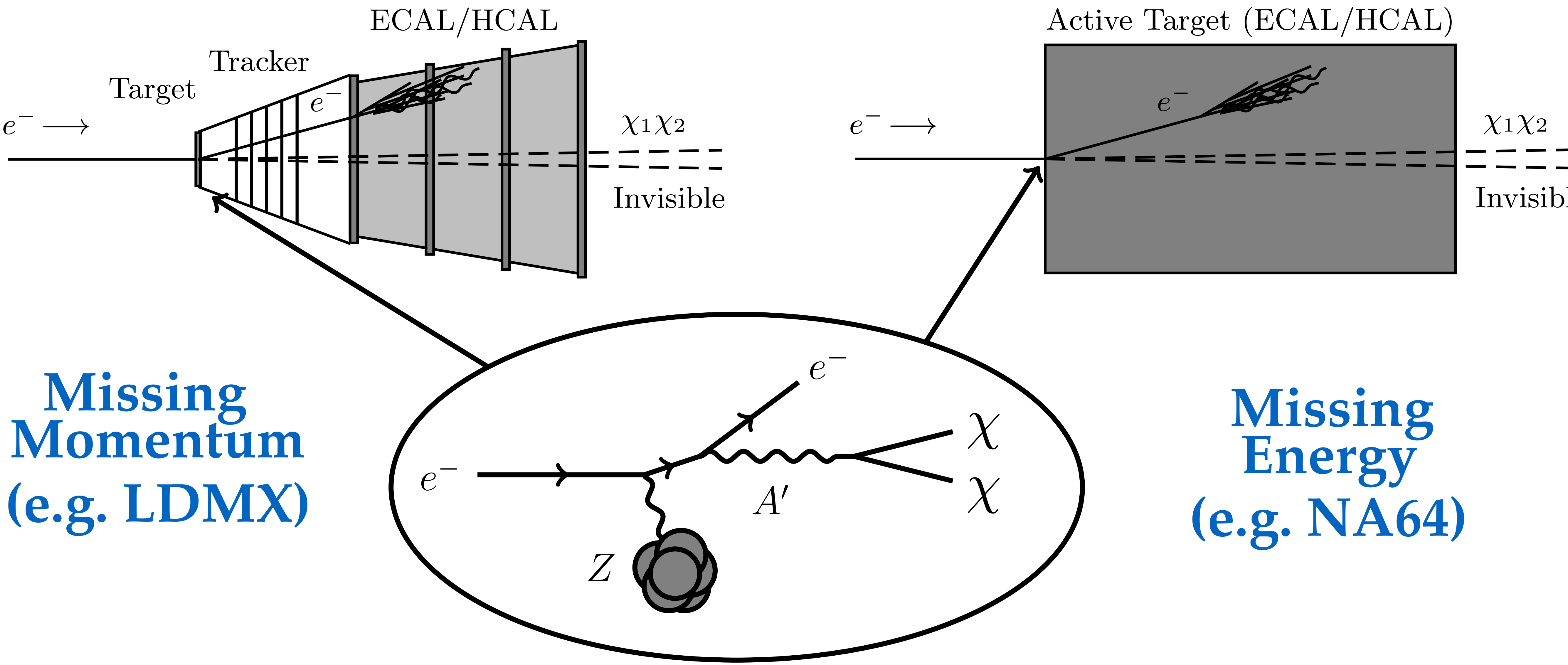
Izaguirre, Kahn, GK, Moschella 1703.06881

Signatures @ Missing Energy & Momentum Experiments



Missing Momentum (e.g. LDMX)

Missing Energy (e.g. NA64)

Observe recoiling electron with large missing energy and/or mass

Izaguirre, GK, Schuster, Toro 1307.6554 **NA64 Collaboration 1610.02988**

Useful Variables

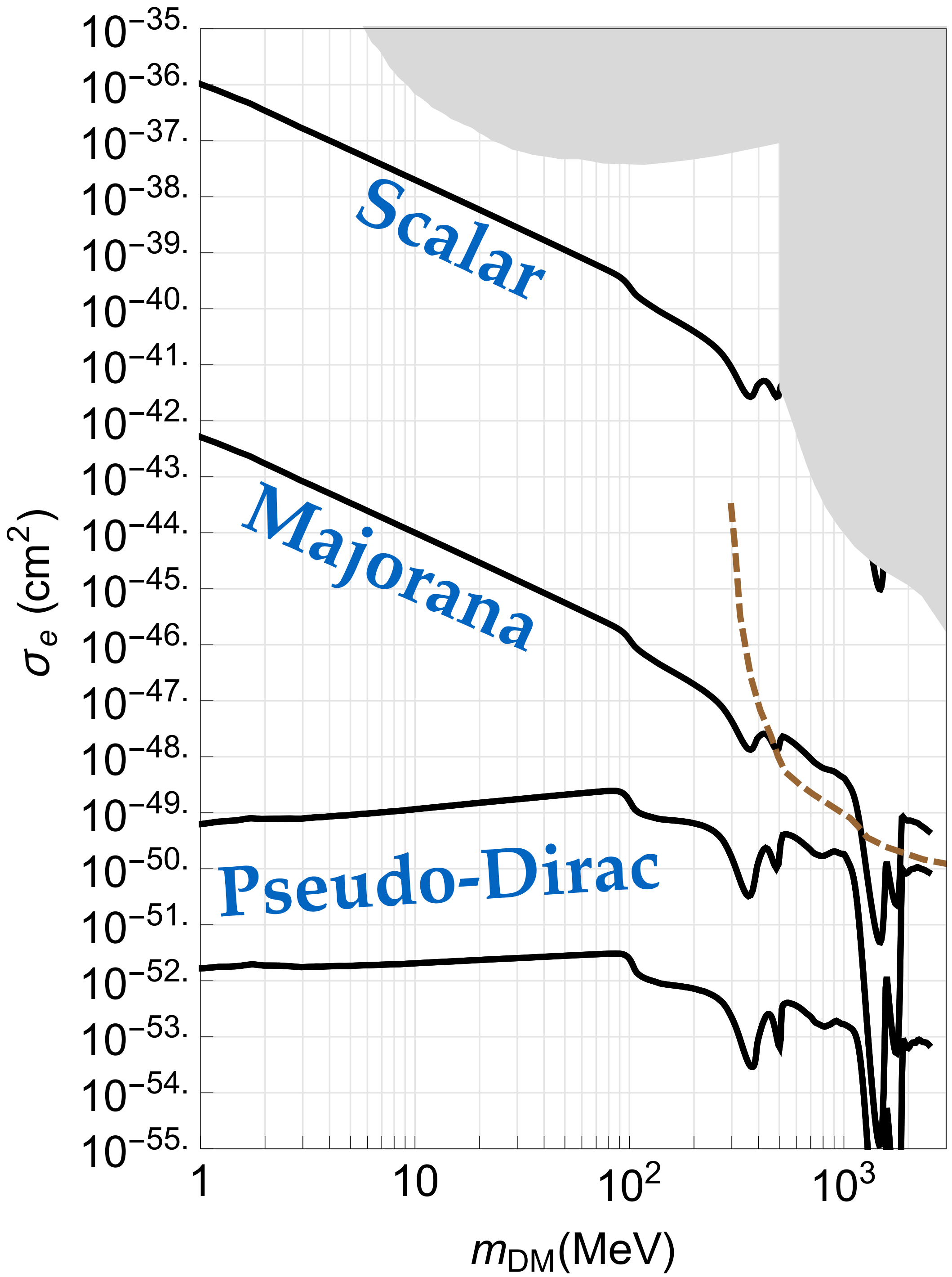
$$\sigma v \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

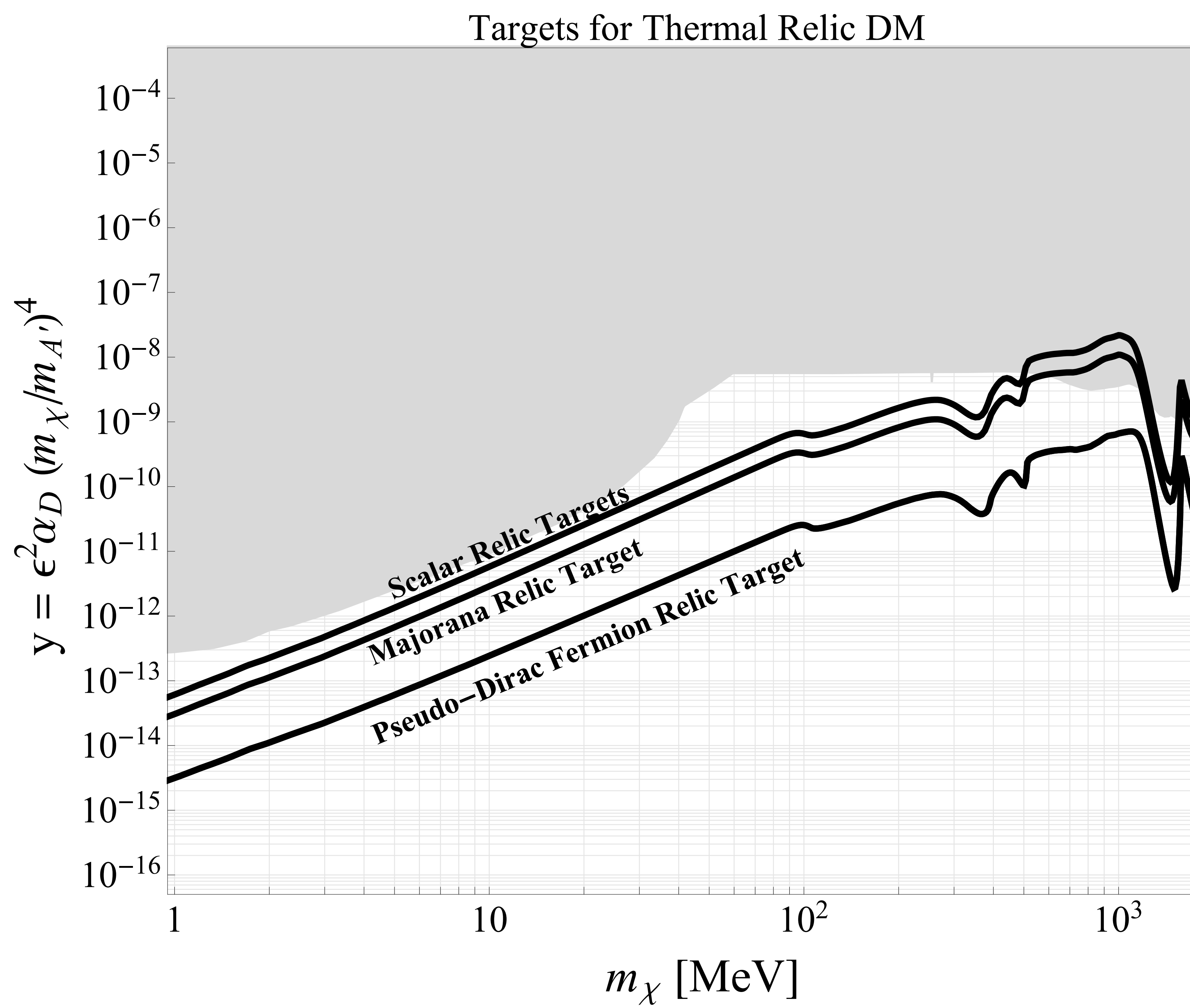
Define new variable optimized for thermal targets

$$\sigma v \propto \alpha_D \epsilon^2 \frac{m_\chi^2}{m_{A'}^4} = \left[\alpha_D \epsilon^2 \left(\frac{m_\chi}{m_{A'}} \right)^4 \right] \frac{1}{m_\chi^2} \equiv \frac{y}{m_\chi^2}$$

Insensitive to ratios of inputs, unique "y" for given mass (up to subleading corrections)

Cross Section vs. Y





Comparing to Experiment

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

Some experiments only bound ϵ^2 **... independently of this** $\alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$

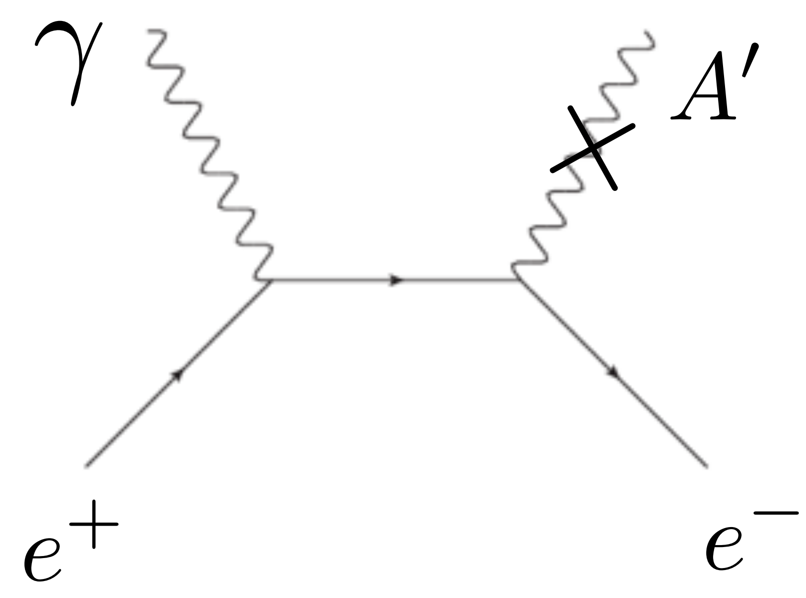
Comparing to Experiment

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

Example: *B*-factory signal $\sigma \sim \frac{\epsilon^2}{E_{\rm cm}^2}$

Conservative "Y" sensitivity

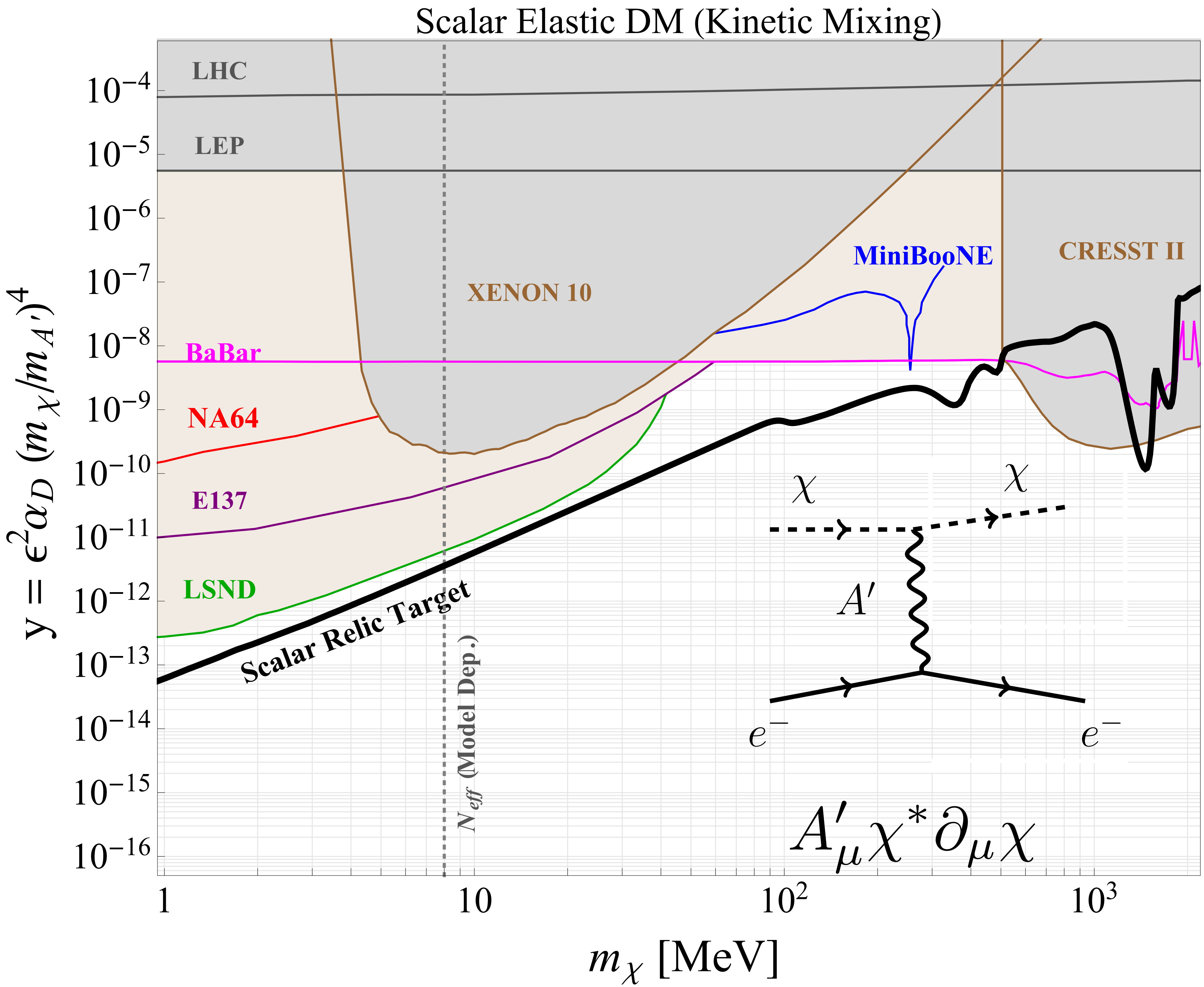
$$y_{\rm exp.} = \epsilon^2_{\rm exp.} \times \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$



Demand the *weakest limit on* "y" for given bound on ϵ

$$\alpha_D \sim \mathcal{O}(1) \quad , \quad m_\chi \sim 2 m_{A'}$$

Maximizing assumed DM params demands smallest ϵ

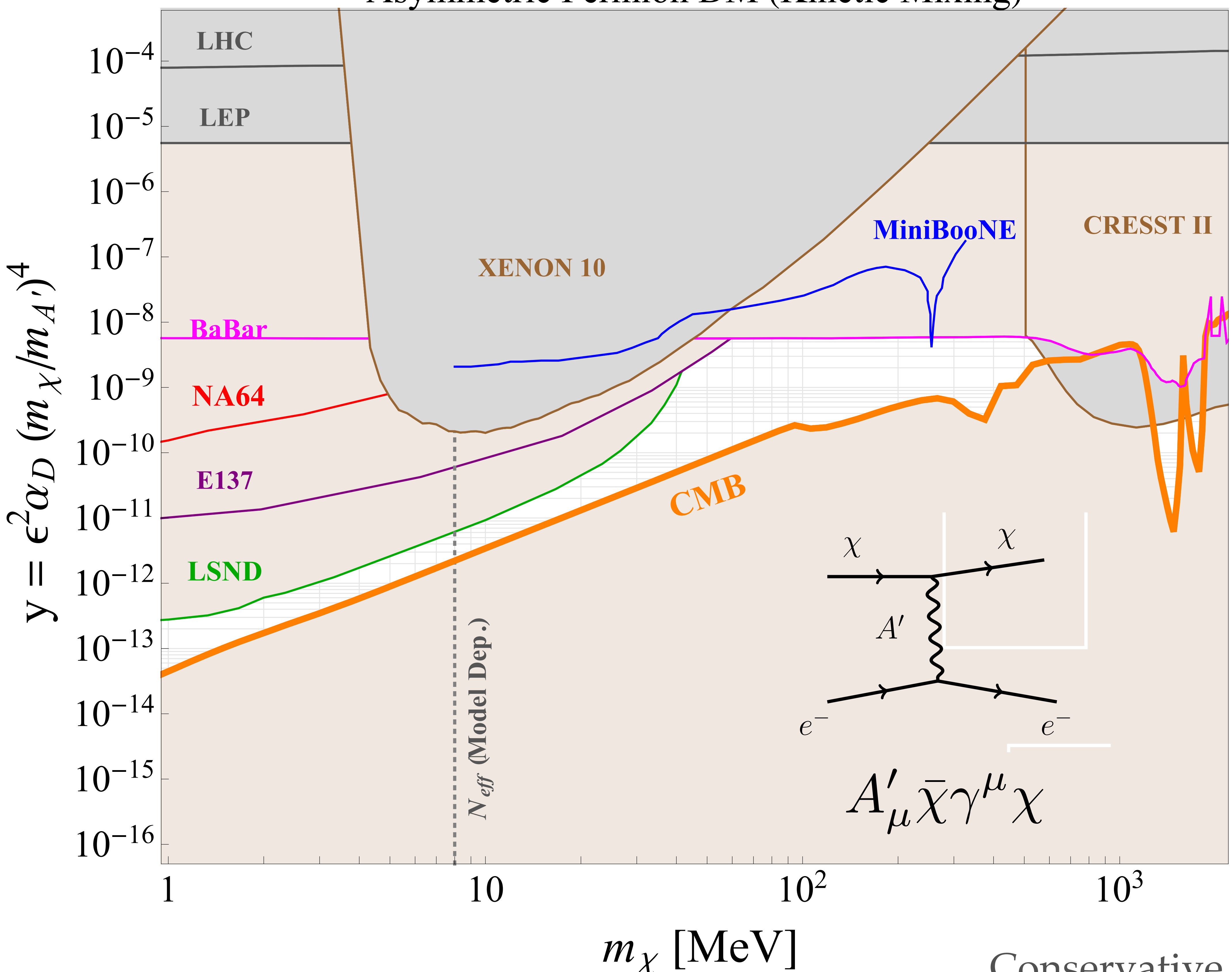


Next gen DD & accelerator exp. will crush this!

Conservative

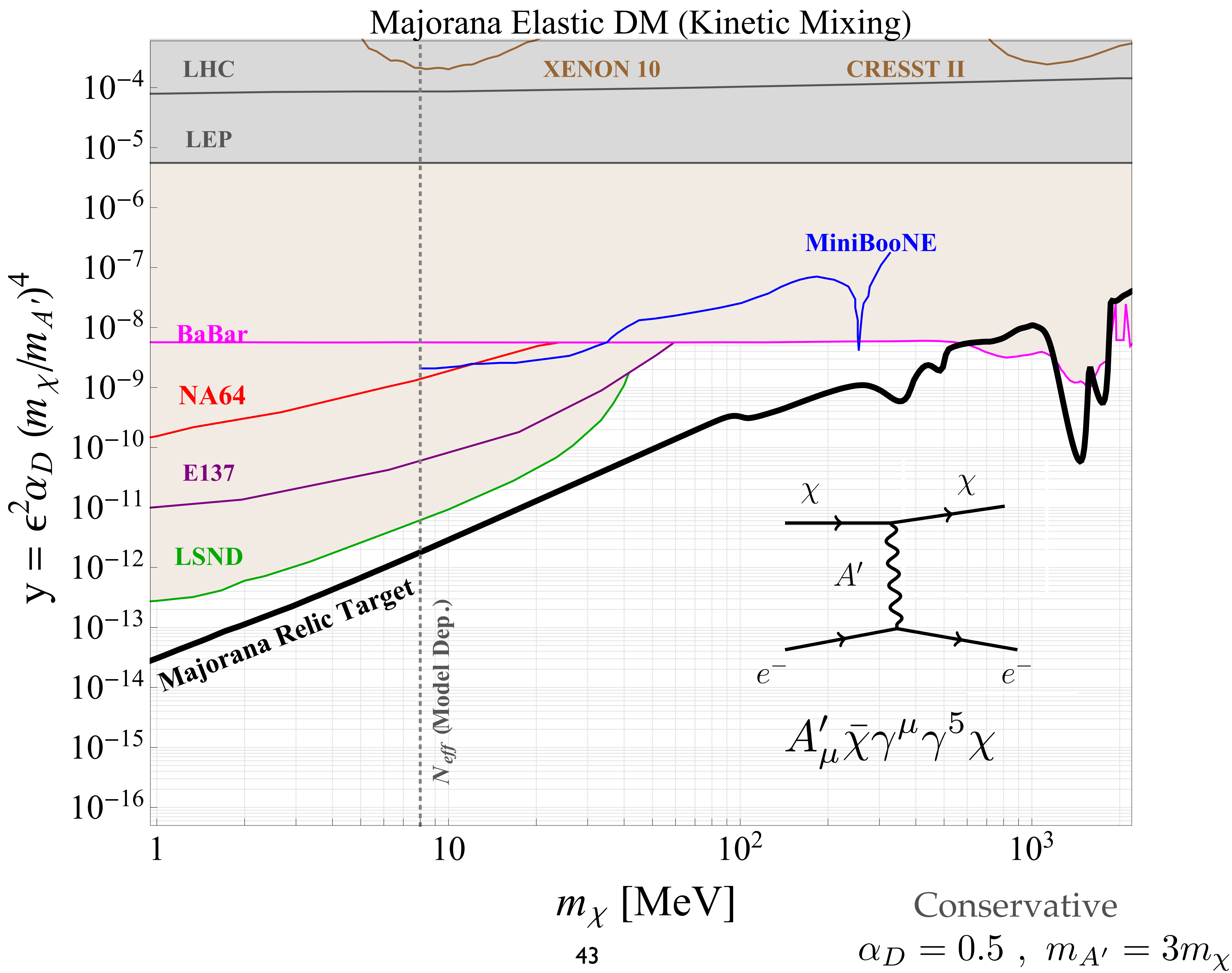
$\alpha_D = 0.5\ ,\ m_{A'} = 3 m_\chi$

Asymmetric Fermion DM (Kinetic Mixing)

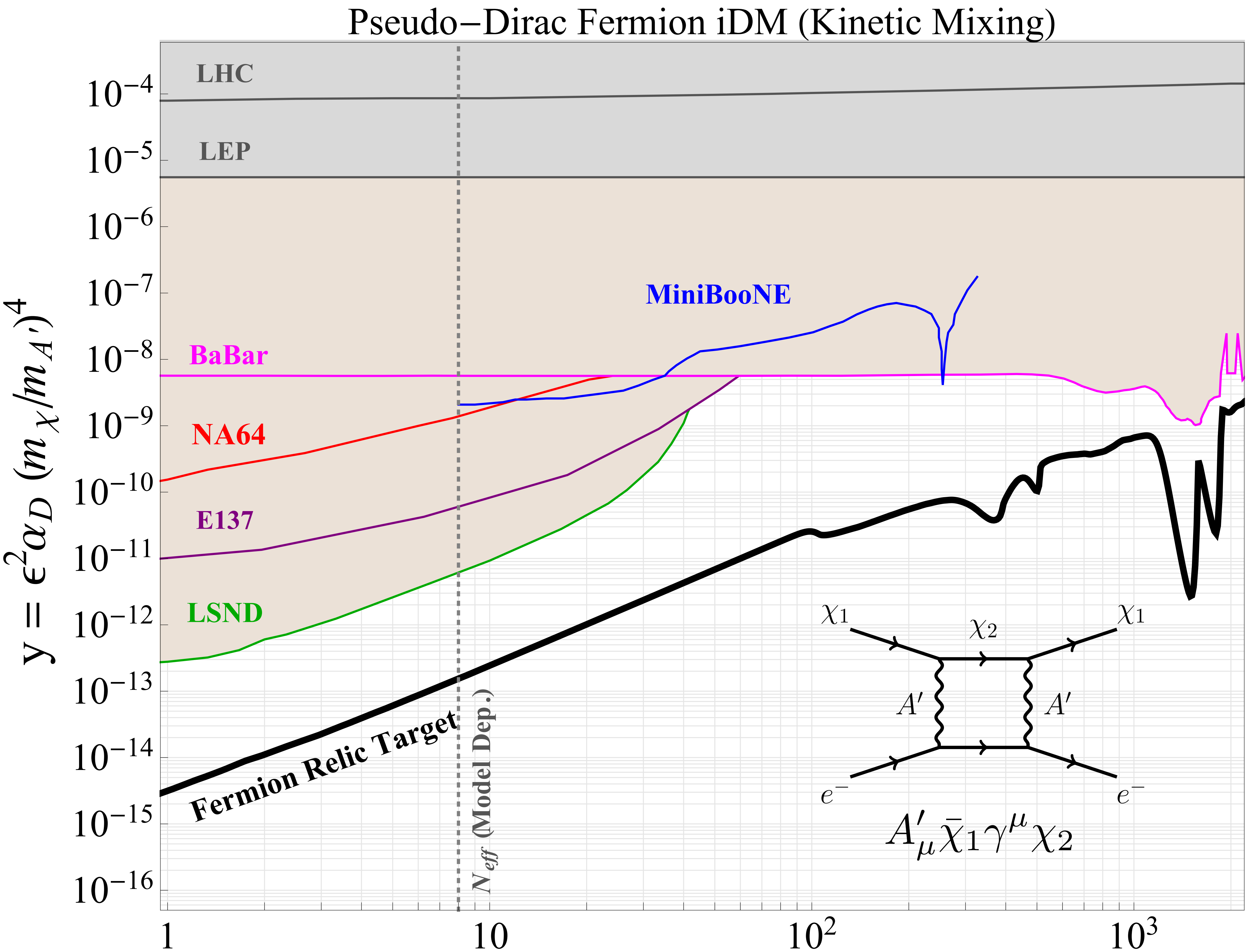


Conservative

$\alpha_D = 0.5\ ,\ m_{A'} = 3m_\chi$

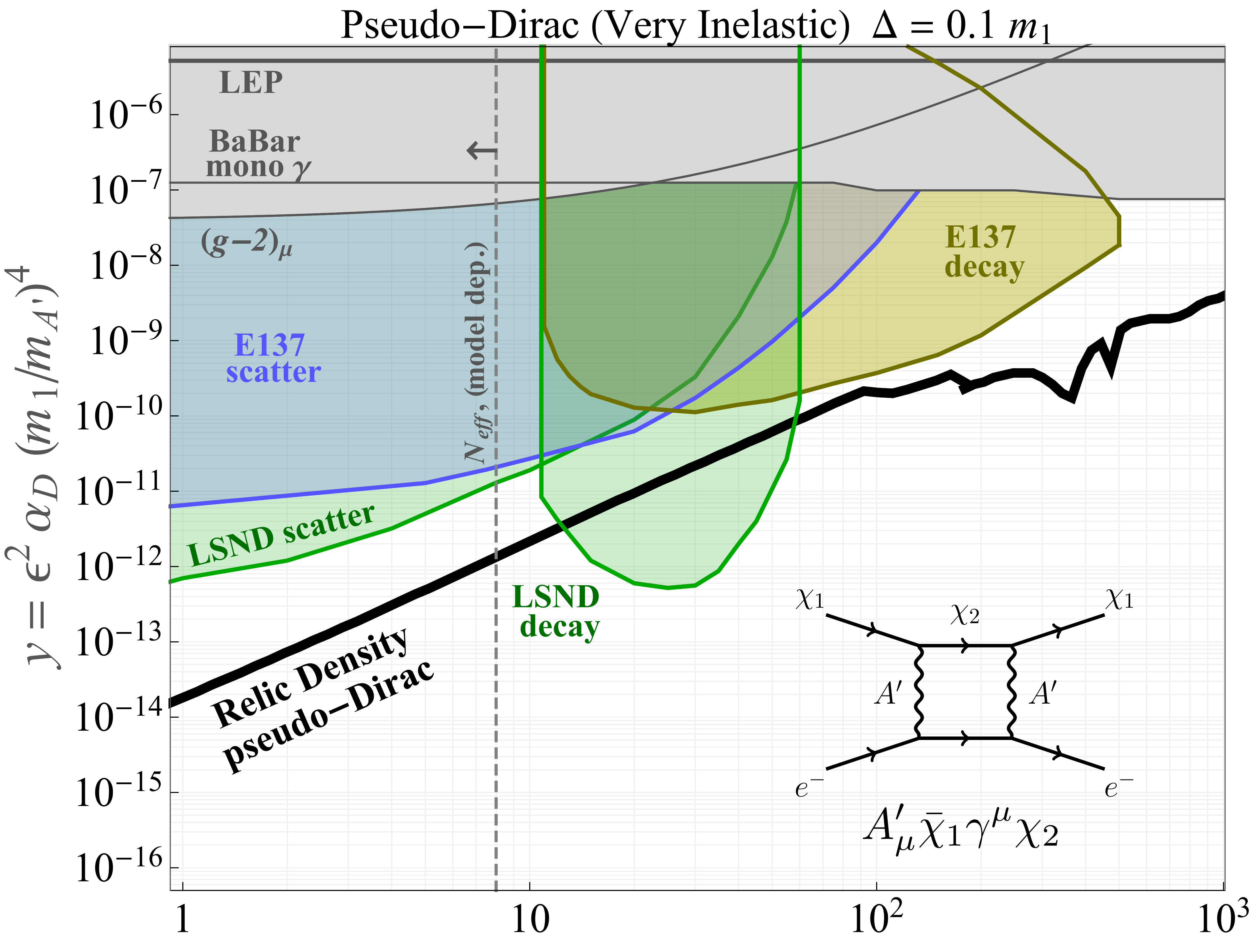


Majorana Elastic DM (Kinetic Mixing)
LHC
XENON 10
CRESST II
LEP
MiniBooNE
BaBar
NA64
E137
LSND
Majorana Relic Target
N_{eff} (Model Dep.)
χ
χ
A'
e^-
e^-
$A'_\mu \bar{\chi}\gamma^\mu\gamma^5\chi$
$y = \epsilon^2\alpha_D\,(m_\chi/m_{A'})^4$
m_χ [MeV]
Conservative
$\alpha_D = 0.5\ ,\ m_{A'} = 3m_\chi$



Small mass splitting
$\Delta m \ll m_\chi$

Conservative
$\alpha_D = 0.5\ ,\ m_{A'} = 3 m_\chi$



Conservative

$\alpha_D = 0.5\ ,\ m_{A'} = 3m_\chi$

Conclusion

Thermal Equilibrium: Physical Organizing Principle

- Easy to reach
- Minimum annihilation rate
- Bounds mass range
- Insensitive to high scales (e.g. inflation)

MeV-GeV scale DM can realize thermal below weak scale

- It's in our neighborhood $m_e < m_{\rm DM} < m_p$
- Finite class of DM+mediator combinations
- Testable thermal targets for direct annihilation

Fixed-Target, Neutrino, & B-Factory Experiments

- Broad program of production/scattering/decay searches
- Can test nearly every direct annihilation model

No lose theorem: genuine opportunity to discover/falsify

Thanks!