Discovering or Falsifying Light Thermal DM

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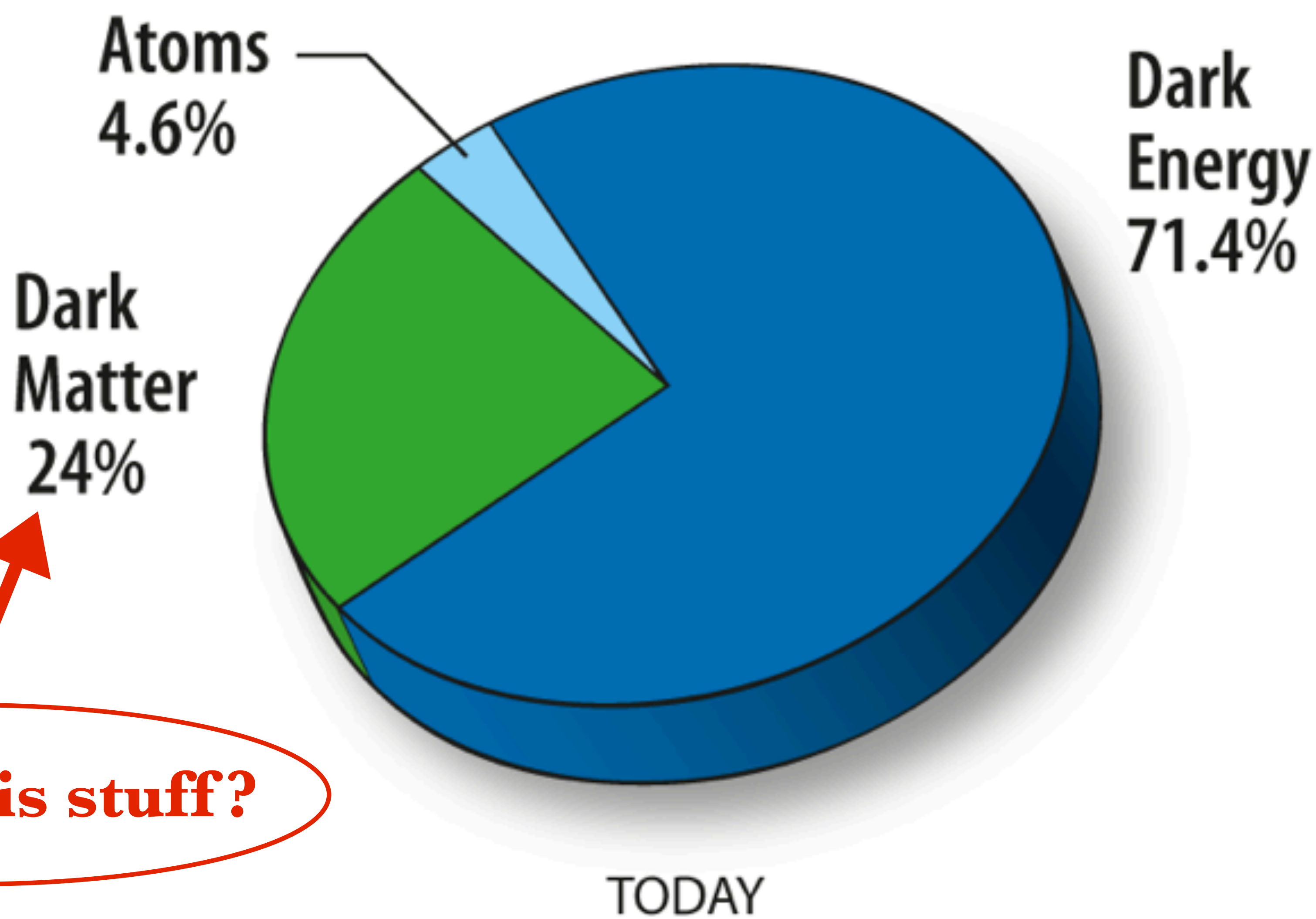
Theoretical Advances in Particle Cosmology
KICP University of Chicago Oct 13, 2016

Zeroth Order Outstanding Problems

Matter Asymmetry
Inflation

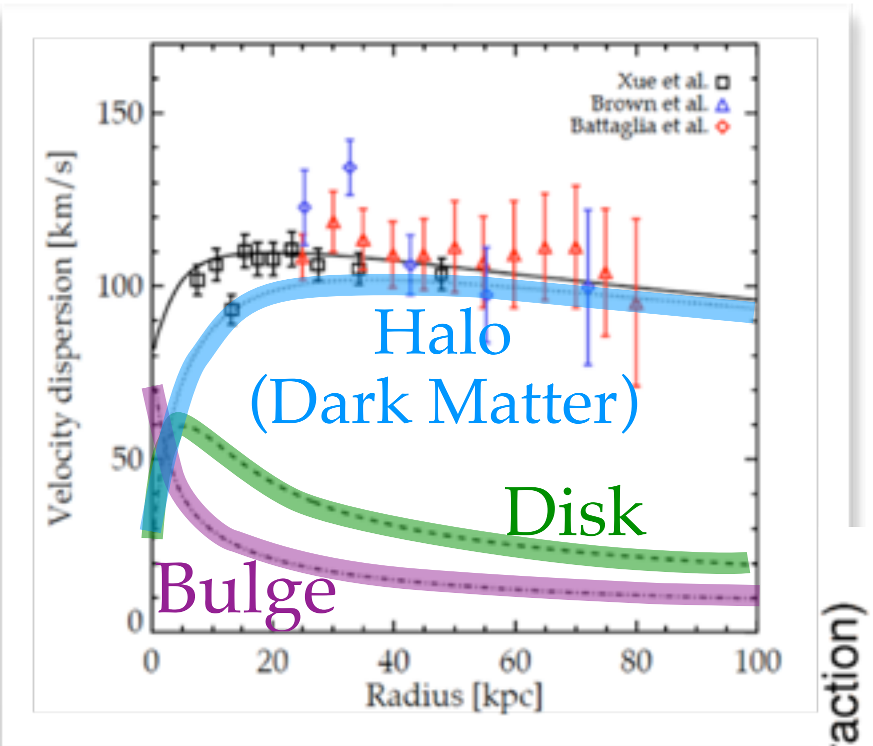
Accelerated Cosmic Expansion



What is this stuff?

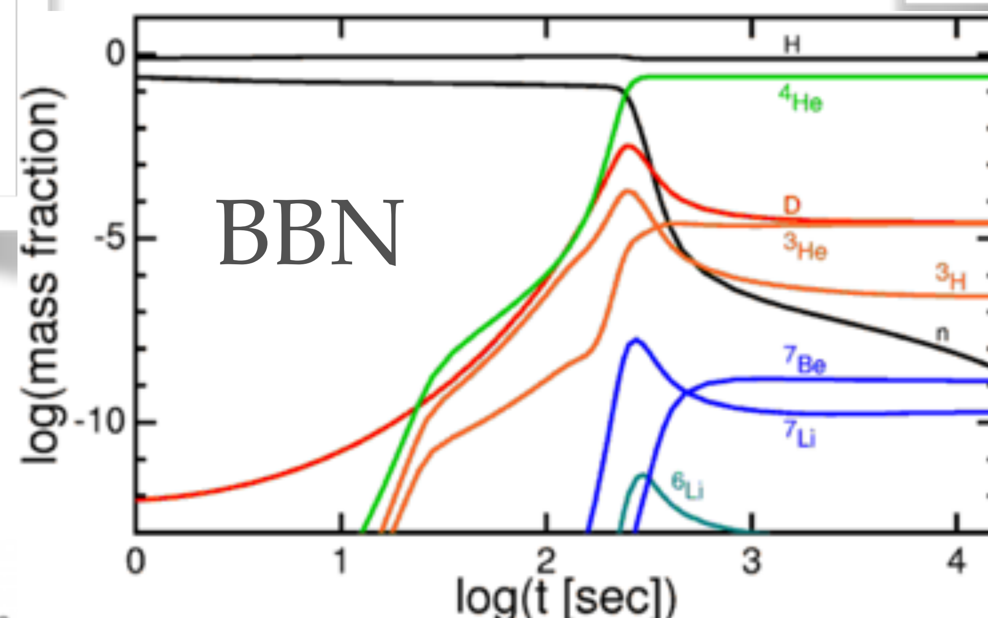
Also Quantum Gravity

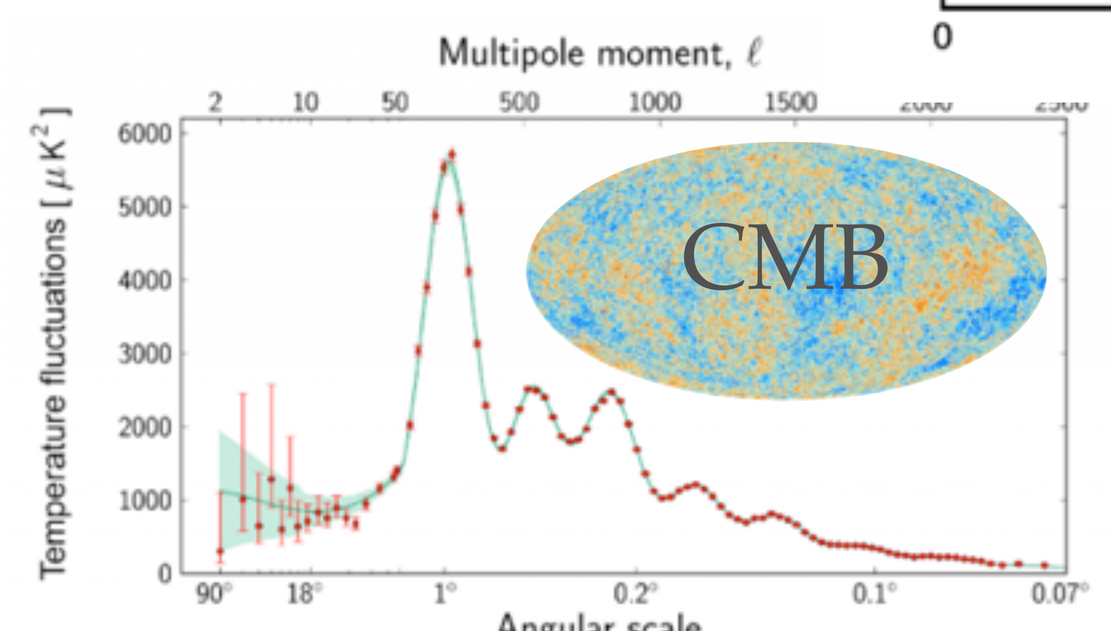
What is Dark Matter?



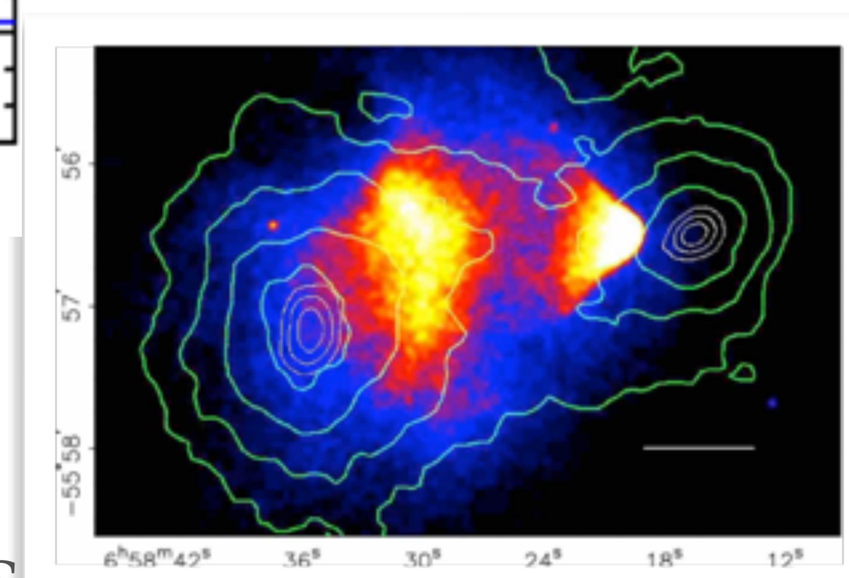
Rotation
Curves

Gravitational
Lensing





Cluster
Collisions



lots of evidence, but all gravitational…

Historical Analogy

Understanding the Weak Force

Discovery of radioactivity		(1890s)
Fermi Scale identified	$G_F \sim \frac{1}{(100\ \mathrm{GeV})^2}$	(1930s)
Non-Abelian Gauge Theory		(1950s)
Higgs Mechanism Introduced		(1960s)
W/Z bosons discovered		(1970s)
Higgs discovered		(2010s)

Each step required revolutionary theoretical/experimental leaps

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

How long will we wait for DM?

Discovery of missing mass	(1930s)
Rotation curves	(1970s)
CMB power spectrum	(1990s)
Relevant scale?	**> 2016**

Non-gravitational interactions not guaranteed
No clear target of opportunity

Discovery time frame? $t > 80\ \text{yrs}$

DM Prognosis?

Bad news: DM-SM interactions are not required

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

$$\sim 10^{-20}\ \text{eV} \ < m_{DM} \ < \ 10^{19}\ \text{GeV}+$$

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

Why is this good news?

Thermal Equilibrium
Advantage #1: Minimum Annihilation Rate

Equilibrium, achieved easily with a tiny DM/SM coupling

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

Generically overproduces DM

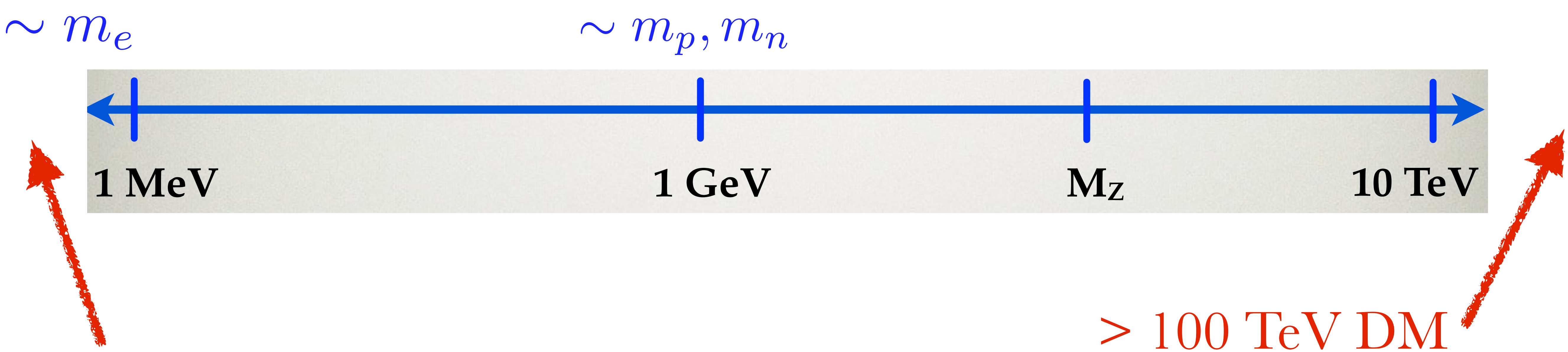
Requires *much larger* annihilation cross section to deplete

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

Potential target for discovery/falsification

Thermal Equilibrium

Advantage #2: Narrow(er) Mass Range



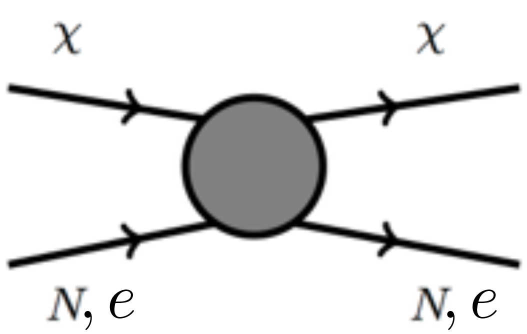
< 10 keV DM too hot
spoils structure formation

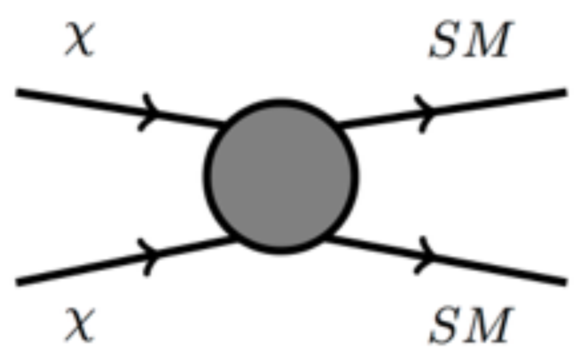
> 100 TeV DM
overproduced*

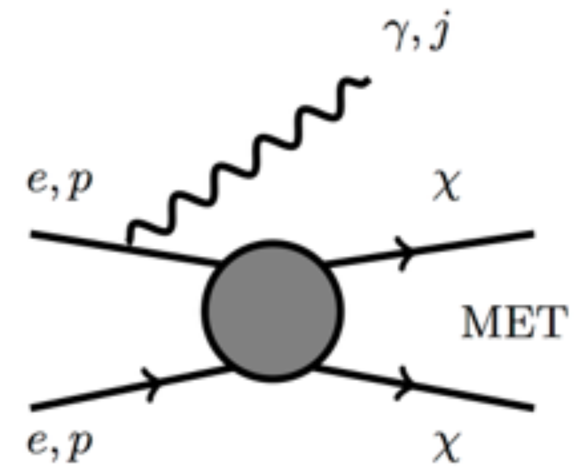
*nontrivial model building
and/or nonstandard cosmology
can evade upper bound

Heavier mass range is conceptually different

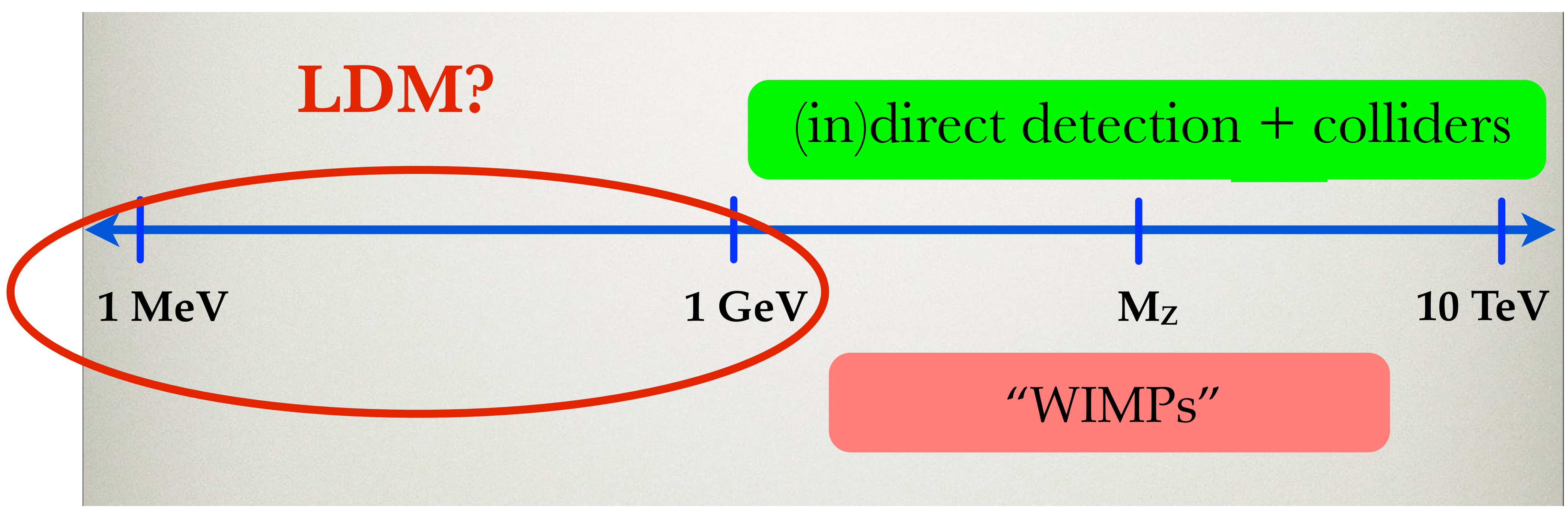
How are we testing this range?







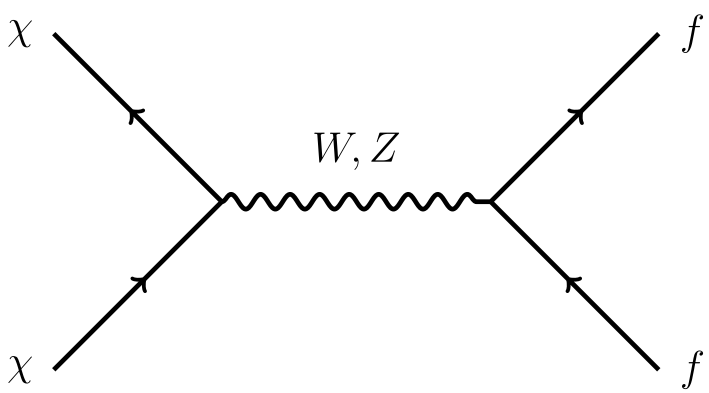
Direct Detection, Indirect Detection, Colliders



What should we expect from thermal LDM?

Heavy vs. Light # 1
Light needs new forces

Heavy DM can yield right abundance w/ SM gauge bosons



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

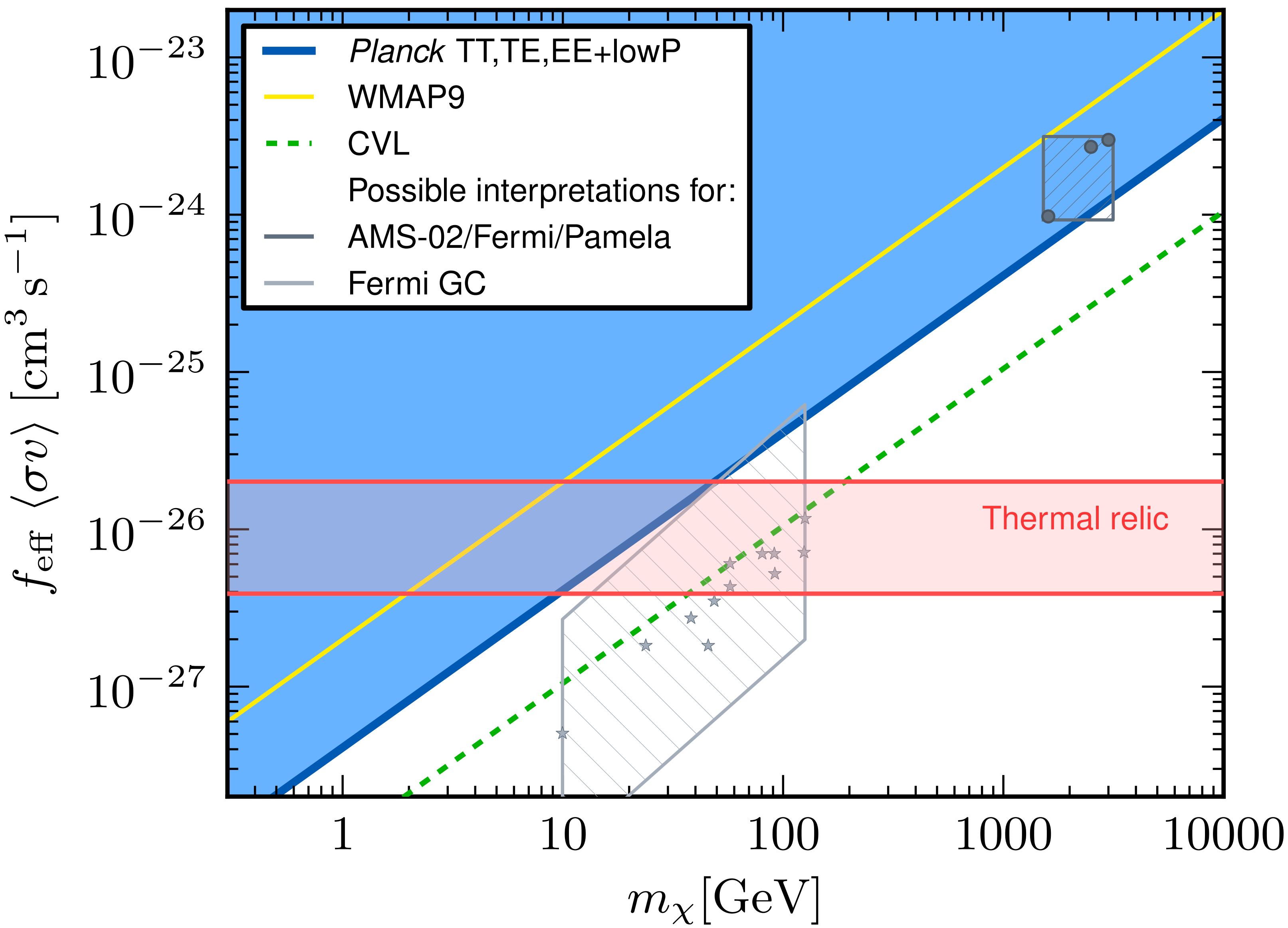
For LDM, annihilation via SM forces is too weak

$$m_\chi \sim \ \mathrm{GeV} \implies \sigma v \ll 3 \times 10^{-26}\ \mathrm{cm^3/s}$$

LDM overproduced unless there are light, new "mediators"

Heavy vs. Light # 2
CMB is a big deal for LDM

Planck
1303.5076



Rules out thermal DM < 10 GeV unless:

Cross section is smaller @ CMB

OR

DM population is different @ CMB (less annihilation)

How to be safe from CMB?

Option 1: Smaller CMB Cross Section

Velocity / Temperature Dependence

$$\sigma v \propto v^2$$

Rate large at freeze-out w/ $v \sim$ 0.1 c

$$\langle \sigma v \rangle \big|_{T=m_\chi} = 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s} \implies \Omega_\chi = \Omega_{\rm DM}$$

Velocity redshifted at late times

$$\langle \sigma v \rangle \big|_{T=\mathrm{eV}} \ll 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s} \implies \text{CMB safe}$$

Choose DM/mediator combination to get v-dependence

*exception: heavier DM bound state enhancement (An, Wise, Zhang 1604.01776)

Option 2: Different Population

Example (a): Asymmetric DM

Annihilation @ $T \sim m$ reduces antiparticle fraction

$$n_\chi \neq n_{\bar{\chi}} \propto \exp(-\langle \sigma v \rangle)$$

Counterintuitive: larger cross section is safer!

$$\frac{f_{\rm eff.} \langle \sigma v \rangle e^{-\langle \sigma v \rangle}}{m_\chi} \ll 2 \times 10^{-28} \text{ cm}^3 \text{ s}^{-1} \text{ GeV}^{-1}$$

Easily satisfies CMB bound with $\langle \sigma v \rangle > 3 \times 10^{-26} \text{cm}^3 \text{ s}^{-1}$ as required for asymm. DM

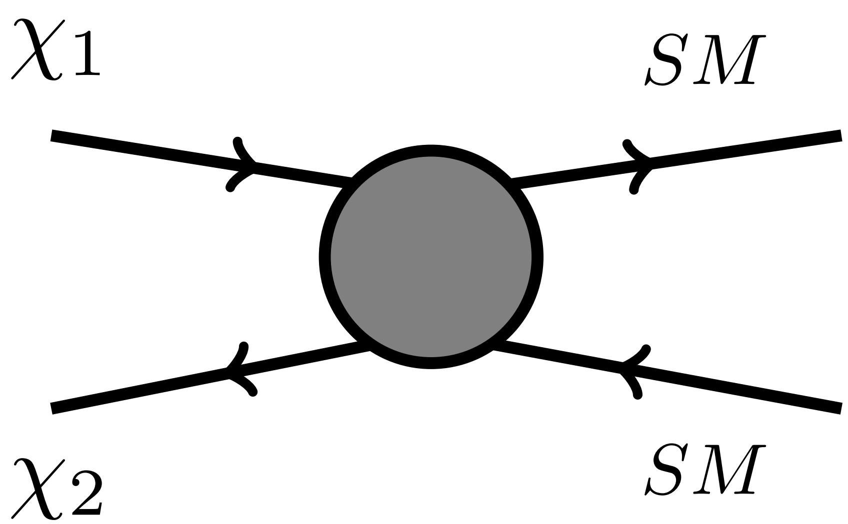
Graeser, Shoemaker, Vecchi 1103.0293

Lin, Yu, Zurek 1111.0293

Option 2: Different Population

Example (b): Inelastic DM (iDM)

Two-level co-annihilating system



$$\Delta \equiv m_2 - m_1$$

As universe cools, heavier state is Boltzmann suppressed

$$n_{\chi_2} \propto e^{-\Delta/T}$$

Automatic consequence if dark Higgs induces Majorana mass

$$\mathcal{L} \supset m_D \bar{\chi}\chi + H_D \overline{\chi}^c \chi \to m_D \bar{\chi}\chi + \langle H_D \rangle \overline{\chi}^c \chi$$

How to realize these strategies?

3 Easy Steps

How to realize these strategies?

Step 1: choose light mediator

Must be SM singlet, options limited by SM gauge invariance

Higgs Portal
Scalar mediator
(mixes w/ Higgs)

$$H^\dagger H \phi$$

couplings scale with mass

Vector Portal
spin-1 mediator
(mixes w/ photon)

$$\epsilon \, F_{\mu\nu} F'_{\mu\nu}$$

couplings scale with charge

How to realize these strategies?

Step 1: choose light mediator

Must be SM singlet, options limited by SM gauge invariance

Higgs Portal
Scalar mediator
(mixes w/ Higgs)

$$H^\dagger H \phi$$

1512.04119 GK

Extremely constrained
(see backup slides)

Vector Portal
spin-1 mediator
(mixes w/ photon)

$$\epsilon \, F_{\mu\nu} F'_{\mu\nu}$$

A' couples to DM with

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

A' couples to SM with ϵe

How to realize these strategies?

Step 1: choose light mediator

There are also viable mediators that don't "mix" with SM but gauge a combination of global quantum numbers

$$U(1)_{B-L}$$

$$U(1)_{e-\mu}$$

$$U(1)_{e-\tau}$$

Similar to dark photon but equal coupling to neutrinos

$$U(1)_{\mu-\tau}$$

Harder to test no electron coupling

Wont mention these again, easy to translate into A' param space

How to realize these strategies?

Step 2: choose LDM candidate

Spin	**Fermion** **vs.** **Scalar**
Abundance	**Symmetric** **vs.** **Asymmetric**
A' **Coupling**	**Elastic** vs. **Inelastic (iDM)**

How to realize these strategies?

Step 2: choose LDM candidate

Spin	**Scalar**
Abundance	**Symmetric** **vs.** **Asymmetric**
A' **Coupling**	**Elastic** vs. **Inelastic (iDM)**

Scalar DM : every permutation is CMB safe

$(\sigma v \propto v^2)$

How to realize these strategies?

Step 2: choose LDM candidate

Spin	**Fermion**
Abundance	**Symmetric** vs. **Asymmetric**
A' **Coupling**	**Elastic** vs. **Inelastic (iDM)**

Fermions are more complicated

[**Symmetric** + **Elastic**] = Dead (CMB)

[**Symmetric** + **iDM**] = Safe

[**Asymmetric** + **Elastic**] = Safe

[**Asymmetric** + **iDM**] = Inconsistent for simple models

How to realize these strategies?

Step 2: choose LDM candidate

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Abundance	**Symmetric** vs. **Asymmetric**
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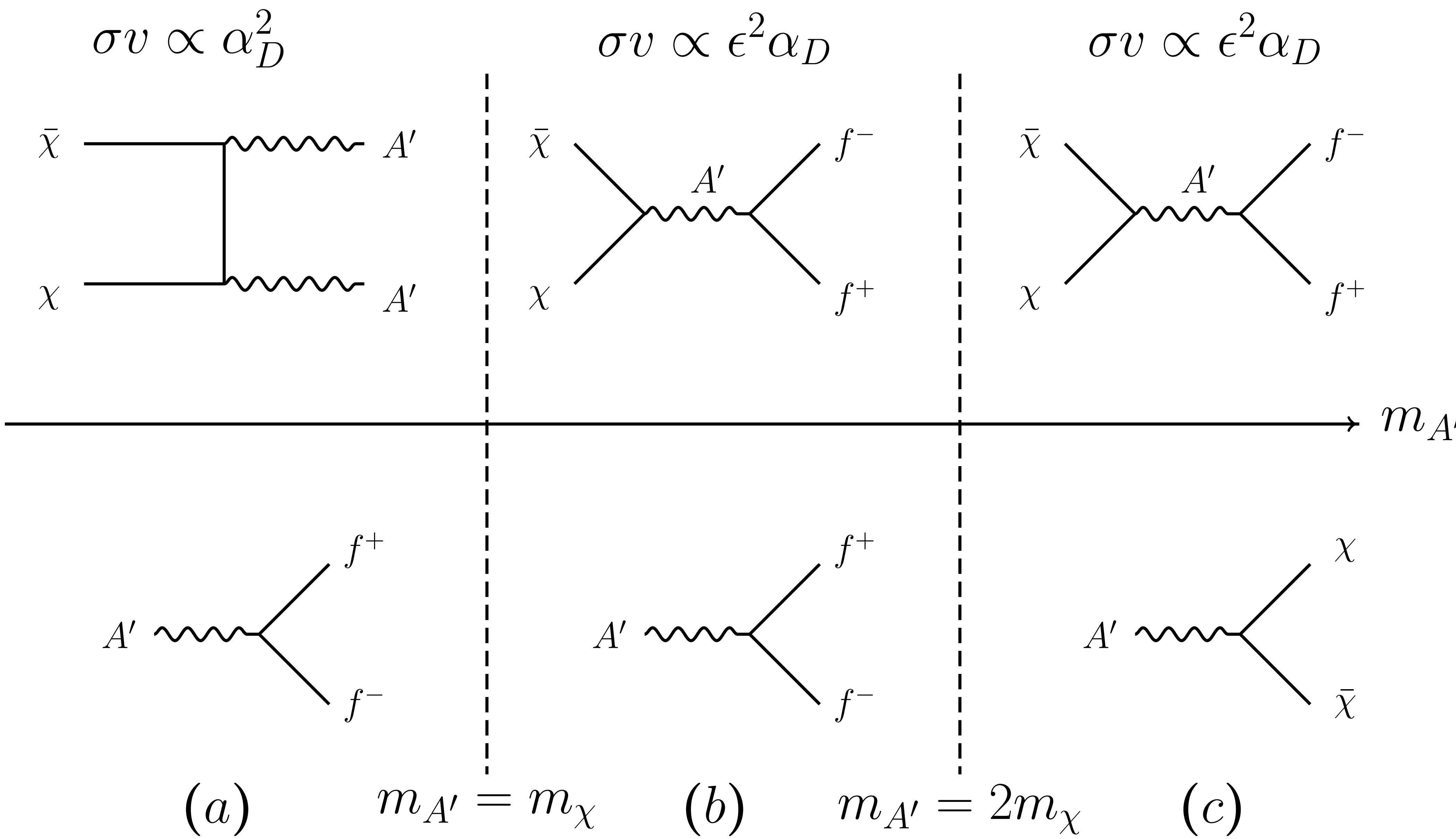
~~[**Asymmetric** + **iDM**] = Inconsistent for simple models~~

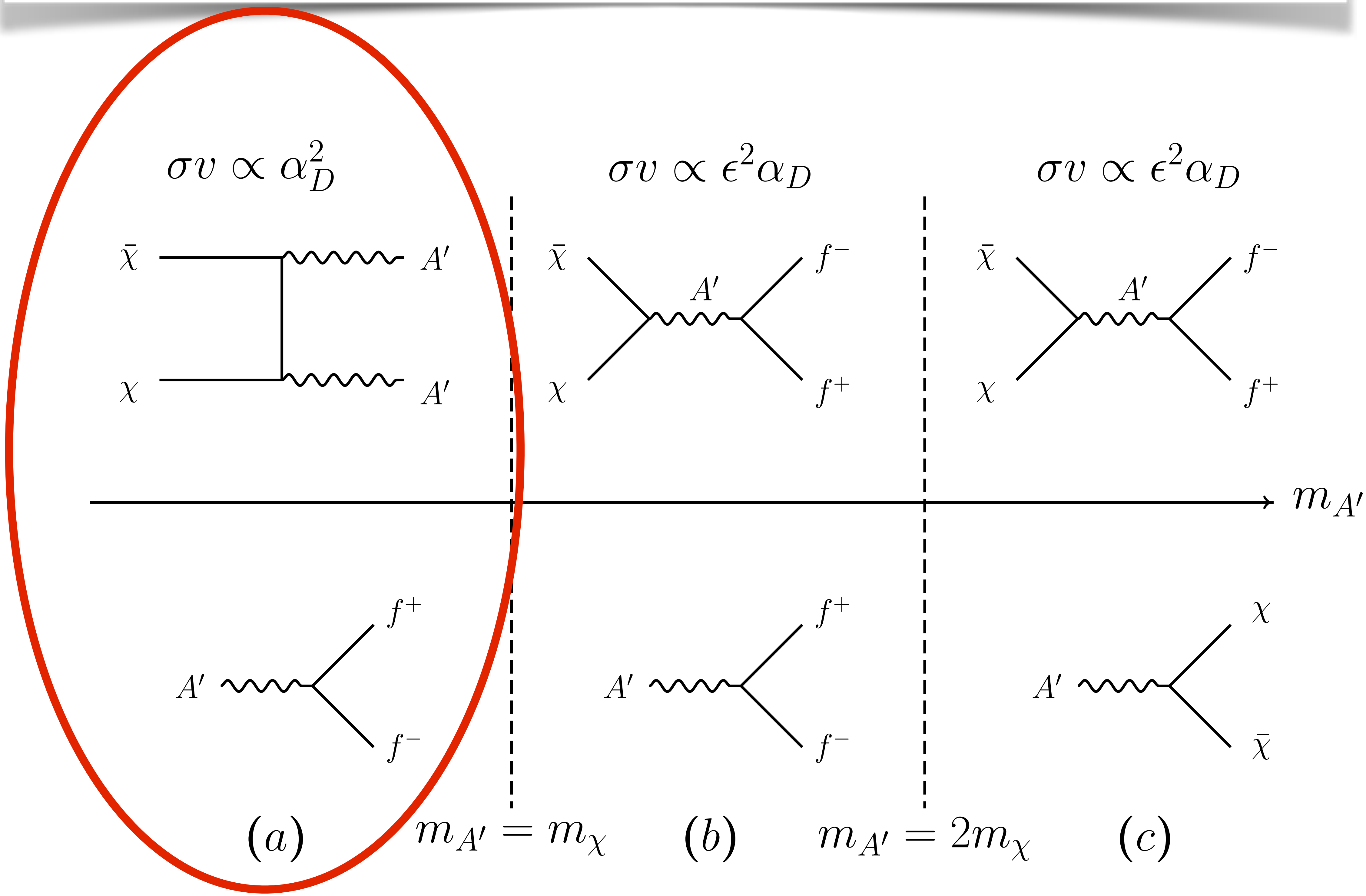
How to realize these strategies?

Step 3: choose mass hierarchy



How to realize these strategies?

Step 3: choose mass hierarchy

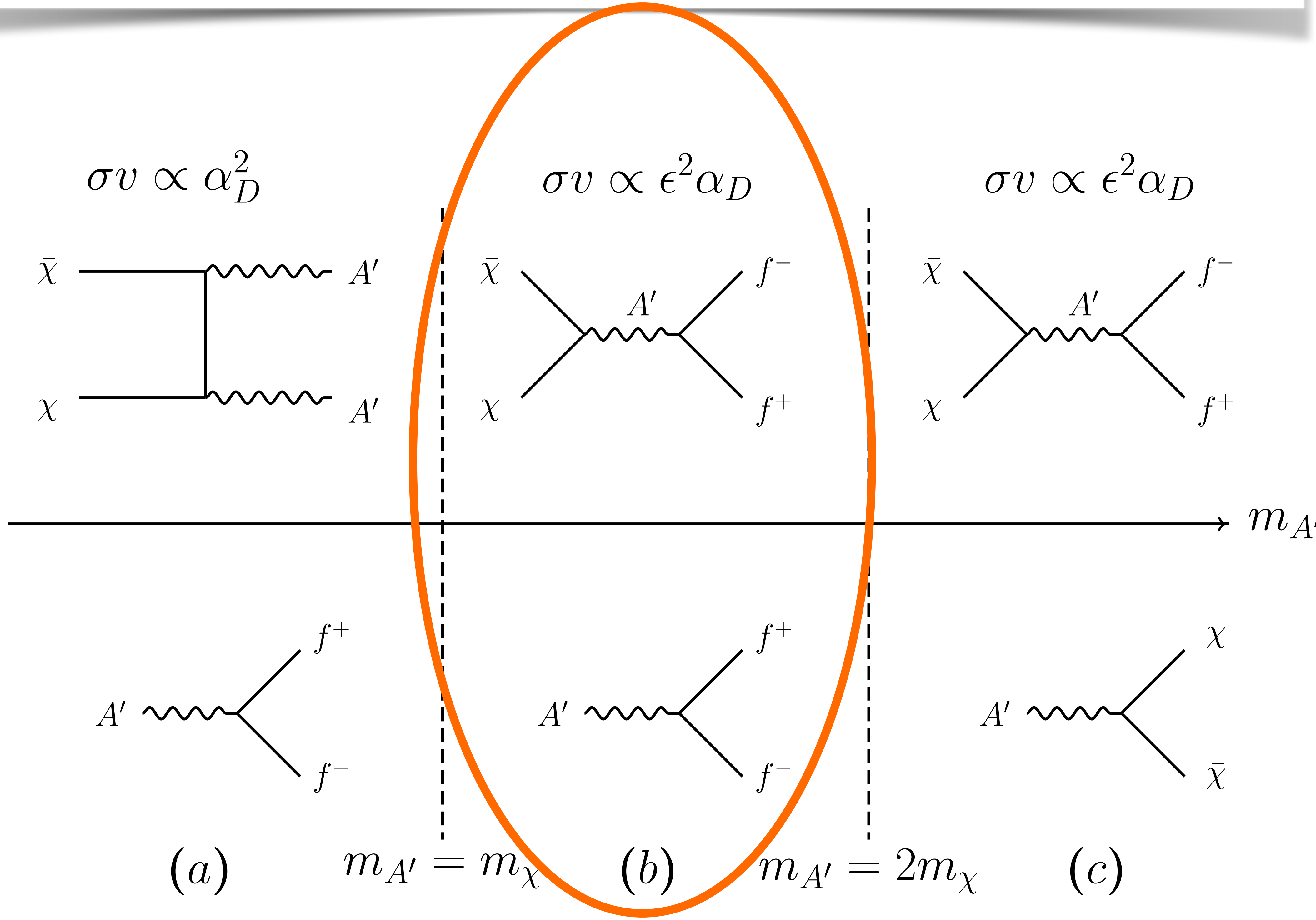


Annihilation independent of SM coupling

No Thermal Target

How to realize these strategies?

Step 3: choose mass hierarchy

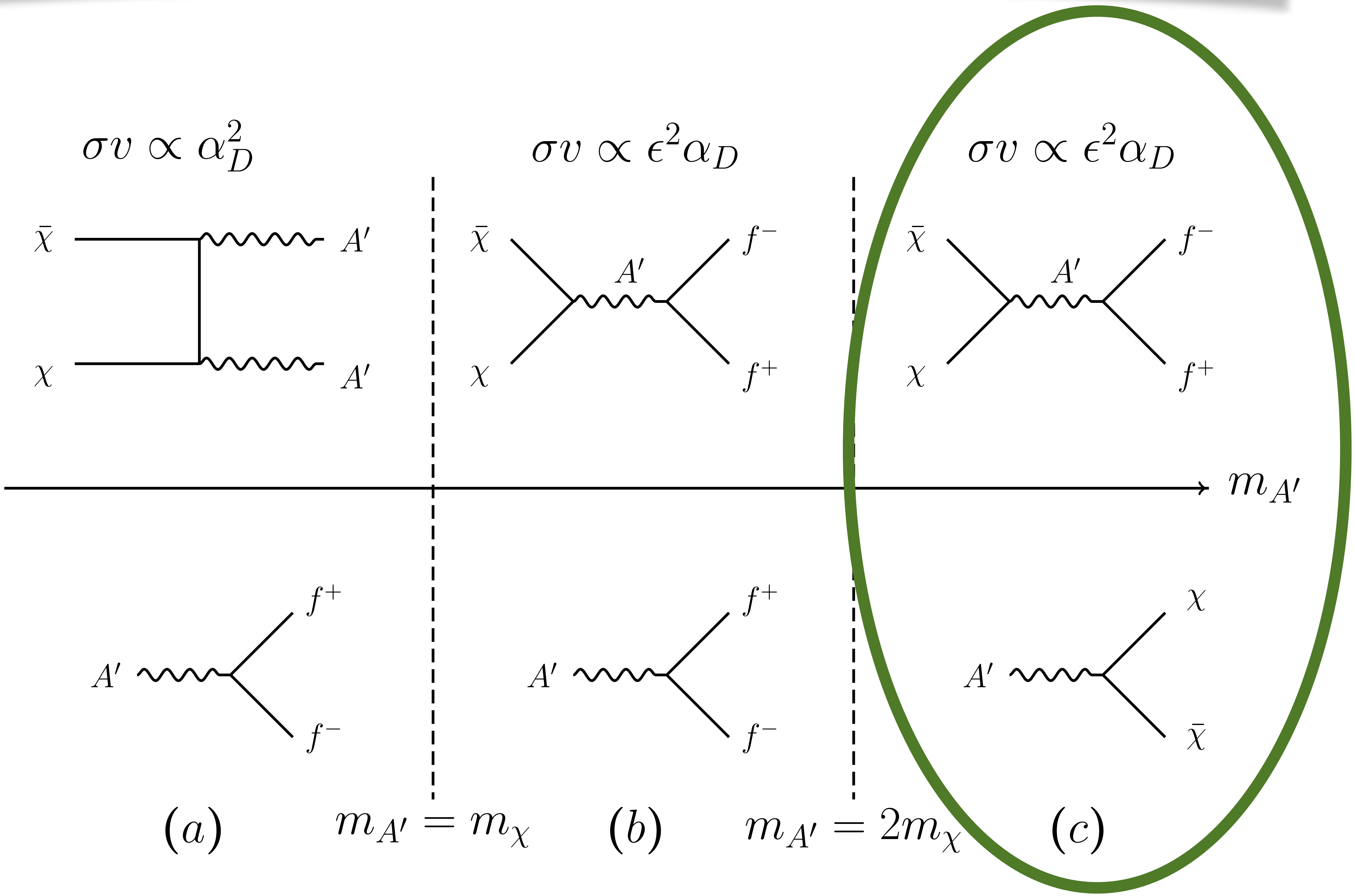


Compressed regime : annihilation dep on DM x SM coupling

Thermal Target: motivates dark photon searches (HPS, Belle II, LHCb...)

How to realize these strategies?

Step 3: choose mass hierarchy



Clear thermal target when mediator decays to DM

Comparing to Thermal Target

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

Comparing to Thermal Target

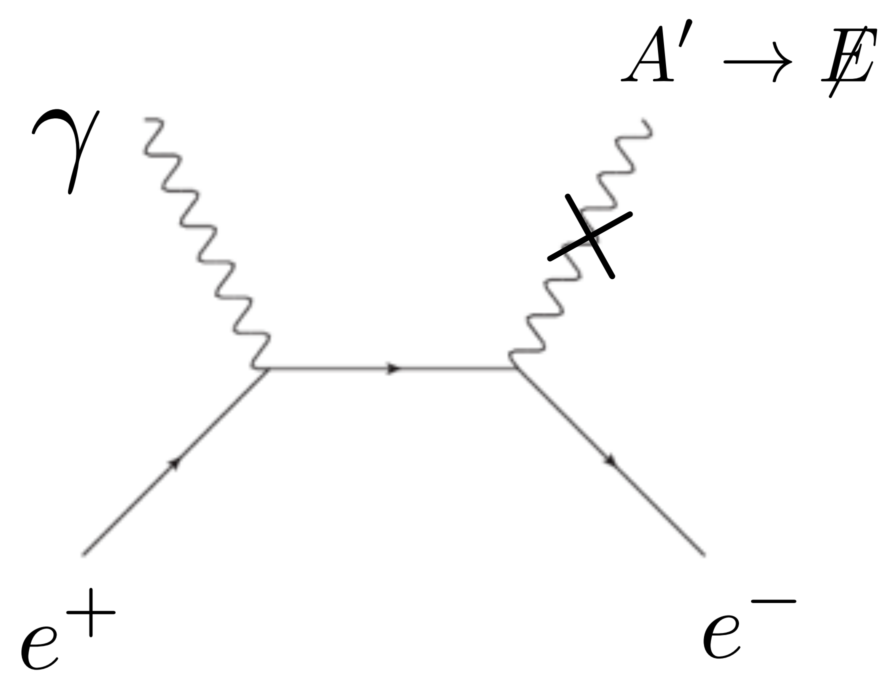
$$\sigma v \propto \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4 \equiv y$$

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

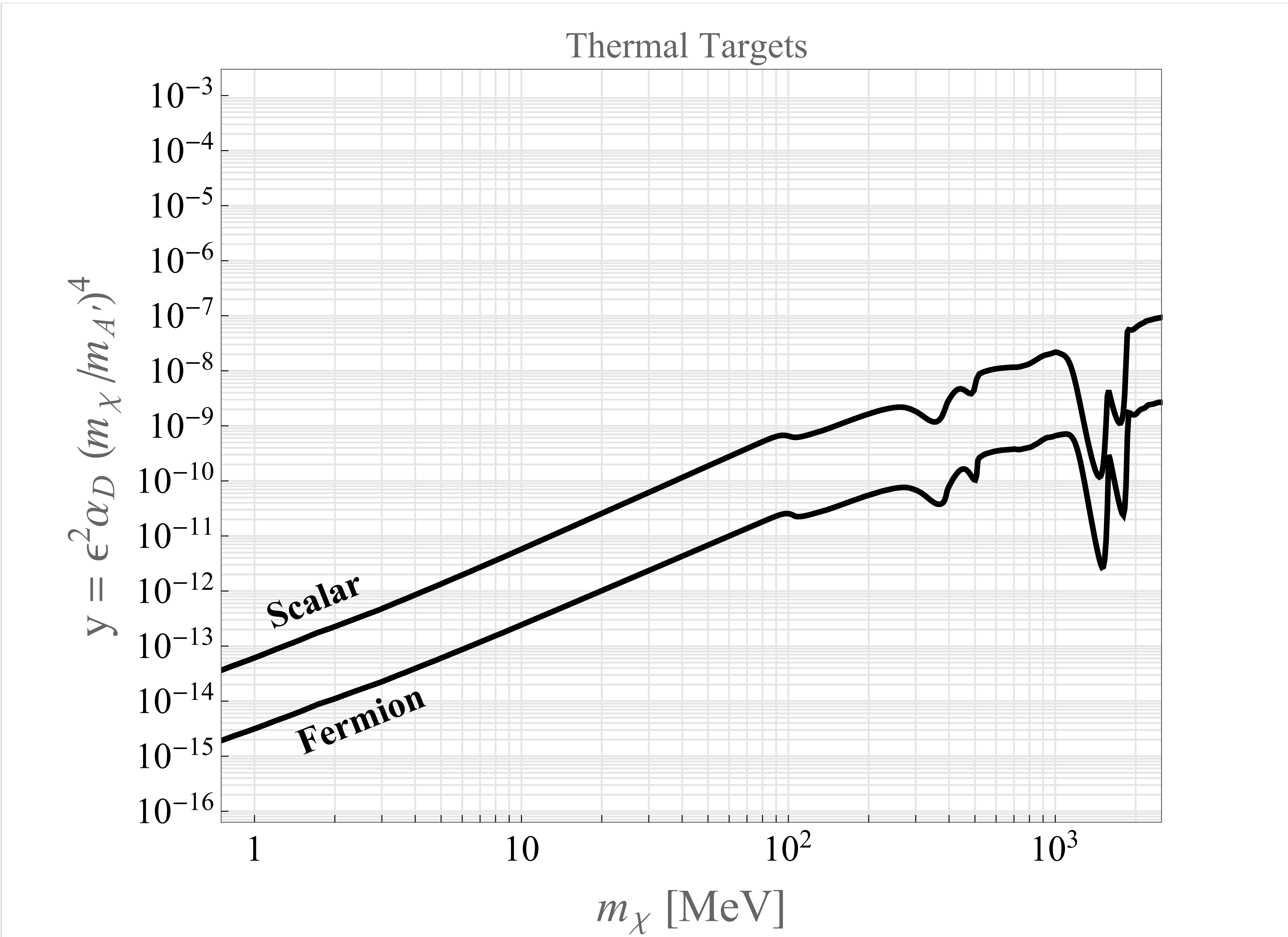
e.g. Collider bounds depend on

$$\sigma \sim \frac{\epsilon^2}{s} = y \times \frac{1}{\alpha_D}\left(\frac{m_{A'}}{m_\chi}\right)^4$$

conservative = multiply by *smallest* value

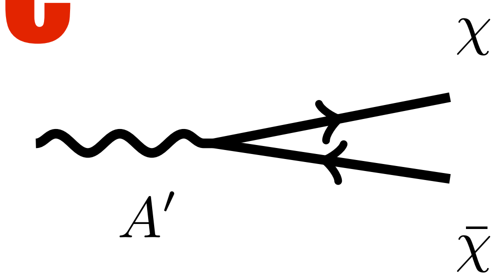


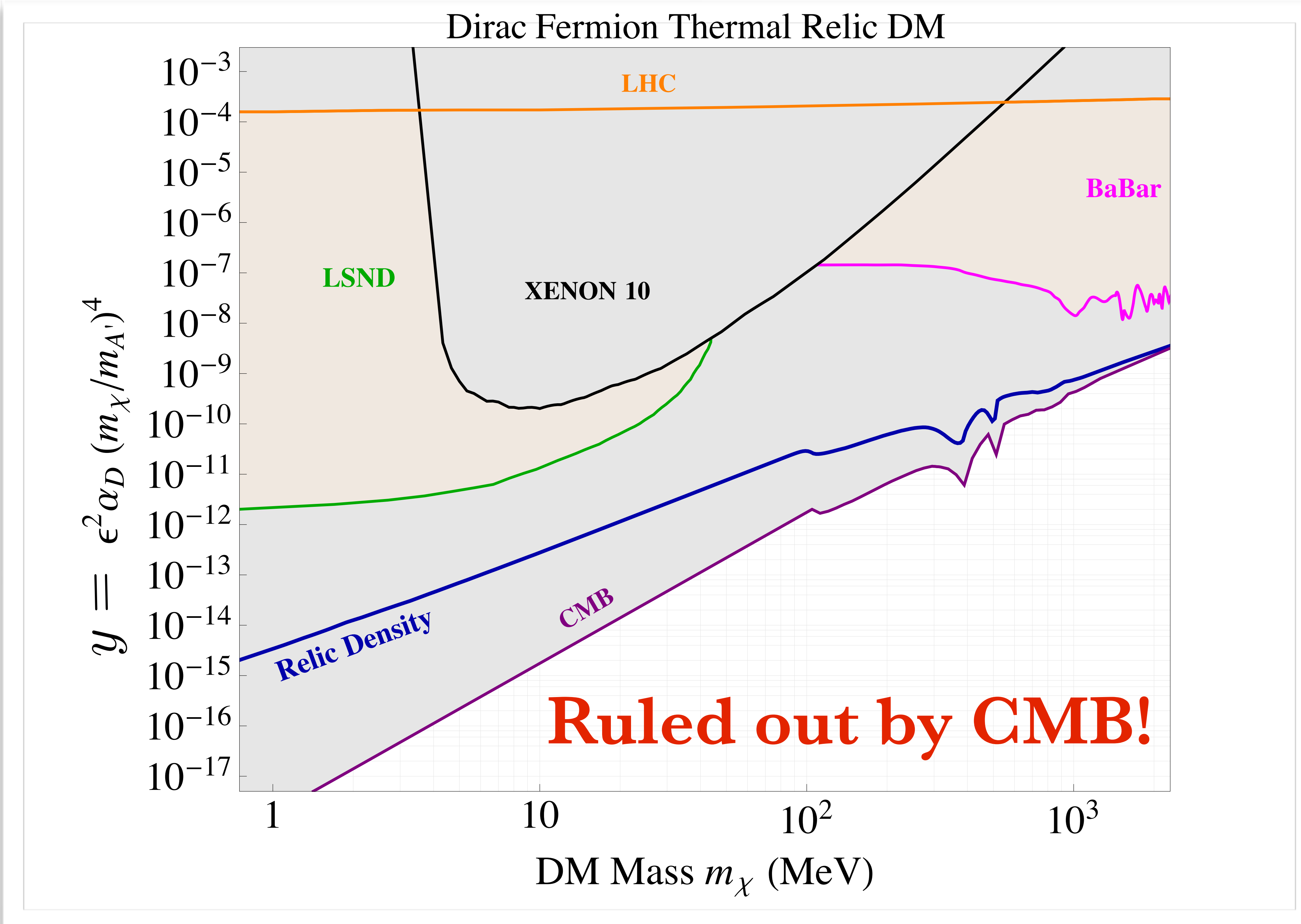
Comparing to Thermal Target



Fermion Symmetric Elastic

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

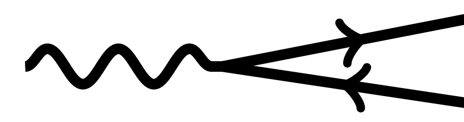


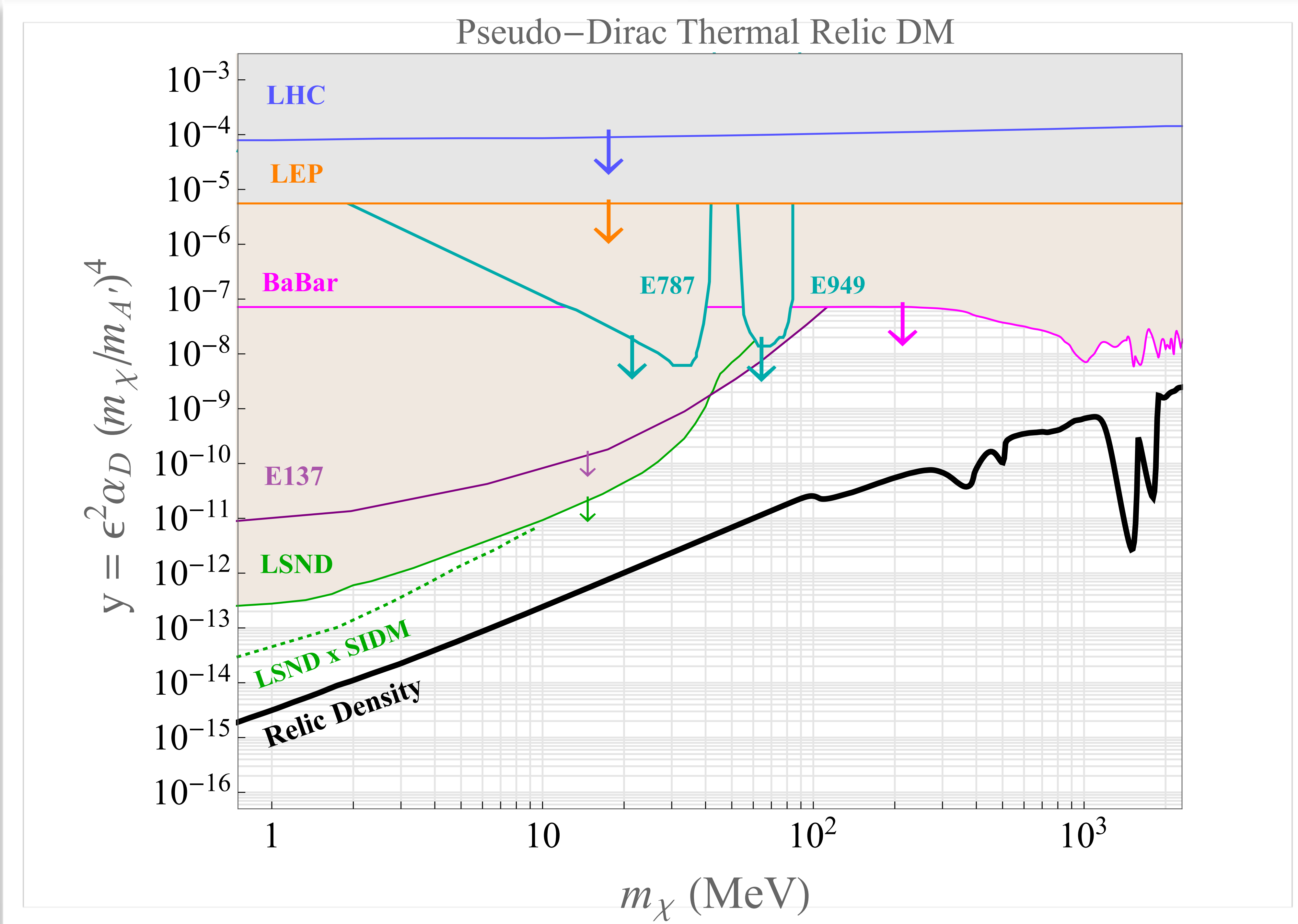


BaBar, LSND, LHC: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$

Fermion Symmetric Inelastic

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



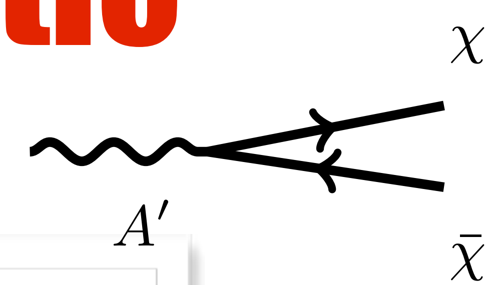


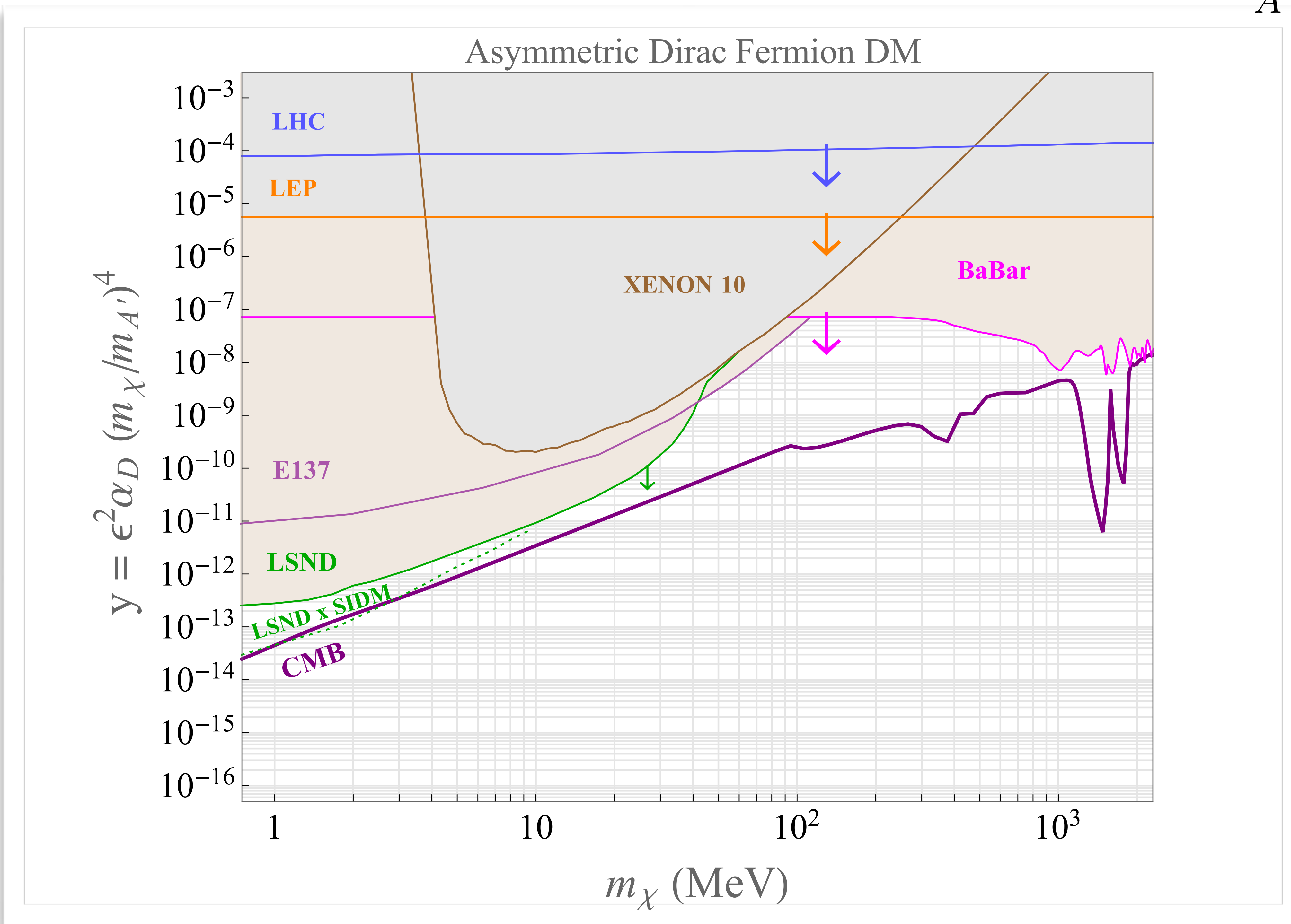
BaBar, LSND, LHC: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$

$\mathrm{keV} < \Delta \ll m_\chi$

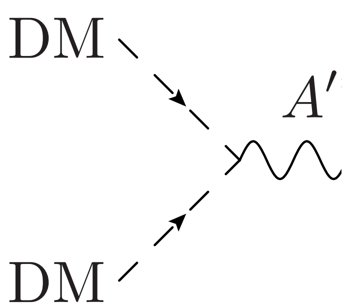
Fermion Asymmetric Elastic

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



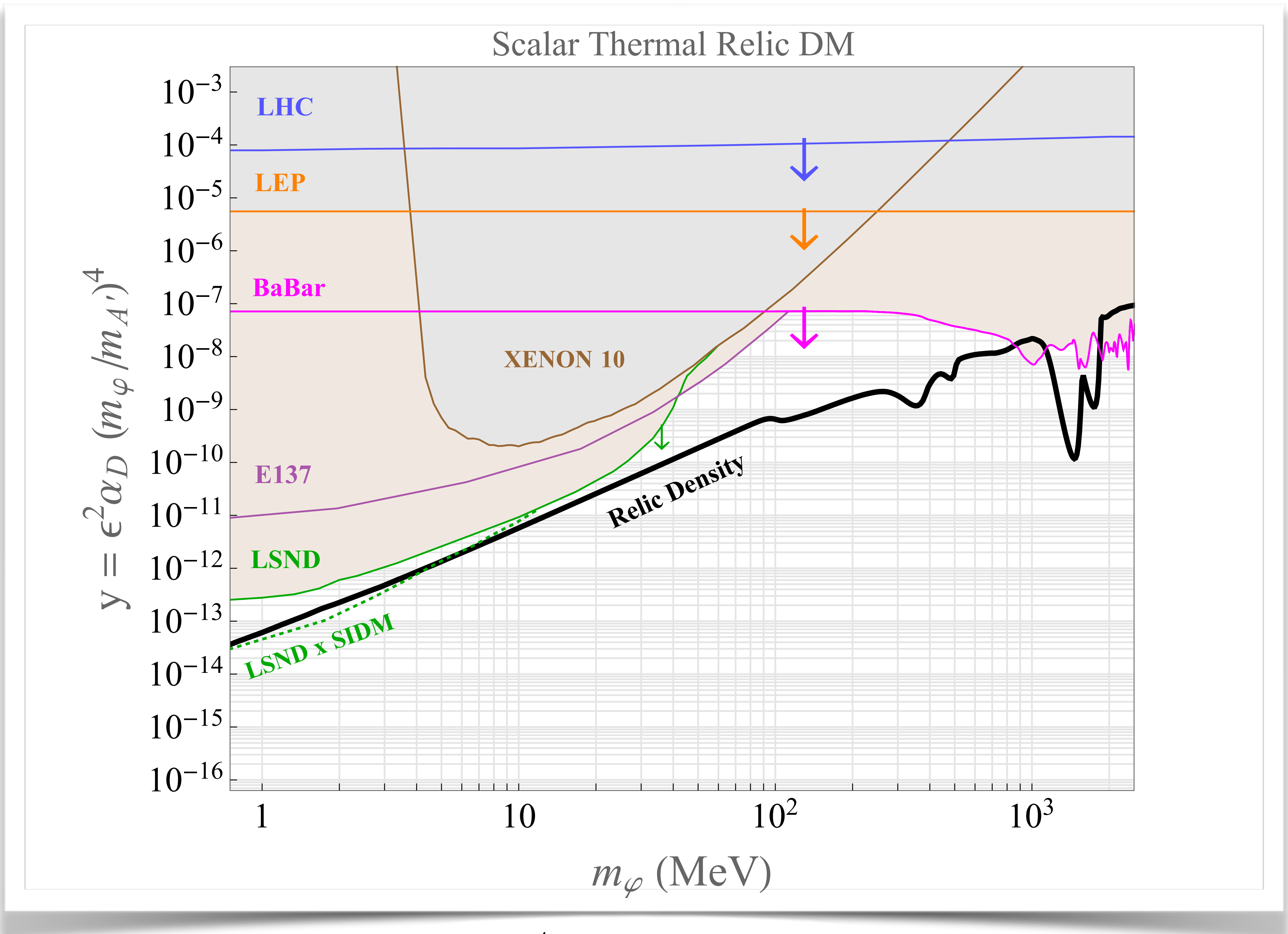


BaBar, LSND, LHC: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$



Scalar Symmetric Elastic

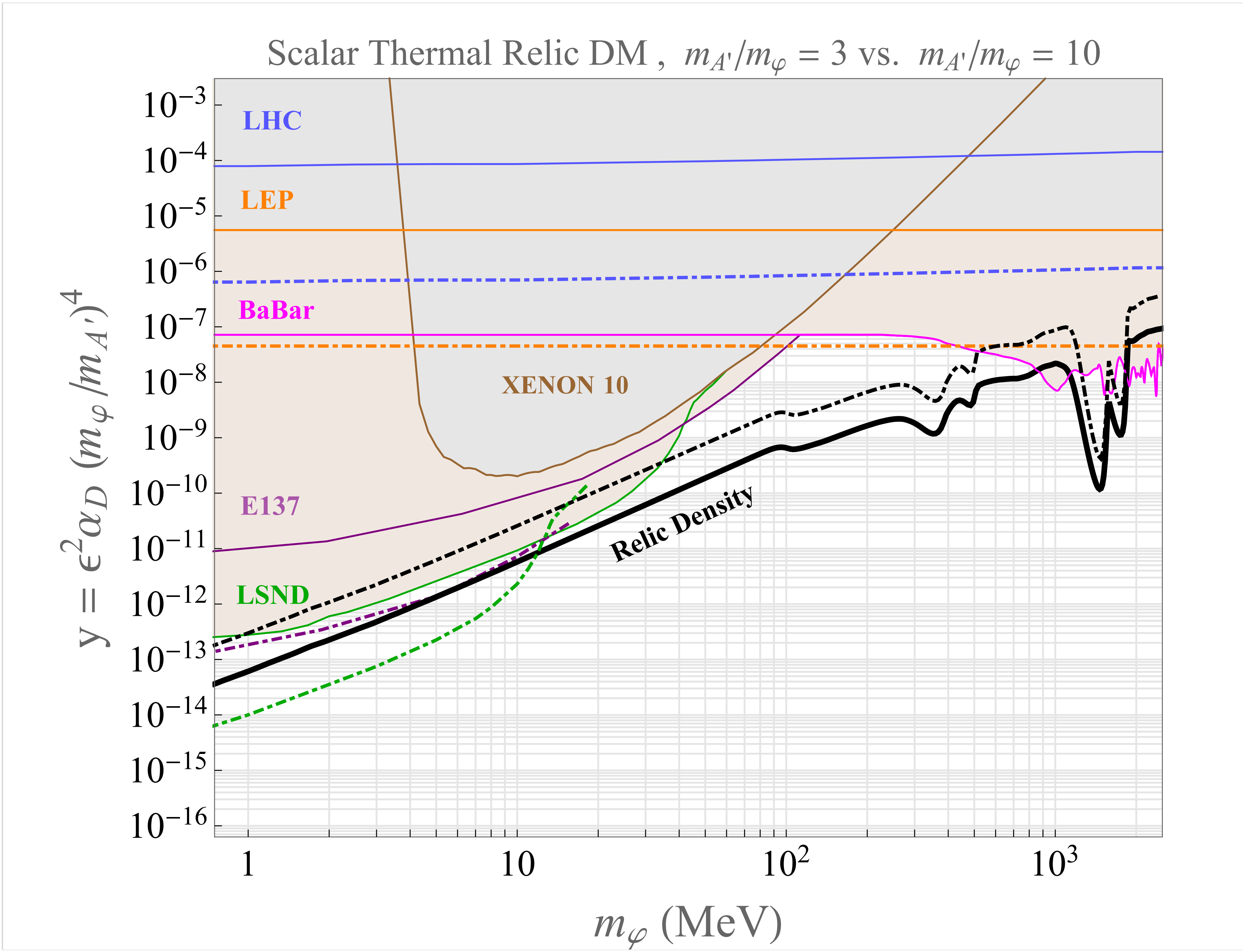
$$n_{\mathrm{DM}} = n_{\overline{DM}}$$



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

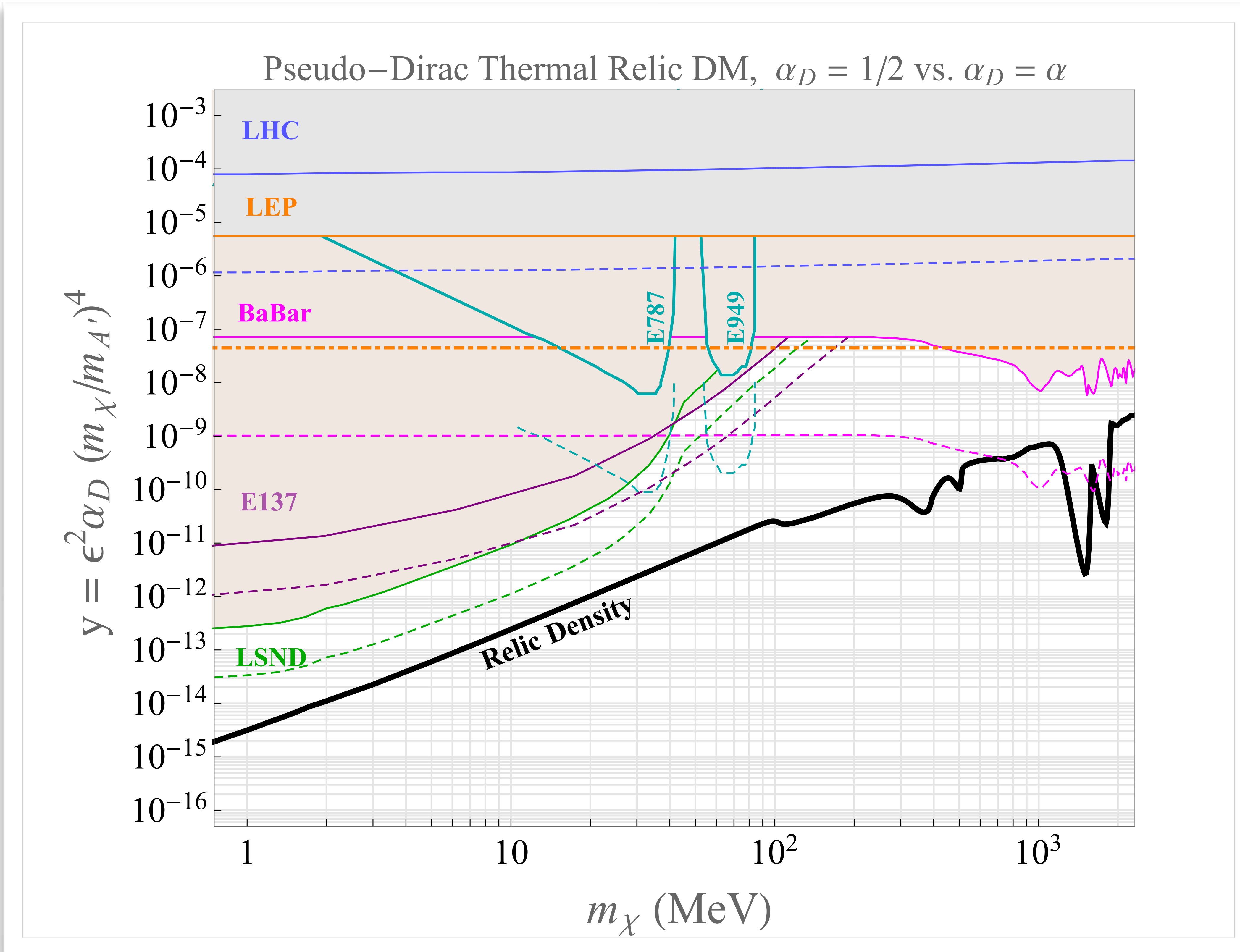
NB : $\sigma v \propto v^2$

Is this actually conservative?



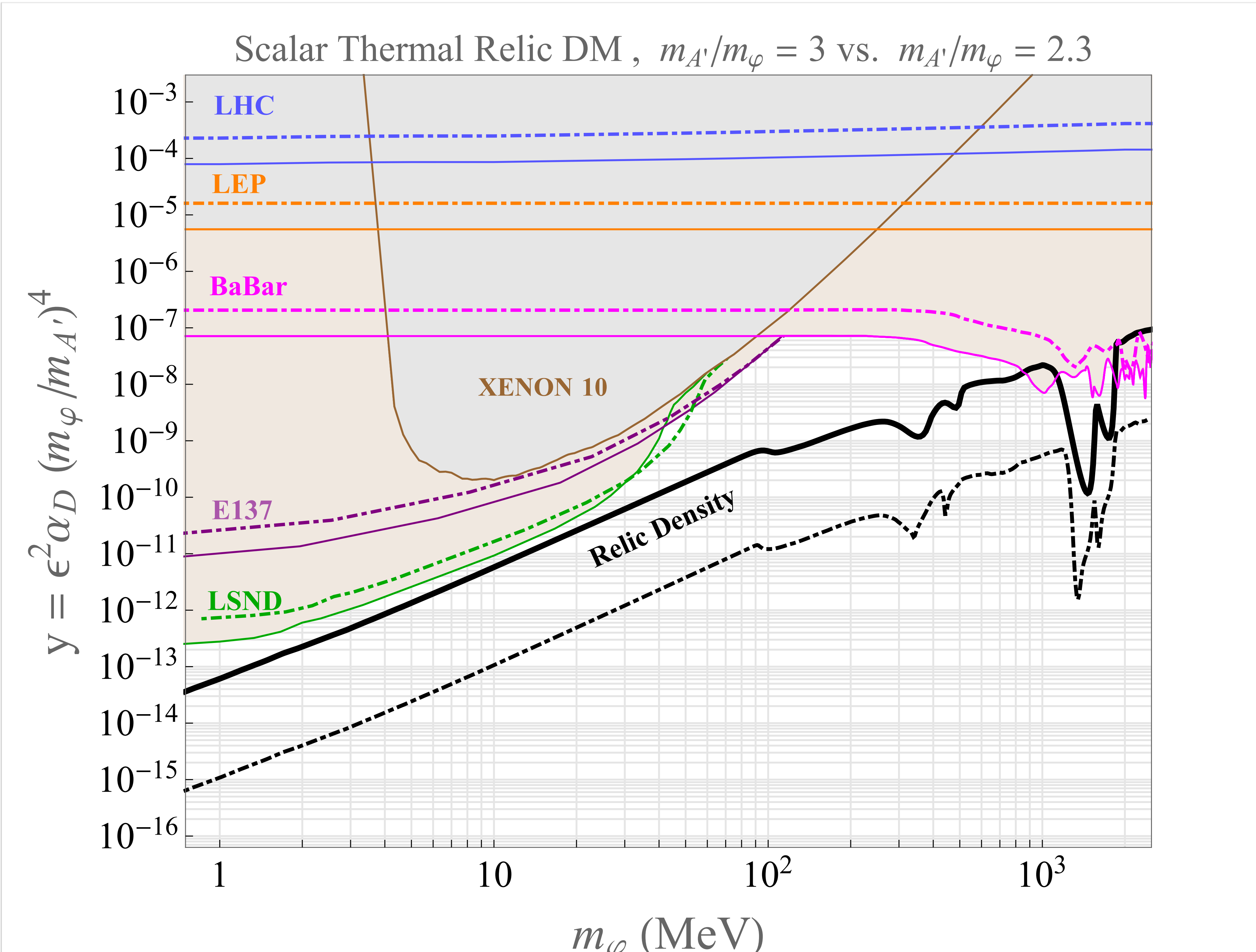
Increase mediator / DM mass ratio

Is this actually conservative?



Decrease DM coupling to mediator α_D

Is this actually conservative?



Caveat : avoid DM resonant annihilation

How to decisively test thermal targets?

Light Dark Matter eXperiment (LDMX):
Letter of Intent

Owen Colegrove,[1] Bertrand Echenard,[2] Norman Graf,[3] Joshua Hiltbrand,[4] David Hitlin,[2] Joseph Incandela,[1] John Jaros,[3] Robert Johnson,[5] Gordan Krnjaic,[6] Jeremiah Mans,[4] Takashi Maruyama,[3] Jeremy McCormick,[3] Omar Moreno,[3] Timothy Nelson,[3] Philip Schuster,[3,7] Natalia Toro,[3,7] Nhan V Tran,[6] and Andrew Whitbeck[6]

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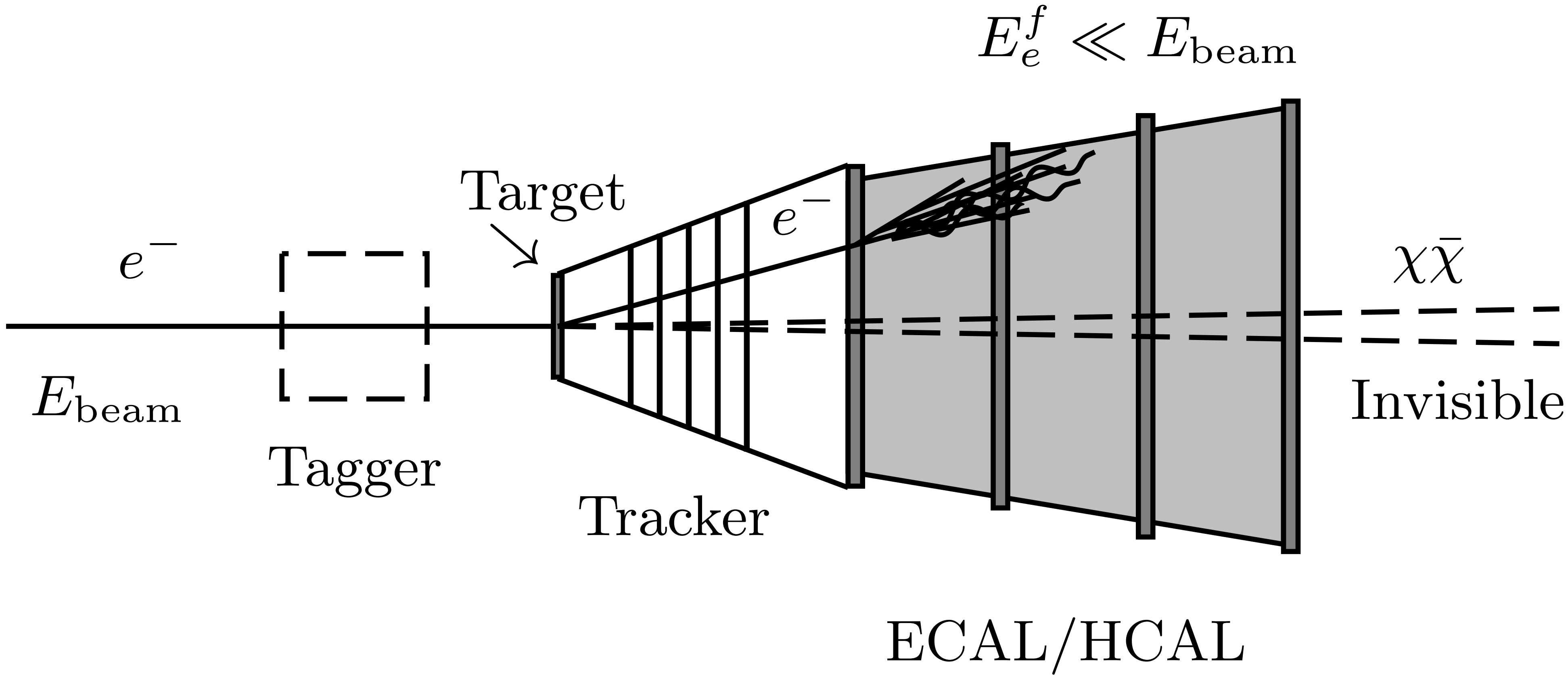
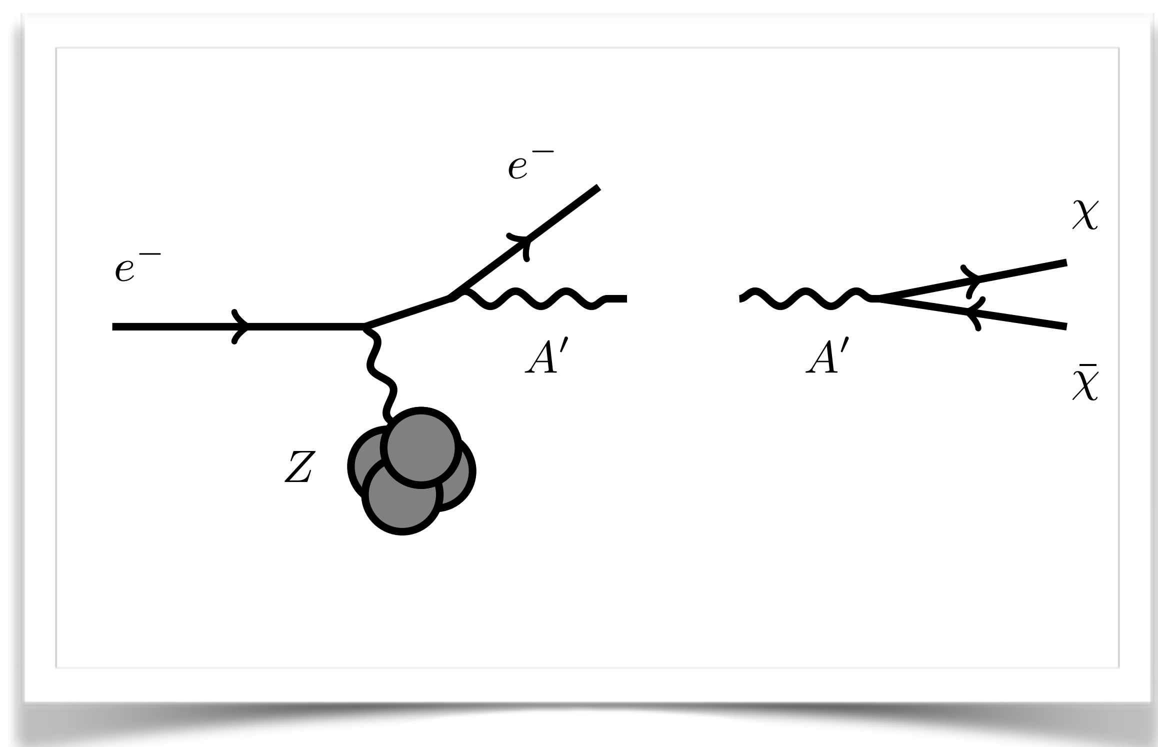
Missing Momentum Approach

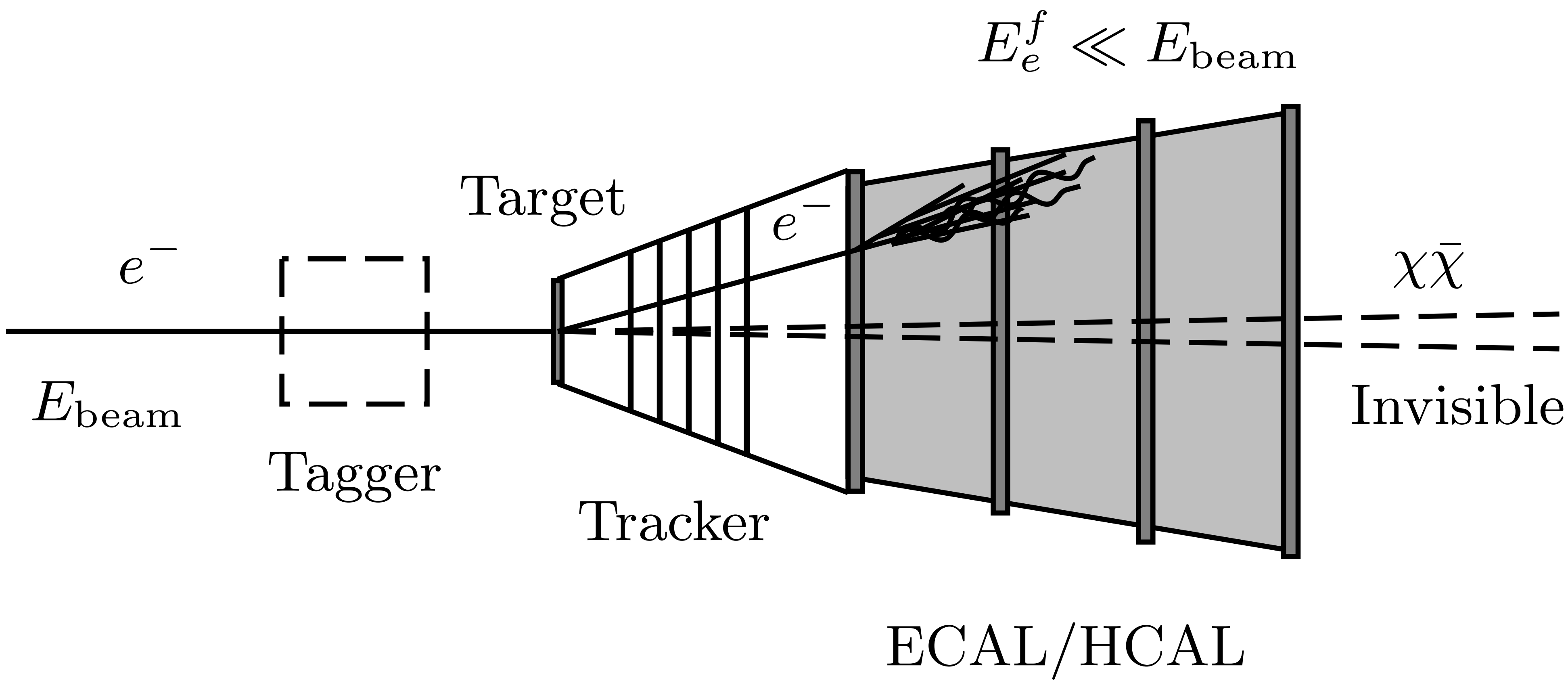


Signal: **a low energy electron & no other activity**

Payoff: **Rate scales as** $\sim \epsilon^2$

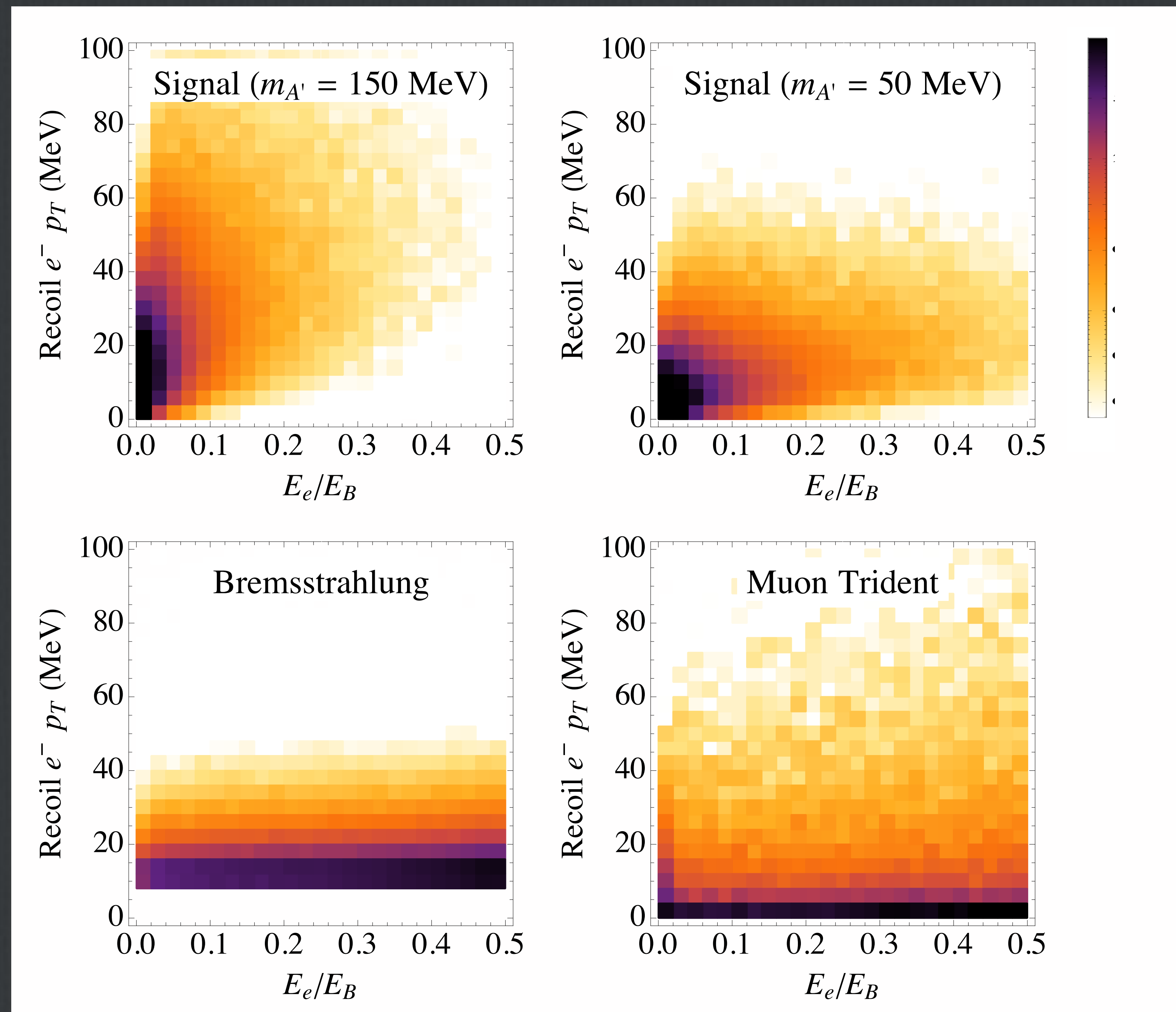


Missing Momentum Approach



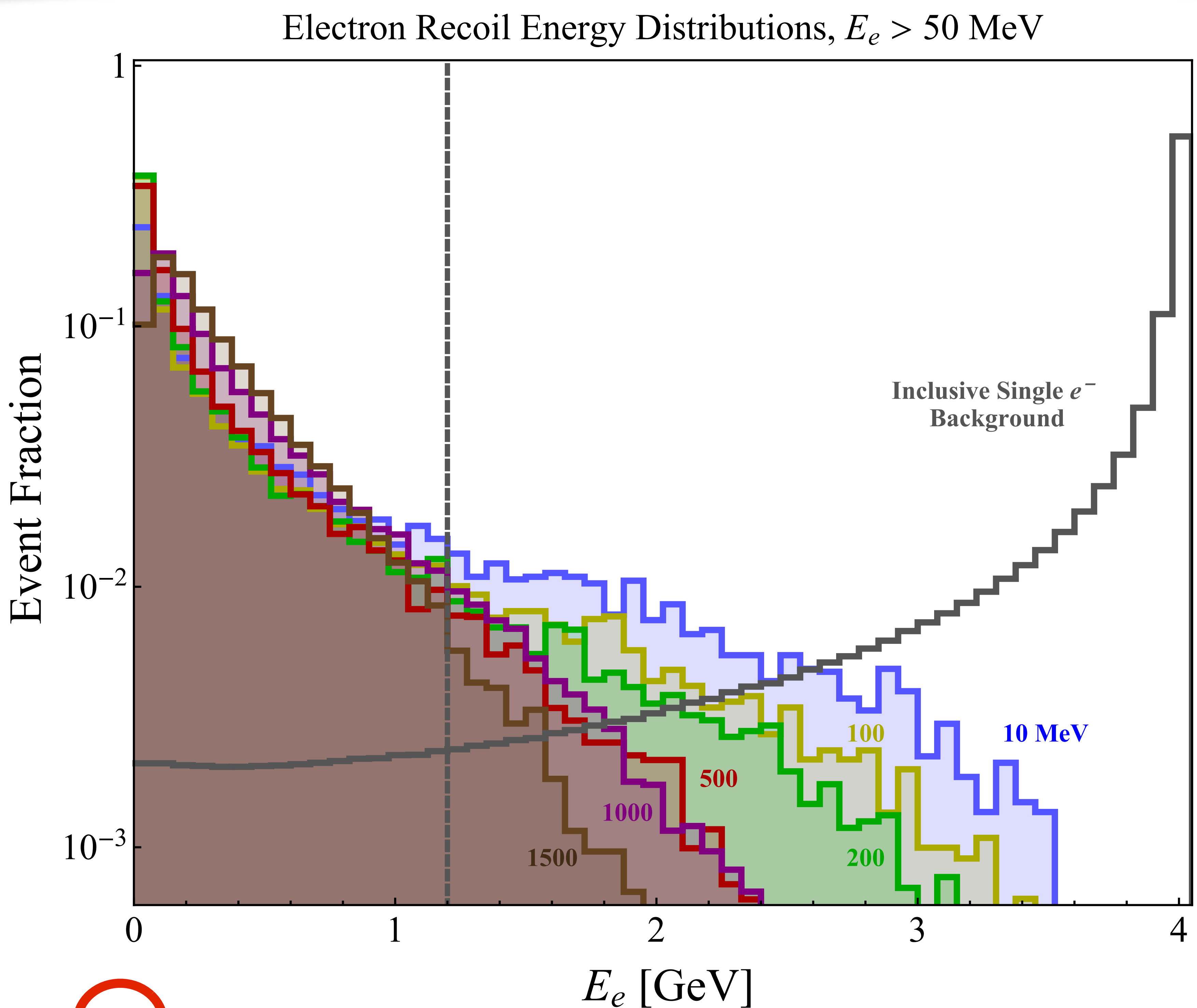
1. Prepare ***low current*** e^- — < 100 pA
2. Measure incident e^- momentum — ~ 10 GeV
3. Send through thin target — ~ 0.1- 0.01 X
4. Measure outgoing e^- E & PT — < 1 GeV

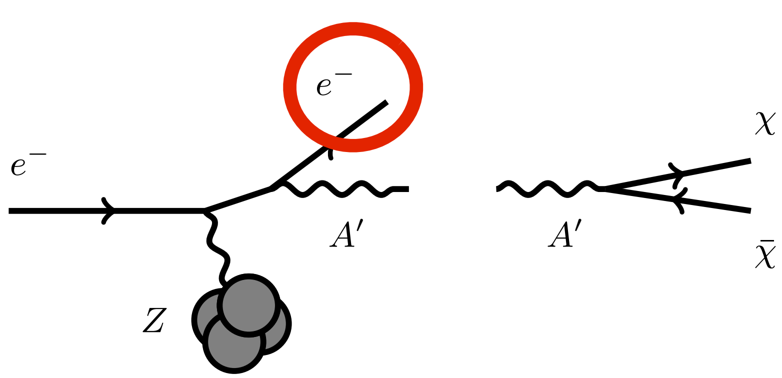
Kinematics of DM Production



Kinematically, these are quite different from typical backgrounds

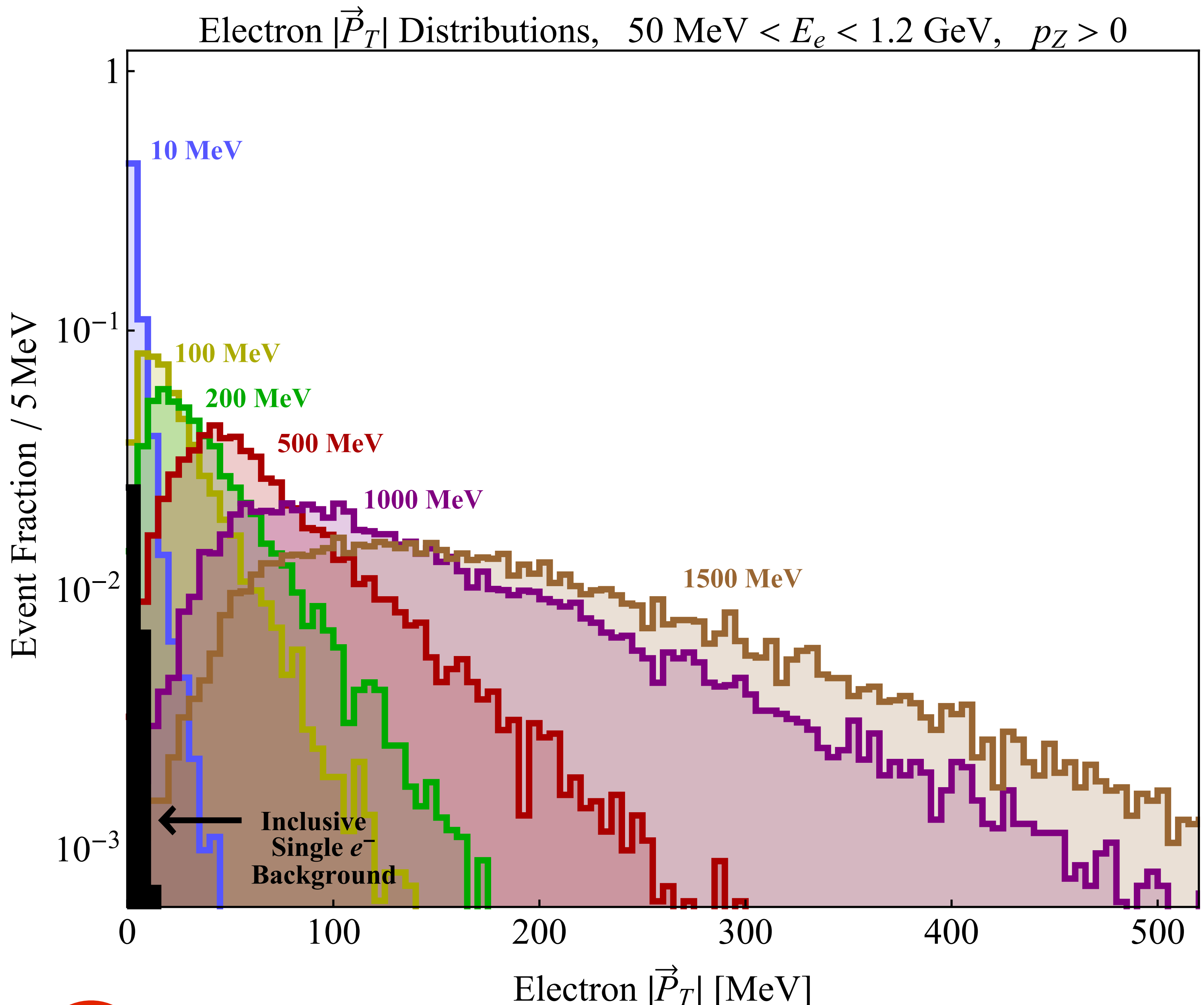
Kinematics of DM Production

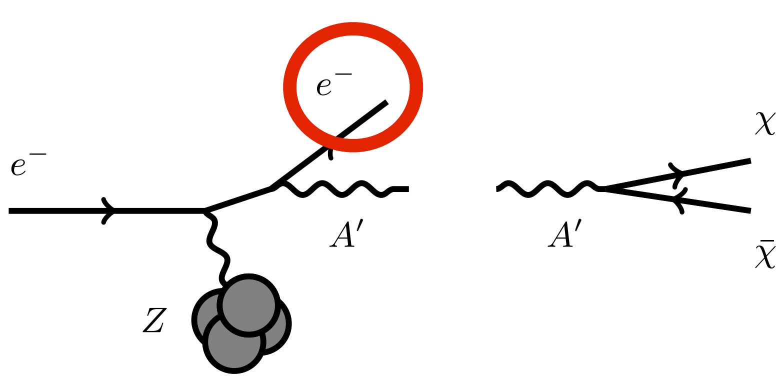




Normalized to geometric acceptance

Kinematics of DM Production





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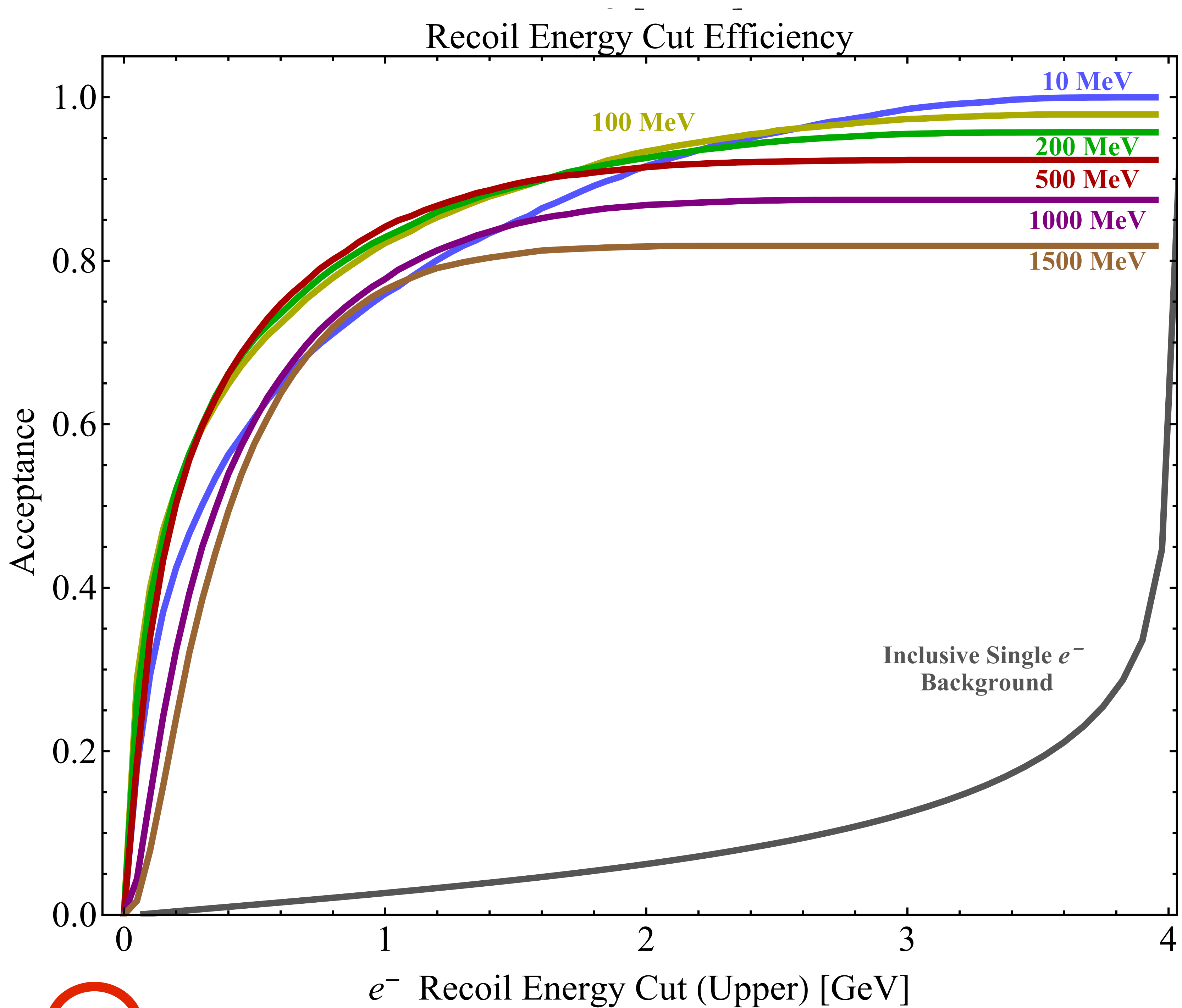
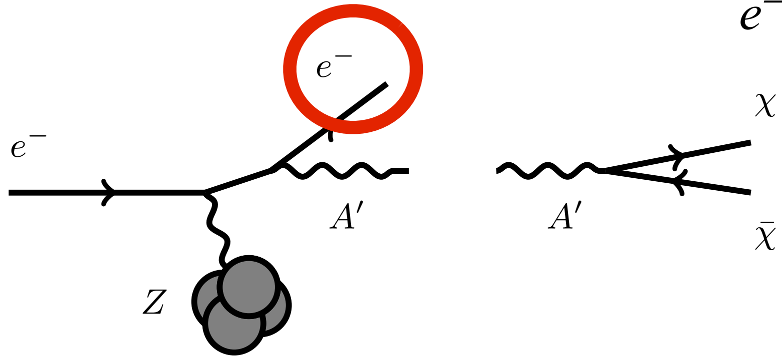
Kinematics of DM Production





Irreducible Backgrounds

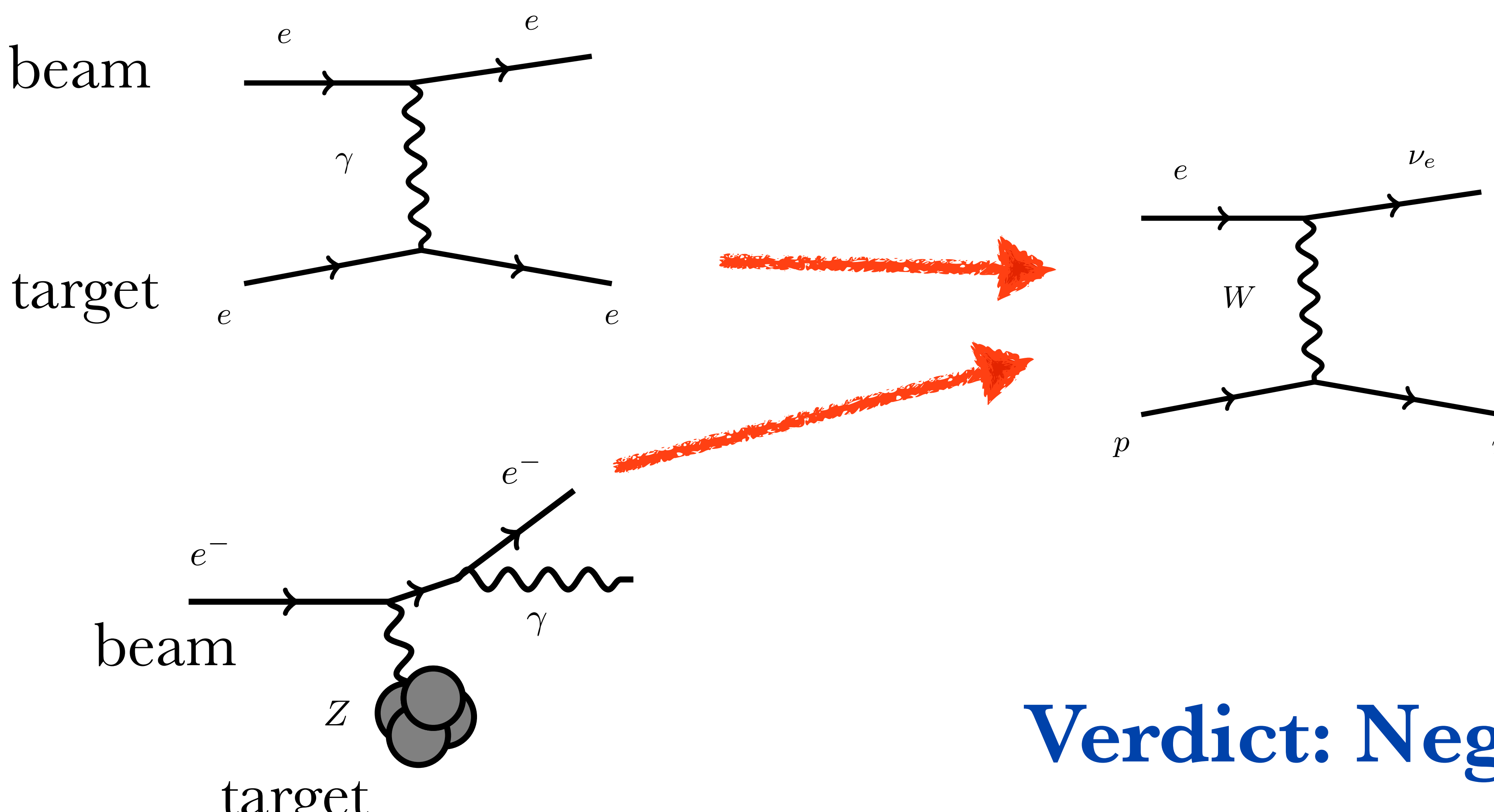
Other sources can carry away missing momentum

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

Brem.



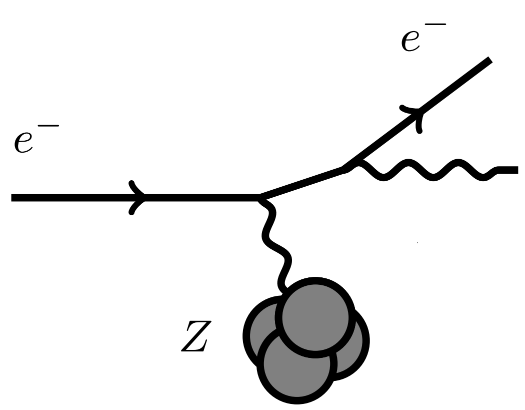
CCQE

Verdict: Negligible

Reducible Backgrounds (Fakes)

Fail to veto SM particles

Bremsstrahlung

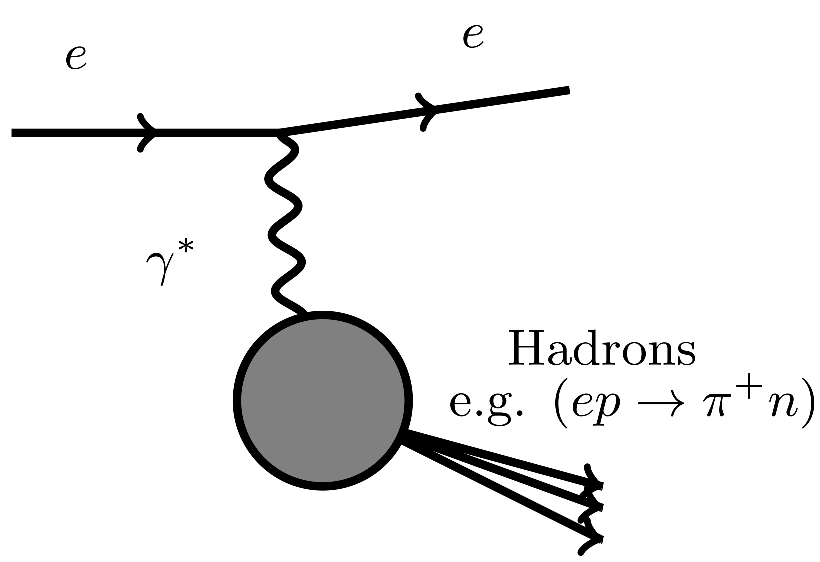


$\gamma(E \sim E_{\mathrm{beam}})$

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} $\textbf{EOT}_{eff}$
γ non-interaction	$\sim 3\times10^{8}e^{-\frac{7}{9}(T/X_0=45)} \ll 1$
$\gamma p\to\pi^+ n$	$\sim 10^2\times\epsilon_\pi\epsilon_n$
$\gamma^* p\to\pi^+ n$ (backscatter π^+)	$\sim 3\times10^1\times\epsilon_n$
$\gamma N\to(\rho,\omega,\phi)N\to\pi^+\pi^- N$	$\sim 2\times10^4\epsilon_\pi^2$
$\gamma^* n\to n\bar{n}n$	$\sim 3\times10^3\times\epsilon_n^3$
$eN\to eN(\mu^+\mu^-,\pi^+\pi^-)$	$\sim 10^4\times\epsilon_{\mu/\pi}^2$
$\gamma N\to N\mu^+\mu^-$	$\sim 6\times10^3\times\epsilon_\mu^2$

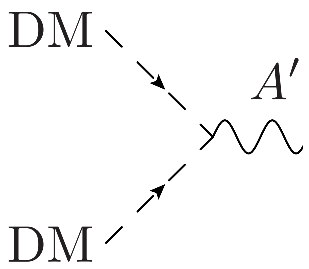
ϵ_X

probability of missing X

Reducible with sufficiently hermitic setup

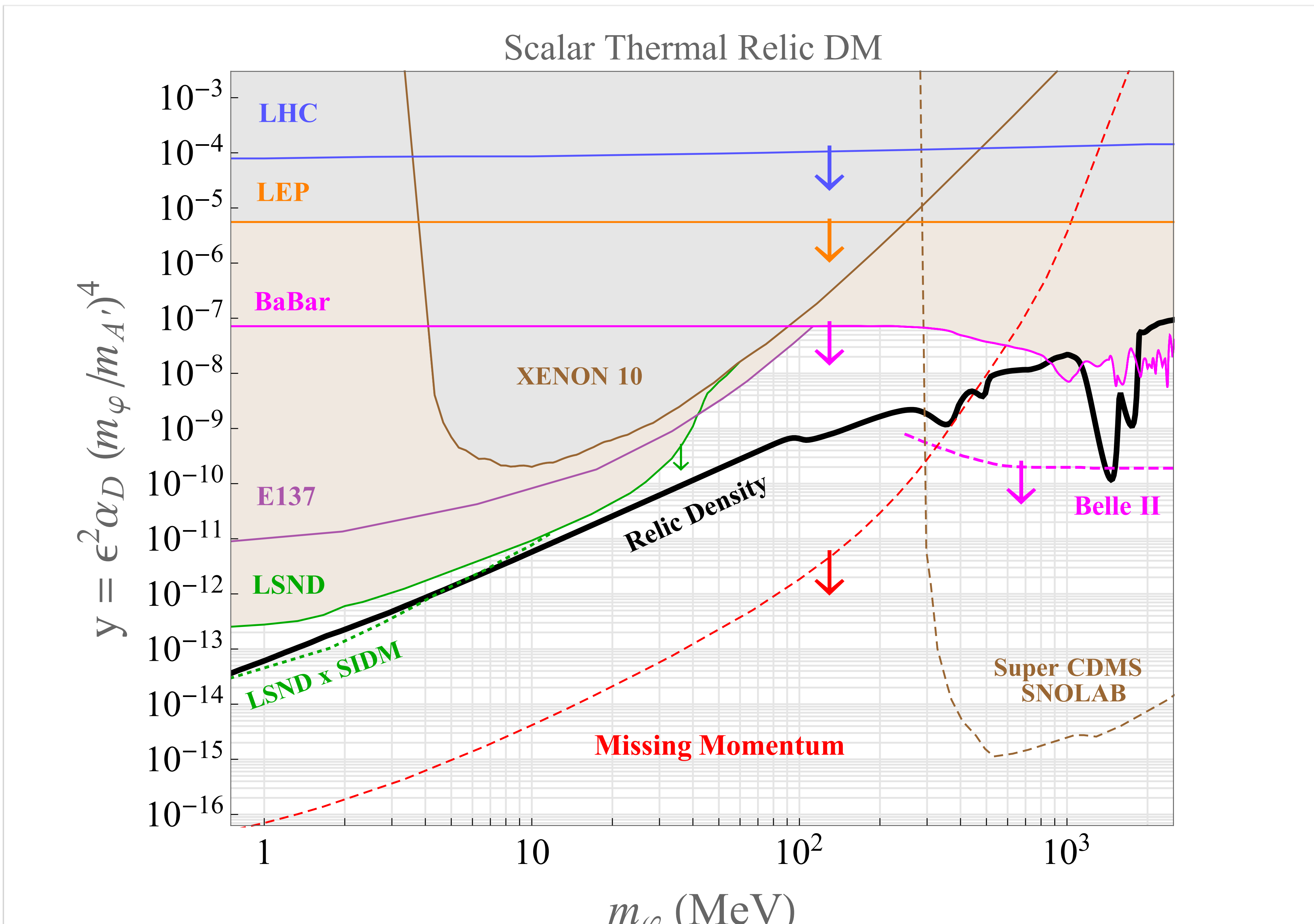
Still work in progress, need to optimize

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



Scalar Symmetric Elastic

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

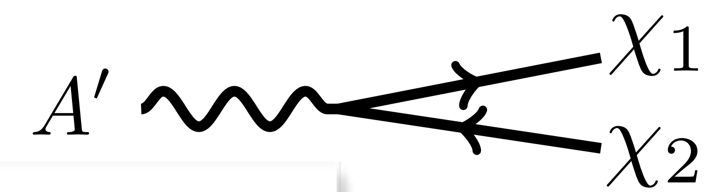


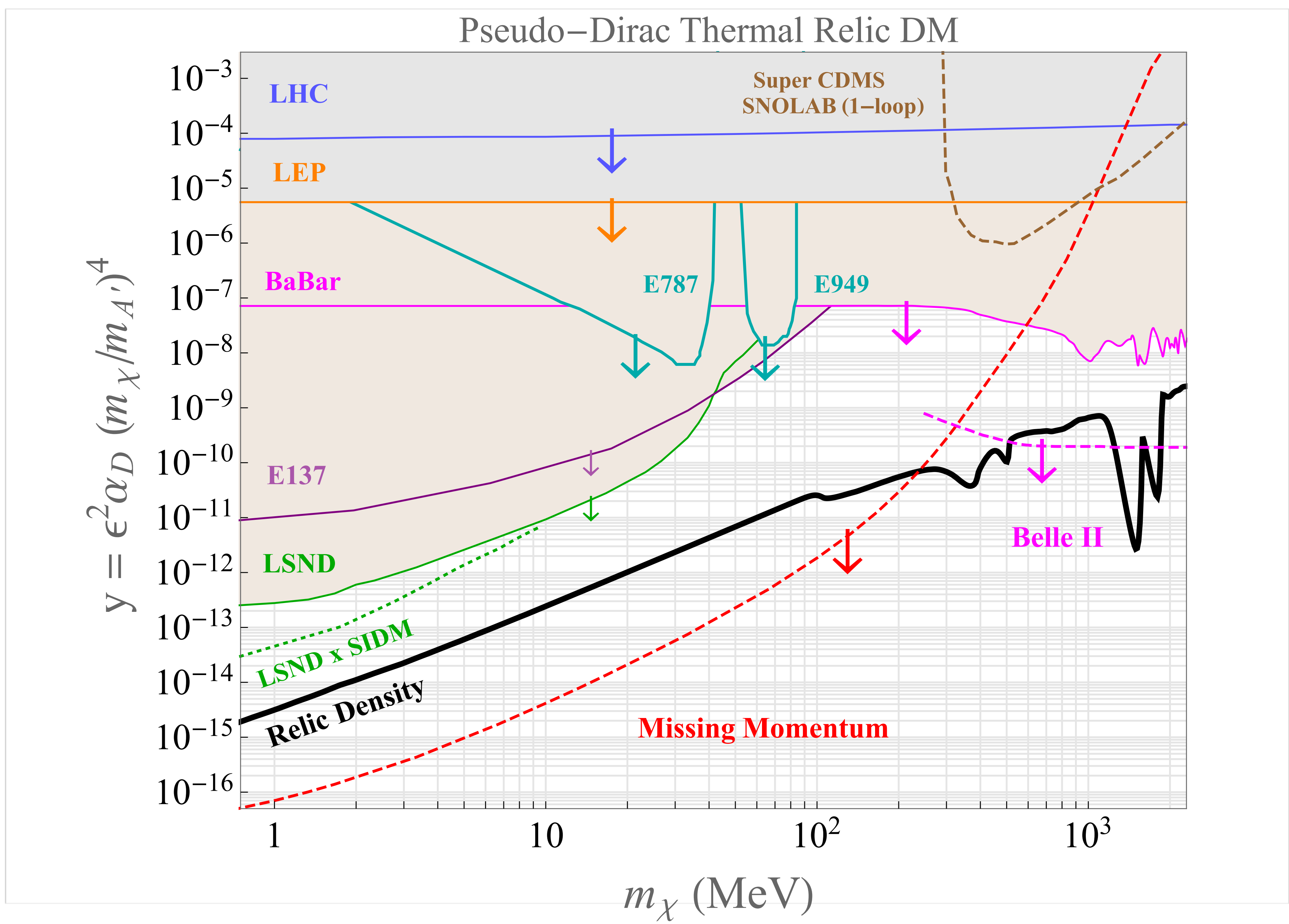
BaBar, LSND, LHC: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$

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

Fermion Symmetric Inelastic

$n_{\rm DM} = n_{\overline{DM}}$ $\quad$ keV $< \Delta \ll m_\chi$

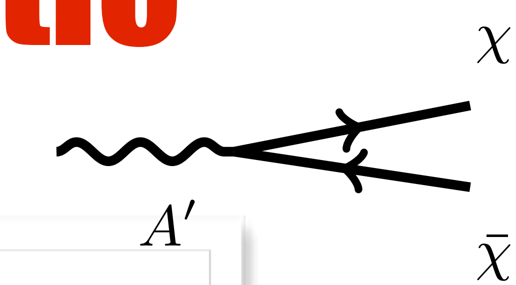


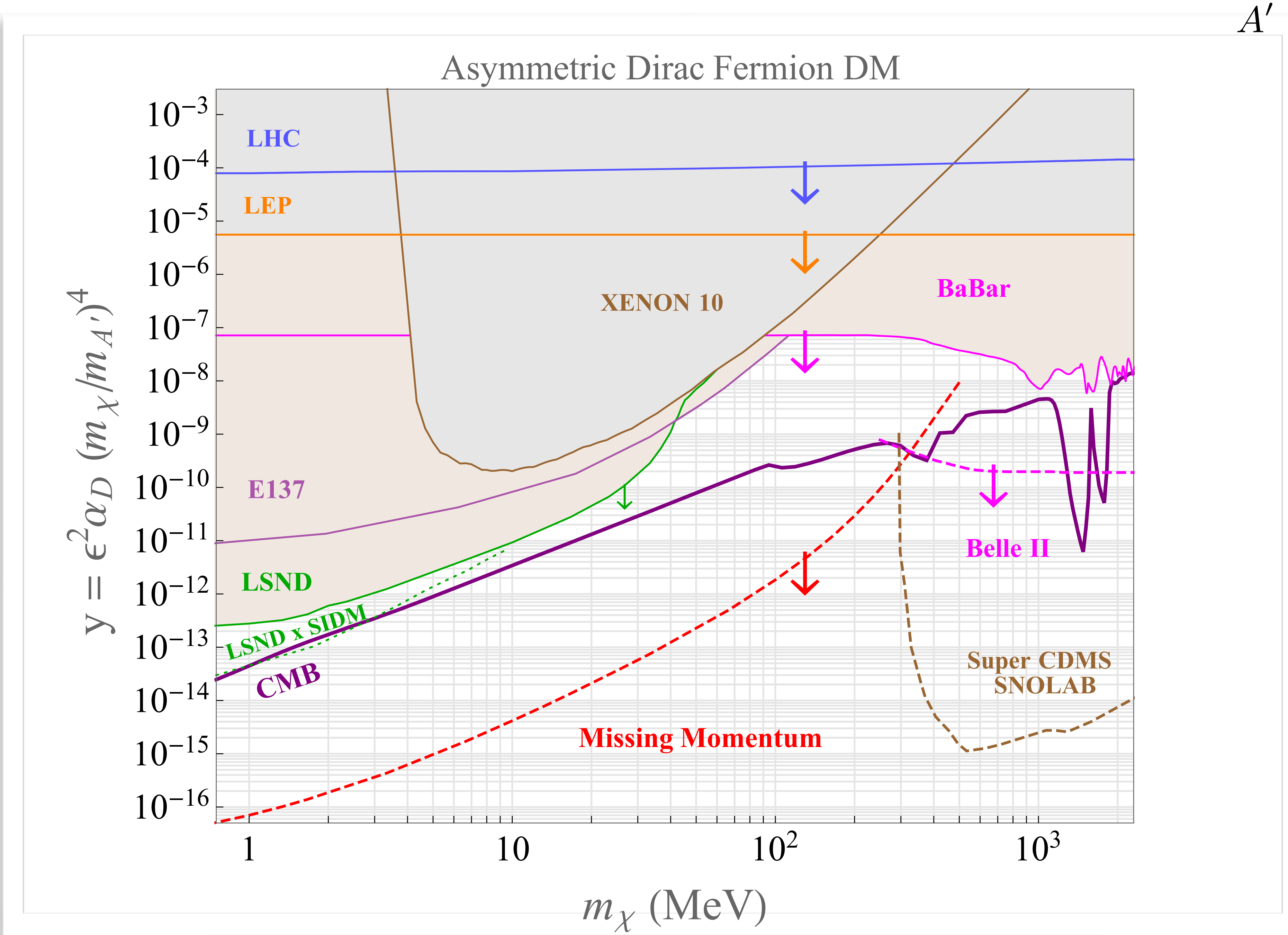


BaBar, LSND, LHC, E137: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$ $\quad 3 \times 10^{16} e^-$

Fermion Asymmetric Elastic

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

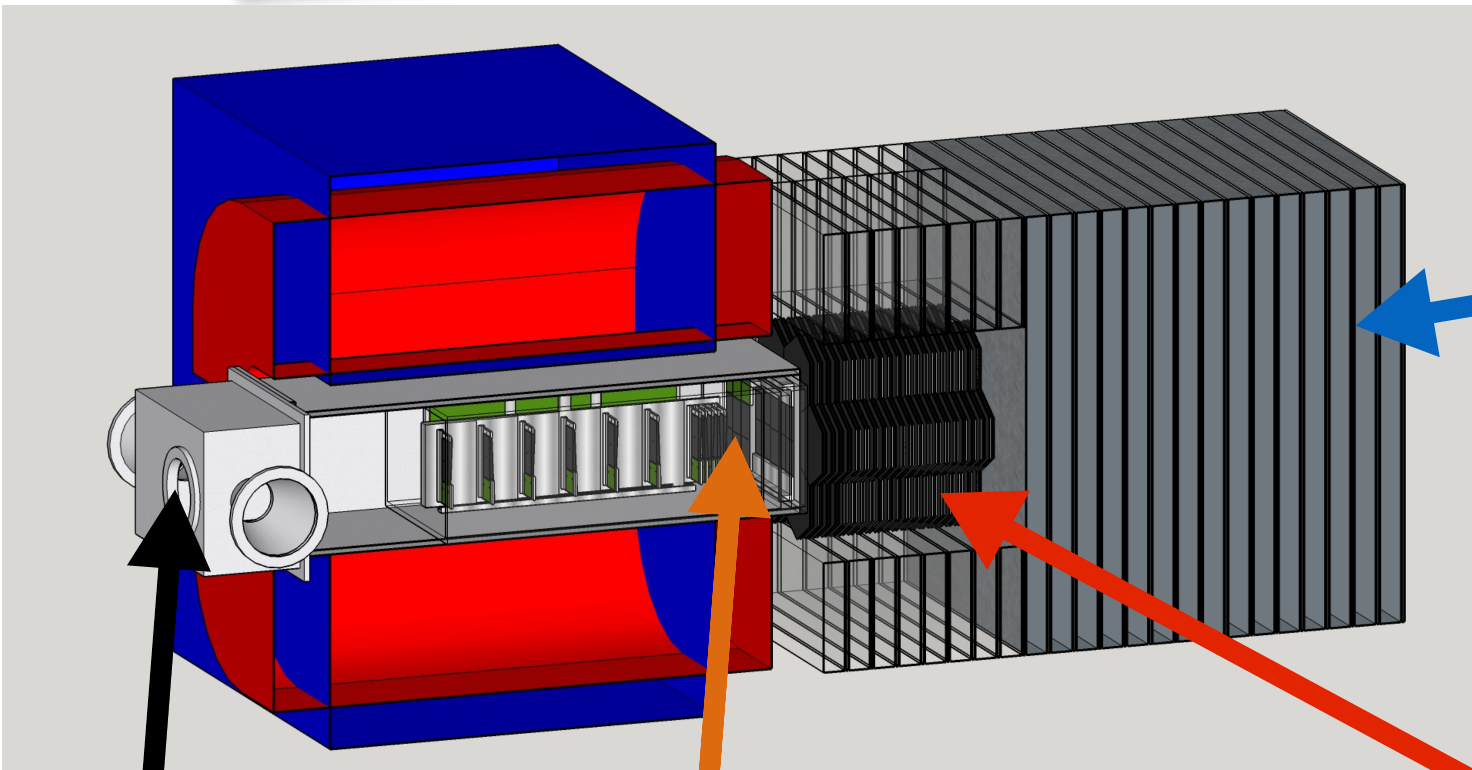




BaBar, LSND, LHC: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$

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

Concrete Realization in Progress @ SLAC



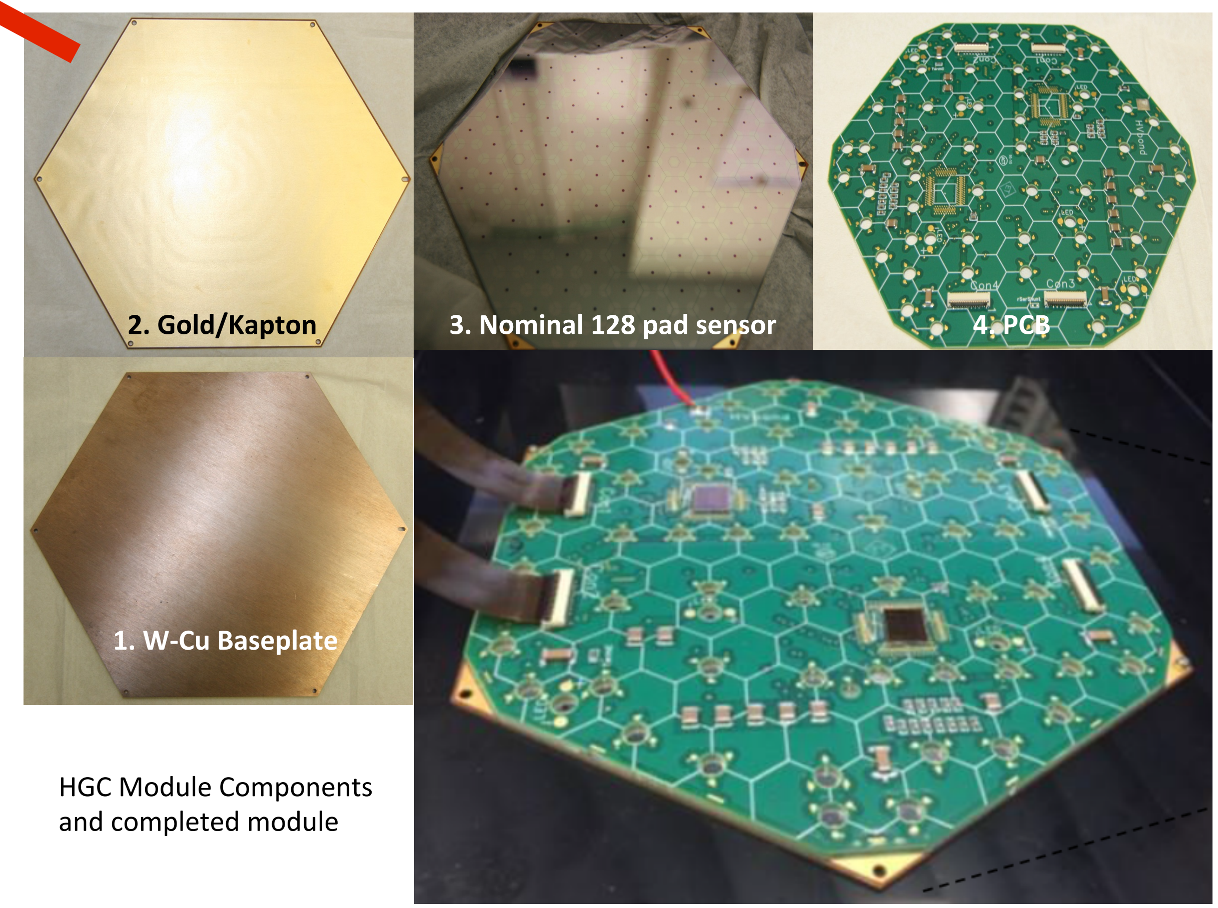
HCAL

ECAL

Target

Beamline

LDMX ECAL based on CMS forward calorimeter design for high luminosity upgrade



HGC Module Components
and completed module

Concluding Remarks

Light thermal DM is viable w/ rich dynamics

-Broad class of testable, predictive models

-Testing these suffices to cover more elaborate cases

-Sharply defined question, not a fishing expedition

-Existing search program wont cover it

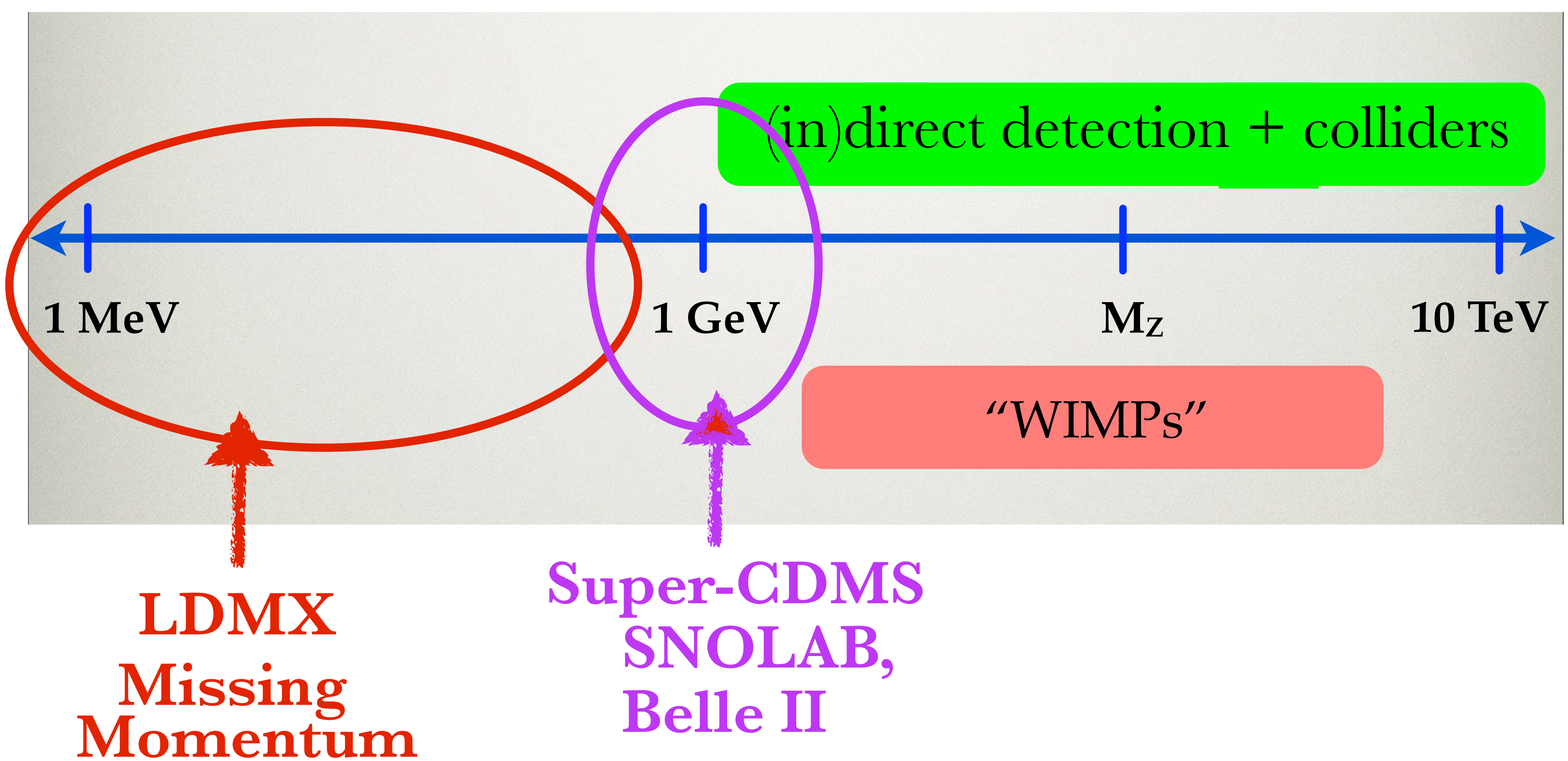
Concluding Remarks

New missing momentum technique

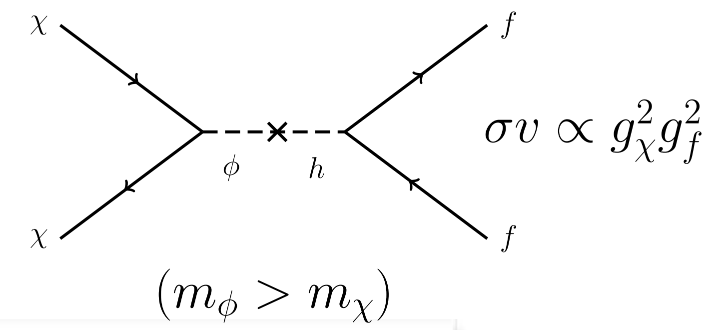
Observe DM production in real time

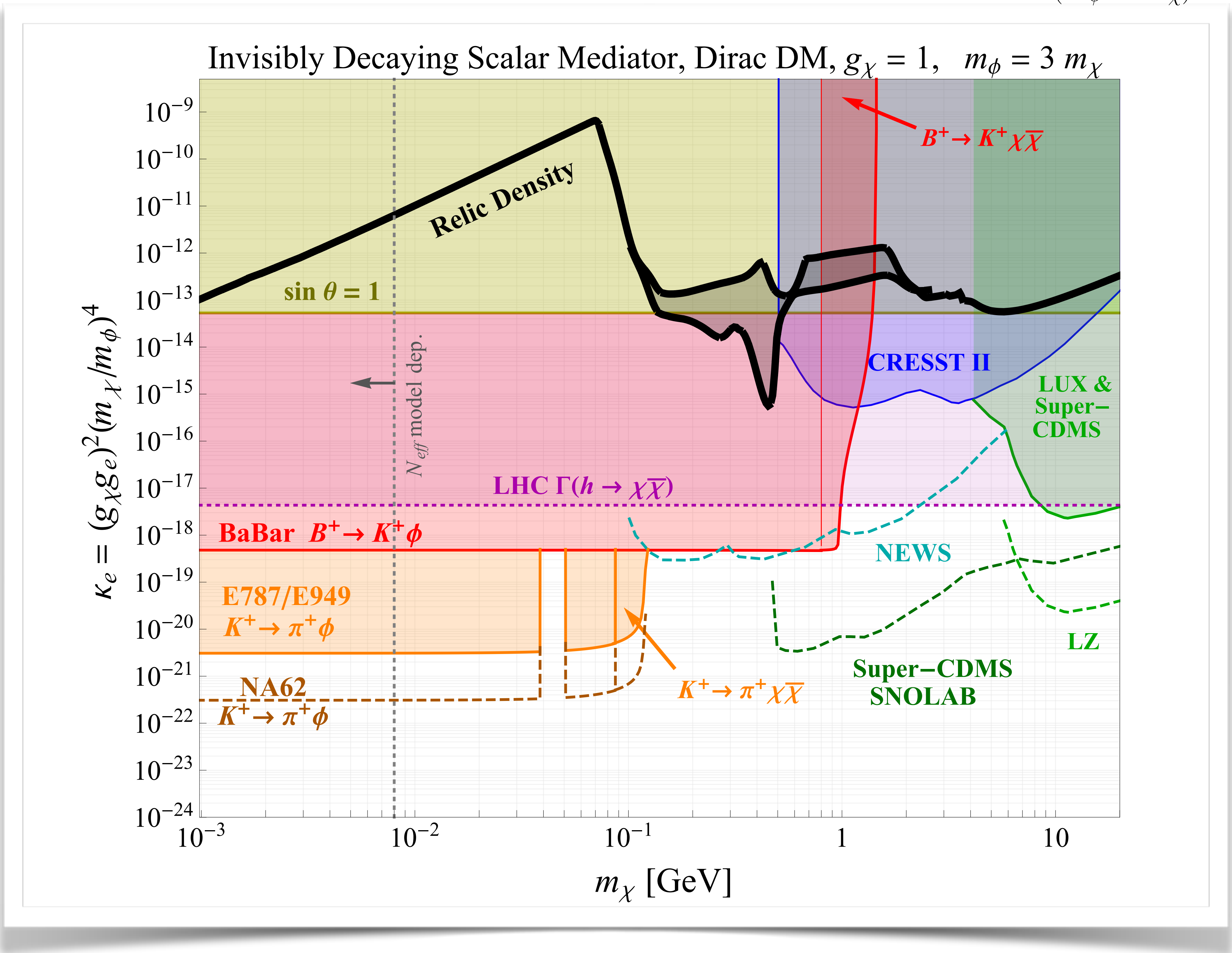
BG from “fakes” is measurable & reducible

Irreducible BG is negligible

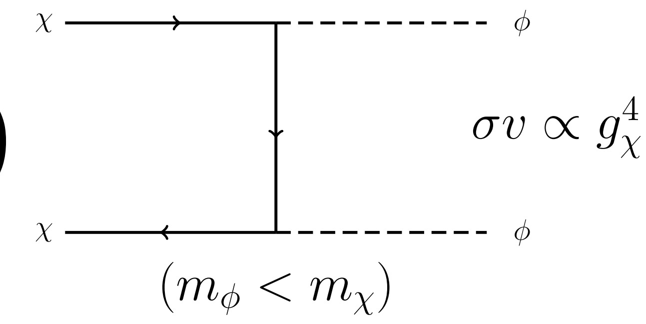


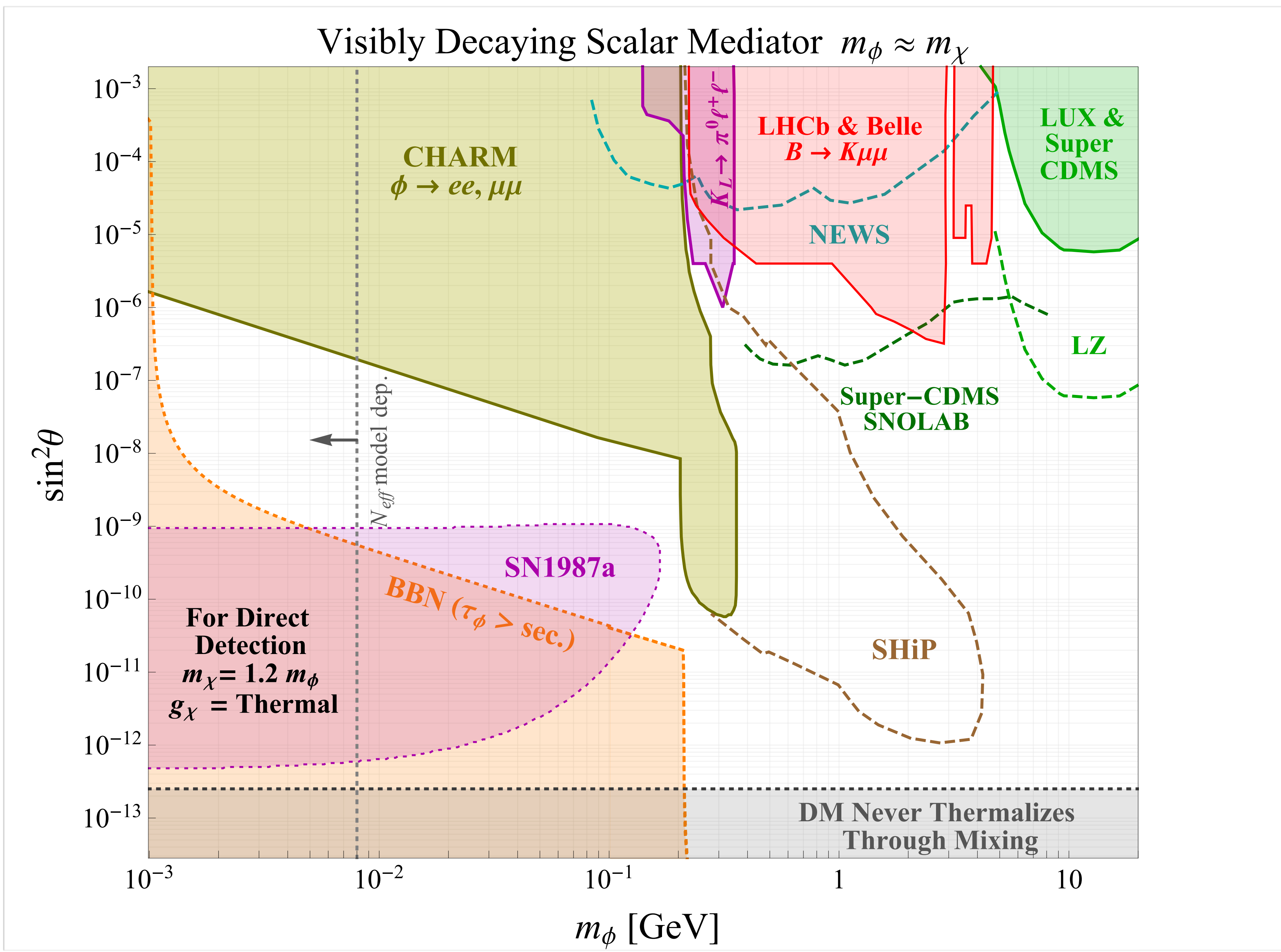
Higgs Portal



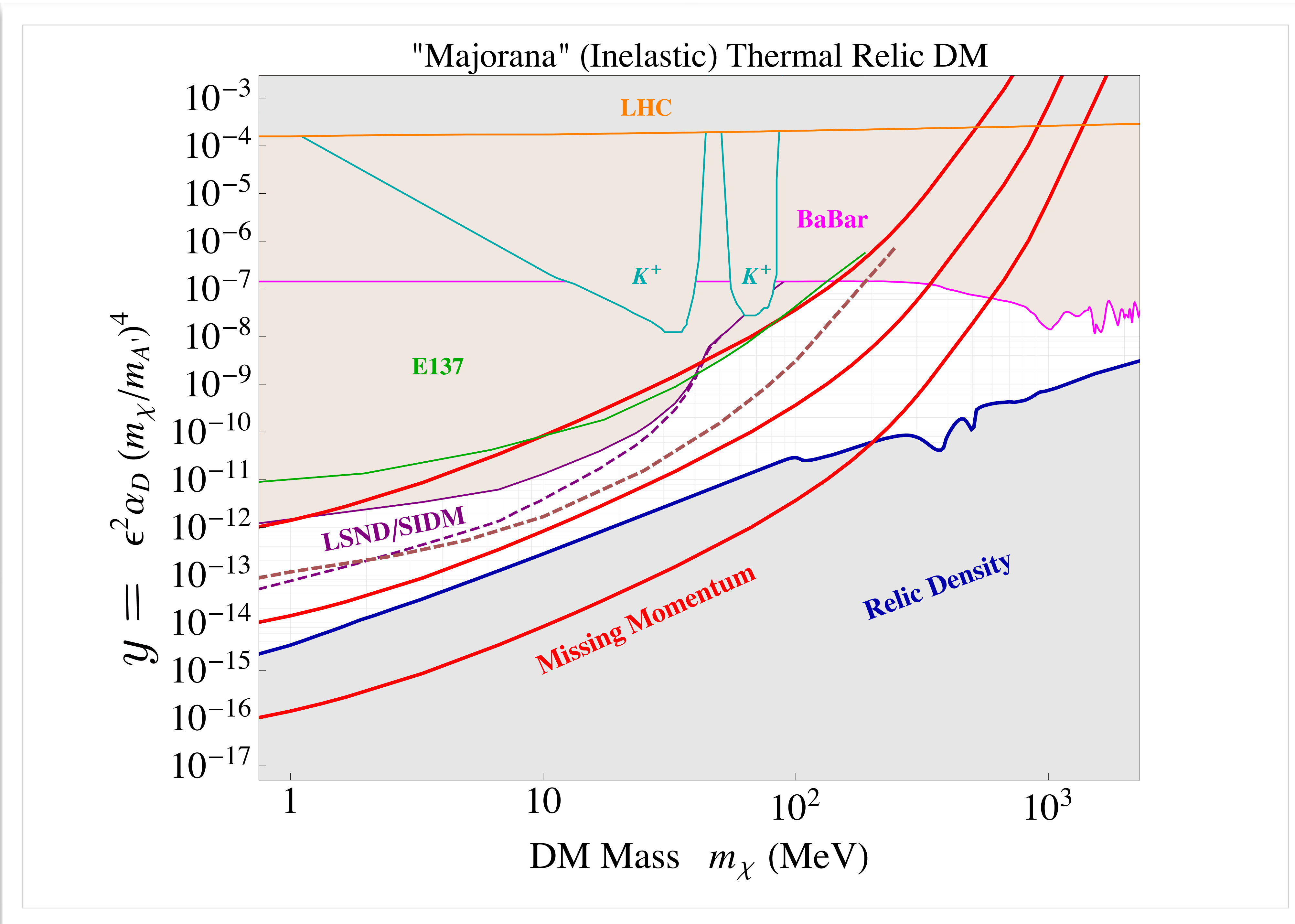


Higgs Portal (secluded)





Reach Projections



3×10^{12} 3×10^{14} 3×10^{16}

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