A New Frontier in the Search for Dark Matter

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FNAL Colloquium April 29, 2020, 4 PM CDT

Collaborators

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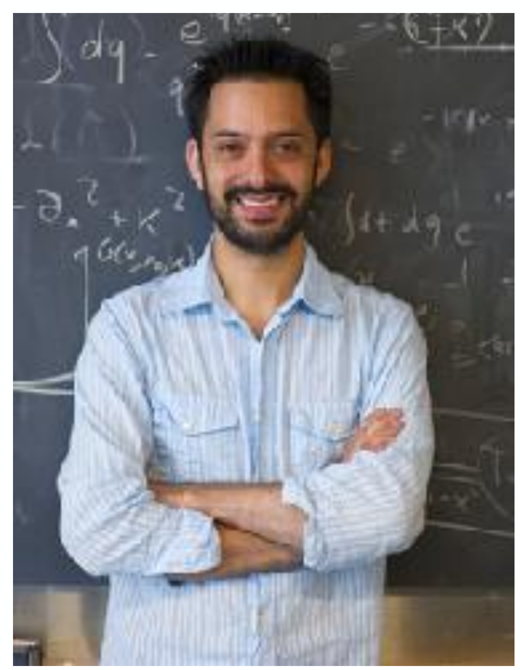
Nhan Tran, FNAL

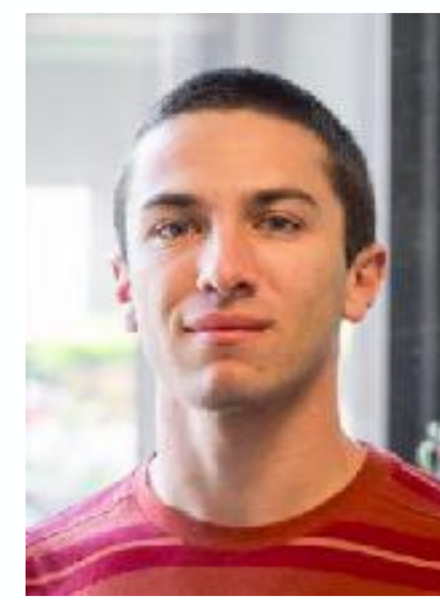
Asher Berlin, NYU

Nikita Blinov, FNAL



Yoni Kahn, UIUC

Andrew Whitbeck
Texas Tech U.

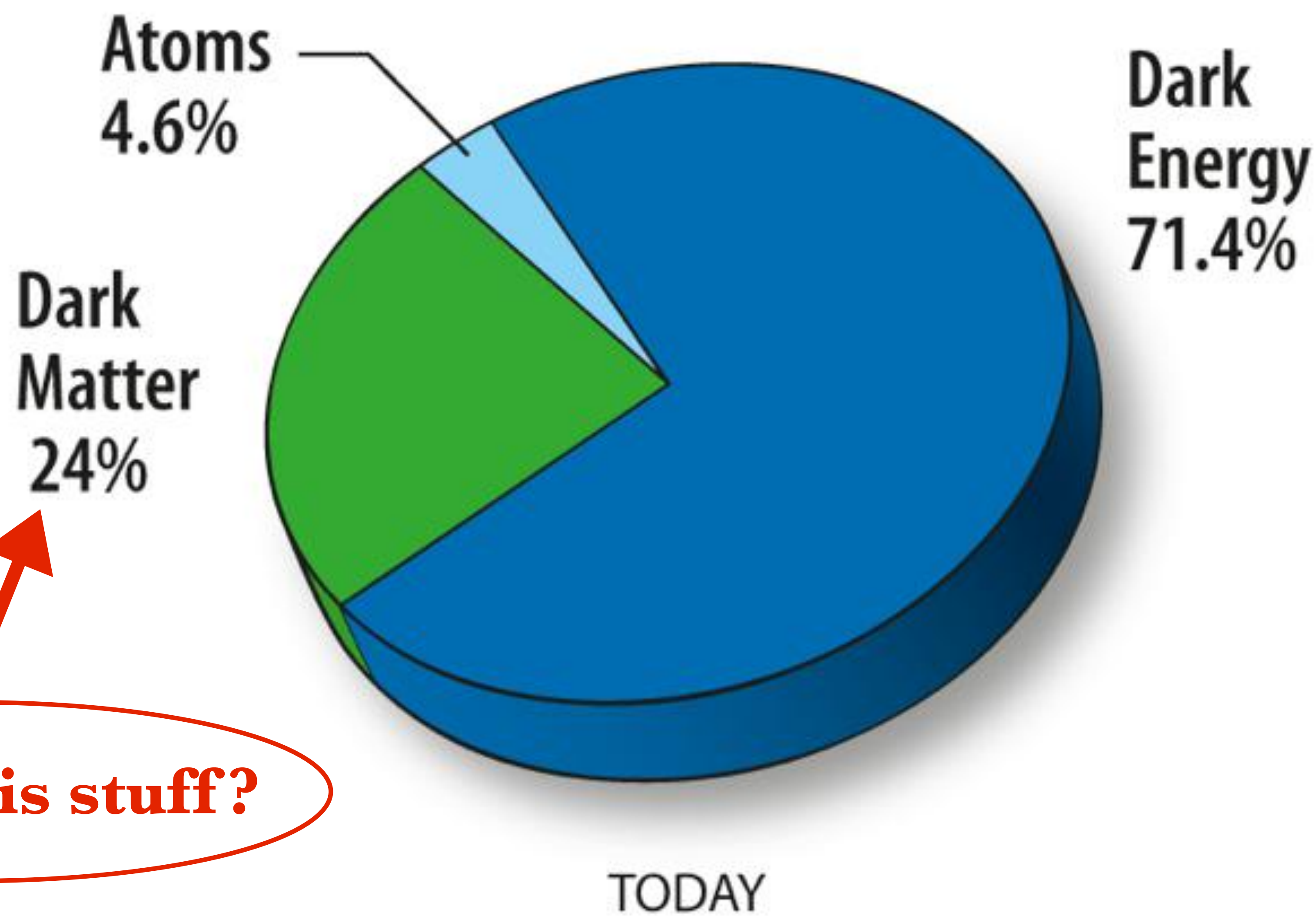


Matt Moschella
Princeton

Open Questions in Fundamental Physics & Cosmology

Neutrino Masses
Matter Asymmetry
Inflation

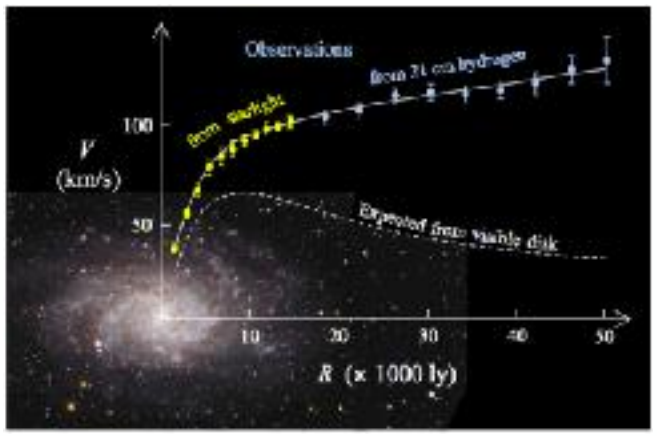
Accelerated Cosmic Expansion



What is this stuff?

Also Quantum Gravity

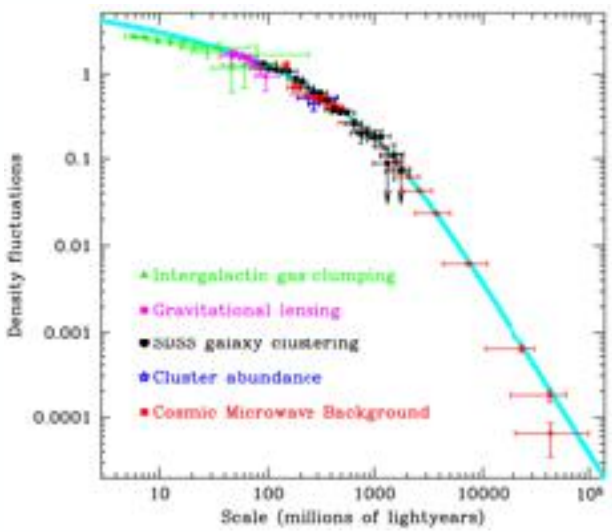
Remarkable Evidence for Dark Matter



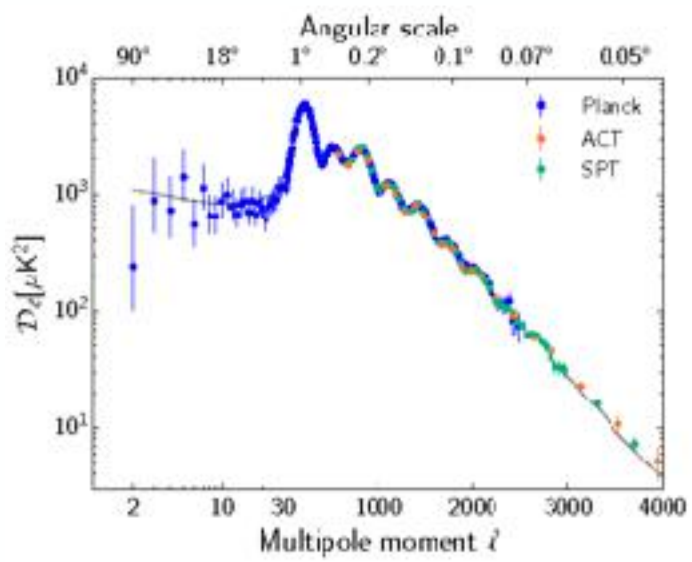
Rotation Curves

Gravitational Lensing

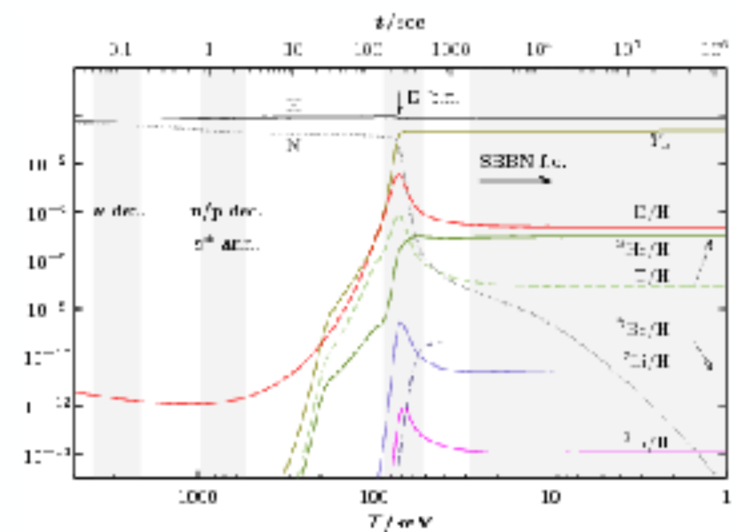
Cluster Collisions



Matter Power Spectrum



CMB Power Spectrum



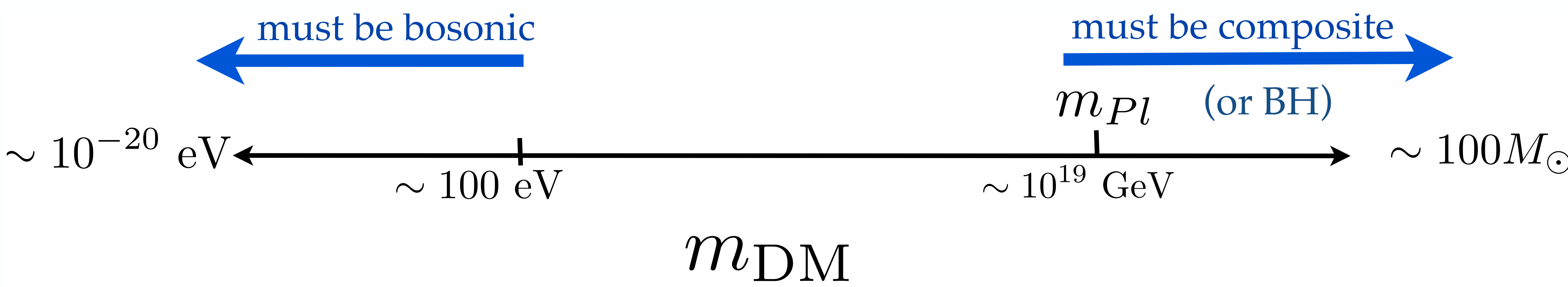
BBN Light Element Yields

Multiple independent, consistent observations

over **nearly** all of spacetime: kpc-Gpc, 13.7 Gyr ago-today

Holy Grail: extend our knowledge to terrestrial scales << kpc

What Clues Do We Have?



Huge space of allowed microscopic theories

Evidence only extends down to ~kpc (dwarf galaxy) scales

Theoretical guidance is essential

Need organizing principle for systematic progress

Overview

1) What's **great** about thermal DM?

2) What's **different** about light thermal DM?

3) How can we **test all** predictive models?

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Was DM ever in equilibrium with SM?

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NO

How was it populated?

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How was it populated?

Initial conditions

Axion / ALP
WIMPzilla
Primordial Black Holes
⋮

Rarely predictive

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NO

How was it populated?

Initial conditions

Axion / ALP
WIMPzilla
Primordial Black Holes
⋮

Rarely predictive

Feeble coupling to us

Sterile Neutrino (Dodelson / Widrow)
Freeze In
SuperWIMP
⋮

Very hard to test [few known examples]

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Nowhere

Today we have measured

$$\rho_\chi \sim 10^3\,\mathrm{eV\,cm^{-3}}$$

$$n_\gamma \sim 10^2\,\mathrm{cm^{-3}}$$

Equilibrium predicts DM mass

$$m_\chi \sim 10\,\mathrm{eV}$$

Too hot for large scale structure

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Stable dark states

Heavy

too much stuff

$\sum \Omega_{\text{dark}} > \Omega_{\text{DM}}$

Light

$N_{\text{eff}} > 3$ spoils

CMB / BBN / LSS

Requires nonstandard cosmology

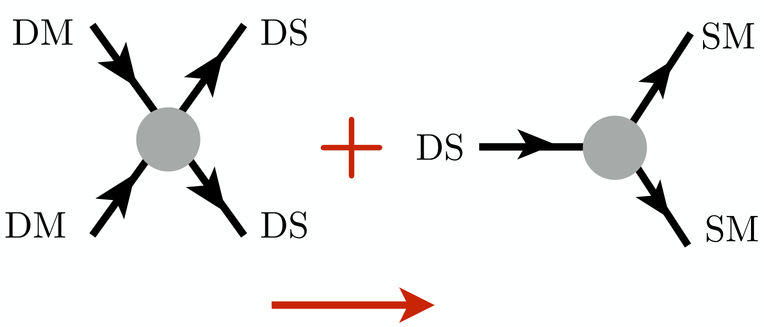
Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Visible matter

"Hidden" Annihilation



Visibly decaying dark state (DS)

Not predictive, hard to test

Was DM ever in equilibrium with SM?

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Visible matter

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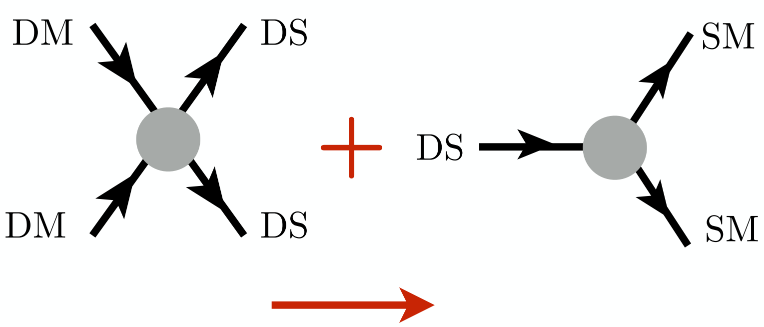
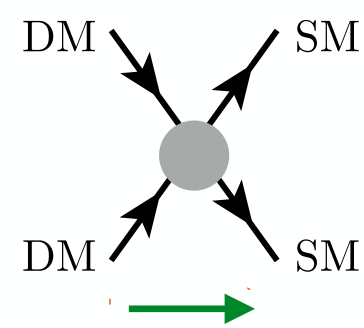


Visibly decaying dark state (DS)

Not predictive, hard to test

Direct Annihilation



Predictive Testable Origin

Light DM & WIMPs

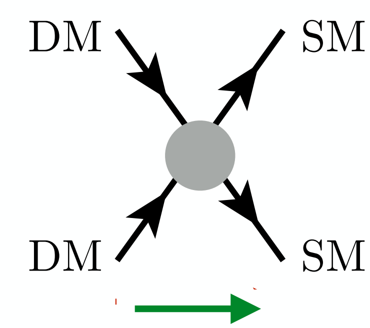
Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Visible matter

Direct Annihilation



Predictive Testable Origin

Light DM & WIMPs

This Talk

Same coupling does both:

Annihilation (cosmology)
Accelerator production (lab)

Q: What's so great about equilibrium?

A: Generic and easy to achieve

Compare interaction rate to Hubble expansion

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

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

Equilibrium is reached even for *tiny* couplings

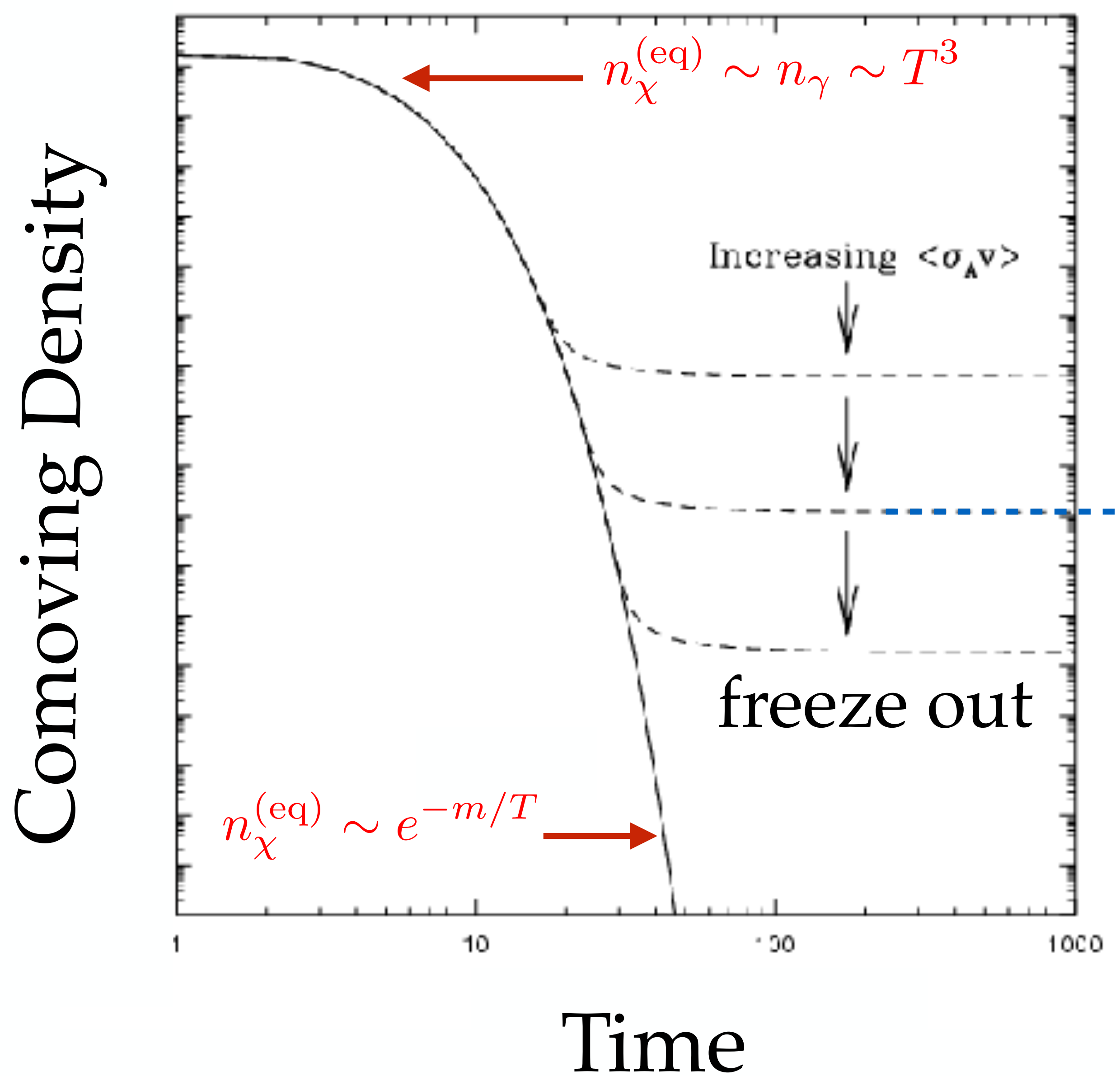
$$g \gtrsim 10^{-8}\left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^2\left(\frac{\mathrm{GeV}}{m_\chi}\right)^{3/2}$$

Nearly all testable models feature equilibrium at early times

Q: What's so great about equilibrium?

A: Minimum annihilation rate

$$n_\chi^{(\mathrm{eq})} = \int \frac{d^3p}{(2\pi)^3}\frac{g_i}{e^{E/T}\pm 1} \propto \begin{cases} T^3 & (T \gg m) \\ e^{-m/T} & (T \ll m) \end{cases}$$

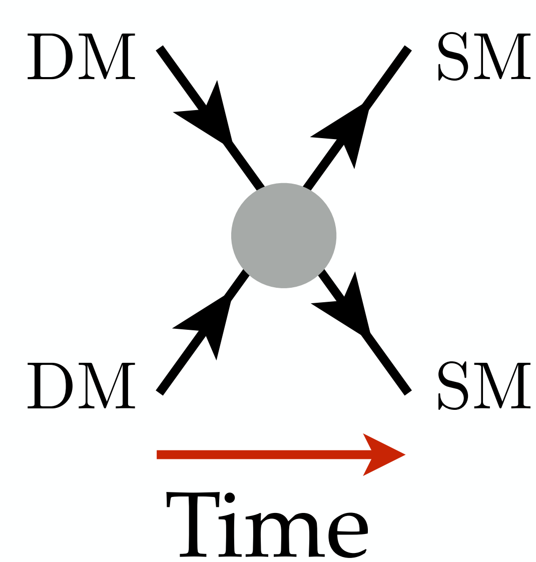


Symmetric DM population

$$n_\chi = n_{\overline{\chi}}$$

Observed density requires

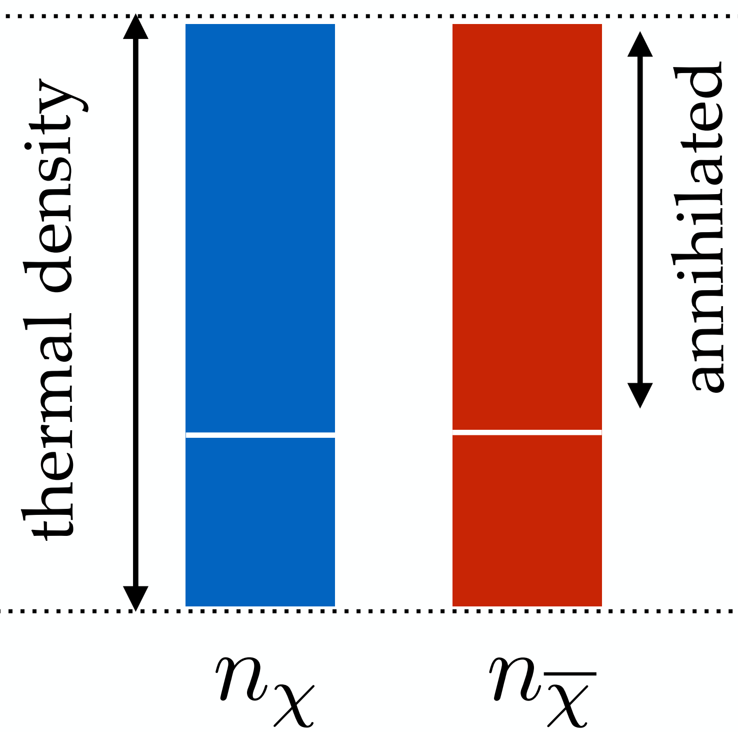
$$\sigma v \sim 2\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$$



Q: What's so great about equilibrium?

A: Minimum annihilation rate

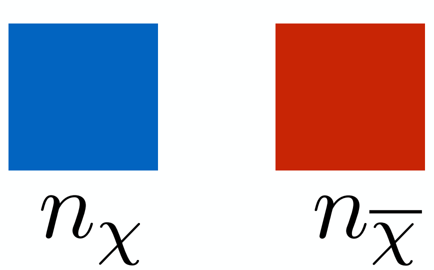
Symmetric DM



Early Universe

$T \gg m_\chi$

$\sigma v \sim 2 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

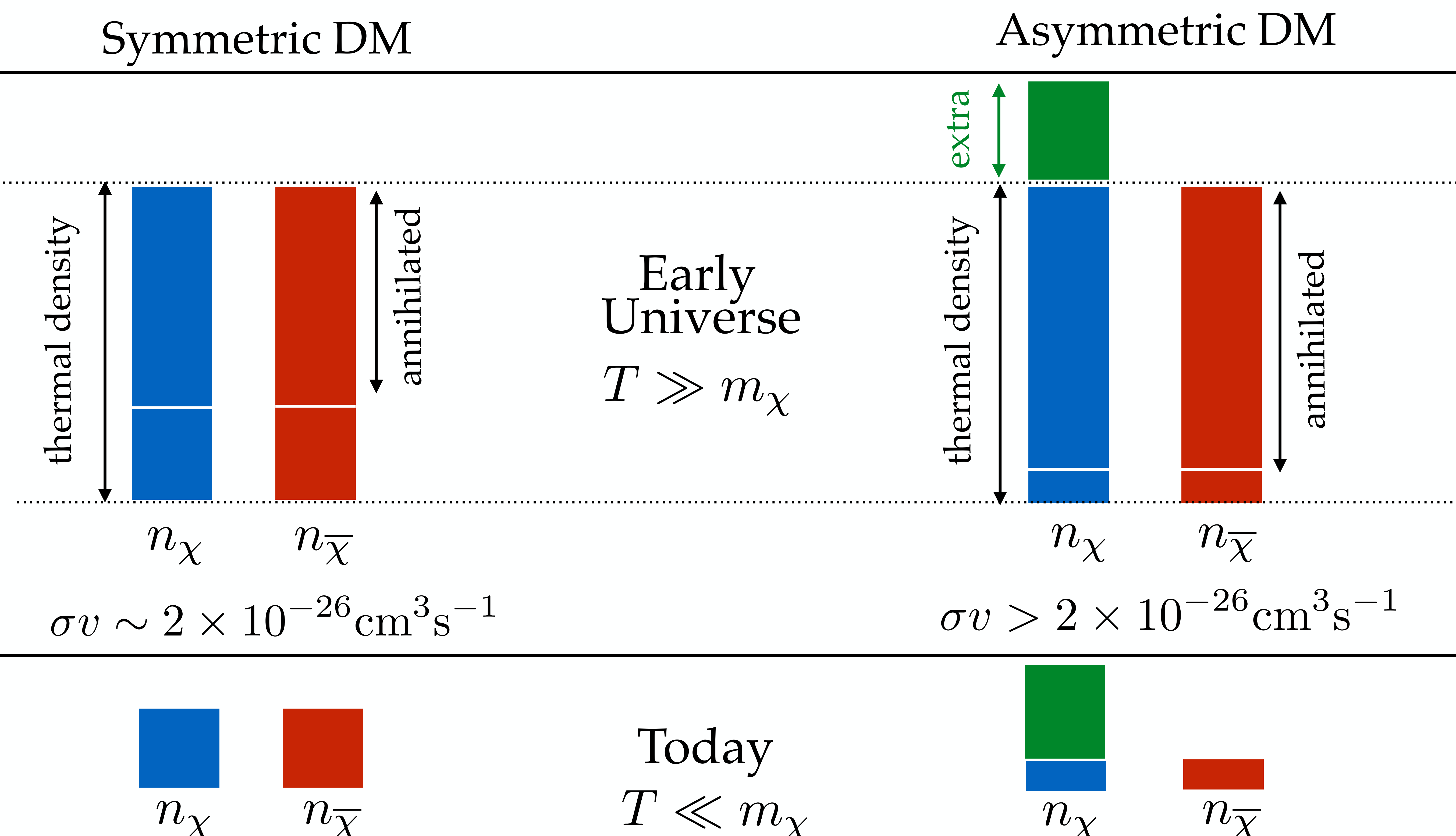


Today

$T \ll m_\chi$

Q: What's so great about equilibrium?

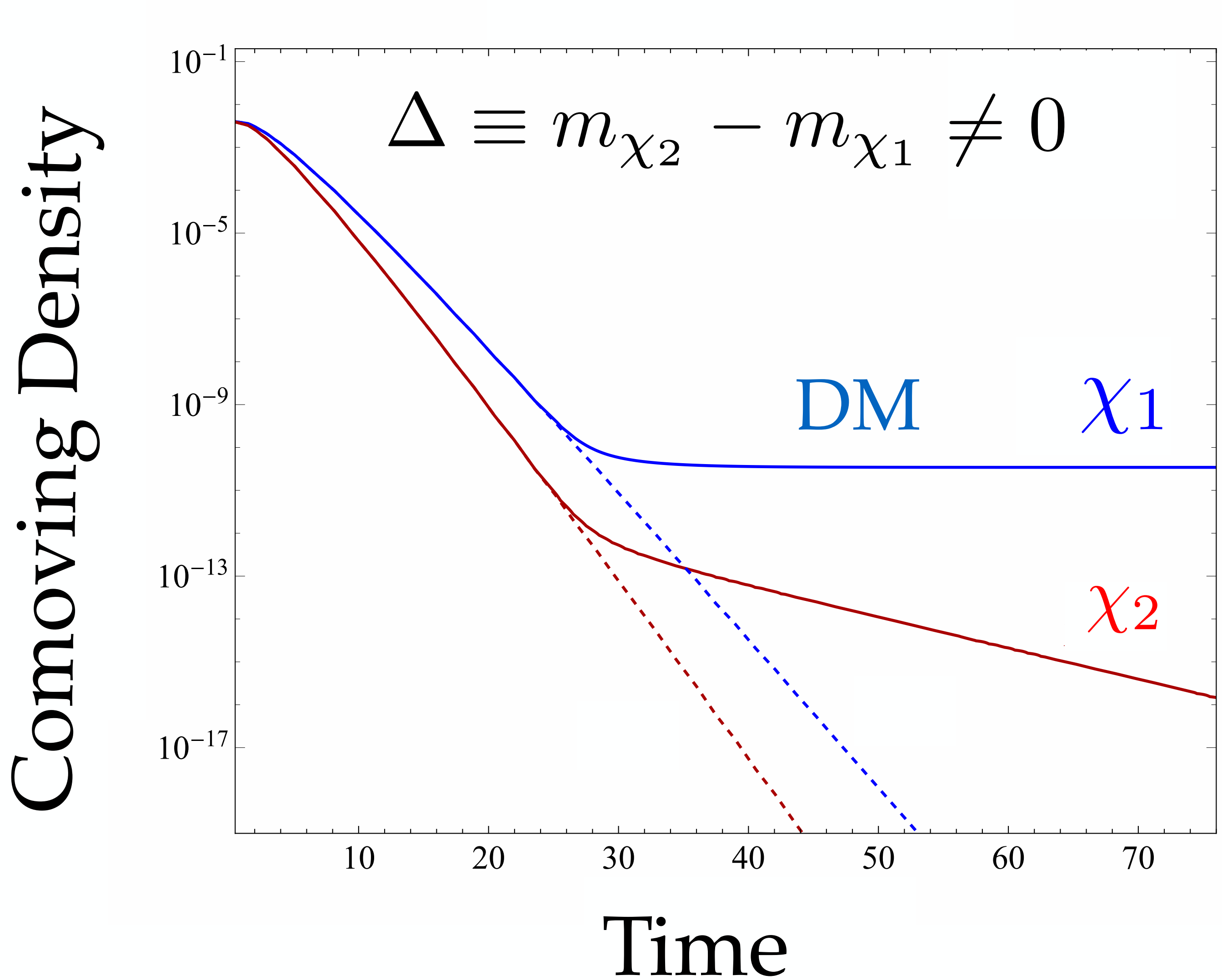
A: Minimum annihilation rate

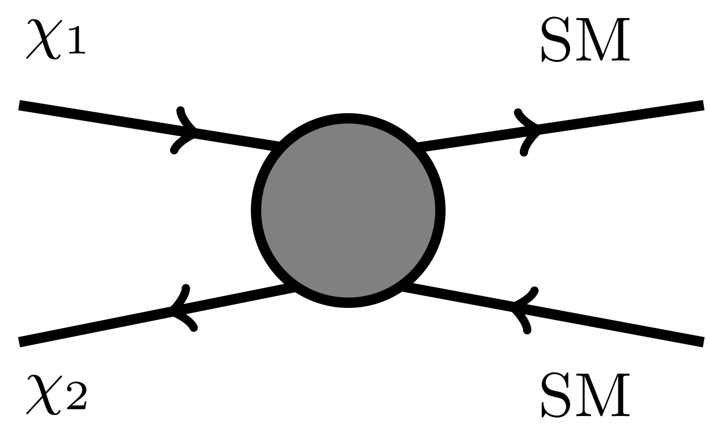


Q: What's so great about equilibrium?

A: Minimum annihilation rate

Coannihilating DM





Unstable "friend" χ_2 more Boltzmann suppressed

$$\frac{n_2}{n_1} \sim e^{-\Delta/T}$$

Increase rate to compensate

$$\sigma v \gg 2 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}$$

Key Point: minimum rate in all equilibrium scenarios

Q: What's so great about equilibrium?

A: Insensitive to unknown high energy physics

Initial condition known

Calculable and independent of inflation, reheating, baryogengesis etc.

Mass & couplings set abundance

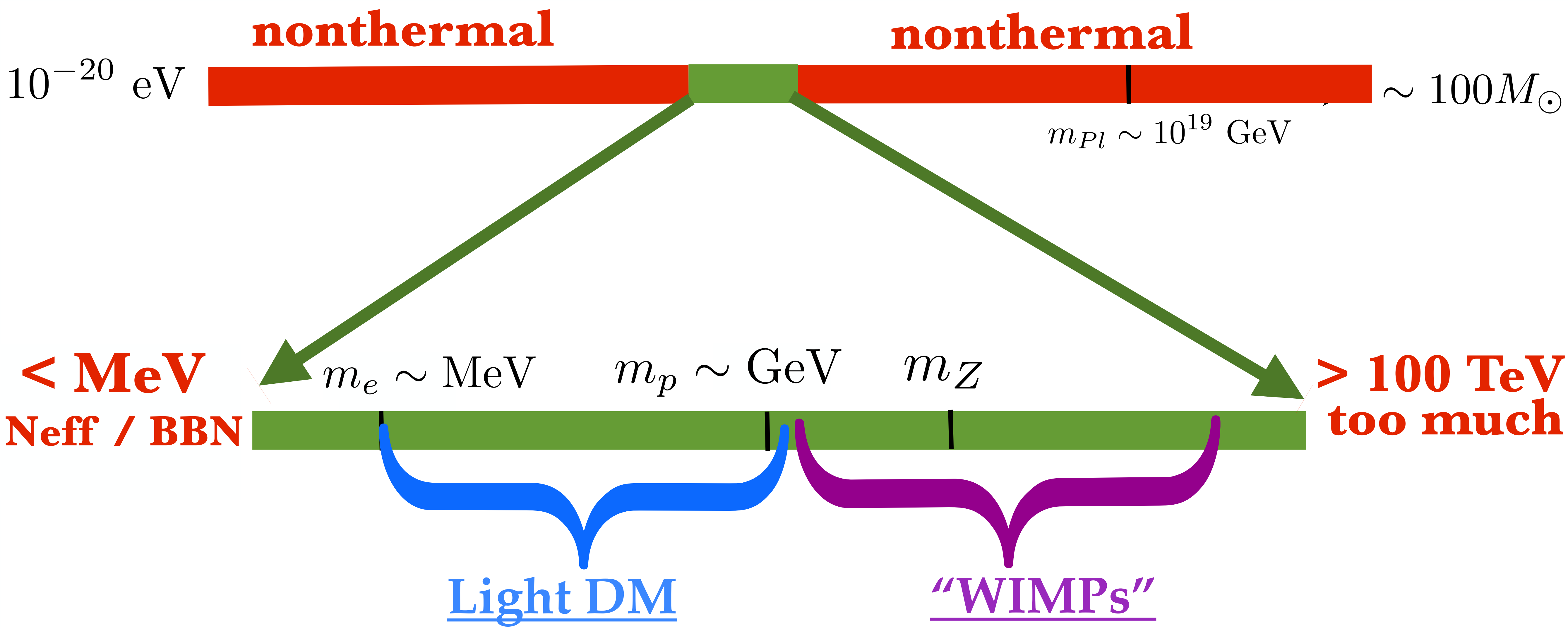
A discovery would directly probe early universe cosmology

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

- Ad hoc initial condition $n_\chi(0) = 0$
- DM produced through tiny couplings, **very hard to test**

Q: What's so great about equilibrium?

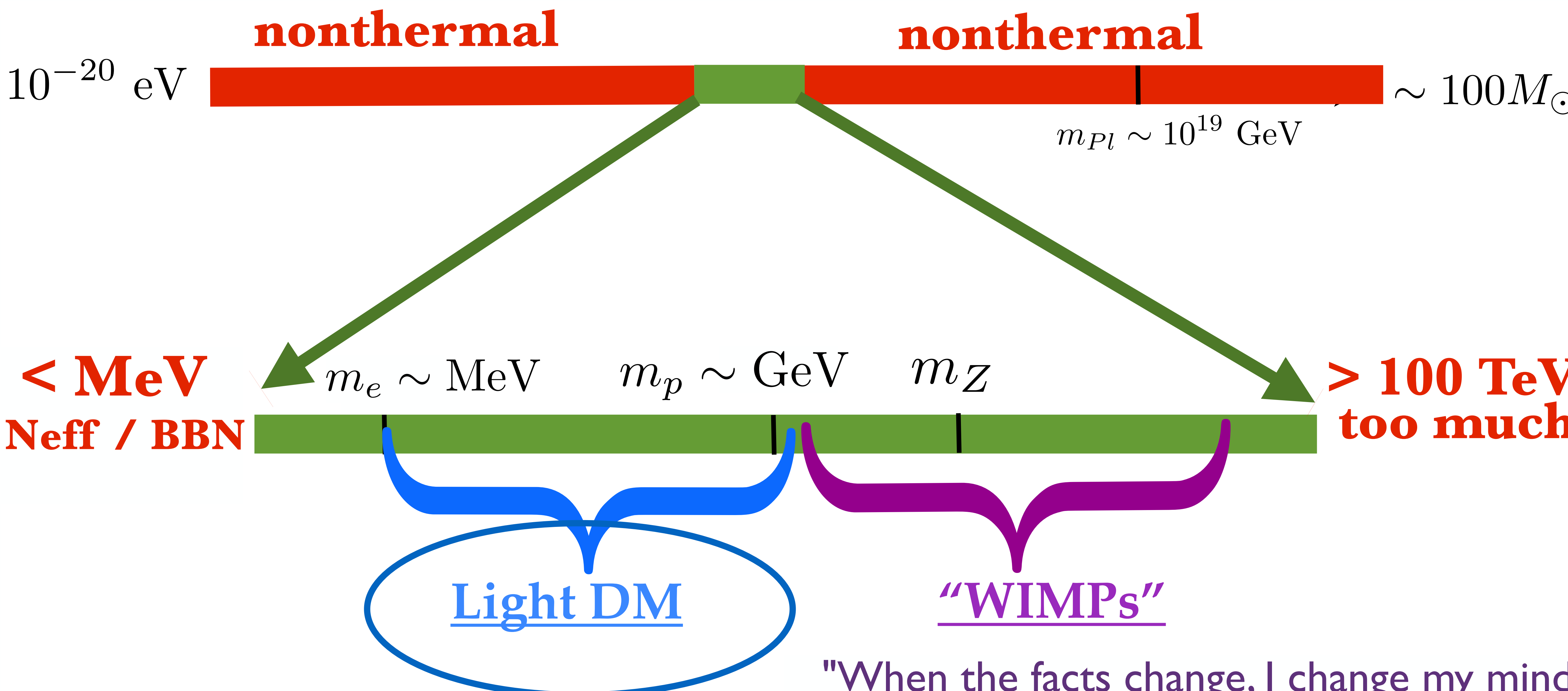
A: Narrows Viable Mass Range (!)



Powerful existing searches
[in]direct detection, colliders…

Q: What's so great about equilibrium?

A: Narrows Viable Mass Range (!)



This talk

"When the facts change, I change my mind. What do you do?"

- John Maynard Keynes

Overview

1) What's **great** about thermal DM?

2) What's **different** about light thermal DM?

3) How can we **test all** predictive models?

Light DM vs. WIMPs

Light DM must be SM neutral

Else would have been discovered (LEP, Tevatron…)

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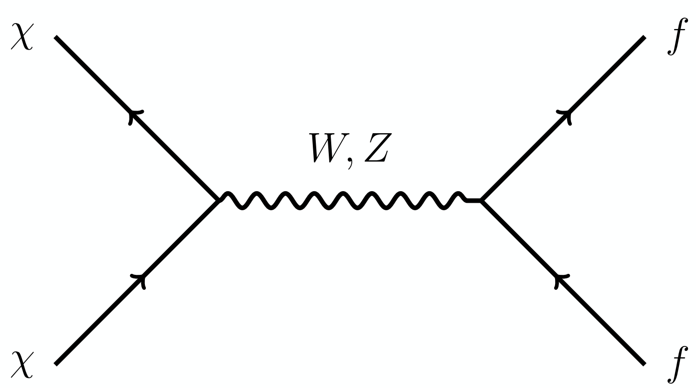
Light DM requires light new force carriers

Weak interactions are too weak   need $\sim 10^{-26}\mathrm{cm}^3/\mathrm{s}$



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

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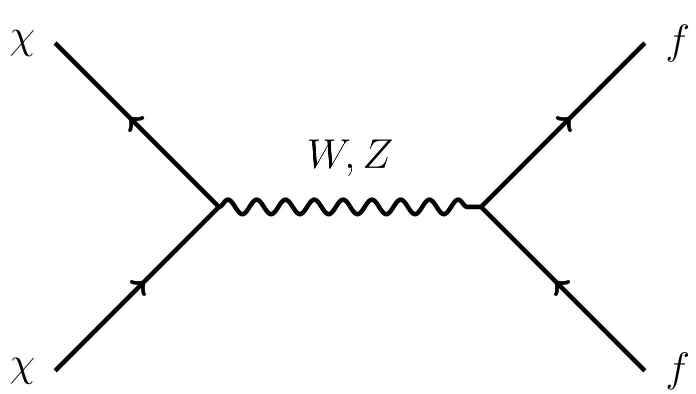


$$\sigma v \sim G_F^2 m_\chi^2 \sim 10^{-29}\,\text{cm}^3\,\text{s}^{-1}\left(\frac{m_\chi}{\text{GeV}}\right)^2$$

Annihilation through renormalizable interactions

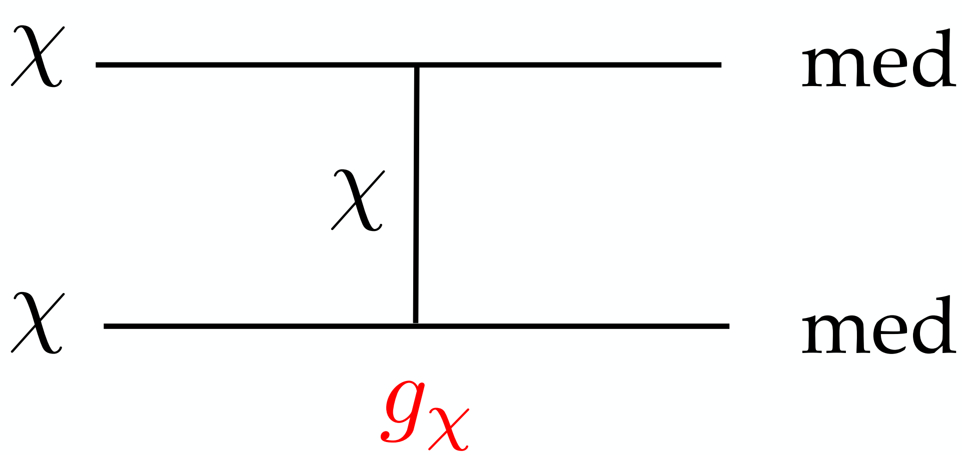
Higher dimension operators have same problem as electroweak forces

Light mediators are not optional!

Who's Heavier: DM or Mediator?

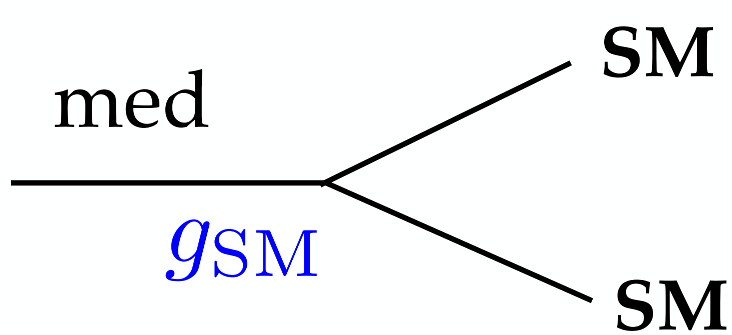
Hidden Annihilation

$m_\chi > m_{\text{med}}$



No clear experimental target

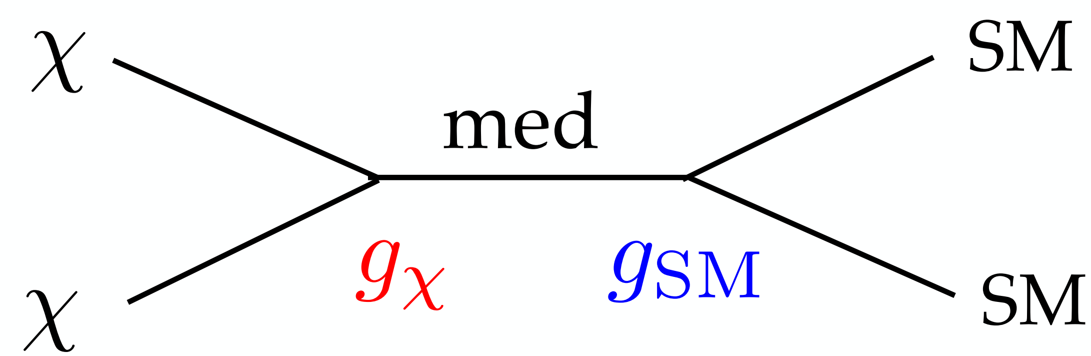
Abundance set by g_χ



Mediator decays **visibly**

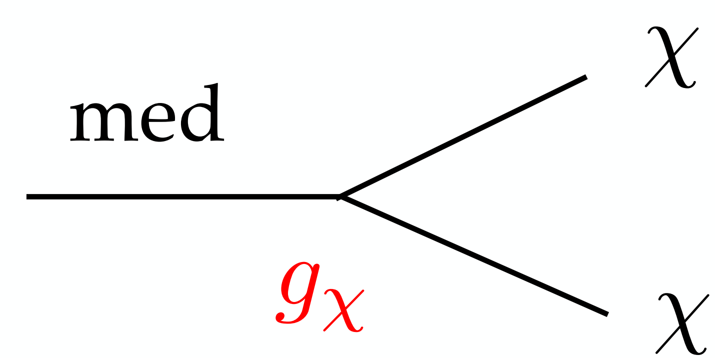
Direct Annihilation

$m_\chi < m_{\text{med}}$



Predictive thermal targets

Abundance depends on g_{SM}

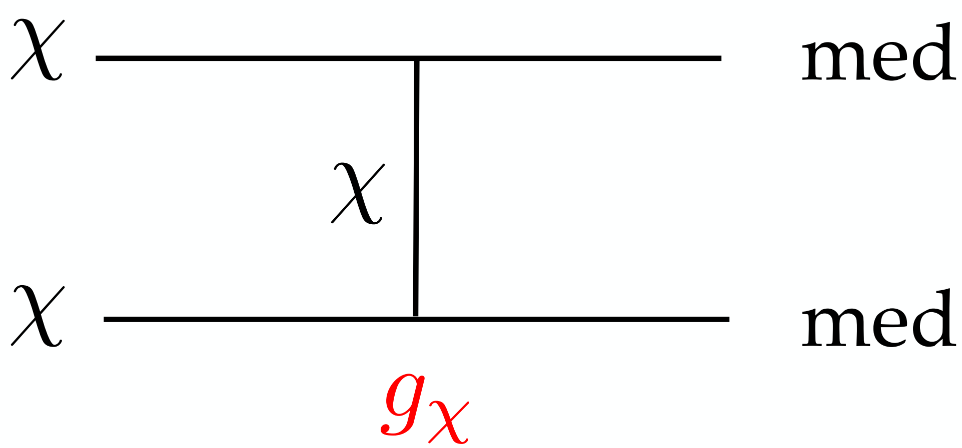


Mediator decays **invisibly***

Who's Heavier: DM or Mediator?

Hidden Annihilation

$m_\chi > m_{\rm med}$



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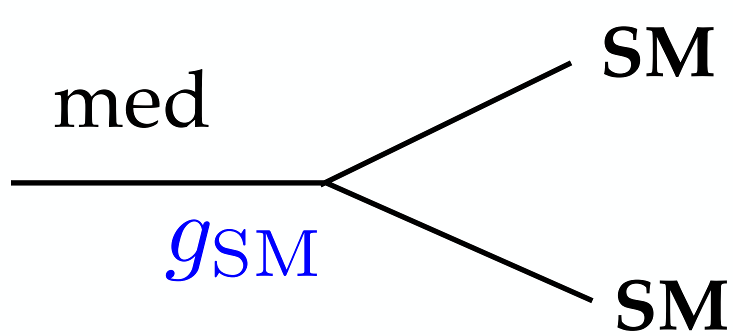
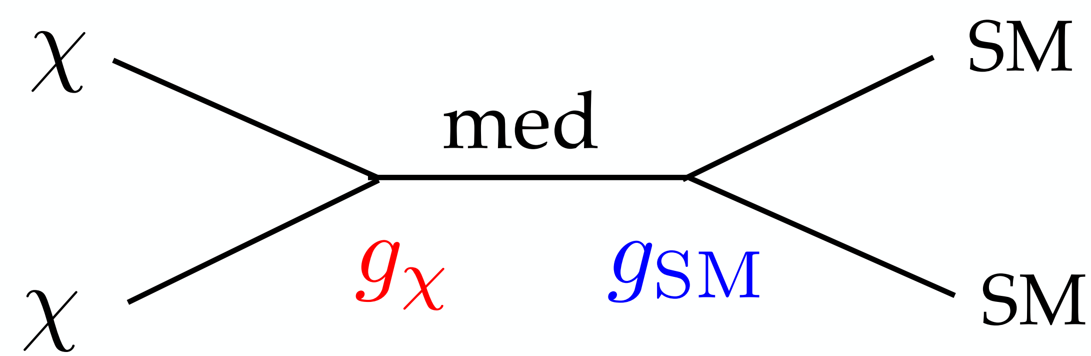


Mediator decays **visibly**

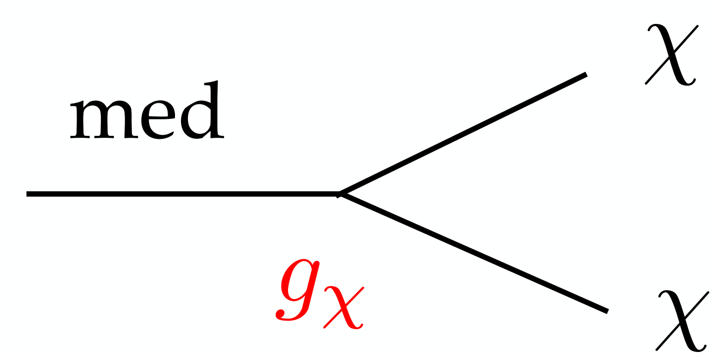
Direct Annihilation

$m_\chi < m_{\rm med}$



Predictive thermal targets

Abundance depends on $g_{\rm SM}$



Mediator decays **invisibly***

What Kind of Mediator?

Neutrality and renormalizability restrict possible interactions

Scalar ϕ mixes with Higgs Boson

Couples to SM **masses** $\epsilon\phi\frac{m_f}{v}\bar{f}f$

Dark photon A' mixes with visible photon

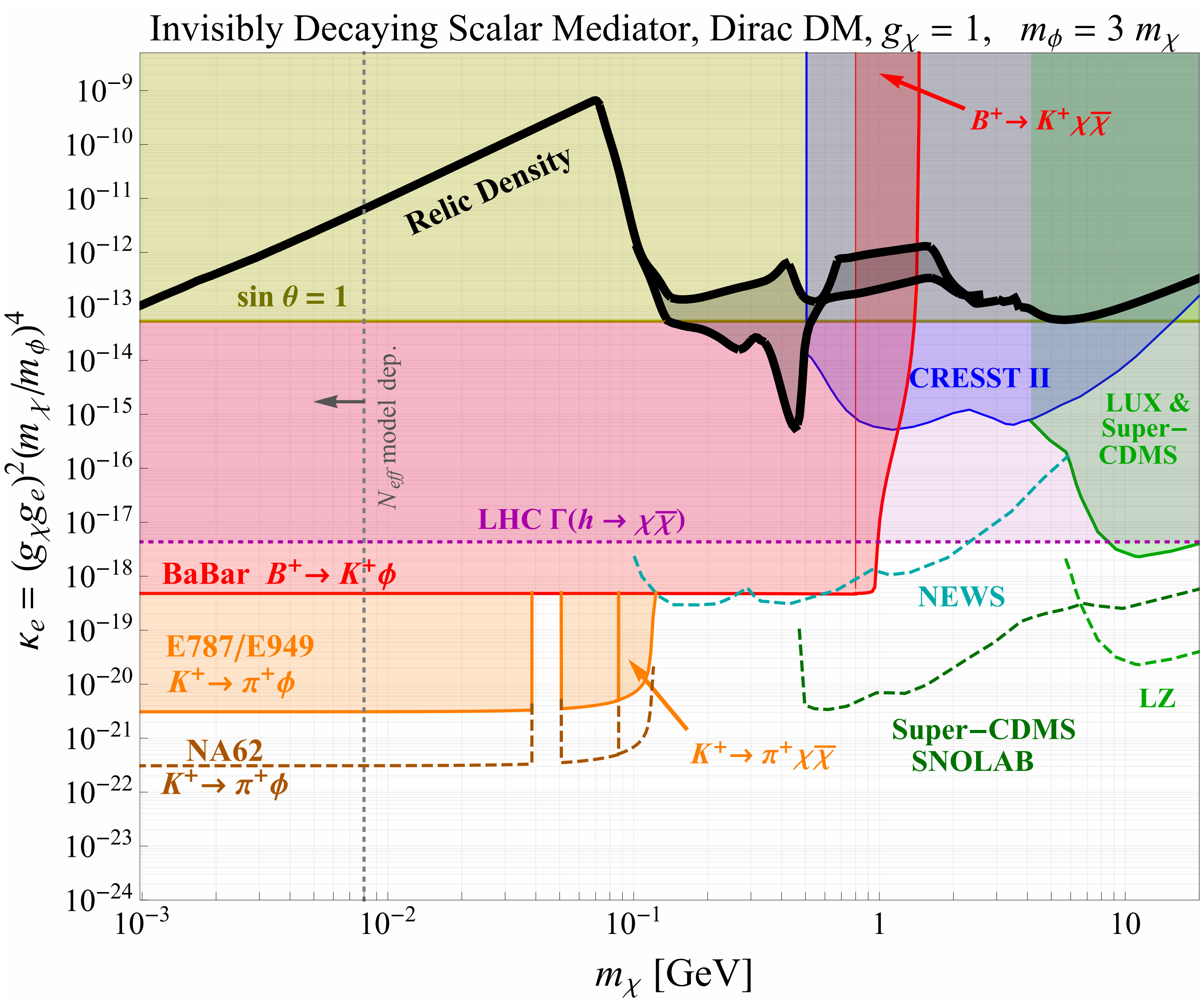
Couples to **EM** current $\epsilon A'_\mu J^\mu_{\text{EM}}$

New force V directly couples to DM & SM

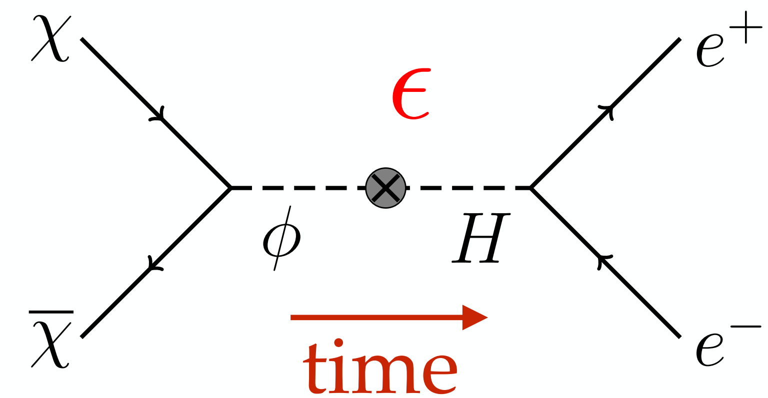
Couples to **different (non EM)** current J^μ_{SM}

$$B-L\ ,\ L_i-L_j\ ,\ B-3L_i$$

Scalar Force: Direct-Annihilation Ruled Out!

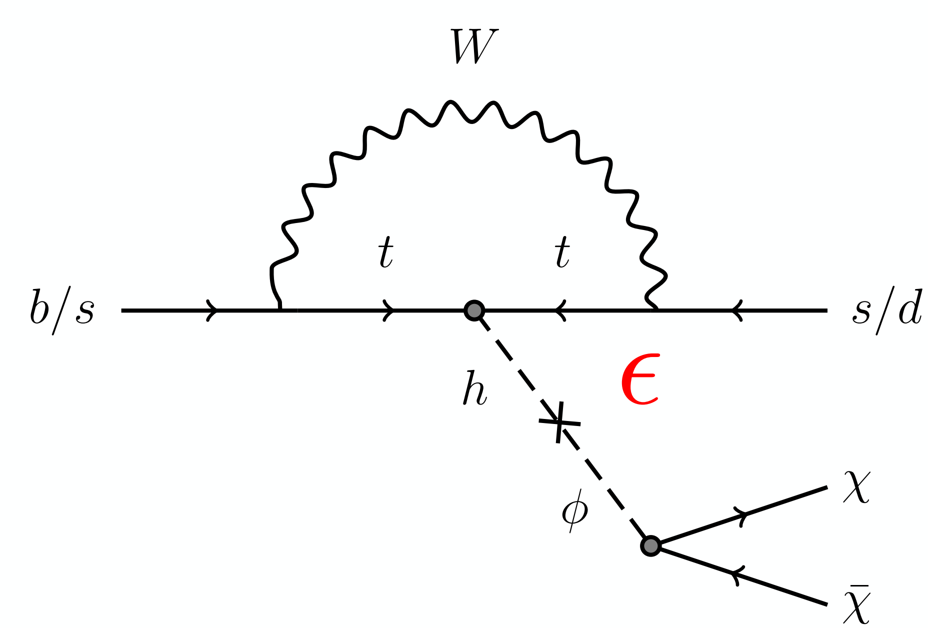


Interaction that sets the DM direct annihilation rate



enhances dangerous decays

$K \to \pi + \text{invisible}$



Conclusion independent of DM particle

GK arXiv:1512.04119 Phys.Rev.D (2016)

What Kind of Mediator?

Neutrality and renormalizability require "portal" interactions

~~**Scalar ϕ mixes with Higgs Boson**~~

~~Couples to SM **masses** $\epsilon\phi\frac{m_f}{v}\bar{f}f$~~

Dark photon A' mixes with visible photon

Couples to **EM** current $\epsilon A'_\mu J^\mu_{\mathrm{EM}}$

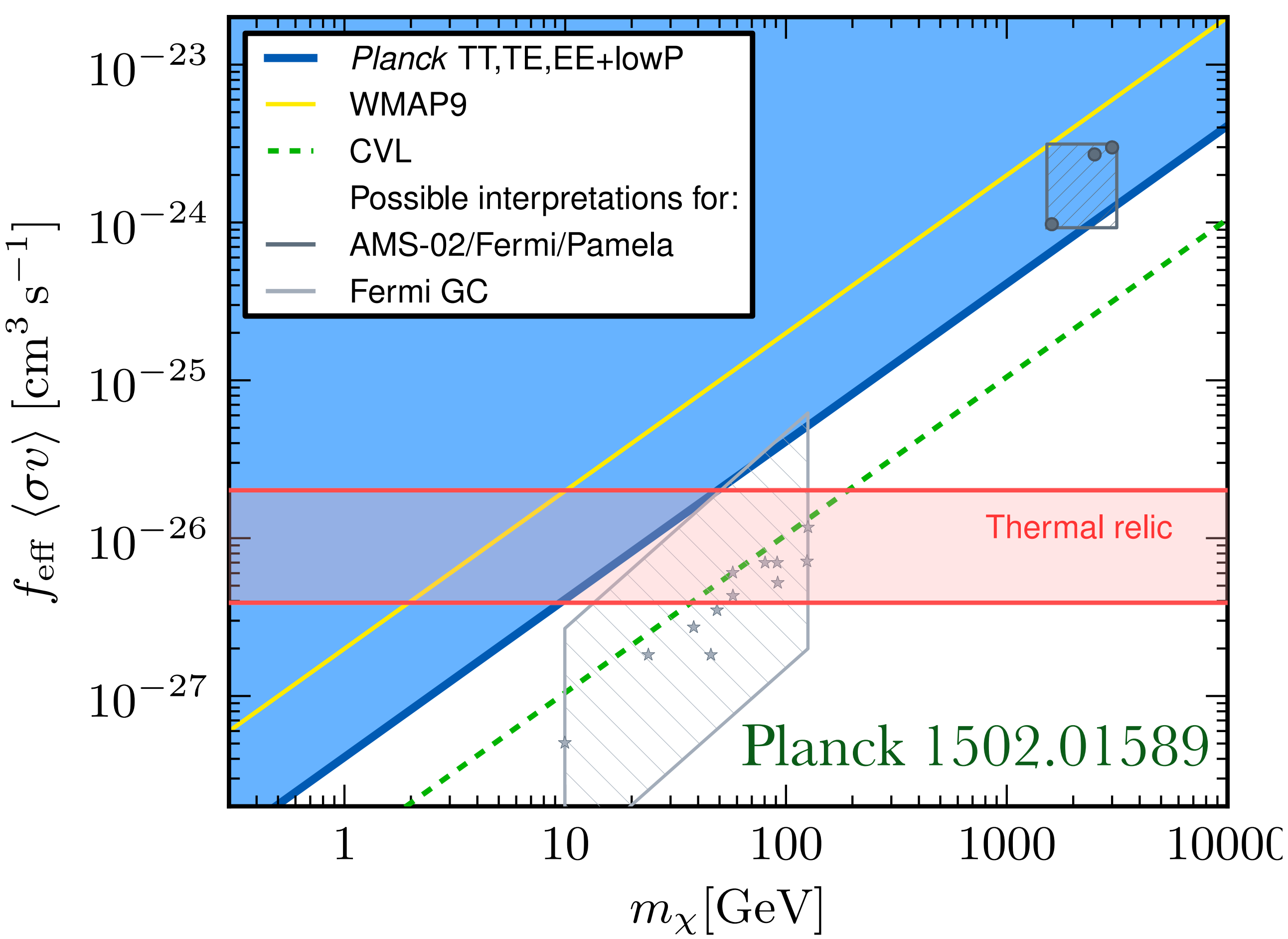
New force V directly couples to DM & SM

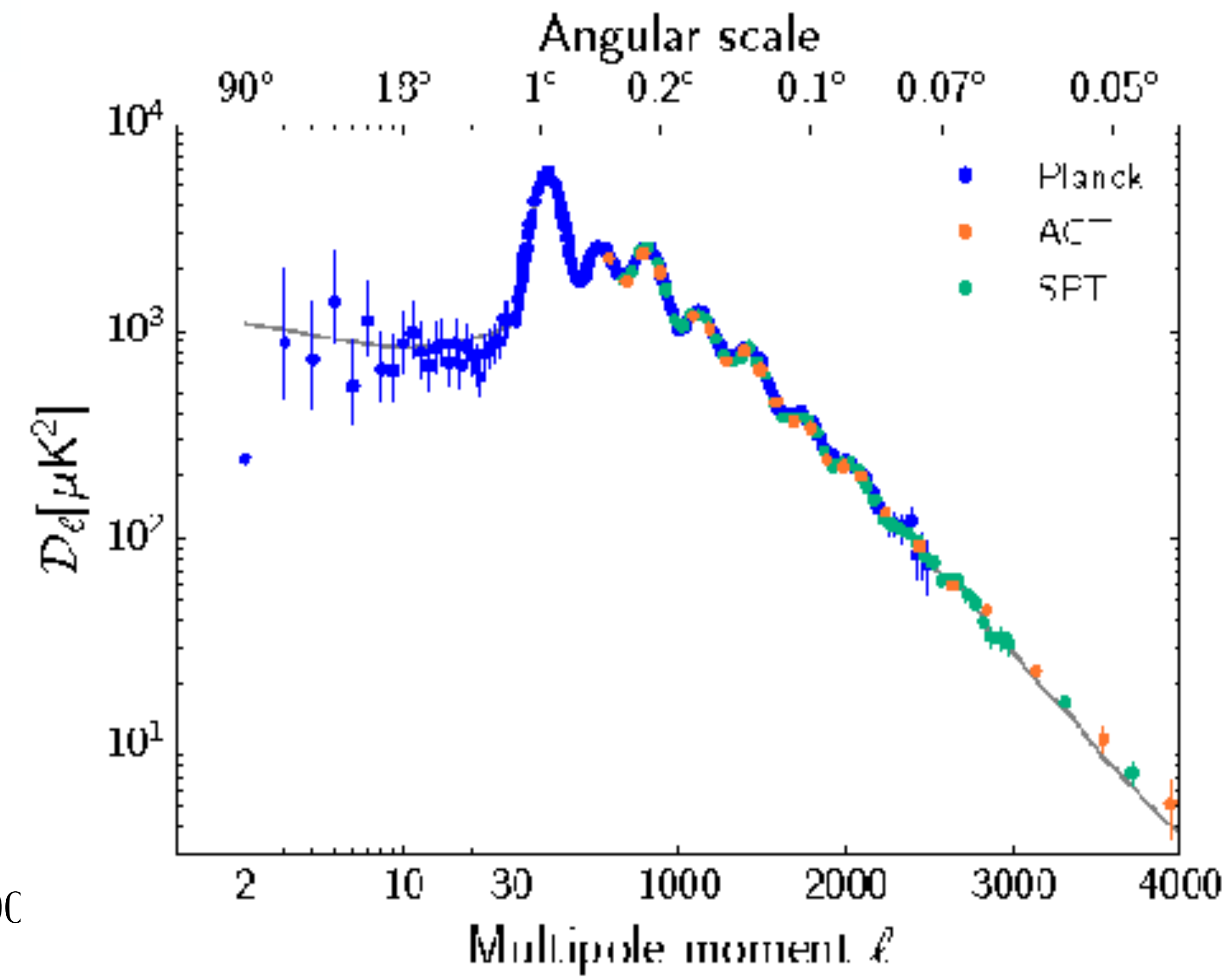
Couples to **different (non EM)** current J^μ_{SM}

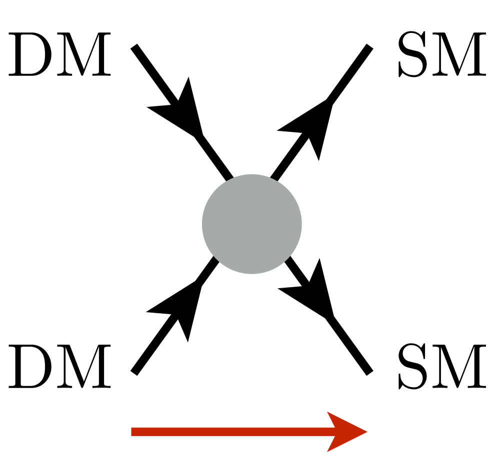
$$B-L\ ,\ L_i - L_j\ ,\ B-3L_i$$

New force models all similar to A′ & also couple to neutrinos

What kind of DM? Use CMB to classify viable options







Rare out-of-equilibrium annihilation ionizes H (z=1100)

CMB photons pass through more plasma (modifies peaks)

Rules out s-wave relic cross section for DM < 10 GeV

Classify DM by Annihilation During CMB Era

$$\mathcal{L} \supset g_D A'_\mu J^\mu_\chi$$

$$J^\mu_\chi = \begin{cases} \overline{\chi}\gamma^\mu\chi & \text{Asym. Dirac} \\ \overline{\chi}_1\gamma^\mu\chi_2 & \text{Pseudo-Dirac} \\ \frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi & \text{Majorana} \\ i\chi^*\partial_\mu\chi & \text{Scalar} \end{cases}$$

Asym. Dirac → $\overline{\chi}$ all annihilate away pre-CMB
no more **annihilation** partners

Pseudo-Dirac → Heavier χ_2 decays pre-CMB
no more **coannihilation** partners

Majorana, Scalar → $\sigma v \propto v^2$ velocity redshifts
tiny annihilation rate at CMB

Safe models require either:

P-wave annihilation
Scalar or Majorana

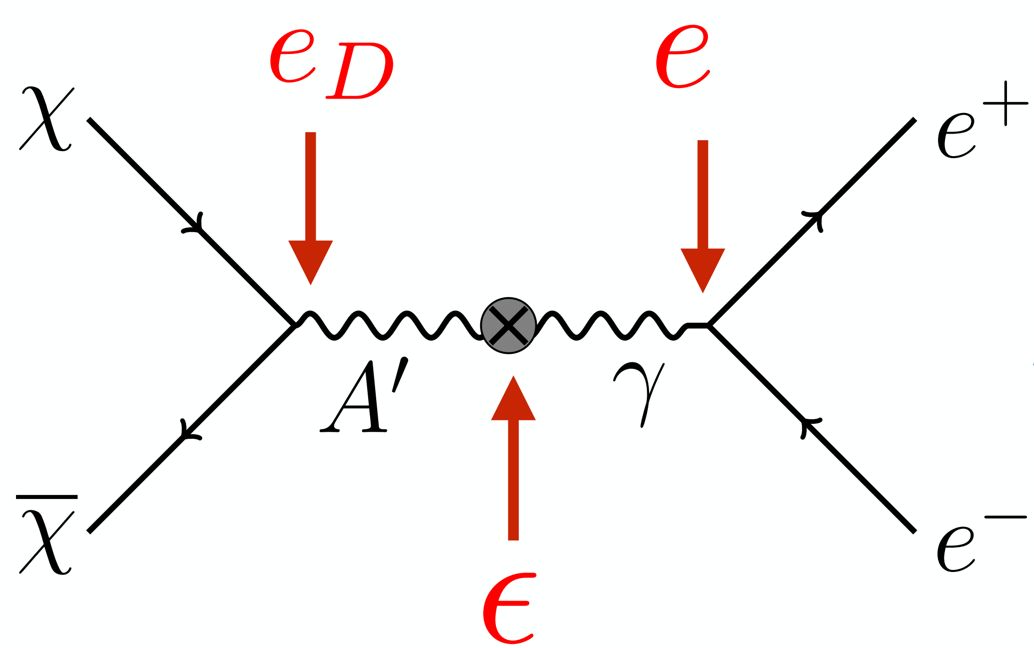
Different DM population @ CMB
Asymmetric or Pseudo-Dirac

NB: both categories suppress (or kill) indirect detection signals

Representative Scenario: Dark Photon Mediator A'

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

DM



SM

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

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'_{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu + A'_\mu J^\mu_\chi + \epsilon A'_\mu J^\mu_{\rm EM}$$

Not the only option, but "morally" similar to all viable variations

Main difference for other scenarios: $J^\mu_{\rm EM} \to J^\mu_{B-L}\ ,\ J^\mu_{L_i - L_i} \cdots$

Overview

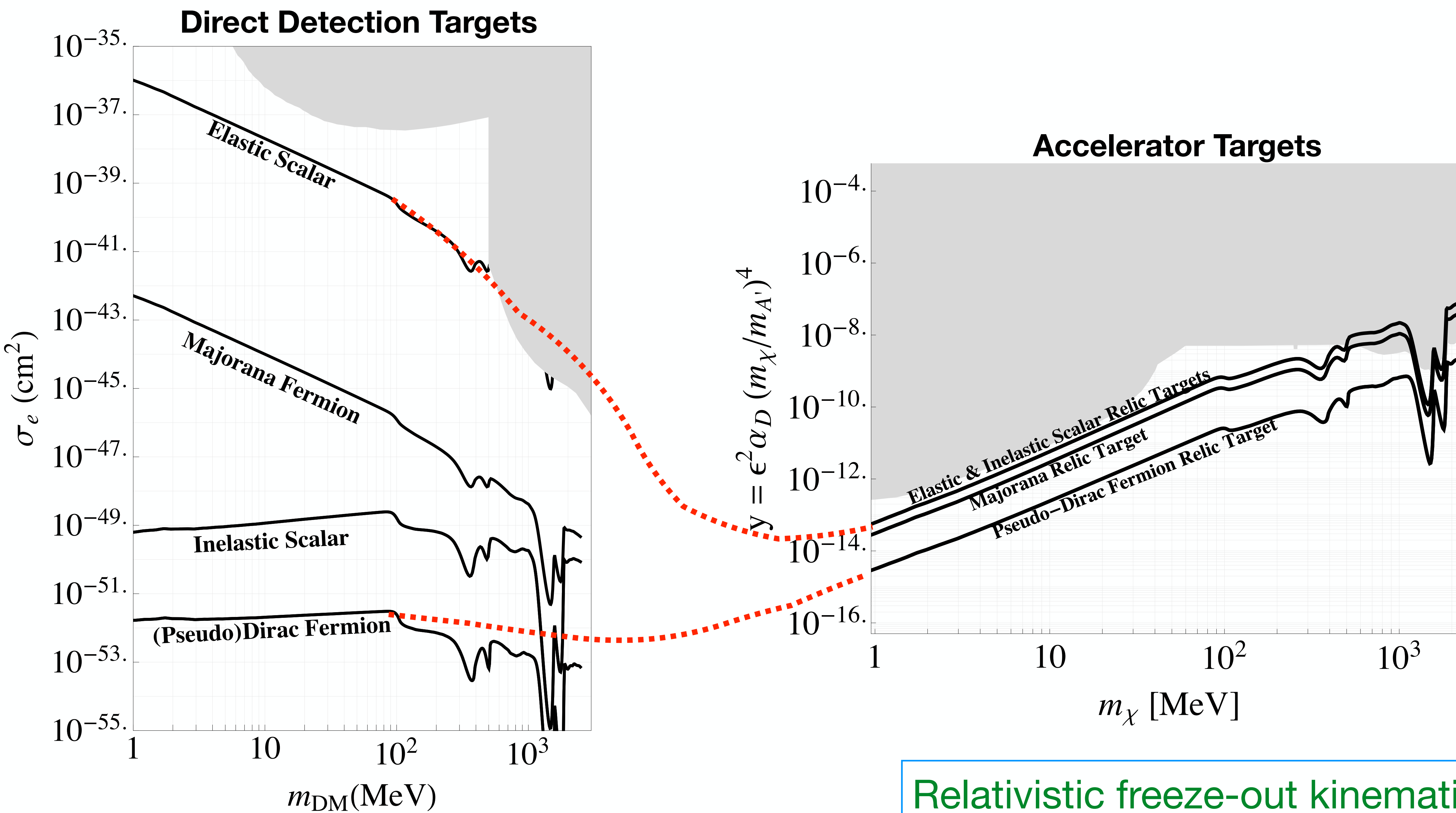
1) What's **great** about thermal DM?

2) What's **different** about light thermal DM (< GeV)?

3) How can we test **all** predictive models?

Fixed-Target Accelerator Searches!

Why Accelerators? Accessible Thermal Targets



non-relativistic cross sections can be loop- or velocity- suppressed

Relativistic freeze-out kinematics

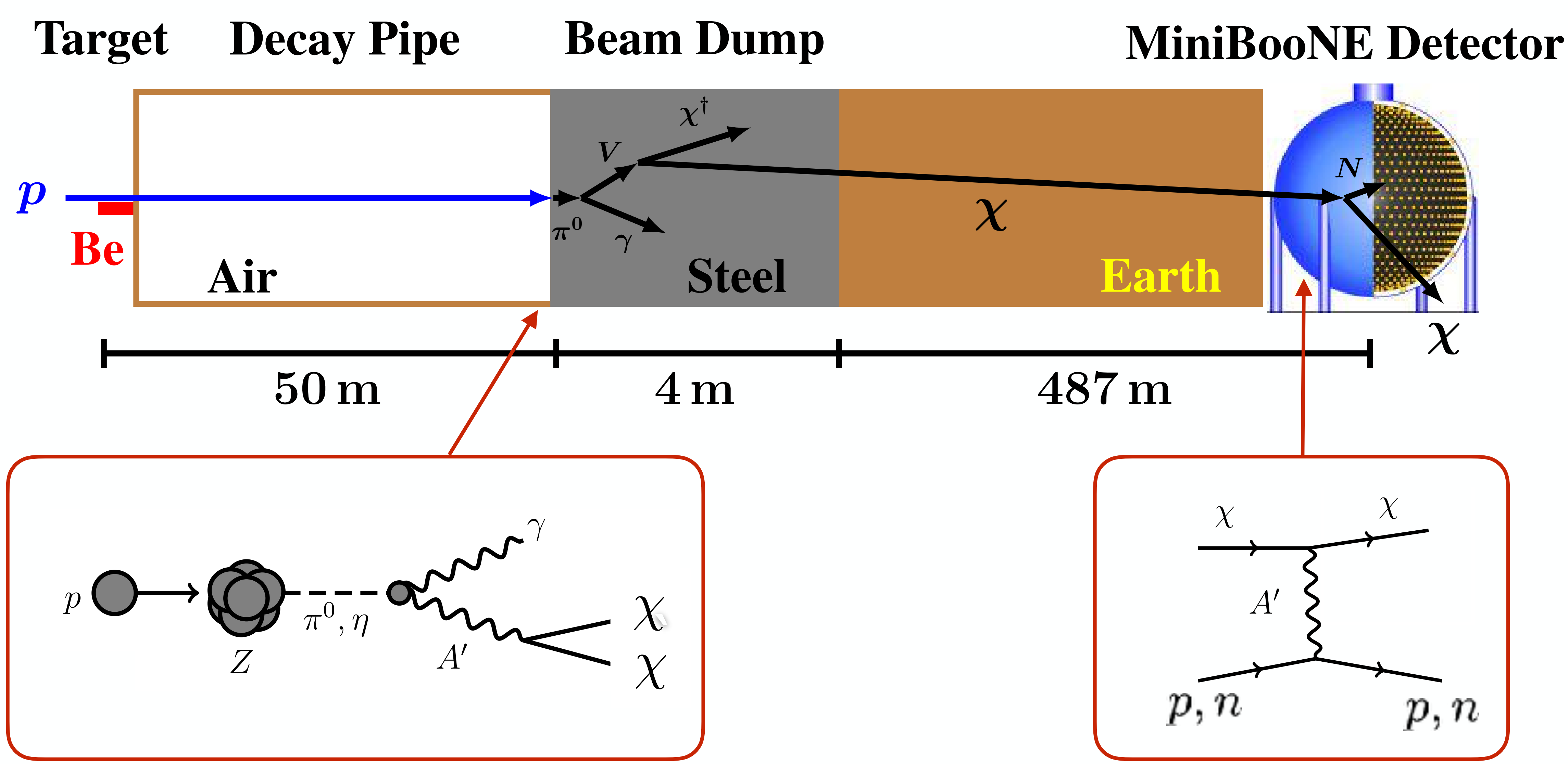
Calculable dark matter rate

No astrophysical uncertainties

All thermal targets within reach

Cosmic Visions Report https://arxiv.org/abs/1707.04591

Neutrino Experiments: Proton Beam Dump Strategy

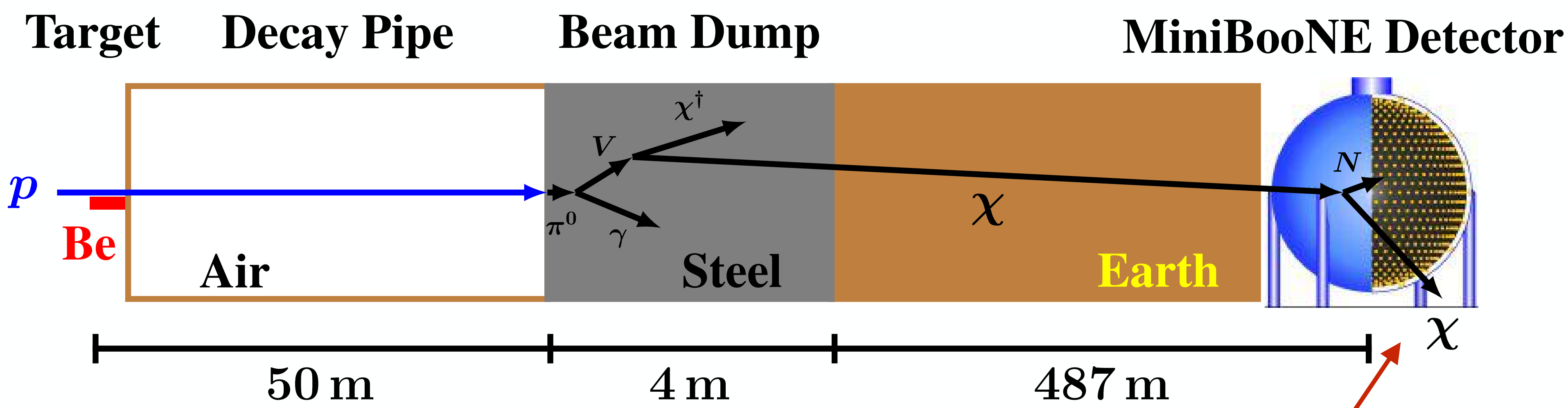


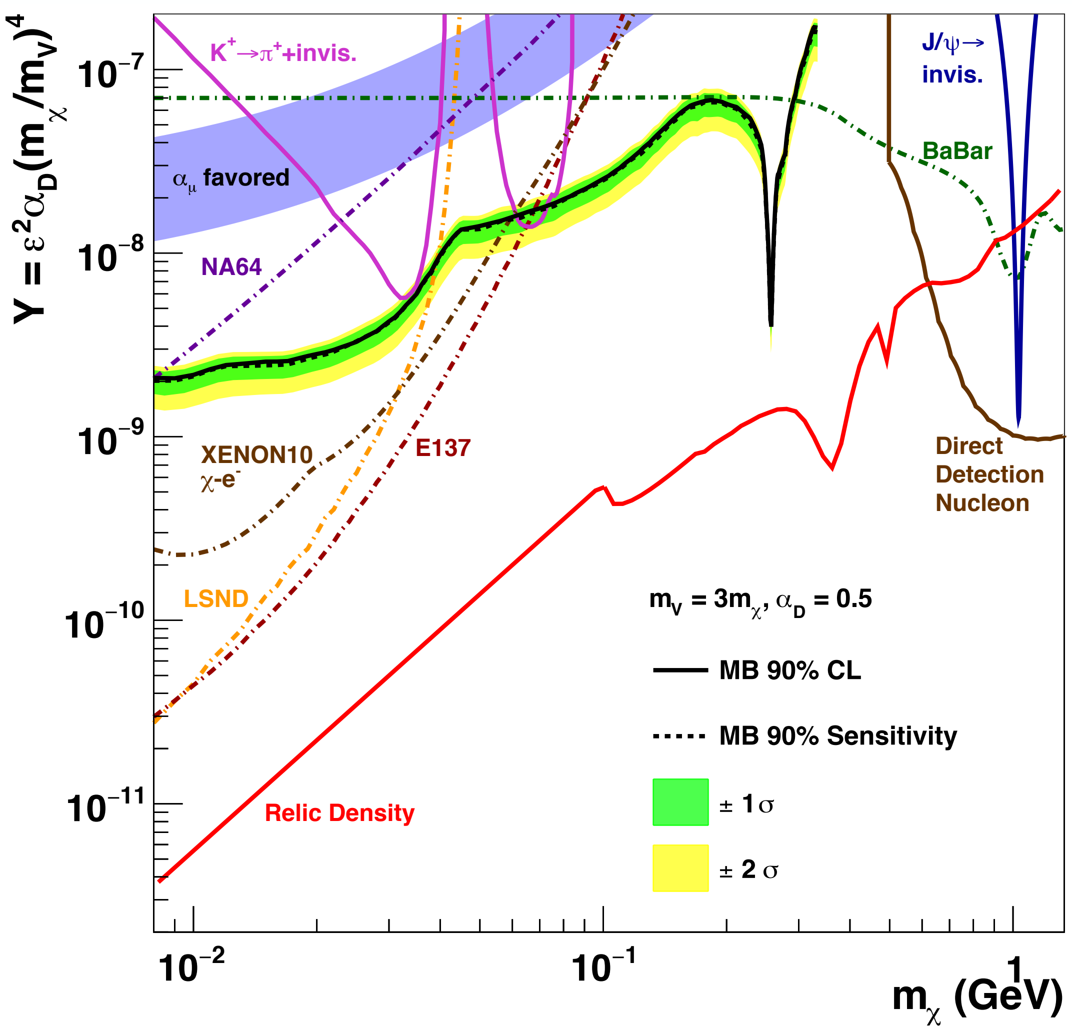
Batell, Pospelov, Ritz 0903.0363
DeNiverville, Pospelov, Ritz 1107.4580
Dobrescu, Friuguele 1410.1566
Kahn, GK, Thaler, Toups 1411.1055
De Niverville Friuguele 1807.06501
De Gouvea, Fox, Harnik, Kelly, Zhang 1809.06388
Berlin, Kling 1810.01879
Mohlabeng 1902.05075
Di Romeri, Kelly, Machado 1903.10505
De Niverville, Tsai, Liu 1908.07525

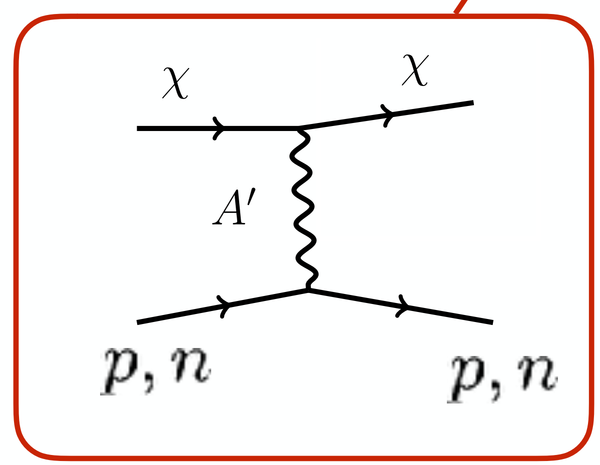
$$[\text{production}] \times [\text{detection}] \propto \epsilon^4$$

$$N_p \sim 10^{20}$$
$$E_{\text{beam}} \sim 10\,\text{GeV}$$

Neutrino Experiments: Proton Beam Dump Strategy







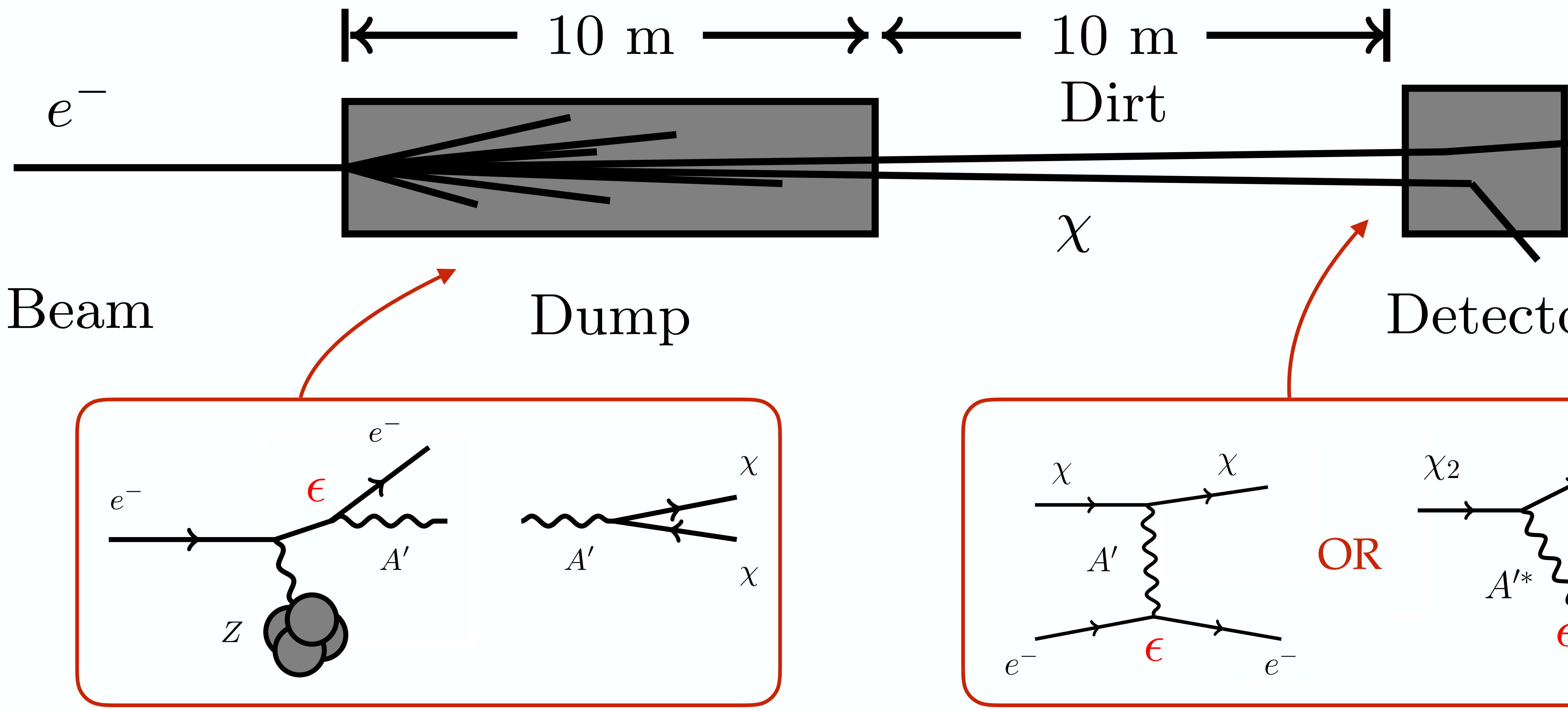
First **ever** dedicated LDM search

Limited by neutrino BG & luminosity

Q: How can we improve?

MiniBooNE Collaboration Phys. Rev. Lett. 118 (2017)

Electron Beam Dump Concept: BDX (Beam Dump eXperiment)



$E_{\text{beam}} \sim 10\,\text{GeV} \quad N_e \sim 10^{22}/\text{yr}$

$[\text{production}] \times [\text{detection}] \propto \epsilon^4$

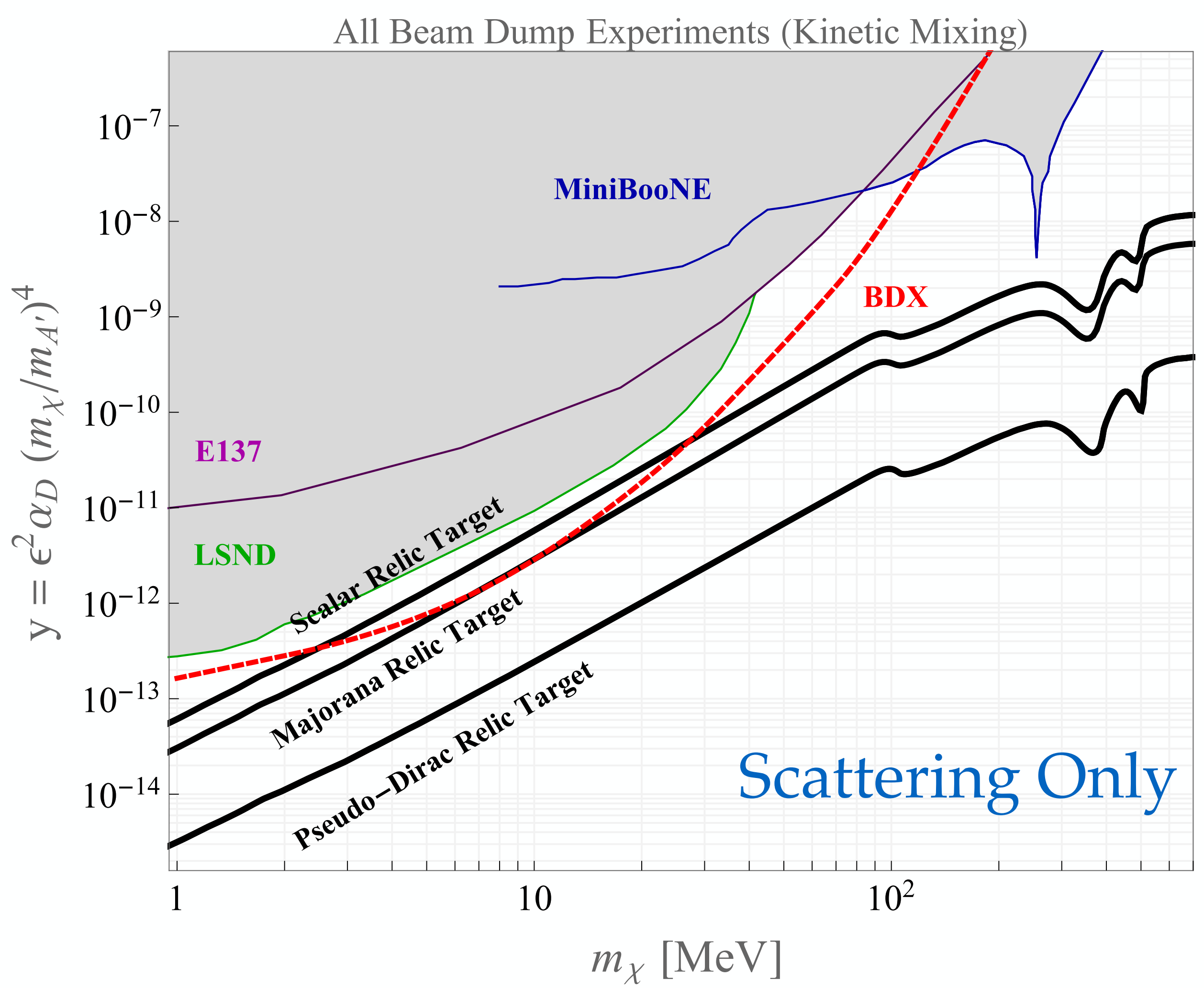
Direct DM production & Detection
Existing Beams/Dumps & Detectors
Low Neutrino & Cosmic BG

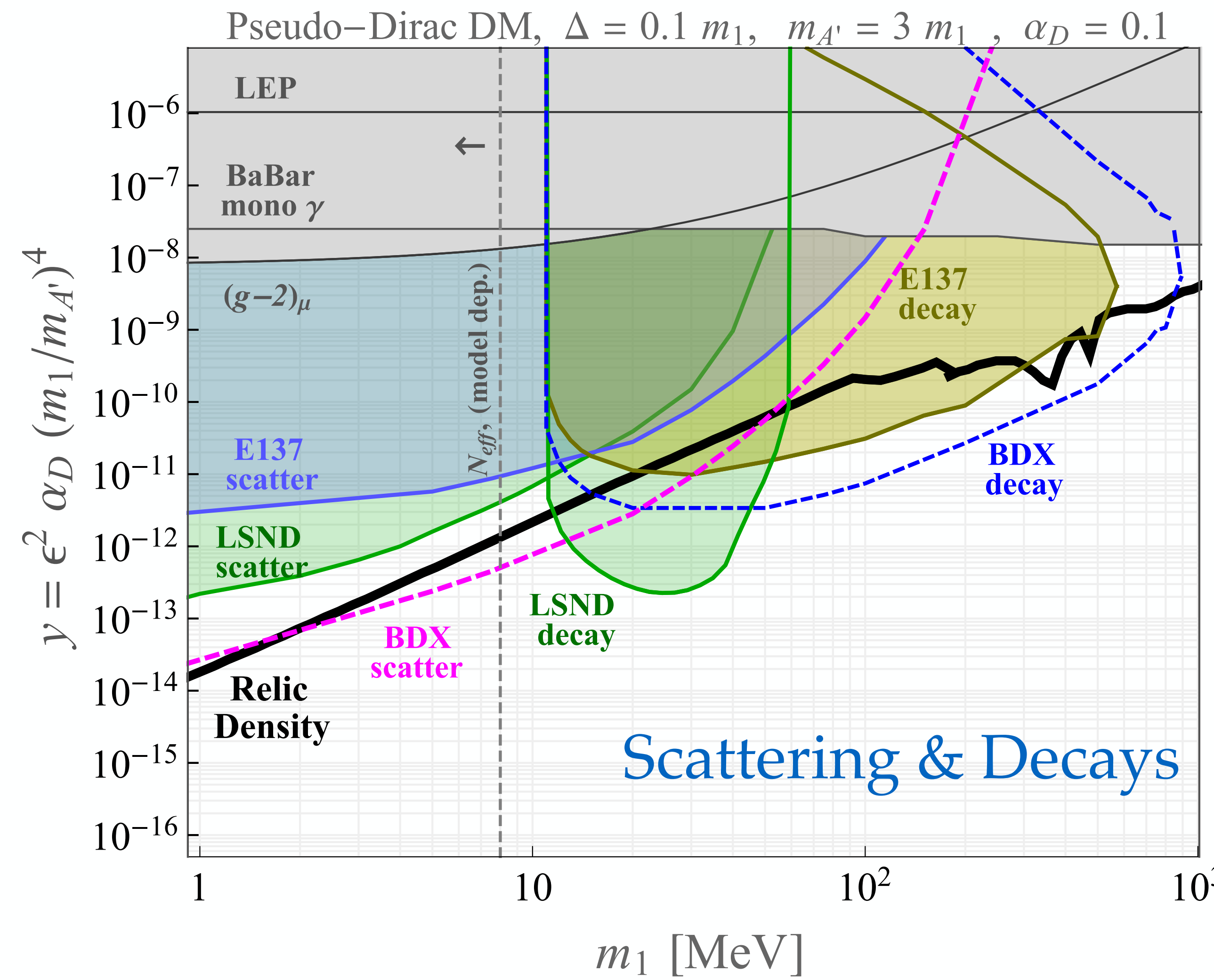
Higher rate and lower BG compared to proton beams

Izaguirre, GK, Schuster, Toro arXiv:1307.6554

BDX Collaboration arXiv:1607.01390

Electron Beam Dump Concept: BDX (Beam Dump eXperiment)





Various DM Candidates

Pseudo-Dirac [large splitting]
Freeze out via coannihilation

Improves upon proton beam approach, but suffers double taxation!

Q: How can we improve reach?

Izaguirre, Kahn, GK, Moschella 1703.06881

Light Dark Matter eXperiment (LDMX)

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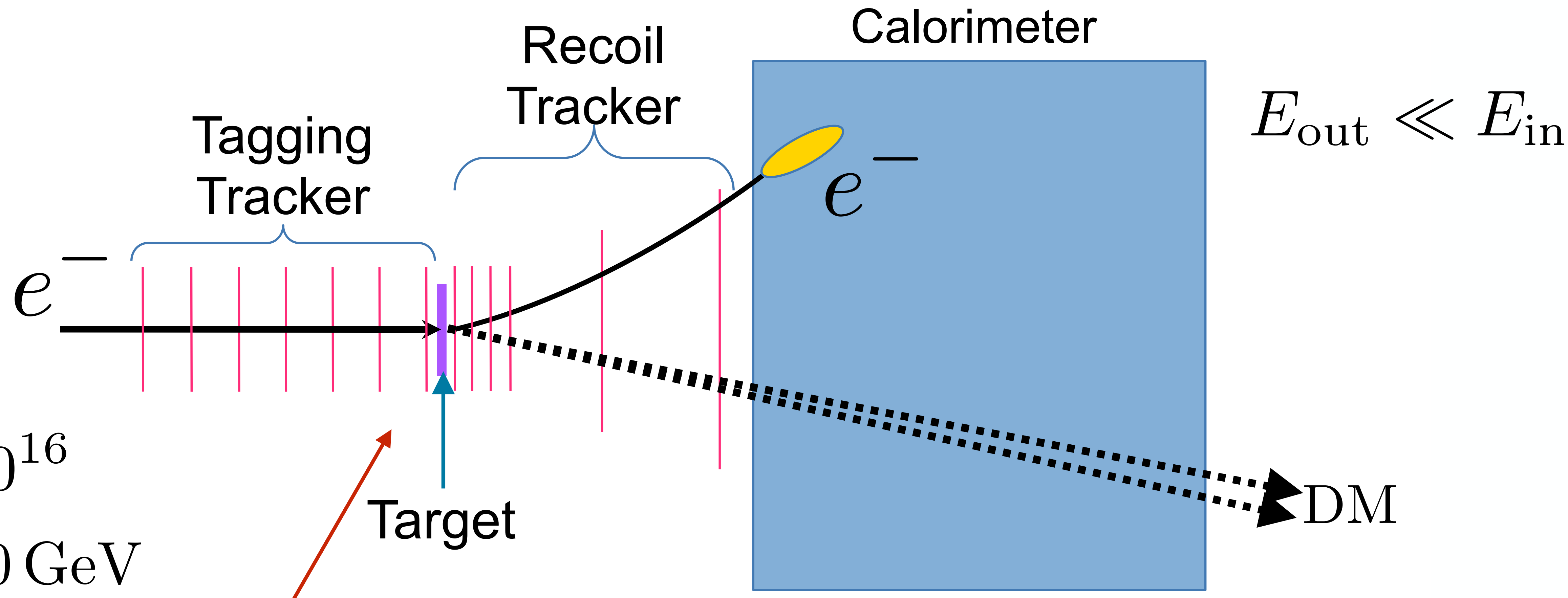
In this paper, we present the physics motivation and a preliminary conceptual design study for an experiment to search for low-mass dark matter utilizing low-current, high repetition rate electron beams. The experiment uses missing momentum to search for dark matter produced via "dark bremsstrahlung" by scattering electrons in a thin target. To identify rare signal events, the Light Dark Matter eXperiment (LDMX) individually tags

LDMX Collaboration 1808.05219
LDMX Collaboration 1912.05535

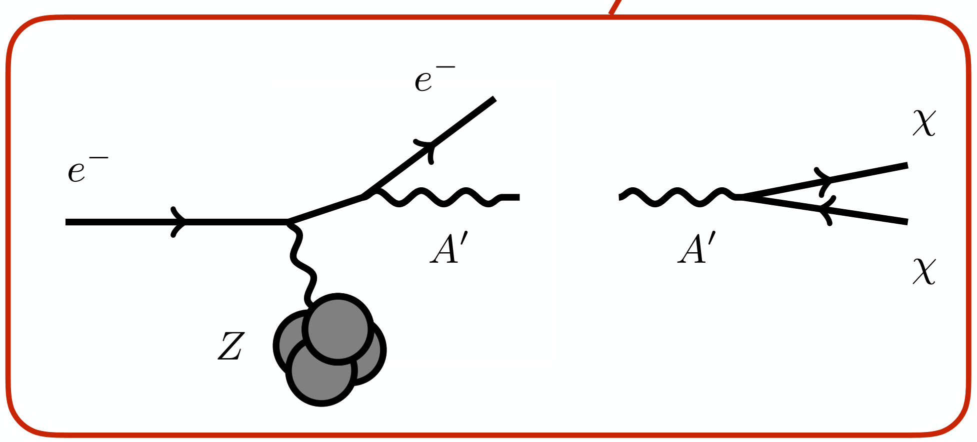
News: Phase 1 funding approved 2020!

Electron Beam Missing Momentum Concept



$N_e \sim 10^{16}$

$E_{\rm in} \sim 10\,{\rm GeV}$



1) Measure **each** e- energy in/out

2) Trigger on missing momentum

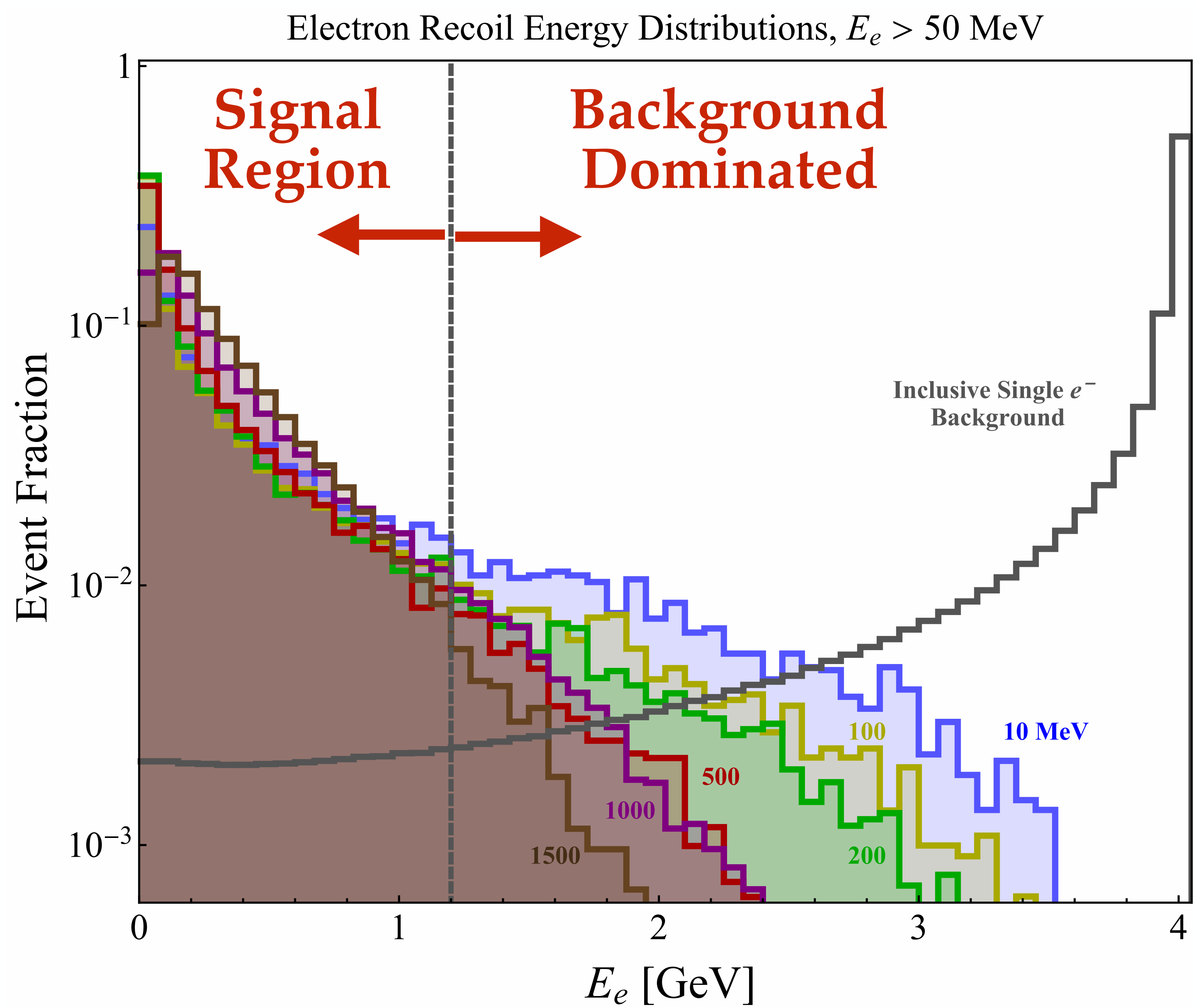
3) Veto additional SM activity

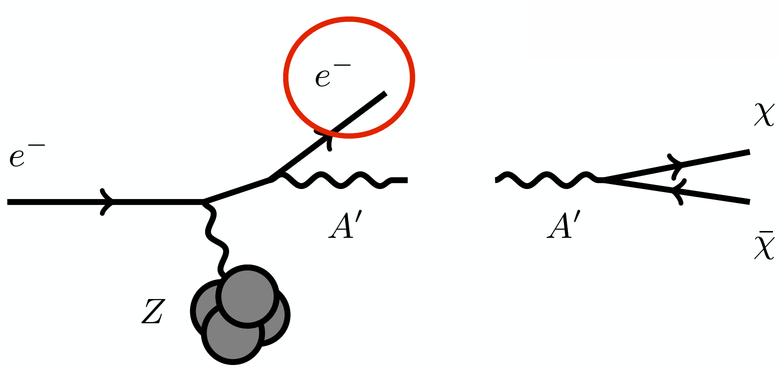
Only measure electron beam — don't require DM to scatter

Signal $\propto \epsilon^2$

Izaguirre, GK, Schuster, Toro arXiv:1411.1404

Kinematics of Fixed Target Production





Emitted DM system receives most of beam energy

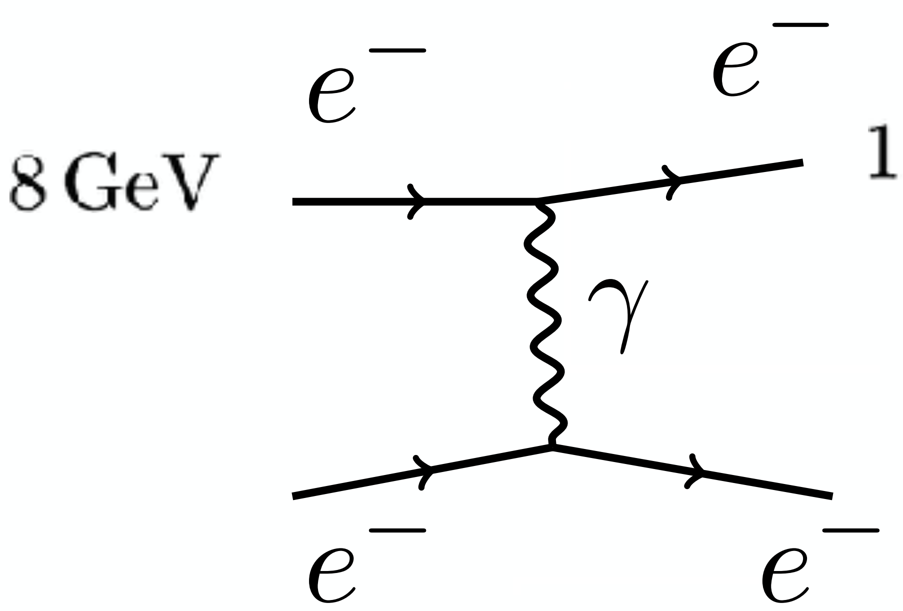
Kinematically distinct from SM backgrounds

Aggressive cuts remove most BG, little signal

LDMX 1808.05219

Irreducible “Invisible ”Backgrounds

Beam particle scatters electron in target & converts to invisible particles

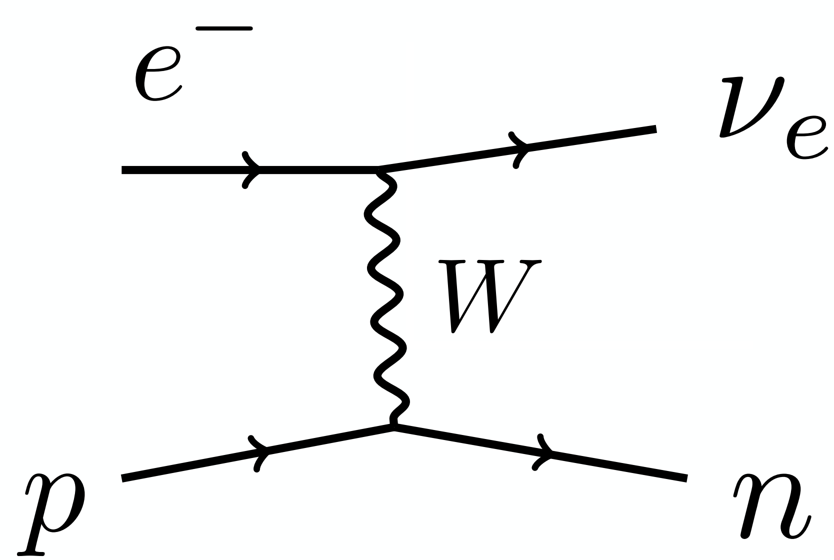


Step1:

Møller Scattering

Step 2:

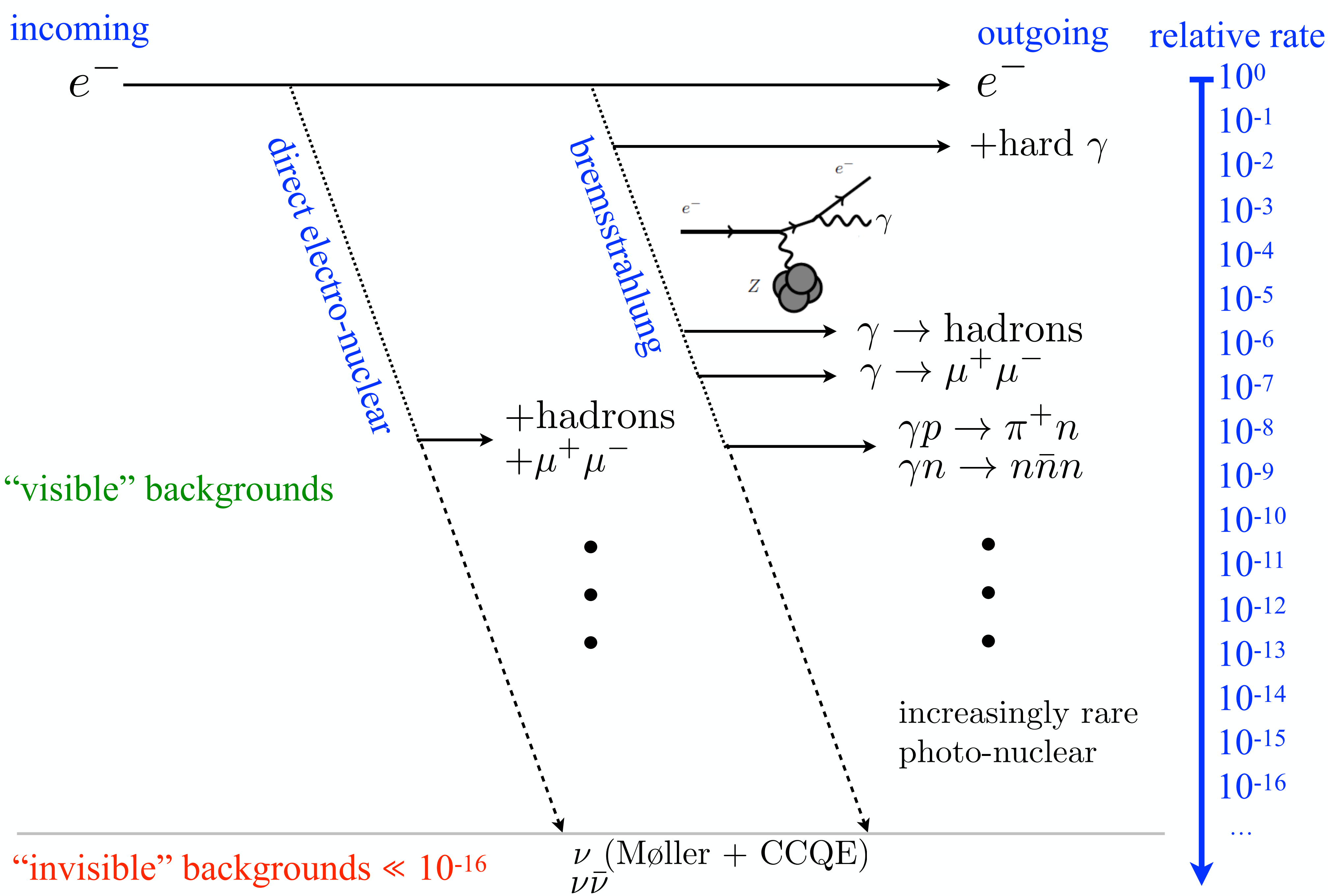
Convert to invisible neutron and neutrino



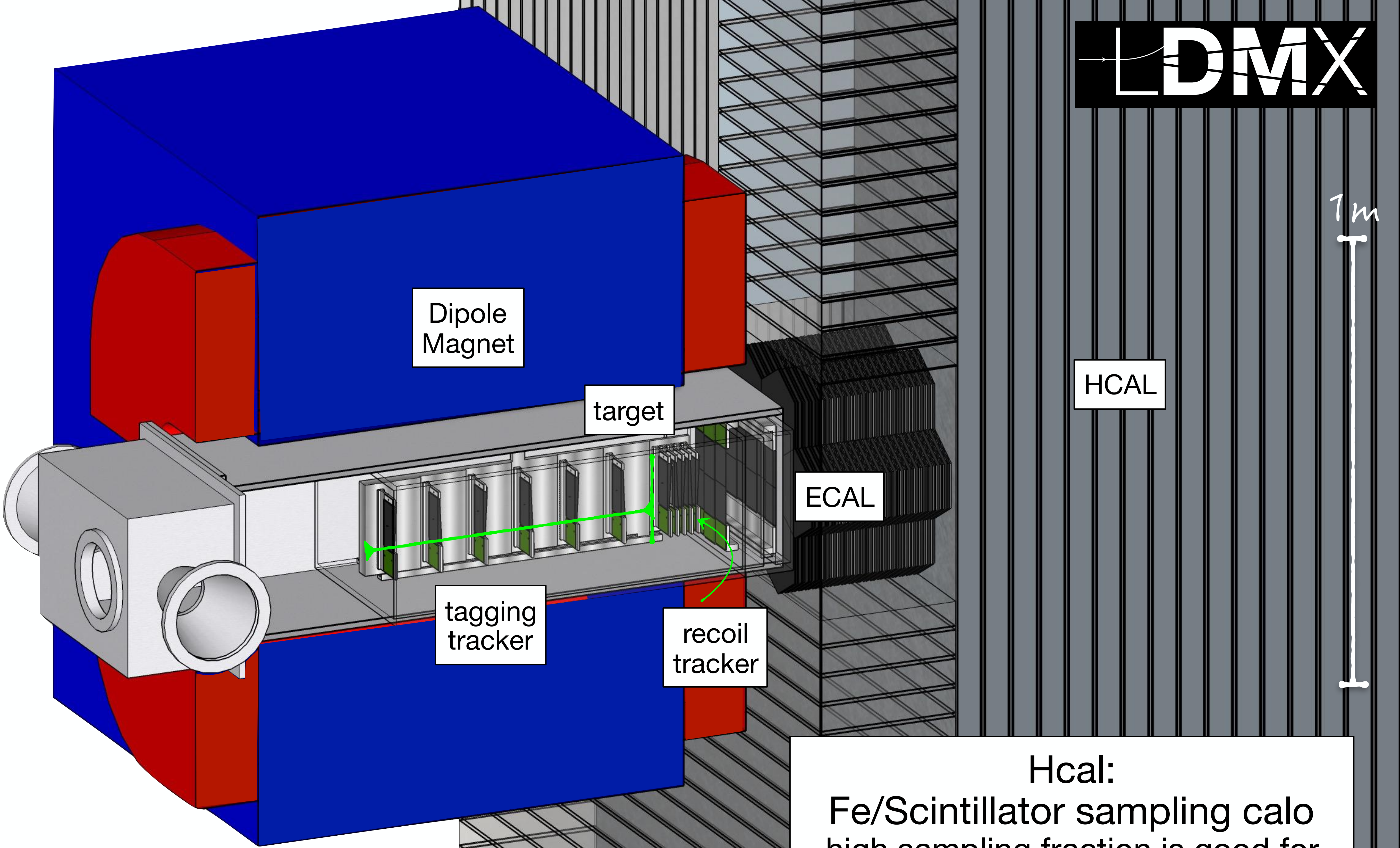
Verdict: Negligible

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

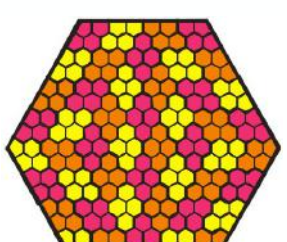
Main Challenge: Undetected Visible Particles



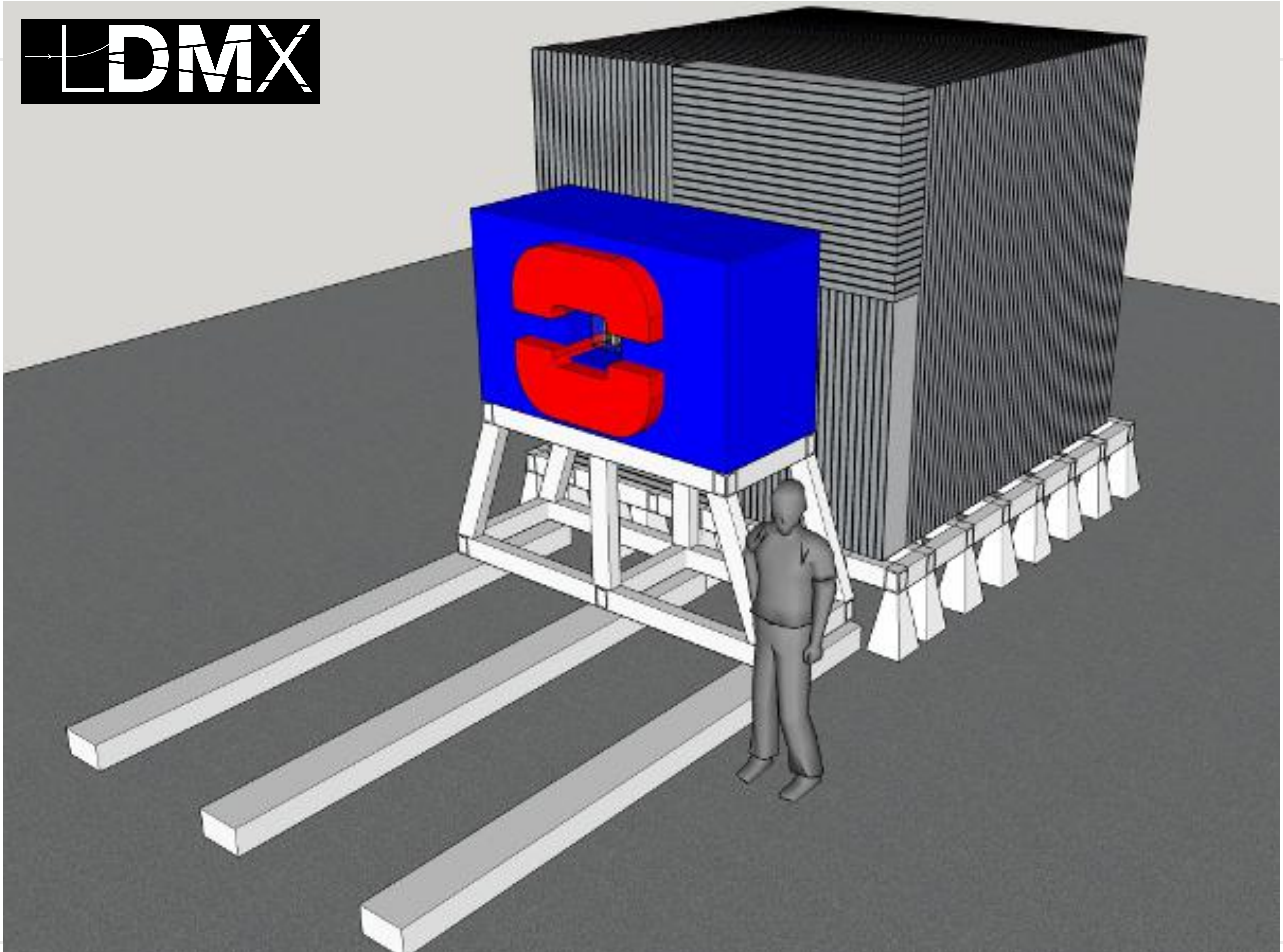
LDMX Collaboration 1912.05535



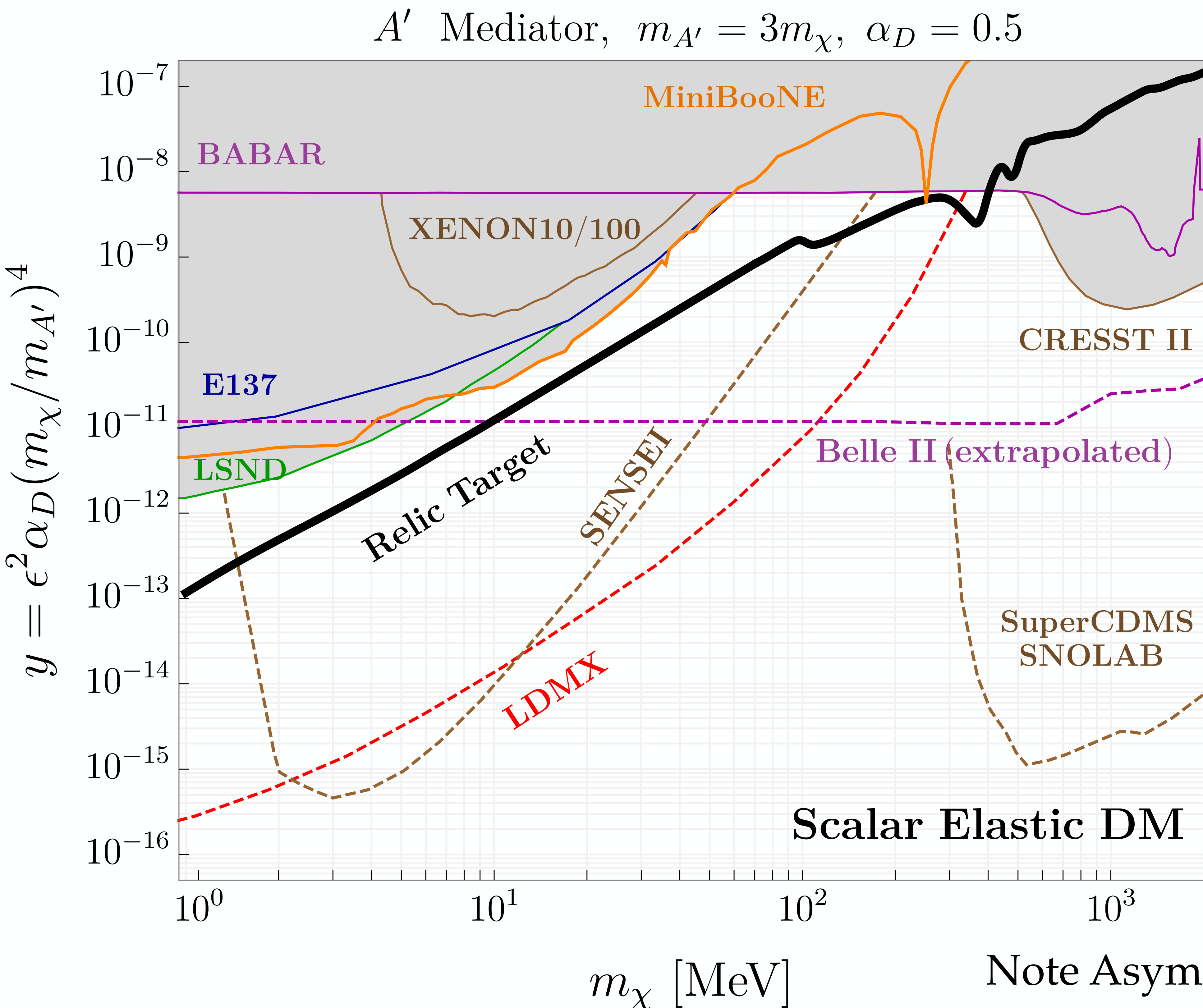
Hcal:
Fe/Scintillator sampling calo
high sampling fraction is good for
high efficiency neutron detection
Synergy with LHC calorimeter
readout electronics



Ecal is based on CMS HGCal
Si calorimeter has high radiation
tolerance and good MIP tracking

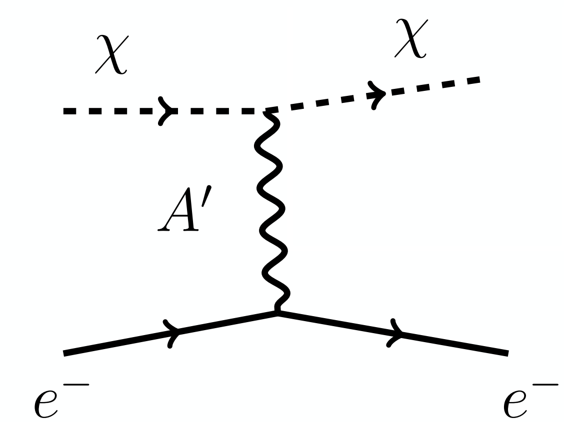

LDMX

Comprehensive Coverage: Dark Photon Mediator A'



Scalar DM

$A'_\mu \chi^* \partial_\mu \chi$



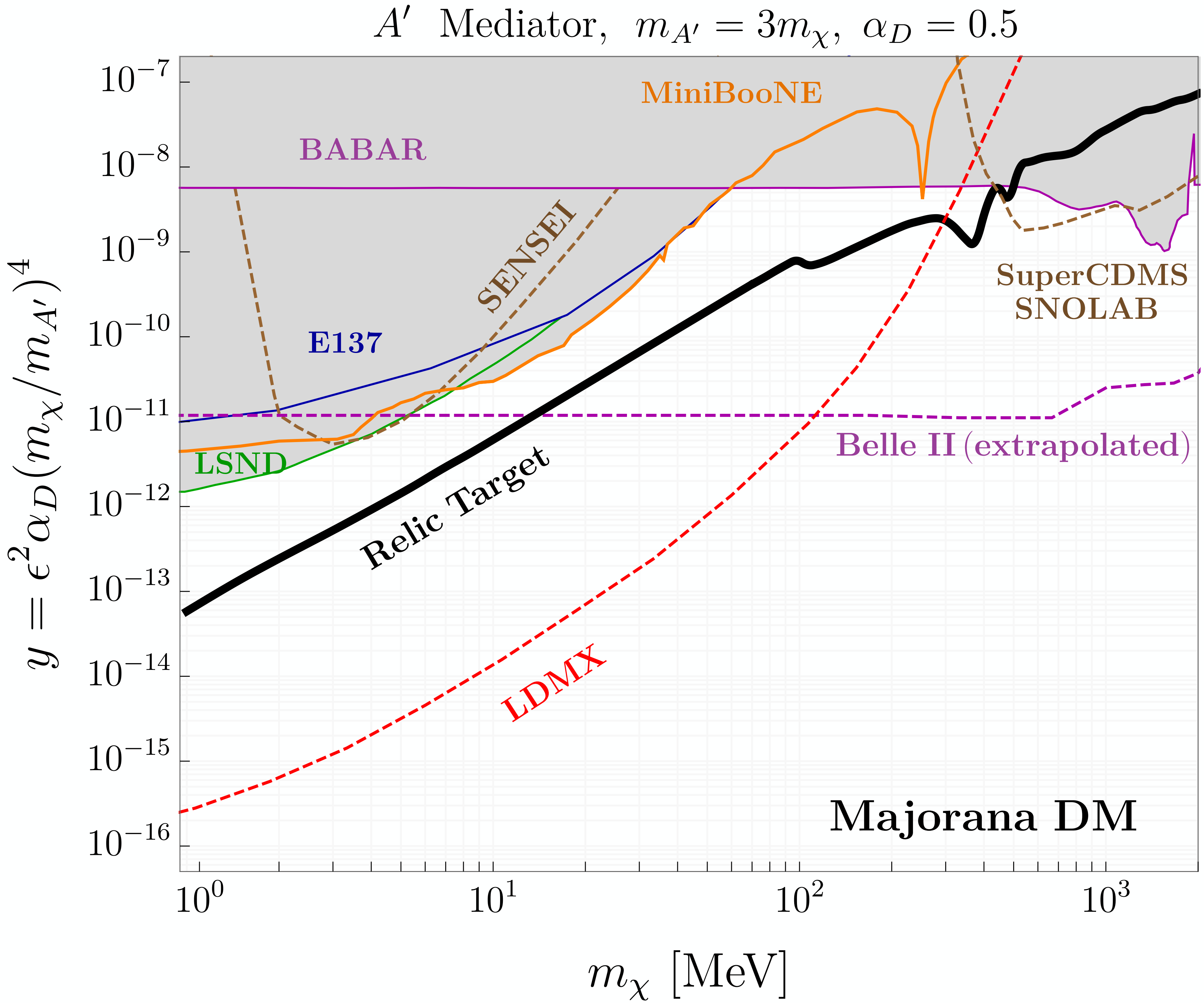
CMB safe

$\sigma v \propto v^2$

Note Asymmetric DM models viable anywhere above the targets

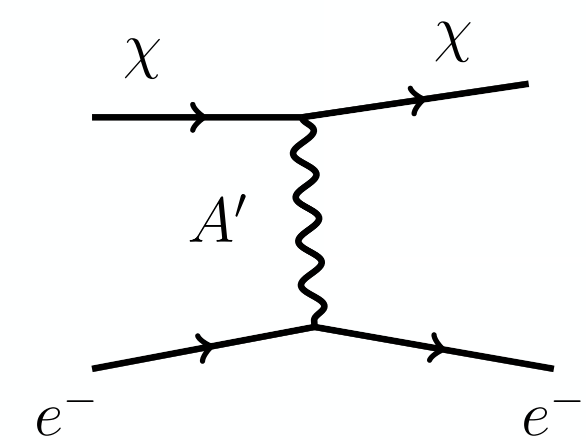
Izaguirre, GK, Schuster, Toro arXiv:1505.00011 Phys.Rev.Lett. 115 (2015)

Comprehensive Coverage: Dark Photon Mediator A'



Majorana DM

$$A'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$



CMB safe

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

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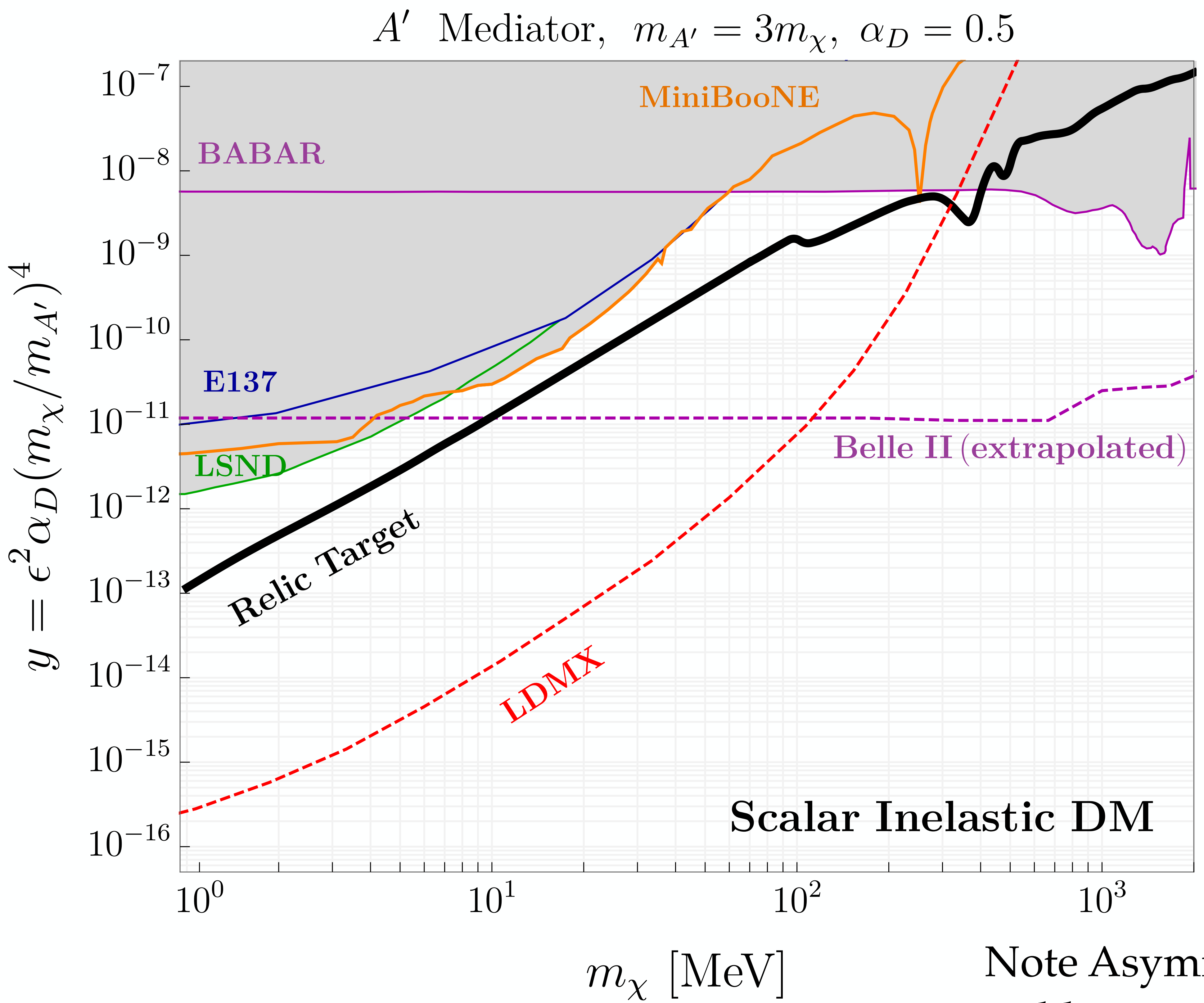
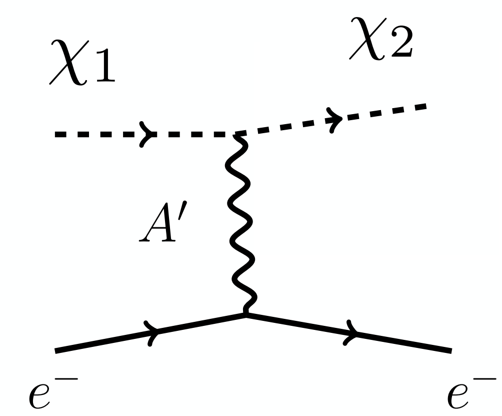
Comprehensive Coverage: Dark Photon Mediator A'



Scalar Inelastic

$$A'_\mu \chi_1^* \partial_\mu \chi_2$$

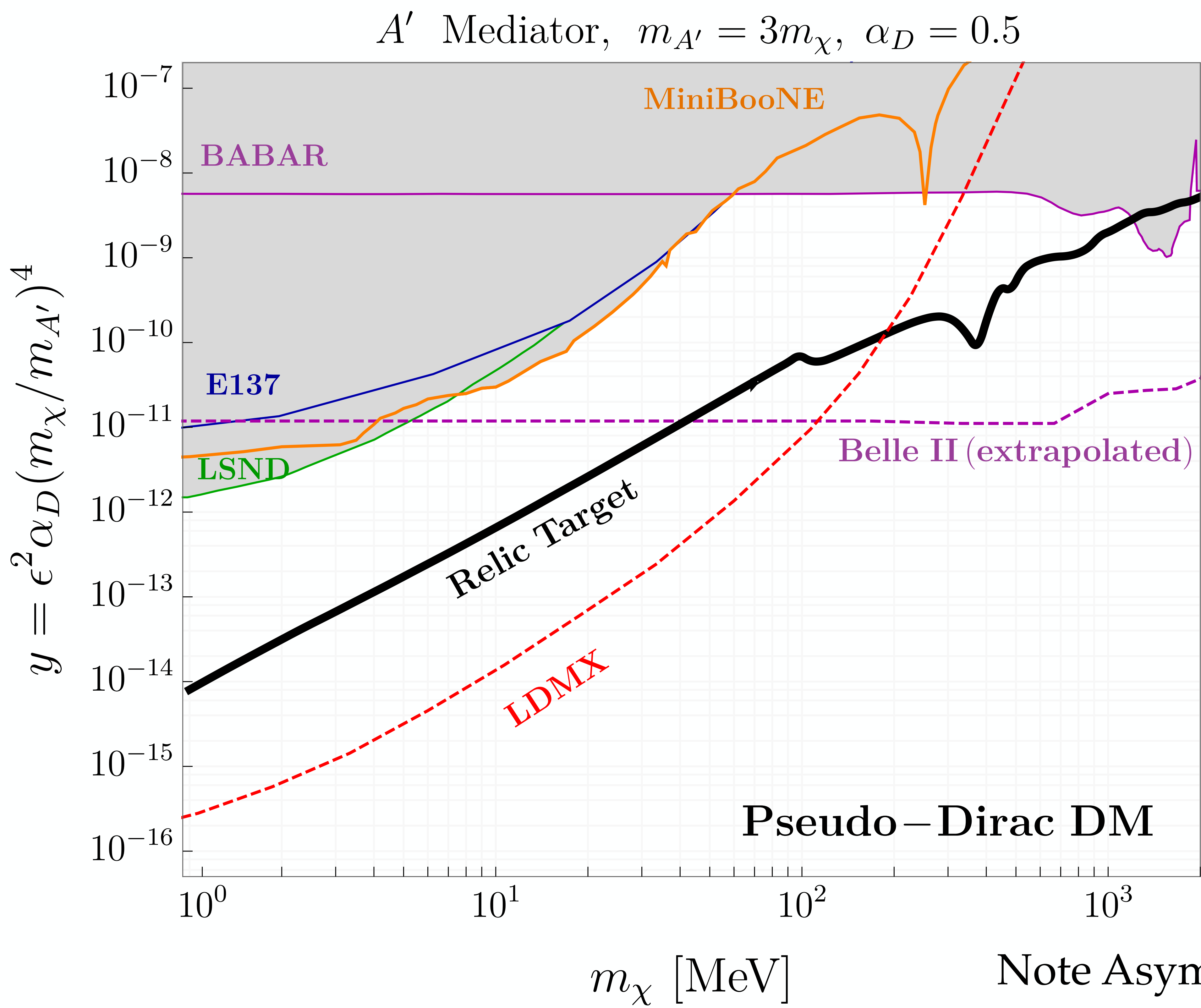


CMB safe

χ_2 gone before rec.

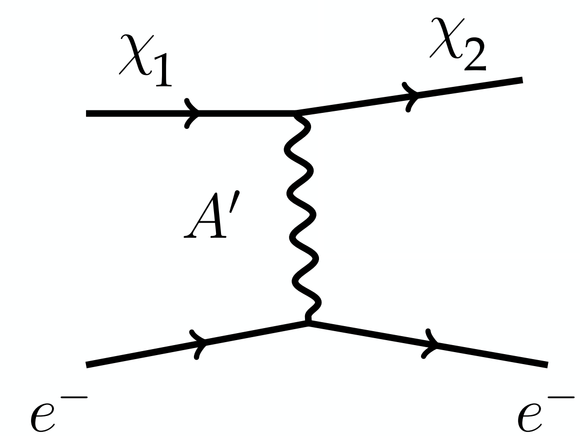
Note Asymmetric DM models viable anywhere above the targets

Comprehensive Coverage: Dark Photon Mediator A'



Pseudo-Dirac

$$A'_\mu \bar{\chi}_1 \gamma^\mu \chi_2$$



CMB safe

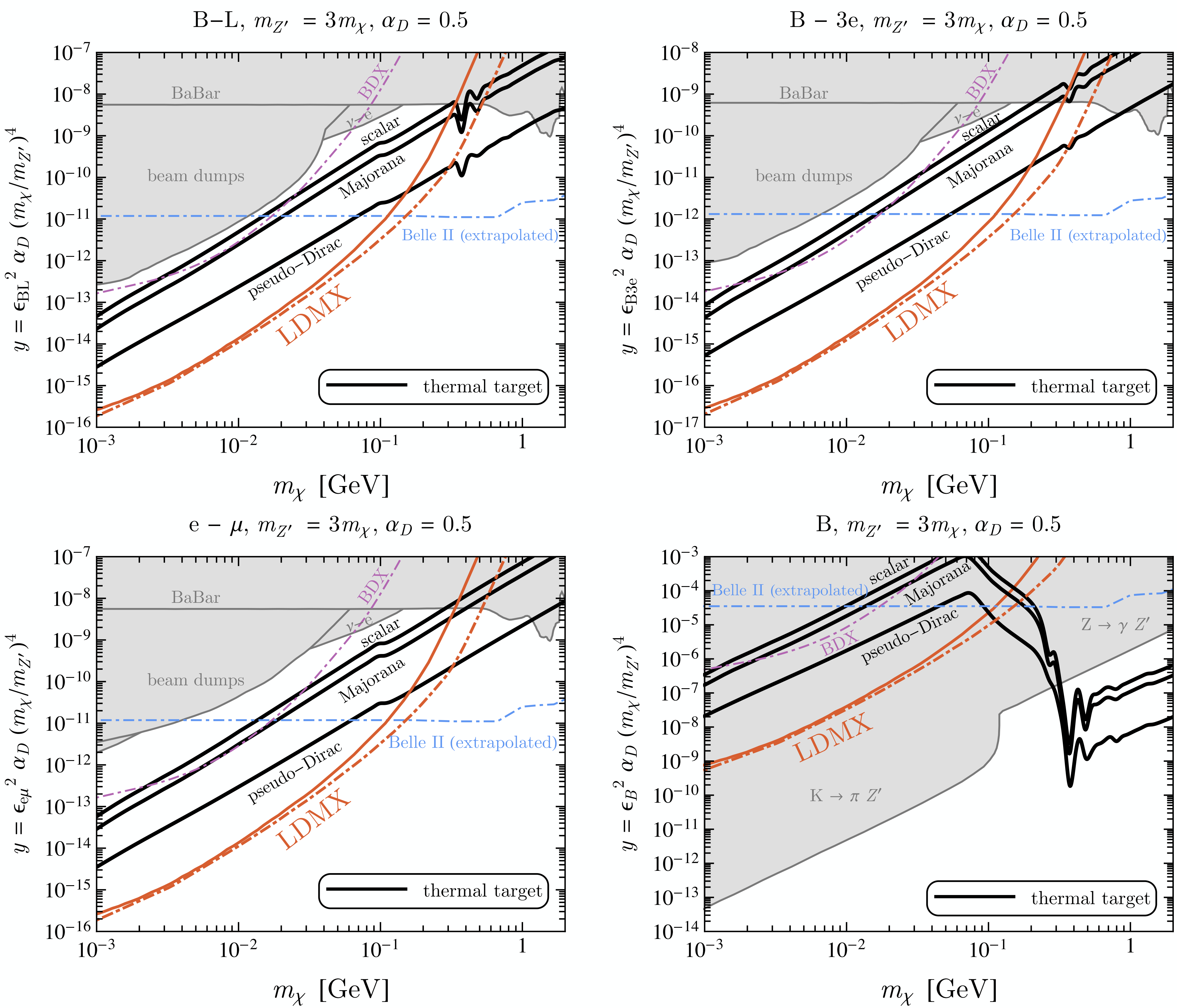
χ_2 gone

before rec.

Note Asymmetric DM models viable anywhere above the targets

Izaguirre, GK, Schuster, Toro arXiv:1505.00011 Phys.Rev.Lett. 115 (2015)

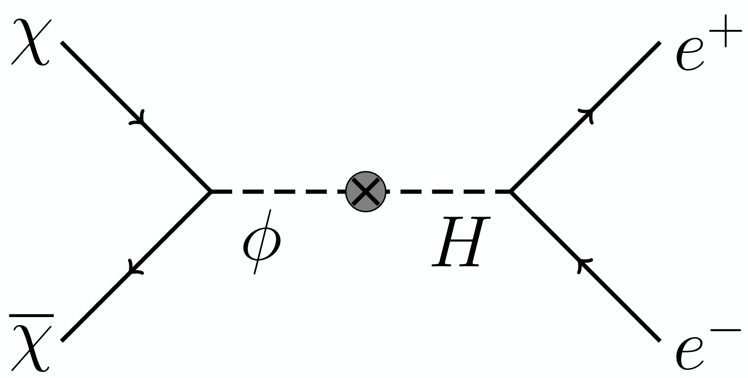
Comprehensive Coverage: Other Viable Forces



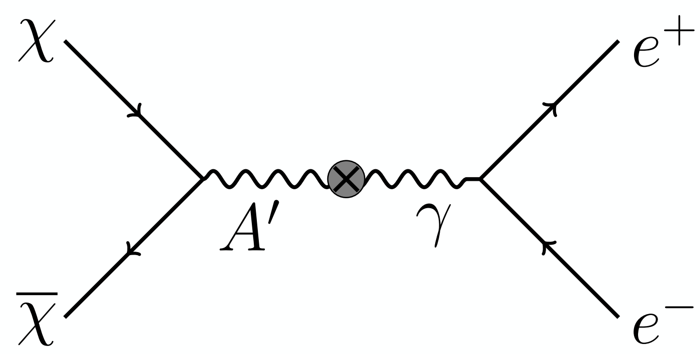
Berlin, Blinov GK, Schuster, Toro arXiv: 1807.01730

Where are the blind spots?

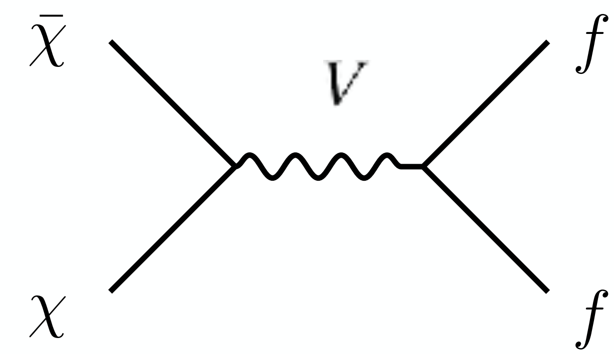
So far we have covered nearly all **predictive** direct annihilation models



Scalar force
Ruled out



Dark photon



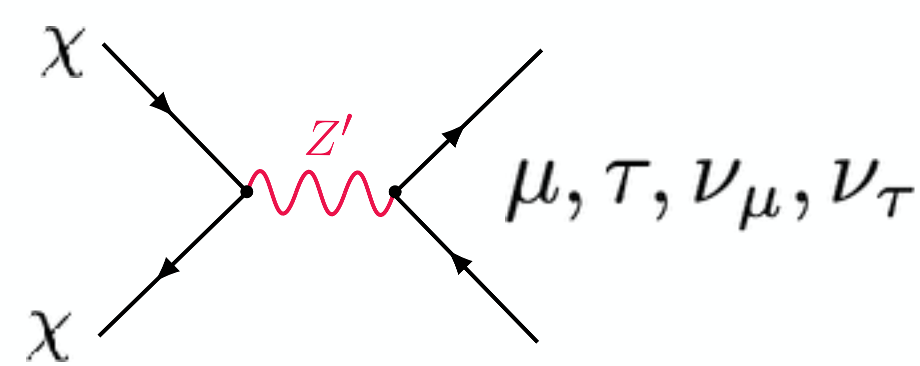
5th Force
B-L, *B-3Le* … etc.

Thermal coverage: missing momentum + beam dumps + electron direct detection

What about mediators w/ mainly 2nd & 3rd generation couplings?

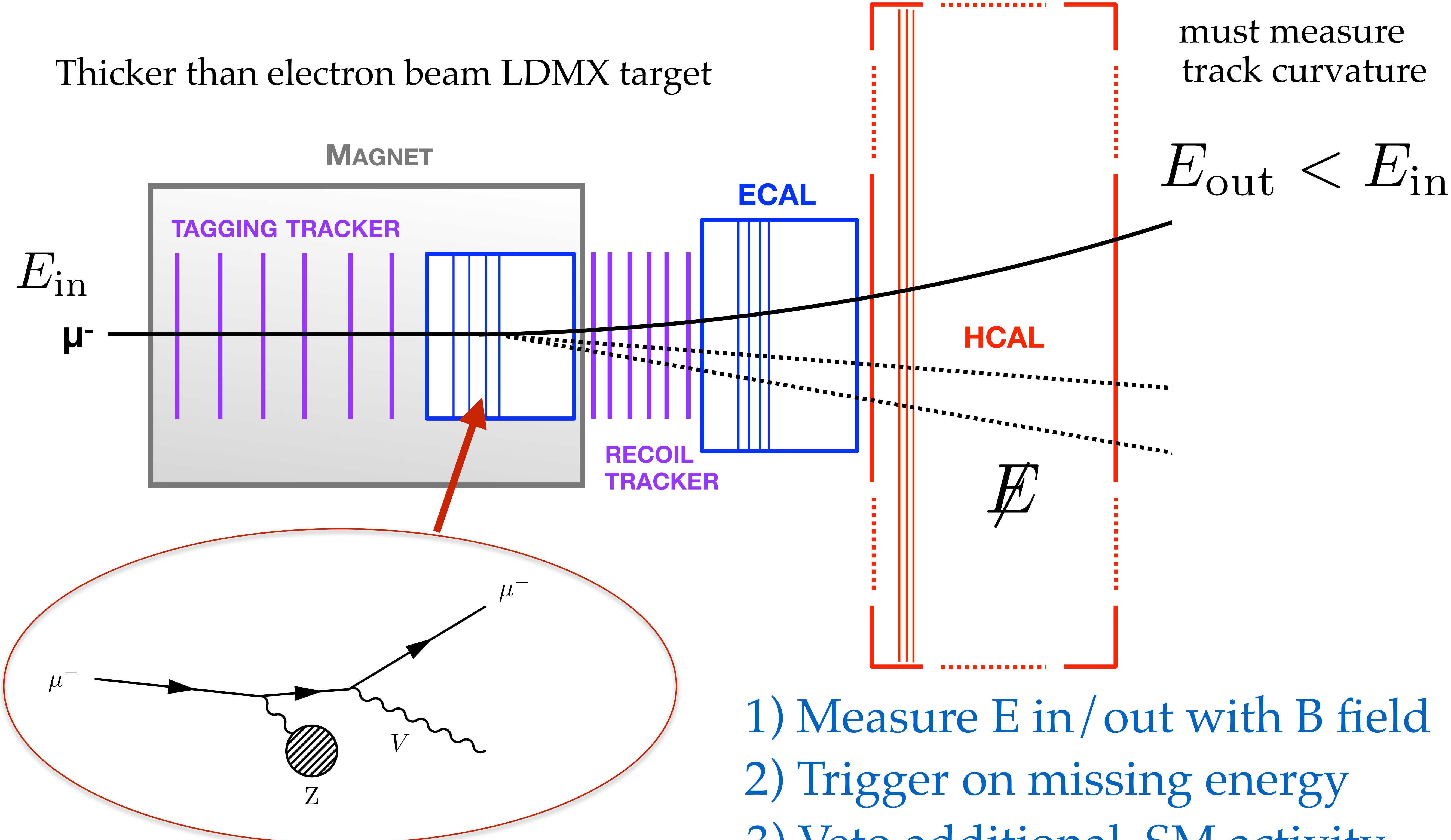
Only one theoretically consistent option

$$L_\mu - L_\tau$$



Muon Missing Momentum: LDMX w/ muon beam

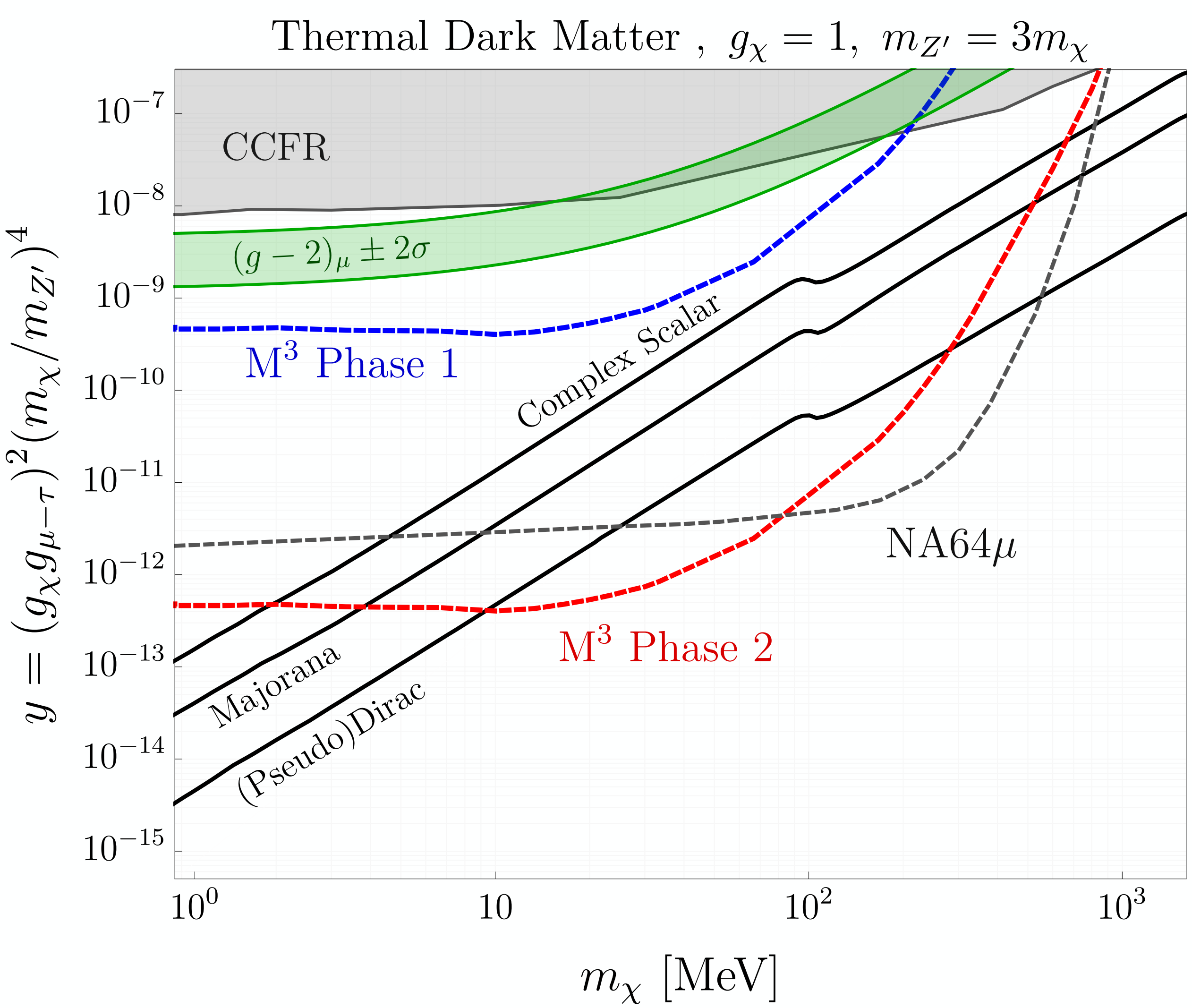
Thicker than electron beam LDMX target

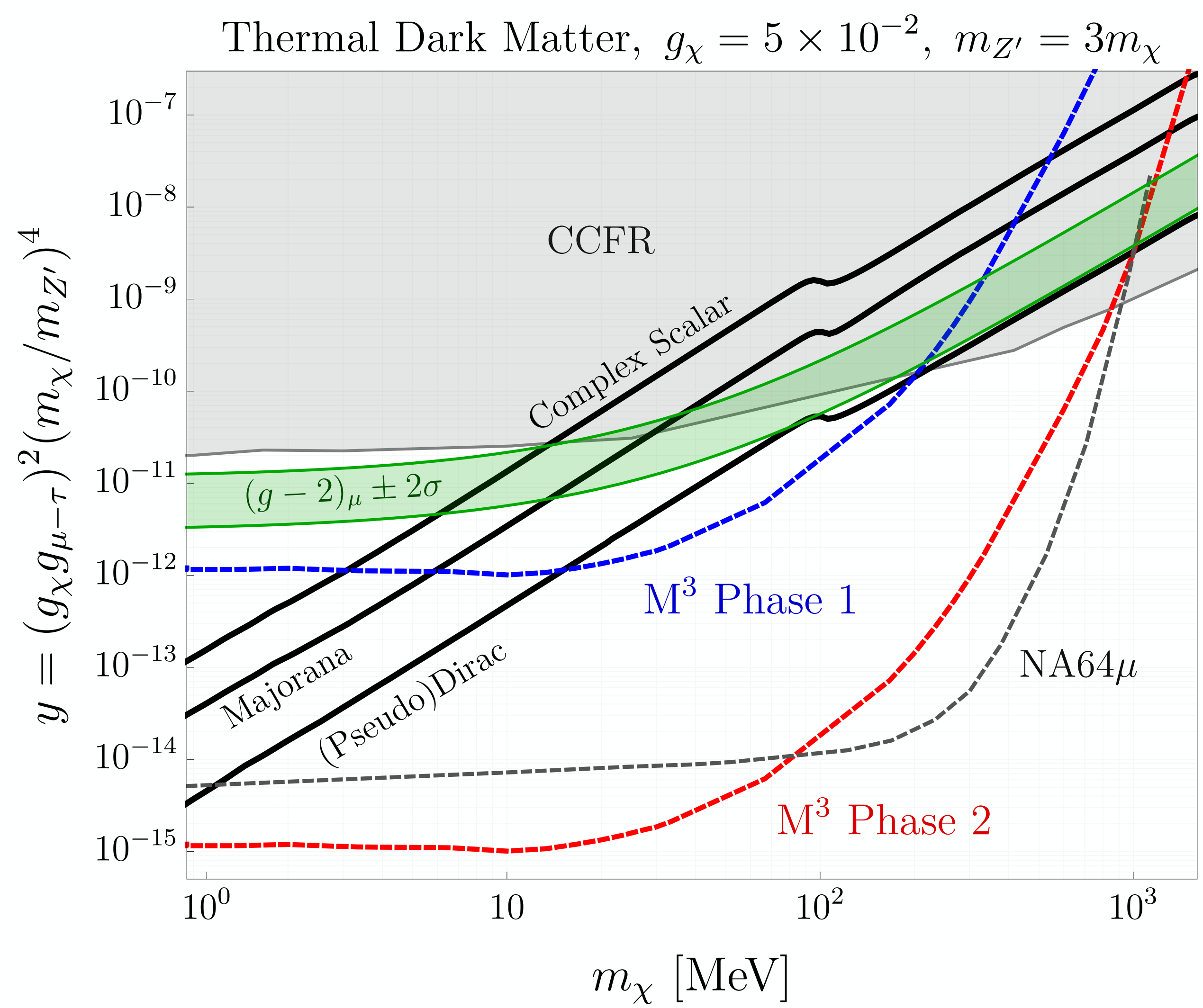


1) Measure E in/out with B field
2) Trigger on missing energy
3) Veto additional SM activity

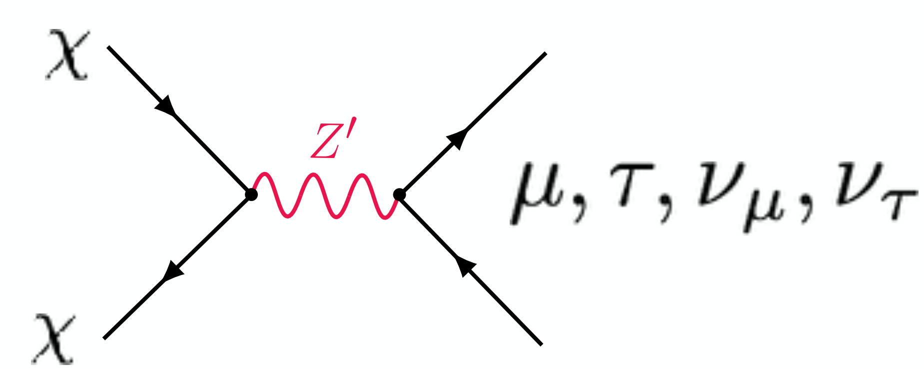
Kahn, GK, Tran, Whitbeck 1804.03144 (JHEP 2018)

Covers Predictive Muon-Philic Models





Gauged $L_\mu - L_\tau$ Interaction



Also resolve muon g-2 with light physics

Compatible parameter space for freeze-out

NB: annihilation to neutrinos also CMB safe

Summary: Thermal Dark Matter

$\mathrm{MeV} \sim m_e$ $\mathrm{GeV} \sim m_p$ $m_{Z,h}$ $\sim 10\mathrm{s\ TeV}$

LDM | **"WIMPs"**

A Modest Proposal

Interaction rate beats Hubble expansion [easy to realize]

Thermodynamic Initial Condition

Insensitive to unknown high scales [inflation, baryogenesis…]

Predicts Minimum Annihilation Rate

Equilibrium overproduces DM, deplete with non-gravitational force

Viable Window In Our Neighborhood

Coincidentally between electron mass and LHC energies

New Frontier of DM Search Strategies

$\text{MeV} \sim m_e$ $\text{GeV} \sim m_p$ $m_{Z,h}$ $\sim 10\text{s TeV}$

LDM	"WIMPs"

Missing Momentum
LDMX, M^3

Beam Dumps:
DUNE, BDX, MiniBooNE
Nova, SBN, DarkQuest…

New Direct Detection Targets

Direct Detection

Indirect Detection

Collider Production

Mature program of searches covers nearly all predictive models

DOE Basic Research Needs Report

Amends P5 report: identify new DM opportunities

https://science.energy.gov/~/media/hep/pdf/Reports/201809_HEP-PI-BRN-Dark-Matter_New_Initiatives.pdf

Thanks!