Discovering or Falsifying sub-GeV Dark Matter

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Where Are We Now?

The LHC has found the Higgs

Questions remain: one, two, many? ... natural or not ? etc.

Top question in particle physics "what triggers EWSB?" is ***answered***

Where Are We Now?

The LHC has … und the Higgs

Questions remain: one, two, … tural or not ? etc.

Top question in particle physic… ggers EWSB?" is ***answered***

Where Are We Now?

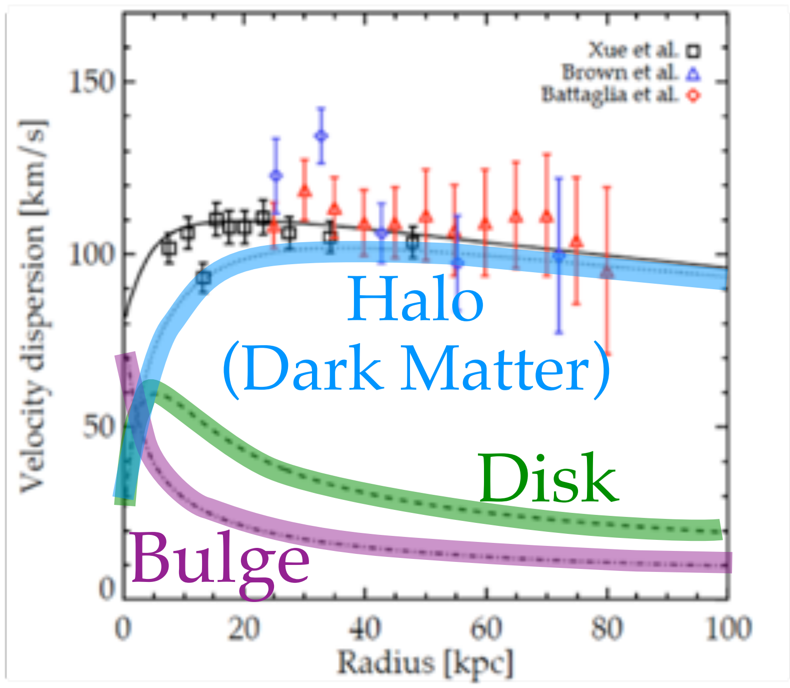
The LHC has … nd the Higgs

Questions remain: one, two, … tural or not ? etc.

Top question in particle physic… ggers EWSB?” is ***answered***

New priority: what is 85% of matter?

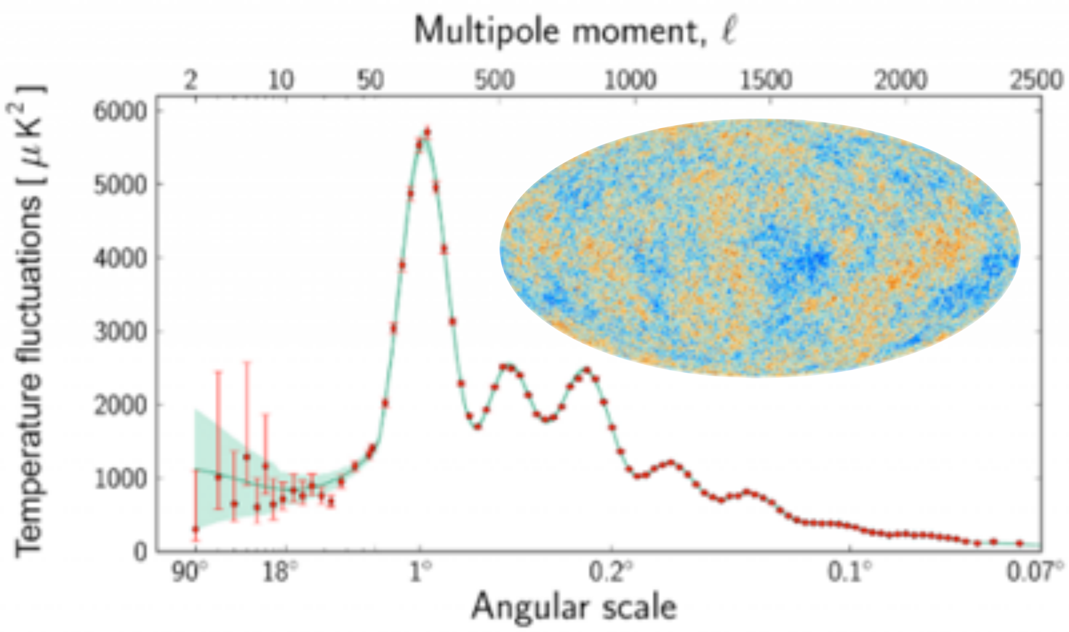
We Know Its Eqn. of State



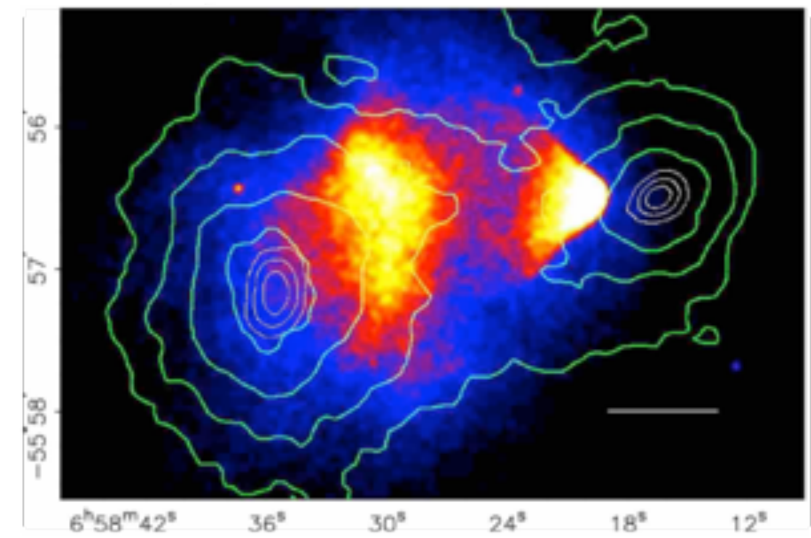
Rotation Curves

Gravitational lensing

CMB



Cluster collisions



but not its particle nature

Overview

- General Remarks
- Light Dark Matter
- Missing Momentum

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Nightmare Scenario

Logical possibility: we may be very unlucky

Dark/visible coupling too weak for thermal equilibrium in the early universe

Mass range remains a mystery forever

$$10^{-33}\ \text{eV} \ < m_{DM} \ < \ 10^{19}\ \text{GeV}$$

But this is not generic

You have to work hard to avoid equilibrium!

Equilibrium Sharpens Focus

Number densities in equilibrium set by temp.

$$n_i(T) = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \sim T^3$$

For visible matter, annihilation is rapid

Antiparticles annihilate away, only the asymmetric part survives.

$$10^{-9} \times (\text{Original Abundance})$$

For DM, if annihilation is too weak, too much survives at late times.

Equilibrium Sharpens Focus

1. Overclosure: Minimum Annihilation Rate

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

Symmetric DM (=)   Asymmetric DM (>)

2. Perturbativity: Maximum DM Mass

$$\sigma v \sim g^4/M^2 \implies M \leq \mathrm{few TeV}$$

3. Structure Formation: Minimum DM Mass

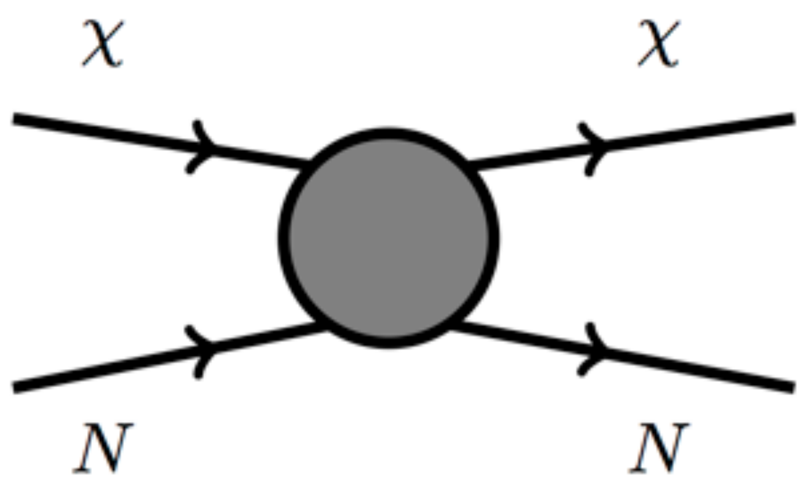
$$M \geq 100\ \mathrm{keV}$$

Existing experimental program covers the GeV-TeV *half*

What about the MeV-GeV *half?*

Current Search Strategy

1. Direct Detection: LUX XENON, CDMS...



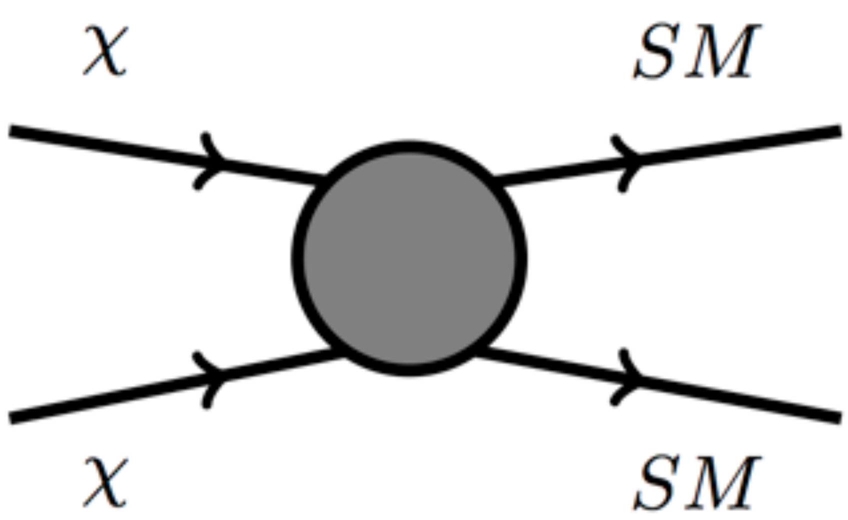
Sensitive to dominant, (meta)stable species

Large BG, tiny recoils for M < few GeV

Astrophysical uncertainties

Current Search Strategy

2. Indirect Detection: FGST, AMS, PAMELA...

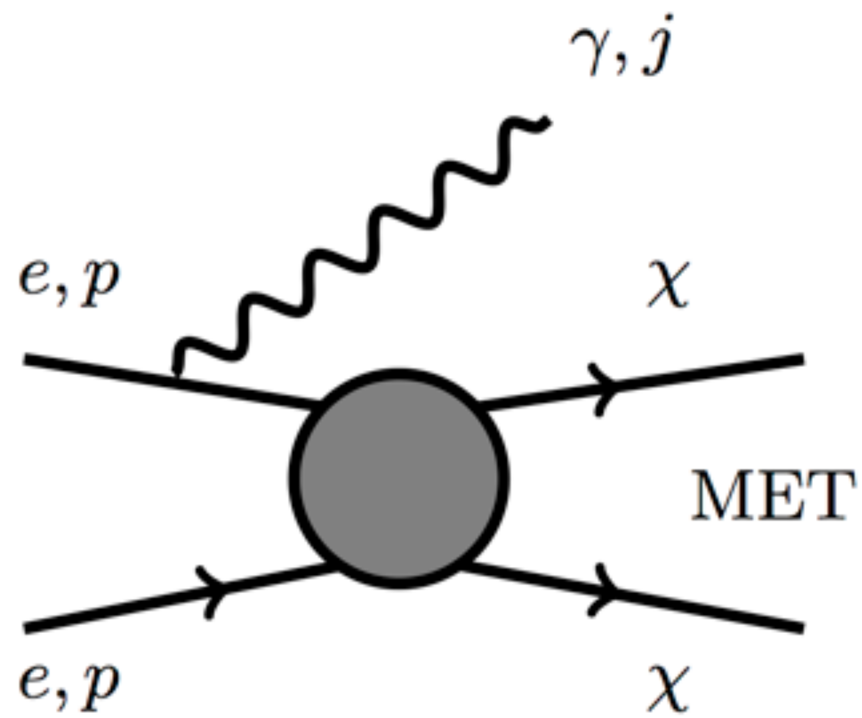


Sensitive to dominant, (meta)stable species

Large BG for DM < few GeV
(Astrophysical uncertainties)^2

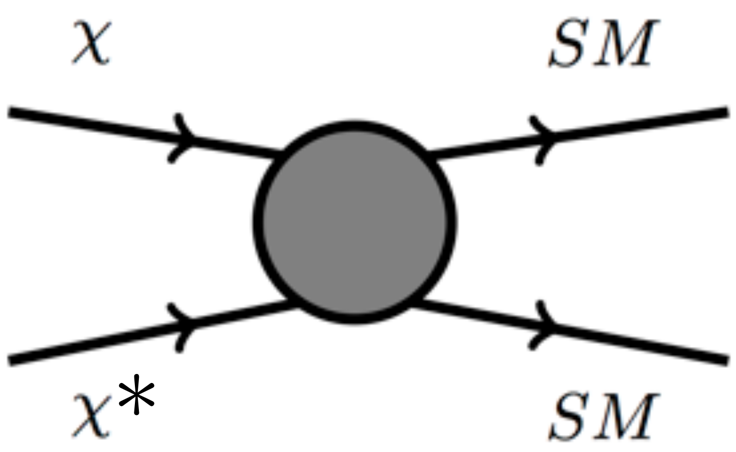
Current Search Strategy

3. Colliders: LHC, Tevatron, LEP...



Weak sensitivity below ~ 10 GeV if not EFT

Why the focus on "heavy"?



$$\Omega_{DM} \implies \sigma v \simeq 3 \times 10^{-26}\text{cm}^3\text{s}^{-1}$$

$$\sim \frac{\alpha^2}{m_Z^2} \sim \frac{1}{(20\,\text{TeV})^2}$$

-DM is heavy ~ TeV

-DM is a thermal relic

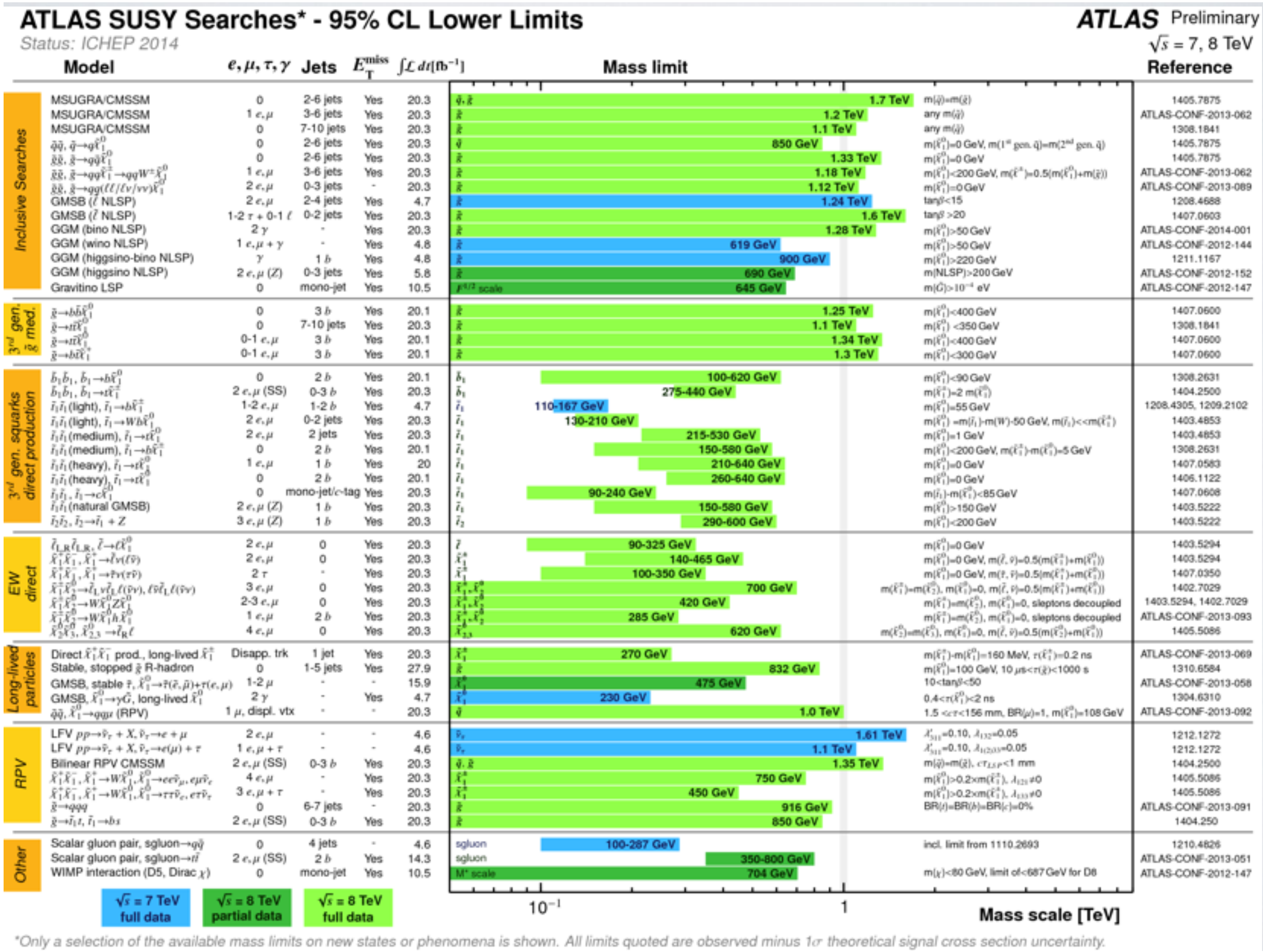
-DM carries SM quantum numbers

-DM is particle/antiparticle symmetric $n_\chi = n_{\chi^*}$

Motivated by Supersymmetry

Many DM experiments require this whole list!

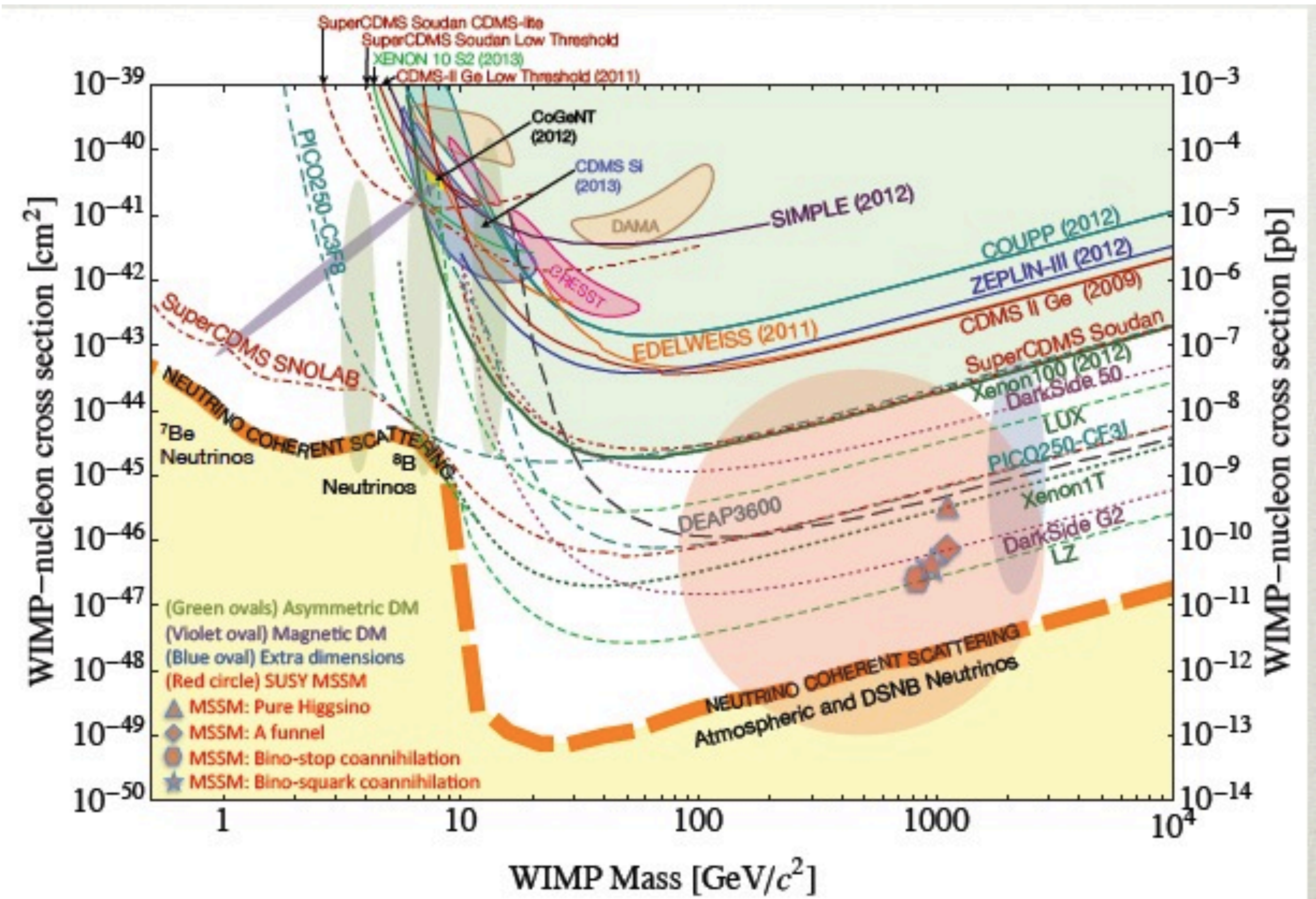
LHC Assault

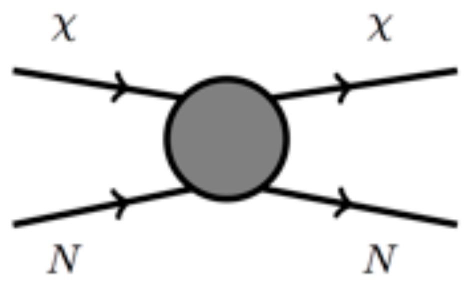


Null LHC SUSY results, strong bounds weak-charged DM

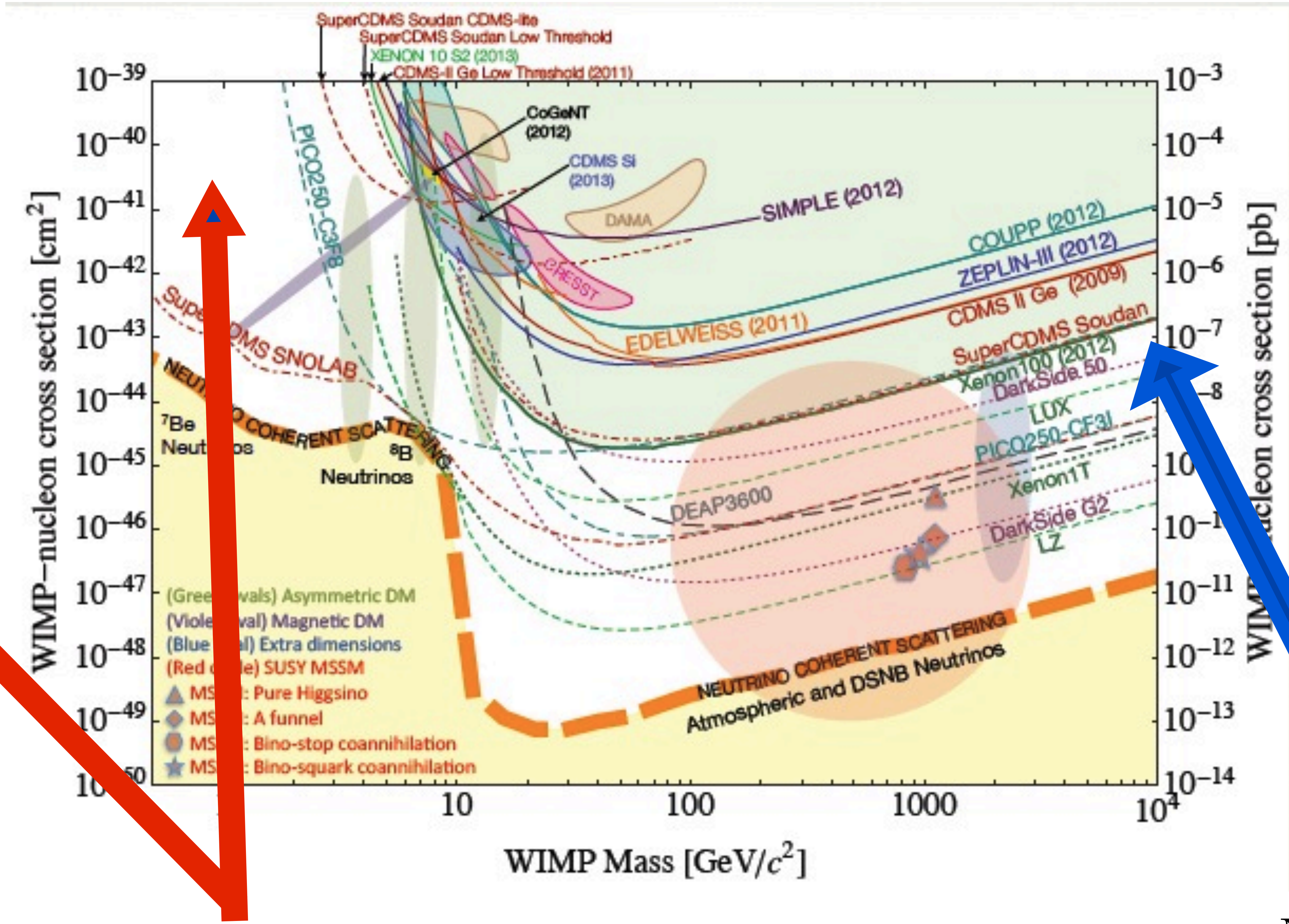
No evidence for connection to the weak scale

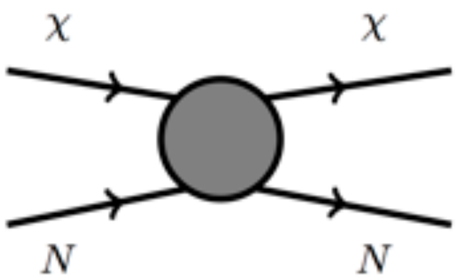
Direct Detection: The End Is Near





Direct Detection: The End Is Near

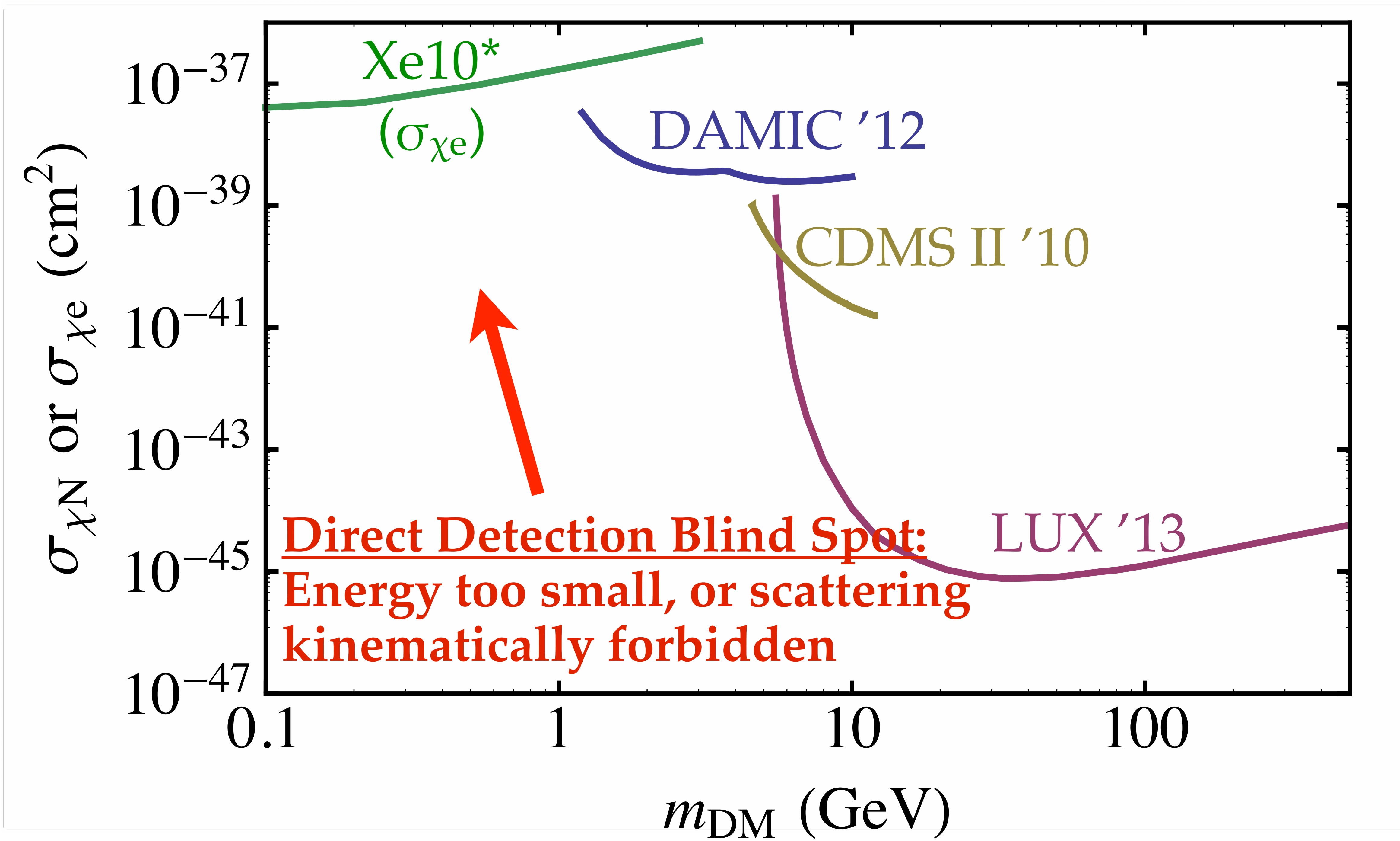




What about here?
… and lower?

Overclosure or Nonperturbative (harder model building)

Direct Detection: The End Is Near



Half of viable range remains to be explored

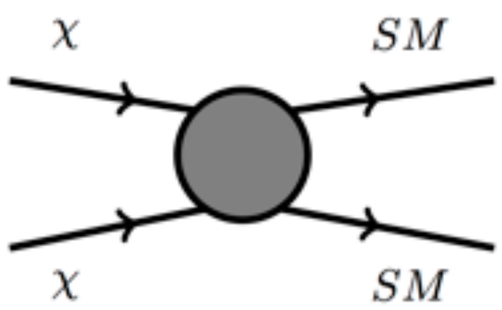
Overview

- General Remarks
- Light Dark Matter
- Missing Momentum

Q: Does sub-GeV DM Make Sense?

Naive concern: You "overclose" the universe

$$\langle \sigma v \rangle \sim \frac{g_V^2 g_D^2 m_\chi^2}{M_{med}^4} \implies \Omega_\chi \gg (\Omega_{DM})_{obs.}$$



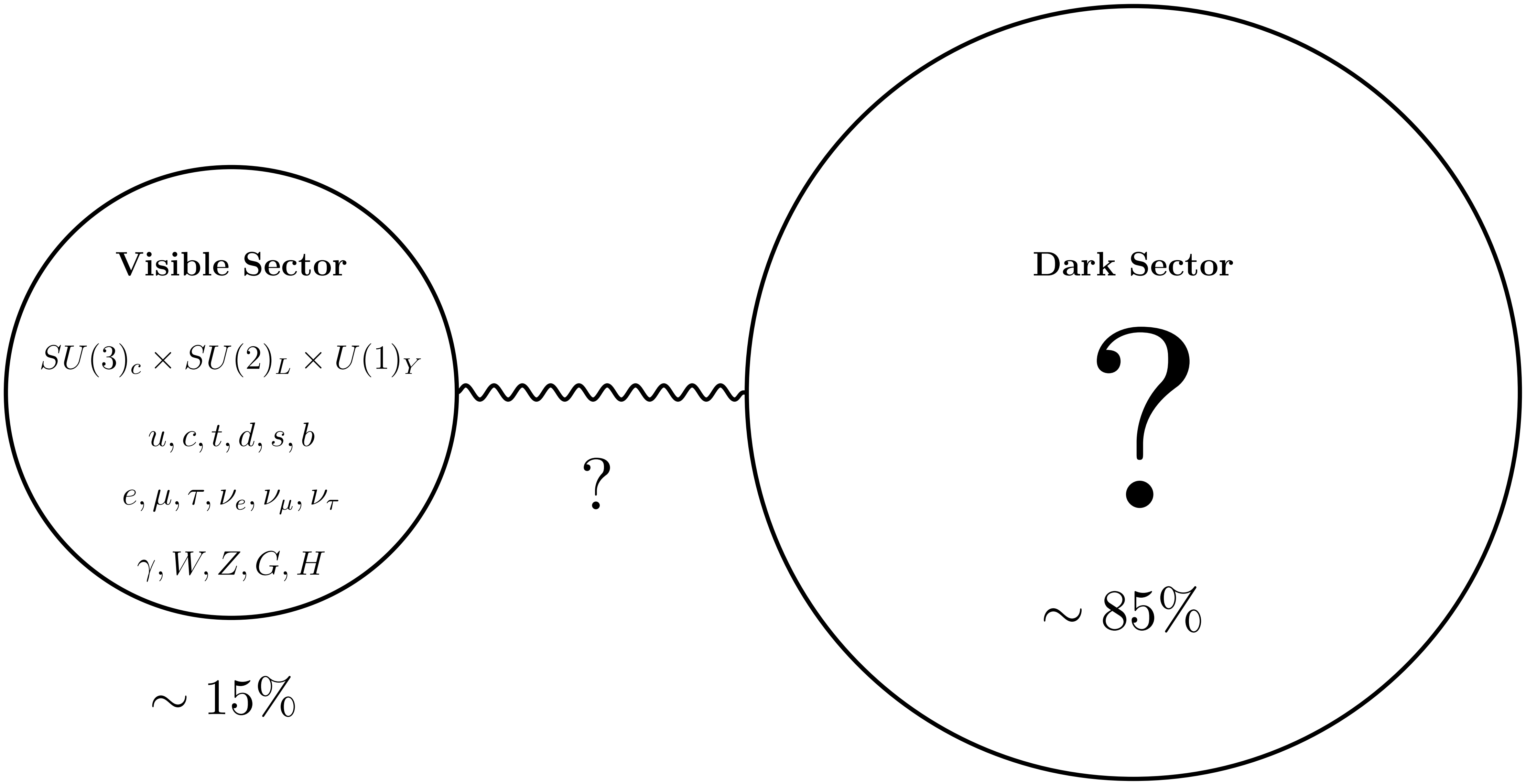
Actually: Just need a lighter "mediator"

$$m_\chi \sim M_{med} \ , \ \langle \sigma v \rangle \sim \frac{\alpha \alpha_D}{m_\chi^2} \implies \frac{\Omega_\chi}{\Omega_{DM}} \sim 10^{-3} \left(\frac{\alpha}{\alpha_D} \right)^2 \left(\frac{m_\chi}{100 \text{ MeV}} \right)^2$$

Any **relic abundance can be generated**

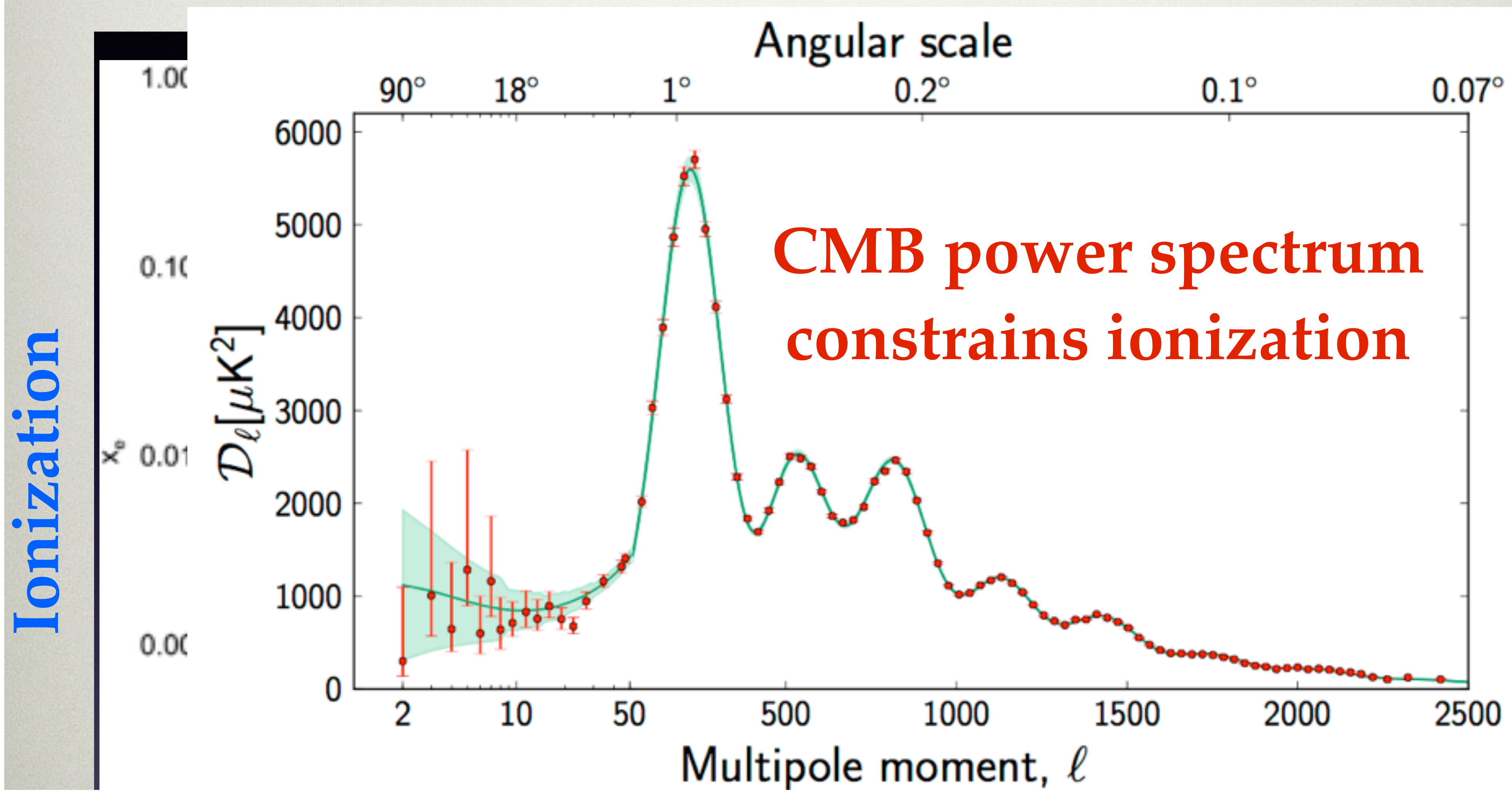
Motivates richer dark sector

Q: Does sub-GeV DM Make Sense?
A: Yes! (too) many possibilities



CMB Constraints on MeV-GeV DM

Late time annihilation of dark matter into charged particles increases ionization of IGM near recombination



CMB Constraints on MeV-GeV DM

$$\cdot f \frac{\langle \sigma v \rangle_{\rm CMB}}{m_X} < \frac{2.42 \times 10^{-27}\ {\rm cm}^3/{\rm s}}{\rm GeV}.$$

But be careful, this assumes:

0. Pure annihilation (not co-annihilation)

1. Dark particle-antiparticle symmetry

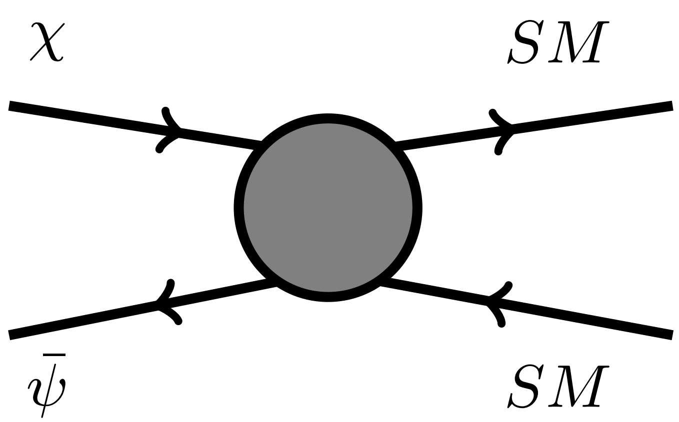
2. Dirac fermion DM, s-wave annihilation (scalar, p-wave ok!)

3. Annihilating species is all of the DM

Model Dependent, easy to evade…

CMB Constraints on MeV-GeV DM

Case Study: Light, Inelastic DM



$$\Delta \equiv m_\psi - m_\chi \gg \text{eV}$$

1. Off-diagonal coupling to mediator in mass eigenbasis

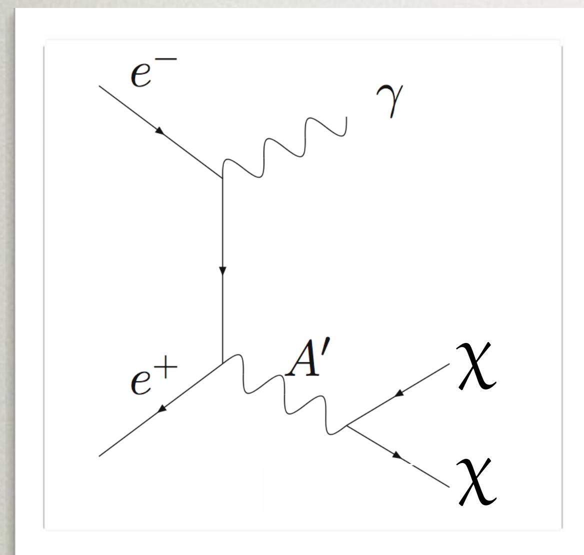
2. Scattering and decays depopulate excited state as universe cools

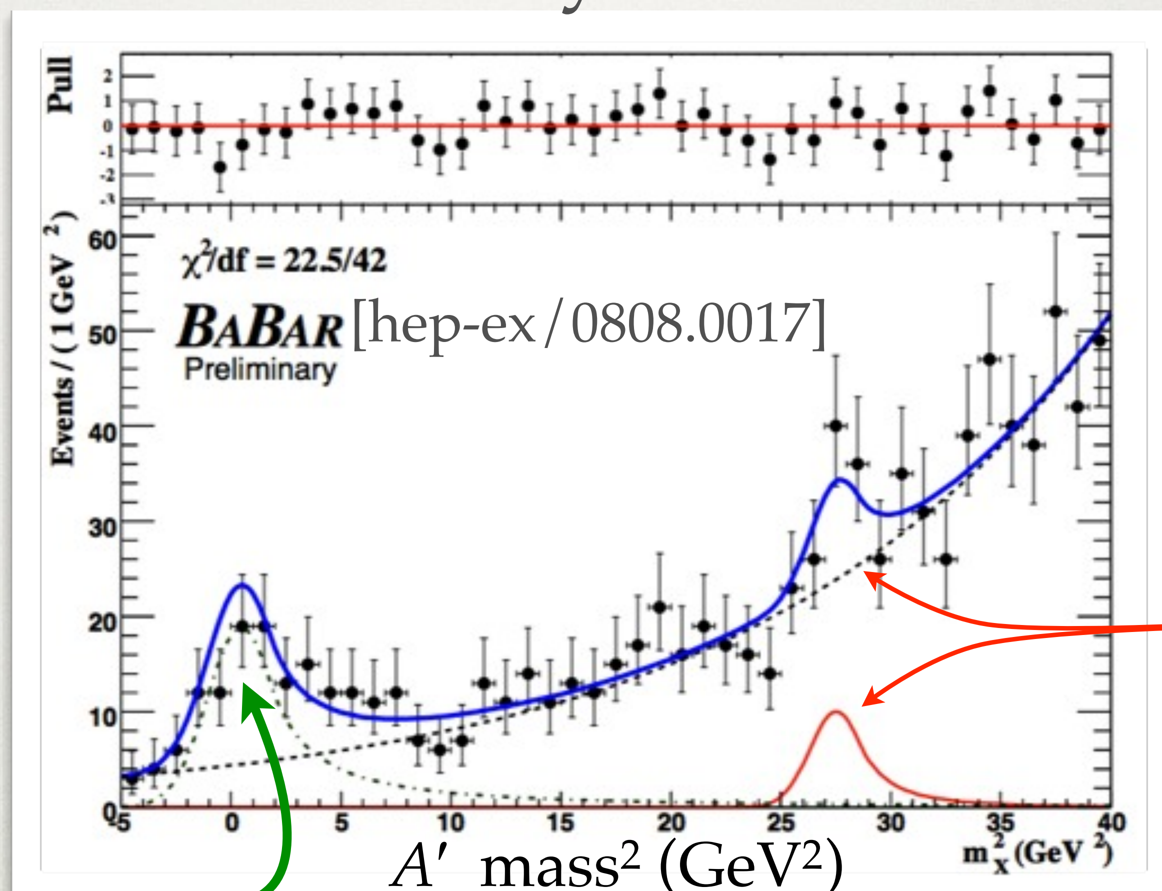
$$n_\psi \sim e^{-\Delta/T}$$

3. Annihilation requires both; shuts off before CMB forms

Collider Constraints on MeV-GeV DM

A′→ χ χ decay constrained by BaBar search



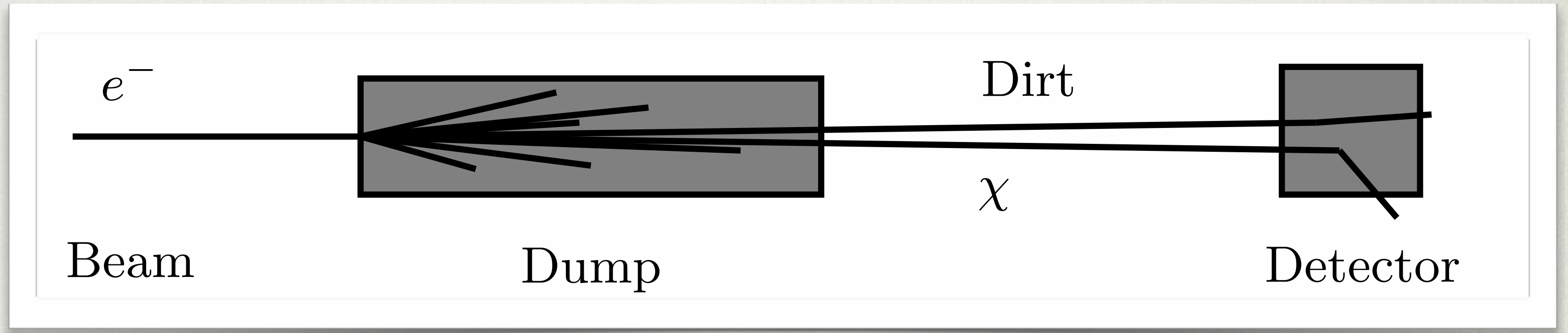


signal fit (not significant)

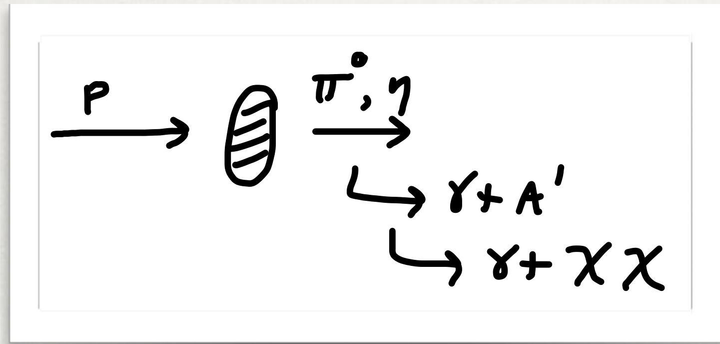
2γ background (signal-faking)

Babar provided best LDM sensitivity from colliders

Beam Dump Constraints



0906.5614,
1107.4580,1205.3499
Batell,DeNiverville,
McKeen, Pospelov, Ritz



Izaguirre, Krnjaic, PS
& Toro
PRD.88.114015 and
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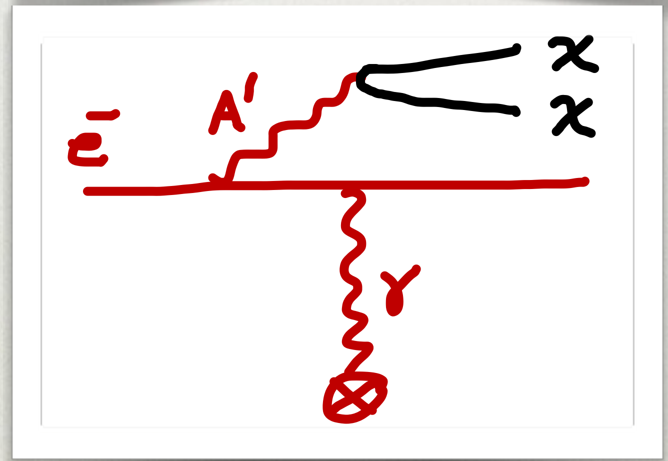
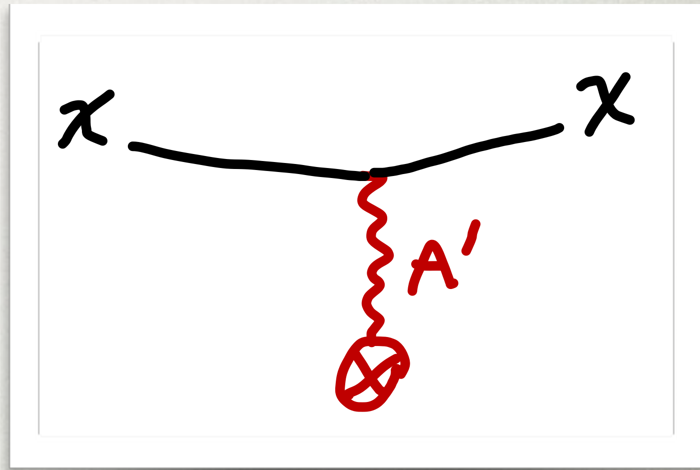




nuclear dissociation;
nucleon, nucleus, or
electron recoil

Good sensitivity (from theorists) for LSND (proton beam + electron scattering)

What kind of mediator interaction?

Higgs Portal $(H^\dagger H)|\phi^\dagger \phi|$

Scalar mediator ϕ , SM couplings mass proportional

"Axion" Portal $\frac{m_f}{f_a} a\bar{f}\gamma^5 f$

Pseudoscalar mediator a, SM couplings mass proportional

Vector Portal $\epsilon F_{\mu\nu} F'_{\mu\nu}$

Spin-1 mediator A', SM couplings charge proportional

(Holdom, Okun)

What kind of mediator interaction?

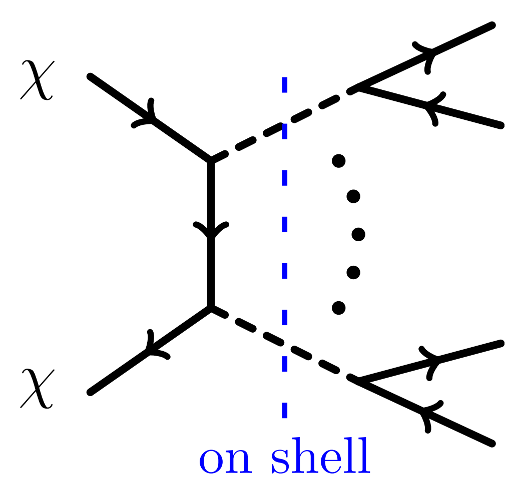
We will always assume the harder case

$$m_{\rm MED} > 2m_{\rm DM}$$

Otherwise, visible decay constraints are generally more powerful

But this also gives a clear target

If mediatory decays visibly, DM annihilation is t-channel



doesn't depend on visible mediator coupling!

CMB & Direct Detection

Late-time annihilation (CMB) and DM scattering with matter (Direct Detection):

$$\sigma v \sim g_D^2 g_{SM}^2 \left(\frac{m_{\rm DM}}{m_{\rm MED}}\right)^4 \frac{1}{m_{\rm DM}^2}$$

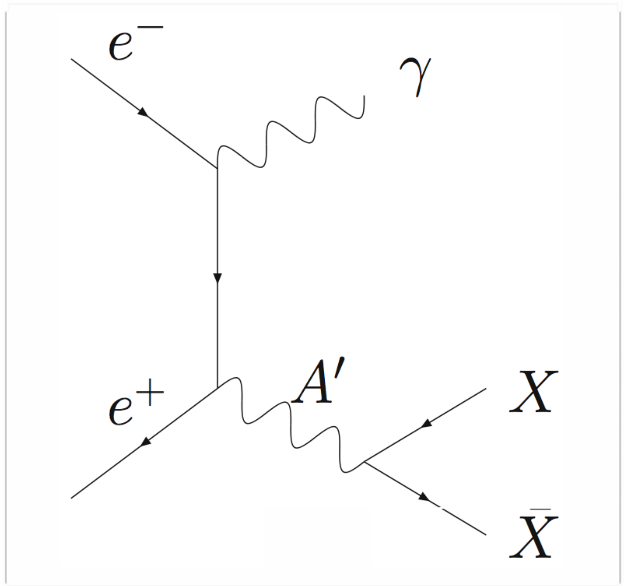
Same scaling as thermal cross-section!

Again motivates:

$$y \equiv g_{SM}^2 g_D^2 \left(\frac{m_{\rm DM}}{m_{\rm MED}}\right)^4 \quad \text{vs.} \quad m_{\rm DM}$$

Colliders

Collider Processes Scale as:



$$\sigma \sim \frac{g_{SM}^2}{E_{CM}^2}$$

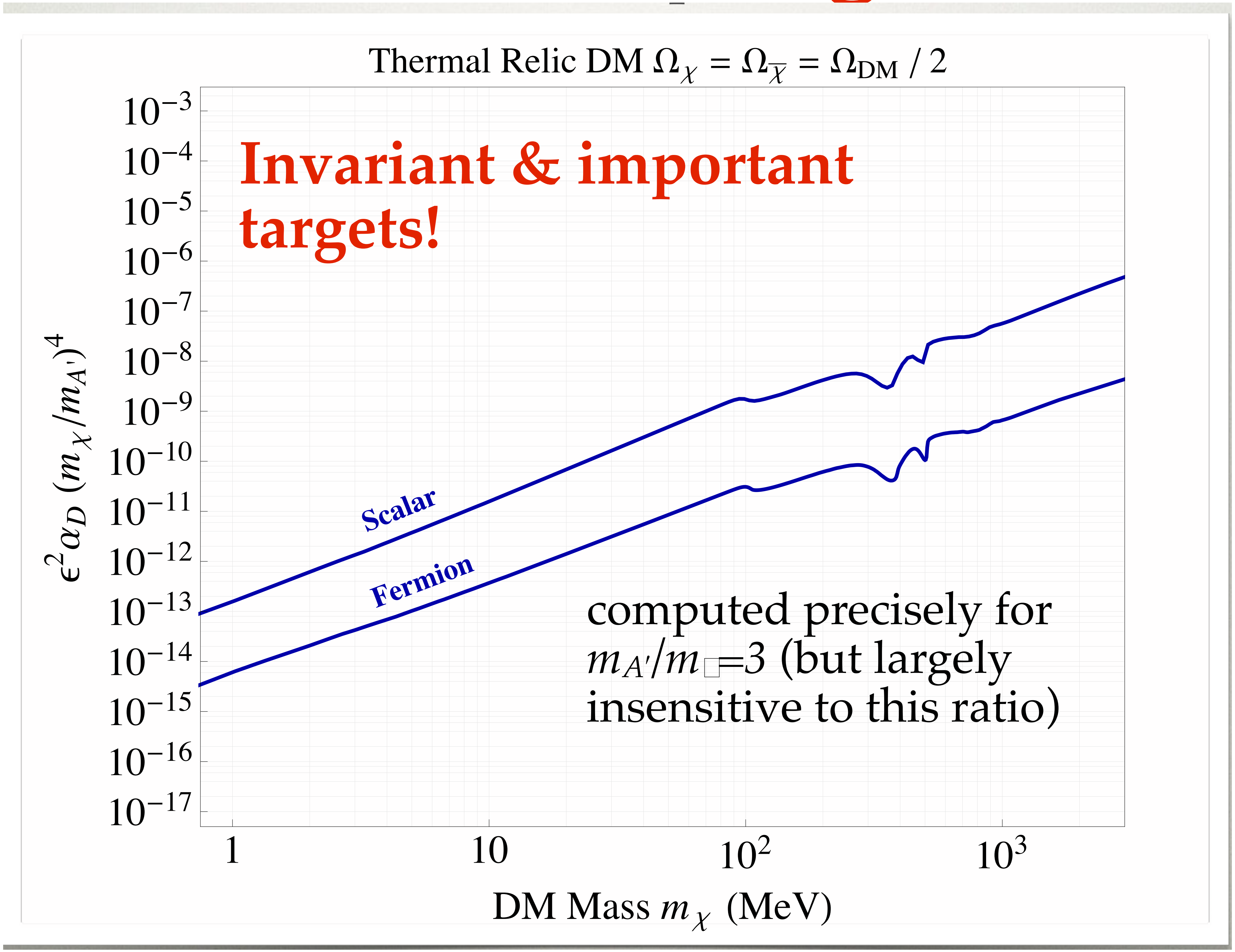
$$\sim y \times \frac{1}{g_D^2}\left(\frac{m_{MED}}{m_{DM}}\right)^4$$

$$y \equiv g_{SM}^2 g_D^2 \left(\frac{m_{\rm DM}}{m_{\rm MED}}\right)^4$$

Scaling is not as intuitive:

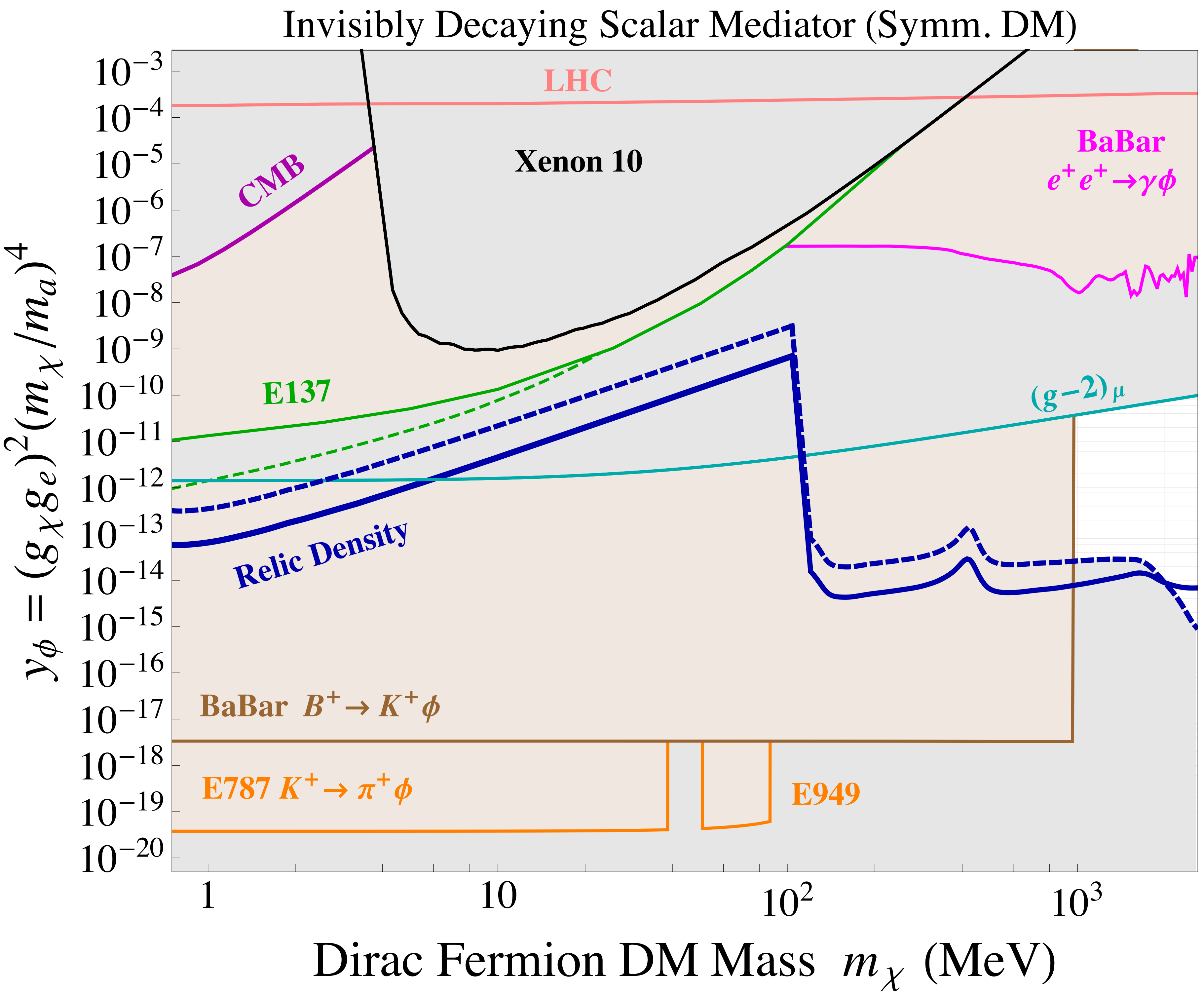
It's easy to overstate existing bounds by choosing *small* DM/mediator coupling! Conservative to choose *large!*

Thermal Targets



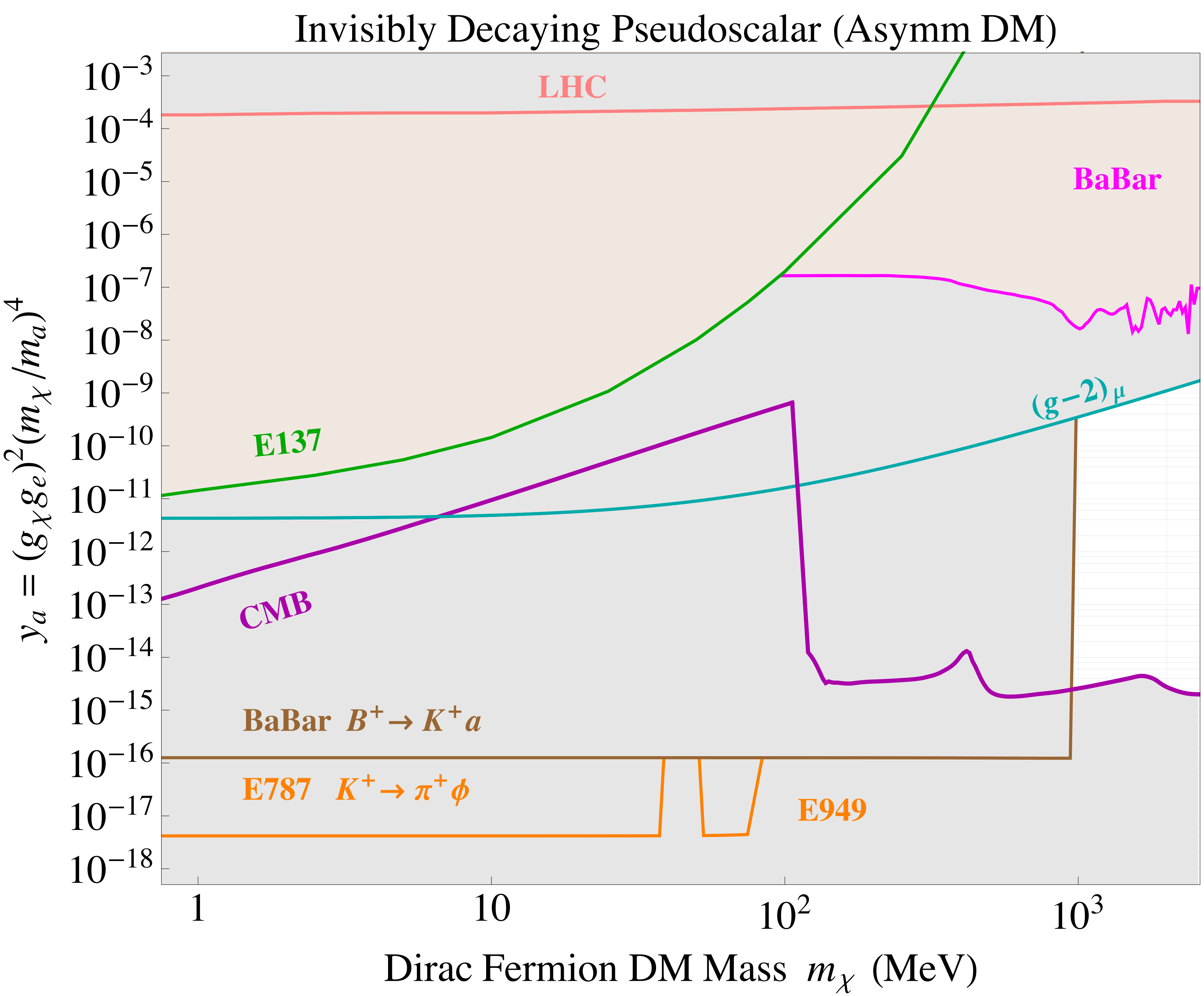
Computed using vector mediator, but qualitatively similar for others

Higgs Portal



Thermal target already ruled out < GeV!

Axion Portal



Already ruled out < GeV! Even worse for Symm. DM

Vector Portal

Scalar/pseudoscalar mediators robustly ruled out < GeV

Dont have to split hairs about the details of the dark sector

For vector mediators, we have to be careful

DM can be **scalar / fermion**

DM can be particle-antiparticle **symmetric / asymmetric**

DM can couple to mediator **elastically / inelastically**

Vector Portal

Simple starting point: "dark massive QED"

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

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

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

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

SM millicharged under dark QED

Vector Portal

Simple starting point: "dark massive QED"

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

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

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

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

SM millicharged under dark QED

Dark "Higgs" Sector

Generic $\mathcal{O}(1)$ DM mass splitting

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

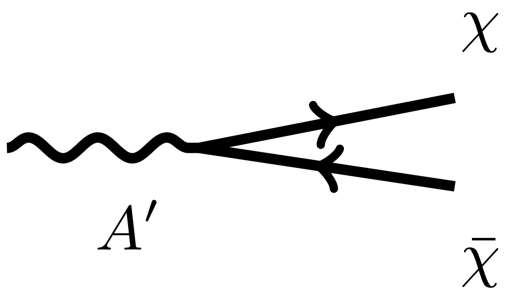
$$\Delta \equiv m_{\text{excited}} - m_{\text{ground}} \neq 0$$

Identical model, Rich pheno, CMB 100% OK!

Elastic vs. Inelastic Coupling

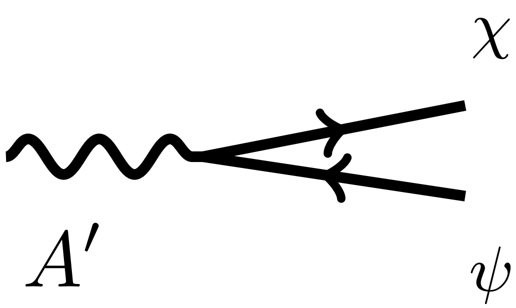
Either can arise with identical field content

Elastic Models(no mass splitting)



May be constrained by CMB or Direct Detection

Inelastic Models (mass splitting)



Generically no CMB or Direct Detection constraints

Symmetric vs. Asymmetric DM

Symmetric thermal relics: $\sigma v \sim 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$

CMB imposes upper bound

Asymmetric models: $\sigma v > 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$

CMB imposes *lower* bound

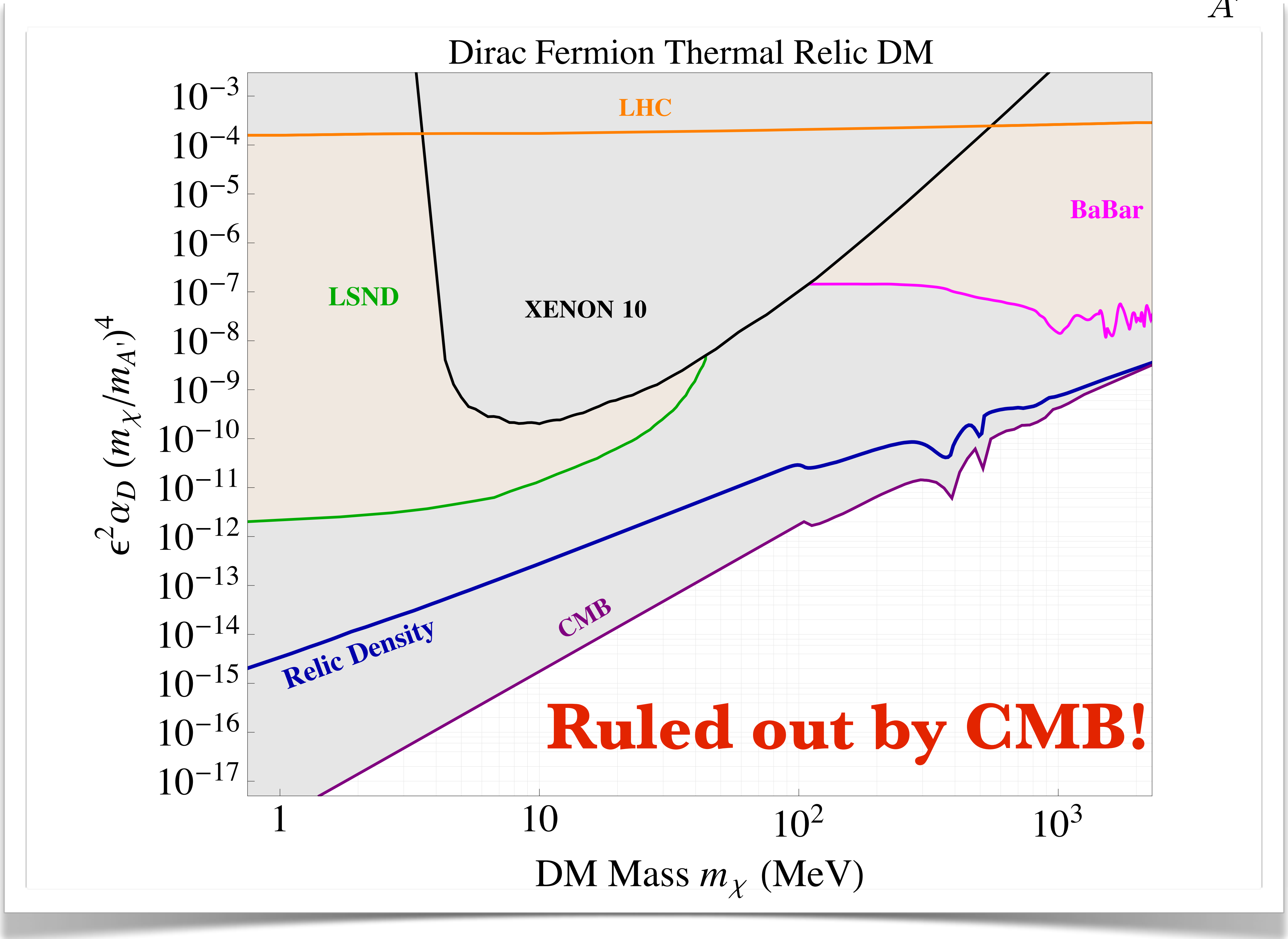
larger cross section = fewer antiparticles, less annihilation

If DM *ever* achieved equilibrium in the early universe

There is a clear target for both scenarios

Fermion Symmetric Elastic

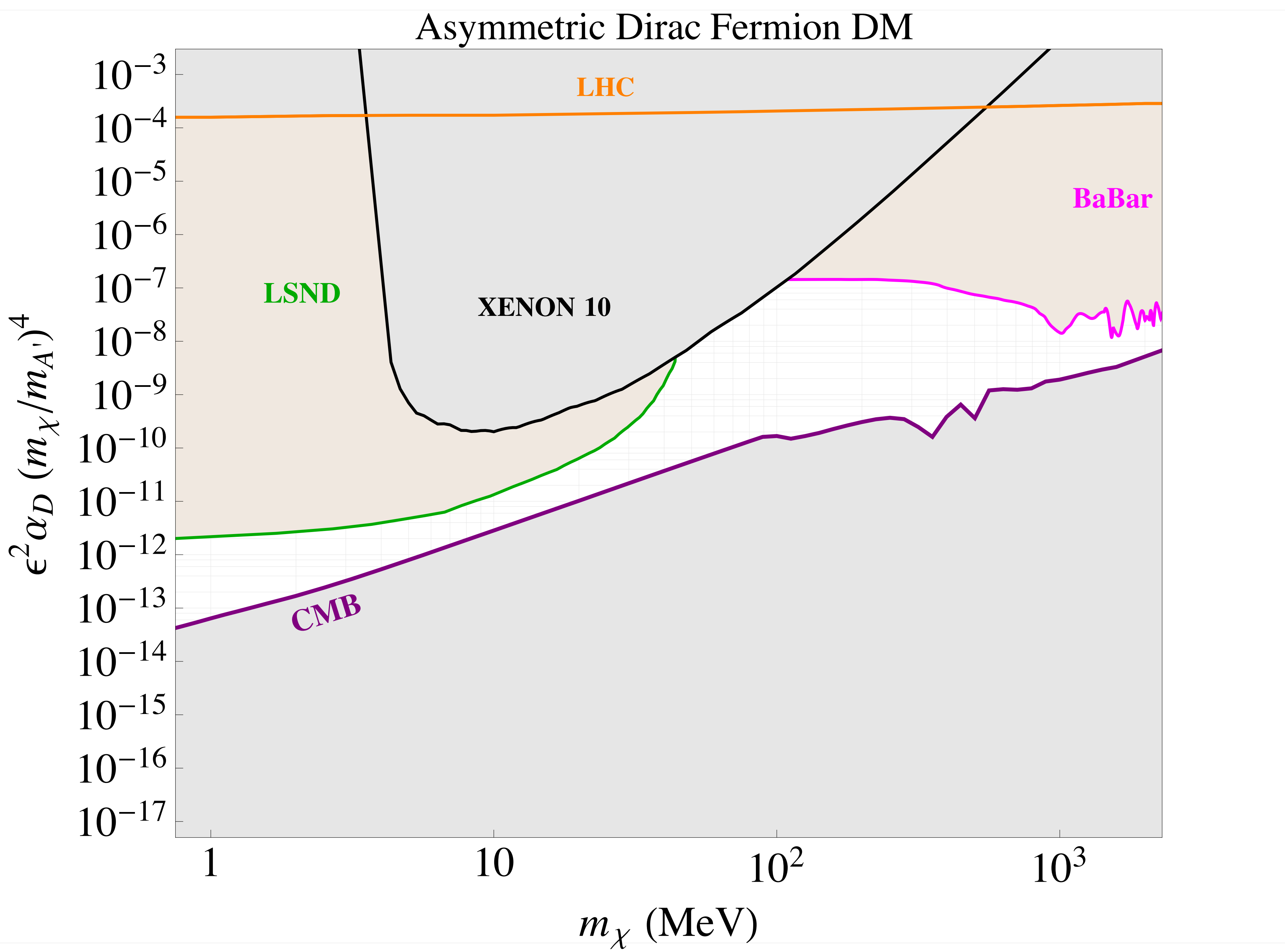
$$n_{\rm DM} = n_{\overline{DM}}$$



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

Fermion Asymmetric Elastic

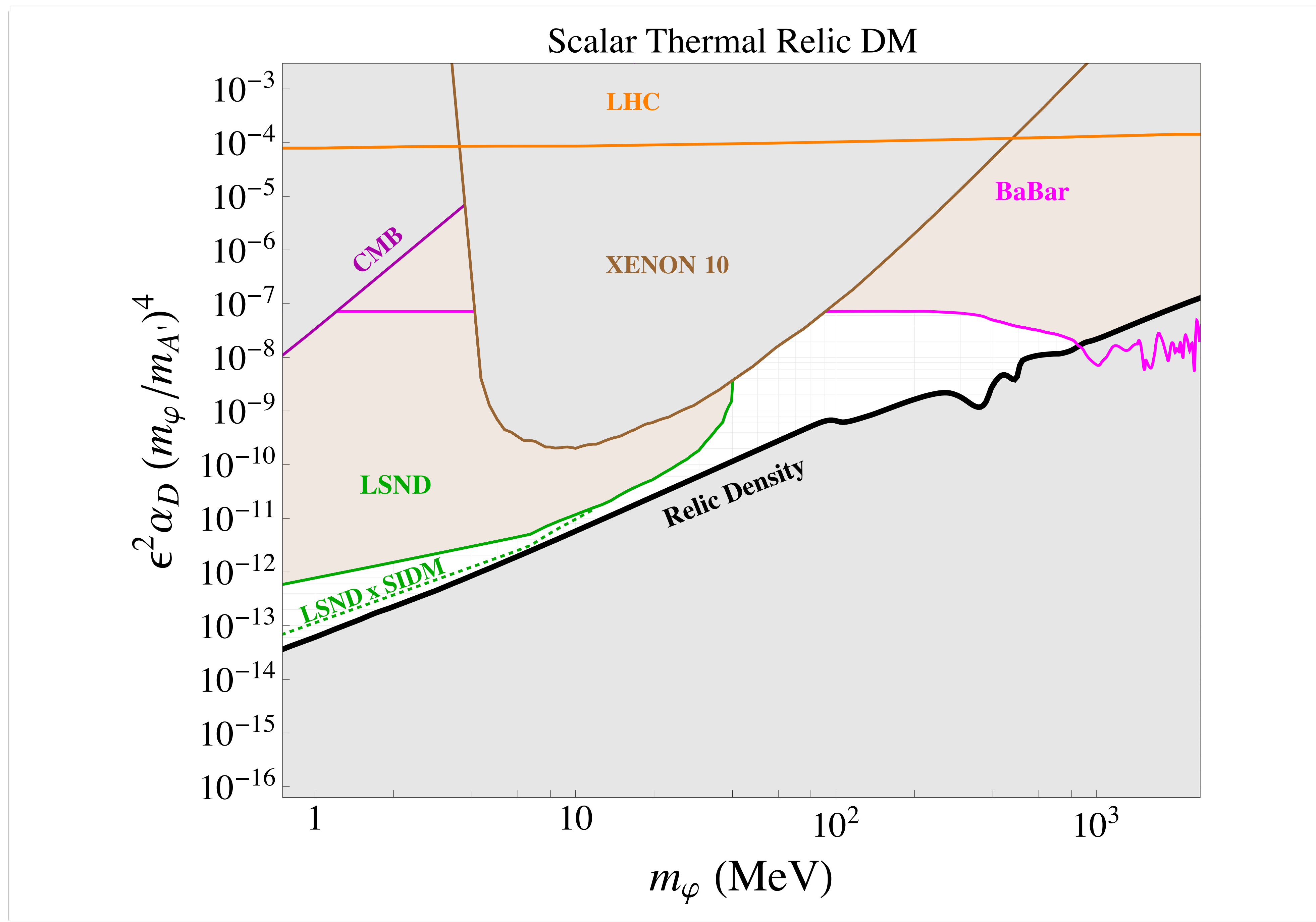
$$n_{\rm DM} \neq n_{\overline{DM}}$$



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

Scalar Symmetric Elastic

$$n_{\text{DM}} = n_{\overline{DM}}$$

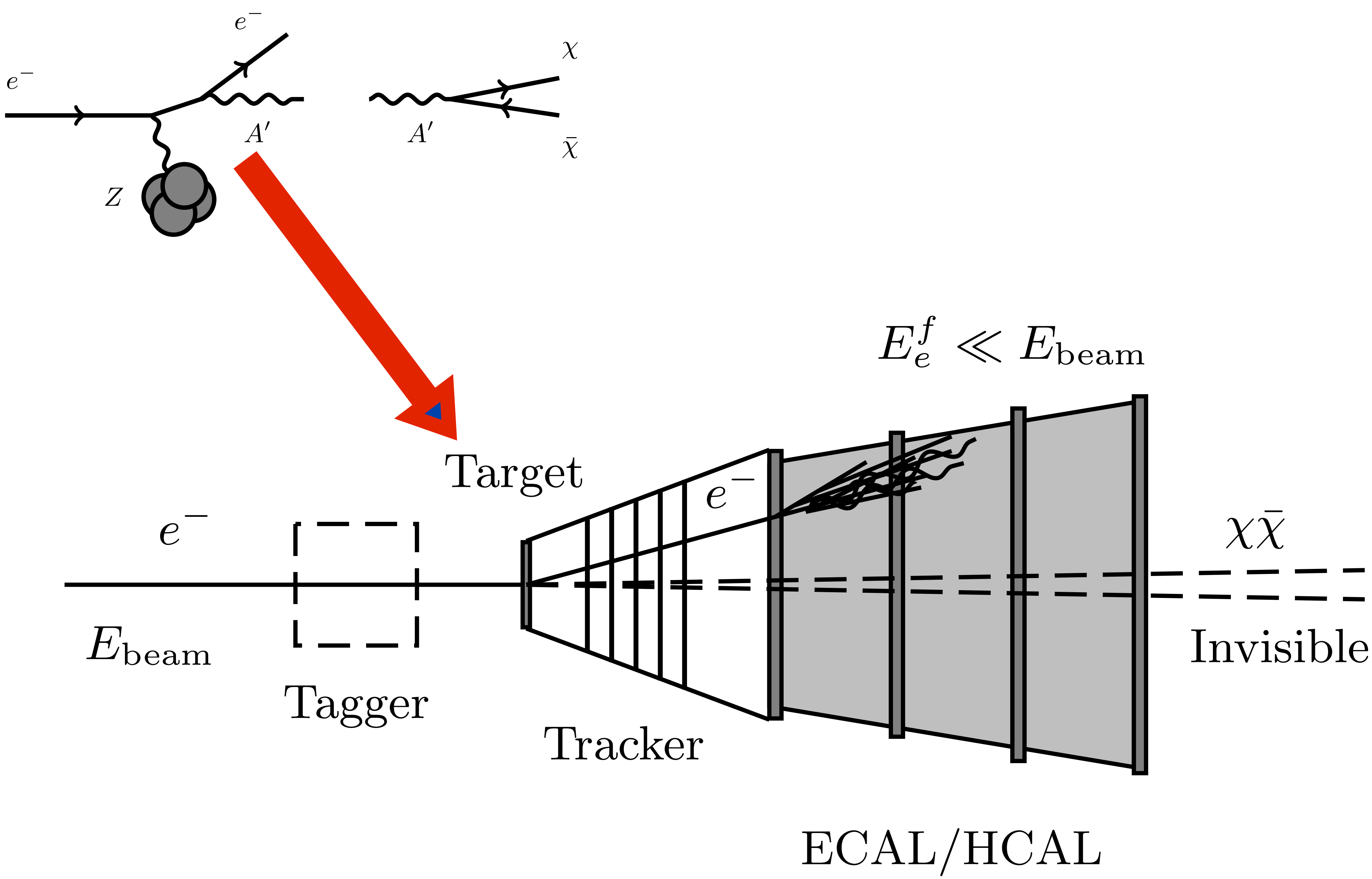


BaBar, LSND, LHC: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$

Overview

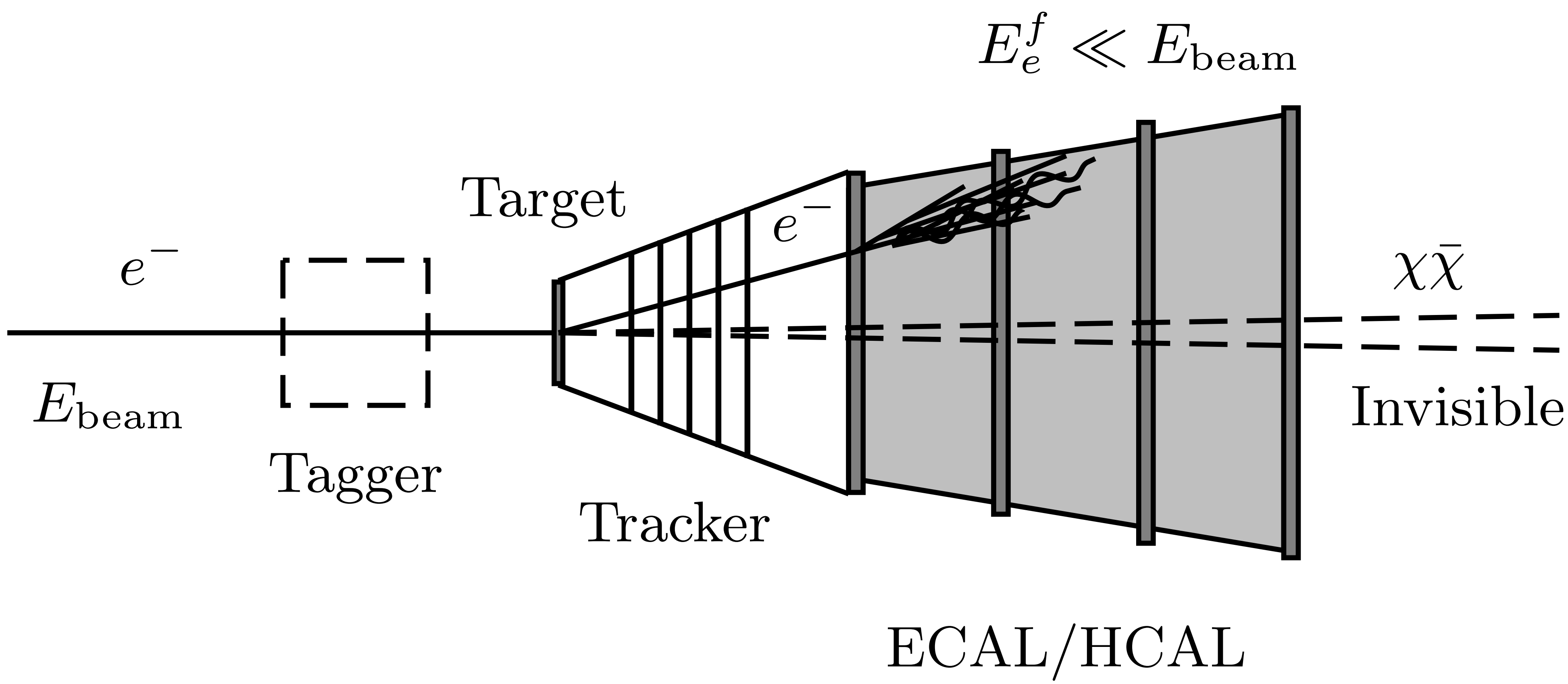
- General Remarks
- Mediators and Portals
- Missing Momentum

New Approach: Missing Momentum



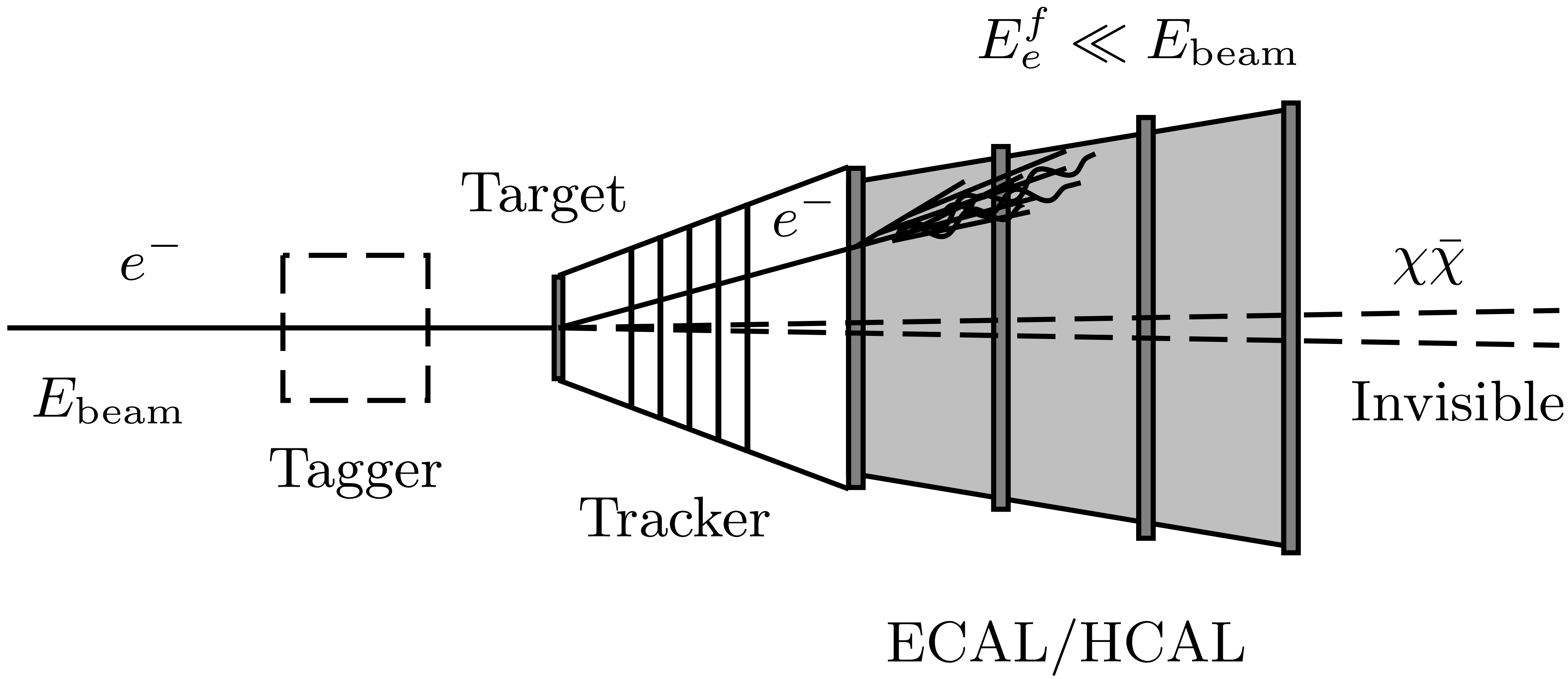
e.g. @Jefferson Lab

Basic Concept



1. Prepare *low current* electrons < 100 pA
2. Measure incident e^- momentum ~ 10 GeV
3. Pass through thin target T ~ 0.1- 0.01 Rad. Length
4. Measure outgoing e^- E & PT < 1 GeV

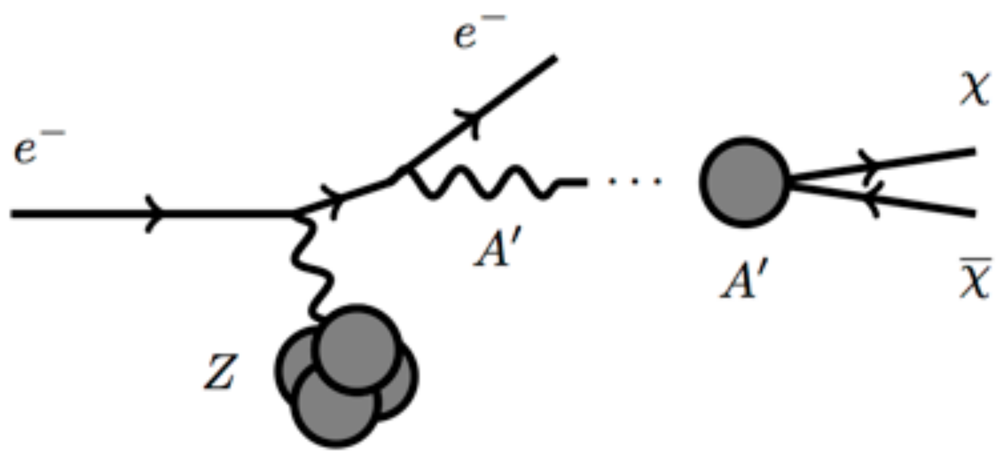
Basic Concept



Signal: a low energy electron & no other activity

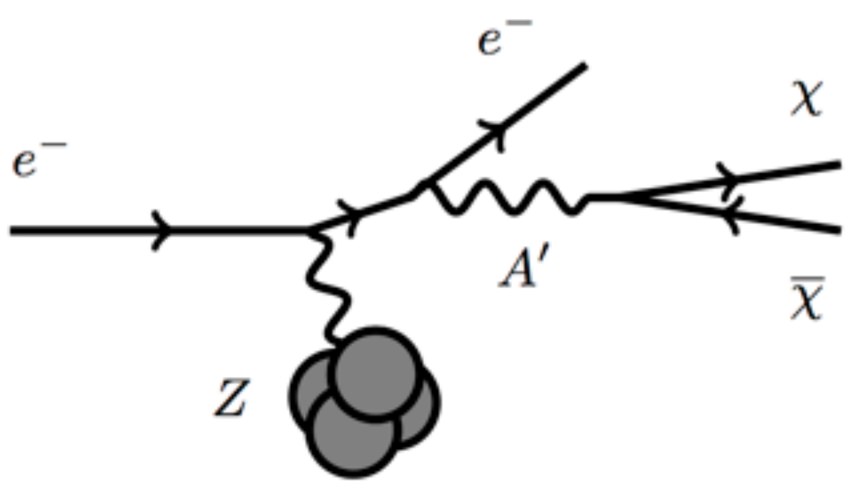
Production Scaling

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



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

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

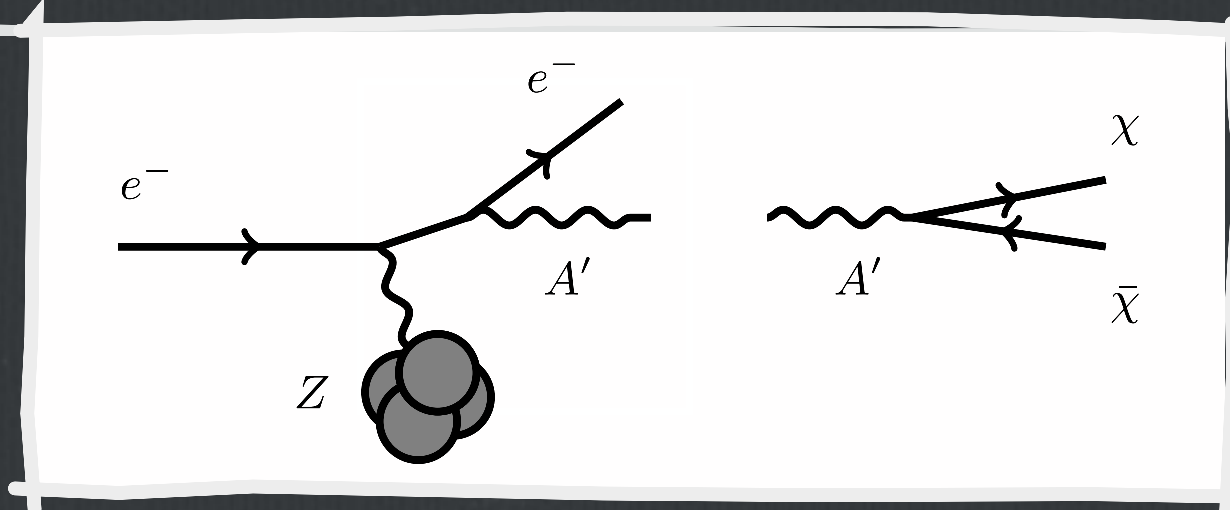


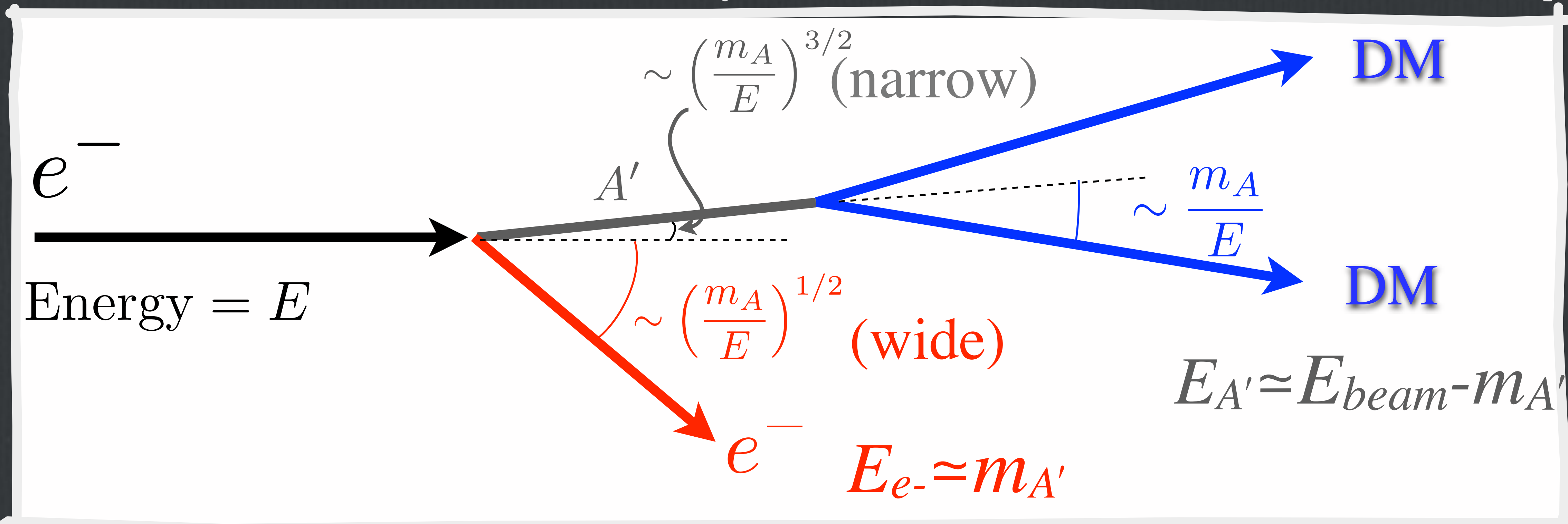
$$\sigma \sim \frac{\alpha_D \epsilon^2}{m_\chi^2}$$

Kinematics of DM Production

(simple generalization to off-shell mediator)

DM Pair Mass ≫ m_e, radiated from electron





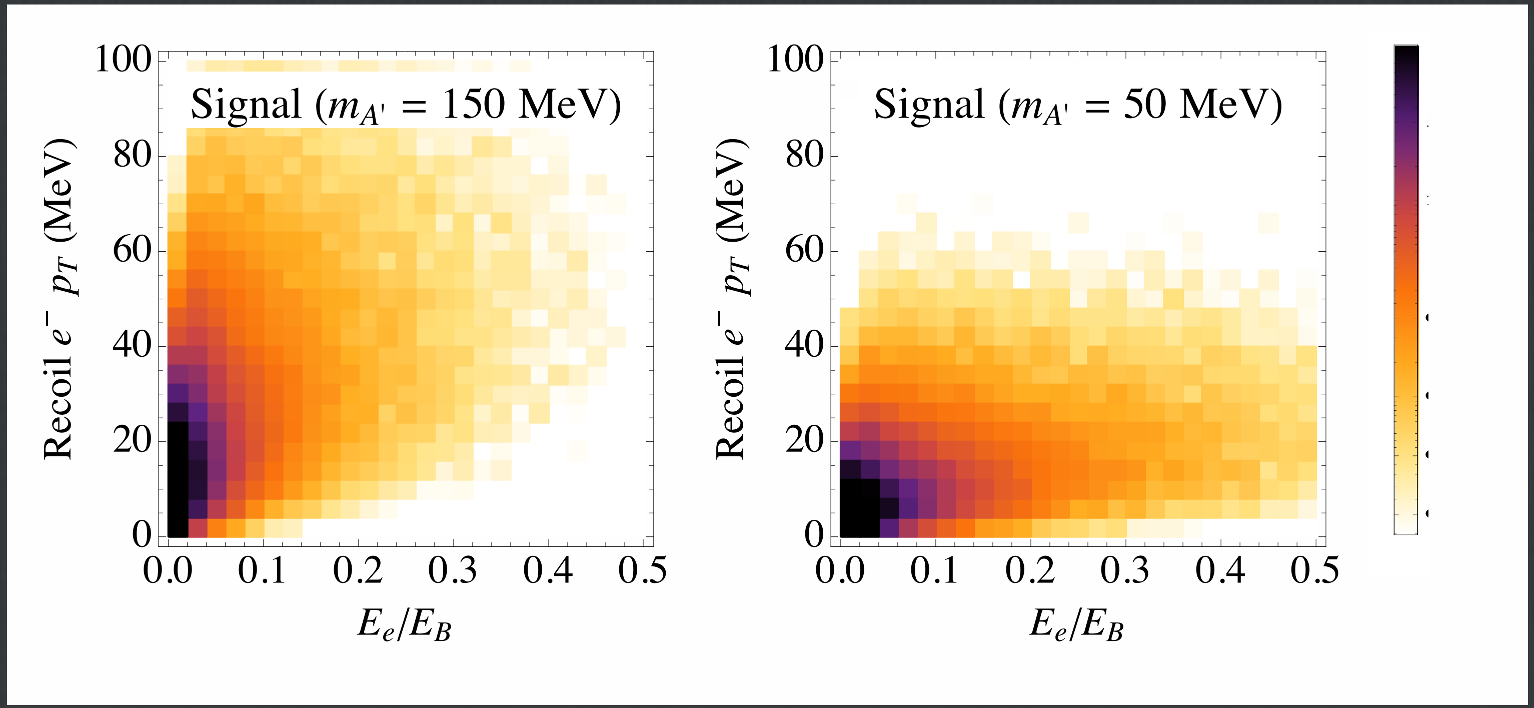
⇒ recoiling electron is soft and wide-angle

Kinematics of DM Production

Signal Events:

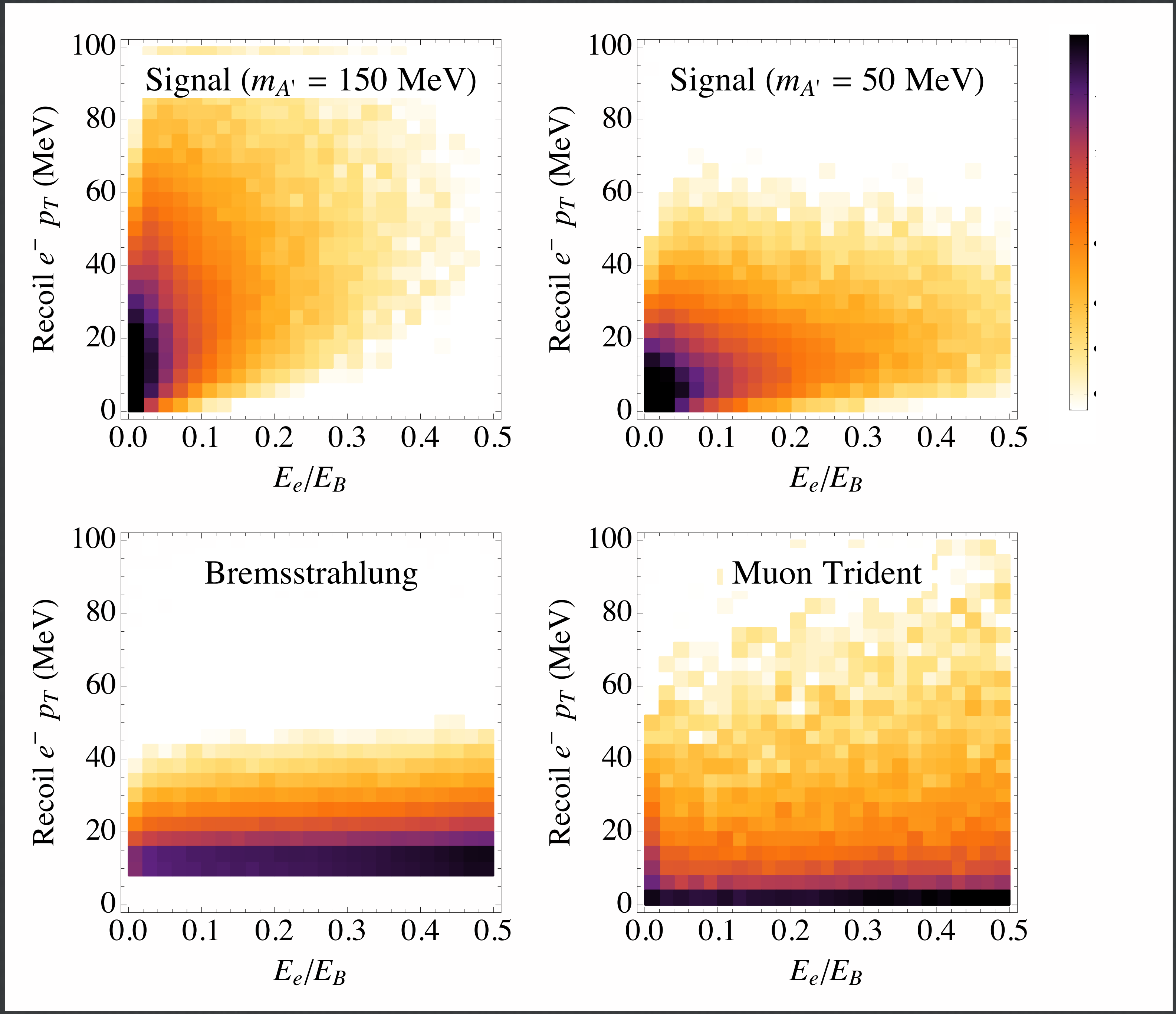
1) Characteristic low E_e, broad spread in p_T

2) No additional deposited energy or tracks



Kinematics of DM Production

Kinematically, these are quite different from typical backgrounds



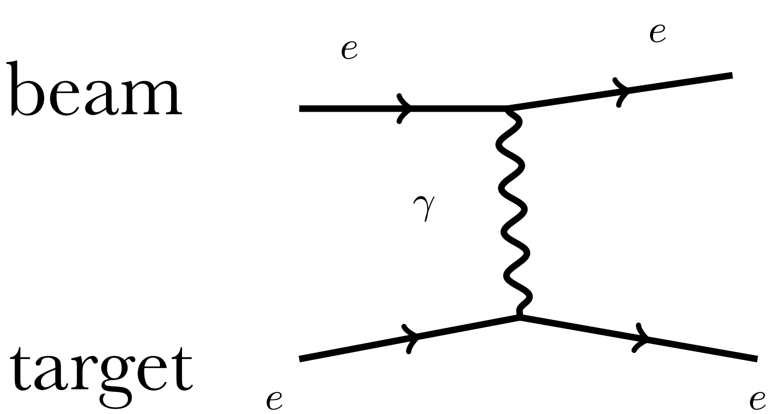
Irreducible Backgrounds

Other sources can carry away missing momentum

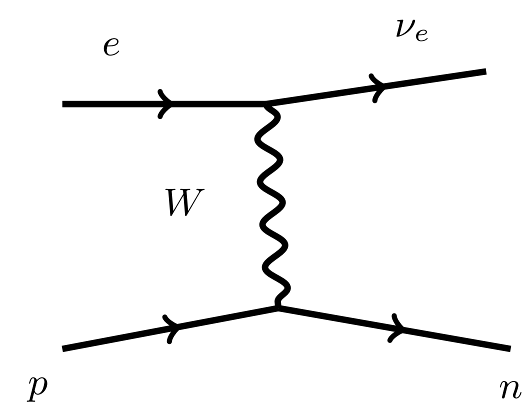
Real Missing Energy	Magnitude (10^{16} $\mathbf{EOT}_{eff}$)
Brem+CCQE	< 1 ($T \lesssim 0.1$)
CCQE+π^0	< 1 ($T \lesssim 0.1$)
Moller+CCQE	$\ll 1$ ($T \lesssim 0.1$)
$eN \to eN\nu\bar{\nu}$	$\sim 10^{-2}$

$$\mathbf{EOT}_{eff} = \mathbf{EOT} \times (T/X_0)$$

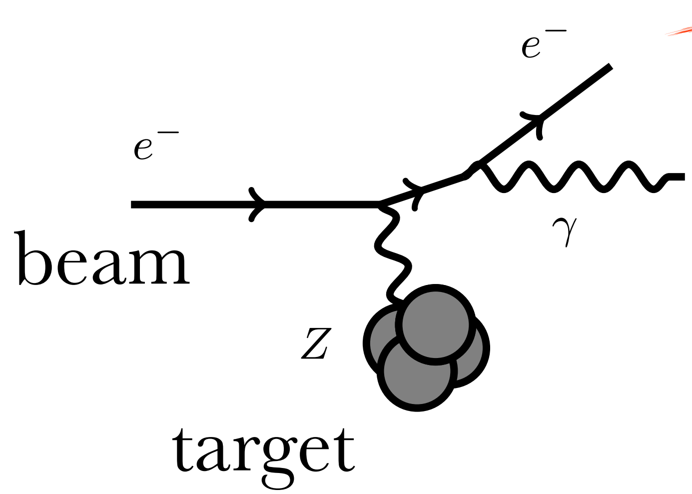
Moller



CCQE



Brem.

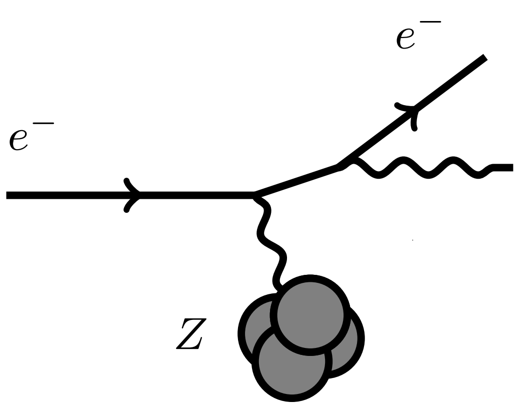


Verdict: Negligible

Reducible Backgrounds(Fakes)

Fail to detect SM particles

Bremsstrahlung

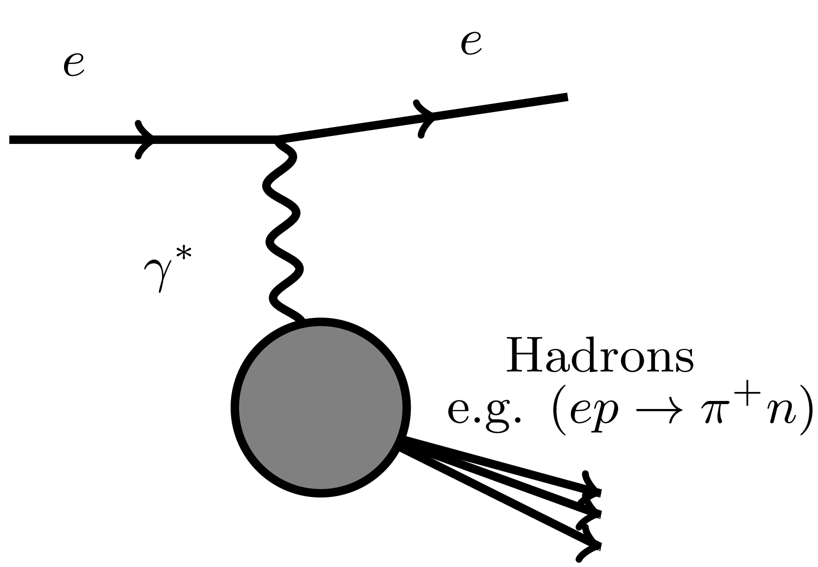


$\gamma(E \sim E_{\rm beam})$

Fail to detect hard photon in ECAL

Sets thickness requirement

Hadron photo-production



Fail to detect pion (or it backscatters)

Need fail probability below

$\sim 10^{-2} - 10^{-3}$

for low BG experiment

Reducible Backgrounds(Fakes)

Fail to detect SM particles

Reducible Backgrounds	Fake Rate/10^{14} $\mathbf{EOT}_{eff}$
γ non-interaction	$\sim 3\times 10^8 e^{-\frac{7}{9}(T/X_0=45)} \ll 1$
$\gamma p \to \pi^+ n$	$\sim 10^2 \times \epsilon_\pi \epsilon_n$
$\gamma^* p \to \pi^+ n$ (backscatter π^+)	$\sim 3\times 10^1 \times \epsilon_n$
$\gamma N \to (\rho,\omega,\phi)N \to \pi^+\pi^- N$	$\sim 2\times 10^4 \epsilon_\pi^2$
$\gamma^* n \to n\bar{n}n$	$\sim 3\times 10^3 \times \epsilon_n^3$
$eN \to eN(\mu^+\mu^-, \pi^+\pi^-)$	$\sim 10^4 \times \epsilon_{\mu/\pi}^2$
$\gamma N \to N\mu^+\mu^-$	$\sim 6\times 10^3 \times \epsilon_\mu^2$

ϵ_X

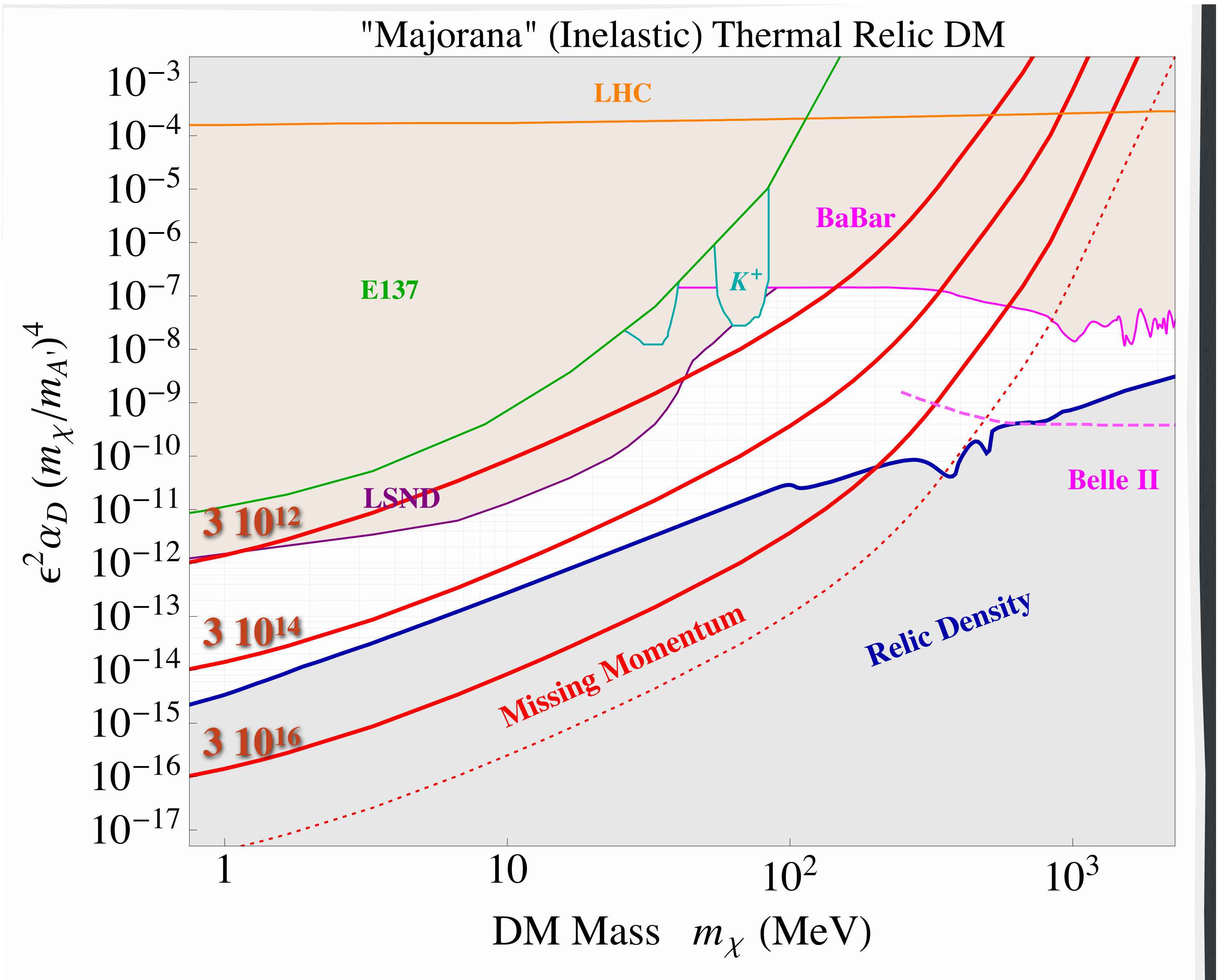
probability of missing X

Reducible with sufficiently hermitic setup

Still work in progress, need to optimize

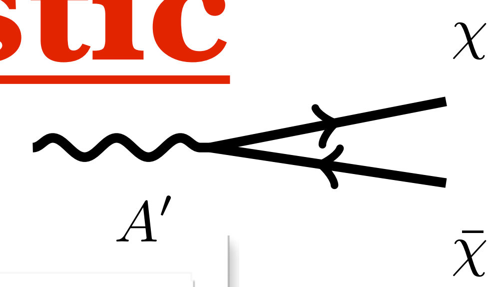
$\mathbf{EOT}_{eff} = \mathbf{EOT} \times (T/X_0)$

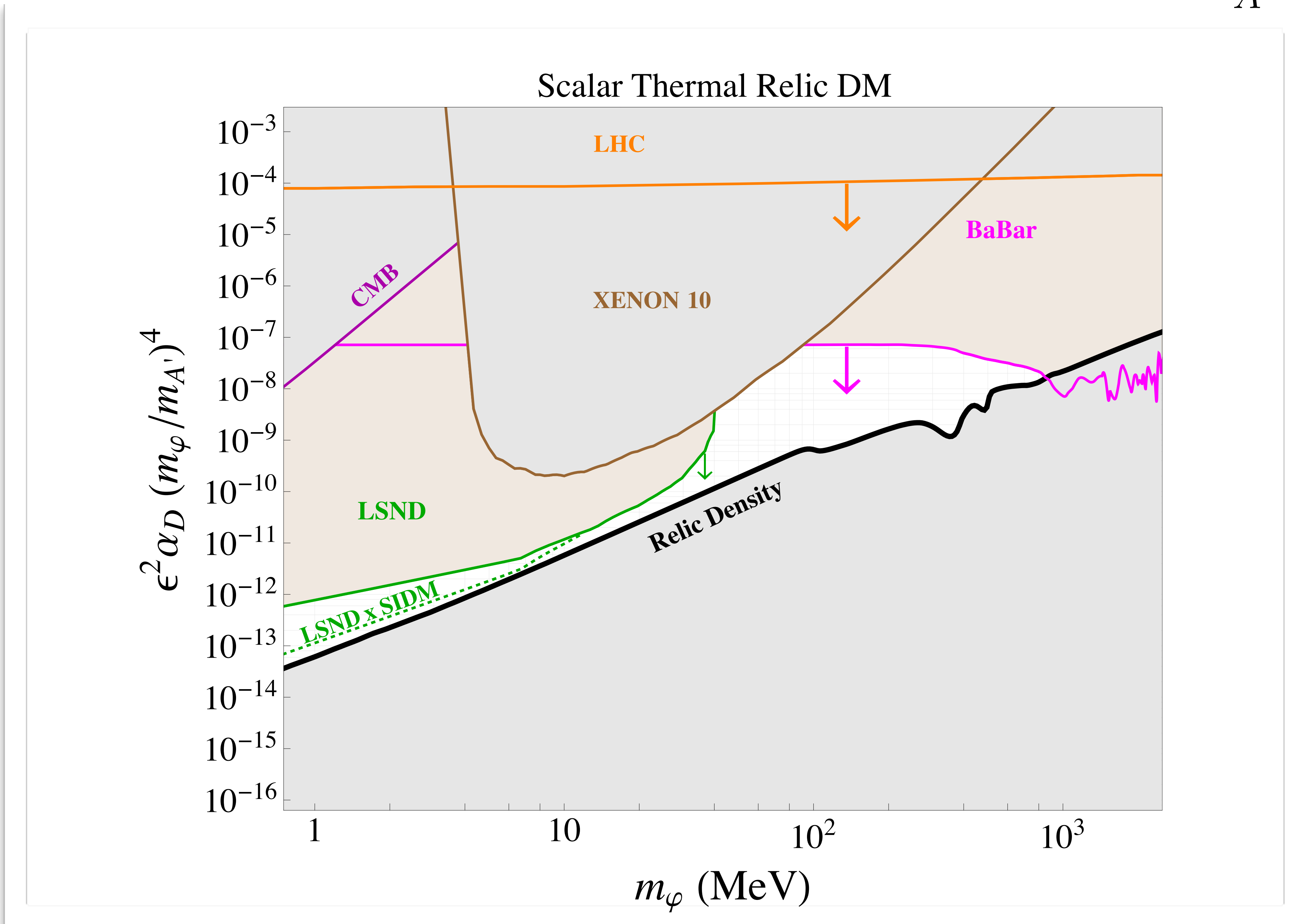
Reducible Backgrounds(Fakes)



Scalar Symmetric Elastic

$$n_{\text{DM}} = n_{\overline{DM}}$$



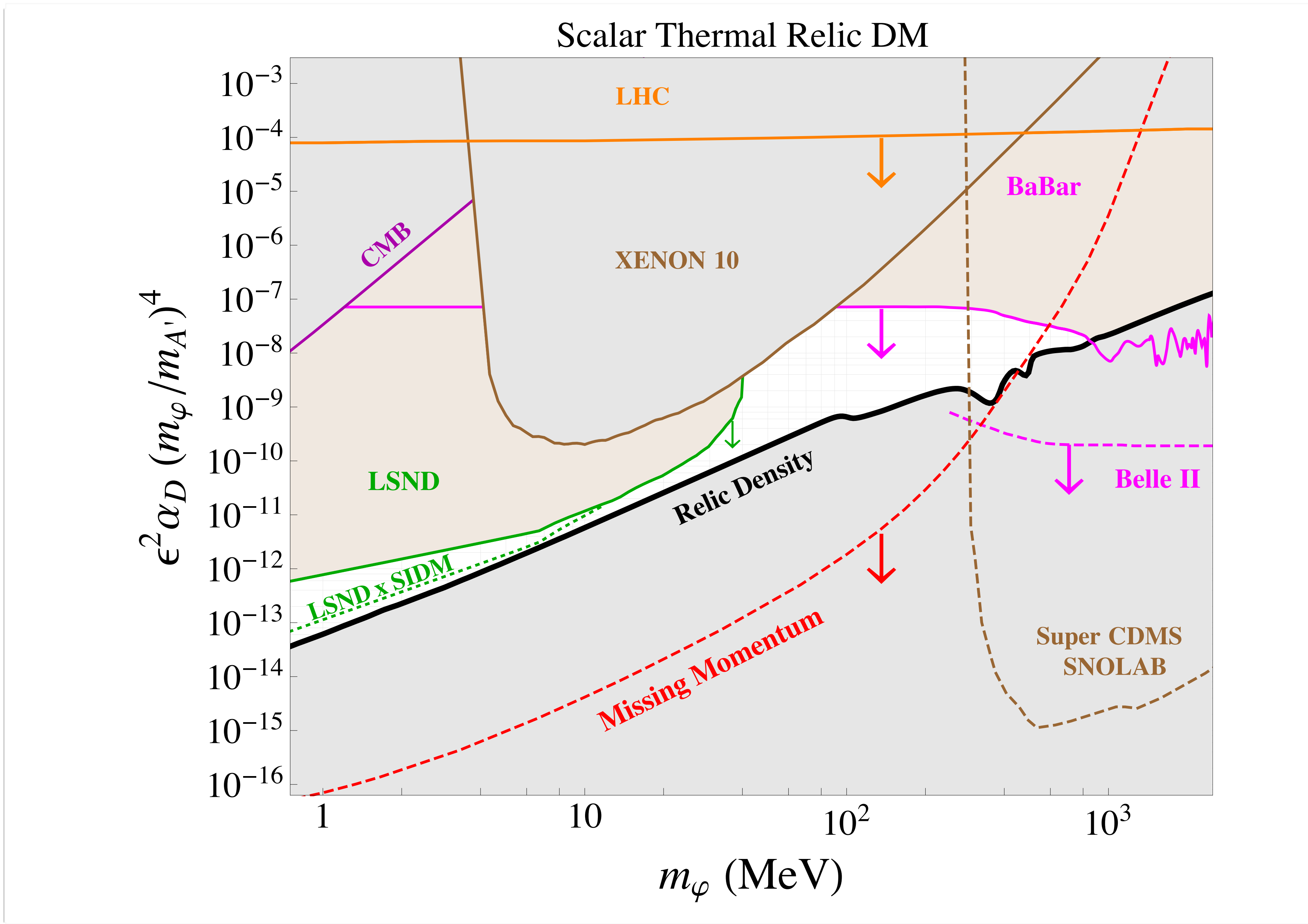


BaBar, LSND, LHC: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$

$3 \times 10^{16} e^-$

Scalar Symmetric Elastic

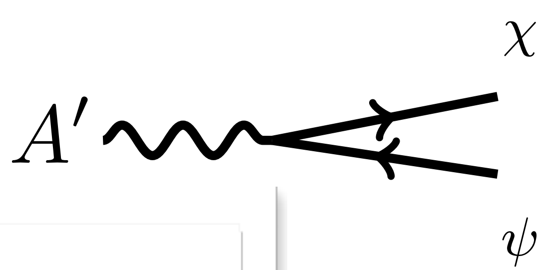
$$n_{\rm DM} = n_{\overline{DM}}$$

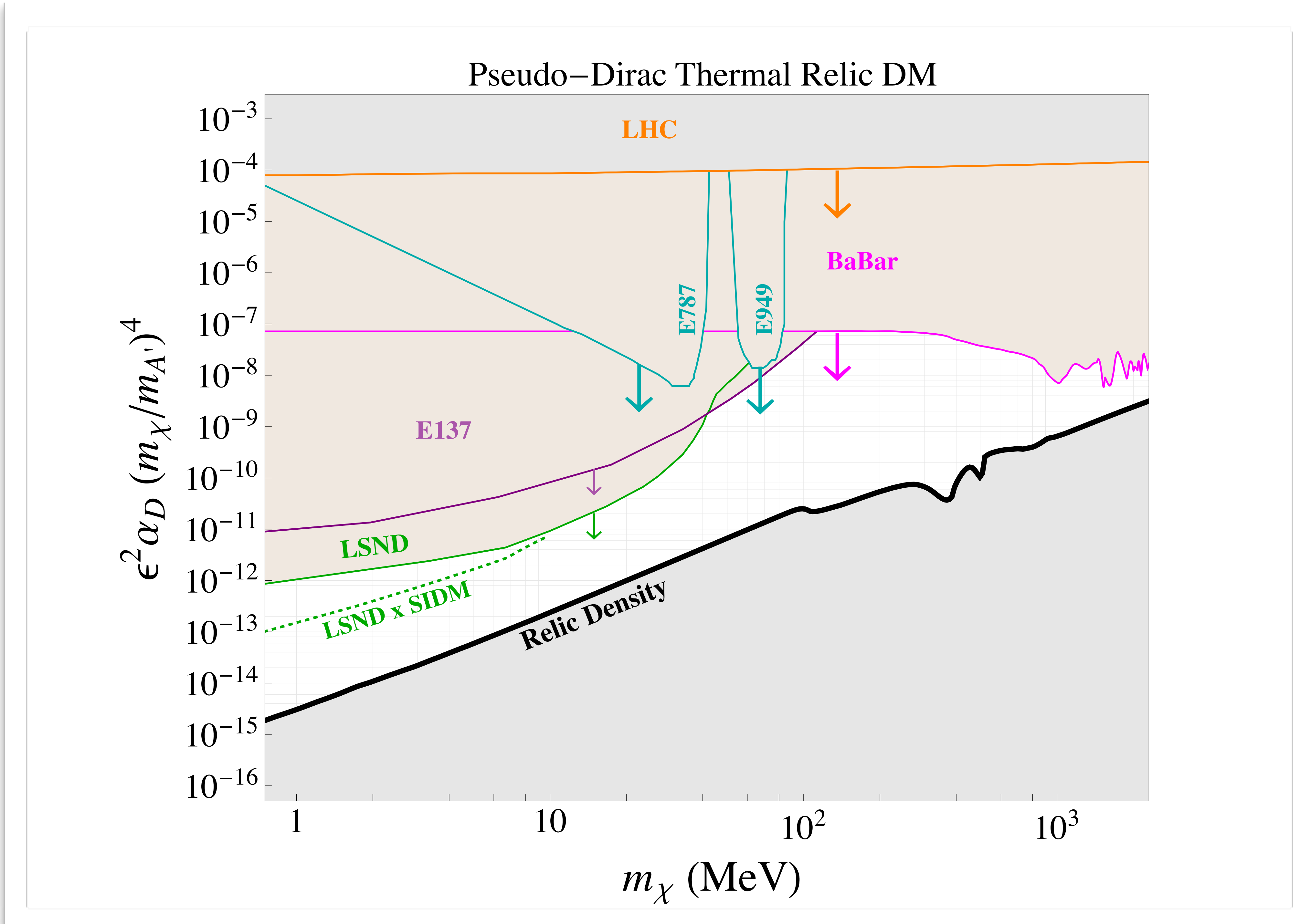


BaBar, LSND, LHC, Belle II : $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$

Fermion Symmetric Inelastic

$$n_{\rm DM} = n_{\overline{DM}} \qquad \Delta \neq 0$$

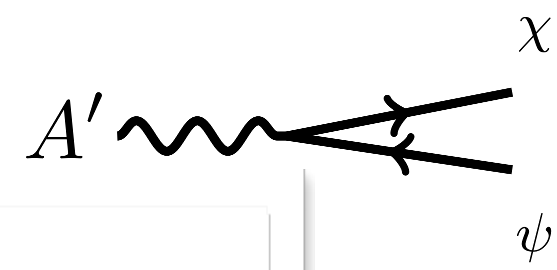


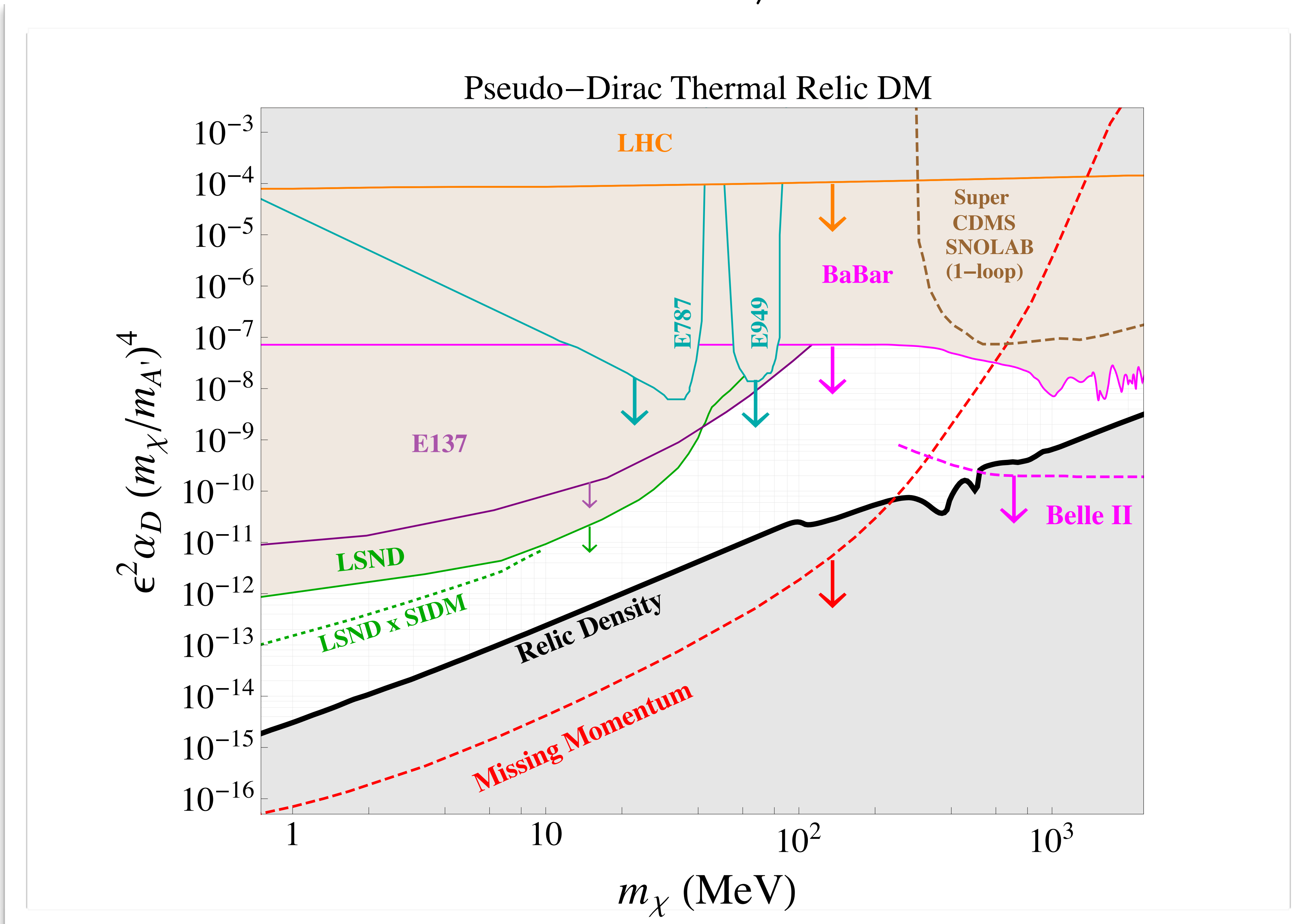


BaBar, LSND, LHC, E137: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$

Fermion Symmetric Inelastic

$n_{\mathrm{DM}} = n_{\overline{DM}}$ $\Delta \neq 0$

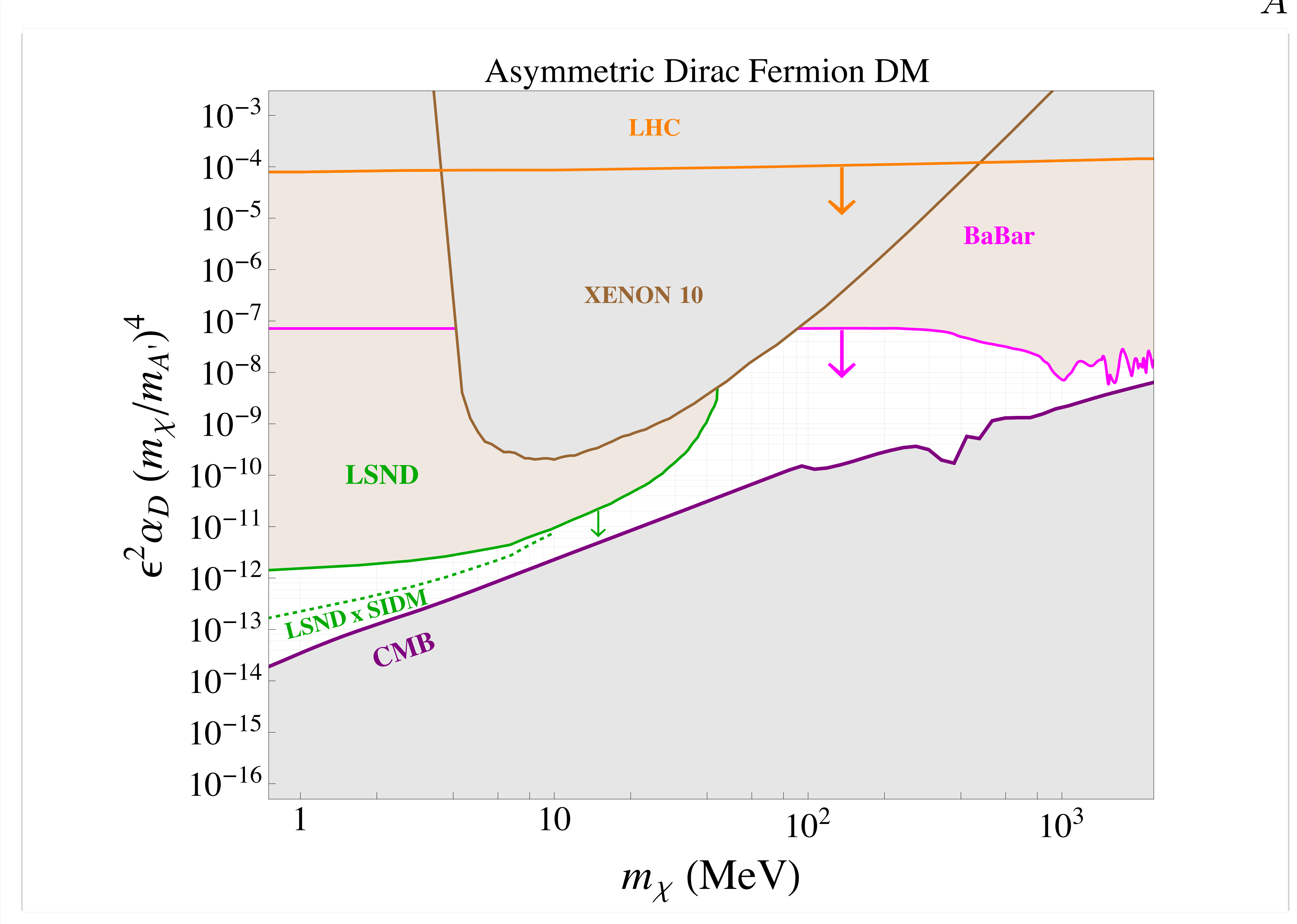




BaBar, LSND, LHC, E137: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$ $3 \times 10^{16} e^-$

Fermion Asymmetric Elastic

$$n_{\rm DM} \neq n_{\overline{DM}}$$

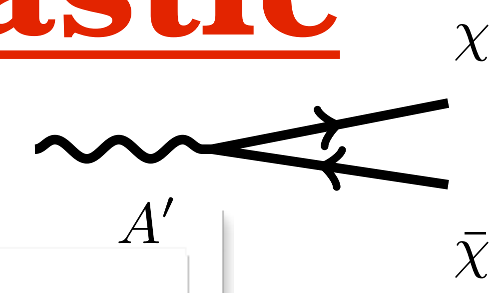


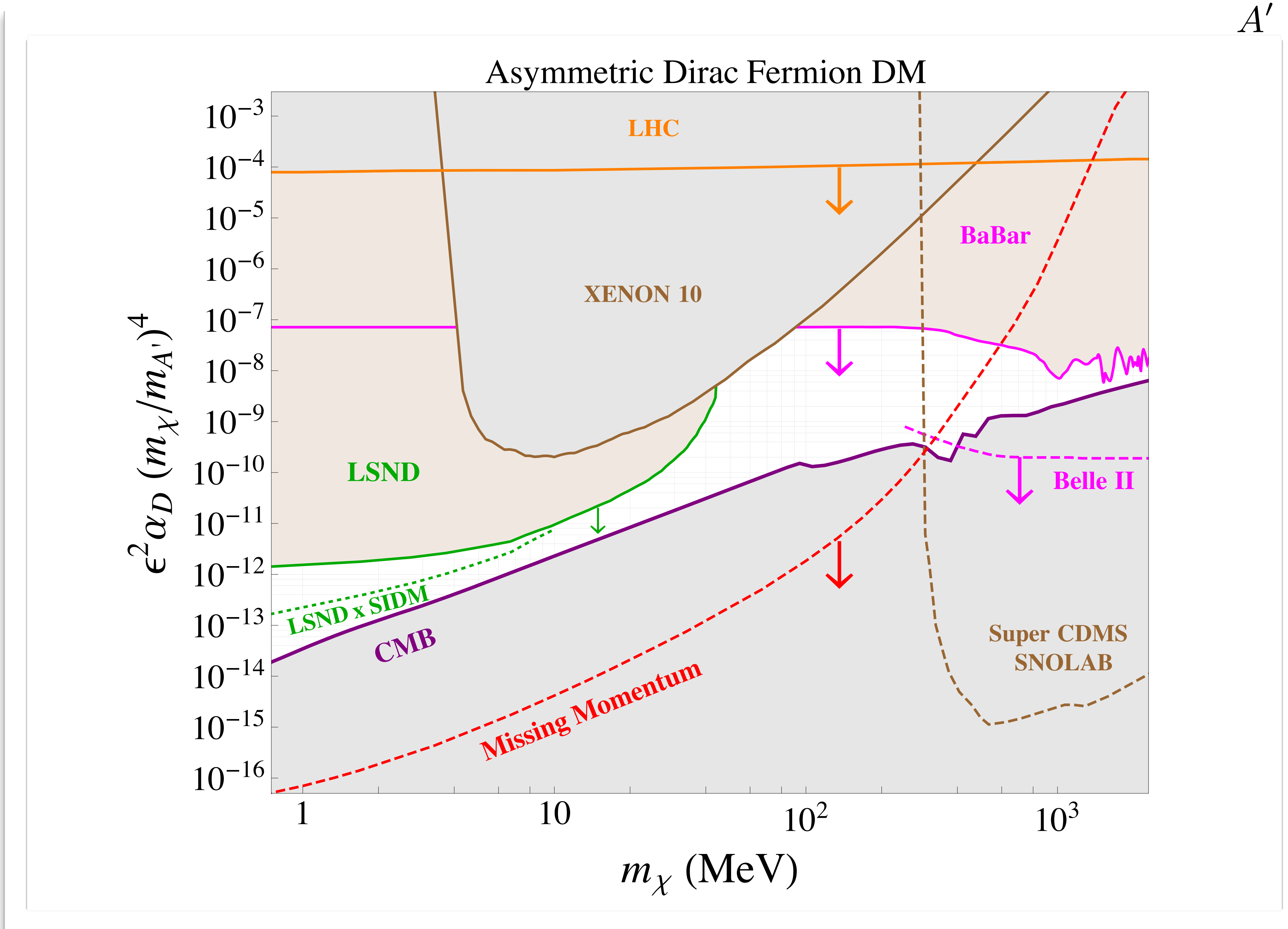
BaBar, LSND, LHC: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$

$3 \times 10^{16} e^-$

Fermion Asymmetric Elastic

$$n_{\rm DM} \neq n_{\overline{DM}}$$





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

$3 \times 10^{16} e^-$

Summary

Light DM remains viable over thermal window

Bulk of existing program is insensitive, lots of territory left!
Billion $ program misses lower *half* of thermal range (MeV-TeV)

Missing Momentum Offers Powerful Handle

- Exploits distinctive production kinematics
- Irreducible BG negligible
- BG from "fakes" challenging but reducible
- Alongside Belle II can cover "worst case" thermal DM targets
- Dedicated experiment covers almost all territory for thermal

(scalar/fermion) x (symm/asymm) x (elastic/inelastic)

Thank You!