Light Dark Matter Coannihilation @ Fixed-Targets & Colliders

Gordan Krnjaic

Fermilab

+ Eder Izaguirre, Yonatan Kahn, Matthew Moschella

1703.06881

+ Eder Izaguirre, Brian Shuve

1508.03050

HPS Collaboration Meeting, SLAC Oct 25, 2017

Thermal/Chemical Eauilibrium

Advantage 1: Easy to achieve (hard to avoid!)

Annihilation rate ~ Hubble

Advantage 2: Minimum annihilation/depletion rate

Many predictive & testable scenarios

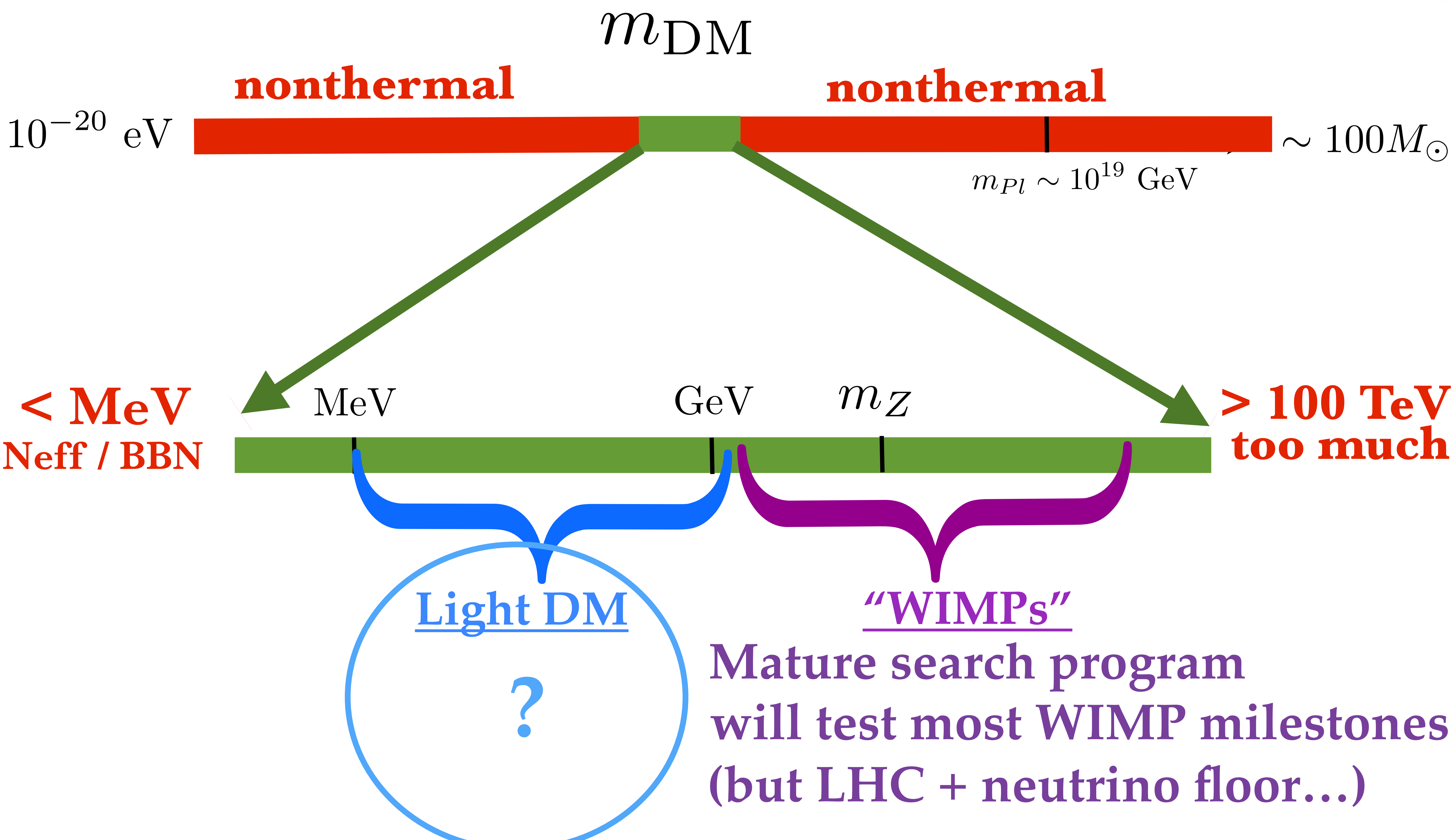
Advantage 3: UV insensitive

Independent of unknown cosmological history (e.g. inflation)

Masses / couplings determine cosmic history

Only “freeze-in” and “freeze-out” have these features

A Mature LDM program?



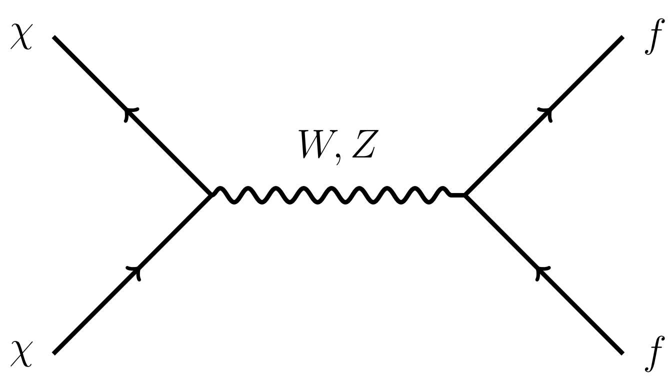
Model Building Requirements

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

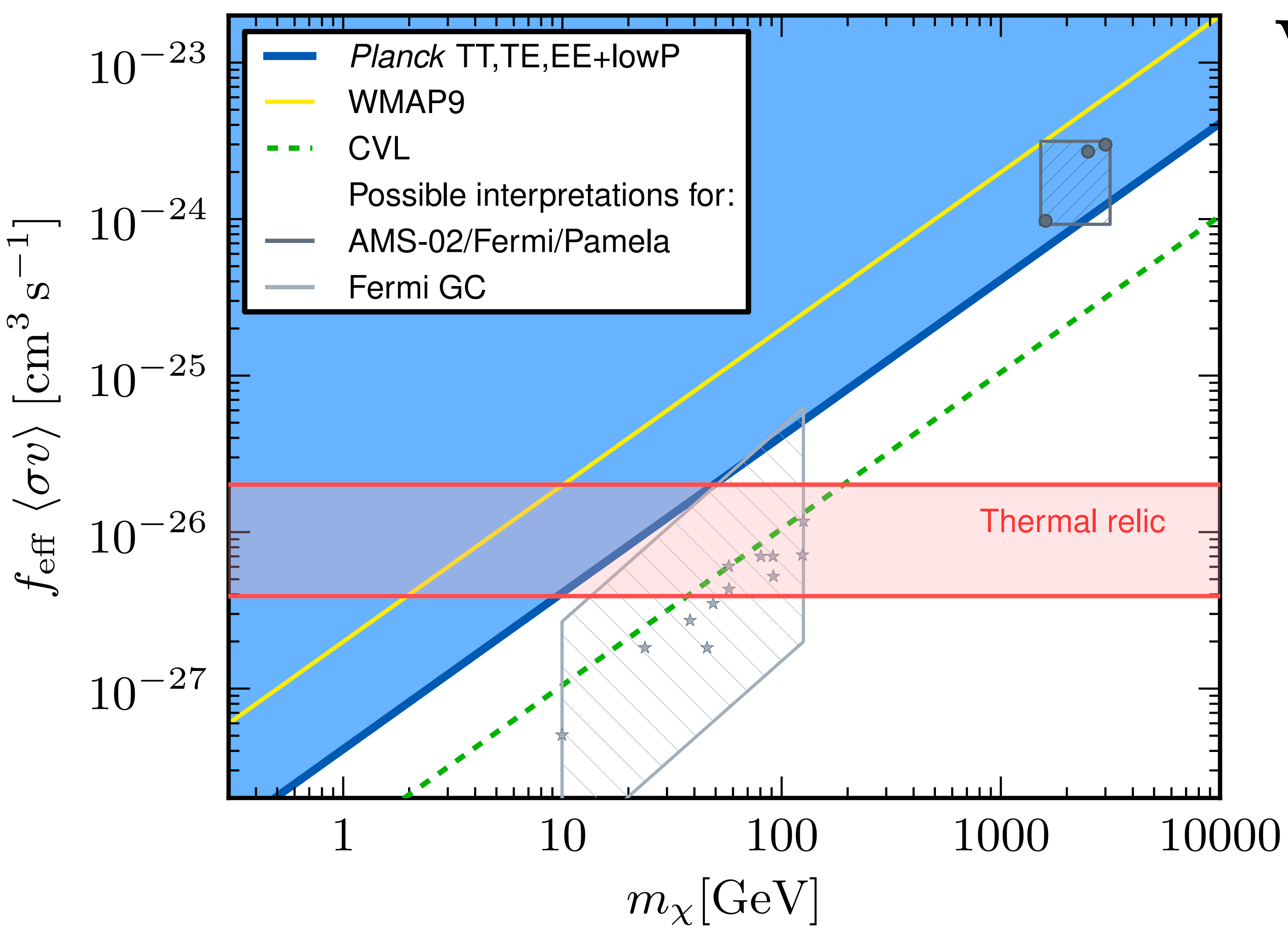
Key point: models must be renormalizable

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

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

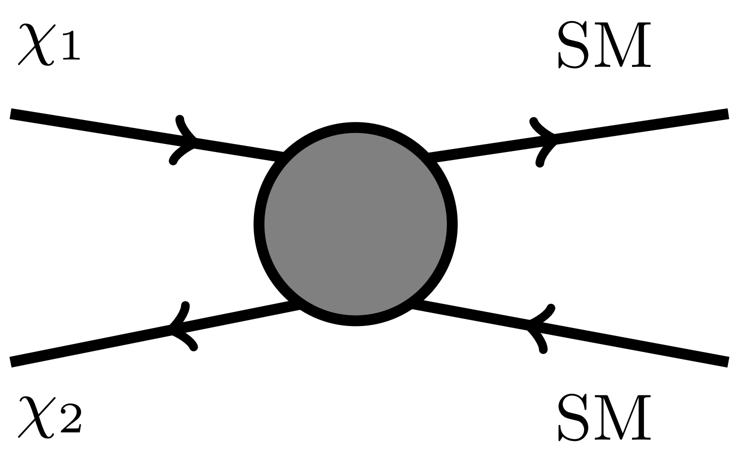
OR

Different DM population during CMB epoch

e.g. asymmetric DM
e.g. Coannihilating DM

Coannihilation is CMB Safe

Direct Coannihilation into SM



$$\Delta \equiv m_{\chi_2} - m_{\chi_1} \gg \text{eV}$$

Heavier state gone before recombination *z*~1100

No indirect detection $n_{\chi_2} \sim e^{-\Delta/T}$

No (tree level) direct detection $\Delta > 100 \text{ keV}$

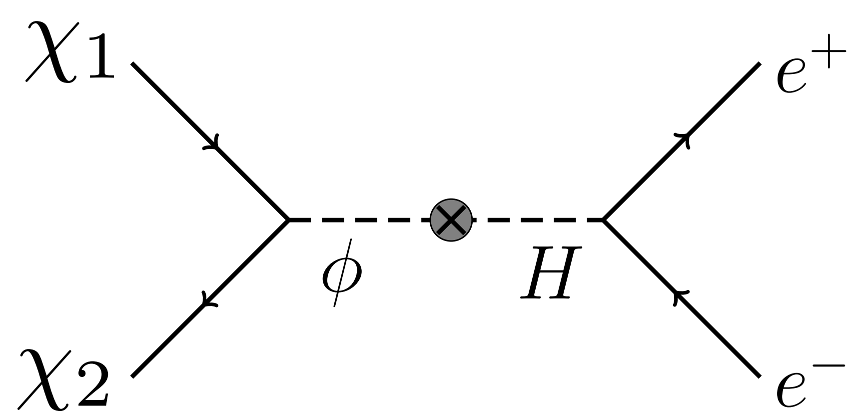
Easy to build, large couplings, hard to test!

Weiner, Tucker-Smith arXiv: 0101338

What Kind of Mediator?

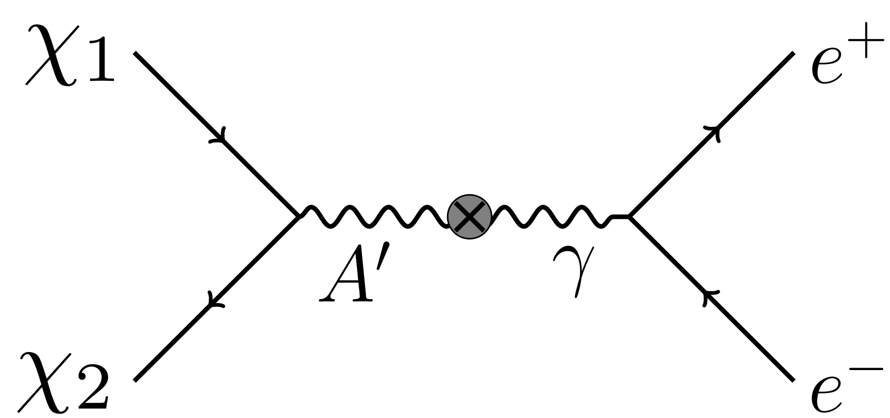
Must also be neutral under SM

New scalar mediator mixing w/ Higgs



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

New vector mediator A' mixing w/ photon



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

Also lepton portal, but hard to get thermal contact $\hat{\mathcal{O}}_\chi (LH)$

(e.g. RH neutrinos)

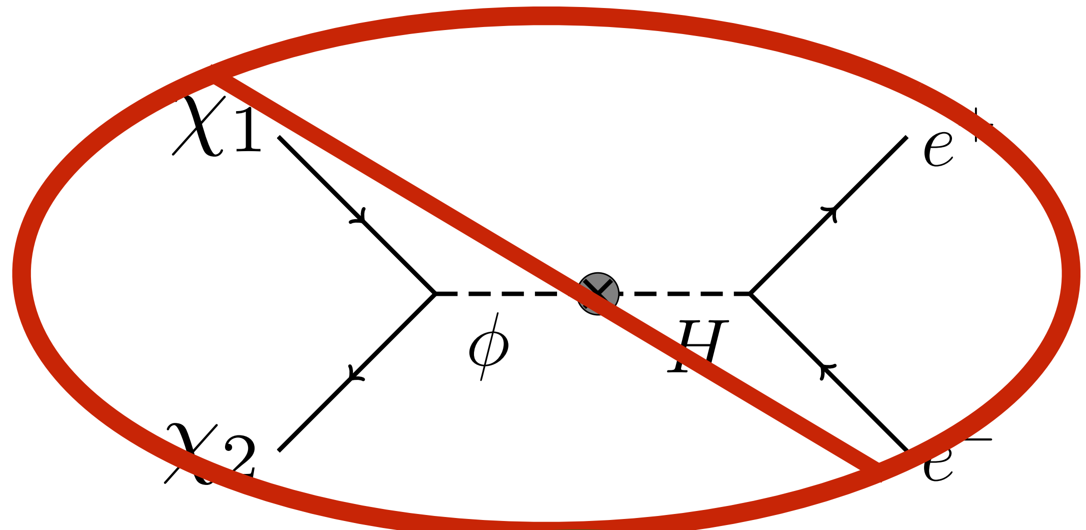
What Kind of Mediator?

Must also be neutral under SM

New scalar mediator mixing w/ Higgs

Direct annihilation ruled out

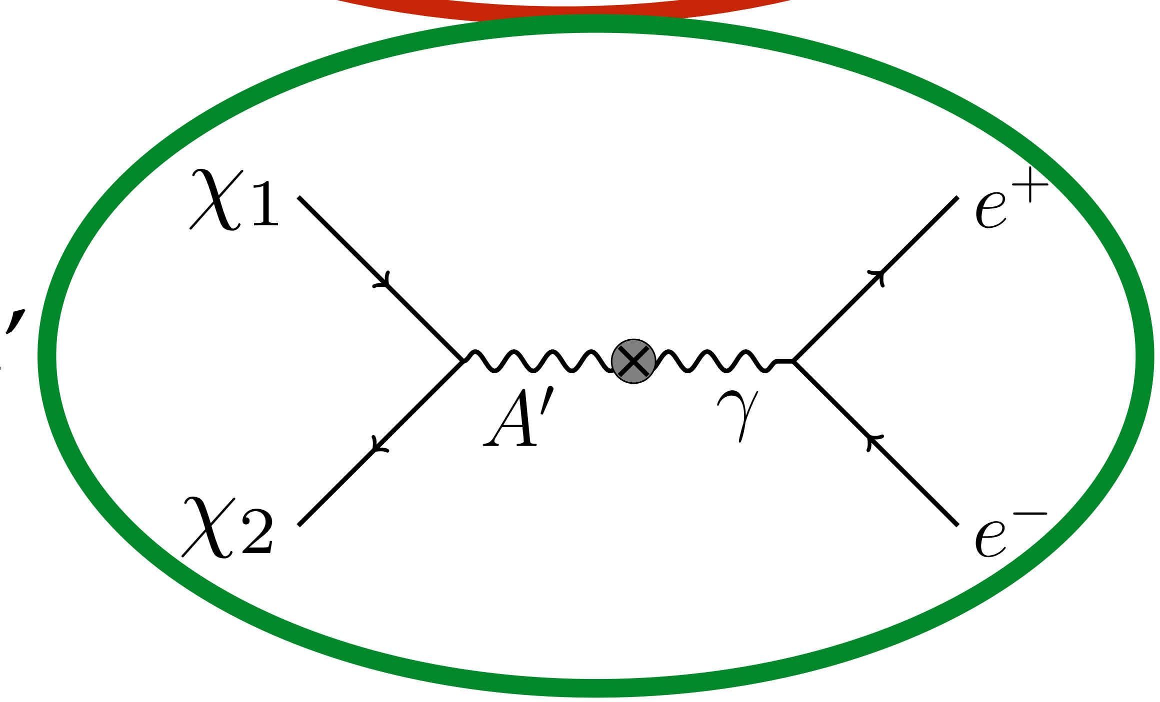
$B \to K\phi \to K\not{E}(\chi_1\chi_2)$



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

1512.04119, GK

New vector mediator A' mixing w/ photon



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

Can also charge both DM & SM under new gauge group (similar pheno, needs more particles)

Representative Model

Four component fermion + dark photon

$$\mathcal{L} \supset g_D A'_\mu \bar{\psi} \gamma^\mu \psi + M \bar{\psi} \psi + H_D \bar{\psi}^c \psi$$

Vector current

Dirac mass

Charge 2 dark Higgs

Representative Model

Four component fermion + dark photon

$$\mathcal{L} \supset g_D A'_\mu \bar{\psi}\gamma^\mu \psi + M\bar{\psi}\psi + H_D \bar{\psi}^c \psi$$

Vector current

Dirac mass

Charge 2 dark Higgs

Break dark U(1) with dark Higgs VEV

$$\mathcal{L}_{\mathrm{mass}} = M\bar{\psi}\psi + \langle H_D \rangle \bar{\psi}^c \psi$$

Dirac

Majorana

Representative Model

Four component fermion + dark photon

$$\mathcal{L} \supset g_D A'_\mu \bar{\psi}\gamma^\mu\psi + M\bar{\psi}\psi + H_D\bar{\psi}^c\psi$$

Vector current | Dirac mass | Charge 2 dark Higgs

Break dark U(1) with dark Higgs VEV

$$\mathcal{L}_{\rm mass} = M\bar{\psi}\psi + \langle H_D\rangle\bar{\psi}^c\psi$$

Dirac | Majorana

Diagonalizing to mass basis splits Dirac components (pseudo-Dirac)

$\psi \equiv (\xi, \eta^\dagger)$ → $(\chi_1, \chi_2)\ ,\ \Delta \equiv m_2 - m_1$

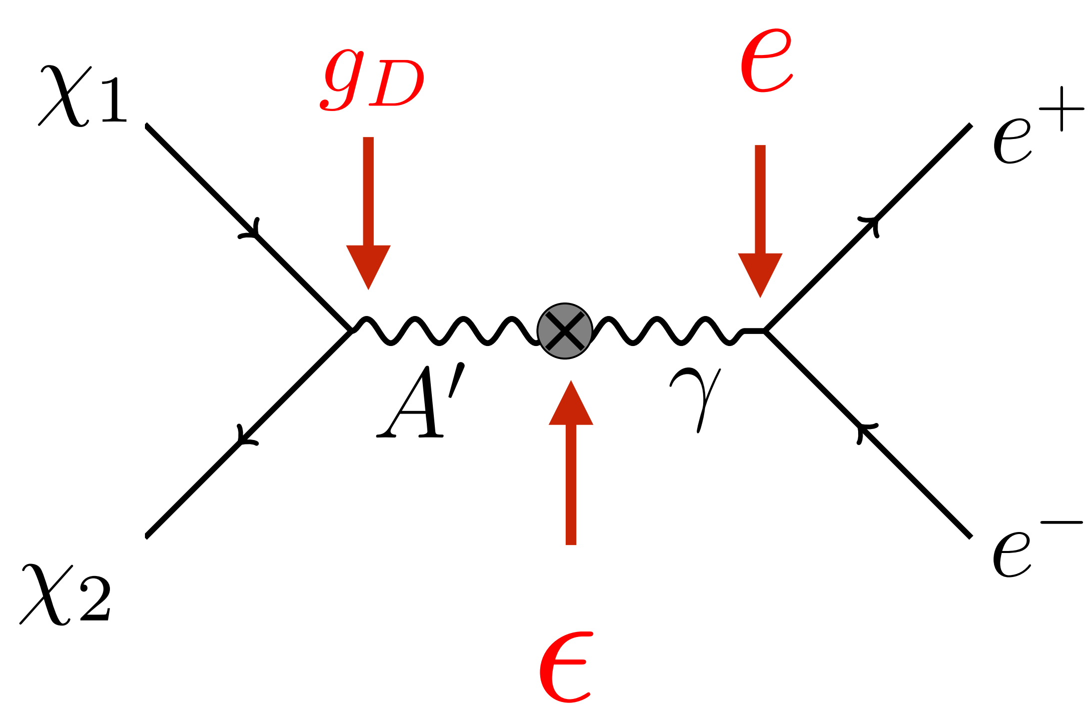
int. eigenstates → mass eigenstates

Representative Model

Vector current off-diagonal in mass basis

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

Dominant process for relic abundance



Direct Coannihilation into SM final states

$$m_{A'} > m_1 + m_2$$

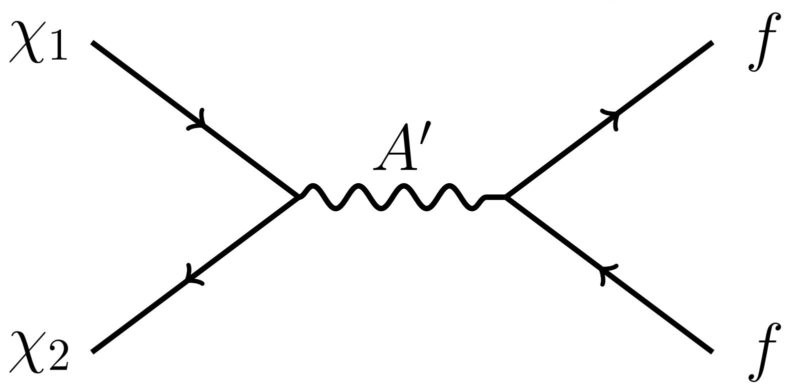
$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$

opposite regime not CMB safe

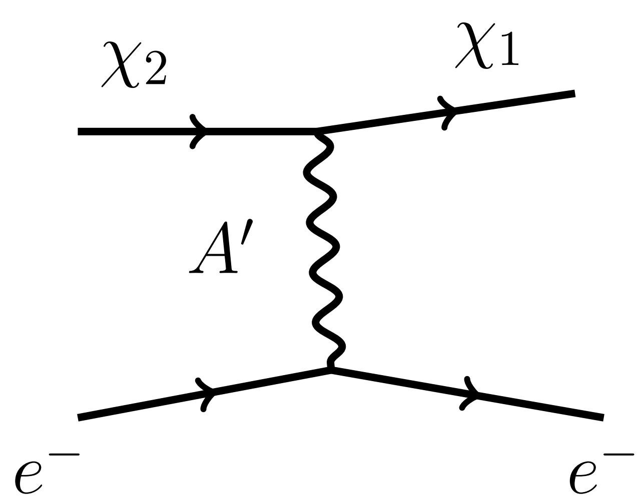
$$\chi_1 \chi_1 \to A' A' \quad \textbf{(s-wave)}$$

Inelastic Novelties

Coannihilation

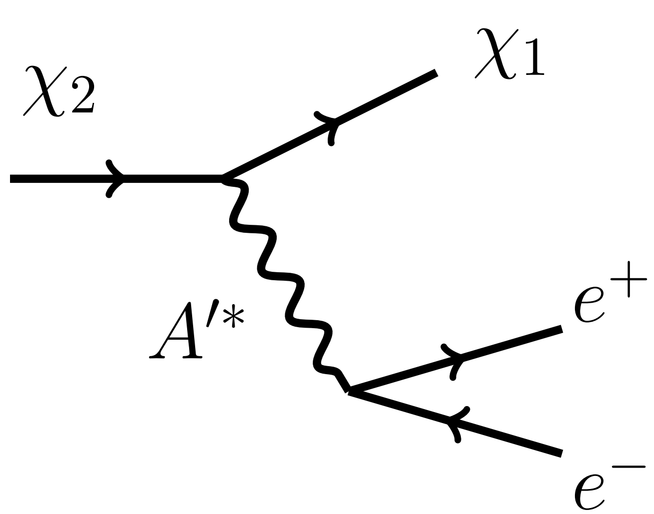


Upscattering & Downscattering

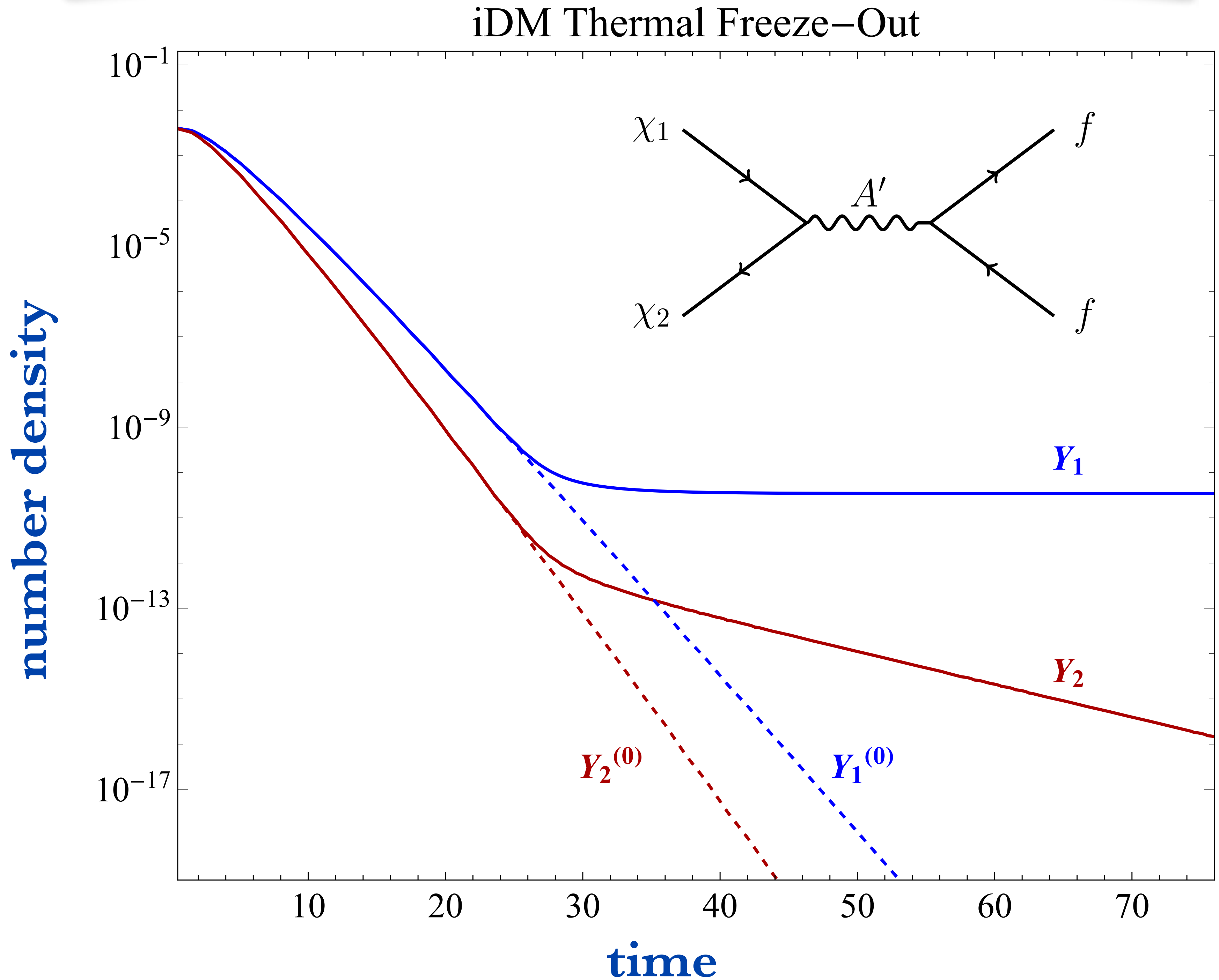


Excited State Decays

$$\Gamma(\chi_2 \to \chi_1 \; e^+ e^-) = \frac{4\epsilon^2 \alpha \alpha_D \Delta^5}{15 \pi m_{A'}^4}$$



Coannihilation Relics



Heavier state feels Boltzmann suppression earlier

Need larger rate to compensate!

Useful Variables

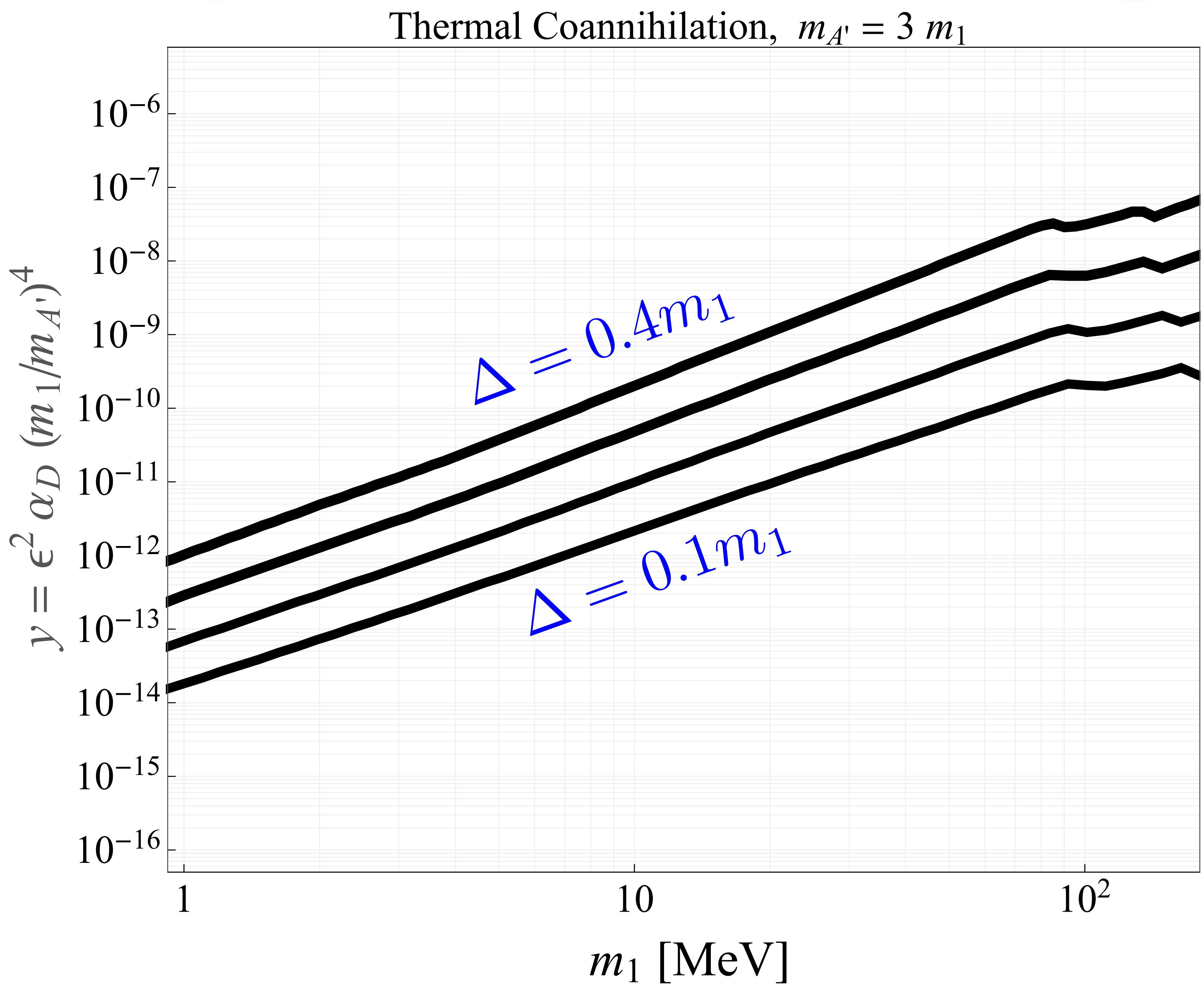
Define new variable optimized for thermal targets

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

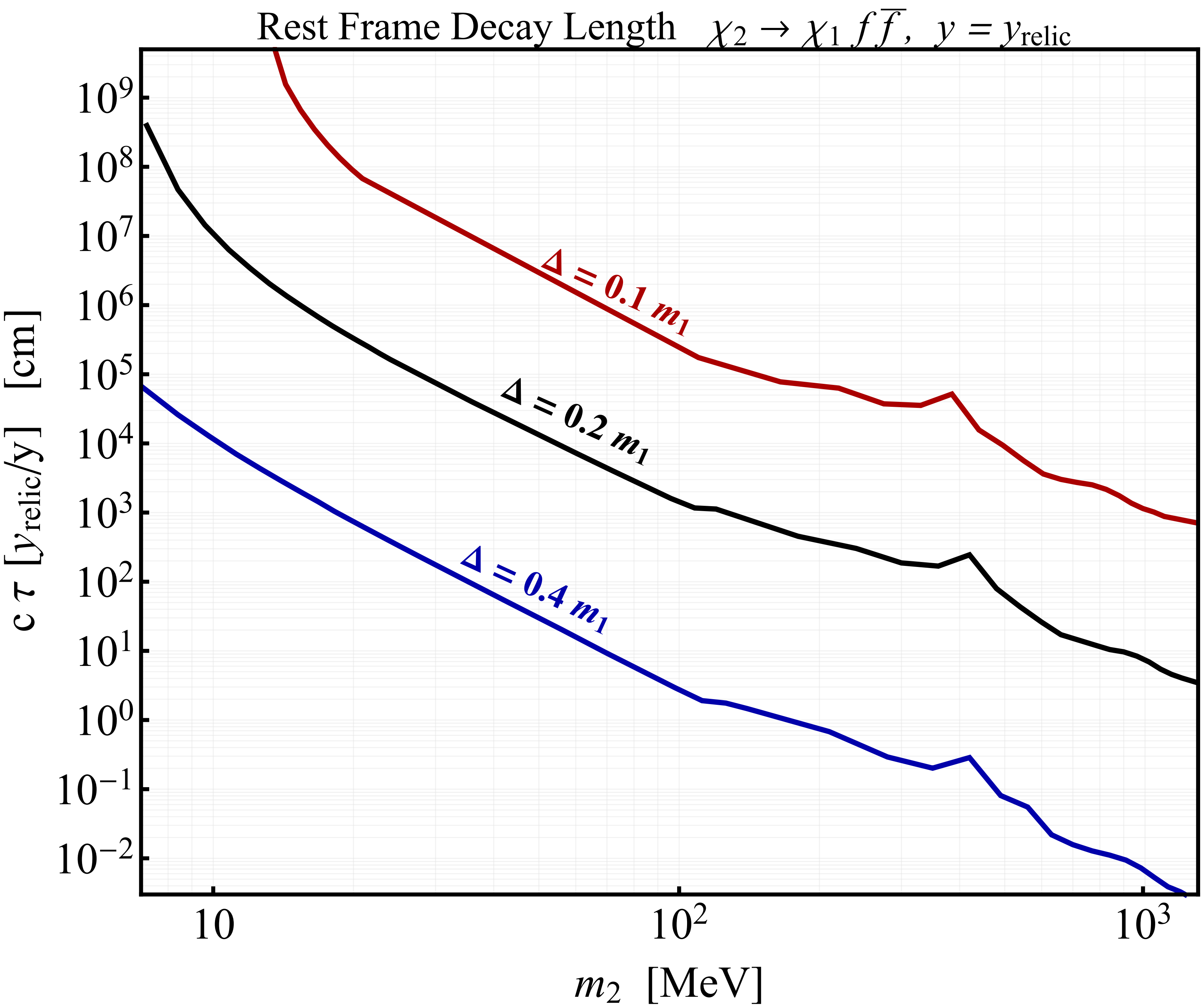
Insensitive to ratios of inputs, unique "y" for each mass and Δ (up to subleading corrections)

Reduces complicated parameter space to 2D comparison

Vary Mass Splitting



Generically Macroscopic Decays



Overview

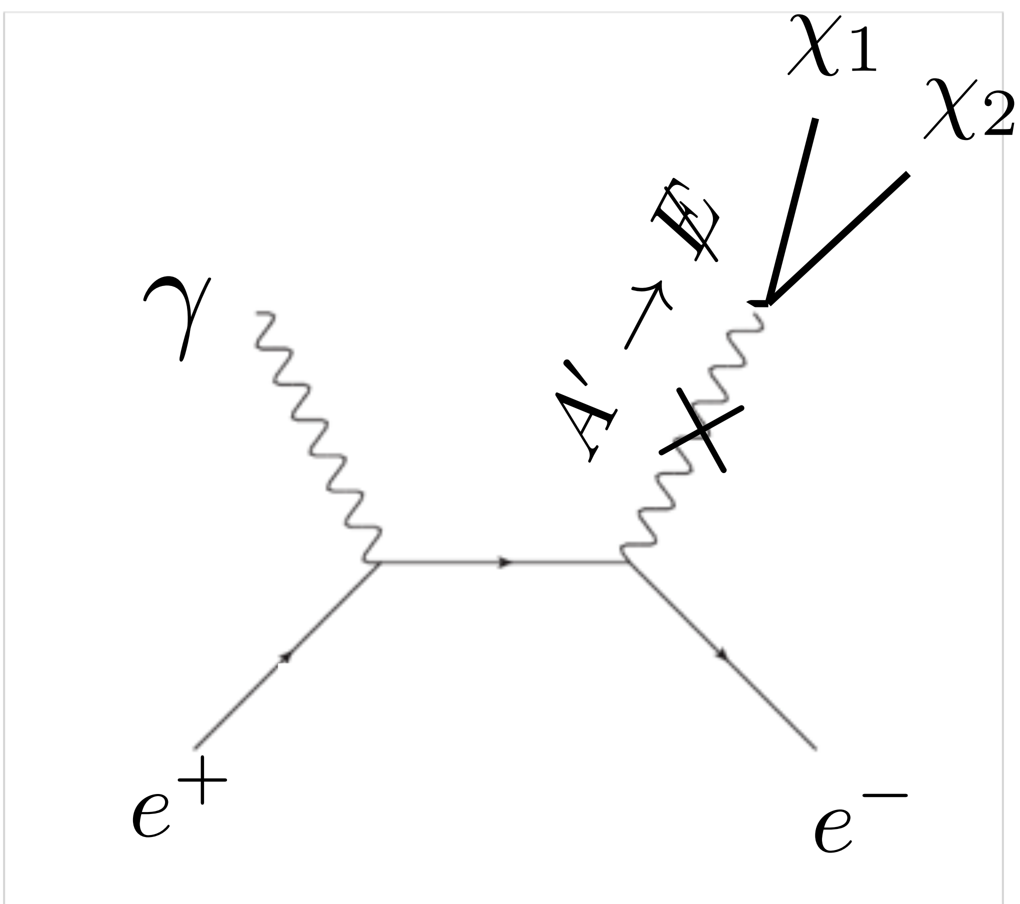
- **Historical Motivation**
  Thermal DM & WIMPs

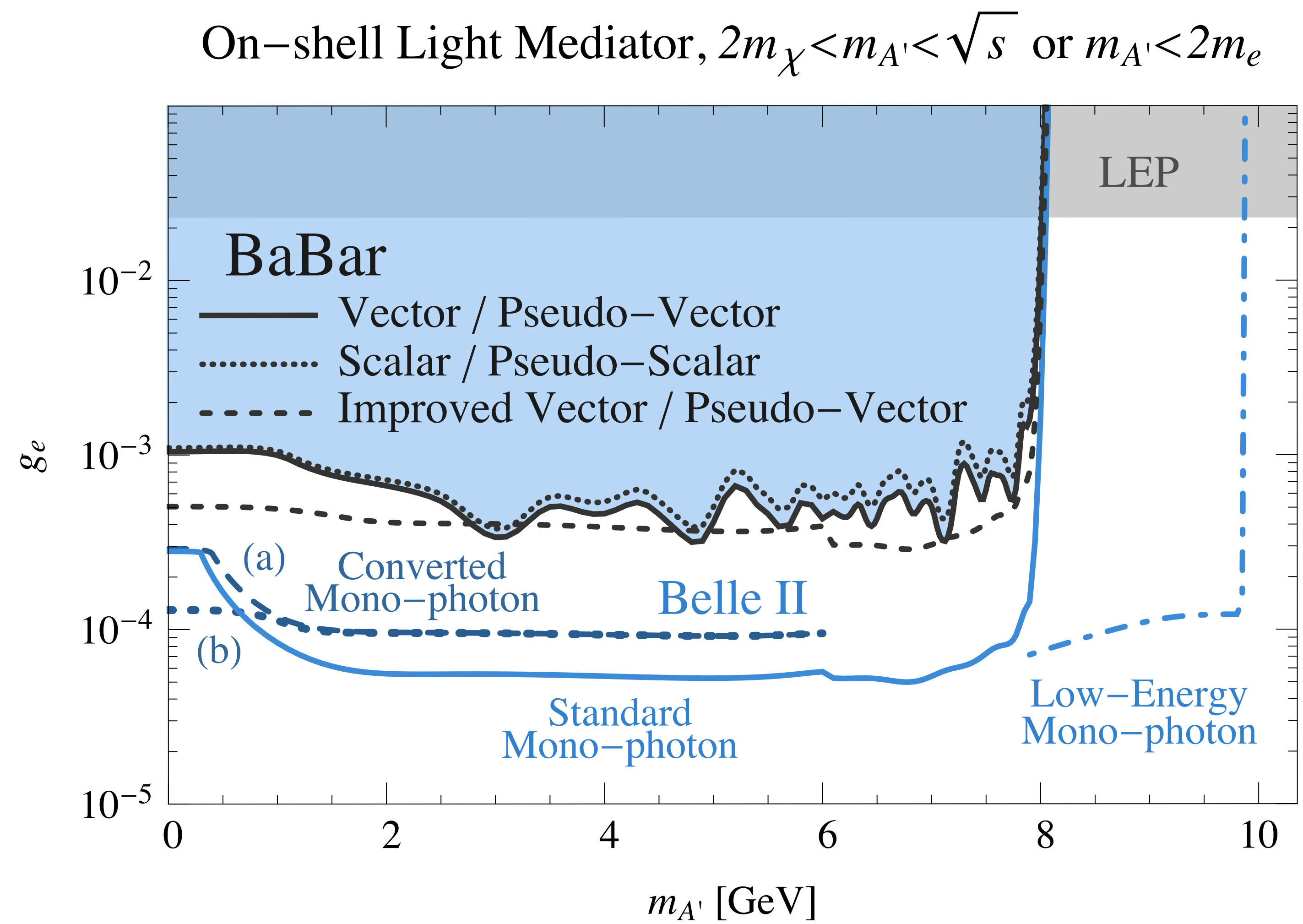
- **DM Coannihilation (<GeV)**
  Models & Milestones

- **New Accelerator Searches**
  Proton & Electron Beams

Signatures @ B-Factories

mono photon + missing energy





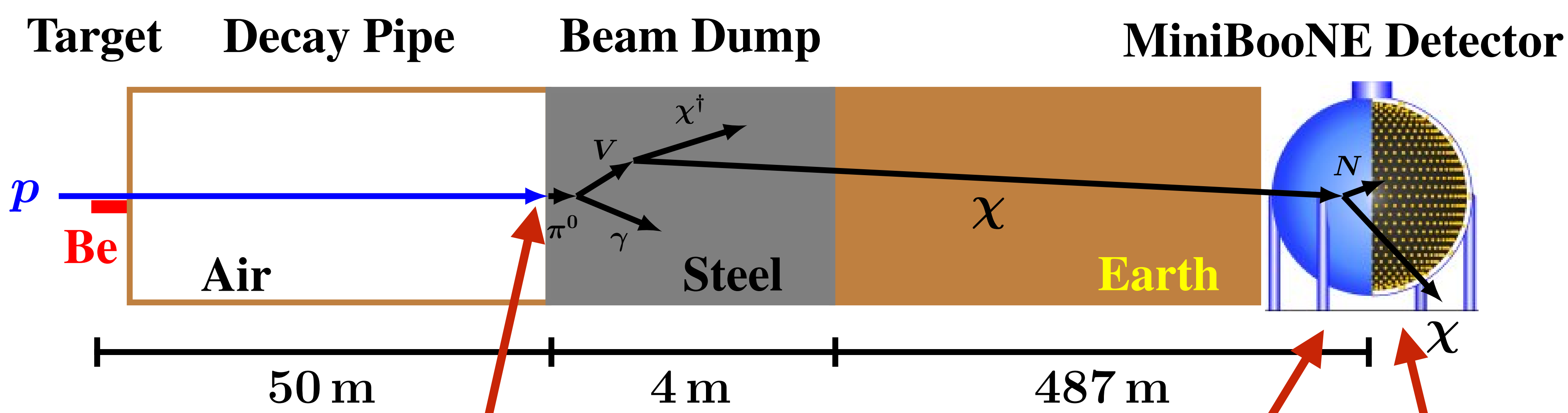
Signatures from displaced vertices and/or missing energy

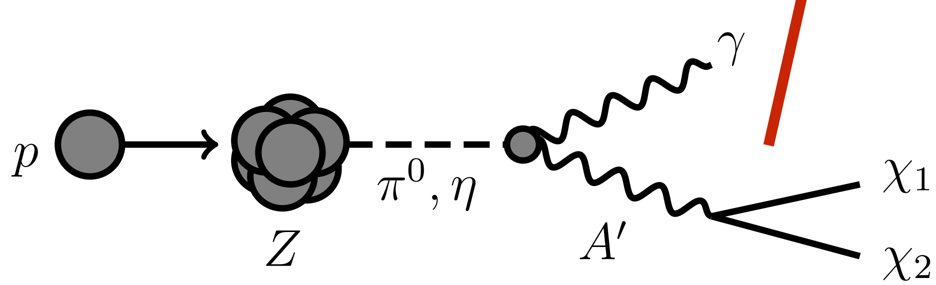
Izaguirre, GK, Schuster, Toro 1307.6554

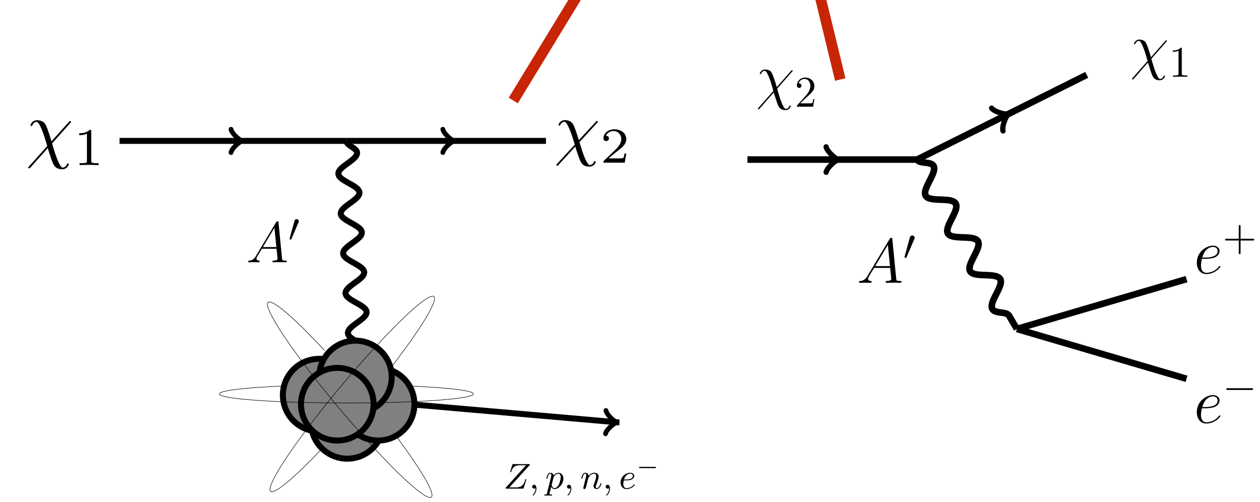
Essig, Mardon, Papucci, Volansky Zhong 1309.5084

Signatures @ Proton Beam Dumps

(quasi) elastic scattering & decays







LSND (2001)

E ~ 800 MeV, 1e24 POT

Pi decays, can recast bound

MiniBooNE (2017)

E ~ 9 GeV, 1e20 POT

Pi+Eta+Brem →

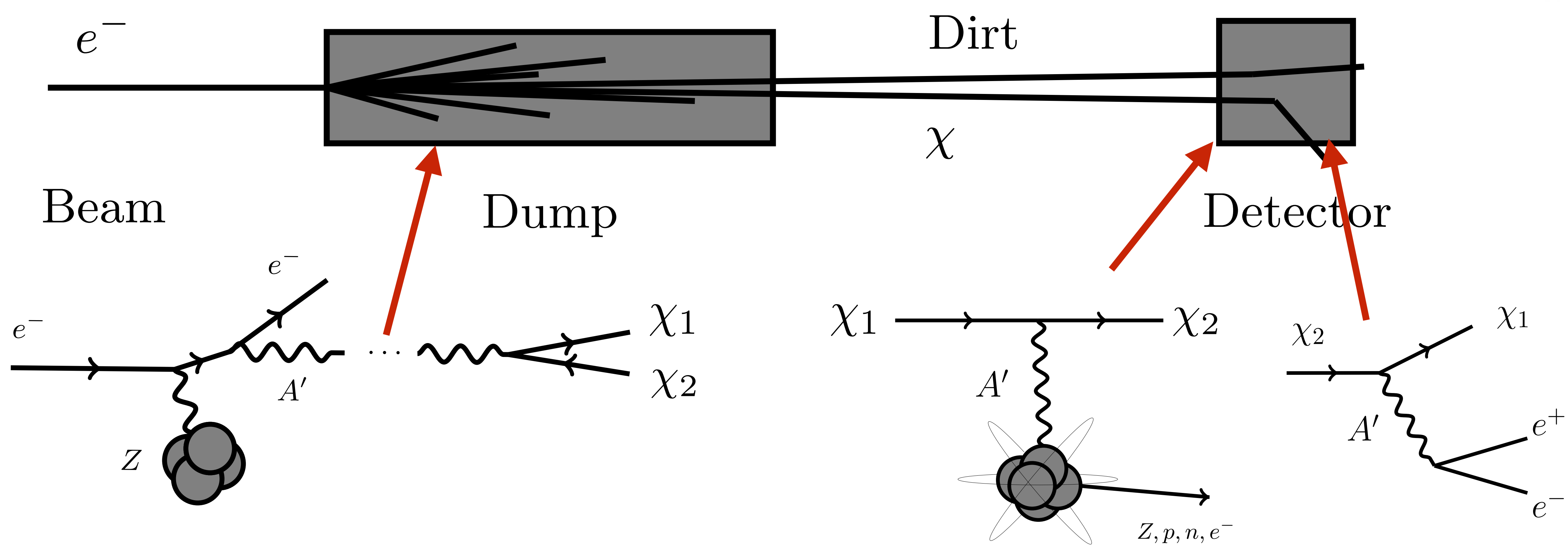
Inelastic DM Izaguirre, Kahn, GK, Moschella 1703.06881

Elastic DM: Batell, Pospelov, Ritz 0903.0363

BdNMC deNiverville, Chen, Pospelov, Ritz 1609.01770

Signatures @ Electron Beam Dumps

(quasi) elastic scattering & decays



E137 (SLAC 1988)

E ~ 20 GeV, 1e20 POT

~ 400 m baseline, no BG

BDX (JLab proposed)

E ~ 11 GeV, 1e22 EOT

~ 20 m baseline, few BG evts.

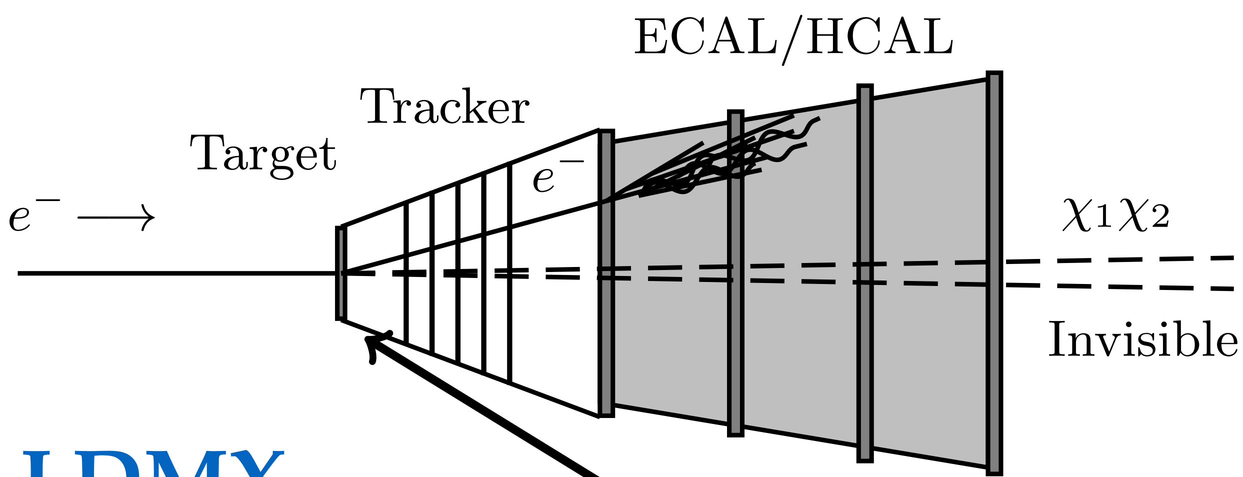
Inelastic DM Izaguirre, Kahn, GK, Moschella 1703.06881

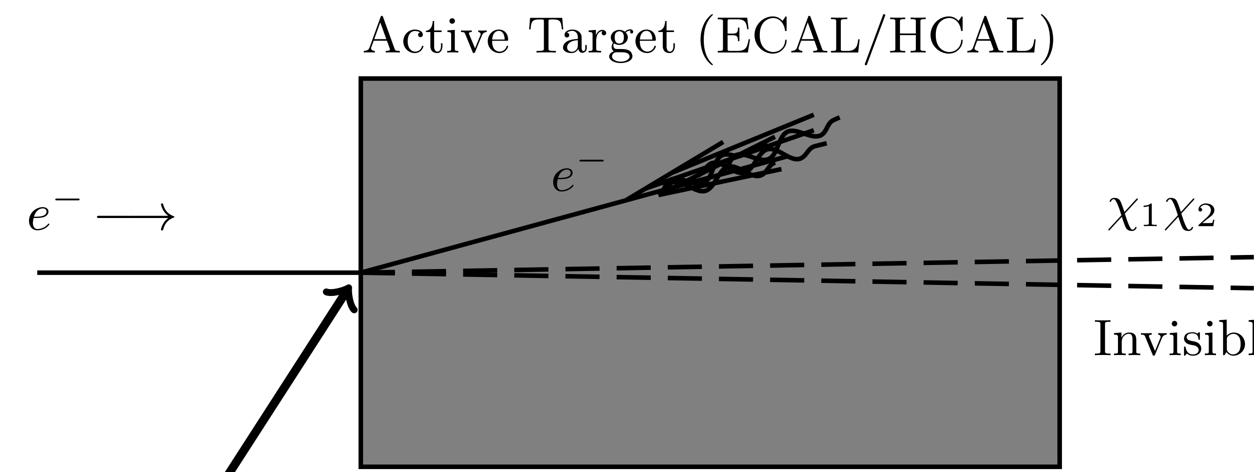
E137 Recast : Batell, Essig, Zurjuron 1406.2698

BDX: Izaguirre, GK, Schuster, Toro 1307.6554

BDX Collaboration 1607.01390

Signatures @ Missing Energy & Momentum Experiments

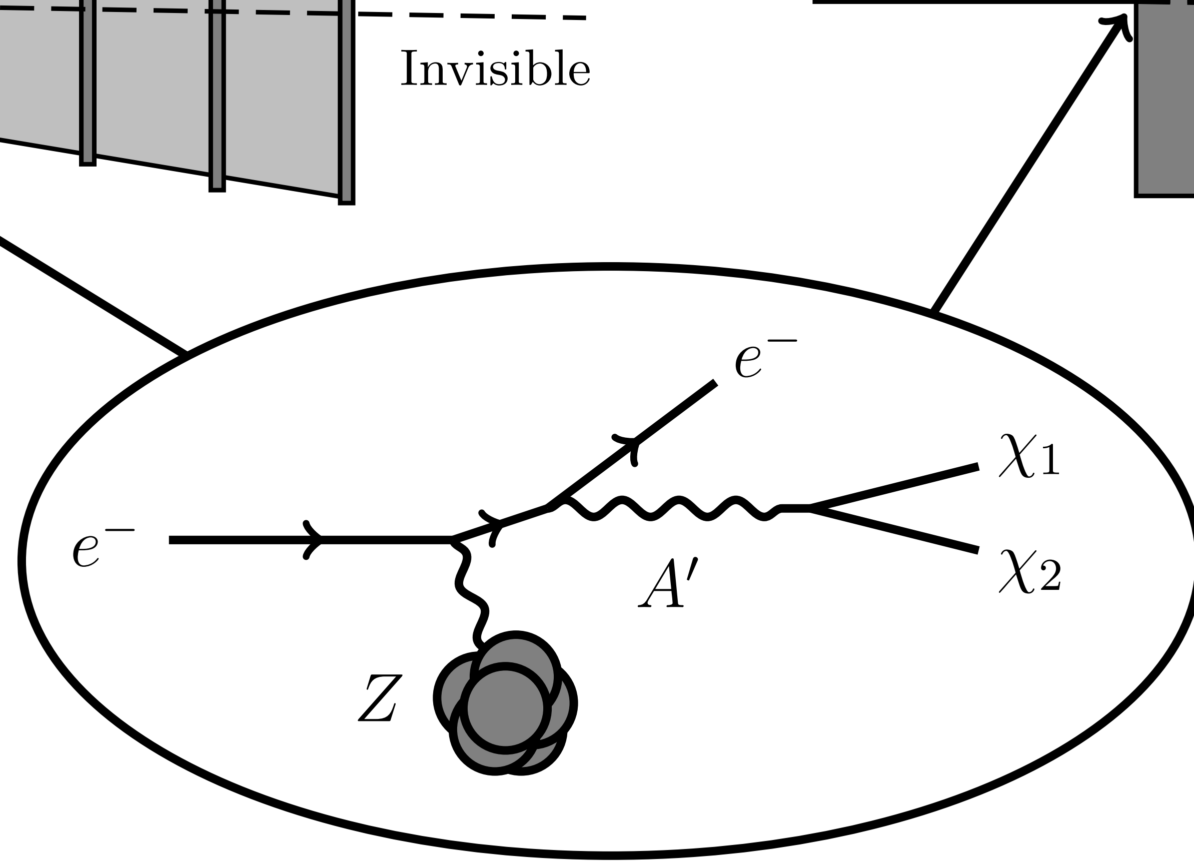




LDMX

E~ 8 GeV
~3e16 EOT

thin target
~0.1 rad. length



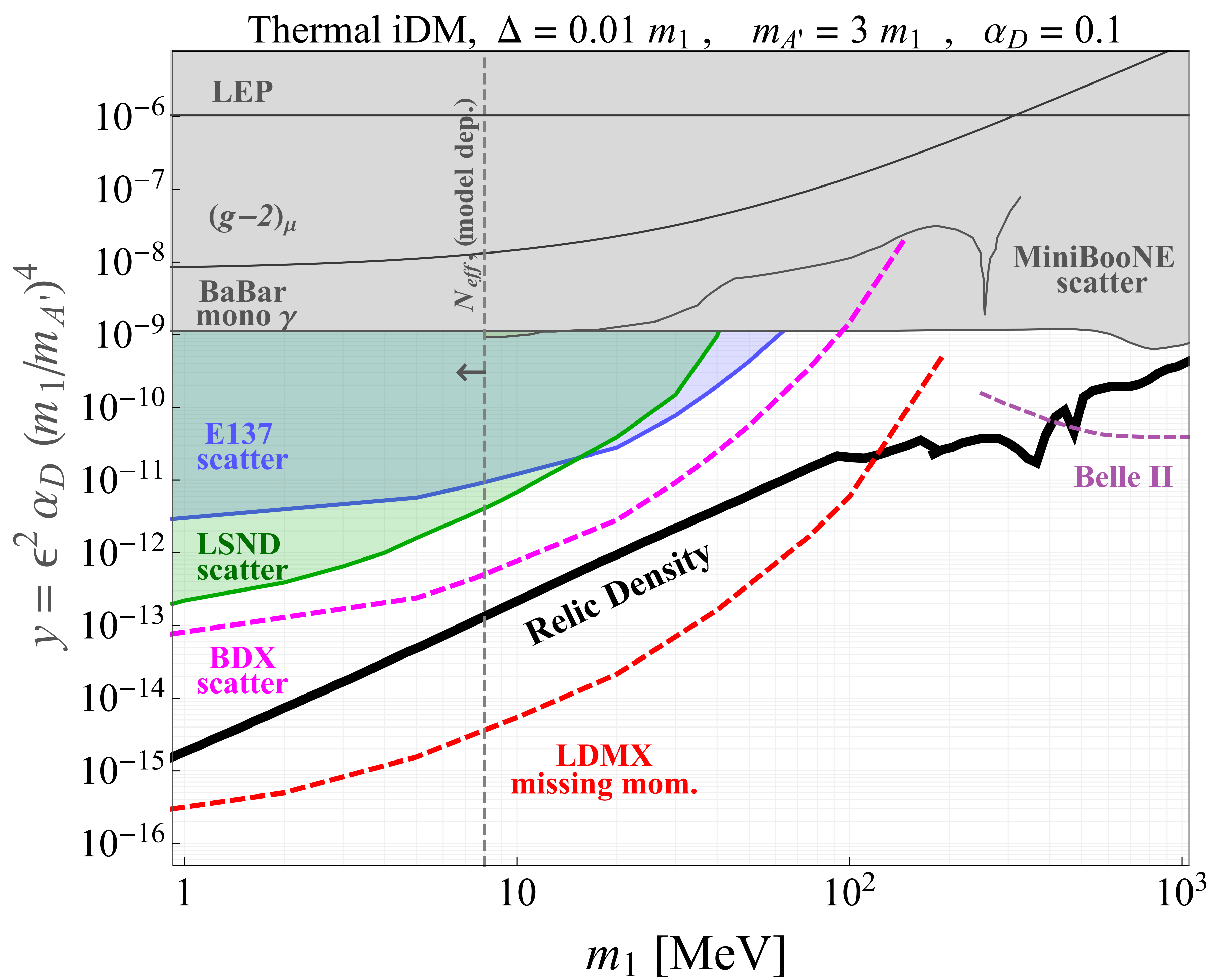
NA64

E~100+ GeV
~1e11 EOT
~2 m thick target

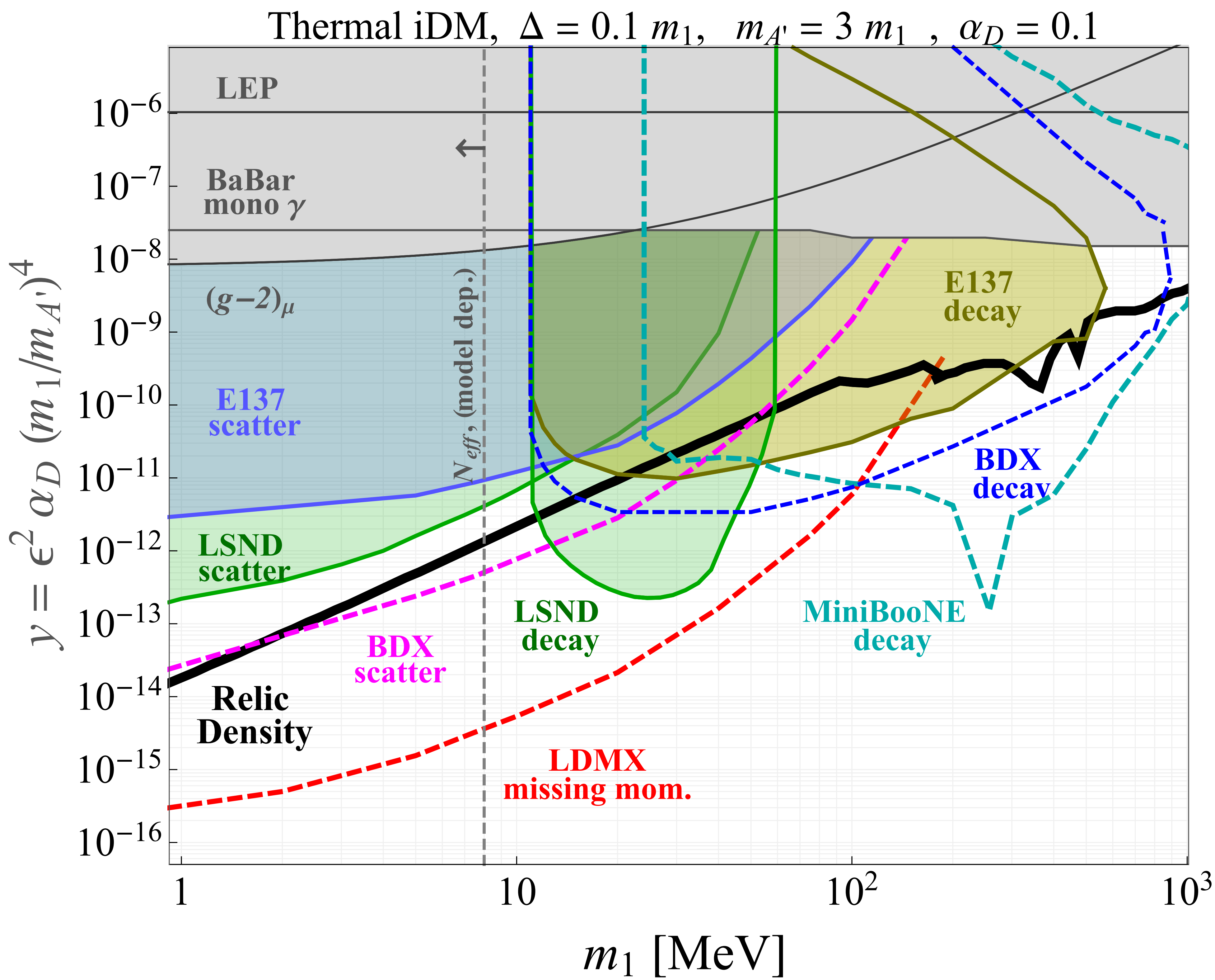
Observe recoiling electron with large missing energy and/or mass (veto SM)

Izaguirre, GK, Schuster, Toro 1411.0051
LDMX Collaboration 1704.XXXXX
NA64 Collaboration 1610.02988

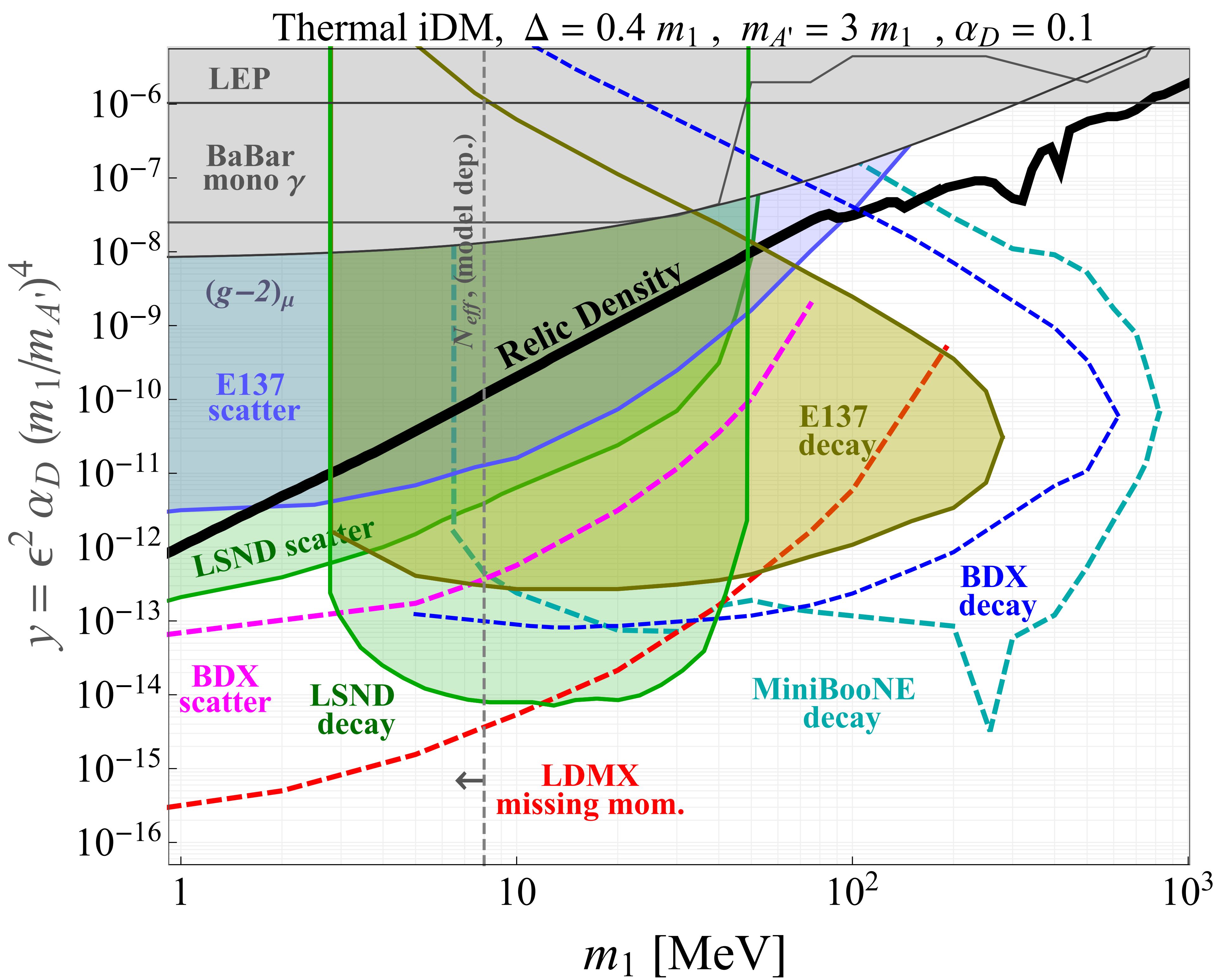
Tiny Splitting ~ 1%



Small Splitting ~ 10%

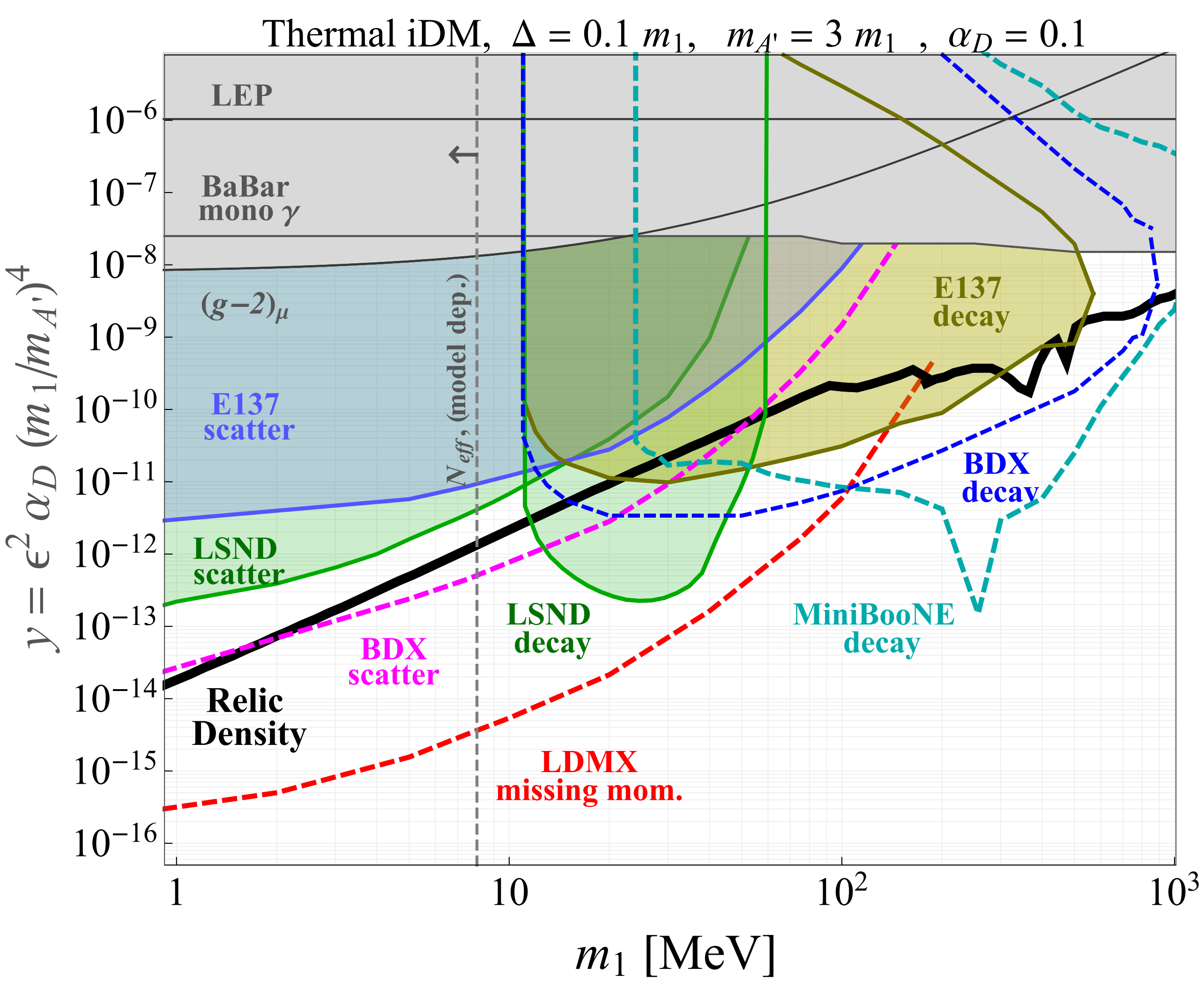


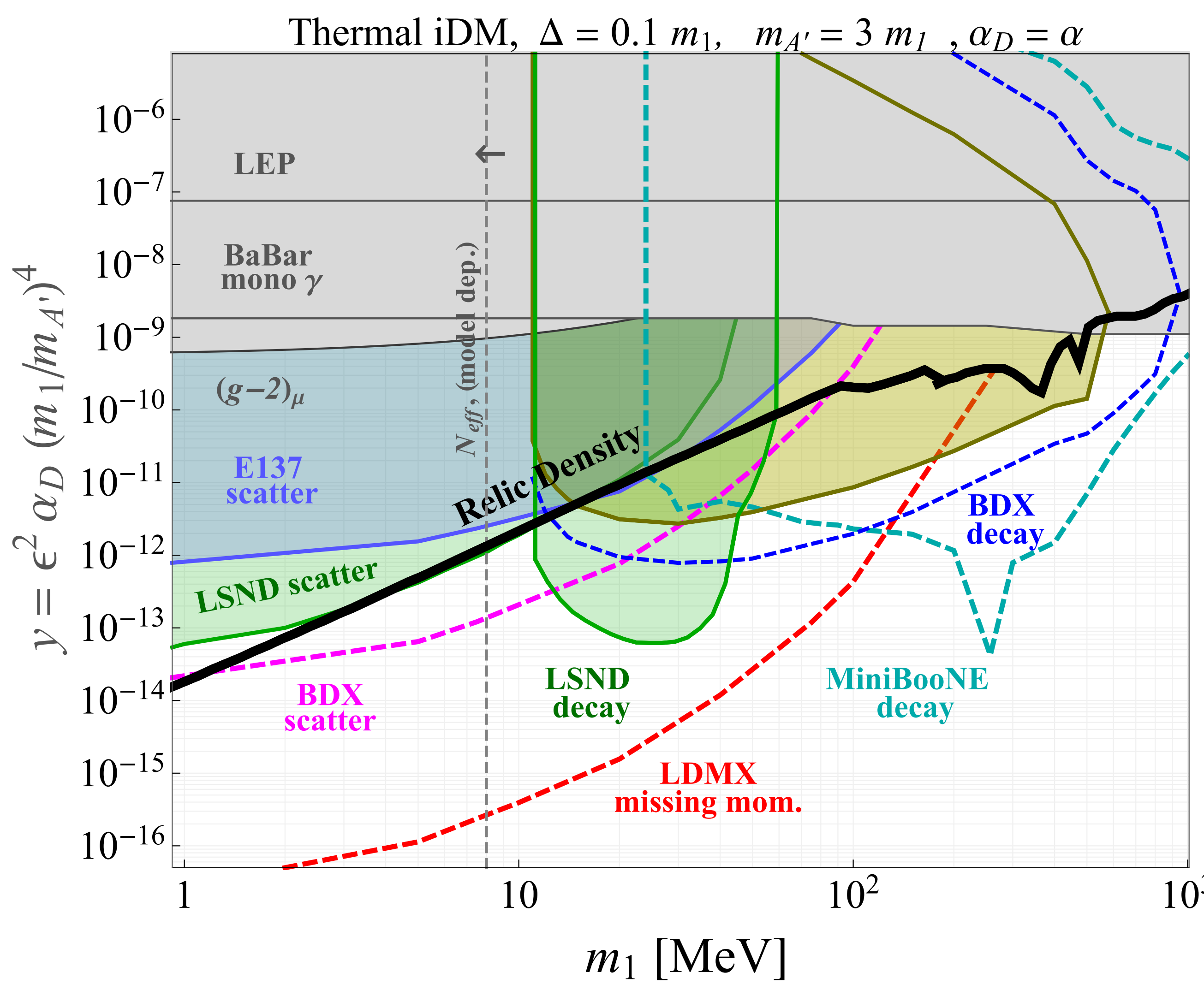
Large Splitting ~ 40%



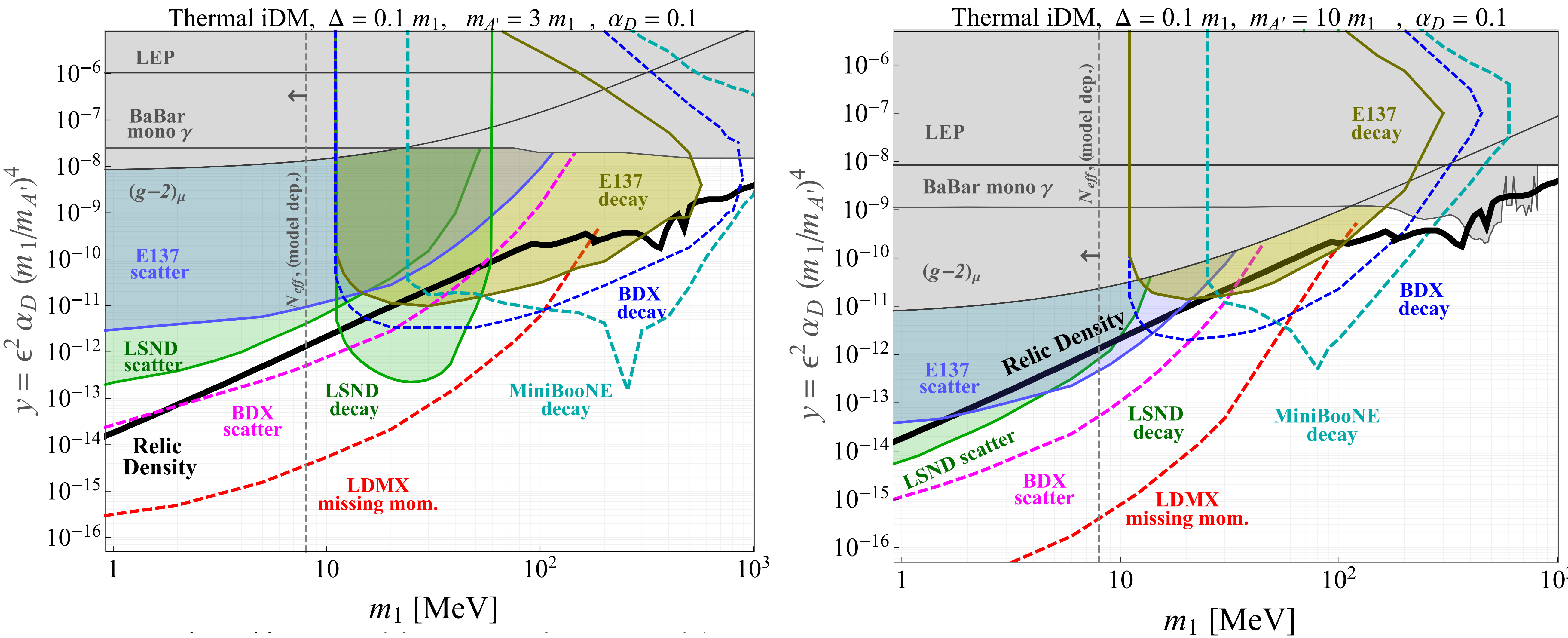
Target moves up, bounds/projections move down

Vary DM/Mediator Coupling





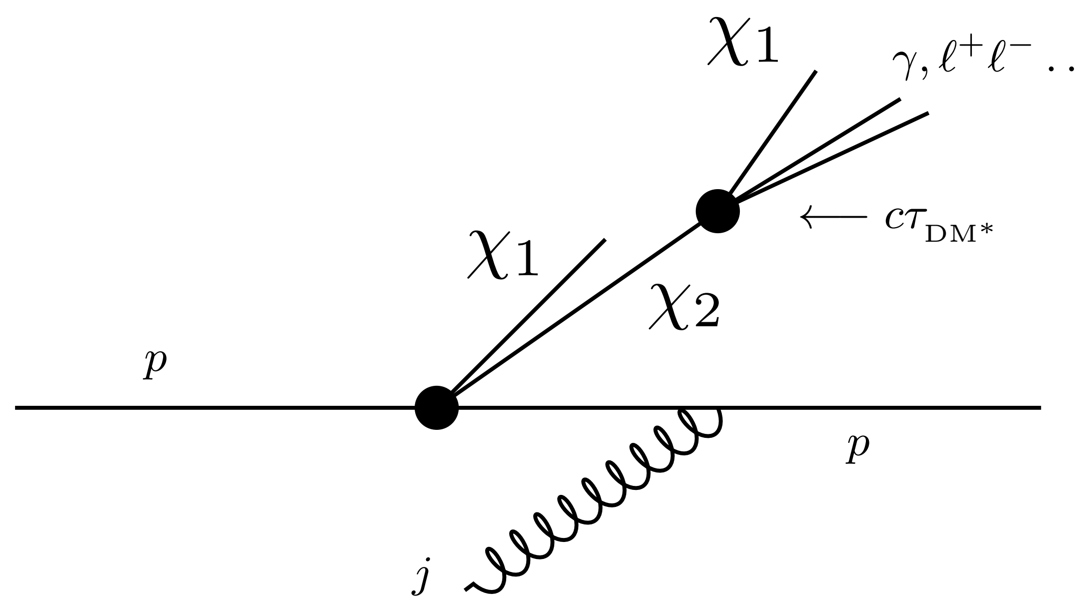
Vary DM/Mediator Mass Ratio



Above the GeV Scale?

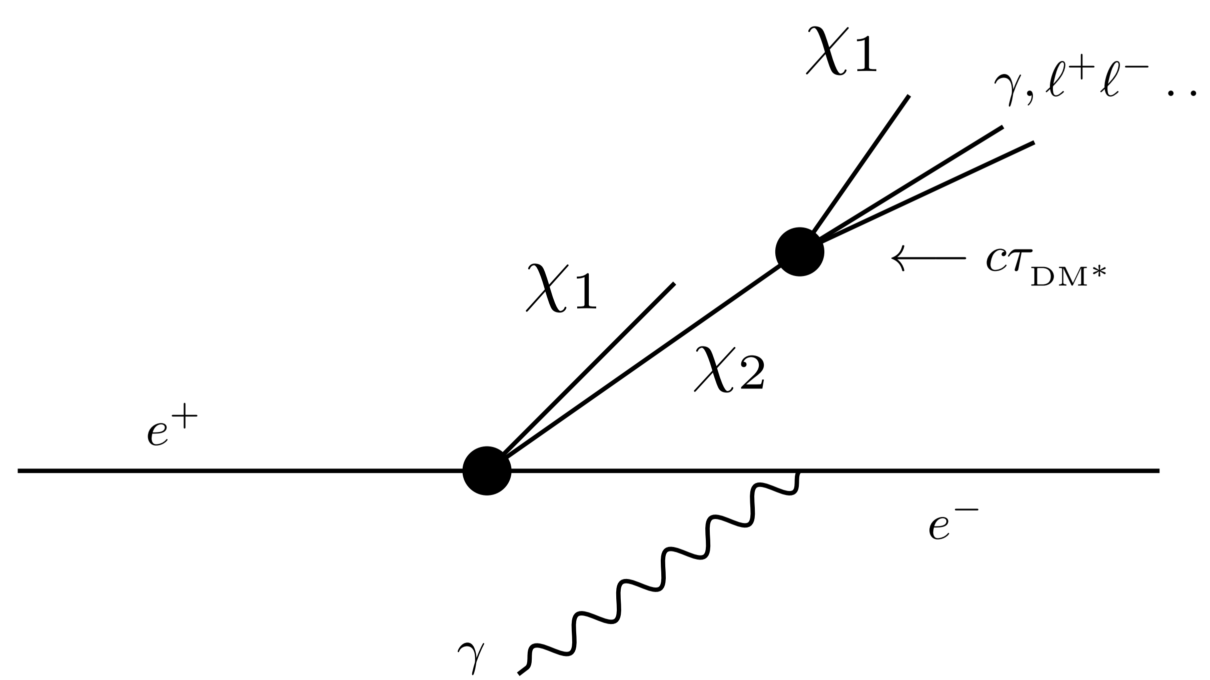
Hadron Collider

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



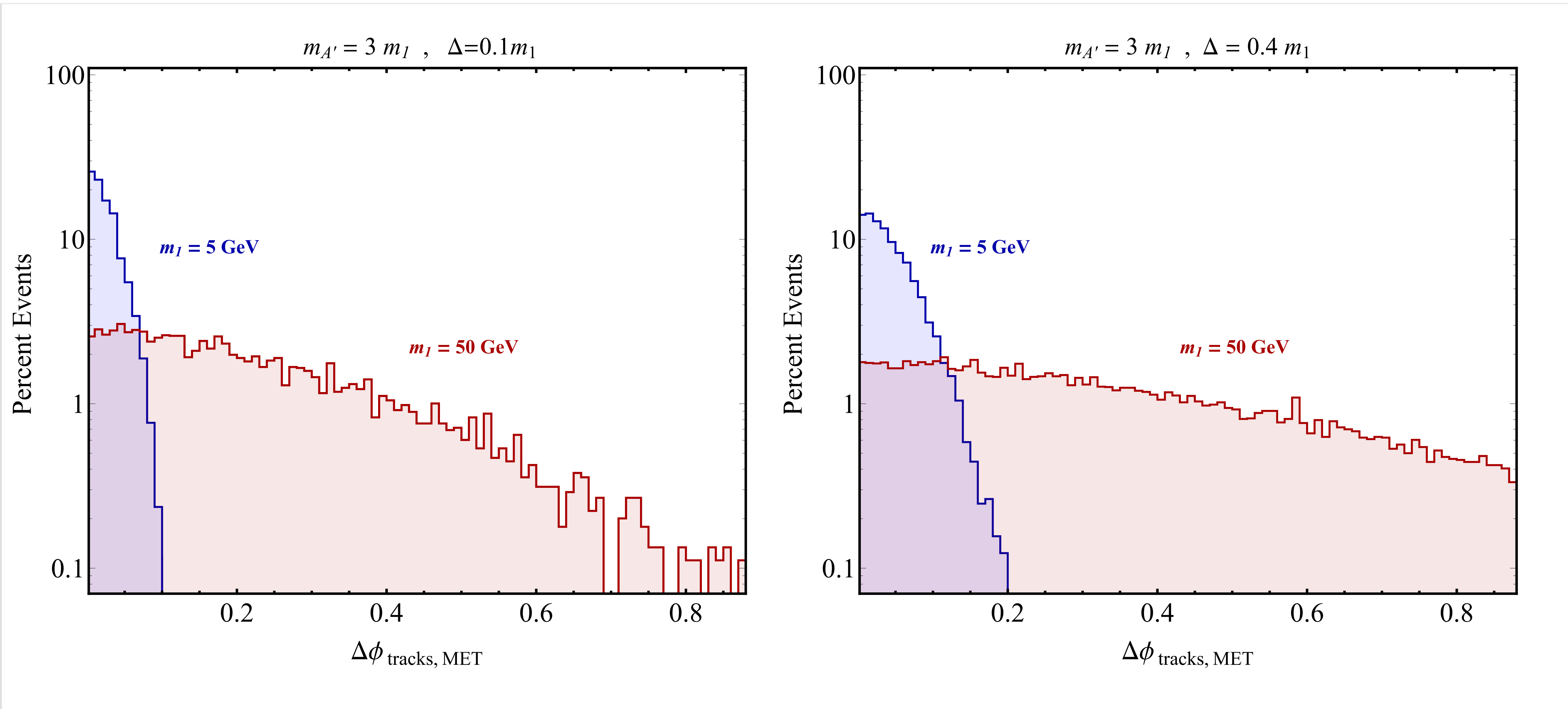
Lepton Collider

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



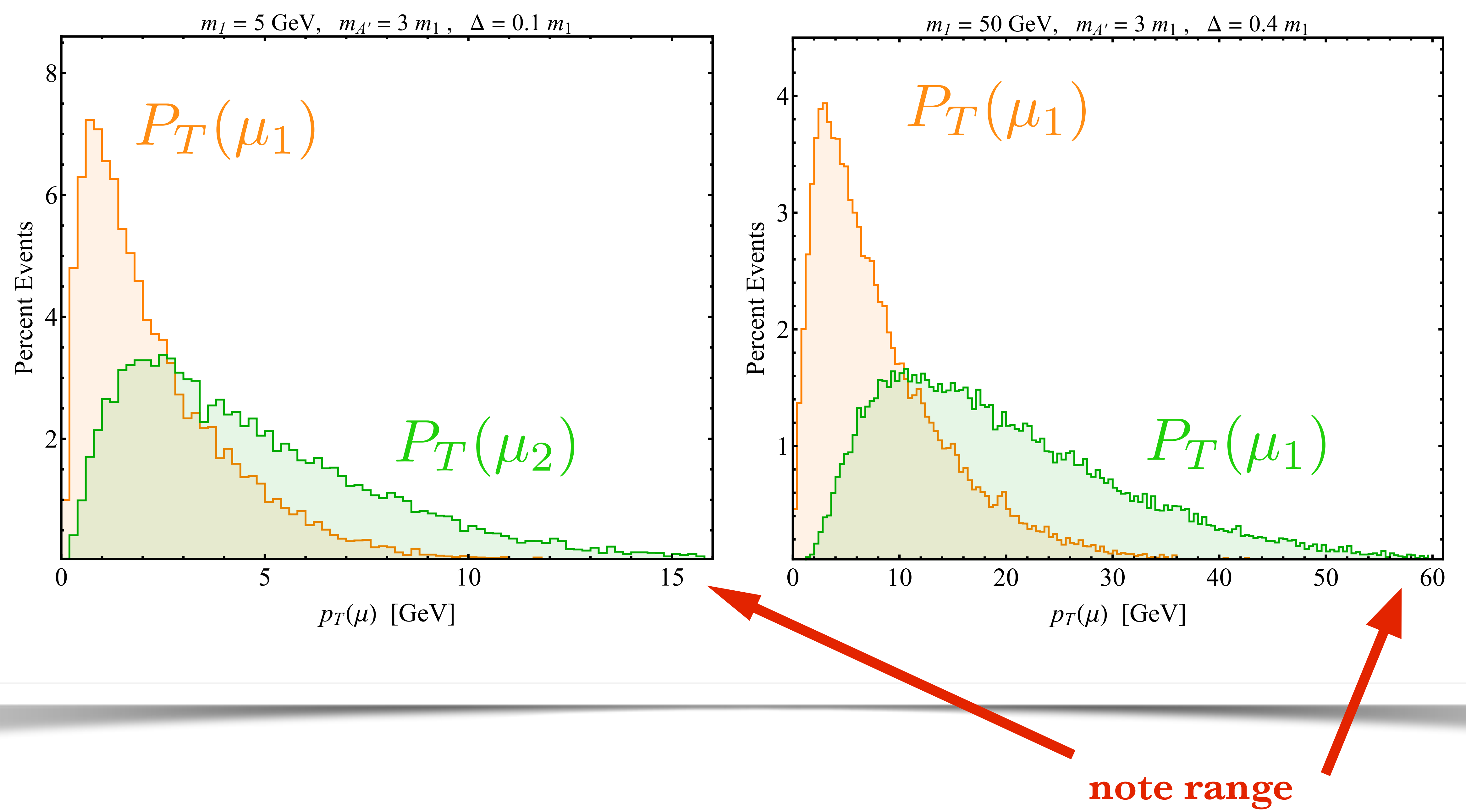
Izaguirre, GK, Shuve
1508.03050

MET/Lepton Correlated



LHC 13 TeV $\alpha_D = 0.1\ ,\ m_1/m_{A'} = 1/3$

Signal Feature(Bug): Soft Leptons



LHC 13 TeV $\alpha_D = 0.1\ ,\ m_1/m_{A'} = 1/3$

LHC 13 Signal Region

- Trigger on monojet + $\not{E}_T > 120$ GeV
- Leading jet $P_T(j) > 120$ GeV
- Leading jet & $\not{E}_T$ back-to-back
- Displaced muon jet $\sim$ 1mm - 30cm
- Muon $P_T(\mu) > 5$ GeV
- Muons not isolated $|\Delta\phi(\not{E}_T, \mu J)| < 0.4.$

BaBar/Belle Search

$$e^+e^- \to \gamma A' \to \gamma \chi_1 \chi_2 \to \gamma \not{E} + \ell^+ \ell^-$$

Potential BGs low:

Hadronic resonances (can reconstruct)

Conversion from $e^+e^- \to \gamma\pi^+\pi^-$ $e^+e^- \to \gamma\gamma$

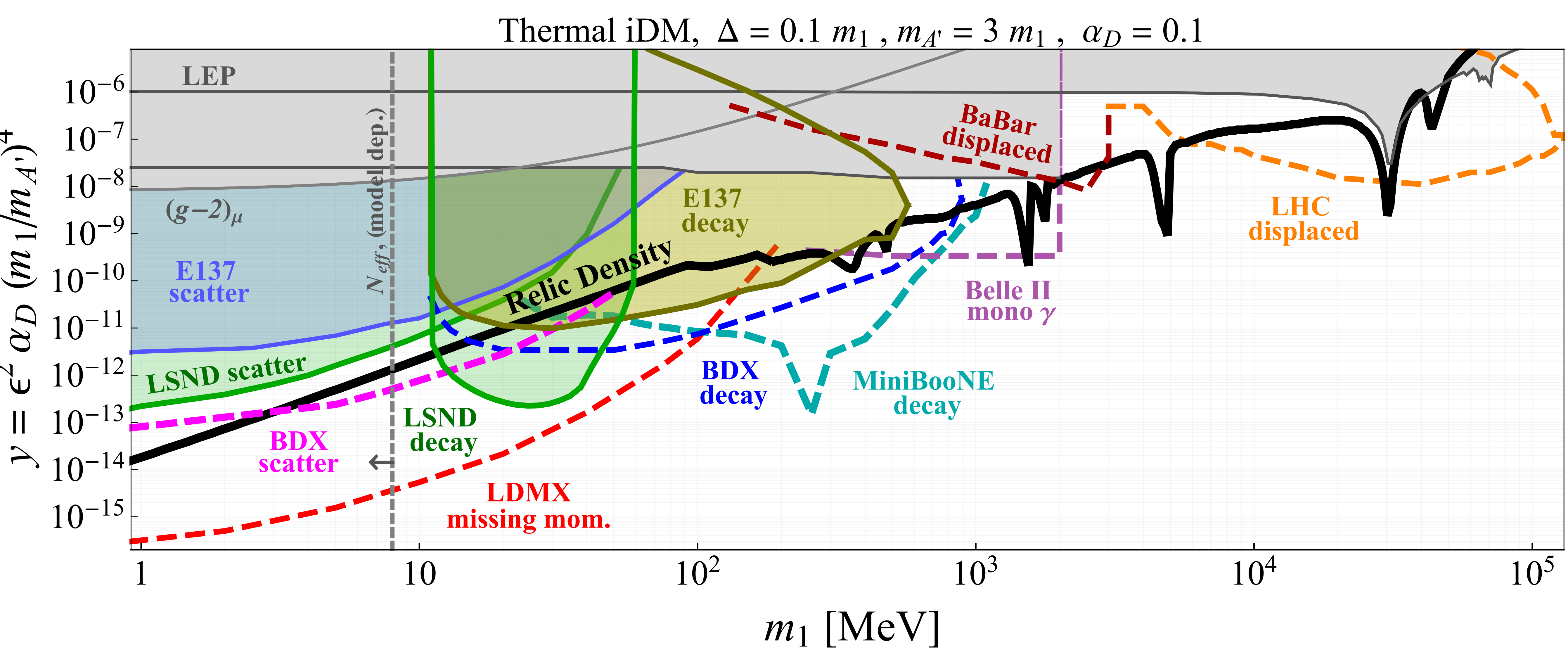
reducible w/ missing mass and displacement

Signal Region

- Trigger on lepton p > 100 MeV
- Transverse impact param. ~ 1mm - 30cm

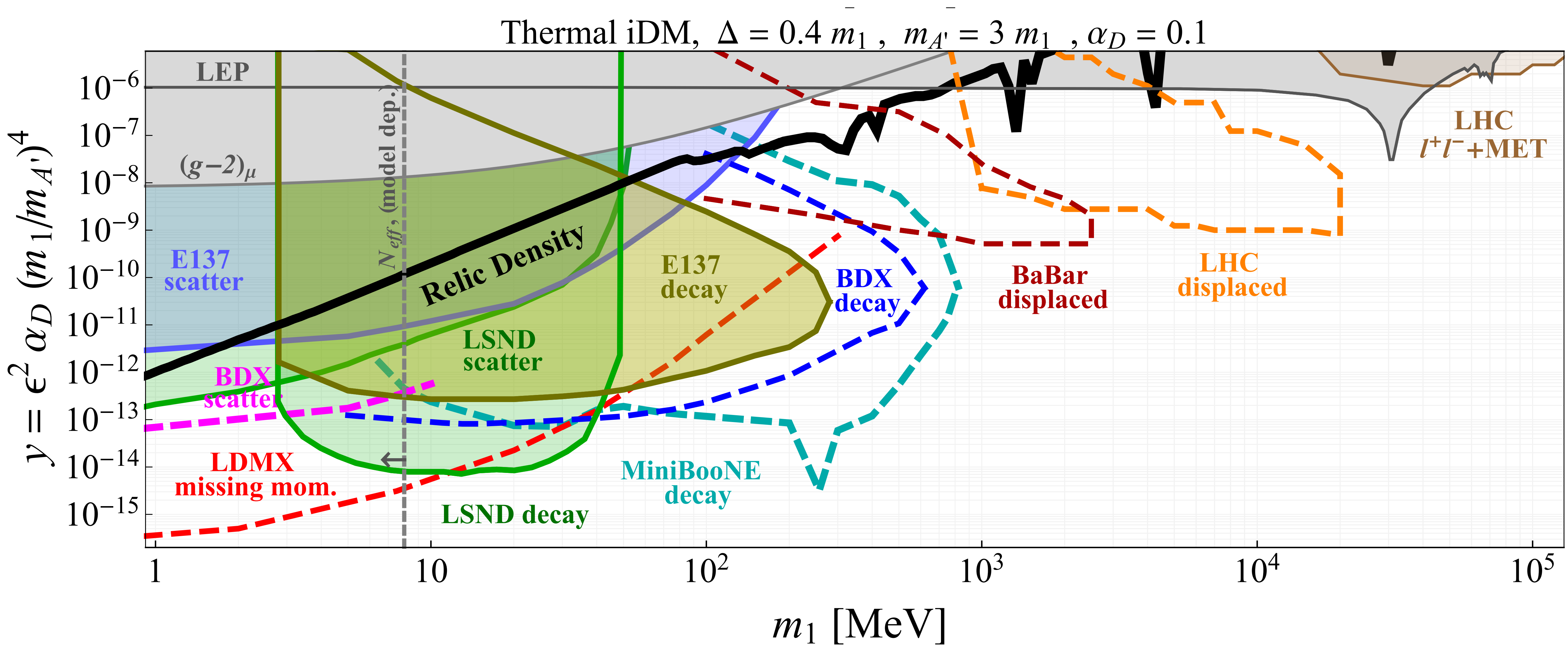
Collider Complementarity

Small Splitting ~ 10%



Collider Complementarity

Large Splitting ~ 40%



Conclusion

Coannihilation Freeze Out

- Two level dark sector (pseudo-Dirac example)
- Mass difference changes freeze out
- Need *larger* couplings (increases with splitting!)

Fixed-Target, Neutrino, & B-Factory Experiments

- Still have scattering / missing energy searches
- Also have powerful decay searches for excited state
- Other experiments? SeaQuest, DUNE, NOvA

Can Test Nearly All Scenarios

- Increasing the splitting doesn't decouple the bounds
- Collider displaced vertex searches @ higher masses
- Covering splittings up to ~ 50% gets everything!

LHC Backgrounds

Leptons from photon conversion in detector

$$pp \to j\gamma Z \to j\gamma(Z \to \nu\nu)\ ,\ \sigma \approx 100\ \text{fb}$$

Reduction Strategy

- Veto (leptons point to detector region)
- Veto (strict lepton isolation)
- Veto (dilepton invariant mass near ~ 0)
- Demand muons, reduce conversion prob.
  $(m_e/m_\mu)^2 \approx 10^{-5}$

Verdict: Very Small

LHC Backgrounds

Leptons from displaced QCD Processes

Difficult to calculate fully, but can estimate by demanding:

- QCD event w/ hard jet + 2 muons
- Muon displacement 1cm - 30 cm
- Point of closest approach < 1 mm

Total prob. $\sim 10^{-7} \implies \sigma_{\rm QCD,BG} < 100$ fb

All this is before demanding large MET

Verdict: Probably Very Small

Similar argument for j + W/Z BG

LHC Backgrounds

Pile Up

High Impact-parameter muons from other vertex

- Signal muons highly collimated from decay of boosted particle
- Dimuon momentum points back to primary vertex
- Same primary vertex as leading jet

Verdict: Probably Very Small, Very Reducible

LHC Backgrounds

Jets + di-tau

Boosted taus decay to yield displaced muons

- Total cross section $\sim$ 10 fb
- Add muon decay penalty $\sim$ 0.1 fb
- Also need both to decay within $\sim \mu$m
- Dimuon distribution will be different (single parent)

Verdict: Very Small, Very Reducible