Light Dark Matter Theory & Searches

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Fermilab

Brookhaven Forum 2017
In Search of New Paradigms

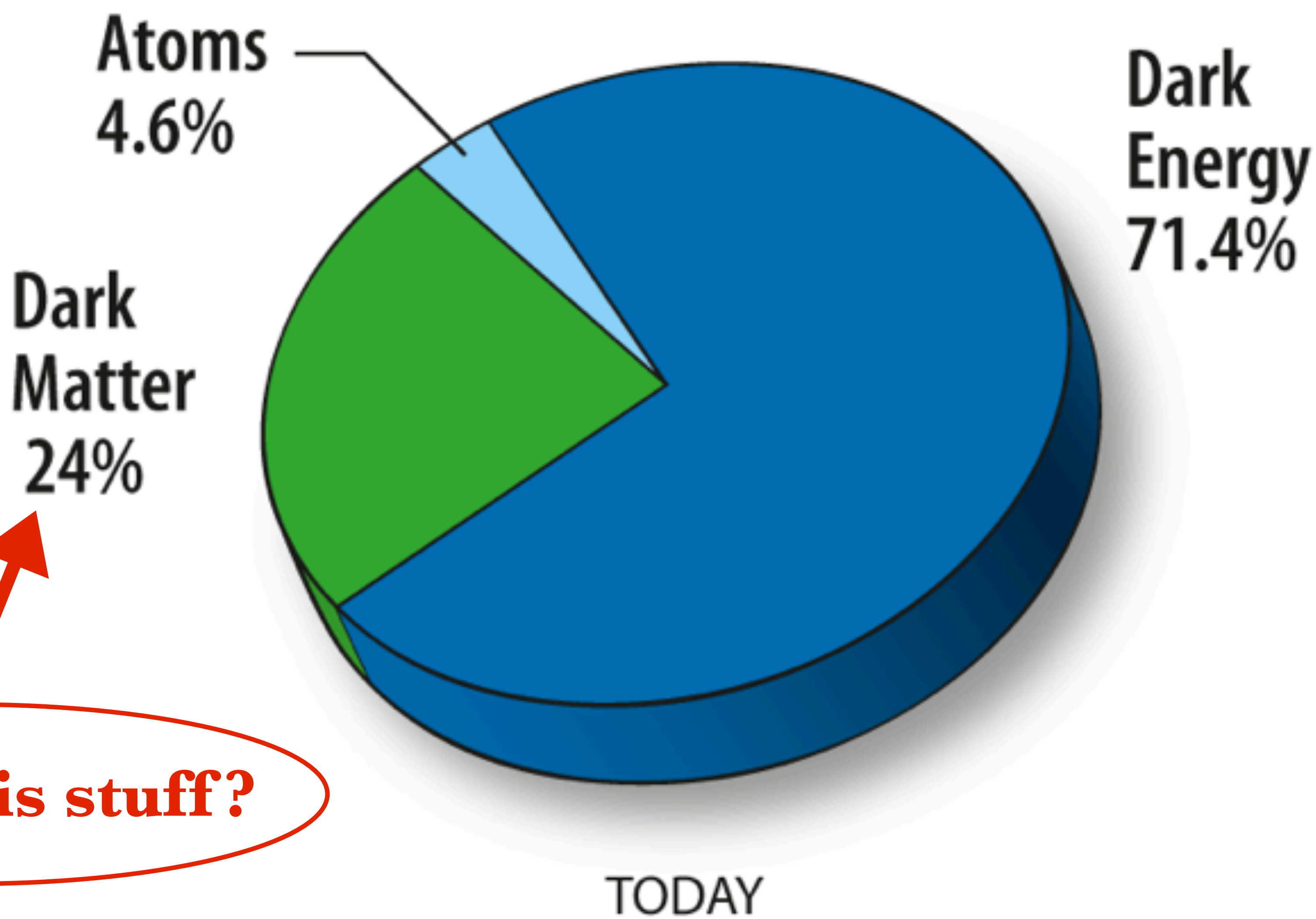
BROOKHAVEN NATIONAL LABORATORY

October 12, 2017

Zeroth Order Outstanding Problems

Matter Asymmetry
Inflation
Neutrino Masses

Accelerated Cosmic Expansion



What is this stuff?

Also Quantum Gravity

Overview

- **Historical Perspective**
  Thermal DM & WIMPs

- **Light DM (<GeV)**
  Models & Milestones

- **Accelerator Searches**
  Proton & Electron Beams

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- **Historical Perspective**
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Understanding the Electroweak Sector

Discovery of Radioactivity	(1890s)
Fermi Scale Identified	(1930s)
Non-Abelian Gauge Theory	(1950s)
Higgs Mechanism	(1960s)
W/Z Bosons Discovered	(1970s)
Higgs Discovered	(2010s)

Each step required revolutionary theoretical/experimental leaps

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

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Understanding the Dark Sector?

Discovery of missing mass	(1930s)
Rotation curves	(1970s)
Precision CMB measurements	(1990s)
Relevant scale?	**> 2017**

No clear target for non-gravitational contact

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

DM Prognosis?

Bad news: DM-SM interactions are not obligatory

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

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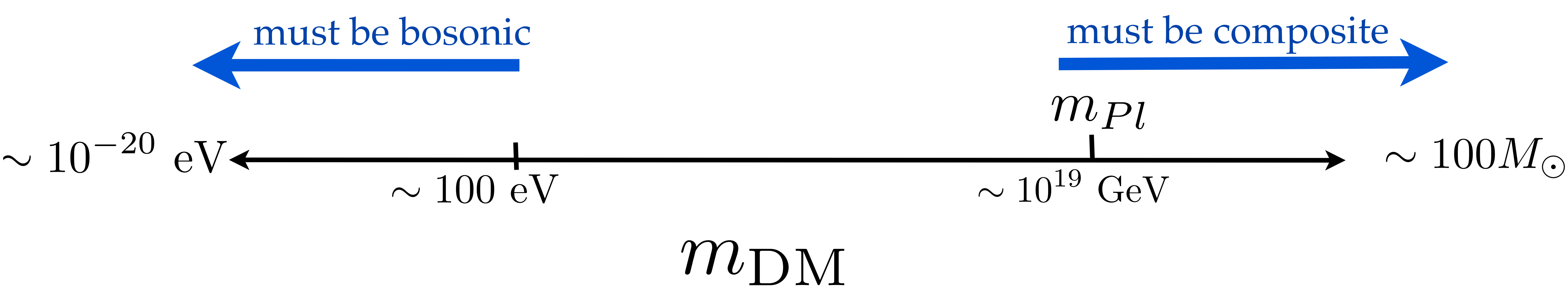


Good news: most *discoverable* DM candidates are in thermal equilibrium with us in the early universe

Why is this good news?

Thermal Equilibrium
Advantage #1: Easily Achieved

If interaction rate exceeds 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 easily achieved in the early universe if

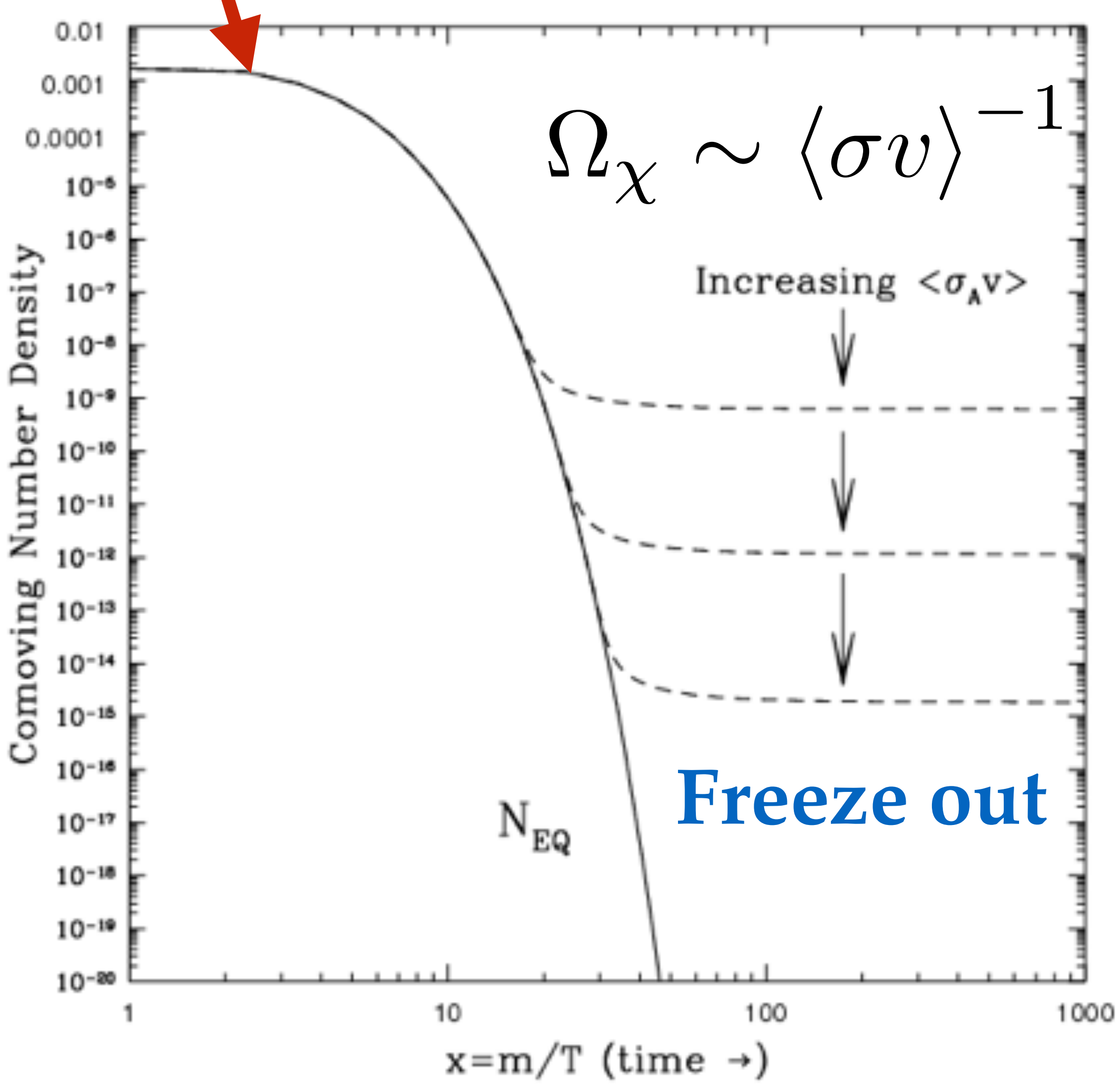
$$g \gtrsim 10^{-8}\left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^2\left(\frac{\mathrm{GeV}}{m_\chi}\right)^{3/2}$$

Trivially satisfied in nearly all *discoverable* models

Thermal Equilibrium
Advantage #2: Minimum Annihilation Rate

DM is overproduced, need to annihilate away the excess!

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



$$\Omega_\chi \sim \langle \sigma v \rangle^{-1}$$

Griest et. al. 1992

Symmetric Thermal DM
Observed density requires

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

Asymmetric Thermal DM:
Just need to deplete antiparticles

$$\sigma v_{\rm asym} > 3\times 10^{-26}{\rm cm}^3{\rm s}^{-1}$$

Rate can be bigger, but not smaller
Either way, there's a target!

Thermal Equilibrium Advantage #3: UV Insensitive

Initial condition known

Compatible with nearly all UV scenarios

Mass & couplings set abundance

Can learn a lot from a discovery!

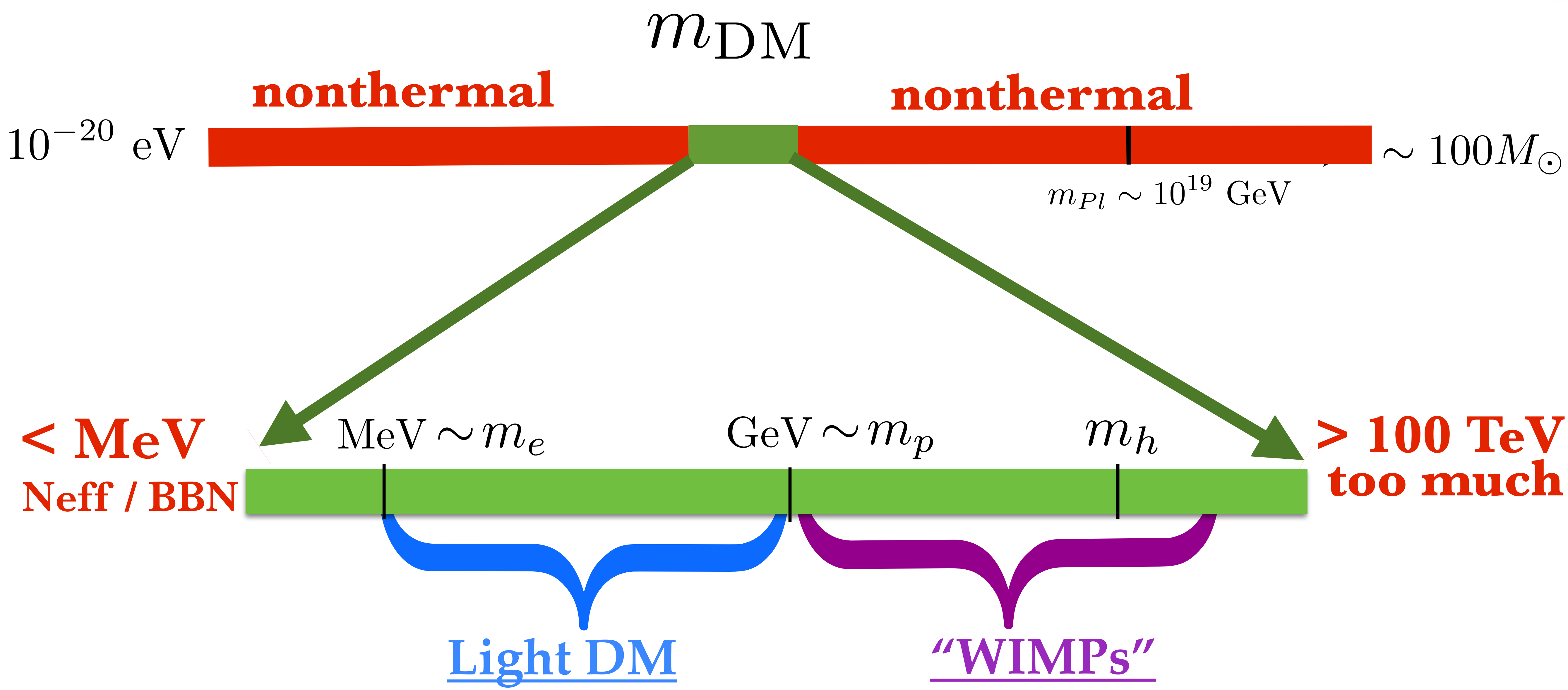
Only two known UV insensitive mechanisms

1) **Freeze out** (thermal + annihilation)

2) **Freeze-in** (nonthremal, no annihilation)

tiny couplings = very hard to test

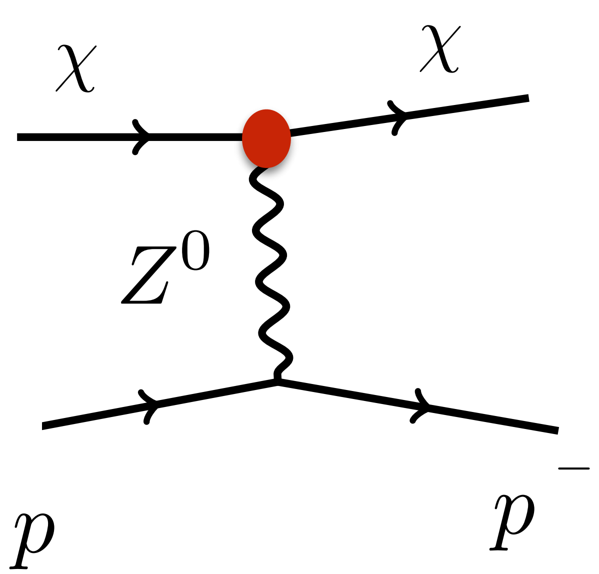
Thermal Equilibrium
Advantage #4: Narrows Viable Mass Range



Luckily the thermal window is in our neighborhood

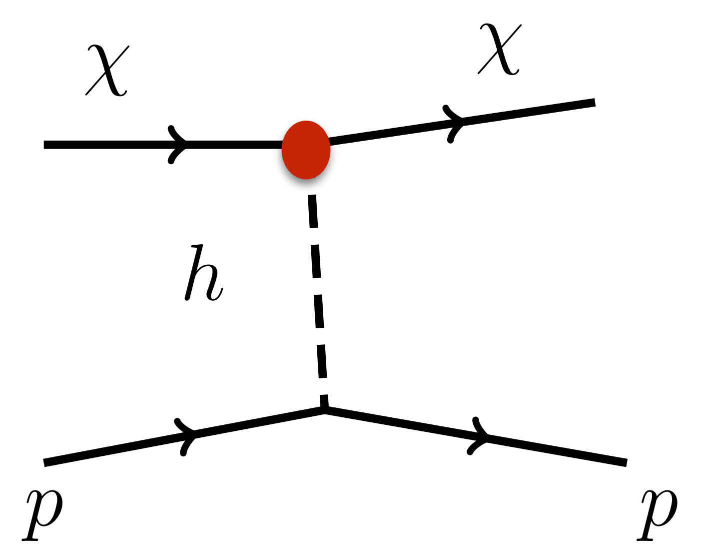
it didn't have to be this way!

Classifying WIMP Interactions



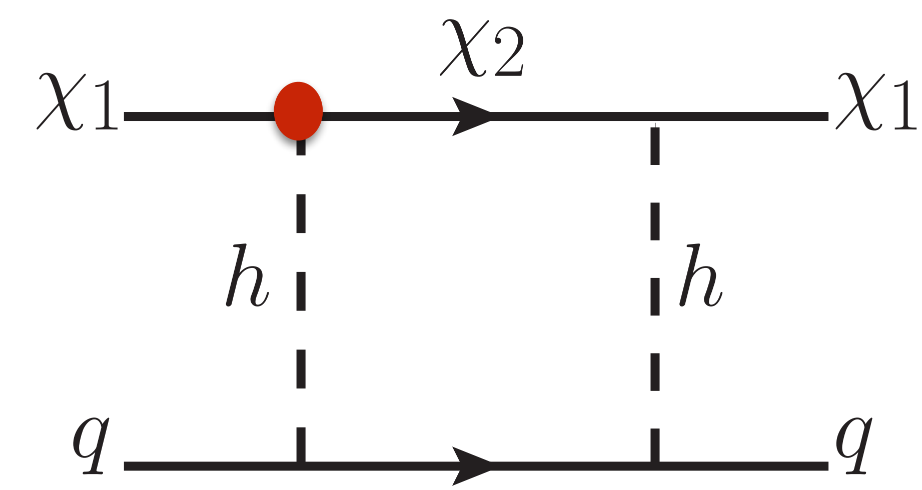
Z Exchange

$$\sigma_p \sim 10^{-39}\,\mathrm{cm}^2$$



Higgs Exchange

$$\sigma_p \sim 10^{-45}\mathrm{cm}^2$$



$$\Delta \equiv m_2 - m_1$$

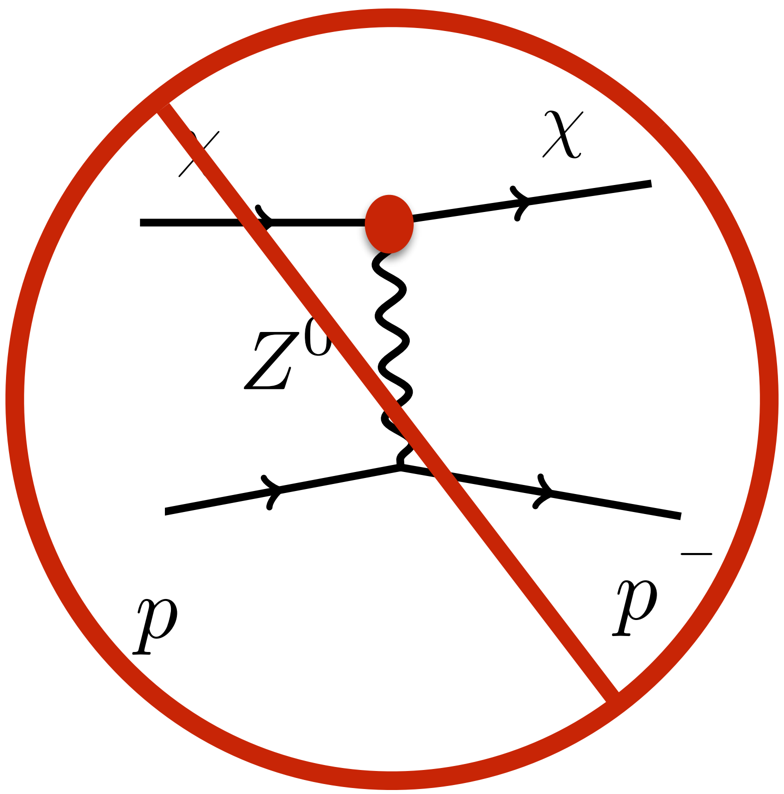
Inelastic coupling EW loop

$$\sigma_p \sim 10^{-47}\mathrm{cm}^2$$

Very different at low energy, despite high energy similarities

Each ● interaction can realize thermal annihilation at *T* ~ *M*

Classifying WIMP Interactions



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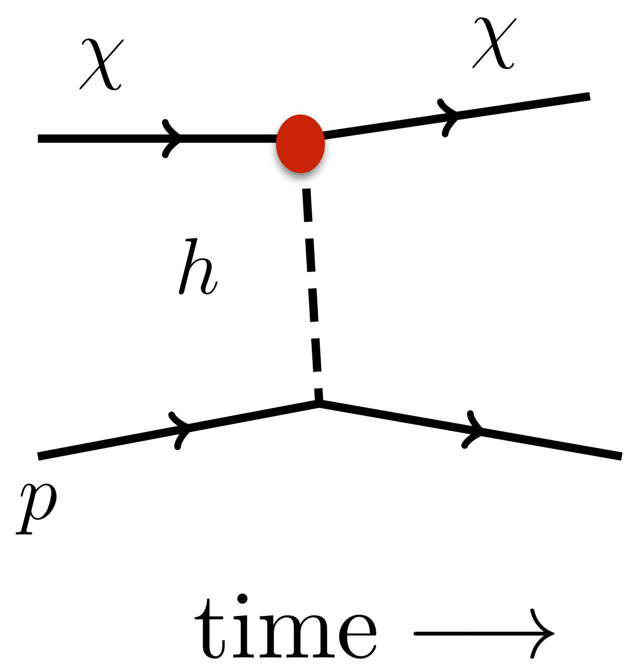

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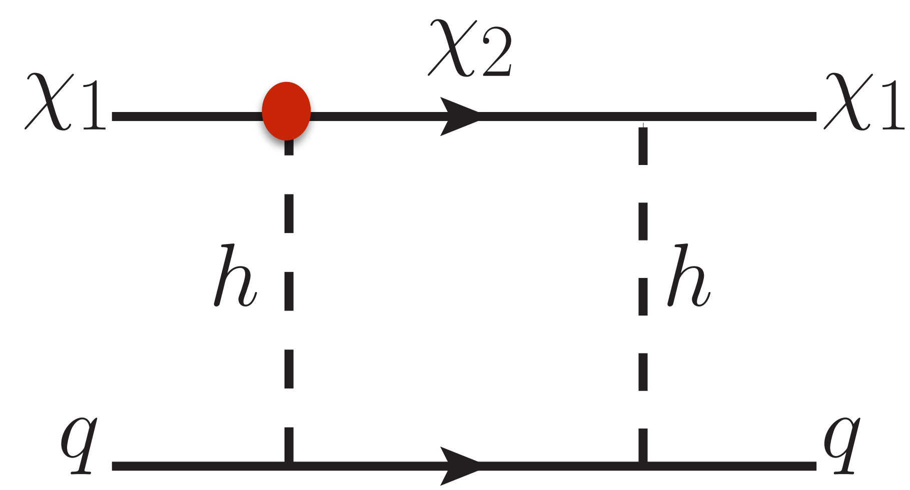


$$\Delta \equiv m_2 - m_1$$

Inelastic coupling
EW loop

$$\sigma_p \sim 10^{-47}\mathrm{cm}^2$$

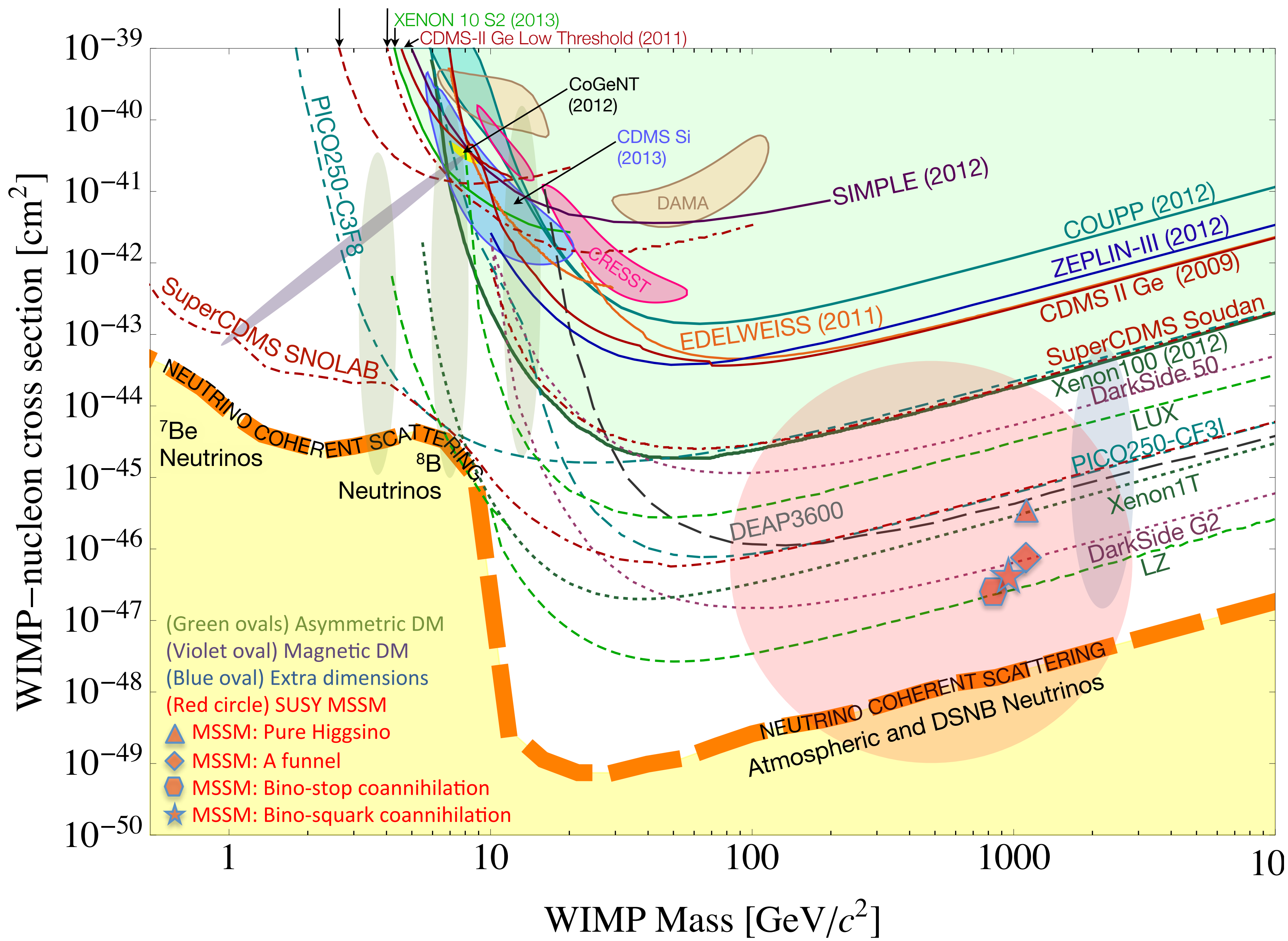
Ruled out with first generation direct detection experiments
But still a long way to go to fully test others …

WIMP Milestones

Elastic Z exchange →

Higgs exchange →

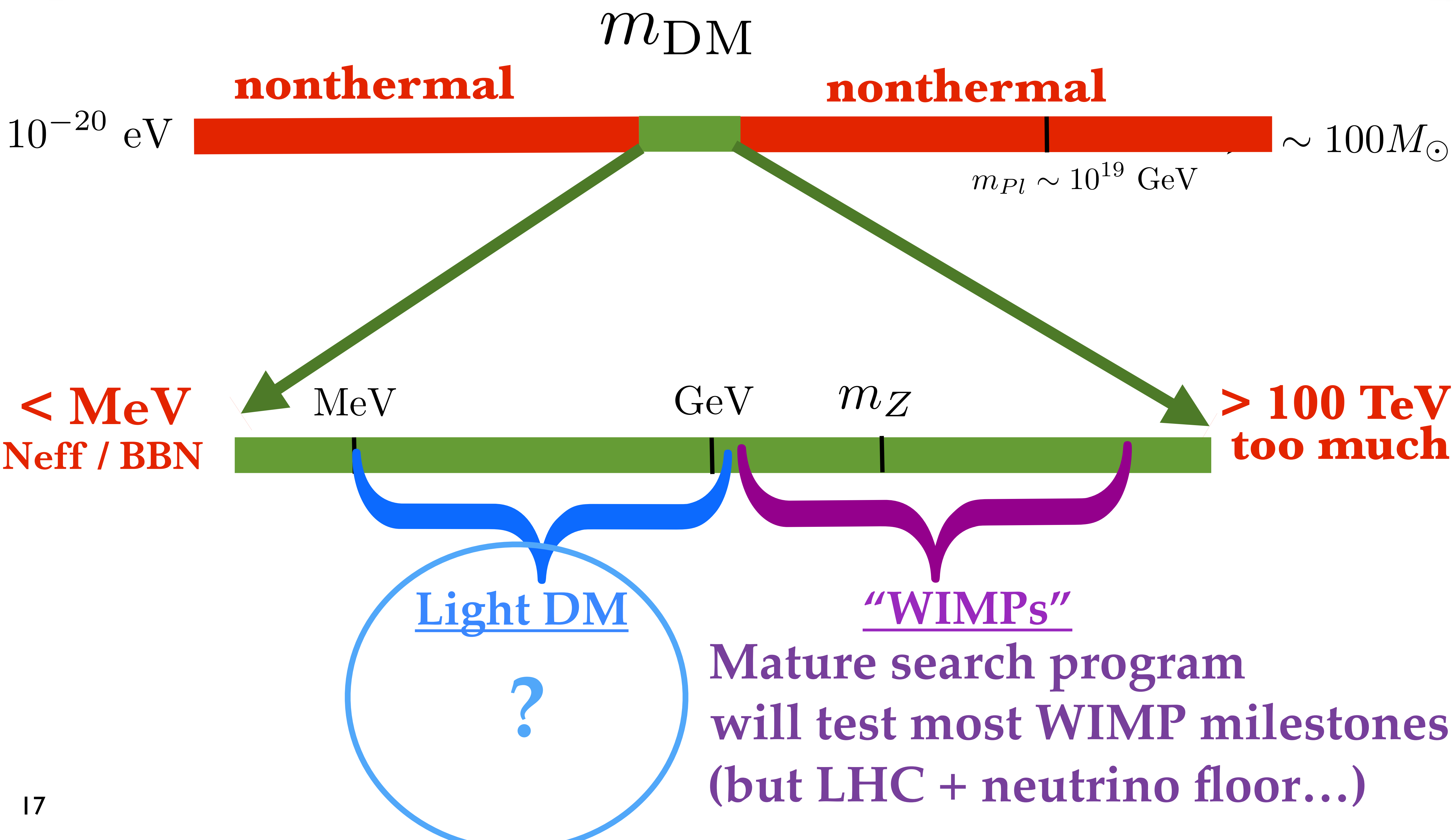
1-Loop EW box →



Rough targets due to WIMP model dependence

Cushman et al. arXiv:1310.8327

A Mature LDM program?



Mature search program
will test most WIMP milestones
(but LHC + neutrino floor…)

Overview

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- **Accelerator Searches**
  B-factories & Fixed Targets

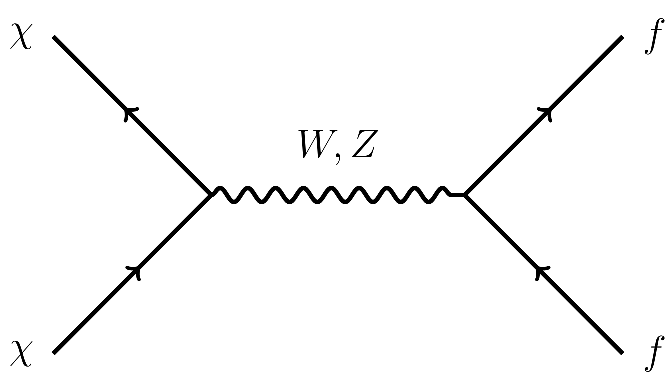
Model Building Requirements

LDM must be a SM singlet

Otherwise would have been discovered (LEP etc.)

LDM needs new forces

Would be overproduced without light "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

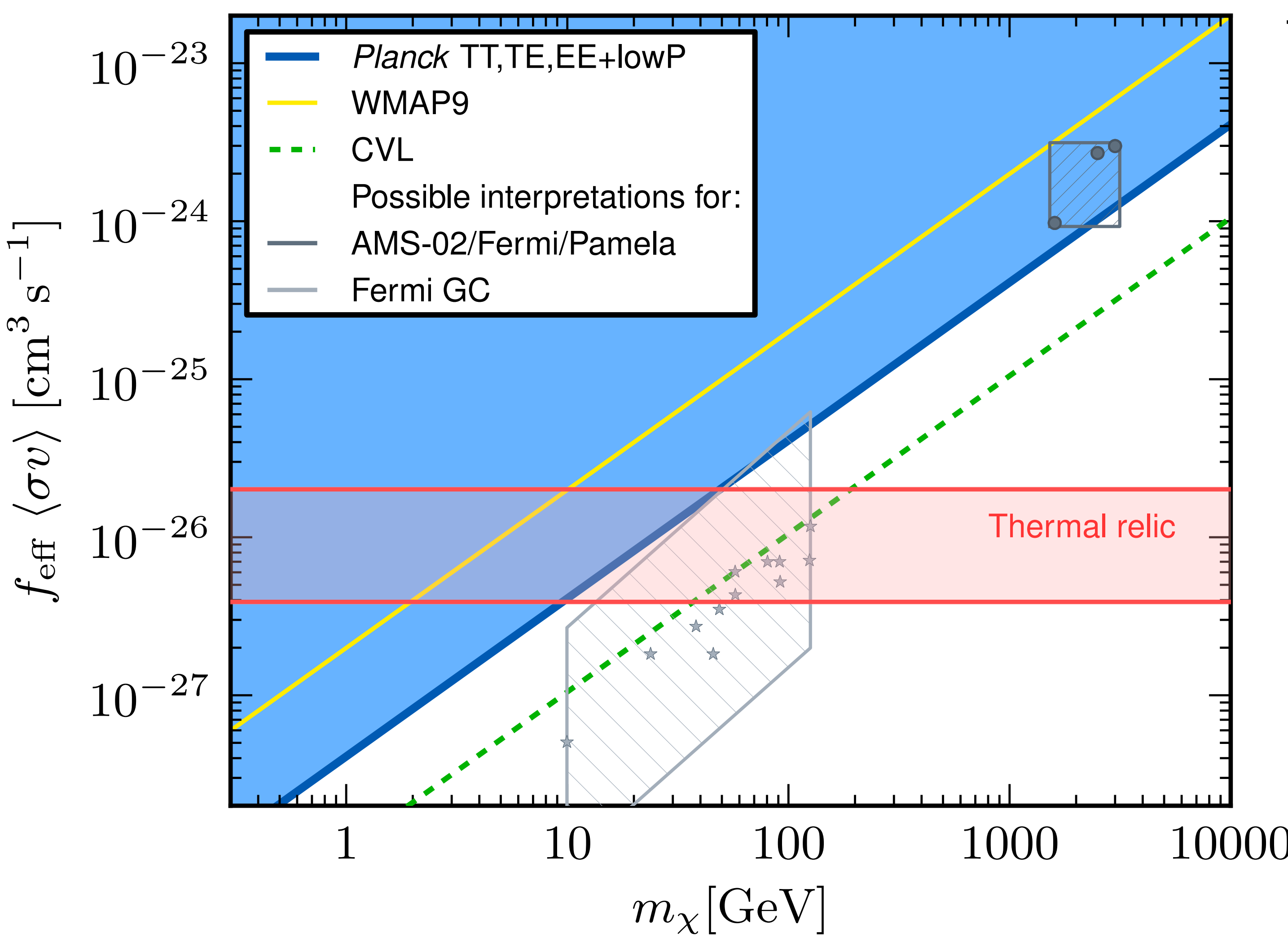
Key point: models must be renormalizable

Greatly simplifies range of viable models

Model Building Requirements

LDM annihilation (after freeze out) can distort CMB

S-wave thermal relic ruled out < 10 GeV



Planck
1303.5076

Viable models need either :

P-wave annihilation

$$\langle\sigma v\rangle_{\rm CMB} \ll \langle\sigma v\rangle_{\rm Freeze\,Out}$$

OR

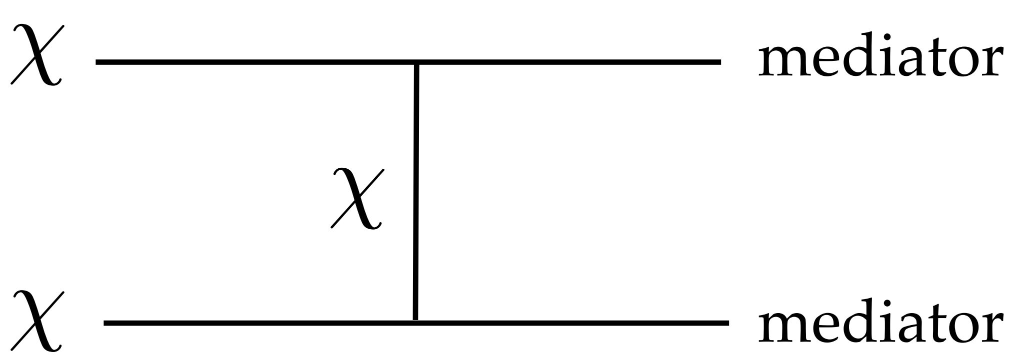
Different DM population during CMB epoch

e.g. asymmetric DM
e.g. pseudo-dirac DM

Hidden vs. Direct Annihilation

Annihilation to Dark Sector

DM transfers entropy indirectly



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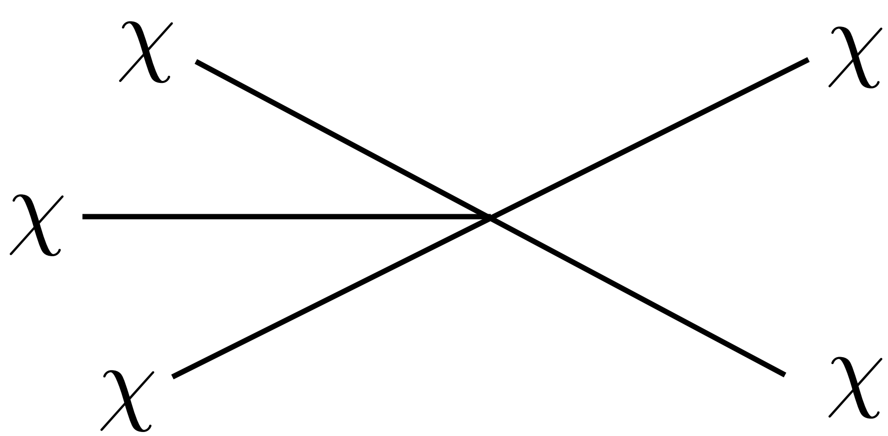
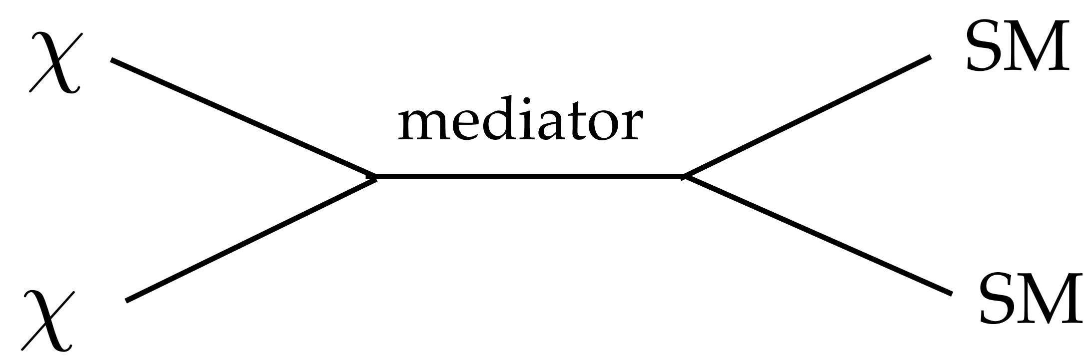


Annihilation to Visible Sector

Entropy transfer from annihilation



Predictive!

Relic abundance set by mediator coupling to SM

Hidden vs. Direct Annihilation

Annihilation to Dark Sector

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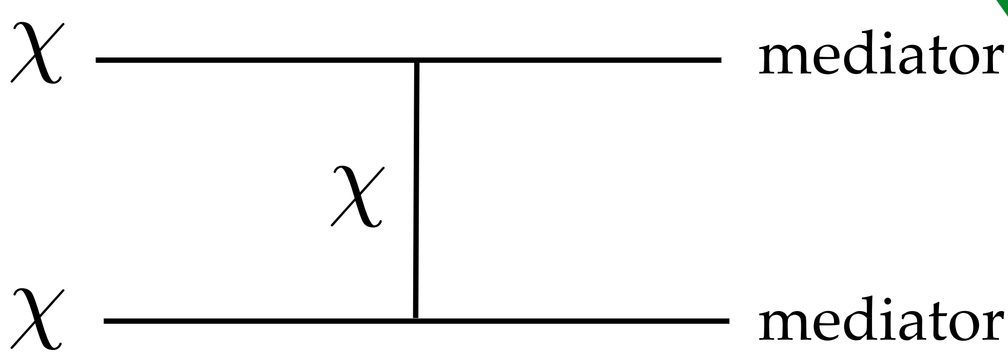

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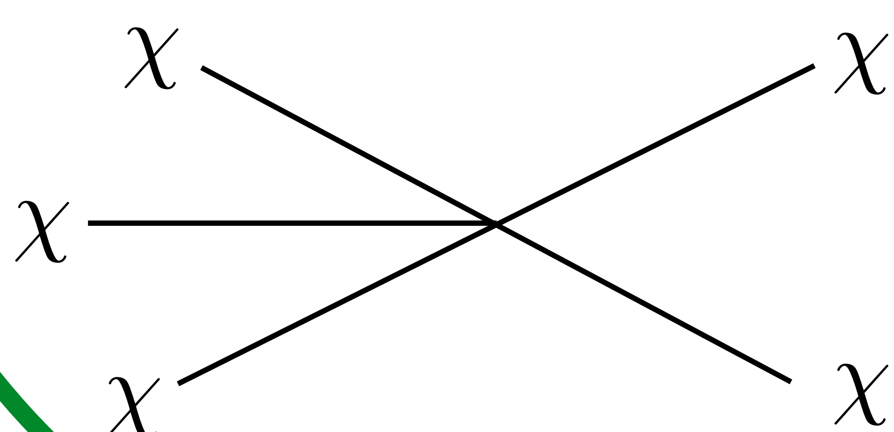

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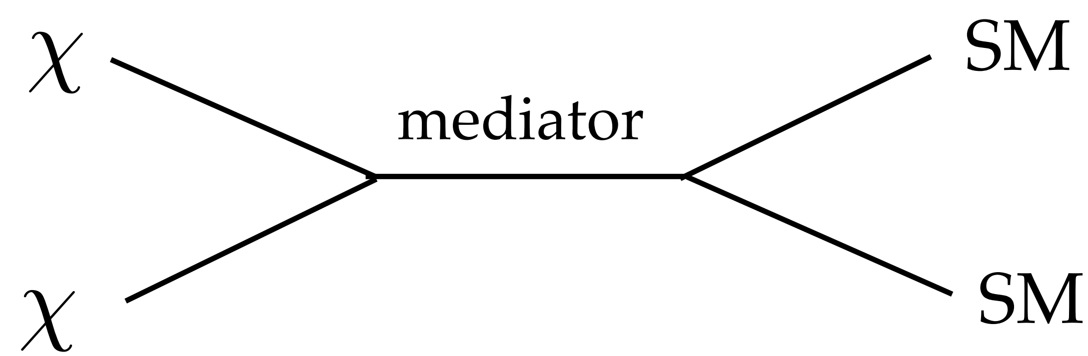


Predictive!

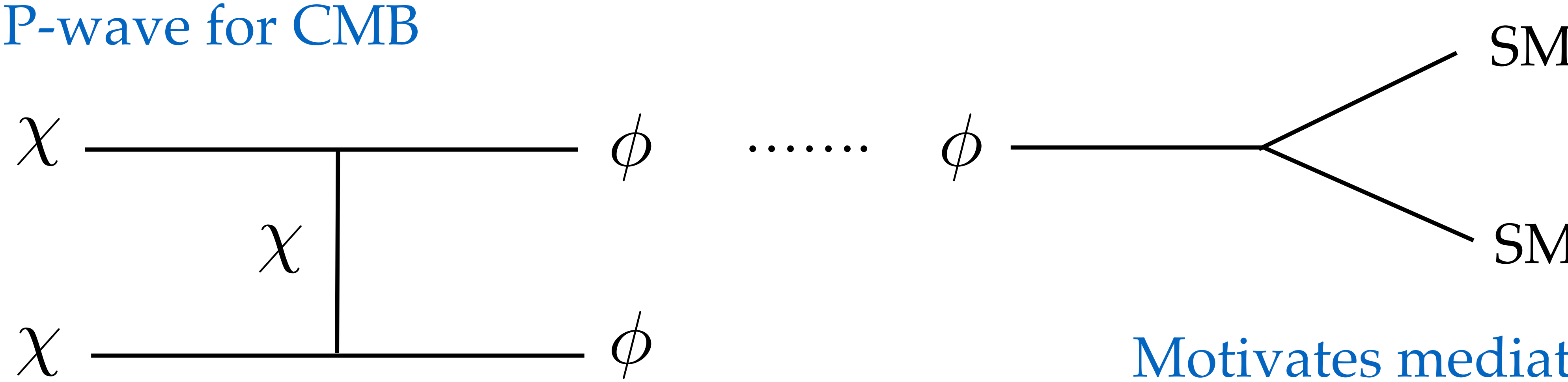
Relic abundance set by mediator coupling to SM

Hidden Annihilation to Mediator

"Secluded" DM $(m_\chi > m_\phi)$

Pospelov, Ritz, Voloshin 0711.4866

P-wave for CMB



Motivates mediator searches

Hard to verify production mechanism

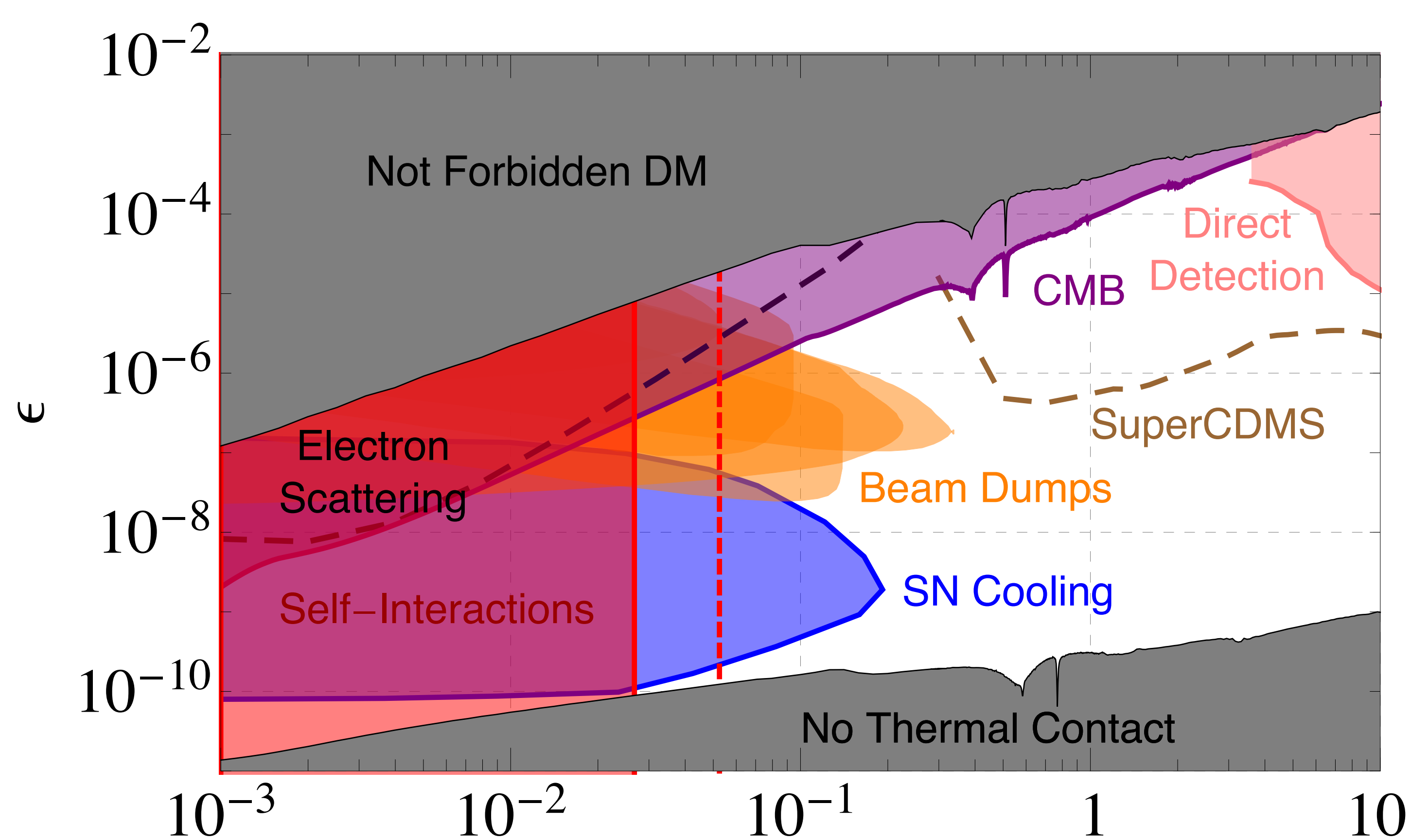
"Forbidden" DM

Annihilation stops after freeze out

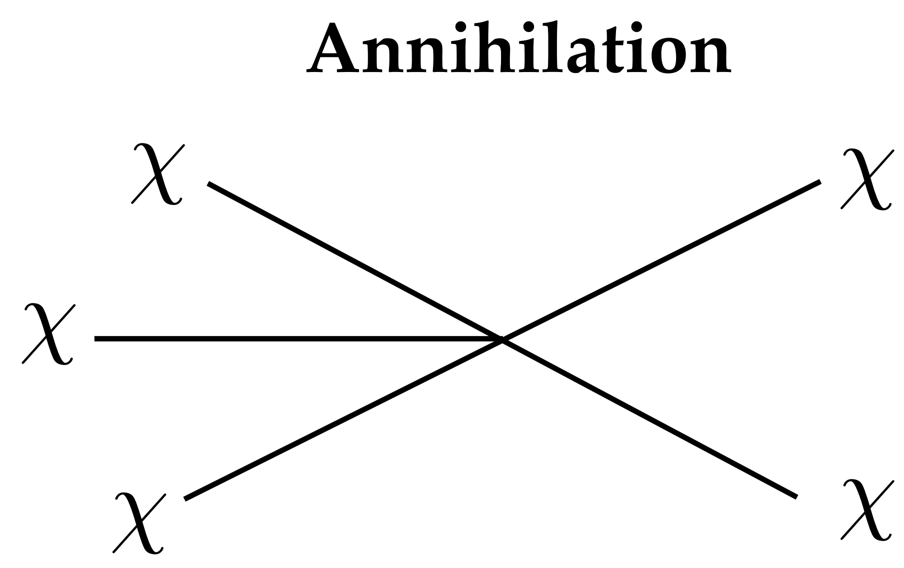
$$(m_\chi < m_\phi)$$

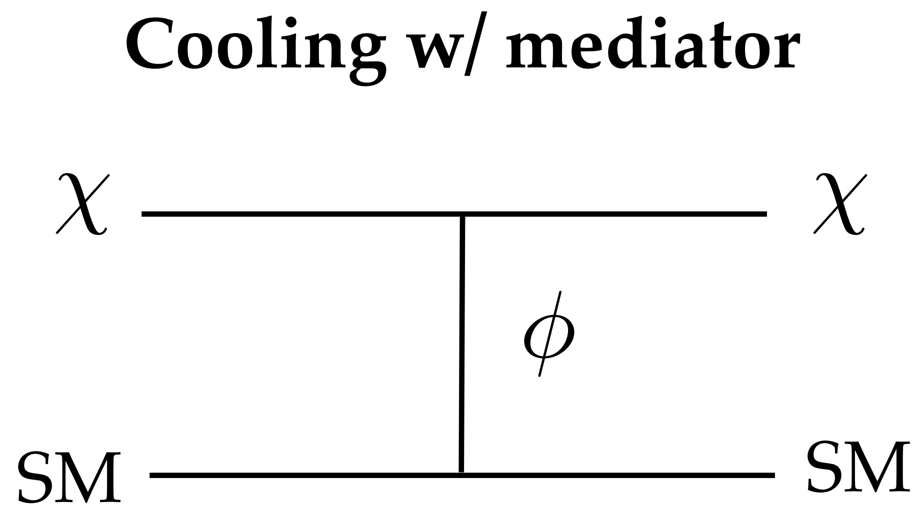
Carlson, Machacek, Hall '92

D'Agnolo, Ruderman 1505.07107



Hidden Annihilation to DM (3+ to 2)





Cannibalization: 3-2 annihilation only (DM hot, ruled out)

Carlson, Machacek, Hall '92

SIMP: 3-2 freeze out, then SM scattering cools DM

Hochberg Kuflik Volansky Wacker 1402.5143

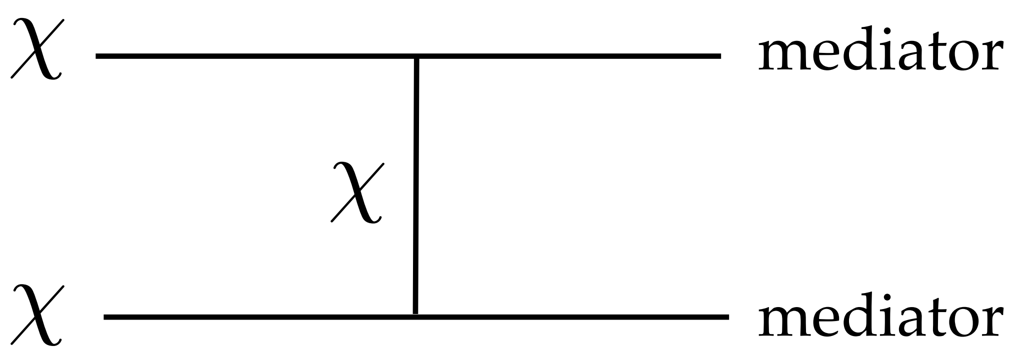
ELDER: SM-DM scattering decouples first, 3-2 freeze out later

Kuflik Prelstein Rey-Le Lorier, Tsai 1512.04545

Hidden vs. Direct Annihilation

Annihilation to Dark Sector

DM transfers entropy indirectly



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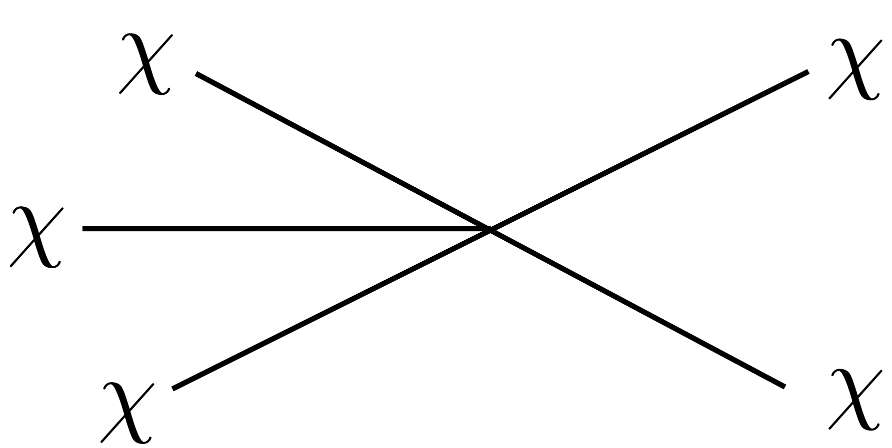

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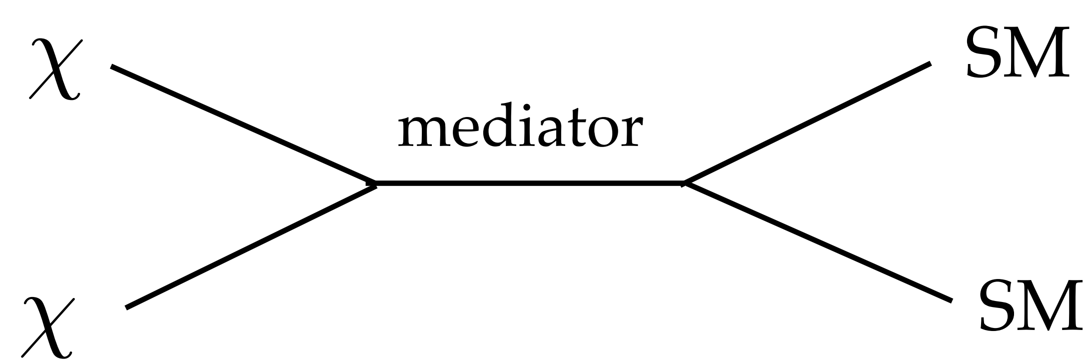
Entropy transfer from annihilation



Predictive!

Relic abundance set by mediator coupling to SM

Direct Annihilation: Which Mediator?

Light neutral particle coupled to both DM & SM

Fermion-neutrino mixing $H L N$

Scalar-Higgs mixing $H^\dagger H \phi$

Vector-photon mixing $F^{\mu\nu} F'_{\mu\nu}$

Vector mediates new force $J^{\mu}_{\rm SM} V_\mu$

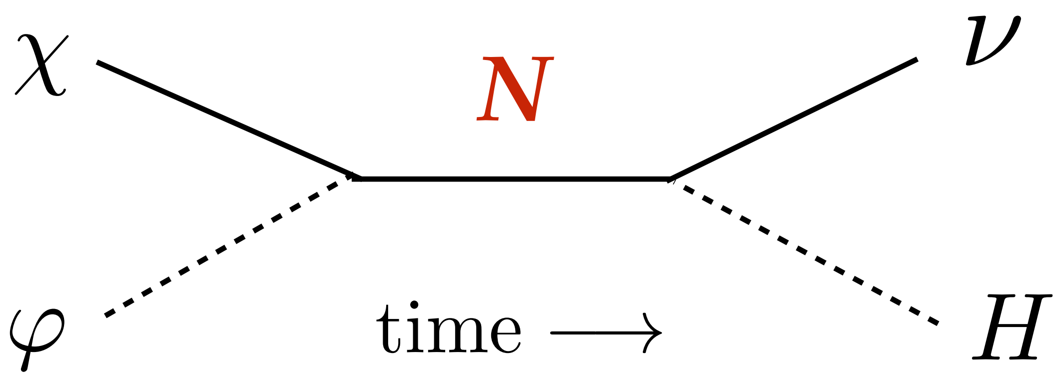
Direct Annihilation: Lepton Portal? HLN

1) If *N* is the DM, it must be non thermal Dodelson & Widrow ‘92

Direct Annihilation: Lepton Portal? HLN

1) If *N* is the DM, it must be non thermal **Dodelson & Widrow '92**

2) If *N* is the mediator for direct annihilation

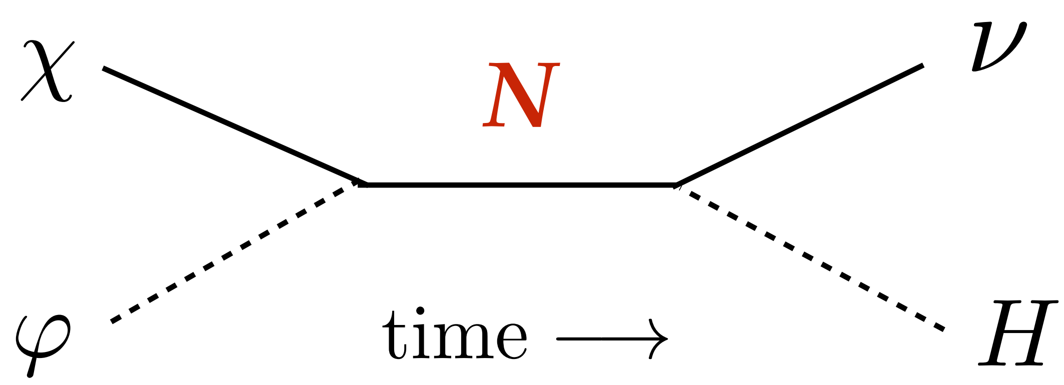


DM must be heavy

Direct Annihilation: Lepton Portal? HLN

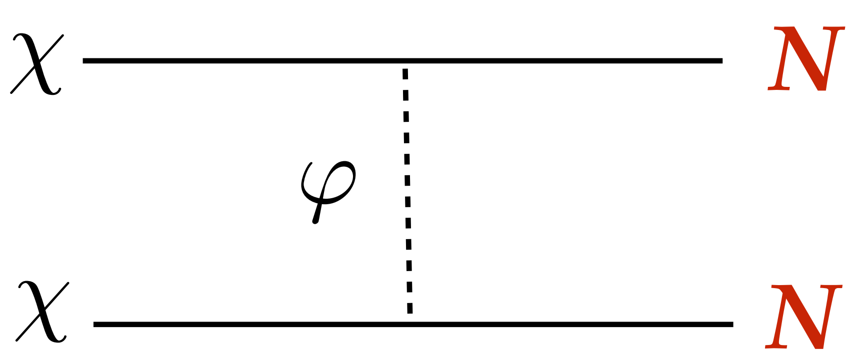
1) If *N* is the DM, it must be non thermal Dodelson & Widrow '92

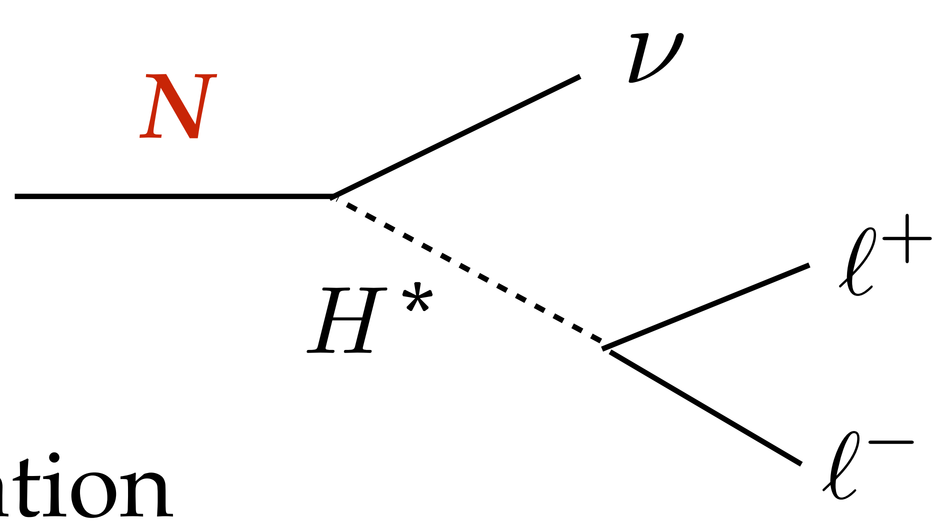
2) If *N* is the mediator for direct annihilation



DM must be heavy

3) If DM annihilates to light *N* (e.g. low scale see-saw)

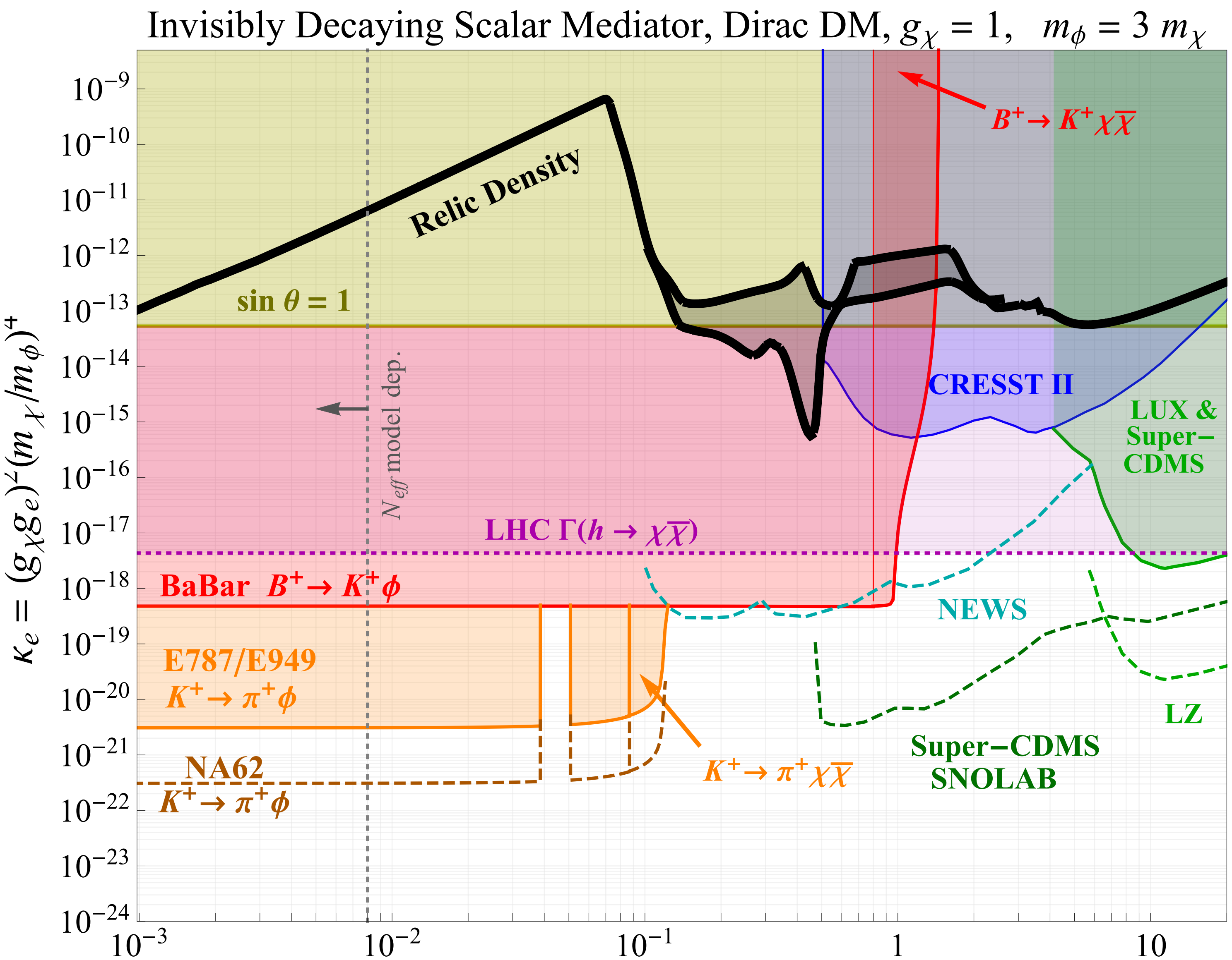


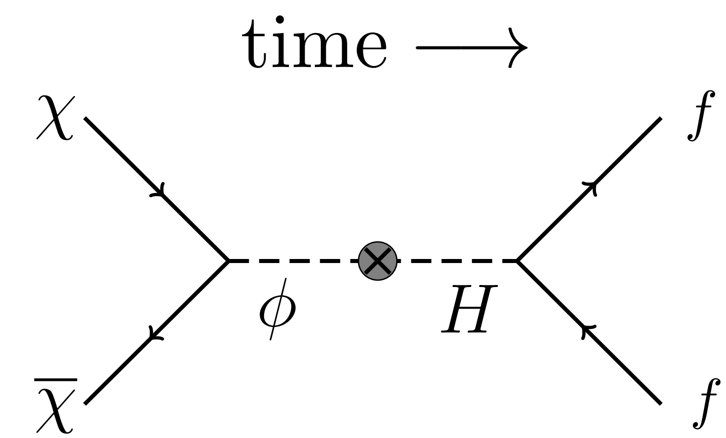


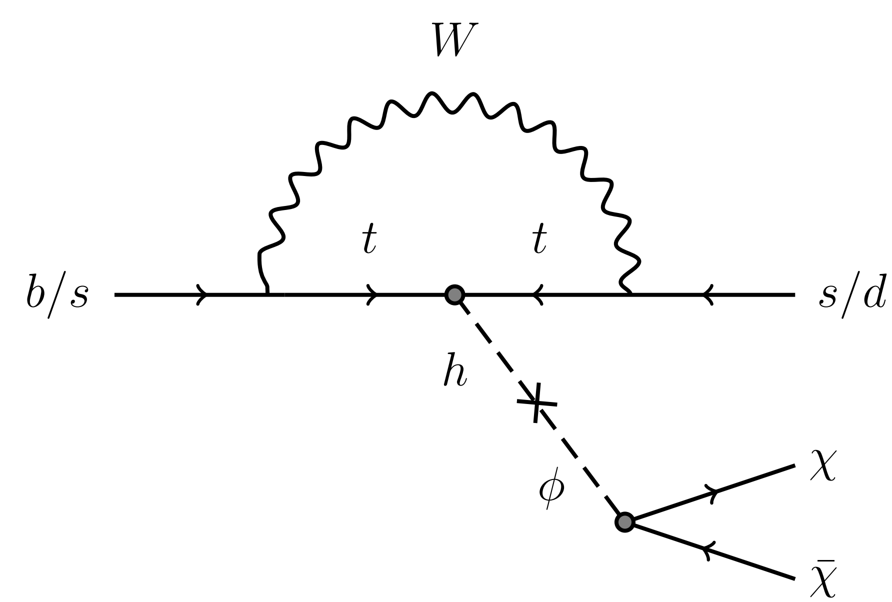
Morally similar to hidden annihilation

Must explain neutrino masses, DM stability etc.

Direct Annihilation: Higgs Portal? $H^\dagger H \phi$







Higgs portal **ruled out**
Independently of DM assumption

GK, 1512.04119

Direct Annihilation:Which Mediator?

Light neutral particle coupled to both DM & SM

~~Fermion-neutrino mixing~~ ~~HLN~~

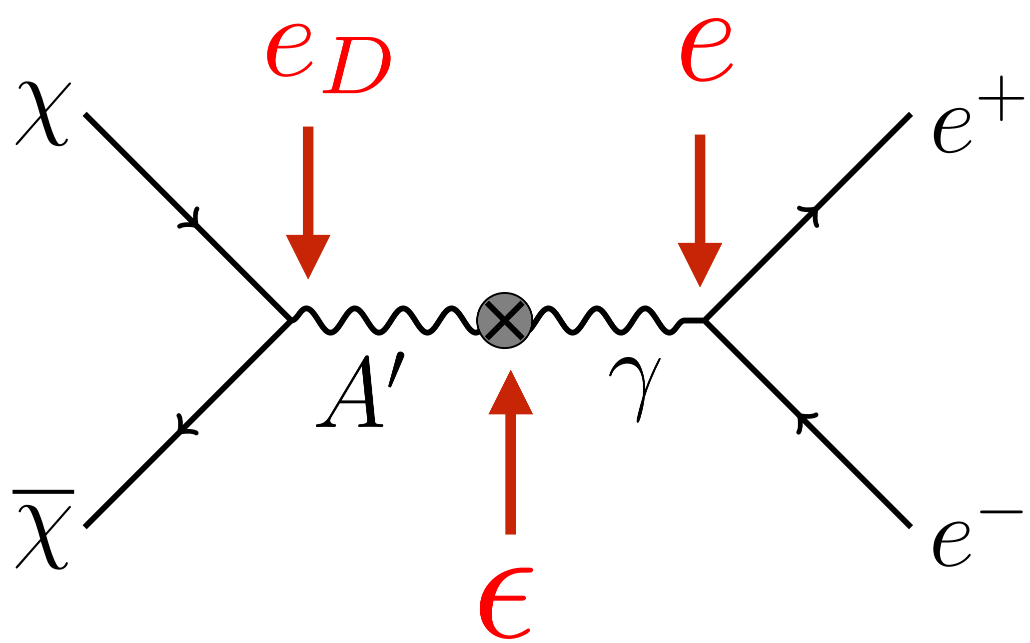
~~Scalar Higgs mixing~~ ~~$H^\dagger H \phi$~~

Vector-photon mixing $F^{\mu\nu} F'_{\mu\nu}$

Vector mediates new force $J^{\mu}_{\rm SM} V_{\mu}$

Representative Model: Dark QED

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



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

DM charged under new force: $e_D \sim e$

Allowed small A'-photon mixing: $\epsilon \ll 1$

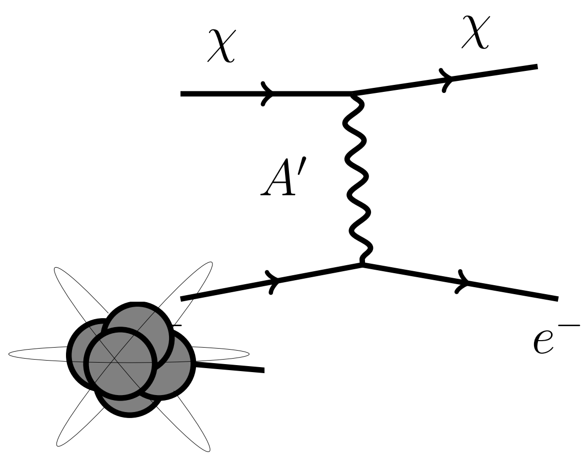
SM acquires small charge under A': $e\epsilon$

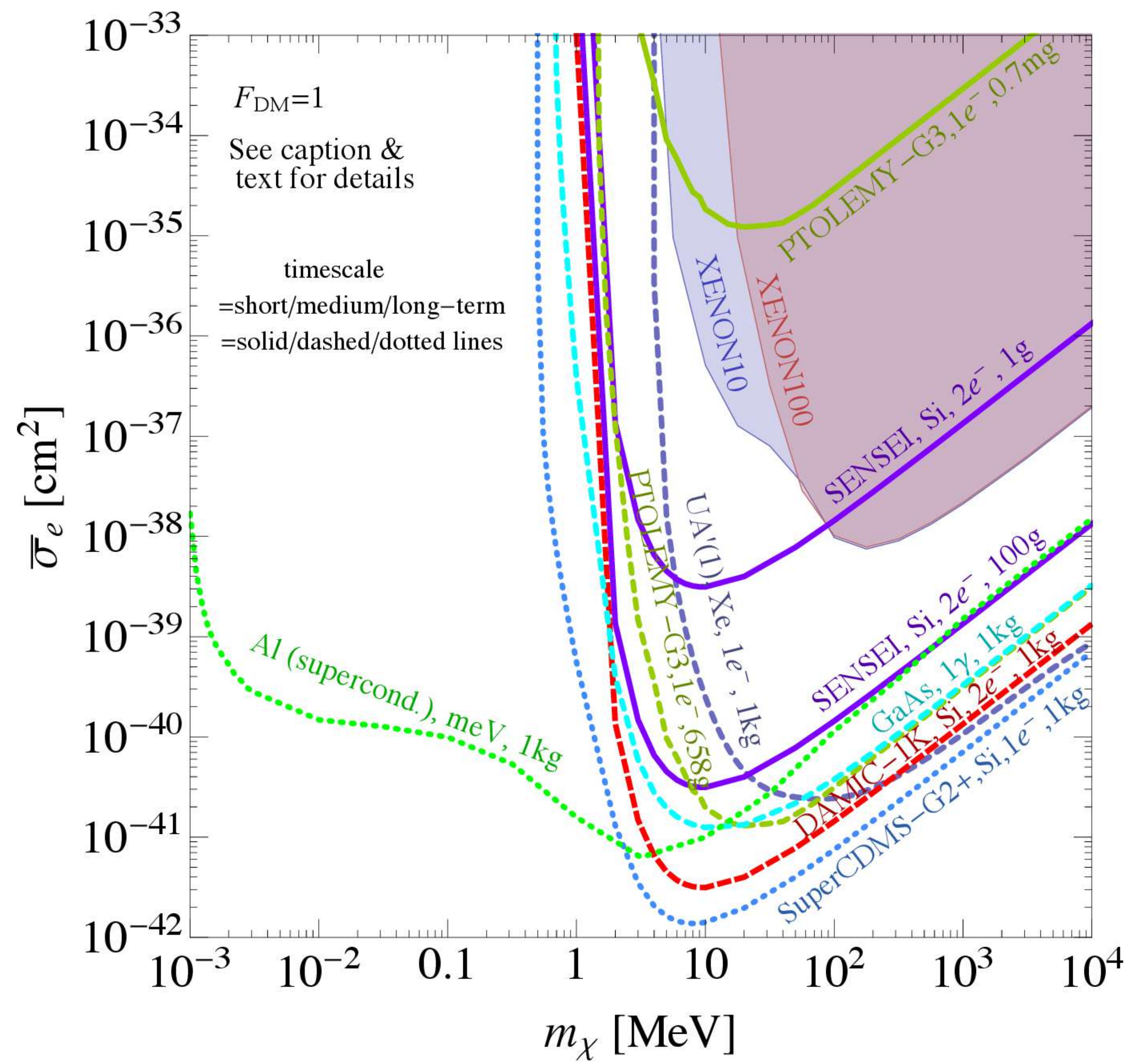
Not the only model, but qualitatively similar to all viable choices

Emerging DD Revolution

DM scatter off atomic electrons

Essig Mardon Volansky 1108.5383





Also semiconductor electrons

Essig, Fernandez-Serra, Mardon, Soto.Volansky,Yu 1509.01598

Superconductor Cooper pairs

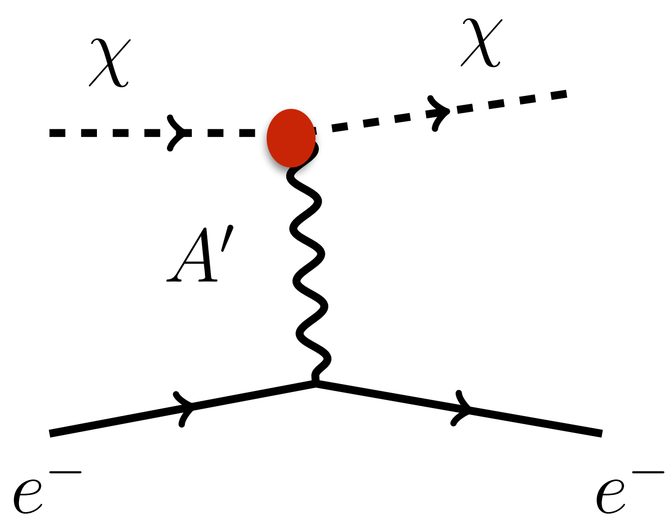
Hochberg, Zhao, Zurek 1504.07237

Cosmic Visions Report 1707.04591

See A. Manasalay's Talk

Classify Viable Models by DD Scattering

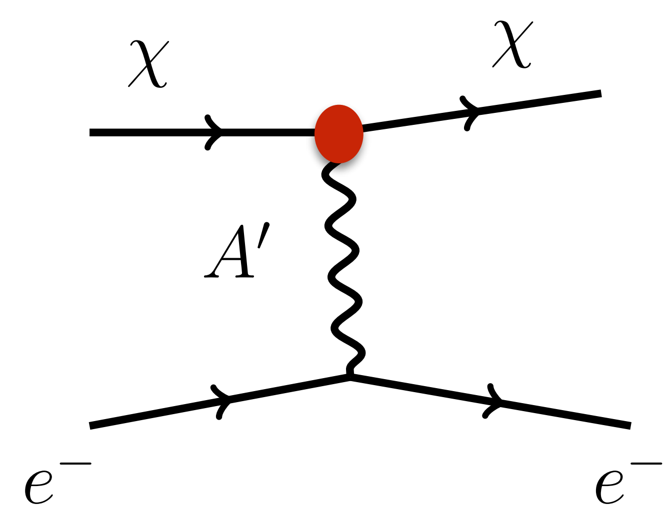
Scalar DM



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

$$\sigma_e \sim 10^{-39} \mathrm{cm}^2$$

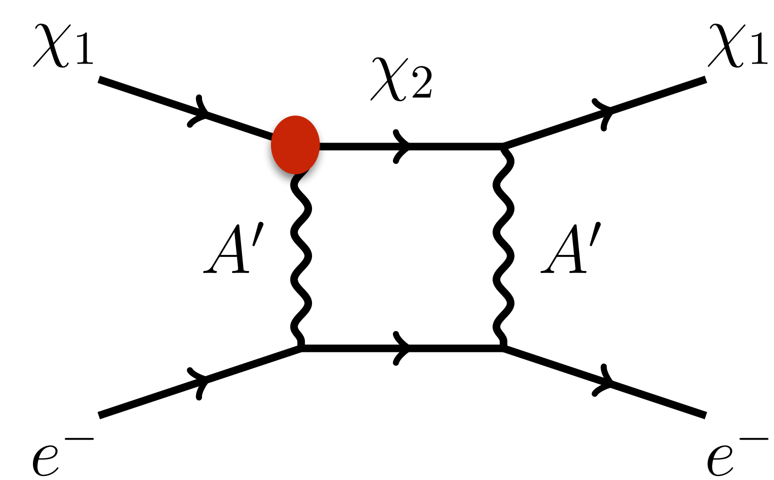
Majorana DM



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

$$\sigma_e \sim 10^{-39}\, v^2\, \mathrm{cm}^2$$
$$\sim 10^{-45}\, \mathrm{cm}^2$$

Pseudo-Dirac DM inelastic



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

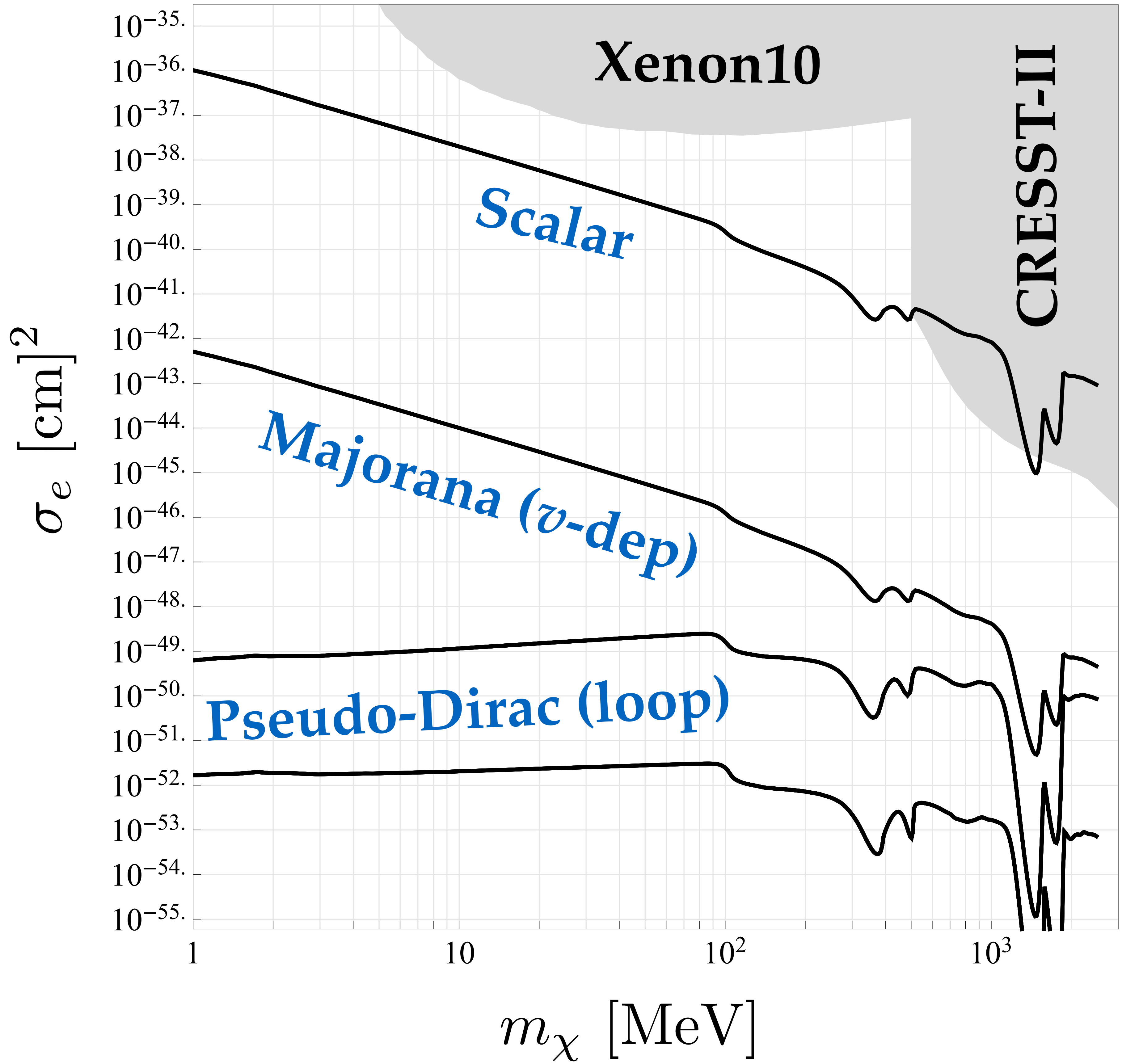
$$\sigma_e \sim 10^{-48}\, \mathrm{cm}^2$$

$$\Delta \equiv m_2 - m_1$$

Very different cross sections despite similarity @ high energy

Each ● interaction can realize thermal annihilation at *T* ~ *M*

Thermal Targets for DD



Natural Variable for Thermal Targets

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

Define new variable optimized for thermal targets

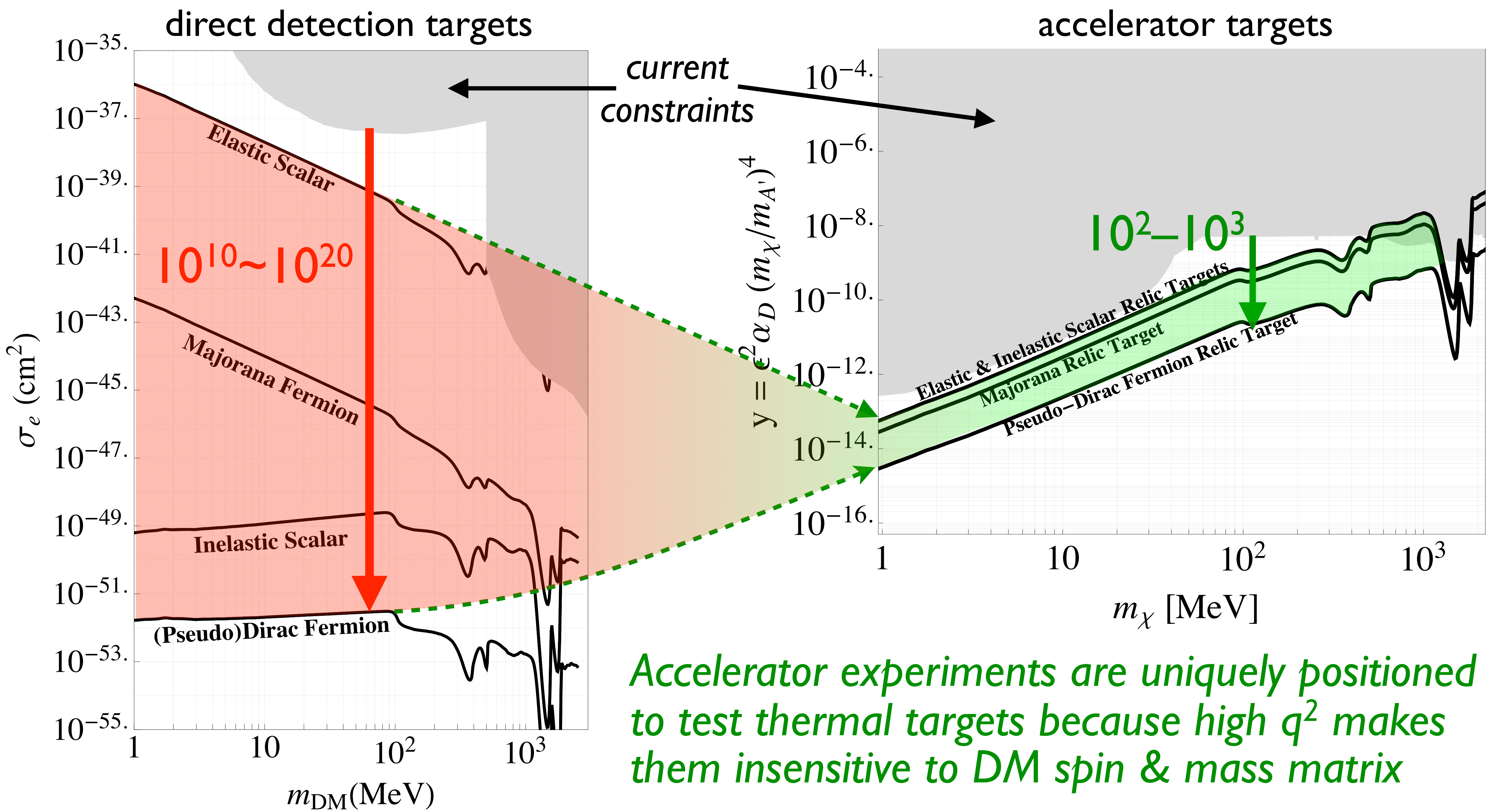
$$\sigma v \propto \alpha_D \epsilon^2 \frac{m_\chi^2}{m_{A'}^4} = \left[\alpha_D \epsilon^2 \left(\frac{m_\chi}{m_{A'}} \right)^4 \right] \frac{1}{m_\chi^2} \equiv \frac{y}{m_\chi^2}$$

Insensitive to ratios of inputs, unique y for given DM mass
up to subleading corrections

NB: not every experiment measures y directly
Important to be conservative in presenting bounds

 Izaguirre, GK, Schuster. Toro 1505.00011

< GeV Thermal Relic Milestones



Accelerator experiments are uniquely positioned to test thermal targets because high q^2 makes them insensitive to DM spin & mass matrix

Slide: Tim Nelson

Overview

- **Historical Perspective**
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- **Light DM (<GeV)**
  Models & Benchmarks

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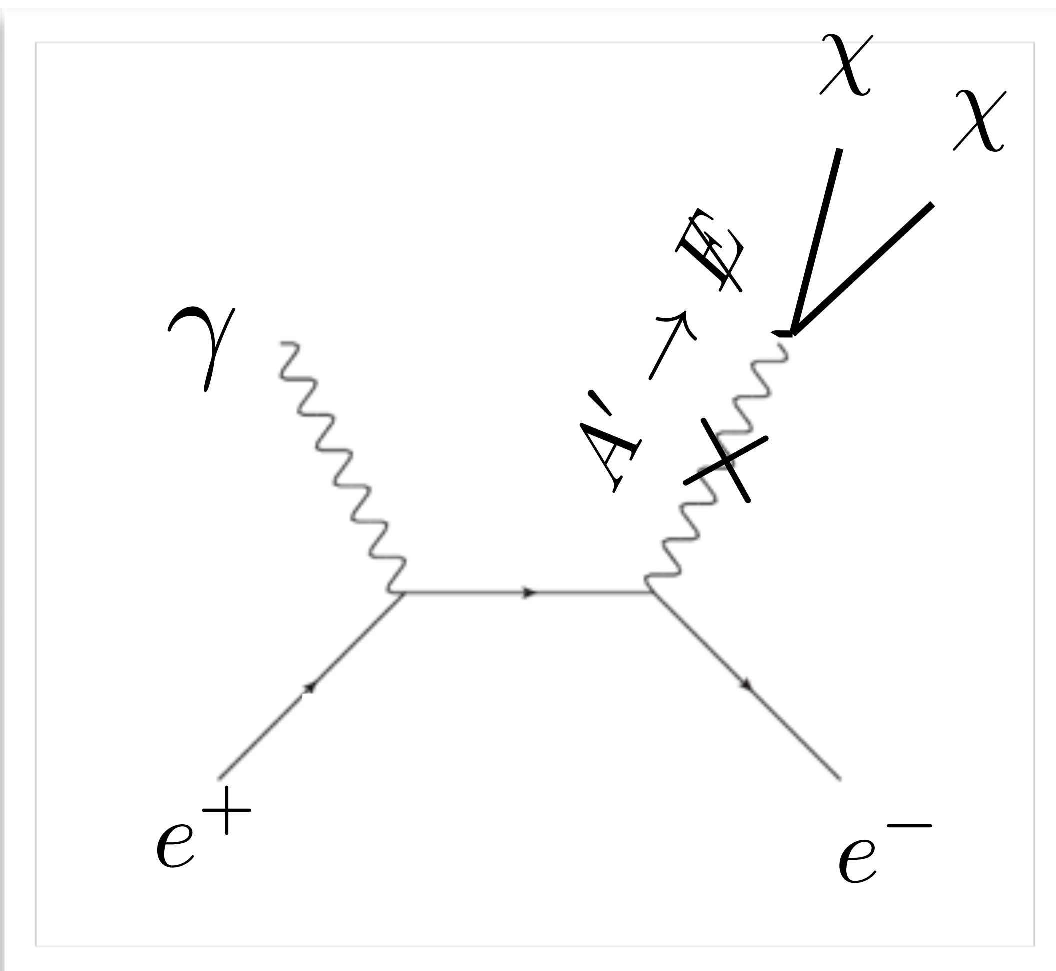
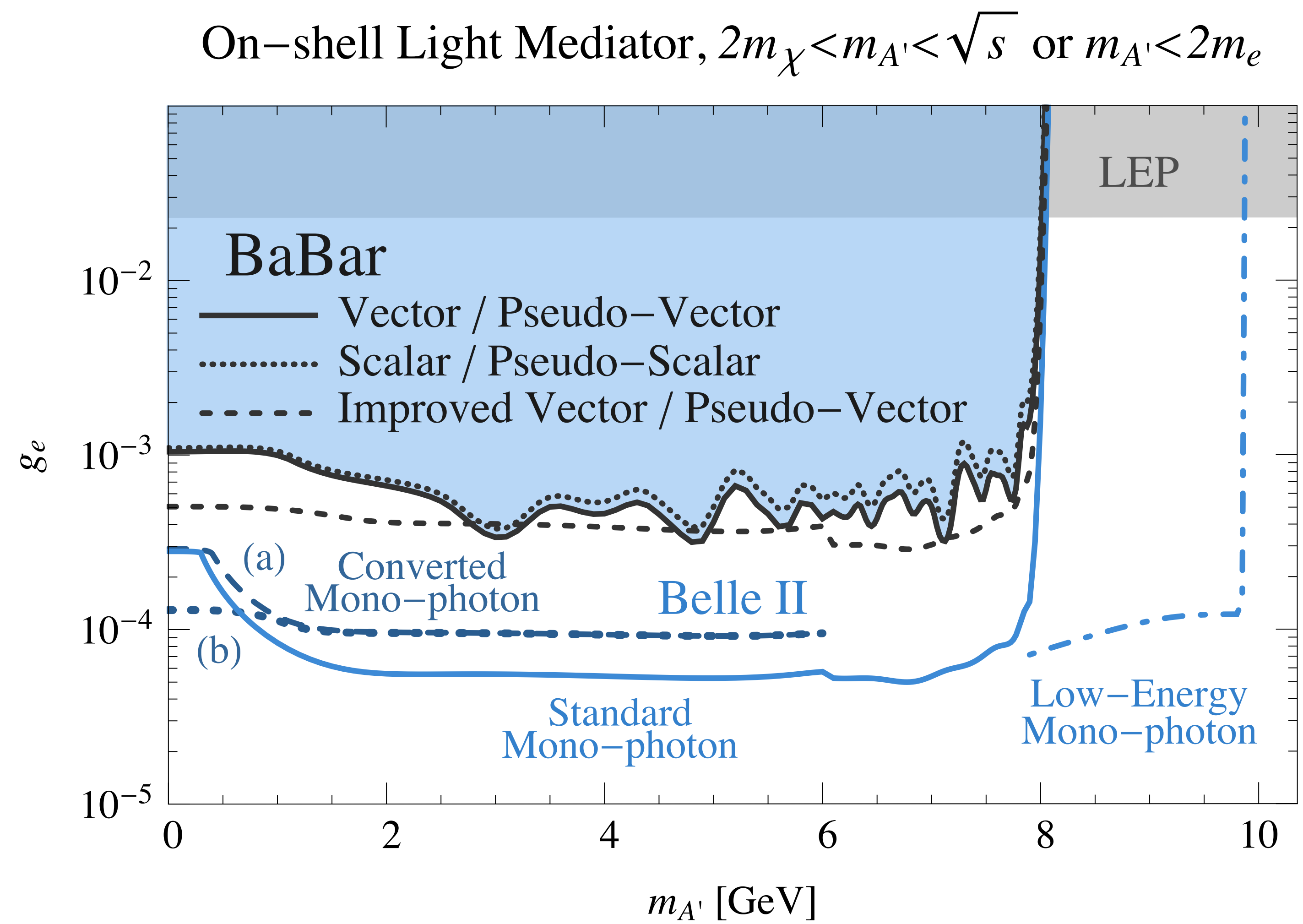
  B-factories & Fixed Targets

Signatures @ B-Factories

mono photon + missing energy





Can explore/test Scalar, Majorana, & pseudo-Dirac DM

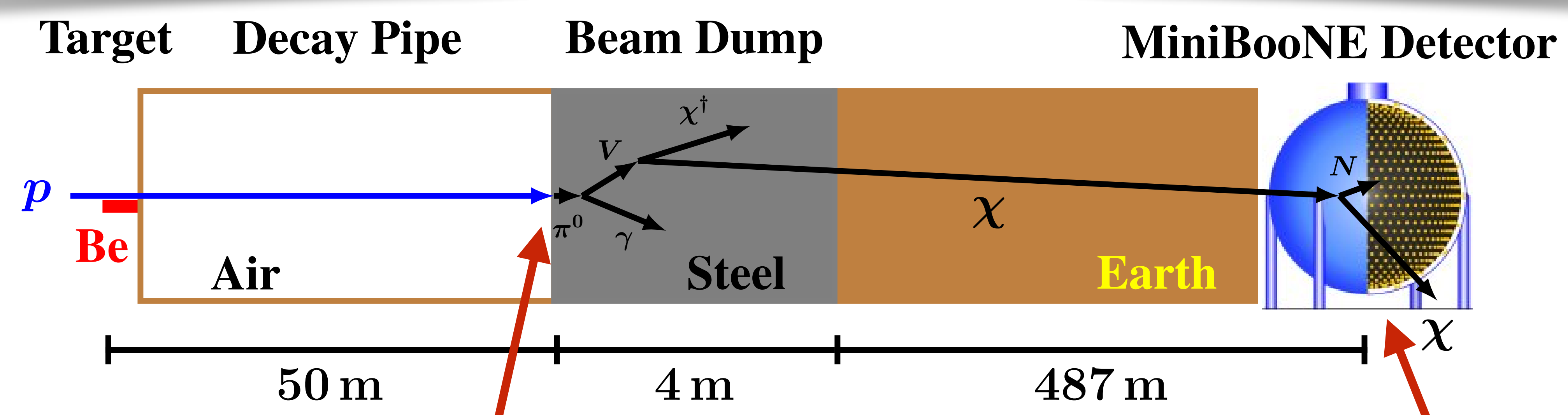
Izaguirre, GK, Schuster, Toro 1307.6554

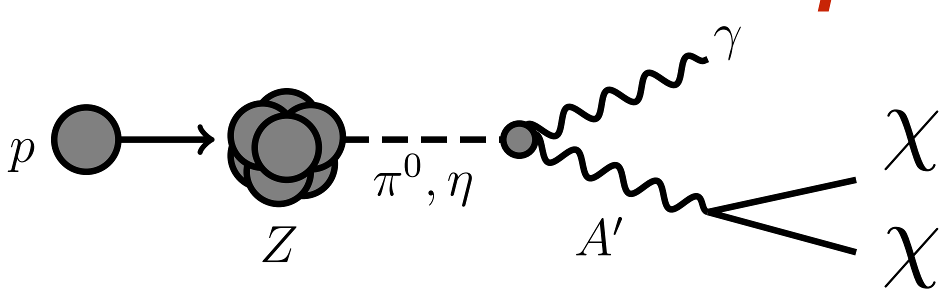
Essig, Mardon, Papucci, Volansky Zhong 1309.5084

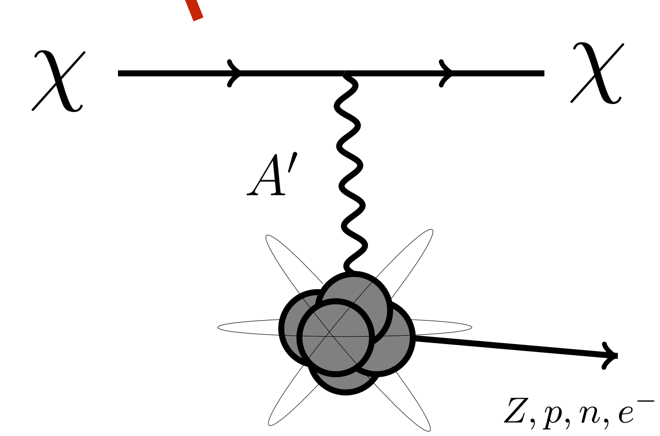
See David Hitlin's slides!

Signatures @ Proton Beam Dumps

1. (quasi)elastic scattering







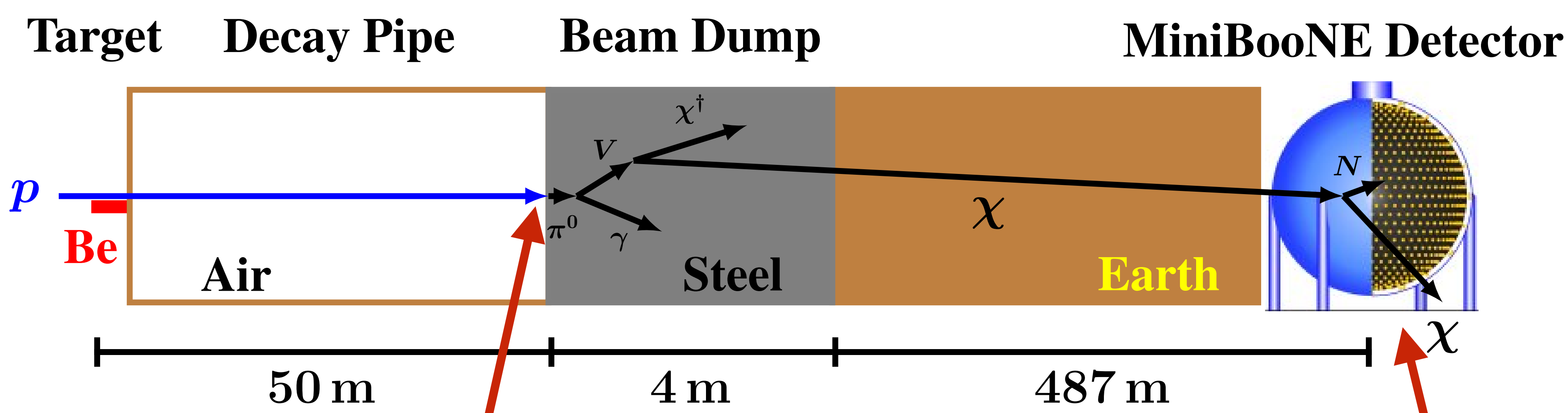
LSND,MiniBooNE, SeaQuest, COHERENT
NOvA, DUNE, SHiP, SBND

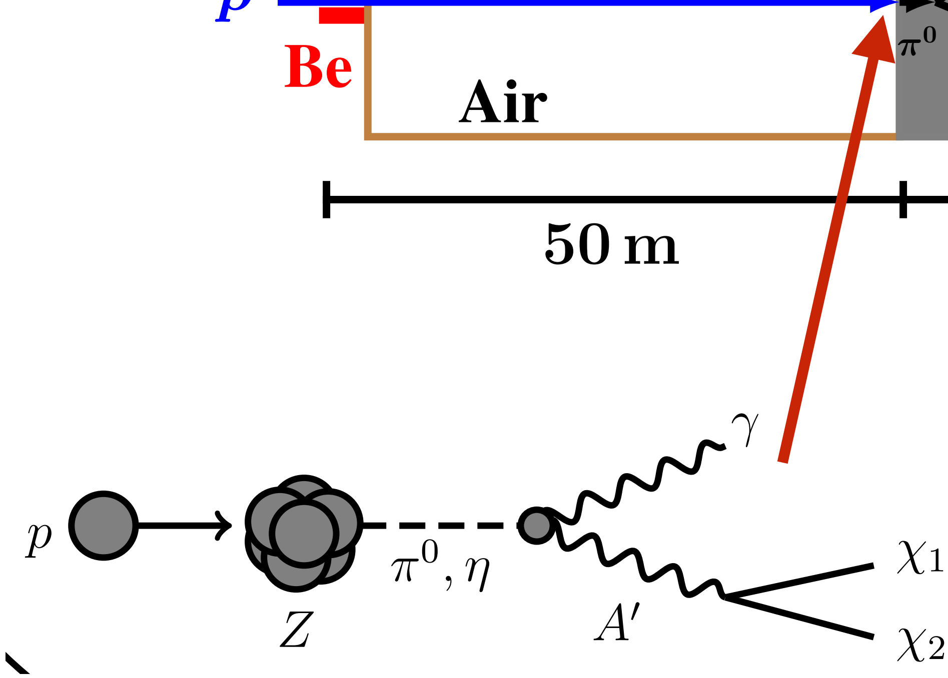
Scalar
Majorana
pseudo-Dirac DM

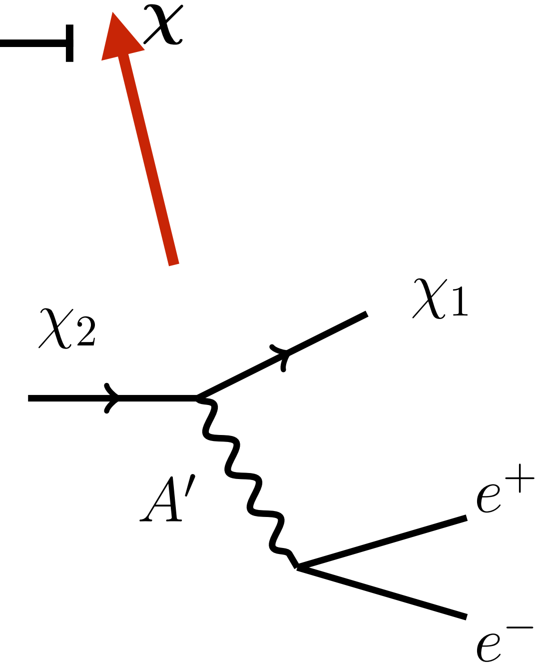
Batell, Pospelov, Ritz 0903.0363
deNiverville, Pospelov, Ritz 1107.4580
Batell, deNiverville, McKeen, Pospelov, Ritz 1405.7049
Coloma, Dobrescu, Frugiuele, Harnik 1512.03852

Signatures @ Proton Beam Dumps

2. inelastic scattering & decays







$$\Delta \equiv m_2 - m_1$$

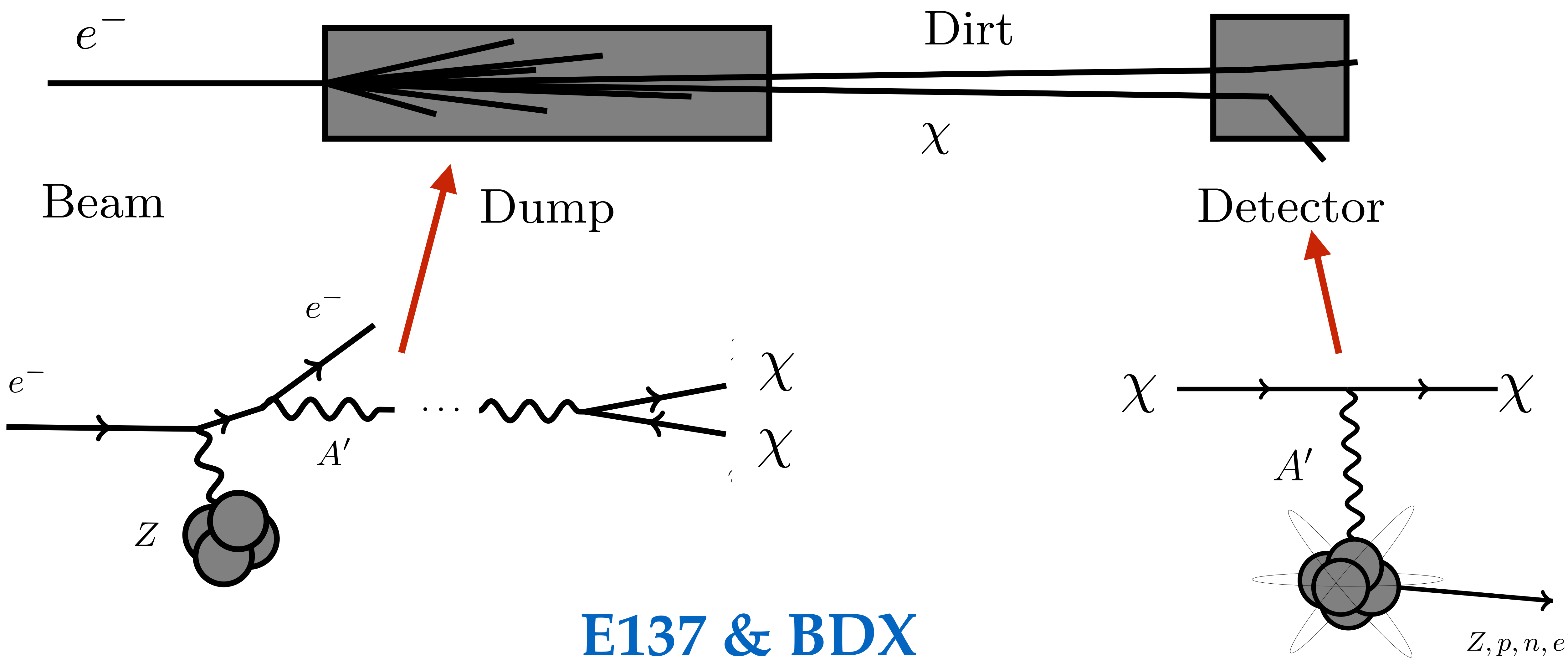
LSND,MiniBooNE, SeaQuest, COHERENT
NOvA, DUNE, SHiP, SBND

Can explore/test
pseudo-Dirac DM

Morrissey, Spray 1402.4817
Izaguirre, Kahn, GK, Moschella 1703.06881
Berlin, Gori, Schuster, Toro 1703.XXXX

Signatures @ Electron Beam Dumps

1. (quasi) elastic scattering



E137 & BDX

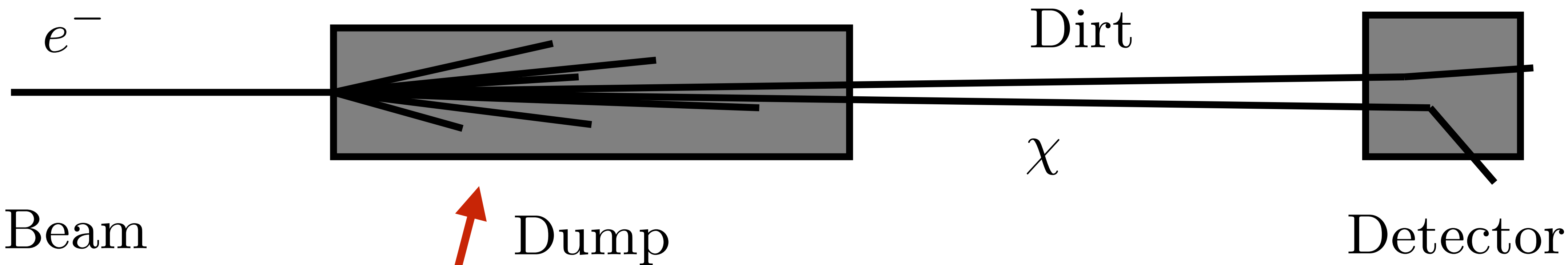
Can explore/test

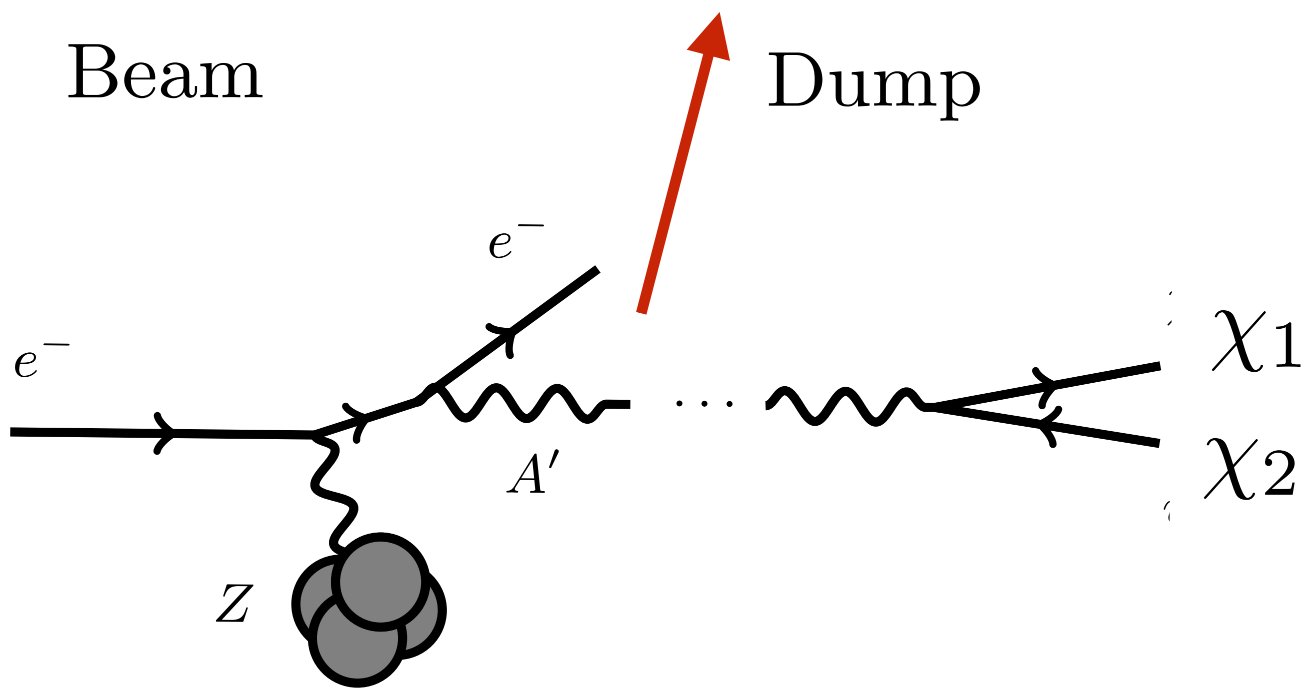
Scalar
Majorana
pseudo-Dirac DM

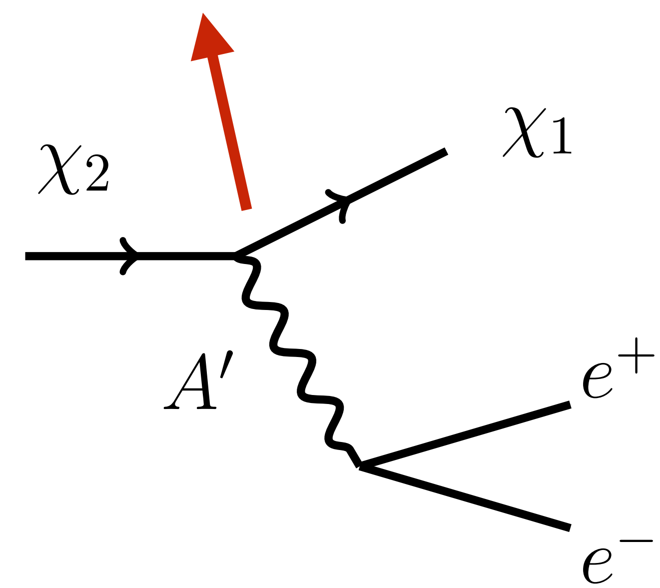
Batell, Essig, Zurjuron 1406.2698
Izaguirre, GK, Schuster, Toro 1307.6554

Signatures @ Electron Beam Dumps

2. inelastic scattering & decay







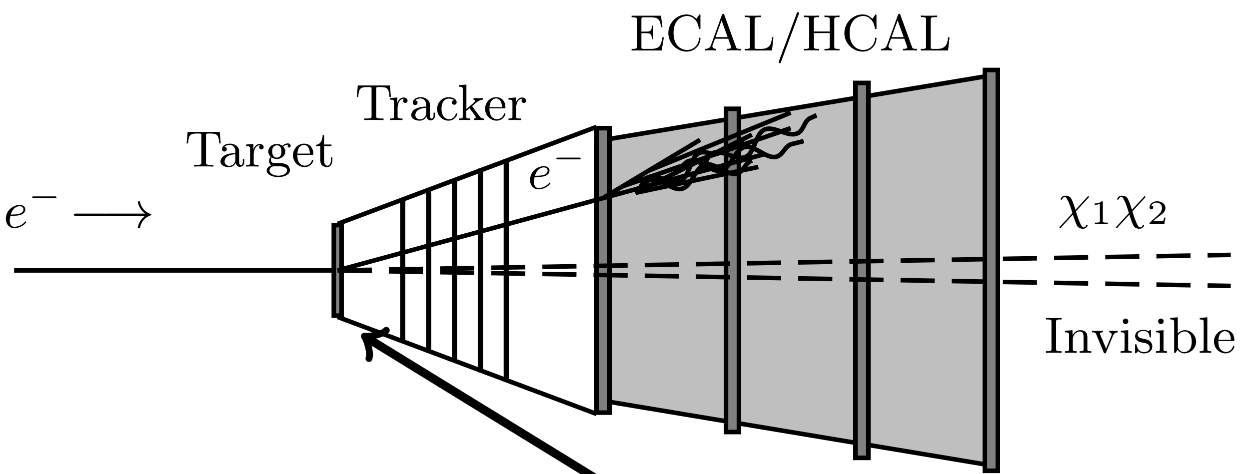
E137 & BDX

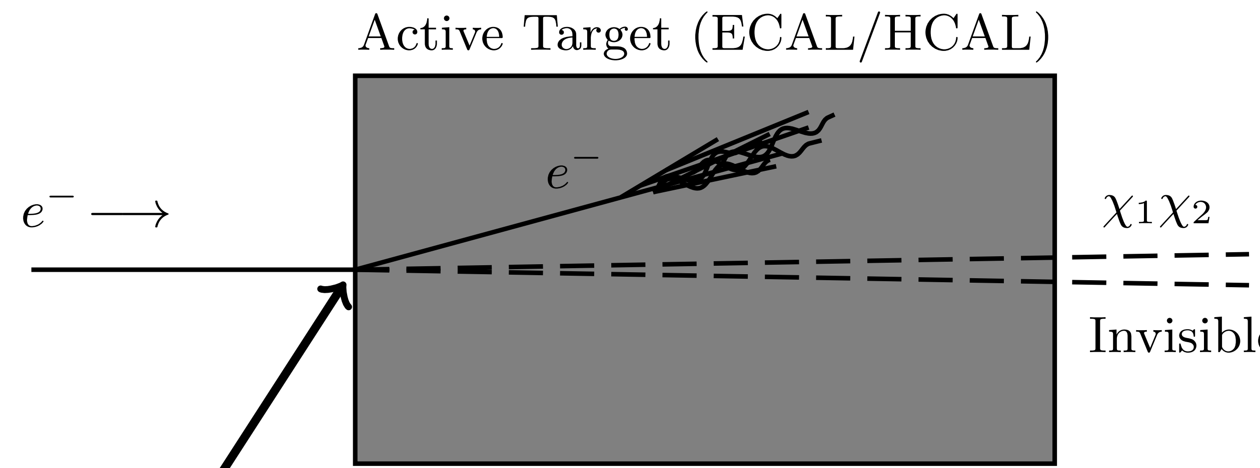
$$\Delta \equiv m_2 - m_1$$

Can explore/test
pseudo-Dirac DM

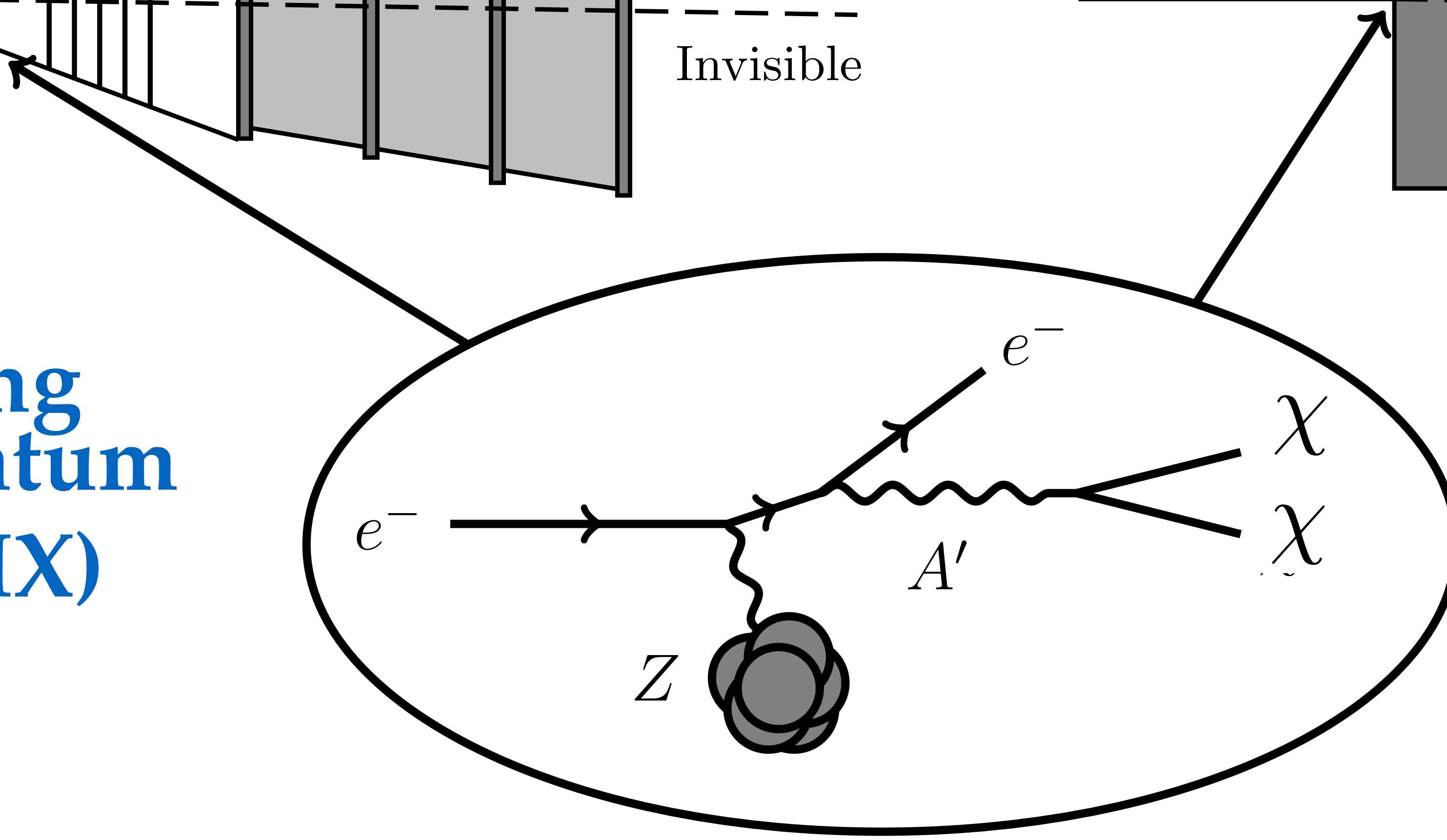
Morrissey, Spray 1402.4817
Izaguirre, Kahn, GK, Moschella 1703.06881

Signatures @ Missing Energy & Momentum Experiments





Missing Momentum (LDMX)

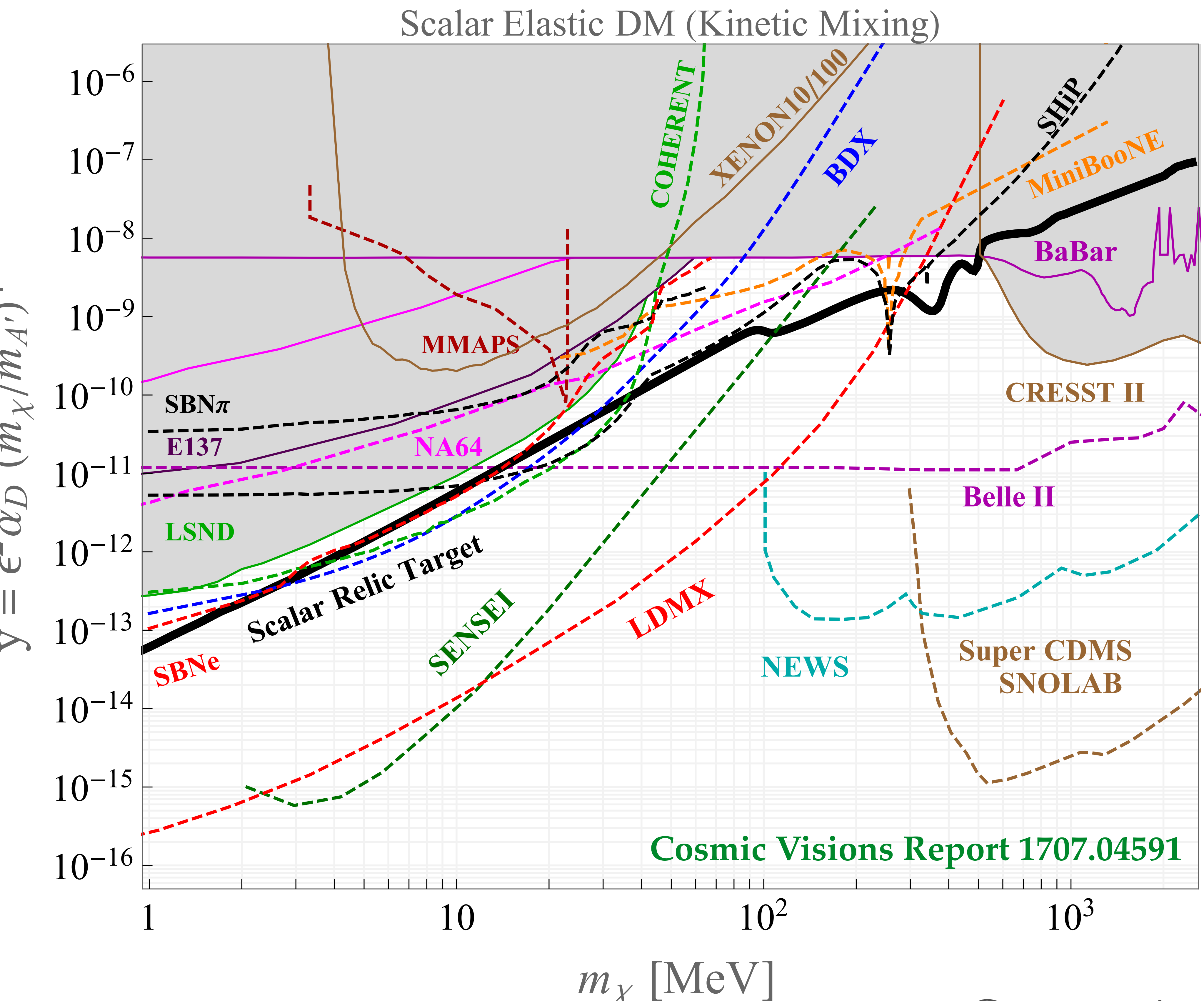


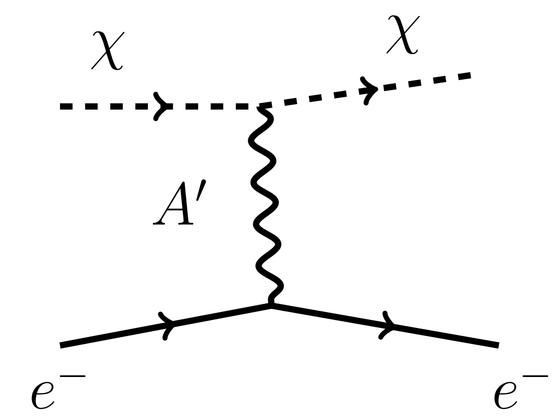
Missing Energy (NA64)

Observe recoiling electron with large missing energy and/or mass

See David Hitlin's slides!

NA64 Collaboration 1610.02988
Izaguirre, GK, Schuster, Toro 1307.6554
LDMX Collaboration 1710.XXXX





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

CMB safe

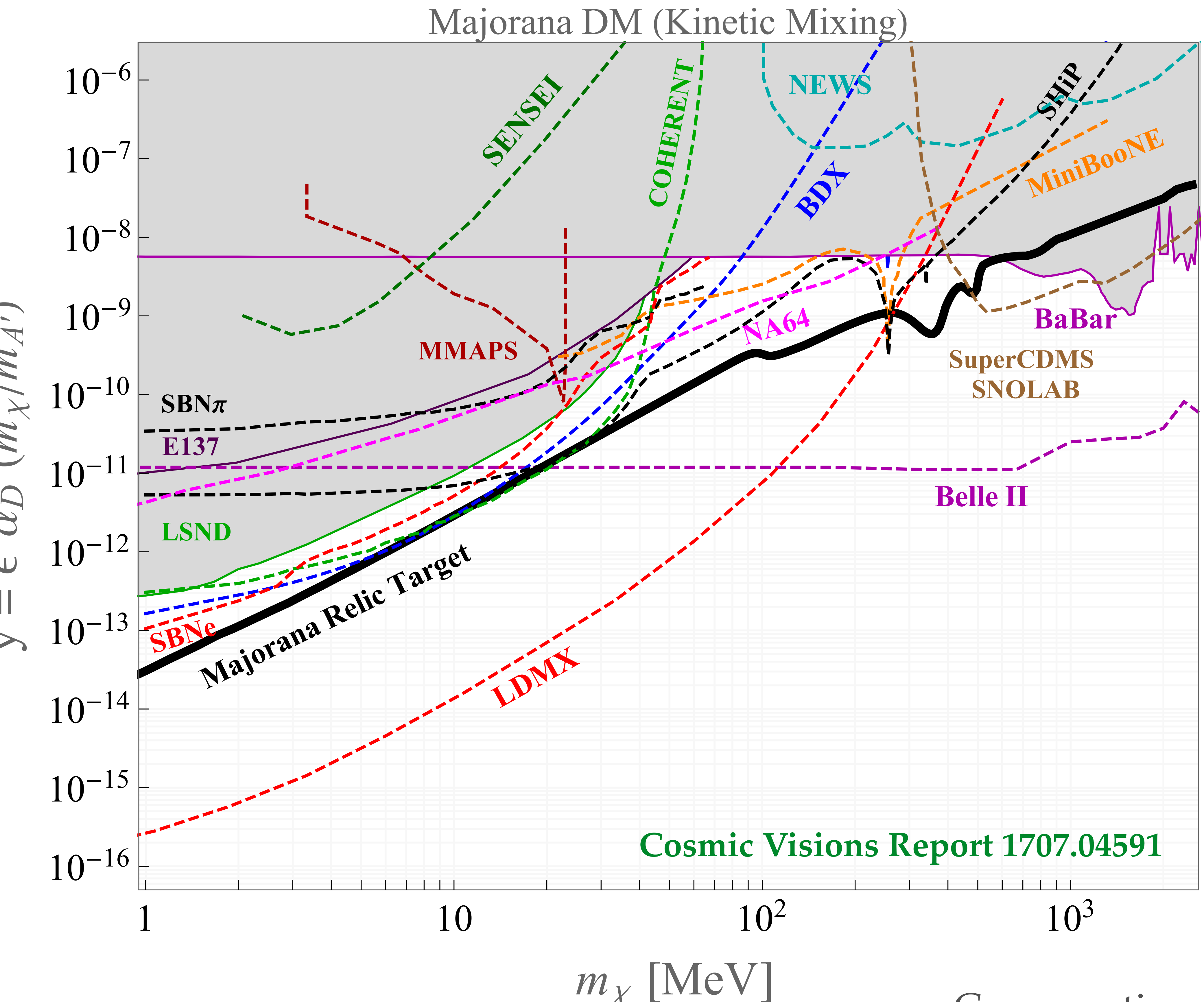
p-wave ann.

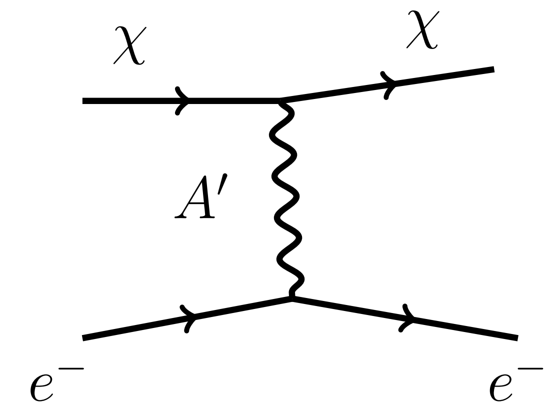
$$\sigma v \propto v^2$$

Conservative where appropriate

$$\alpha_D = 0.5 \; , \; m_{A'} = 3 m_\chi$$

Combination of efforts will crush this!





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

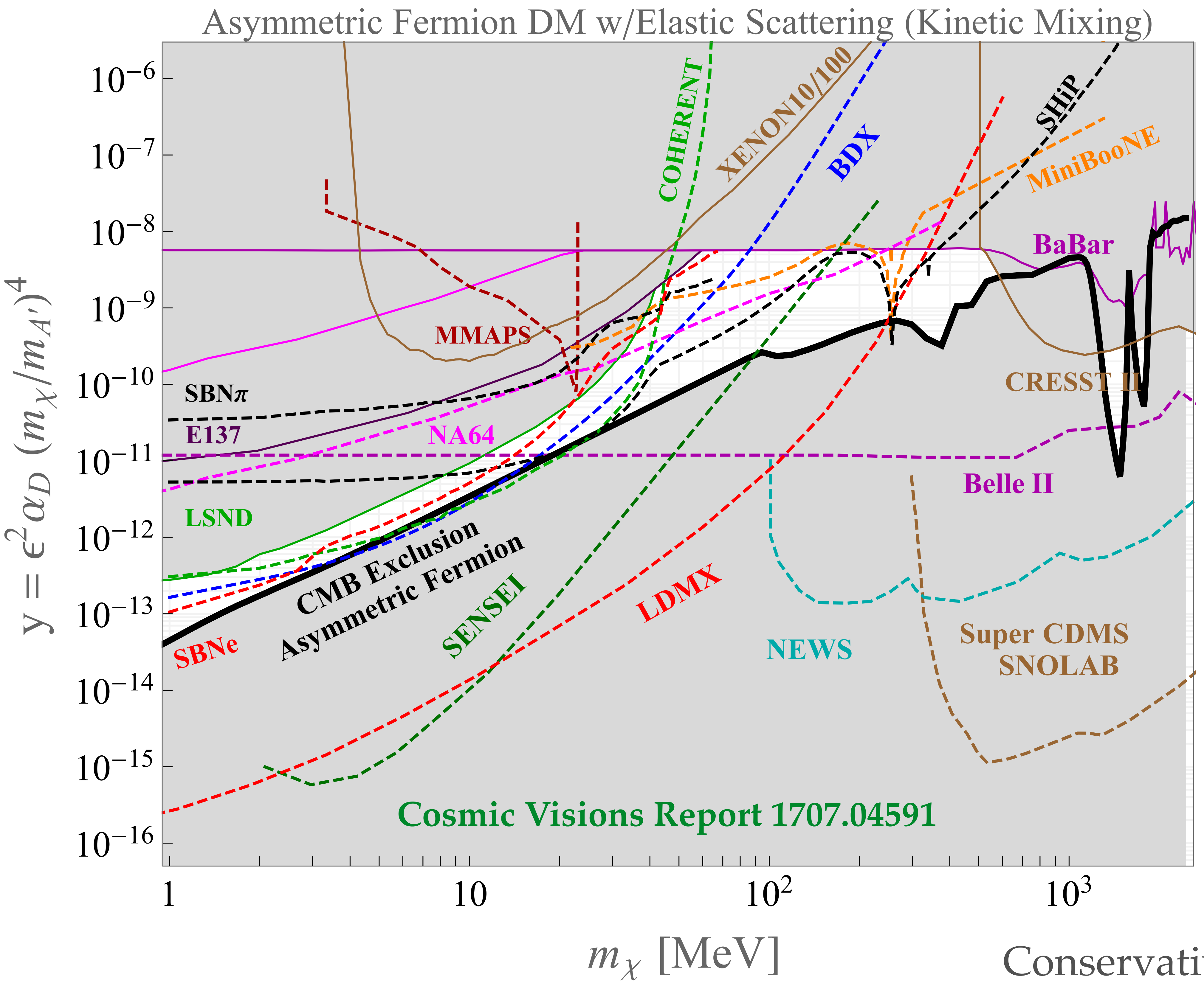
CMB safe

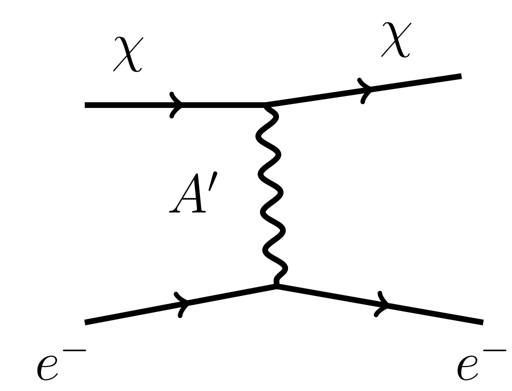
p-wave ann.

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

Conservative where appropriate

$$\alpha_D = 0.5\ ,\ \ m_{A'} = 3 m_\chi$$





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

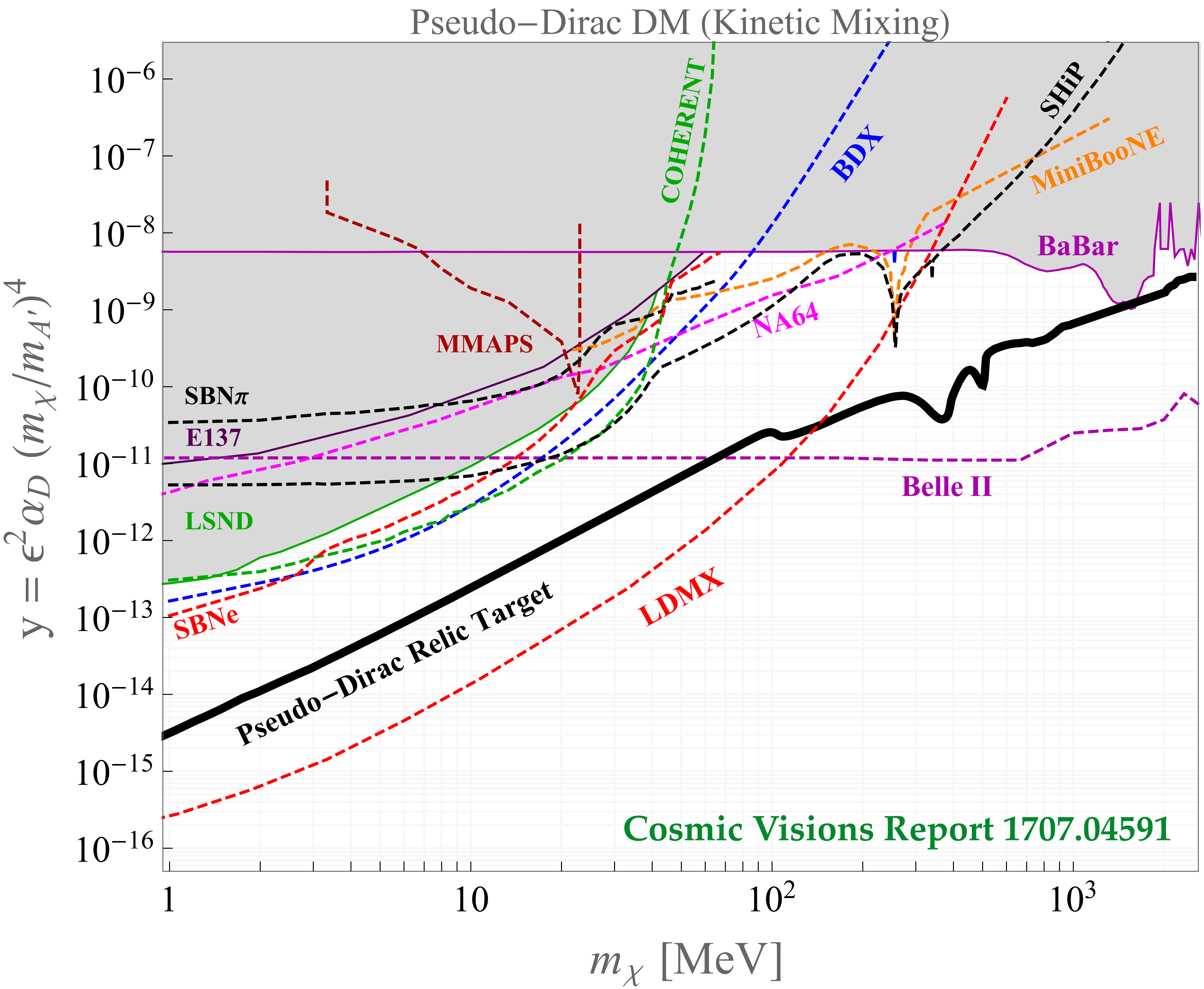
CMB safe

antiparticles are gone by CMB era (no annihilation)

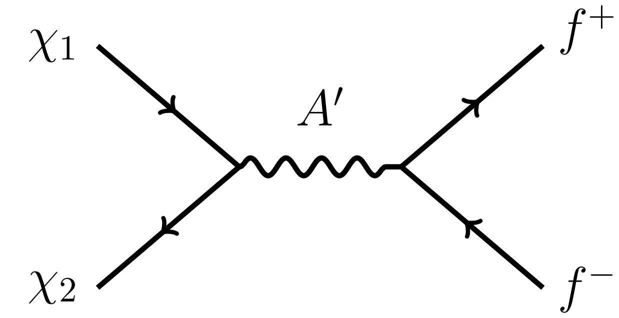
Conservative where appropriate

$$\alpha_D = 0.5\ ,\ \ m_{A'} = 3 m_\chi$$

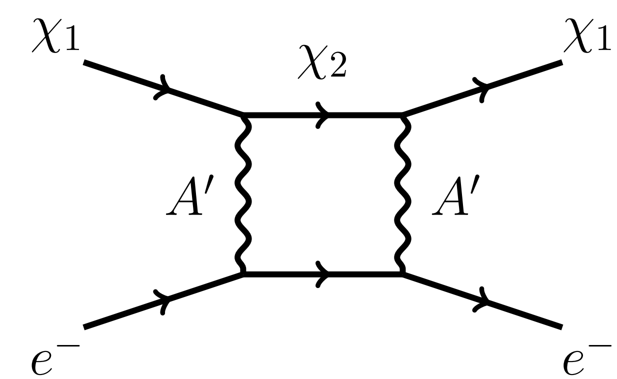
Unlike symmetric relics, unshaded region can viably yield total DM abundance (different asymm)



Annihilation



Direct Detection



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

CMB safe

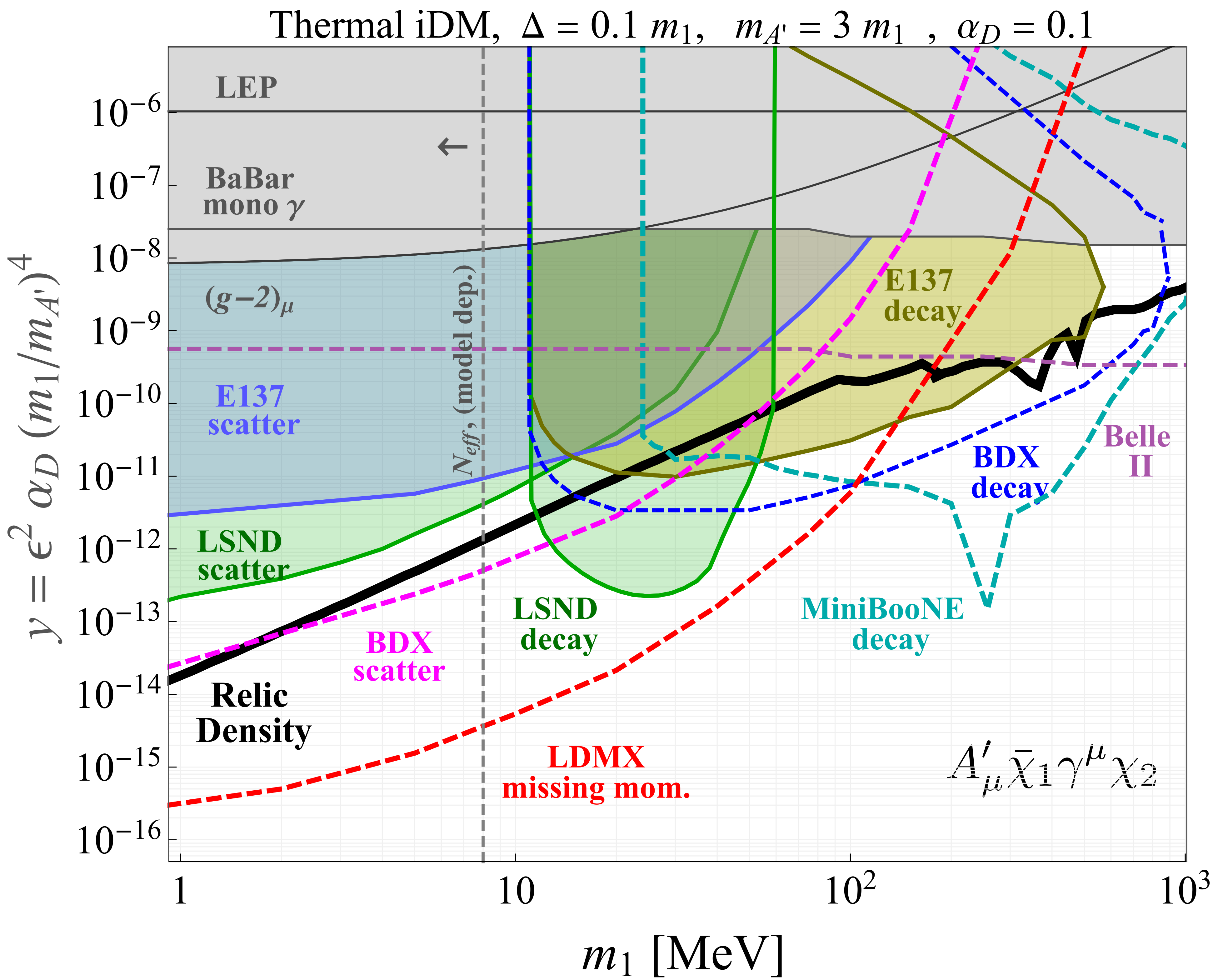
heavier state gone by CMB era (no annihilation)

Small mass splitting

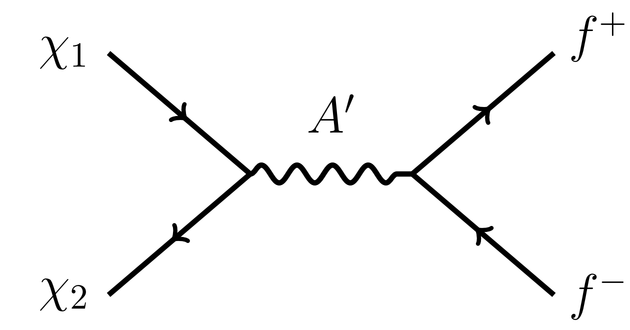
$$\Delta m \ll m_\chi$$

Conservative where appropriate

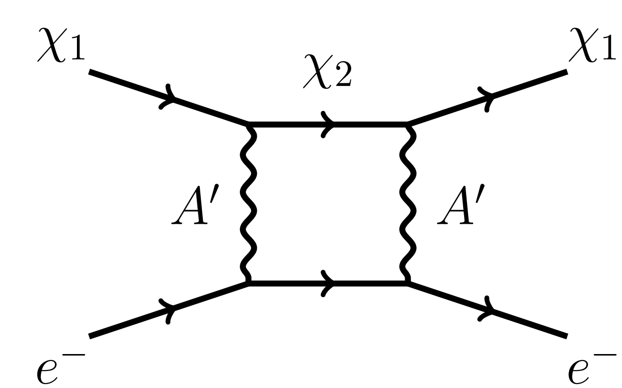
$$\alpha_D = 0.5 \ , \ m_{A'} = 3 m_\chi$$



Annihilation



Direct Detection



CMB safe

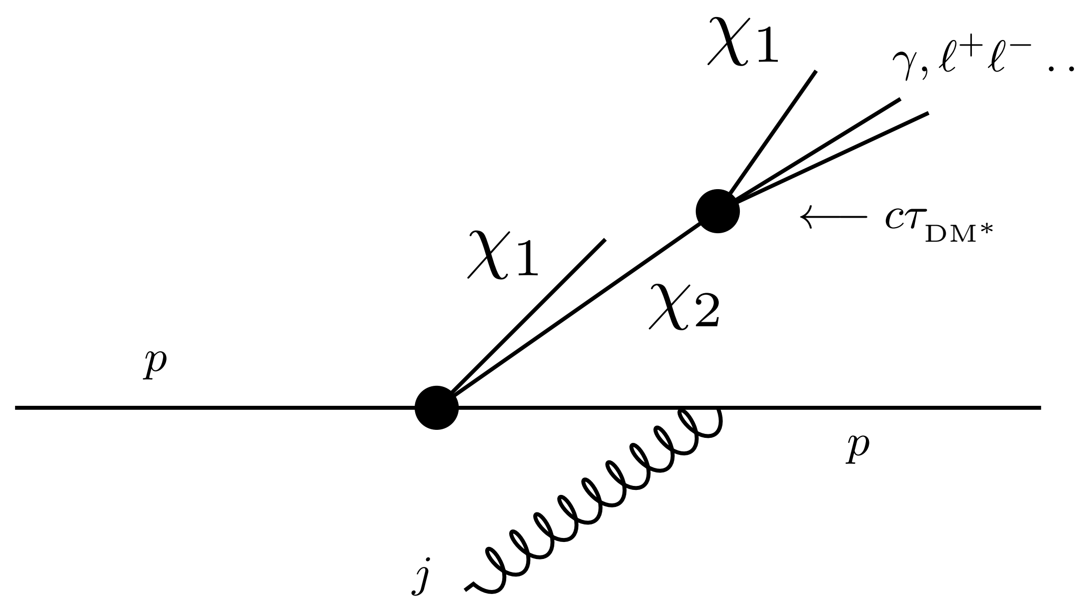
heavier state gone by CMB era (no annihilation)

Pseudo-Dirac DM
Mass Splitting ~ 40%

Pseudo-Dirac @ Colliders?

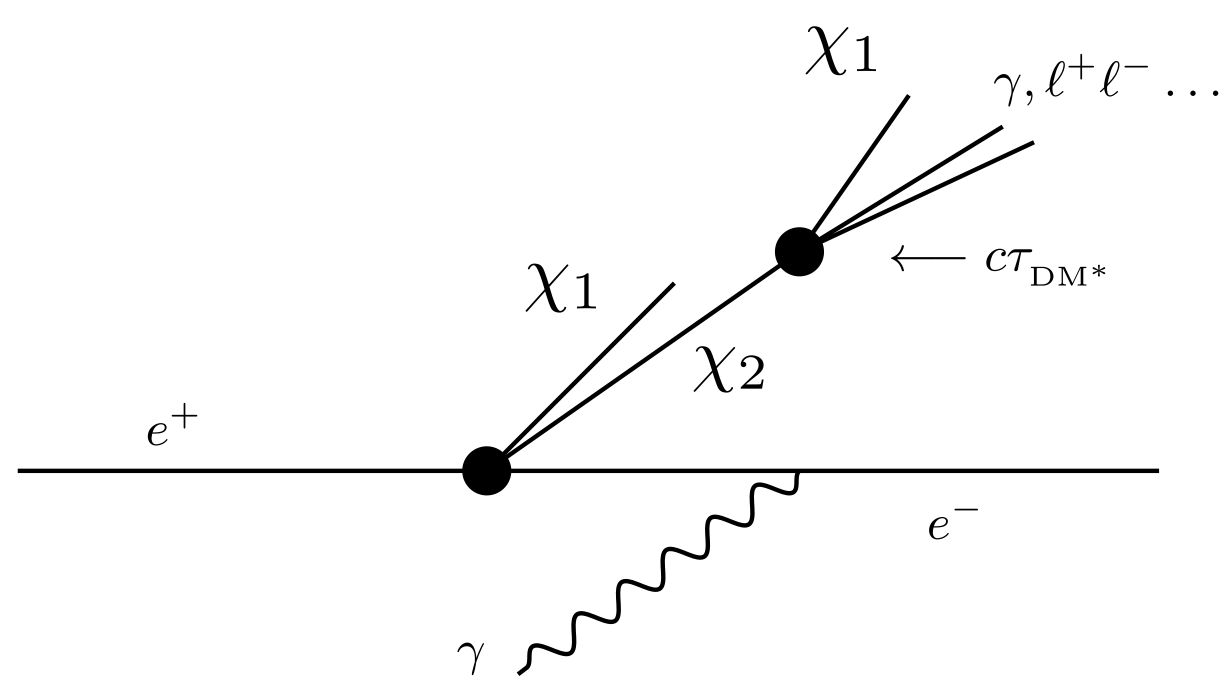
Hadron Collider

$$J + \not{E}_T + \ell^+\ell^-$$



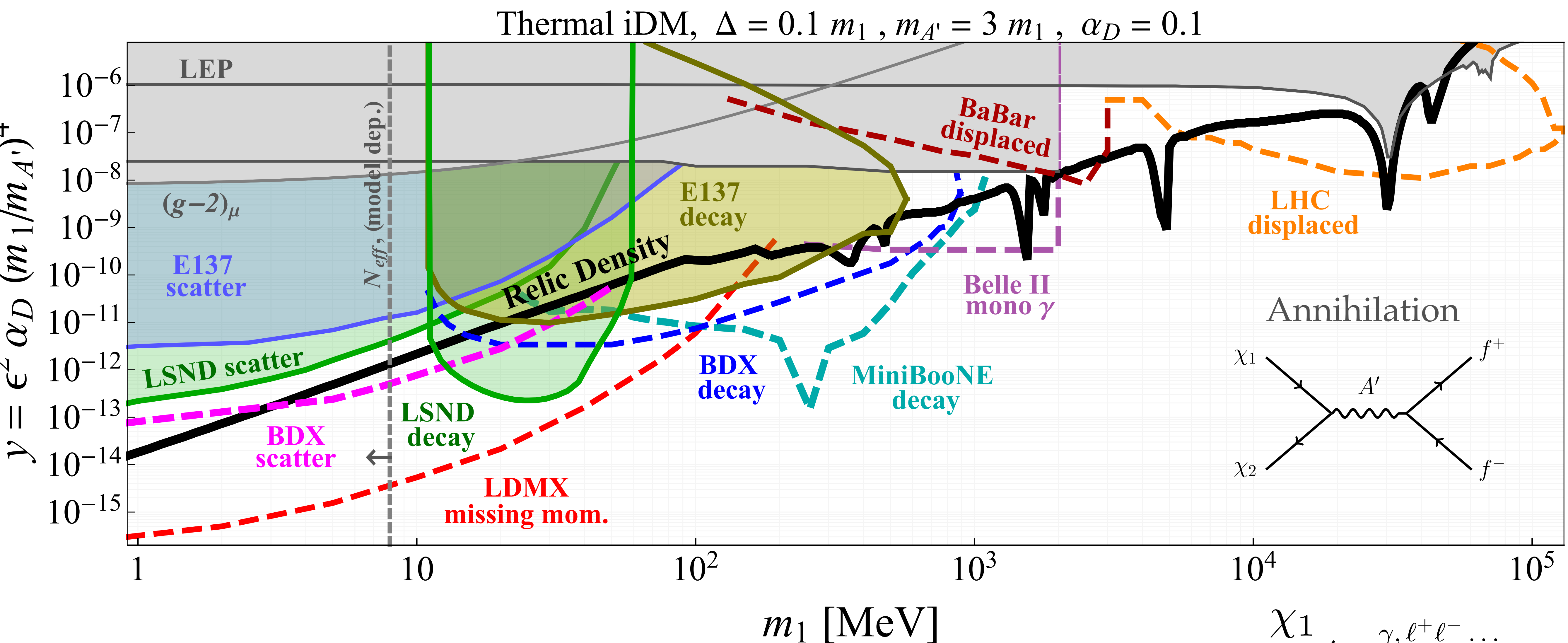
Lepton Collider

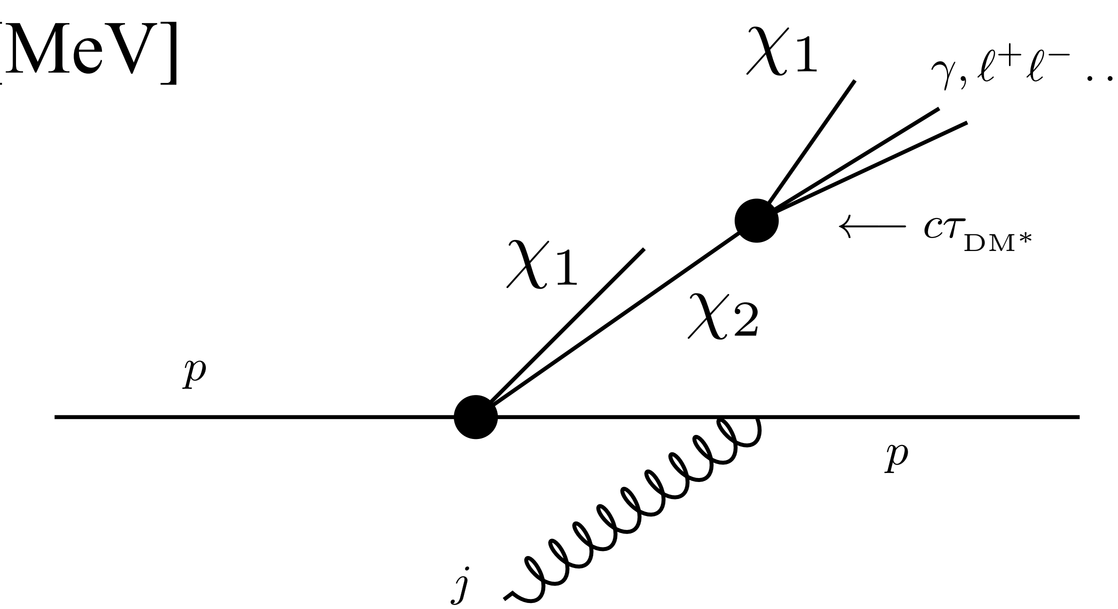
$$\gamma + \not{E} + \ell^+\ell^-$$



Izaguirre, GK, Shuve 1508.03050

Collider Complementarity

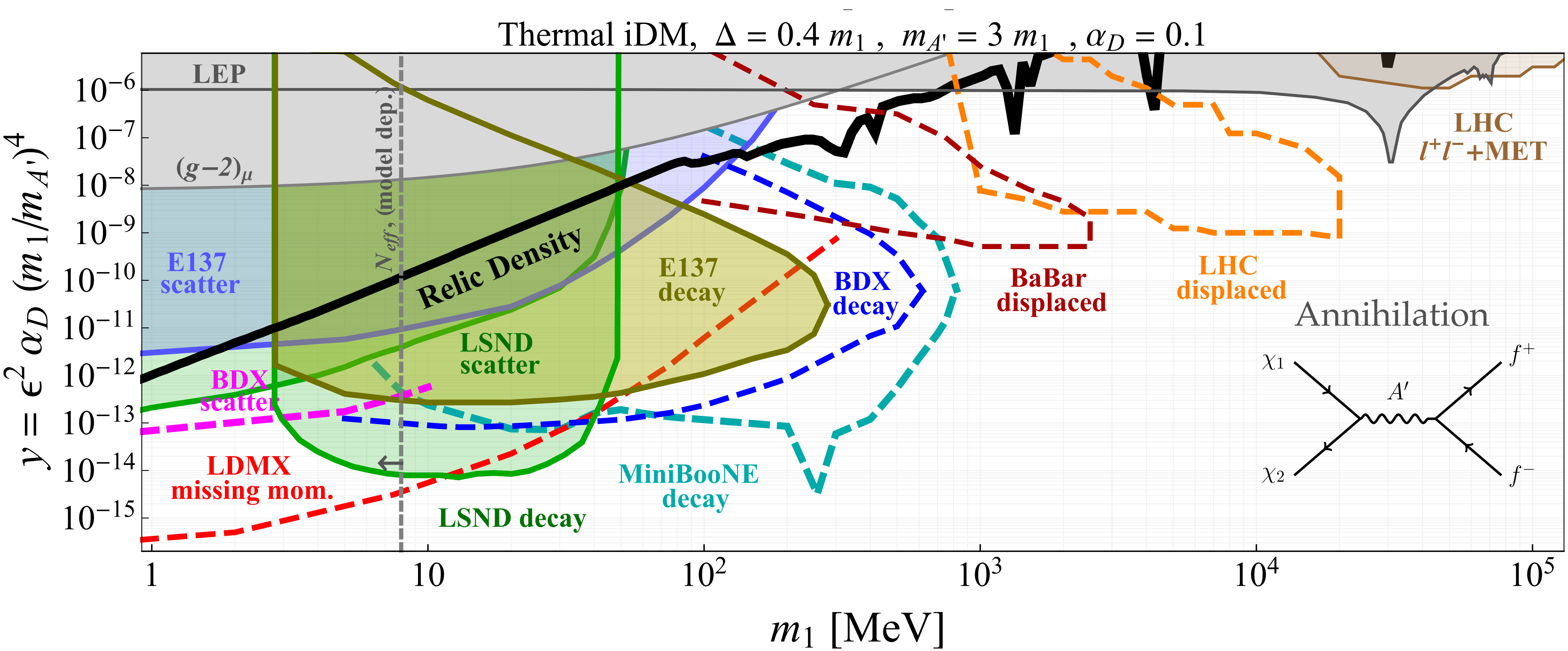


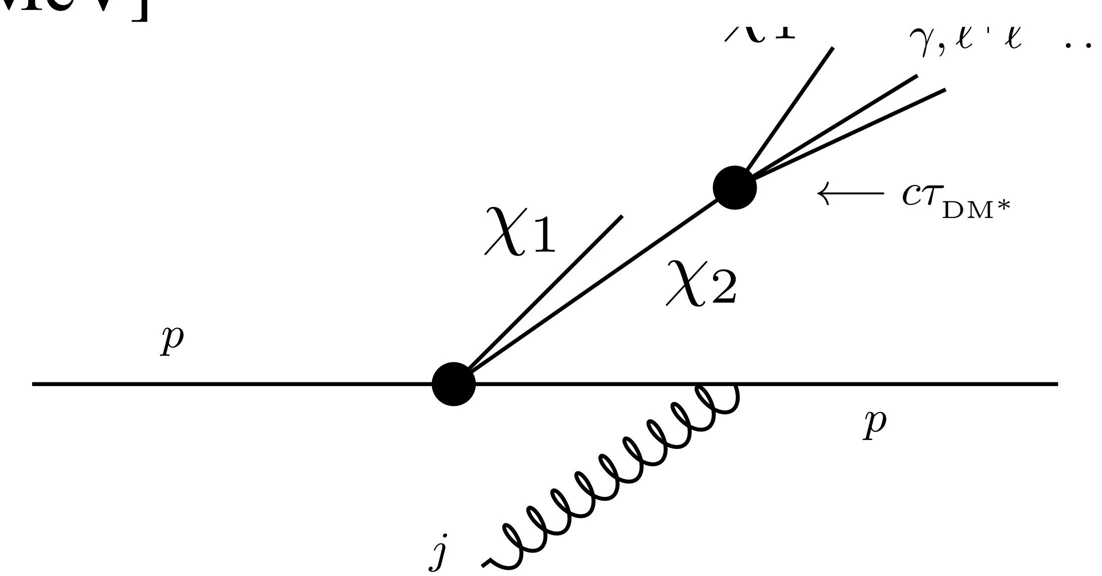


Pseudo-Dirac DM

Large Mass Splitting ~ 10%

Collider Complementarity





Pseudo-Dirac DM
Large Mass Splitting ~ 40%

Concluding Remarks

Thermal Equilibrium: Physical Organizing Principle

- Easy to achieve
- Minimum annihilation rate
- Insensitive to high scales (e.g. inflation)
- Bounds DM mass range

MeV-GeV scale DM can realize thermal below weak scale

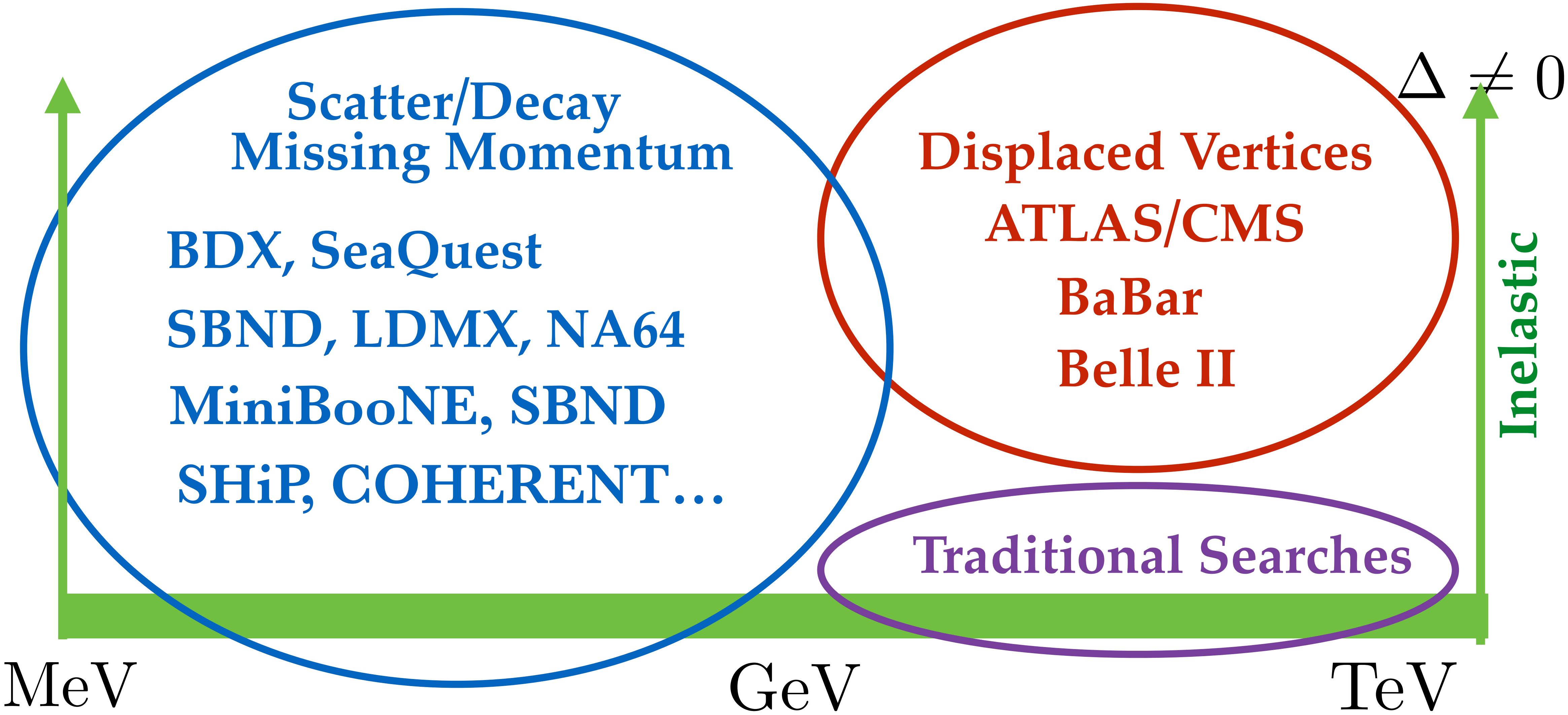
- It's in our neighborhood $m_e < m_{\rm DM} < m_p$
- Finite class of DM+mediator combinations
- Testable thermal targets for direct annihilation

Fixed-Target, Neutrino, & B-Factory Experiments

- Broad program of production/scattering/decay searches
- Can test nearly every direct annihilation model

No lose theorem: genuine opportunity to discover/falsify

Towards a mature LDM program



Light DM

Neutrino Factories
Proton Fixed Targets
Electron Direct Detection
Electron Beam Dumps
Electron Fixed Targets

"WIMPs"

Direct Detection
Indirect Detection
Collider Production

Thanks!