Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

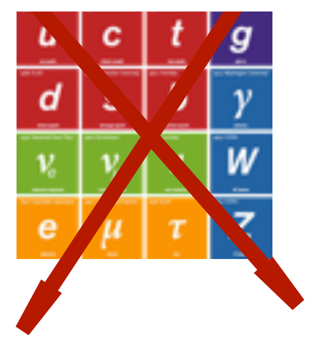
Discovering Dark Matter @ Neutrino Experiments

Gordan Krnjaic

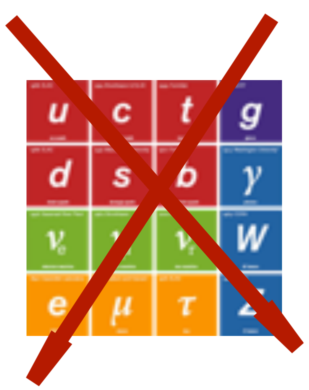
NuFact 2018, Virginia Tech, August 17, 2018

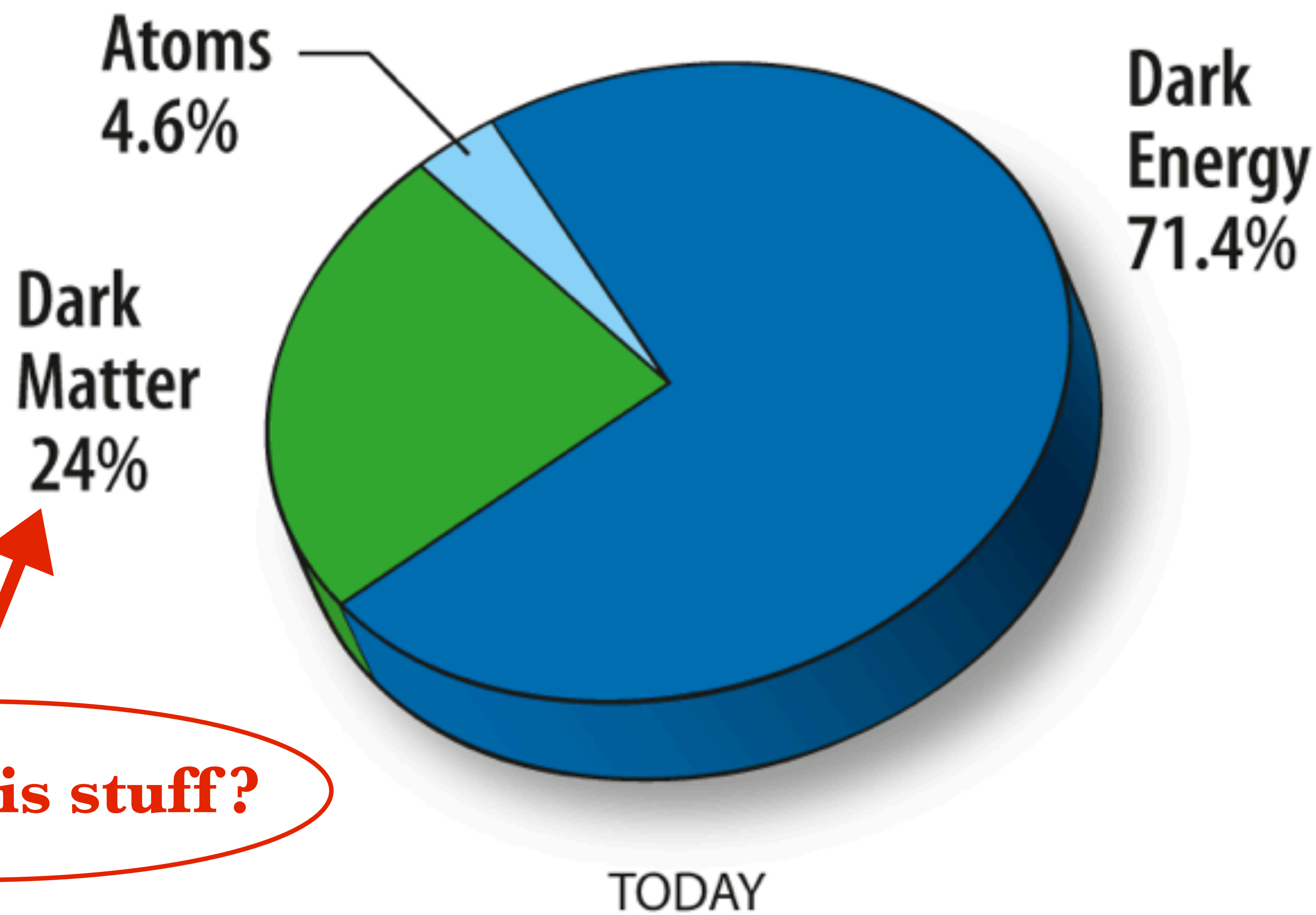
Open Questions in Fundamental Physics

Neutrino Masses
Matter Asymmetry
Inflation



Accelerated Cosmic Expansion

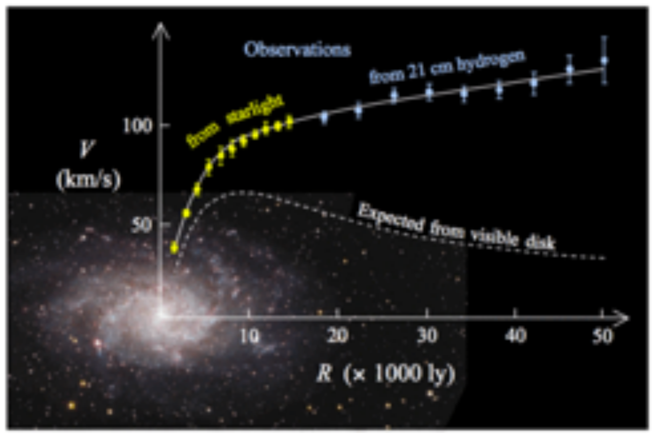




What is this stuff?

Also Quantum Gravity

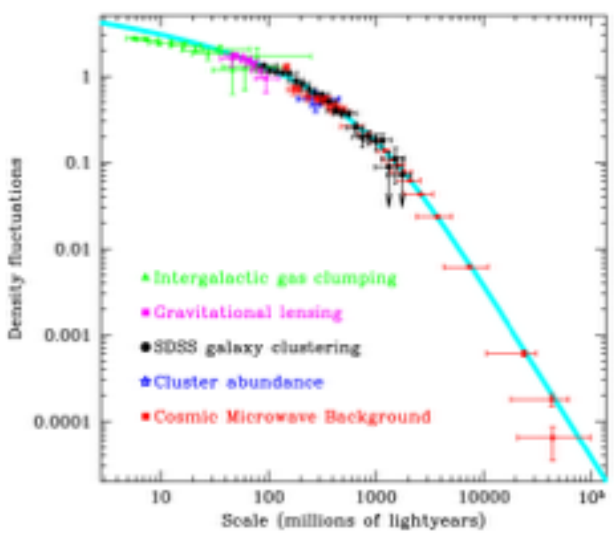
Remarkable Evidence for Dark Matter



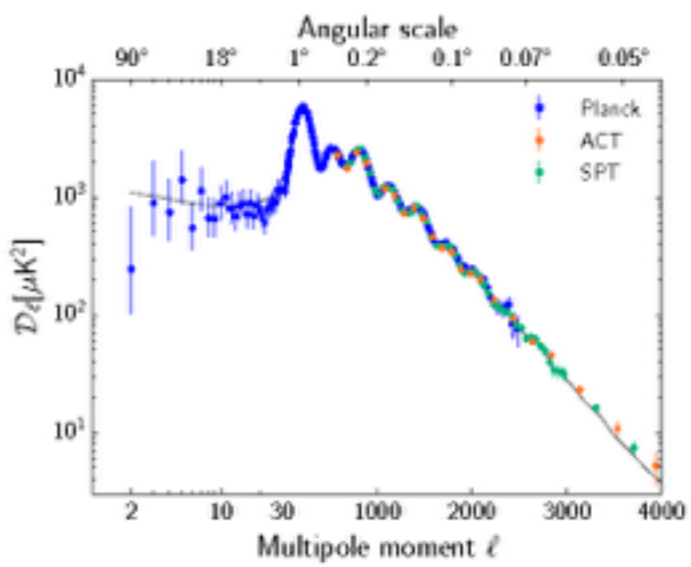
Rotation Curves

Gravitational Lensing

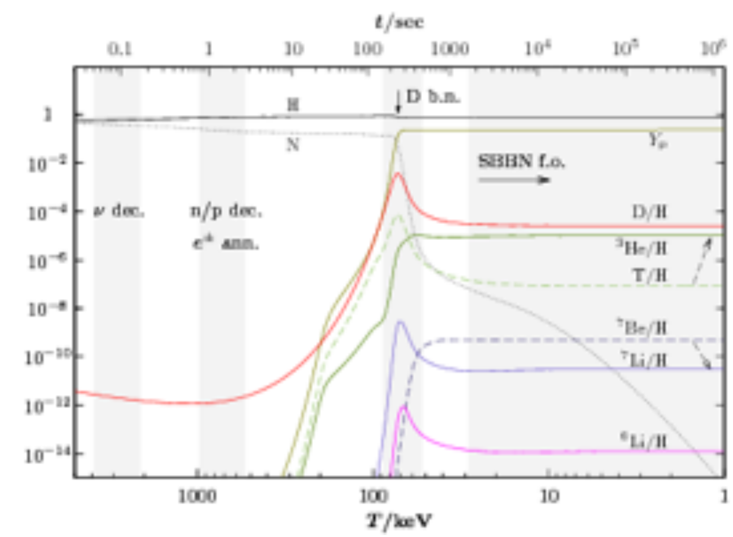
Cluster Collisions



Matter Power Spectrum



CMB Power Spectrum

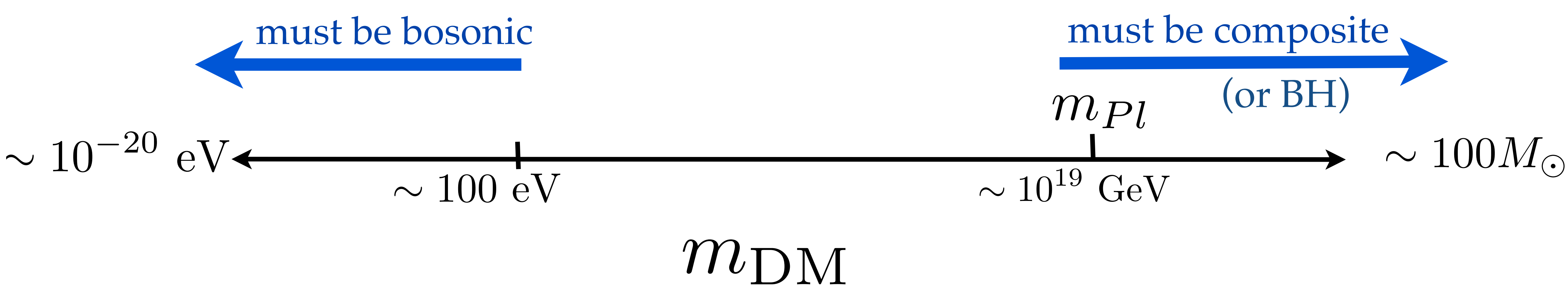


BBN Light Element Yields

Multiple independent, consistent observations
over **nearly** all of spacetime (!)

Ultimate Goal: extend our knowledge down to laboratory scales

What Clues Do We Have?



Huge space of allowed microscopic theories

Evidence only extends down to ~kpc (dwarf galaxy) scales

Theoretical guidance is essential

Need organizing principle for systematic progress

Overview

1) What's **great** about thermal DM?

2) What's **different** about light thermal DM (< GeV)?

3) **Signals** at accelerator based neutrino experiments?

Overview

1) What’s **great** about thermal DM?

2) What’s **different** about light thermal DM (< GeV)?

3) **Signals** at accelerator based neutrino experiments?

Q: What's so great about equilibrium?

A: Generic and easy to achieve

Compare interaction rate to 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

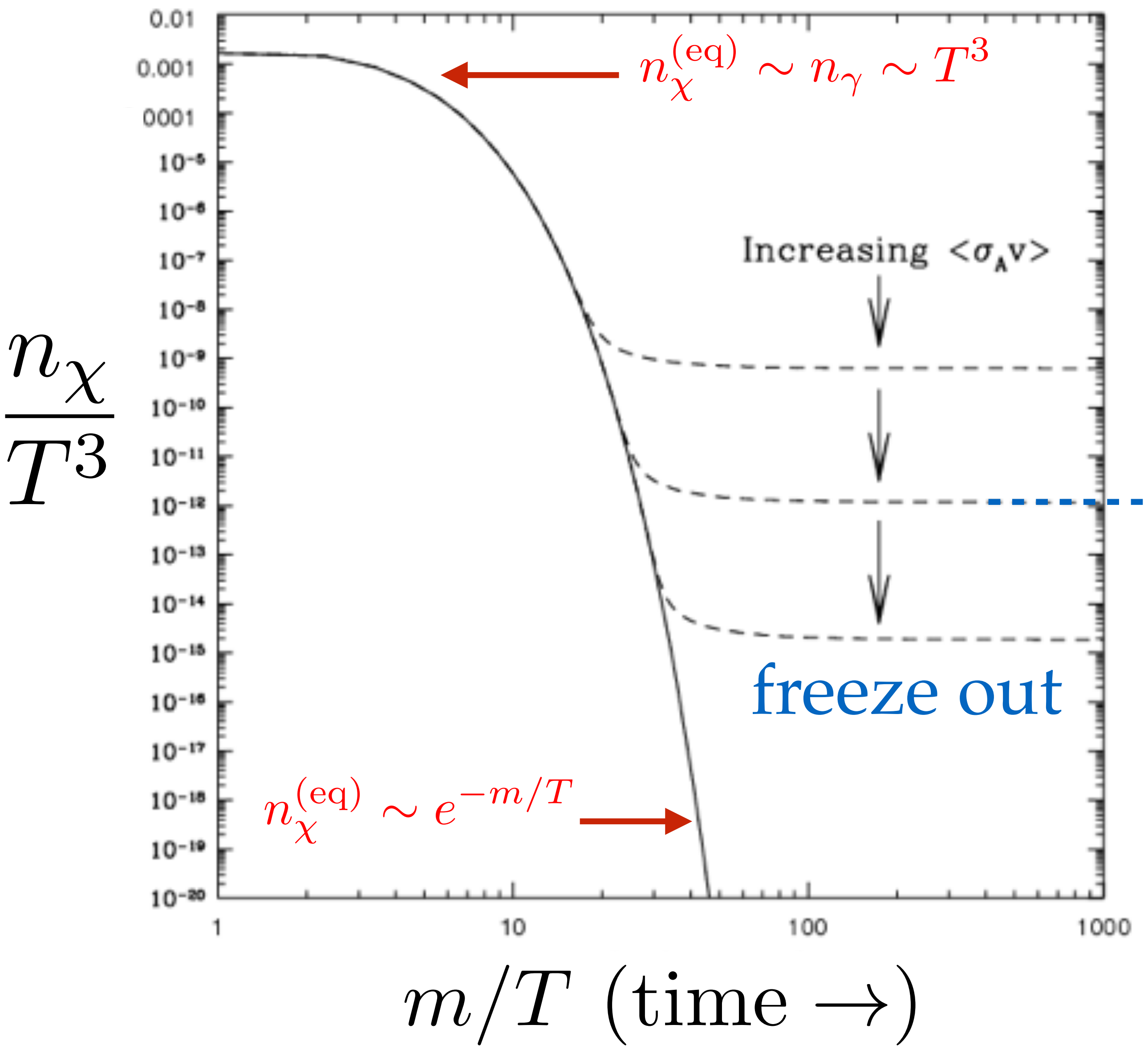
$$g \gtrsim 10^{-8}\left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^2\left(\frac{\mathrm{GeV}}{m_\chi}\right)^{3/2}$$

Nearly all **testable** models feature equilibrium at early times (especially those testable at accelerators!)

Q: What's so great about equilibrium?

A: Minimum annihilation rate

$$n_\chi^{(\mathrm{eq})} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \propto \begin{cases} T^3 & (T \gg m) \\ e^{-m/T} & (T \ll m) \end{cases}$$



Symmetric DM population

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

Observed density requires

$$\sigma v \sim 2 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

Griest et. al. 1992

Q: What's so great about equilibrium?

A: Insensitive to unknown high energy physics

Initial condition known

Calculable and independent of inflation, reheating, baryogengesis etc.

Mass & couplings set abundance

A discovery would directly probe early universe cosmology

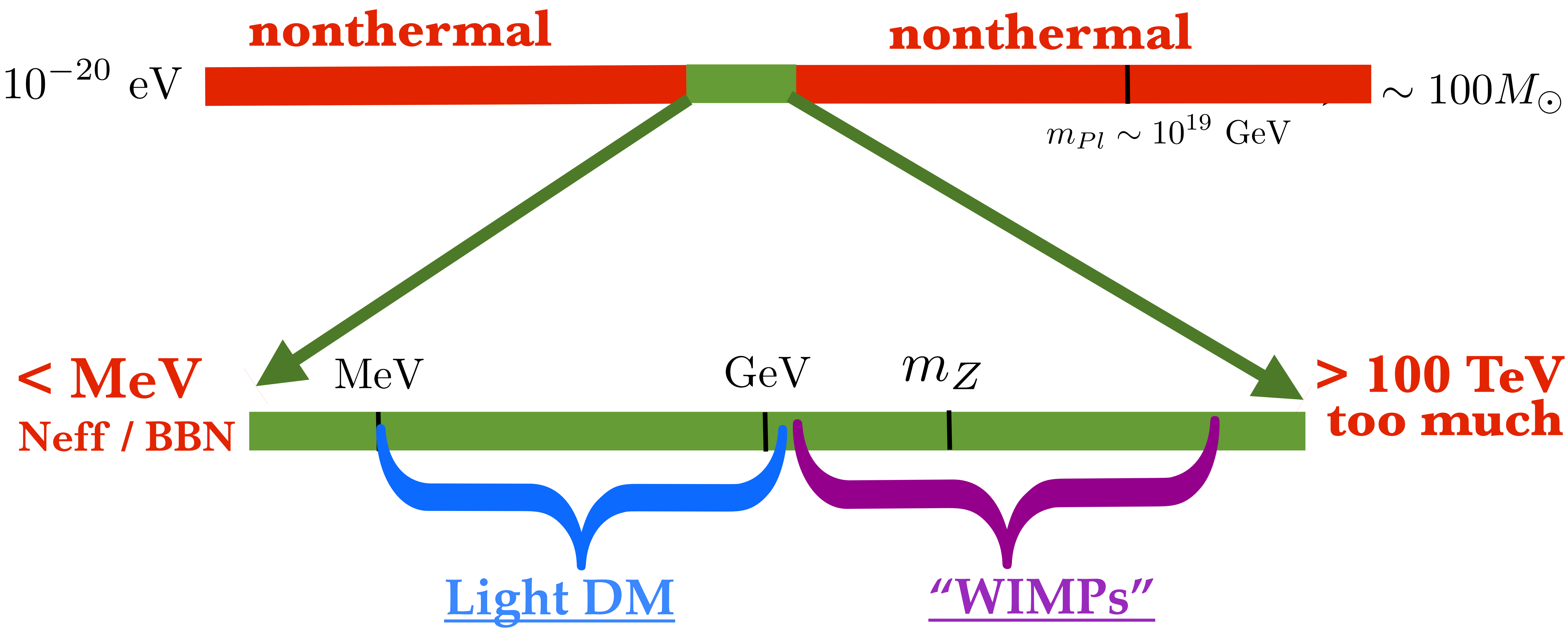
Only *other* UV insensitive mechanism is "freeze-in"

- Ad hoc initial condition $n_\chi(0) = 0$
- DM produced through tiny couplings, **very hard to test**

None of these features depends on SUSY/WIMPs

Q: What's so great about equilibrium?

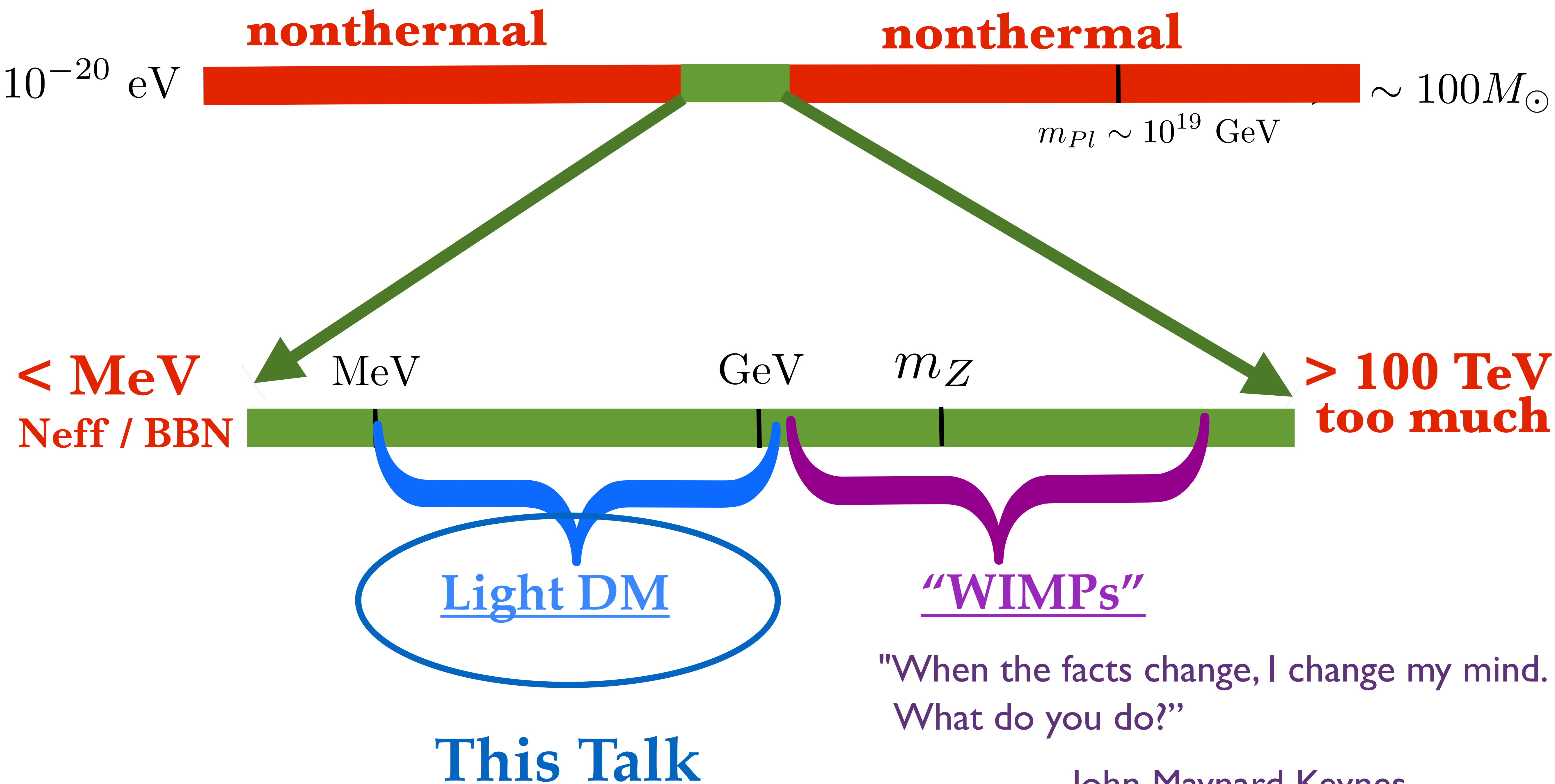
A: Narrows Viable Mass Range (!)



Powerful existing searches
[in]direct detection, colliders…

Q: What's so great about equilibrium?

A: Narrows Viable Mass Range (!)



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

- John Maynard Keynes

Overview

1) What’s **great** about thermal DM?

2) What’s **different** about light thermal DM (< GeV)?

3) Signals at accelerator based neutrino experiments?

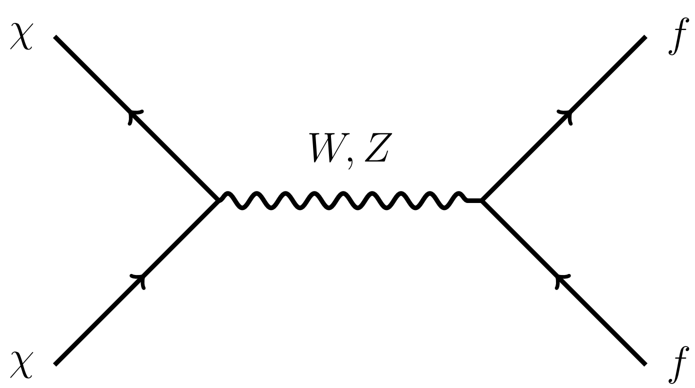
Light DM vs. WIMPs

1) Light DM must be SM neutral

Else would have been discovered at LEP

2) Light DM requires light new forces

Overproduced without comparably light, neutral “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

3) Annihilation involves renormalizable interactions

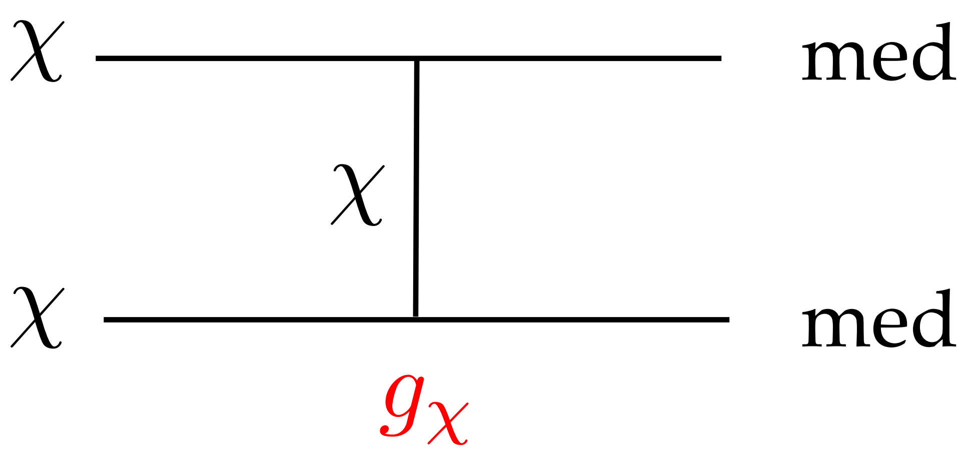
Higher dimension operators have same problem as W / Z mediators

Light mediators are not optional — they’re essential

Who's Heavier: DM or Mediator?

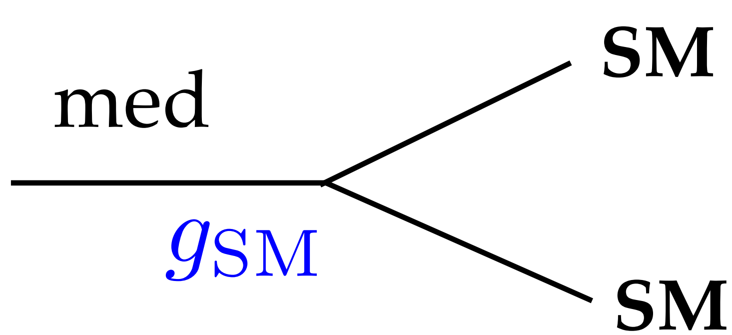
Secluded Annihilation

$m_\chi > m_{\rm med}$



No clear experimental target

Abundance set by g_χ

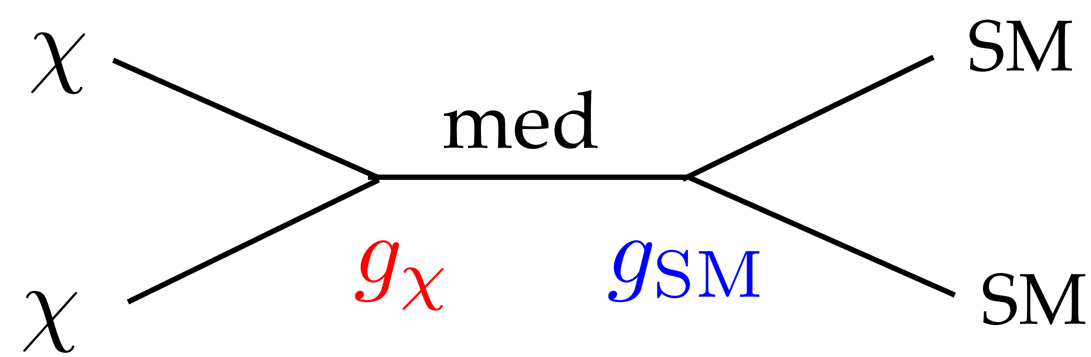


Mediator decays **visibly**

Motivates hidden force searches

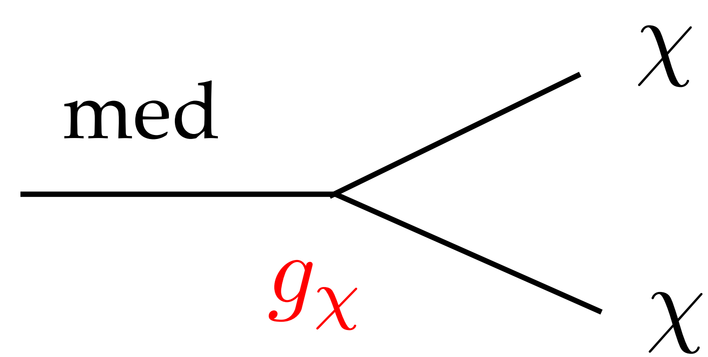
Direct Annihilation

$m_\chi < m_{\rm med}$



Predictive thermal targets

Abundance depends on $g_{\rm SM}$



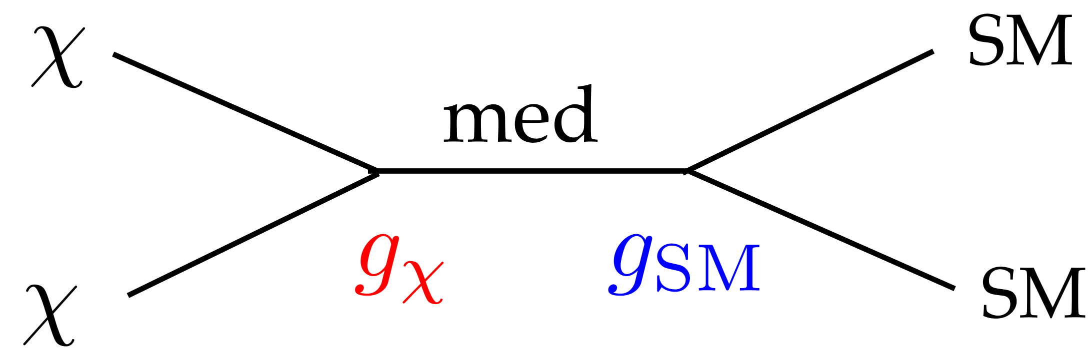
Mediator decays **invisibly***

Motivates missing energy probes

Who's Heavier: DM or Mediator?

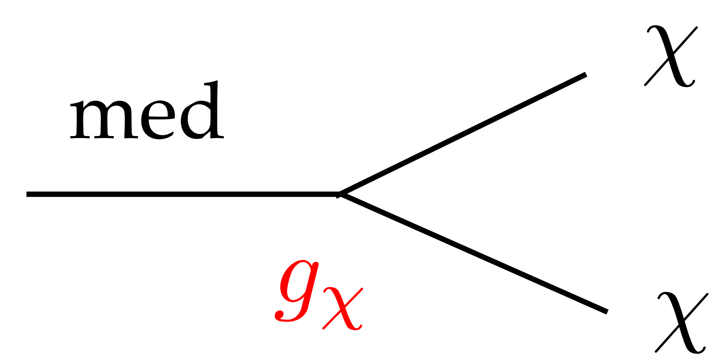
Direct Annihilation

$m_\chi < m_{\text{med}}$



Predictive thermal targets

Abundance depends on g_{SM}

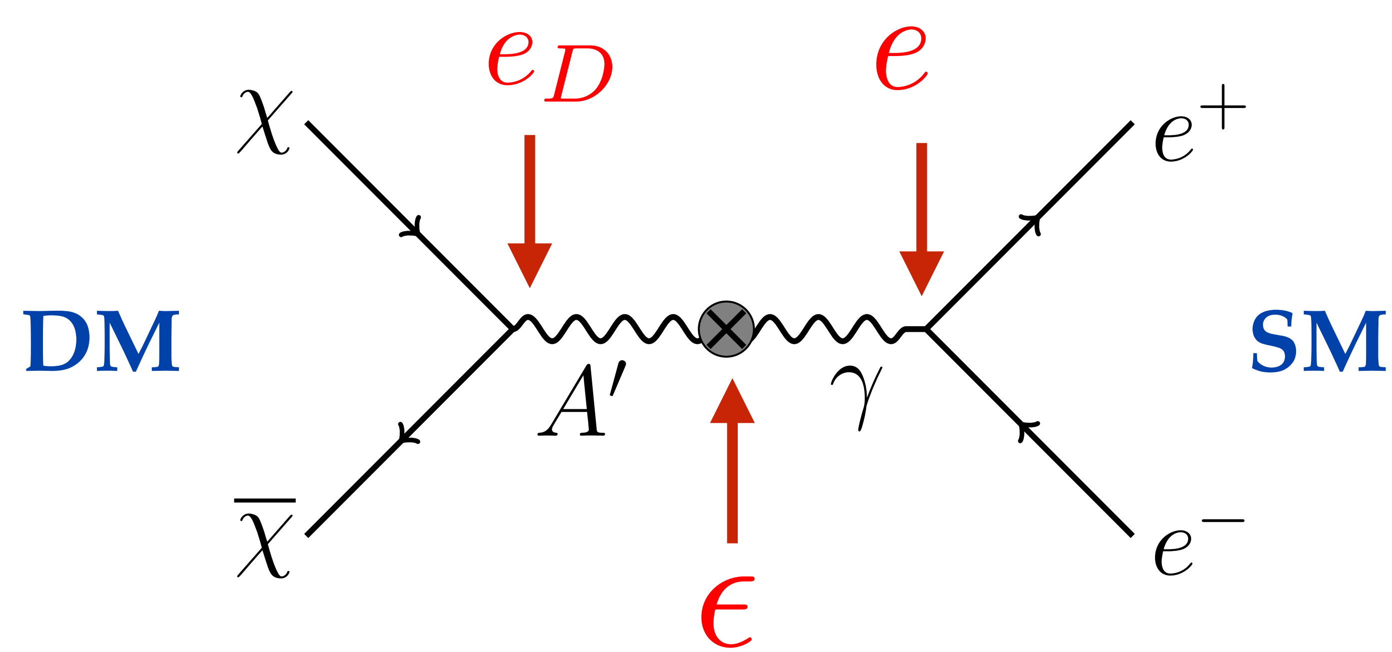


Mediator decays **invisibly***

Motivates missing energy probes

Representative Model: Dark QED

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



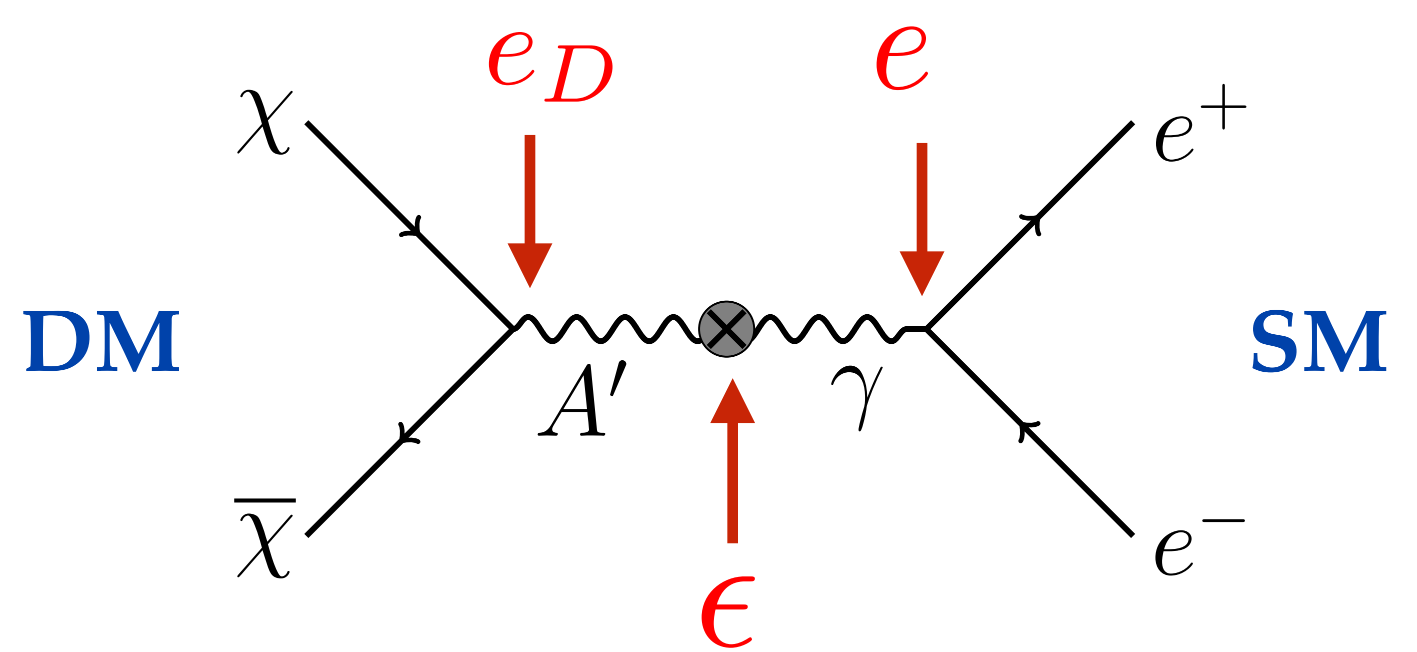
$$\alpha \equiv \frac{e^2}{4\pi}$$

Interaction basis: "dark photon" A' mixes with visible photon A

$$\mathcal{L} \supset \epsilon F'_{\mu\nu} F^{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu + e_D A'_\mu J^\mu_\chi$$

Representative Model: Dark QED

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



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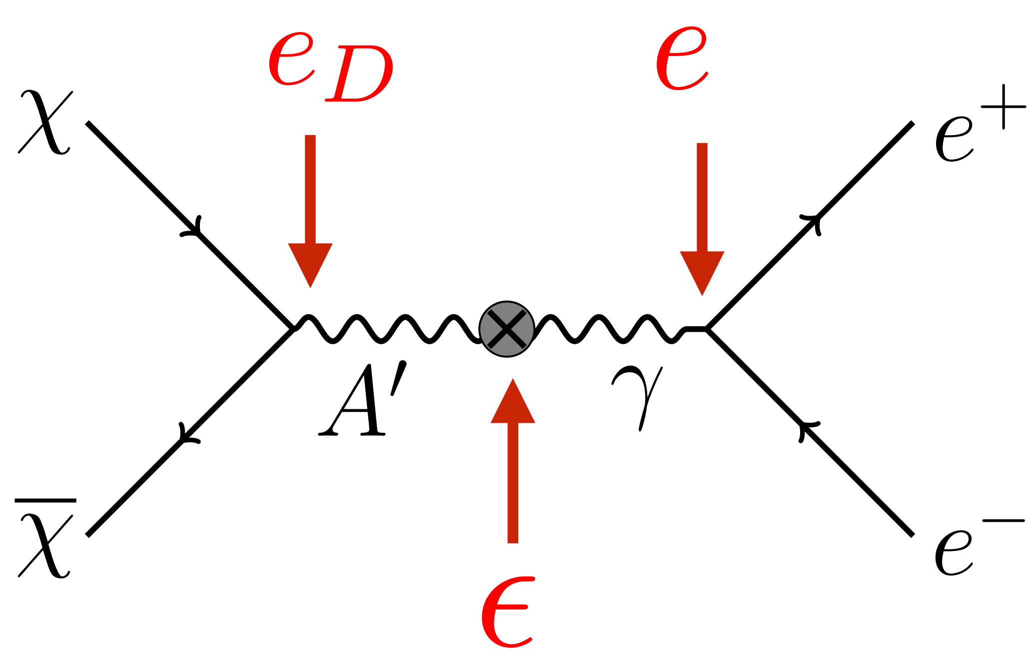
Mass basis: A' acquires tiny coupling to EM current

$$\mathcal{L} \to e_D A'_\mu J^\mu_\chi + \epsilon e A'_\mu J^\mu_{\mathrm{EM}}$$

Representative Model: Dark QED

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

DM



SM

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

Interaction basis: "dark photon" A' mixes with visible photon A

$$\mathcal{L} \supset \epsilon F'_{\mu\nu} F^{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu + e_D A'_\mu J_\chi^\mu$$

Mass basis: A' acquires tiny coupling to EM current

$$\mathcal{L} \to e_D A'_\mu J_\chi^\mu + \epsilon e A'_\mu J_{\mathrm{EM}}^\mu$$

Not only model, but similar to others $\quad J_{\mathrm{EM}}^\mu \to J_{B-L}^\mu \;,\; J_{L_i-L_i}^\mu \cdots$

Overview

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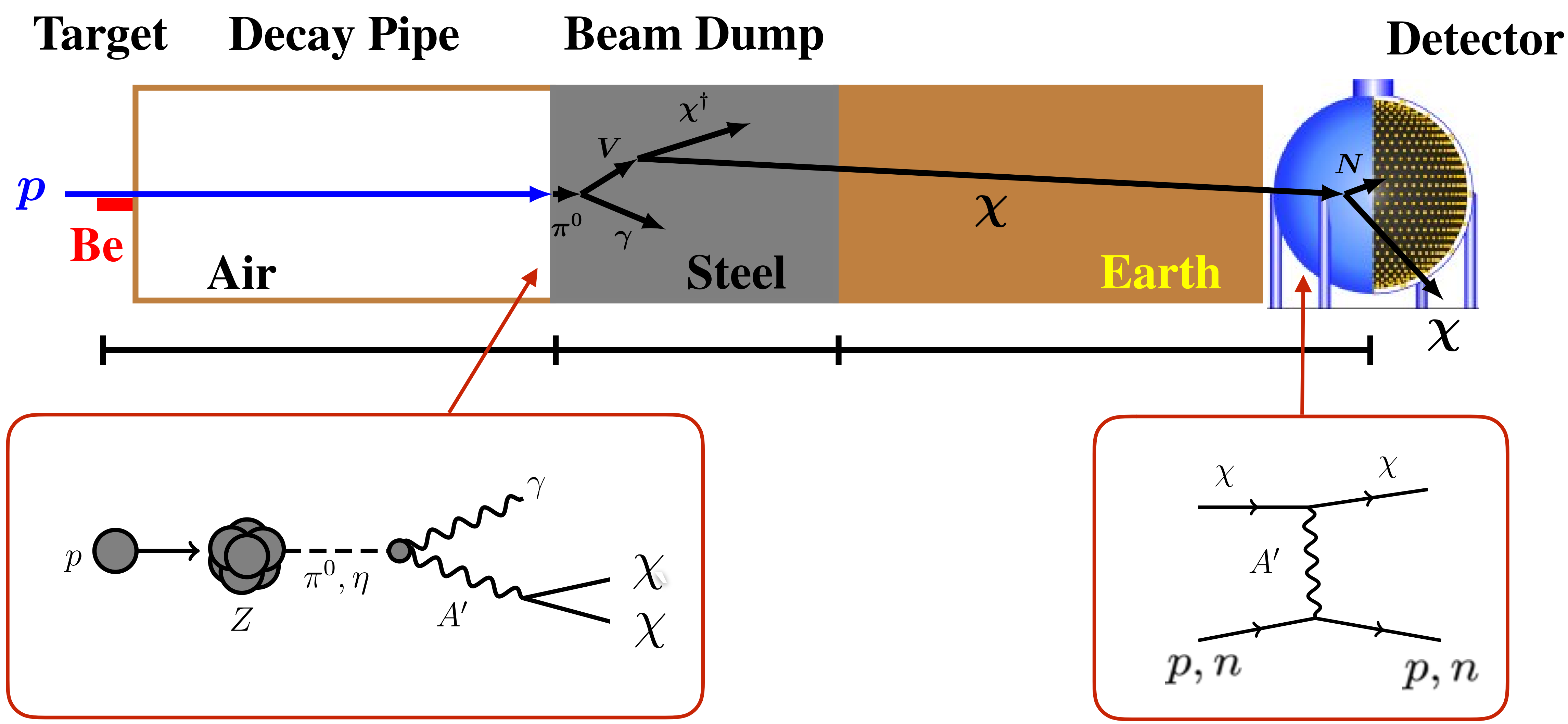
2) What’s **different** about light thermal DM (< GeV)?

3) **Signals** at accelerator based neutrino experiments?

Neutrino Experiments: Relativistic Direct Detection!



Produce Mediator in *Beam Dump*

DM scatters in (near) detector

Neutral meson decays

Proton bremsstrahlung

Deep inelastic scattering

Mediator Decays to make DM beam

Batell, Pospelov, Ritz 0903.0363

deNiverville, Pospelov, Ritz 1107.4580

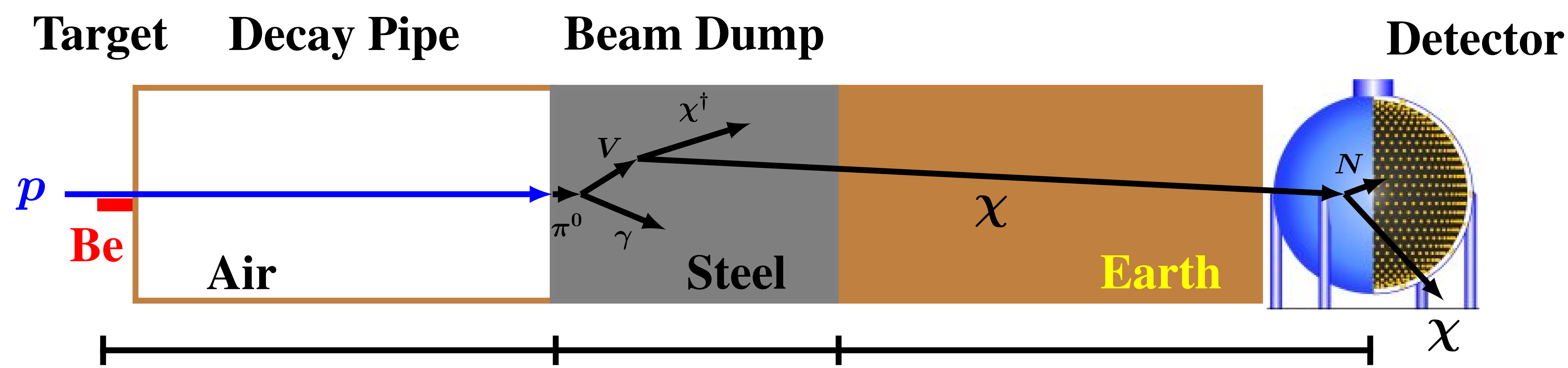
Kahn, GK, Thaler, Toups 1411.1055

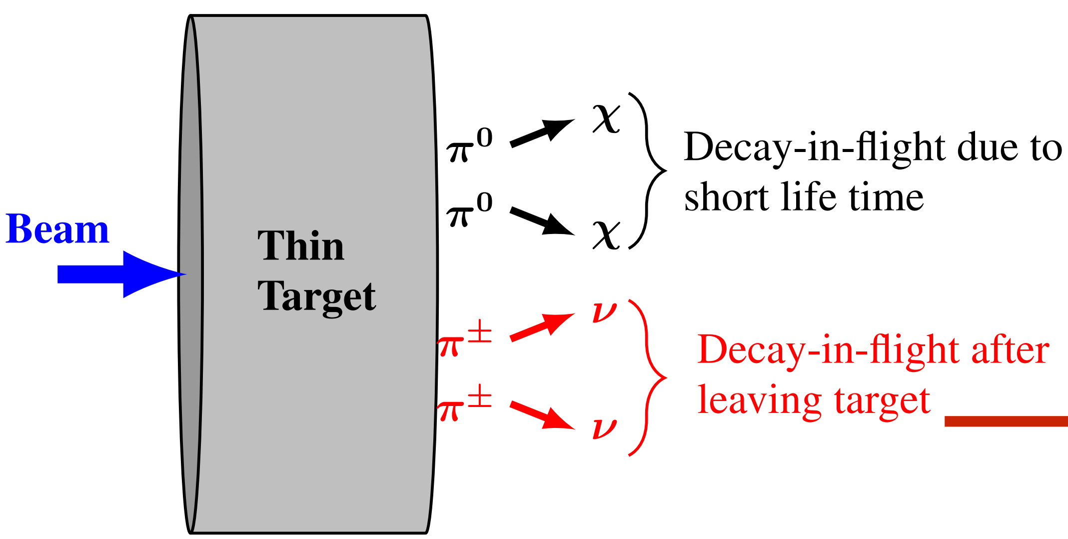
Batell, deNiverville, McKeen, Pospelov, Ritz 1405.7049

Coloma, Dobrescu, Frugiuele, Harnik 1512.03852

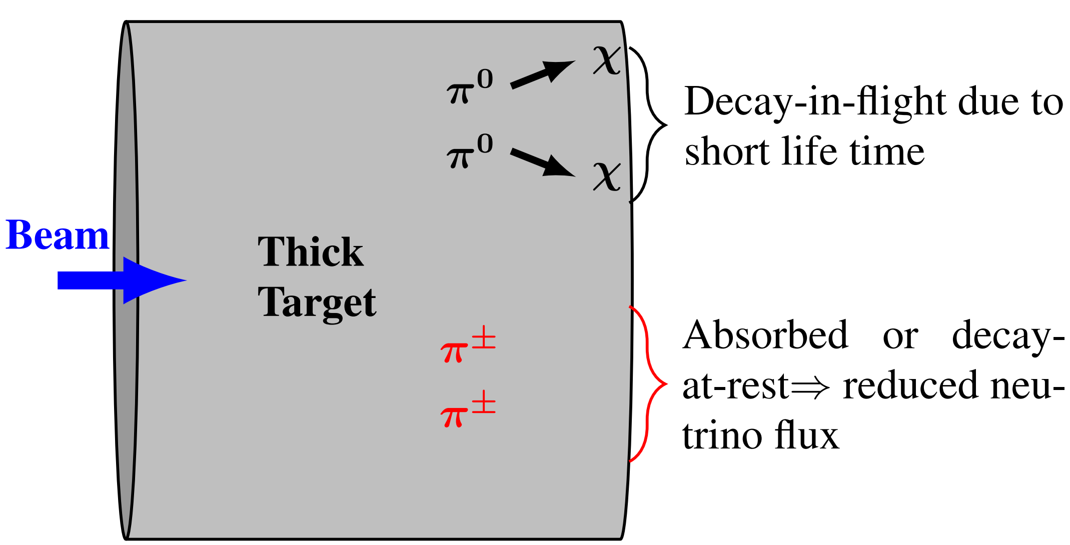
Frugiuele 1701.05464

Why use the beam dump?





Large neutrino BG

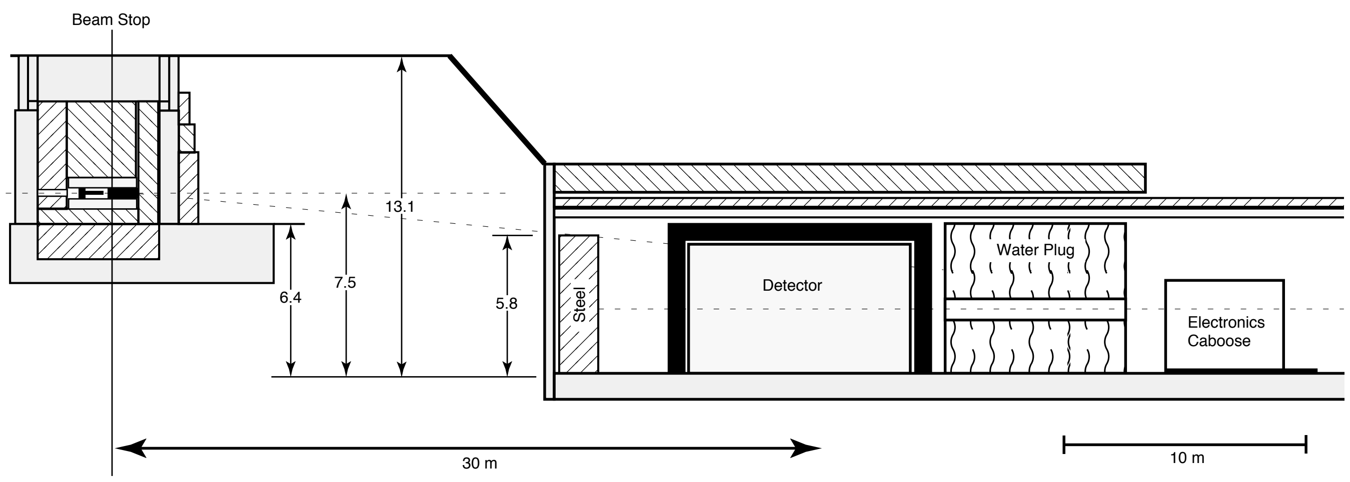


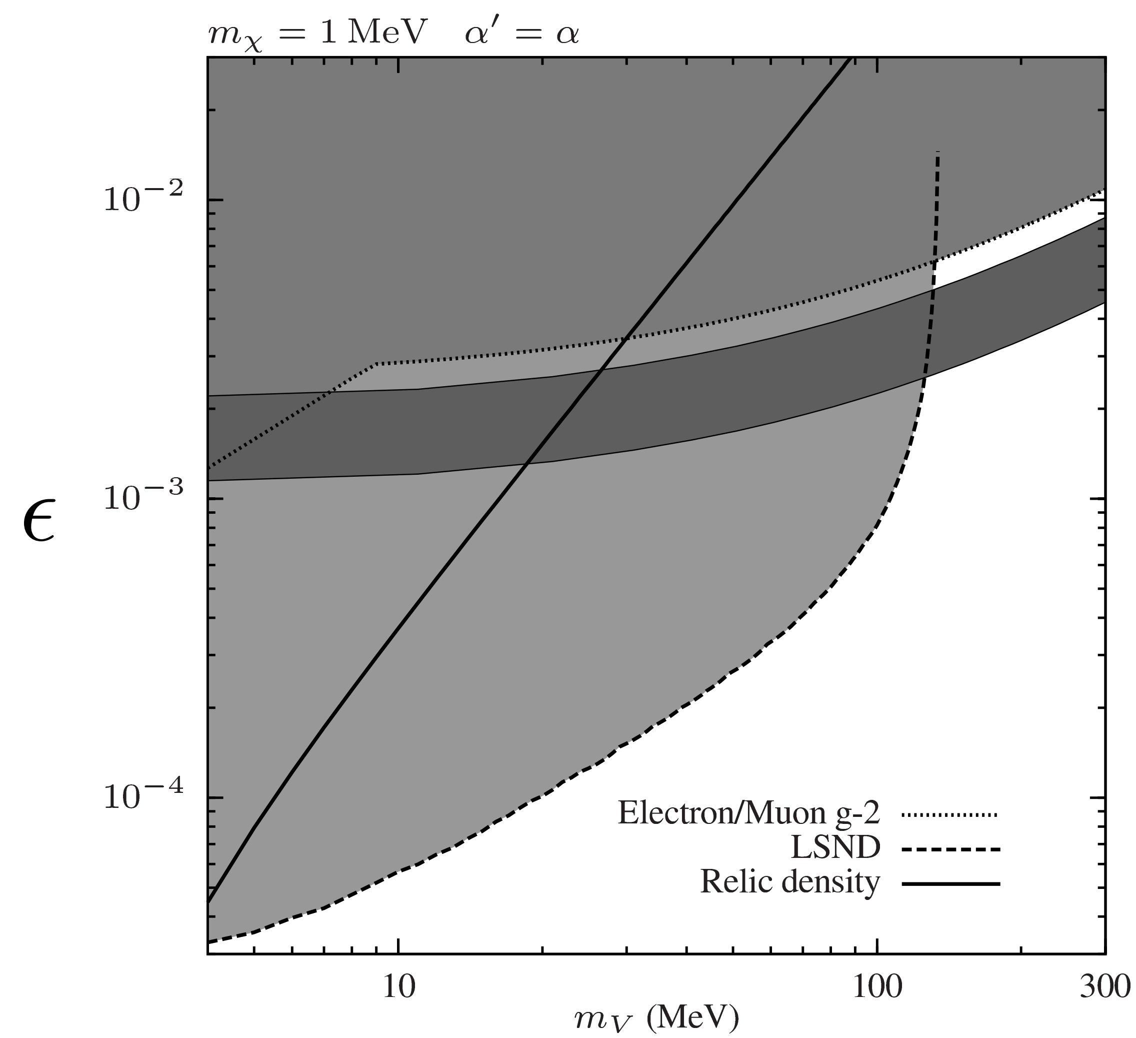
Beam dump avoids target & focusing horn

no charged pion DIF in decay pipe

MiniBooNE-DM Collaboration arXiv:1807.06137

Case Study 1: Constrain DM with LSND NC data





DM beam from pi0 decays

$E_p \simeq 800\,\mathrm{MeV}$, 10^{24} POT **(!!)**

Signal from e-recoils in detector

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

$\cos\theta < 0.9$

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

Reinterpret $\nu_\mu e \to \nu_\mu e$

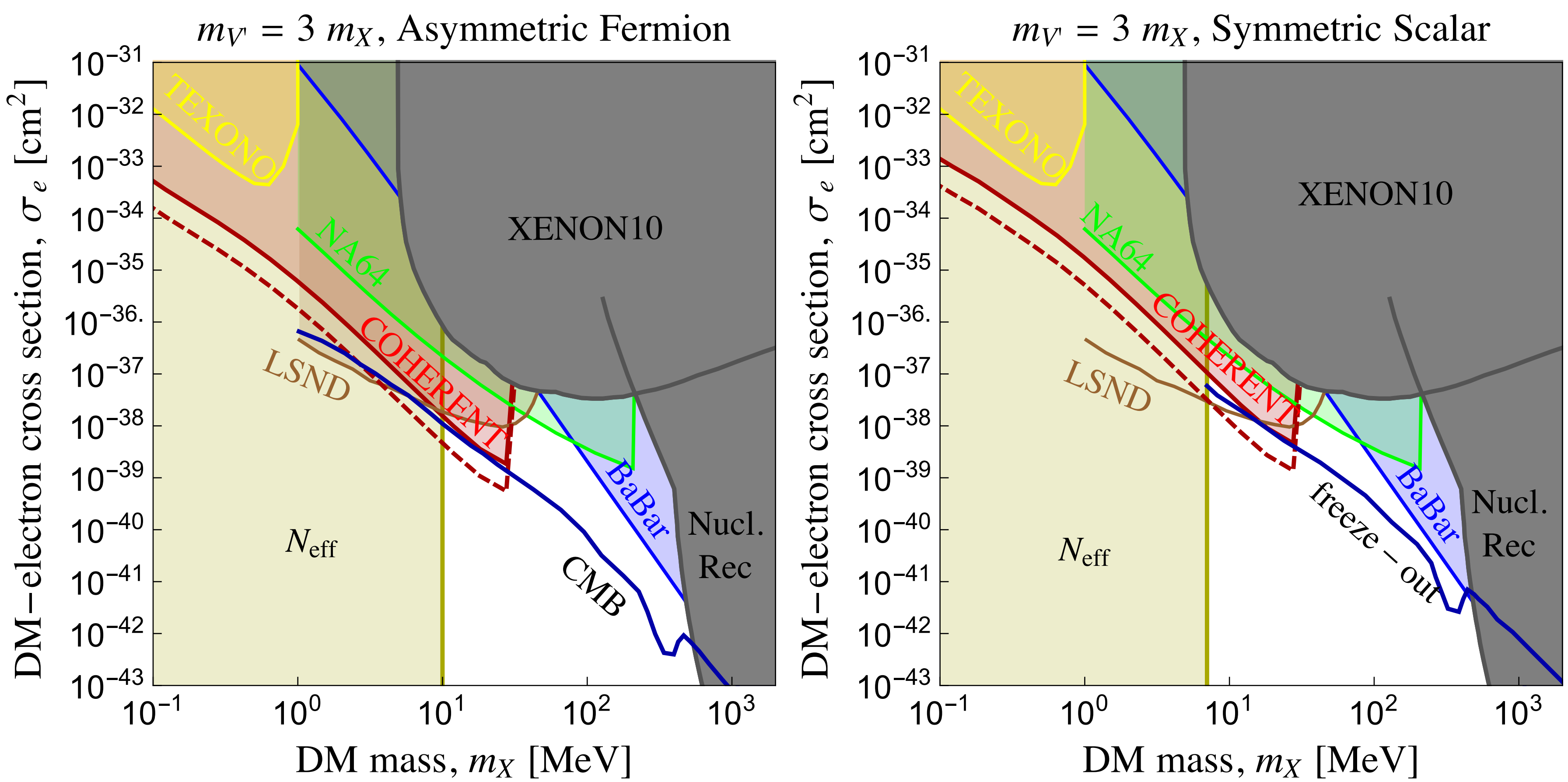
LSND arXiv/0101039

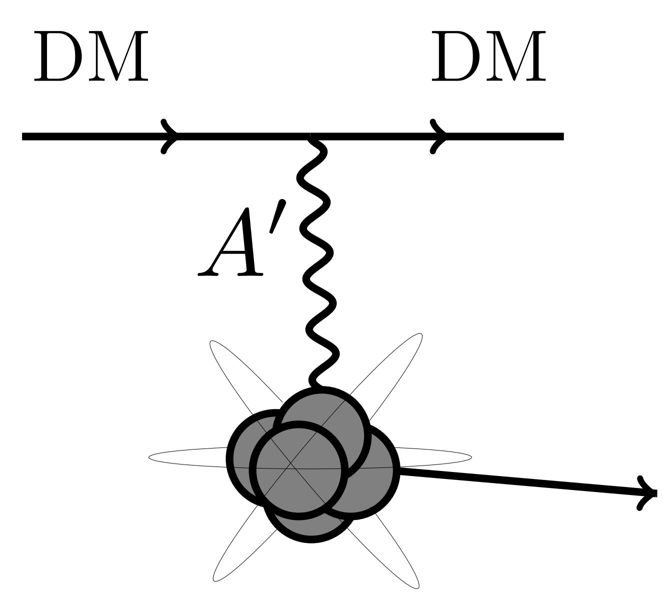
Simulate pi0 production Sanford/Wang

deNiverville, Chen, Pospelov, Ritz 1609.01770

deNiverville, Pospelov, Ritz 1107.4580

Case Study 2: Constrain DM with COHERENT





Reinterpret data $\nu N \to \nu N$

Hg target, DM beam from pi0 decays

$E_p \sim \text{GeV}\ ,\ 2 \times 10^{23}\text{POT}$

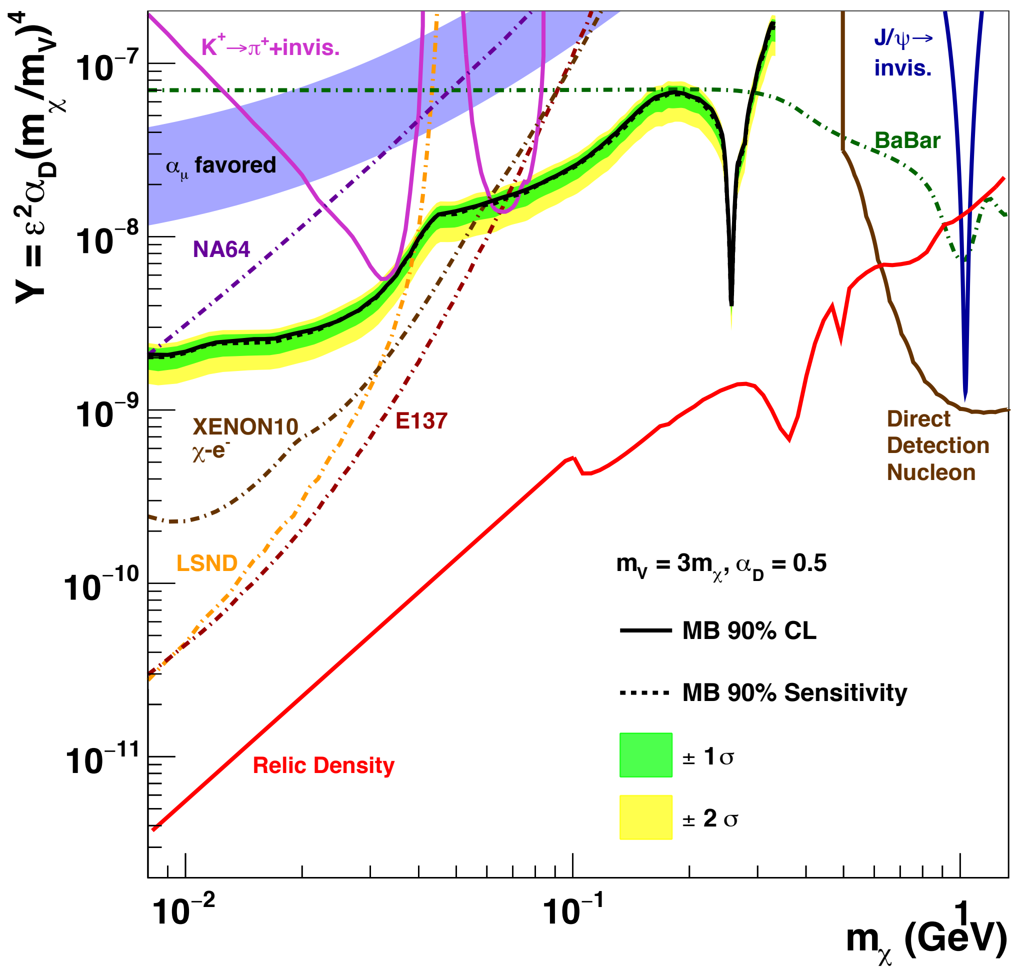
Signal: coherent nuclear recoil

14.6 kg CsI target, ~keV threshold

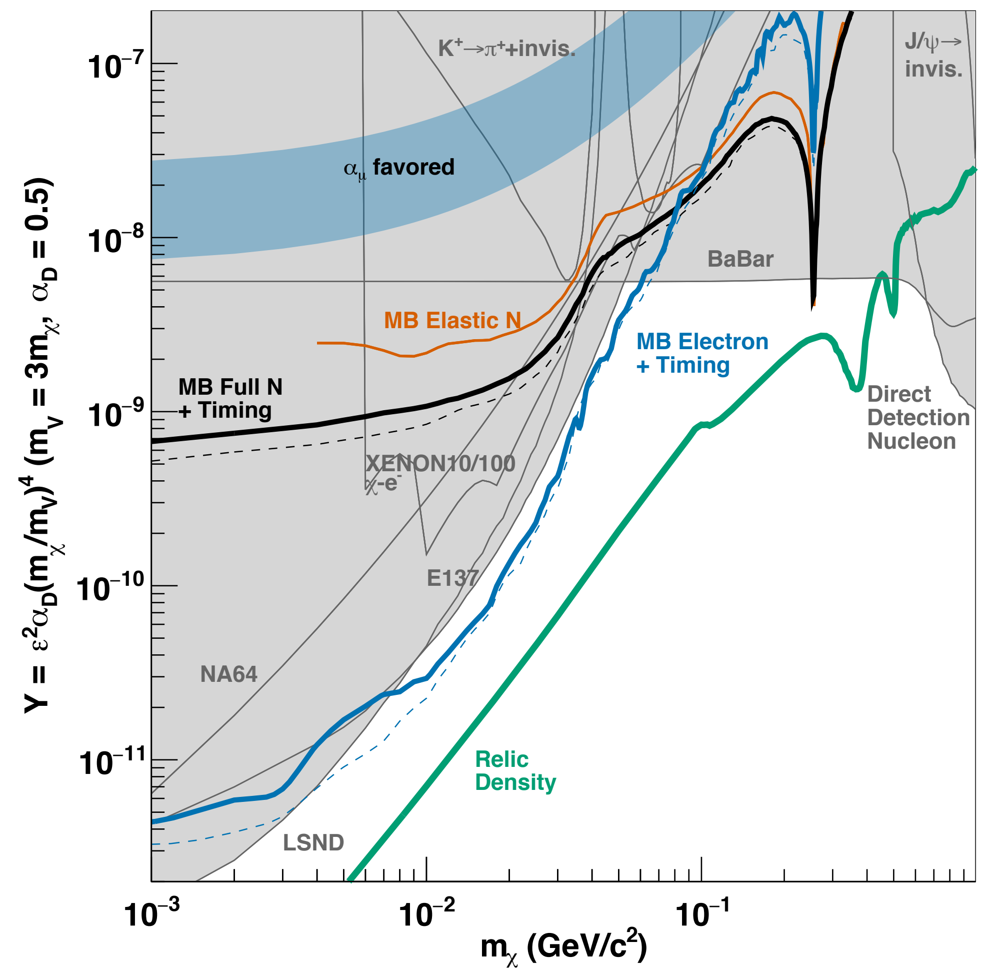
COHERENT Collaboration 1708.01294

Shao-Feng Ge, Ian Shoemaker 1710.10889

The experimental era has arrived: MiniBooNE-DM



nucleon recoils (PRL 2017)

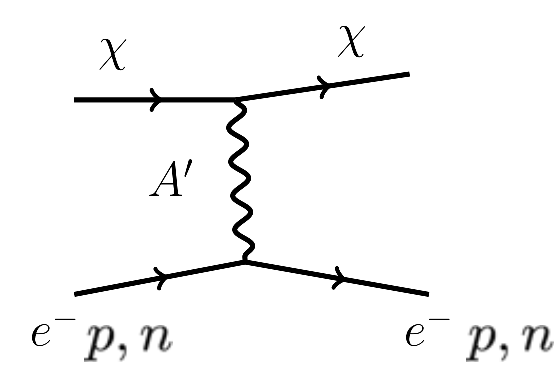


electron recoils (2018)

First ever dedicated search for light < GeV DM

DM beam from pi0/eta decays

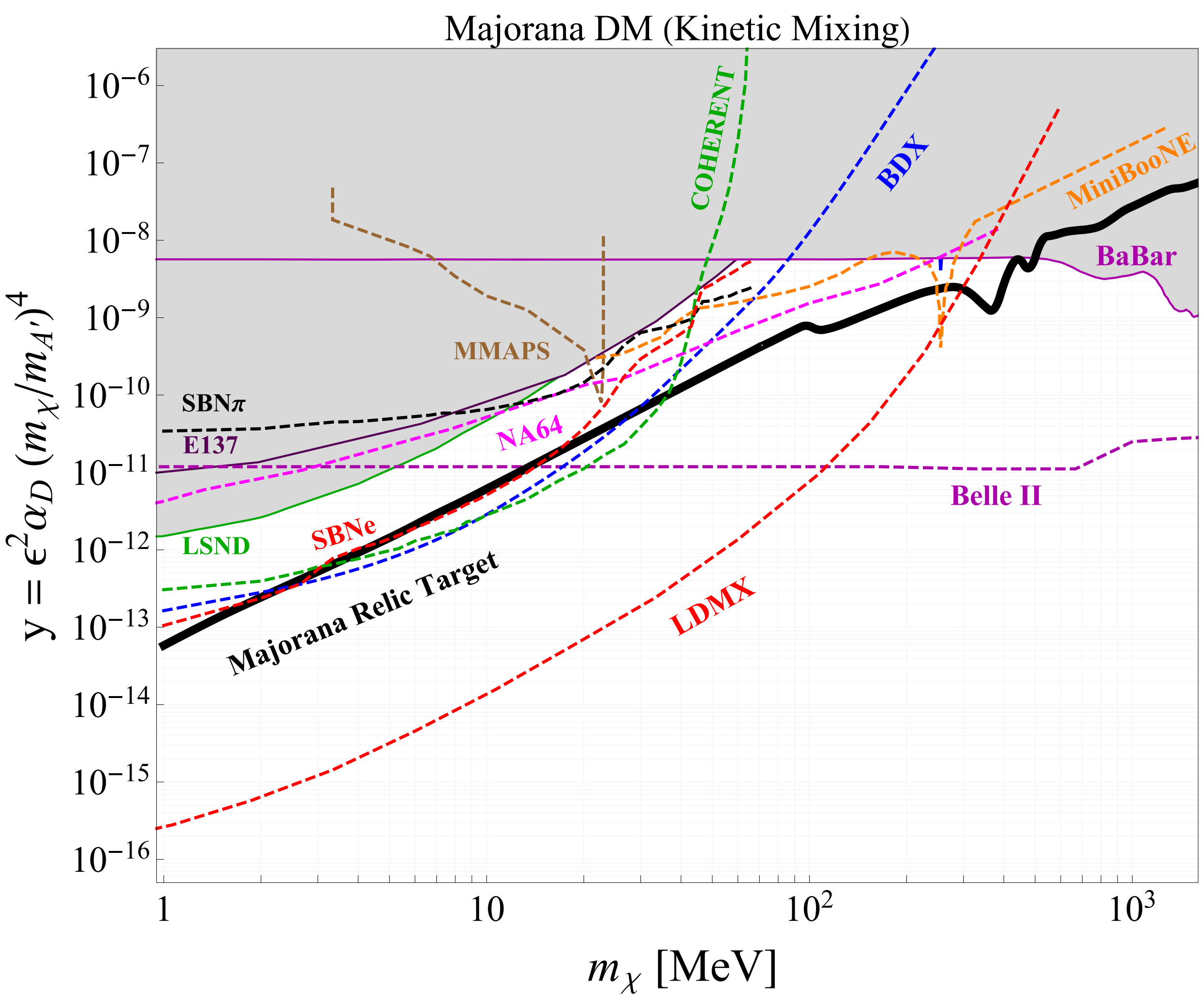
$E_p \sim 8$ GeV , 2×10^{20} POT

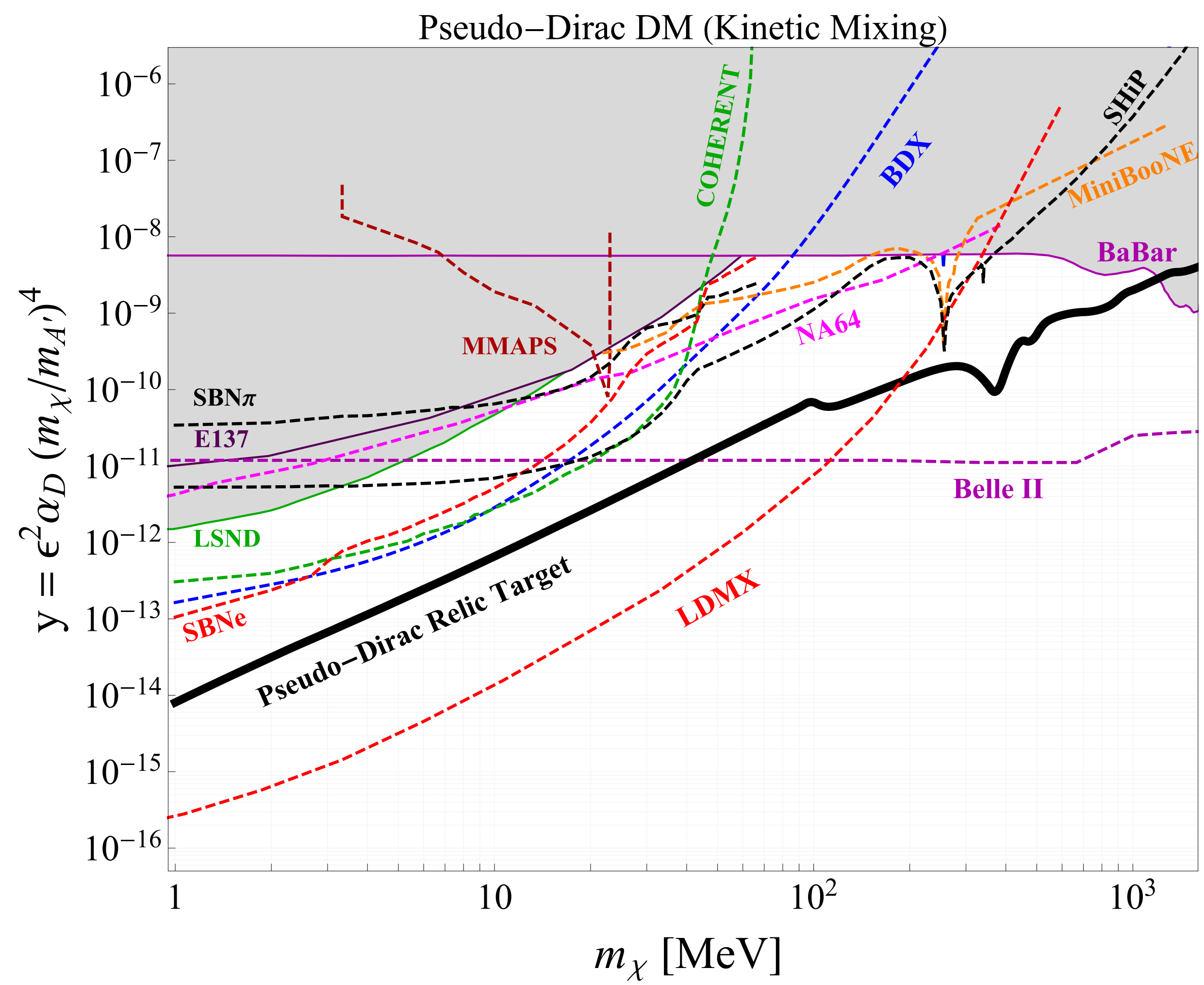


MiniBooNE-DM Collaboration arXiv:1807.06137

MiniBooNE-DM Collaboration Phys. Rev. Lett. 118 (2017)

Lots of interest in future searches





However:

1) Most future facilities are intensity limited $\sim 10^{20}$ POT

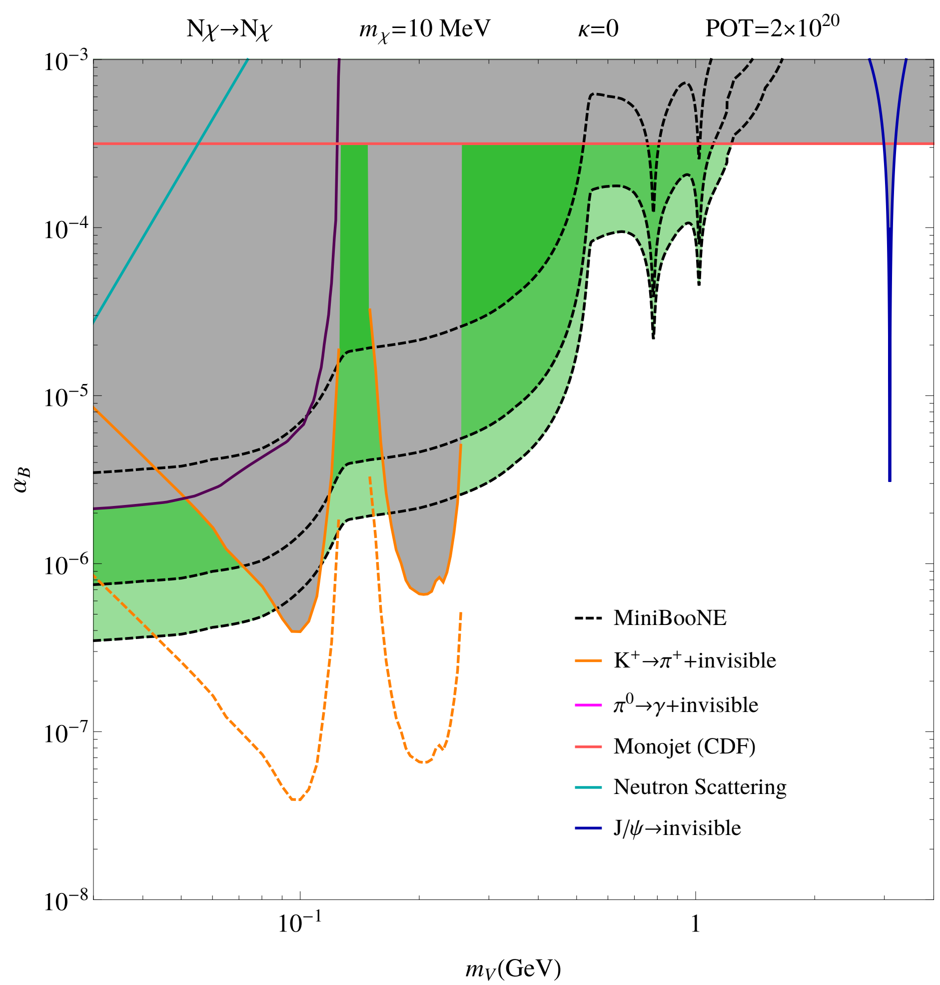
2) Competition from electron beam experiments (higher lumi, lower BG)

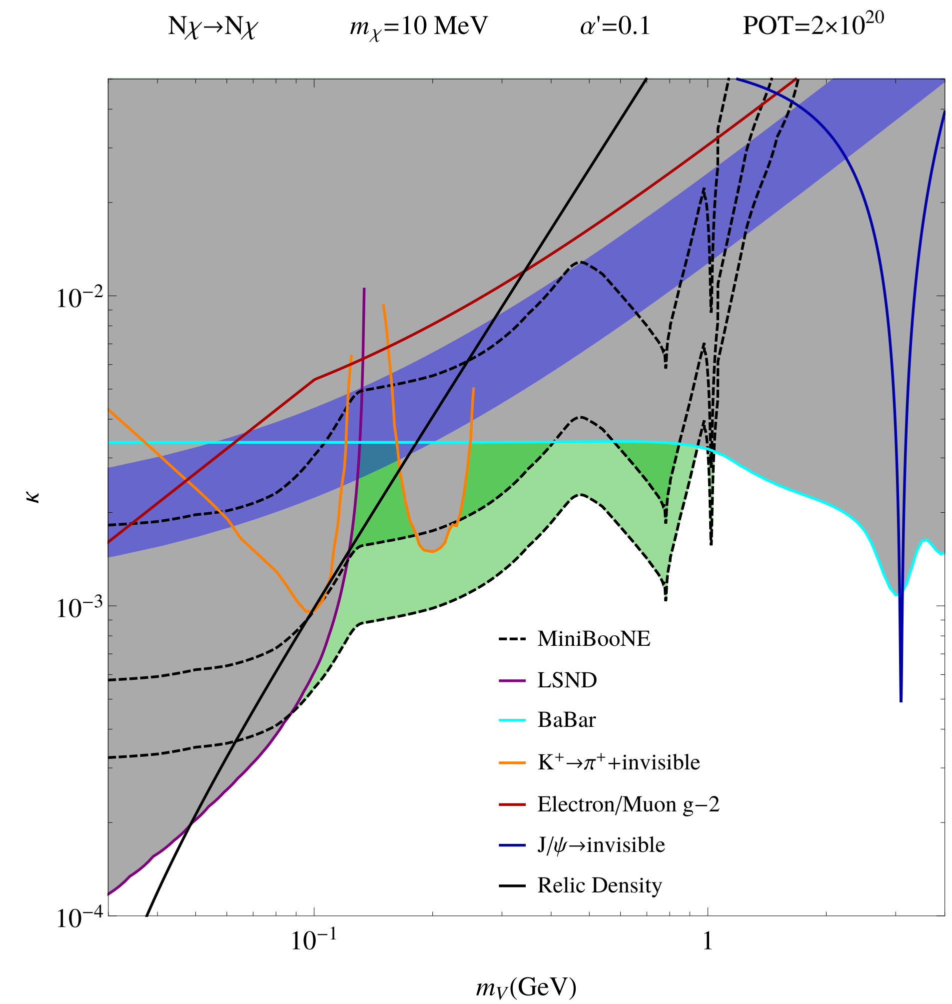
How do we get maximum value from neutrino experiments?

Izaguirre, GK, Schuster, Toro arXiv:1505.00011

DOE Cosmic Visions Report 1707.04591

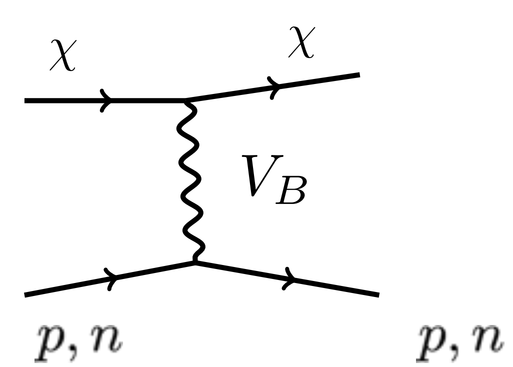
Variation 1: Leptophobic DM





Mediator couples mainly to baryons

$$\mathcal{L} \supset V_B^\mu \left(g_\chi \bar{\chi} \gamma^\mu \chi + g_B \sum_q \bar{q} \gamma^\mu q \right)$$



Caveat: needs additional TeV scale colored particles to cancel anomalies

Batell, de Niverville, McKeen, Pospelov, Ritz 1405.7049

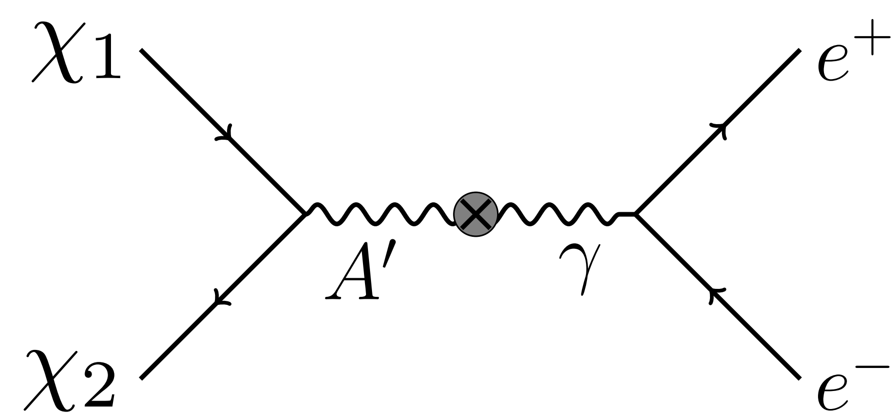
Variation 2: Inelastic DM

Dirac and Majorana masses split a Fermion into two mass eigenstates $\chi_{1,2}$

Off diagonal coupling to A'

$\Delta \equiv m_2 - m_1$

$$\mathcal{L} \supset A'_\mu \left(e_D \bar{\chi}_1 \gamma^\mu \chi_2 + \epsilon e J^\mu_{\mathrm{EM}} \right)$$

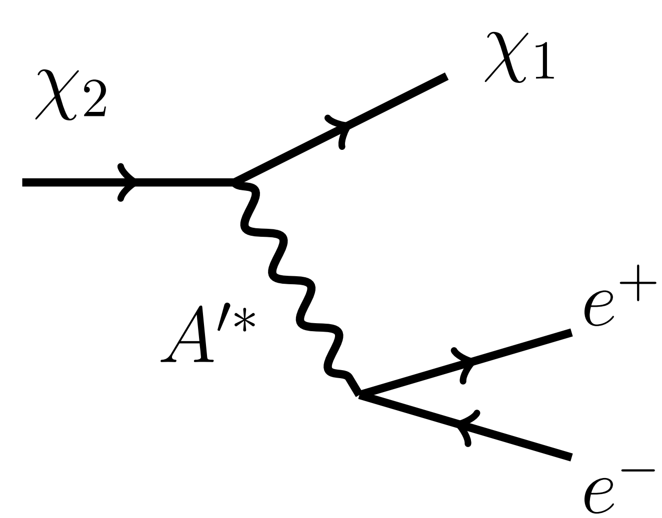


Relic abundance

"coannihilation" during early universe

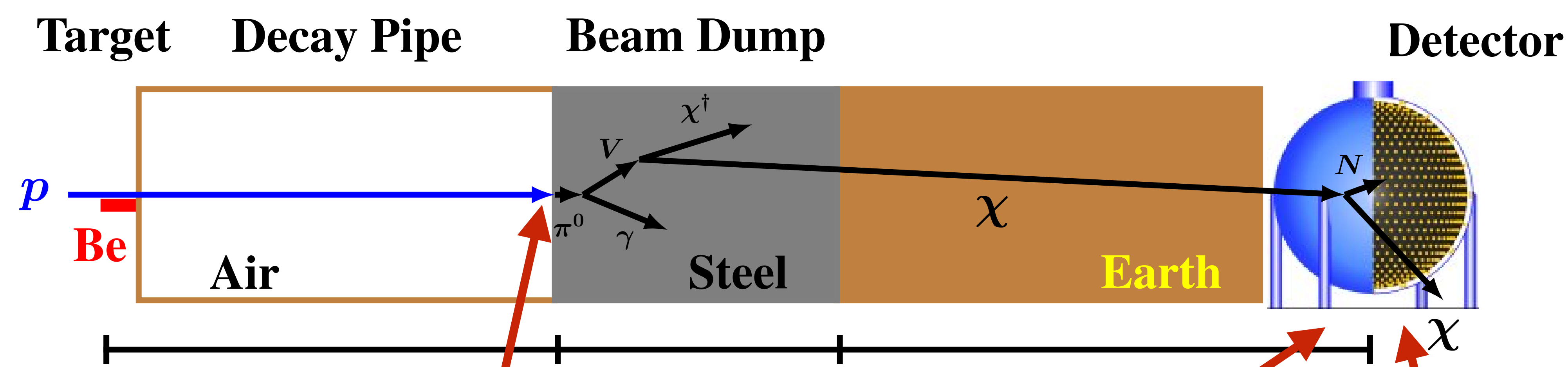
Heavier state is unstable

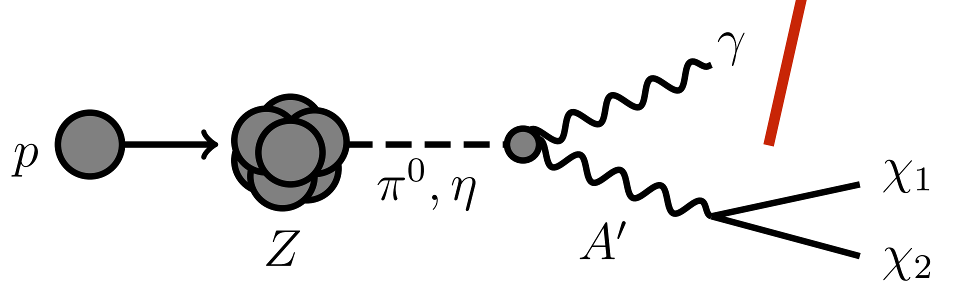
New decay signatures in accelerators

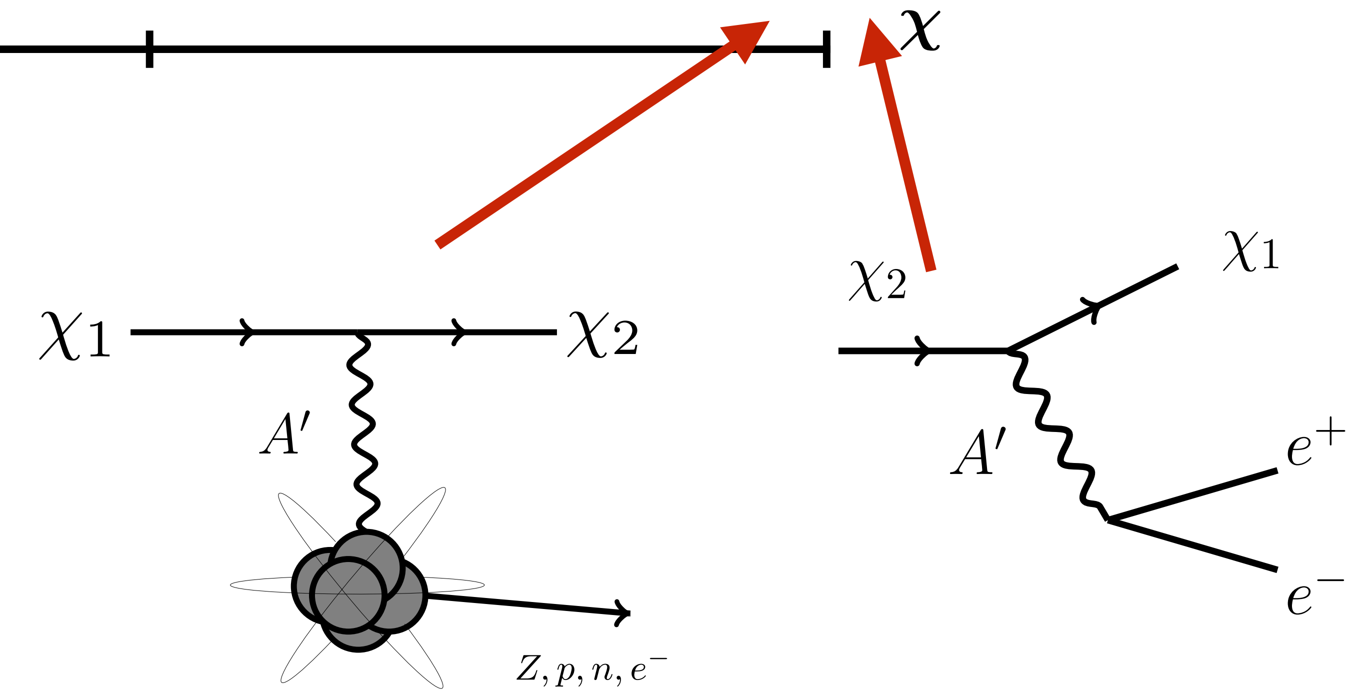


Izaguirre, GK, Shuve arXiv: 1508.03050
Izaguirre, Kahn, GK, Moschella arXiv: 1703.06881
Jordan, Kahn, GK, Moschella, Spitz arXiv: 180.06137

Variation 2: Inelastic DM







Production and scattering same as before

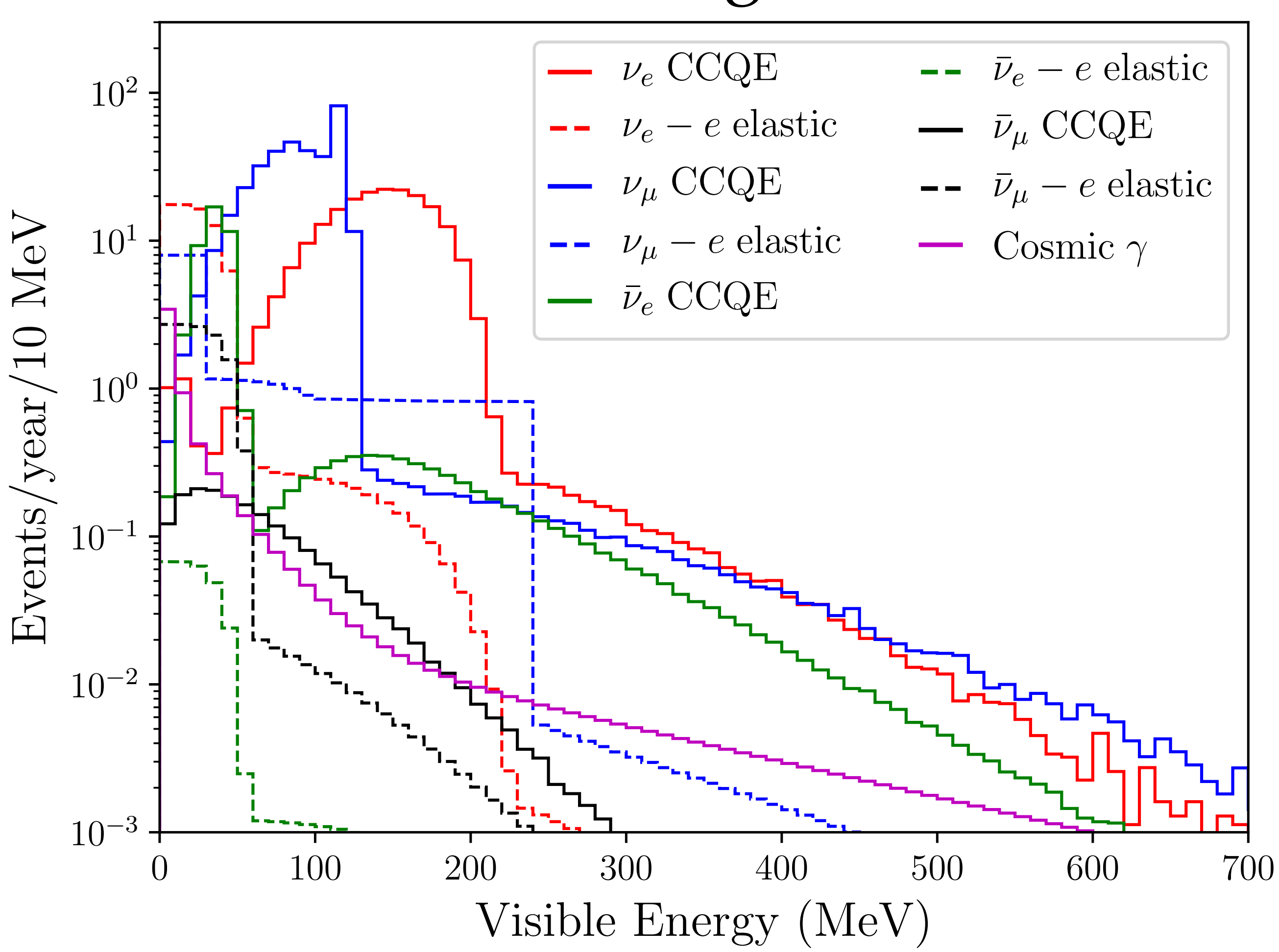
Decays qualitatively different

Variation 2: Inelastic DM @ JSNS^2

DM beam from pi0& eta decays $\sim 10^{23}\,\mathrm{POT}, E_p = 3\,\mathrm{GeV}$, Hg target

Similar to LSND, ~30 ton scintillator det. , 24 m target-detector dist.

Beam Backgrounds



GEANT4

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

demand $S/\delta B = 2$

Assuming:

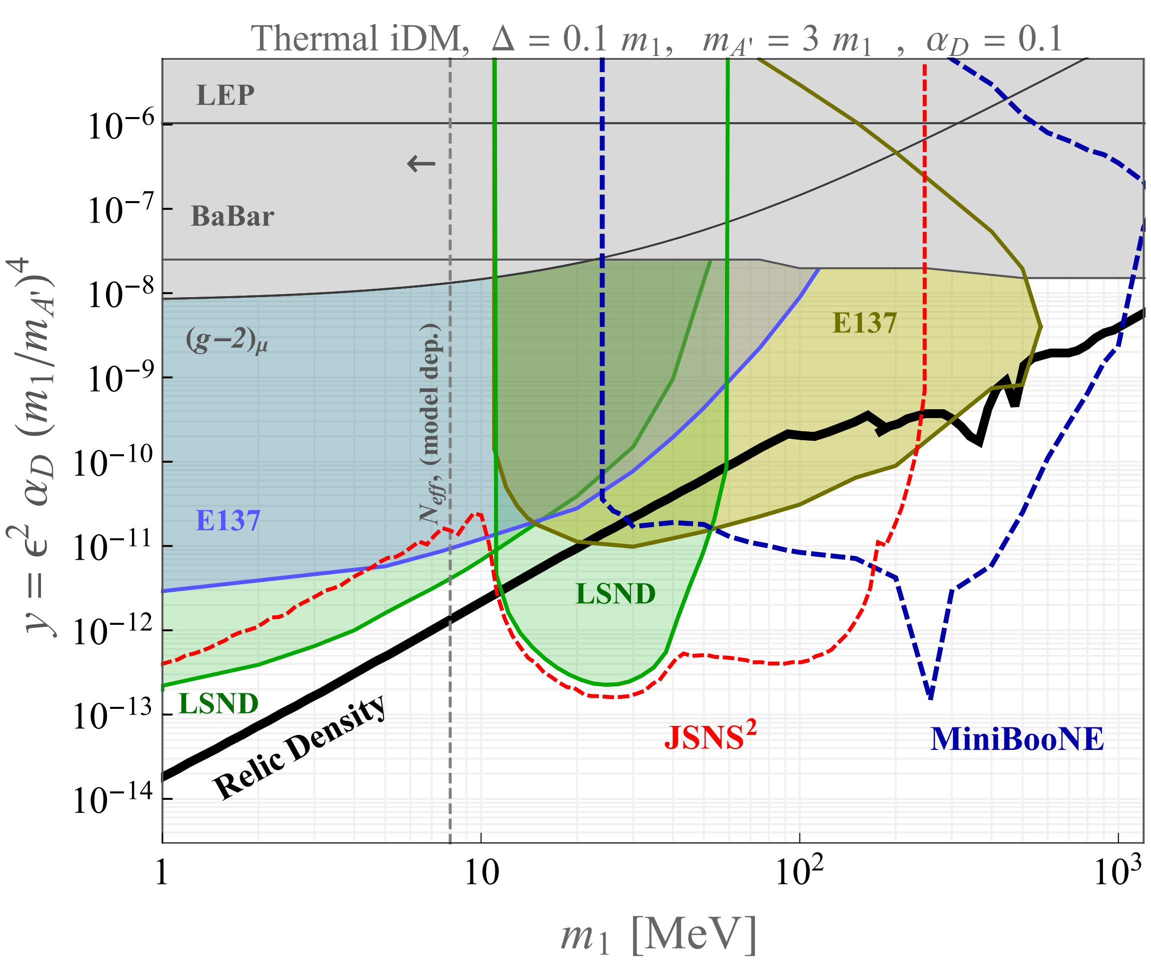
20% systematic uncertainty on BG

7cm extra shielding for comics

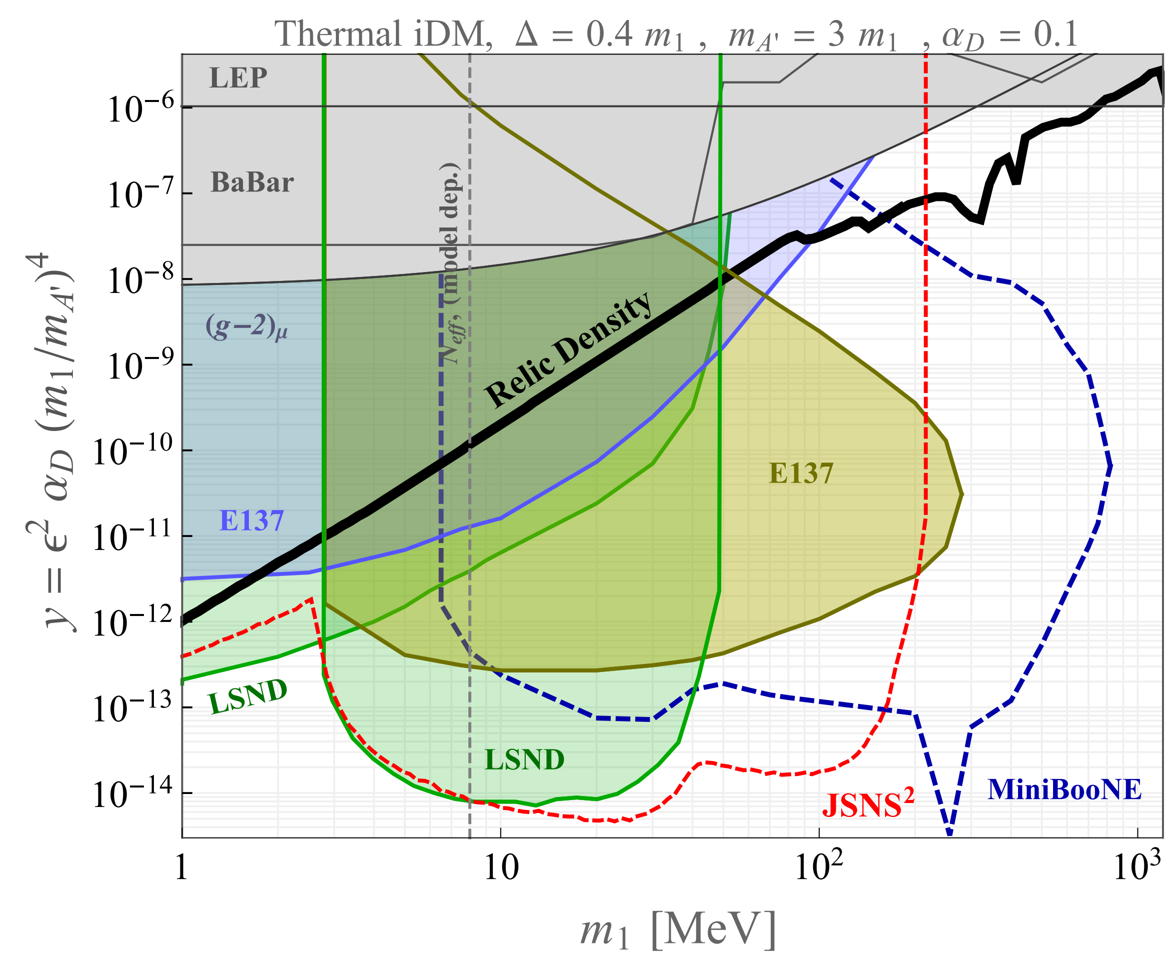
JSNS2 TDR 1705.08629

Jordan, Kahn, GK, Moschella, Spitz arXiv: 1703.06881

Variation 2: Inelastic DM @ JSNS^2



small mass splitting ~ 10%

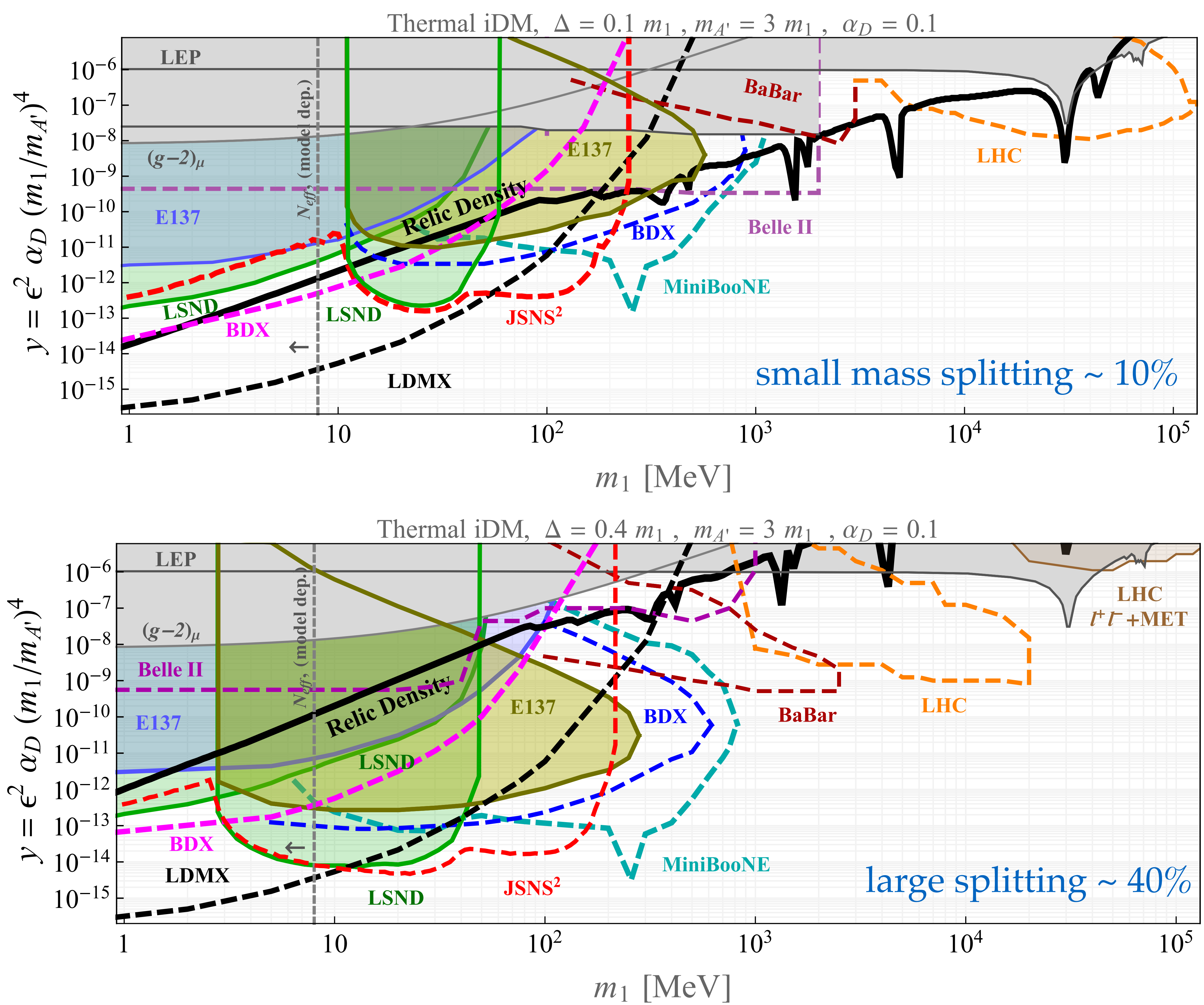


large mass splitting ~ 40%

- Traditional direct detection kinematically forbidden
- Heavier state decayed away in early universe (no indirect detection)

Jordan, Kahn, GK, Moschella, Spitz arXiv: 1703.06881

Neutrino experiments + electron fixed targets + B-factories + LHC



Summary

Thermal DM is extremely well motivated

A Modest Proposal $\Gamma(\mathrm{DM} \leftrightarrow \mathrm{SM}) > H$

Rate beats Hubble expansion at *some* point [easy to realize]

Initial Condition Known $n_{\mathrm{DM}} \sim T^3$

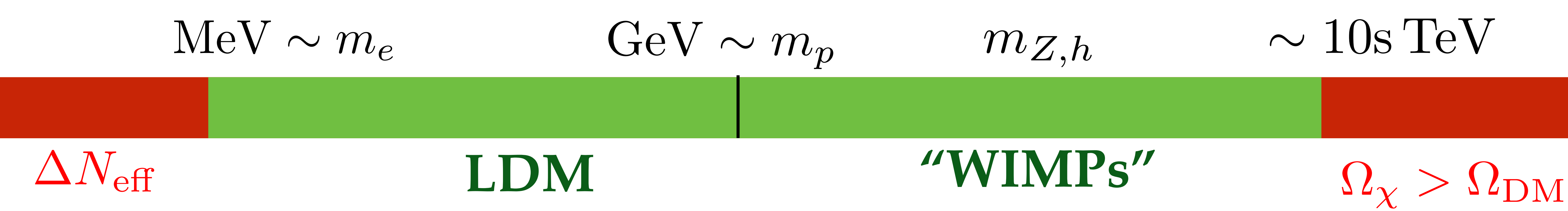
Insensitive to unknown high scales [inflation, baryogenesis…]

Predicts Min. Annihilation Rate $\sigma v \gtrsim 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$

Equilibrium overproduces DM, must deplete with annihilation

Viable Window In Our Neighborhood

Coincidentally in broad vicinity of the electroweak scale



Concluding Remarks

Dawn of a new era of accelerator DM searches

Neutrino experiments leading the way!

- Test thermal targets in predictive models
- Almost completely free (just need new analysis)
- MiniBooNE first **ever** dedicated search
- Lots of new signatures (especially decays)
- Complementarity with electron beam & collider searches

No longer have to trust theorists to reinterpret old data