# (light) Dark Matter Overview

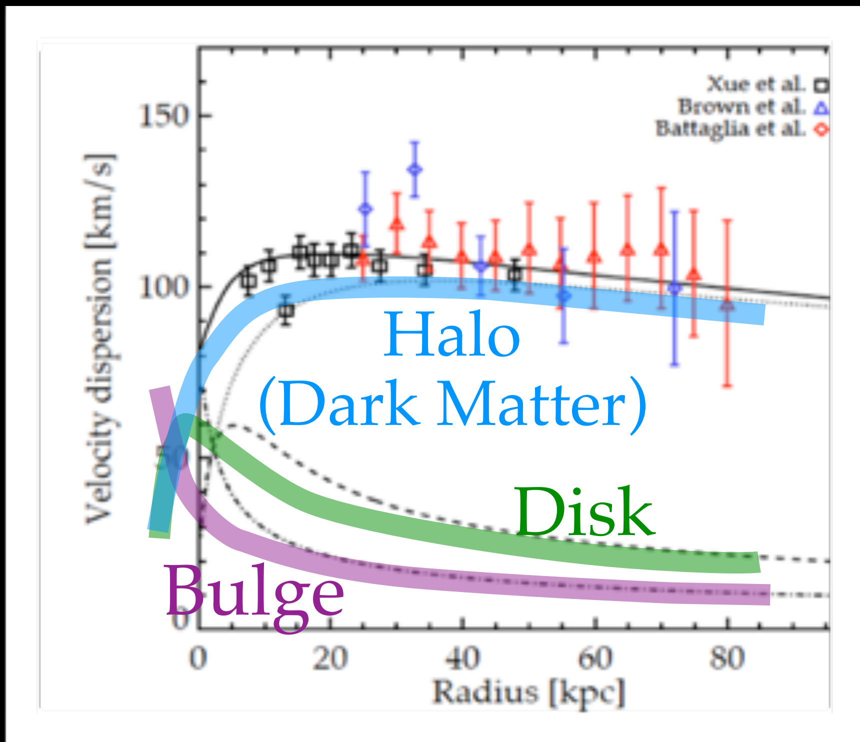

## Gordan Krnjaic



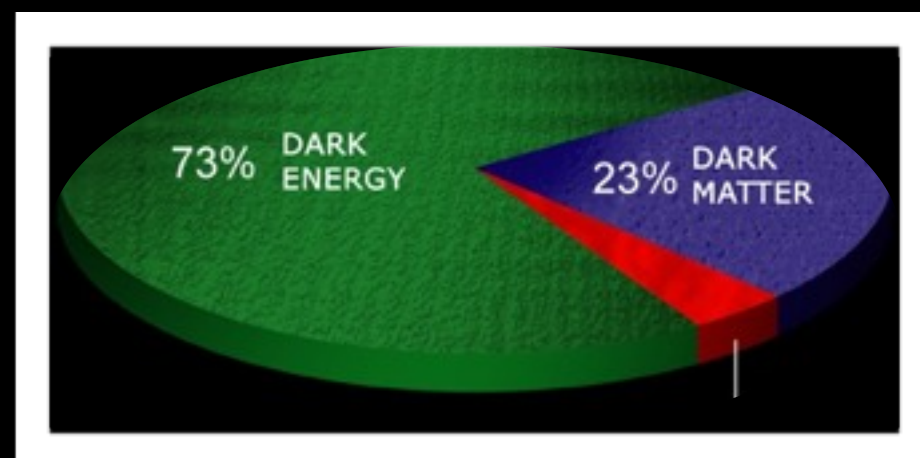
**Intense Electron Beam Workshop**

**Cornell University, June 18, 2015**

# Impressive Indirect Evidence for DM

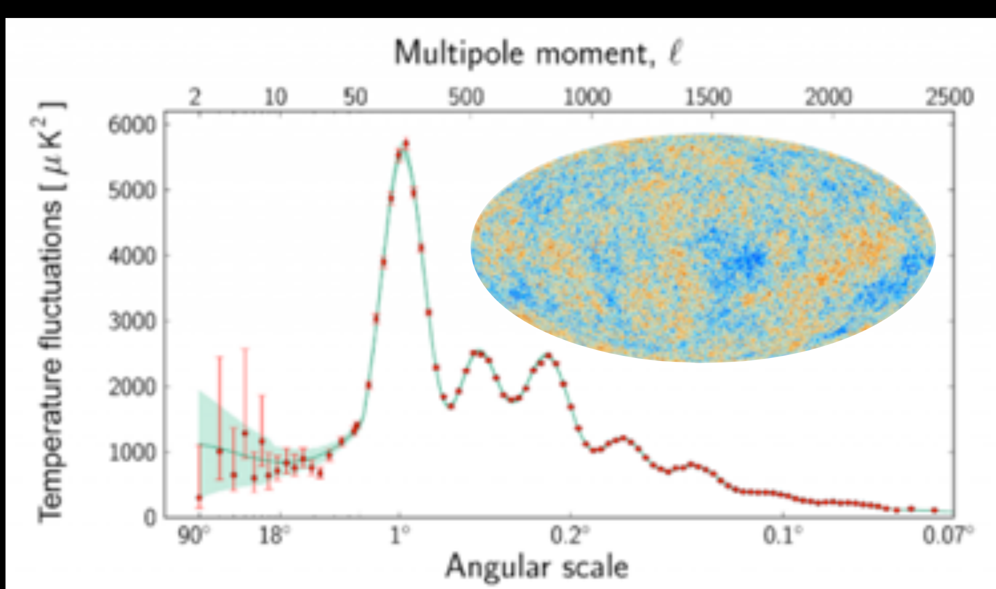



Rotation
Curves

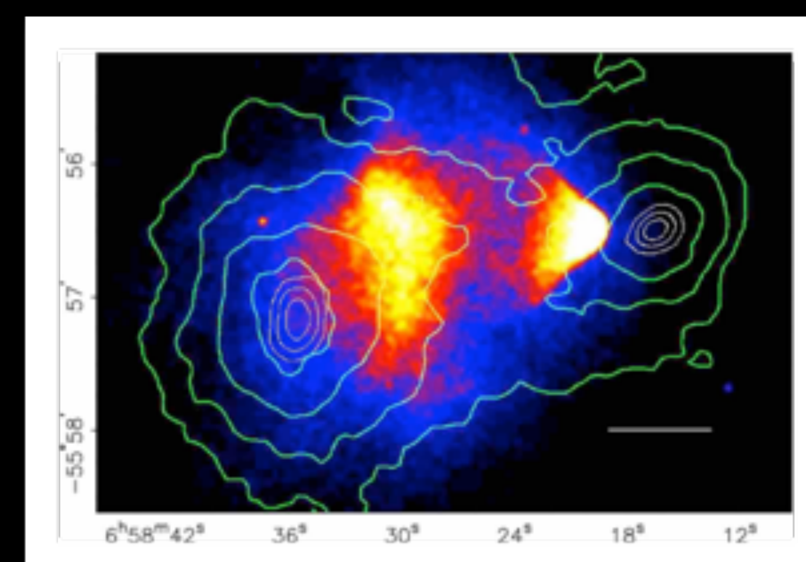



Gravitational
lensing

CMB




Cluster
collisions



**but no direct observation (yet)!**

# Discovery challenge: no clear scale

## DM viable over enormous mass range

$$10^{-33}\ \text{eV} \longleftarrow m_{\text{DM}} \longrightarrow 10^{19}\ \text{GeV}+$$

Hubble sized axion-like particle

Black hole/MACHO

## Many scenarios are undiscoverable

**Fortunately, "thermal" history narrows scope**

Applies to most* interesting /discoverable models
& lots of room for progress

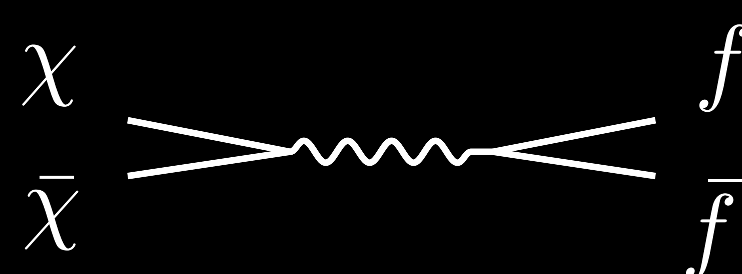
# Thermal Origin is Predictive

## Feature # 1: huge early universe density!

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

Requires <u>minimum</u> annihilation rate

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



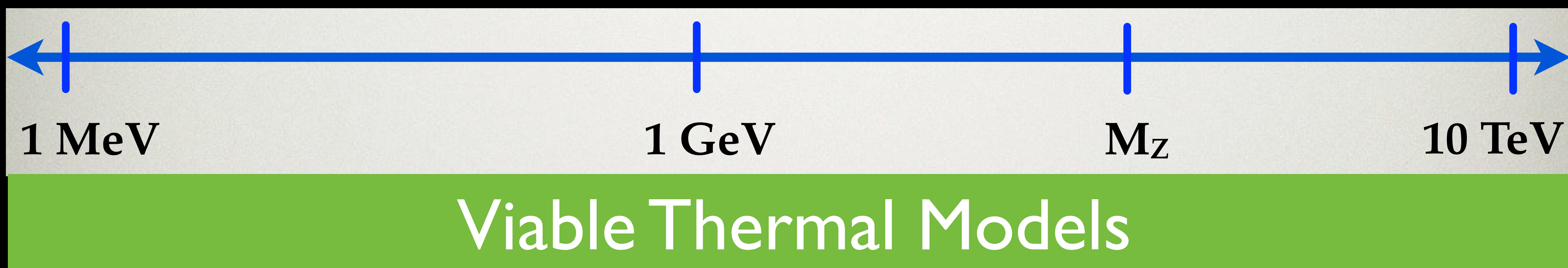

$=$ symmetric DM

$>$ asymmetric or subdominant DM

**Important target for discovery or falsifiability**

# Thermal Origin is Predictive

## Feature # 2: most masses can't be thermal



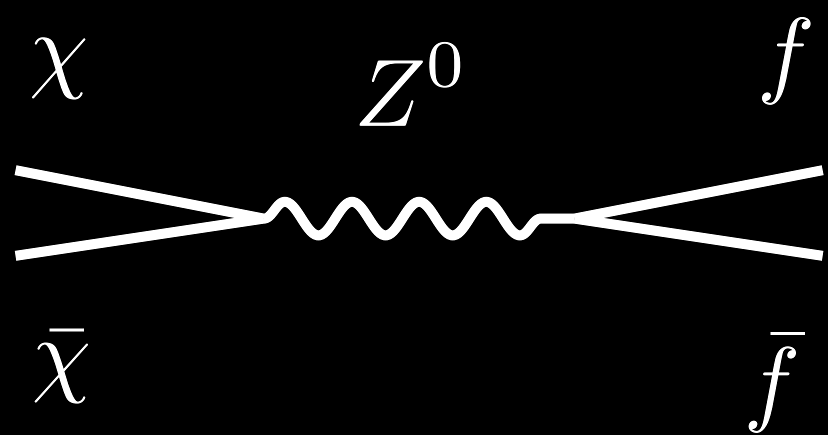

<10 keV DM too hot
spoils structure formation

> 10 TeV DM
overproduced
and/or nonperturbative

## Equilibrium reduces viable mass & coupling range

# Annihilation "mediators"

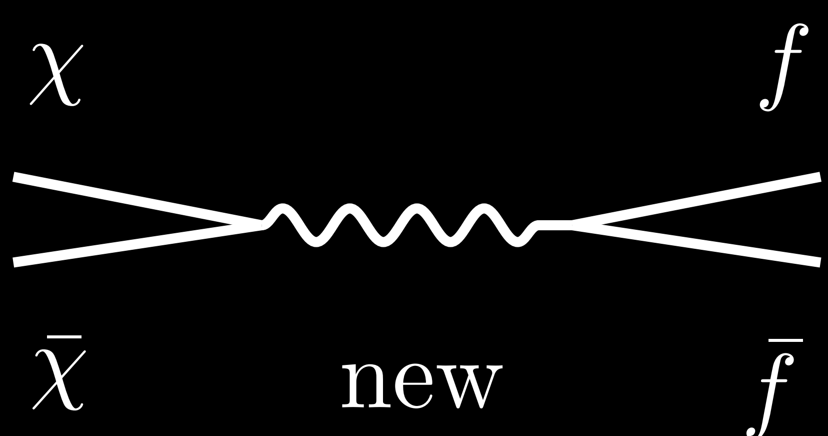
**> GeV DM : Mediator can carry SM charge**




**"wimp miracle"**

$$\sigma v \propto \frac{m_\chi^2}{m_Z^4} \implies \Omega_\chi \sim \Omega_{DM}$$

**< GeV DM : W/Z/H too heavy!**




**"wimpless miracle"**

$$\sigma v \propto \frac{m_\chi^2}{m_{\rm new}^4} \implies \Omega_\chi \sim \Omega_{DM}$$

$\implies$ Need light new mediator

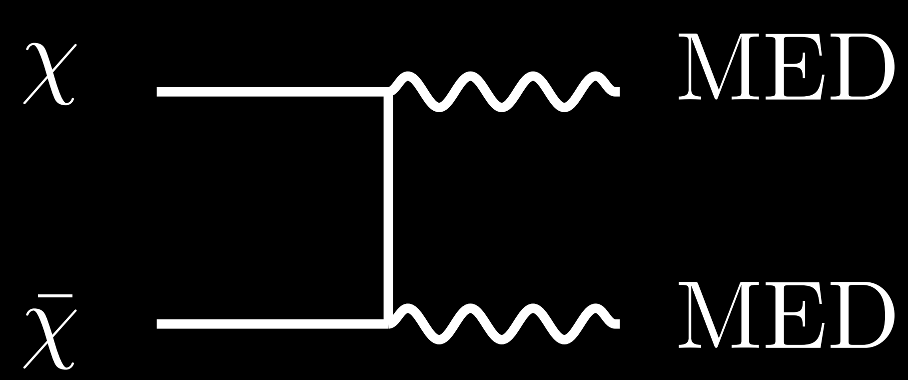
# What kind of new "mediator"?

**Direct annihilation = invisibly decaying mediator**

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

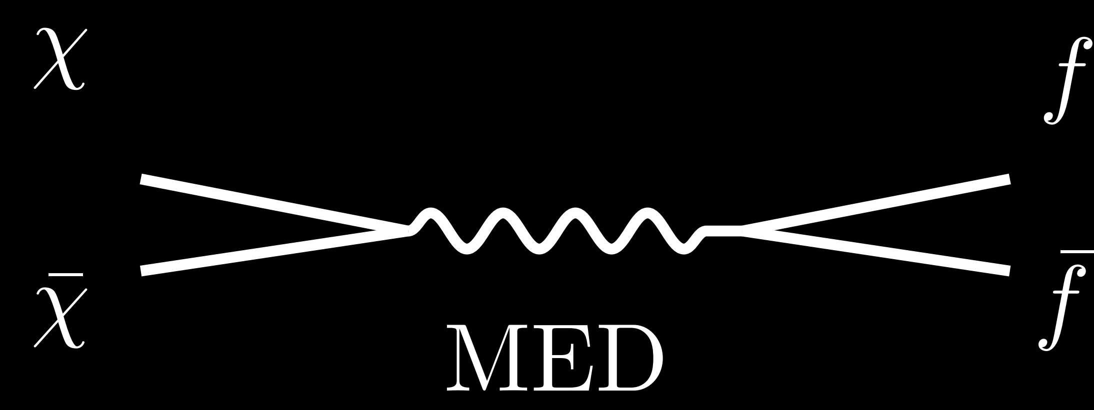
**offers clear & testable target**

Visible mediator decay
t-channel DM annihilation




insensitive to SM coupling

Invisible mediator decay
s-channel DM annihilation




sensitive to DM x SM coupling

# What kind of new "mediator"?

**Direct annihilation = invisibly decaying mediator**

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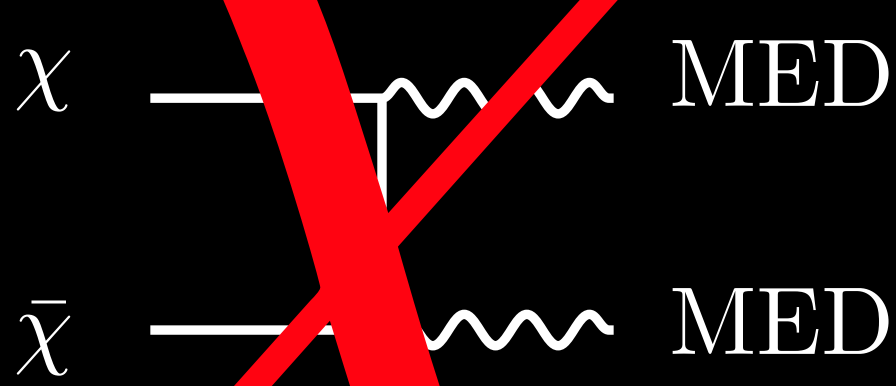
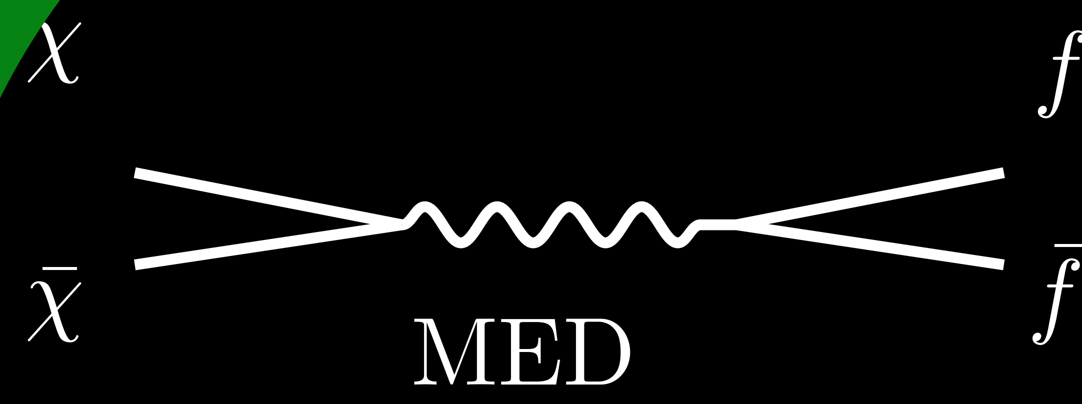
Visible mediator decay
t-channel DM annihilation




insensitive to SM coupling

I...ble mediator decay
...annel DM a...ation




...sitive to DM x SM c...g

# What kind of new "mediator"?

## Light mediator must be SM neutral

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

**couplings scale with mass**

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

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

**Invisibly decaying A' mediator**

**couplings scale with charge**

**A' to SM:** $\epsilon e$

**A' to DM:** $g_D$

Some caveats (see Natalia Toro's talk)

# What kind of new "mediator"?

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

**Thermal Ruled out by rare meson decays**

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

[Izaguirre, GK, Schuster, Toro]
(to appear)

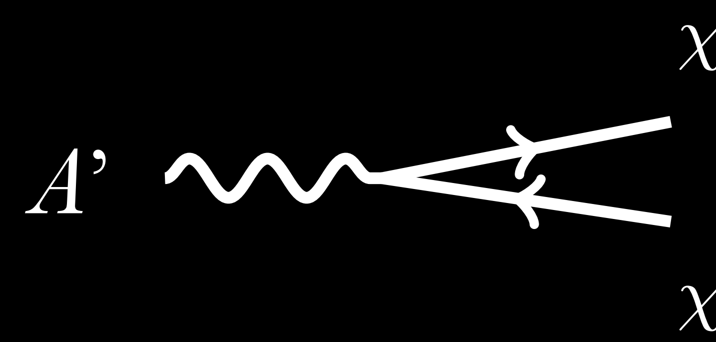
**Vector Portal** $\epsilon F_{\mu\nu} F'_{\mu\nu}$

**Many viable sub-GeV scenarios**

# What kind of DM?

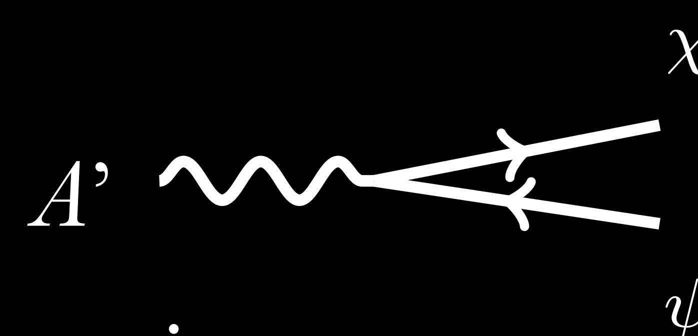
## Classify by Coupling/Spin/Abundance

**Elastic (no mass splitting)**




Constrained by CMB & Direct Detection

**Inelastic (mass splitting)**




Easily evades CMB & Direct Detection constraints

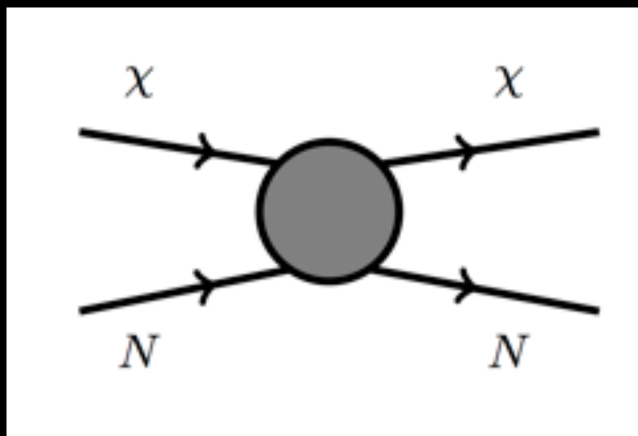
$$\Delta \equiv m_\psi - m_\chi$$

**Either can be (fermion/scalar) x (symmetric/asymmetric)**

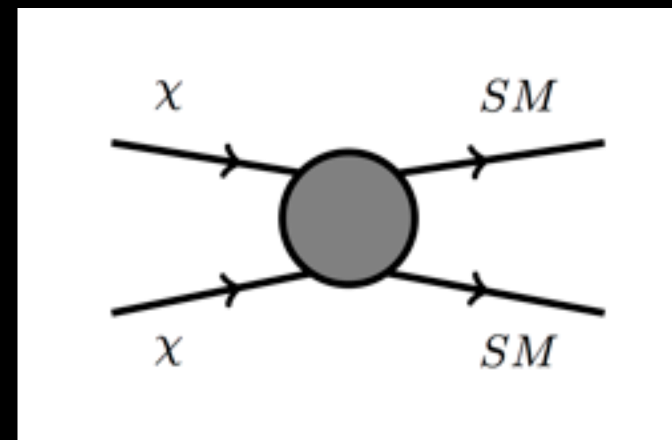
**How constrained are these?**

# Traditional Search Program

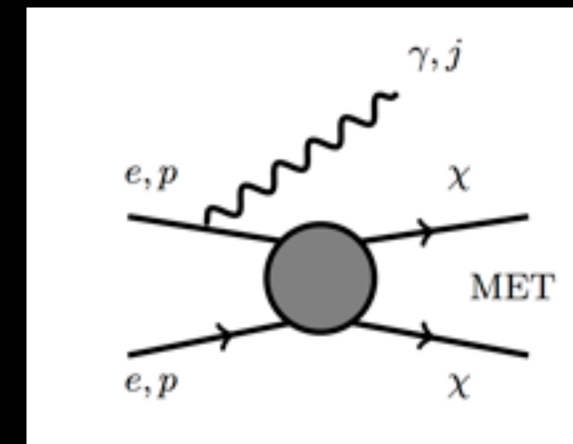
Direct Detection



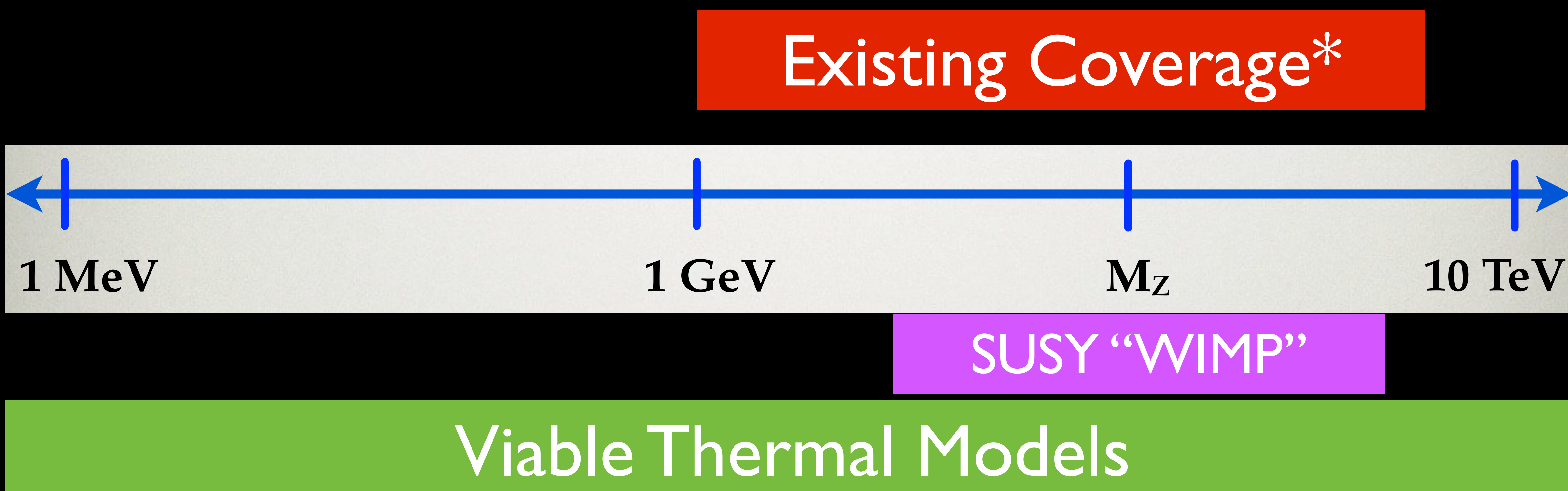

Indirect Detection




Colliders

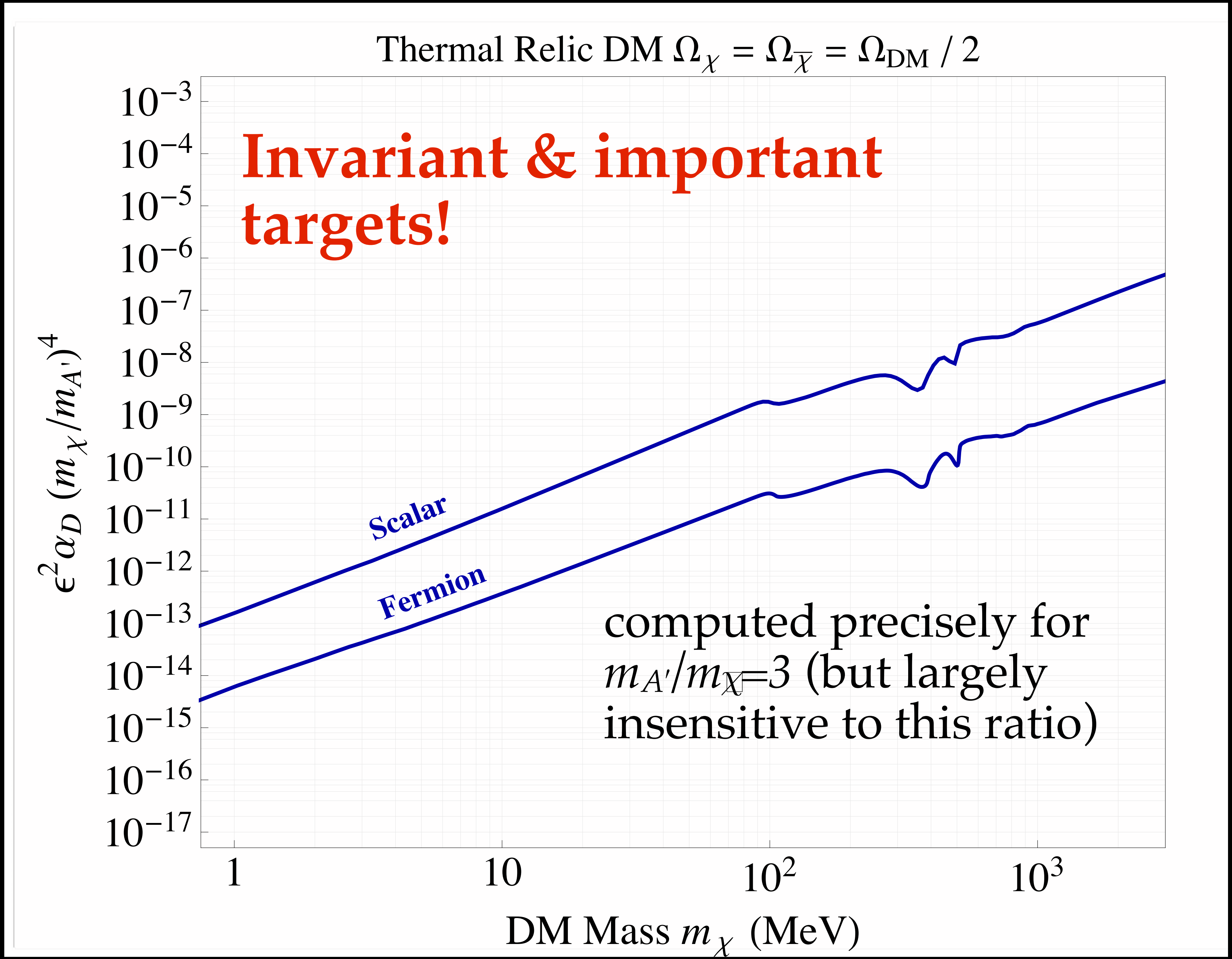



**Insensitive to sub-GeV thermal DM**




* = elastic & symmetric

# Thermal Target



# Bounds: Electron Direct Detection

Xenon10 electron scattering constrains

$$\sigma_{\chi e} \propto \epsilon^2 \alpha \alpha_D \frac{\mu_{\chi e}^2}{m_{A'}^4}$$

Theorist reinterpretation
Essig Mardon, Papucci, Volansky, Zhong
1206.2644

**Same scaling as thermal relic target, compare by plotting:**

$$y \equiv \epsilon^2 \alpha_D \left( \frac{m_\chi}{m_{A'}} \right)^4 \quad \text{vs.} \quad m_\chi$$

**Model Dependent!**

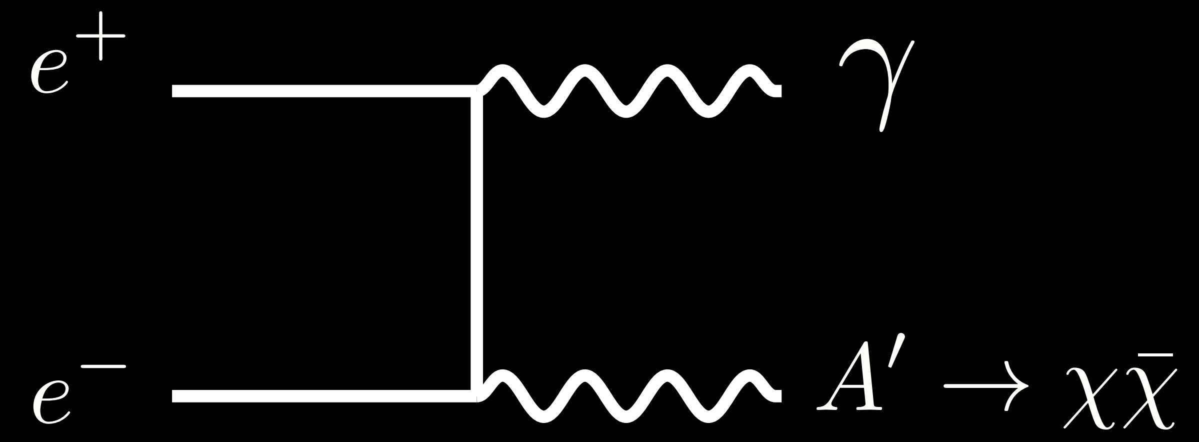
**Trivially evaded with inelastic coupling**

# Bounds: Colliders/B-Factories

## BaBar Production:

$$\sigma \sim \frac{\epsilon^2 \alpha}{E_{CM}^2}$$

$$\sim y \times \frac{1}{g_D^2} \left( \frac{m_{A'}}{m_\chi} \right)^4$$




Theorist reinterpretation

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

**Not intuitive: must assume some dark coupling (and mass ratio) to compare with thermal target**

**Conservative to choose <u>large</u> DM coupling (order-one mass ratio) demands tiny visible coupling for fixed annihilation rate**

# Bounds: CMB

If* DM can annihilate during CMB epoch, it can reionize Hydrogen

$$\sigma v \propto \epsilon^2 \alpha \alpha_D \left( \frac{m_\chi}{m_{A'}} \right)^4 \frac{1}{m_\chi^2}$$

Slatyer et. al. 1206.2644
Theorist reinterpretation

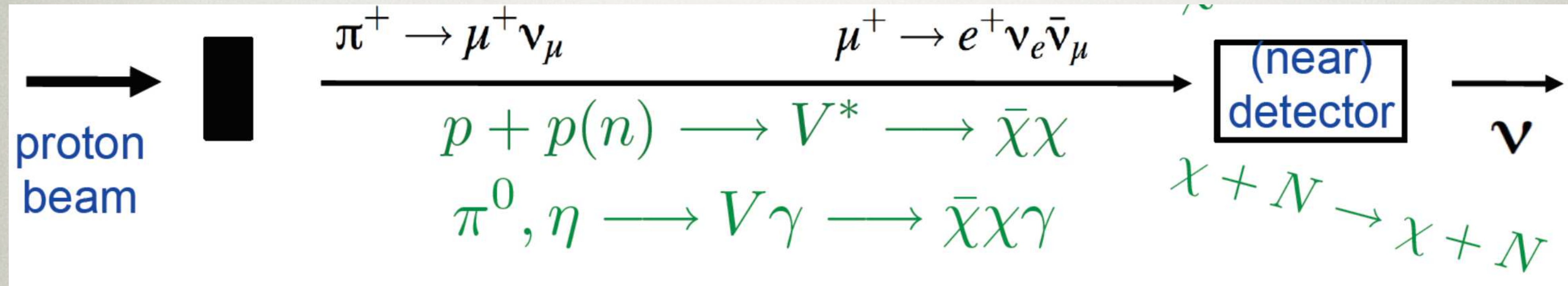
**Same scaling as thermal relic target, compare by plotting:**

$$y \equiv \epsilon^2 \alpha_D \left( \frac{m_\chi}{m_{A'}} \right)^4 \quad \text{vs.} \quad m_\chi$$

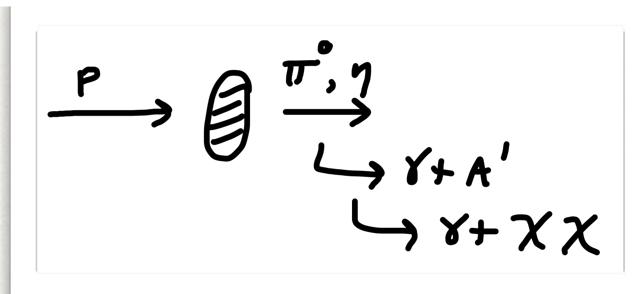
Model Dependent!

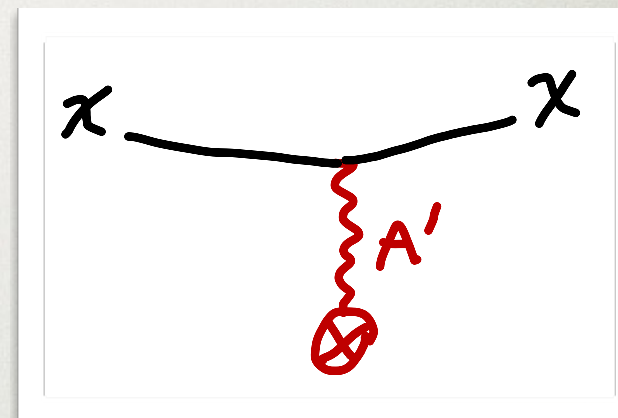
**Weaker [absent] for p-wave [inelastic] coupling!**

# Bounds: Beam Dumps

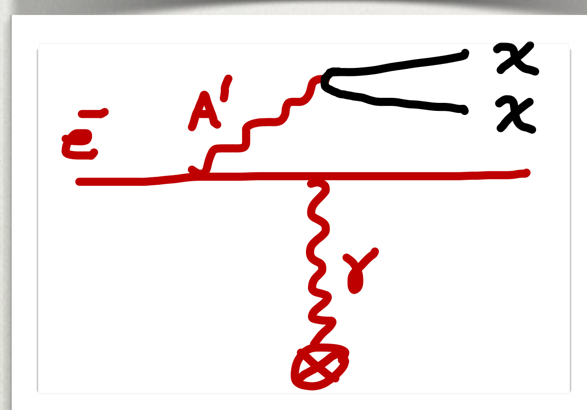



0906.5614,
1107.4580,1205.3499
Batell,DeNiverville,
McKeen, Pospelov, Ritz




Izaguirre, Krnjaic, PS
& Toro
PRD.88.114015 and
1403.6826




nuclear dissociation;
nucleon, nucleus, or
electron recoil

**Good sensitivity (from theorists) for LSND**

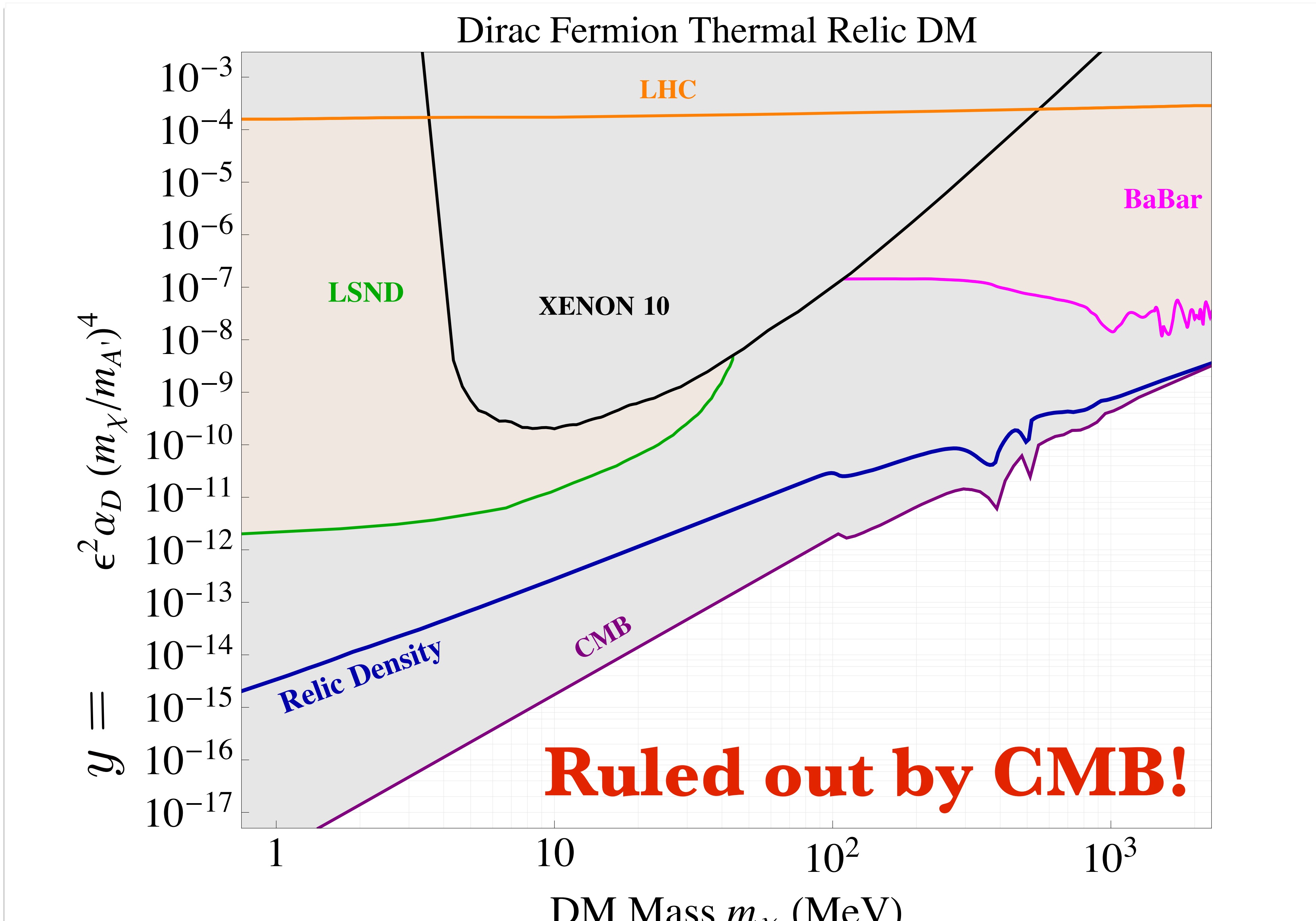
Essig, Batell, Surujon 1406.2698

Rate $\propto \epsilon^4 \alpha_D / m_{A'}^2$

**Conservative Comparison**

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

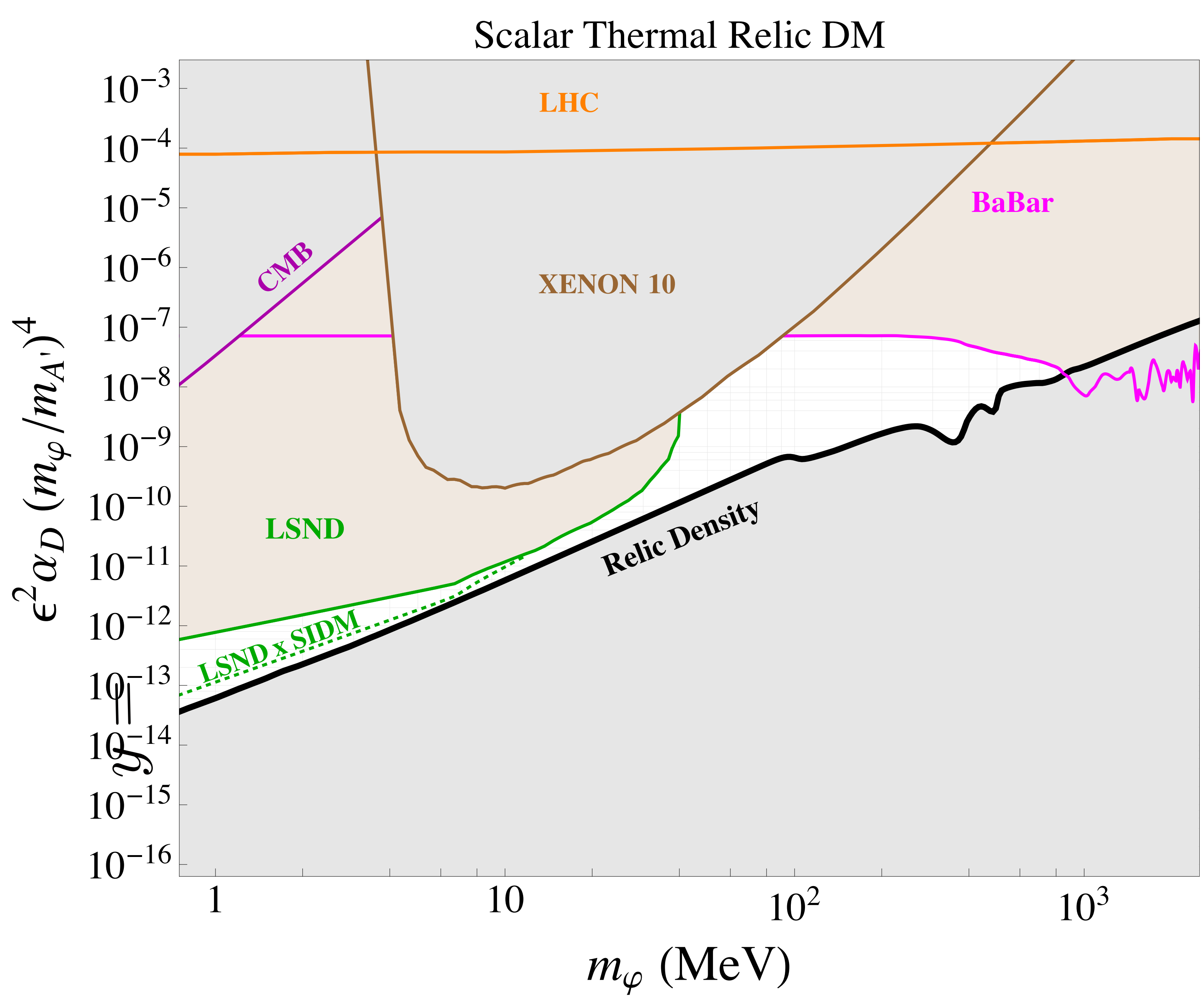
# Status: Fermion Symmetric Elastic




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

Izaguirre, GK, Schuster, Toro 1504.00011

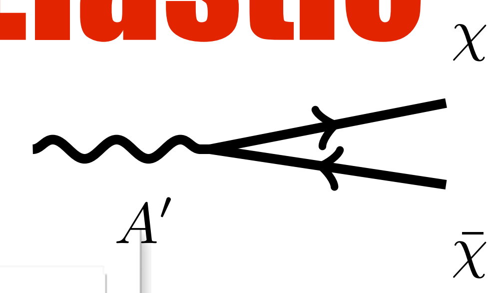
# Status: Scalar Symmetric Elastic

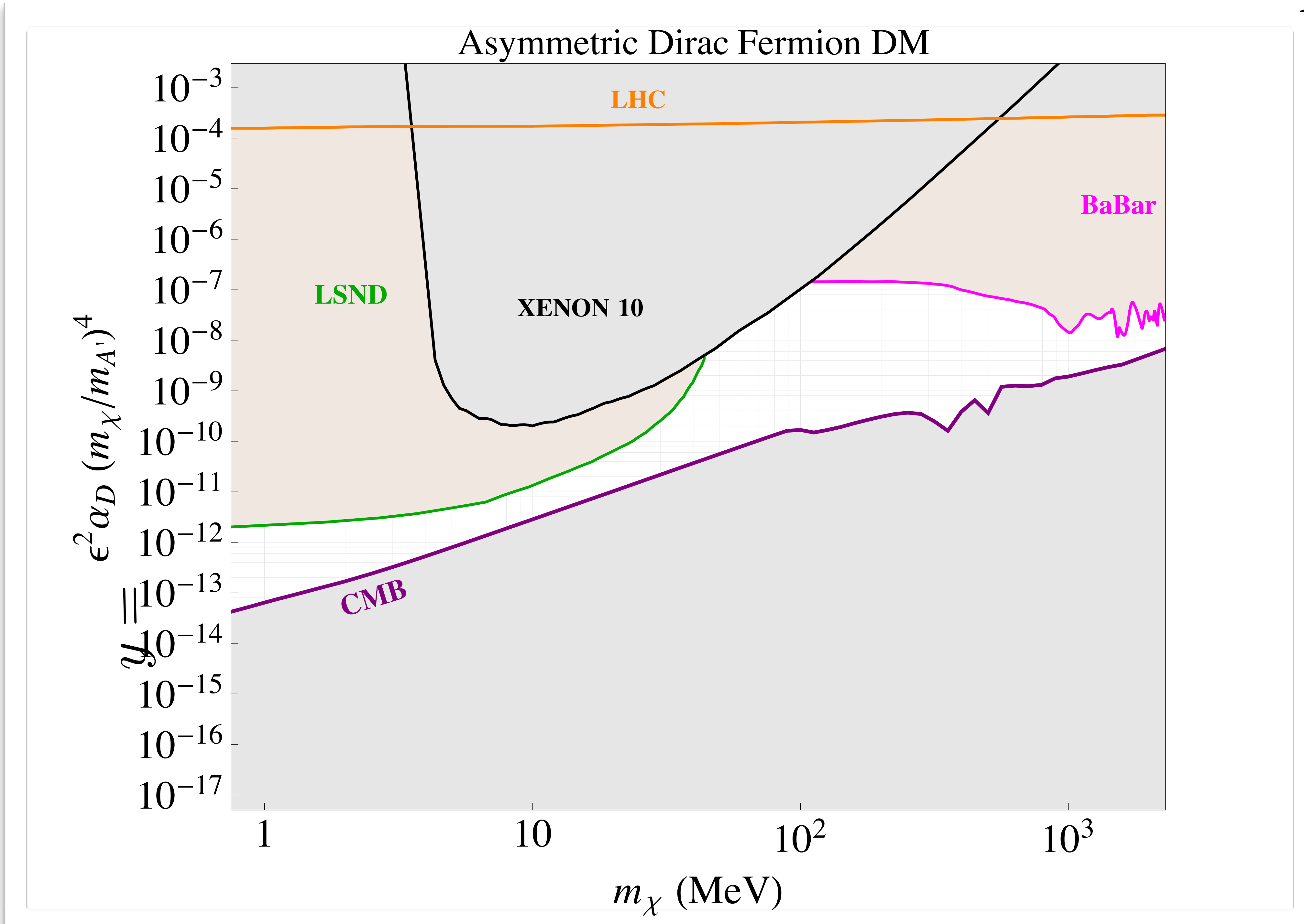

BaBar, LSND, LHC: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$

Izaguirre, GK, Schuster, Toro 1504.00011

# Status: Fermion Asymmetric Elastic




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

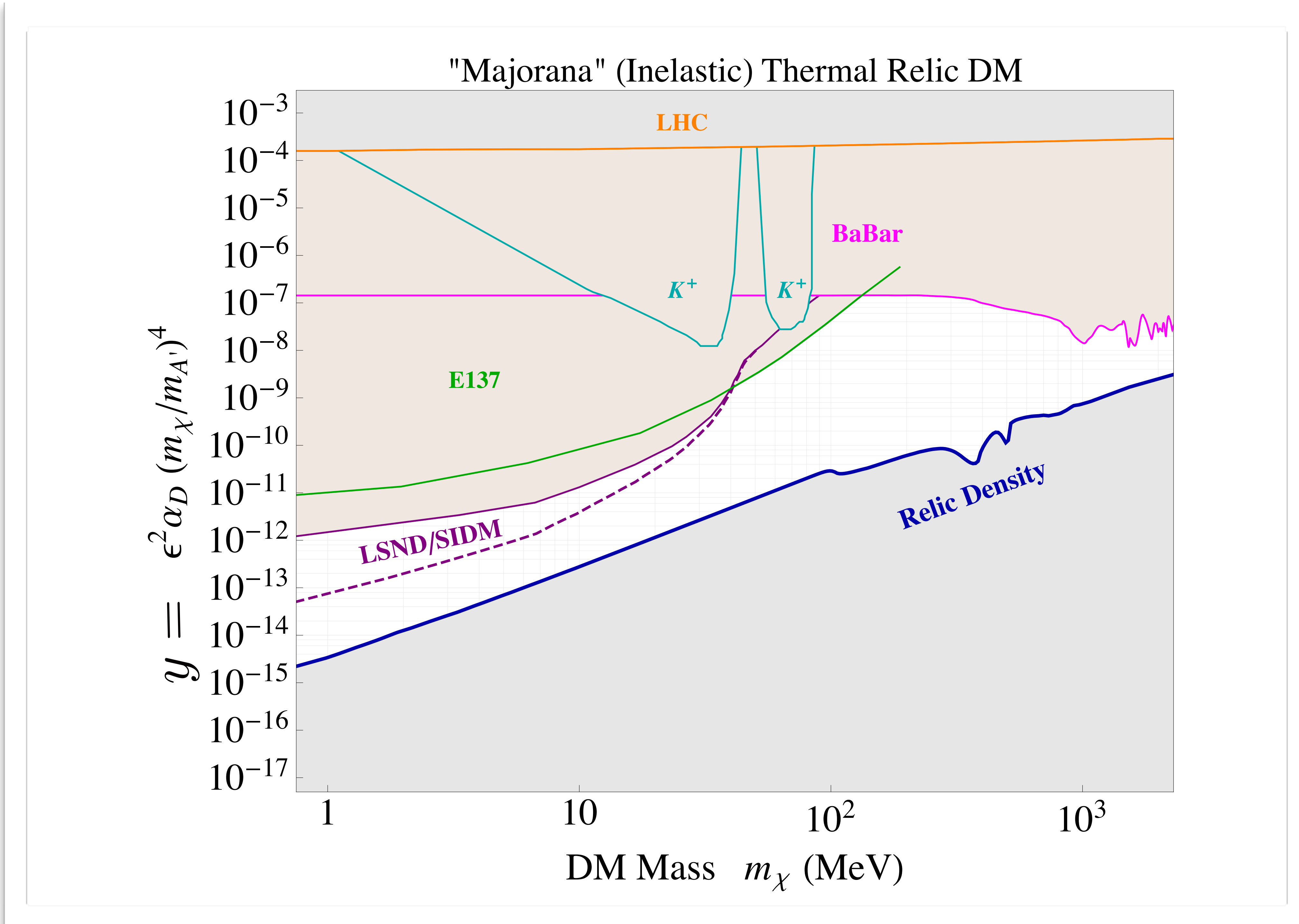



BaBar, LSND, LHC: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$

Izaguirre, GK, Schuster, Toro 1504.00011

# Status: Fermion Symmetric Inelastic

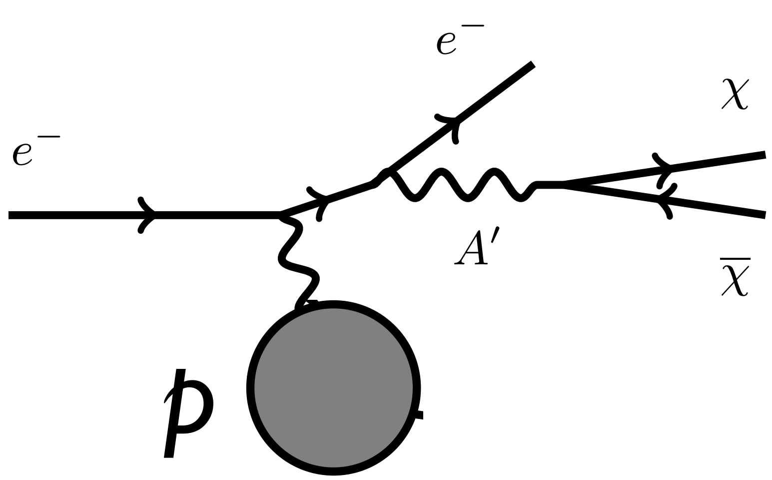
$$\text{keV} < \Delta \ll m_\chi$$

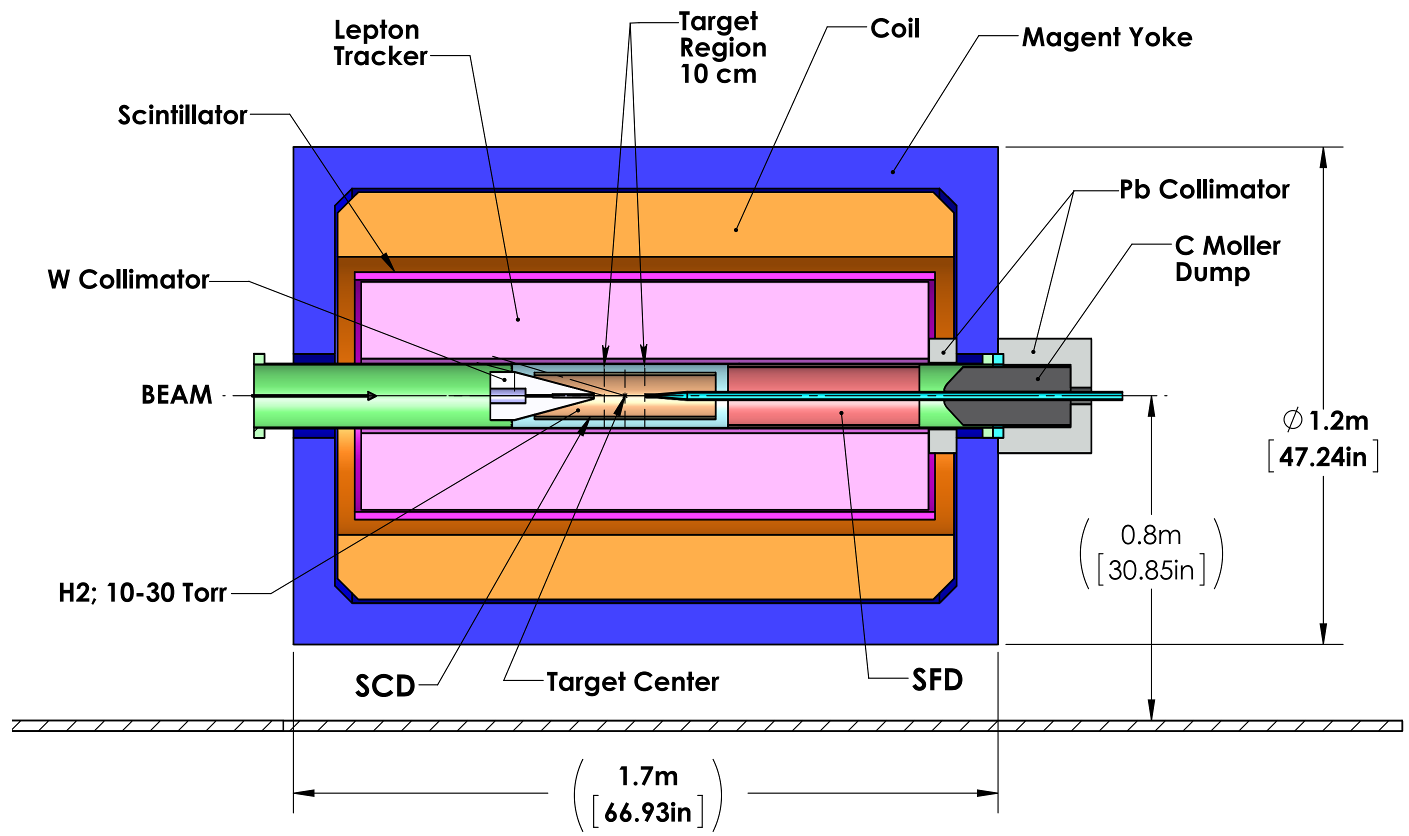




BaBar, LSND, LHC: $\alpha_D \times \left(\frac{m_\chi}{m_{A'}}\right)^4 = \frac{1}{81}$

Izaguirre, GK, Schuster, Toro 1504.00011

# DarkLight @ Cornell linac?




**Reconstruct e & p kinematics, look for resonance**

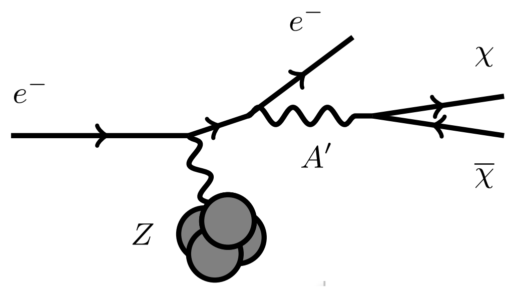
**Agnostic: production/detection insensitive to $\alpha_D$**

**Good photon rejection required**

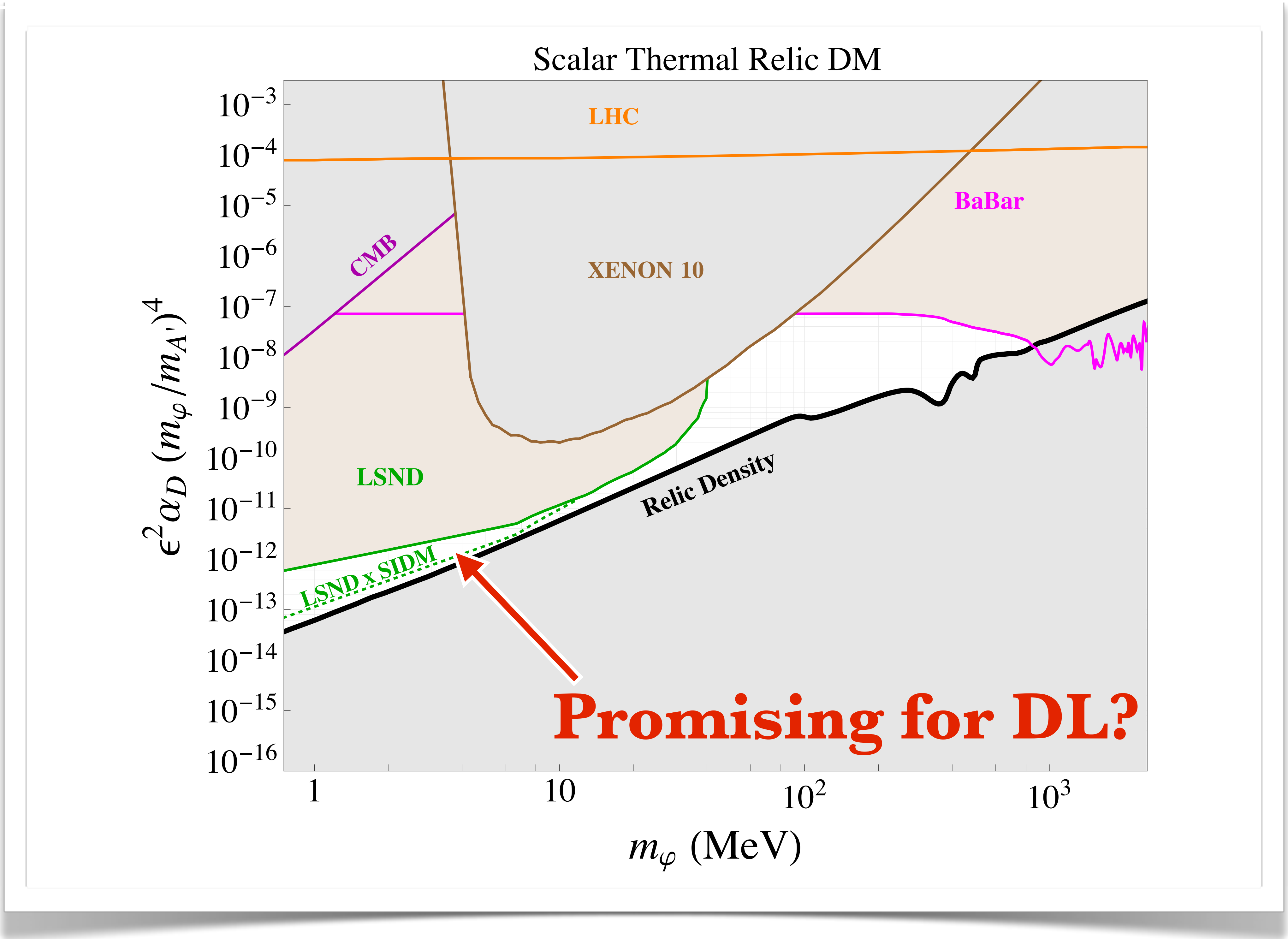
**Relevant e-linac features comparable to JLab effort**

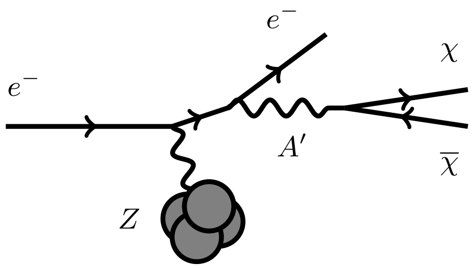
Invisible decay projection (@ JLab)
Kahn, Thaler 1209.0777

Balewski, Fisher et. al. (DarkLight Collaboration)
http://dmtpc.mit.edu/DarkLight/

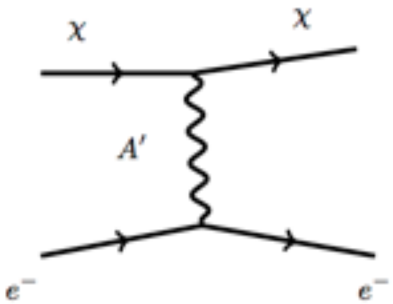


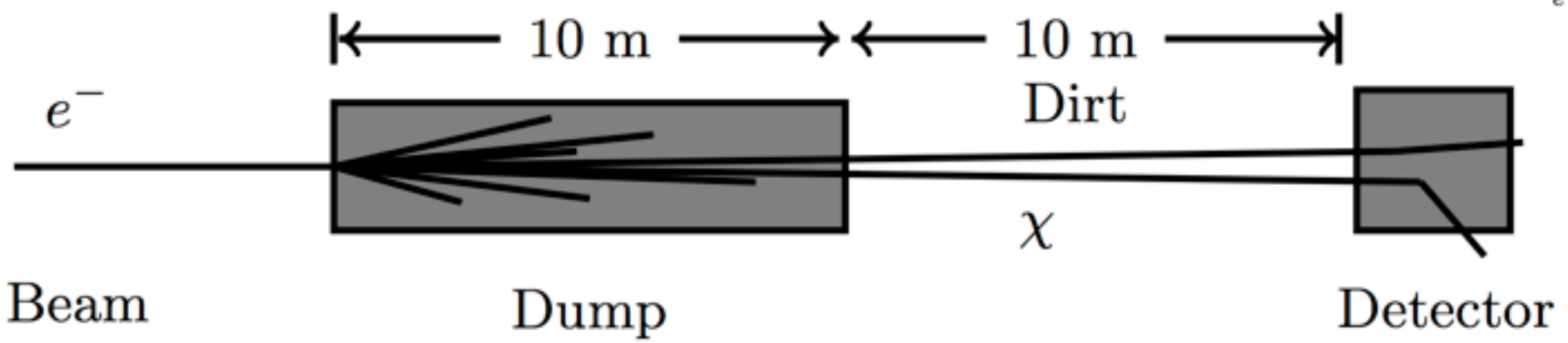

# DarkLight @ Cornell linac?



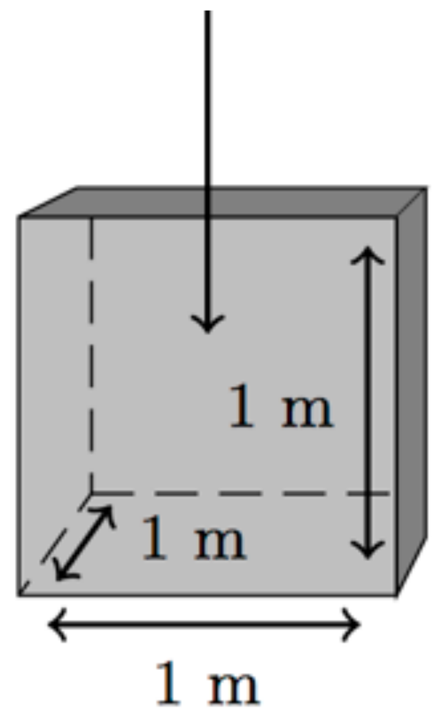



# BDX @ Cornell linac?




**Radiative DM production,**
**Requires downstream scattering**




**Beam BG small/negligible**

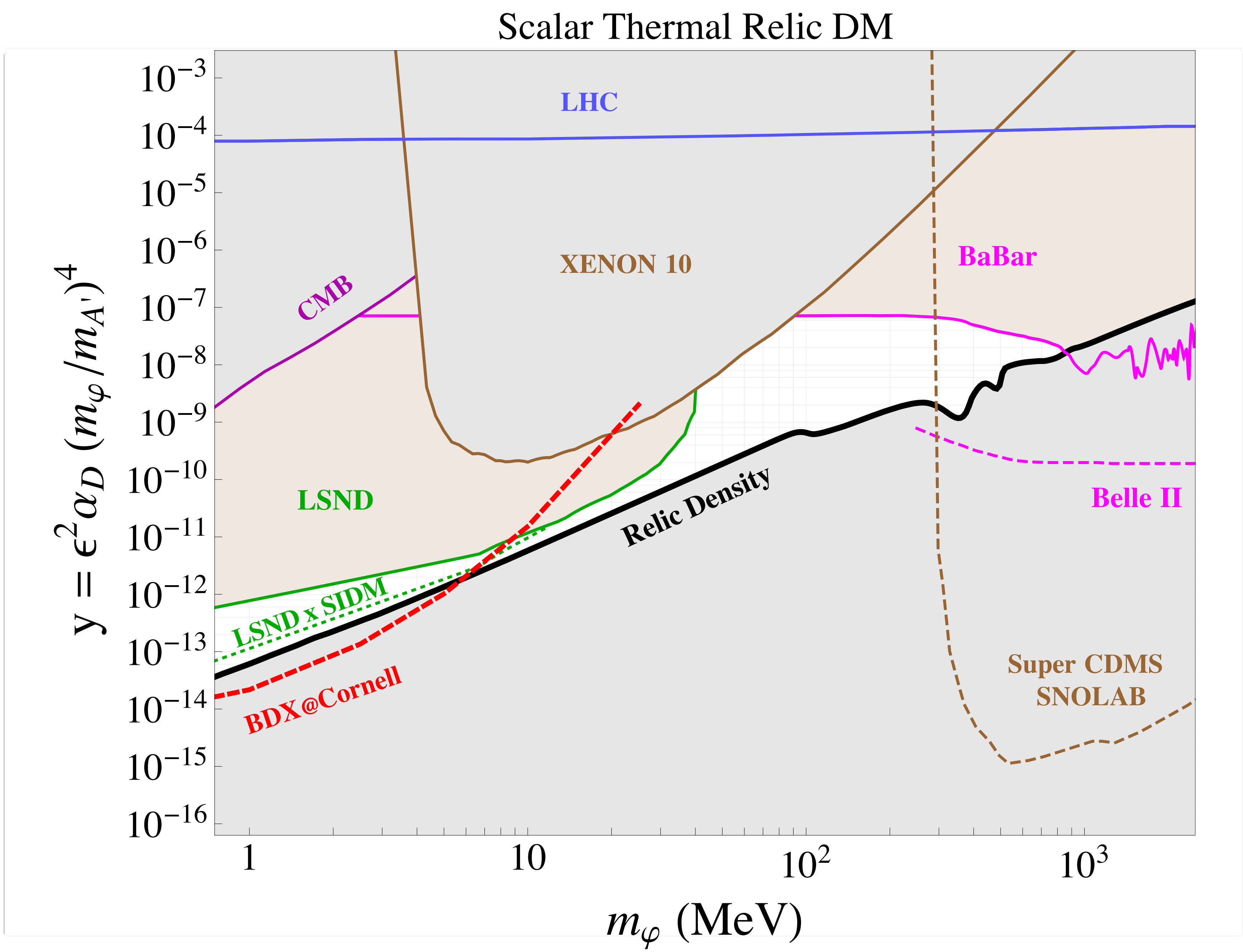
**Cosmic BG reduction necessary**
**(pulsed beam ok)**

cubic-meter
fiducial

Izaguirre, GK, Schuster, Toro
1307.6554 & 1403.6836

Battaglieri et. al. (BDX collaboration)
1406.3028

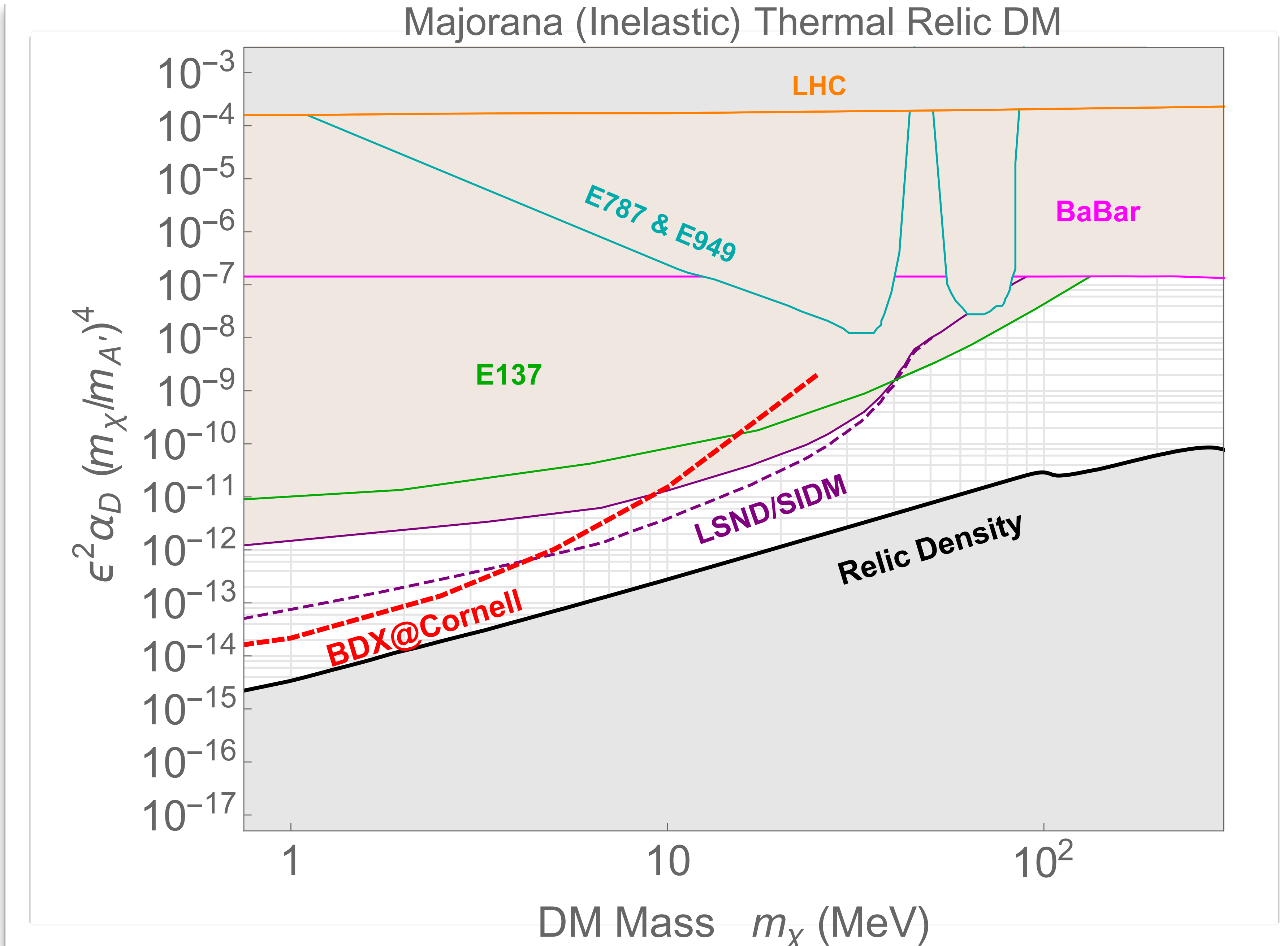
# BDX @ Cornell linac?




**E(beam)= 400 MeV, $10^{22}$ EOT, E(recoil) > 50 MeV**

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

# BDX @ Cornell linac?

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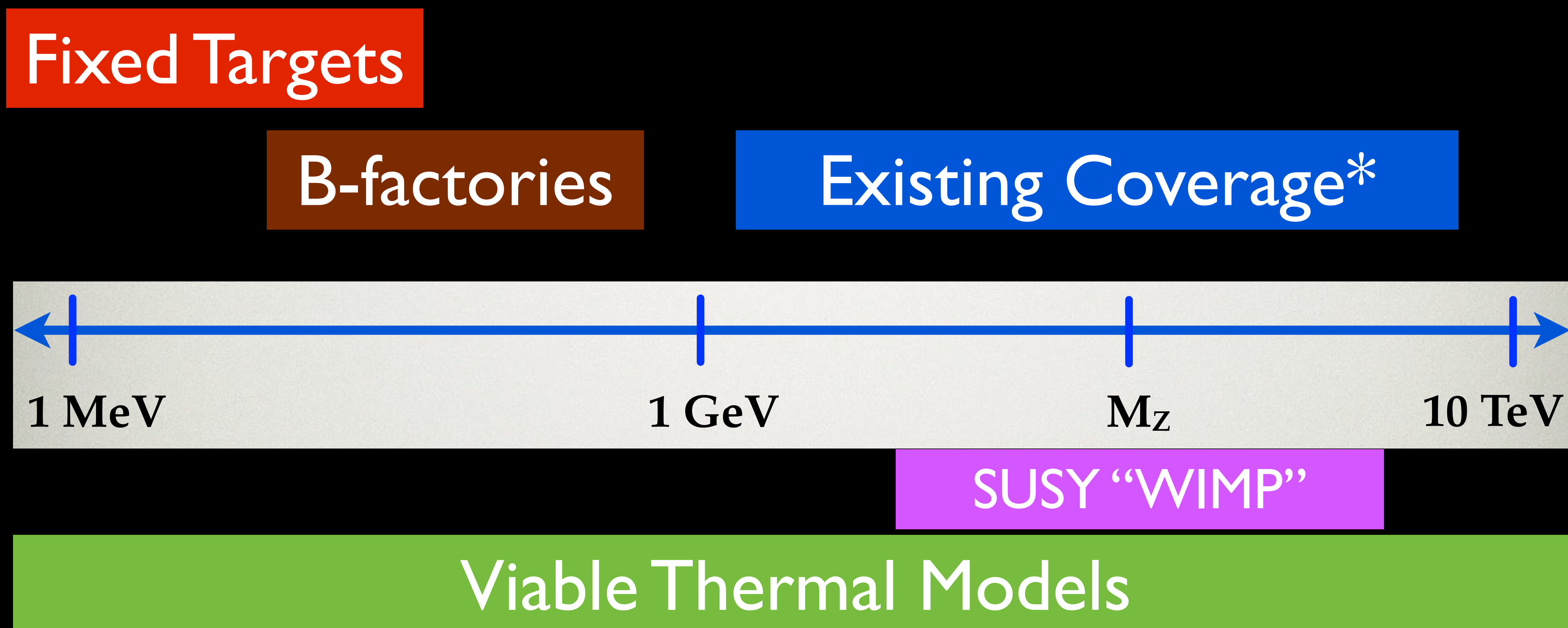
# Status: Thermal Light DM

## Interesting Times Ahead




* = elastic & symmetric

# Status: Thermal Light DM

Best limits from nontraditional searches

Fixed targets & B-factories especially powerful

Best hope for probing harder scenarios

Most from theorists reinterpreting old experiments

There are no dedicated efforts (yet!)

contrast w/ billion $ heavy DM program

Lots of viable param-space left for < GeV DM

Lots of room for improvement

**New way forward @ Cornell?**

# Thank You