Discovering or Falsifying Predictive Thermal Dark Matter (<GeV)

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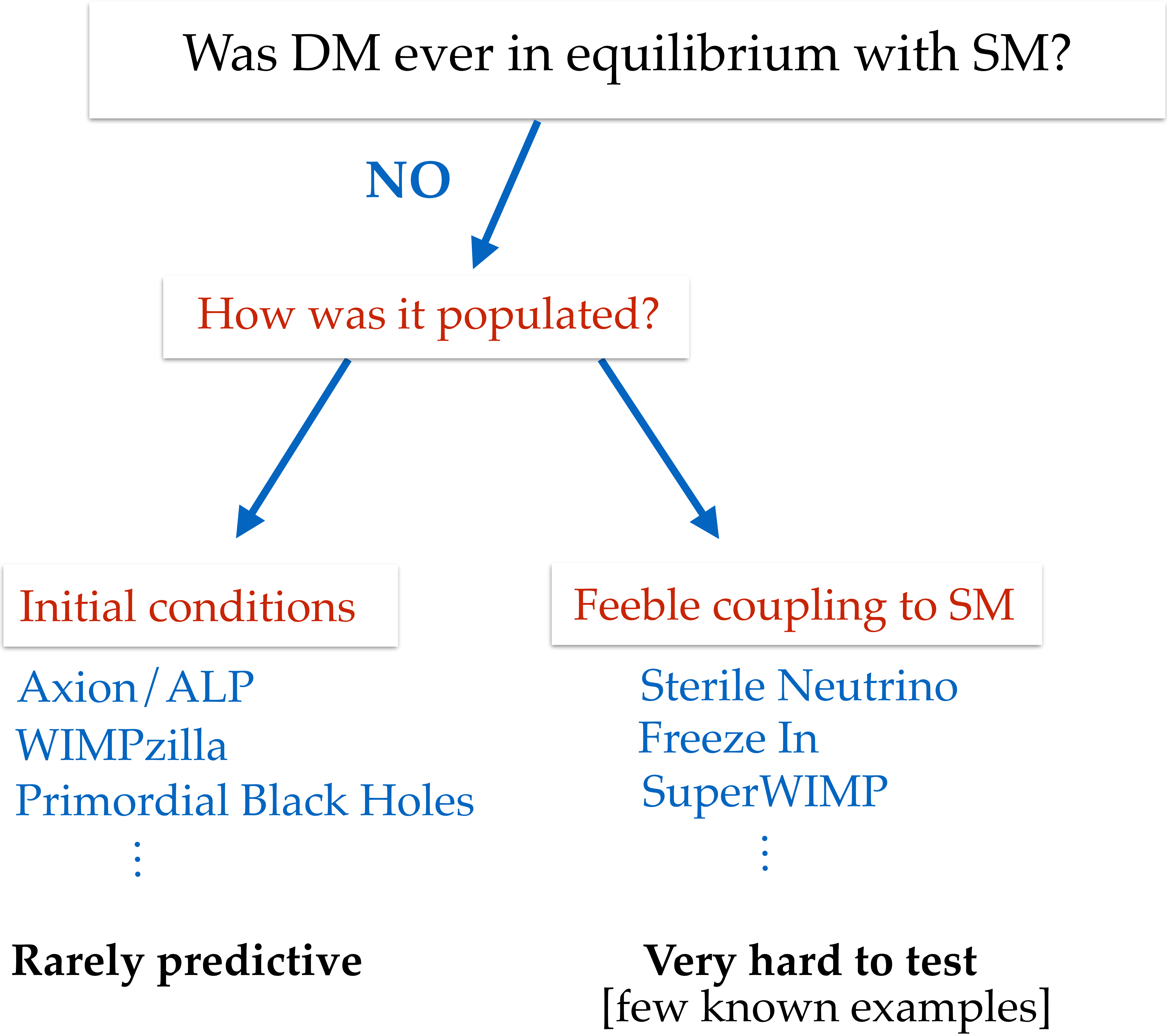
IPA 2018 Cincinnati, Ohio Oct 9, 2018

Overview

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

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

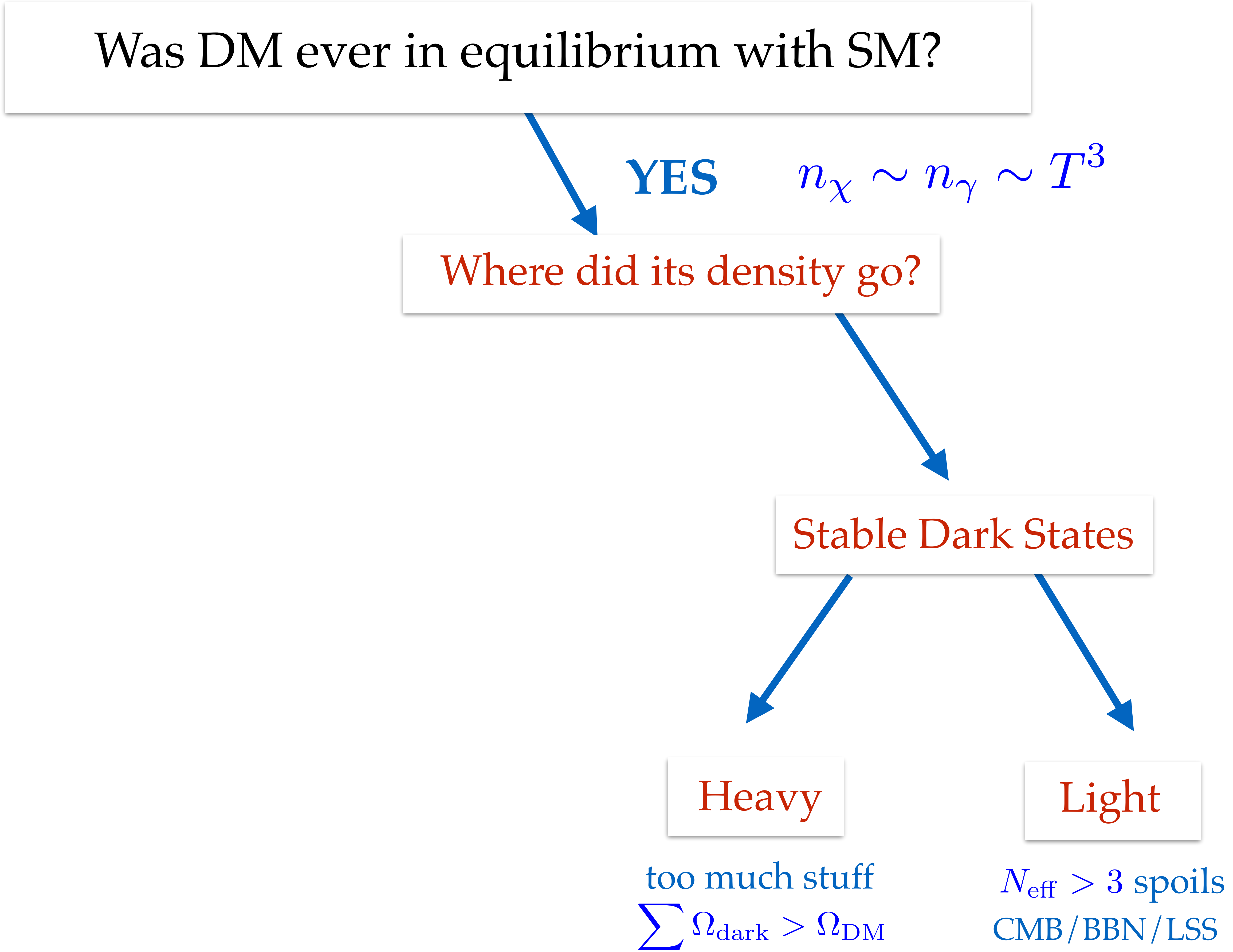
3) How can we test **all** predictive models?


Was DM ever in equilibrium with SM?
NO
How was it populated?
Initial conditions
Feeble coupling to SM
Axion / ALP
WIMPzilla
Primordial Black Holes
⋮
Sterile Neutrino
Freeze In
SuperWIMP
⋮
Rarely predictive
Very hard to test
[few known examples]

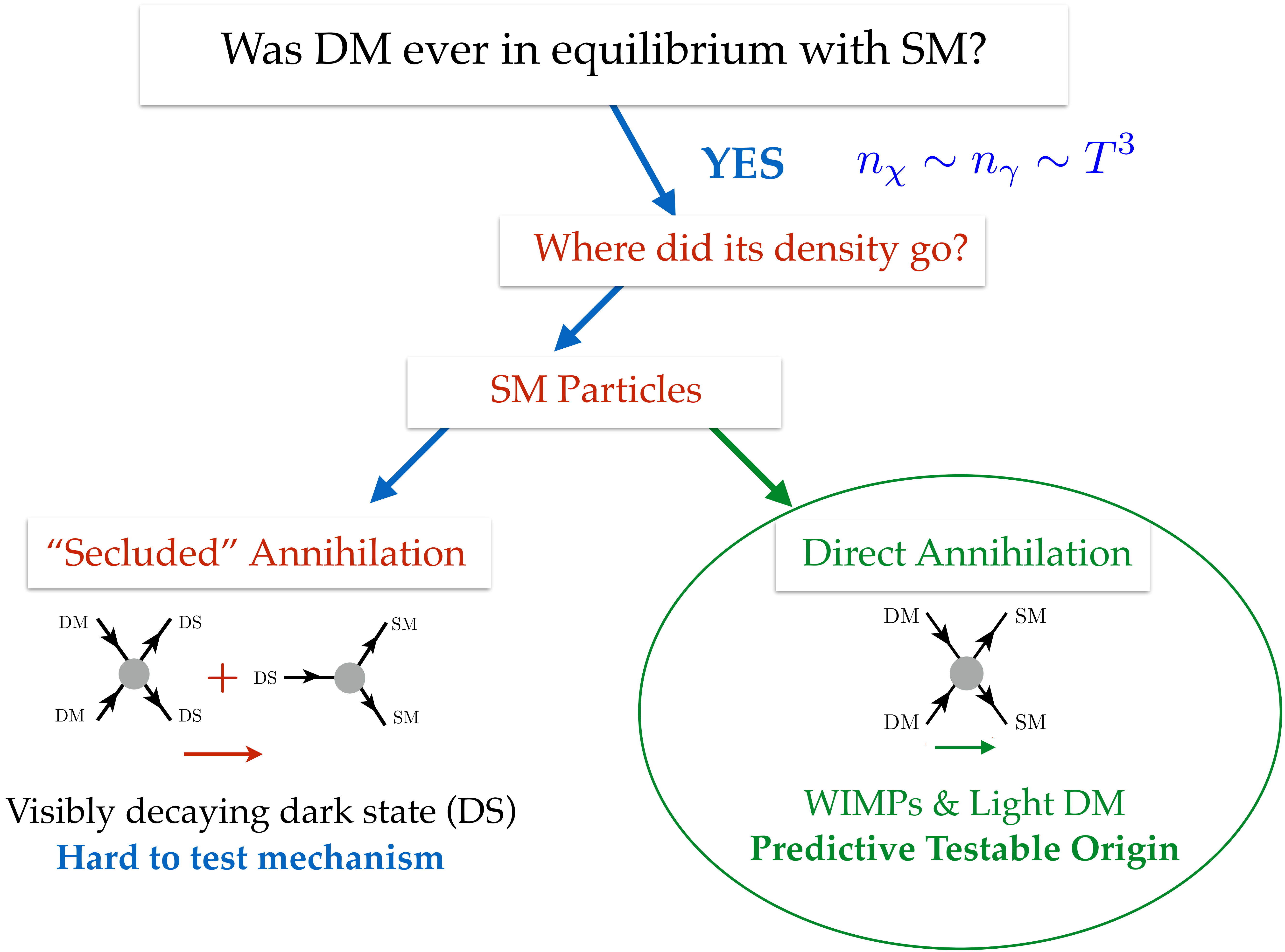
Was DM ever in equilibrium with SM?

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

Where did its density go?



Requires nonstandard cosmology



Was DM ever in equilibrium with SM?
YES
$n_\chi \sim n_\gamma \sim T^3$
Where did its density go?
SM Particles
"Secluded" Annihilation
DM
DS
DM
DS
DS
SM
SM
Visibly decaying dark state (DS)
Hard to test mechanism
Direct Annihilation
DM
SM
DM
SM
WIMPs & Light DM
Predictive Testable Origin

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 in the early universe if

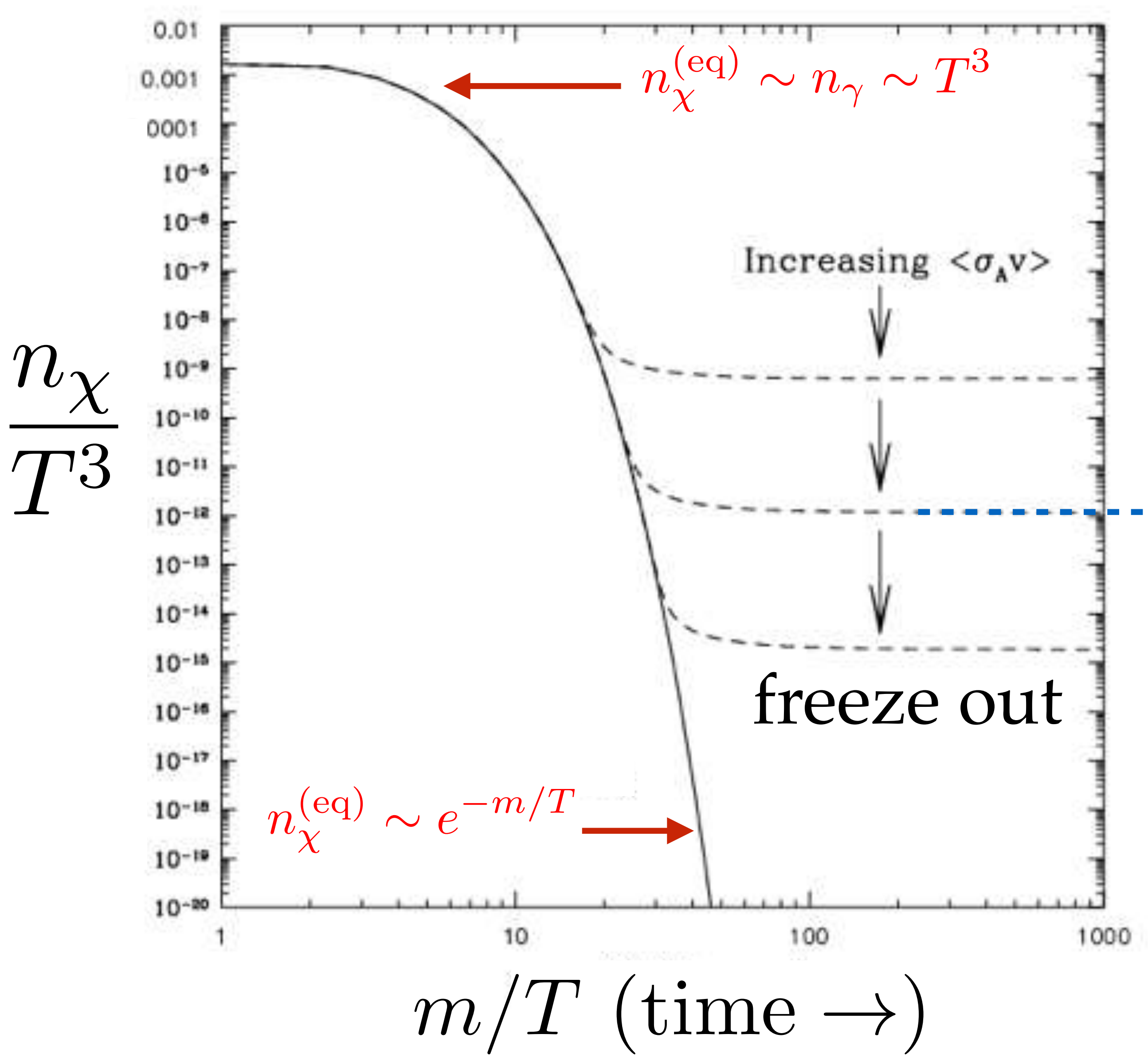
$$g \gtrsim 10^{-8}\left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^2\left(\frac{\mathrm{GeV}}{m_\chi}\right)^{3/2}$$

Nearly all testable models feature equilibrium at early times

Q: What's so great about equilibrium?

A: Minimum annihilation rate

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



Observed density requires

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

However, minimum target in all equilibrium scenarios

… asymmetric DM

… coannihilating DM

Griest et. al. 1992

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

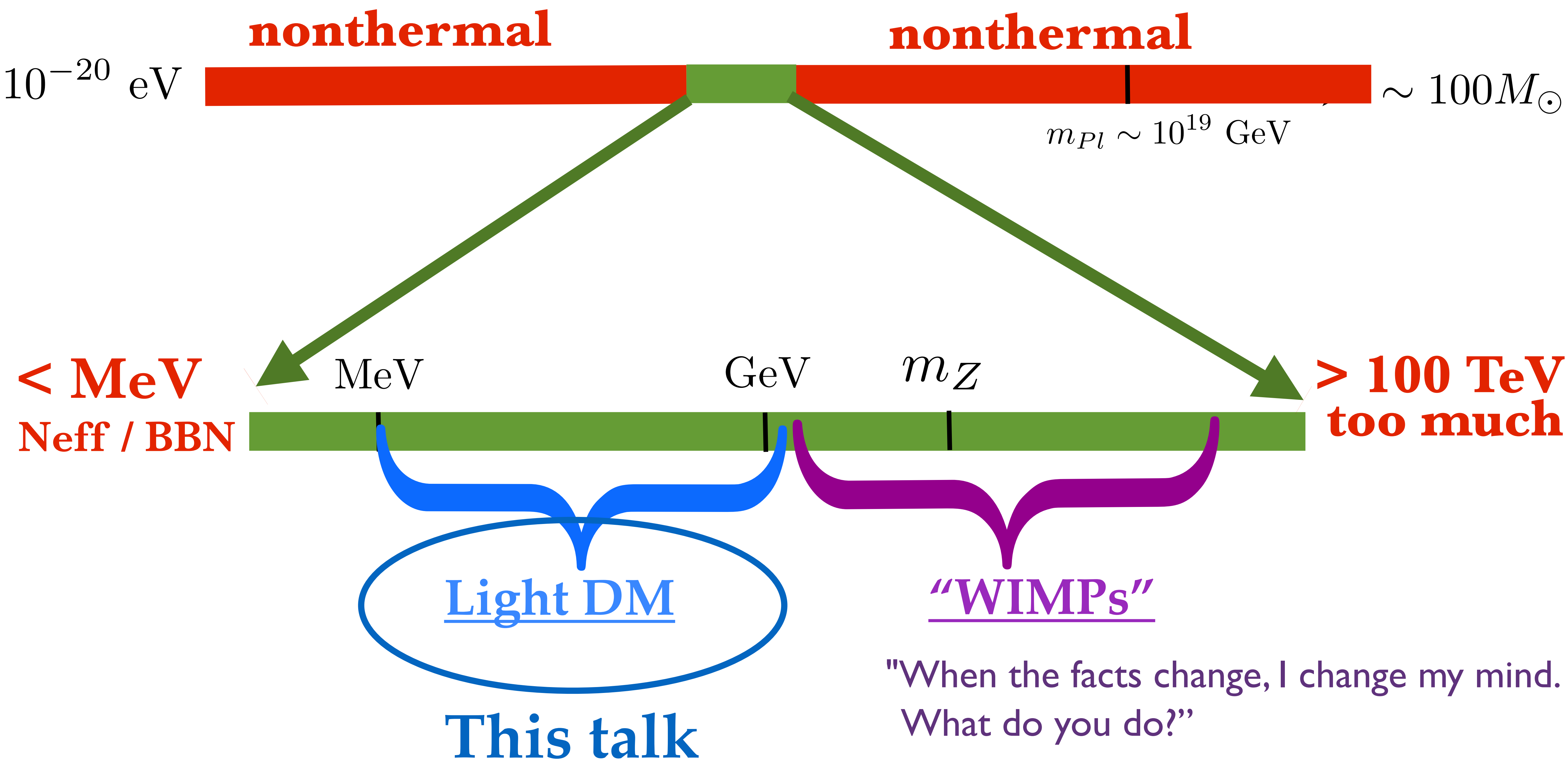
A discovery would directly probe early universe cosmology

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 (!)



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

- John Maynard Keynes

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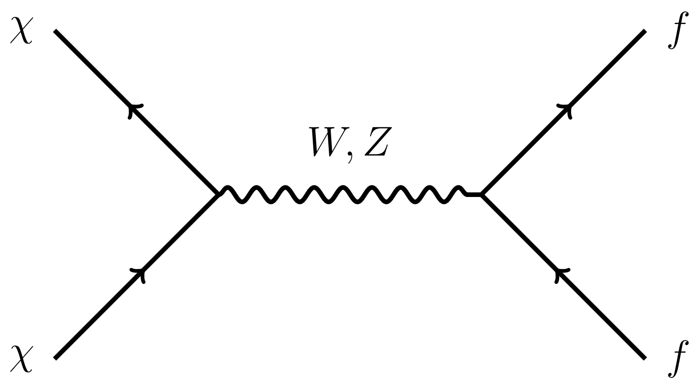
Light DM vs. WIMPs

LDM must be SM neutral

Otherwise would have been discovered at LEP

LDM requires light new forces

Overproduced without comparably light, neutral "mediators"



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

Lee / Weinberg '79

Annihilation through renormalizable interactions

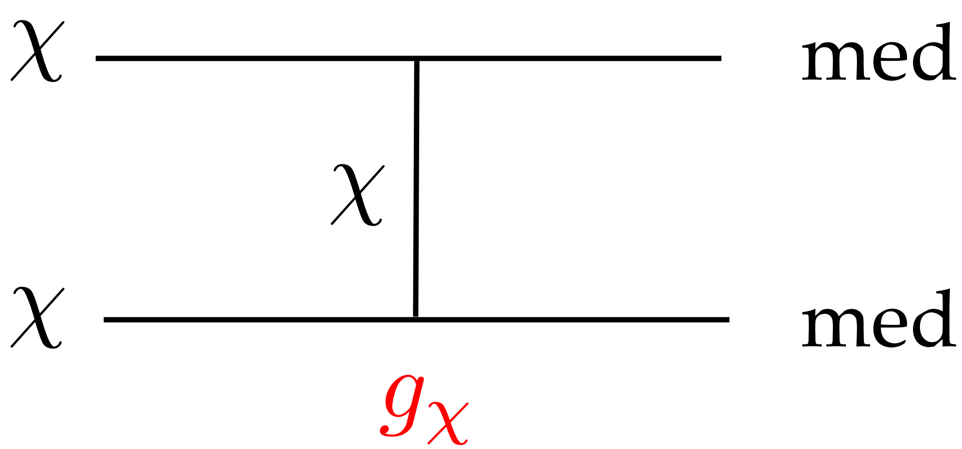
Higher dimension operators have same problem as electroweak mediators

Light mediators are not optional; they're essential

Who's Heavier: DM or Mediator?

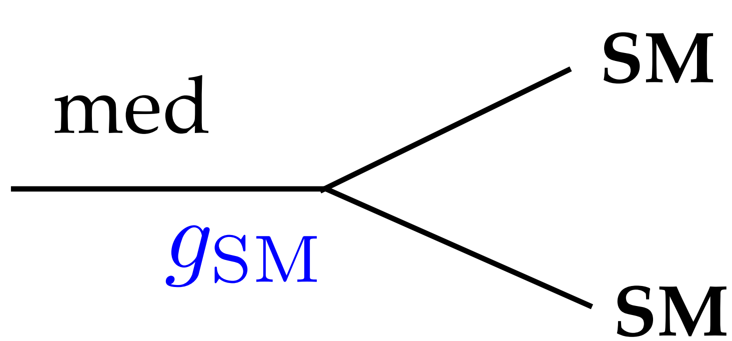
Secluded Annihilation

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



No clear experimental target

Abundance set by g_χ

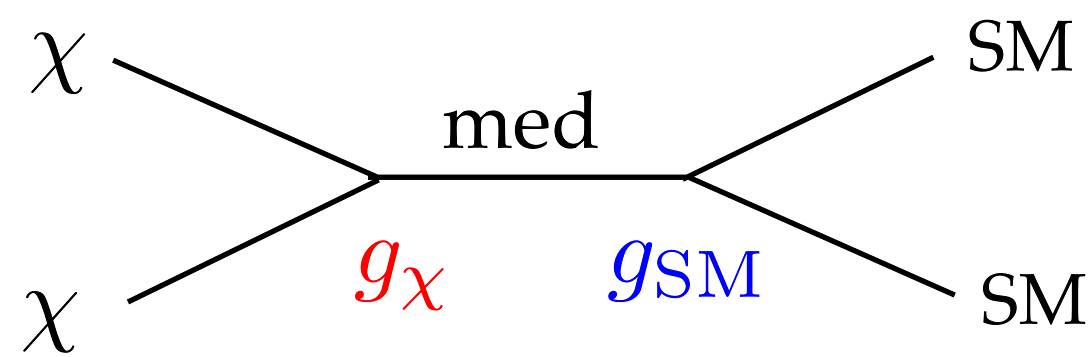


Mediator decays **visibly**

Motivates hidden force searches

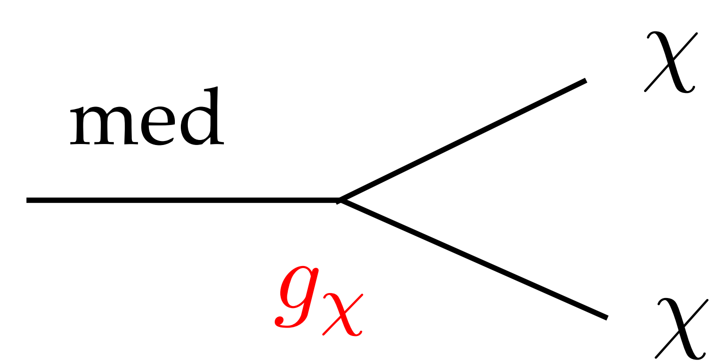
Direct Annihilation

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



Predictive thermal targets

Abundance depends on g_{SM}



Mediator decays **invisibly***

Motivates missing energy probes

Who's Heavier: DM or Mediator?

Secluded Annihilation

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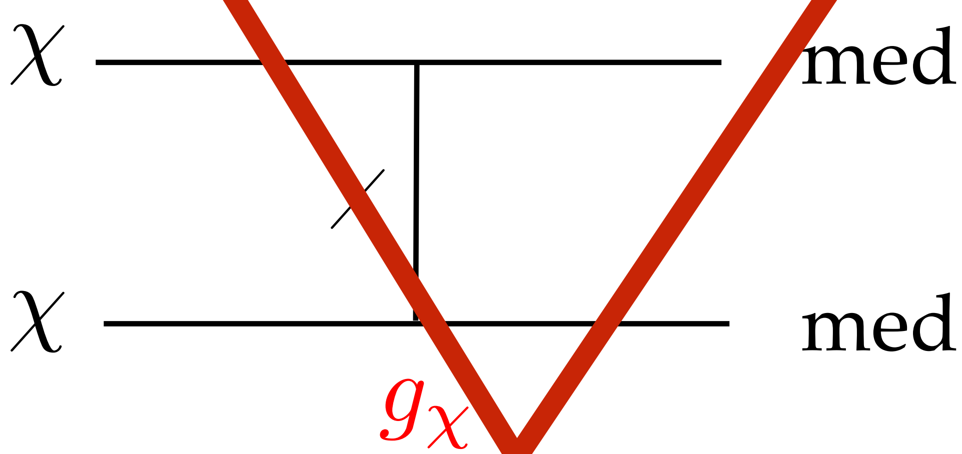

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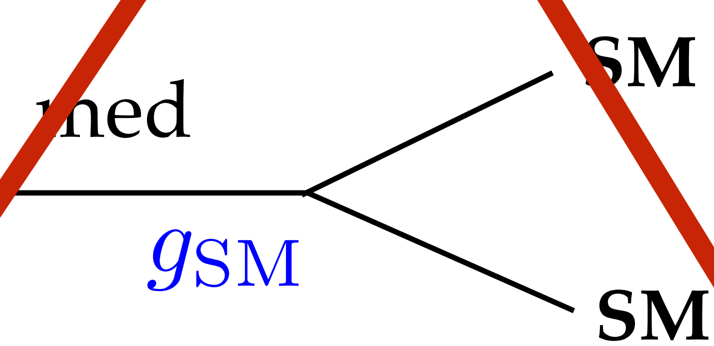

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Motivates hidden force searches

Direct Annihilation

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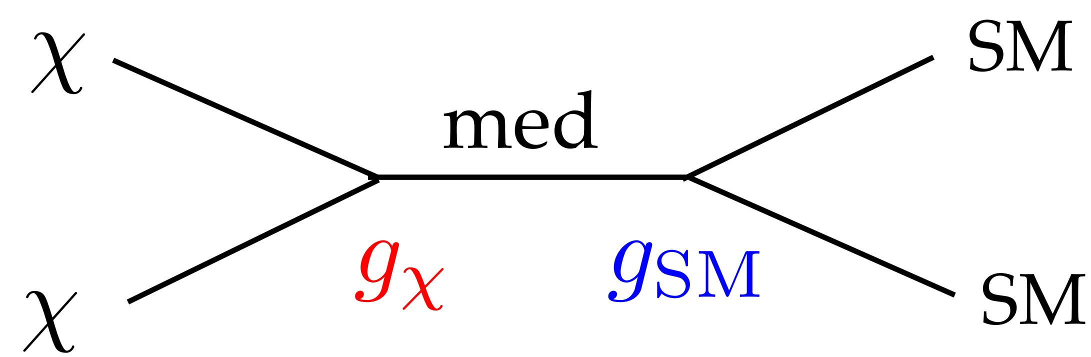
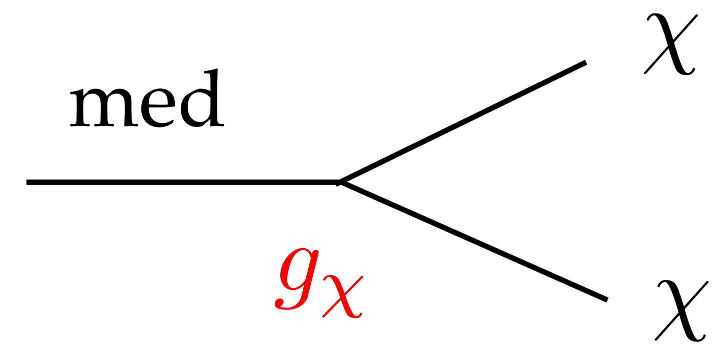


Predictive thermal targets

Abundance depends on $g_{\rm SM}$



Mediator decays **invisibly***

Motivates missing energy probes

What Kind of Mediator?

Neutrality and Renormalizability require "portal" interactions

$\epsilon \, \phi H^\dagger H$ → **Scalar ϕ mixes with Higgs after EWSB**

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

$\epsilon \, F'_{\mu\nu} F^{\mu\nu}$ → **Dark photon A' mixes with SM photon**

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

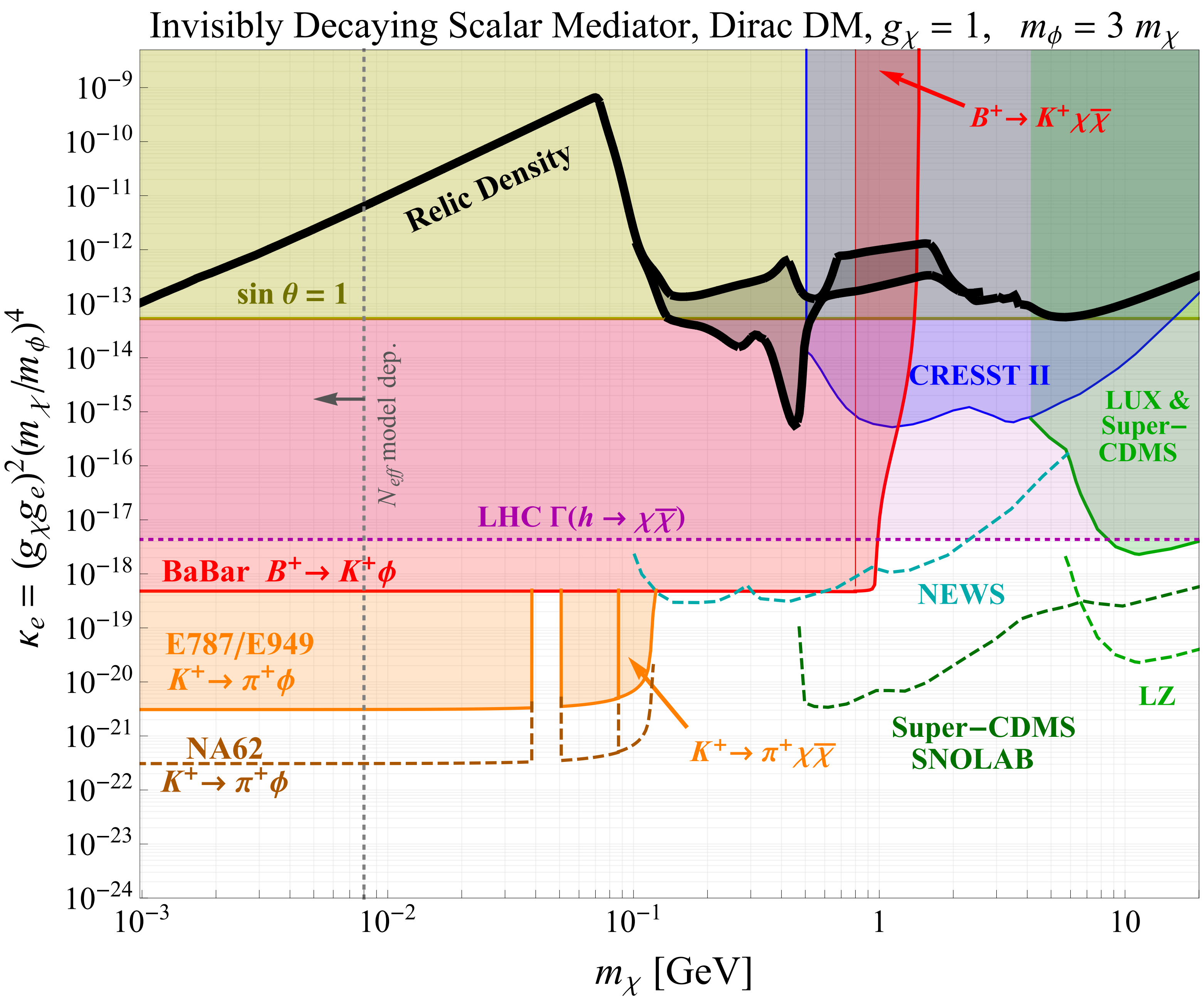
$\epsilon \, V_\mu J^\mu_{\rm SM}$ → **Vector V directly couples to DM & SM**

Couples to **different** current $J^\mu_{\rm SM}$

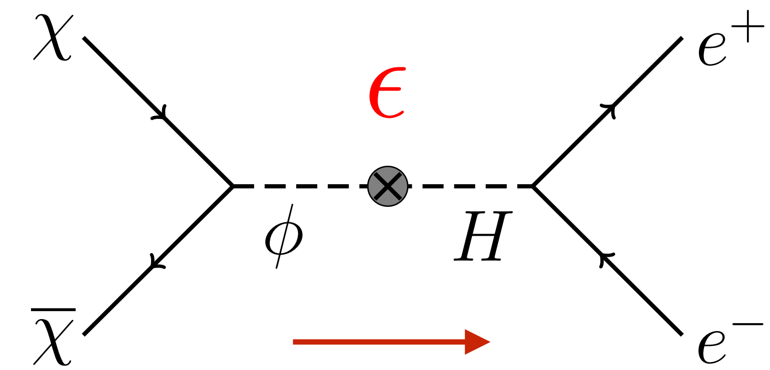
Anomaly free options $B - L \; , \; L_i - L_j \; , \; B - 3L_i$

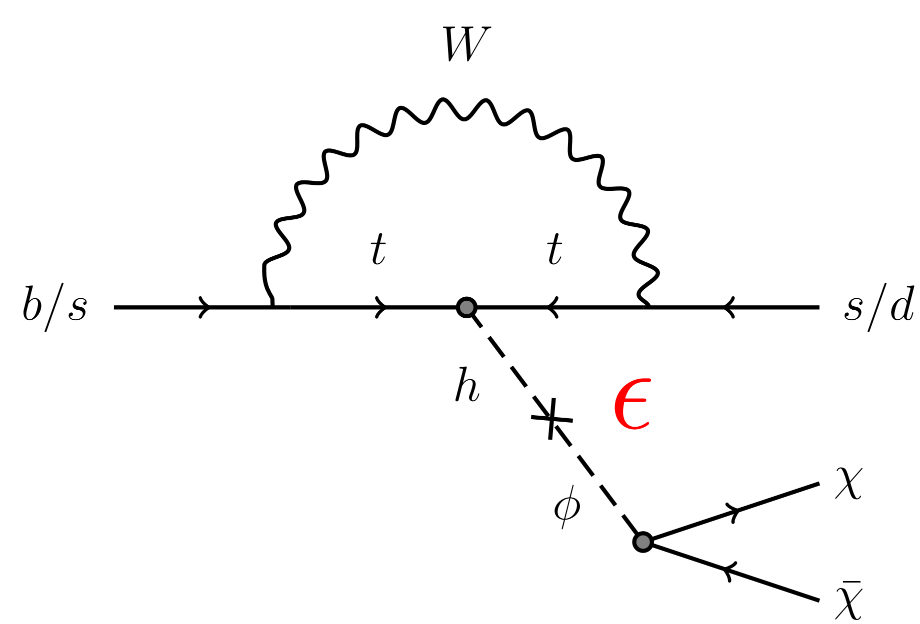
Vector models all similar, but also couple to neutrinos

Higgs Portal Direct-Annihilation Ruled Out!



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





Conclusion independent of DM candidate

Similar situation for pseudo-scalar mediator etc.

GK arXiv:1512.04119

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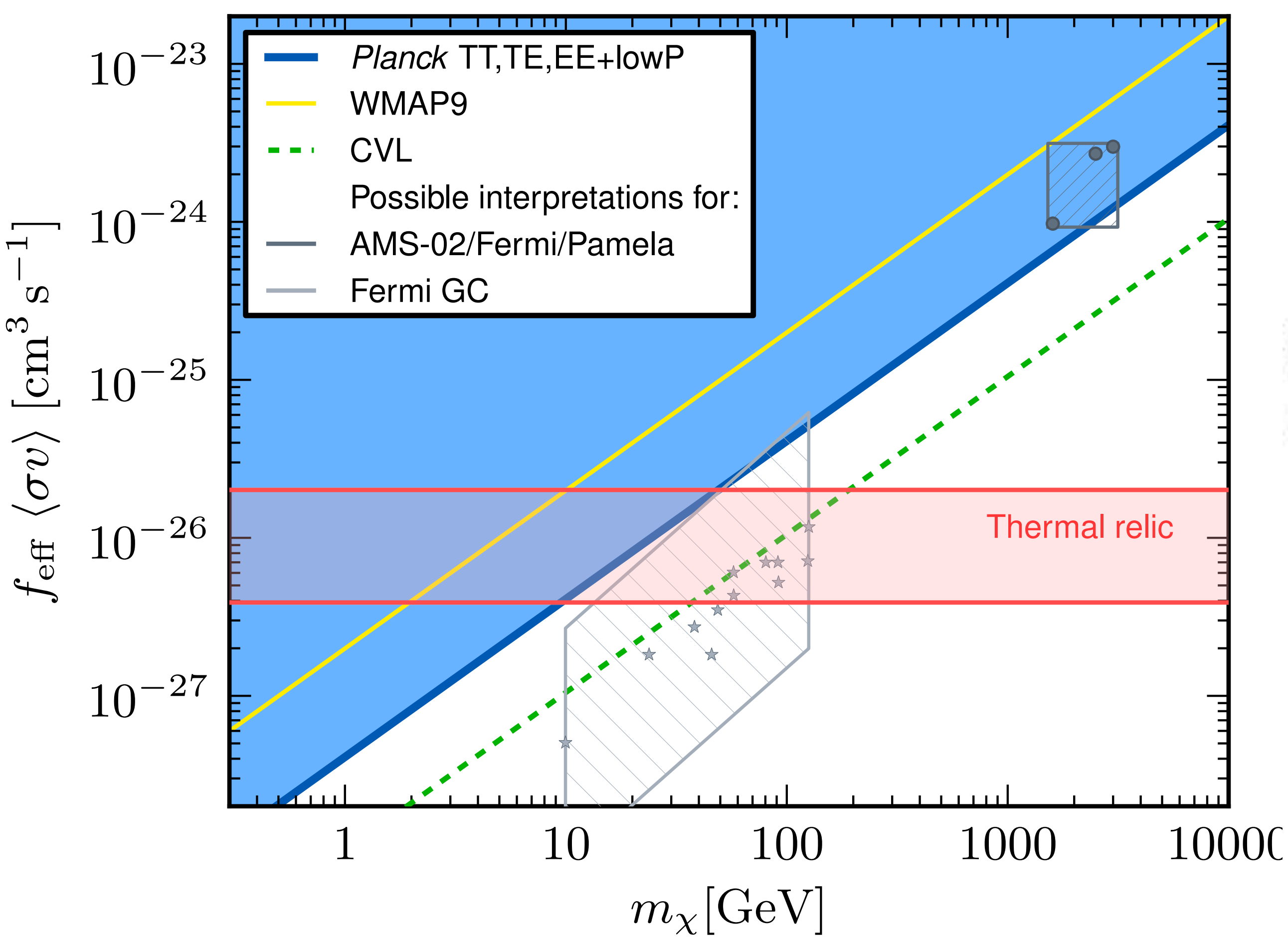
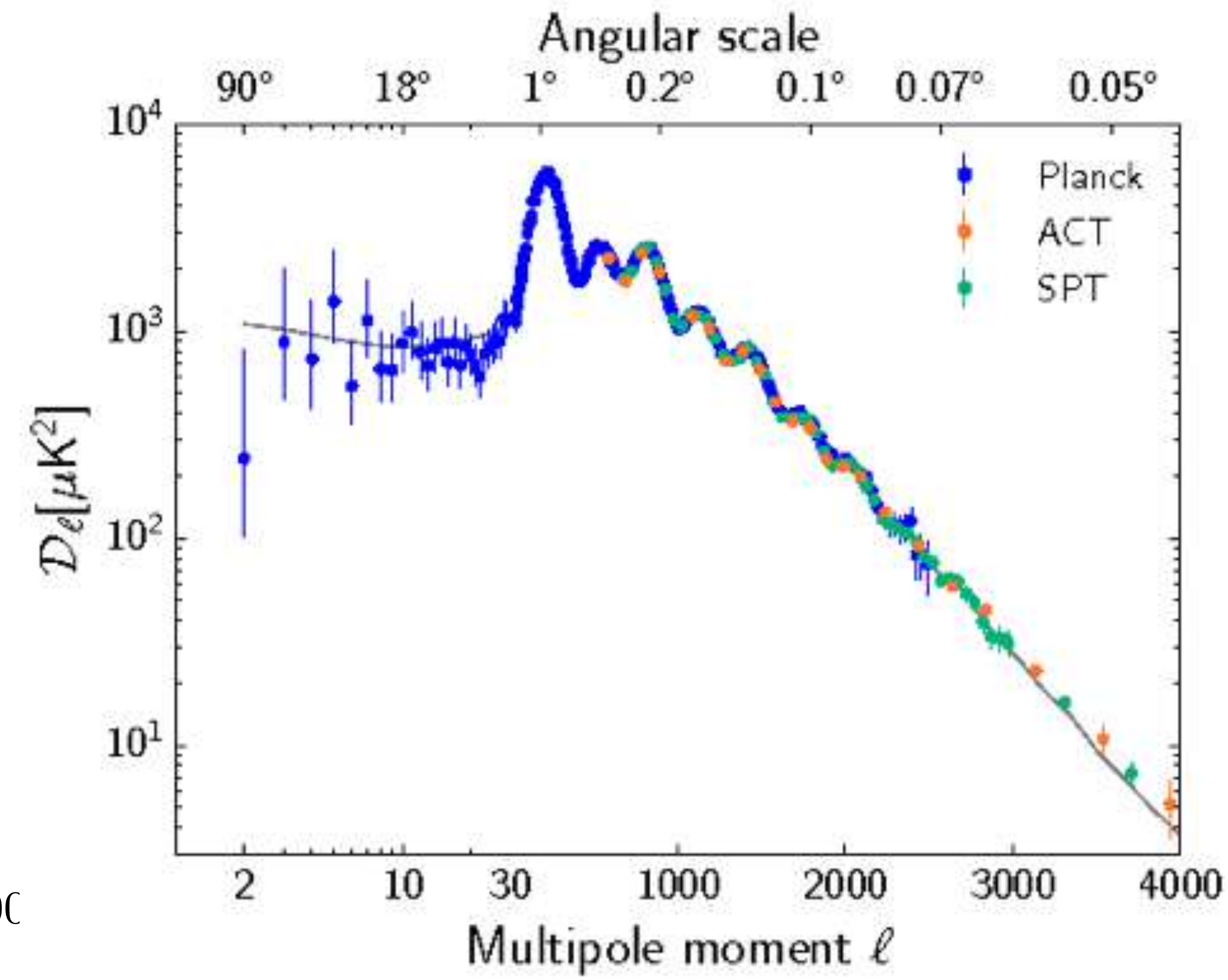
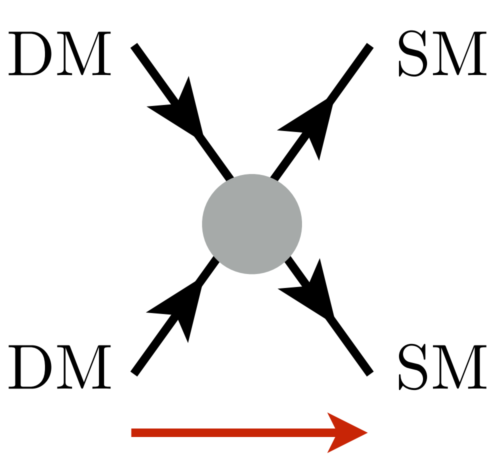
Classify DM by Annihilation During CMB Era





Planck Collaboration 1502.01589



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

CMB photons pass through more ions (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

No observable indirect detection for < GeV thermal DM

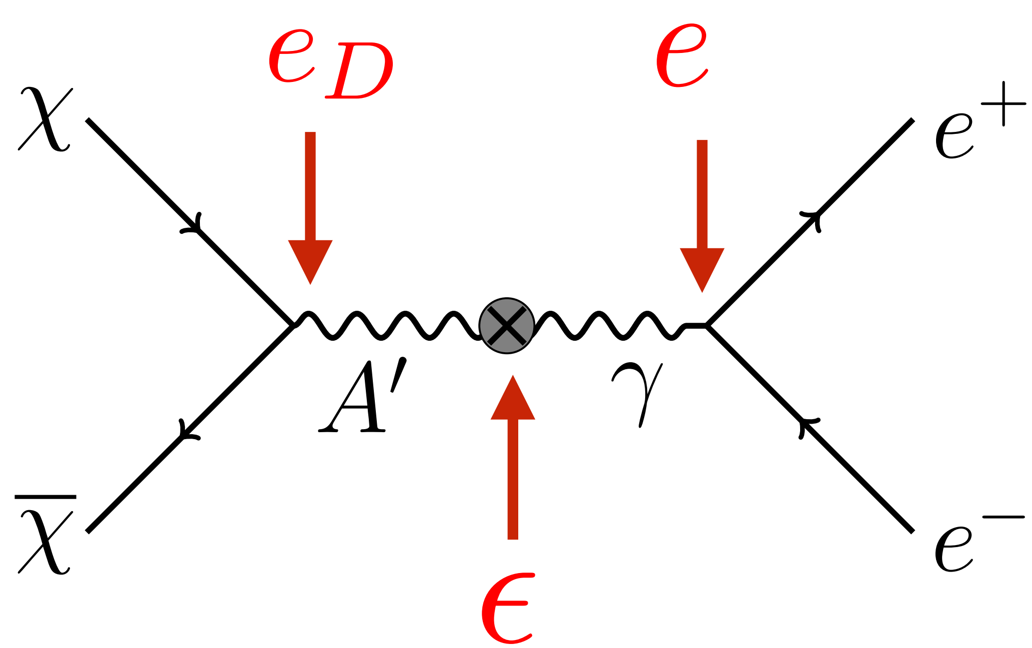
Safe models require either:

P-wave annihilation	**Different DM population @ CMB**
Scalar or Majorana	Asymmetric Dirac or Pseudo-Dirac

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 model, but qualitatively similar to viable variations

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

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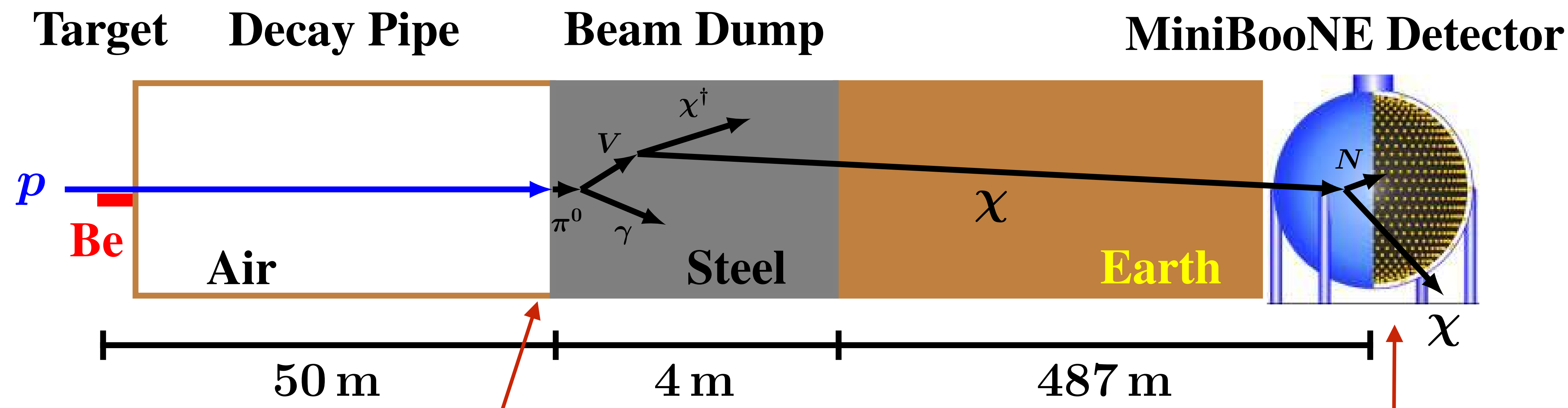
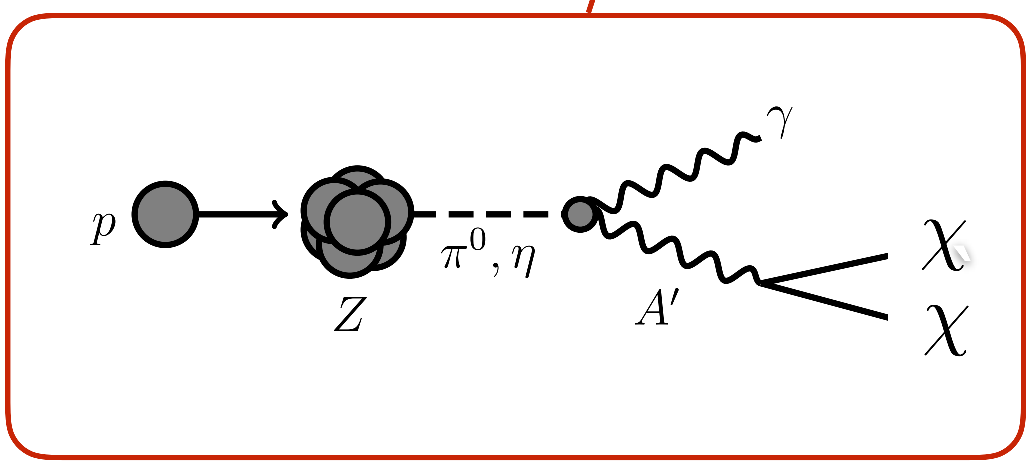
Accelerator Searches

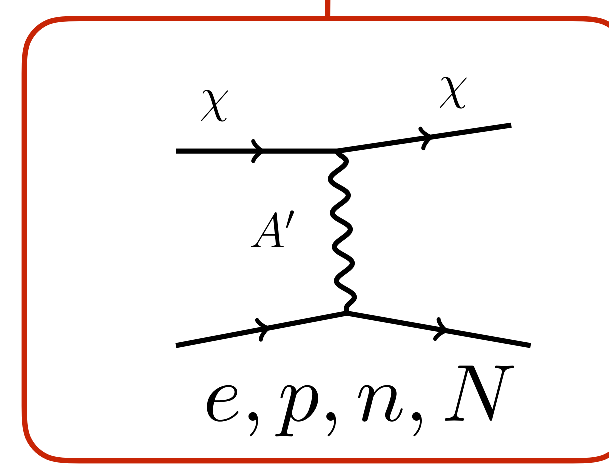
- Beam Dumps [DM production + detection]

-Missing Energy/Momentum [DM production only]

Neutrino Experiments: Proton Beam Dump Strategy







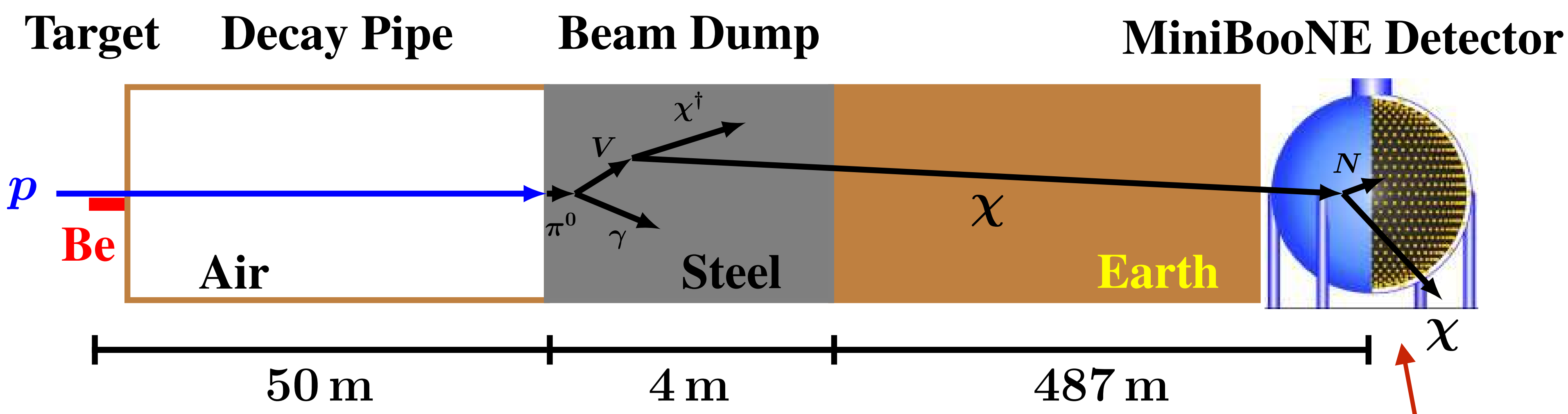
Rare meson decays, brem, DIS…

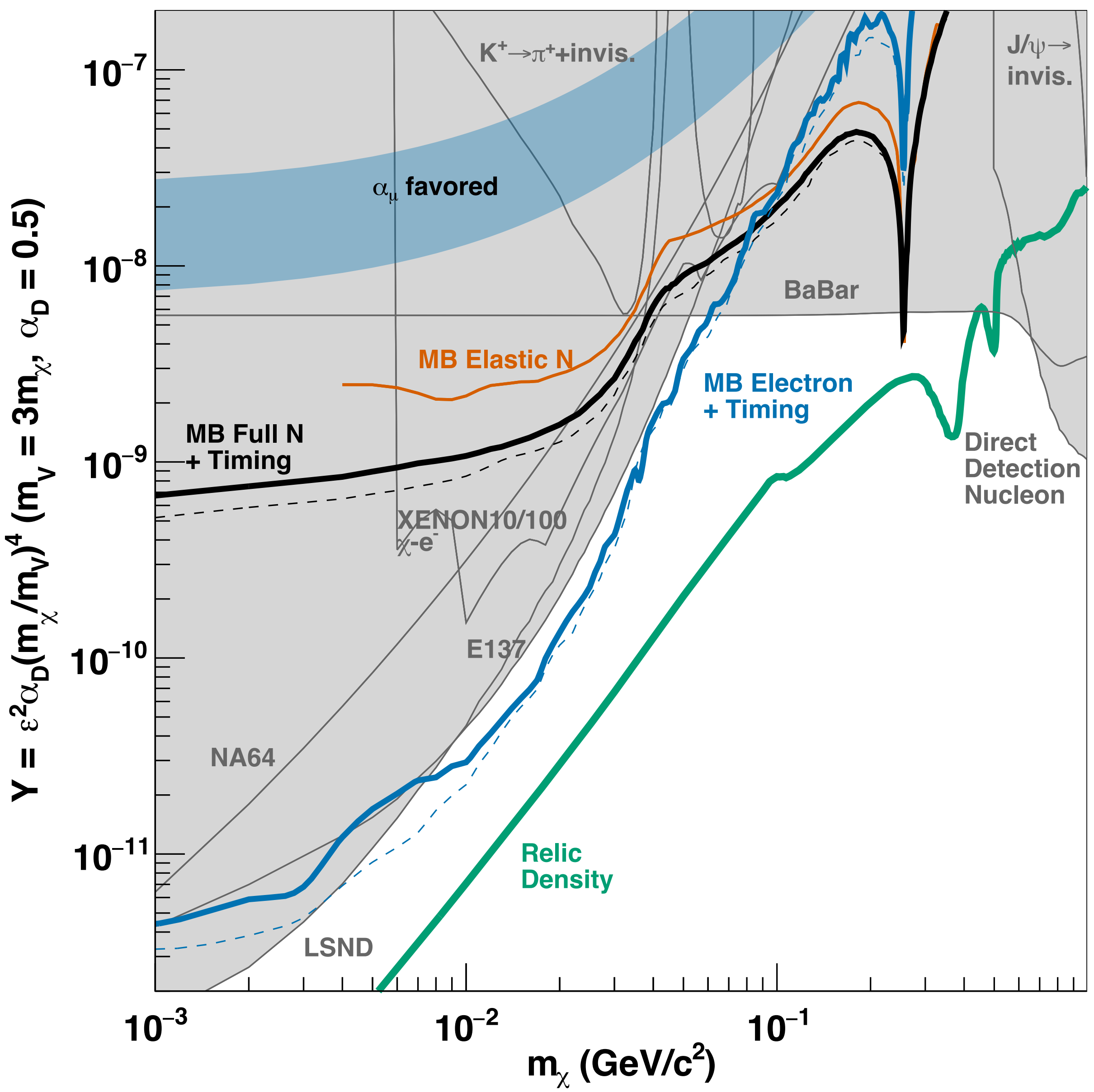
Relativistic
direct detection

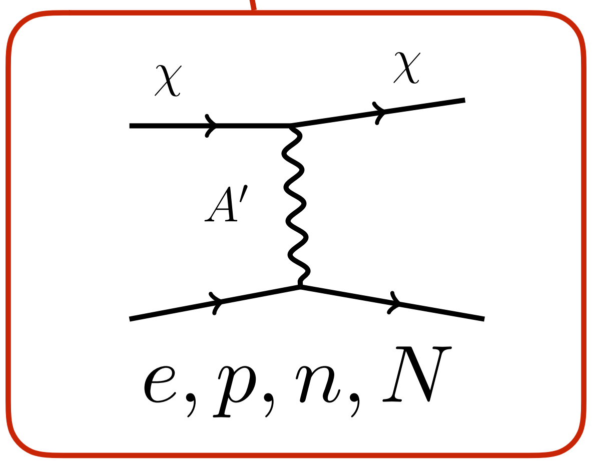
…but we control flux!

Batell, Pospelov, Ritz 0903.0363
deNiverville, Pospelov, Ritz 1107.4580
Batell, deNiverville, McKeen, Pospelov, Ritz 1405.7049
Coloma, Dobrescu, Frugiuele, Harnik 1512.03852
Frugiuele 1701.05464

Neutrino Experiments: MiniBooNE-DM Collaboration Search







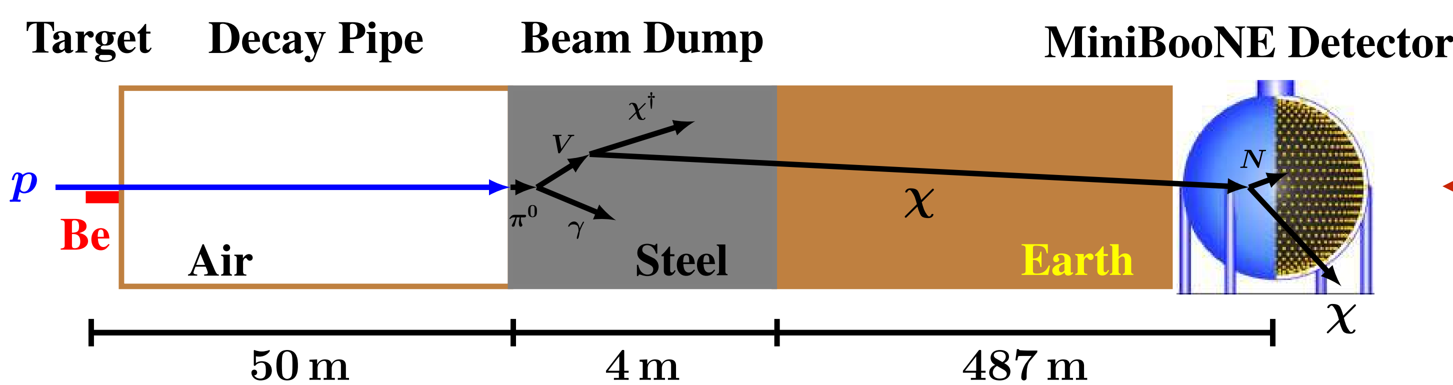
First **ever** dedicated search

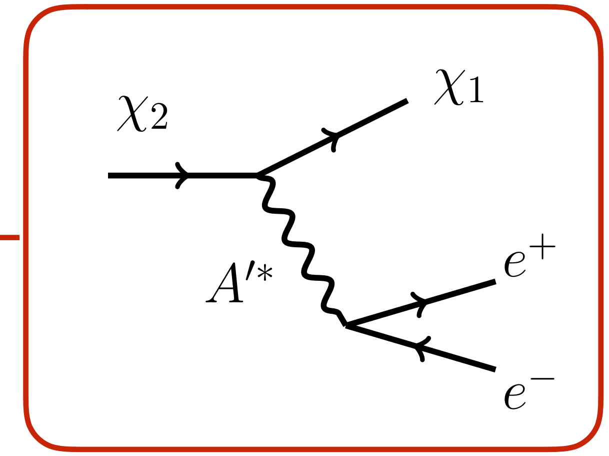
$E_p \sim 9$ GeV $\quad \sim 10^{20}$POT

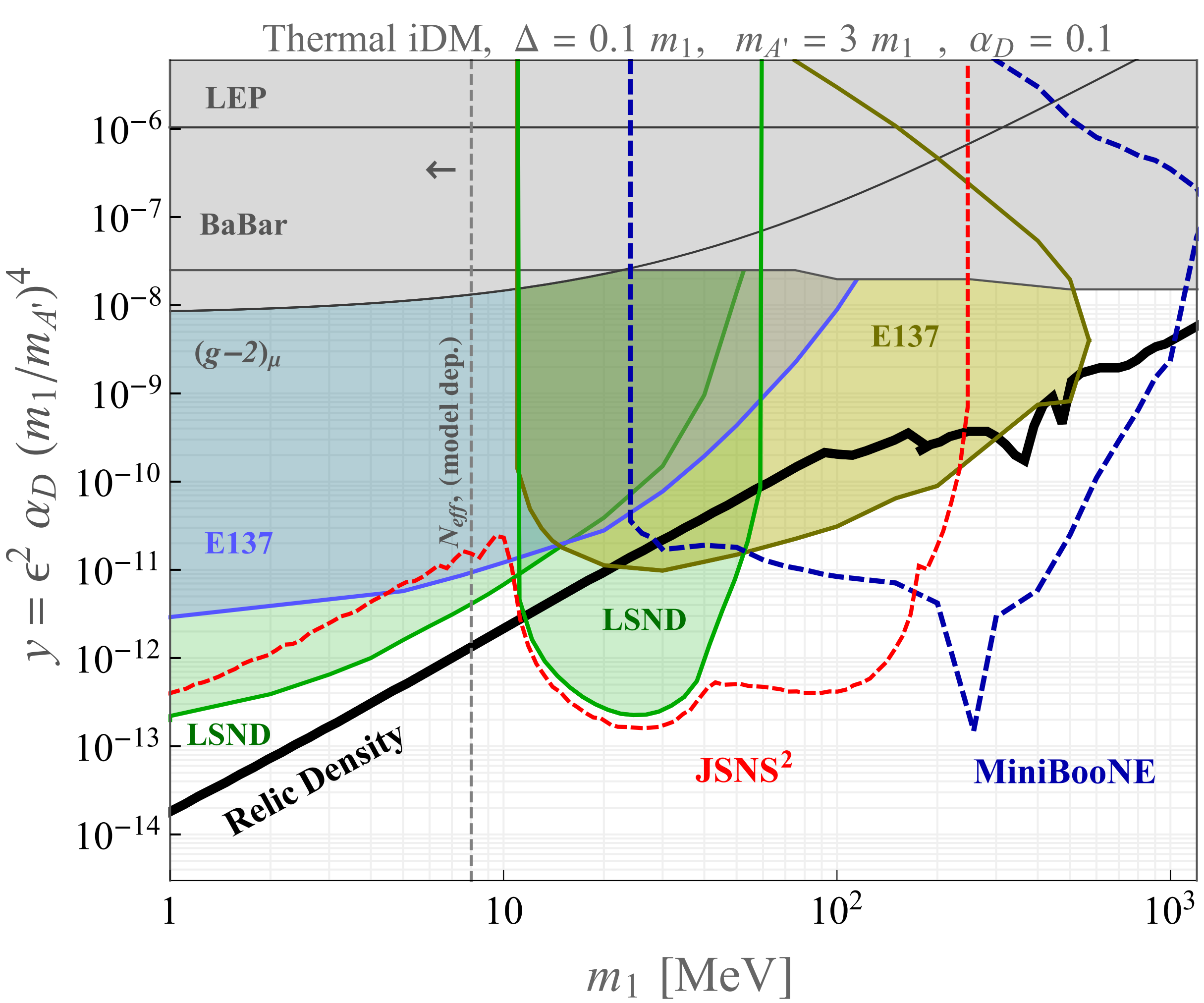
Q: How can we improve reach?

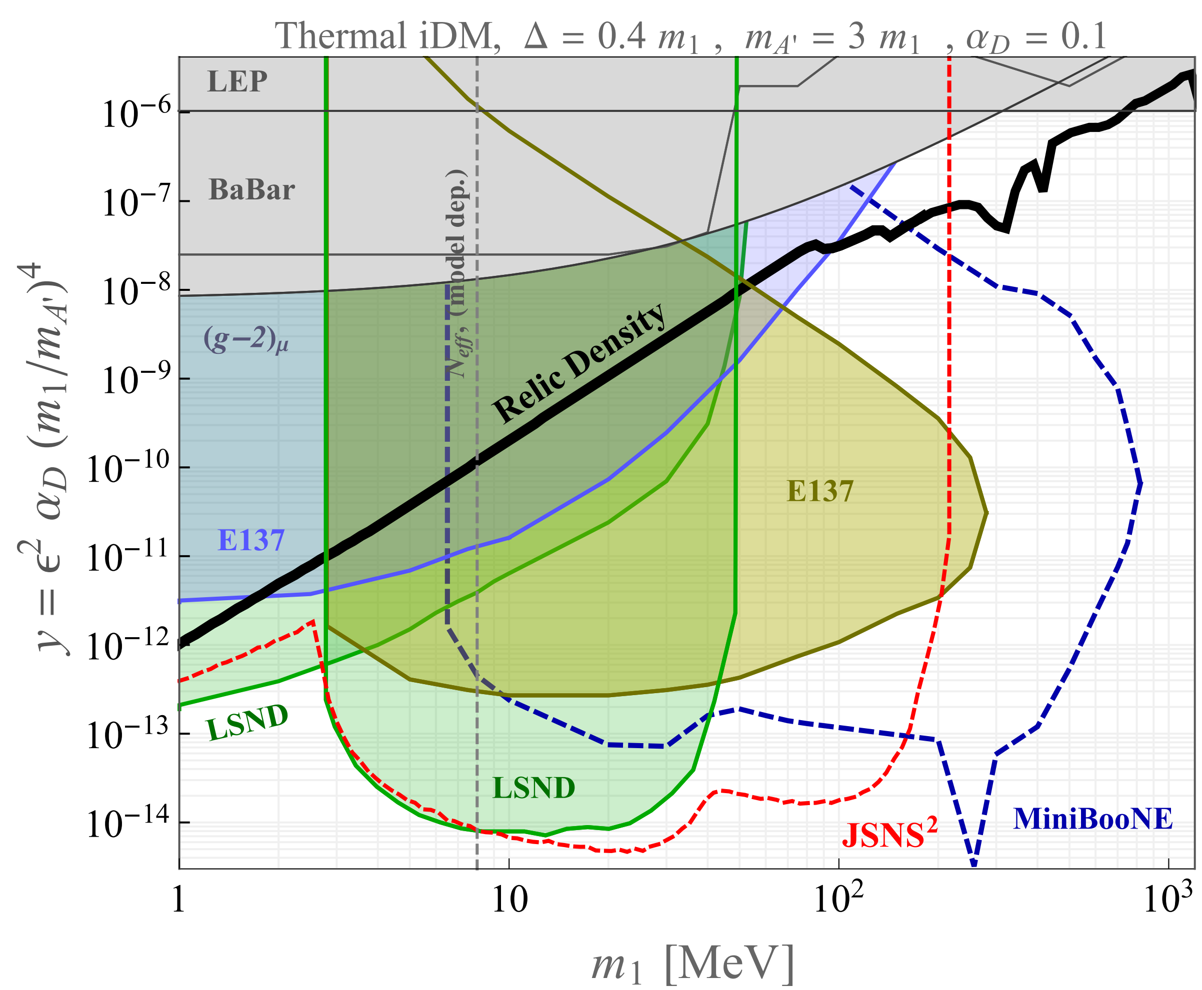
MiniBooNE Collaboration Phys. Rev. Lett. 118 (2017)

Neutrino Experiments: Superior Probes of Coannihilation







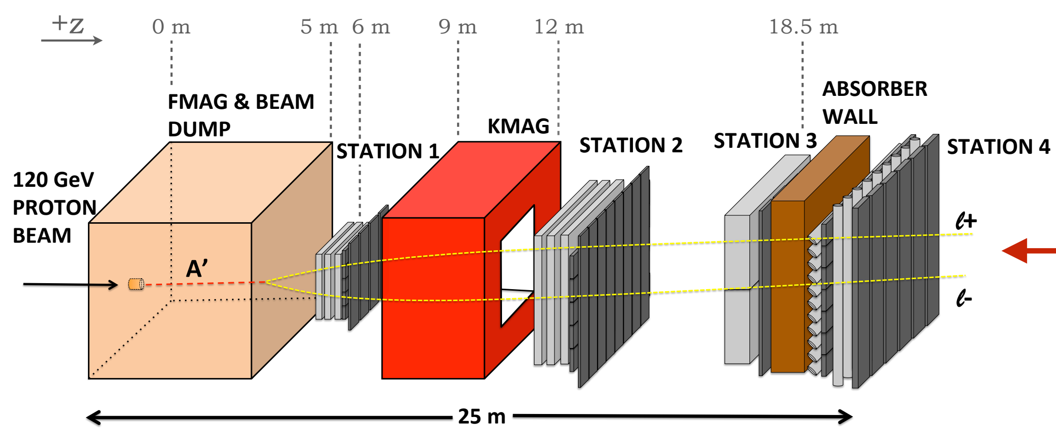


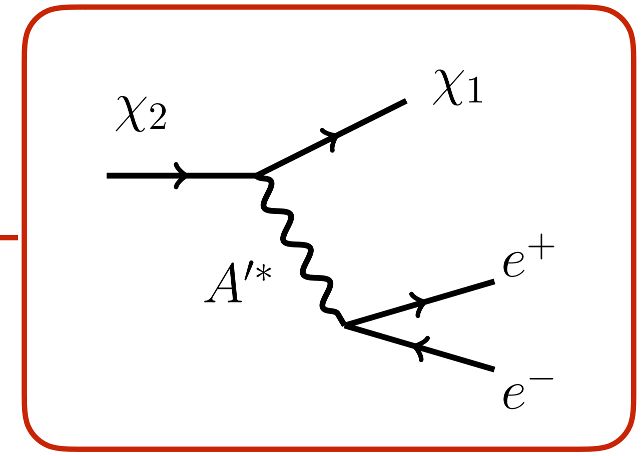
Izaguirre, Kahn, GK, Moschella 1703.06881

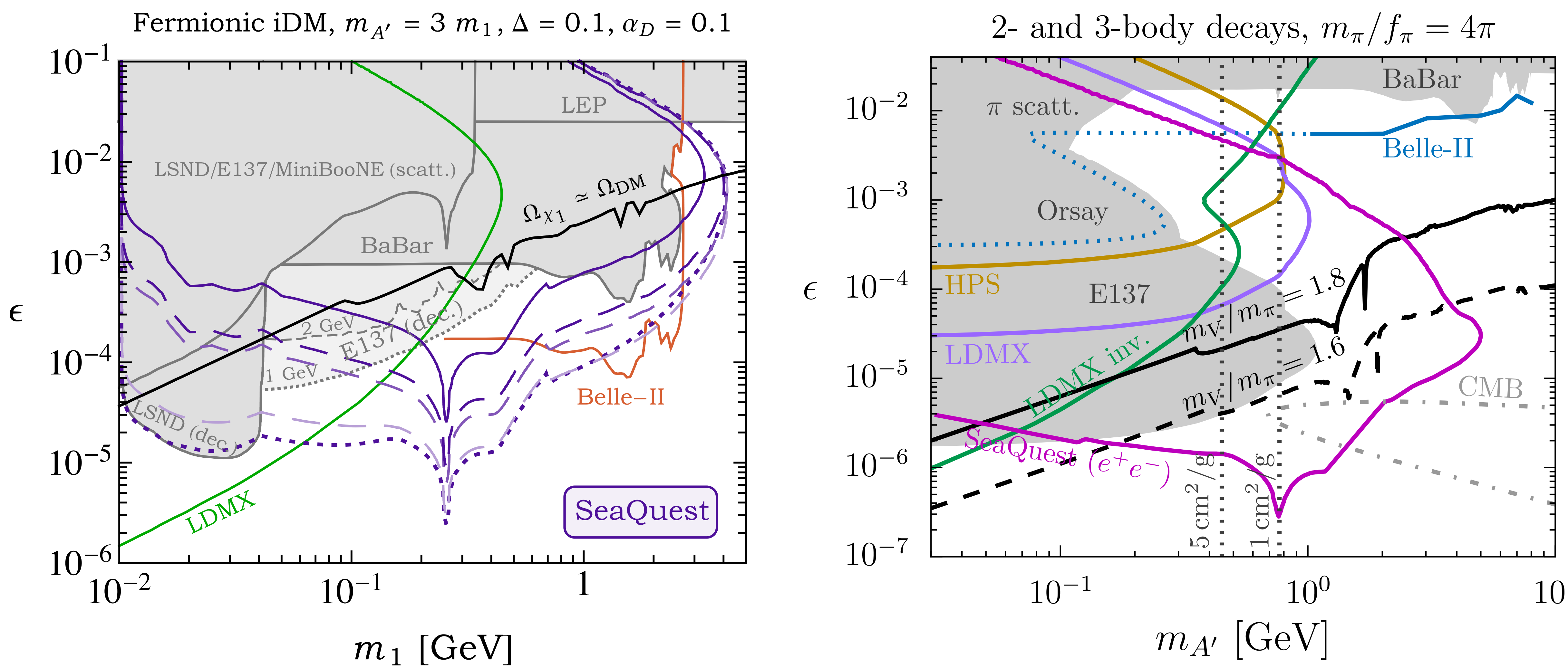
Jordan, Kahn, GK, Moschella, Spitz 1806.05185

$$\mathcal{L} \supset g_D A'_\mu \bar{\chi}_2 \gamma^\mu \chi_1$$

Proton Fixed Target: SeaQuest @ Fermilab



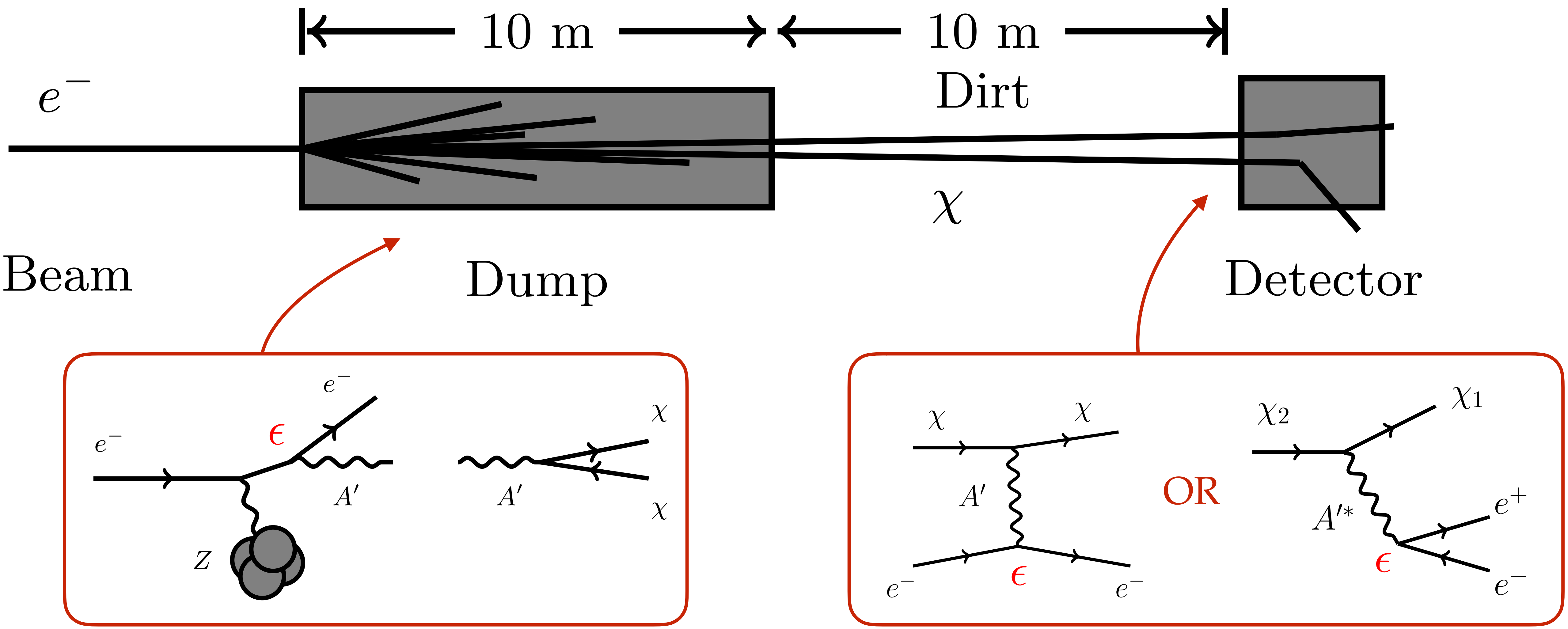




$$E_p \sim 120 \text{ GeV} \;,\; 10^{18} - 10^{20} \text{ POT}$$

Berlin, Gori, Schuster, Toro 1801.05805, 1804.00661

Electron Beam Dump Strategy: BDX @ JLab



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

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

Direct DM production & Detection

Existing Beams/Dumps & Detectors

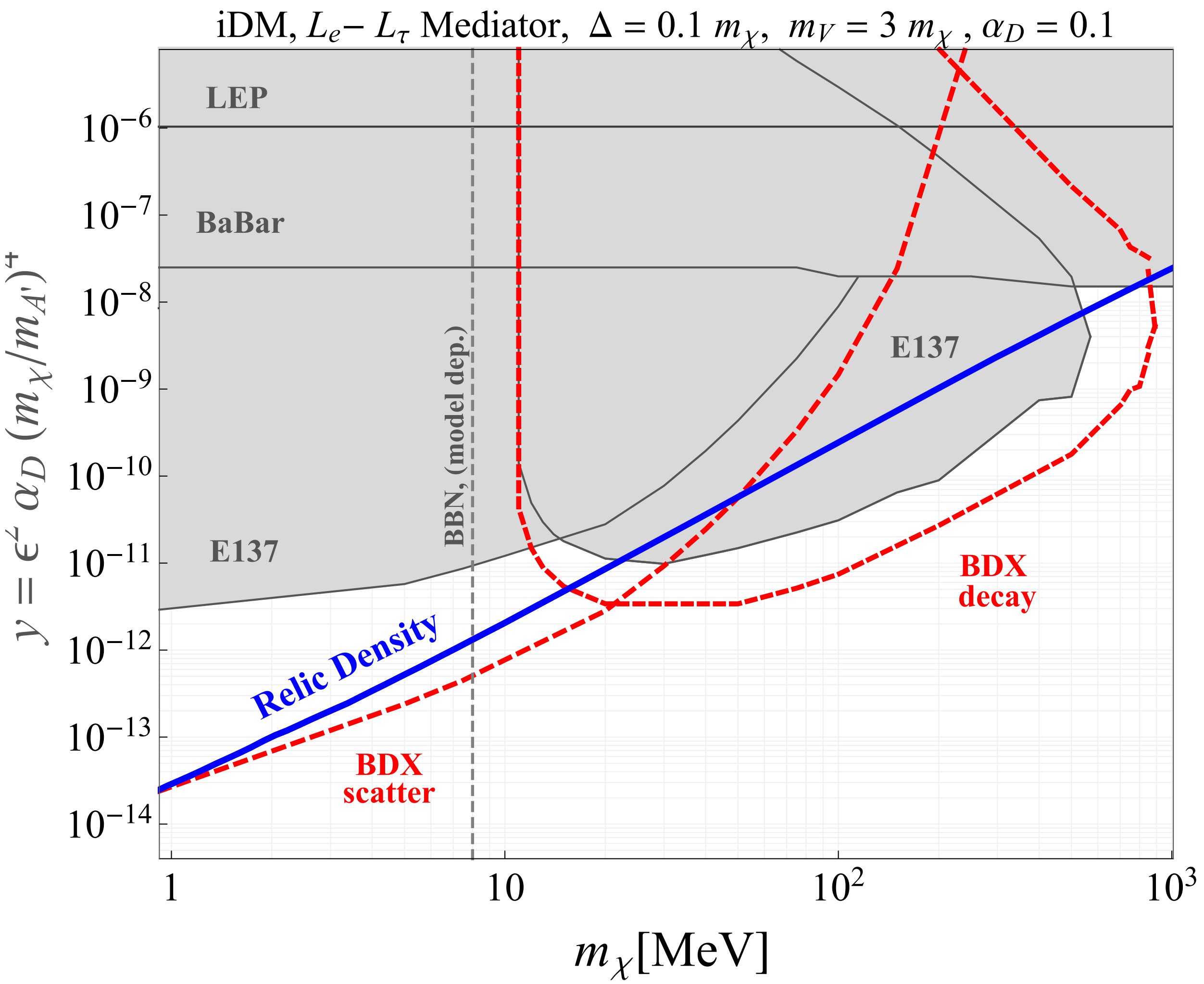
Low Neutrino & Cosmic BG

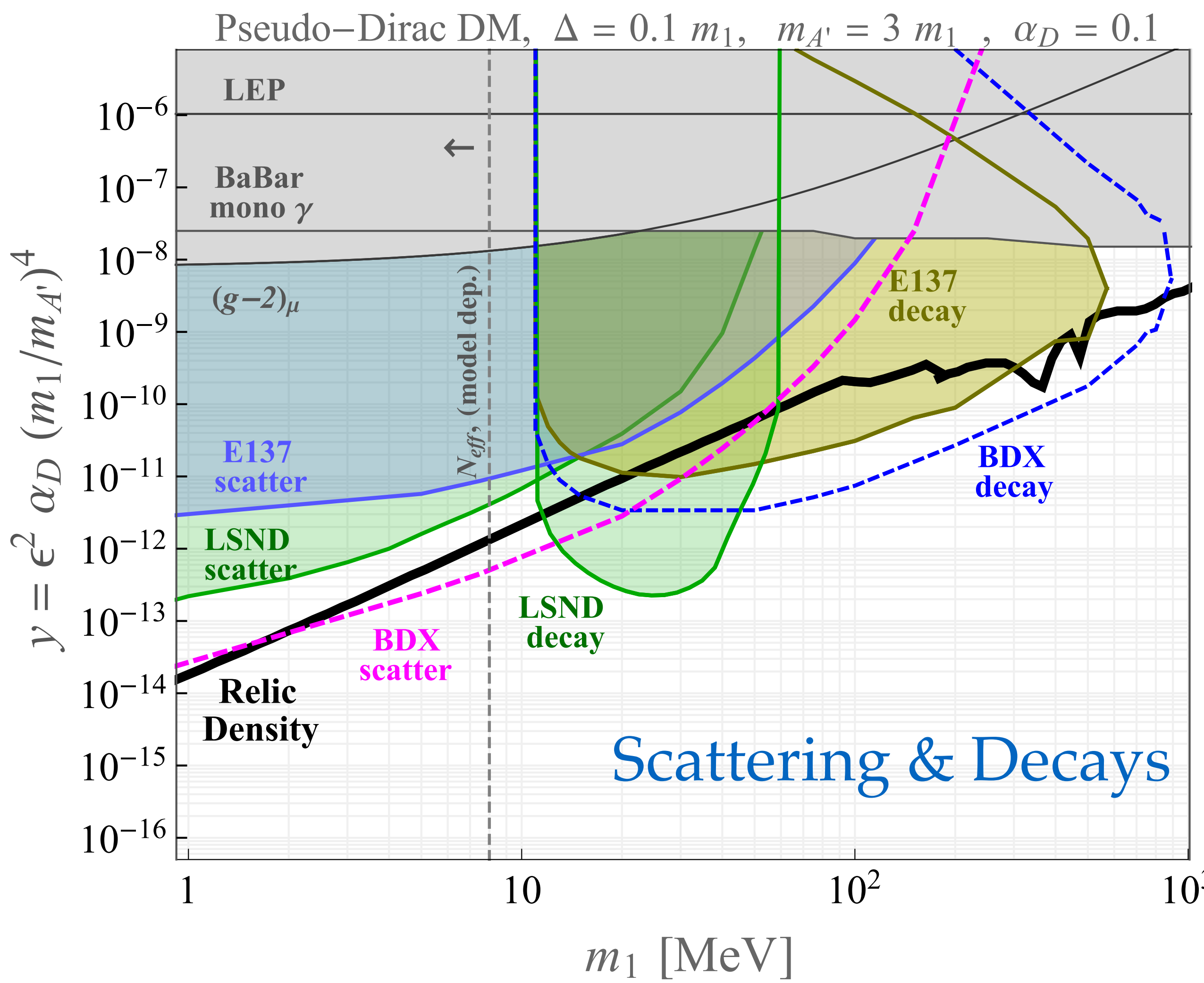
Relativistic direct detection with calculable DM flux

Izaguirre, GK, Schuster, Toro arXiv:1307.6554
BDX Collaboration 1712.01518

Approved by JLab PAC 43 (2018)

BDX: Dark Photon & Leptophilic DM Mediators





Freeze out via coannihilation

Note Asymmetric DM models are viable anywhere above the targets

But still double taxation for beam dumps. How do we improve?

BDX Collaboration 1712.01518

Izaguirre, Kahn, GK, Moschella 1703.06881

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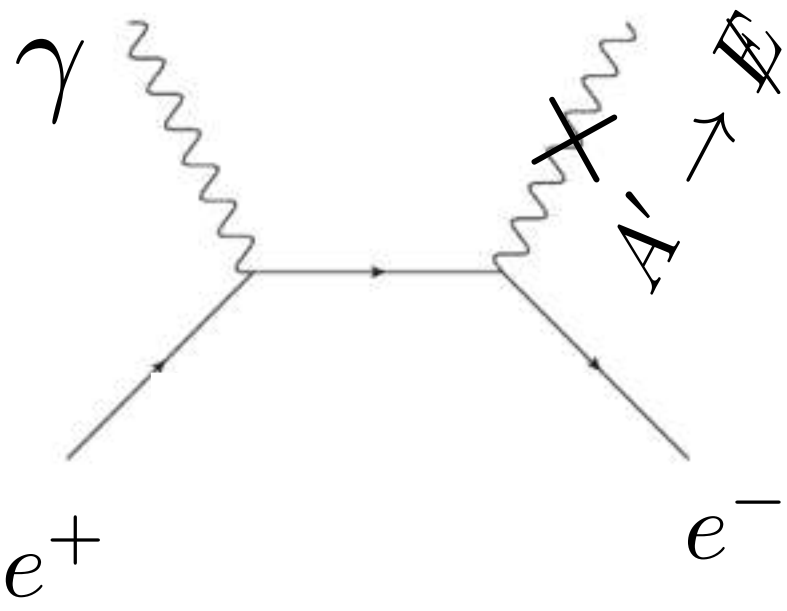
Accelerator Searches

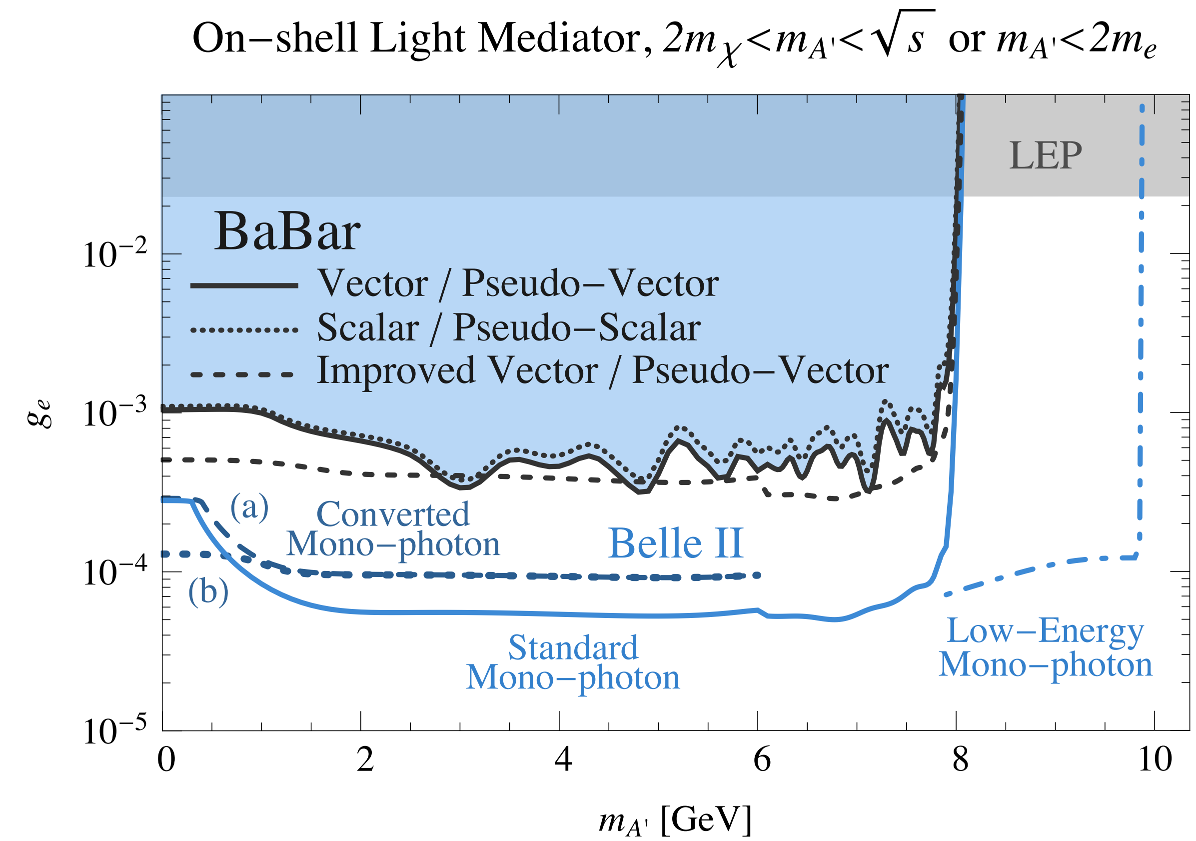
- Beam Dumps [DM production + detection]

-Missing Energy/Momentum [DM production only]

B-Factory Searches: BaBar + Belle II

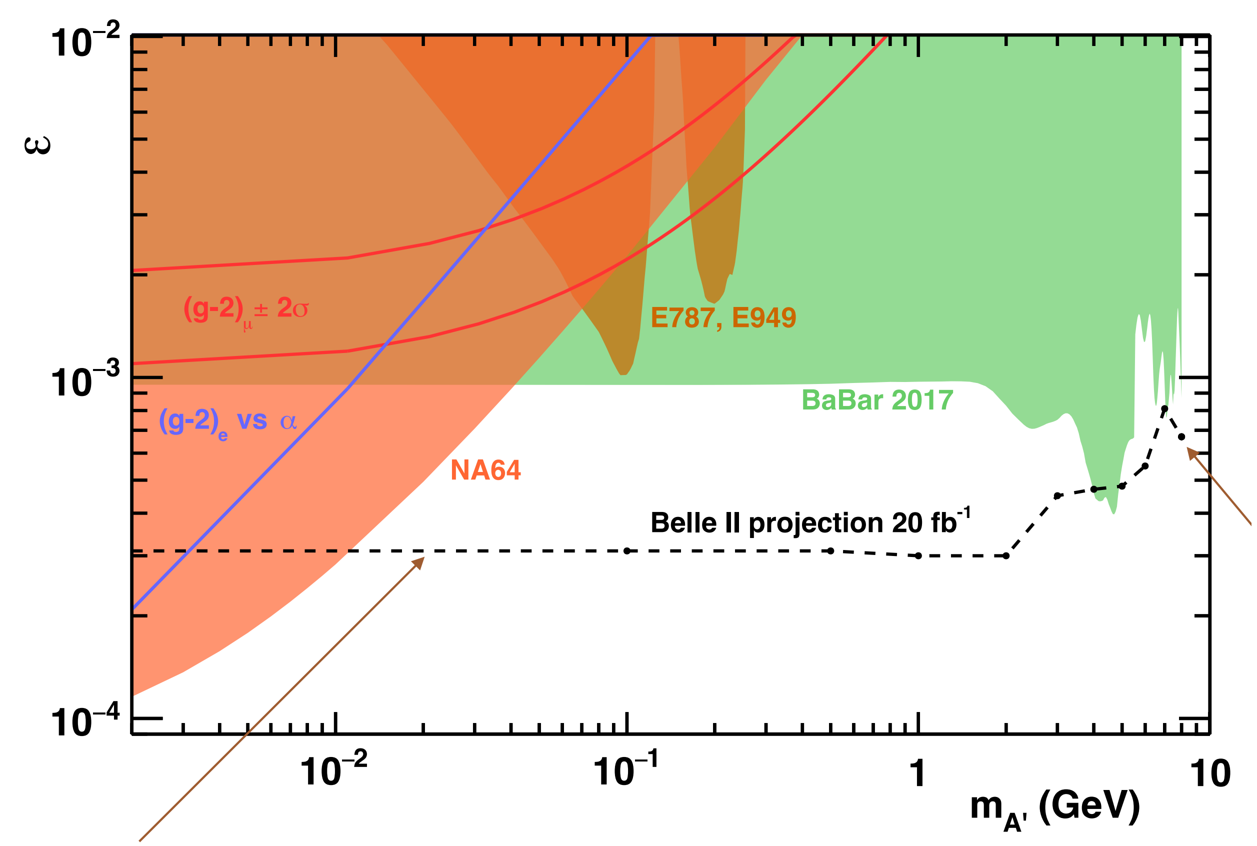


$$\sqrt{s} = 10.58 \text{ GeV } [\Upsilon(4s)]$$



Resonance search for A'

$$m^2_{A'} = (p_\gamma - p_{e^+} - p_{e^-})^2$$



BABAR: 53/fb, Belle II: 50/ab (!)

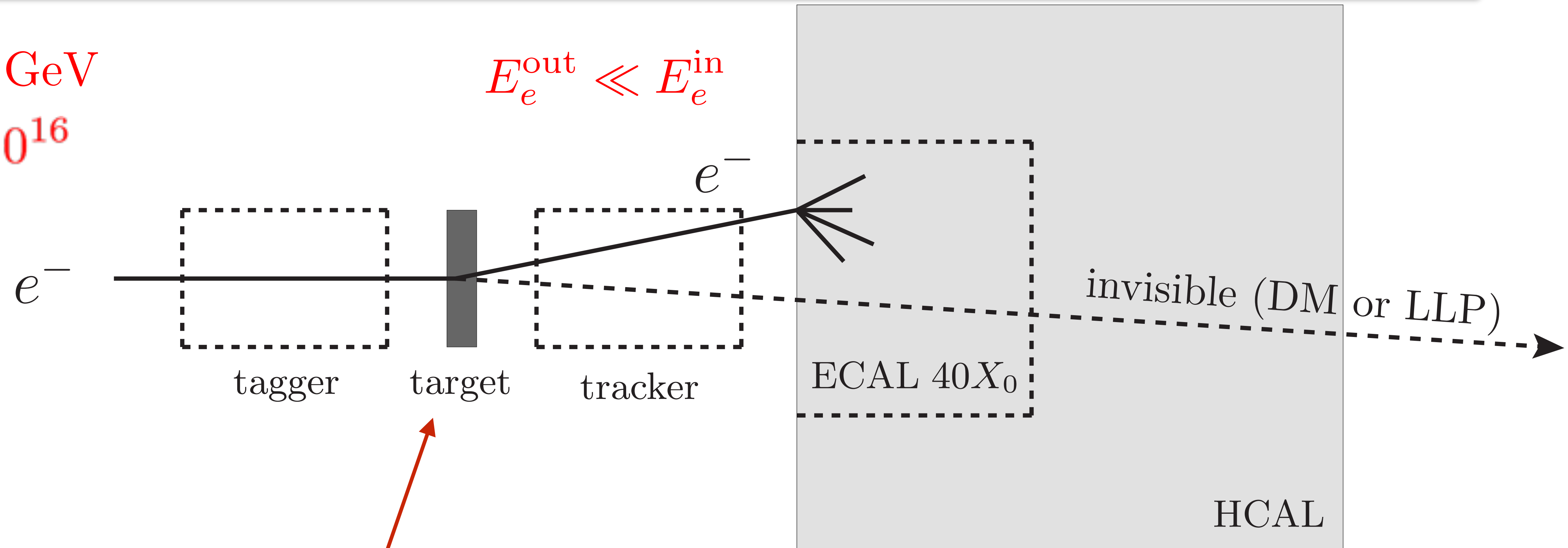
Essig, Mardon, Papucci, Volansky Zhong 1309.5084
Izaguirre, GK, Schuster, Toro 1307.6554
BABAR Collaboration 1702.03327
C. Hearty, Cosmic Visions Workshop Talk

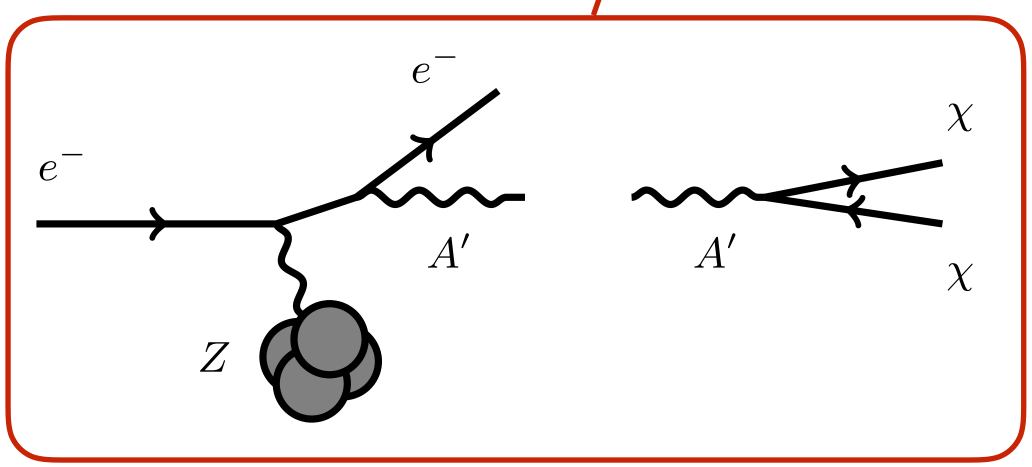
Electron Beam Missing Momentum Strategy: LDMX

$E_e^{\rm in} \simeq 8\,{\rm GeV}$

$N_e \simeq 10^{16}$

$E_e^{\rm out} \ll E_e^{\rm in}$





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

2) Trigger on missing momentum

3) Veto additional SM activity

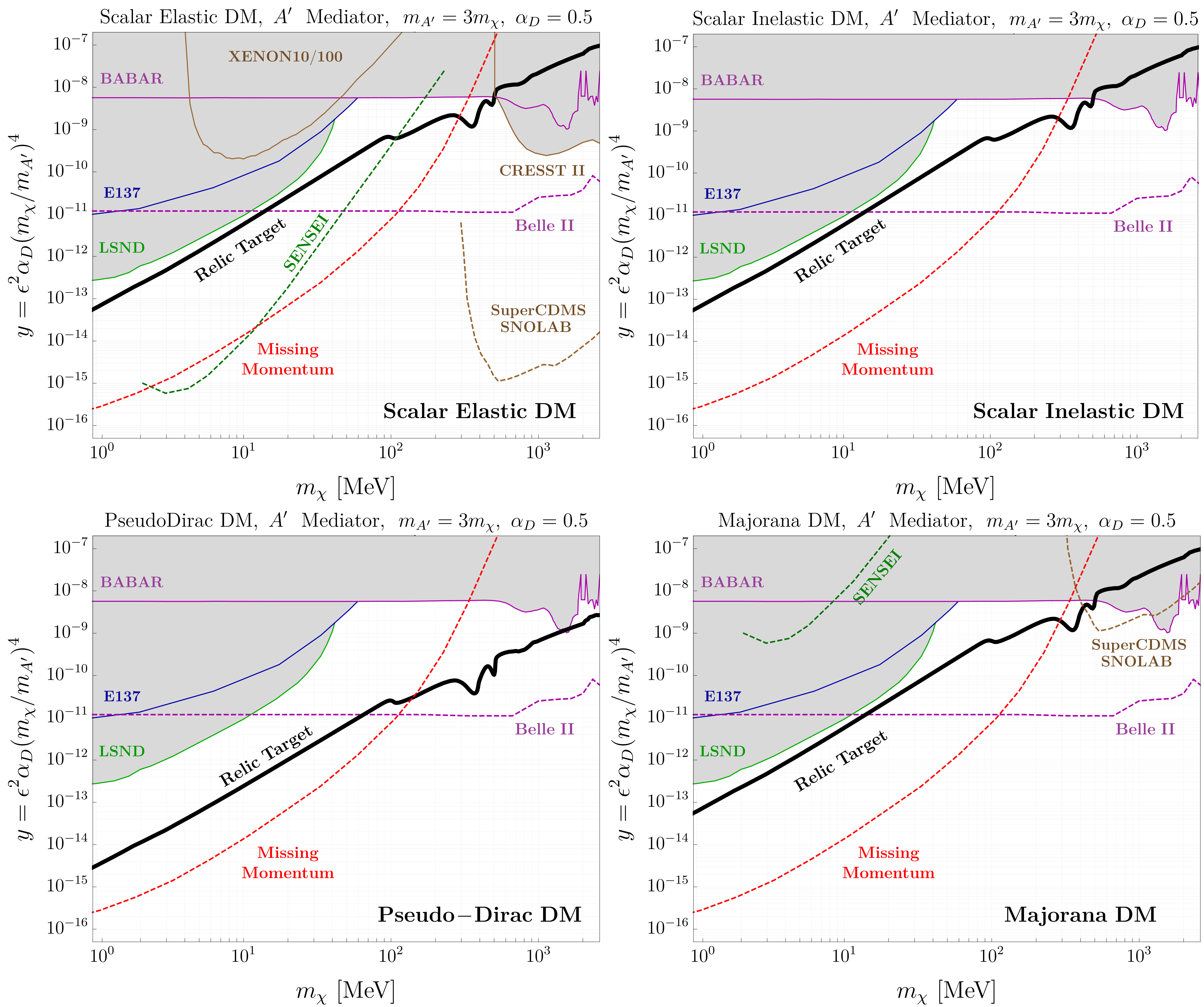
Only track the beam particle — don't require DM to scatter

$$[\text{production}] \propto \epsilon^2$$

Izaguirre, GK, Schuster, Toro arXiv:1411.1404

LDMX Collaboration1808.05219

Comprehensive Coverage: Dark Photon Mediator A'



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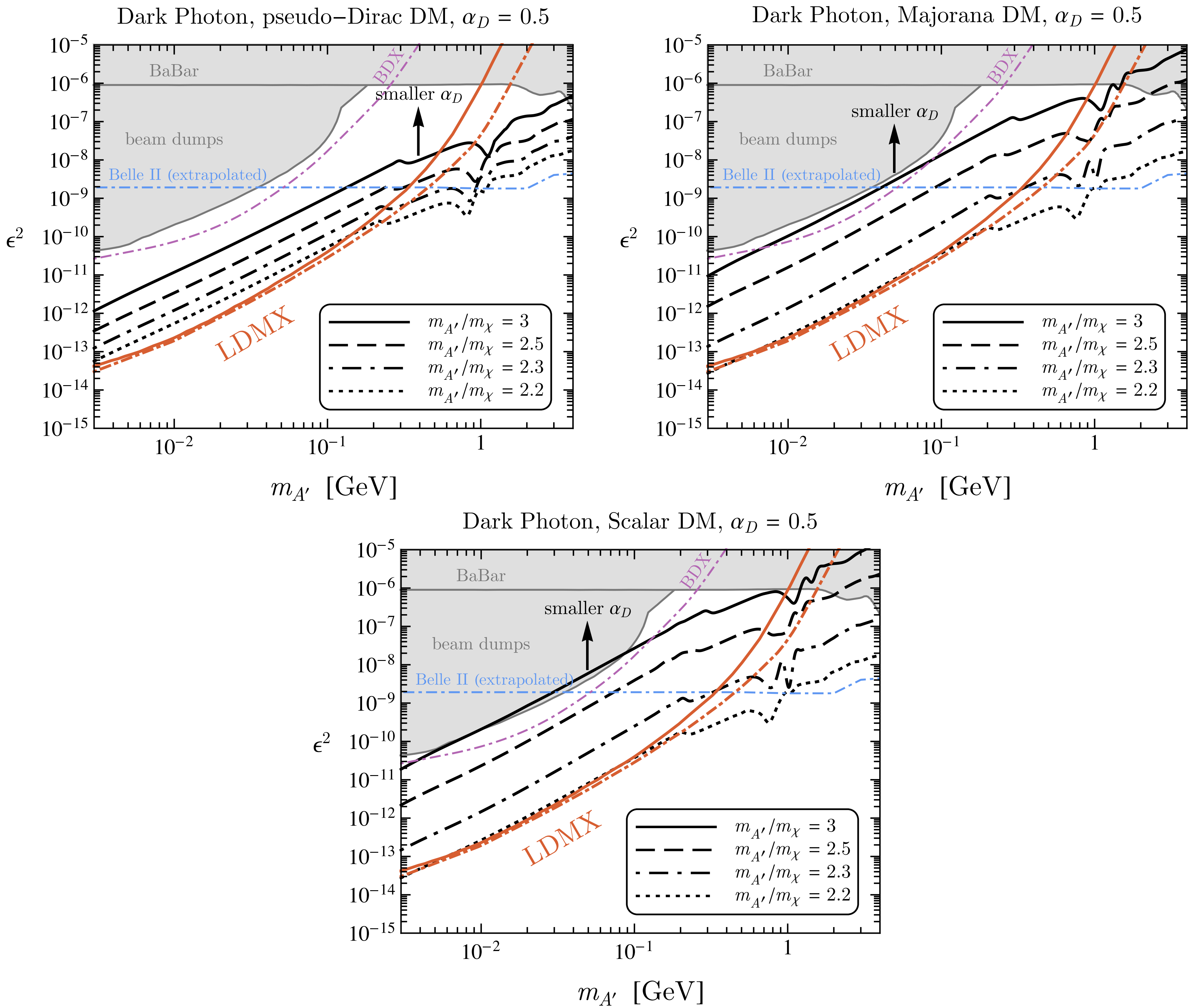
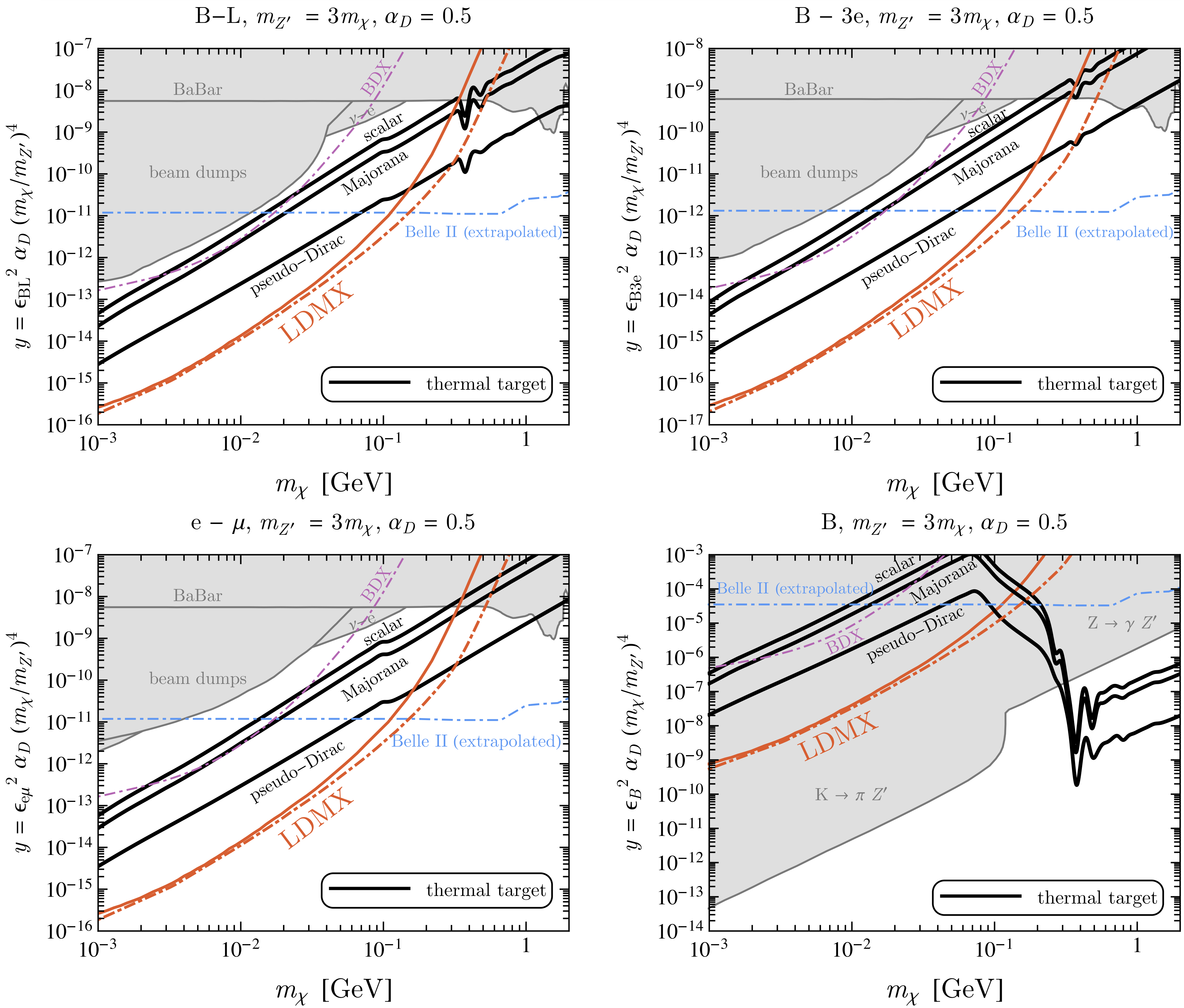


Near resonance, the targets depend on A′ decay width: hardest case to cover

Feng & Smolinsky 1707.03835

Berlin, Blinov GK, Schuster, Toro: 1807.01730

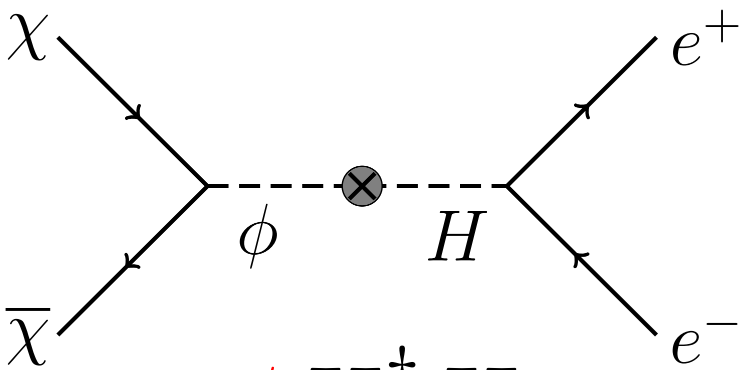
Comprehensive Coverage: Other Viable Mediators



Berlin, Blinov GK, Schuster, Toro arXiv: 1807.01730

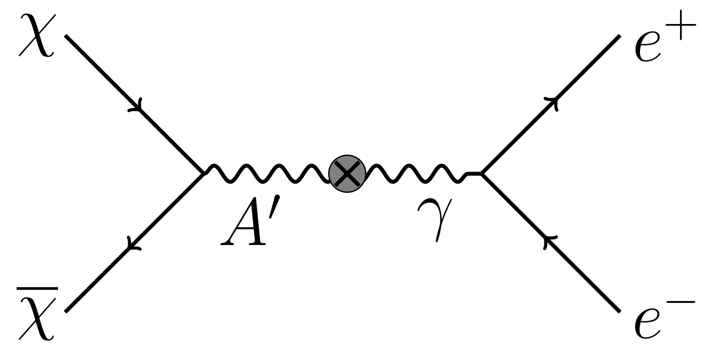
Where are the blind spots?

So far we have covered nearly all **predictive** < GeV models



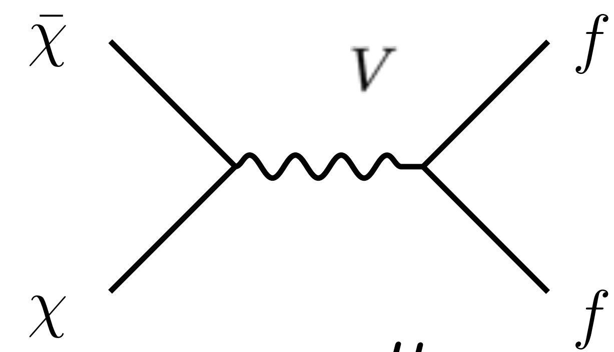
$\phi H^\dagger H$

Scalar
Ruled out



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

Dark photon



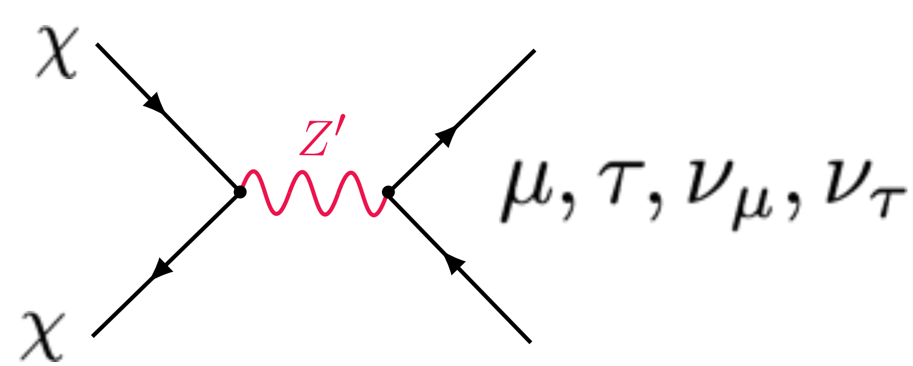
$V_\mu J^\mu_{\mathrm{SM}}$

Anomaly free U(1)
B-L, B-3Le … etc.

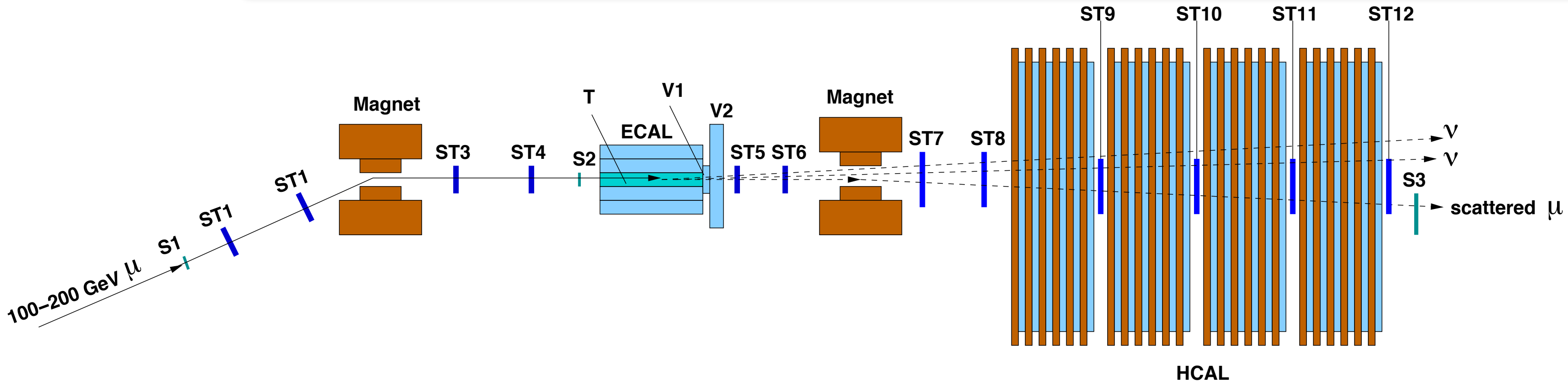
What about mediators w/ mainly 2nd & 3rd generation couplings?

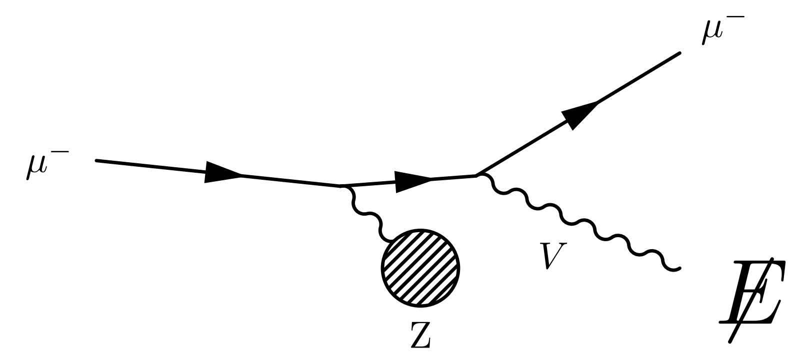
Only one anomaly free U(1) group

$L_\mu - L_\tau$



Muon Beam Missing Energy: NA64 @ CERN





~ 100-200 GeV muon beam

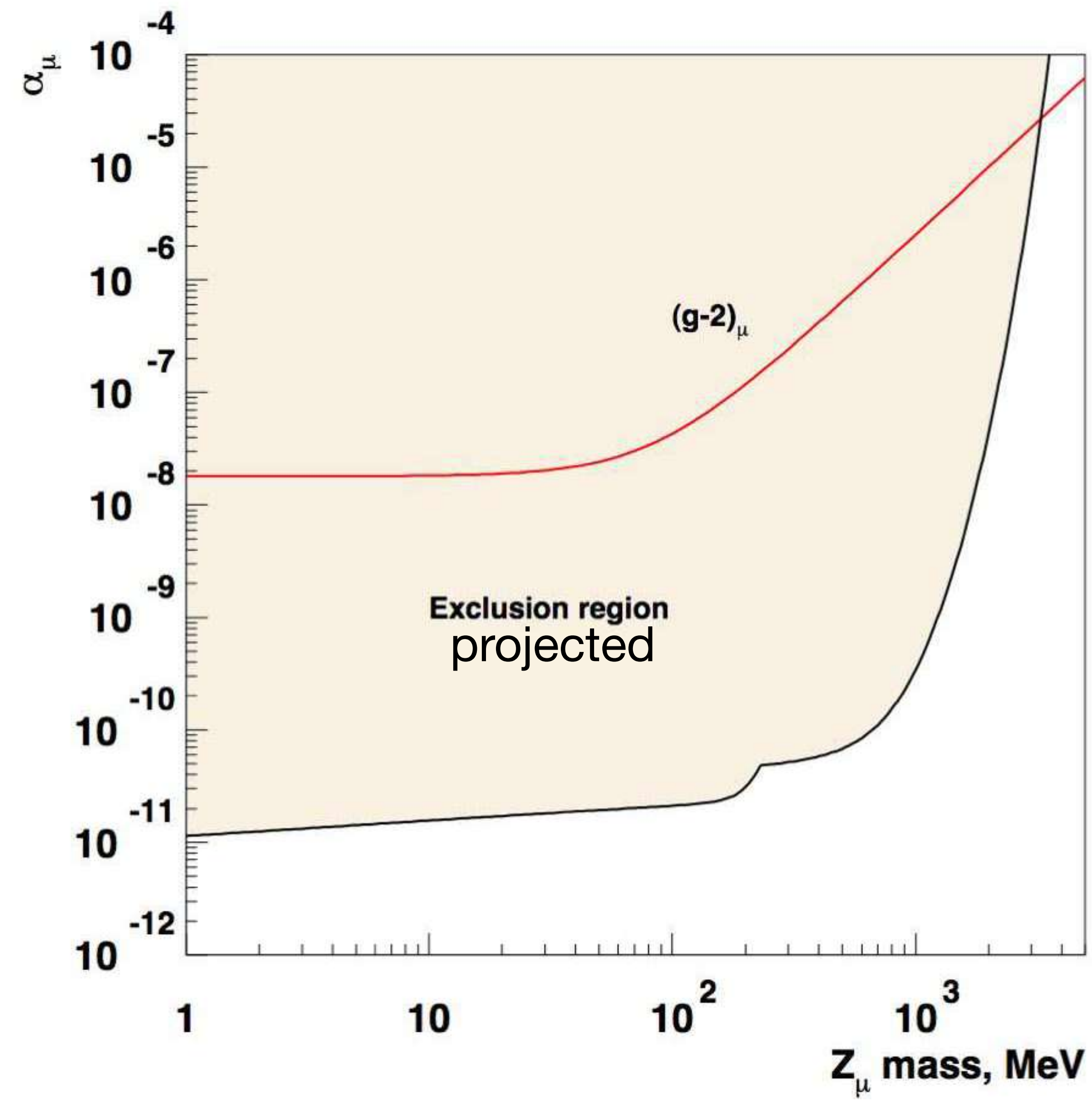
~ 10s meter baseline

$\sim 10^{11} - 10^{12}\ \mu$

1) Measure E in/out

2) Trigger on missing energy

3) Veto additional SM activity

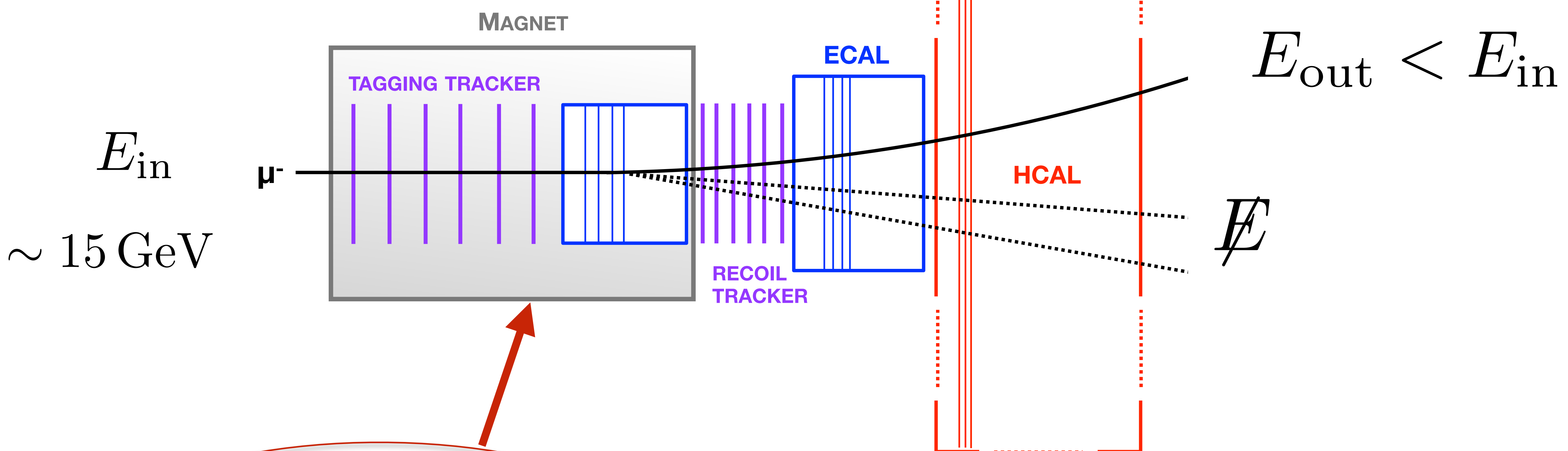


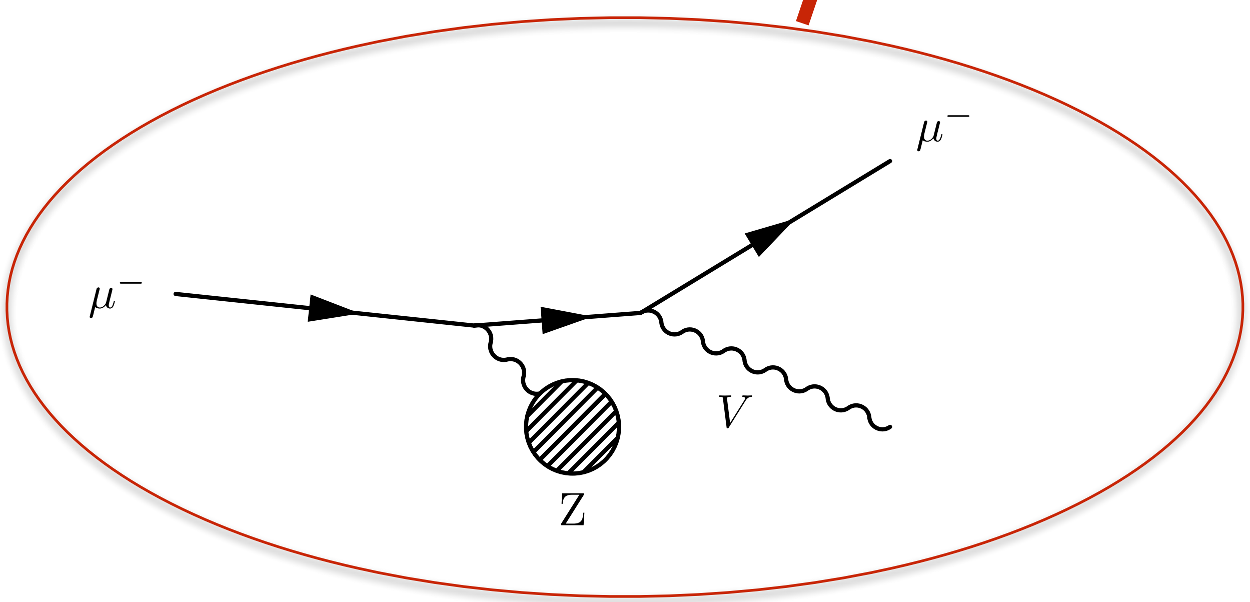
Gninenko, Krasnekov, Mateev, arXiv: 1412.1400

M^3 Muon Missing Momentum

Lower energy, smaller baseline than NA64 (few meter scale)

must measure track curvature





Lower BG allows thicker target, similar detector concept to LDMX

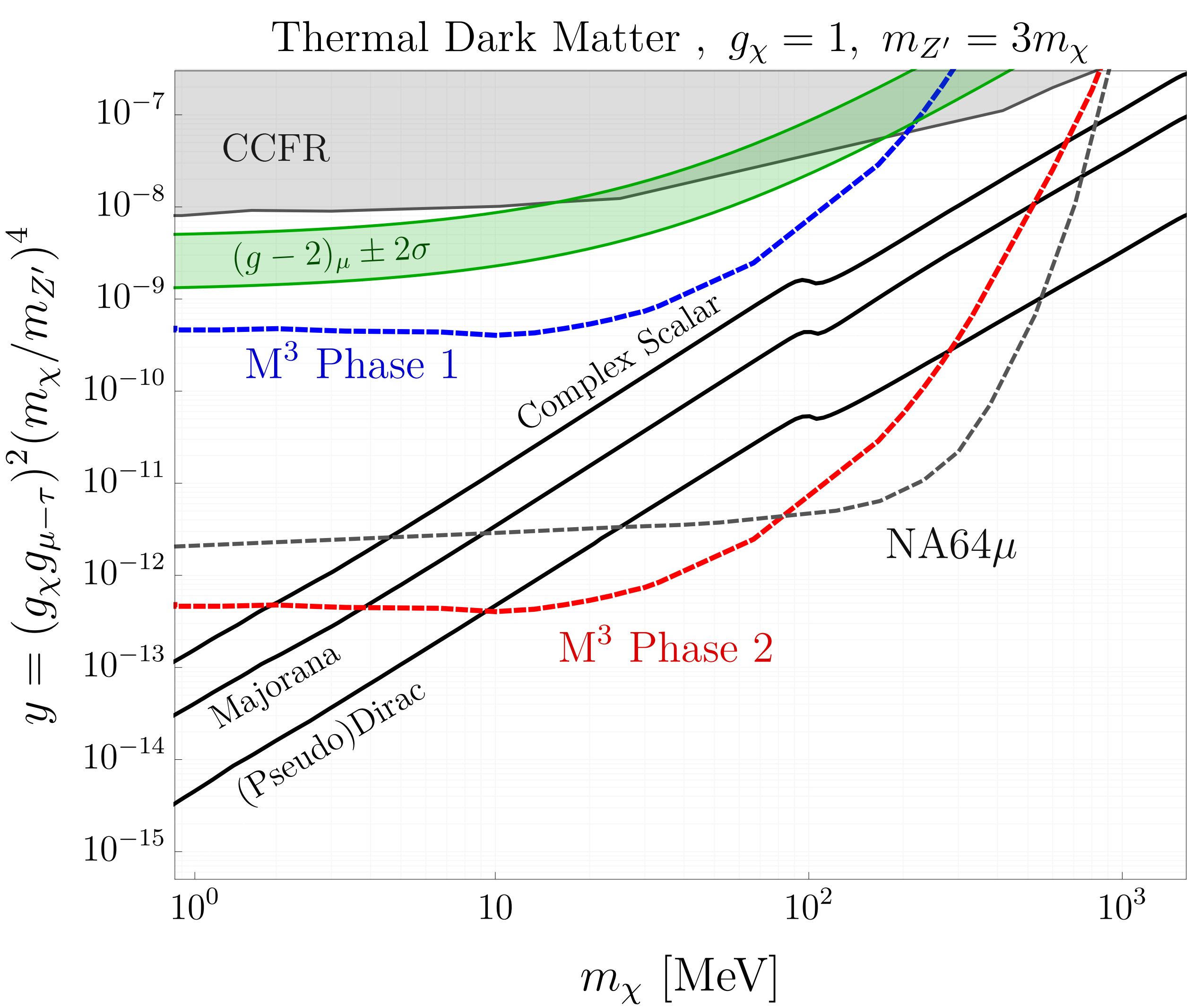
1) Measure E in/out

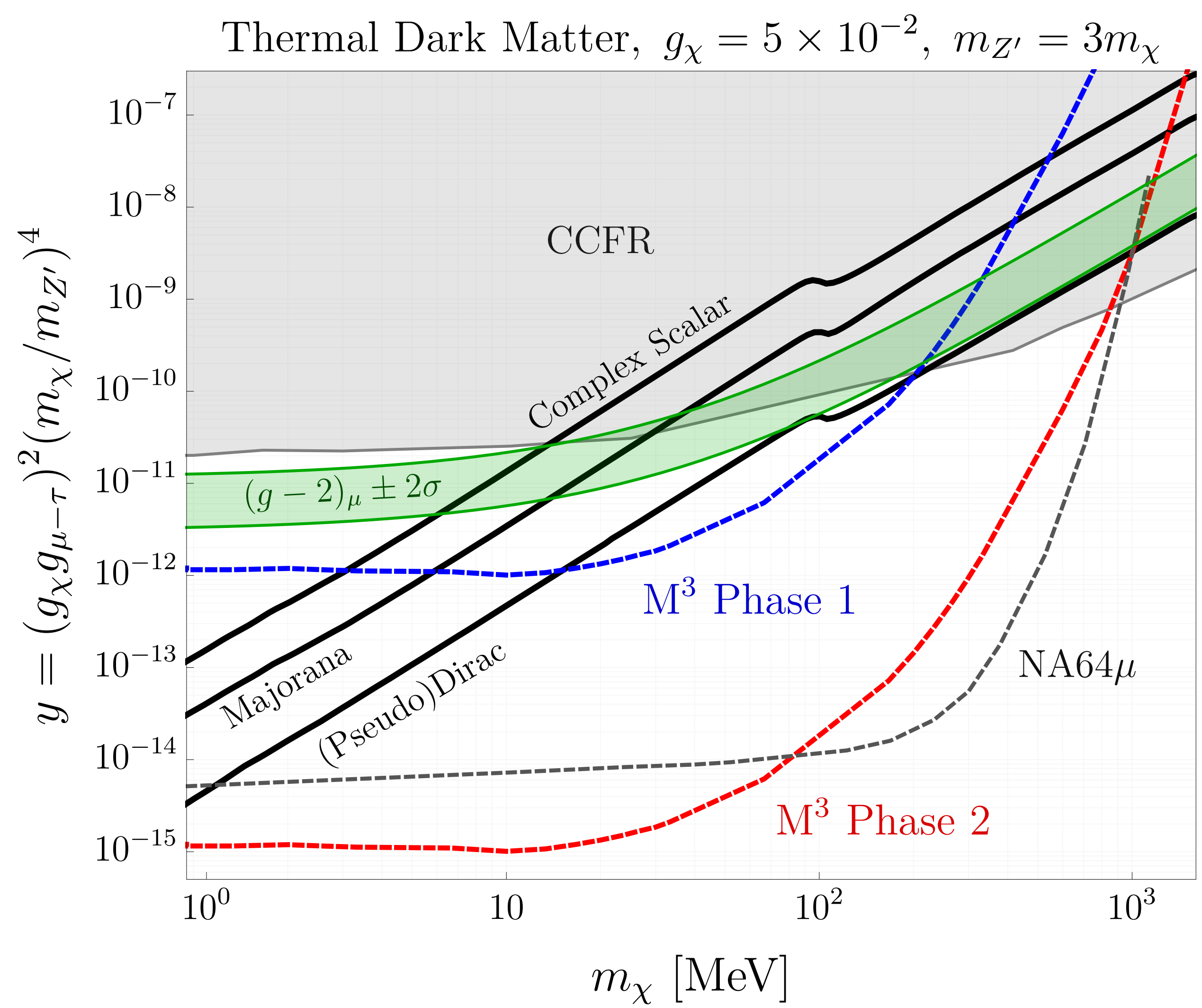
2) Trigger on missing momentum

3) Veto additional SM activity

Kahn, GK, Tran, Whitbeck 1804.03144

Covers Predictive Muon-Philic Models

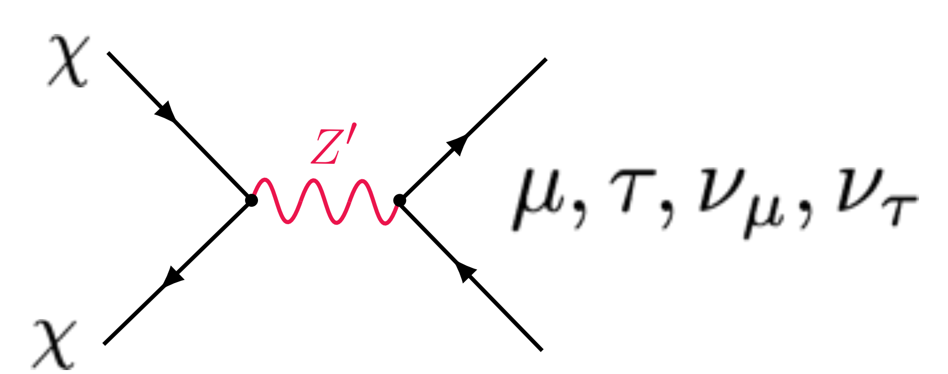




Gauged $L_\mu - L_\tau$ Interaction

Also resolve muon g-2 with light physics

Compatible parameter space for freeze-out



NB: annihilation to neutrinos also CMB safe

Summary

A Modest Proposal $\Gamma(\mathrm{DM} \leftrightarrow \mathrm{SM}) > H$

Rate beats Hubble expansion at *some* point [easy to realize]

Thermodynamics Set Initial Condition $n_{\mathrm{DM}} \sim T^3$

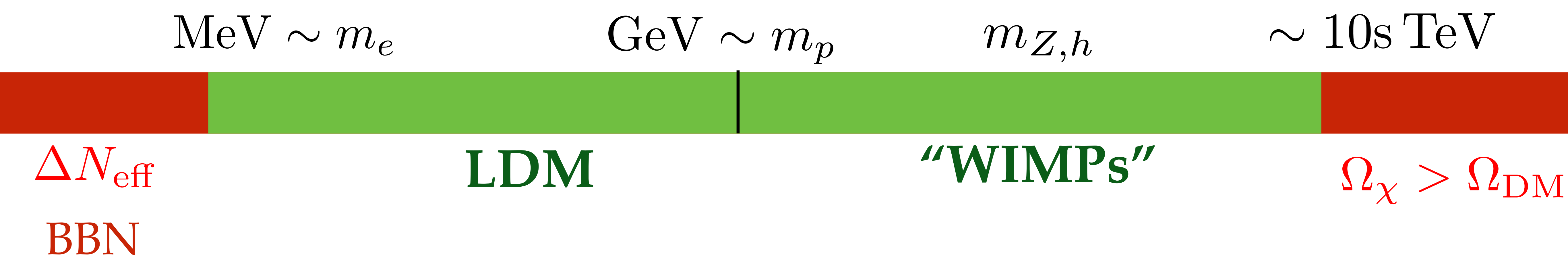
Insensitive to unknown high scales [inflation, baryogenesis…]

Predicts Min. Annihilation Rate $\sigma v \gtrsim 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$

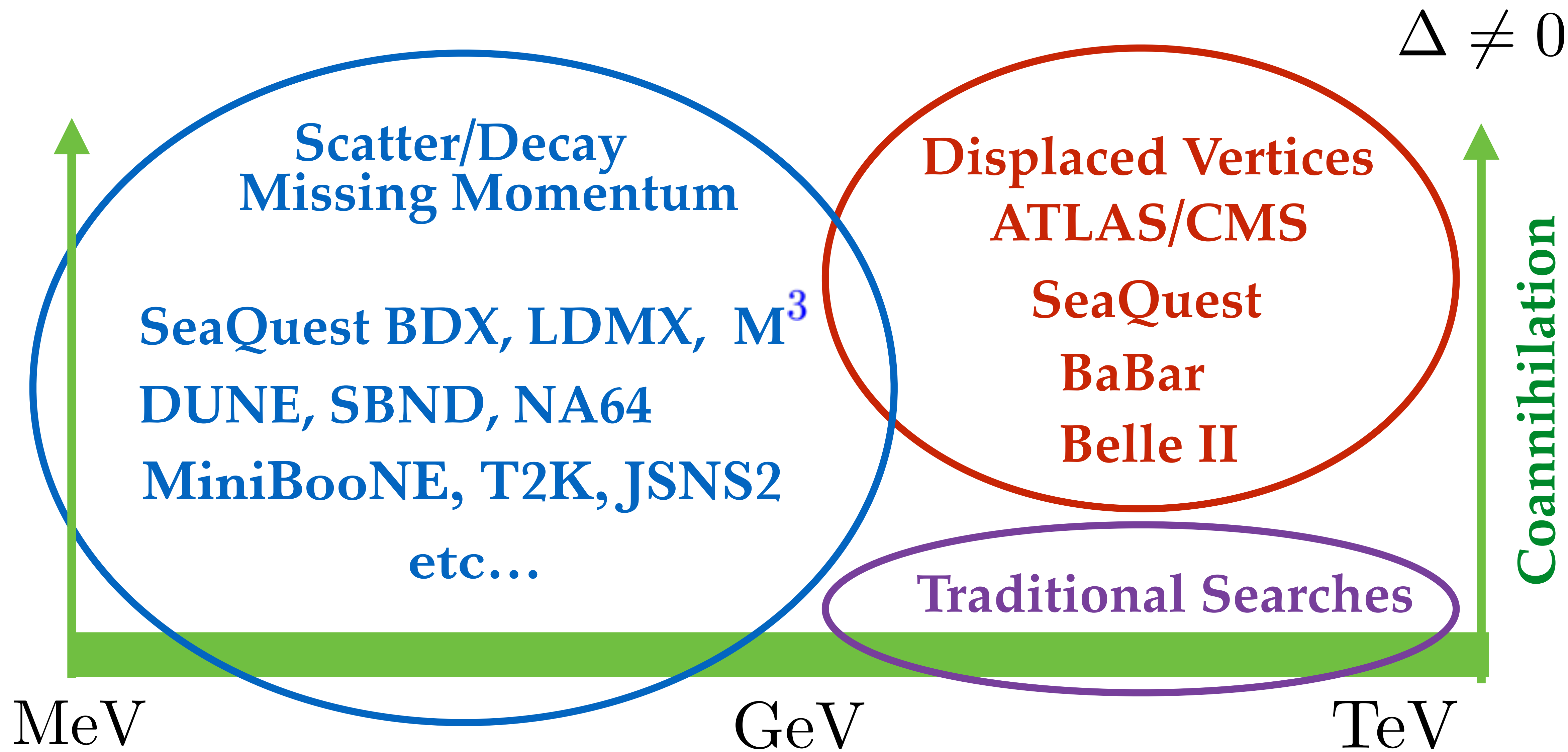
Equilibrium overproduces DM, must deplete with non-gravitational force

Viable Window In Our Neighborhood

Coincidentally in broad vicinity of the electroweak scale



Summary



Light DM

B-Factories
Proton Fixed Targets
Electron Direct Detection
Electron Beam Dumps
Electron Missing Momentum
Muon Fixed Targets

“WIMPs”

Direct Detection
Indirect Detection
Collider Production

Thanks!