Discovering Inelastic Thermal Dark Matter

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1703.06881

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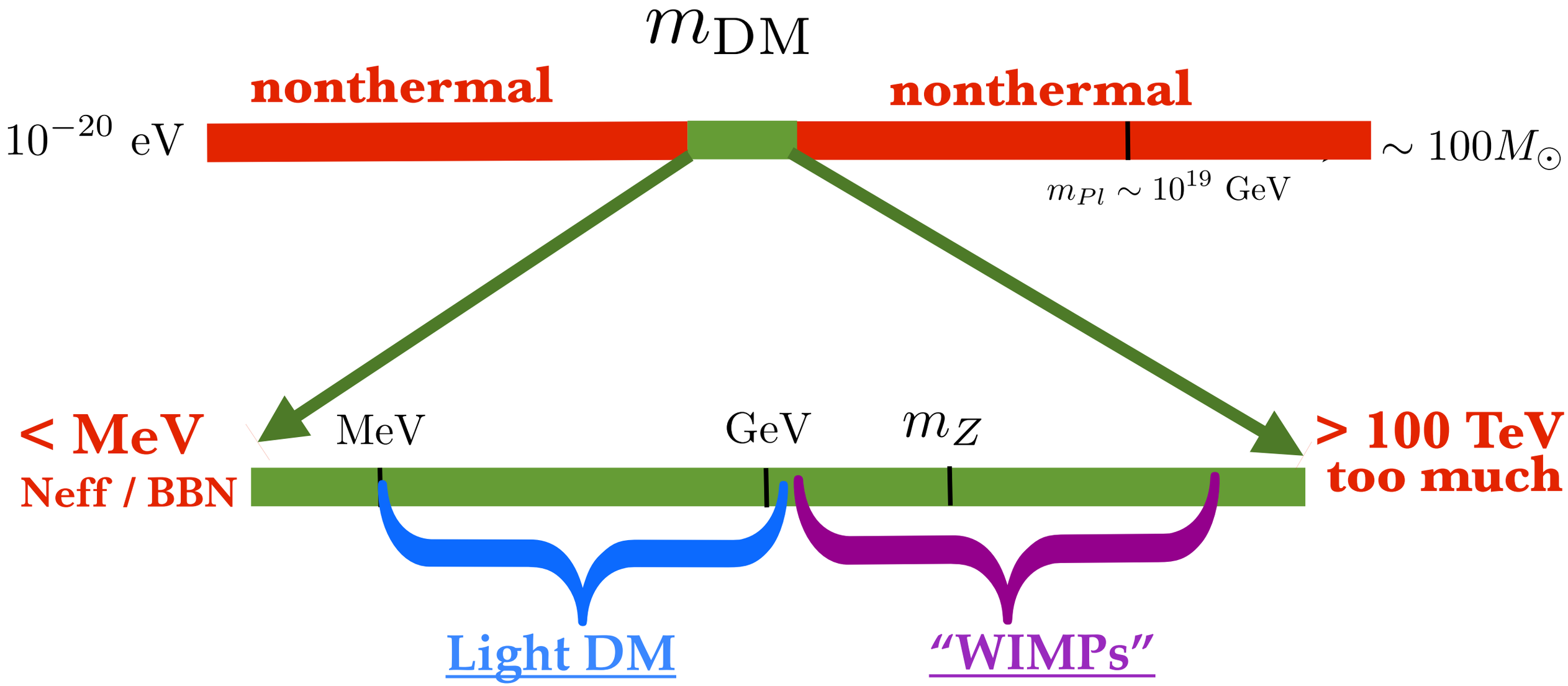
1508.03050

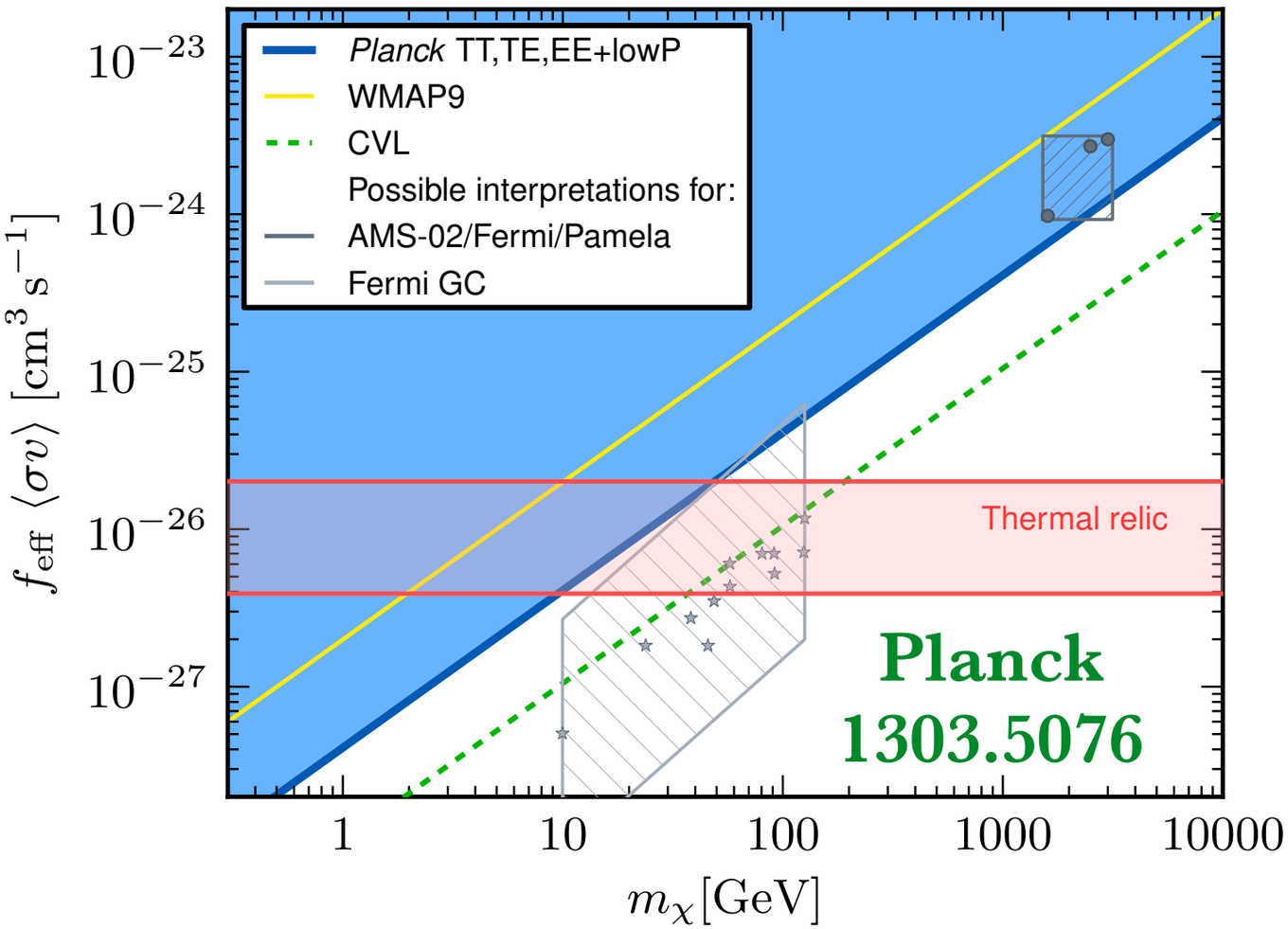
Cosmic Visions, UMD March 24, 2017

Thermal Contact Narrows Mass Range



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

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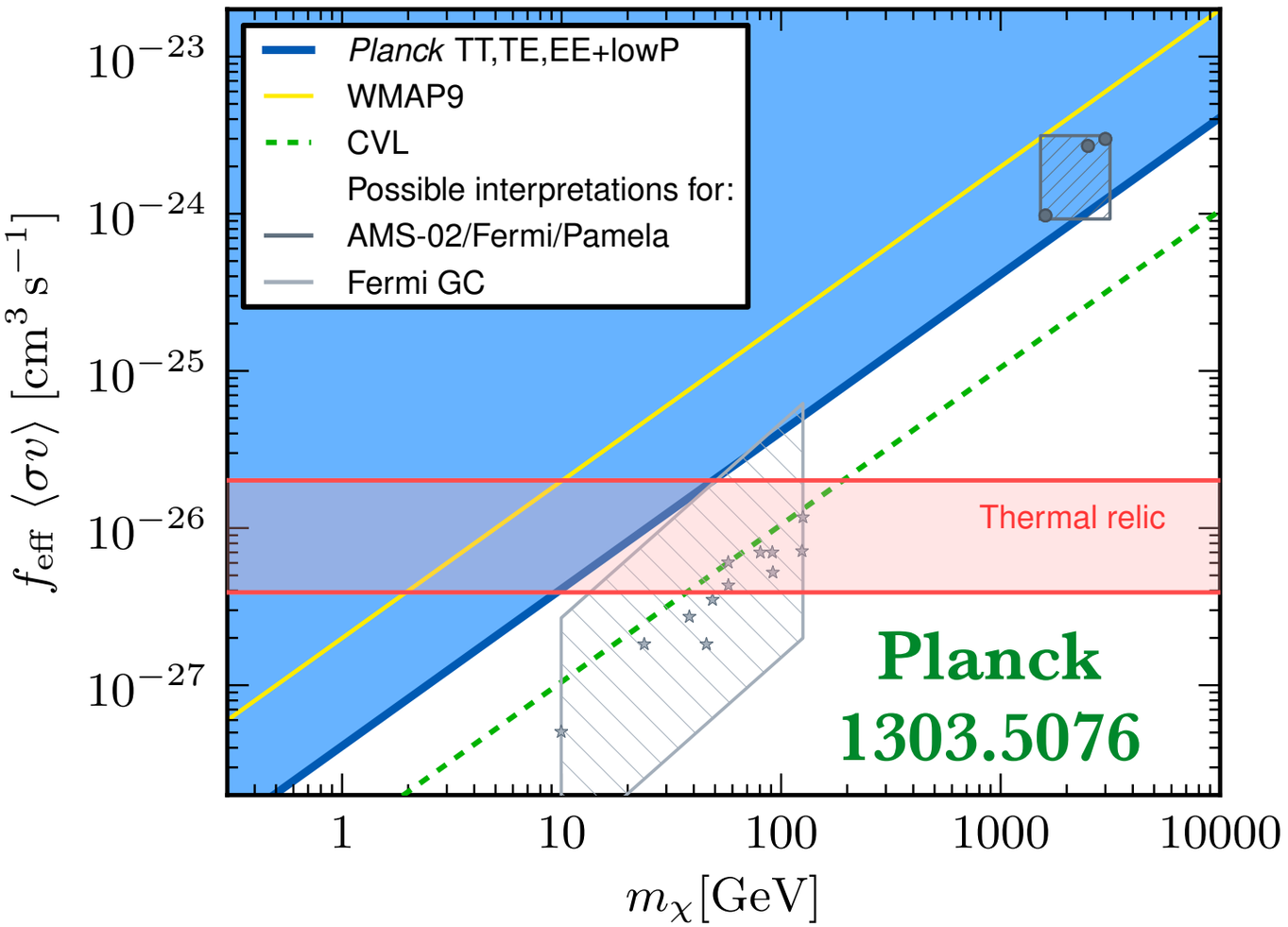

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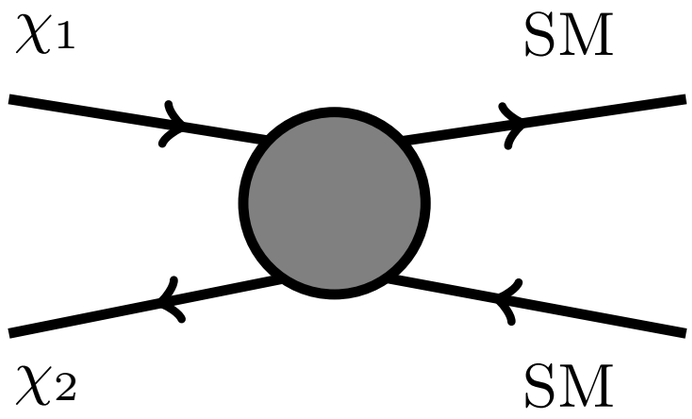
(1) p-wave annihilation

OR

(2) annihilation shuts off before CMB

Inelastic DM is CMB Safe

Direct Coannihilation into SM



$$\Delta \equiv m_{\chi 2} - m_{\chi 1} \gg \mathrm{eV}$$

Heavier state disappears before z~1100

No indirect detection $\quad n_{\chi 2} \sim e^{-\Delta/T}$

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

Easy to build, large couplings, hard to test!

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

Example Model

Four component fermion + familiar 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

Example Model

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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

Example Model

Four component fermion + familiar 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)

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

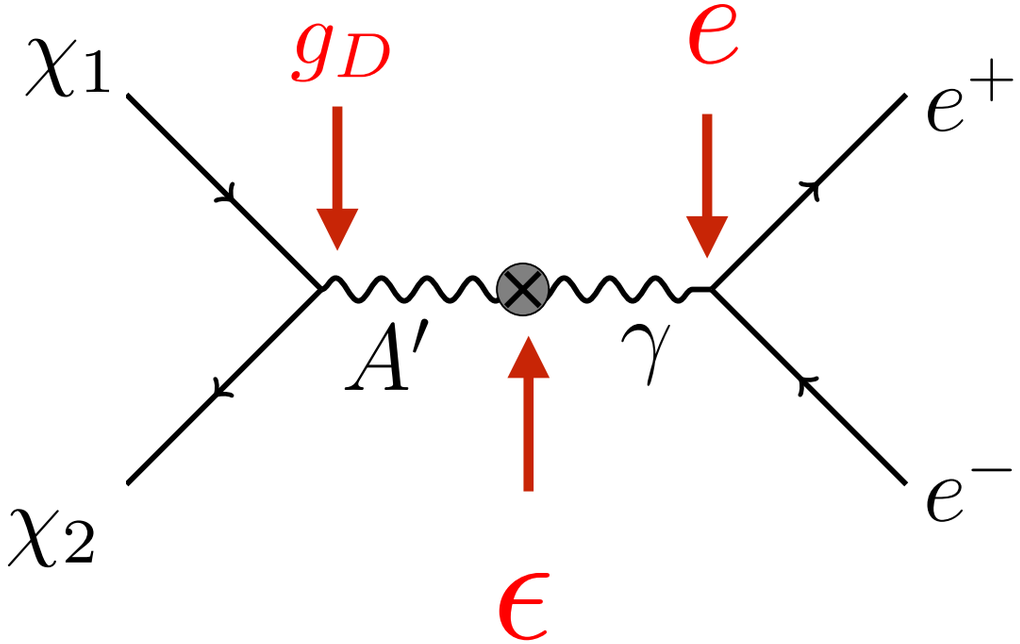
int. eigenstates — mass eigenstates

Example Model

Vector current is now off-diagonal in mass basis

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

As before, define relic density variable



direct annihilation

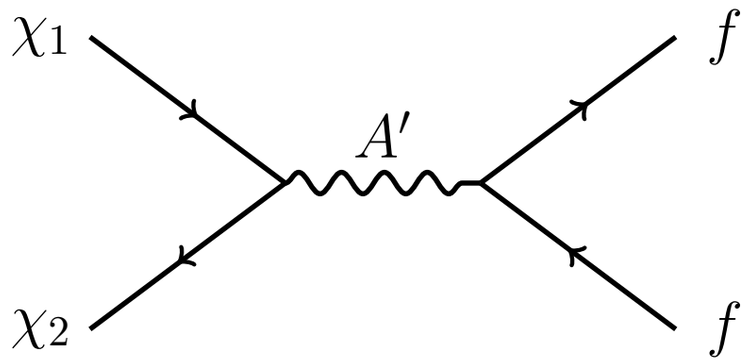
$$m_{A'} > m_1 + m_2$$

$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_1}{m_{A'}} \right)^4$$

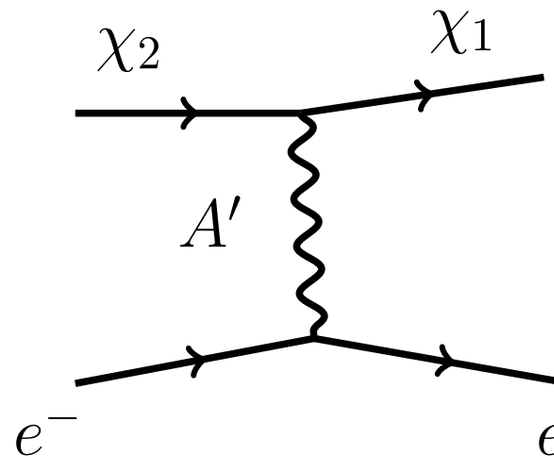
Different "y" for each Δ freeze out is subtle…

Inelastic Novelties

Coannihilation

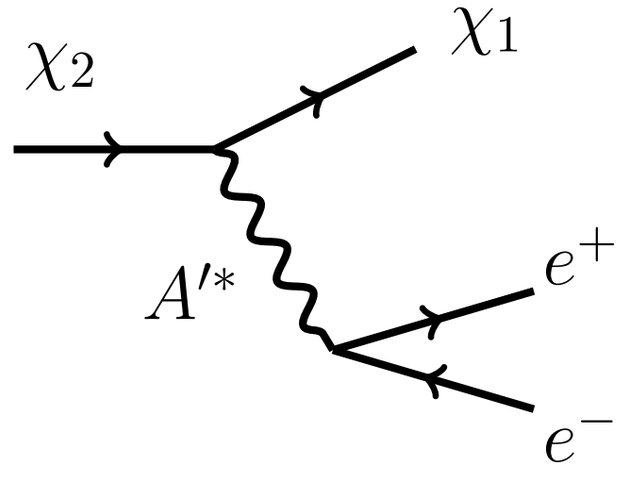


Upscahttering & Downscattering

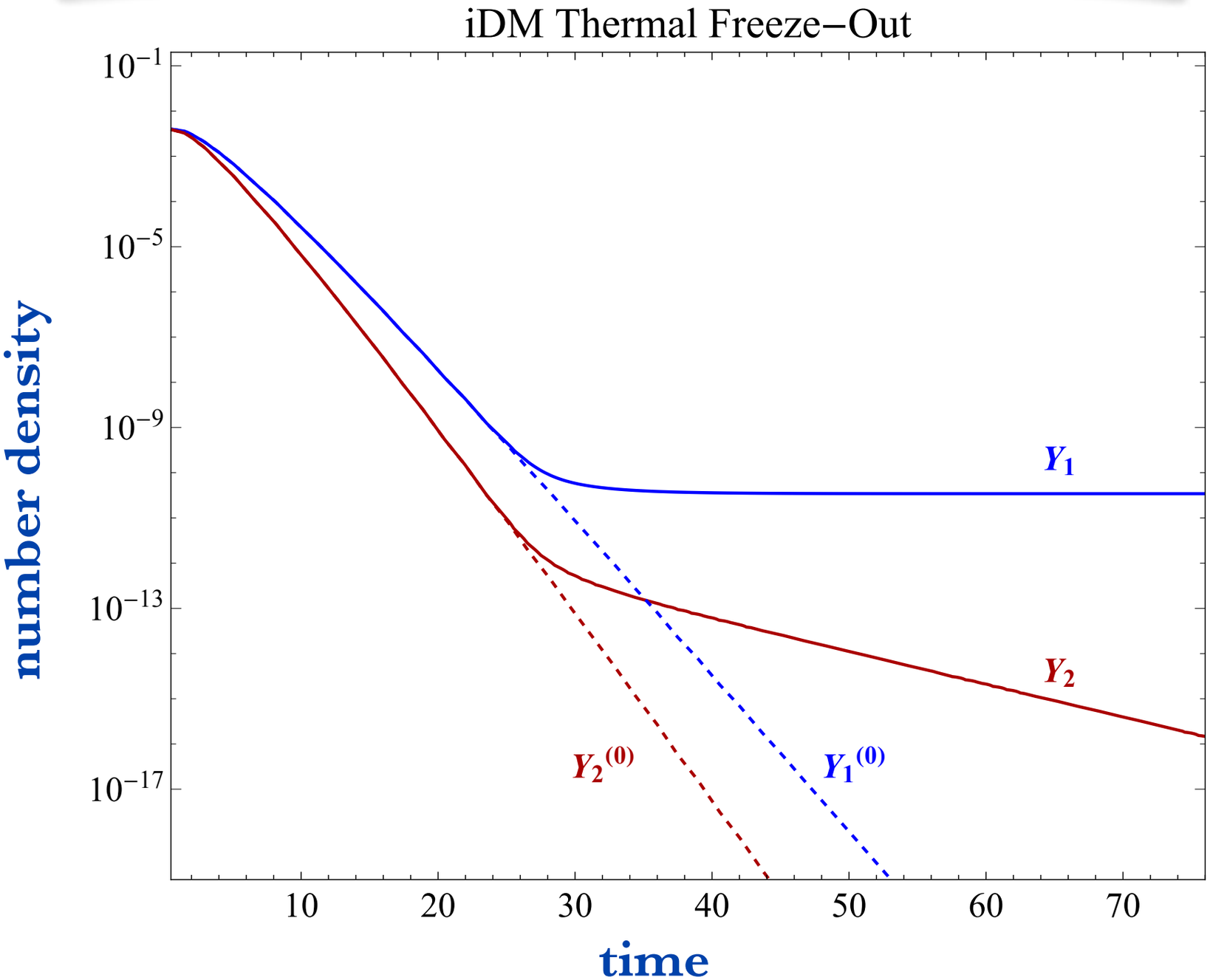


Excited State Decays

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



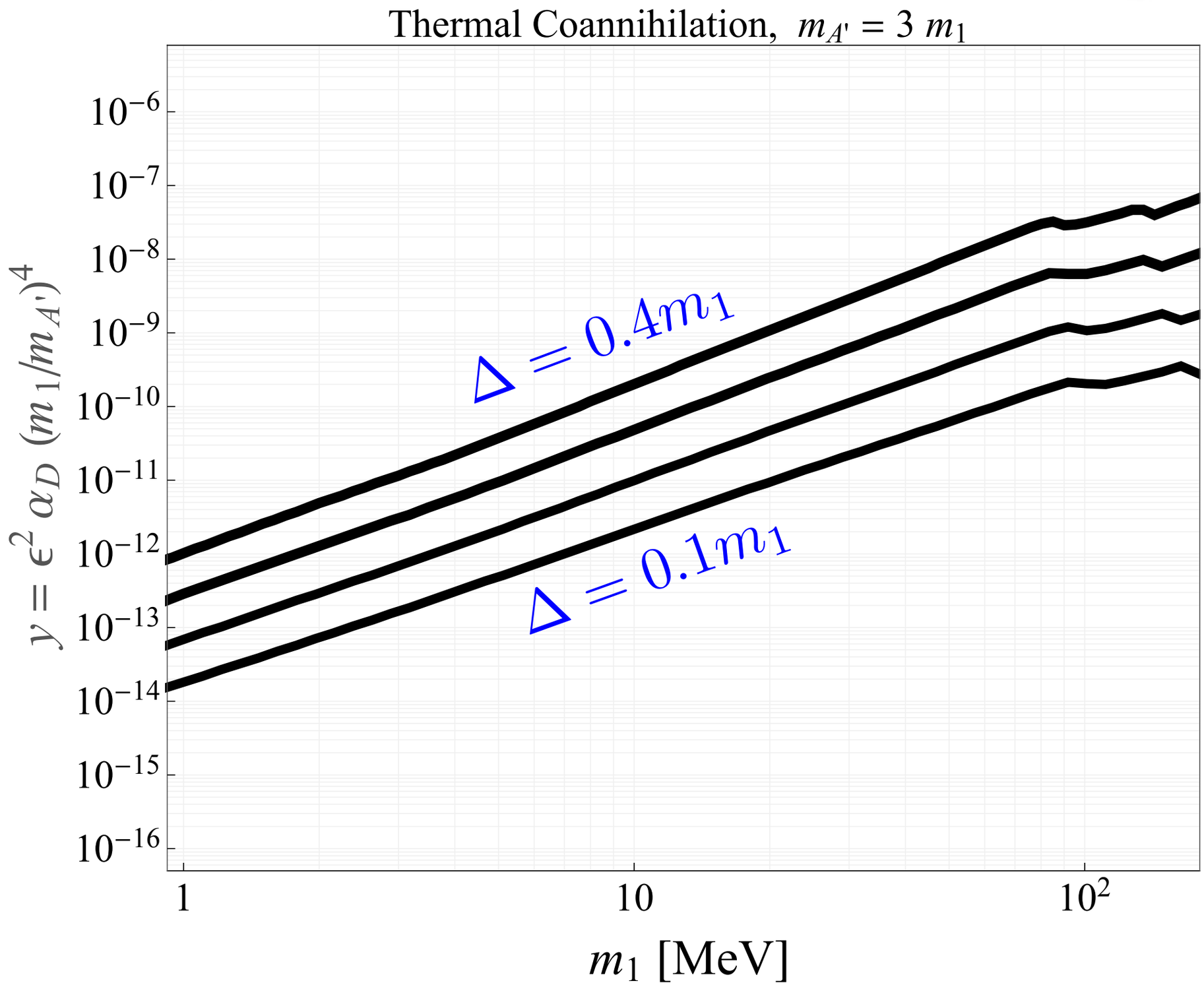
Coannihilation Relics



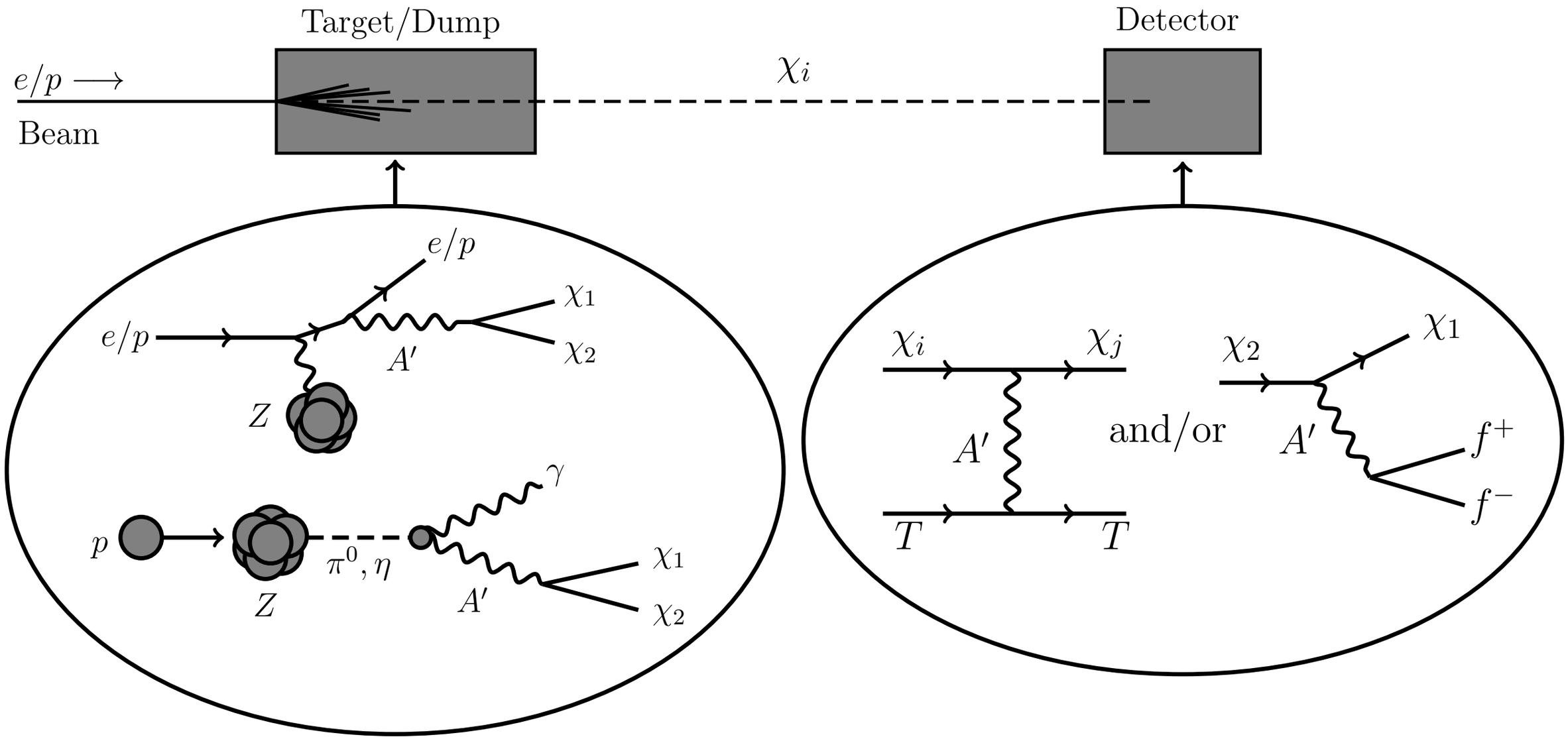
Heavier state feels Boltzmann suppression earlier

Need larger rate to compensate!

Vary Mass Splitting



Beam Dump Signals

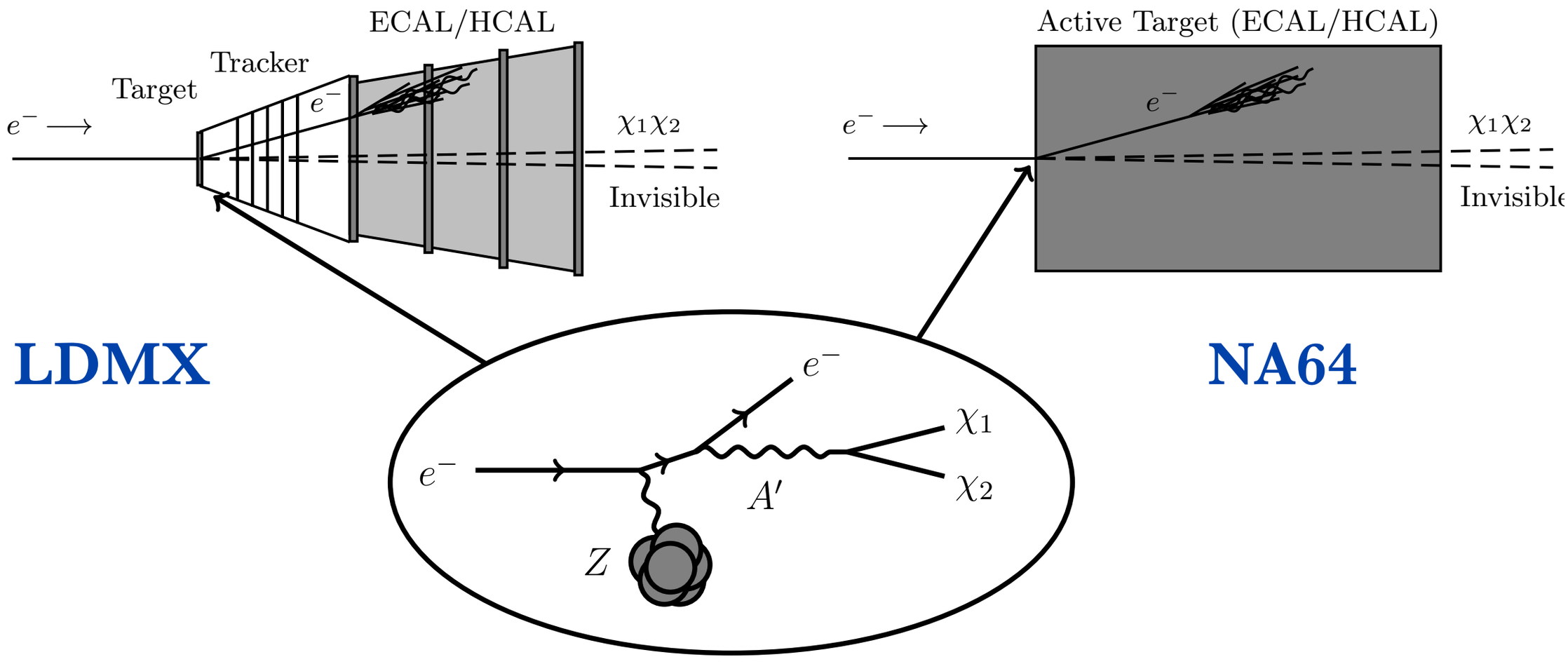


Proton	**Electron**
LSND	E137
MiniBooNE	BDX

Others possible (SeaQuest, T2K, DUNE…)

Morrissey, Spray 1402.4817
Kim Park Shin 1612.06867
BdNMC deNiverville, Chen, Pospelov, Ritz 1609.01770

Missing Energy/Momentum



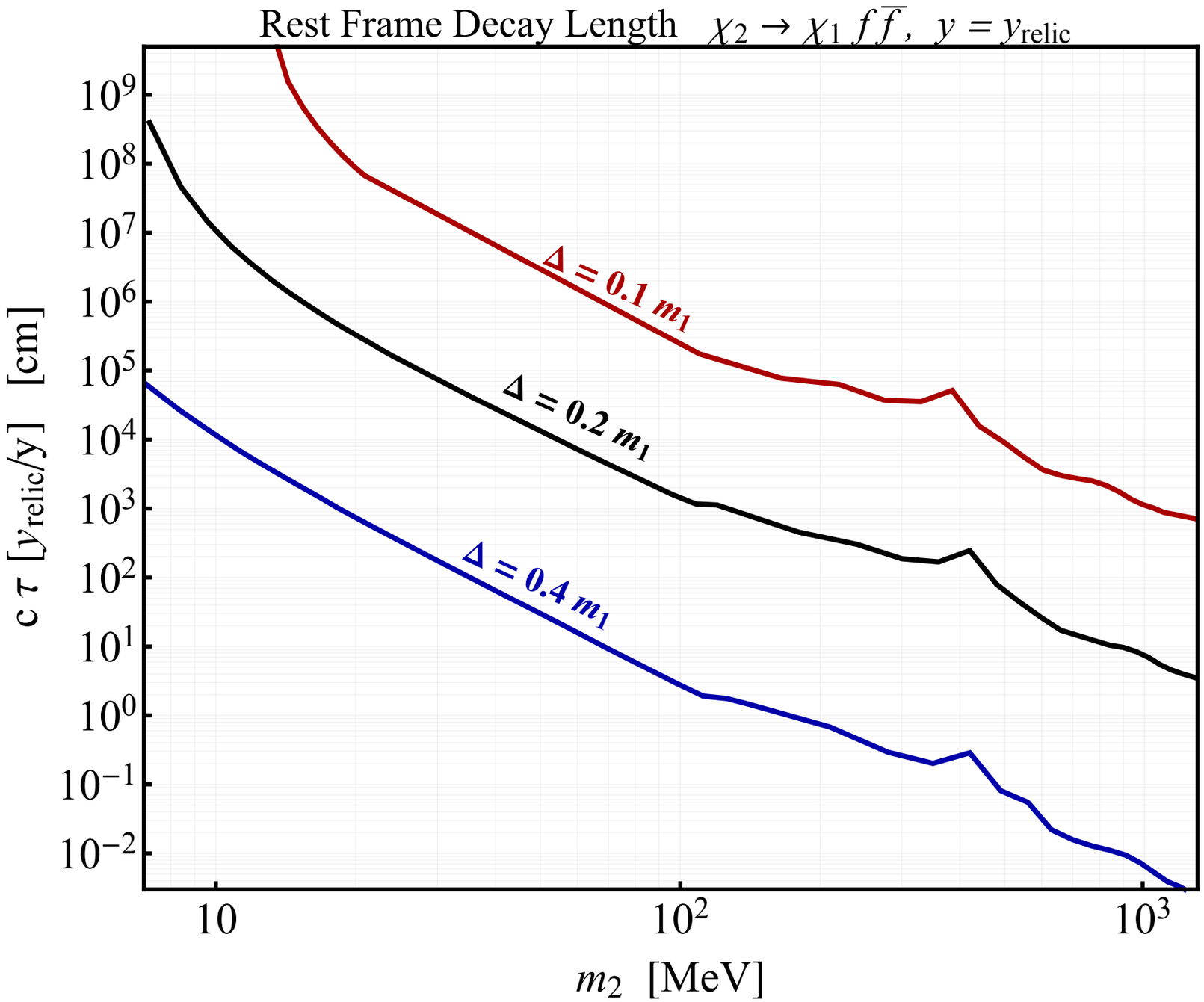
LDMX **NA64**

Heavier state decays outside veto region

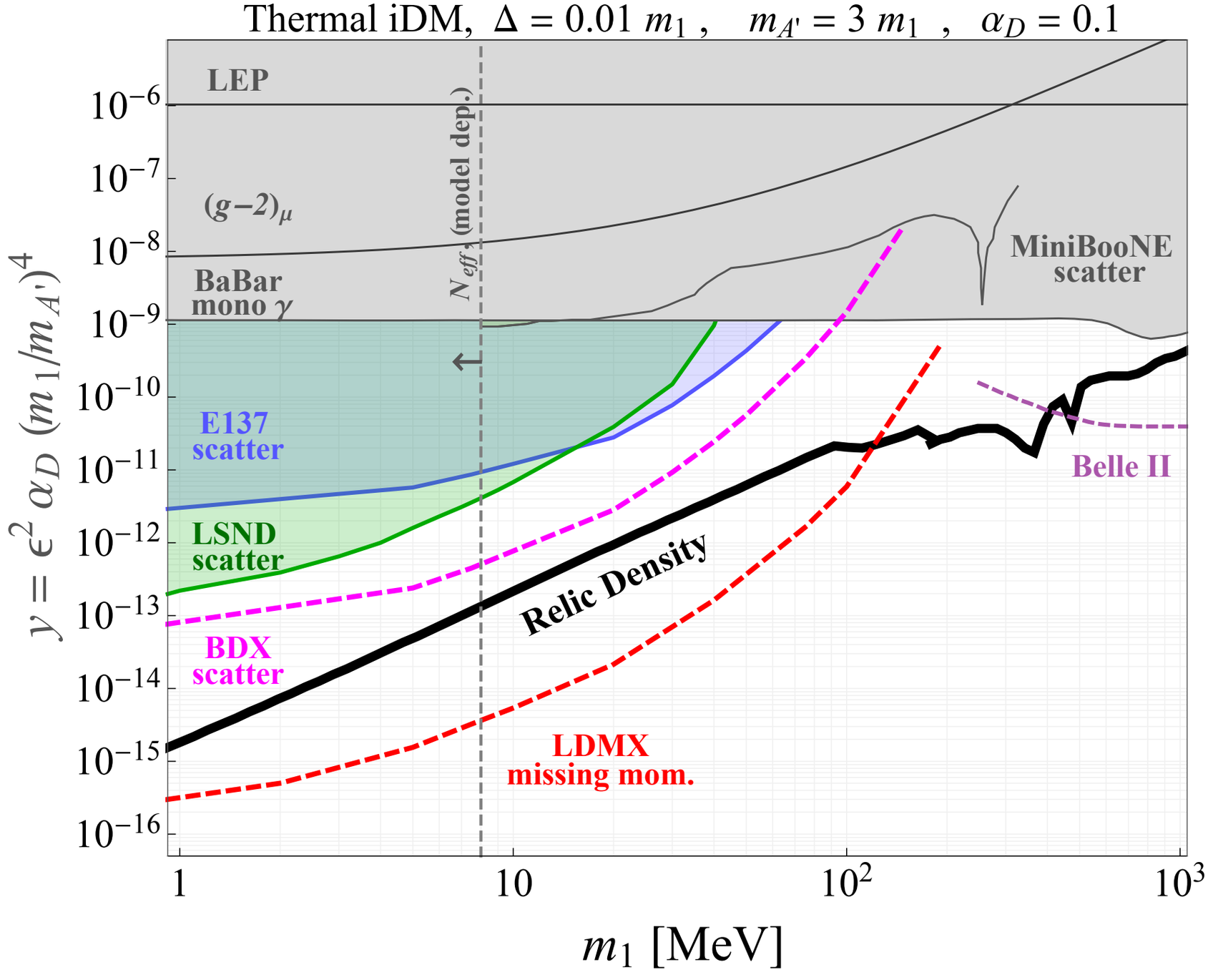
Signal looks like missing energy/momentum

May also be sensitive to the decay!

Generically Macroscopic Decays

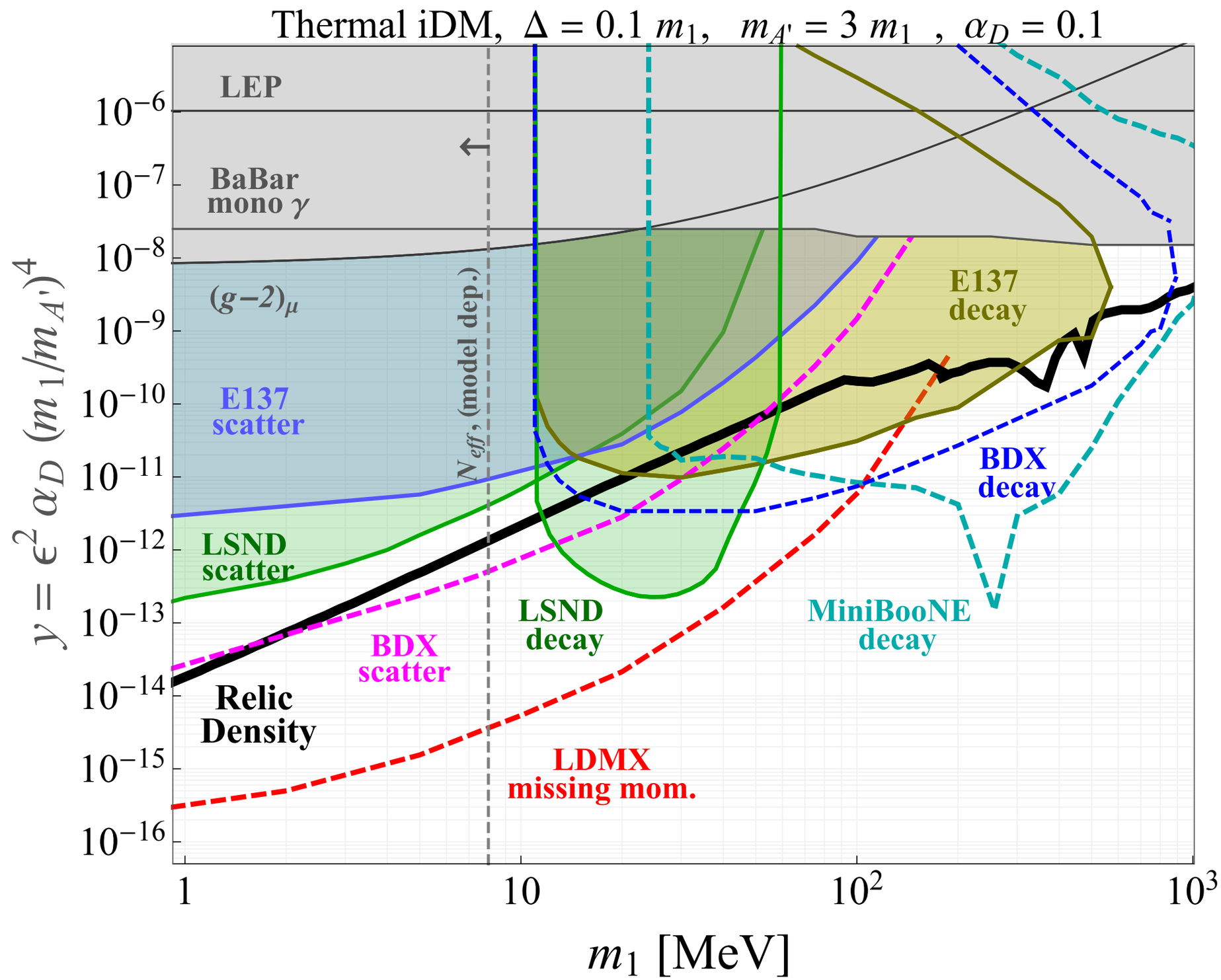


Tiny Splitting ~ 1%

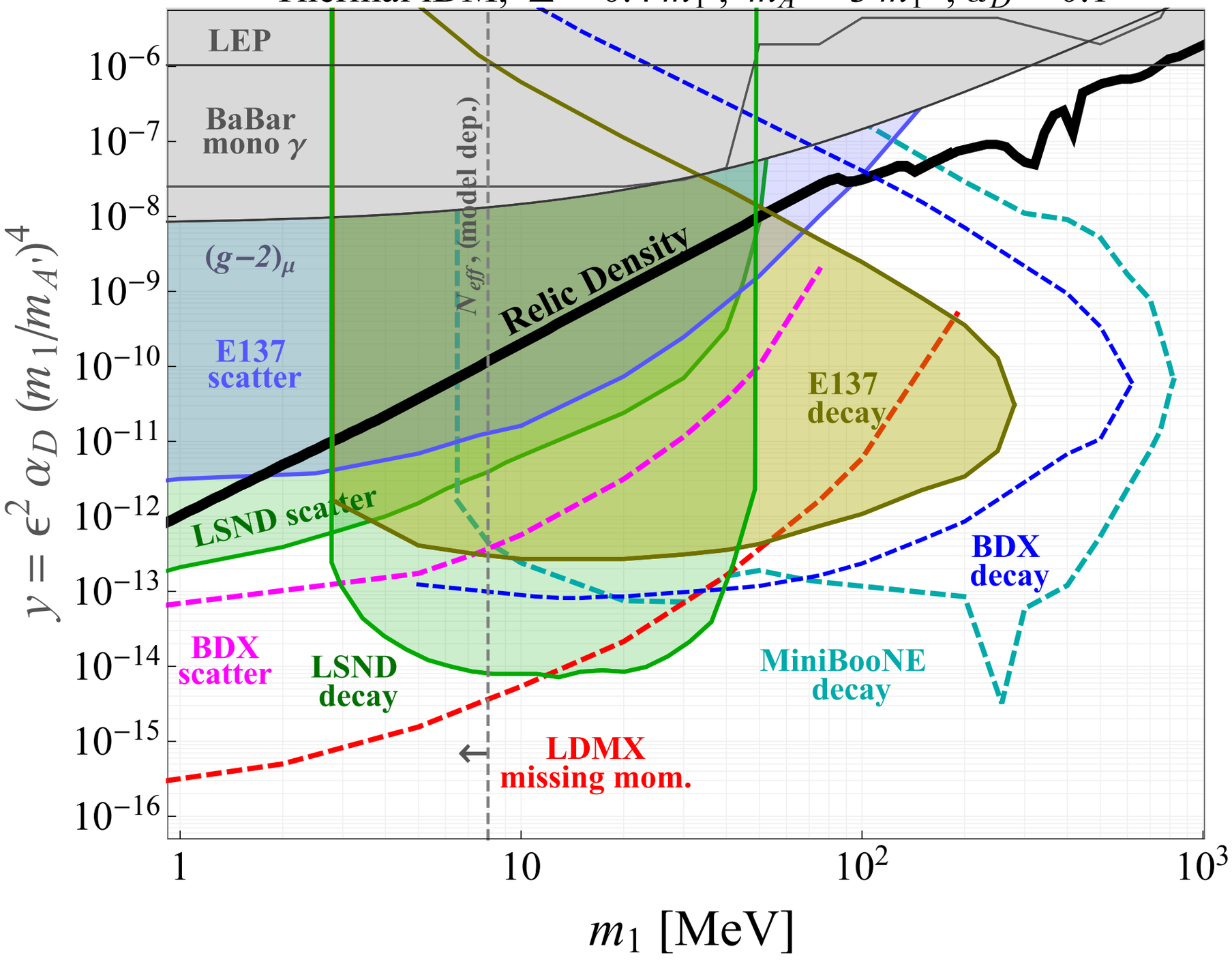


Similar to plots from plenaries

Small Splitting ~ 10%

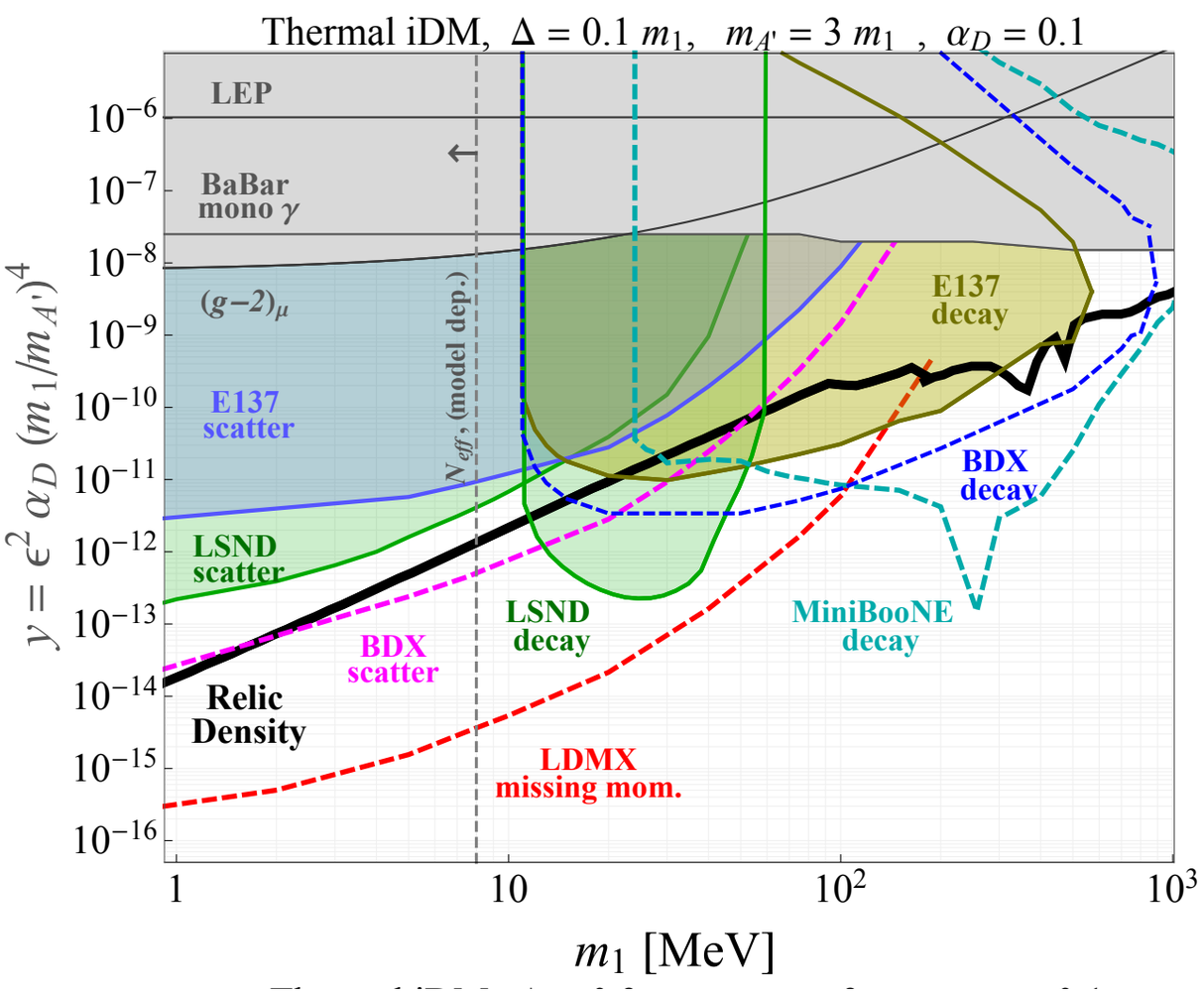


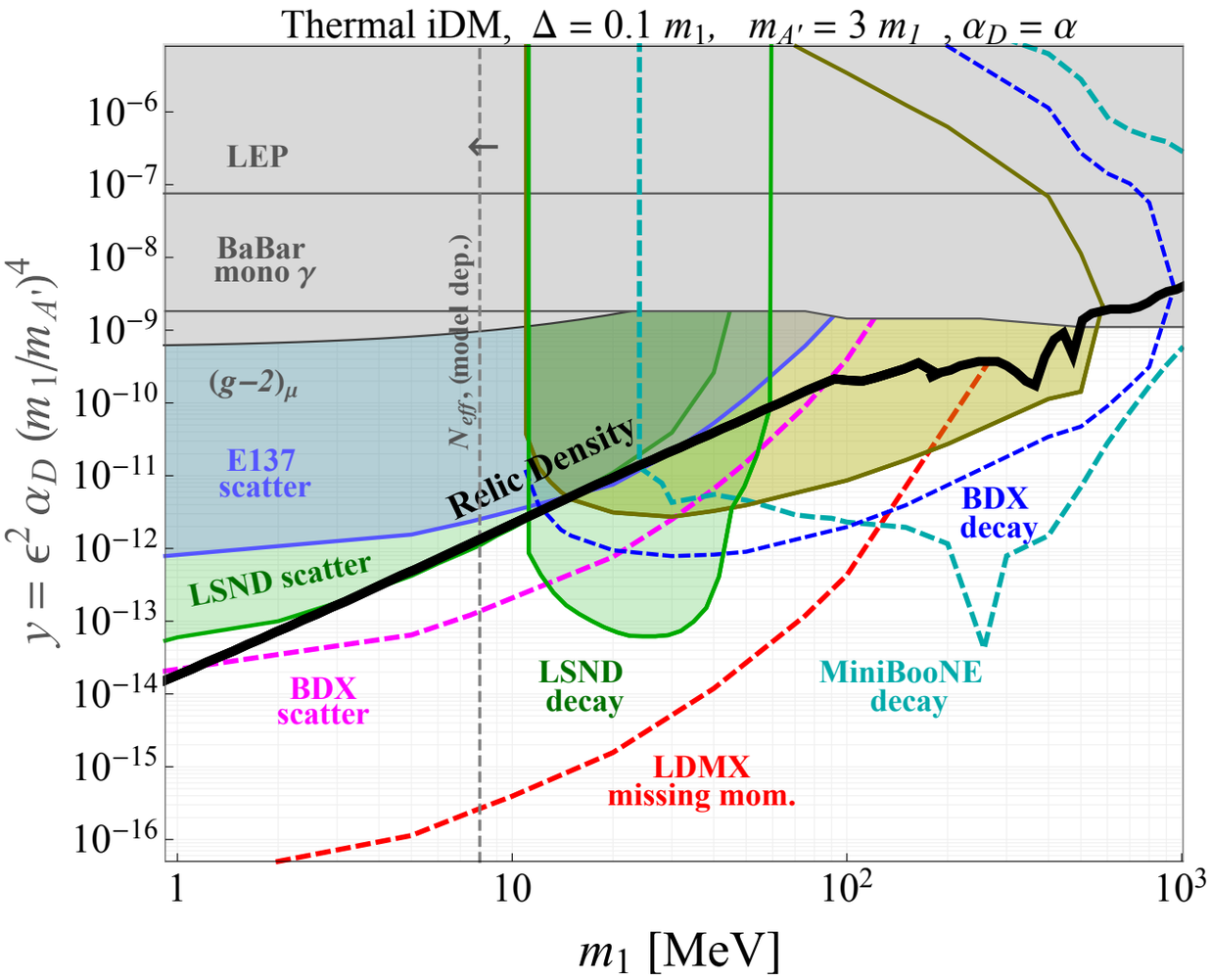
Large Splitting ~ 40%



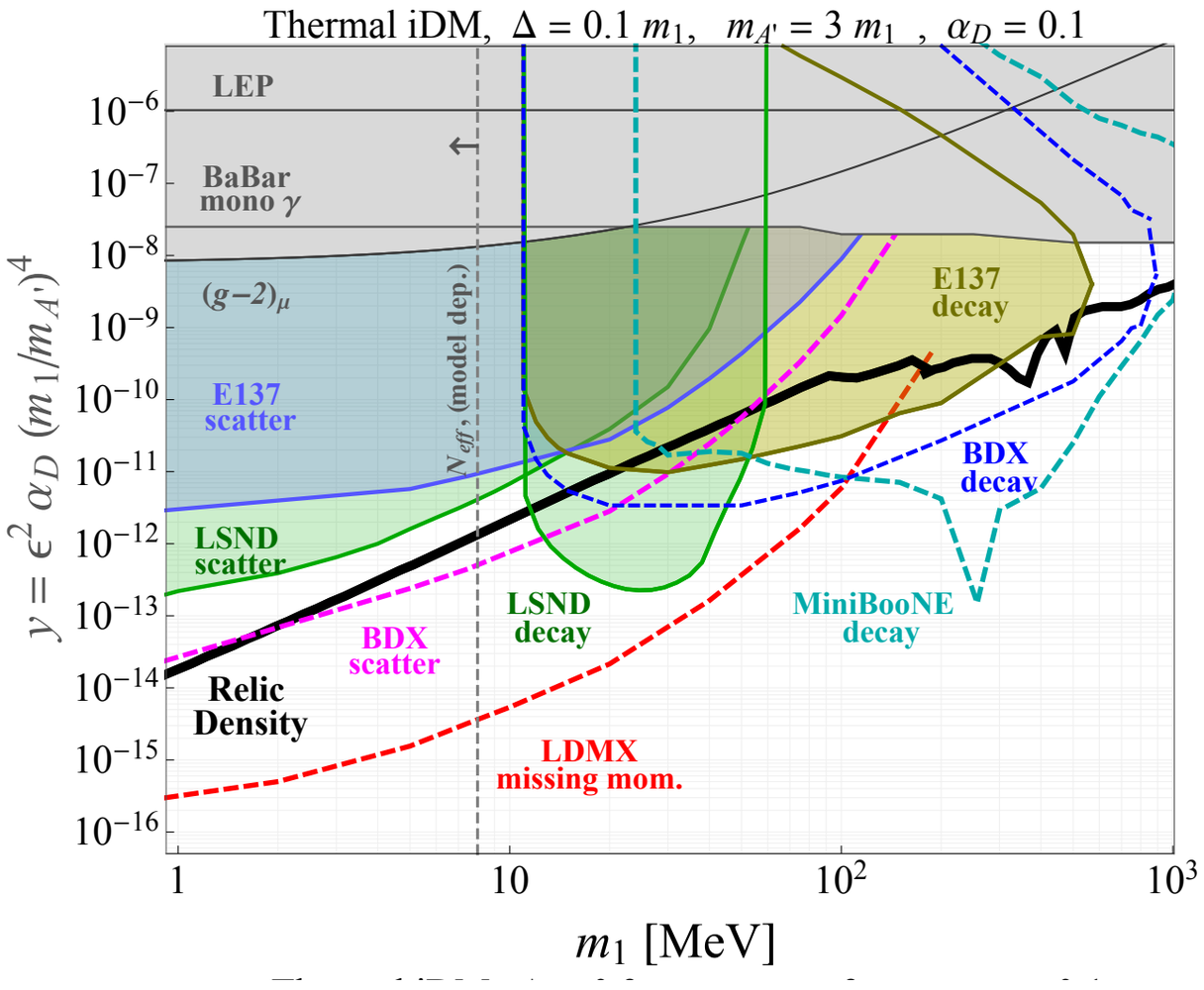
Target moves up, bounds/projections move down

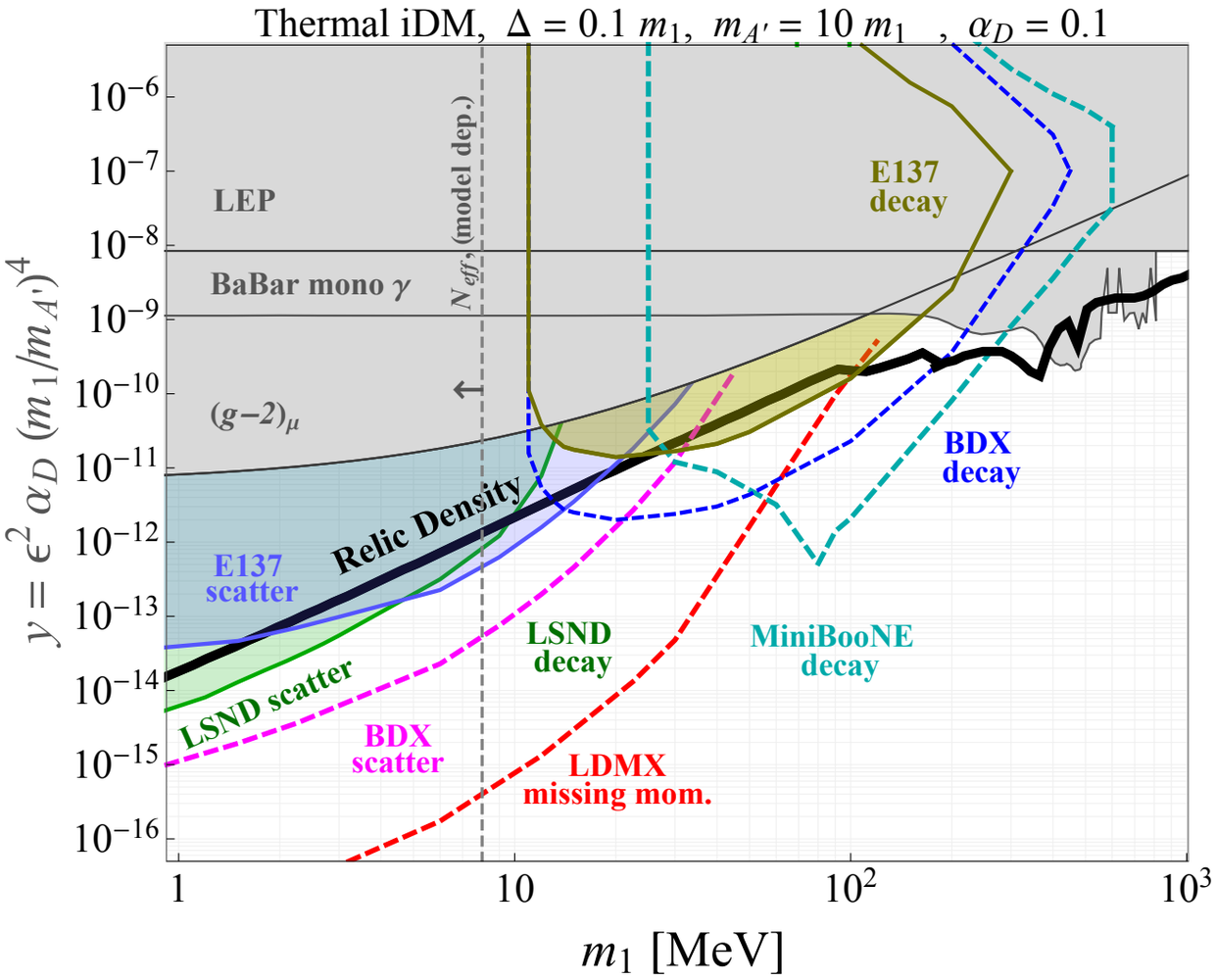
Vary DM/Mediator Coupling





Vary DM/Mediator Mass Ratio

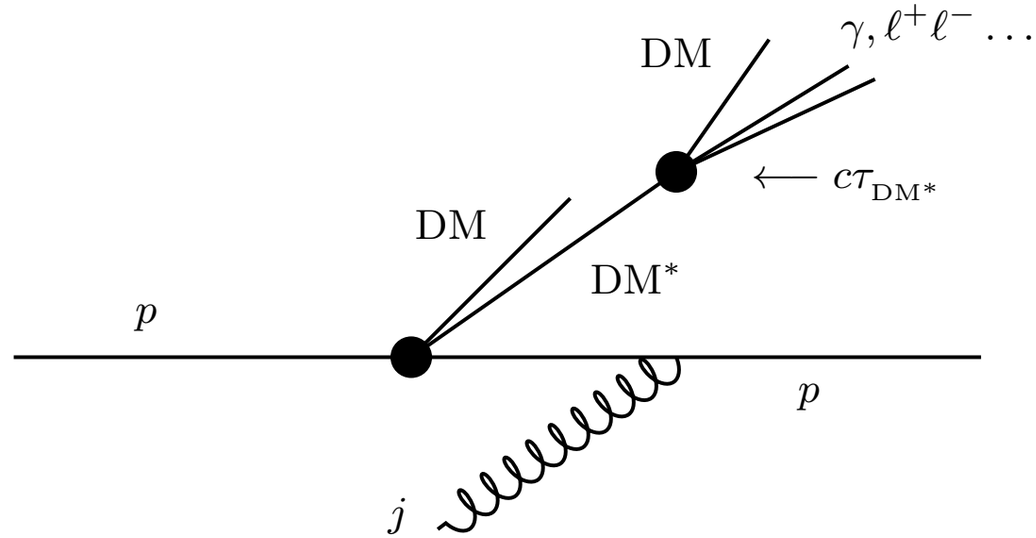




Above the GeV Scale?

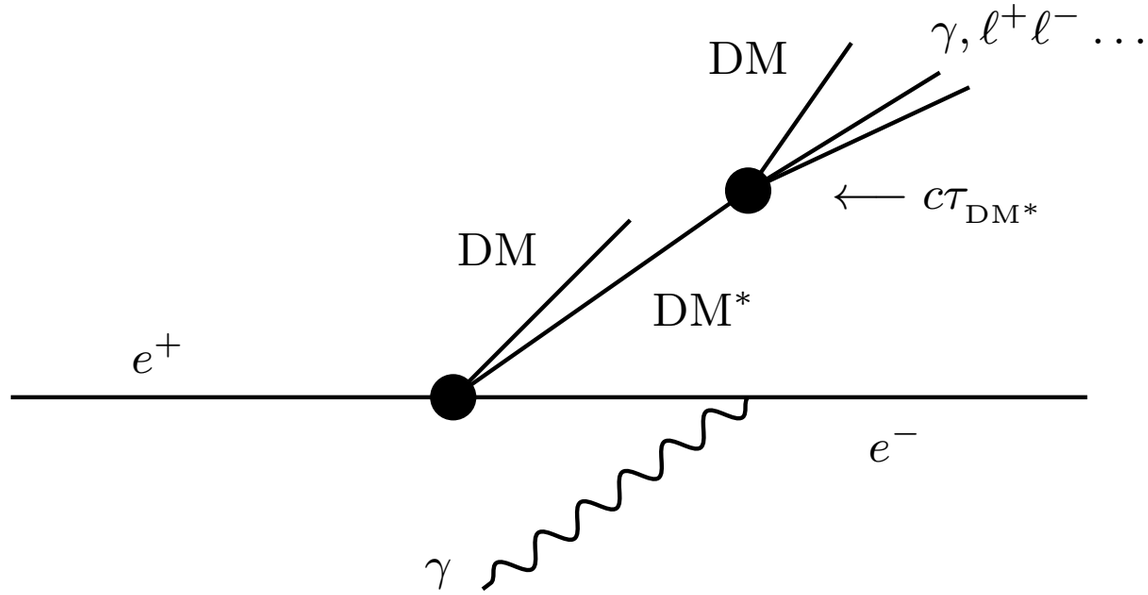
Hadron Collider

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



Lepton Collider

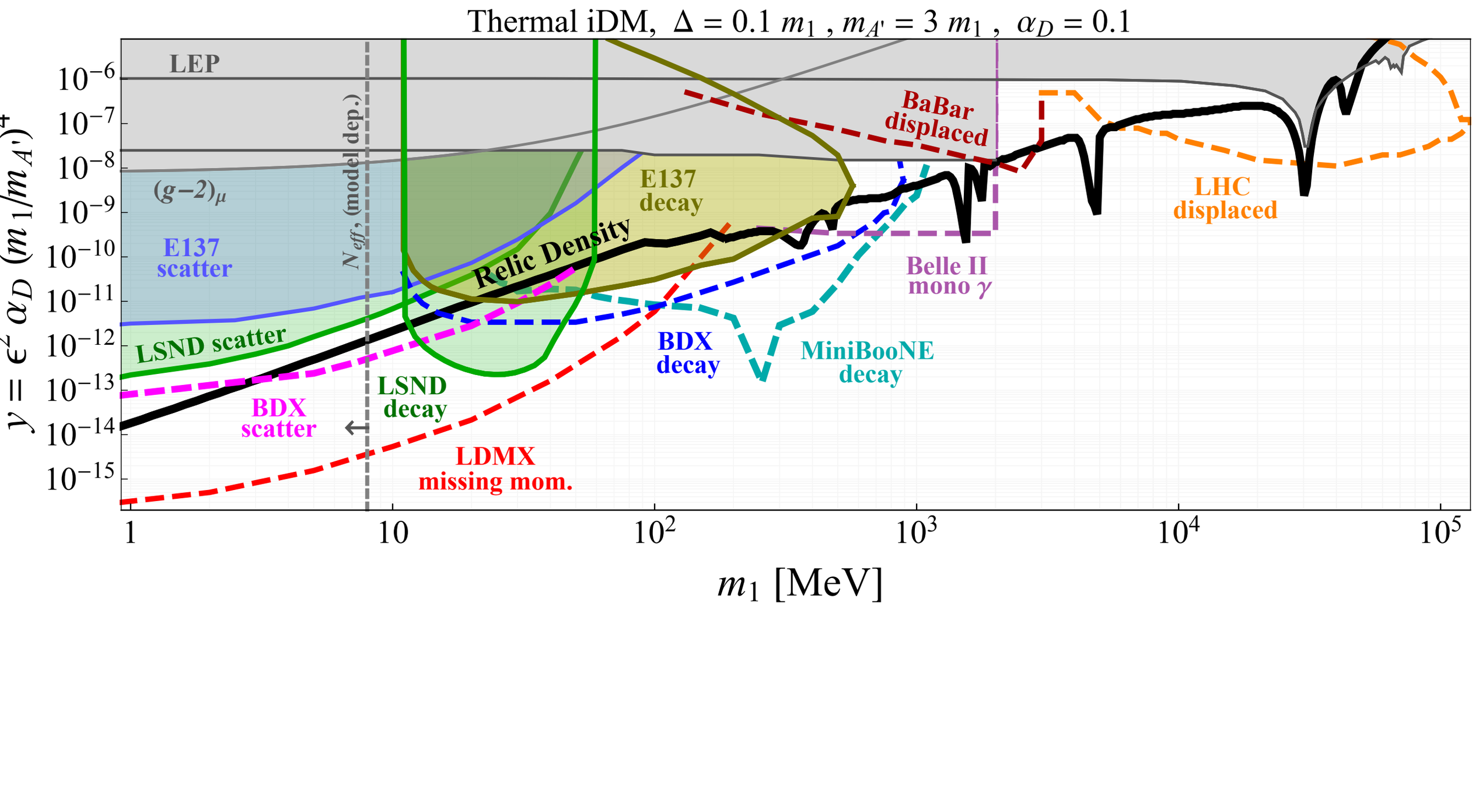
$$\gamma + \not{E} + \ell^+\ell^-$$



Izaguirre, GK, Shuve
1508.03050

Collider Complementarity

Small Splitting ~ 10%



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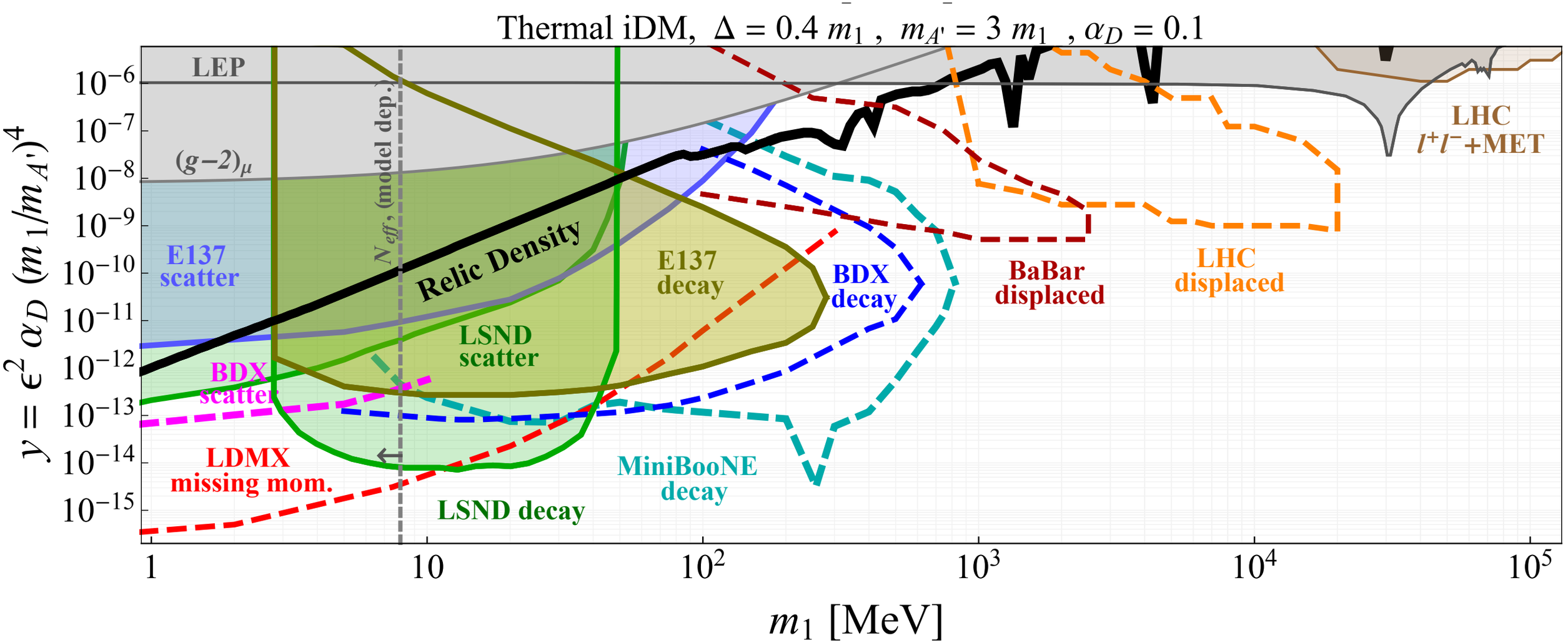

Conclusion

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, 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!