



# Breaking the Dark Force

*arXiv: 0902.3271*

*work done with Raman Sundrum*

Andrey Katz

University of Maryland

# Outline

## 1. Motivation

- Experimental evidence
- Unified explanation and GeV-scale force

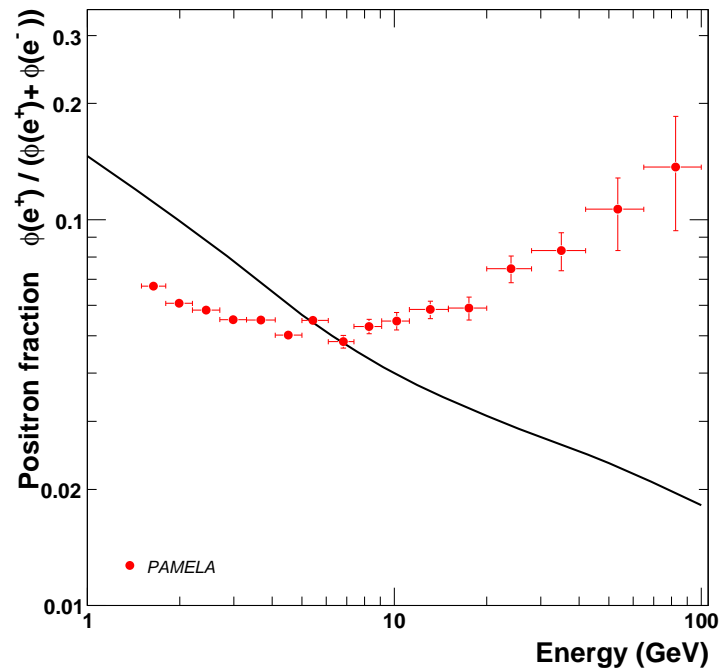
## 2. Model of DM:

- framework
- DM structure
- Dark sector masses and structure

## 3. Phenomenology: signals and constraints

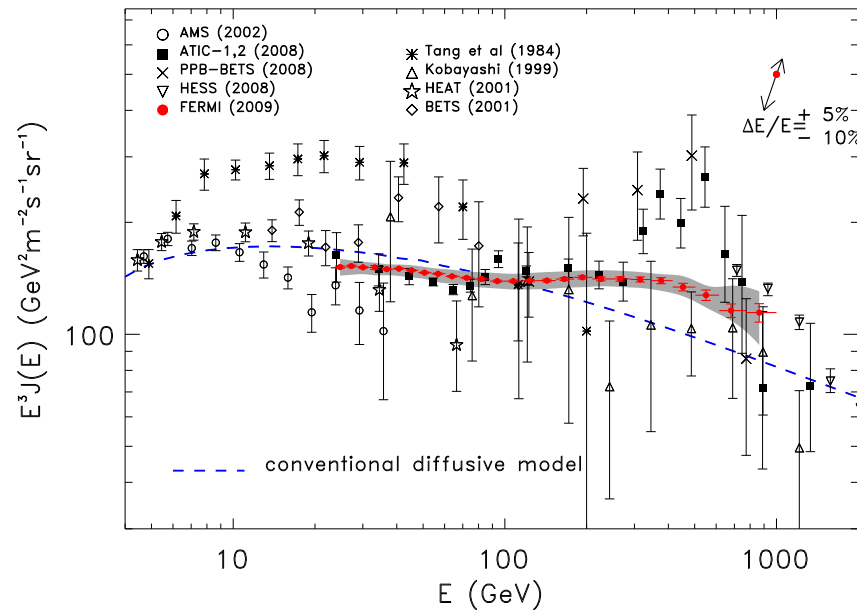
## 4. Conclusions

# Motivation I: PAMELA



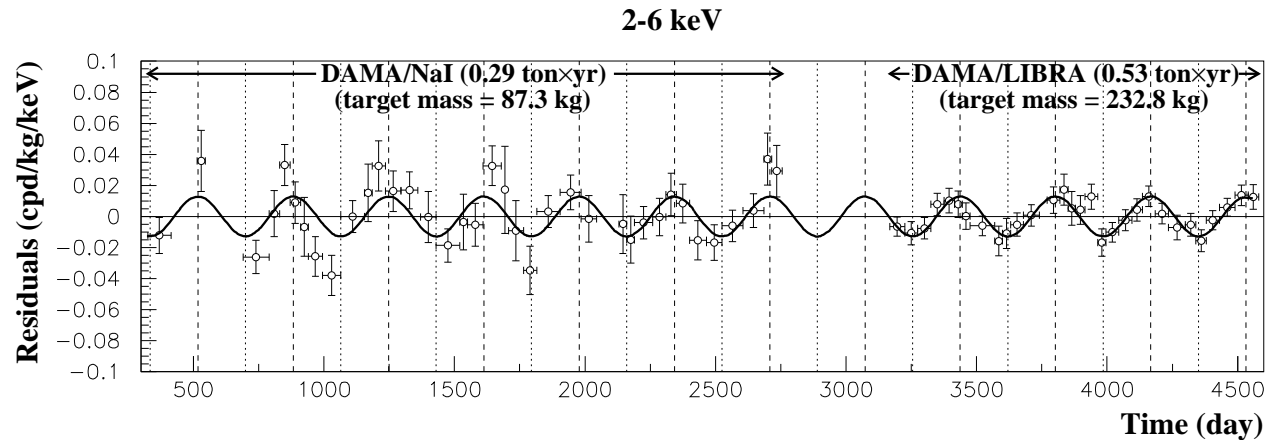
Satellite experiment;  $e^+e^-$  in cosmic rays  
Anomalous positron flux

# Motivation II: ATIC/FERMI



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

# Motivation III: DAMA/LIBRA



Direct detection

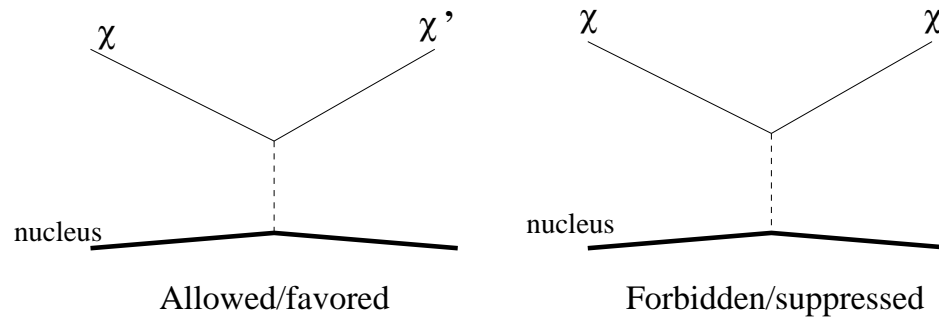
Signal is incompatible w/ other direct detection experiments

inelastic scattering? preferred  $\Delta m \sim 100$  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  $\gamma$ -rays
- 511 keV line from the center of the Galaxy
- if due to DM annihilation: requires enhanced annihilation cross-section
- excited DM (XDM)

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

non relativistic electrons  $\Rightarrow$   
positronium annihilation

# Unified explanation

*Arkani-Hamed, Finkbeiner, Slatyer, Weiner*

- weak scale DM  $\rightarrow$  charged under GeV scale force
- large annihilation cross section from Sommerfeld enhancement
- ATIC (FERMI) + 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

⇒ we will assume **Abelian** force

# Unified explanation - constraints

- PAMELA - no antiproton excess
- HESS - constraints from  $\gamma$ -rays
- no significant  $\pi^0$  signal

“Leptophilic” DM, SM channels suppressed

**Motivates: DM neutral under the SM**

$$\chi\chi \rightarrow \gamma_D\gamma_D$$

If  $\gamma_D$  decays:

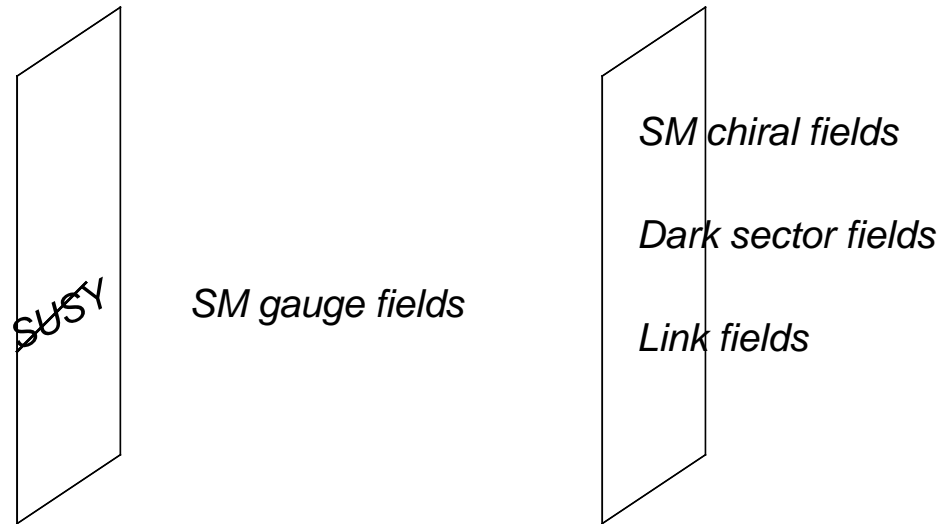
- no  $\pi^0$
- no  $\tau, p \dots$  due to kinematics

# 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 GeV scale mass?

generalized Giudice-Masiero mechanism:

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

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

Rescale  $\phi X \rightarrow X$ :

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

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

# DM structure

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

complex  
scalar

$$m^2 = (c^2 + c)m_{3/2}^2$$

Dirac fermion

$$m^2 = c^2 m_{3/2}^2$$

complex  
scalar

$$m^2 = (c^2 - c)m_{3/2}^2$$

Stable state

- 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 content:

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

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  $m \sim \sqrt{\epsilon v} \sim \gtrsim 1 \text{ GeV}$
2. AMSB  $m \sim \frac{m_{3/2}}{16\pi^2} \sim 1 \text{ GeV}$
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<sup>2</sup> to  $\bar{T}$  - positive; to  $T$  - tachyonic!
- $\epsilon \sim 10^{-4} \implies m \sim \text{GeV}$   
 $\epsilon \sim 10^{-3} \implies m \sim 5 \text{ GeV}$

# Dark sector masses - AMSB

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

$$\text{One-loop A-terms: } a \propto \beta$$

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

**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  $\implies$  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  $\psi_{\bar{T}}$
- $\lambda$  gets Majorana mass from AMSB (and non-decoupling effects)
- $\psi_T$  - mass from  $U(1)$  breaking, mixes w/  $\lambda$

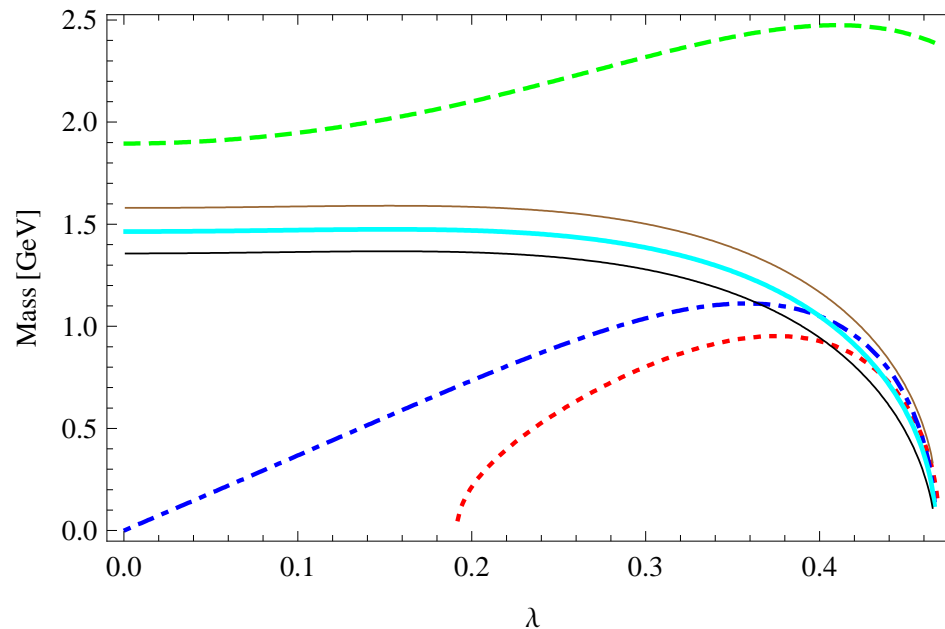
**All fermions are massive!**

# 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:

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

Red, green – scalars; blue – Dirac fermion;  
brown, black – Majorana fermions.

# Partial summary

- DM has  $\gtrsim 100$  GeV
- AMSB + FI term break  $U(1)$  and SUSY in the dark sector
- the mass spectrum is  $\sim 1$  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?

# Viabale spectrum

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

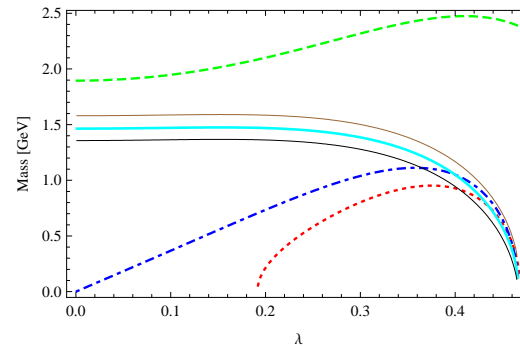
Hidden sector LSP  $\Rightarrow$  coexistent light DM (LDM)

**The lightest dark fermion is stable!**

Two possibilities for the lightest dark state:

1. Majorana fermion,  $\lambda$  &  $\psi_{\bar{T}}$  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.  $\epsilon^2$  & 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/FERMI signal

Preferable region – complex scalar is the lightest particle

Should decay into leptons – PAMELA signal

I. Assume:  $\epsilon$  is the *only* contact term with the SM

Leading order effect: two-loop decays,  $\epsilon^4$  suppression in  $\Gamma$

Leads to  $\tau \gtrsim 1000$  years

Why is it bad?

- BBN – D overproduction
- no natural  $\pi^0$  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  $\mathbf{5} + \bar{\mathbf{5}}$ . Decays

$$S \rightarrow \mu^+ \mu^-$$

$$S \rightarrow e^+ e^- \text{ suppressed}$$

$$S \rightarrow q^+ q^- \text{ dangerous}$$

# New contact terms -2

Range for  $\Lambda$ :

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

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

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

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

Needed: mild fundamental 2-3 splitting

# Collider Signatures - Lepton Jets

## Why lepton jets?

Visible LSP is not stable, decays into the Dark Sector.

Cascade decays in the Dark Sector typically include the “dark stable” particle, further decaying leptonically into the SM particles. If dark photon is not dark stable, the fate of lepton jets depends on  $\Lambda$ .

Bounds on  $\Lambda$  depend on the flavor structure of the contact terms which can be:

- roughly proportional to  $Y_{SM} \Rightarrow l \gtrsim 10 m$
- MFV  $\Rightarrow$  prompt decays possible
- flavor anarchy:  $m_s < 2m_{\pi^0}$  and  $\mu e$  pair production possible

# Dark Stable Dark Photon

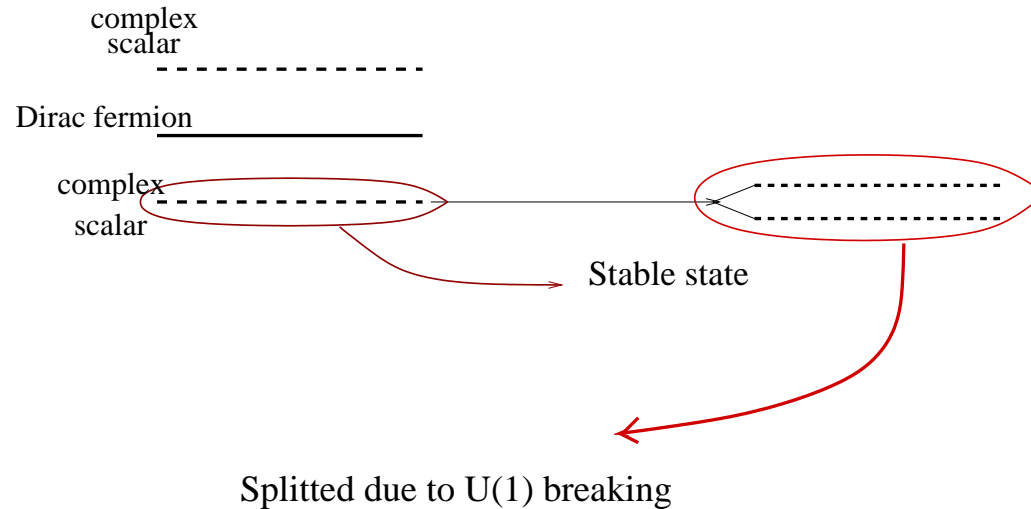
$\gamma_D$  usually is not the lightest dark state.

But  $m_{\gamma_D} < 2m_S$  and  $m_{\gamma_D} < 2m_\psi$  –  
large part of parameter space.

**Dark photon can be dark stable**

- contact terms – still needed to overcome BBN constraints
- astrophysical signal – not distinguishable from  $\gamma_D$  dark unstable
- lepton jets – available even with  $\Lambda \gg 10^8$  GeV

# iDM/XDM splittings



Needed: direct coupling to dark Higgses  
if  $\Delta m \sim \mathcal{O}(\text{MeV})$  - Yukawa is too strong, but

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

# 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  $\gamma$ -ray emission