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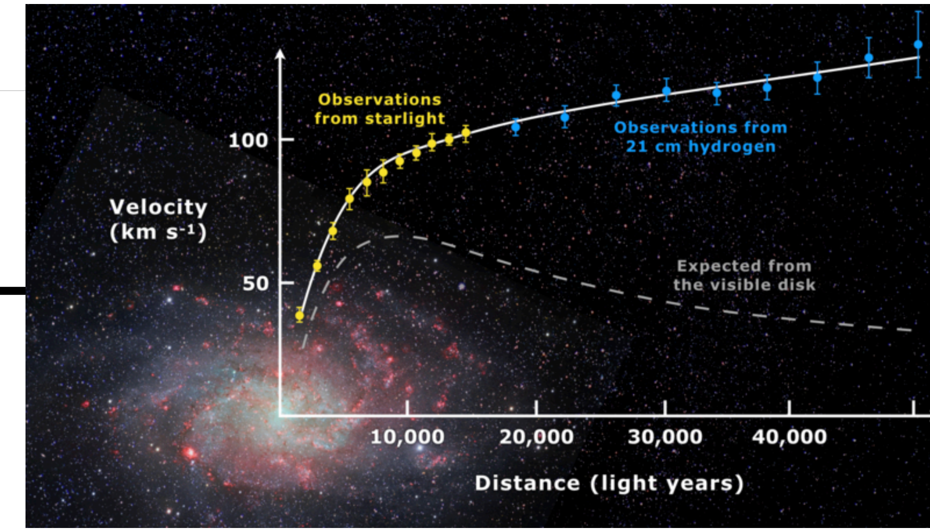
Dark Matter Decay in Dark Unification

Takumi Kuwahara
CHEP, Peking U.

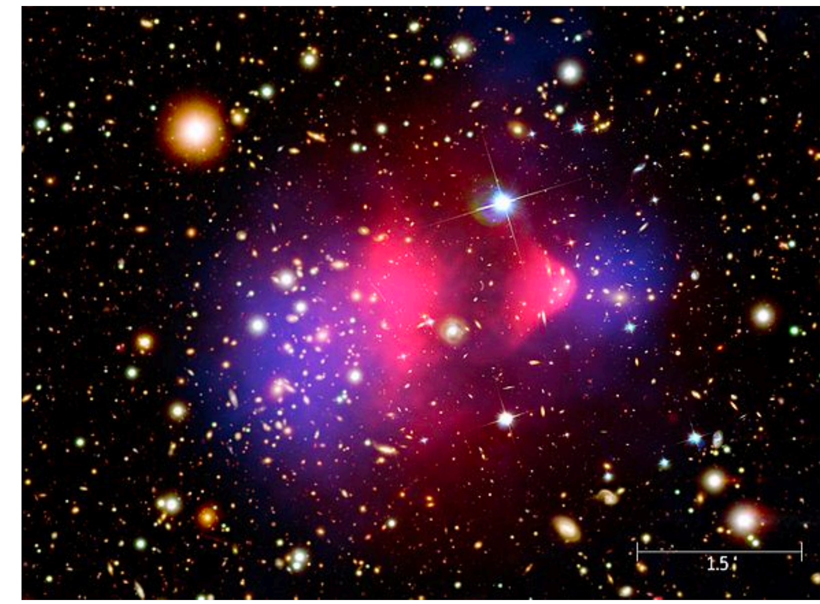
in collaborations with
A. Kamada (Warsaw U,), S. Das (Florida U.), K. Murase (YITP, Penn State U), D. Song (YITP) [2412.15641]

Introduction



Particle DM

- Stable (or long lifetime until today)
- Electromagnetically neutral (or milicharged)
- Cold DM (non-relativistic)



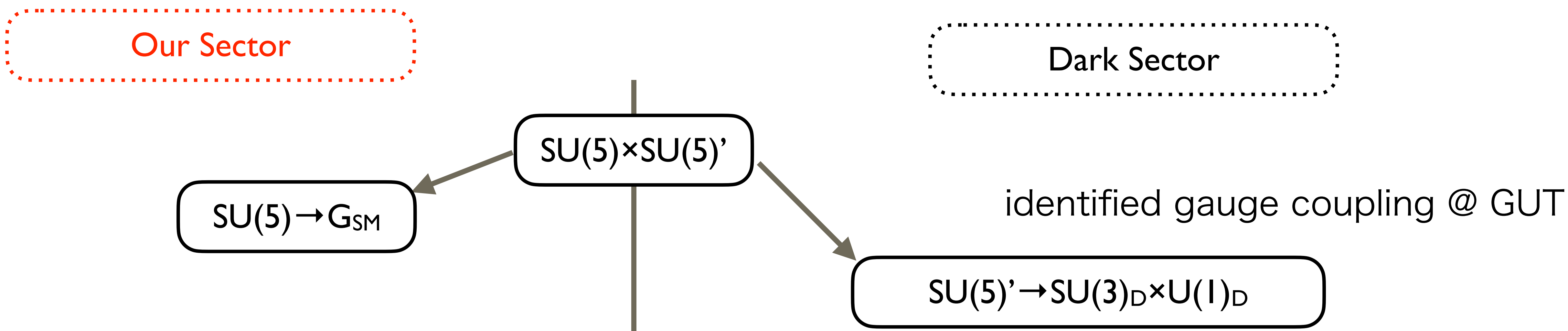
Dark Sector

- ✦ Dark matter and associated particles reside in
- ✦ its own (gauge) interaction inside dark sector (avoiding constraints)
- ✦ Secluded from the SM sector except for portal matters

Dark 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



Low-energy d.o.f.

hadrons/leptons/photon

Low-energy d.o.f.

dark hadrons/dark leptons/dark photon

DM candidate

to avoid $\Delta N_{\rm eff}$ constraints

- decoupled dark leptons
- massive dark photon

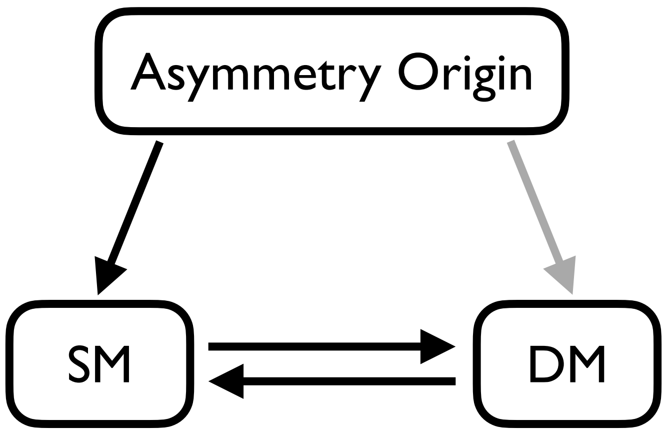
Dark Baryon DM as ADM

Dark baryons have

- large annihilation into dark pion
- dark nucleon with mass of 1GeV
- Dark baryon number conservation

An analogy to the SM nucleons

Lightest dark baryon can be **Asymmetric Dark Matter**



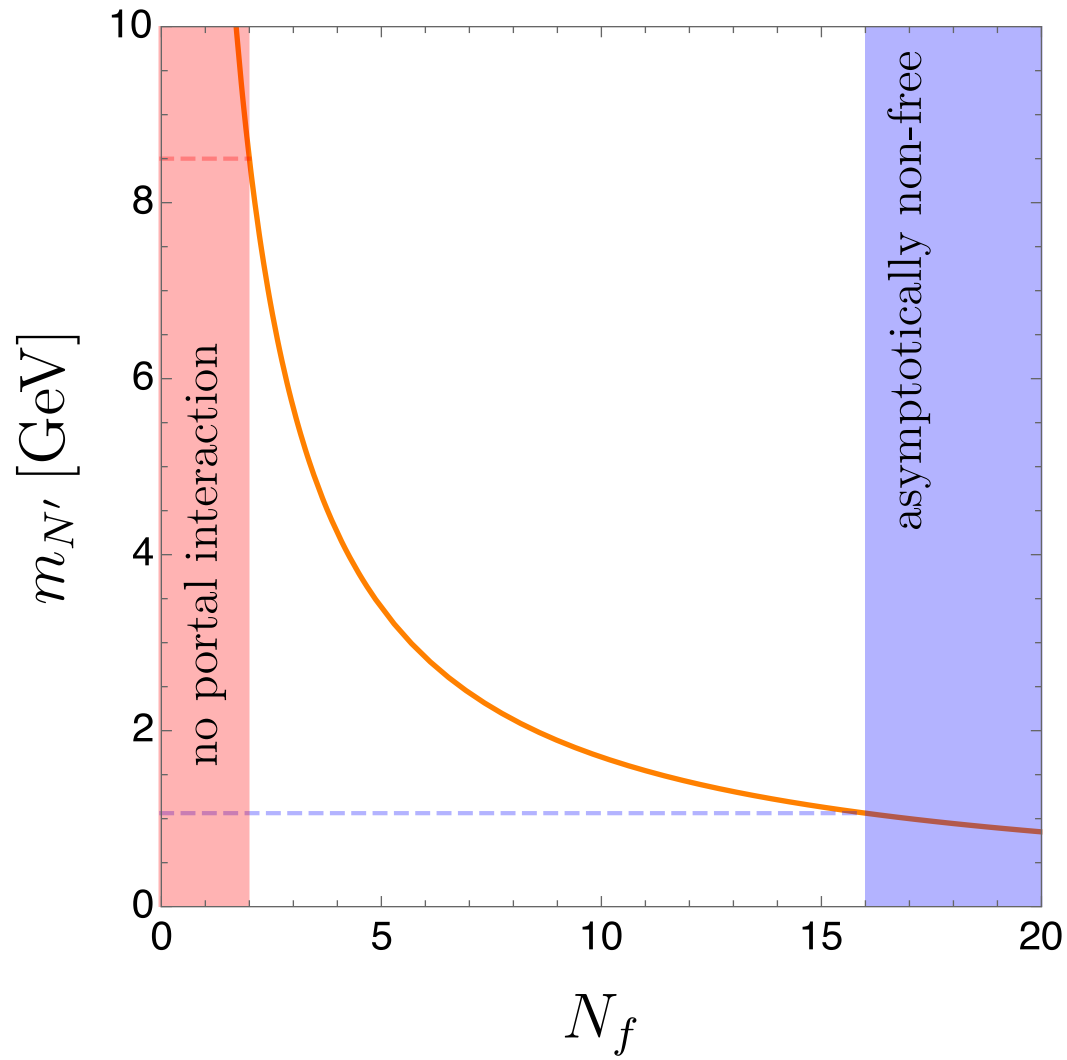
Both asymmetry related with each other

- ✤ sharing generated asymmetry (via such as leptogenesis)
- ✤ cogenesis (via e.g. PBH evaporation: TK, Uchida in progress)

similar number 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 ~ 5 GeV

Dark Baryon DM as ADM



ADM mass: $m_{\rm DM} \simeq \frac{17}{N_f}\mathrm{GeV}$

Weinberg, **Cosmology**
Ibe, Matsumoto, Yanagida (2011)
Fukuda, Matsumoto, Mukhopadhyay (2015)

- **Portal interaction sharing asymmetry**

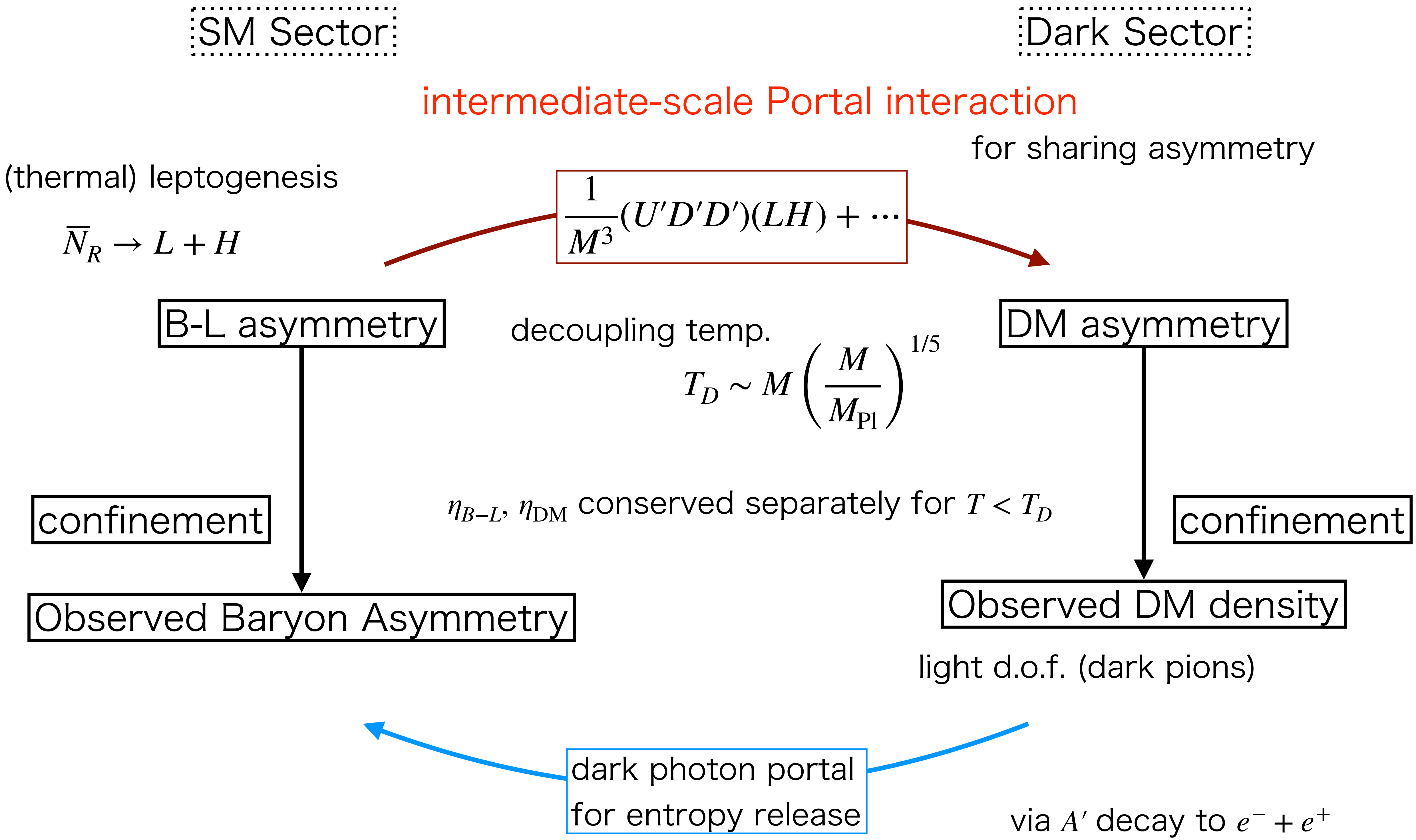
  L# => DM# via $\frac{1}{M^3}(U'D'D')(LH) + \cdots$

  $N_f \geq 2$ at least for DS neutral operator

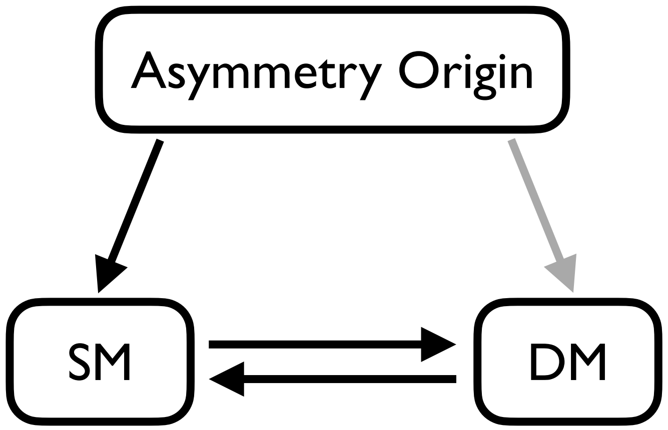
- **asymptotically free for $N_f \leq 16$**

  assume no dark quark decoupled

A Sketch of thermal history -asymmetry sharing-



DM Decay via Portal interaction



Generated asymmetry is transferred via B-L charged portal

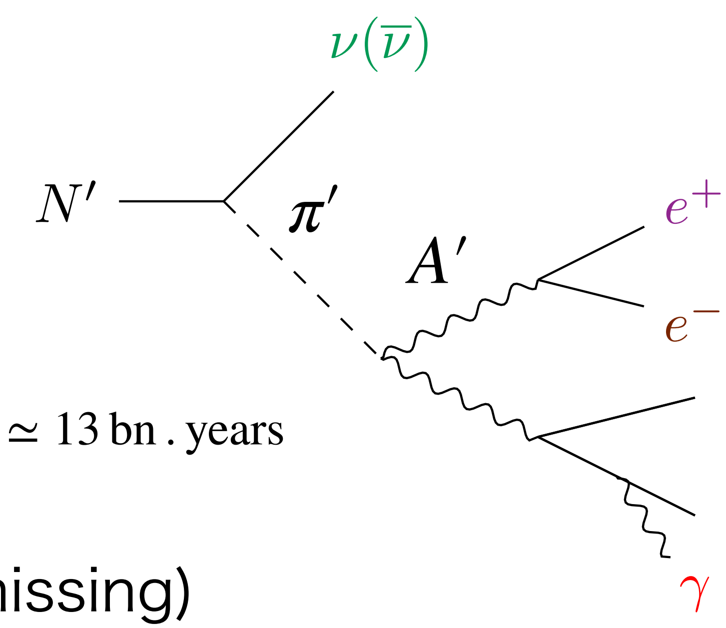
$$\mathscr{L}_{\rm portal} \supset \frac{1}{M^3}(U'D'D')(LH) + \frac{1}{M'^3}(\overline{U}'^\dagger \overline{D}'^\dagger D')(LH) + {\rm h.c.}$$

leading to late-time decay of dark baryons

typical lifetime:

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

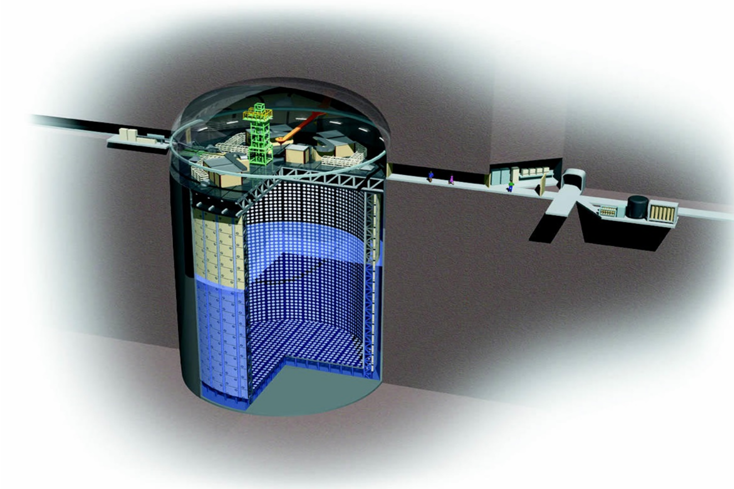
c.f) $\tau_U \simeq 4.2\times 10^{17}\,{\rm s} \simeq 13\,{\rm bn.years}$



- "charged" baryon ⇛ (anti-)neutrino + dark meson (missing)
- "neutral" baryon ⇛ (anti-)neutrino + dark meson (cascade decay)

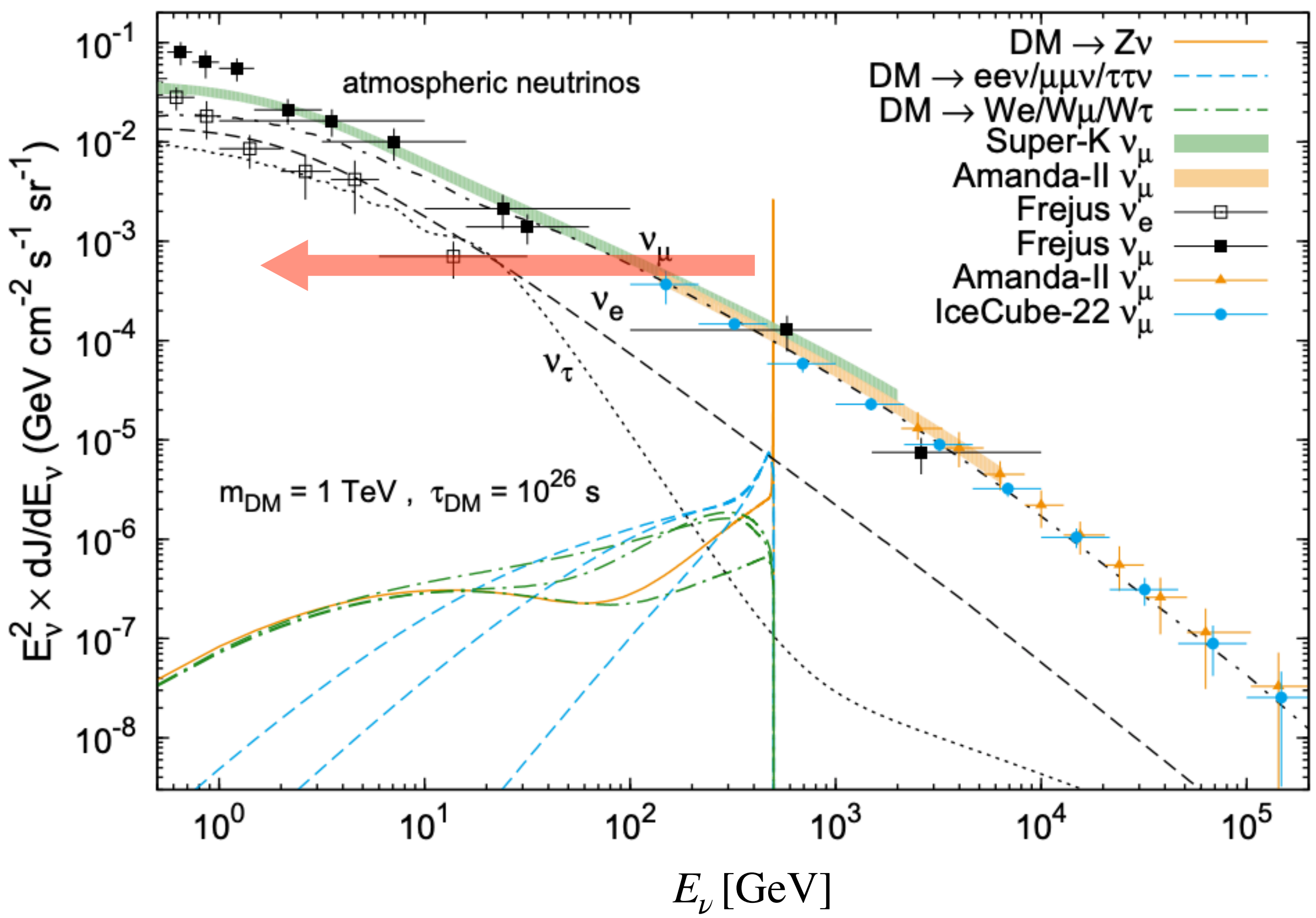
Multimessenger Indirect Detection Constraints

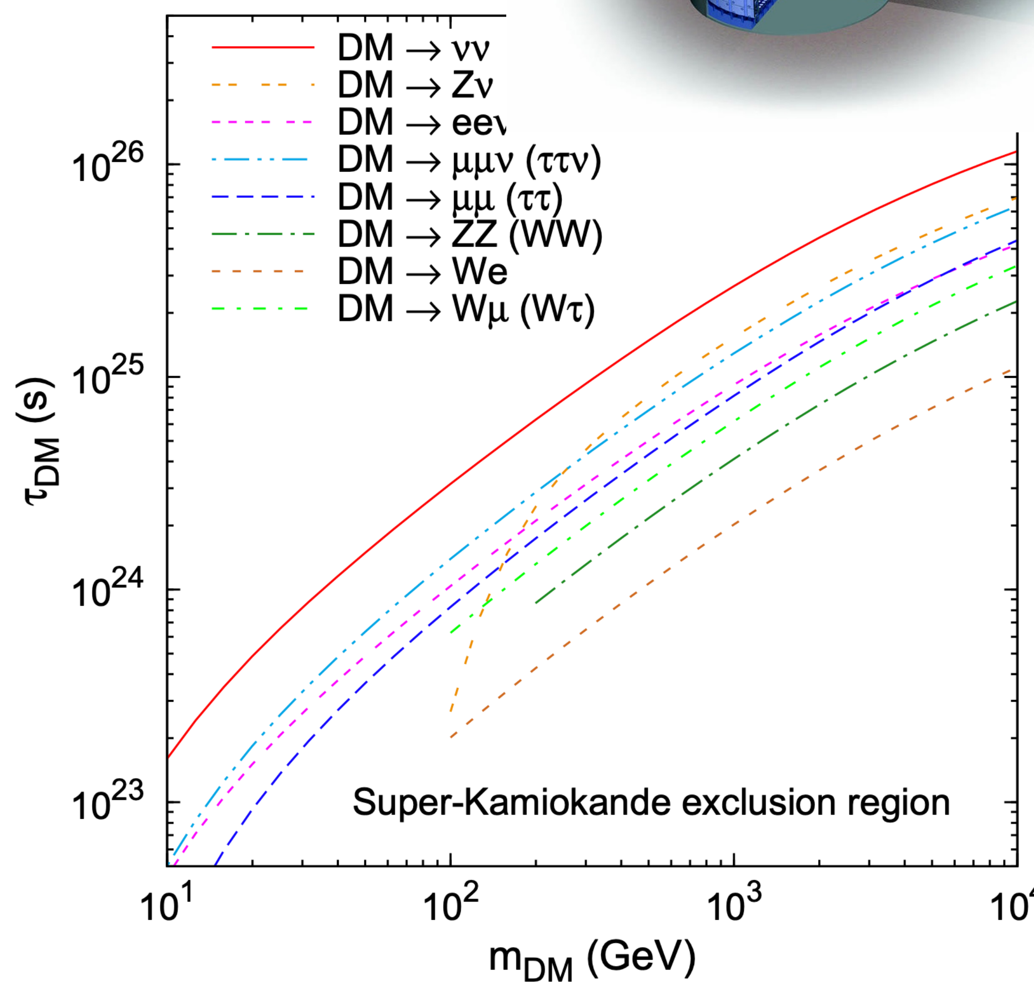
Super-Kamiokande



Neutrino-Line Signals

Covi, Grefe, Ibarra, Tran (2010)



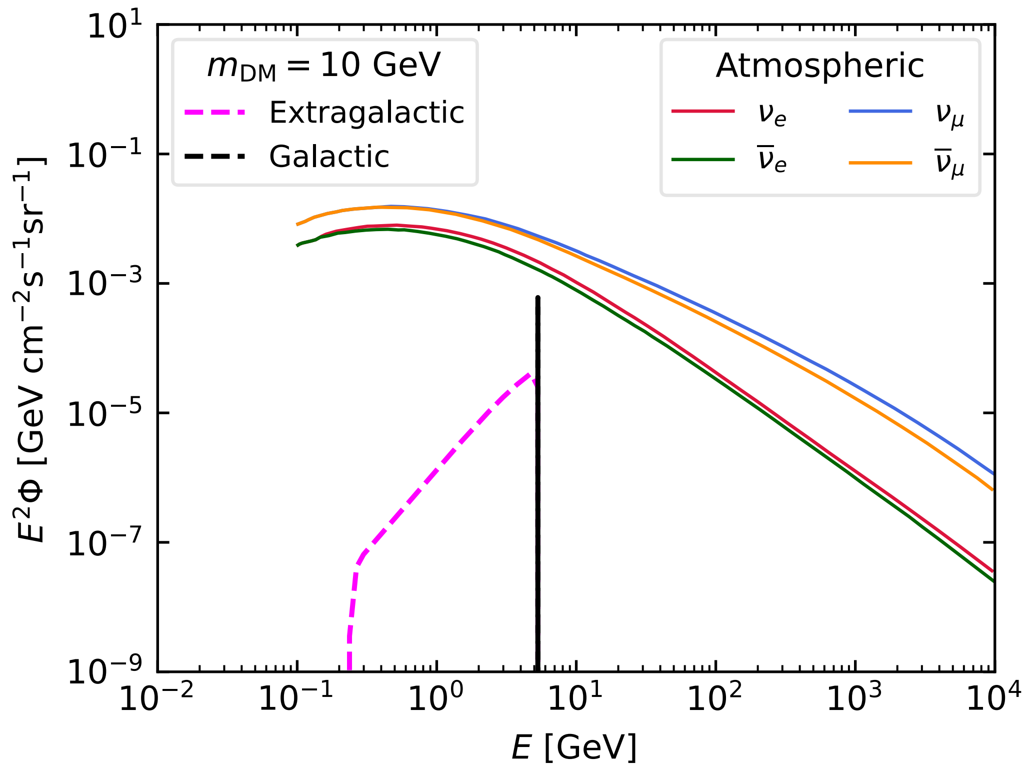


Super-K

typical energy of $E_\nu \lesssim 1\,\mathrm{TeV}$

huge bkg. atm. ν for low E_ν region: naive extrapolation not valid for $m_{\rm DM} \lesssim 10\,\mathrm{GeV}$

Neutrinos flux constraints



monochromatic neutrino energy

$$E_\nu \simeq \frac{m_{N'}}{2}$$

Covi, Grefe, Ibarra, Tran (2010)
Feldstein, Fitzpatrick (2010)
Fukuda, Matsumoto, Mukhopadhyay (2014)

assuming ADM decay with universal neutrino species

} atmospheric neutrino background

Honda, Saijad Ather,
Kajita, Kasahara, Midorikawa (2015)

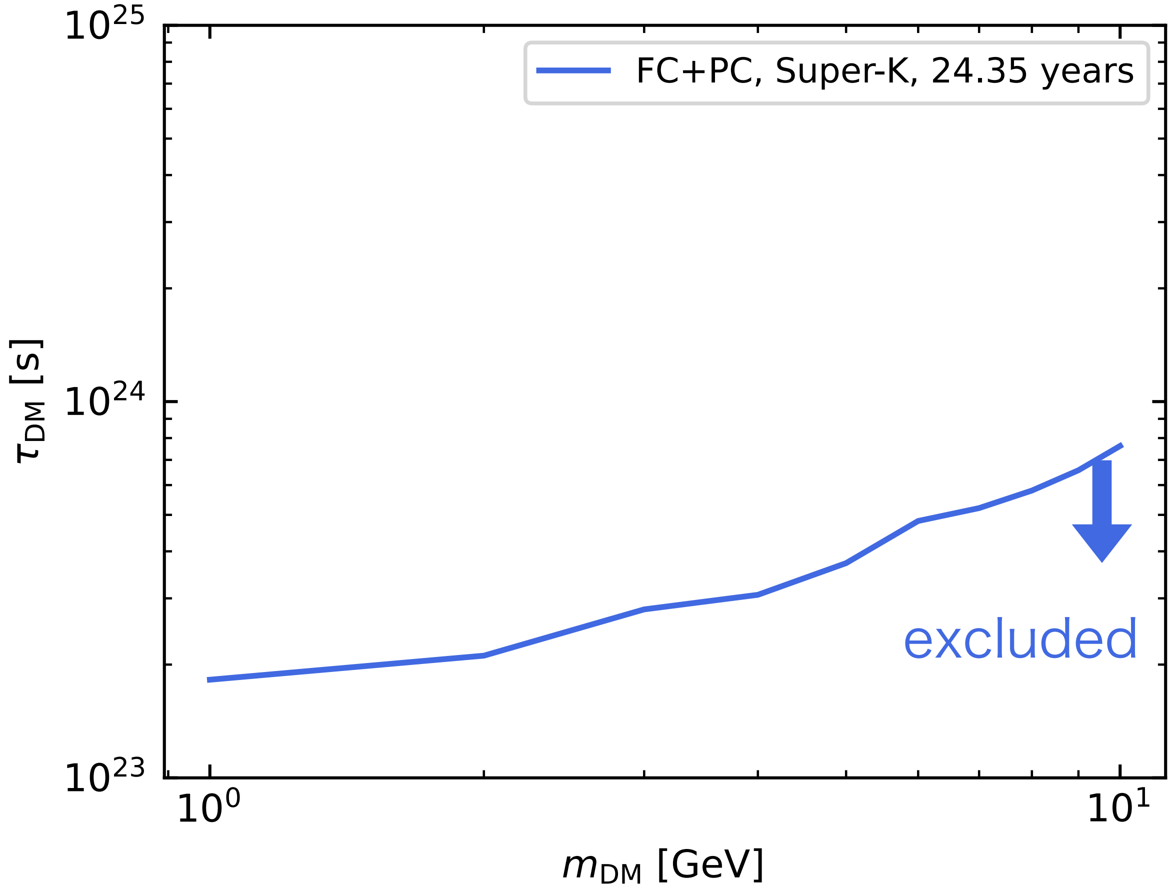
galactic component:

a monochromatic signal from decay

extragalactic component:

integral over the redshifted signals

Neutrinos flux constraints

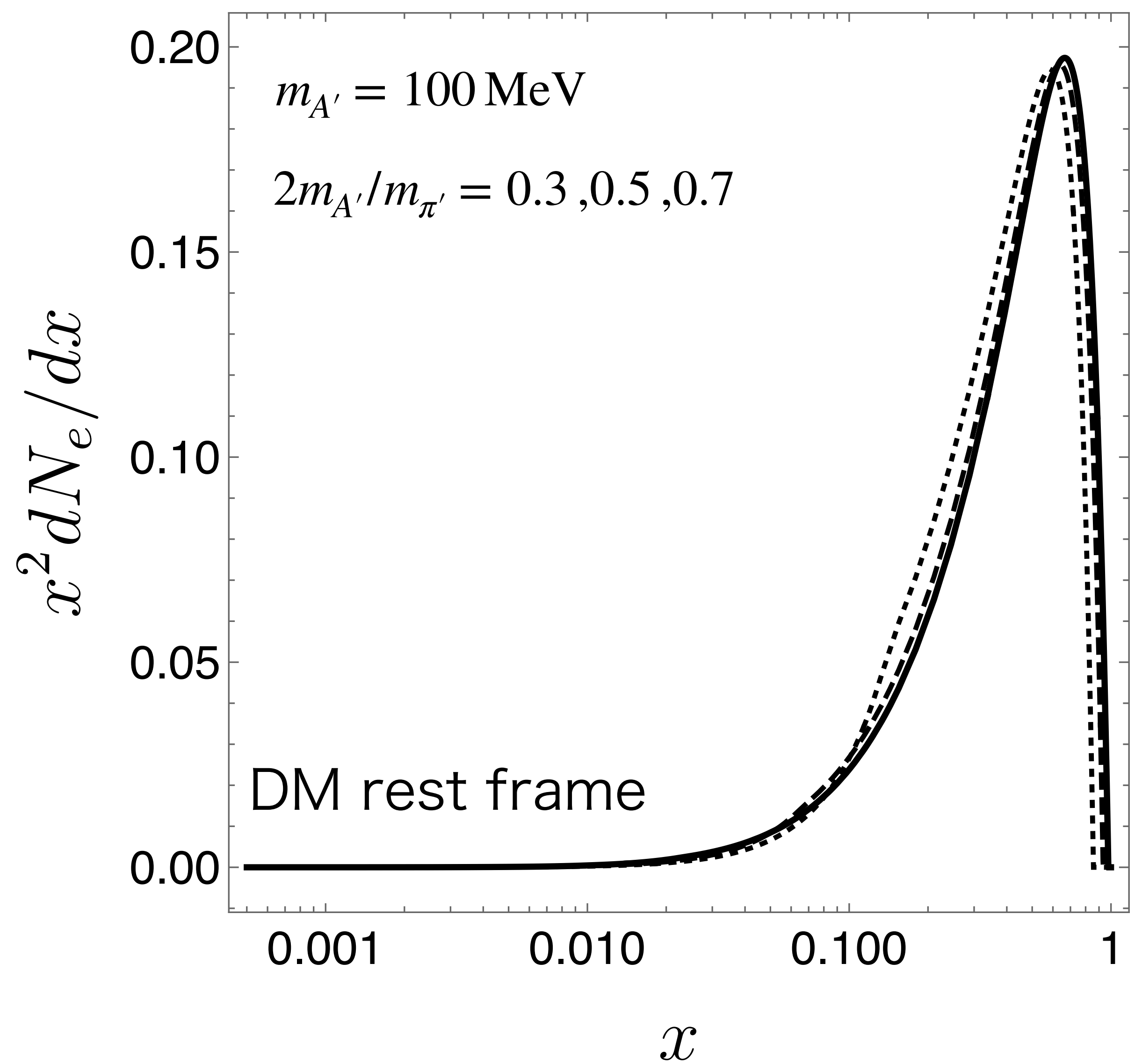


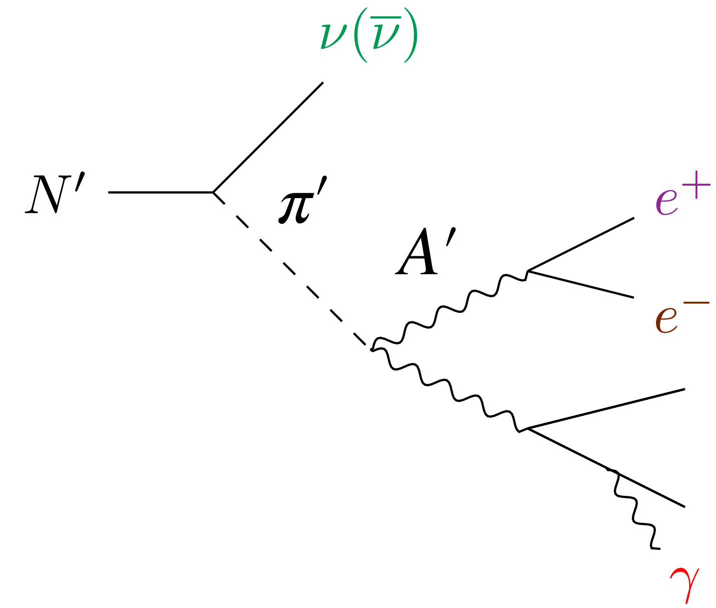
Neutrino flux
= ADM decay + atm. neutrino bkg

DM hypothesis excluded
by p-value = 0.05 (χ^2 with presence of DM)

SN relic neutrinos: Super-K (2002)
DM ann: Palomares-Ruiz, Pascoli(2007)

Cascade decay spectrum





e$^\pm$ energy spectrum @ A' rest frame

$$\frac{dN_e}{dx_0} = \delta(1 - x_0)$$

$$x_0 = 2E_e^{(0)}/m_{A'}$$

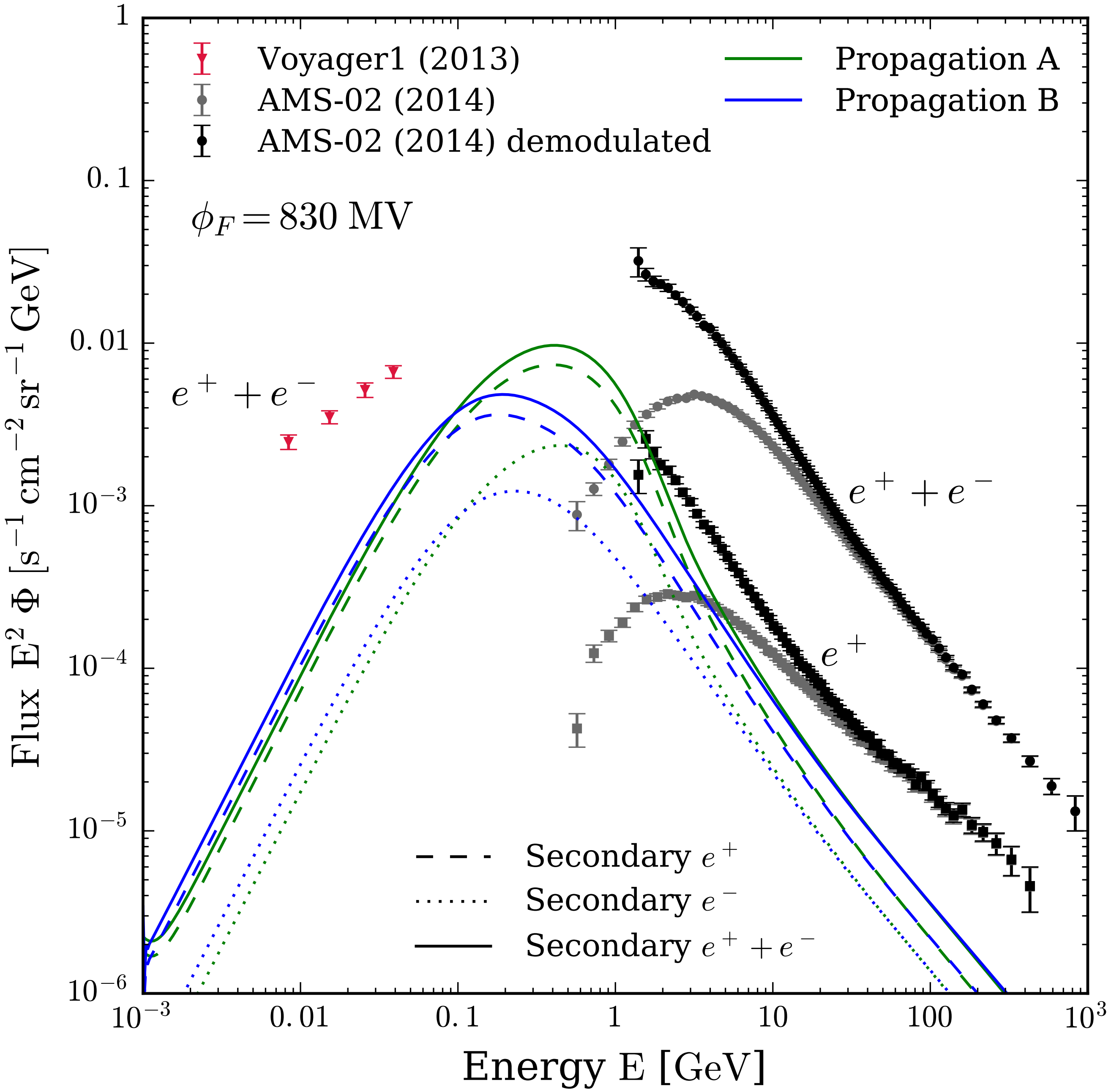
cascade decay softens energy spectrum

non-negligible low-energy fluxes

e$^\pm$ energy normalized by rest frame mass: $x = 2E_e^{(2)}/m_{N'}$

electron/positron fluxes observations

Boudaud, Lavalle, Salati (2016)



AMS-02 (near earth)

with solar modulation

typical energy of $E \gtrsim 1\,\mathrm{GeV}$

Voyager-1 (outside solar hemisphere)

unmodulated

typical energy of $E \lesssim 100\,\mathrm{MeV}$

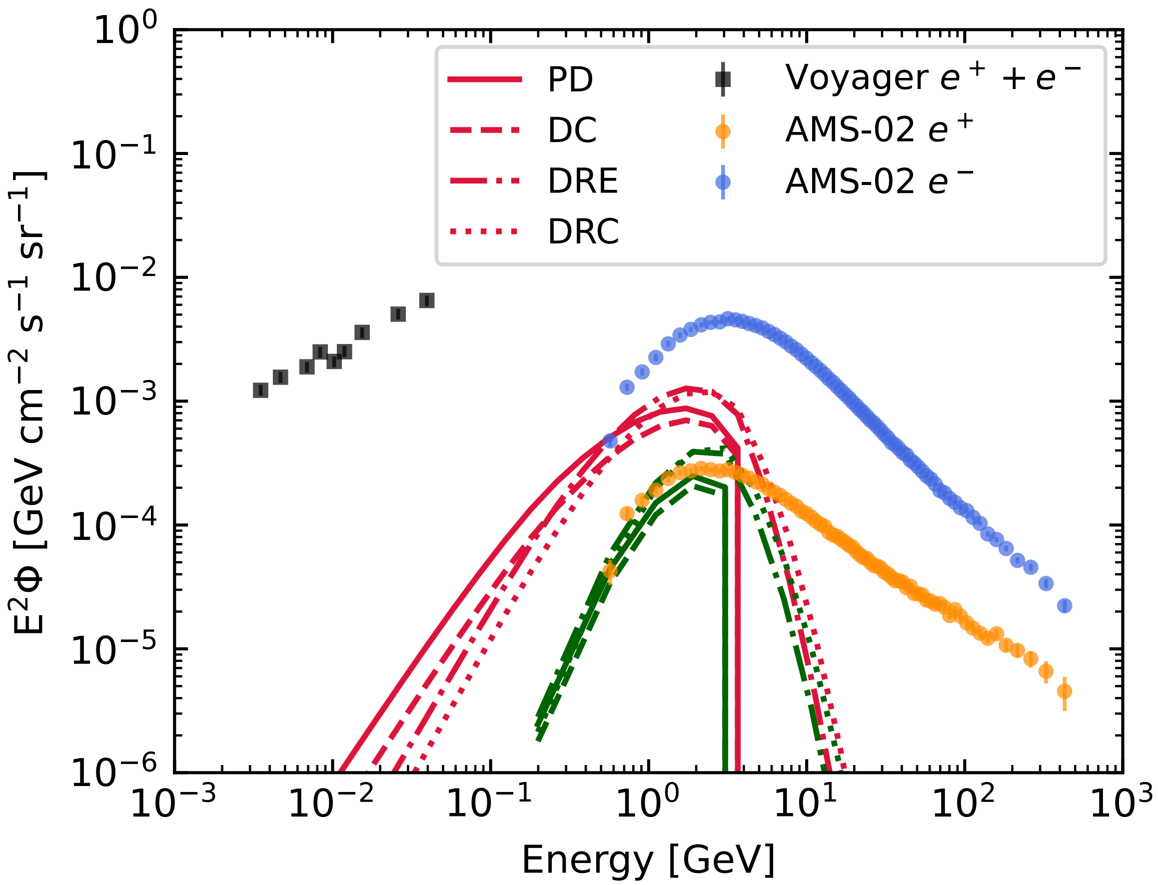
GeV-scale cascade decaying DM

constrained by both observations

secondary $e^{\pm}$ from

CR nuclei and interstellar gas

electron/positron flux constraints



cosmic-ray $e^{\pm}$ with propagation

four different propagation scenarios

Silver, Orlando (2024)

- PD (pure diffusion)
- DC (with convection by galactic wind)
- DRE (with reacceleration in interstellar med.)
- DRC (with reacceleration and convection)

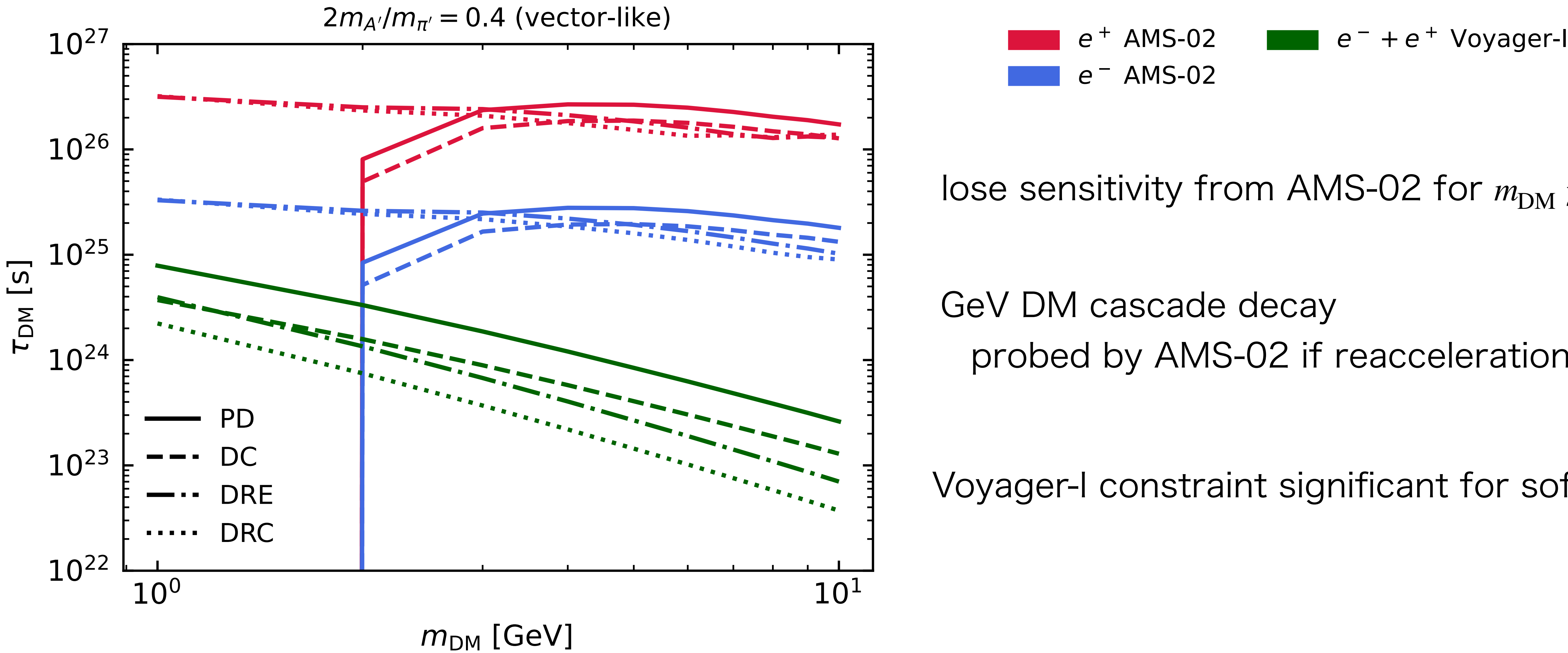
with solar modulation

AMS-02 (near earth)

with unmodulated

Voyager-1 (outside solar hemisphere)

electron/positron flux constraints



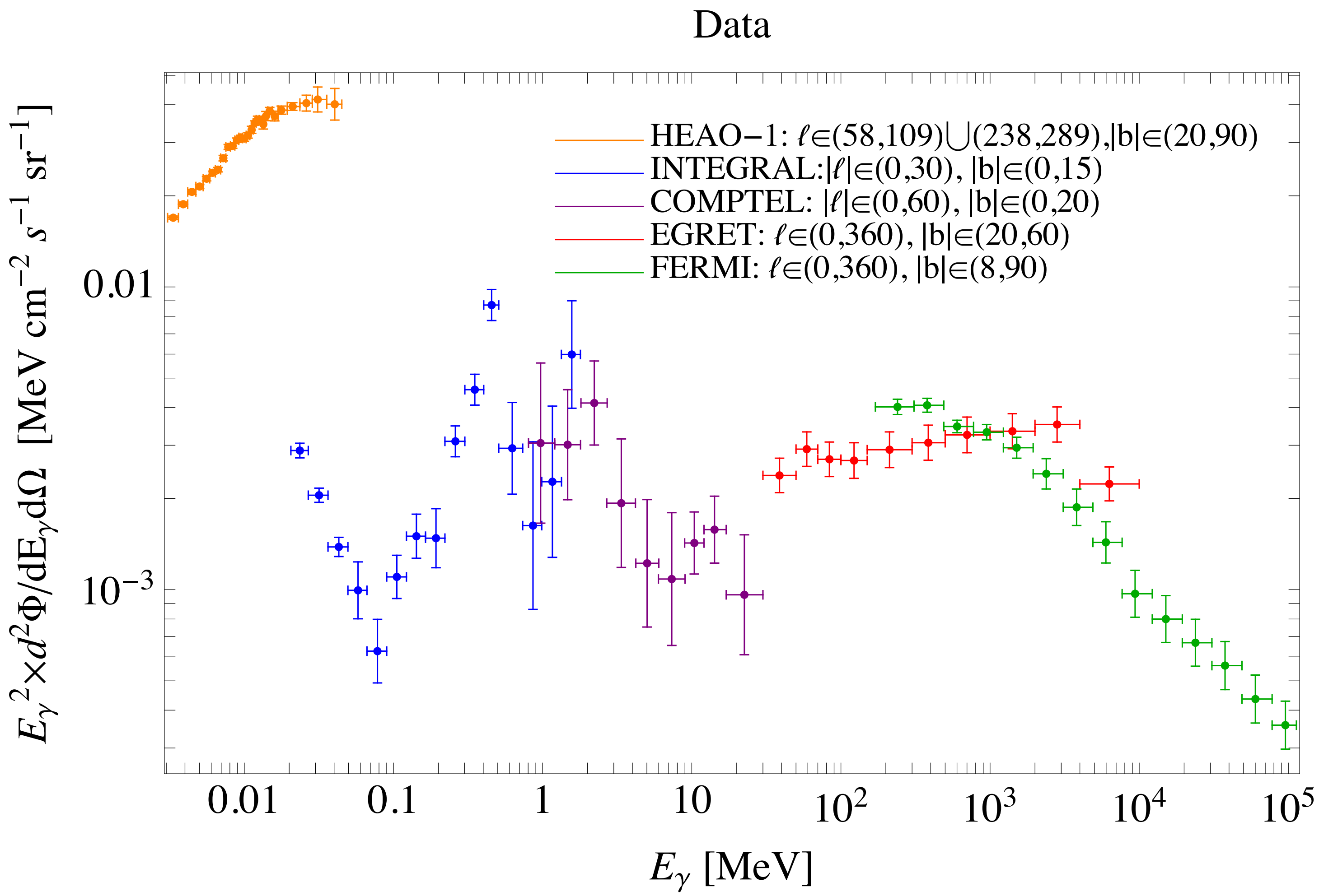
lose sensitivity from AMS-02 for $m_{\rm DM} \lesssim 2\,{\rm GeV}$

GeV DM cascade decay
probed by AMS-02 if reacceleration present

Voyager-I constraint significant for soft $e^{\pm}$

Das, Kamada, TK, Murase, Song (2024)

Gamma-ray observations



Essig, Kuflik, McDermott, Volansky, Zurek (2013)

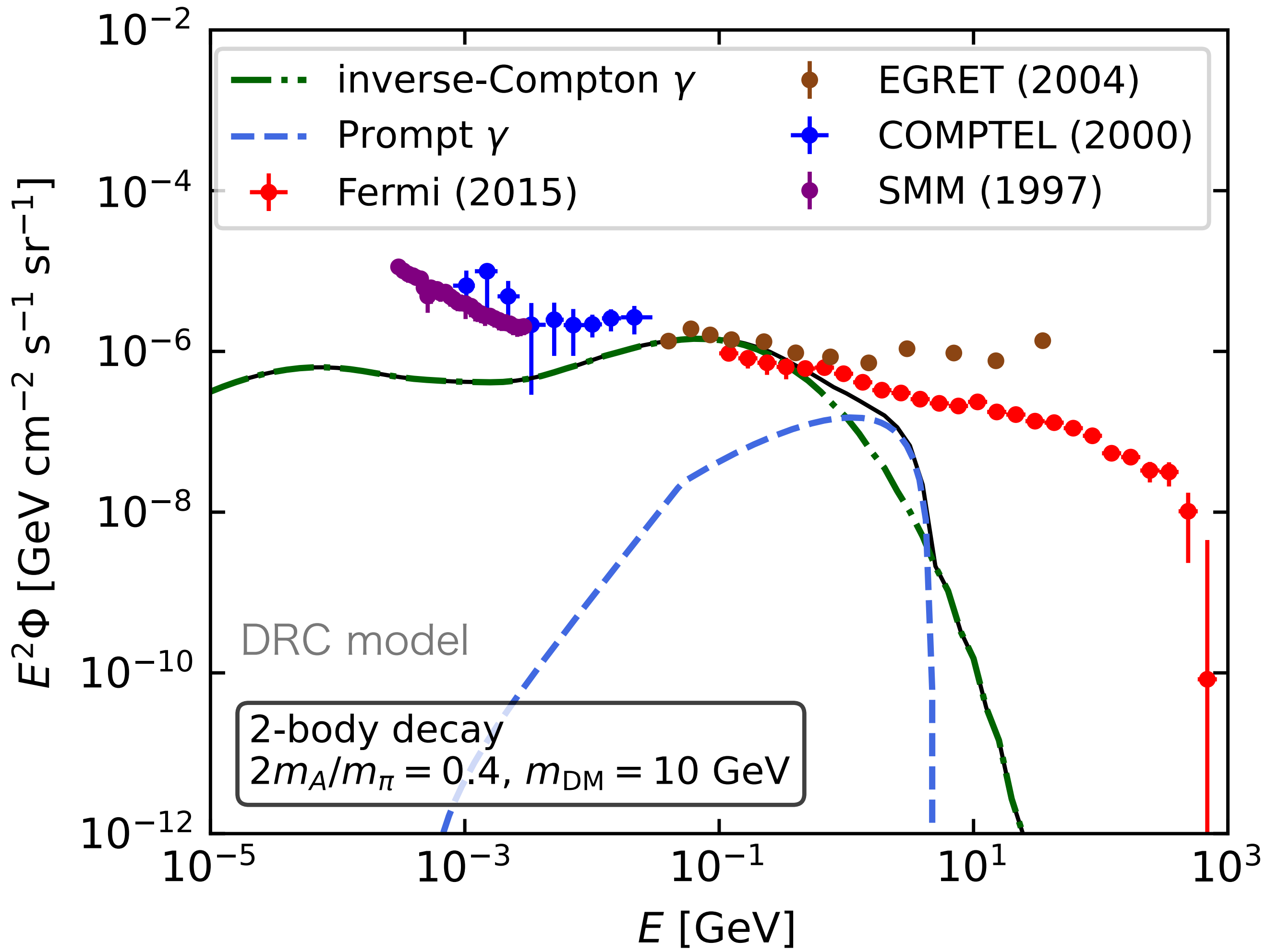
Fermi-LAT

- diffuse γ-ray emission
- typical energy of $E \gtrsim 1\,\mathrm{GeV}$

other observations

- compiling several data from diffuse X- and γ-ray obs.
- energy of $E \lesssim 1\,\mathrm{GeV}$

Gamma-ray flux constraints



γ-ray sources from

- prompt ADM decay
- inverse Compton emission with energetic $e^{\pm}$ from ADM decay

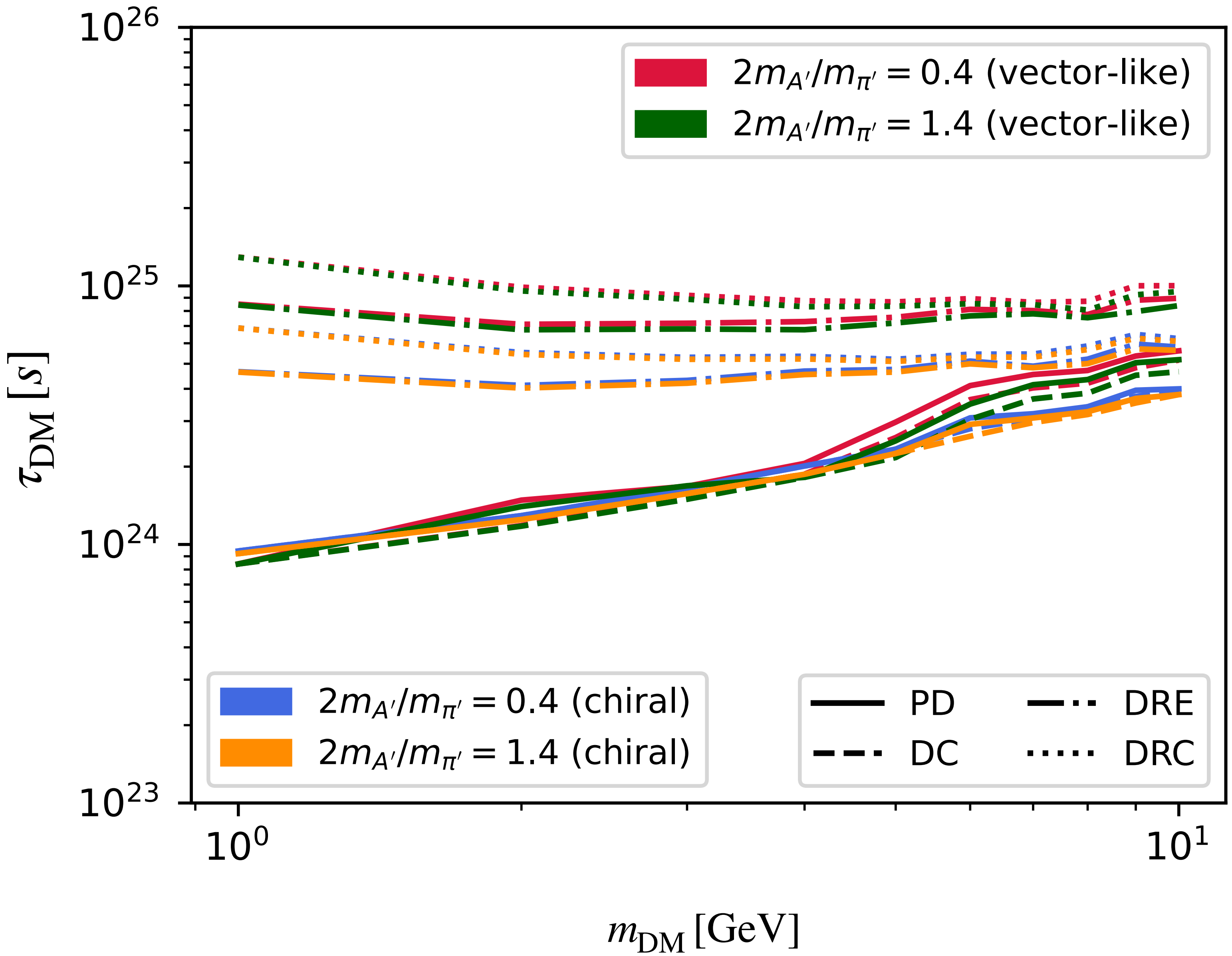
prompt γ is less significant

since γ-ray appears as FSR

inverse-Compton γ

soft (and energetic) γ-ray from $e^{\pm}$

Gamma-ray flux constraints



depending on propagation models

inverse Compton process via reaccelerated $e^{\pm}$

diffuse X-ray/soft γ-ray

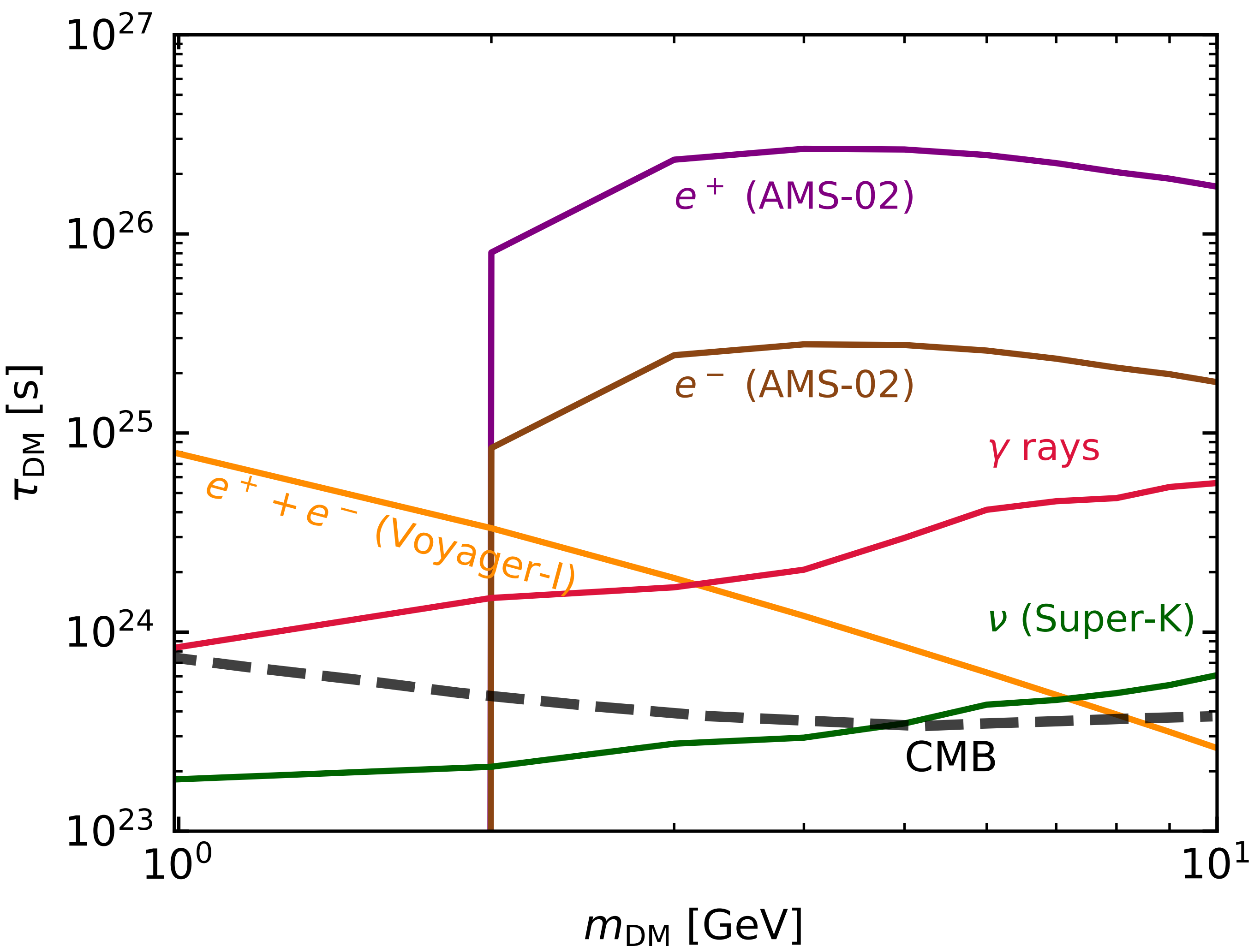
non-negligible for $m_{\rm DM} \simeq 1\,\rm GeV$

reacceleration can enhances fluxes

diffuse γ-ray by Fermi

dominant for $m_{\rm DM} \simeq 10\,\rm GeV$

Summary plots of multi-messenger constraints



Das, Kamada, TK, Murase, Song (2024)

- assuming pure propagation (PD) for $e^{\pm}$
- CMB constraints on decaying DM with branching fraction of ~ 0.1

Slatyer, Wu (2016)

- heavy ADM: strong constraints from e^+ flux

Constraints on Wilson coefficient of intermediate portal interaction

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

Summary and Discussions

Confining Dark Sector

- A framework providing "natural" masses, interactions, and multiple particles
- various exp/obs signals from dark hadrons via portal
- dark photon plays important roles in early universe

Dark Matter Decay

- predicted mass scale: 1-10 GeV
- cascade decay: softened em spectrum (importance of compiling several data)

Multi-messenger probes

- Good probes for feeble dark sectors
- DM decay into dark meson + νs via portal interaction sharing asymmetries
- dark mesons/dark photon decay into EM particles via dark photon portal
- energetic $e^{\pm}$ via reacceleration provides high-energy $e^{\pm}$/(inverse-Compton) γ

Backup Slides

Cascade Decay

formulae for two-body cascade decay

decay of scalar: $\phi_1 \to 2\phi_0 \to 2(\psi + X)$

light final states ψ

some irrelevant particles X

spectrum at ϕ_0 rest frame $\to$ spectrum at ϕ_1 rest frame

$$\frac{dN_\psi}{dx_1} = 2\int_{-1}^{1} d\cos\theta_0 \int_{\epsilon_0}^{1} dx_0 \frac{dN_\psi}{dx_0} \frac{1}{2}\delta\left[x_1 - \frac{1}{2}\left(x_0 + \sqrt{(1-\epsilon_1^2)(x_0^2 - \tilde{\epsilon}_0^2)}\cos\theta_0\right)\right]$$

energy relation

normalized energy of ψ : $x_i = 2E_i/m_i$

dimensionless mass parameters: $\tilde{\epsilon}_0 = 2m_\psi/m_0, \quad \epsilon_1 = 2m_0/m_1$

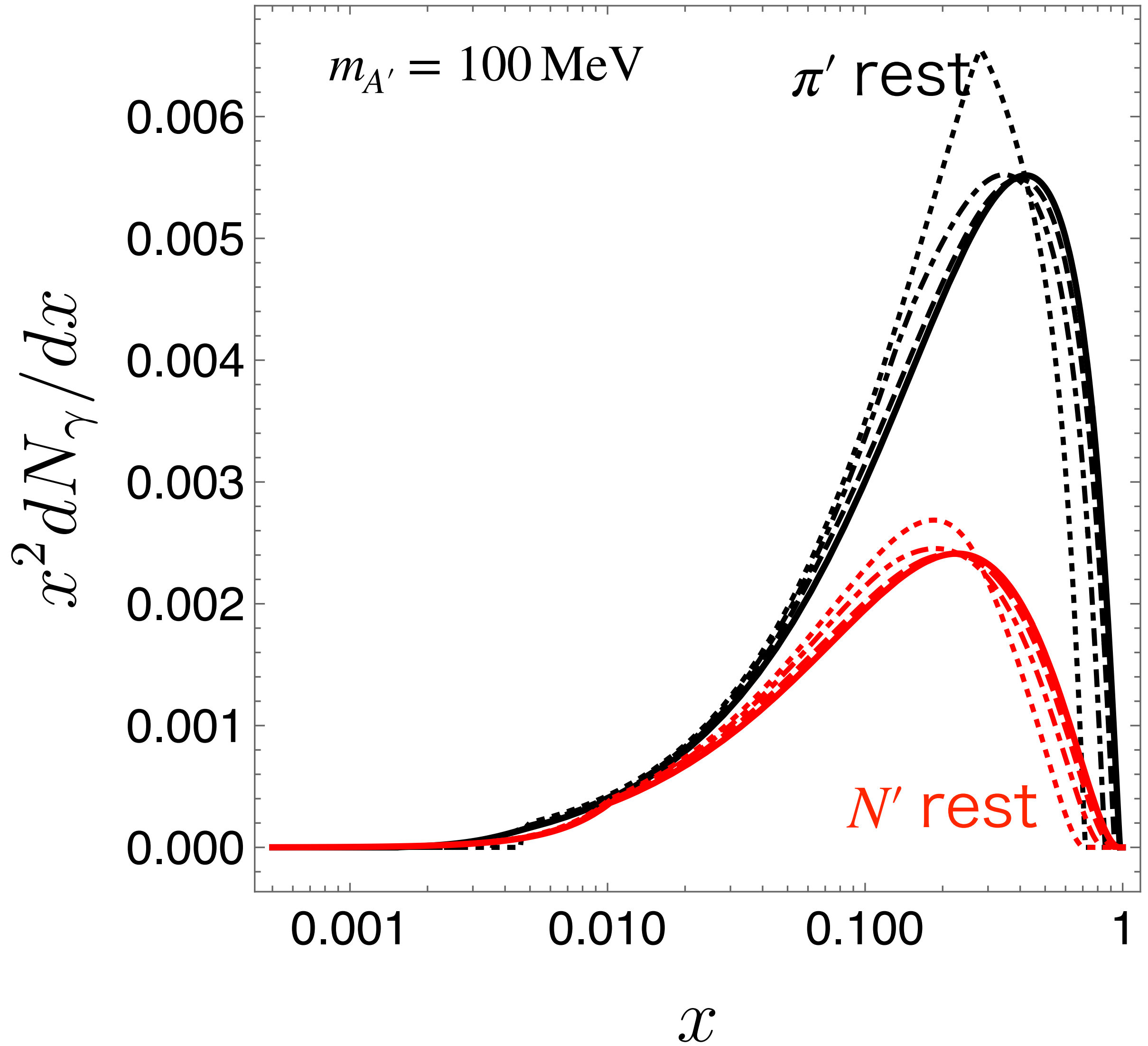
decay with massless emission a: $\phi_2 \to \phi_1 + a \to 2\phi_0 + a \to 2(\psi + X) + a$

spectrum at ϕ_1 rest frame $\to$ spectrum at ϕ_2 rest frame

$$\frac{dN_\psi}{dx_2} = \int_{-1}^{1} d\cos\theta_1 \int_{\tilde{\epsilon}_1}^{1} dx_1 \frac{dN_\psi}{dx_1} \frac{1}{2}\delta\left(x_2 - \frac{1+\epsilon_2^2}{2}x_1 - \frac{1-\epsilon_2^2}{2}\sqrt{x_1^2 - \tilde{\epsilon}_1^2}\cos\theta_1\right)$$

dimensionless mass parameters: $\tilde{\epsilon}_1 = 2m_\psi/m_2, \quad \epsilon_2 = m_1/m_0$

photon energy spectrum



several choice of $2m_{A'}/m_{\pi'} \in [0.3\,,0.9]$

$$2m_{\pi'}/m_{N'} = 0.1$$

photon energy normalized by rest frame mass

$$x = 2E_\gamma^{(i)}/m_i$$

photon spectrum widely distributed
at a higher step in cascade decay

ADM decay spectrum

NFW DM profile $$\rho_\chi(R) = \rho_{\rm sc}\left(\frac{R}{R_{\rm sc}}\right)^{-\gamma}\left(\frac{1+R/R_c}{1+R_{\rm sc}/R_c}\right)^{-(3-\gamma)},$$

$\gamma = 1.2$ and the core radius $R_c = 20$ kpc

distance of the Sun form the GC $R_{\rm sc} = 8.5$ kpc

DM density @ solar system: $\rho_{\rm sc}c^2 = 0.43$ GeV/cm^3

fluxes originating from the direction θ

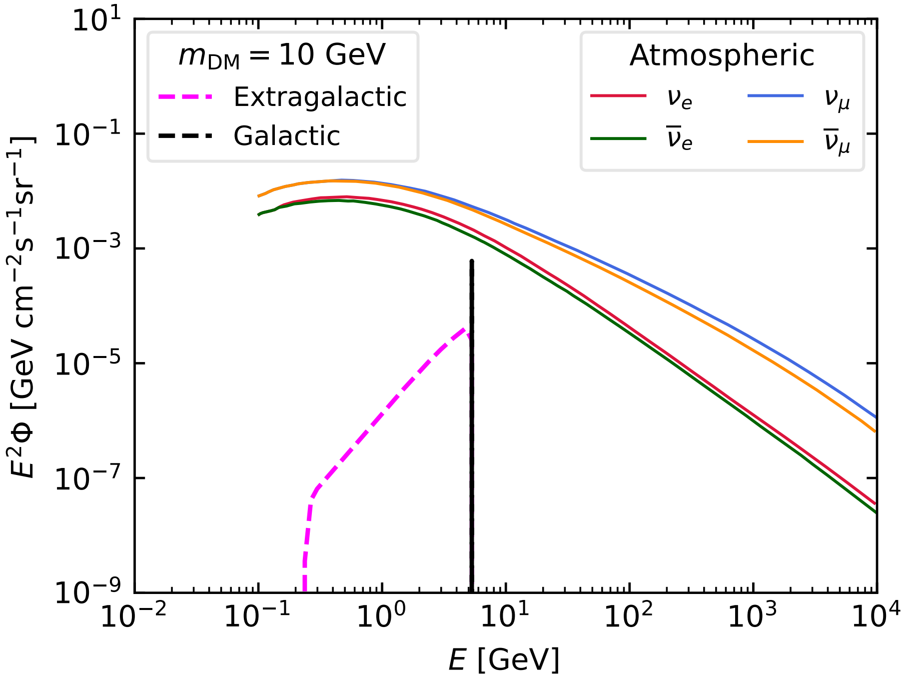
$$\Phi(E,\theta) = \frac{1}{4\pi m_\chi \tau_\chi}\frac{dN_s}{dE}\int_0^{s_{\rm max}(\theta)}\rho_\chi(R(s))ds = \frac{\rho_{\rm sc}R_{\rm sc}}{4\pi m_\chi \tau_\chi}\frac{dN_s}{dE}\mathcal{J}^{\rm dec}(\theta)$$

$$s_{\rm max}(\theta) = R_{\rm sc}\cos\theta + \sqrt{R_h^2 - R_{\rm sc}^2\sin^2\theta}$$

Galactic contribution: integration up to $\theta = \pi$

ADM decay spectrum

extragalactic component for neutrinos: integration over redshift z



$$\Phi^{\rm dec}_{\rm EG}(E) = \frac{\Omega_{\rm DM}\rho_c}{4\pi m_{\rm DM}} \int dz \left|\frac{dt}{dz}\right| F(z) \frac{dN_s^{\rm ob}}{dE}(z_s = z)$$

uniform DM distribution in redshift z (up to $z = 20$)

$F(z)$: redshift evolution of extragalactic DM population (= 1)

$\Omega_{\rm DM}h^2 = 0.113$ and $\rho_c h^{-2} = 1.05 \times 10^{-5}$ GeV/cm3

$|dt/dz|$: cosmological line element

$dN_s^{\rm ob}/dE$: observed neutrino spectrum on Earth after propagation of the prompt DM decay spectrum originating at z

GALPROP

Silver, Orlando (2024)

	PD	DC	DRE	DRC
$D_{0,xx}$ [10^{28} cm^2 s^{-1}]	4.5767	3.6183	4.7776	4.4452
δ_1	0.4047	0.4448	0.4052	0.4163
δ_2	0.1928	0.1975	0.2315	0.2404
$\rho_{\rm break}$ [GV]	290.67	283.29	308.04	308.04
η	0.0004	0.8196	0.3851	0.4373
v_A [km s^{-1}]	…	…	26.727	32.187
dV/dz [kms^{-1}kpc^{-1}]	…	10.022	…	6.3482
solar mod. Φ [MV]	368	375	612	622

- PD (pure diffusion)
- DC (with convection by galactic wind)
- DRE (with reacceleration in interstellar med.)
- DRC (with reacceleration and convection)

$\psi = \psi(p, \vec{r}, t)$

CR density per unit of

total particle momentum p at position $\vec{r}$.

$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot \left(D_{xx} \vec{\nabla} \psi - \vec{V} \psi \right) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right],$$

CR source

diffusion convection

diffusive reacceleration

momentum loss

model of spatial/model diffusion coefficient

$$D_{xx} = D_{xx,0} \beta^{\eta} \left(\frac{\rho}{4\,\mathrm{GV}} \right)^{\delta_1}, \qquad \rho < \rho_{\rm break}$$

$$D_{xx} = D_{xx,0} \beta^{\eta} \left(\frac{\rho_{\rm break}}{4\,\mathrm{GV}} \right)^{\delta_1} \left(\frac{\rho}{\rho_{\rm break}} \right)^{\delta_2}, \qquad \rho > \rho_{\rm break}$$

$D_{pp} D_{xx} =$ (constant) $p^2 v_A^2$

convection velocity

$$\vec{V} = V \vec{\hat{z}}, \quad V = dV/dz \cdot dz$$

Neutrino Signal Bound

χ^2 function $$\chi^2 = \sum_{l=1}^{3} \frac{(\alpha A_l + \beta B_l - N_l)^2}{\sigma_{\rm stat}^2 + \sigma_{\rm sys}^2}$$

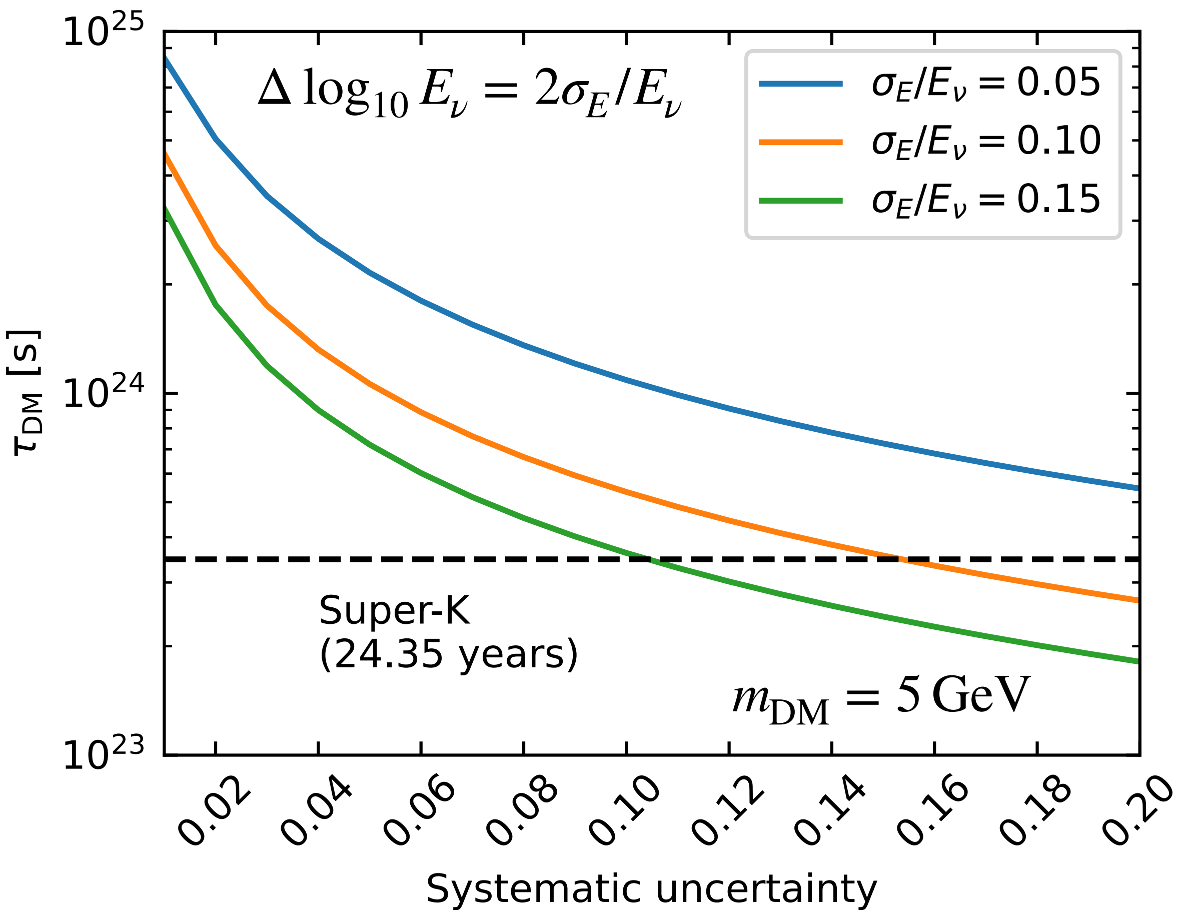
similar analysis

SN relic neutrinos: Super-K (2002)

DM ann: Palomares-Ruiz, Pascoli(2007)

three energy bins: $10^{-0.3}E_0\,, E_0\,, 10^{0.3}E_0$ with a width of $\Delta \log_{10} E_\nu = 0.2$ (SK)

$\sigma_{\rm sys}/N_l = 15\,\%\,,\quad \sigma_{\rm stat}^2 = N_l^2$ assumed



Barr et al (2006), Evans et al (2016)

N_l : # of background in l-th bin

A_l : fraction of DM decay neutrino events

B_l : fraction of atm. bkg. neutrino events

$\alpha\,/\,\beta$: free parameters of strength of signal/bkg

non-zero $\alpha = 1,2,3,\cdots$ and find the best-fit β for each α

to normalize $P(\alpha) \propto e^{-\chi^2(\alpha)}$

calculate α_{95} (95% C.L.) such that p-value = 0.05

DM event #: $n_{\rm DM} = \sum_l \alpha_{95} A_l$

ADM mass and Asymmetries

If the asymmetry is fully shared b/w dark and visible sectors

$$m_{\rm DM} = \frac{\Omega_{\rm DM}}{\Omega_B} m_B \frac{\eta_B}{\eta_{\rm DM}} \simeq 5{\rm GeV}\frac{\eta_B}{\eta_{\rm DM}}$$

- chemical equilibrium
- conservation of charges (B-L, Q/Y)
- rapid sphaleron & top decoupled before EWSB

$$\frac{\eta_B}{\eta_{\rm SM}} = \frac{30}{97}, \qquad \frac{\eta_{\rm SM}}{\eta_{\rm DM}} = \frac{237}{44 n_{g'}}$$

Weinberg, **Cosmology**
Ibe, Matsumoto, Yanagida (2011)
Fukuda, Matsumoto, Mukhopadhyay (2015)

$n_{g'}$: # of generations, $U', \overline{U}', D', \overline{D}'$

the ADM mass

$$m_{\rm DM} \simeq \frac{8.5}{n_{g'}} {\rm GeV}$$

(massless) particle asymmetries

$$n_i - \bar{n}_i = \frac{T^2}{6}\tilde{g}_i \mu_i$$

$\tilde{g}_i$: spin d.o.f. and the flavors (factor 2 for bosons)

chemical potential in terms of conserved charges: $\mu_i = \sum_a q_{ai}\mu_a$

μ_a : chemical potential for conserved quantities

q_{ai} : conserved charge

asymmetry of conserved quantum number Q_a

$$A_a \equiv \sum_i q_{ai}(n_i - \bar{n}_i) = \sum_b M_{ab}\mu_b$$

with a matrix $M_{ab} = \sum_i \tilde{g}_i q_{ai} q_{bi}$

particle asymmetry in terms of asymmetry A_a

$$n_i - \bar{n}_i = \tilde{g}_i \sum_{a,b} q_{ai} M^{-1}_{ab} A_b$$

resultant asymmetry from non-zero initial asymmetry

$$A_{\mathrm{Q}} = \sum_i Q_i (n_i - \bar{n}_i) = \sum_i Q_i \tilde{g}_i \sum_{a,b} q_{ai} M^{-1}_{ab} A_b$$

B-L sharing between SM sector and dark sector

$$\frac{A_{\rm DM}}{A_{\rm SM}} = \frac{n_{g'}(20n_g + 6m)}{3n_g(22n_g + 13m)}$$

$n_{g'}$: # of DS generations

n_g: # of SM generations

m: # of light Higgs

Particle	$\tilde{g}$	B	L	T_3	Y
u_L	3	1/3	0	1/2	−1/6
d_L	3	1/3	0	−1/2	−1/6
u_R	3	1/3	0	0	−2/3
d_R	3	1/3	0	0	1/3
ν_L	1	0	1	1/2	1/2
e_L	1	0	1	−1/2	1/2
e_R	1	0	1	0	1
W^+	4	0	0	1	0
φ^+	2	0	0	1/2	−1/2
φ^0	2	0	0	−1/2	−1/2
gluons	4	0	0	0	0

$$\frac{A_B}{A_{\rm SM}} = \frac{8n_g + 4m}{22n_g + 13m}$$

sphaleron decoupled after EWSB

$$\frac{A_B}{A_{\rm SM}} = \frac{8n_g + 4(m+2)}{24n_g + 13(m+2)}$$

rapid sphaleron after EWSB

$$\frac{A_B}{A_{\rm SM}} = \frac{2(2n_g - 1)(2n_g + m + 2)}{24n_g^2 + 14n_g - 4 + m(13n_g - 2)}$$

rapid sphaleron after EWSB + top q decoupling

Dark Unification

A Supersymmetric Model

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

$SU(5) \to G_{\rm SM}$ for visible, $SU(5)' \to SU(4)_D$ for dark

Superpotential for Yukawa and Higgs sectors

$$W_S = \Psi_S Y_u \Psi_S H_S + \Psi_S Y_d \Phi_S \overline{H}_S$$

$$+ H_S (M_S + \lambda \Sigma_S) \overline{H}_S$$

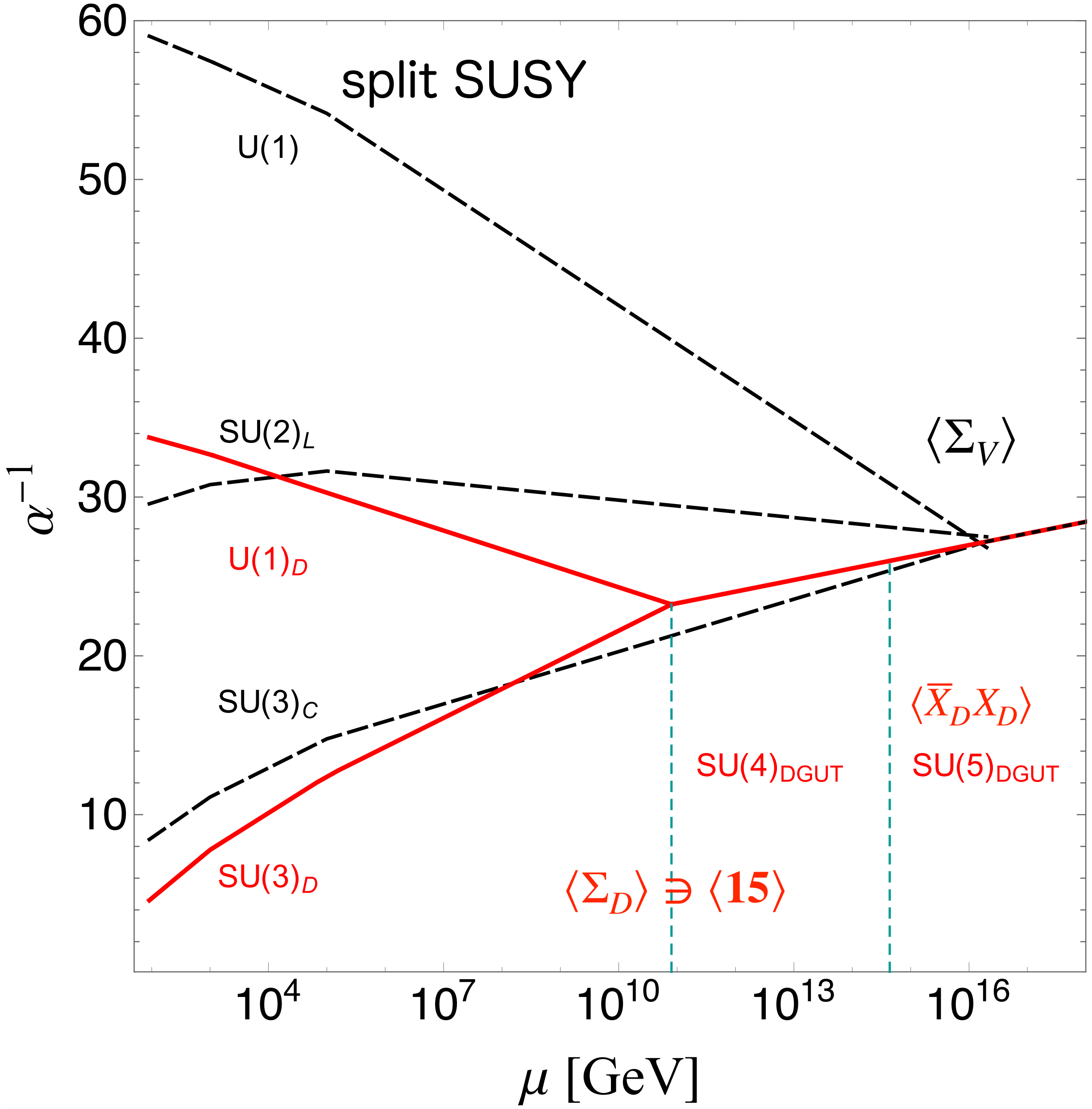
$$+ \mu_S {\rm tr}(\Sigma_S^2) + \lambda_\Sigma {\rm tr}(\Sigma_S^3) \longrightarrow \langle \Sigma_S \rangle = 0 \quad {\rm or} \quad \mathcal{O}(\mu_S)$$

$$+ M'_S X_S \overline{X}_S - \xi \frac{(X_S \overline{X}_S)^2}{M_{\rm Pl}} \longrightarrow \langle X_S \overline{X}_S \rangle = 0 \quad {\rm or} \quad \mathcal{O}(M_{\rm Pl} M'_S)$$

Coupling Unification/Coincidence of Confinement Scales

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

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



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 & $\overline{X}_D$

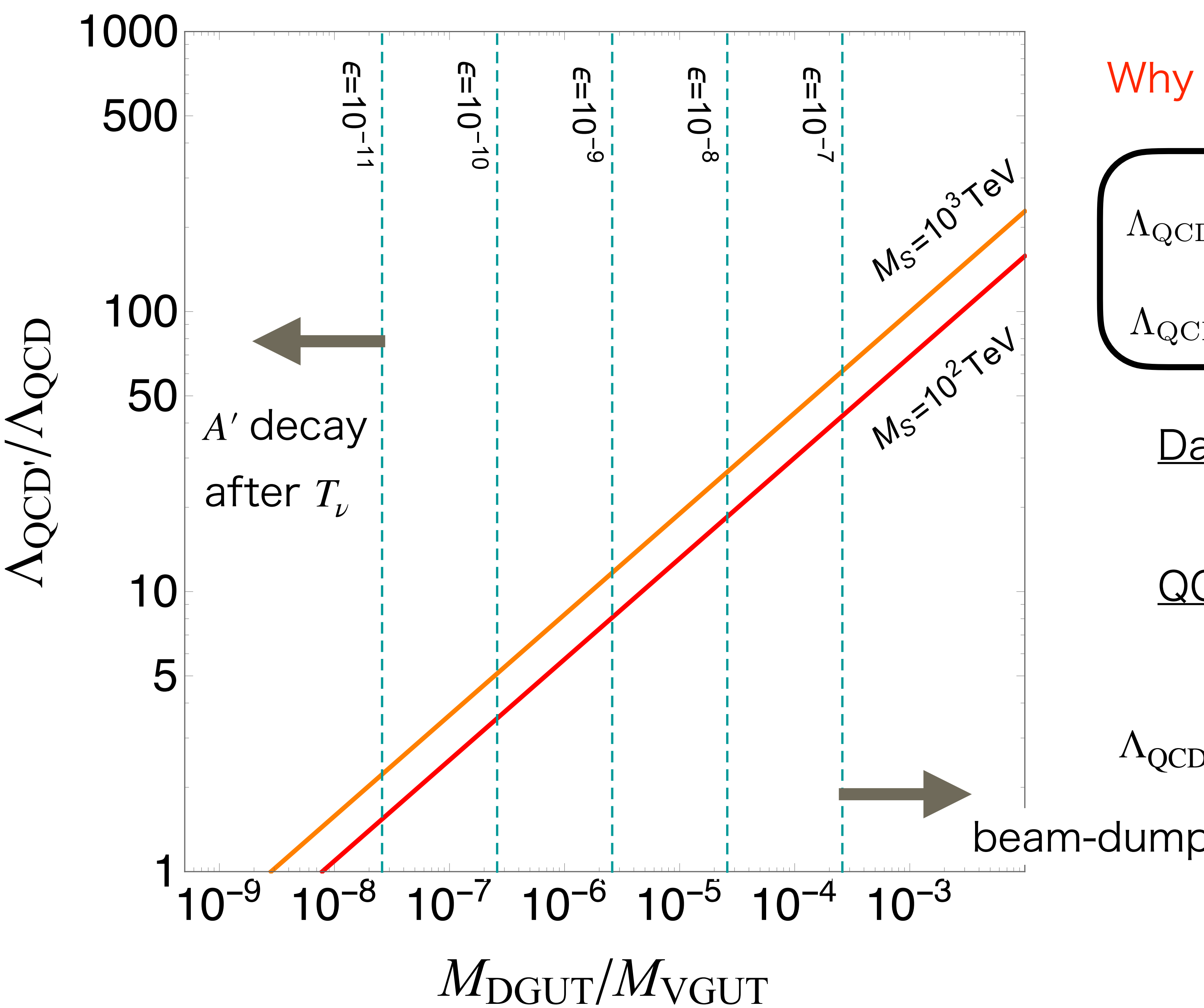
  = tuning of vector-like dark quark masses
- $M_D = 8 \times 10^{10}$ GeV

Split Supersymmetry: enough for unification

Giudice, Romanino (2003)

Relation of Confinement scales

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



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

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

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

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!

Dark neutrinos and Dark electrons

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

Superpotential for N_R sector

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

no see-saw mechanism for dark neutrinos

Call for tuning mechanism?

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

$$W = y_u \Psi_D \Psi_D X_D + y_d \Psi_D \Phi_D \overline{X}_D + \frac{y_e'}{M_{\rm Pl}} \Psi_D \Sigma_D \Phi_D \overline{X}_D \ ,$$

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

Intermediate-scale breaking

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.