Chiral Dark Sector

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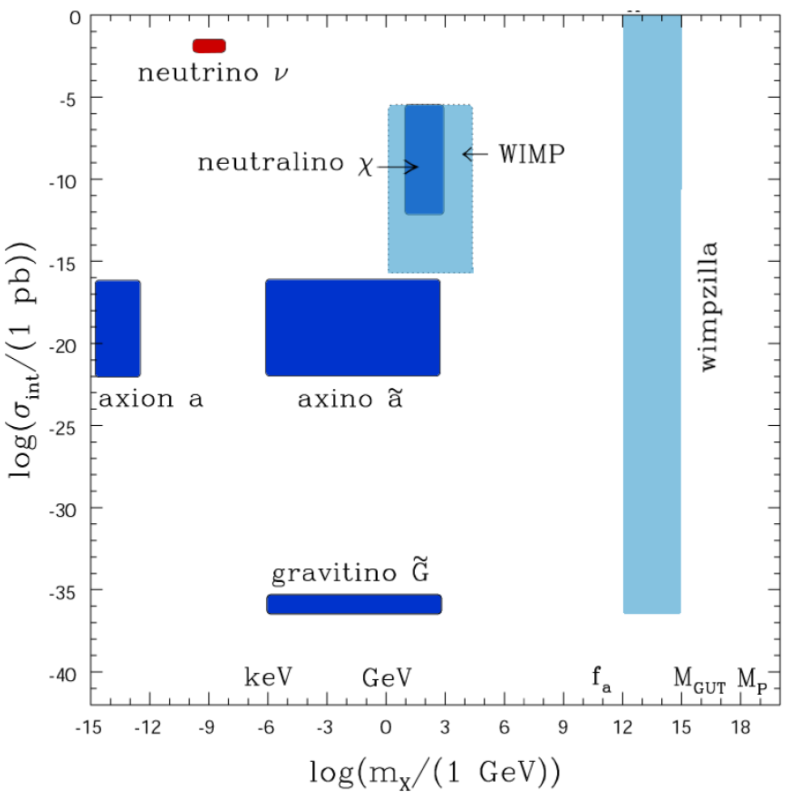
Dark Matter

— clear indication for physics beyond the standard model

• We do not know much about it



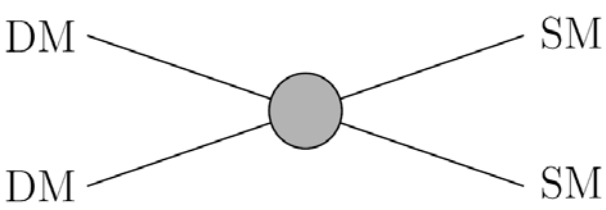
Roszkowski

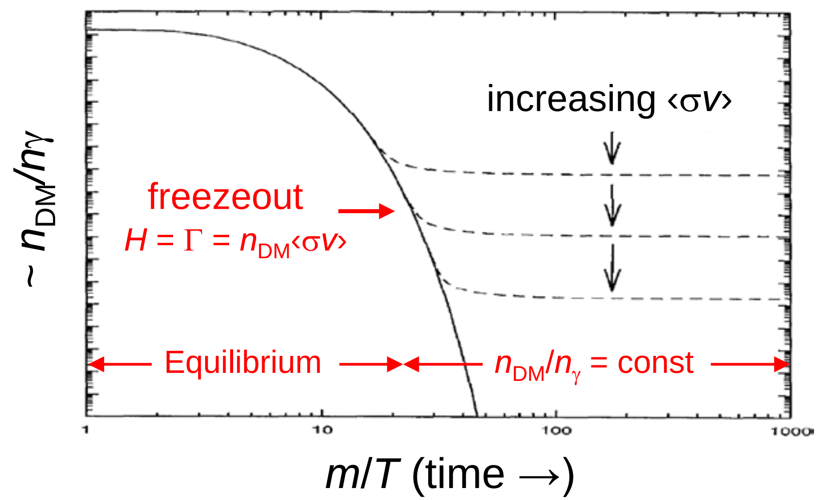
— Huge range of mass and cross section allowed (it may even not be a particle)

… Important to search without a prejudice

Connection to particle physics?

DM as a thermal relic of the early universe





Annihilation cross section determined

$$\Omega_{\rm DM}h^2 \simeq \frac{3\times 10^{-27}\,{\rm cm^3\,s^{-1}}}{\langle\sigma v\rangle} \Longrightarrow \langle\sigma v\rangle \sim \frac{g^2}{8\pi}\frac{1}{({\rm TeV})^2}$$

weak interaction strength

… Weakly Interacting Massive Particle (WIMP)

Has been considered as a part of a solution to the hierarchy problem

— Lightest SUSY particle

— Techni particle

— Lightest KK particle

— …

A few reasons to be "skeptical"

— No discovery of natural physics (so far)

… the origin of the Higgs mass may be environmental in the multiverse

— Connection to TeV is loose

… the coincidence with TeV may also be environmental

— …

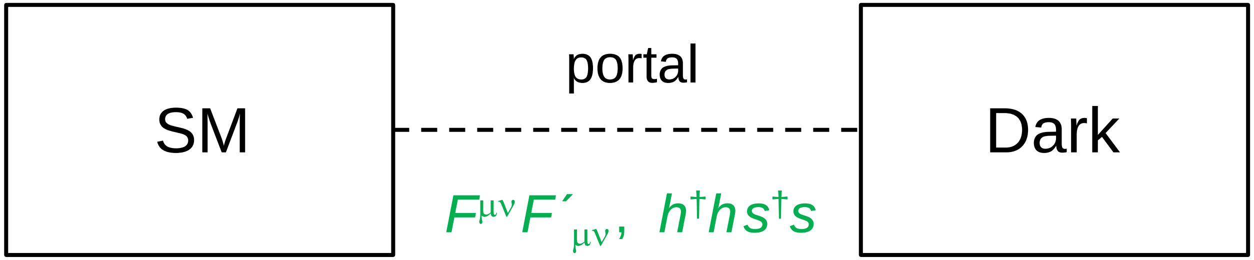
Does not mean that the WIMP picture is wrong

(although no longer "guarantee")

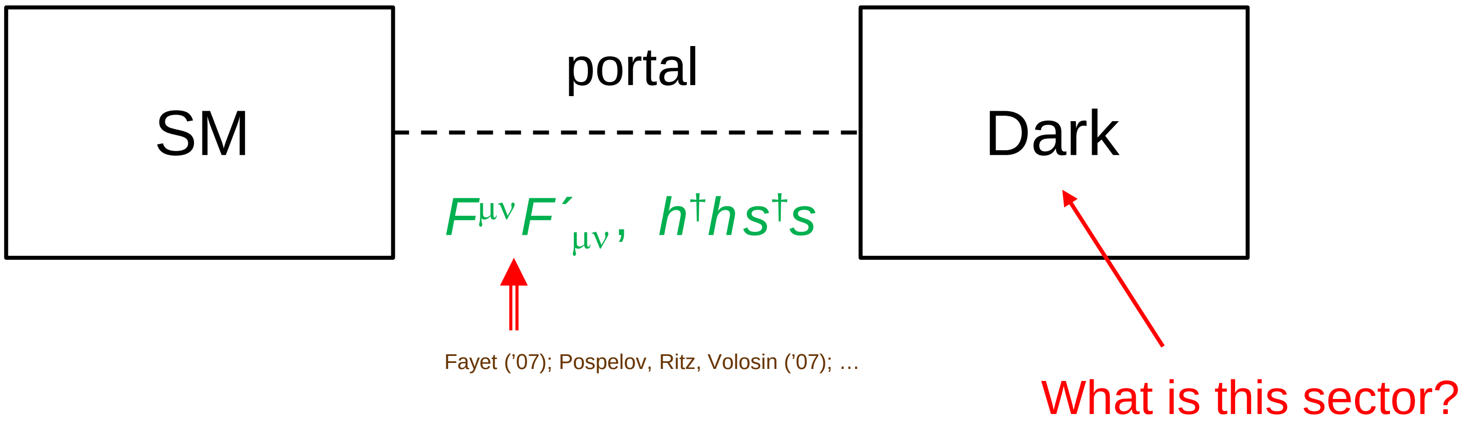
→ A sector "weakly" interacting with the SM

not a part of the extended SM (e.g. SUSY SM)

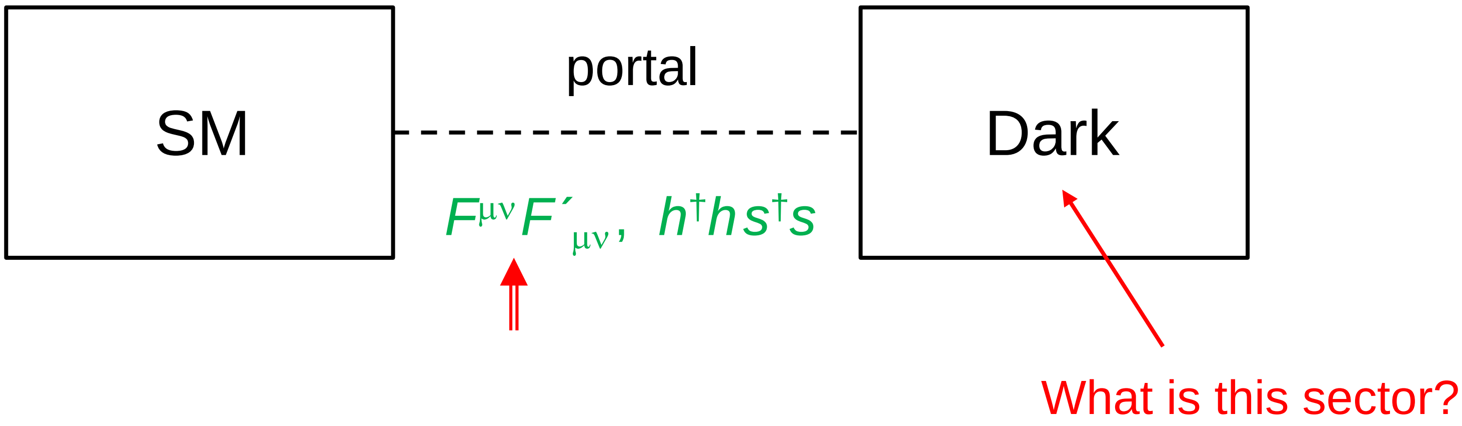
A new sector through a portal



A new sector through a portal



A new sector through a portal



A simple and elegant sector can lead to rich phenomenology

— All the masses generated dynamically

… chiral theory (no tree-level mass term)

… both dark matter and portal masses by a single dynamics

— A small number of parameters

— Rich phenomenology

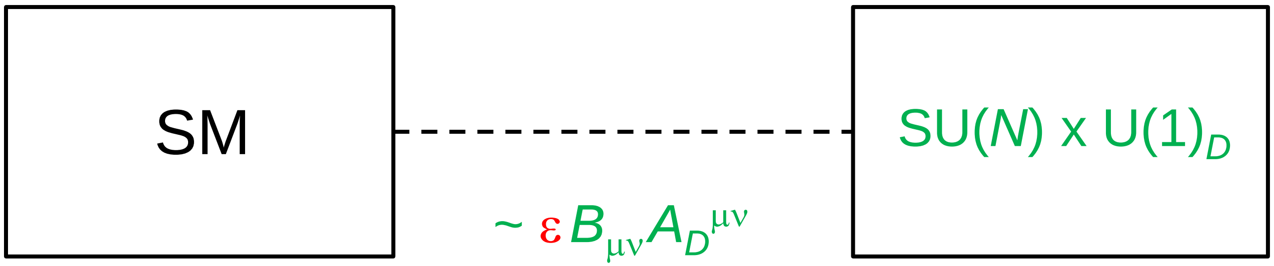
… light (~ GeV) scale $\rightarrow$ dark sector spectroscopy, …

… weak scale $\rightarrow$ multi-component DM, …

Chiral Dark Sector

Harigaya, Y.N., PRD94, 035013 ('16) [arXiv:1603.03430]
Co, Harigaya, Y.N., to appear

The structure



$\sim \varepsilon B_{\mu\nu} A_D^{\mu\nu}$

	$G_D = SU(N)$	$U(1)_D$
Ψ_1	$\Box$	1
Ψ_2	$\Box$	-1
$\bar{\Psi}_1$	$\bar{\Box}$	$-a$
$\bar{\Psi}_2$	$\bar{\Box}$	a

Chiral theory
(no tree-level mass term)

$(0 < a < 1)$

- Only 3 free parameters

$\Lambda, \; e_D, \; \varepsilon$

- Global symmetry

	$G_D = SU(N)$	$U(1)_D$	$U(1)_B$	$U(1)_P$
Ψ_1	$\Box$	1	1	1
Ψ_2	$\Box$	-1	1	-1
$\bar{\Psi}_1$	$\bar{\Box}$	$-a$	-1	-1
$\bar{\Psi}_2$	$\bar{\Box}$	a	-1	1

$$SU(2)_L \times SU(2)_R \times U(1)_B \xrightarrow{e_D} U(1)_D \times U(1)_B \times U(1)_P$$

The dynamics

SU(N) strong dynamics

$$\left\langle \Psi_1 \bar{\Psi}_1 + \Psi_1^\dagger \bar{\Psi}_1^\dagger \right\rangle = \left\langle \Psi_2 \bar{\Psi}_2 + \Psi_2^\dagger \bar{\Psi}_2^\dagger \right\rangle \sim \Lambda^3$$

→ 3 (would-be & paseudo) Nambu-Goldstone bosons $\pi_{1,2,3}$

associated with $SU(2)_L \times SU(2)_R \to SU(2)_V$

(All other excitations have masses of ~ Λ)

- π_3 … eaten by $U(1)_D$ gauge boson

$$m_{A_D} \sim \frac{e_D}{4\pi}\Lambda$$

- $\phi = (\pi_1 + i\pi_2)/\sqrt{2}$ … remain as a light scalar

$$m_\phi \sim \frac{e_D}{4\pi}\Lambda$$

$U(1)_P$ symmetry (extremely good accidental symmetry) → ϕ is stable

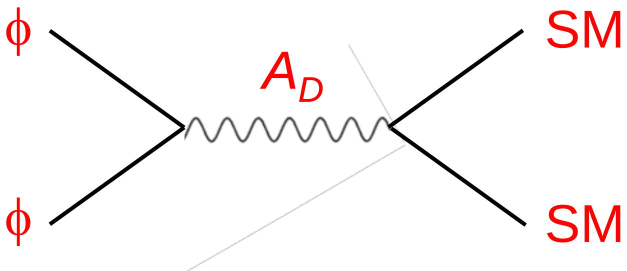
… **A composite pseudo Nambu-Goldstone dark matter**

Masses of DM and portal comparable (generated by the same dynamics)

(I) Light dark matter

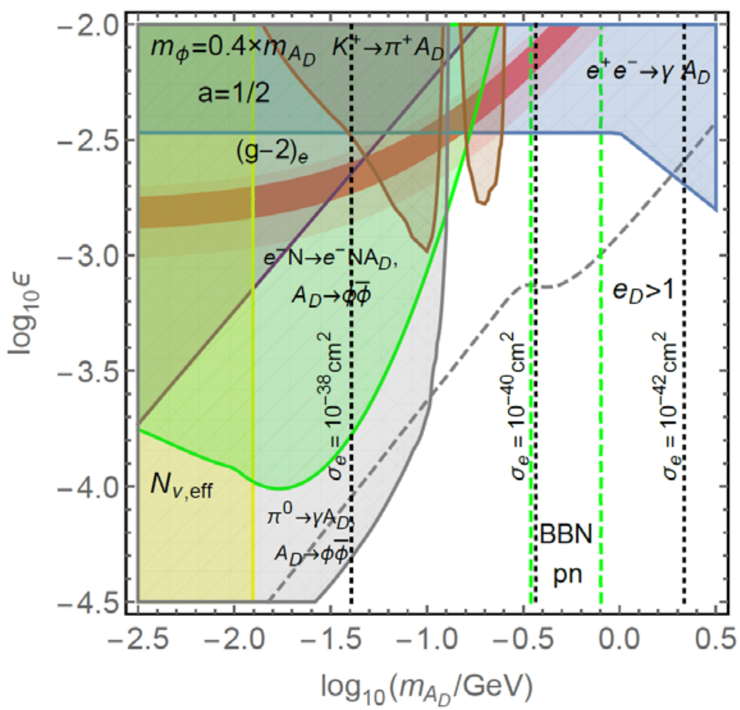
$\Lambda \sim$ GeV

- DM … scalar, *p*-wave (CMB)
- $m_{DM} \sim m_{A_D}$



… *p*-wave

(i) $m_\phi < m_{A_D}/2$



$m_\phi = 0.4\,m_{A_D}$

$a = ½$

$e_D \leftarrow \Omega_{DM}$

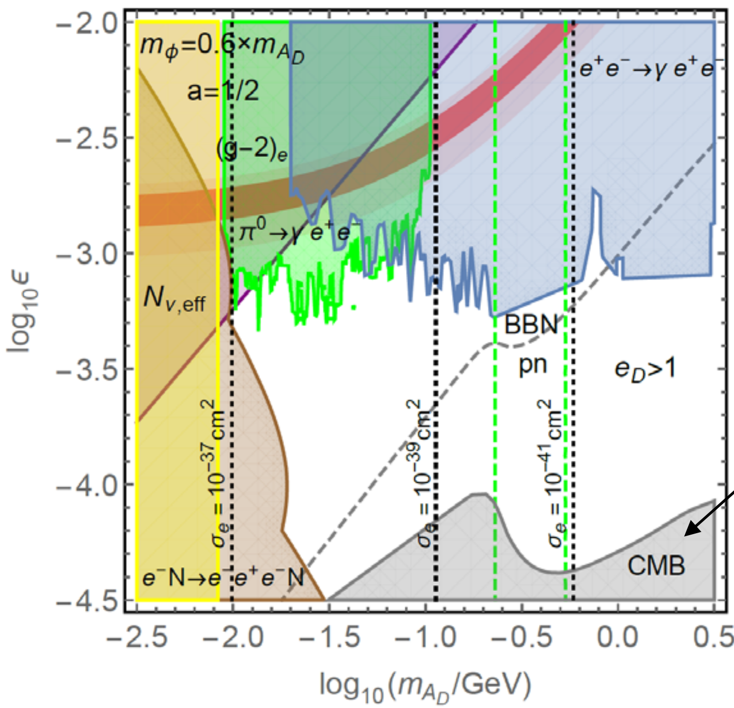
Motivate new analyses/experiments

$$\sigma_{\phi e} \sim 10^{-42}\text{–}10^{-39}\ \text{cm}^2$$

… semiconductor target experiments

e.g. Essig, Mardon, Volansky, 1108.5385

(ii) $m_{A_D}/2 < m_\phi < m_{A_D}$

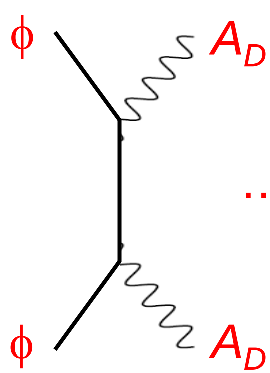


$\phi\bar{\phi} \to A_D A_D^* \to A_D f\bar{f}$ becomes important at late times (*s*-wave)

$m_\phi = 0.4\, m_{A_D}$
a = ½
$e_D \leftarrow \Omega_{\text{DM}}$

$$\sigma_{\phi e} \sim 10^{-40}\text{–}10^{-37}\ \text{cm}^2$$

(iii) $m_\phi > m_{A_D}$



… *s*-wave

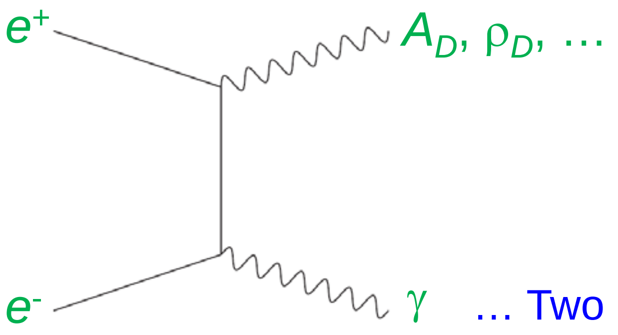
… excluded by BBN & CMB

Dark spectroscopy

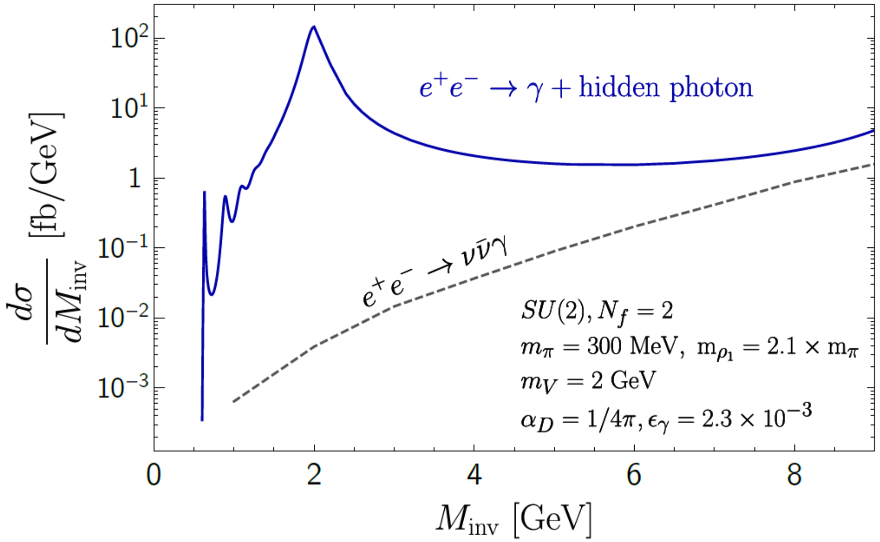
A plethora of new resonances at ~ GeV

ex. Dark ρ meson

$$m_{\rho_D} \sim \Lambda \sim \frac{4\pi}{e_D} m_{A_D}$$



… Two (or more) monochromatic photons



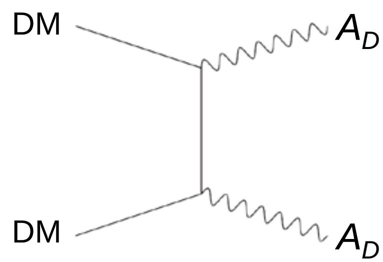
Hochberg, Kuflik, Murayama, 1512.07917

(II) Heavy (weak scale) dark matter

Co, Harigaya, Nomura

The same theory can be used for weak ~ multi-TeV scale dark matter

Λ ~ TeV



We need to have

$m_\phi > m_{A_D}$

… The other case is excluded by direct detection experiment (the opposite to the light case!)

$U(1)_P$ ensures the stability of dark pion

$U(1)_B$ ensures the stability of dark baryon

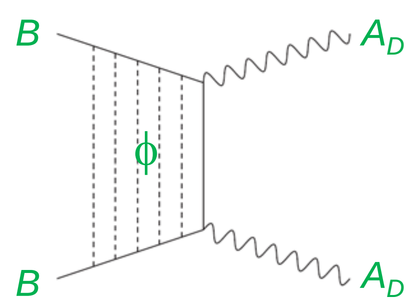
→ Multi-component DM

The annihilation cross section of dark baryons

$$\sigma_B v = \frac{4\pi}{m_B^2 v}\delta$$

unknown coefficient (δ)

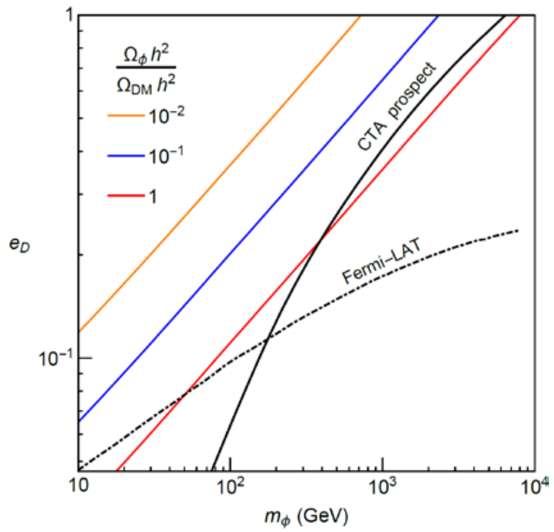
Sommerfeld enhancement ($1/v$)

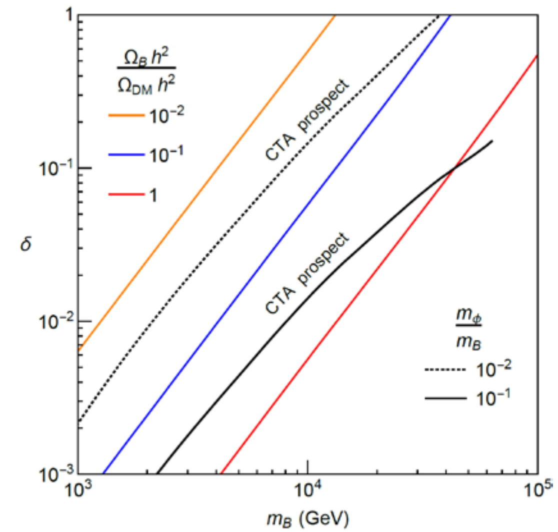


$$v_{\min} \sim \frac{m_\phi}{m_B}$$

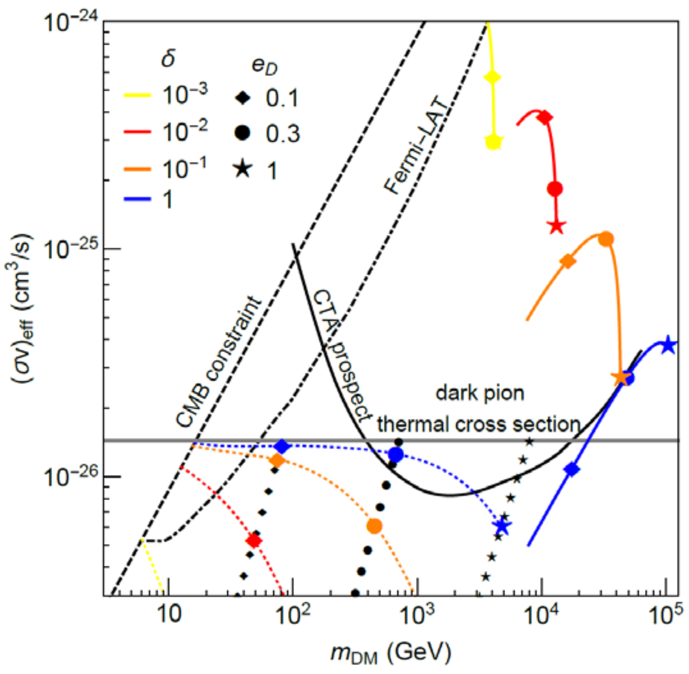
Dark pion: ϕ

Dark baryon: B





$\Omega_\phi + \Omega_B = \Omega_{DM}$



$$(\sigma_\phi)_{\text{eff}} = (\sigma_\phi v)_{\text{FO}} \left(\frac{n_\phi}{n_{\text{DM}}}\right)^2$$

$$(\sigma_B)_{\text{eff}} = (\sigma_B v)_{\text{FO}} \left(\frac{n_B}{n_{\text{DM}}}\right)^2 \left(\frac{v_{\text{FO}}}{v_{\min}}\right)^2$$

… most of the region probed

Summary

The identity of DM is still unknown

The argument connecting to the hierarchy problem may not be warranted

Weakly interacting DM is still a possibility

→ A dark sector interacting with the SM through a portal

Chiral Dark Sector

… A simple theoretical structure leads to rich phenomenology

— All the masses are generated by a single dynamics

→ automatically stable pseudo Nambu-Goldson boson DM

— Consistent ~ GeV DM

→ possibility of dark sector spectroscopy

— Weak ~ multi-TeV scale DM

→ experimentally probable multi-component DM