Workshop on Grand Unified Theory, Phenomenology and Cosmology
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Unification and Composite ADM

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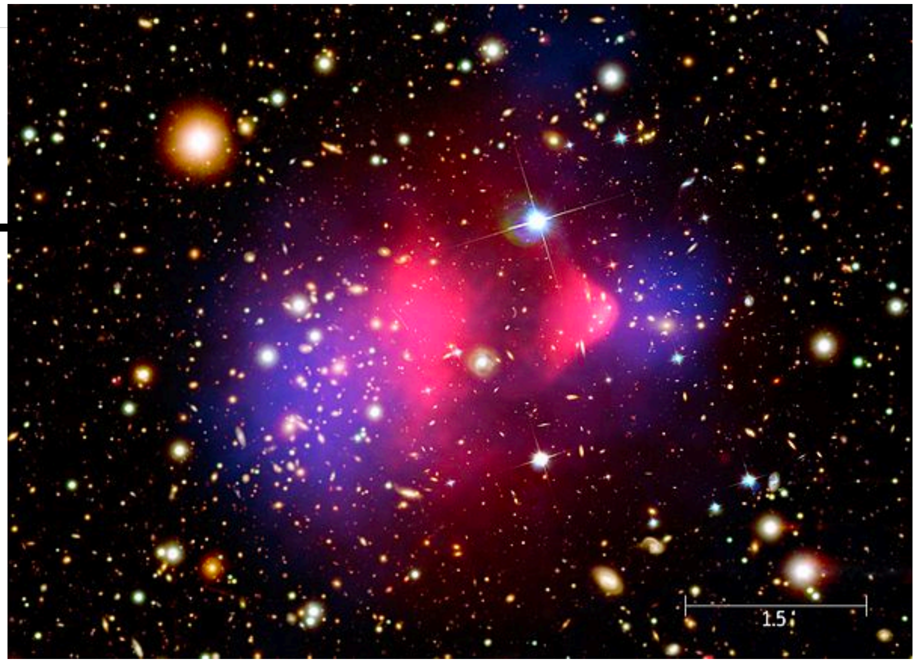
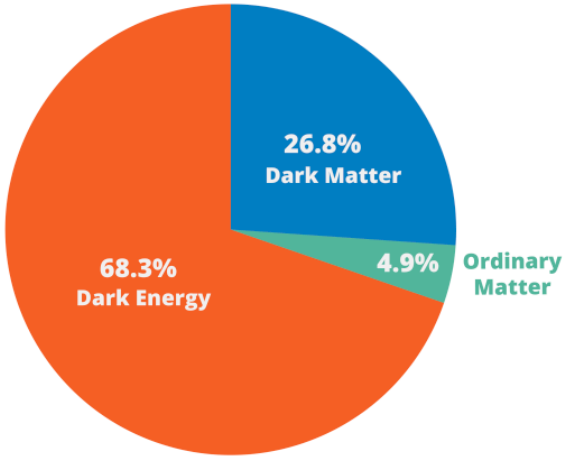
in collaborations with
arXiv:1811.10232, 1907.03404 (on model building)
with M. Ibe (ICRR), A. Kamada (U of Warsaw), S. Kobayashi, W. Nakano (ICRR)
arXiv:2112.01202, 2303.03736 (on beam-dump/collider signals)
with A. Kamada/ S. Yuan (PKU)
2404.xxxxx (on astrophysical signals)
with S. Das(YITP), A. Kamada, K. Murase (Penn State U.), D.Song, (YITP), K. Watanabe (ICRR)

Introduction



Particle properties of Dark Matter

- Stable (or long lifetime until today)
- Electromagnetically neutral (or milicharged)



Baryon-Dark Matter Coincidence

total energy density of the Universe:
its matter component is composed of dark matter (27%) and baryonic matter (4%)

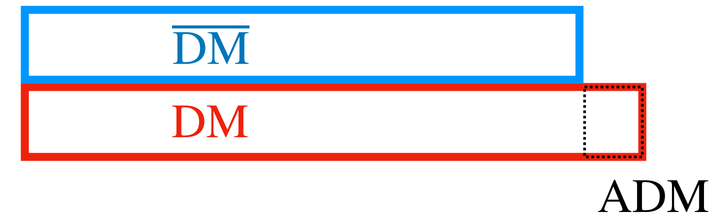
$$\Omega_{\rm DM} \simeq 5\,\Omega_{\rm Baryon}$$

c.f.) $\Omega_{\rm DM} \sim 10^3\,\Omega_\nu \quad (\sum m_\nu = 0.1{\rm eV})$

Just a coincidence, or some mechanism behind?

Asymmetric DM

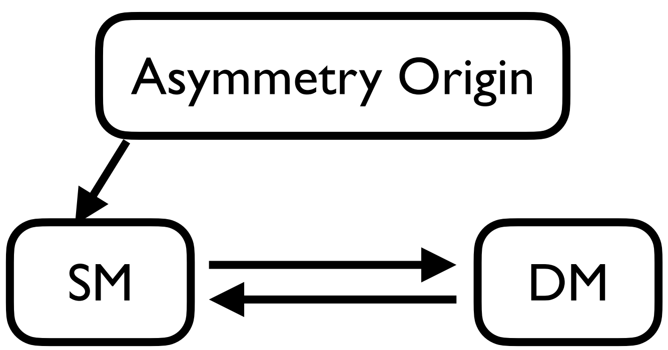
Nushinov (1985); Barr, Chivukula, Farhi (1990); D.B.Kaplan (1992); Kuzmin (1998); Kitano, Low (2005); D. E. Kaplan, Luty, Zurek (2009)



✓ particle-antiparticle asymmetries

$$\eta_B \equiv \frac{n_B - \bar{n}_B}{n_\gamma} \quad \text{and} \quad \eta_{\rm DM} \equiv \frac{n_{\rm DM} - \bar{n}_{\rm DM}}{n_\gamma}$$

generated via sharing asymmetry: $\eta_B \sim \eta_{\rm DM}$



$$\frac{\Omega_{\rm DM}}{\Omega_B} = \frac{m_{\rm DM}\,\eta_{\rm DM}}{m_B\,\eta_B} \sim 5$$: DM mass ~ O(1) GeV

✓ Safe from astrophysical/cosmological constraints

no anti-particle -> no late-time energy injection to EM channel

Why compositeness?

- strong depletion of symmetric component as with QCD
- GeV-scale mass (dimensional transmutation)
- stability by dark baryon number

ADM and Leptogenesis

- Leptogenesis as asymmetry origin — Fukugita Yanagida (1986)

  known as generation mechanism of B-L asymmetry in the SM sector

$$\mathscr{L}_N = M_R \overline{N}_R \overline{N}_R + y_N H \overline{N}_R L + \mathrm{h.c.}$$

right-handed neutrino $\overline{N}_R$ (with $M_R > 10^9$ GeV)

- DM number ∝ B-L

  Since $\overline{N}_R$ is the SM singlet, it can couples to the dark sector

$$\mathscr{L} \supset \frac{1}{M'^2} \overline{U}' \overline{D}' \overline{D}' \overline{N}_R + \mathrm{h.c.}$$

$$\to \frac{y_N^2}{M_R} (LH)^2 + \mathrm{h.c.} \qquad \text{neutrino mass}$$

$$+ \frac{y_N}{M'^2 M_R} \overline{U}' \overline{D}' \overline{D}' (LH) + \mathrm{h.c.} \qquad \text{portal interaction}$$

- The portal interaction connects two sectors until $T \sim T_D \sim M' \left(M'/M_{\mathrm{Pl}}\right)^{\frac{1}{2(n-1)}}$.
- DM decays through the portal interaction: SK constraint on $\bar{\nu}$ signal

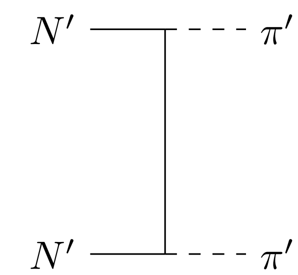
  Fukuda, Matsumoto, Mukhopadhyay (2014)

  -> $M' \gtrsim 10^{8.5}$ GeV

<u>Composite ADM with Dark Photon</u>

Ibe, Kamada, Kobayashi, Nakano (2018)

Symmetric components of dark baryons -> dark pions via (dark) strong interaction

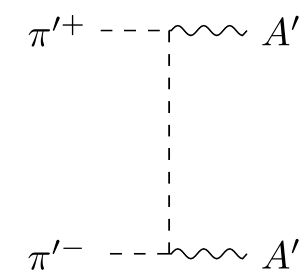


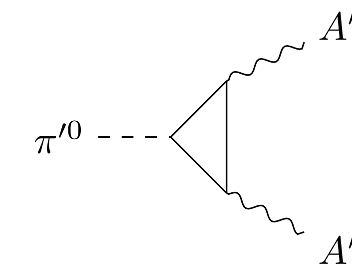
$$\sigma v \sim \frac{4\pi}{m_{n_D}^2}$$

Heating up only the dark sector (carrying enormous entropy, constrained by $\Delta N_{\rm eff}$).

QCD' + QED' evades from the $\Delta N_{\rm eff}$ constraint.

✓ dark pion annihilation/decay into dark photon

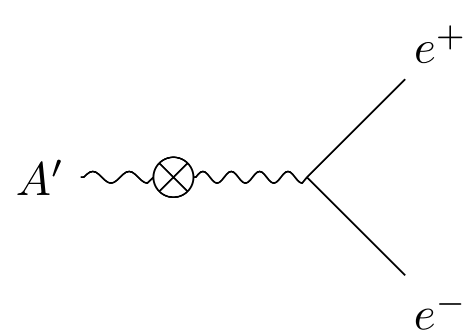




✓ dark photon decay into SM particles via kinetic mixing

$$\mathscr{L}_{A'} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu$$

all light particles converted to SM particles (except for dark nucleon)



Questions

Why does dark confinement scale coincide with the QCD scale?

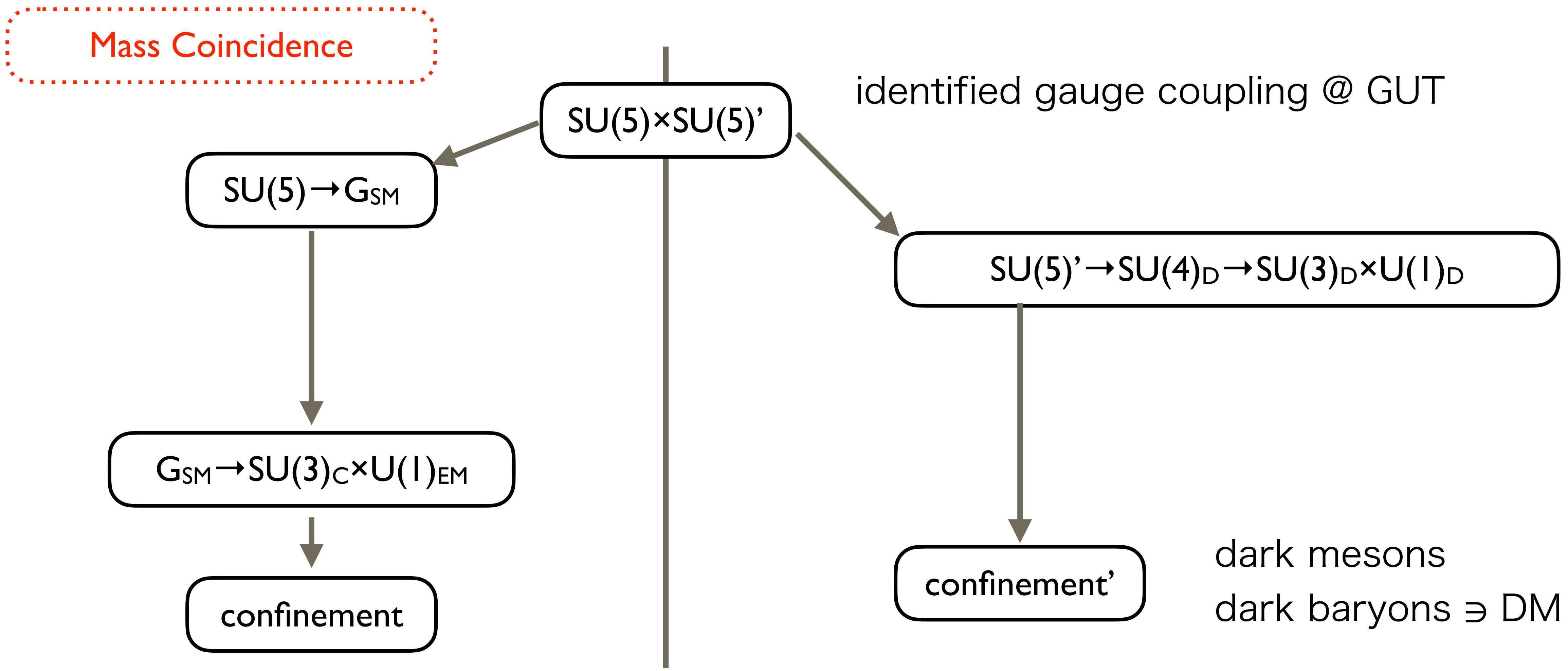
- Does composite ADM really explain why $\Omega_{\rm DM} \sim 5\Omega_B$?
  - DM mass via dimensional transmutation → O(1) GeV
- The origin of the high-energy portal interaction?
  - New particles should appear around the portal interaction scale: $M' \gtrsim 10^{8.5}$ GeV
- Tiny kinetic mixing $\epsilon \ll 1$?
  - U(1) kinetic mixing: renormalizable
  - Dark photon → SM particles via γ-A' kinetic mixing: releasing entropy in the dark sector

Mirrored grand unification gives an interesting solution

Composite ADM and Mirrored Unification

Based on a $SU(5) \times SU(5)'/\mathbb{Z}_2$ unification model Ibe, Kamada, Kobayashi, TK, Nakano (2019)

- Dark sector consists of a perfect copy of visible sector
- $\mathbb{Z}_2$ breaking by vacuum choices @ unification scale
- B-L (= DM #) is approximately conserved separately below T_{dec}



Even if low-energy EFTs are different in two sectors, $m_{\rm DM} \simeq m_{\rm Baryon}$ is realized.

Composite ADM and Mirrored Unification

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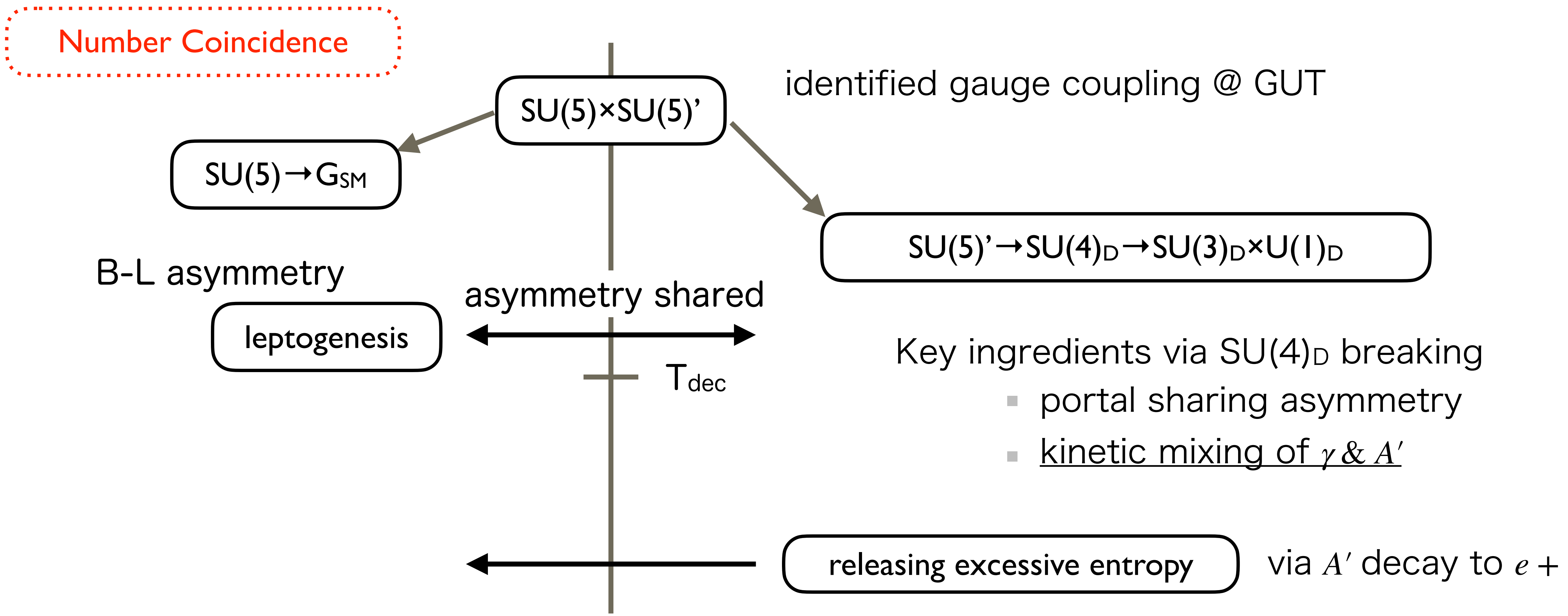

☑ two kinds of portals are important for
number coincidence and viable cosmology

A Simple Realization

Ibe, Kamada, Kobayashi, TK, Nakano (2019)

	$SU(5)$	$U(1)_X$
Ψ_{Si}	$\mathbf{10}$	1
Φ_{Si}	$\overline{\mathbf{5}}$	-3
$\overline{N}_i, \overline{N}'_i$	$\mathbf{1}$	5
H_S	$\mathbf{5}$	-2
$\overline{H}_S$	$\overline{\mathbf{5}}$	2
X_S	$\mathbf{5}$	-2
$\overline{X}_S$	$\overline{\mathbf{5}}$	2
Σ_S	$\mathbf{24}$	0

$SU(5)_V \times SU(5)_D$ supersymmetric gauge theory with (softly broken) $\mathbb{Z}_2$

- gauge coupling unification
- existence of degenerate vacua

$U(1)_X$: unification compatible global B-L (technically natural M_R)

> Assumption: mirror symmetry is broken only by mass parameters
> but same scales in each sector: $M_V \sim O(10^{16})$ GeV $\gg M_D$

$SU(5)_V \times SU(5)_D$

$\langle \Sigma_V \rangle$: $SU(5)_V \to G_{\rm SM}$

$SU(5)_D \xrightarrow{\langle X_D \rangle} SU(4)_D$ ➡ Dark leptons get massive

$SU(4)_D \xrightarrow{\langle \Sigma_D \rangle} SU(3)_D \times U(1)_D$ ➡ Portal interaction ➡ Kinetic mixing

Coupling Unification/Coincidence of Confinement Scales

Ibe, Kamada, Kobayashi, TK, Nakano (2019)

	$SU(5)$	$U(1)_X$
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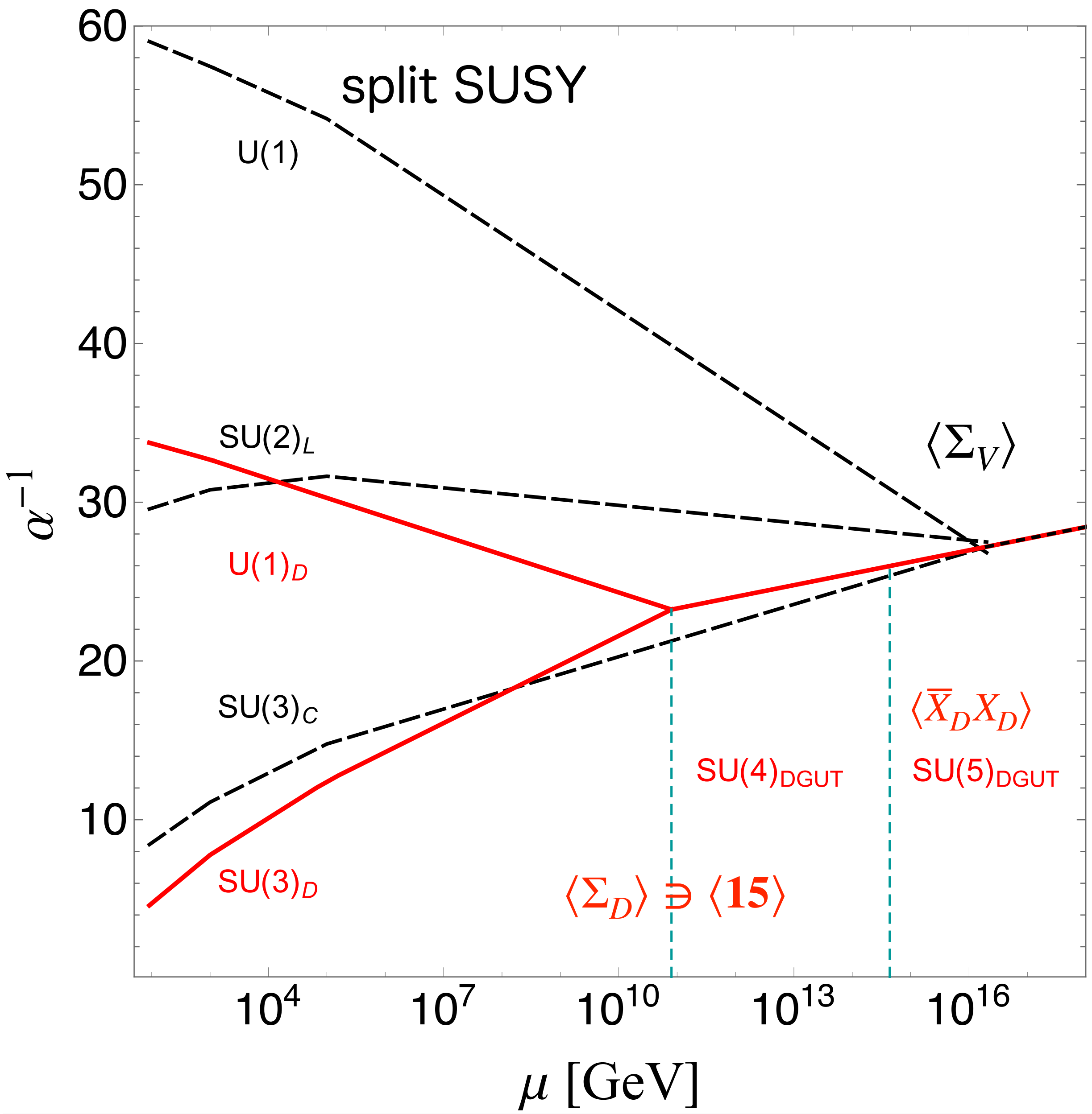


above 10^{16} GeV

visible/dark gauge couplings coincide

below 10^{16} GeV

due to different breaking chain

→ gauge dynamics develops separately

Assumption:

- fine-tuned couplings of Ψ_D & Φ_D to X_D & $\overline{X}_D$

  = tuning of vector-like dark quark masses
- $M_D = 8 \times 10^{10}$ GeV

Key ingredients: low-energy portal interactions

Ibe, Kamada, Kobayashi, TK, Nakano (2018)

embedding U(1) into non-Abelian group:

$$\mathscr{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$$

	$SU(5)$	$U(1)_X$
Ψ_{Si}	$\mathbf{10}$	1
Φ_{Si}	$\overline{\mathbf{5}}$	-3
$\overline{N}_i\,,\overline{N}'_i$	$\mathbf{1}$	5
H_S	$\mathbf{5}$	-2
$\overline{H}_S$	$\overline{\mathbf{5}}$	2
X_S	$\mathbf{5}$	-2
$\overline{X}_S$	$\overline{\mathbf{5}}$	2
Σ_S	$\mathbf{24}$	0

- Kinetic mixing from bi-charged fields (if present)

$$\epsilon \simeq -\frac{g_Y g_{Y'}}{16\pi^2}\sum_i Y_i Y'_i \ln\frac{M_i^2}{\mu^2}$$

$$\simeq 10^{-2}\left(\frac{g_{Y'}}{g_Y}\right)\sum \ln\left(1+\Delta M^2\right)$$

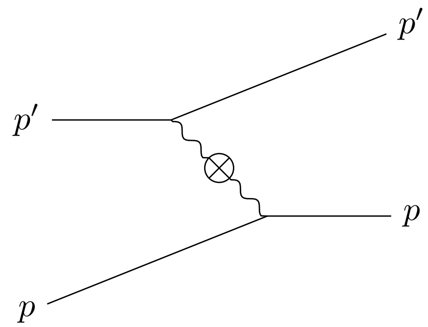
- Kinetic mixing from non-renormalizable operator

non-renormalizable operator with non-Abelian breaking fields

$$\mathscr{L} \supset \frac{1}{M_{\mathrm{P}}^2}\mathrm{tr}\left(F_{G\mu\nu}\Sigma_V\right)\mathrm{tr}\left(F_D^{\mu\nu}\Sigma_D\right)$$

$$\epsilon \simeq \frac{v_V v_D}{M_{\mathrm{P}}^2} \simeq 10^{-9}\left(\frac{v_V}{2\times10^{16}\,\mathrm{GeV}}\right)\left(\frac{v_D}{5\times10^{10}\,\mathrm{GeV}}\right)$$

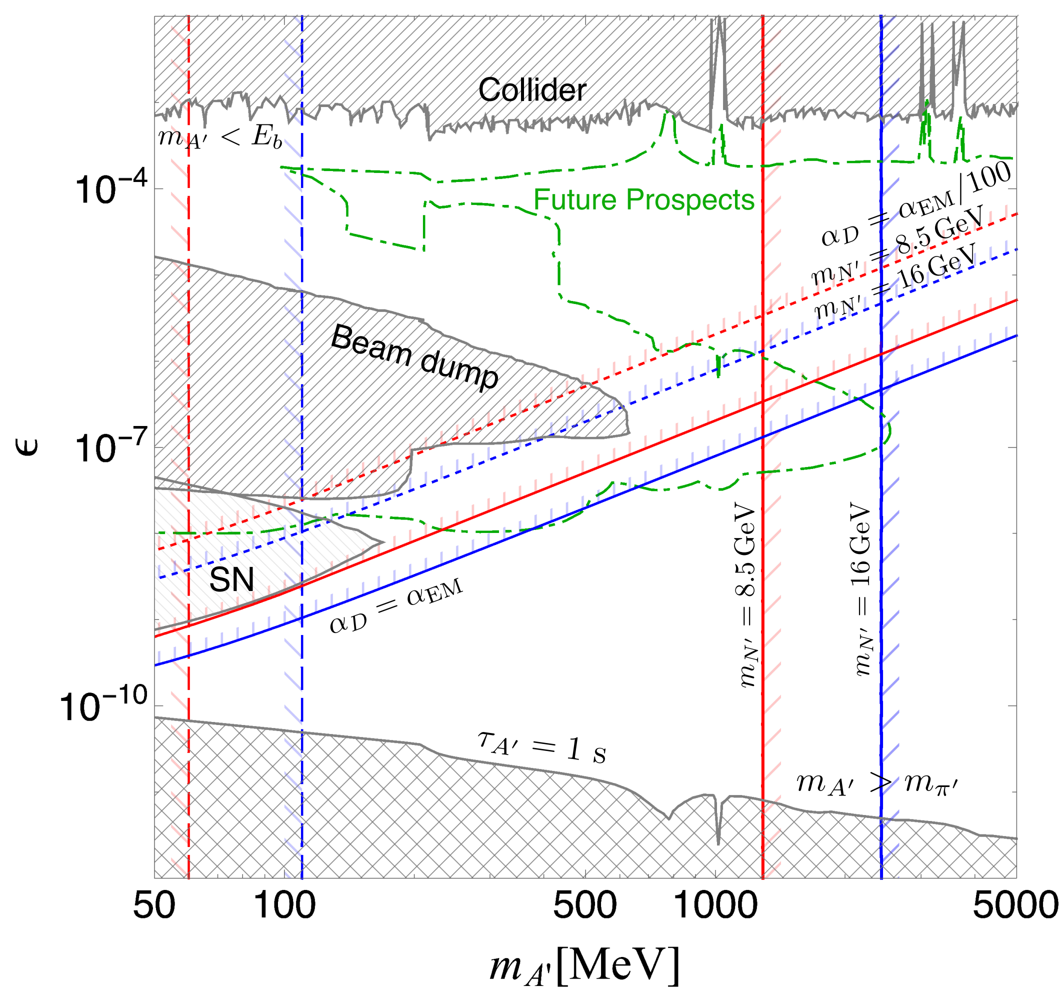
Phenomenology: low-scale portal



- ✓ dark baryons can couples to SM proton via dark photon

tested by direct detection experiments

Ibe, Kamada, Kobayashi, Nakano (2018)



Kamada, Kim, TK (2020)

direct detection experiment

Panda-X (54 ton×day)

$\sigma > 10^{-44}\ \mathrm{cm}^2$ 1802.06912

DM ratio $p' : n' = 1 : 1$

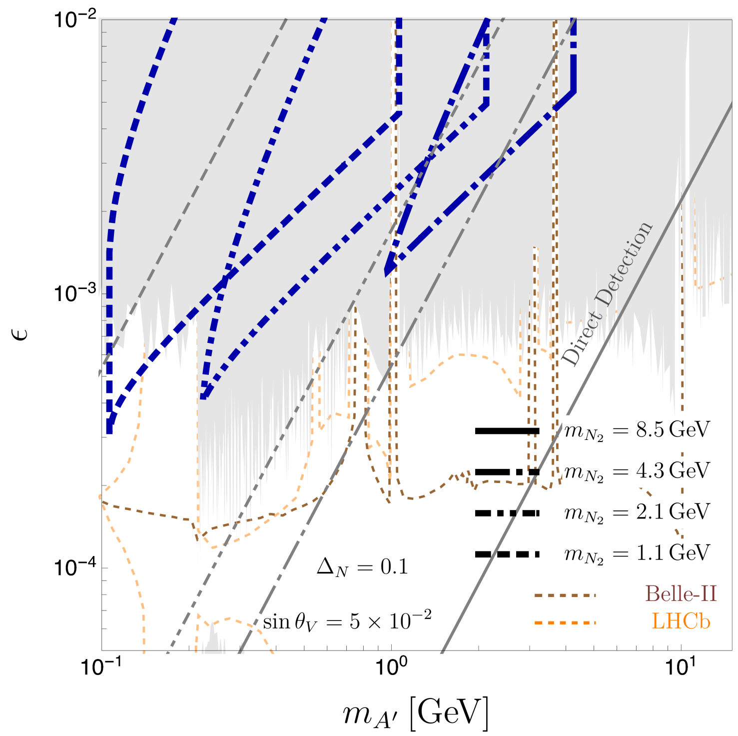
strong upper bound on kinetic mixing ϵ

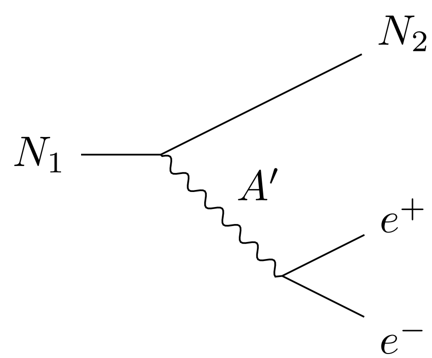
✓ Long-lived signals from dark-hadron processes

Search for dark hadrons with degenerate spectra

Kamada, TK (2021)

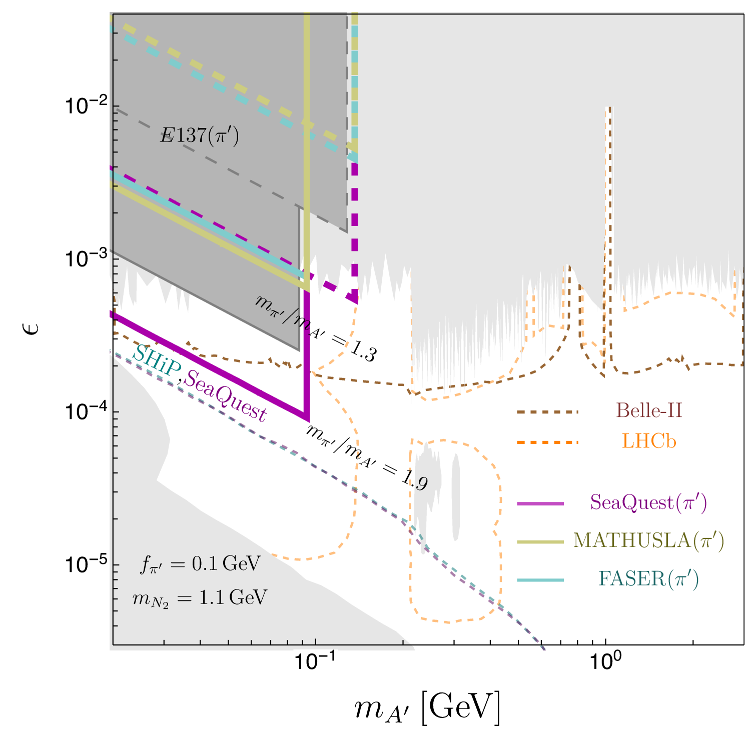
dark nucleon transition @ FASER

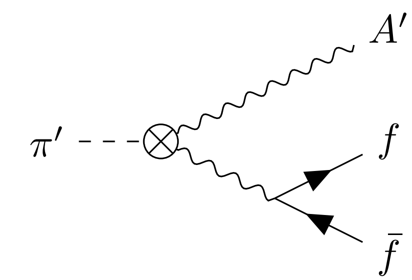




$$\Delta_N m_{N_2} < m_{A'}$$

Dark pion decay @ DarkQuest





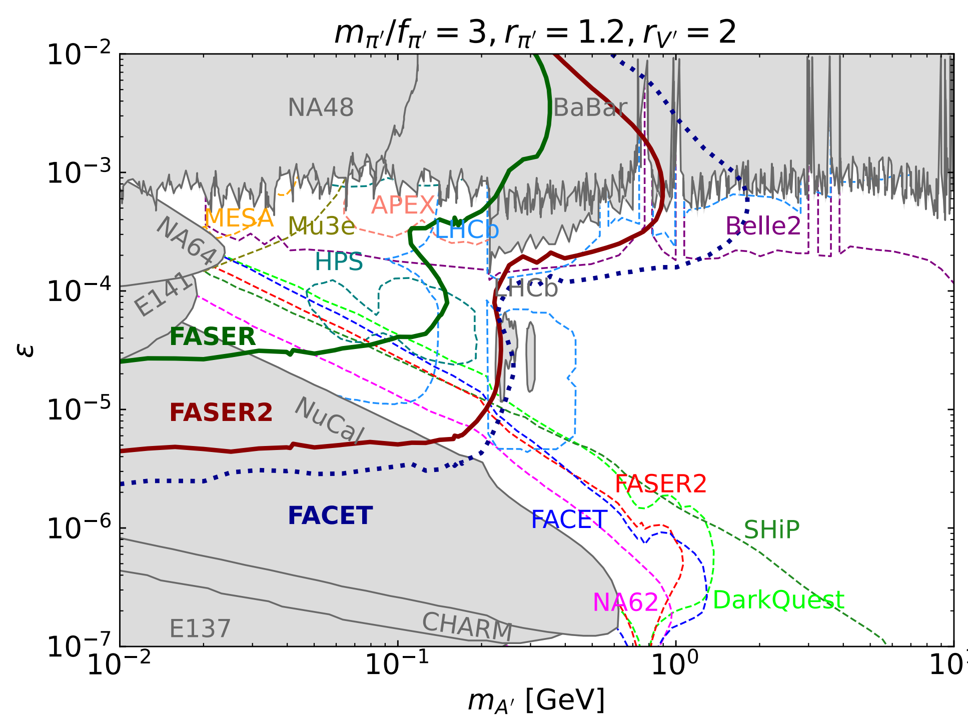
$$m_{A'} < m_{\pi'} < 2m_{A'}$$

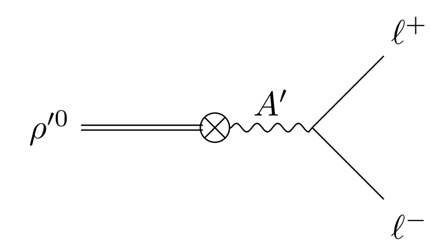
dark vector meson decay

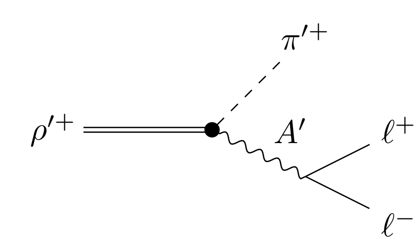
@ FASER

$$m_{\rho'} < 2m_{\pi'}, m_{A'} + m_{\pi'}$$

TK, Yuan (2023)







Key ingredients: intermediate scale portal

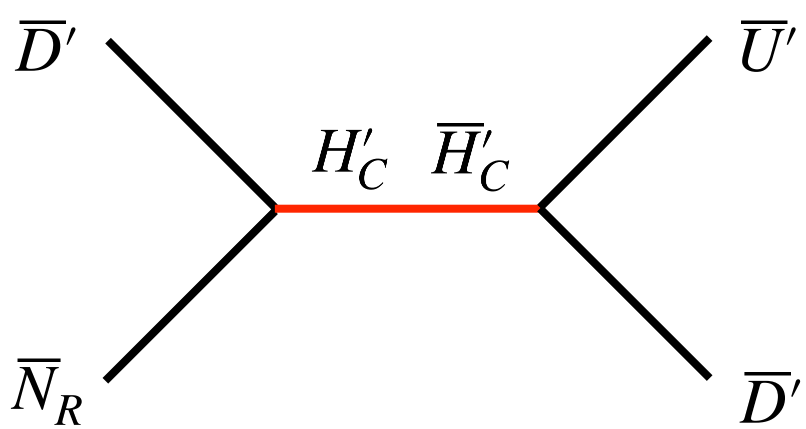
Ibe, Kamada, Kobayashi, TK, Nakano (2018)

✓ Portal interaction sharing asymmetry

	$SU(5)$	$U(1)_X$
Ψ_{Si}	$\mathbf{10}$	1
Φ_{Si}	$\overline{\mathbf{5}}$	-3
$\overline{N}_i\,,\overline{N}_i'$	$\mathbf{1}$	5
H_S	$\mathbf{5}$	-2
$\overline{H}_S$	$\overline{\mathbf{5}}$	2
X_S	$\mathbf{5}$	-2
$\overline{X}_S$	$\overline{\mathbf{5}}$	2
Σ_S	$\mathbf{24}$	0

Dark GUT sector contains massive colored state: $H_C', \overline{H}_C'$

$$\mathscr{L} \supset Y_N H_D \Phi_D \overline{N}_R + Y_u H_D \Psi_D \Psi_D + Y_d \overline{H}_D \Phi_D \Psi_D + \mathrm{h.c.}$$



Generated asymmetry shared by effective interaction

$$\mathscr{L} \supset \frac{Y_d Y_N}{M_H^2} \overline{U}' \overline{D}' \overline{D}' \overline{N}_R + \mathrm{h.c.}$$

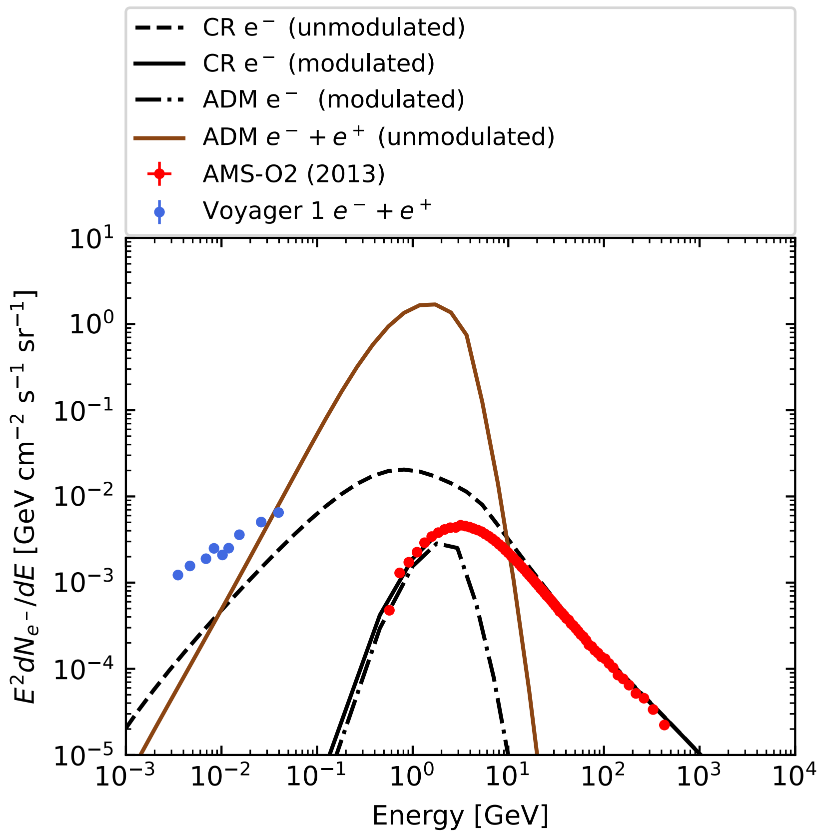
$$\to -\frac{Y_d Y_N y_N}{M_H^2 M_R} \overline{U}' \overline{D}' \overline{D}' (LH) + \mathrm{h.c.}$$

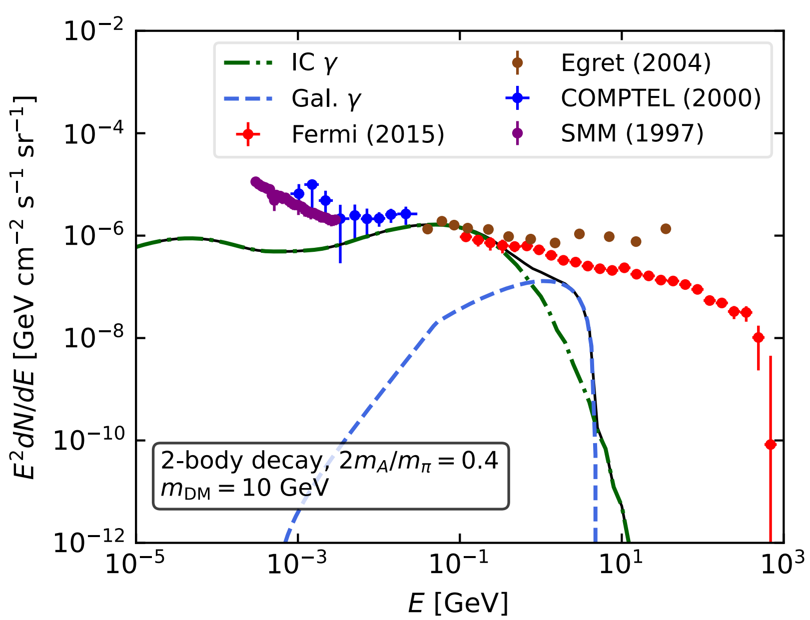
(c.f. nucleon decay in GUT)

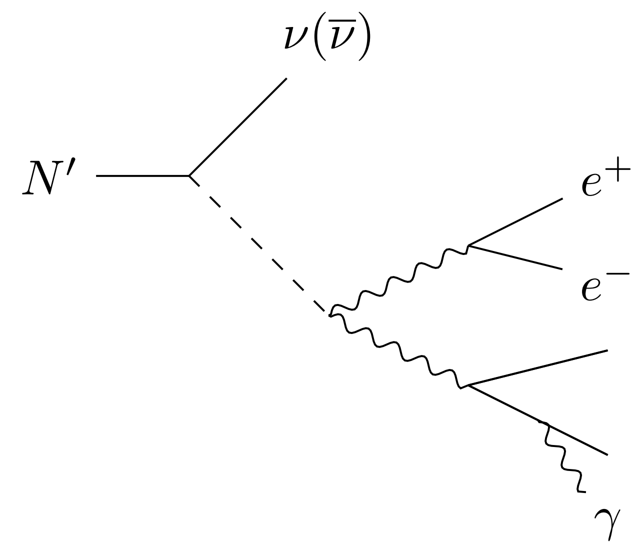
✓ Late-time decay of dark baryons

Fukuda, Matsumoto, Mukhopadhyay (2014)
Das, Kamada, TK, Murase, Song, Watanabe (2024)

Cascade decay of dark baryons



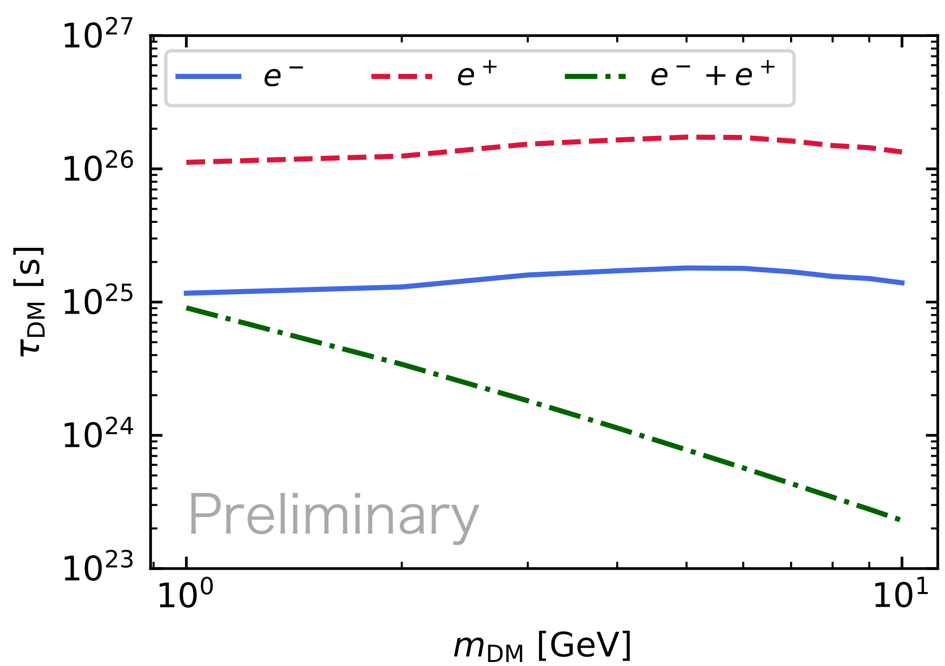


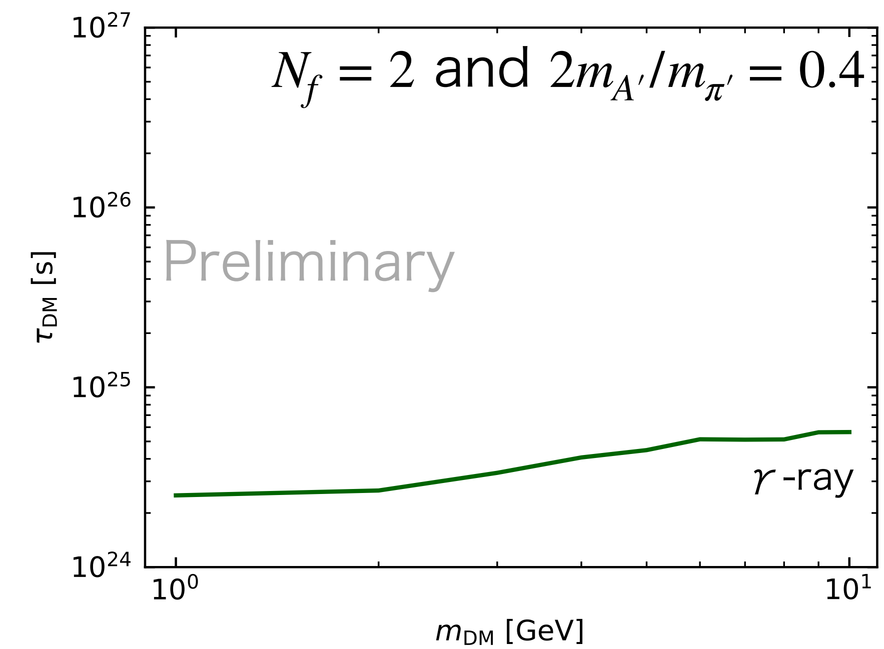


Decay: $\mathrm{DM} \to M' + \bar{\nu}$

$$\Gamma_{\mathrm{DM}} \simeq \frac{1}{64\pi}\frac{v^2 m_{N'}}{M_*^6}|W|^2$$

$$\tau_{\mathrm{DM}} \simeq 10^{26}\,\mathrm{s}\left(\frac{M_*}{2\times10^9\,\mathrm{GeV}}\right)^6\left(\frac{10\,\mathrm{GeV}}{m_{N'}}\right)^5$$





Summary and Discussion

- ✓ We propose a UV framework for Ω_B-$\Omega_{\rm DM}$ coincidence based on unification
  - ✓ coincidence of masses: mirror $\mathbb{Z}_2$ @ unification scale
  - ✓ coincidence of number densities: composite ADM scenario
- ✓ Composite ADM with dark photon predicts many signals
  - $\bar{\nu}$ signal from DM decay/electromagnetic flux from cascade DM decay
  - Long-lived particle signals
  - etc.
- ▸ Model-buildings
  - baryogenesis mechanisms
  - models without/with a few fine-tunings
  - different gauge dynamics?

Backup

Superpotential in a specific model

Ibe, Kamada, Kobayashi, TK, Nakano (2019)

	$SU(5)$	$U(1)_X$
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Σ_S	$\mathbf{24}$	0

Superpotential for Yukawa and Higgs sectors

$$
\begin{aligned}
W_S = {} & \Psi_S Y_u \Psi_S H_S + \Psi_S Y_d \Phi_S \overline{H}_S \\
& + H_S (M_S + \lambda \Sigma_S) \overline{H}_S \\
& + \mu_S \mathrm{tr}(\Sigma_S^2) + \lambda_\Sigma \mathrm{tr}(\Sigma_S^3) \\
& + M'_S X_S \overline{X}_S - \xi \frac{(X_S \overline{X}_S)^2}{M_{\mathrm{Pl}}}
\end{aligned}
$$

$\mu_S \mathrm{tr}(\Sigma_S^2) + \lambda_\Sigma \mathrm{tr}(\Sigma_S^3) \rightarrow \langle \Sigma_S \rangle = 0 \ \text{or} \ \mathcal{O}(\mu_S)$

$M'_S X_S \overline{X}_S - \xi \frac{(X_S \overline{X}_S)^2}{M_{\mathrm{Pl}}} \rightarrow \langle X_S \overline{X}_S \rangle = 0 \ \text{or} \ \mathcal{O}(M_{\mathrm{Pl}} M'_S)$

Superpotential for N_R sector

$$
\begin{aligned}
W_N = {} & \Phi_V y_N \overline{N} H_V + \Phi_D y_N \overline{N}' H_D \\
& + \Phi_V Y_N \overline{N}' H_V + \Phi_D Y_N \overline{N} H_D \\
& + (\text{mass terms}) \, ,
\end{aligned}
$$

Several fields get their masses through interactions to X_D and $\overline{X}_D$

$$
\begin{aligned}
W = {} & y_u \Psi_D \Psi_D X_D + y_d \Psi_D \Phi_D \overline{X}_D \\
& + \frac{y'_e}{M_{\mathrm{Pl}}} \Psi_D \Sigma_D \Phi_D \overline{X}_D \, ,
\end{aligned}
$$

The fine-tuning of couplings is required to realize good mass spectrum.. ..

Intermediate Scale Theory: SU(4)D

Ibe, Kamada, Kobayashi, TK, Nakano (2018)

X_D and $\overline{X}_D$ are decoupled at SU(5)D breaking scale

Other fields decomposed into

$$\Psi_D \to A_D(\mathbf{6}) \oplus Q_D(\mathbf{4}) \ , \ \ \Phi_D \to \overline{Q}_D(\overline{\mathbf{4}}) \oplus N_D(\mathbf{1}) \ ,$$
$$H_D \to H_D(\mathbf{4}) \oplus S_D(\mathbf{1}) \ , \ \ \overline{H}_D \to \overline{H}_D(\overline{\mathbf{4}}) \oplus \overline{S}_D(\mathbf{1}) \ ,$$
$$\Sigma_D \to \Xi(\mathbf{15}) \oplus h'_D(\overline{\mathbf{4}}) \oplus \overline{h}'_D(\overline{\mathbf{4}}) \oplus S'_D(\mathbf{1}) \ .$$

dark neutrino mass?

$$W_{N_D} = \frac{1}{M_{\rm Pl}}(X_D\Phi_D)^2 + M_{R_D}\overline{N}'\overline{N}' + y_{N_D}\Phi_D\overline{N}'\overline{X}_D$$

Majorana/B-L violating Dirac Mass

counter part to the visible sector: X_D and $\overline{X}_D$ do not develop their VEV.

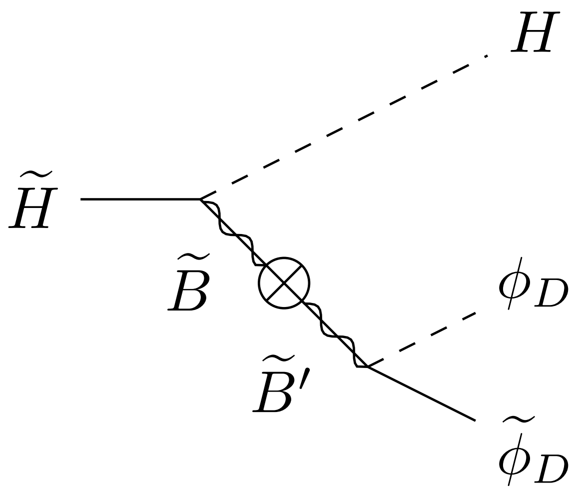
LSP in two sectors

Ibe, Kamada, Kobayashi, TK, Nakano (2018)

Lightest Supersymmetric Particles are also stable in two sectors

- LSPs should be subdominant components of DM
  -> prediction of light sparticles
- feeble connection b/w visible and dark sectors
  -> overclosure of the Universe
  or problematic late-time decay of heavier LSPs?

Higgsinos (MSSM & U(1)D) LSPs help!



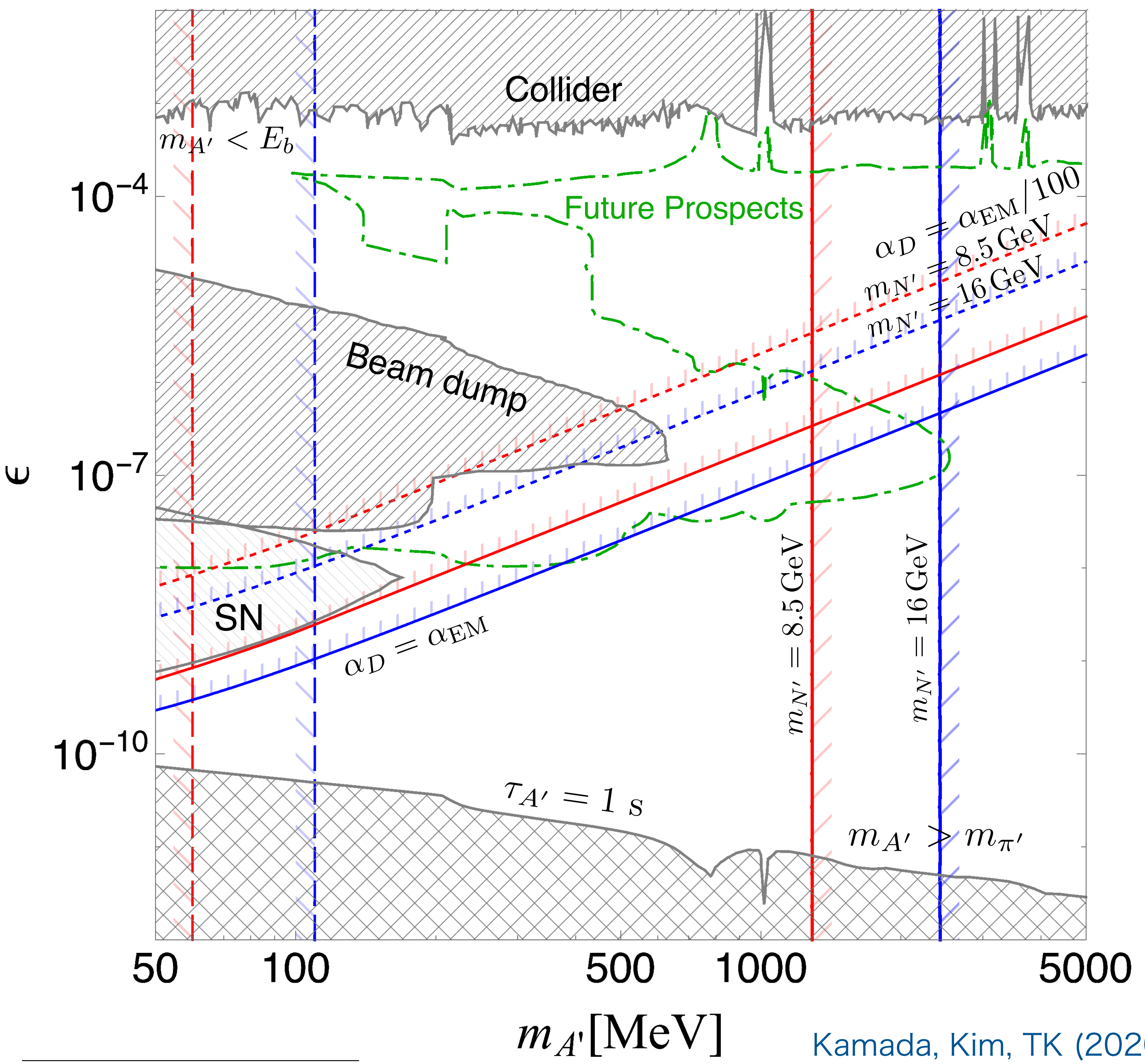
heavy higgsino decay via supersymmetric kinetic mixing

$$\tau(\widetilde{H} \to \phi_D H \widetilde{\phi}_D) \sim \frac{8\pi}{\epsilon^2 \alpha_Y \alpha' m_{\widetilde{H}}}$$

$$\sim 2 \times 10^{-5}\ \mathrm{sec} \left(\frac{10^{-9}}{\epsilon}\right)^2 \left(\frac{8 \times 10^{-2}}{\alpha'}\right) \left(\frac{1\ \mathrm{TeV}}{m_{\widetilde{H}}}\right)$$

dark higgsino $\tilde{\phi}_D$: less constrained/could have the mass with O(100) GeV or lighter

Bounds on Dark Photon Parameters



Kamada, Kim, TK (2020)

direct detection experiment

Panda-X (54 ton×day)

$\sigma > 10^{-44}$ cm^2 1802.06912

DM ratio $p' : n' = 1 : 1$

Dark photon:
- lightest in dark sector
- Collider&Beam-dump
- Supernova 1987A

A' recoupling after ν decoupling

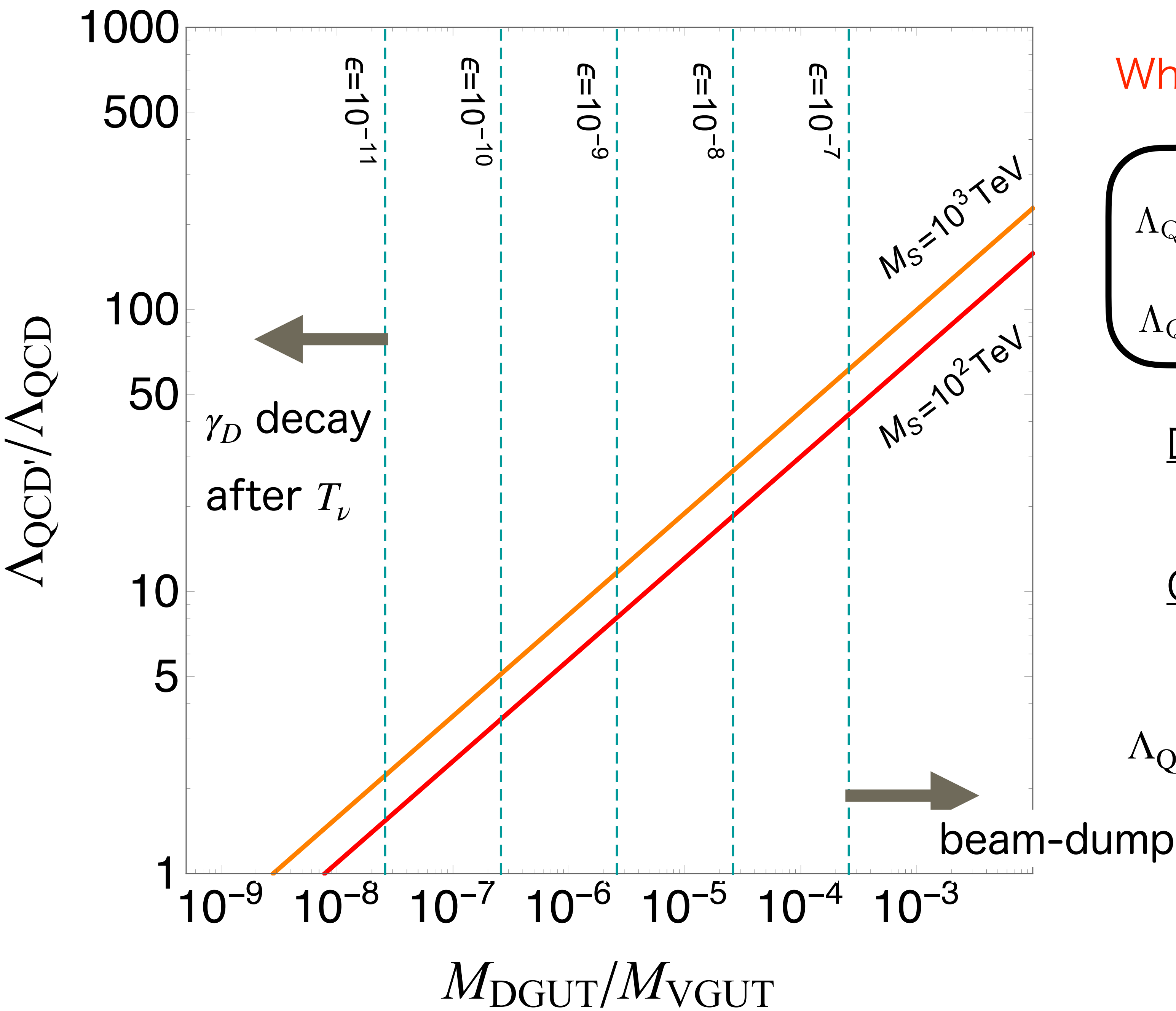
reheats only γ, e^+, e^-

- change T_ν/T_γ i.e. $N_{\rm eff}$

roughly $\tau_{A'} \lesssim 1$ s

Relation of Confinement scales

Ibe, Kamada, Kobayashi, TK, Nakano (2019)



Why $\Lambda_{\mathrm{QCD}'}/\Lambda_{\mathrm{QCD}}$ ~ O(1) ?

$$\Lambda_{\mathrm{QCD}'} \simeq 2.8\,\mathrm{GeV}\left(\frac{M_{\mathrm{SUSY}}}{10^2\,\mathrm{TeV}}\right)^{\frac{4}{25}}\left(\frac{M_D}{8\times10^{10}\,\mathrm{GeV}}\right)^{\frac{9}{25}}$$

$$\Lambda_{\mathrm{QCD}} \simeq 0.3\,\mathrm{GeV}$$

Dark GUT scale

~ 7 orders of magnitude

QCD' scale

~ 2 orders of magnitude

$\Lambda_{\mathrm{QCD}'}/\Lambda_{\mathrm{QCD}}$ is no longer a free parameter!