JOHANNES GUTENBERG UNIVERSITÄT MAINZ

TAUP Topics in Astroparticle and Underground Physics

Impeded Dark Matter

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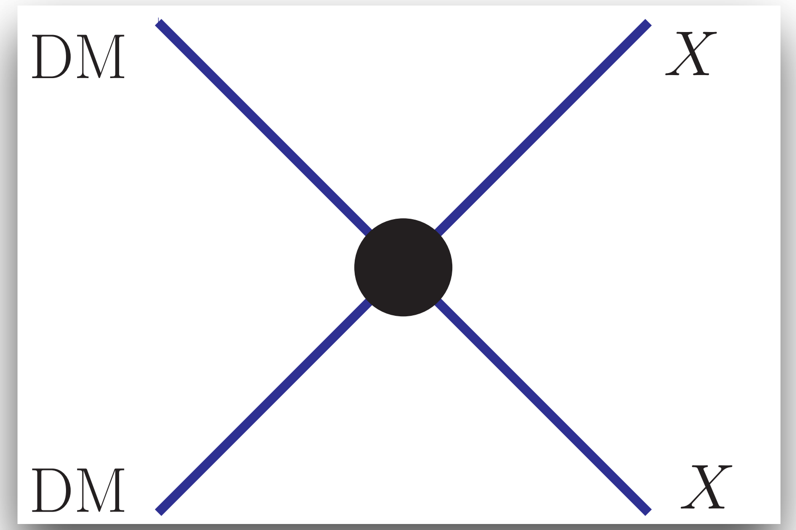
July, 26, 2017 @ TAUP 2017

JHEP12(2016)033 [arXiv:1609.02147]

Collaborated with Joachim Kopp, Jia Liu,Tracy R. Slatyer and Wei Xue

Motivation



$$\Delta = m_{\rm DM} - m_{\rm X}$$

$$\langle \sigma v_{\rm rel} \rangle \simeq \sigma_0 \sqrt{\frac{v_{\rm rel}^2}{4} + \frac{2\Delta}{m_{\rm DM}}}$$

- Linear dependence on $v_{\rm rel}$
- DM lighter than X: $\Delta < 0$
- DM heavier than X: $\Delta > 0$

Outline

✤**Dark SU(2) Gauge Boson as Impeded DM with** $\Delta < 0$

- Relic Density
- Direct Detection
- CMB
- Indirect Detection

✤**Dark Pion as Impeded DM with** $\Delta > 0$

Dark SU(2) Gauge Boson

$$\mathcal{L}_{\rm D} = -\frac{1}{4} K^a_{\mu\nu} K^a_{\mu\nu} + (D_\mu \Phi)^\dagger (D_\mu \Phi) - \mu^2 \Phi^\dagger \Phi + \frac{\lambda}{2} (\Phi^\dagger \Phi)^2$$

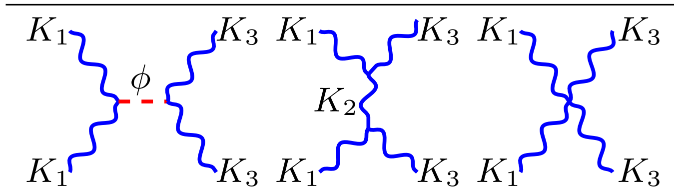
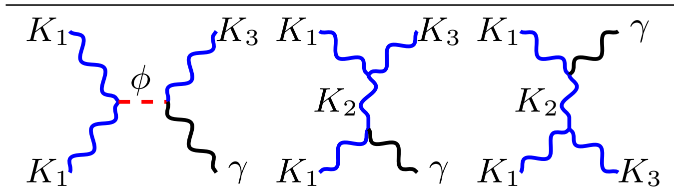
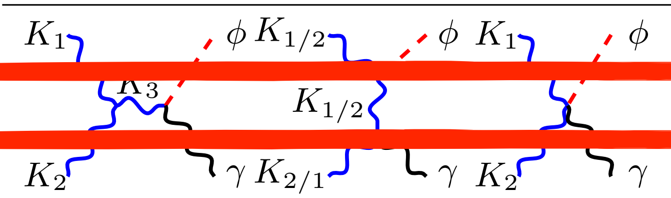
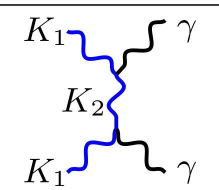
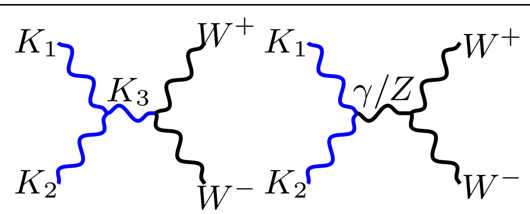
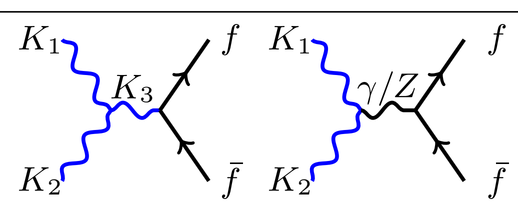
$$\mathcal{L}_{\rm mix} = \frac{1}{\Lambda^2} (\Phi^\dagger T^a \Phi) K^a_{\mu\nu} B_{\mu\nu}$$

$$\supset \frac{\varepsilon}{2} \left(1 + \frac{\phi}{v_d}\right)^2 \left[\partial_\mu K^3_\nu - \partial_\nu K^3_\mu + g_d (K^1_\mu K^2_\nu - K^2_\mu K^1_\nu)\right] \frac{1}{\cos\theta_w} B_{\mu\nu}$$

$$\Delta \equiv m_k - m_{K_3} \simeq -\frac{m_k}{2} \frac{\varepsilon^2}{\cos^2\theta_w} \frac{(m_k^2 - \cos^2\theta_w m^2_{Z,\rm SM})}{m_k^2 - m^2_{Z,\rm SM}}$$

$$\mathcal{L} \supset K_3^\mu \left(\varepsilon\, e J^\mu_{\rm em} - \varepsilon g \tan\theta_w \frac{m_k^2}{m_k^2 - m_Z^2} J^\mu_Z \right)$$

Relic Density

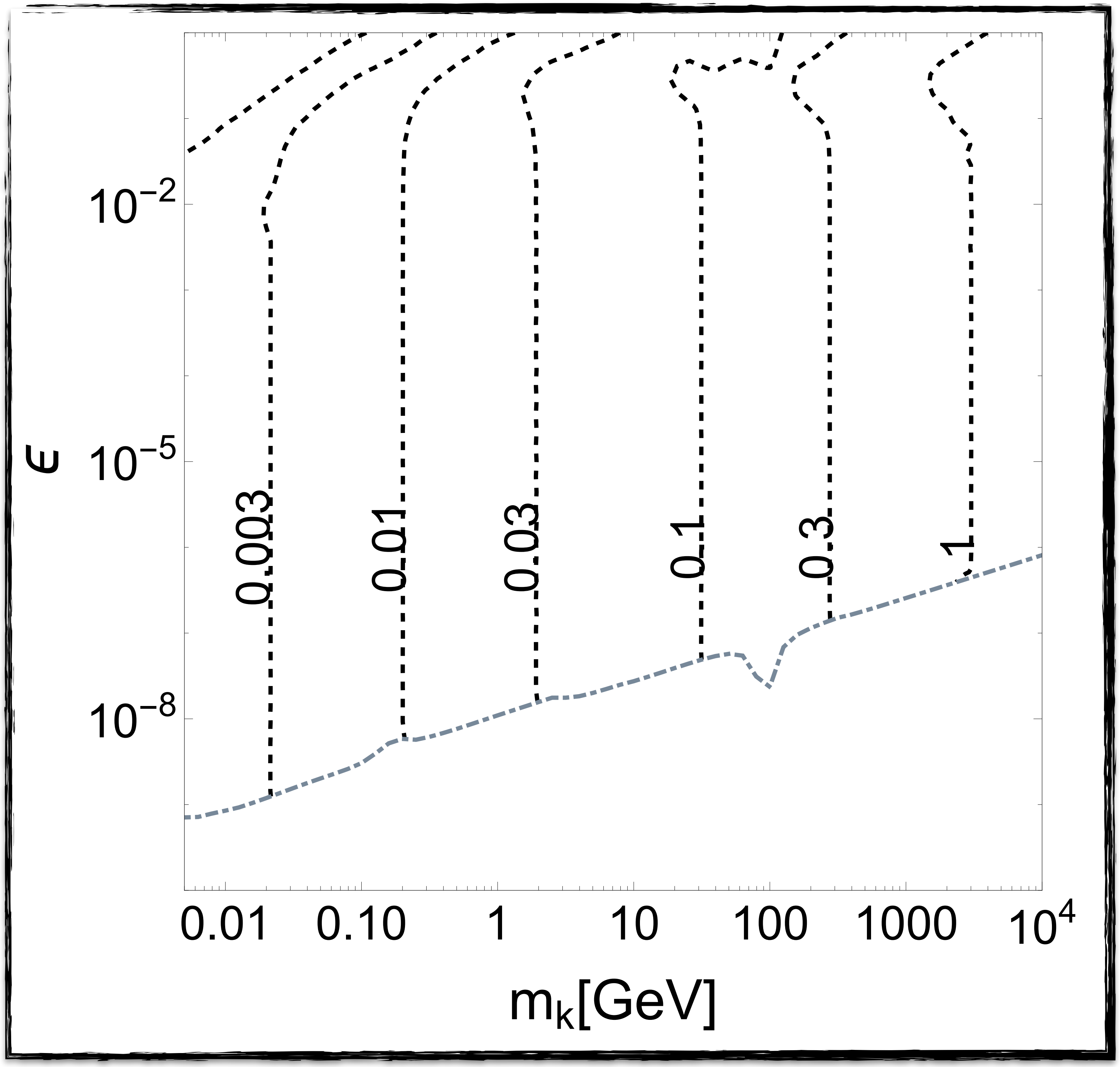
process	$v_{\rm rel}$-dependence	ε-dependence	freeze-out
	$\sqrt{\frac{v_{\rm rel}^2}{4} + \frac{2\Delta}{m_{\rm DM}}}$	1	dominant
	1	ε^2	subdominant
	1	ε^2	subdominant (requires $m_\phi < 2m_k$)
	1	ε^4	negligible
	$v_{\rm rel}^2$	ε^2	subdominant
	$v_{\rm rel}^2$	ε^2	subdominant

Relic Density

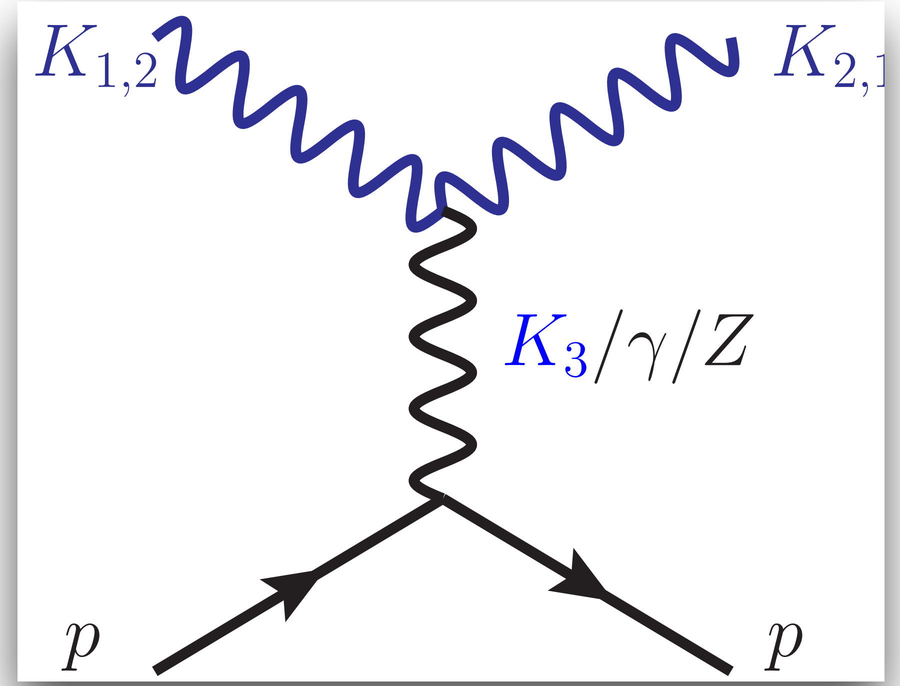
$$\dot{n}_{12} + 3Hn_{12} = -\frac{1}{2}\langle\sigma v\rangle_{11\to 33}\left[n_{12}^2 - n_3^2\left(\frac{n_{12}^{\rm eq}}{n_3^{\rm eq}}\right)^2\right] - \frac{1}{2}\langle\sigma v\rangle_{11\to 3\gamma}\left[n_{12}^2 - (n_{12}^{\rm eq})^2\frac{n_3}{n_3^{\rm eq}}\right] - \frac{1}{2}\langle\sigma v\rangle_{12\to f\bar{f},W^+W^-}\left[n_{12}^2 - (n_{12}^{\rm eq})^2\right]$$

$$\dot{n}_3 + 3Hn_3 = \frac{1}{2}\langle\sigma v\rangle_{11\to 33}\left[n_{12}^2 - n_3^2\left(\frac{n_{12}^{\rm eq}}{n_3^{\rm eq}}\right)^2\right] + \frac{1}{4}\langle\sigma v\rangle_{11\to 3\gamma}\left[n_{12}^2 - (n_{12}^{\rm eq})^2\frac{n_3}{n_3^{\rm eq}}\right] - \Gamma_{K_3}\left[n_3 - n_3^{\rm eq}\right]$$

Relic Density

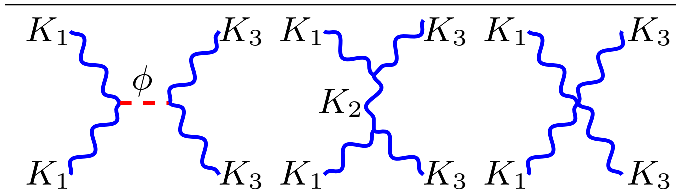
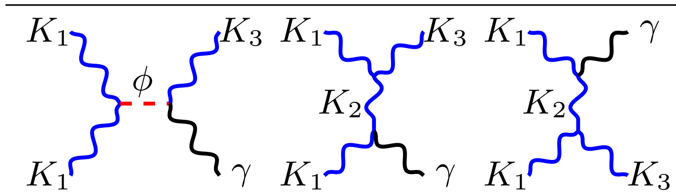
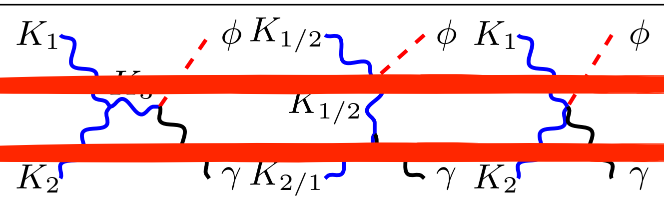
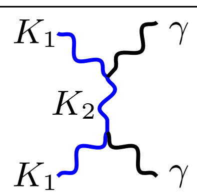
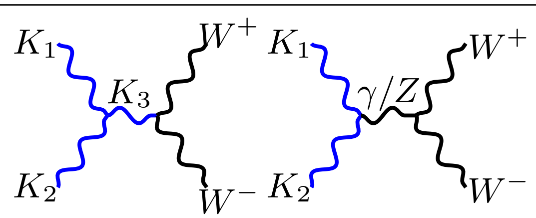
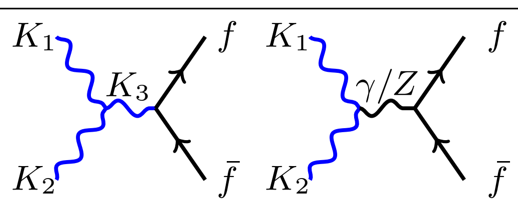


Direct Detection

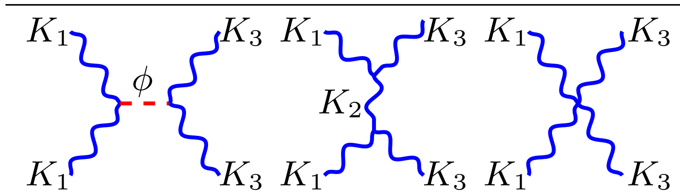
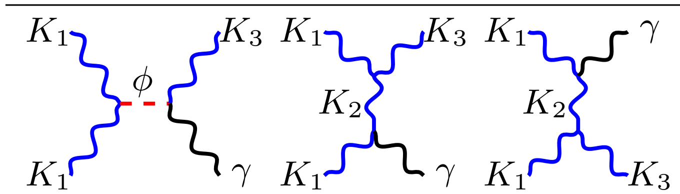
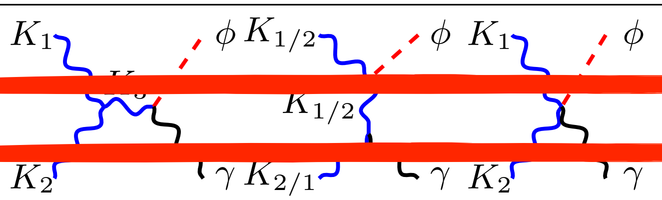
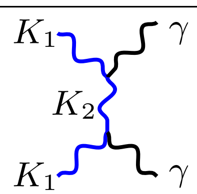
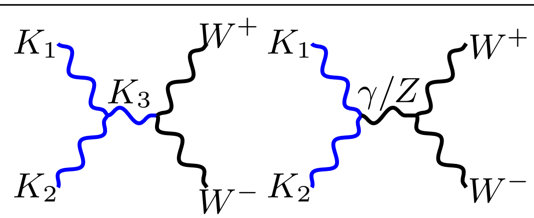
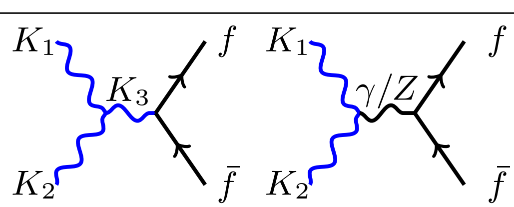


$$\frac{d\sigma_{\rm SI}}{dE_r} = \frac{2\pi\alpha_{\rm em}\alpha_d(Z\varepsilon)^2}{3m_k^2 E_r}\left(1 + \frac{E_r}{4E_{\rm in}}\frac{m_N^2 - 2m_k m_N - m_k^2}{m_k m_N}\right)F_{\rm SI}^2(E_r)$$

CMB

process	v_{rel}-dependence	ε-dependence	CMB
	$\sqrt{\frac{v_{\text{rel}}^2}{4} + \frac{2\Delta}{m_{\text{DM}}}}$	1	negligible
	1	ε^2	dominant
	1	ε^2	dominant (requires $m_\phi < 2m_k$)
	1	ε^4	negligible
	v_{rel}^2	ε^2	negligible
	v_{rel}^2	ε^2	negligible

CMB

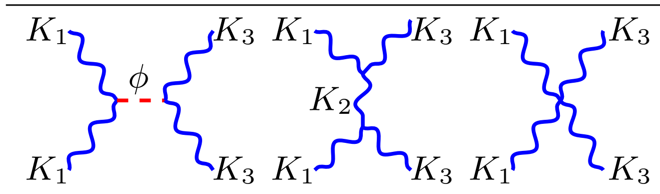
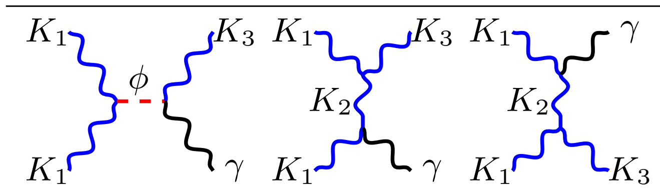
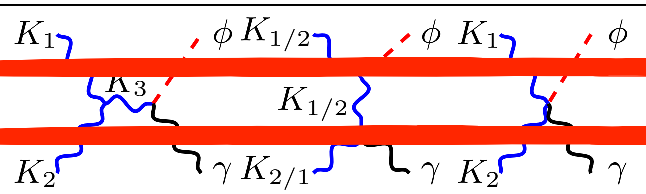
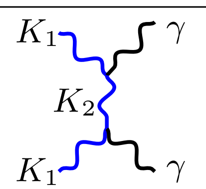
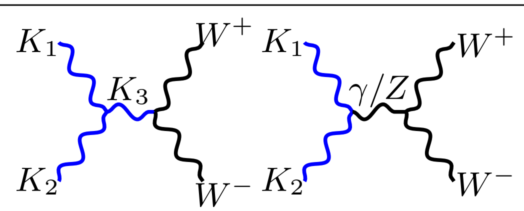
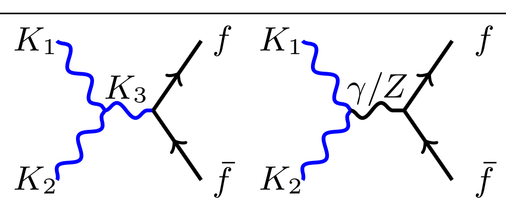
process	$v_{\rm rel}$-dependence	ε-dependence	CMB
	$\sqrt{\frac{v_{\rm rel}^2}{4}+\frac{2\Delta}{m_{\rm DM}}}$	1	negligible
	1	ε^2	dominant
	1	ε^2	dominant (requires $m_\phi < 2m_k$)
	1	ε^4	negligible
	$v_{\rm rel}^2$	ε^2	negligible
	$v_{\rm rel}^2$	ε^2	negligible

$$p_{\rm ann} = f_{\rm eff}\frac{\langle\sigma v\rangle}{m_{\rm DM}}$$

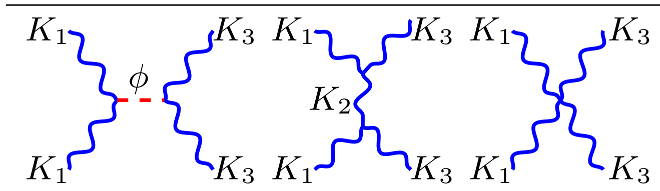
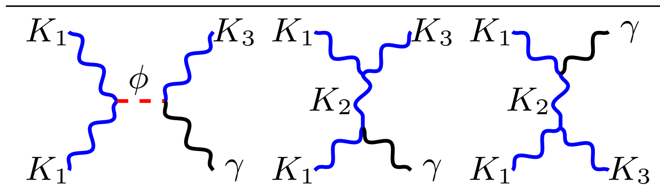
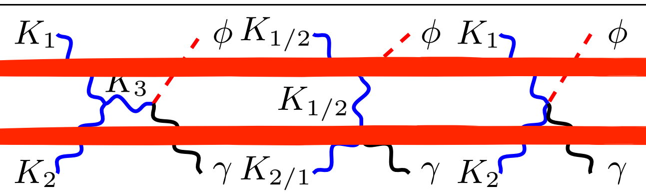
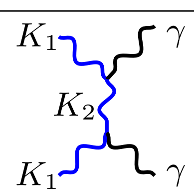
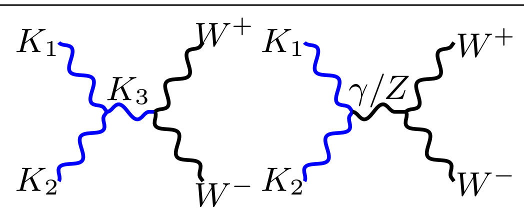
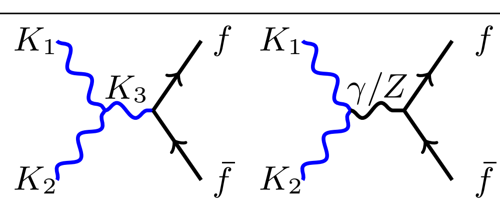
$$f_{\rm eff} = \frac{E_{K_3}}{E_{K_3}+E_\gamma} f_{\rm eff}^{K_3}(E_{K_3}) + \frac{E_\gamma}{E_{K_3}+E_\gamma} f_{\rm eff}^{\gamma}(E_\gamma)$$

$$\sum_i \mathrm{BR}_{\mathrm{K_3\to SM_iSM_i}}(\mathrm{m_k},\epsilon)\,\mathrm{f}_{\mathrm{eff}}^{\mathrm{SM_iSM_i}}(\mathrm{E_{K_3}}/2)$$

Indirect Detection

process	$v_{\rm rel}$-dependence	ε-dependence	Indirect Detection
	$\sqrt{\frac{v_{\rm rel}^2}{4}+\frac{2\Delta}{m_{\rm DM}}}$	1	✓
	1	ε^2	✓ (γ line)
	1	ε^2	✓ (γ line if $m_\phi < 2m_k$)
	1	ε^4	negligible
	$v_{\rm rel}^2$	ε^2	negligible
	$v_{\rm rel}^2$	ε^2	negligible

Indirect Detection

process	$v_{\rm rel}$-dependence	ε-dependence	Indirect Detection
	$\sqrt{\frac{v_{\rm rel}^2}{4} + \frac{2\Delta}{m_{\rm DM}}}$	1	✓
	1	ε^2	✓ (γ line)
~~~~	~~1~~	~~ε^2~~	~~✓ (γ line if $m_\phi < 2m_k$)~~
	1	ε^4	negligible
	$v_{\rm rel}^2$	ε^2	negligible
	$v_{\rm rel}^2$	ε^2	negligible

- Gamma Spectrum Limit

$$\frac{d\Phi}{dE_\gamma d\Omega} = \frac{1}{8\pi c m_{\rm DM}^2} J(\theta,\phi) \sum_X \langle\sigma v\rangle_X \frac{dN_\gamma^X}{dE_\gamma}$$

$$J(\theta,\phi) = \int_{\rm l.o.s.} ds\, \rho_{\rm DM}^2(s,\theta,\phi)$$

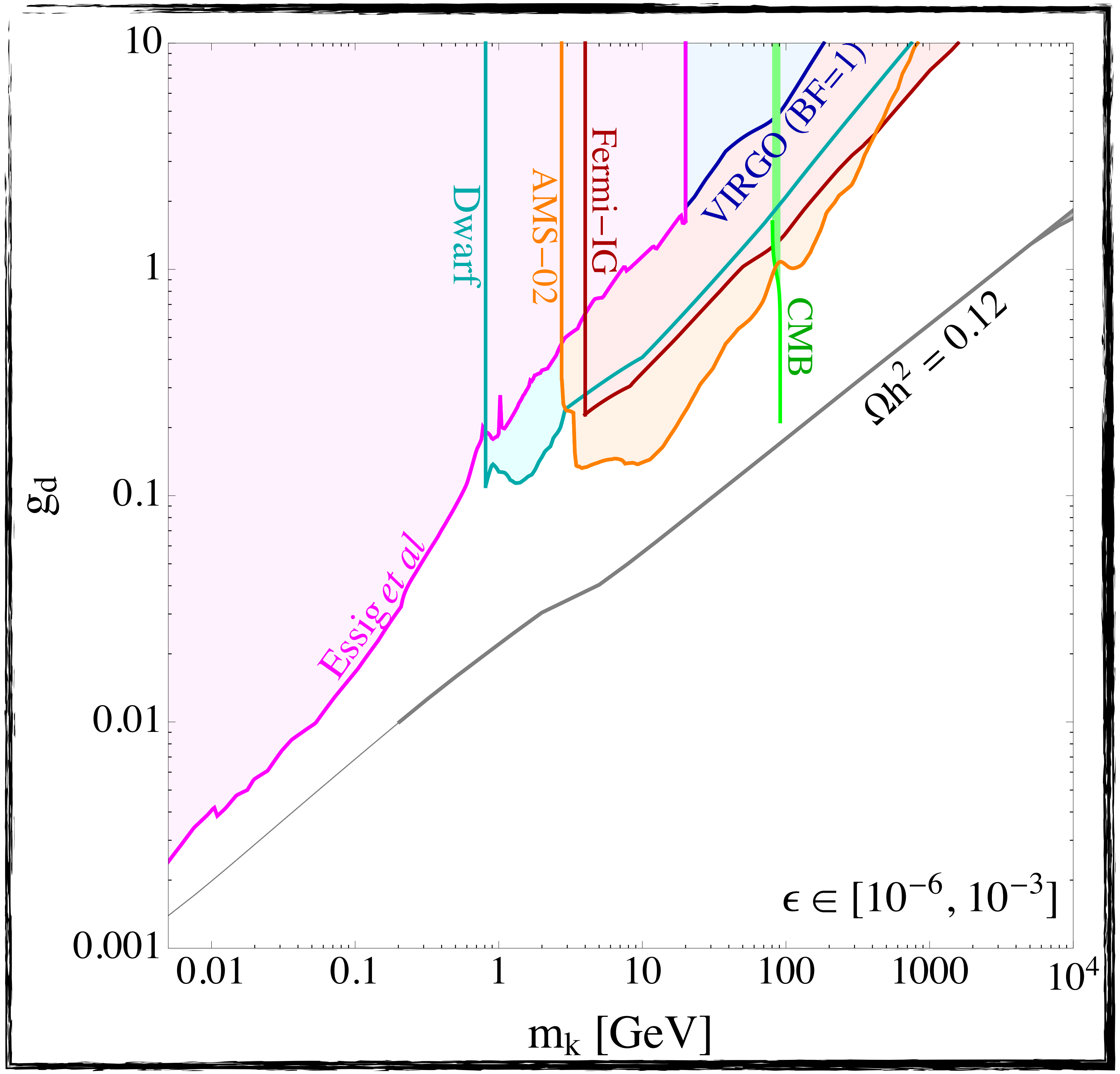
- e+ e- Limit

$$\frac{2}{c}\left[\langle\sigma v_{\rm rel}\rangle_{11\to33} + \langle\sigma v_{\rm rel}\rangle_{22\to33}\right]$$

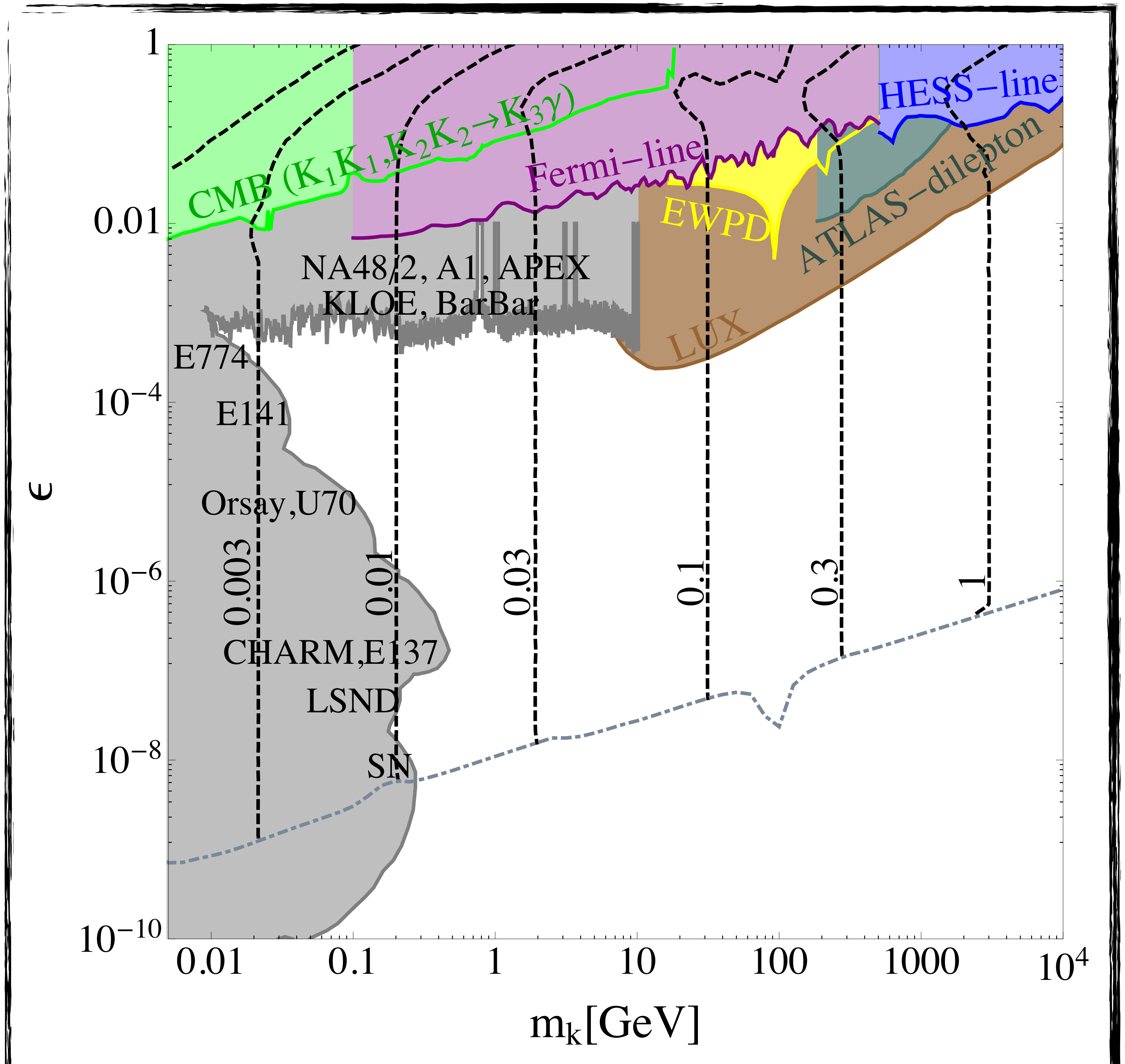
- Gamma Line Limit

$$\langle\sigma v\rangle_{11\to\gamma3} + \langle\sigma v\rangle_{22\to\gamma3}$$

Indirect Detection



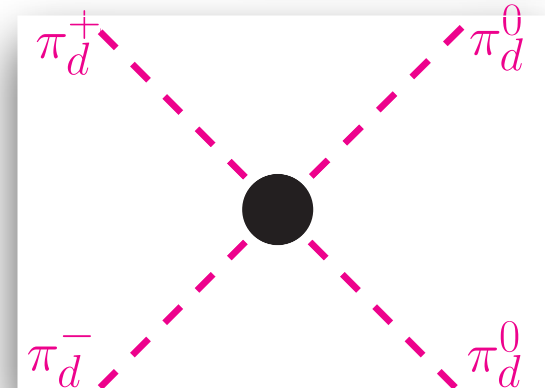
Combined Result



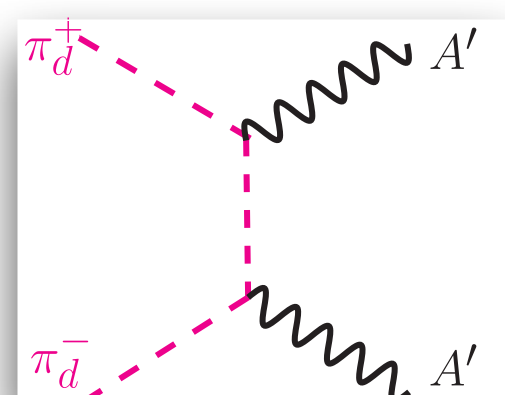
Dark Pion

$$\mathcal{L} = \frac{1}{4} f_\pi^2 \mathrm{Tr}\left[\partial_\mu U^\dagger \partial^\mu U\right] + \mu \frac{f_\pi^2}{2} \mathrm{Tr}\left[U^\dagger M + M^\dagger U\right]$$

$$\Delta \equiv m_{\pi_d^\pm} - m_{\pi_d^0} \approx \frac{g'^2}{16\pi^2} \frac{\Lambda_N^2}{2m_\pi}$$



$$(\sigma v_{\mathrm{rel}})_{00} = \sigma_0 \times \sqrt{\frac{v_{\mathrm{rel}}^2}{4} + \frac{2\Delta}{m_\pi}}$$
$$\simeq 6 \times 10^{-26} \mathrm{cm}^3 \, \mathrm{sec}^{-1} \times \left(\frac{m_\pi / f_\pi^2}{7 \times 10^{-4} \mathrm{GeV}^{-1}}\right)^2$$



$$(\sigma v_{\mathrm{rel}})_{A'A'} \simeq \frac{g'^4}{8\pi m_\pi^2}\left(1 - \frac{m_{A'}^2}{m_\pi^2} + \frac{3m_{A'}^4}{8m_\pi^4}\right) \frac{\sqrt{1 - m_{A'}^2/m_\pi^2}}{\left[1 - m_{A'}^2/(2m_\pi^2)\right]^2}$$

Constraint on dark pion

- **Thermal Equilibrium Condition**

$$\Gamma(\pi_d^0 \to A'A') = \frac{g'^4 m_\pi^3}{1024\pi^5 f_\pi^2}\left(1 - \frac{4m_A'^2}{m_\pi^2}\right)^{3/2} > H(T = m_\pi)$$

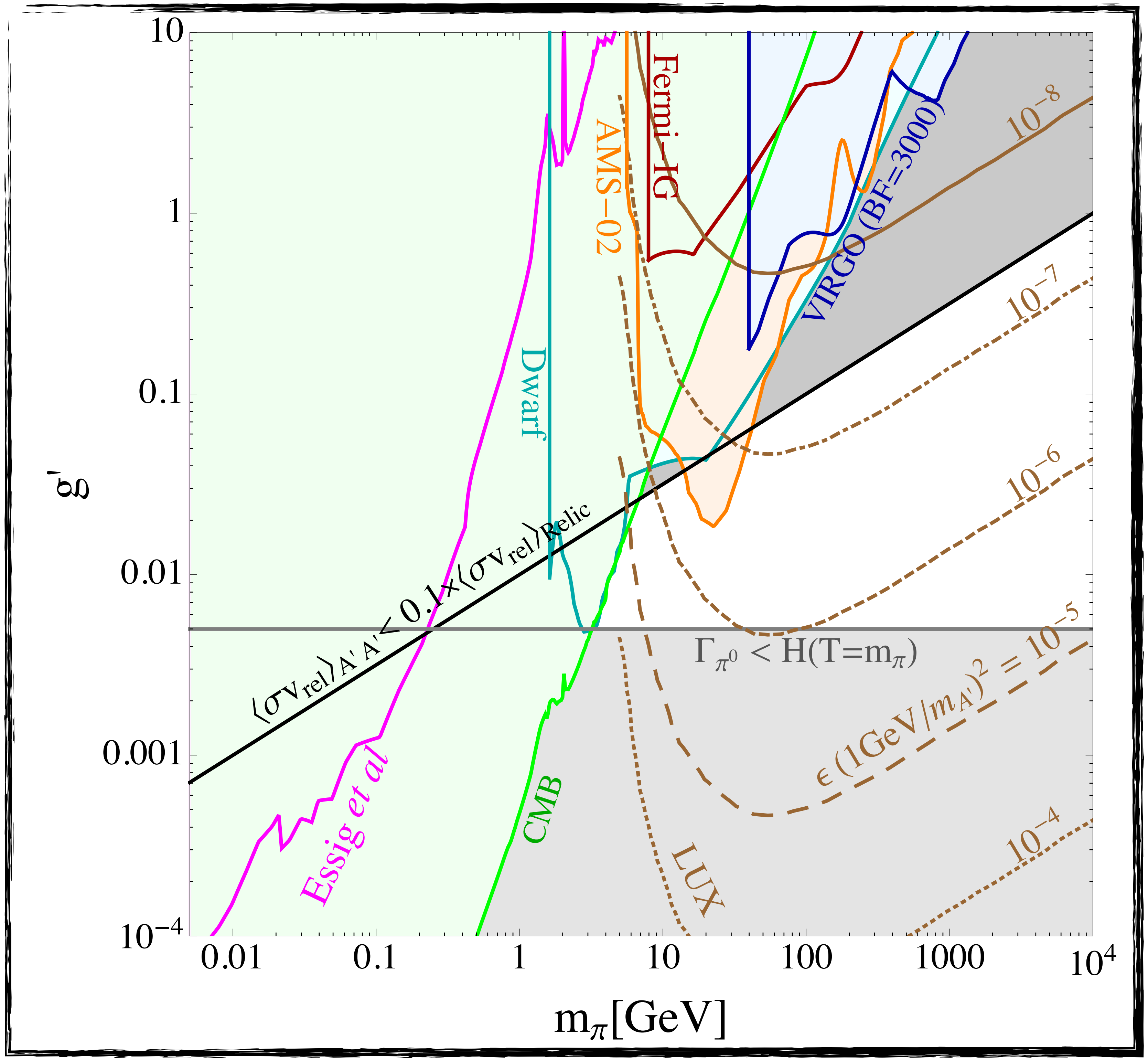
- **Direct detection**

$$\sigma_p = e^2\epsilon^2 g'^2 \frac{(m_\pi m_p)^2}{\pi m_{A'}^4 (m_\pi + m_p)^2} \simeq 10^{-47}\mathrm{cm}^2 \left(\frac{g'}{10^{-2}}\right)^2 \left(\frac{\epsilon}{10^{-7}}\right)^2 \left(\frac{\mathrm{GeV}}{m_{A'}}\right)^4$$

- **Indirect detection**

$$\sigma v_{\mathrm{rel}} \simeq 6 \times 10^{-26}\mathrm{cm}^3\,\mathrm{sec}^{-1} \times \left(\frac{m_\pi / f_\pi^2}{7 \times 10^{-4}\mathrm{GeV}^{-1}}\right)^2$$

Constraint on dark pion




Thank You
Thank You!
Thanks!