Testing Light Dark Matter Coannihilation w/ Fixed-Targets

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LDMA'17

Overview

- **DM Coannihilation (<GeV)**

  Models & Milestones

- **New Accelerator Searches**

  Proton & Electron Beams

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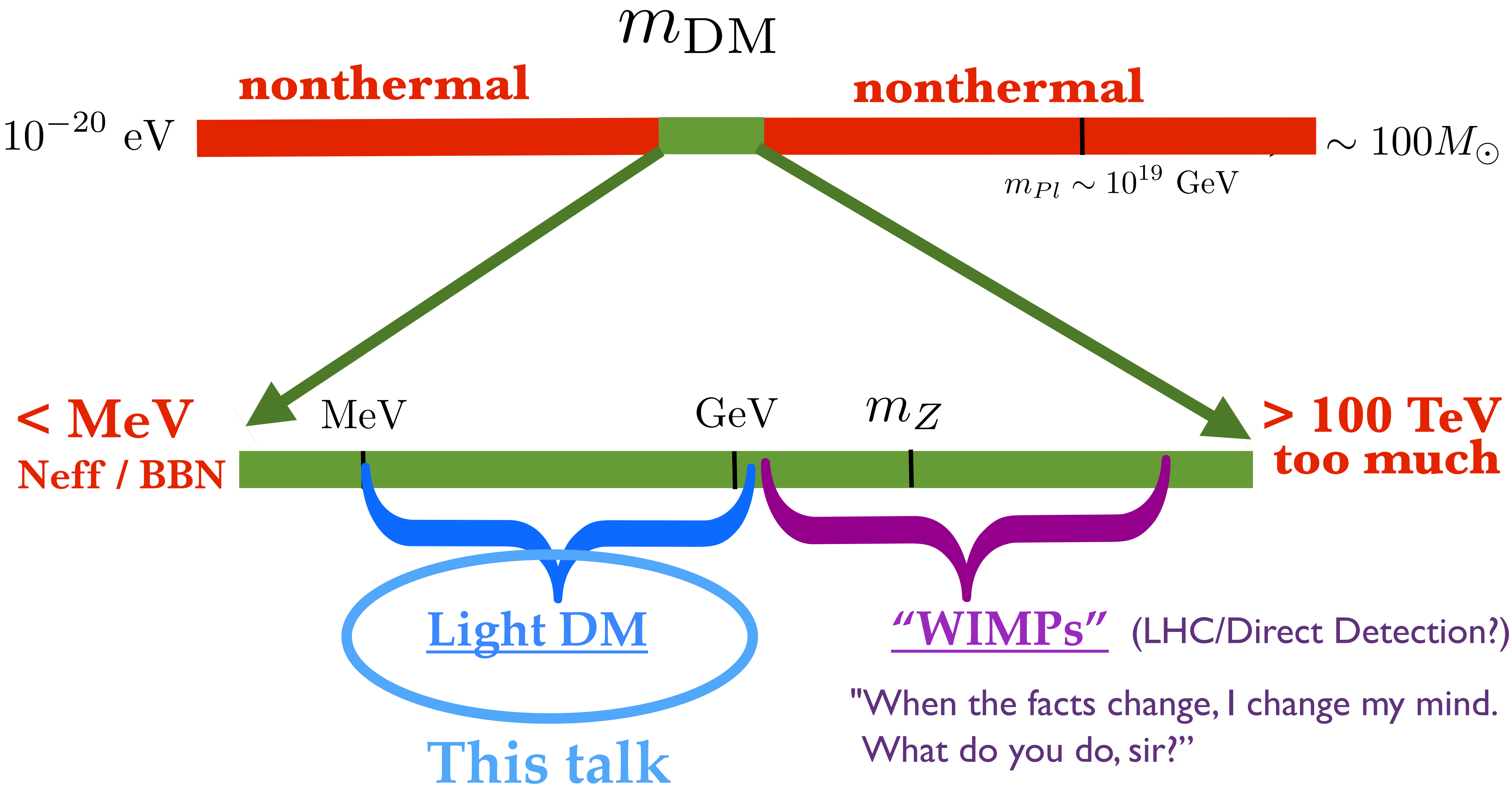
Thermal Equilibrium Narrows Viable DM Mass Range



(LHC/Direct Detection?)

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

- John Maynard Keynes

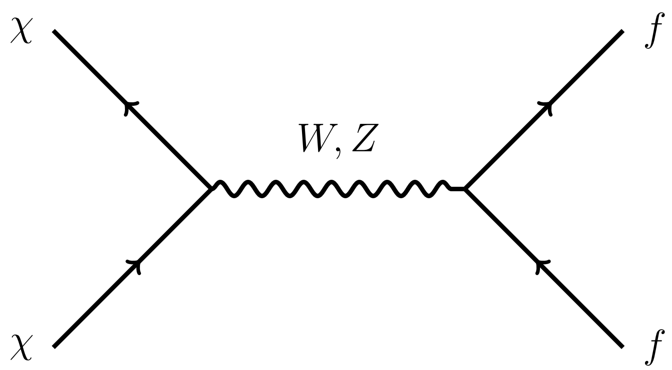
< GeV Model Building

DM must be a SM singlet

Else would have been discovered (LEP…)

Even if it weren't, freeze out still needs new forces

DM overproduced unless there are light new "mediators"



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

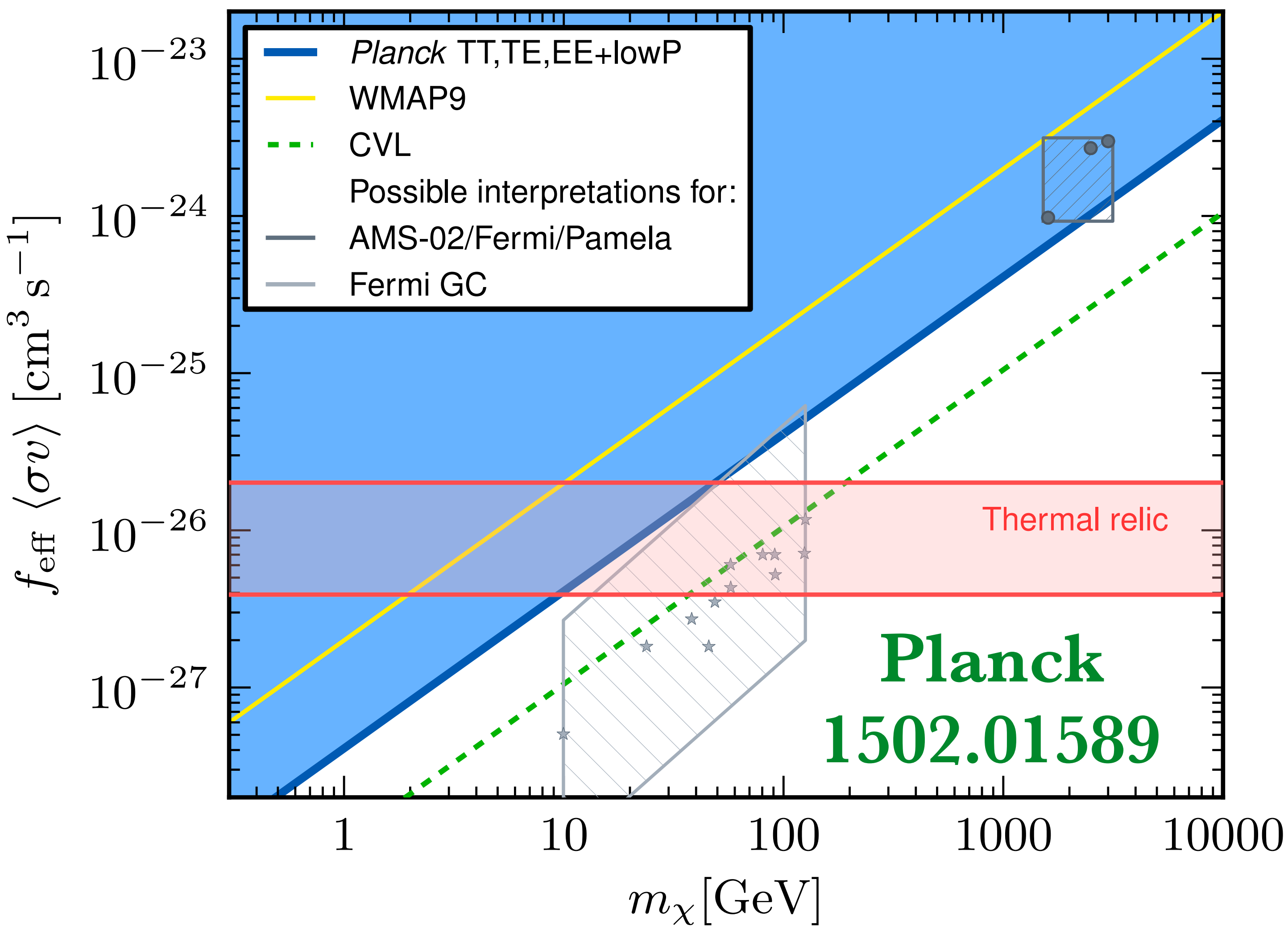
Lee / Weinberg '79

Simplicity: can't use higher dimension operators

Requires renormalizable interactions

CMB Bounds for light DM

Rules out *s*-wave annihilation < 10 GeV



For viable models need:

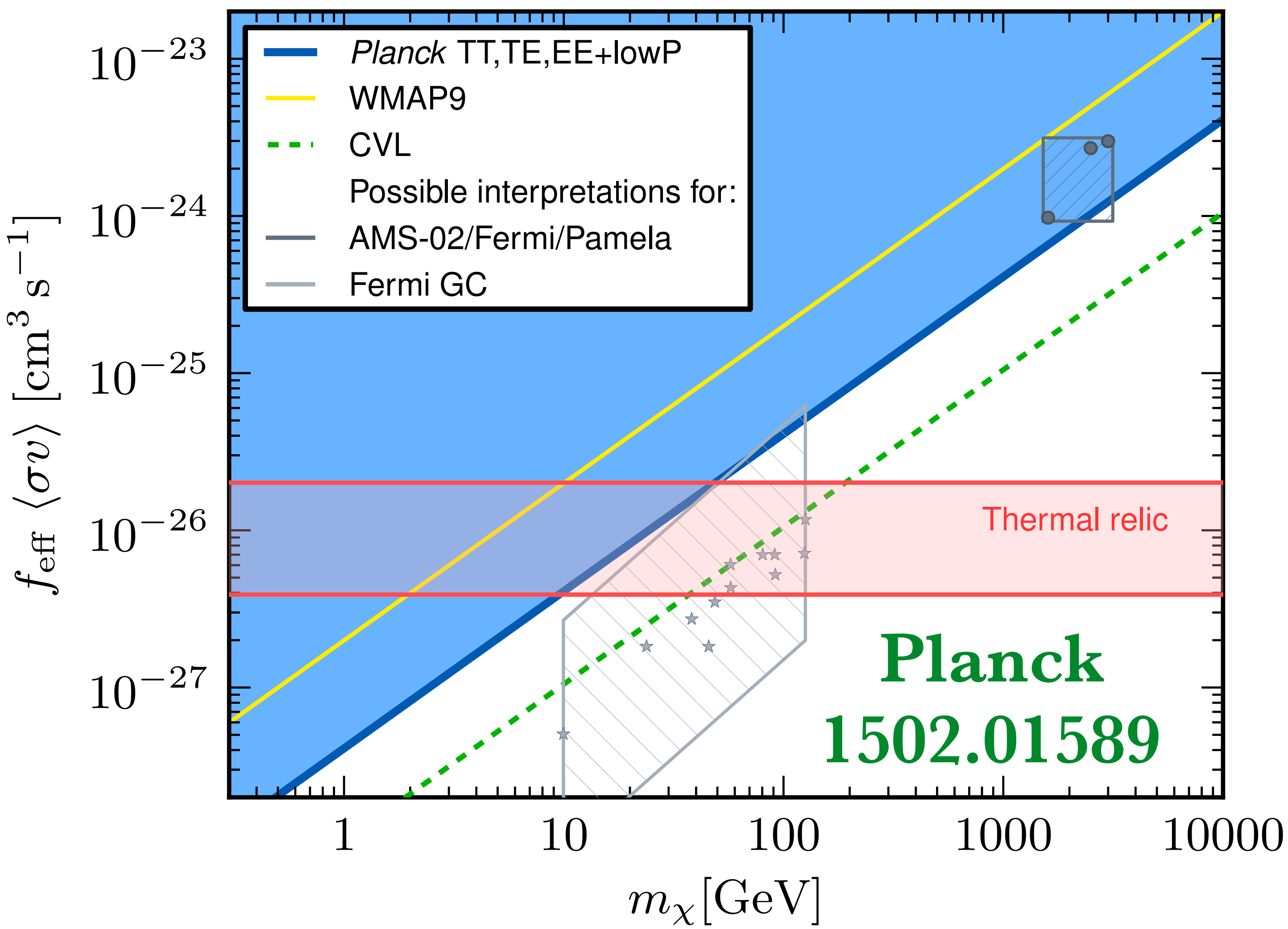
(1) p-wave annihilation

OR

(2) annihilation shuts off before CMB

CMB Bounds for light DM

Rules out *s*-wave annihilation < 10 GeV



For viable models need:

(1) p-wave annihilation

OR

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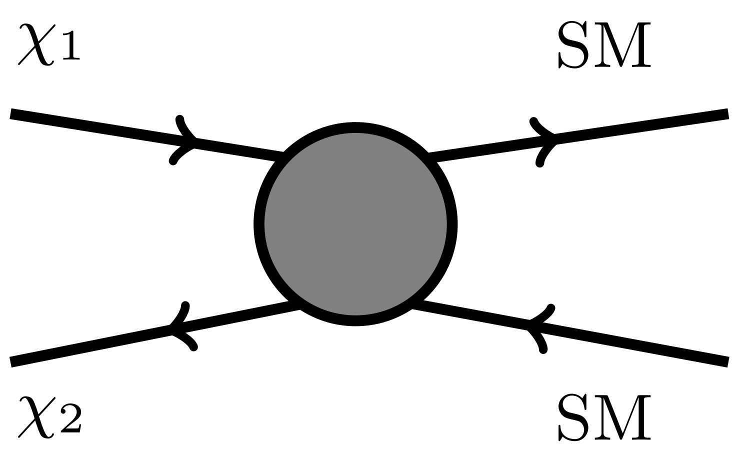
This talk

Coannihilation is CMB Safe

Direct Coannihilation into SM



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

Heavier state gone before recombination $z{\sim}1100$

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

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

Easy to build, large couplings, hard to test!

iDM direct detection: Weiner, Tucker-Smith arXiv: 0101338

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

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Vector current

Dirac mass

Charge 2 dark Higgs

Break dark U(1) with dark Higgs VEV

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

Dirac

Majorana

Representative Model

Four component fermion + dark photon

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Vector current | Dirac mass | Charge 2 dark Higgs

Break dark U(1) with dark Higgs VEV

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

Dirac | Majorana

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

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

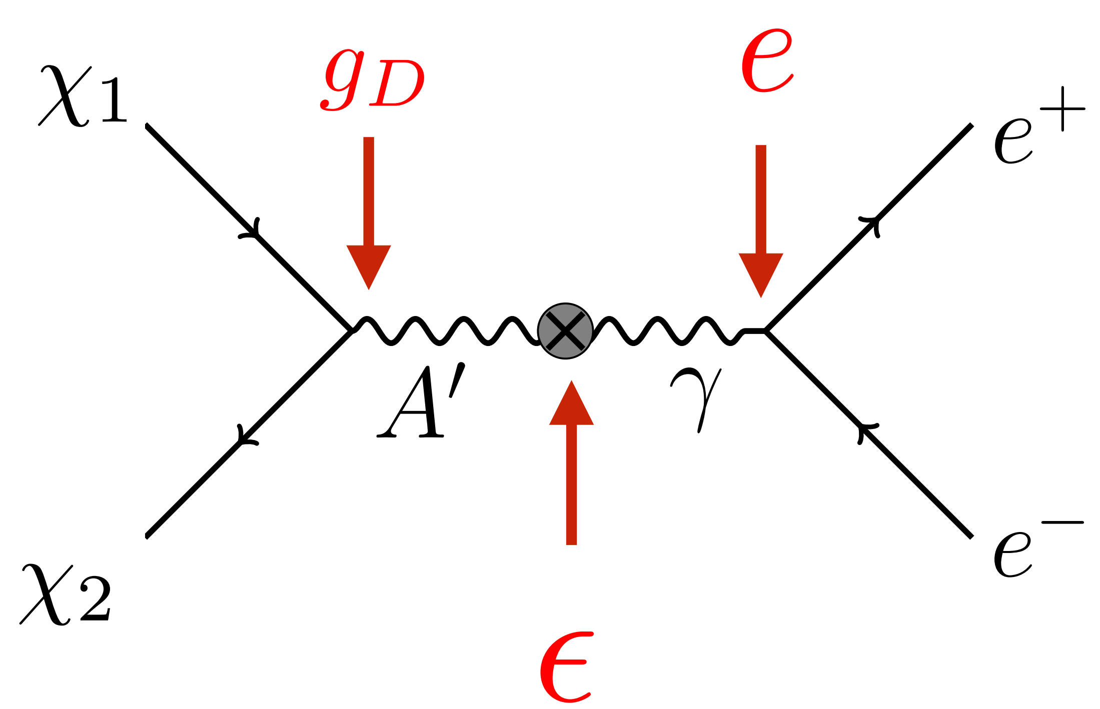
int. eigenstates → mass eigenstates

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

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

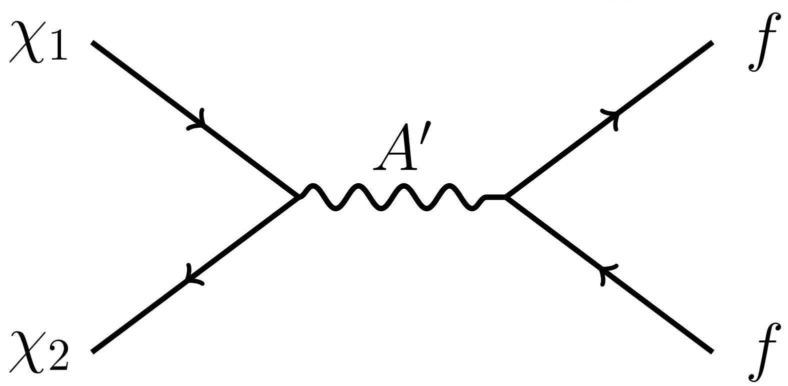
$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$

opposite regime not CMB safe

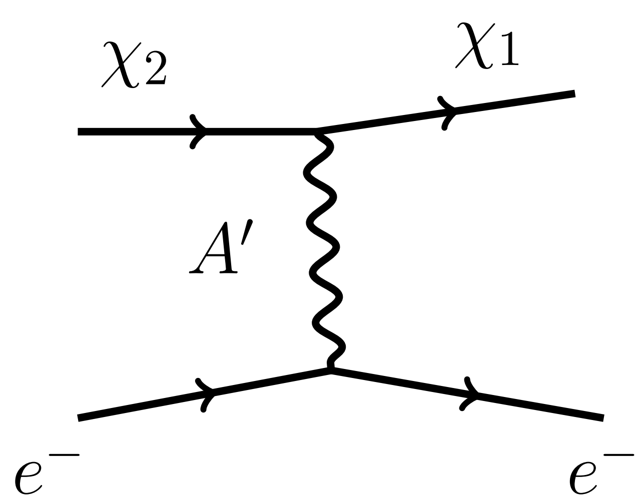
$\chi_1 \chi_1 \to A' A'$ **(s-wave)**

Inelastic Novelties

Coannihilation

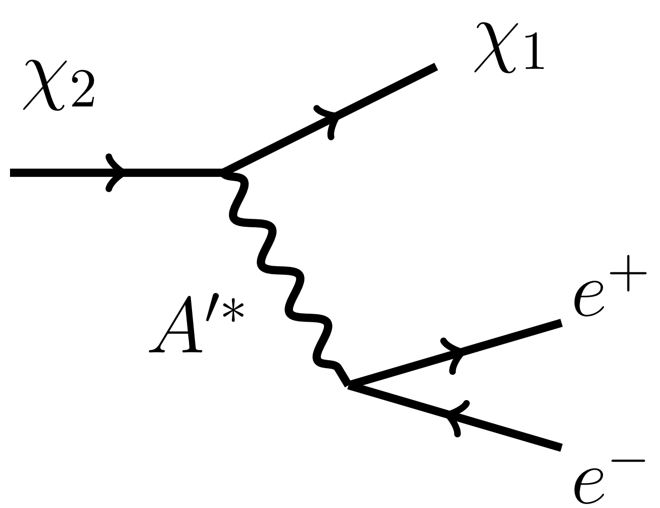


Upscattering & Downscattering

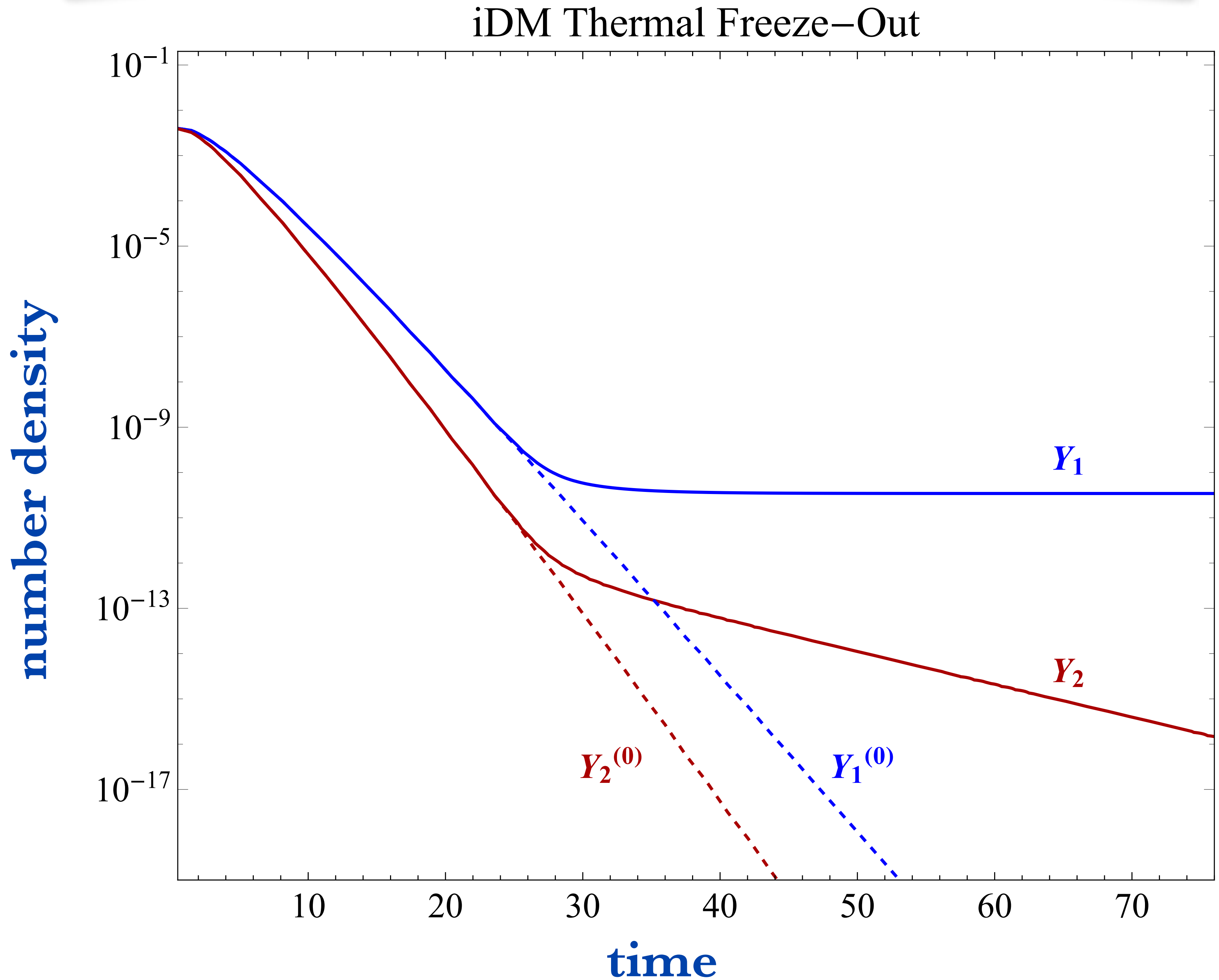


Excited State Decays

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



Coannihilation Relics



Heavier state feels Boltzmann suppression earlier

Need larger rate to compensate!

also see Josh Ruderman's talk

Useful Variables

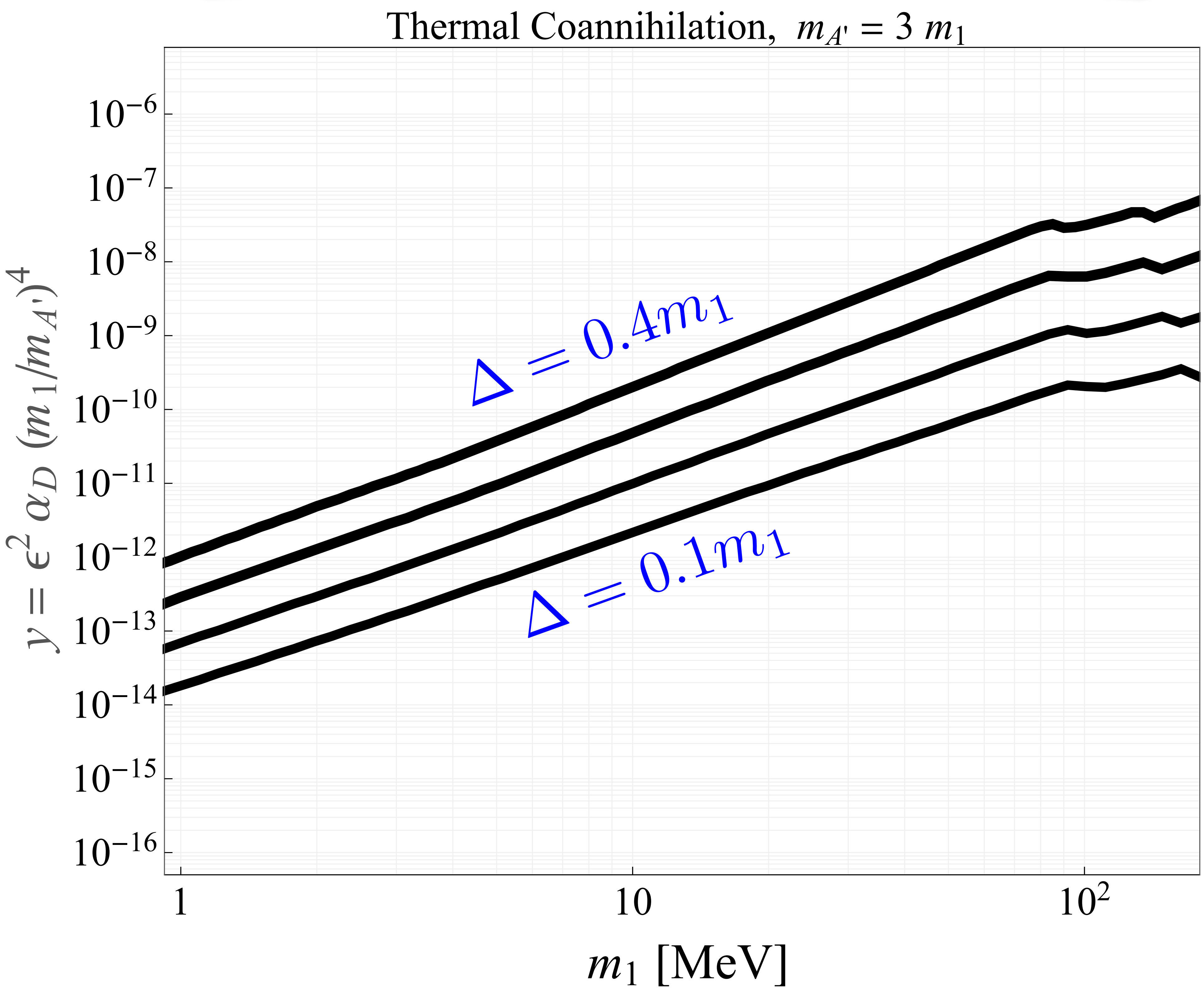
Define new variable optimized for thermal targets

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

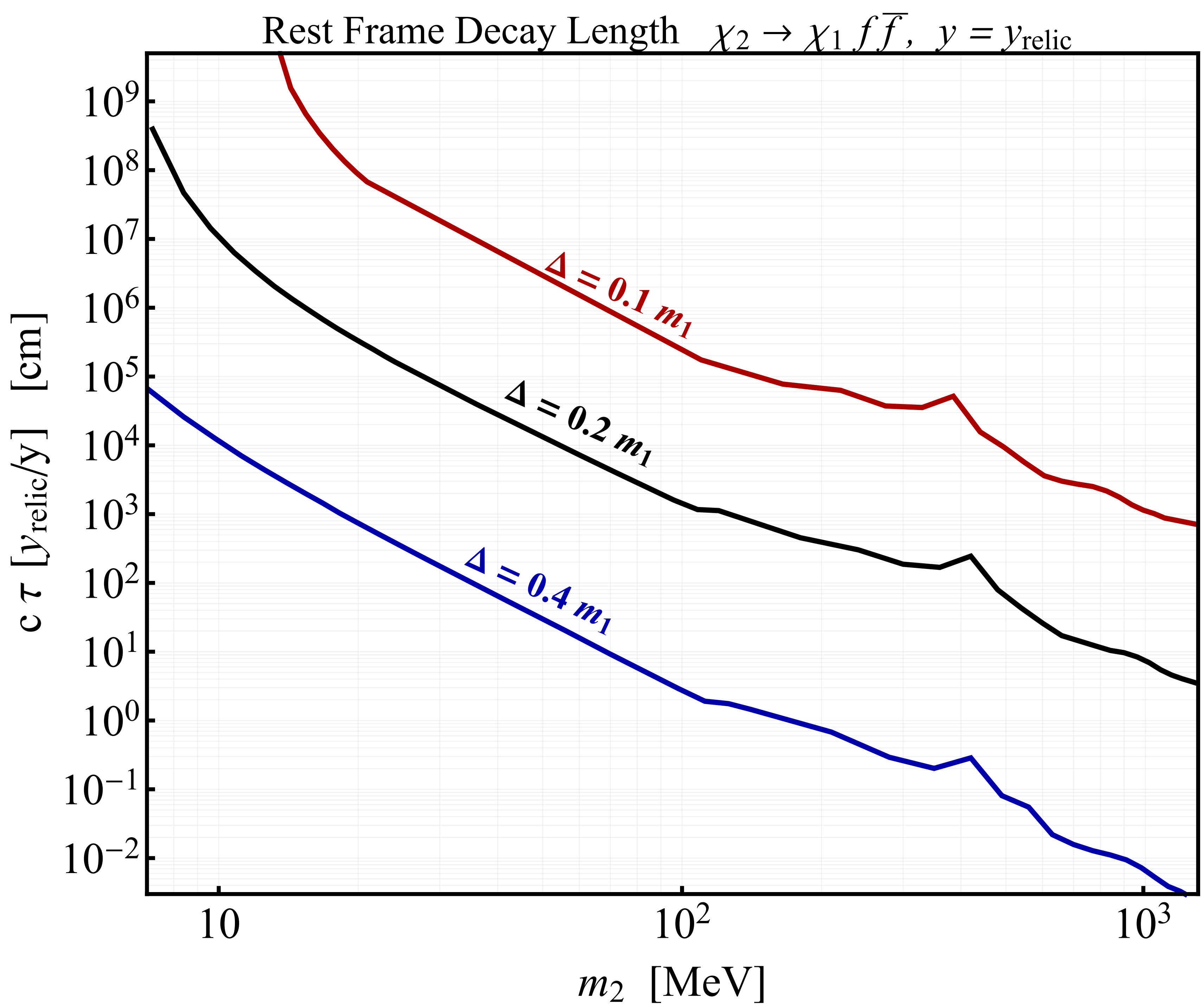
Insensitive to ratios of inputs, unique "y" for each mass and Δ (up to subleading corrections)

Reduces complicated parameter space to 2D comparison

Vary Mass Splitting



Generically Macroscopic Decays



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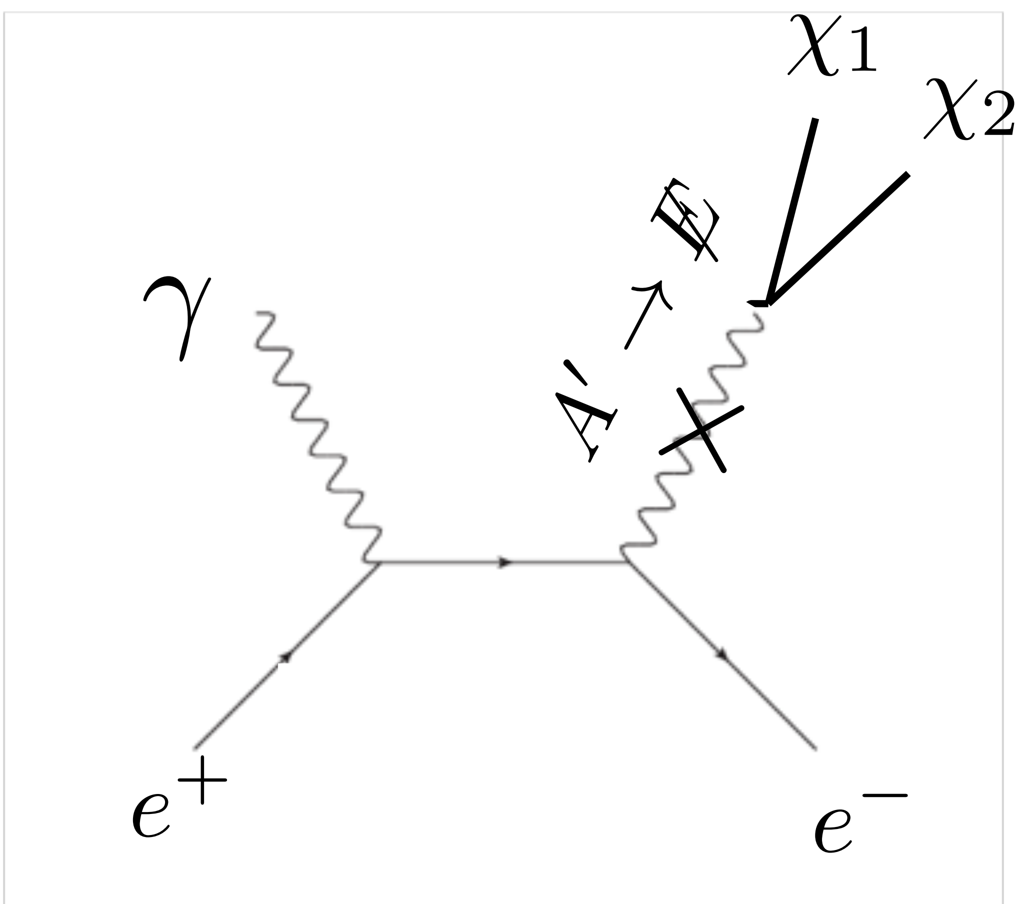
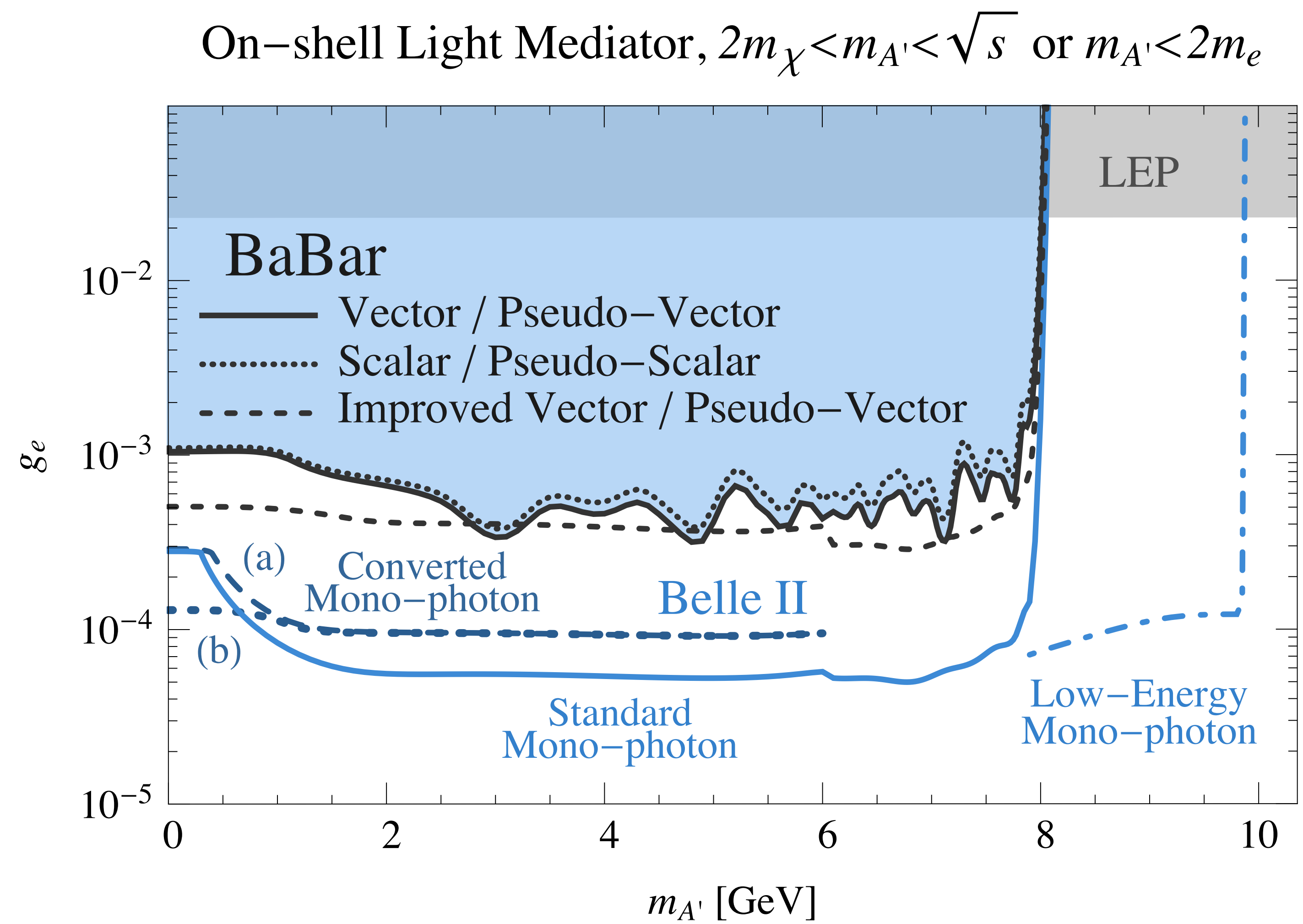
Signatures @ B-Factories

mono photon + missing energy





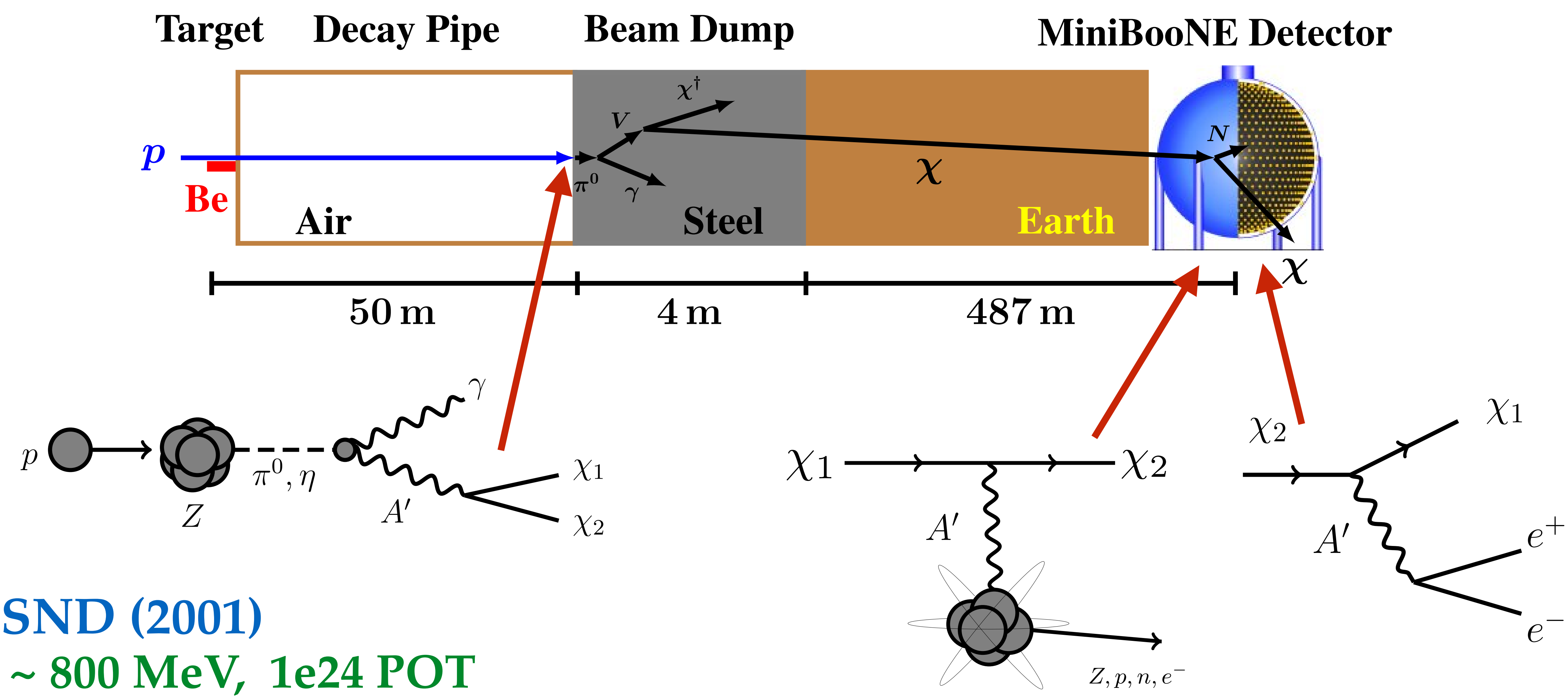
Signatures from displaced vertices and/or missing energy

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

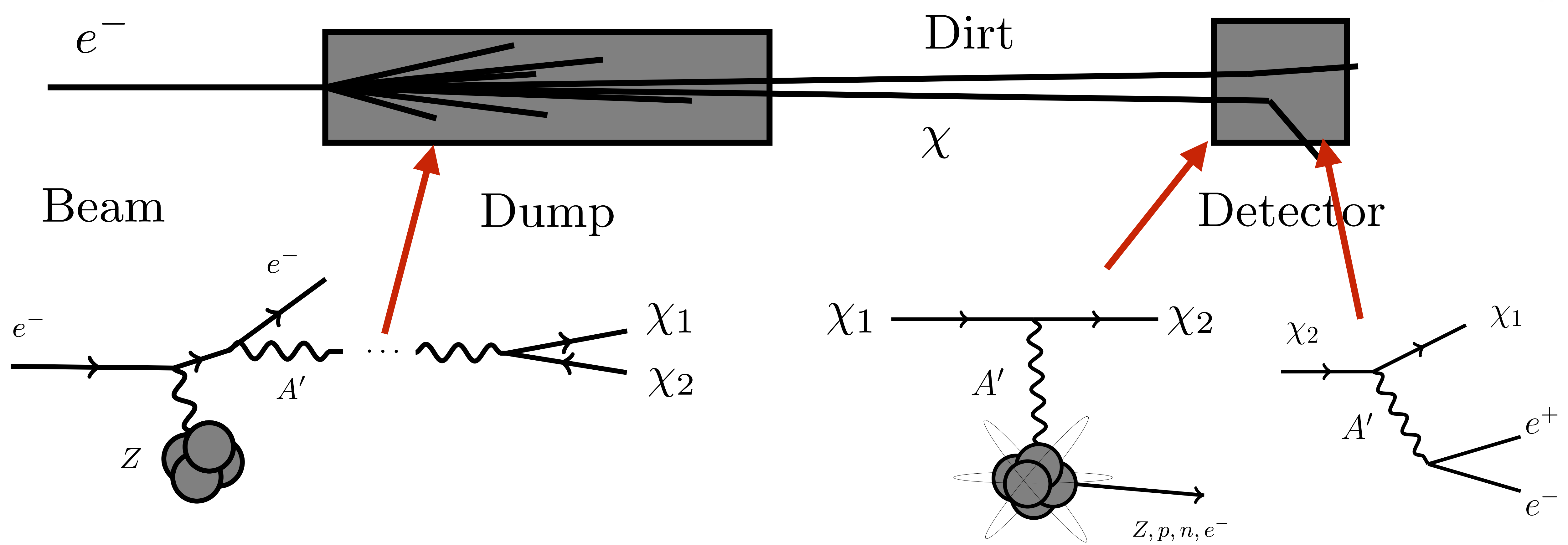
Pi+Eta+Brem

Elastic DM: Batell, Pospelov, Ritz 0903.0363

BdNMC deNiverville, Chen, Pospelov, Ritz 1609.01770

Signatures @ Electron Beam Dumps

(quasi) elastic scattering & decays



E137 (SLAC)

E ~ 20 GeV, 1e20 POT

~ 400 m baseline, no BG

BDX (JLab, proposed)

E ~ 11 GeV, 1e22 EOT

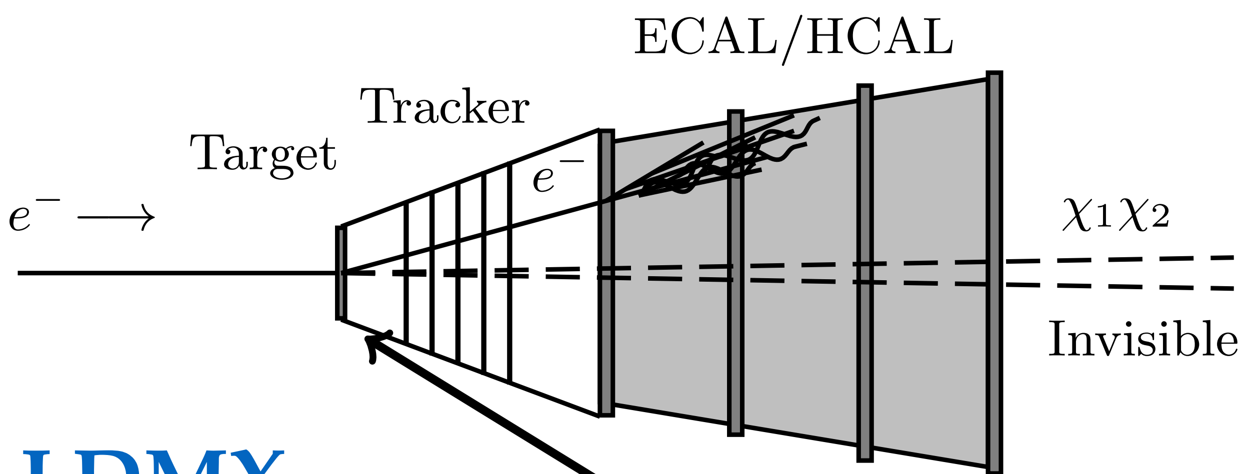
~ 20 m baseline, few BG evts.

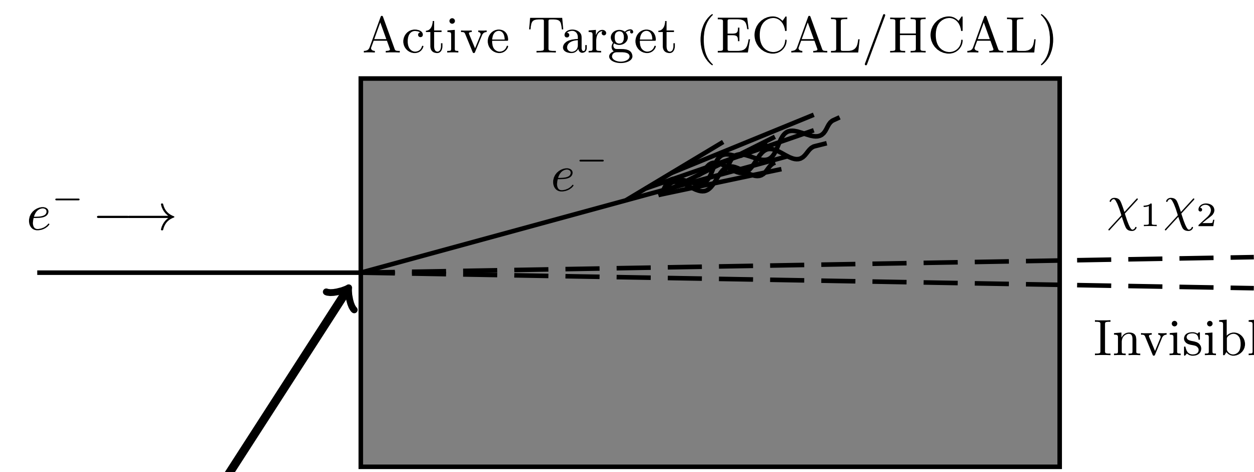
E137 Recast : Batell, Essig, Zurjuron 1406.2698

Izaguirre, GK, Schuster, Toro 1307.6554

BDX Collaboration 1607.01390

Signatures @ Missing Energy & Momentum Experiments

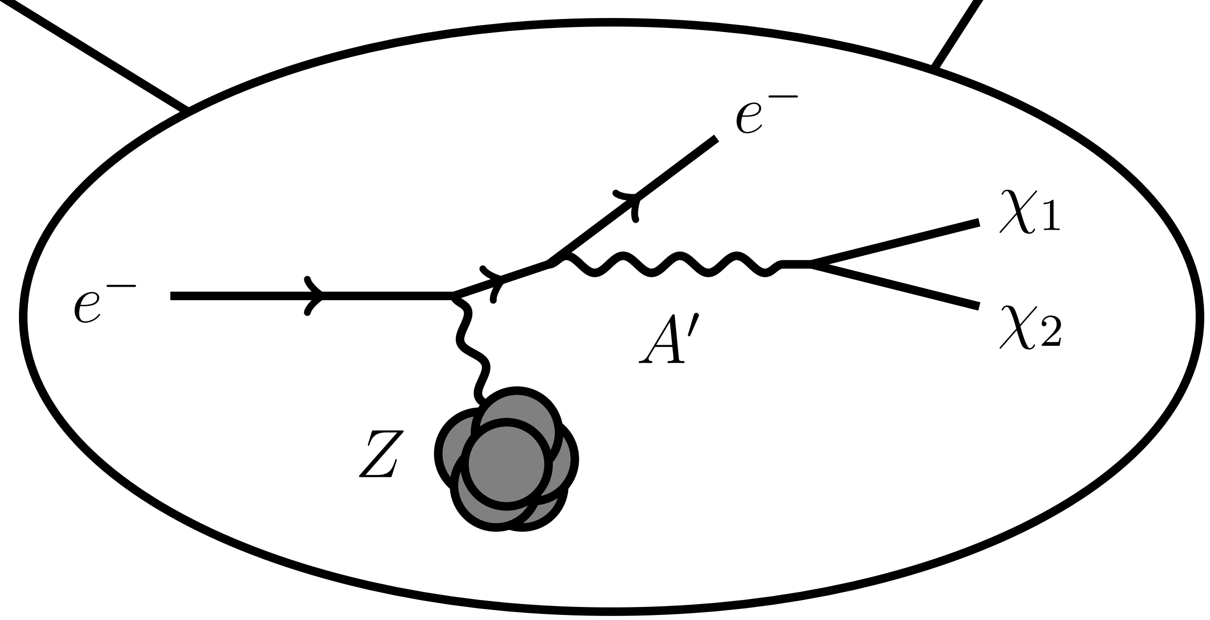




LDMX

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 1307.6554
LDMX Collaboration 1706.XXXXX
https://confluence.slac.stanford.edu/display/MME/Light+Dark+Matter+Experiment

NA64 Collaboration 1610.02988

Comparing to Experiment

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

Some experiments only bound **... independently of this**

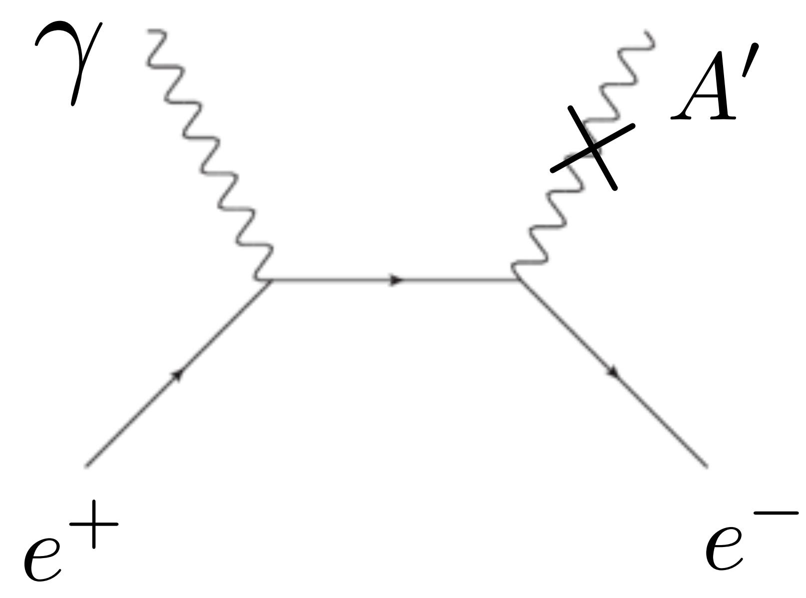
Comparing to Experiment

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

Example: *B*-factory signal $\sigma \sim \frac{\epsilon^2}{E_{\rm cm}^2}$

Conservative "Y" sensitivity

$$y_{\rm exp.} = \epsilon^2_{\rm exp.} \times \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

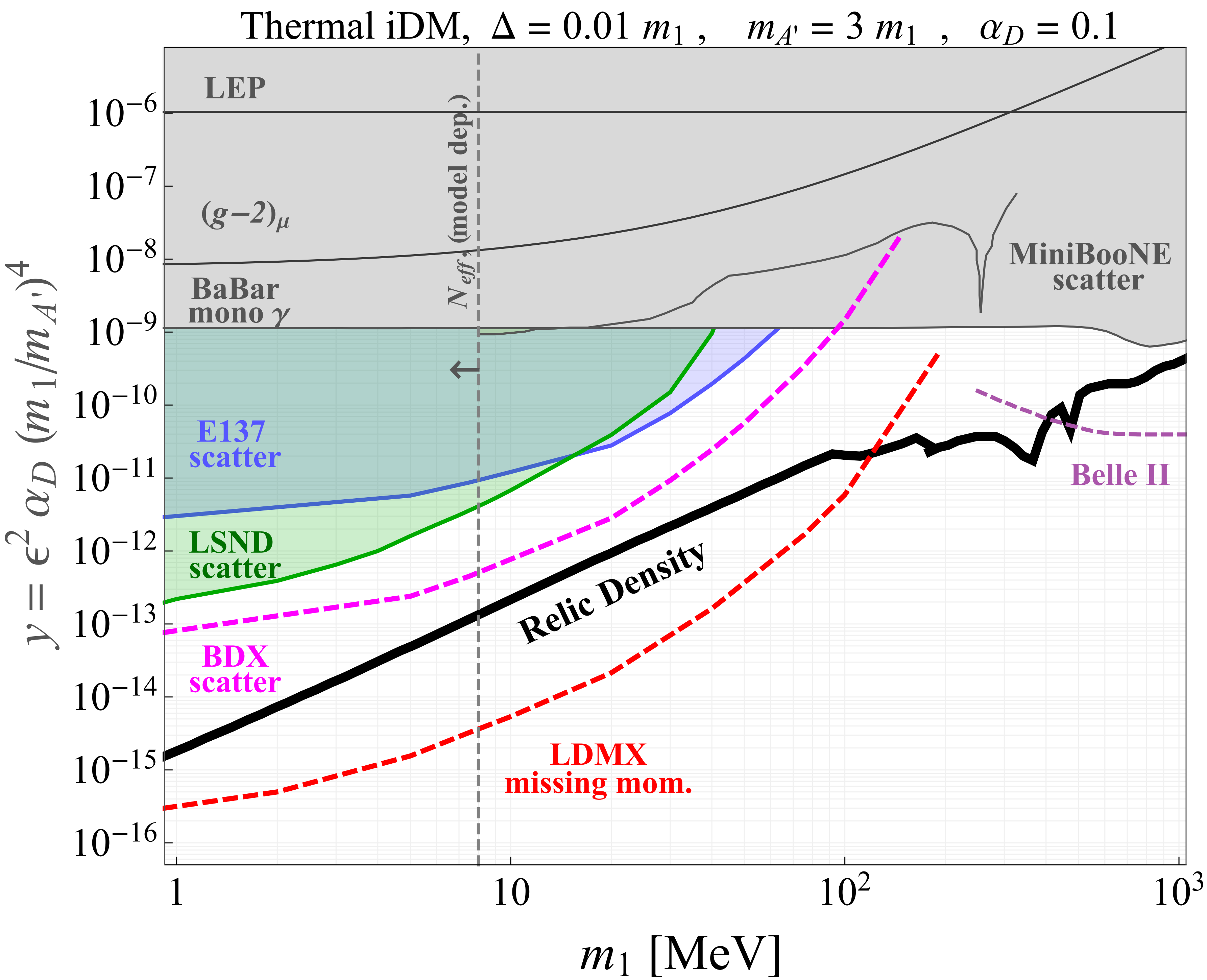


Demand the *weakest limit on* "y" for given bound on ϵ

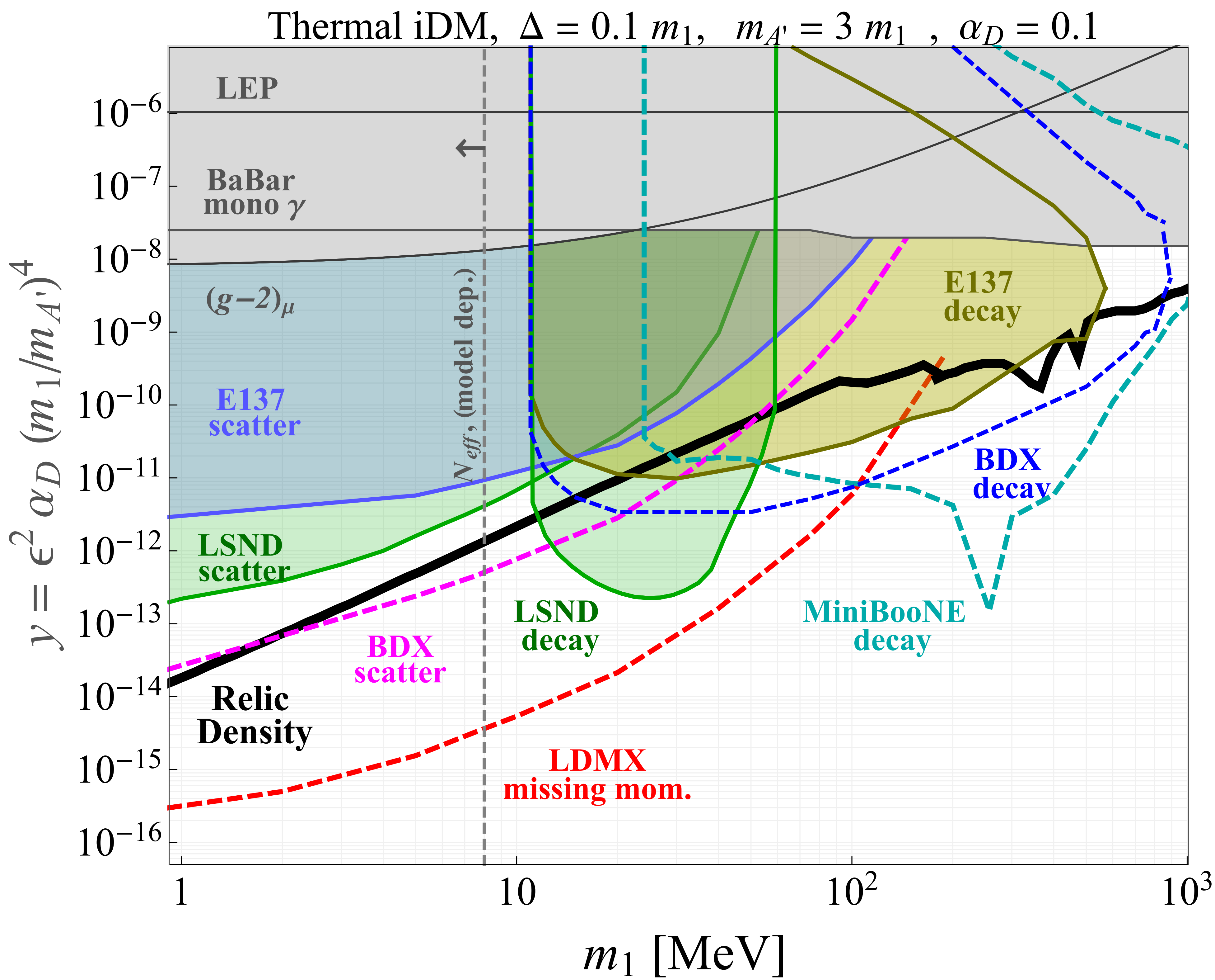
$$\alpha_D \sim \mathcal{O}(1) \quad , \quad m_\chi \sim 2 m_{A'}$$

Maximizing assumed DM params demands smallest ϵ

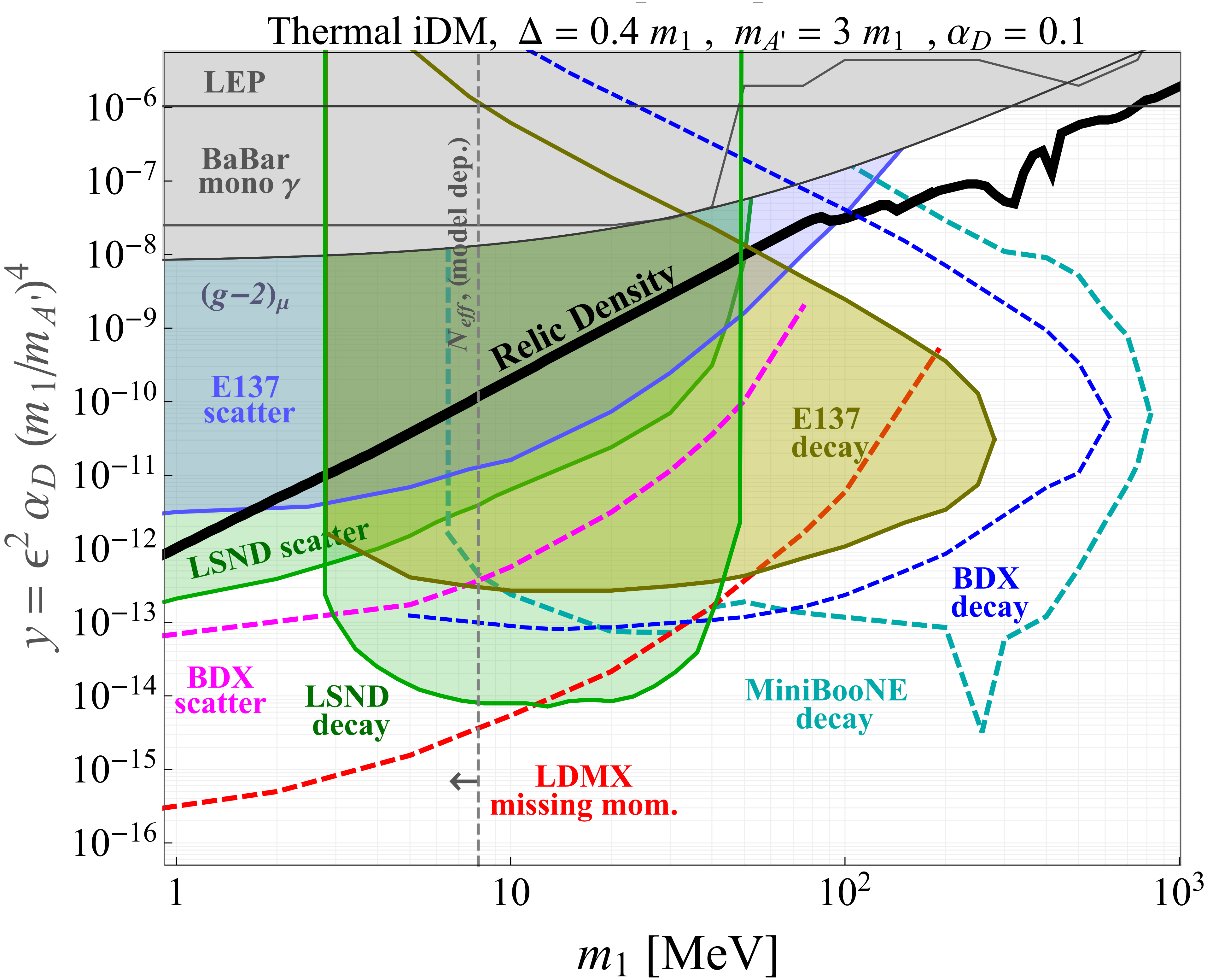
Tiny Splitting ~ 1%



Small Splitting ~ 10%

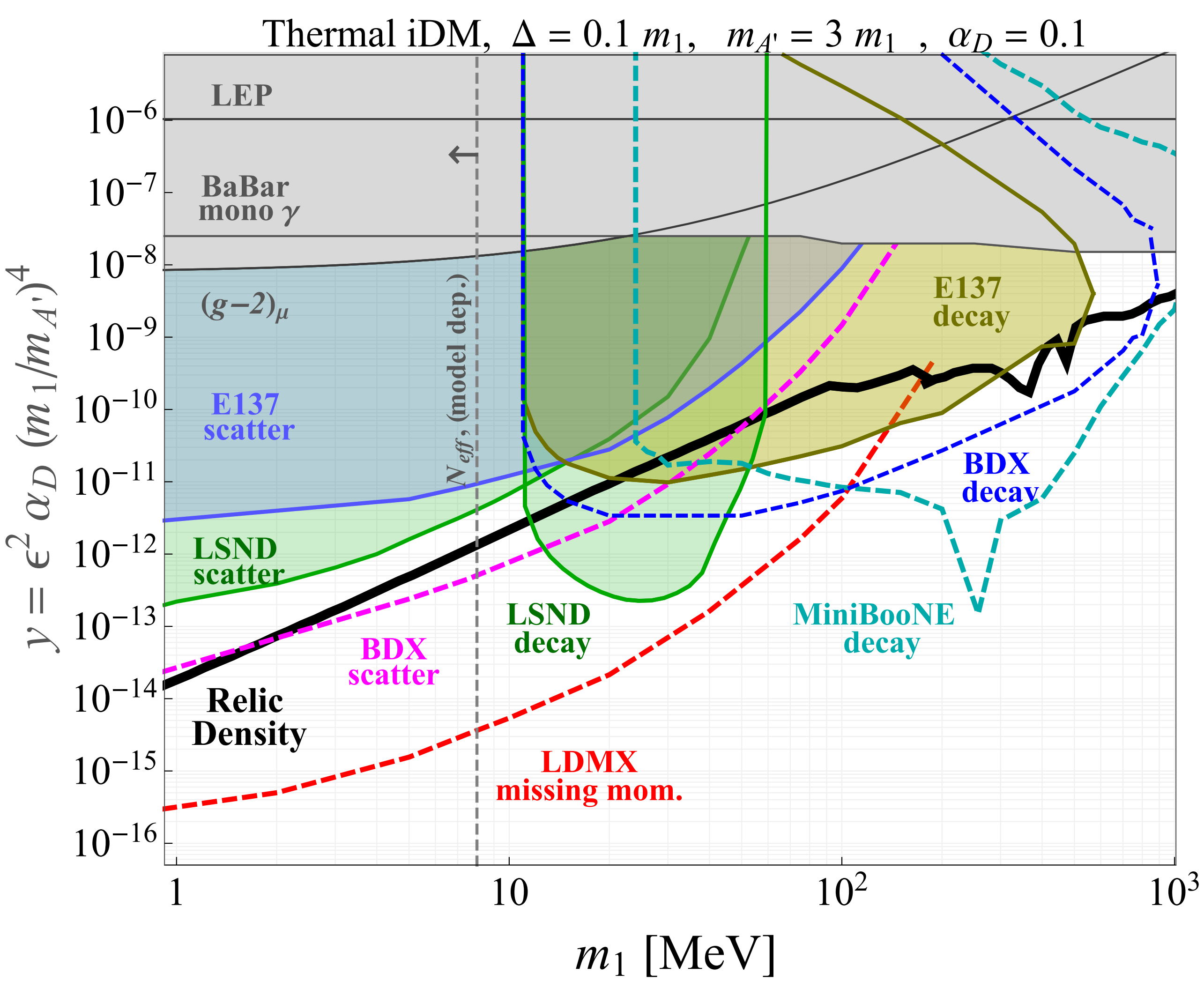


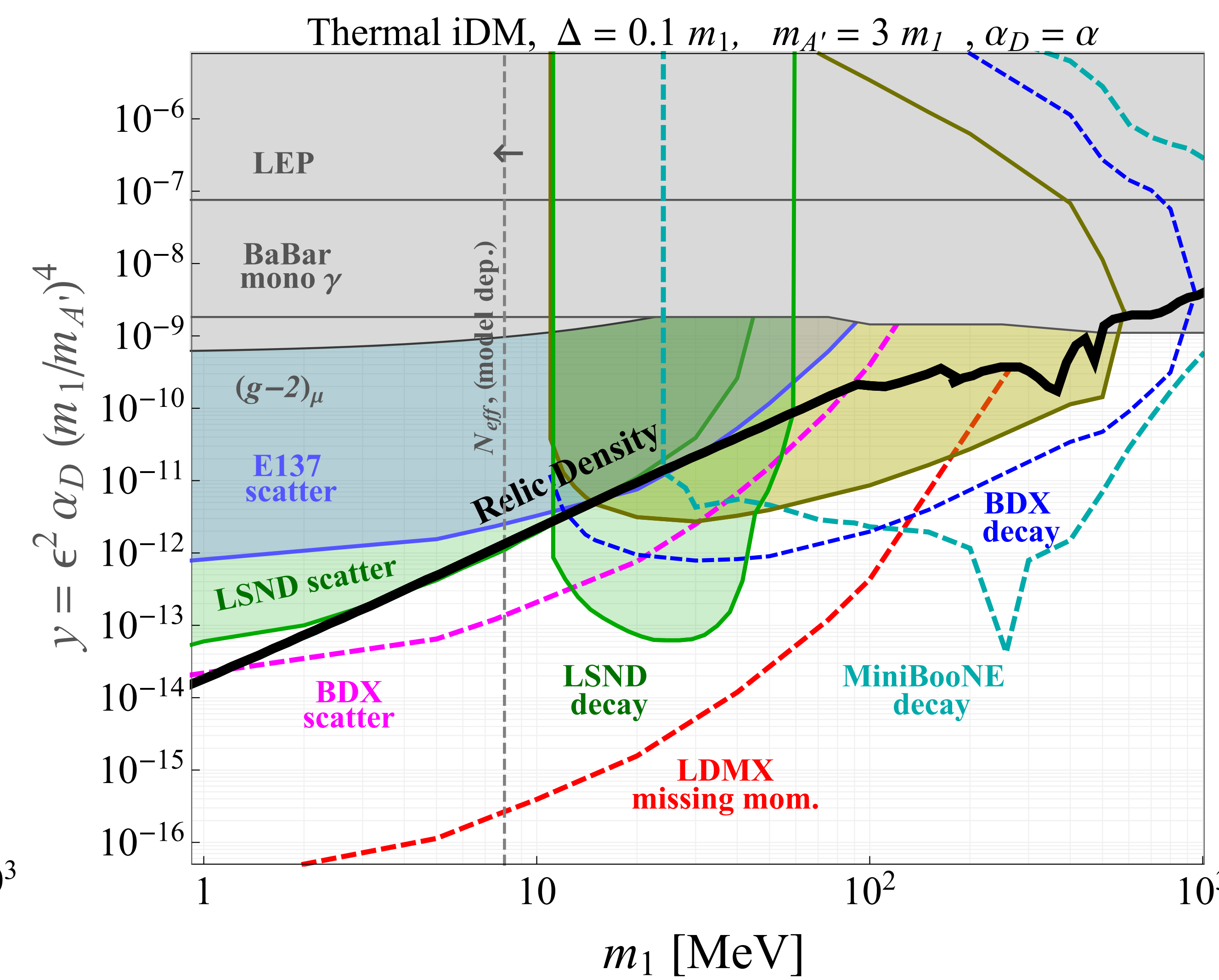
Large Splitting ~ 40%



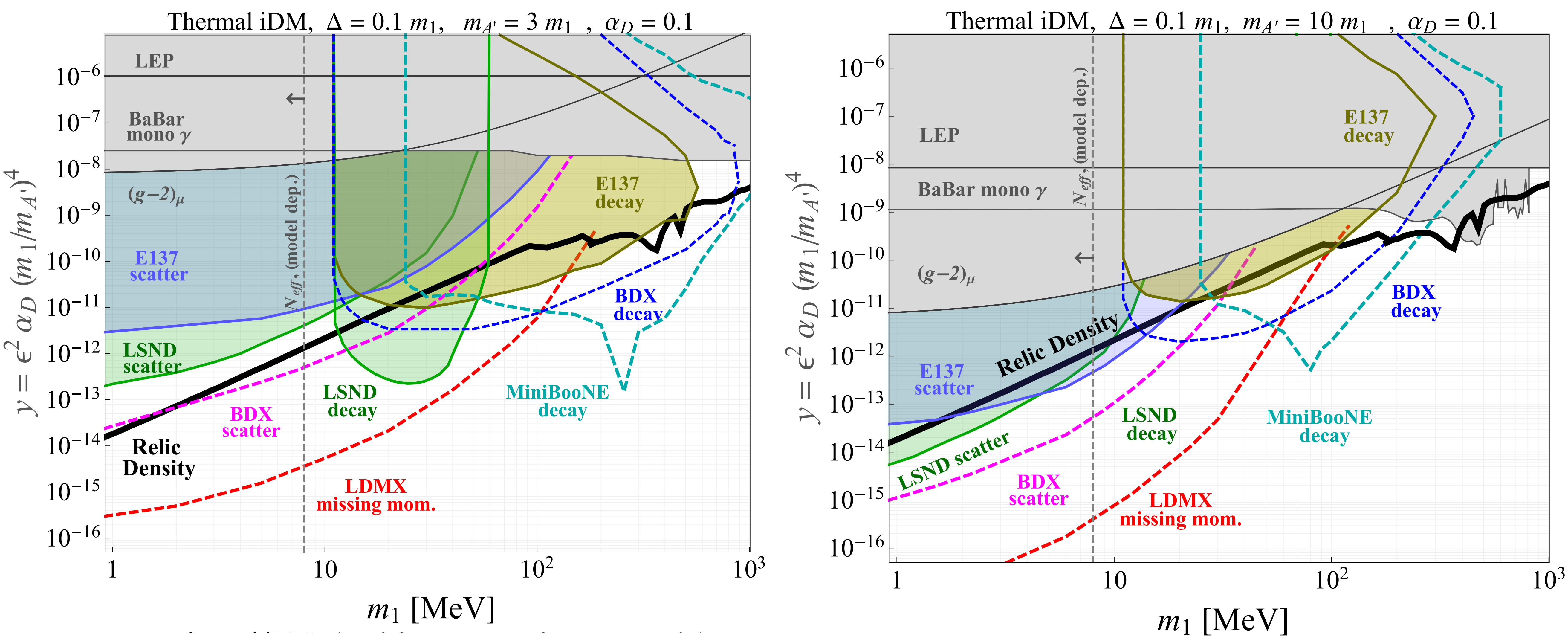
Target moves up, bounds/projections move down

Vary DM/Mediator Coupling





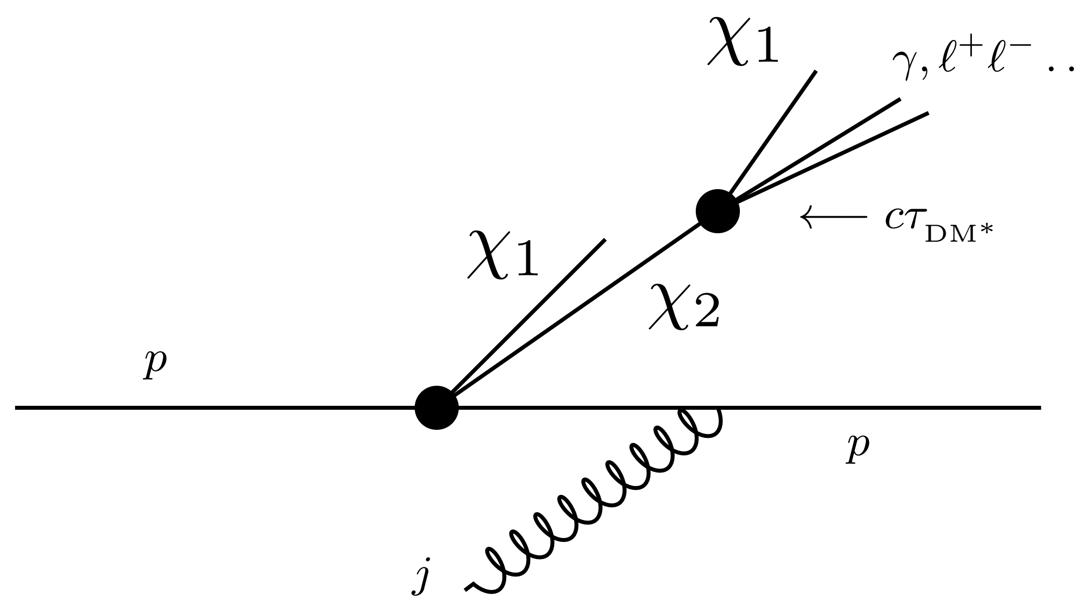
Vary DM/Mediator Mass Ratio



Above the GeV Scale?

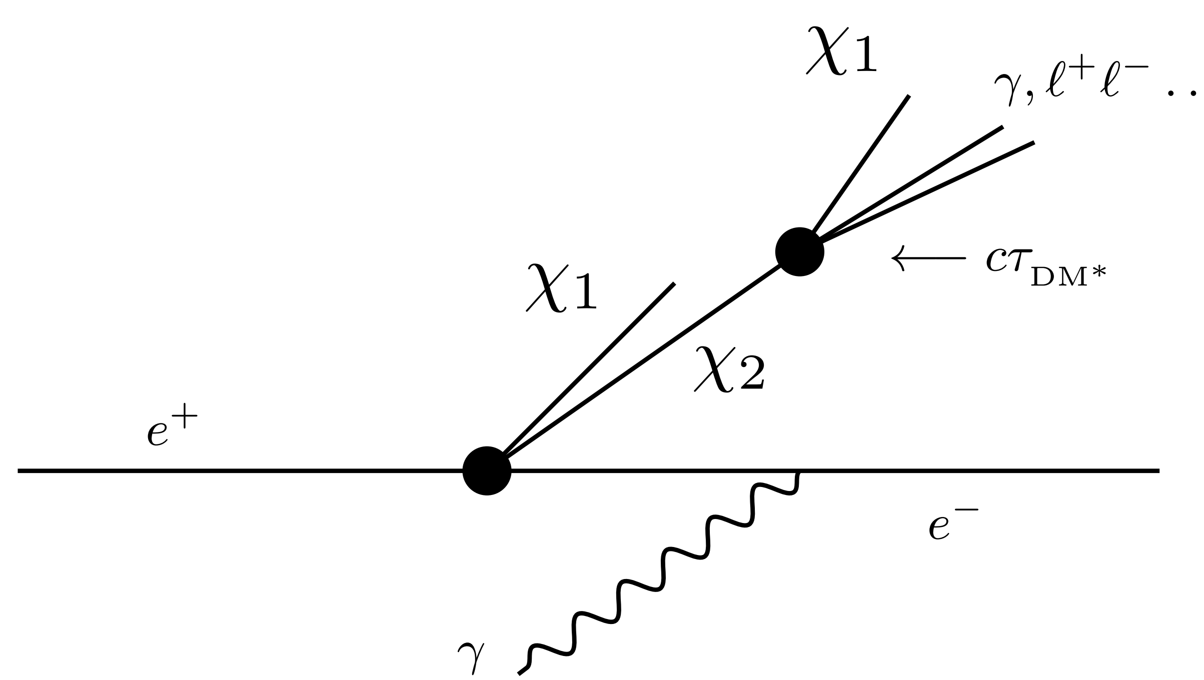
Hadron Collider

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



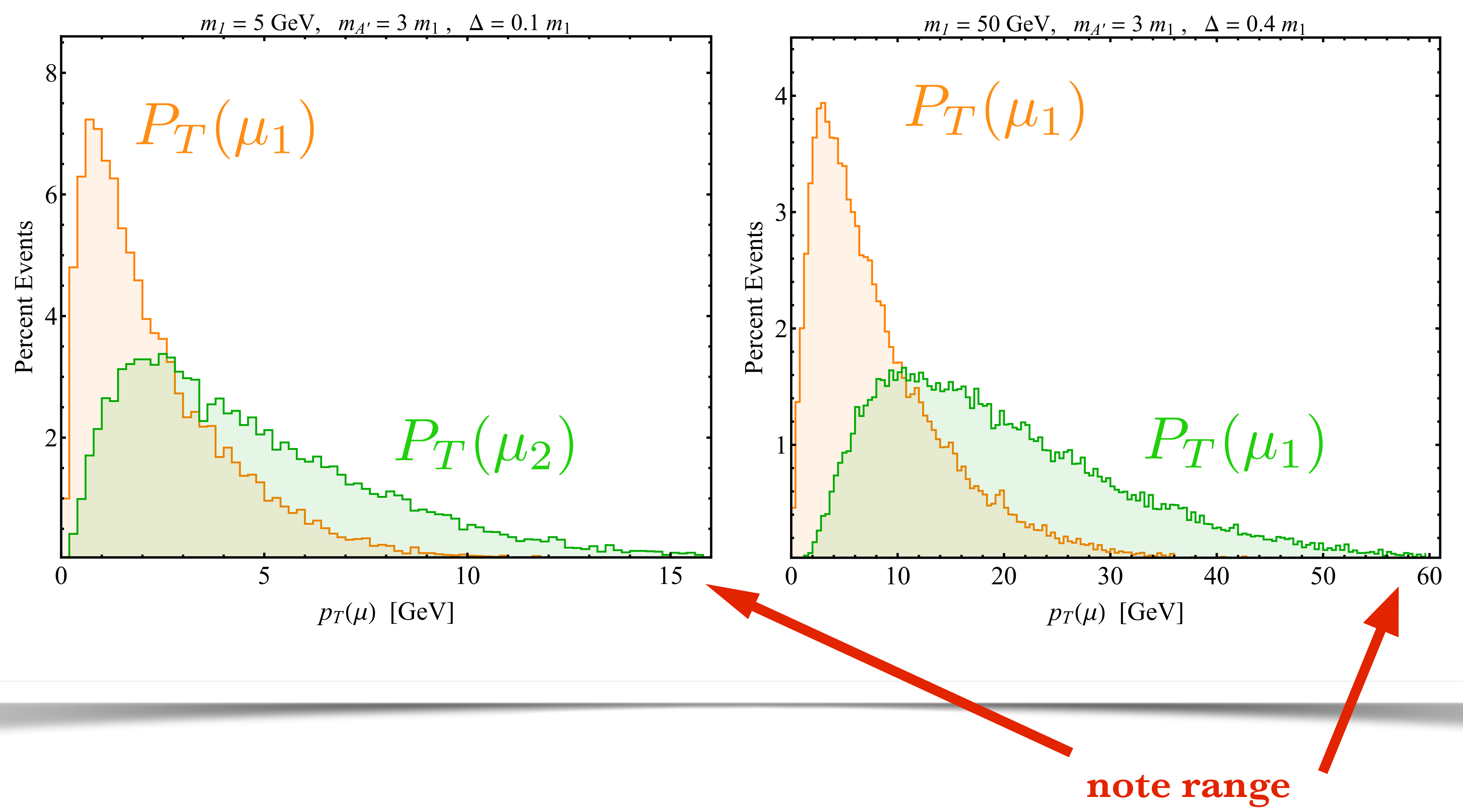
Lepton Collider

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



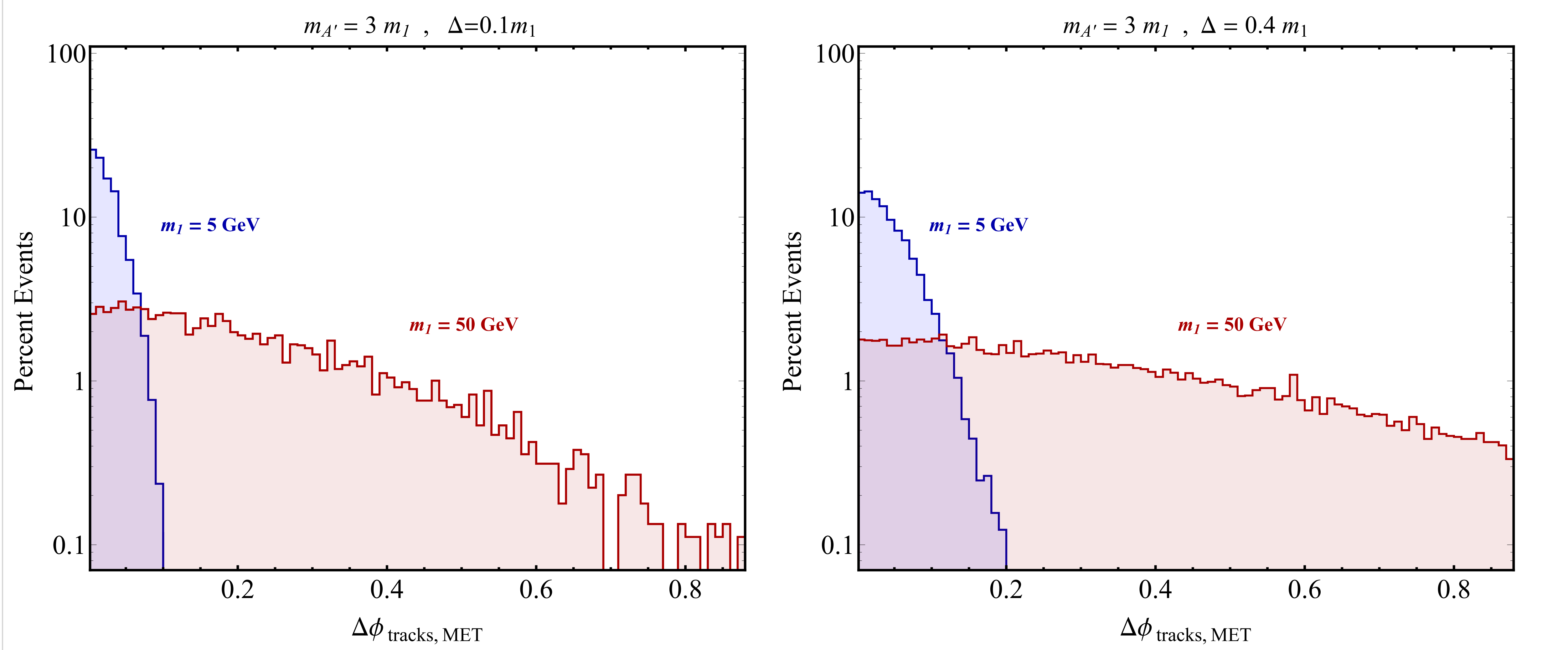
Izaguirre, GK, Shuve
1508.03050

Signal Feature(Bug): Soft Leptons



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

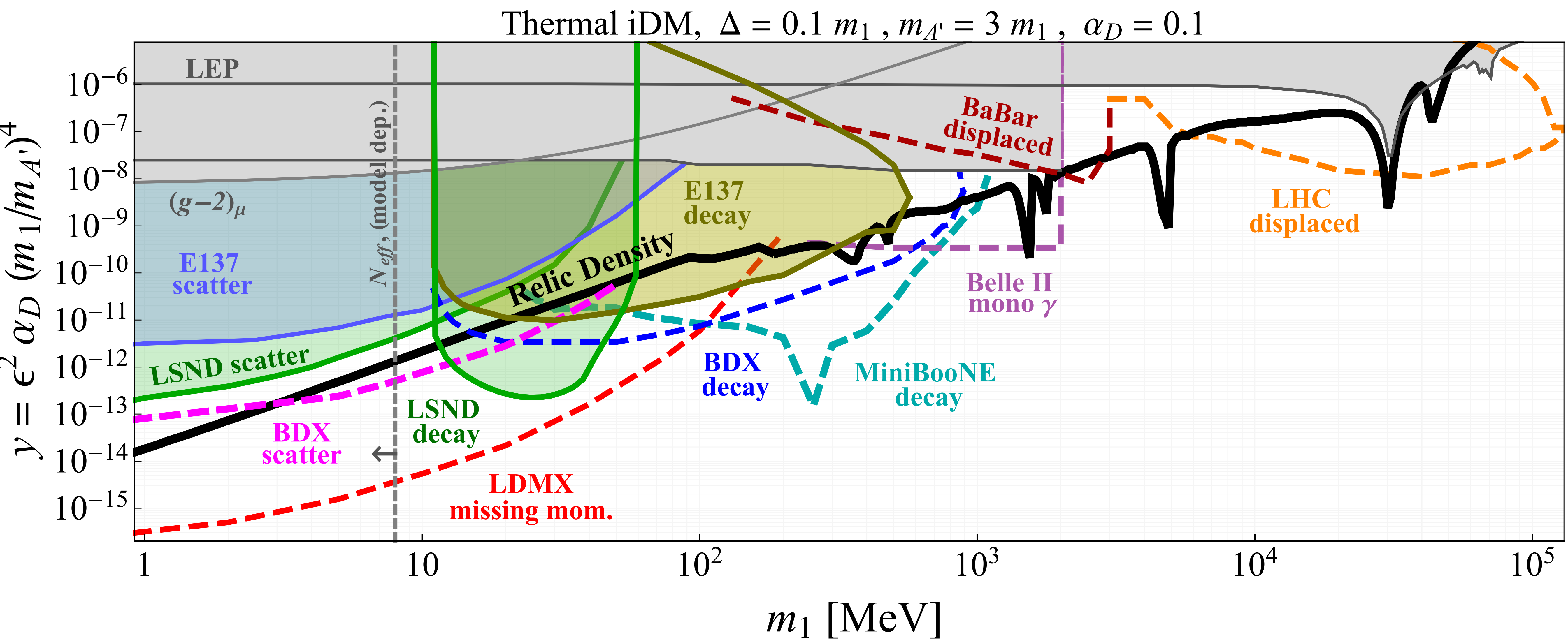
MET/Lepton Correlated



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

Collider Complementarity

Small Splitting ~ 10%



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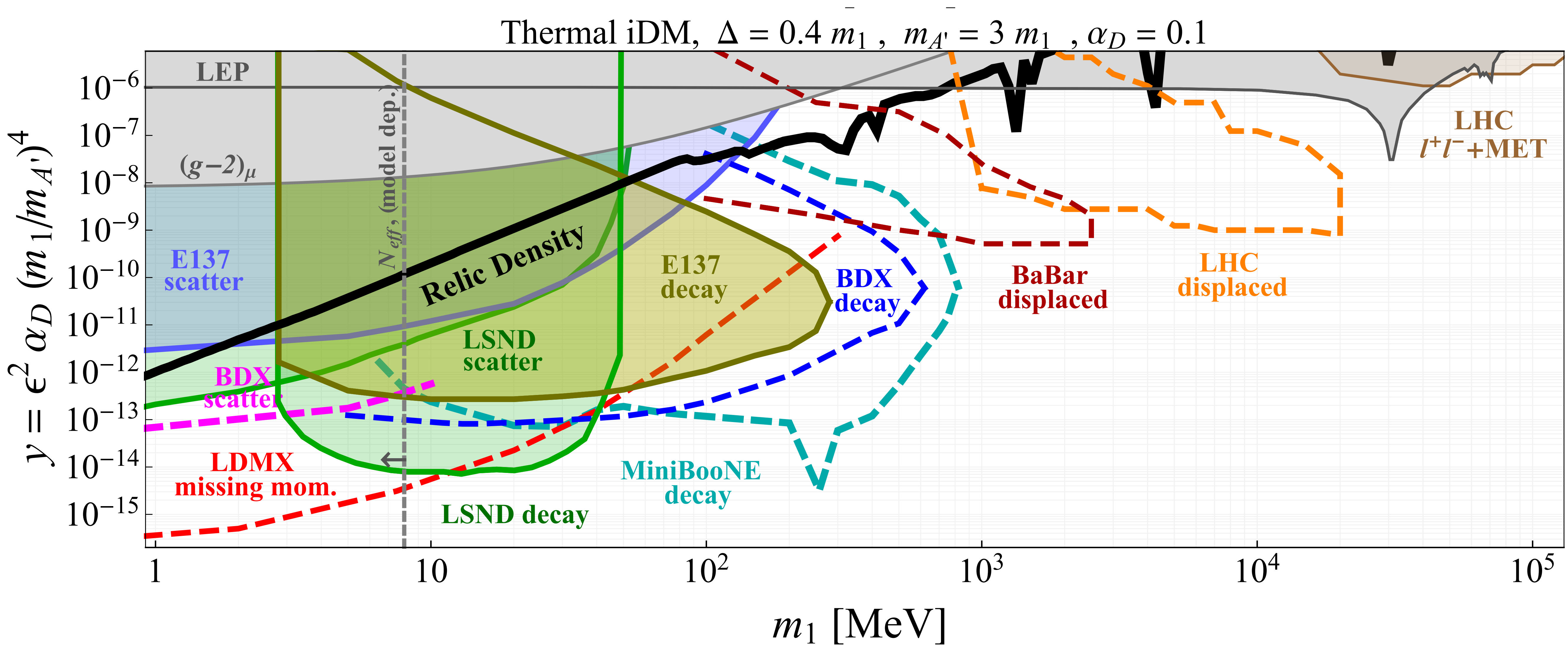


Conclusion

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, SHiP, DUNE…

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!

Thank You!

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 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

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. $\sim 10^{-7} \Longrightarrow \sigma_{\mathrm{QCD,BG}} < 100$ 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)

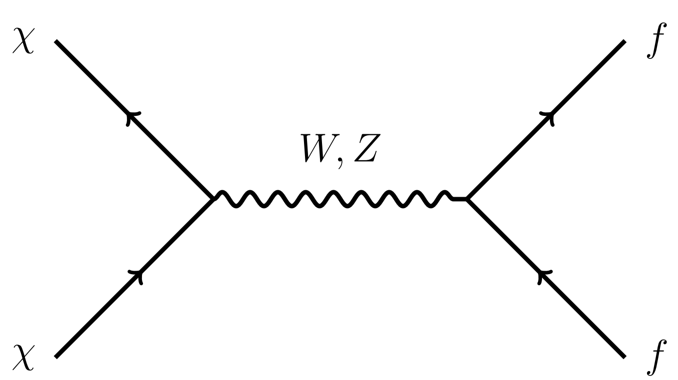
Verdict: Very Small, Very Reducible

< GeV DM General Issues

DM must be a SM singlet

Else would have been discovered (LEP…)

DM overproduced without new "mediators"



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