Breaking the Dark Force

based on arXiv: 0902.3271

work done with Raman Sundrum

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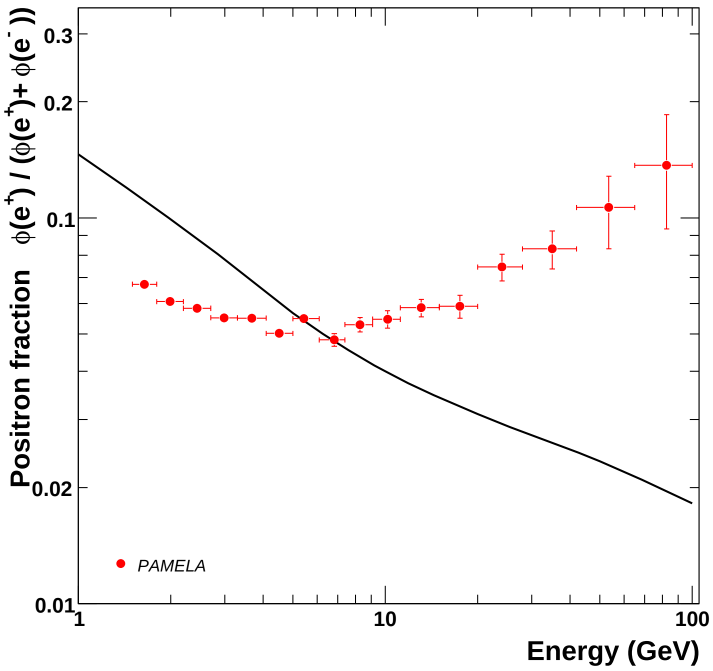
Outline

1. Motivation
   - Experimental evidence
   - Unified explanation and GeV-scale force
2. Model of DM:
   - framework
   - DM structure
   - Dark sector masses and structure
3. Phenomenology: signals and constraints
4. Conclusions

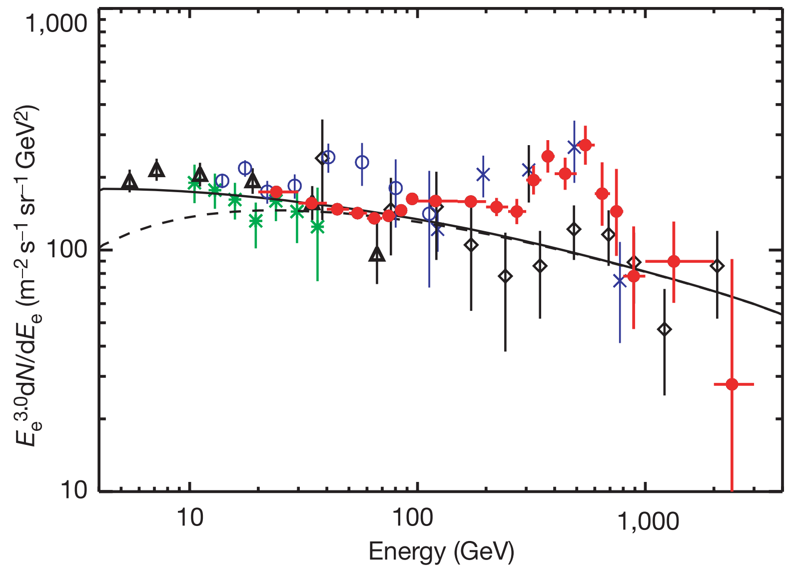
Motivation I: PAMELA



Satellite experiment; e^+e^- in cosmic rays

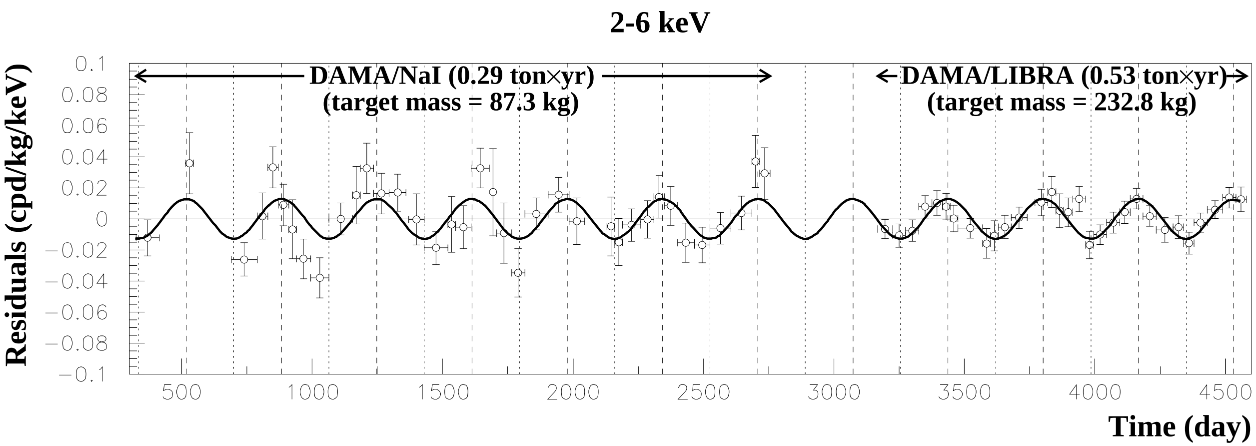
Anomalous positron flux

Motivation II: ATIC



Balloon experiment; overall e^+e^- flux
PAMELA & ATIC from DM $\Rightarrow$
annihilation cross section too big

Motivation III: DAMA/LIBRA



Direct detection

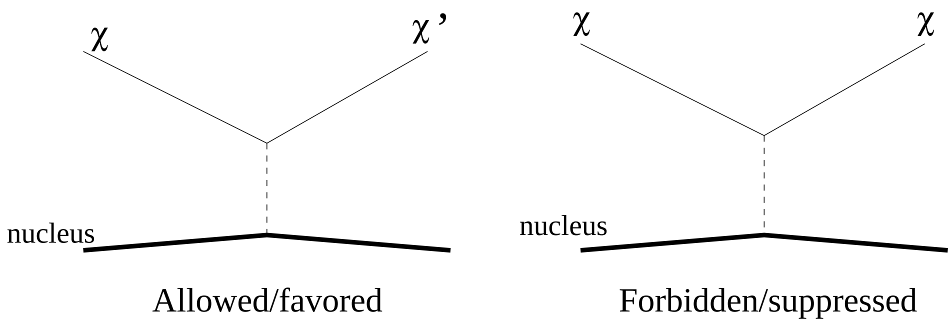
Signal is incompatible w/ other direct detection experiments

inelastic scattering? preferred $\Delta m \sim 100\ \mathrm{keV}$

iDM paradigm

Tucker-Smith and Weiner

DAMA vs. other experiments



$$\beta_{min} = \sqrt{\frac{1}{2m_N E_R}} \left(\frac{m_N E_R}{\mu} + \Delta m \right)$$

- increase $m_N \Rightarrow \beta_{min}$ falls
- $A_I = 127$ (DAMA) vs. $A_{Ge} = 73$ (CDMS)
- amplifies signal when orbiting the Sun

Motivation IV: INTEGRAL

- measures γ-rays
- $511\ \mathrm{keV}$ line from the center of the Galaxy
- if due to DM annihilation: requires enhanced annihilation cross-section
- excited DM (XDM)

$$\chi\chi \to \chi'\chi' \to \chi\chi e^+e^-e^+e^-$$

non relativistic electrons $\Rightarrow$

positronium annihilation

Unified explanation

Arkani-Hamed, Finkbeiner, Slatyer, Weiner

- weak scale DM –> charged under GeV scale force
- large annihilation cross section from Sommerfeld enhancement
- ATIC + PAMELA: $M_{DM} \sim 700 - 800 \text{ GeV}$
- iDM/XDM splittings: induced radiatively ? higher-dim. operators

Unified explanation - 2

Dark force - Abelian or non-Abelian?

Interaction w/ the SM: kinetic mixing

$$\mathcal{L} \supset \epsilon F_d^{\mu\nu} F_{\mu\nu} :$$

- $\epsilon \lesssim 10^{-3}$ $(g-2)_\mu$
- $\epsilon \gtrsim 10^{-4}$ to explain DAMA

Must have an Abelian component

iDM+XDM together - easier w/ non-Abelian, not necessary

$\Rightarrow$ we will assume **Abelian** force

Unified explanation - constraints

- PAMELA - no antiproton excess
- HESS - constraints from γ-rays
- no significant π^0 signal

“Leptophilic” DM, SM channels suppressed

Motivates: DM neutral under the SM

$$\chi\chi \to \gamma_D\gamma_D$$

If γ_D decays:

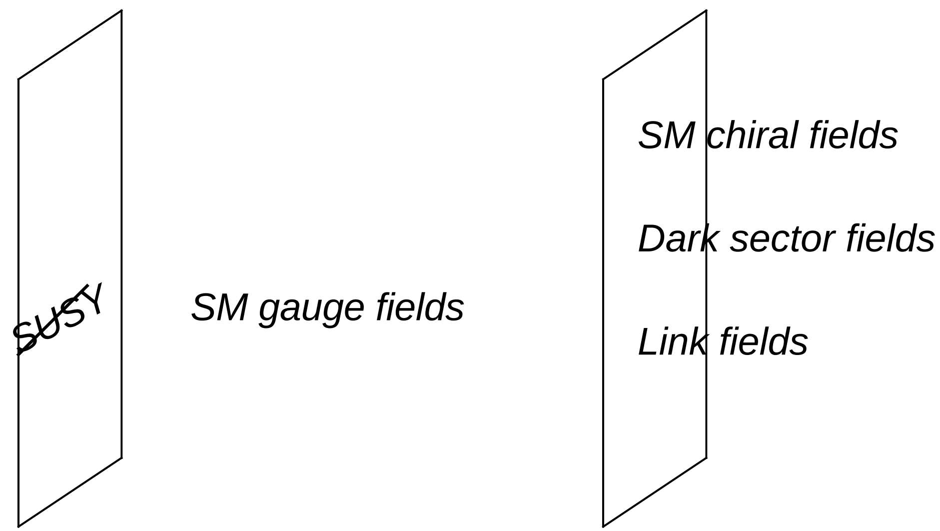
- no π^0
- no $\tau,\ p \ldots$ due to kinematics

Model building - challenges

- DM mass: $\mu/B\mu$ type mechanism $\sim$ EW scale
- How does GeV scale *naturally* emerge?
- Higgsing the dark sector: no massless particles, long-living particles - BBN constraints

$\mu/B\mu$ - generalized Giudice-Masiero mechanism

High scale SUSY-breaking



- SM - $\tilde{g}$MSB
- dark sector - sequestered - AMSB+

DM mass

DM: not charged under the SM; sequestered

Why $100\ \mathrm{GeV}$ scale mass?

generalized Giudice-Masiero mechanism:

$X, \bar{X}$ - vector-like DM

$$K = |\phi|^2 \left(|X|^2 + |\bar{X}|^2 + c(X\bar{X} + \mathrm{c.c.})\right), \quad \phi \equiv 1 + m_{3/2}\theta^2$$

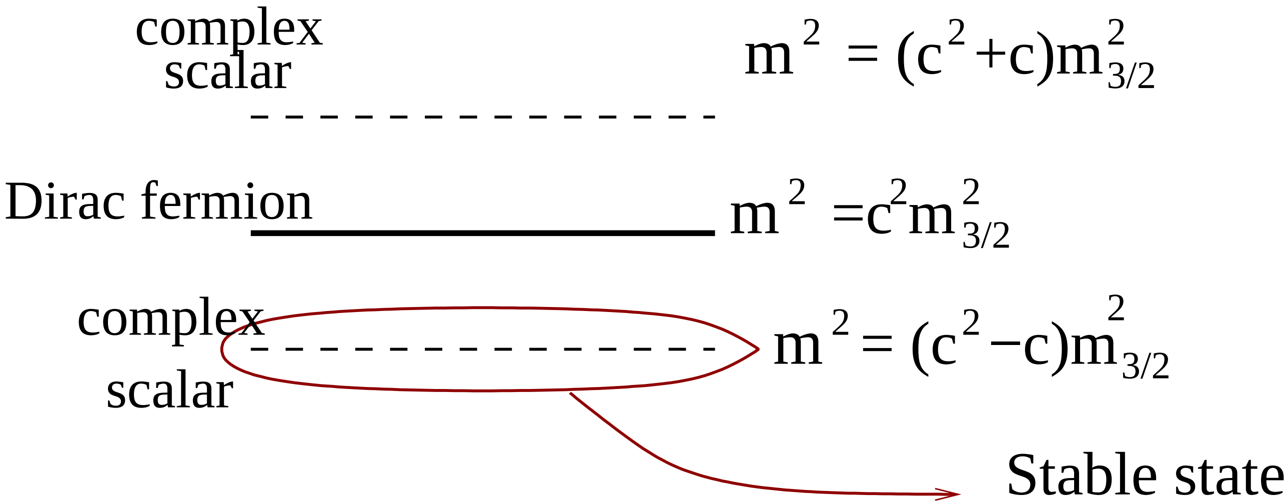
Rescale $\phi X \to X$:

$$K = |X|^2 + |\bar{X}|^2 + c\frac{\phi^\dagger}{\phi}(X\bar{X} + \mathrm{c.c.})$$

Effective $\mu/B\mu$: $\mu = cm_{3/2}, \quad B\mu = cm_{3/2}^2$

DM structure

Stability: impose $\mathbb{Z}_2$ - $X, \bar{X}$ are odd



- avoid tachyons: $c > 1$
- $U(1)$ broken - DM can be splitted
- both iDM & XDM: at least two flavors of DM

(will be) GeV scale sector

We need it to

- supply DM annihilation channels
- enhance $\langle \sigma v \rangle$

Dark gauge group: $U(1)$

Field contest:

$$T(+1), \quad \bar{T}(-1), \quad S(0)$$

Superpotential:

$$W = \lambda T \bar{T} S + \frac{\kappa}{3!} S^3$$

No mass scale at this point

Dark sector masses

What are the origins of mass?

1. Kinetic mixing $\Rightarrow$ effective FI term in the dark sector $m \sim \sqrt{\epsilon} v \sim \gtrsim 1\ \mathrm{GeV}$
2. AMSB $m \sim \frac{m_{3/2}}{16\pi^2} \sim 1\ \mathrm{GeV}$
3. non-decoupling effects

Needed: tachyonic masses to break the dark force

No massless particles (including fermions)

Dark sector masses - FI term

FI term:

$$\mathcal{L} \supset \xi_{FI} \int d^4\theta V \implies \mathcal{L} \supset \xi_{FI} D$$

We develop *effective* FI term

$$\mathcal{L} \supset \frac{\epsilon}{2} \int d^2\theta W_D^\alpha W_{\alpha\ Y} + \text{c.c.} \implies \mathcal{L} \supset \epsilon D_D \langle D_Y \rangle$$

- *Does not* break SUSY
- masses^2 to $\bar{T}$ - positive; to T - tachyonic!
- $\epsilon \sim 10^{-4} \;\Rightarrow\; m \sim \text{GeV}$
  $\epsilon \sim 10^{-3} \;\Rightarrow\; m \sim 5\,\text{GeV}$

Dark sector masses - AMSB

Order: $m \sim \frac{m_{3/2}}{16\pi^2} \sim 1\ \mathrm{GeV}$

One-loop A-terms: $a \propto \beta$

$$m^2 \propto \beta \frac{\partial \gamma}{\partial g}$$

Sign: Yukawa, UV free gauge interaction $\Rightarrow$ positive mass squared

IR free force $\Rightarrow$ tachyonic scalar masses

Effective FI + AMSB: if $\lambda \sim g$ (or smaller), dark $U(1)$ is broken

Dark sector - fermion masses

FI + AMSB $\Longrightarrow$ soft masses of T, $\bar{T}$ are **not** symmetric

Consider: only T condenses

$$W = \lambda T \bar{T} S$$

- $\bar{T}$ and S form Dirac state with mass $\lambda \langle T \rangle$
  Need S to give mass to $\psi_{\bar{T}}$
- λ gets Majorana mass from AMSB (and non-decoupling effects)
- ψ_T - mass from $U(1)$ breaking, mixes w/ λ

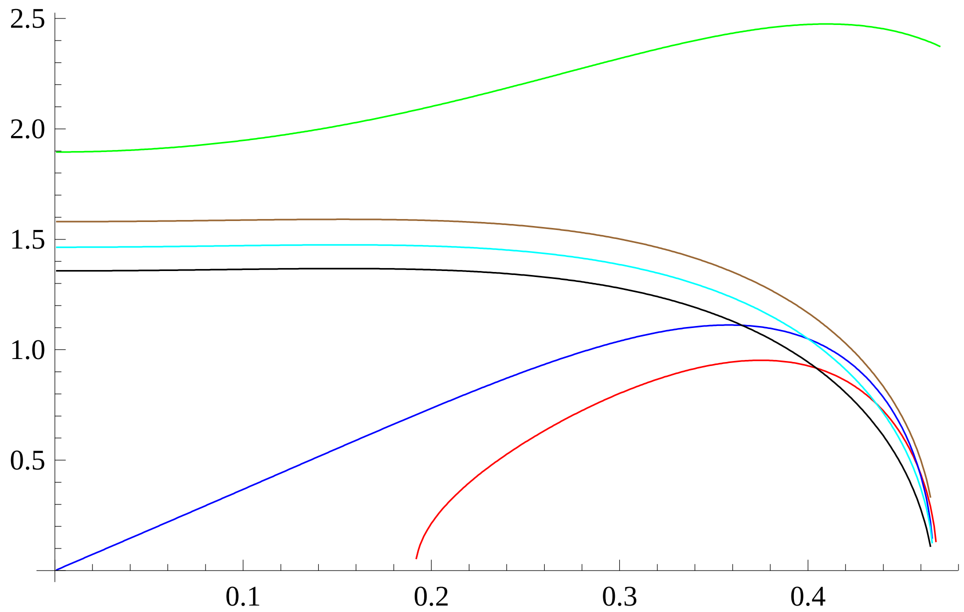
All fermions are massive!

Dark sector - boson masses

- dark photon is massive $m_\gamma = g\langle T \rangle$
- phase of T is eaten by dark photon
- absolute value of T gets mass $g\langle T \rangle$
- S and $\bar{T}$ mix due to A-terms: two complex scalar states

Full mass spectrum

Example:



Values:

$\epsilon = 10^{-4}, \tan\beta = 10, \; g_D = 0.4, \; m_{3/2} = 110 \text{ GeV}$

Partial summary

- DM has $\gtrsim 100\ \mathrm{GeV}$
- AMSB + FI term break $U(1)$ and SUSY in the dark sector
- the mass spectrum is $\sim 1\ \mathrm{GeV}$, no massless particles

Questions:

1. What parts of the spectrum are viable?
2. How do we get PAMELA signal?
3. How do we get iDM/XDM splittings?

Viable spectrum

R-parity is still imposed $\Rightarrow$ LSP is stable

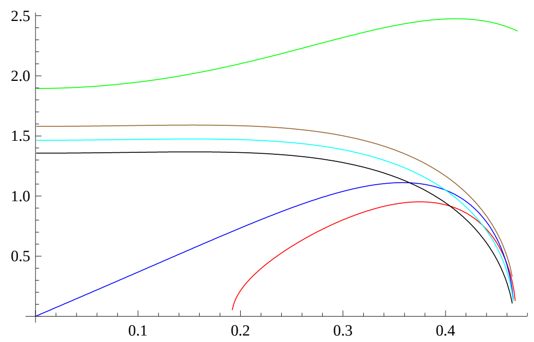
Hidden sector LSP $\Rightarrow$ coexistent light DM (LDM)

The lightest dark fermion is stable!

Two possibilities for the lightest dark state:

1. Majorana fermion, λ & $\psi_{\bar{T}}$ mixture
2. Complex scalar, S & $\bar{T}$ mixture

LDM annihilation



Majorana $\lambda + \psi_{\bar{T}}$ vs. Dirac $\psi_S + \psi_{\bar{T}}$

LDM annihilation cross sections:

1. ϵ^2 & p-wave suppressed, not enough
2. LDM - Dirac fermion, annihilates into scalars

$$\langle \sigma v \rangle \sim \frac{\alpha_\lambda^2 |\lambda \langle T \rangle|^2}{m_T^4} \quad \text{large enough}$$

PAMELA/ATIC signal

Preferable region – complex scalar is the lightest particle

Should decay into leptons – PAMELA signal

I. Assume: ϵ is the *only* contact term with the SM

Leading order effect: two-loop decays, ϵ^4 suppression in Γ

Leads to $\tau \gtrsim 1000$ years

Why is it bad?

- BBN – D overproduction
- no natural π^0 suppression

New contact terms

II. Consider more contact terms between dark/visible sector

$$W = \frac{SLH_d\bar{e}}{\Lambda_1} + \frac{SQH_d\bar{d}}{\Lambda_2}$$

Assumption: proportional to the SM Yukawa matrices

Arise from integration out $5 + \bar{5}$. Decays

$$\begin{aligned} S &\rightarrow \mu^+\mu^- \\ S &\rightarrow e^+e^- \quad \text{suppressed} \\ S &\rightarrow q^+q^- \quad \text{dangerous} \end{aligned}$$

New contact terms -2

Range for Λ:

- MFV assumption $\Lambda > 100\ \mathrm{TeV}$
- w/o MFV , Yukawa-like structure ($K - \bar{K}$ constraints) $\Lambda \gtrsim 100.000\ \mathrm{TeV}$
- BBN constrains $\Lambda \lesssim 10^{15}\ \mathrm{GeV}$

Suppressing $\pi^0\pi^0$ channel:

$u\bar{u}$, $d\bar{d}$ - Yukawa suppressed, $s\bar{s}$ - dangerous

$$\frac{\Gamma_{S\to\pi^0\pi^0}}{\Gamma_{S\to\mu^+\mu^-}} \sim \frac{1}{16}\left(\frac{\Lambda_1}{\Lambda_2}\right)^2\left(\frac{m_s}{m_\mu}\right)^2$$

Needed: mild fundamental 2-3 splitting

Colliders and “lepton jets”

Original proposal:

$$\gamma_D \to l^+ l^-$$

decay through ϵ: collider lepton jets

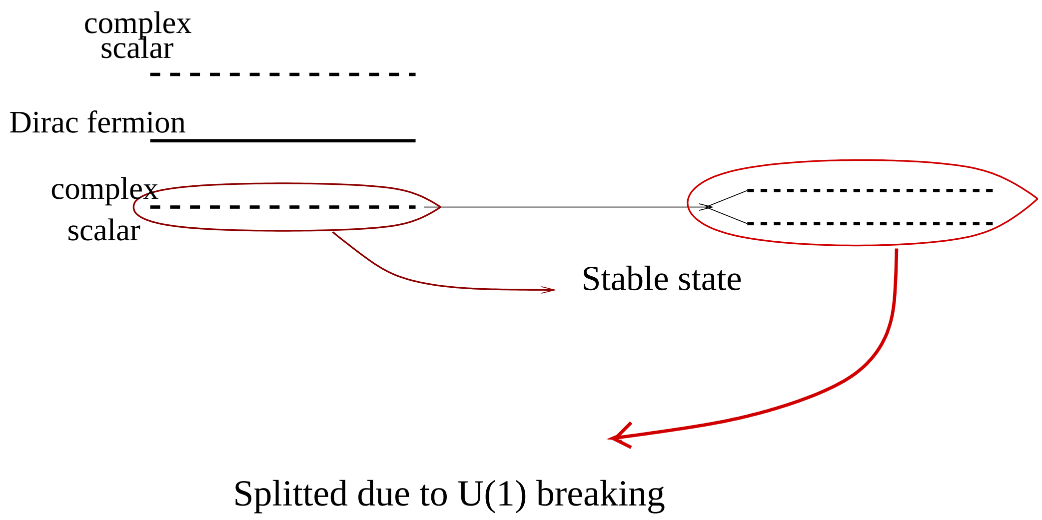
But we have other mechanism for decays.

Lepton jets depend on the particle lifetime

Possibilities:

- BBN bound $\tau \sim 100\ \mathrm{sec}$ - no distinct signature
- $\Lambda \sim 100\ \mathrm{TeV} \ \Rightarrow \ \tau \gtrsim 10^{-12}\ \mathrm{sec}$ lepton jets available
- intermediate Λ scales: displaced vertexes, inside-detector decays...

iDM/XDM splittings



Needed: direct coupling to dark Higgses

if $\Delta m \sim \mathcal{O}(\mathrm{MeV})$ - Yukawa is to strong, but

$$W \sim \frac{T^2 \bar{X}^2}{M_{DM}} - - \text{enough}$$

iDM/XDM splittings - 2

- two DM flavors: iDM & XDM
- ensure stability of both flavors $\mathbb{Z}_2 \times \mathbb{Z}_2$
- two flavors of singlets A_i
- A_i get masses through GM mechanism
- A_i are odd under $\mathbb{Z}_2 \times \mathbb{Z}_2$

$$W = \eta T \bar{X}_i A_i + \mu_A A^2$$

A integrated out, T gets VEV:

$$\mathcal{L} \supset \frac{\mu}{M_{DM}} \langle T \rangle^2 \bar{X}^2 + \text{c.c.} \;\Rightarrow\; \Delta m \sim \frac{T^2}{M_{DM}} \sim \mathcal{O}(\text{MeV})$$

Conclusions

1. introduced framework, which can accommodate the "unified picture" of DM
2. build explicit model of DM within the "unified picture"
3. GeV scale can naturally emerge from sequestering, DM mass from GM mechanism
4. lepton jets collider signature are not robust, but may emerge in certain parts of the parameter space
5. the decaying particle and the dark force carrier can naturally be different particles, further suppressing γ-ray emission