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Composite Asymmetric Dark Matter with a Dark Photon Portal: Multi-messenger tests

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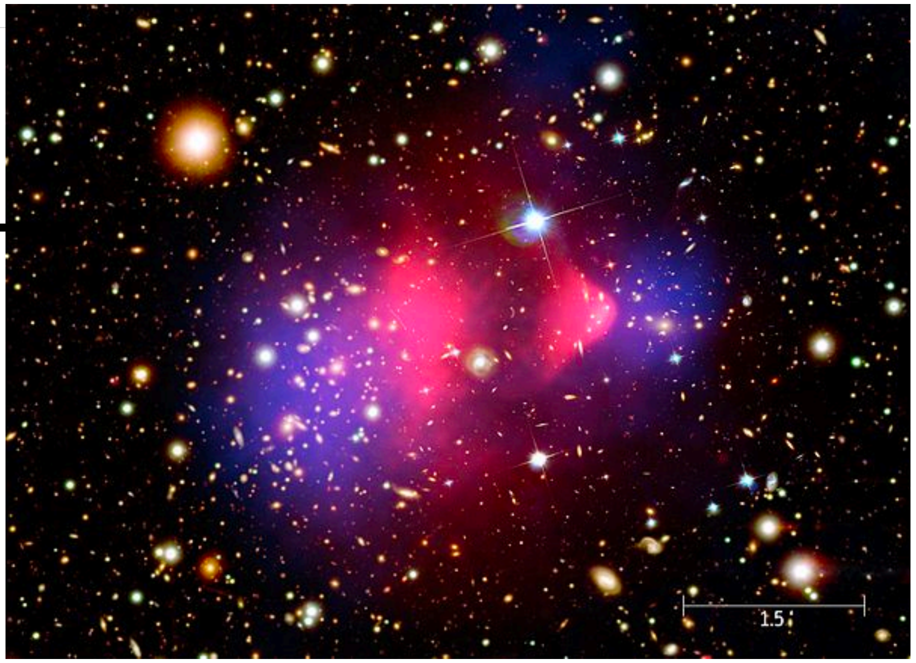
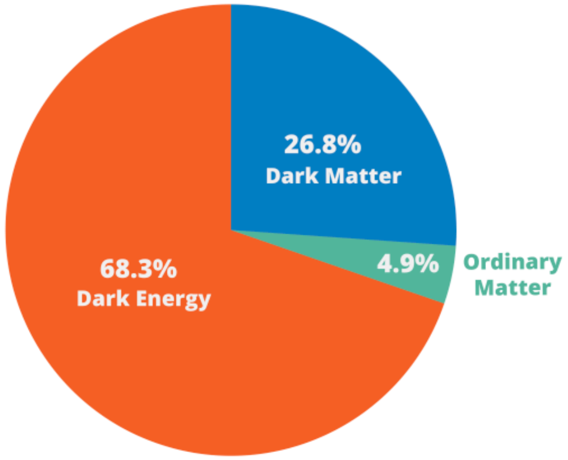
Dark Matter



Particle properties of Dark Matter

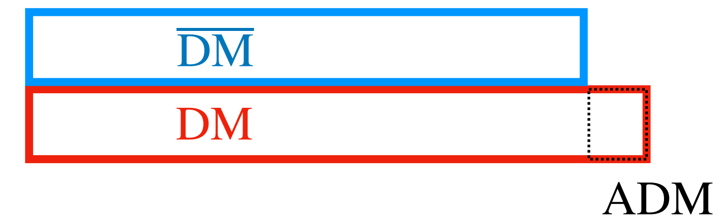
- Stable (or long lifetime until today)
- Electromagnetically neutral (or milicharged)
- Cold DM (non-relativistic)



Many models have been proposed

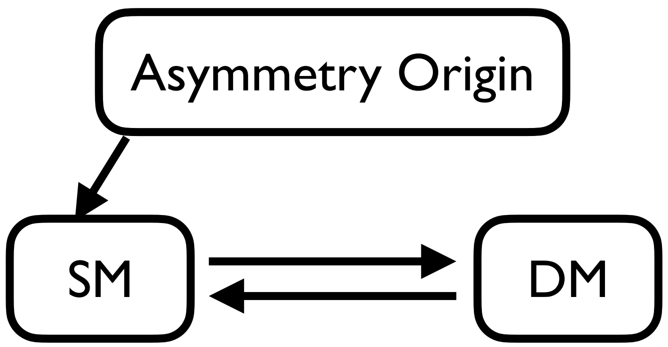
- weakly-interacting massive particles (WIMPs)
- axion/fuzzy DM
- (non-)topological objects/solitons (Q-ball/quark nugget/..)
- Asymmetric DM
- ...

Asymmetric DM



✓ <u>particle-antiparticle asymmetries</u>

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



by sharing asymmetry: $\eta_B \sim \eta_{\mathrm{DM}}$

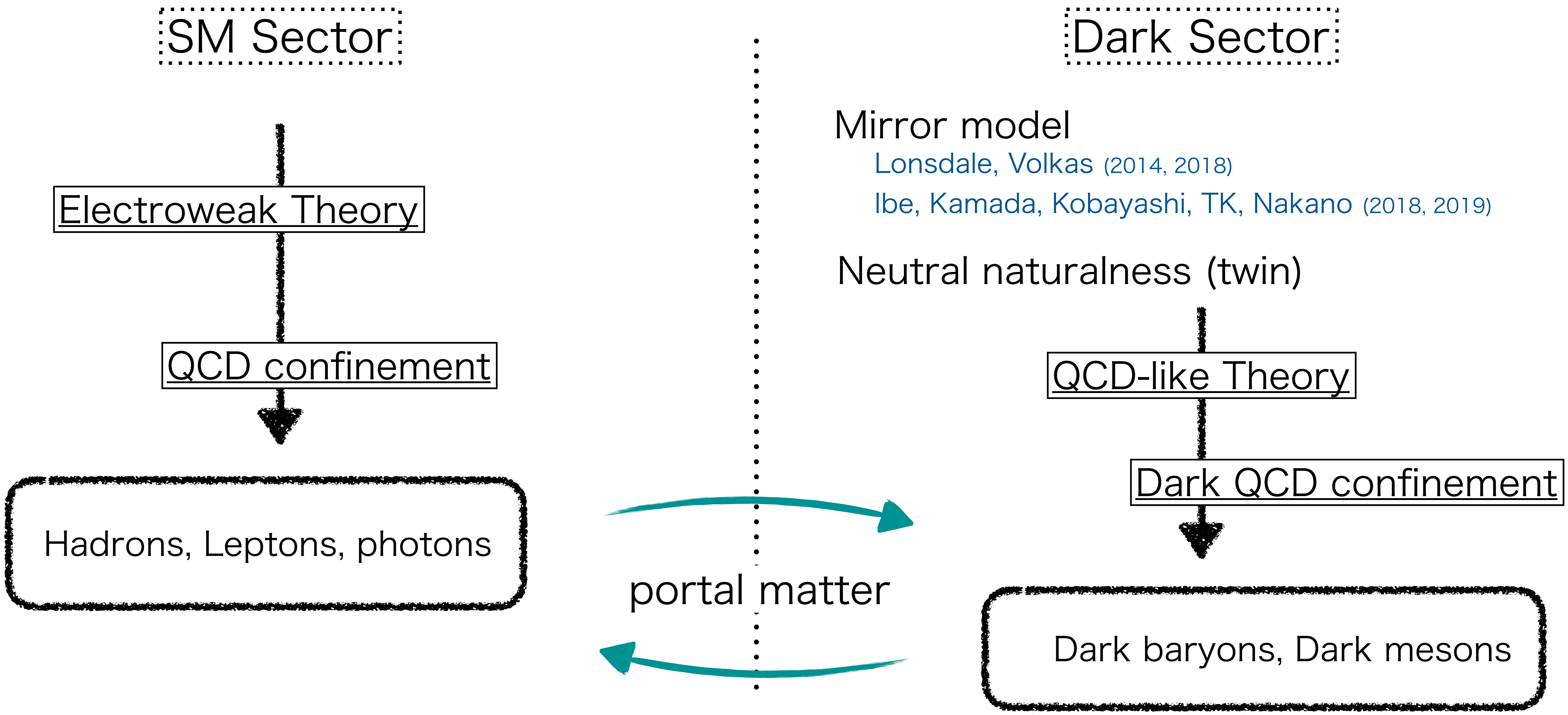
$$\frac{\Omega_{\mathrm{DM}}}{\Omega_B} = \frac{m_{\mathrm{DM}}\,\eta_{\mathrm{DM}}}{m_B\,\eta_B} \sim 5$$: DM mass ~ O(1) GeV

✓ <u>Safe from astrophysical/cosmological constraints</u>

no anti-particle in the current Universe

-> no late-time energy injection to EM channel from annihilation

Composite Asymmetric DM



- Similar confinement scale $\Lambda'_{\mathrm{QCD}} \sim 1\,\mathrm{GeV}$ is expected in models with the SM copy
- Dark hadron DM
  - dark baryons (ex. composite asymmetric DM ...) Ibe, Kamada, Kobayashi, Nakano (2018)
  - dark pions (ex. SIMP ...) Hochberg, Kuflik, Murayama, Volansky, Wacker (2015)
  - other resonances?

Why Compositeness?

ADM scenarios require

- large annihilation cross section
- DM mass O(1) GeV
- DM number conservation

SM baryons have

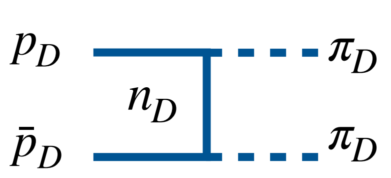
✓ large annihilation into pion

✓ nucleon with mass of 1GeV

✓ Baryon number conservation

Dark QCD seems to be a good candidate of ADM

- dark-baryon efficiently depleted into dark-pion



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

- DM mass : dimensional transmutation
- DM number = dark baryon number

- How to generate an asymmetry and to share the asymmetry?
- stable dark pions can be problematic.

A Sketch of thermal history -asymmetry sharing-

SM Sector

Dark Sector

intermediate-scale Portal interaction

for sharing asymmetry

(thermal) leptogenesis

$\overline{N}_R \to L + H$

$$\boxed{\frac{1}{M^3}(U'D'D')(LH) + \cdots}$$

B-L asymmetry

DM asymmetry

decoupling temp.

$$T_D \sim M \left(\frac{M}{M_{\rm Pl}}\right)^{1/5}$$

confinement

$\eta_{B-L}, \eta_{\rm DM}$ conserved separately for $T < T_D$

confinement

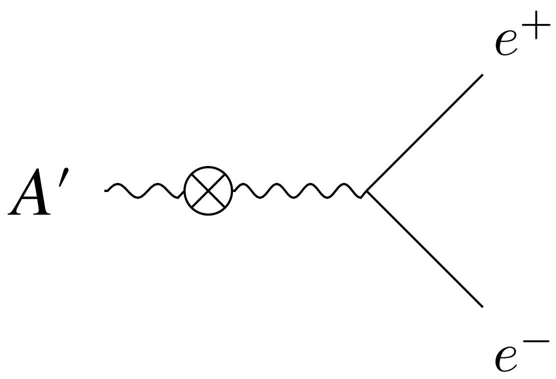
Observed Baryon Asymmetry

Observed DM density

light d.o.f. (dark mesons)

Dark Photon as Low-energy Portal

Cosmological problems in composite ADM



- overdensity of the Universe (annihilation into dark mesons)
- or contribute to dark radiation (light and stable mesons)

Blennow, Fernandez-Martinez, Mena, Redondo, Serra (2012)

introduce dark photon kinematically mixing with SM photon

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

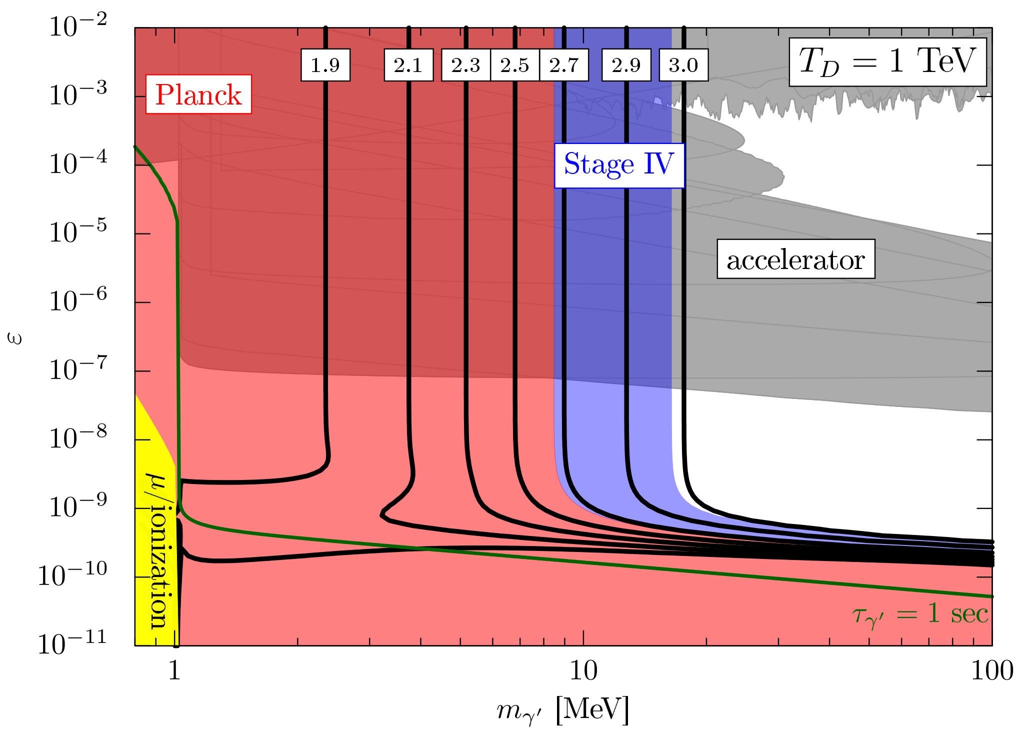
- <u>dark pion annihilation/decay into A'</u>
- <u>A' decay into SM particles via kinetic mixing</u>

constraints on dark photon parameters from $\delta N_{\rm eff}$

Ibe, Kamada, Kobayashi, Nakano (2018)

thermalize $e^-\gamma$ plasma below $T_{\nu\rm dec}$

Ibe, Kobayashi, Nakayama, Shirai (2019)

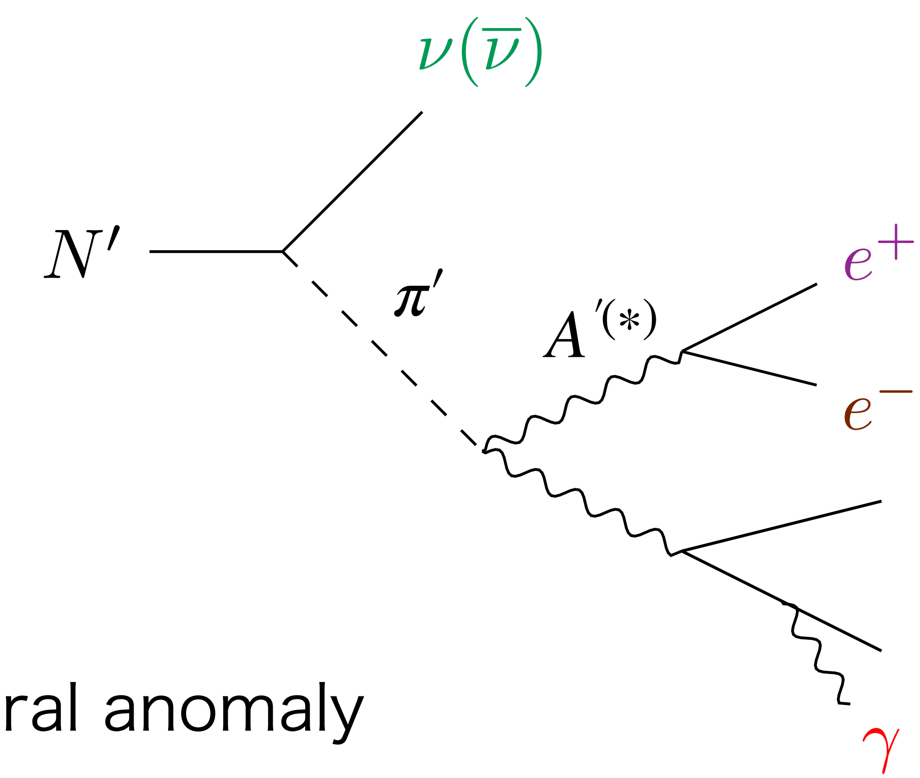


Multi-Messenger Signals

- DM decay as with nucleon decay in GUT via intermediate portal

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

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



- Dark-"neutral" meson decays via "dark" chiral anomaly

$$\pi'^0 \to 2A' \qquad \text{BR}(\pi'^0 \to 2A') \simeq 1$$

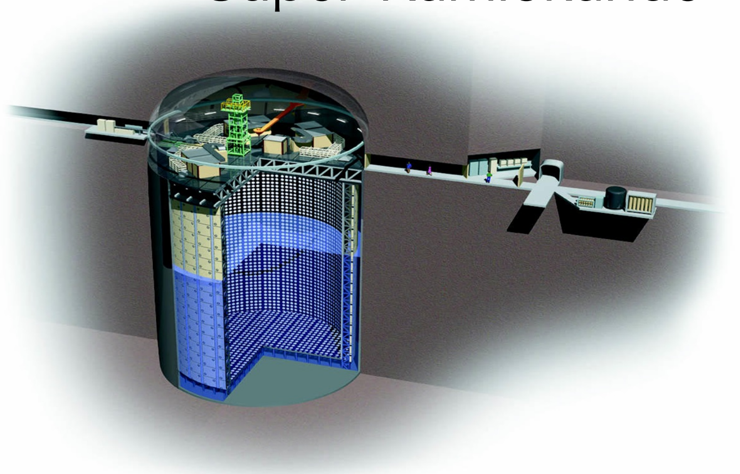
- Dark photon decay via kinetic mixing (low-E portal)

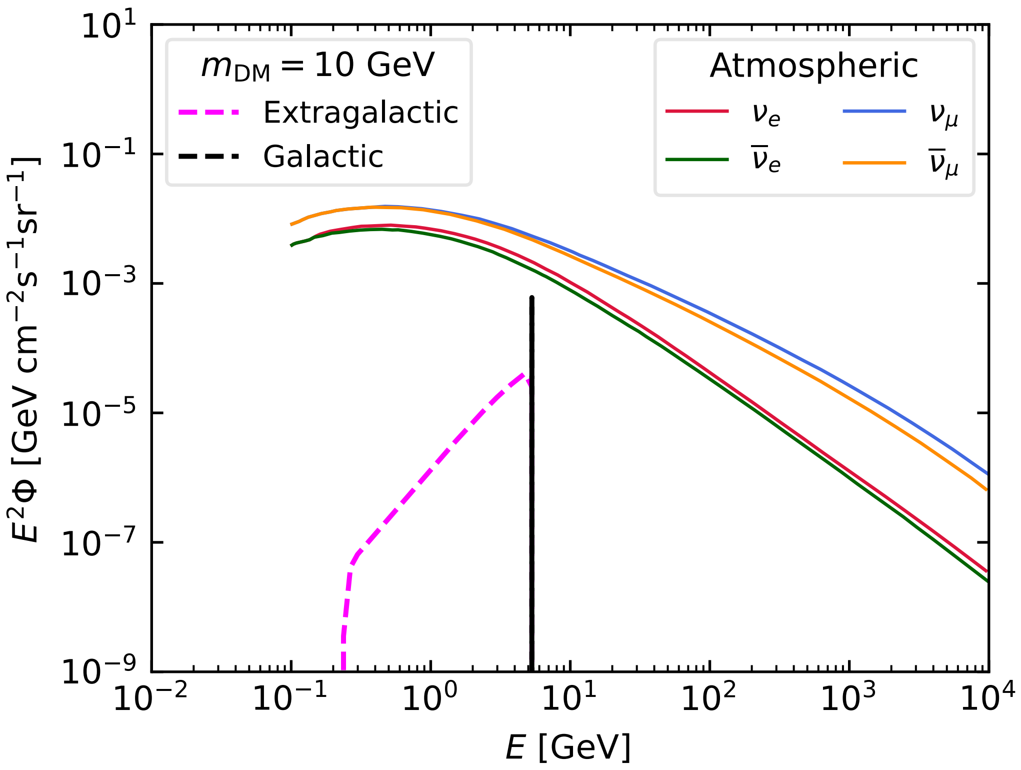
A' lifetime $\lesssim$ O(1) s (to avoid late-time reheating EM plasma)

A' mass $\lesssim$ 100 MeV (only e^+e^- channels)

Neutrinos flux constraints

Super-Kamiokande





monochromatic neutrino energy

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

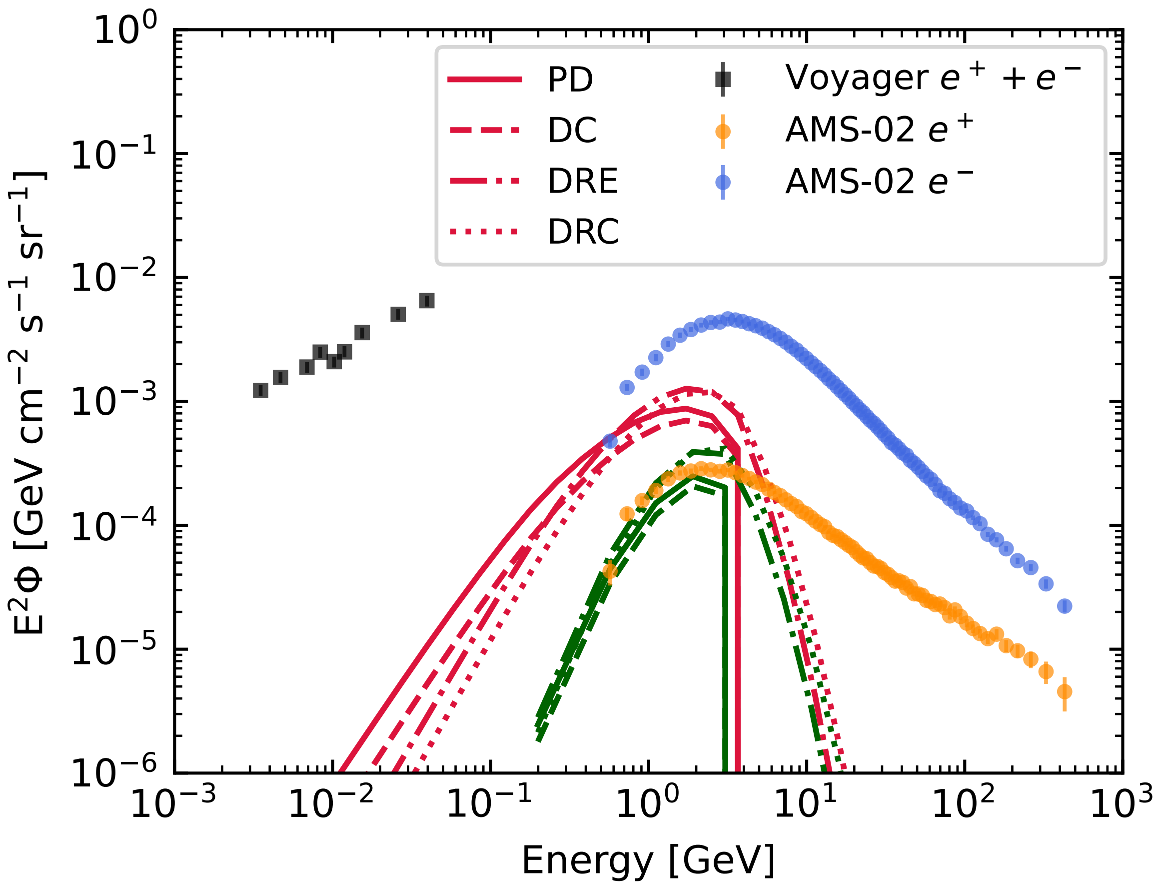
Covi, Grefe, Ibarra, Tran (2010)
Feldstein, Fitzpatrick (2010)
Fukuda, Matsumoto, Mukhopadhyay (2014)

assuming ADM decay with universal neutrino species

galactic component: a monochromatic signal
extragalactic component: integral over the redshifted signals

neutrino flux from ADM decay + Background neutrinos
should not exceed the observed atmospheric neutrino fluxes at super-K

electron/positron flux constraints



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

four different propagation scenarios

Silver, Orlando (2024)

- with/without convection by galactic wind
- with/without reacceleration in intersteller medium

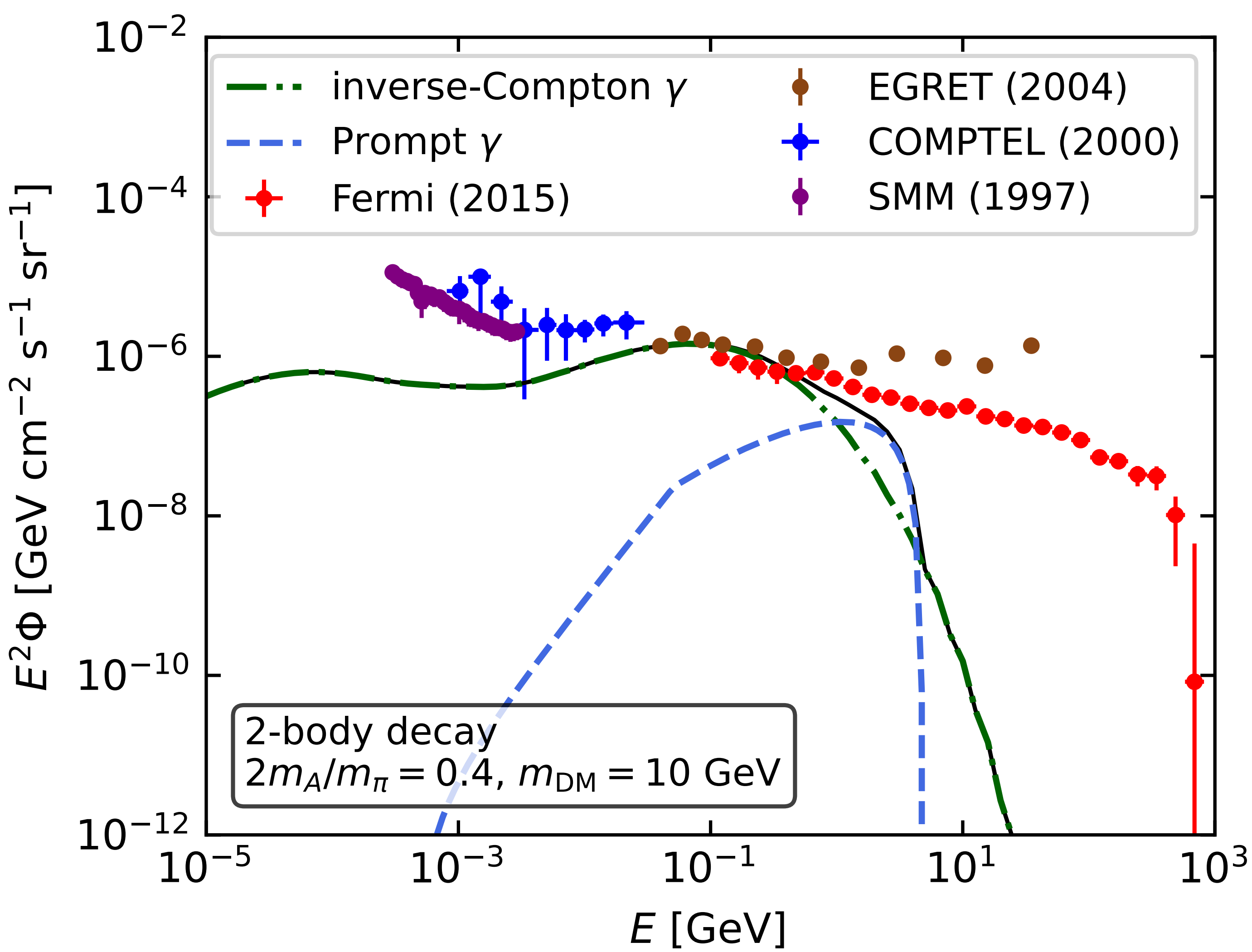
with solar modulation (green)

AMS-02 (near earth)

unmodulated (red)

Voyager-1 (outside solar hemisphere)

Gamma-ray flux constraints



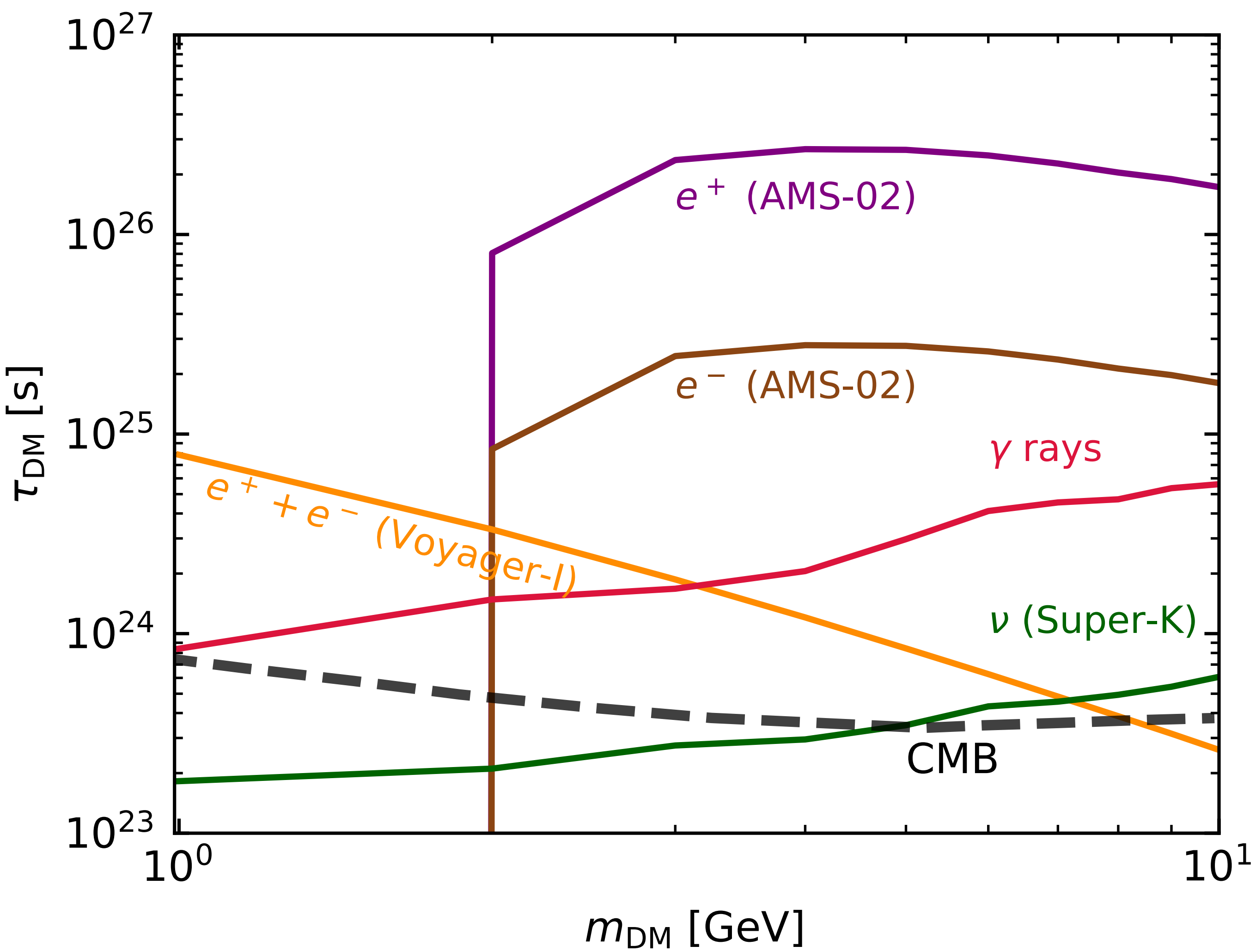
two gamma-ray sources from

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

prompt γ is less significant

since γ-ray appears as FSR

Summary plots of multi-messenger constraints



Das, Kamada, **TK**, Murase, Song (2025)

- assuming pure propagation model for $e^{\pm}$
- CMB constraints on decaying DM
  branching fraction ~ 0.1

Slatyer, Wu (2016)

- heavy ADM: strong constraints from e^+ flux

Constraints on Wilson coefficient of intermediate portal interaction

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

Summary and Discussions

Composite ADM with A' portal

- DM abundance by particle-antiparticle asymmetry
- Compositeness plays crucial role of providing key ingredients for ADM
- dark photon plays a role of releasing entropy in dark sector in early universe

Multi-Messenger probes

- Good probes for feeble dark sectors

- DM decay via portal interaction sharing asymmetries (neutrino signals)
- dark mesons/dark photon decay into EM particles via dark photon portal

Backup Slides

Formulae for primary spectrum with cascade decay

decay of scalar: $\phi_1 \to 2\phi_0 \to 2(\psi + X)$ $\pi' \to 2A' \to 2(e^+e^-(\gamma))$

light final states ψ

some irrelevant particles X

spectrum at ϕ_0 rest frame → 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: $\phi_2 \to \phi_1 + a \to 2\phi_0 + a \to 2(\psi + X) + a$ $N' \to \pi' + \nu$

spectrum at ϕ_1 rest frame → 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: $\tilde{\epsilon}_1 = 2m_\psi/m_2\,, \quad \epsilon_2 = m_1/m_0$

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 → 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

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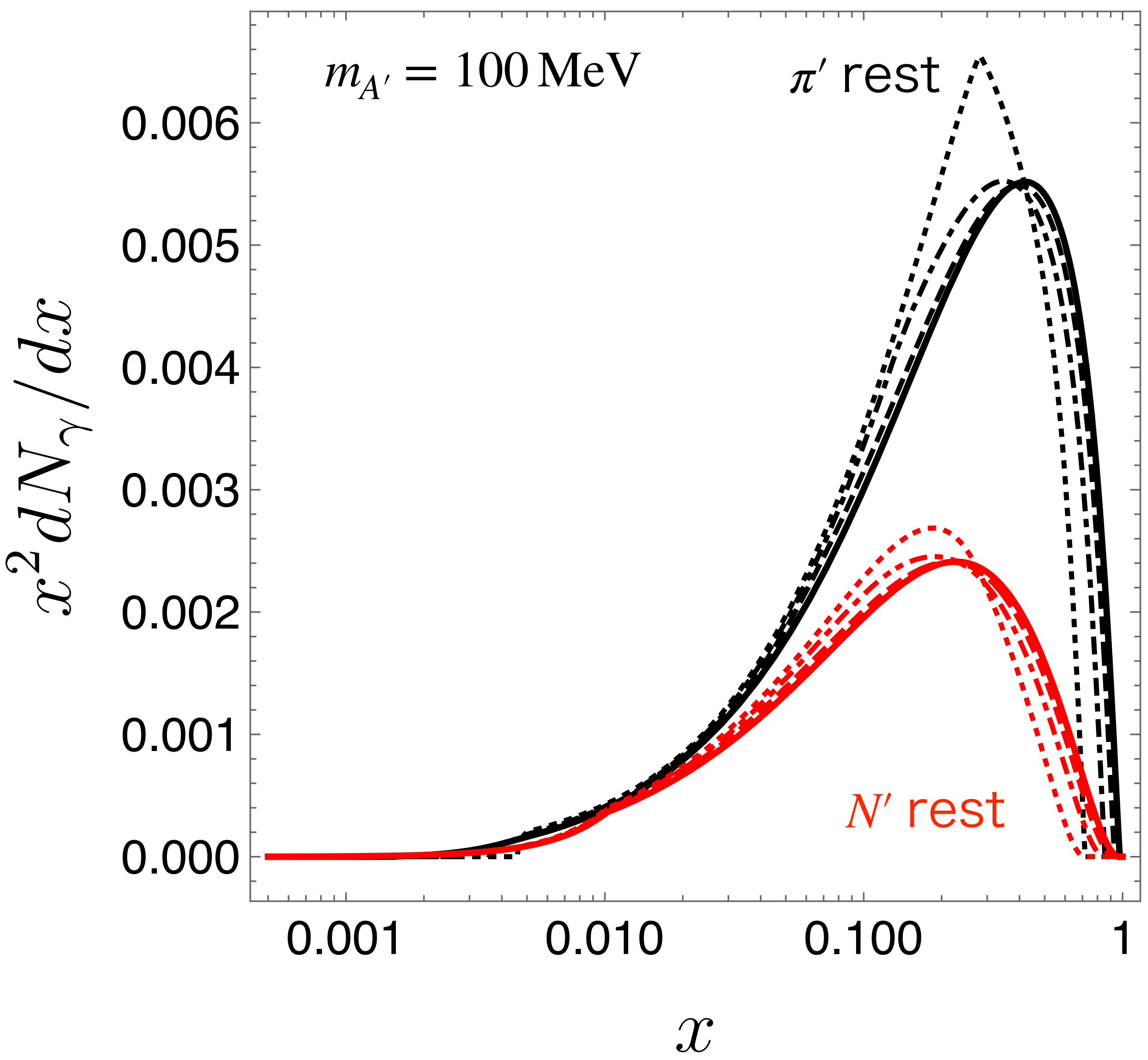
dimensionless mass parameters: $\tilde{\epsilon}_1 = 2m_\psi/m_2\,, \quad \epsilon_2 = m_1/m_0$

photon energy spectrum



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

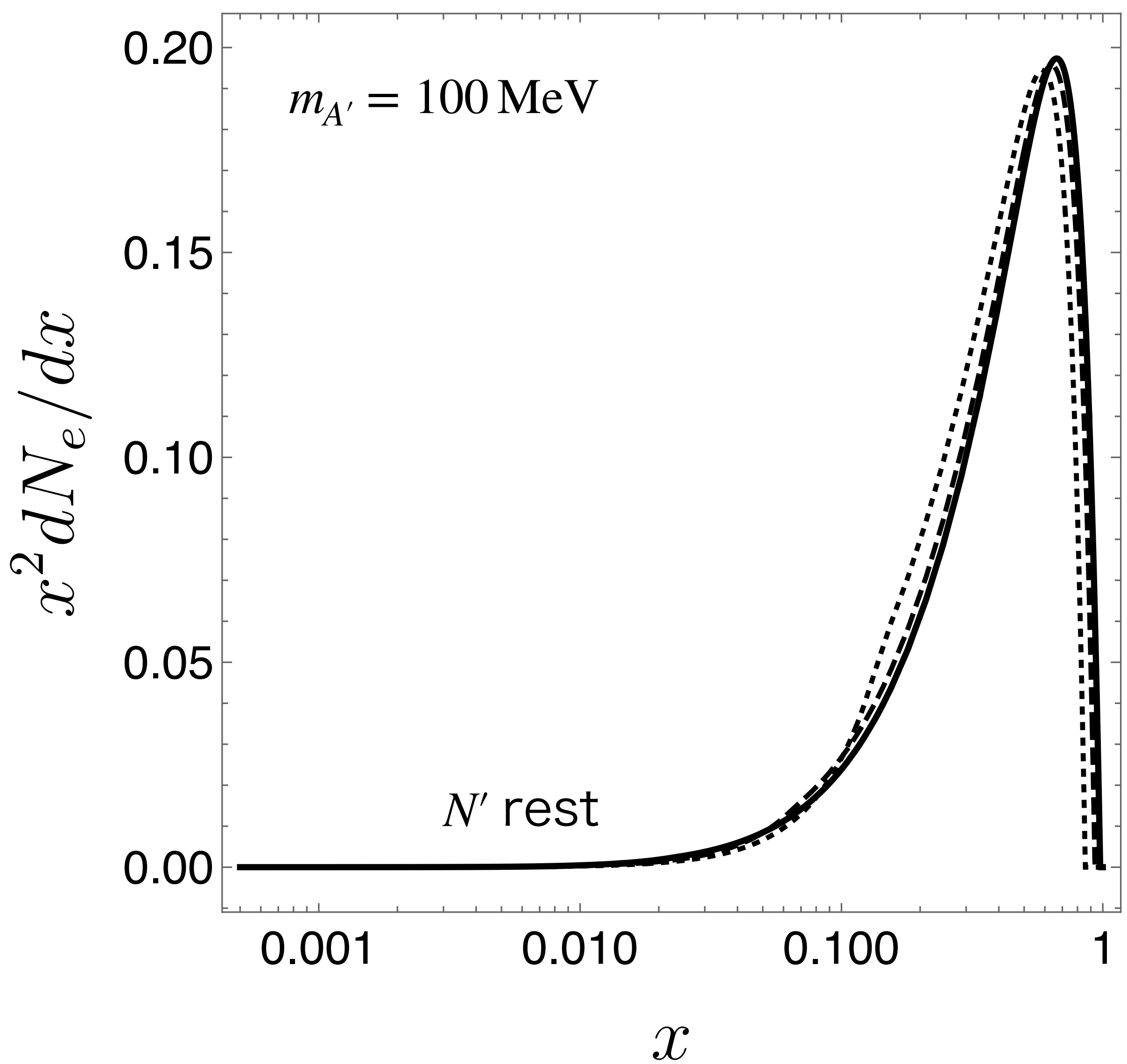
$2m_{\pi'}/m_{N'} = 0.1$

photon energy normalized by rest frame mass

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

photon spectrum widely distributed at a higher step in cascade decay

$e^{\pm}$ 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

$x = 2E_{e^-+e^+}/m_{N'}$

electron spectrum sharply distributed

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/cm3

fluxes originating from the direction θ

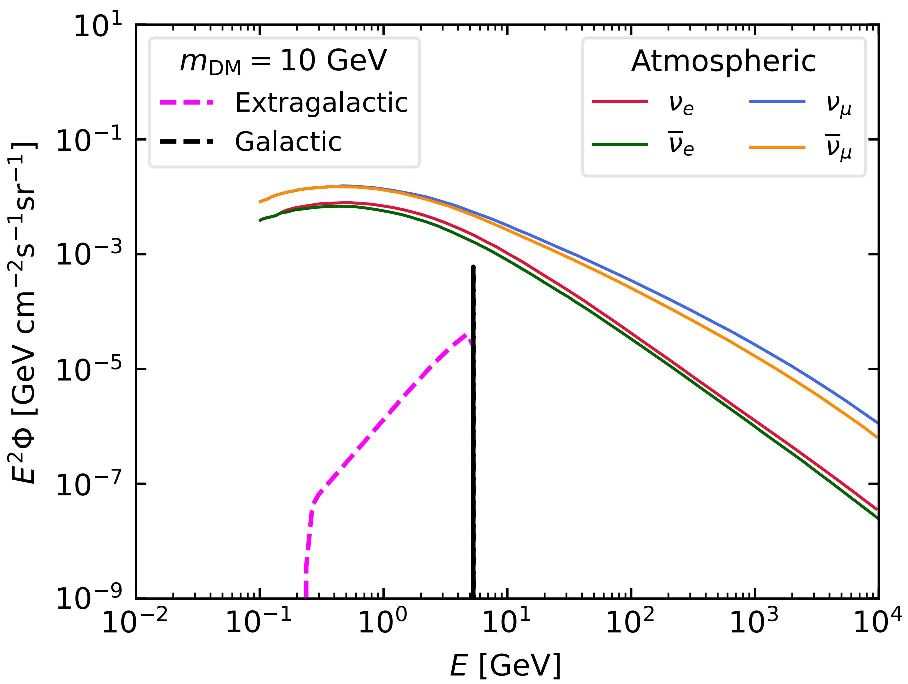
$$\Phi(E,\theta) = \frac{1}{4\pi m_\chi \tau_\chi}\frac{dN_s}{dE}\int_0^{s_{\rm max}(\theta)} \rho_\chi(R(s))ds = \frac{\rho_{\rm sc}R_{\rm sc}}{4\pi m_\chi \tau_\chi}\frac{dN_s}{dE}\mathcal{J}^{\rm dec}(\theta)$$

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

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

ADM decay spectrum

extragalactic component for neutrinos: integration over redshift z



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

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

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

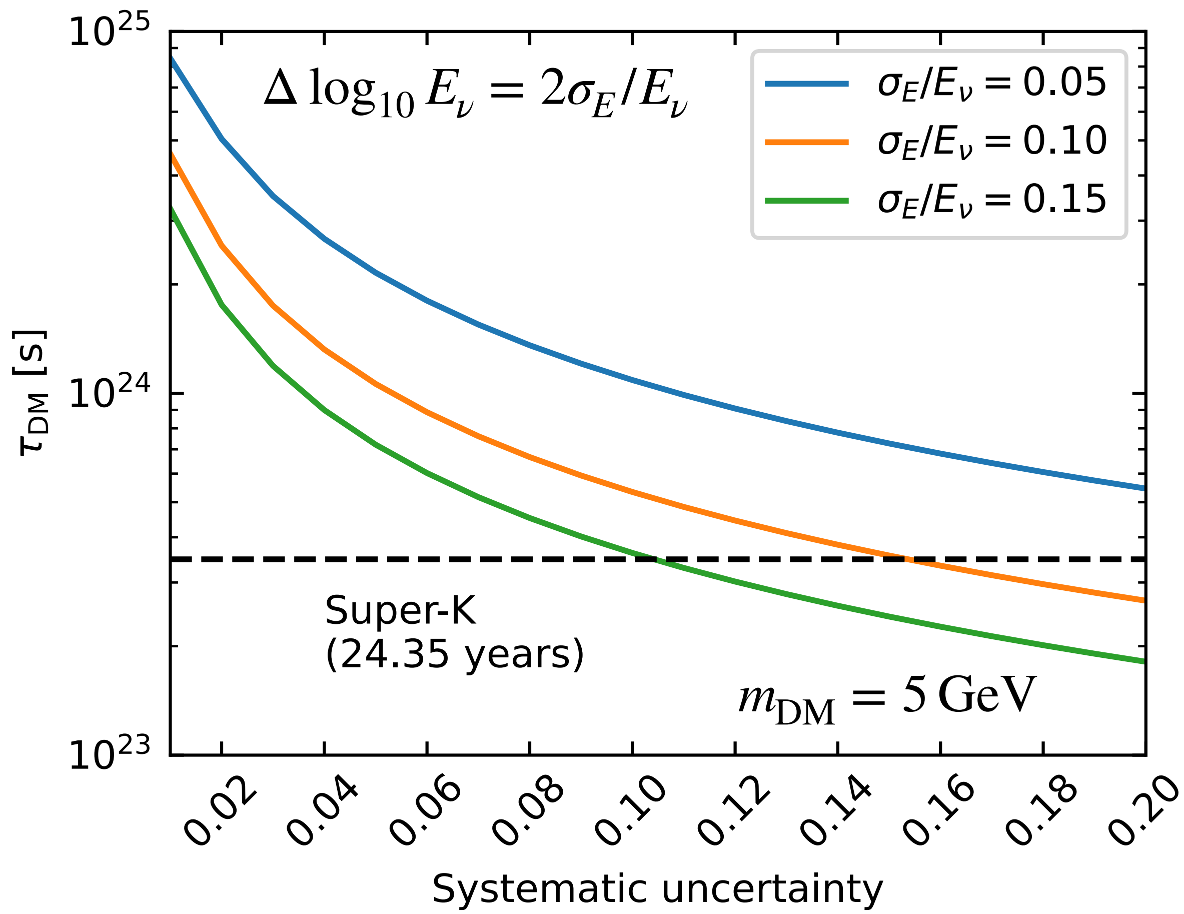
SN relic neutrinos: Super-K (2002)

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

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

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