Testing Dark Matter Coannihilation With Neutrino Experiments

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1805.XXXXX

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1703.06881

+ Eder Izaguirre, Brian Shuve

1508.03050

FNAL Neutrino Seminar May 24, 2018

Overview

- **Historical Motivation**
  Thermal DM & WIMPs

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

- **Proton Beam Dump Searches**
  LSND, MiniBooNE, JSNS2, (DUNE ?)

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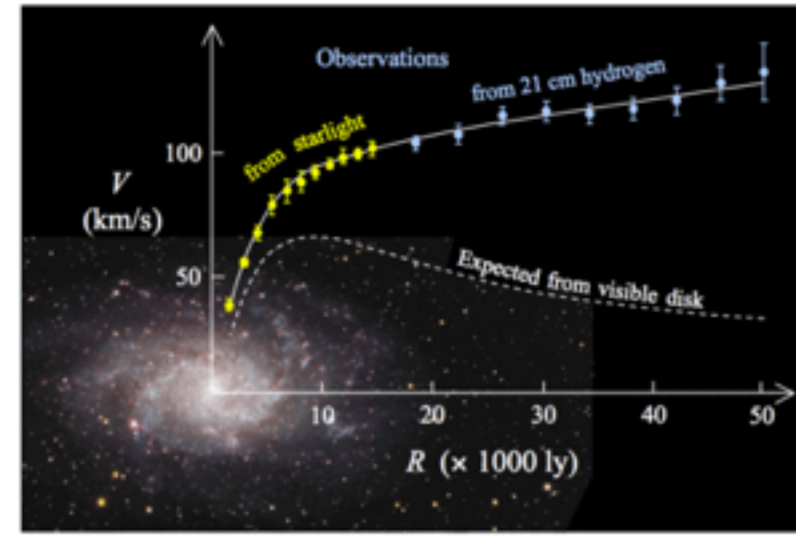
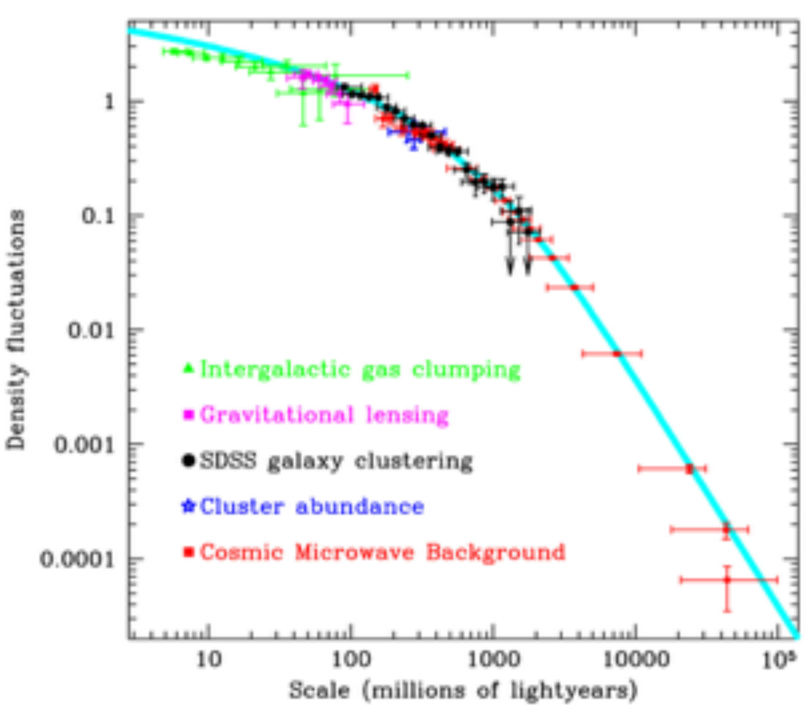
Remarkable Evidence for Dark Matter

Cluster Collisions

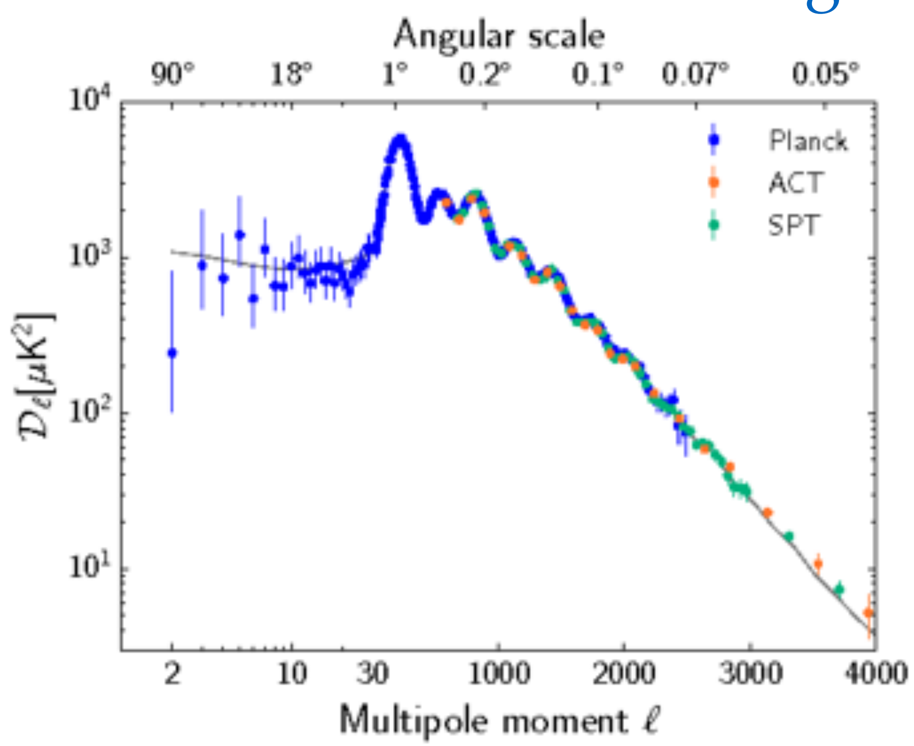
Gravitational Lensing



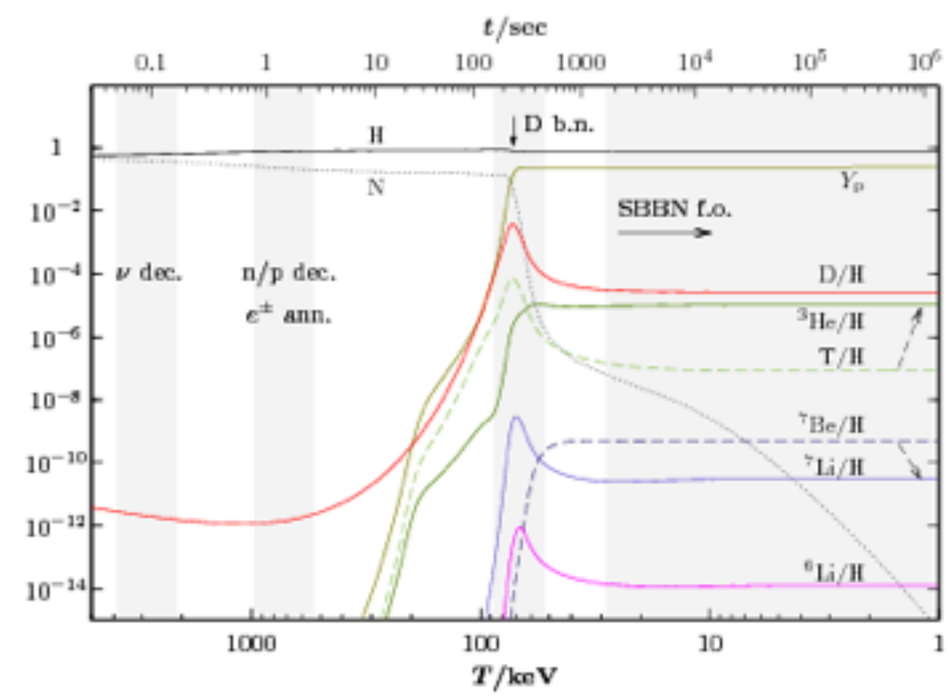
Rotation Curves



Matter Power Spectrum



CMB Power Spectrum



BBN Light Element Yields

... but still no clue about its particle identity

Comparison with 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

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

Understanding the Electroweak Sector

Discovery of Radioactivity		(1890s)
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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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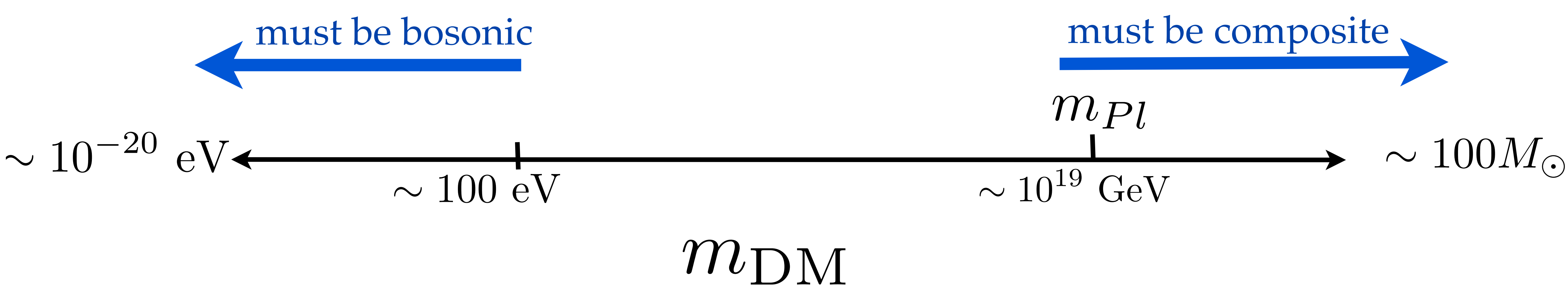


Good news: most *discoverable* DM candidates are in thermal equilibrium with us in the early universe

Why is this good news?

Thermal Equilibrium
Advantage #0: Easily Realized

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 reached in the early universe if

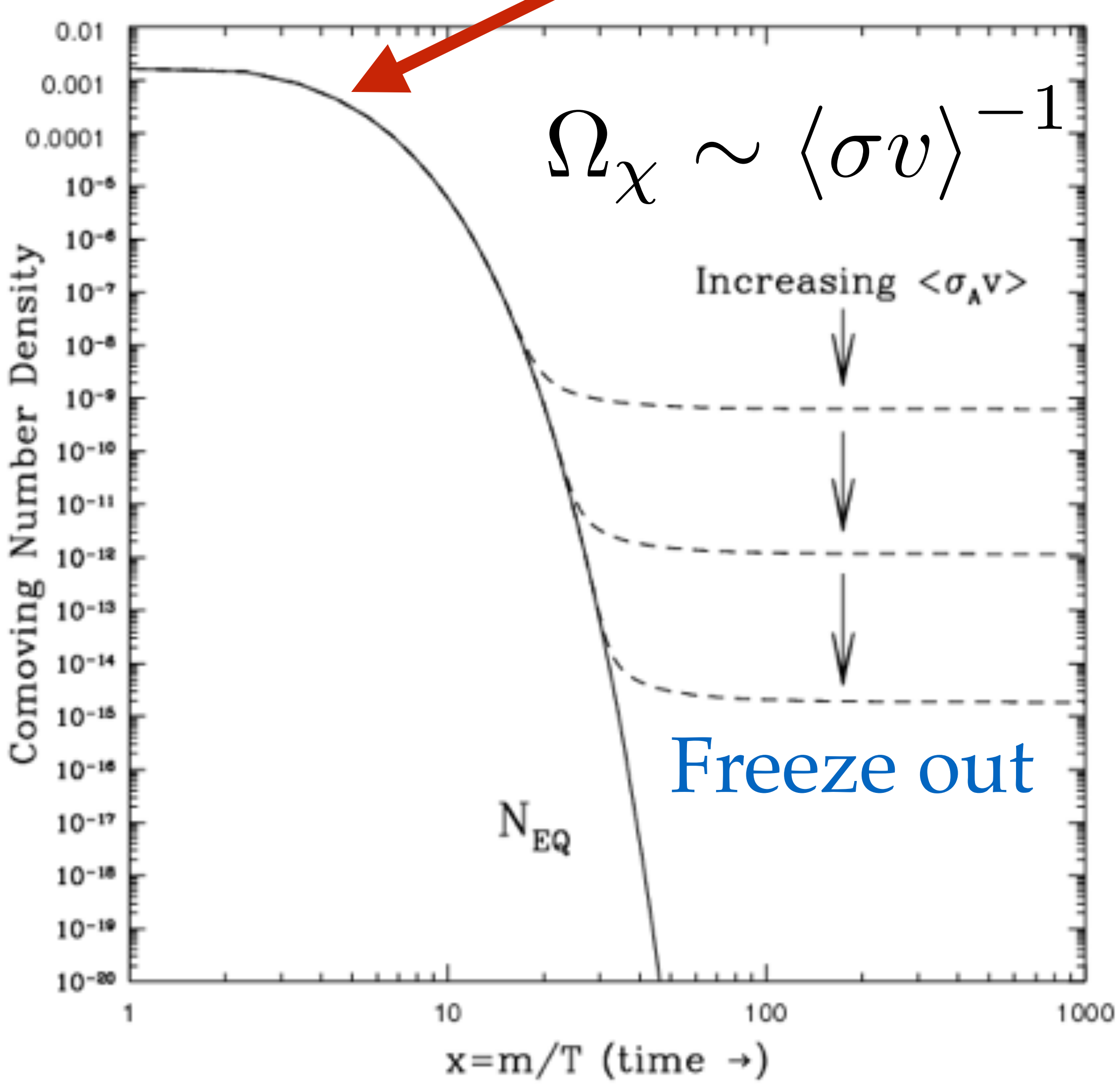
$$g \gtrsim 10^{-8}\left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^2\left(\frac{\mathrm{GeV}}{m_\chi}\right)^{3/2}$$

Applies to *nearly* all models with couplings large enough for detection (rare counterexamples: axion or sterile neutrino)

Thermal Equilibrium
Advantage #1: Minimum Annihilation Rate

DM is overproduced, need to annihilate away the excess!

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



Griest et. al. 1992

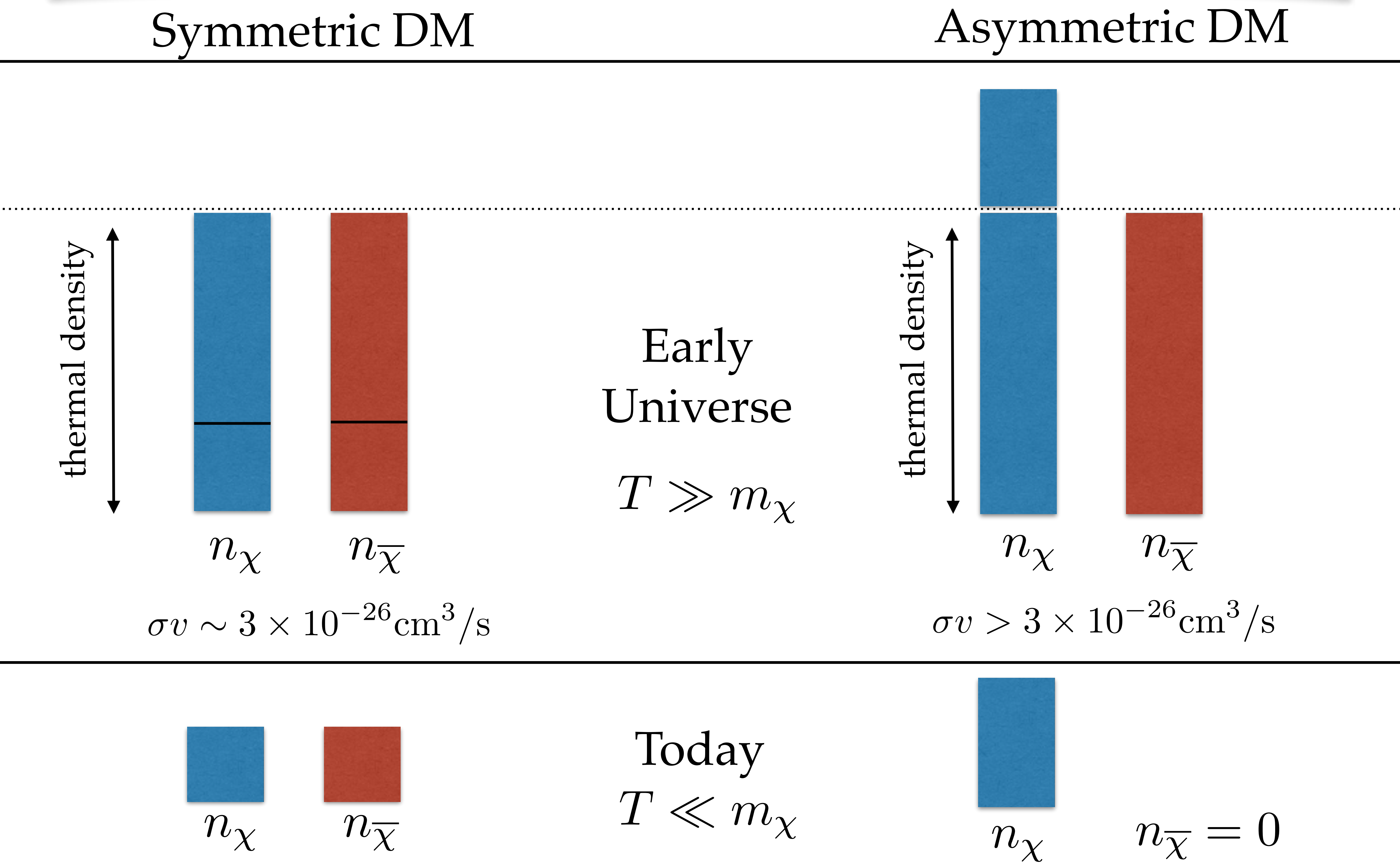
Symmetric Thermal DM

$$n_\chi = n_{\overline{\chi}}$$

Observed density requires

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

Thermal Equilibrium
Advantage #1: Minimum Annihilation Rate



Thermal Equilibrium
Advantage #2: Insensitive to high scales

Known initial condition

Calculable & compatible with nearly all high energy scenarios

Mass & couplings set abundance

Can learn a lot from a discovery!

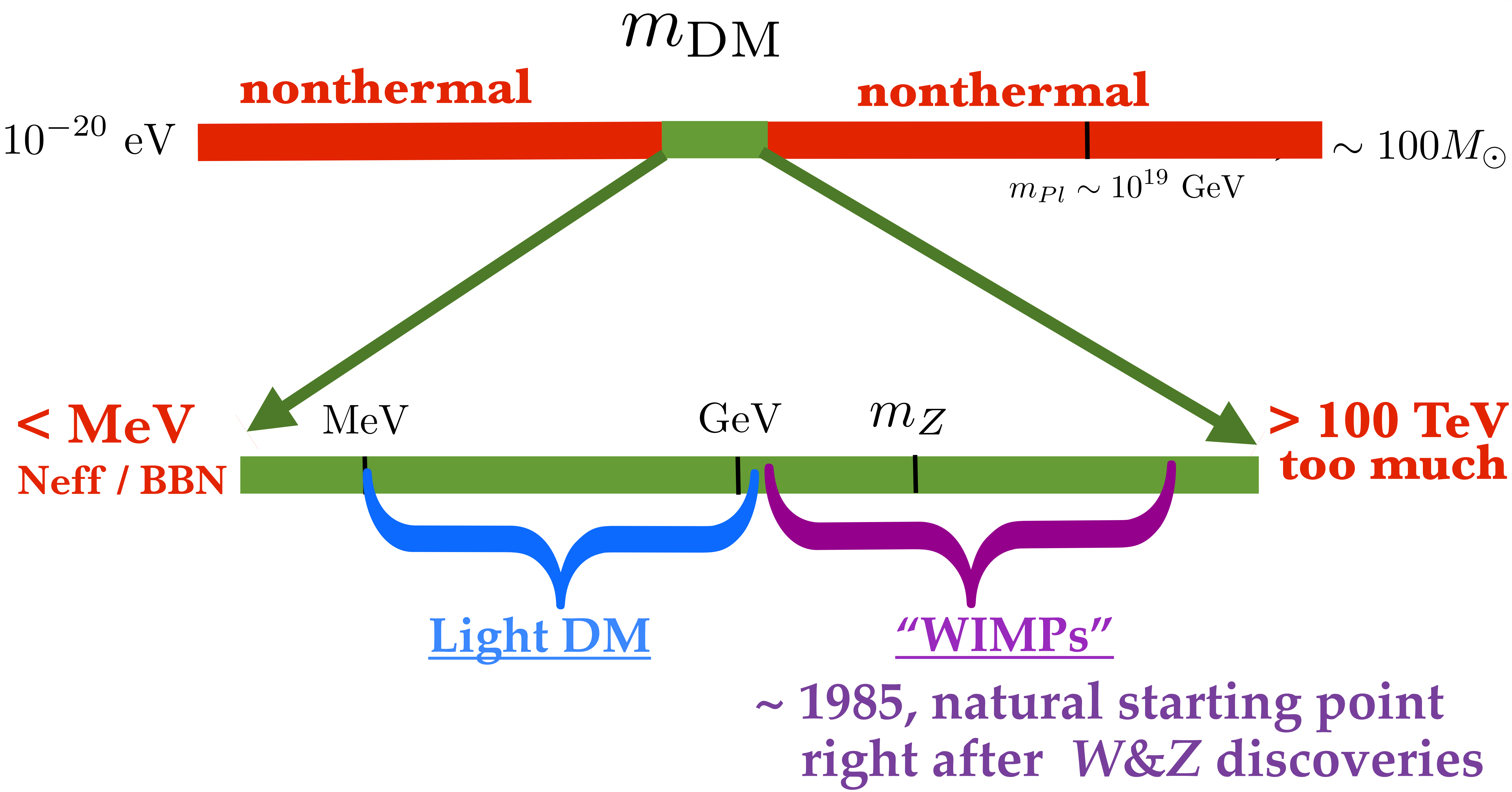
Only *other* insensitive mechanism is "freeze-in"

Very wide mass range $\text{keV} \lesssim m_{\text{DM}} \lesssim m_{Pl}$

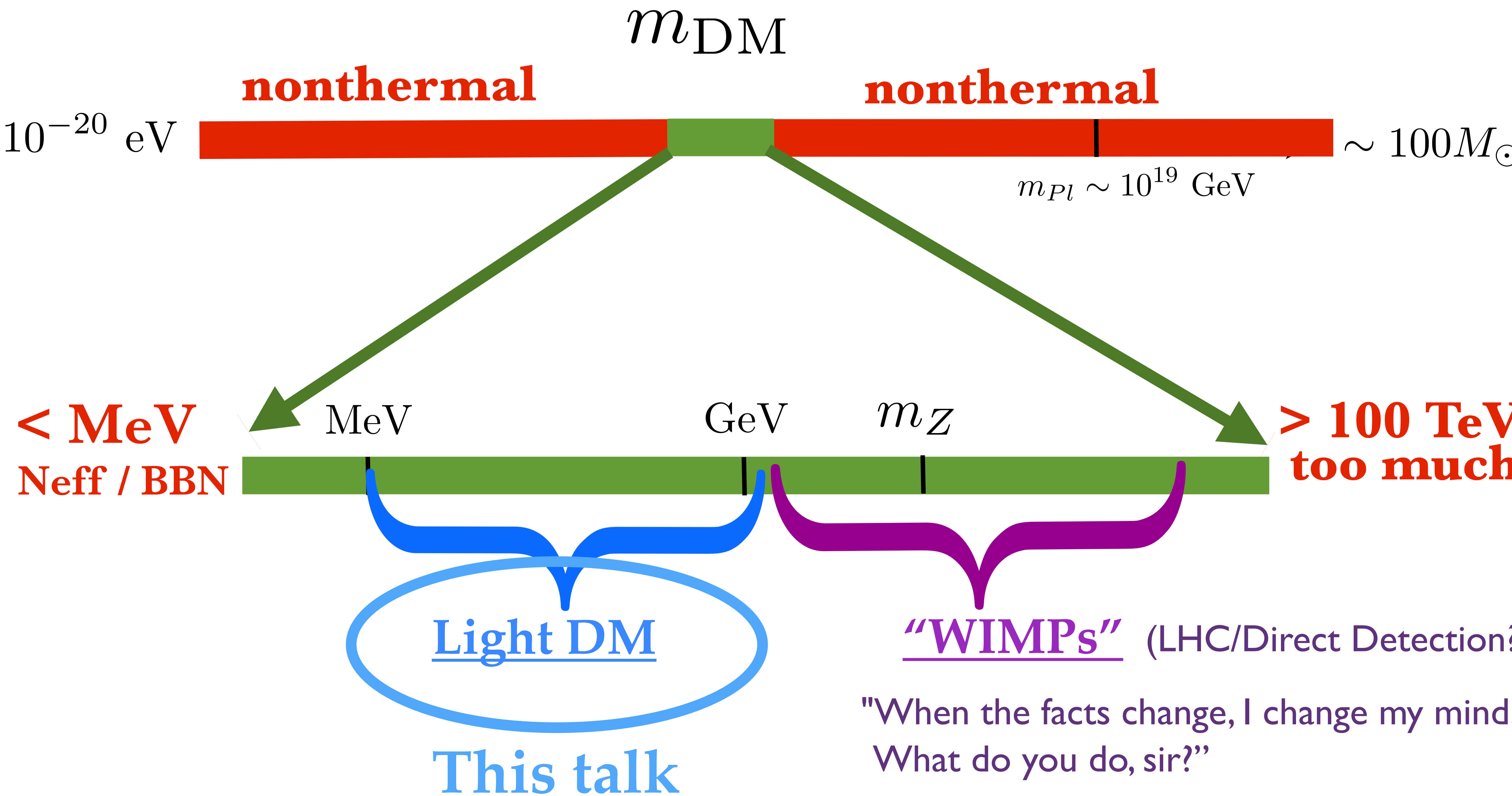
DM produced through tiny couplings, **very** hard to test

Example: Sterile neutrino DM production through mixing

Thermal Equilibrium
Advantage #3: Narrows Viable Mass Range



Thermal Equilibrium
Advantage #3: Narrows Viable Mass Range



(LHC/Direct Detection?)

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

- John Maynard Keynes

Overview

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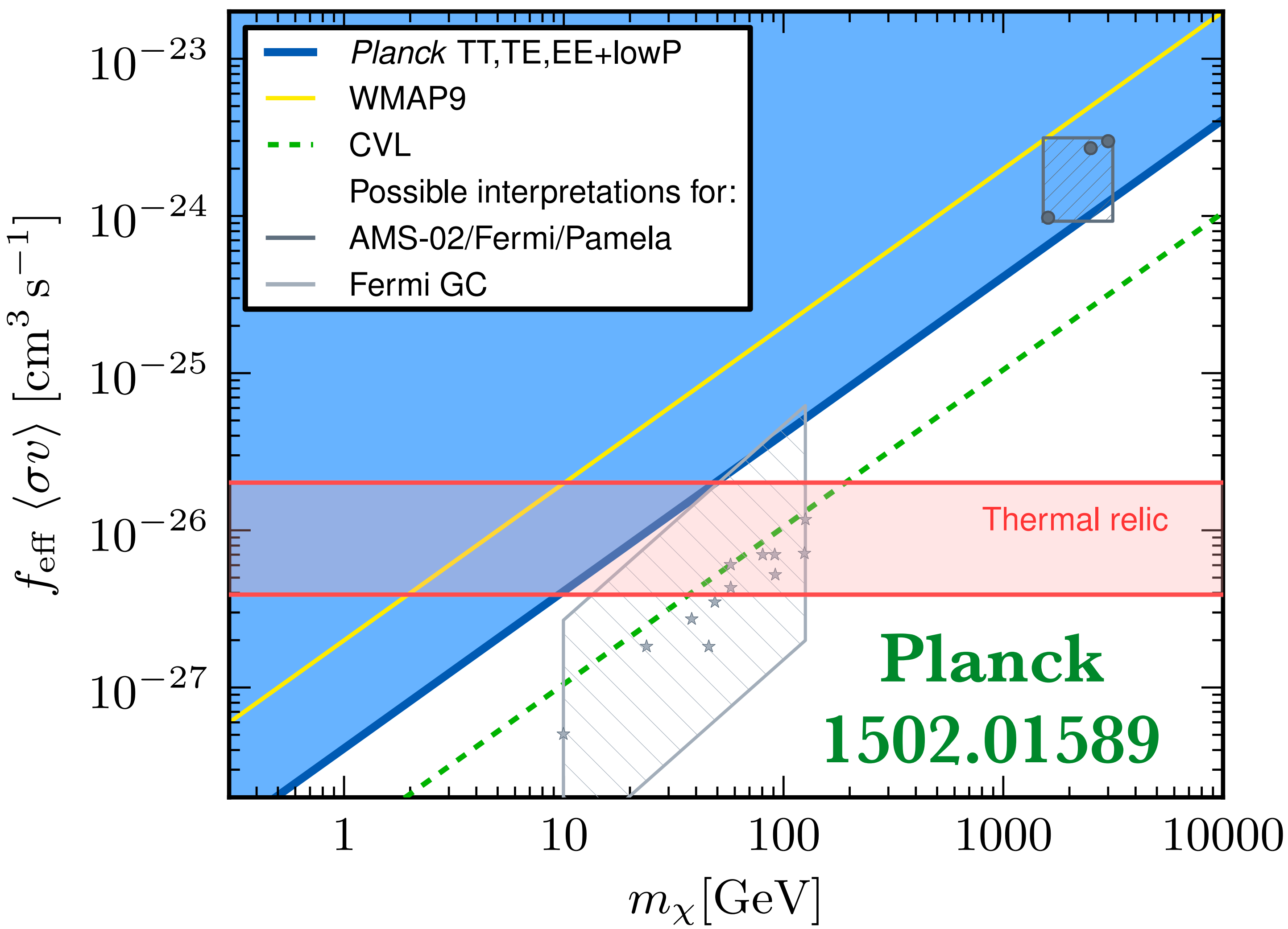
- **New Fixed Target Searches**
  LSND, MiniBooNE, JSNS2, DUNE(?)…

CMB Bounds for light DM

Rules out *s*-wave annihilation < 10 GeV



For viable models need:

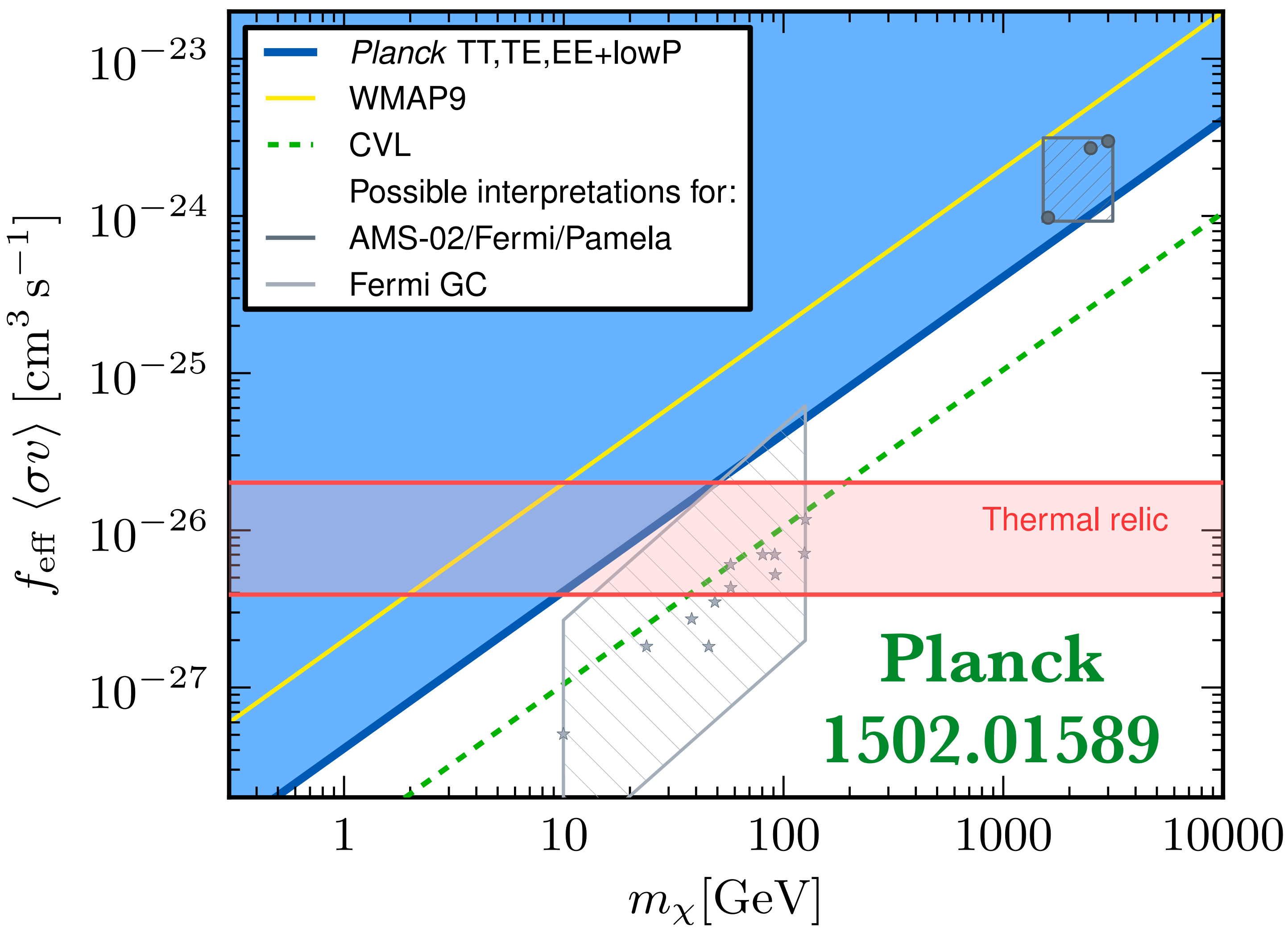
(1) p-wave annihilation

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

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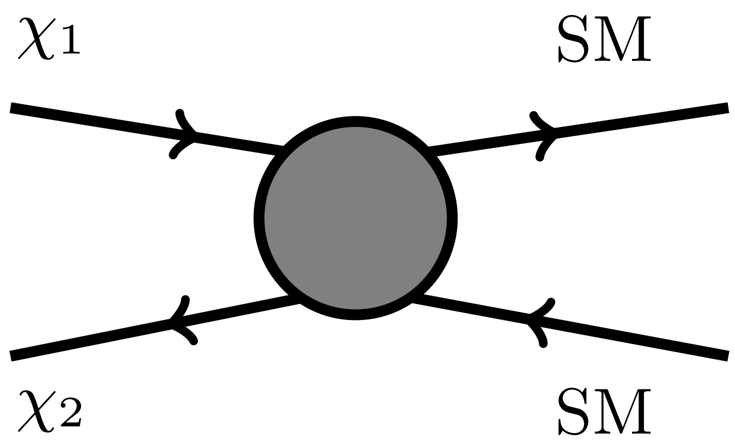
This talk

Inelastic DM is CMB Safe

Direct Coannihilation into SM



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

Heavier state gone before atoms form at T~ 0.1 eV

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

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

Easy to build, features large couplings, but hard to test!

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

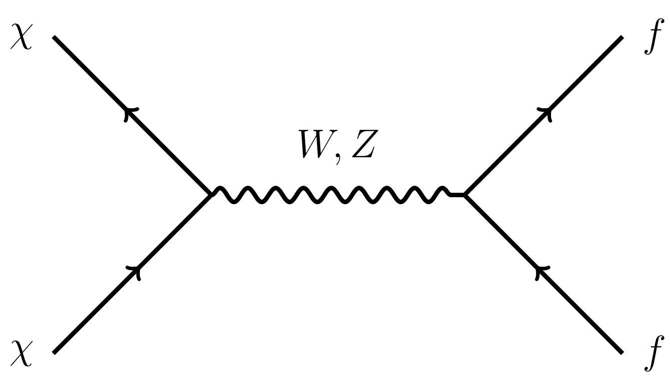
< *GeV Model Building*

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

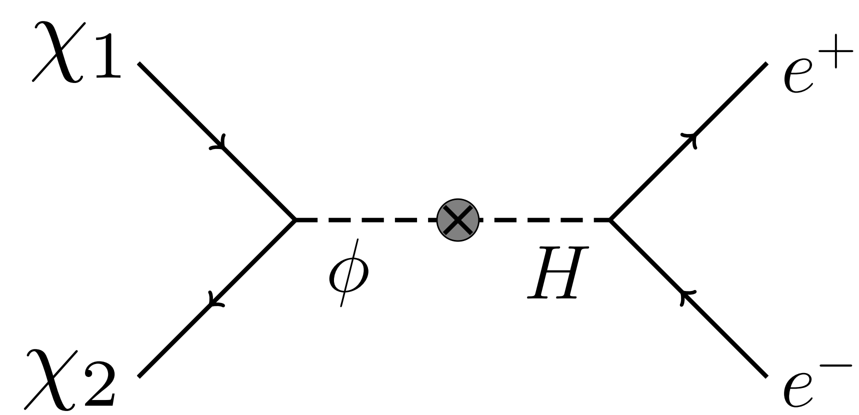
Simplicity: can't use higher dimension operators

Requires renormalizable interactions

What Kind of New Force?

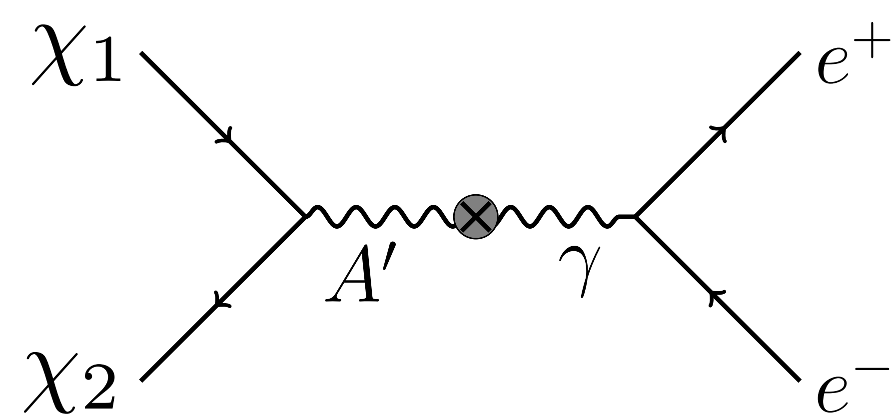
Must also be neutral under SM

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)

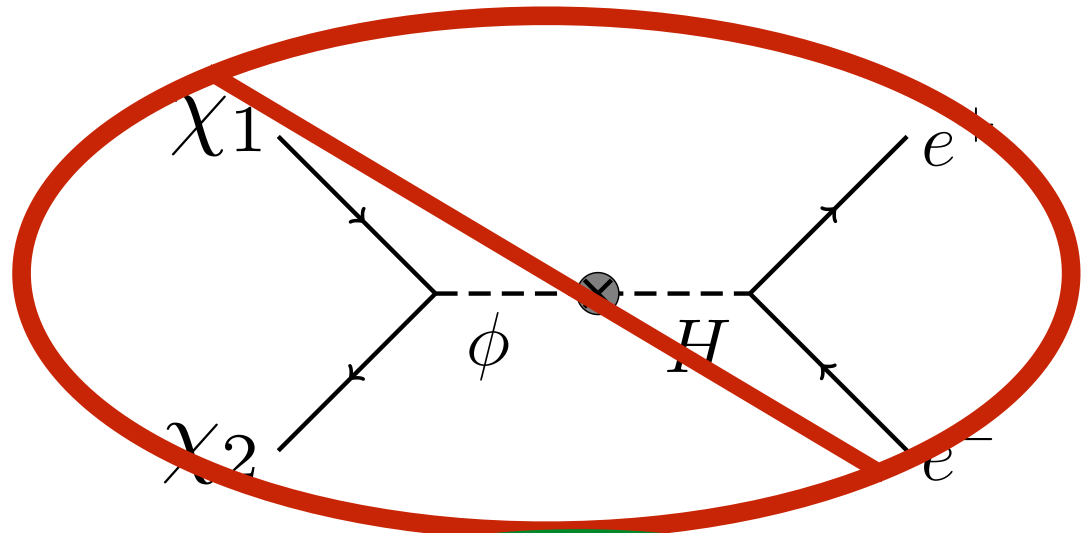
What Kind of New Force?

Must also be neutral under SM

New scalar mediator mixing w/ Higgs

Direct annihilation ruled out

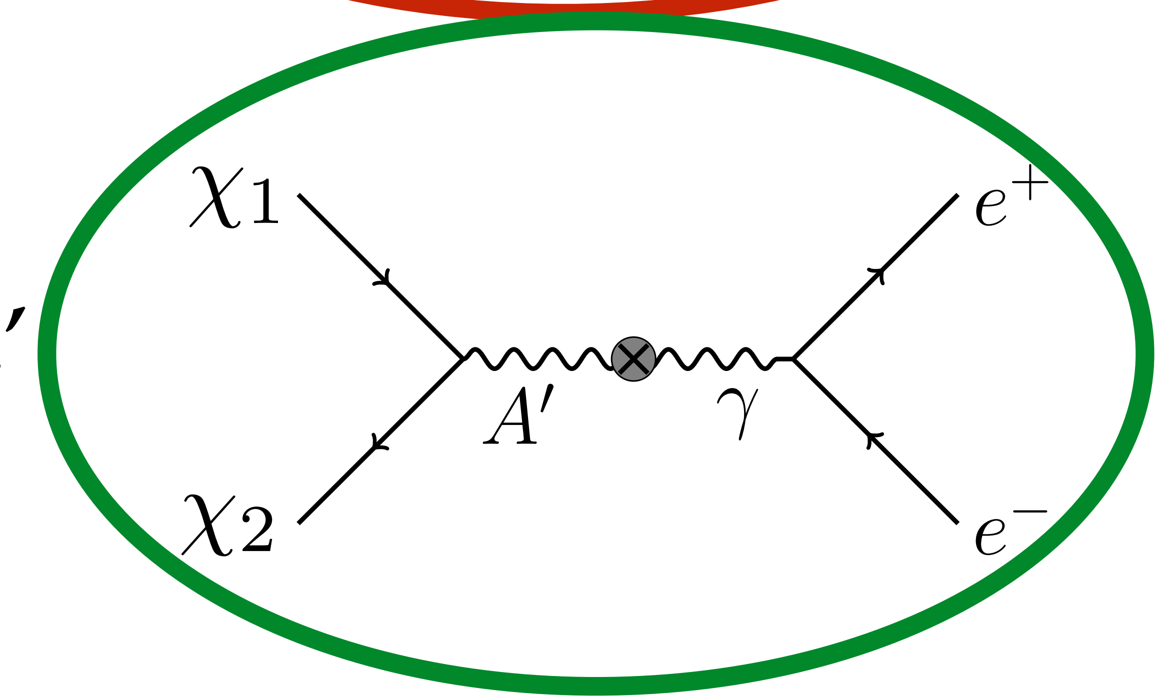
$B \to K\phi \to K\not{E}(\chi_1\chi_2)$



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

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 phone to photon mixing case)

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

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

Dirac — Majorana

Exactly like the electron in QED
if E&M were broken with a charge +2 "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

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

Dirac — Majorana

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

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

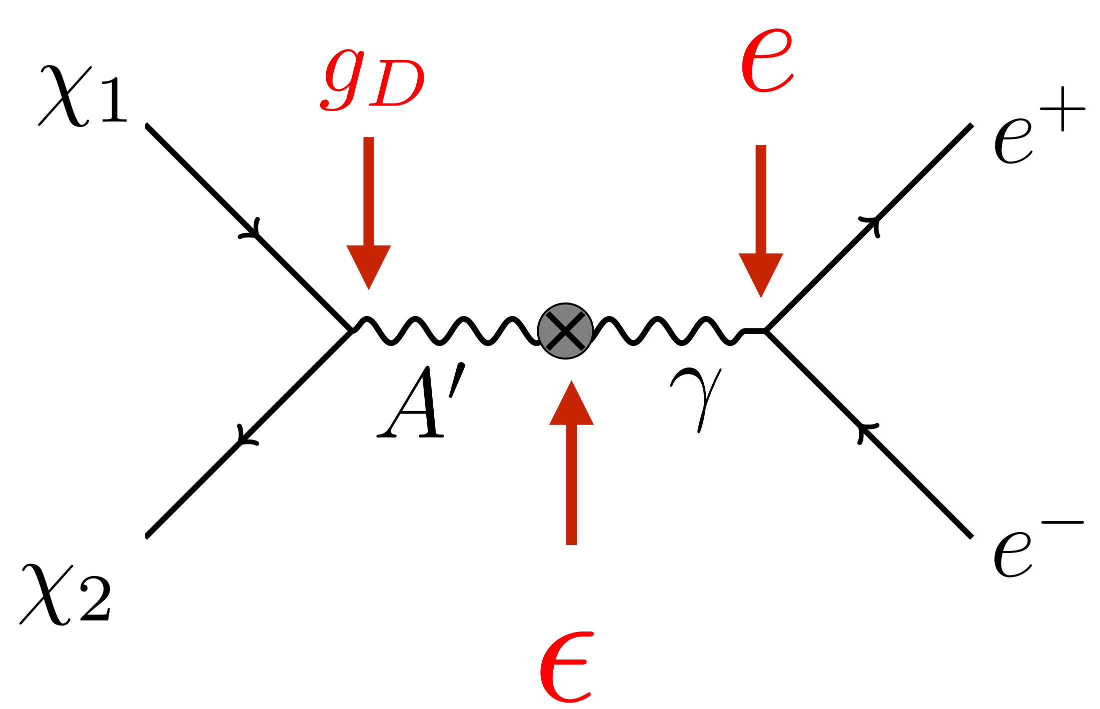
int. eigenstates — mass eigenstates

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

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

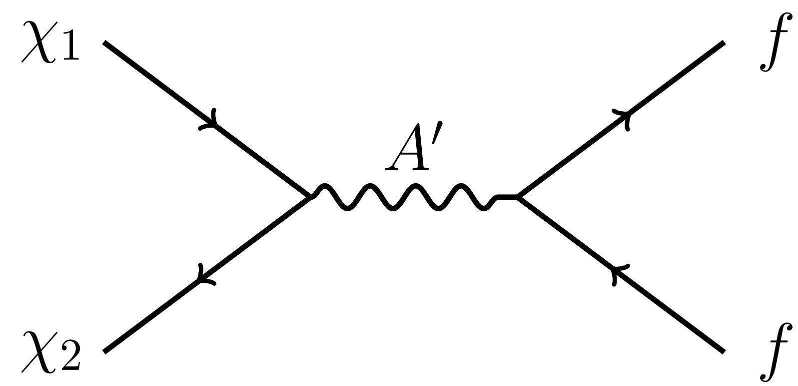
$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$

opposite regime not CMB safe

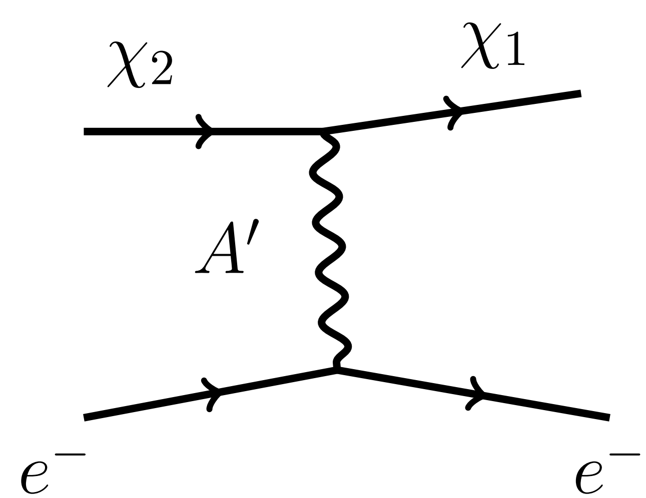
$$\chi_1 \chi_1 \rightarrow A' A' \quad \textbf{(s-wave)}$$

Inelastic Novelties

Coannihilation

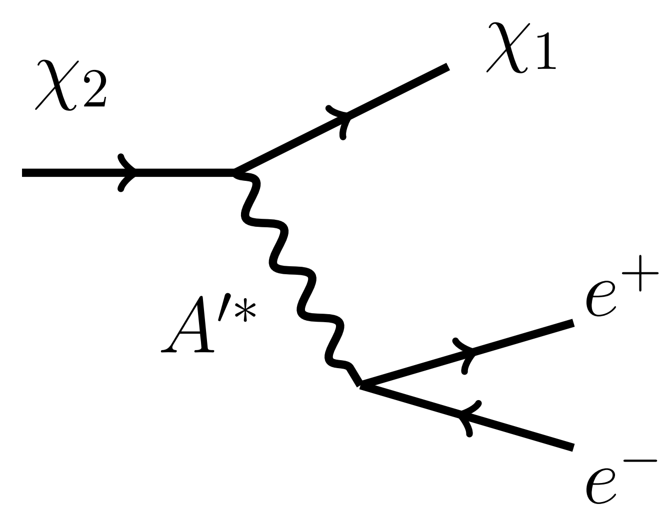


Upscattering & Downscattering

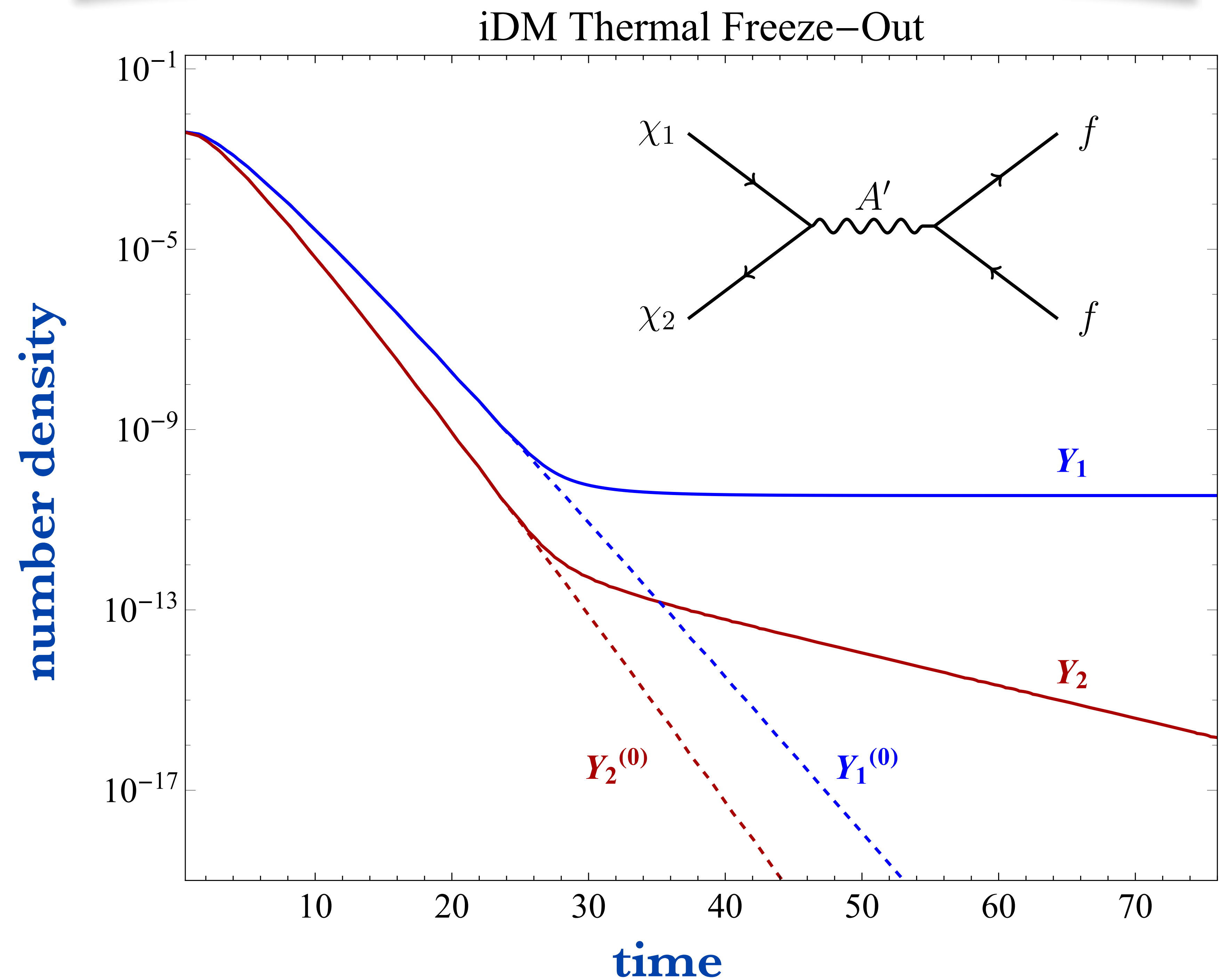


Excited State Decays

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



Coannihilation Relics



Heavier state feels Boltzmann suppression earlier

Need larger rate to compensate!

Useful Variables

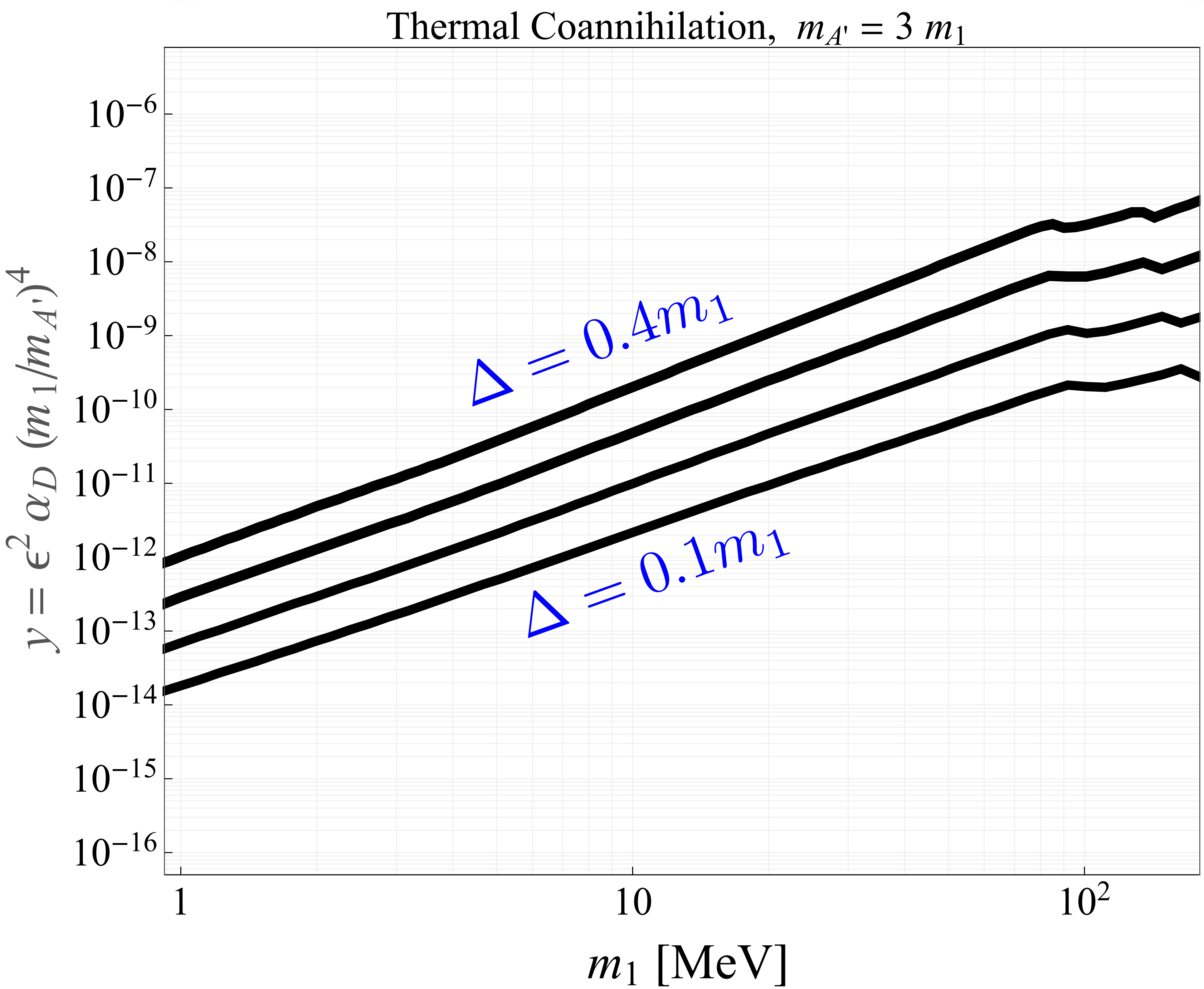
Define new variable optimized for thermal targets

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

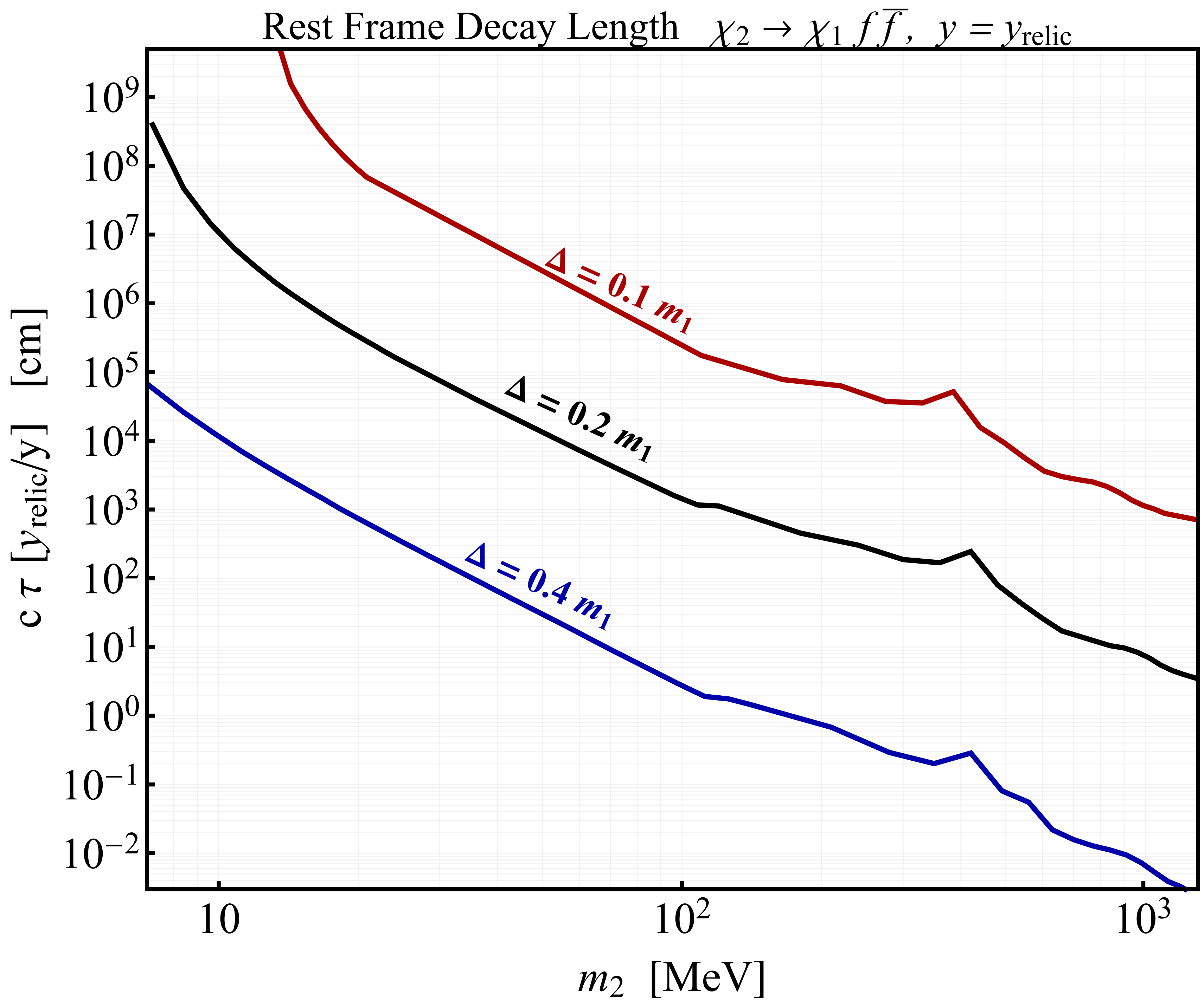
Insensitive to ratios of inputs, unique "y" for each mass and Δ (up to subleading corrections)

Reduces complicated parameter space to 2D comparison

Thermal Relic Targets



Generically Macroscopic Decays



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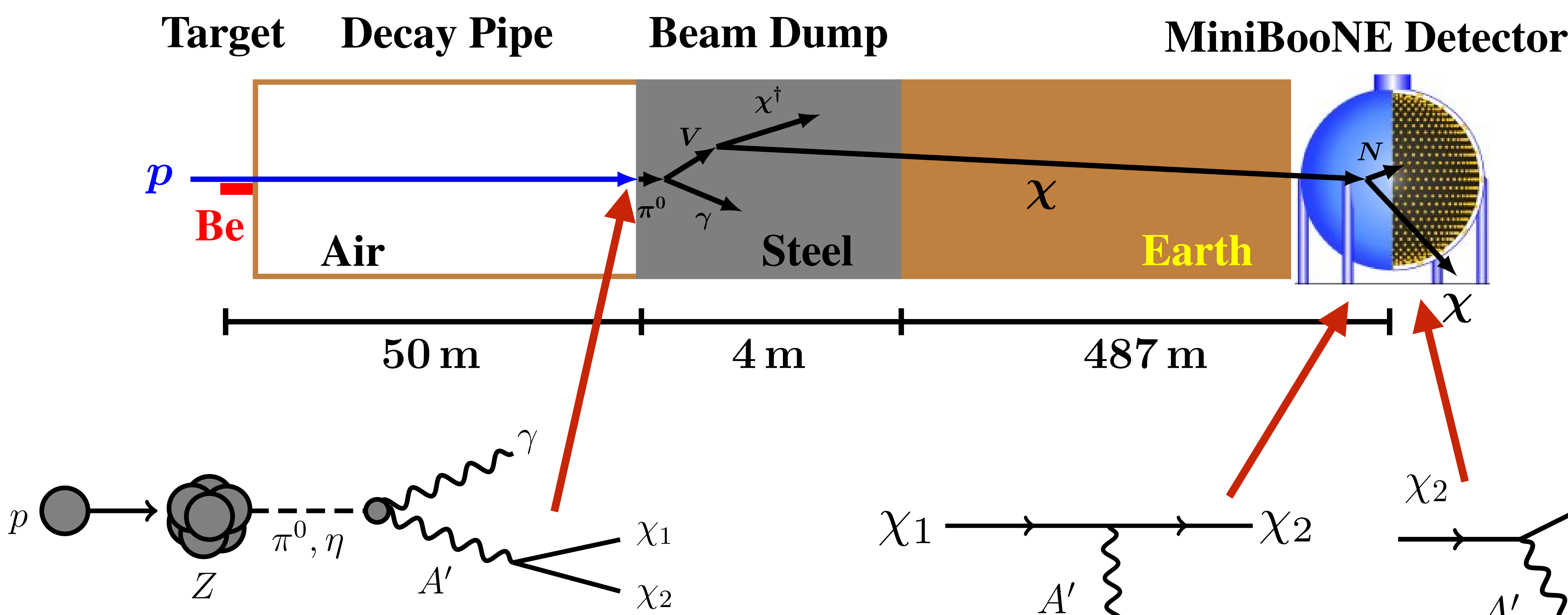
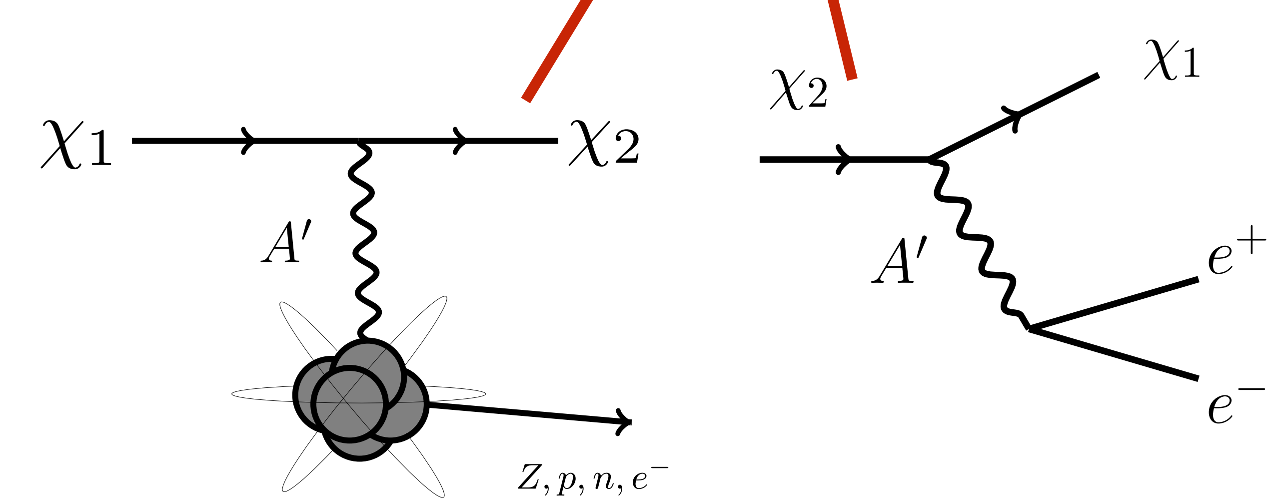
Signatures @ Proton Beam Dumps

inelastic scattering & decays





For elastic DM studies, see also:

Batell, Pospelov, Ritz 0903.0363

Batell, deNiverville, McKeen, Pospelov, Ritz 1405.7049

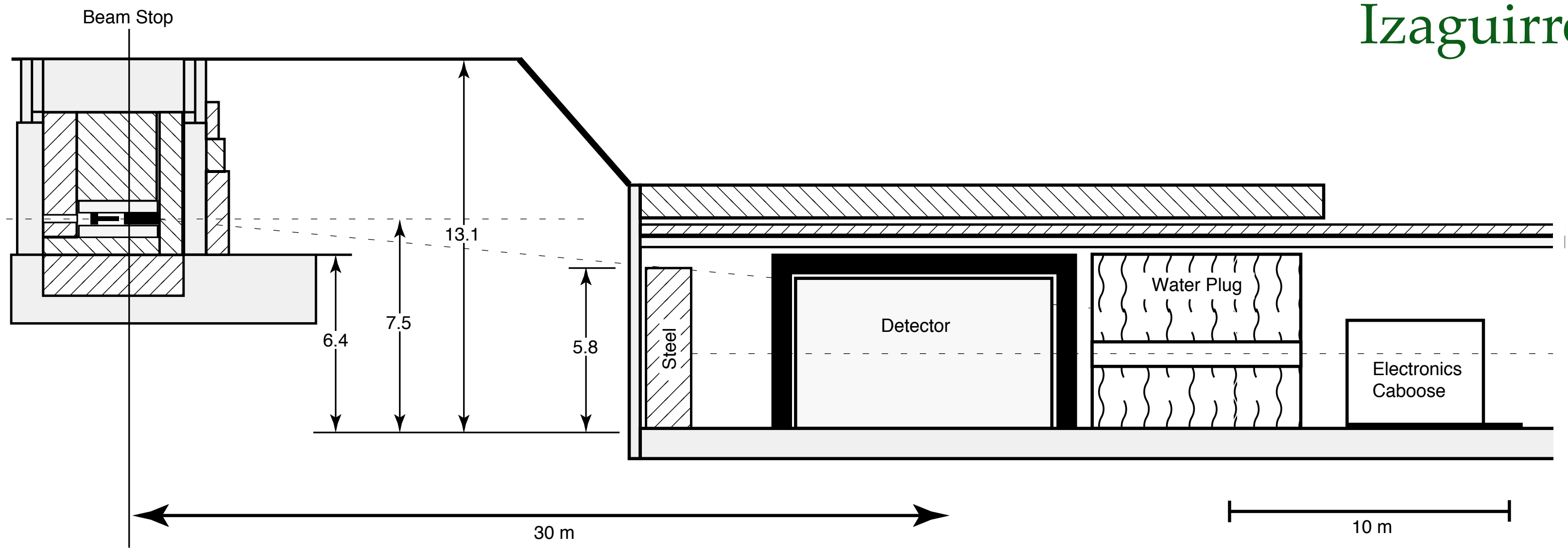
Coloma, Dobrescu, Frugiuele, Harnik 1512.03852

Frugiuele 1701.05464

Kahn, GK, Thaler, Toups 1411.1055

Revisiting LSND

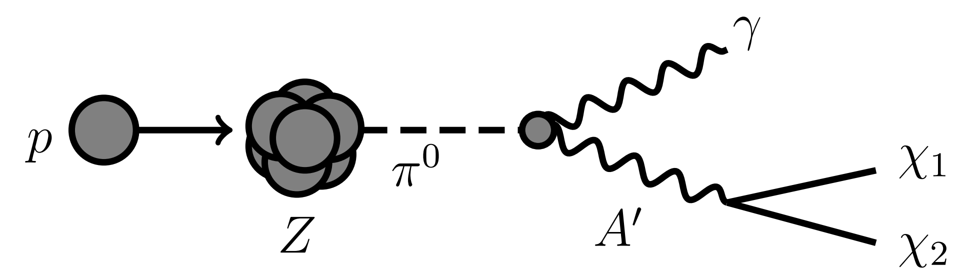
Izaguirre, Kahn, GK, Moschella 1703.06881



DM beam from pion decays

$E_p \simeq 800\,\mathrm{MeV}$, 10^{24} POT

Mineral oil detector 3m x 10 m cylinder

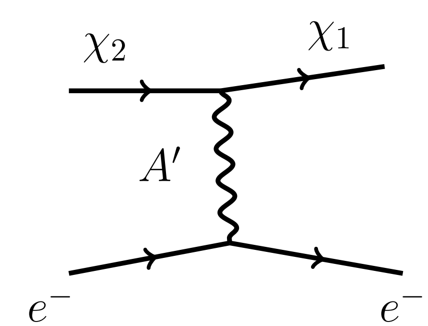


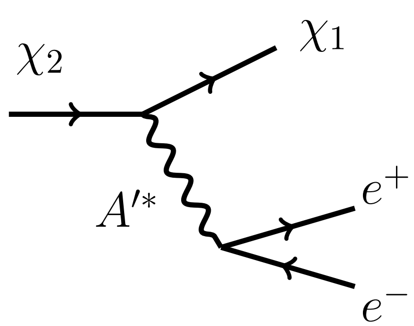
Heavier state scatters or decays in detector

$$18\,\mathrm{MeV} < E_{\mathrm{vis}} < 50\,\mathrm{MeV}$$

$$\cos\theta < 0.9$$

$$\Delta N_{\mathrm{obs}} = 55$$





Simulate pi0 production Sanford/Wang

deNiverville, Chen, Pospelov, Ritz 1609.01770

deNiverville, Pospelov, Ritz 1107.4580

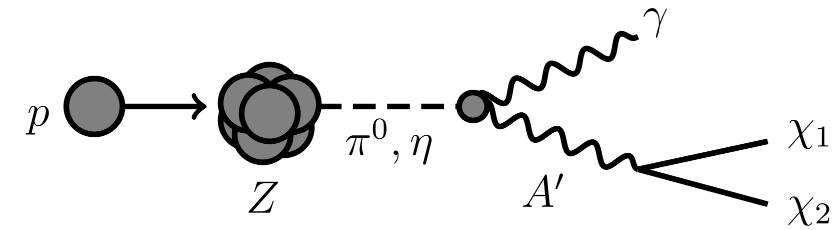
Recast $\nu_e e \to \nu_e e$

DM decays mimic e-scatter

$\theta_{e^+e^-} < 12^\circ$ LSND arXiv/0101039

Projections for JSNS^2

JSNS2 TDR 1705.08629



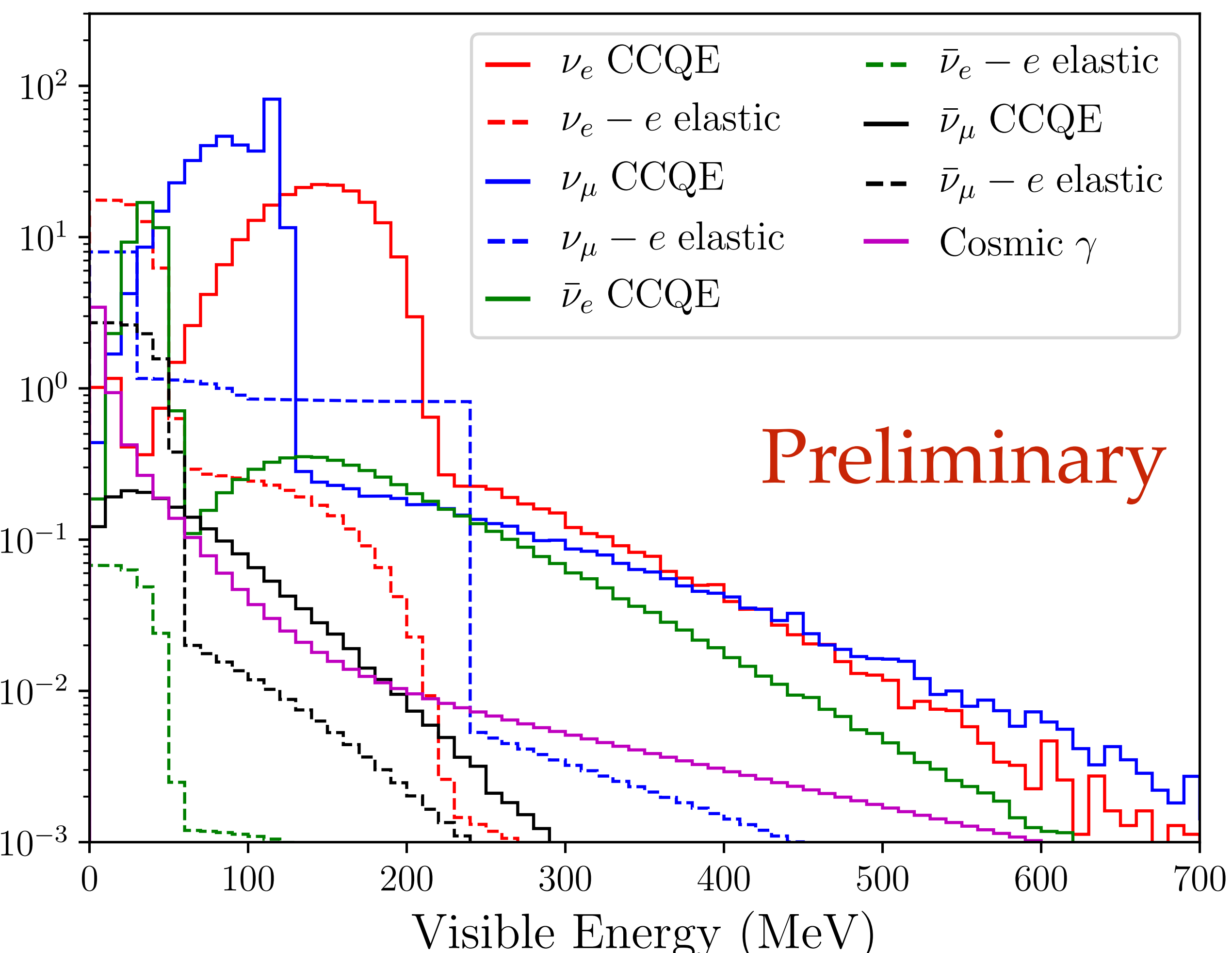
DM beam from pion& eta decays

$\sim 10^{23}$ POT, $E_p = 3\,\mathrm{GeV}$, Hg target

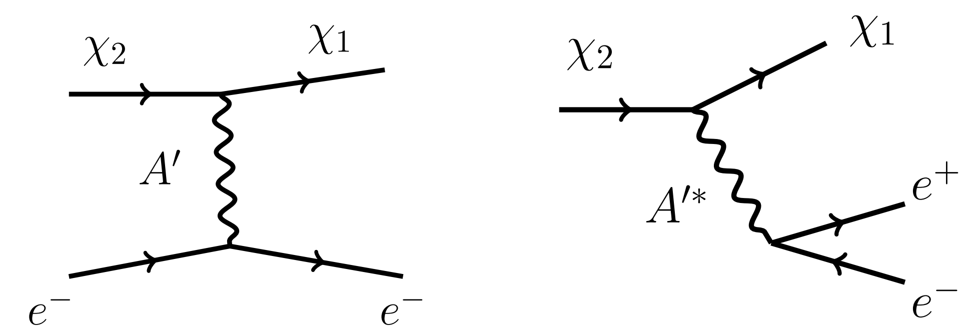
~ LSND geometry, ~30 ton scintillator det. , 24 m target-detector dist.
GEANT4 simulation for signal and BG production

Heavier state scatters or decays in detector

Beam Backgrounds



GEANT4



Assume 20% systematic uncertainty on BG
Assume 7cm extra shielding for comics

$$\delta B = \sqrt{B_{\mathrm{beam-off}}} + 0.2 B_{\mathrm{beam-on}}$$

demand $S/\delta B = 2$

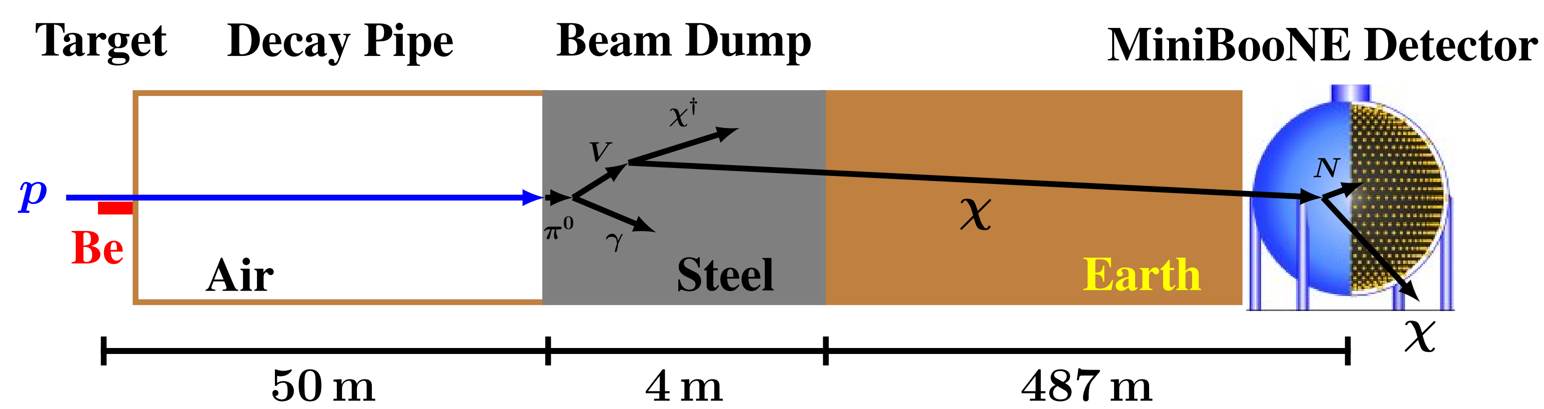
Optimal cuts depend on DM mass

Projections for MiniBooNE

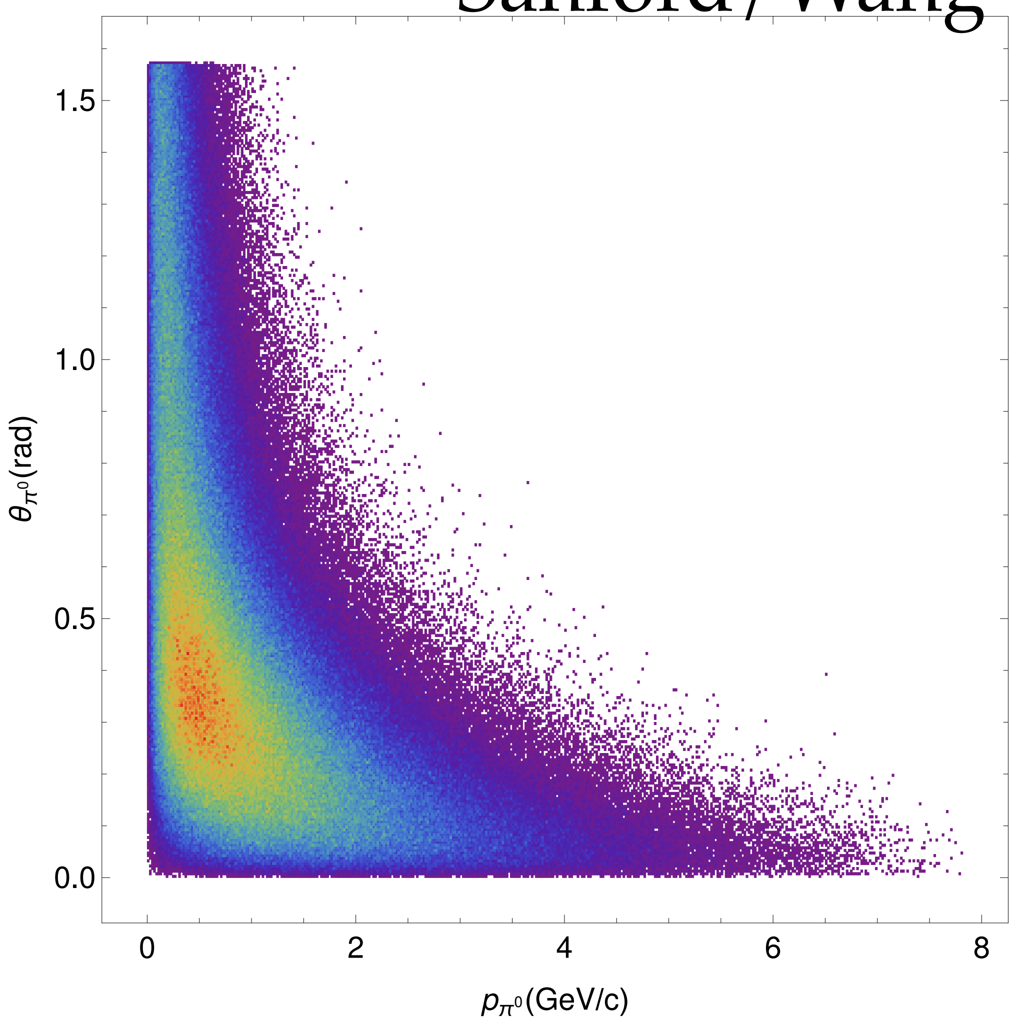
Input parameters

$$E_p \simeq 9\mathrm{GeV}\ ,\ 10^{20}\ \mathrm{POT}$$

~ 500 m baseline



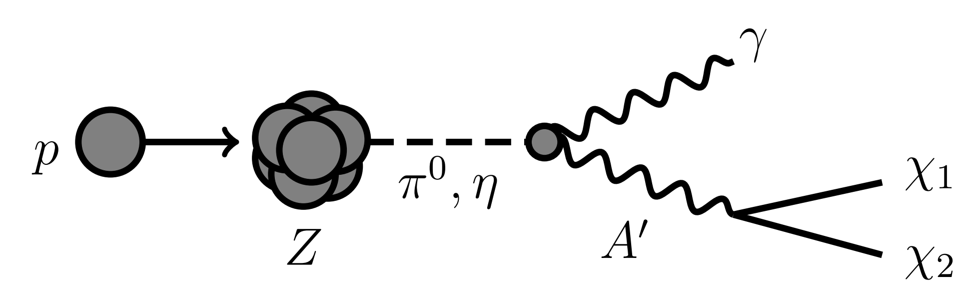
π^0/η Distributions Sanford/Wang



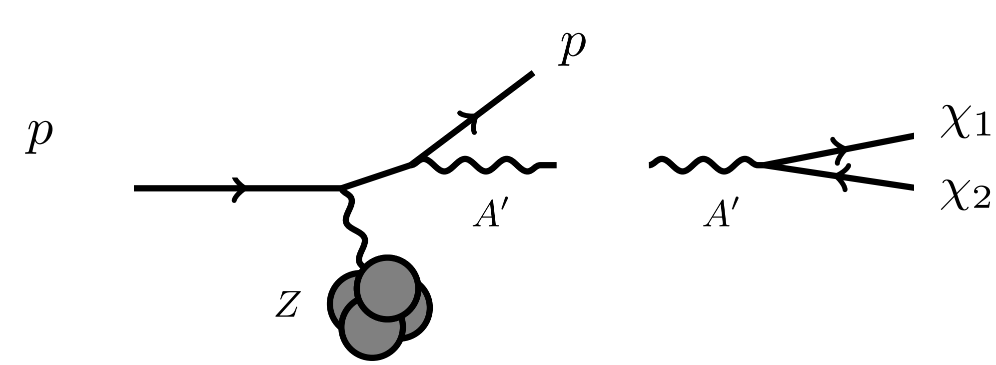
deNiverville, Chen, Pospelov, Ritz 1609.01770

DM Production beam dump mode

Meson Decays

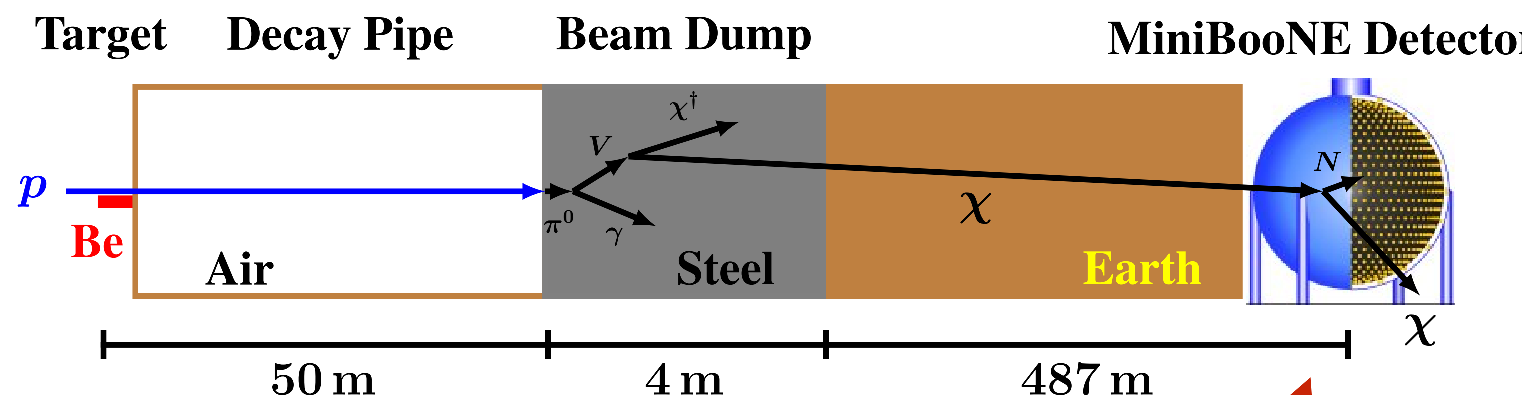


Bremsstrahlung



Exploit full beam energy phase space

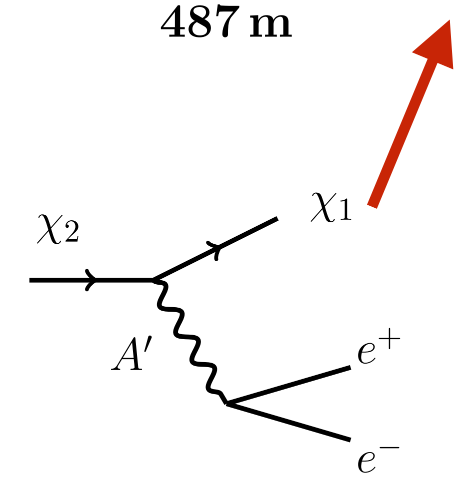
Projections for MiniBooNE



Input parameters

$E_p \simeq 9\text{GeV}\ ,\ 10^{20}\ \text{POT}$

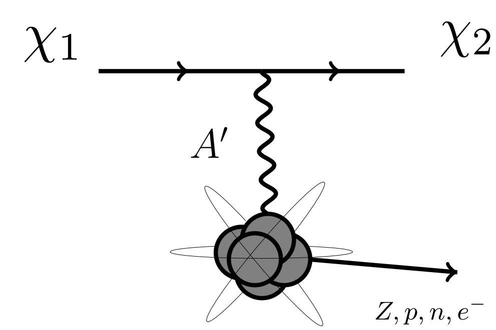
R ~ 5 m mineral oil detector



Heavier state scatters or decays in detector
Similar to cuts from MiniBooNE 1702.02688

$50\,\text{MeV} < E_{\text{vis}} \simeq 600\,\text{MeV}$

$\cos\theta < 0.99 \qquad \theta_{e^+e^-} > 2^\circ$



Lepton detection efficiency ~ 35%

Patterson et. al 0902.2222

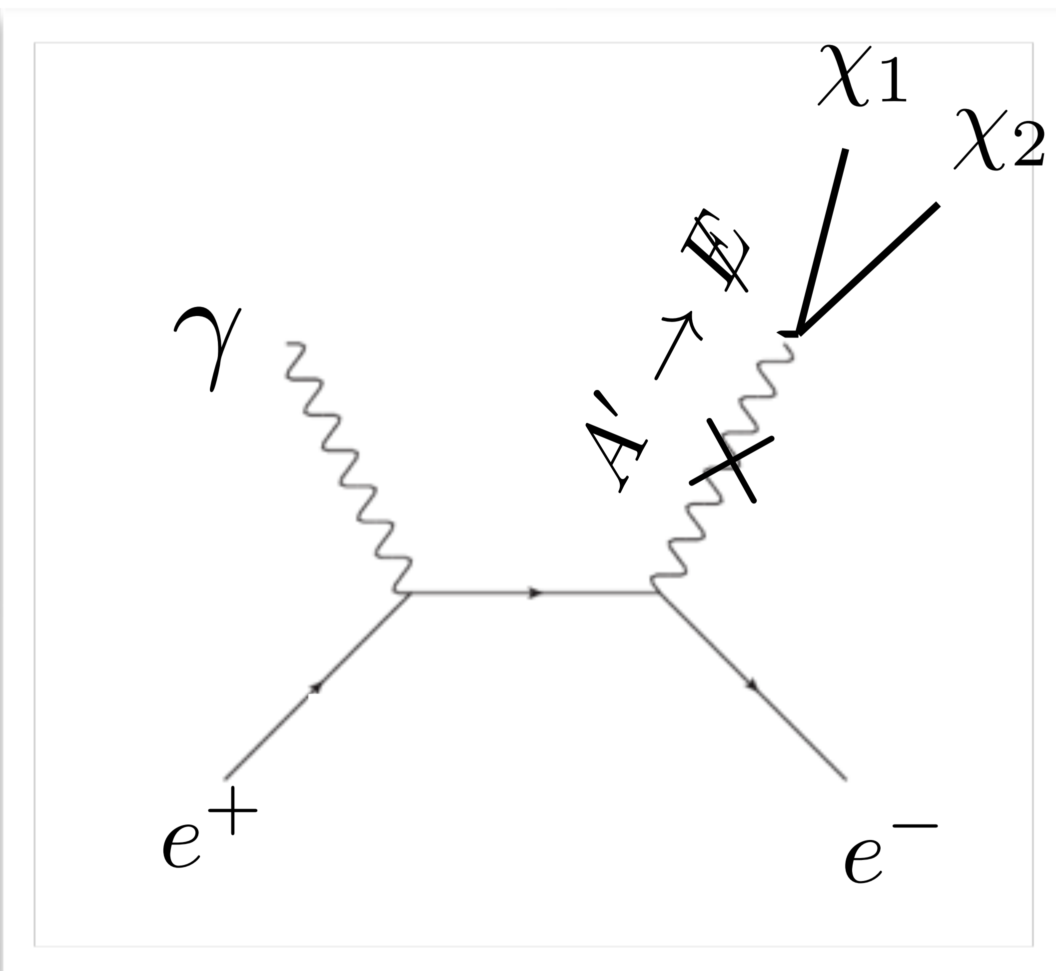
Smaller acceptance, larger energy relative to LSND/JSNS2

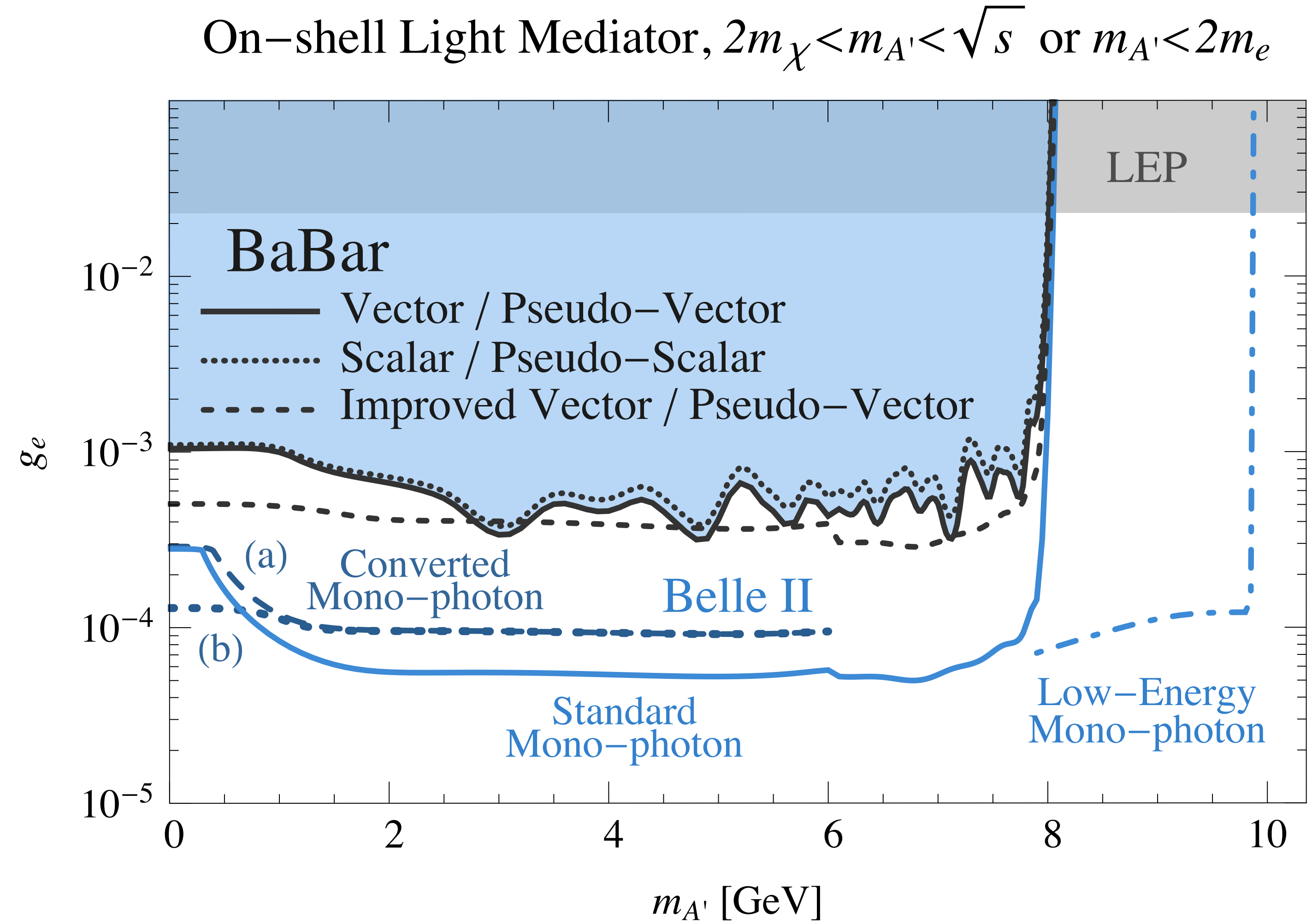
Dominant in the high DM mass range

Other Experiments & Techniques

Signatures @ B-Factories

mono photon + missing energy





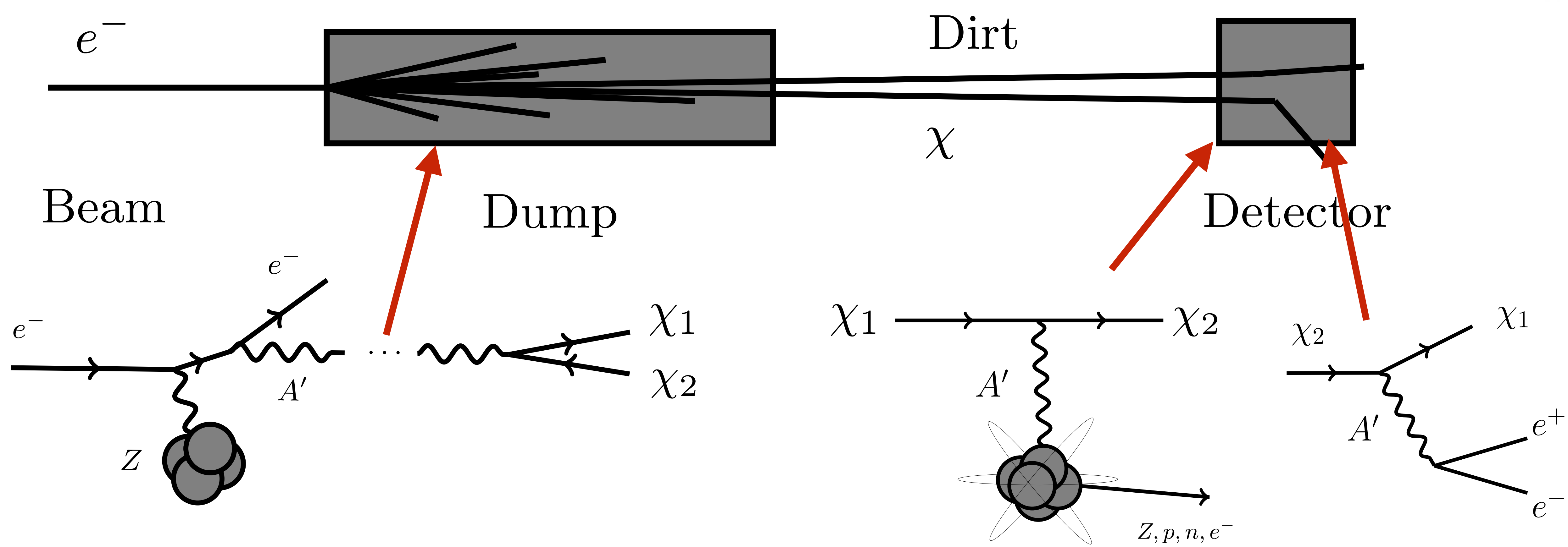
Signatures from displaced vertices and/or missing energy

Izaguirre, GK, Schuster, Toro 1307.6554

Essig, Mardon, Papucci, Volansky Zhong 1309.5084

Signatures @ Electron Beam Dumps

inelastic scattering & decays



E137 (SLAC 1988)

E ~ 20 GeV, 1e20 EOT

~ 400 m baseline, no BG

BDX (JLab 2020?)

E ~ 11 GeV, 1e22 EOT

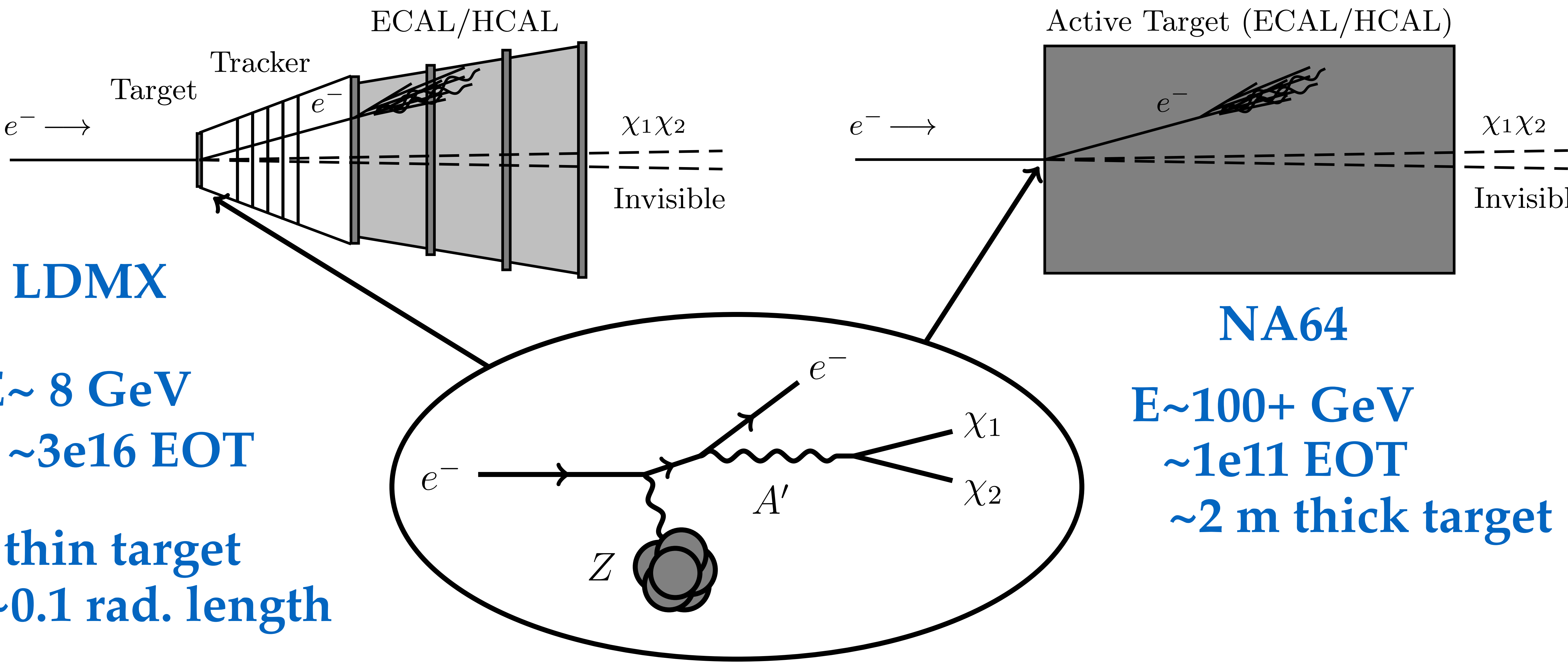
~ 20 m baseline, few BG evts.

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

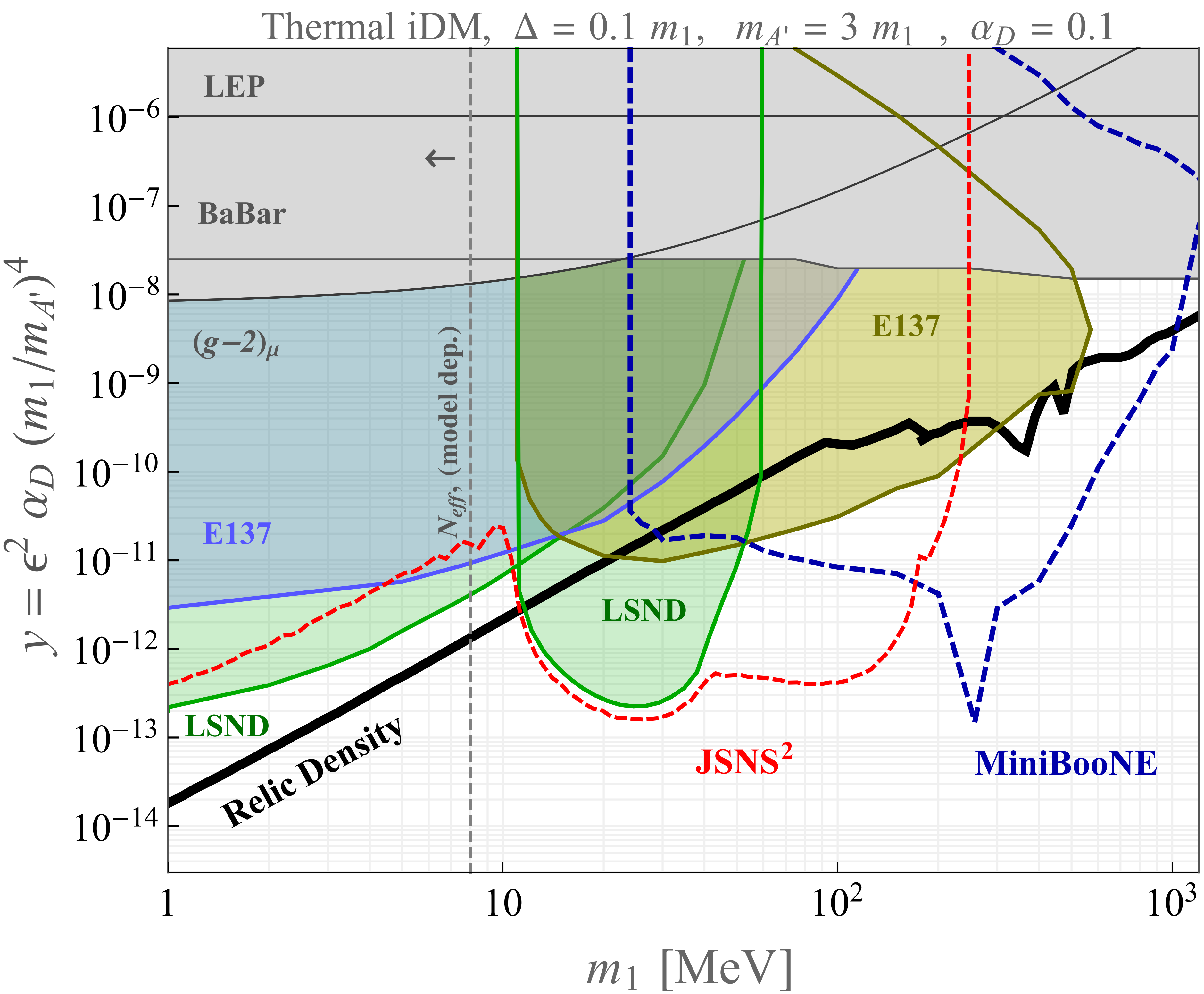
E~100+ GeV
~1e11 EOT
~2 m thick target

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

Izaguirre, GK, Schuster, Toro 1307.6554
LDMX Collaboration 1805.XXXXX

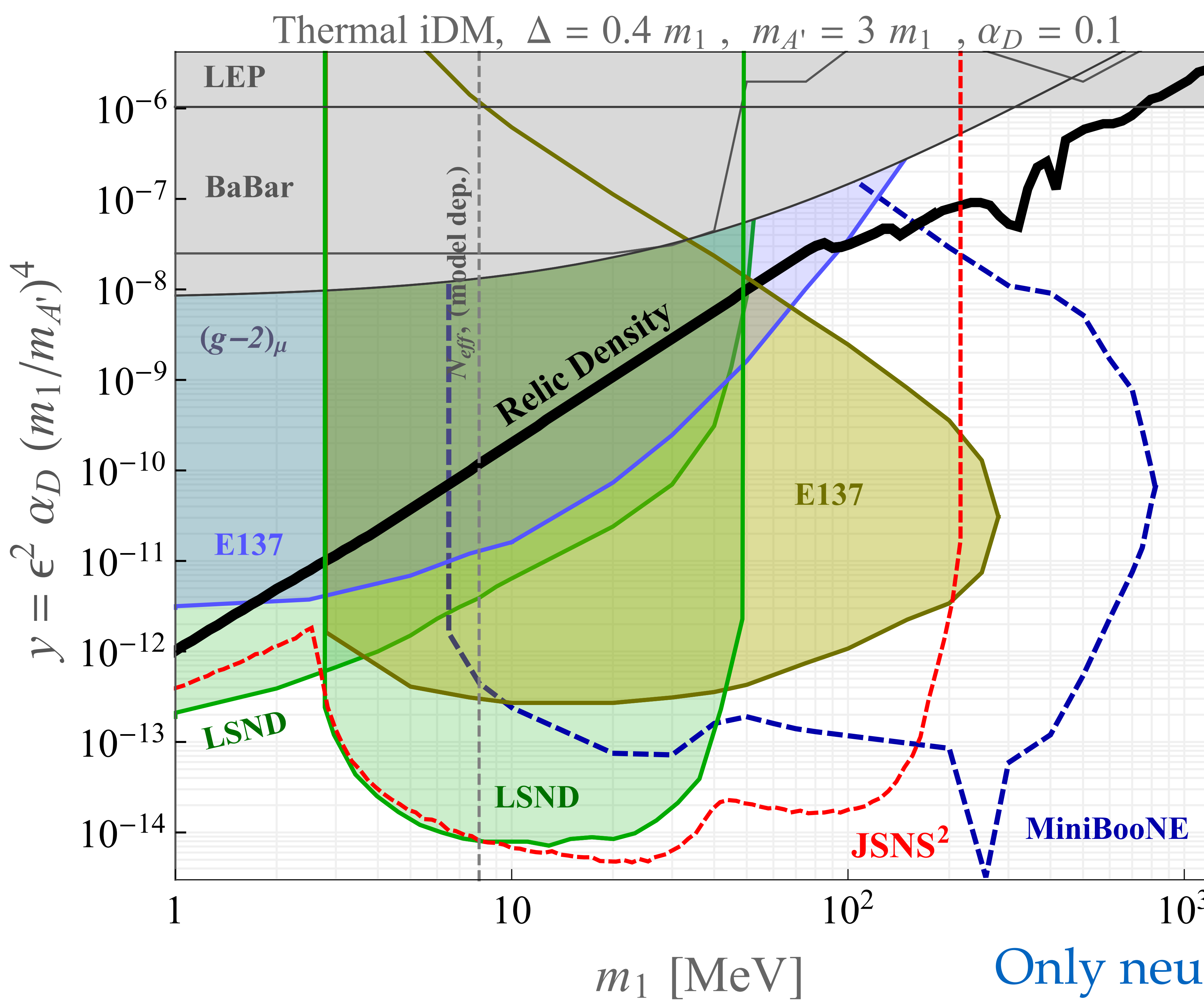
NA64 Collaboration 1610.02988

Small Splitting ~ 10%



Only neutrino projections

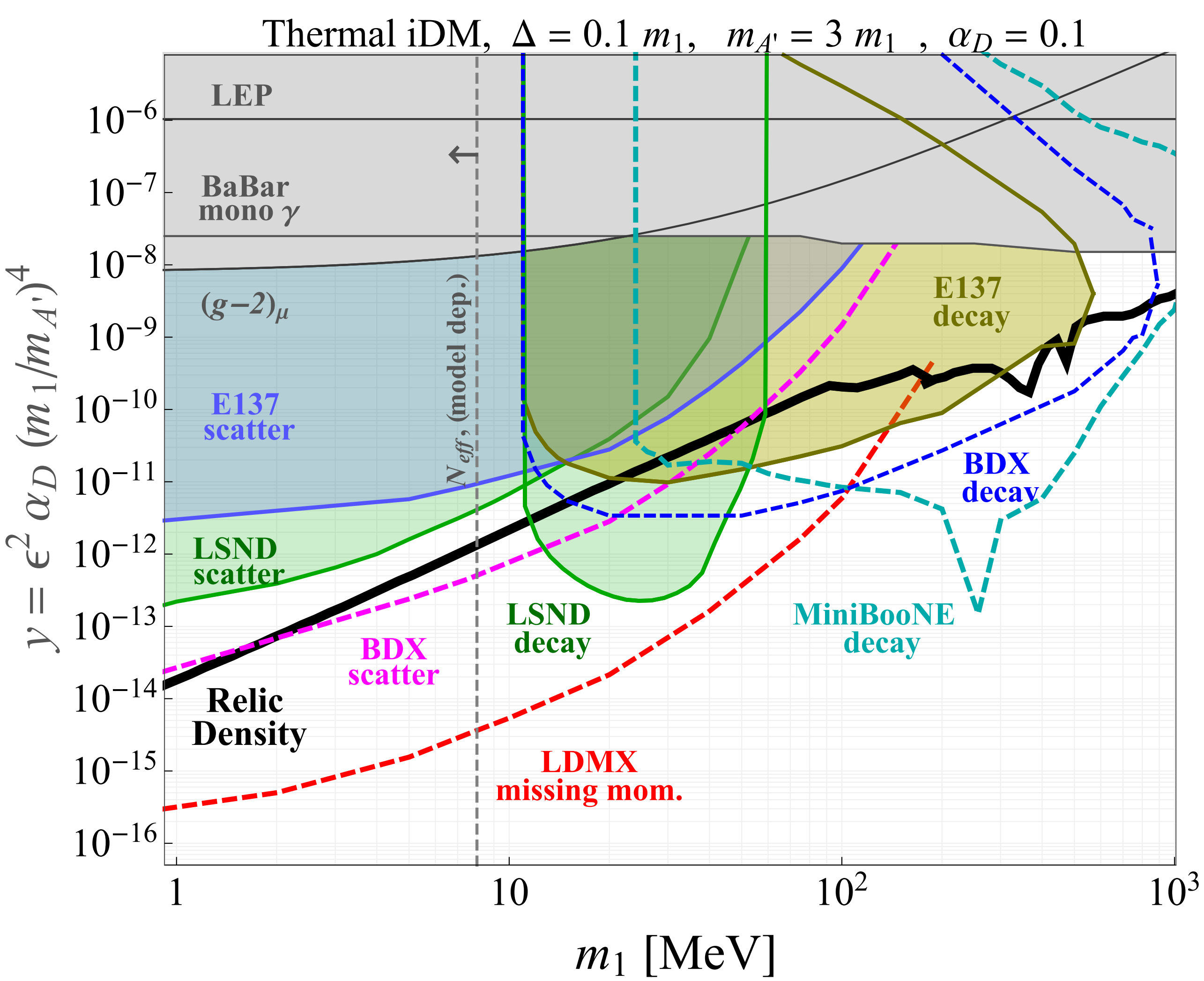
Large Splitting ~ 40%

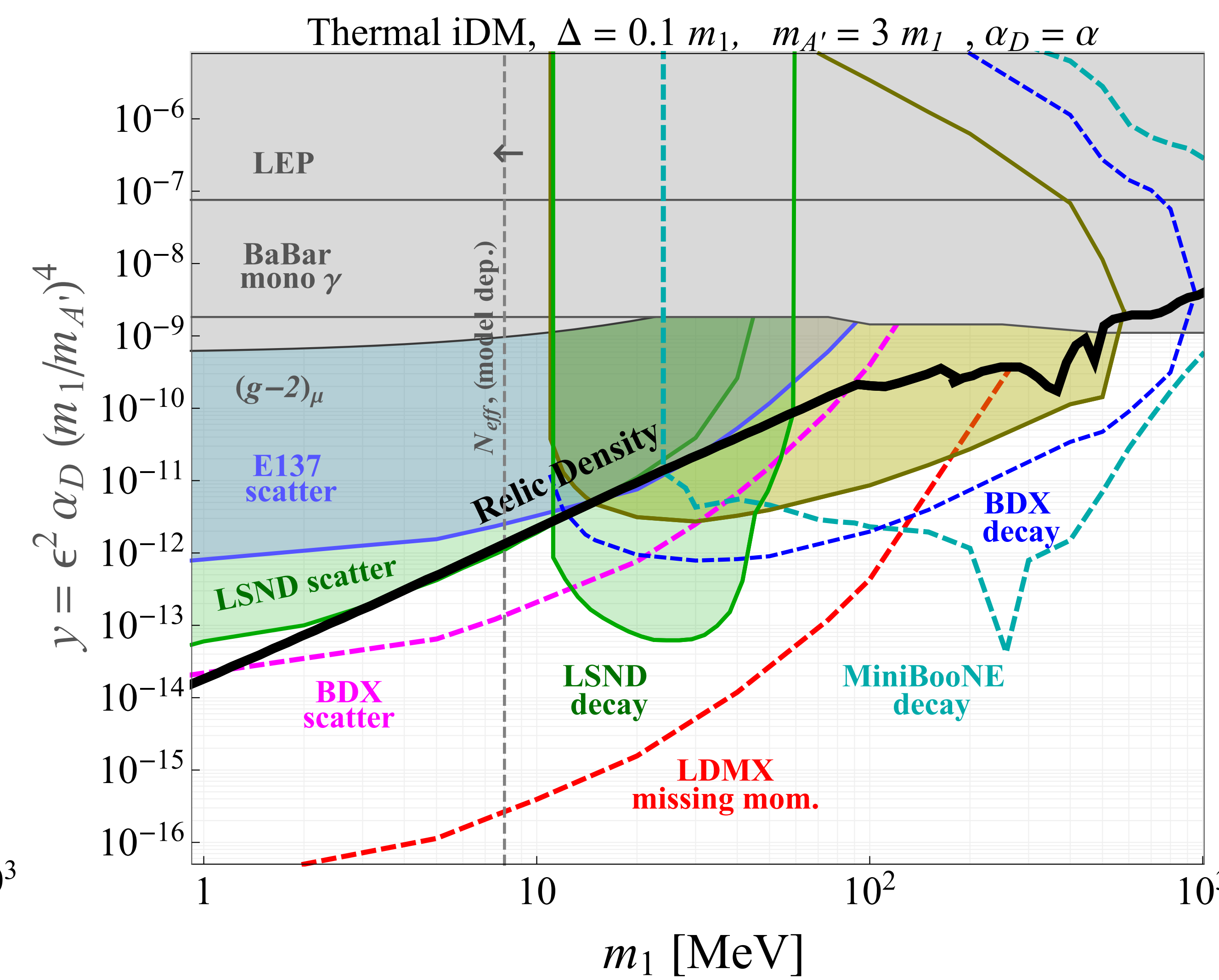


Only neutrino projections

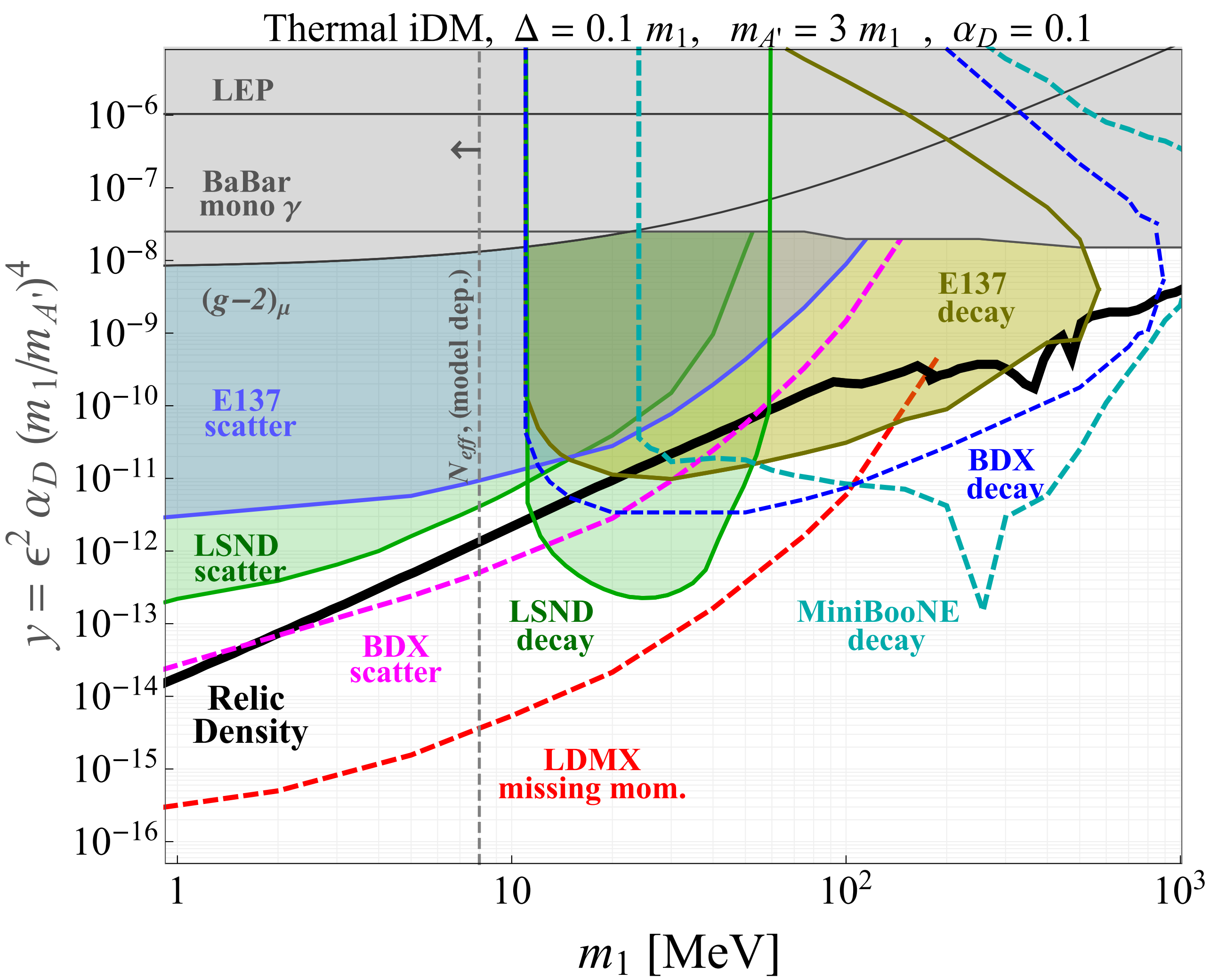
Target moves up, bounds/projections move down

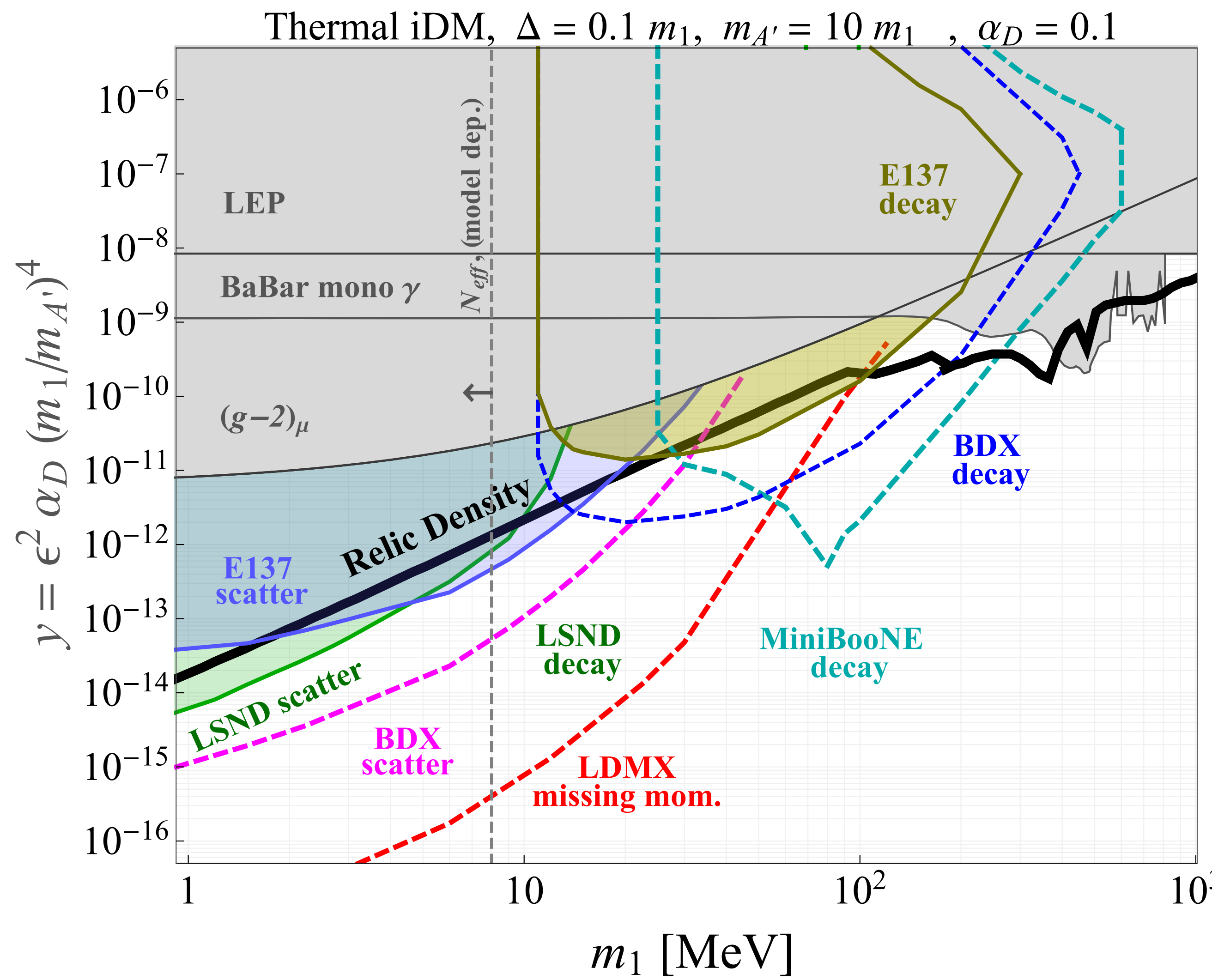
Vary DM/Mediator Coupling





Vary DM/Mediator Mass Ratio

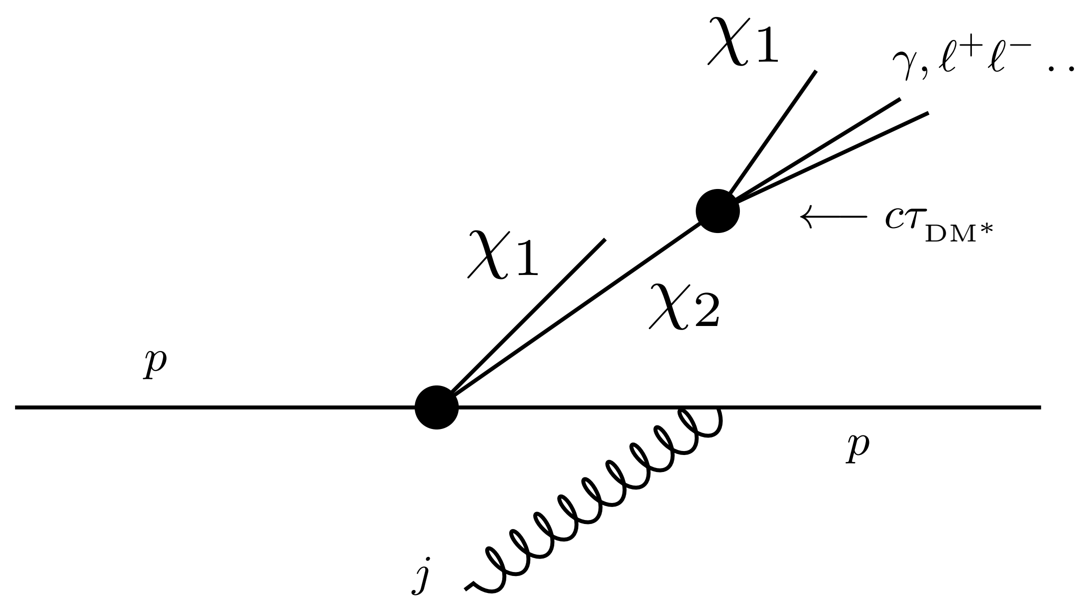




Above the GeV Scale?

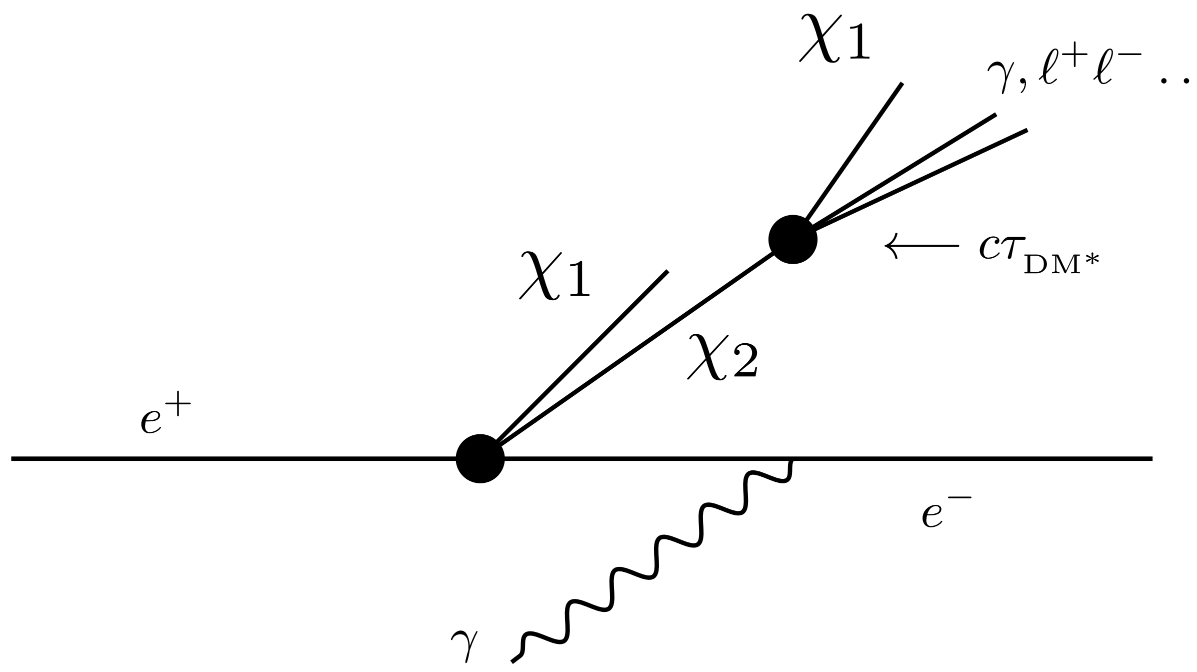
Hadron Collider

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



Lepton Collider

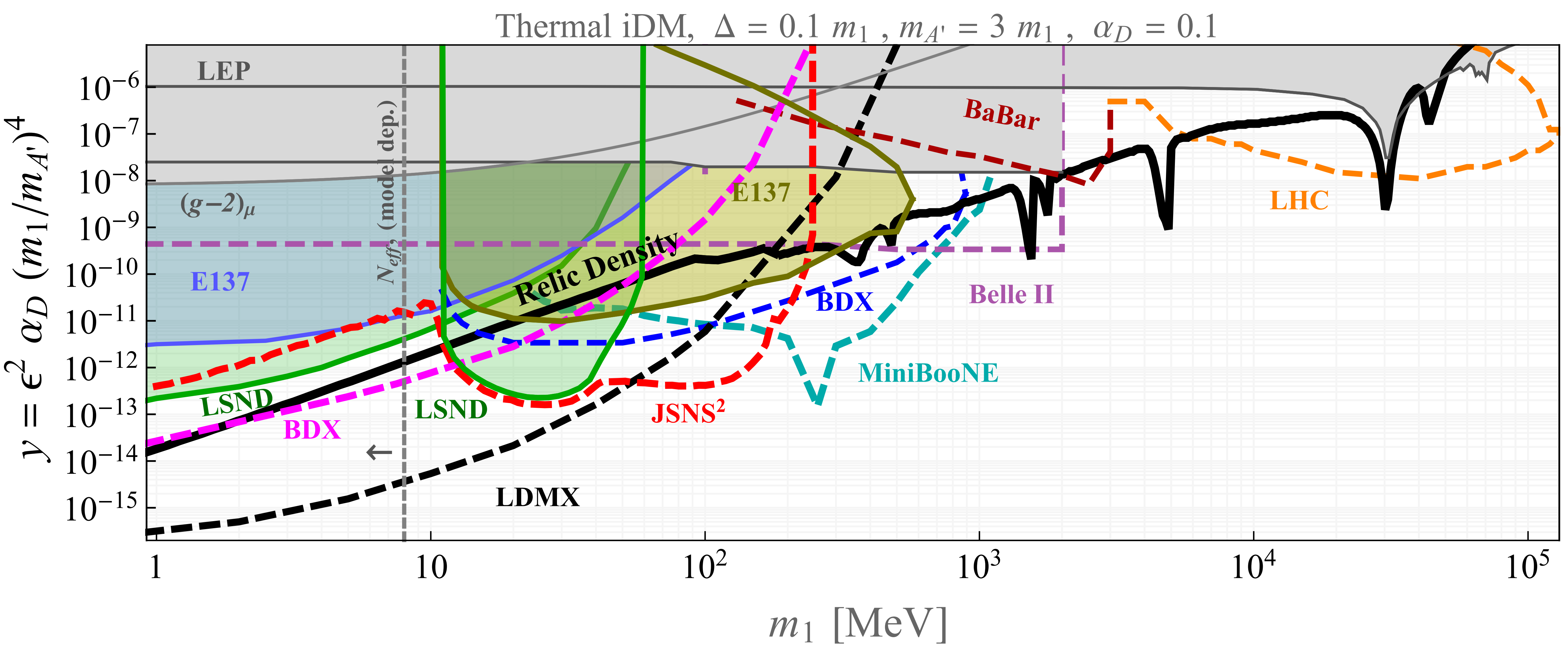
$$\gamma + \not{E} + \ell^+\ell^-$$



Izaguirre, GK, Shuve
1508.03050

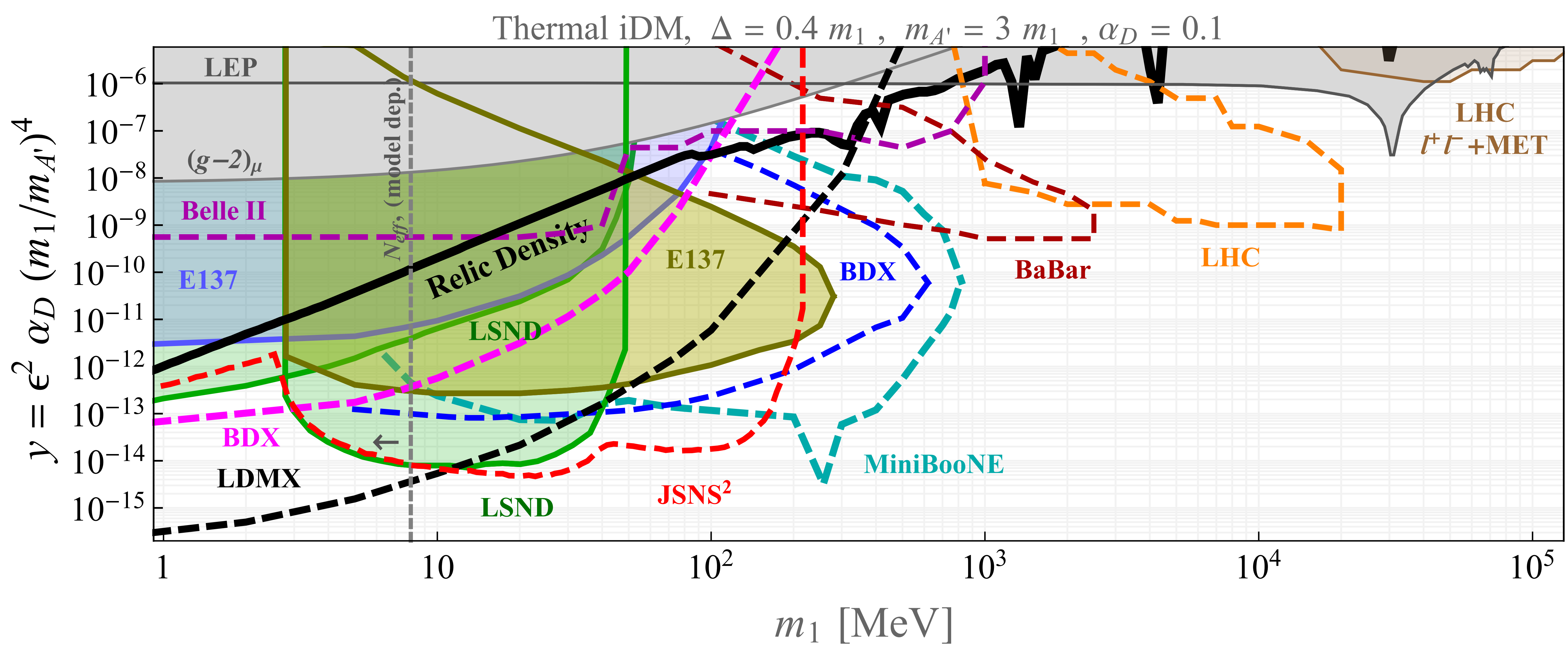
Collider Complementarity

Small Splitting ~ 10%



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!)

Neutrino, Electron Fixed Target, & 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!

Comparing to Experiment

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

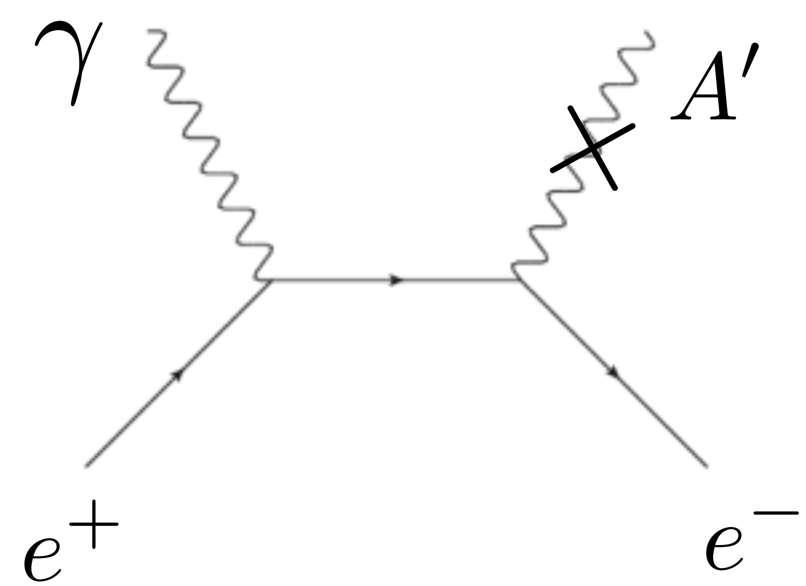
Some experiments only bound **... independently of this**

Comparing to Experiment

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

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

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