Hidden Monopole Dark Matter via Axion Portal and its Implications for Direct Search and Beam-Dump experiments

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Hidden monopole dark matter

- **Hidden monopole is a good dark matter (DM) candidate.**
  - **It is an inevitable topological object if the universe experiences a phase transition in the hidden sector.**
  - **Its stability is ensured by the topological nature.**

Can we detect the hidden monopole DM?

A : No, at least in the minimum setup. One has to introduce certain couplings with the standard model (SM) sector.

Hidden monopole DM-SM interactions

- There are three possible portals connecting the hidden monopole DM and the SM sector.
  - Higgs portal (expected scattering cross-section is very small)
  - Vector portal (strictly constrained by many exps. and obs.)

    (c.f. Jaeckel & Ringwald, 2010)
  - Axion portal ← Our main interest

    (c.f. W. Fischler & J. Preskill 83')

’t Hooft-Polyakov monopole

- It is well-known that a magnetic monopole can arise when a non-abelian gauge symmetry is spontaneously broken via the Higgs mechanism.

’t Hooft, Polyakov '74

$$\mathrm{SU}(2)_{\mathrm{H}} + \boldsymbol{\phi} = (\phi_1, \phi_2, \phi_3)$$

$$\mathcal{L}_{\mathrm{H}} = -\frac{1}{4}\boldsymbol{F}_{\mathrm{H}}^{\mu\nu} \cdot \boldsymbol{F}_{\mathrm{H}\mu\nu} + \frac{1}{2}\mathcal{D}^{\mu}\boldsymbol{\phi} \cdot \mathcal{D}_{\mu}\boldsymbol{\phi} - \mathcal{V}(\phi)$$

$\times$: products in the

$\cdot$ group space

$$\boldsymbol{F}_{\mathrm{H}}^{\mu\nu} = \partial^{\mu}\boldsymbol{A}_{\mathrm{H}}^{\nu} - \partial^{\nu}\boldsymbol{A}_{\mathrm{H}}^{\mu} + e_{\mathrm{H}}\boldsymbol{A}_{\mathrm{H}}^{\mu} \times \boldsymbol{A}_{\mathrm{H}}^{\nu}$$

$$\mathcal{D}^{\mu}\boldsymbol{\phi} = \partial^{\mu}\boldsymbol{\phi} + e_{\mathrm{H}}\boldsymbol{A}_{\mathrm{H}}^{\mu} \times \boldsymbol{\phi} \qquad \mathcal{V}(\phi) = \frac{1}{4}\lambda_{\phi}\left(\phi^2 - v_{\mathrm{H}}^2\right)^2$$

hidden gauge coupling

vev of the scalar field

't Hooft-Polyakov monopole

- **Expand the Lagrangian density around the vacuum state**

$$\phi \to \phi + (0, 0, v_{\rm H}) \quad \longrightarrow \quad {\rm SU}(2)_{\rm H} \xrightarrow{\langle\phi\rangle} {\rm U}(1)_{\rm H}$$

- **Particle spectrum in the hidden sector** $\alpha_{\rm H} = e_{\rm H}^2/(4\pi)$
  - **Monopole is a static solution with finite energy configuration.**

Particle	Mass	Hidden electric charge	Hidden magnetic charge
$\gamma_{\rm H}$	0	0	0
φ	$m_\varphi = \sqrt{2\lambda_\phi}\, v_{\rm H}$	0	0
$W_{\rm H}^{\pm}$	$m_{W'} = \sqrt{4\pi\alpha_{\rm H}}\, v_{\rm H}$	$Q_{\rm E} = \pm e_{\rm H}$	0
${\rm M}(\overline{\rm M})$	$m_{\rm M} = \sqrt{4\pi/\alpha_{\rm H}}\, v_{\rm H}$	$Q_{\rm E} = \pm e_{\rm H}\theta_{\rm H}/(2\pi)$	$Q_{\rm M} = \pm 4\pi/e_{\rm H}$

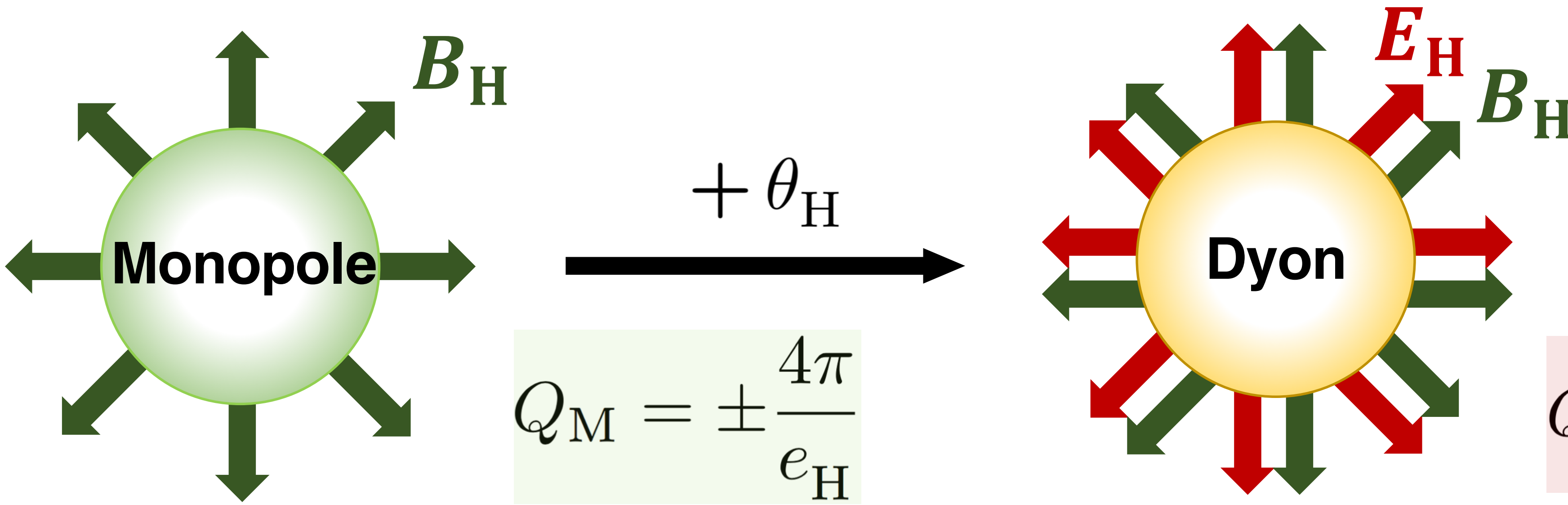
The Witten effect

Witten '79

- The theta term of hidden U(1) gauge symmetry

$$\mathcal{L}_\theta = \theta_\mathrm{H} \frac{e_\mathrm{H}^2}{32\pi^2} F_\mathrm{H}^{\mu\nu} \widetilde{F}_{\mathrm{H}\mu\nu} = -\theta_\mathrm{H} \frac{e_\mathrm{H}^2}{8\pi^2} \boldsymbol{E}_\mathrm{H} \cdot \boldsymbol{B}_\mathrm{H}$$

  - This term usually has no effect since it is a total derivative. However, it has physical effect in the monopole background.

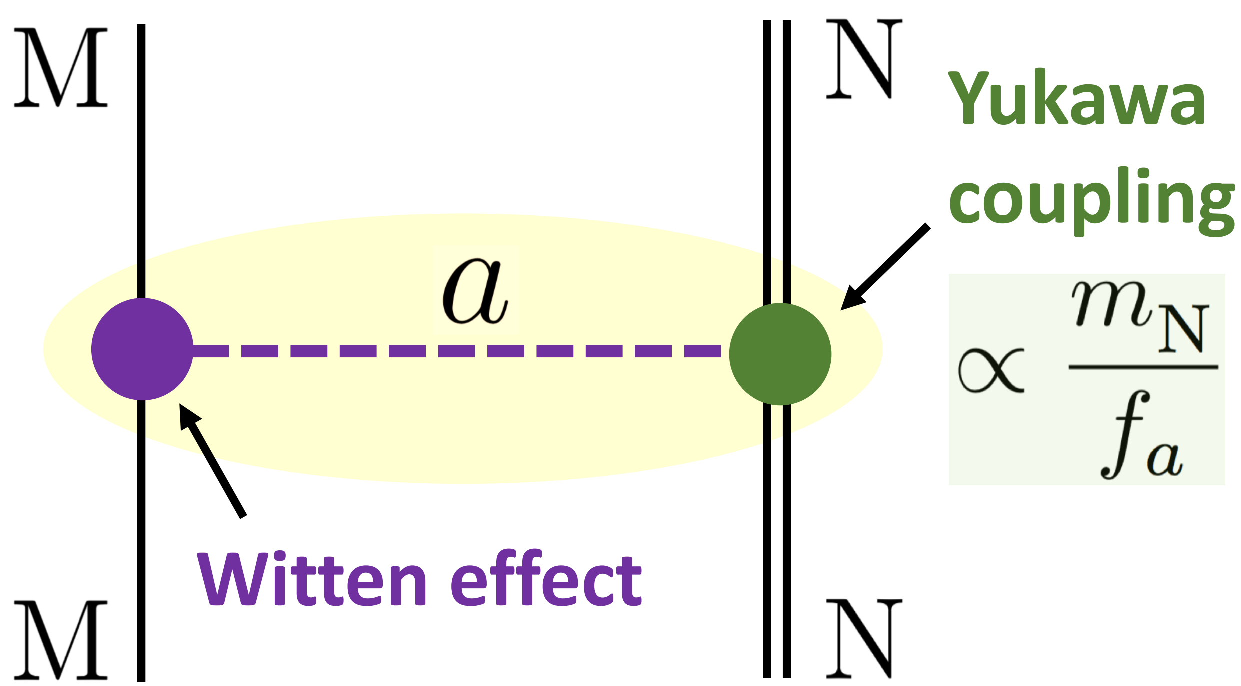


$$Q_\mathrm{M} = \pm \frac{4\pi}{e_\mathrm{H}}$$

$$Q_\mathrm{E} = \pm \frac{e_\mathrm{H}\theta_\mathrm{H}}{2\pi}$$

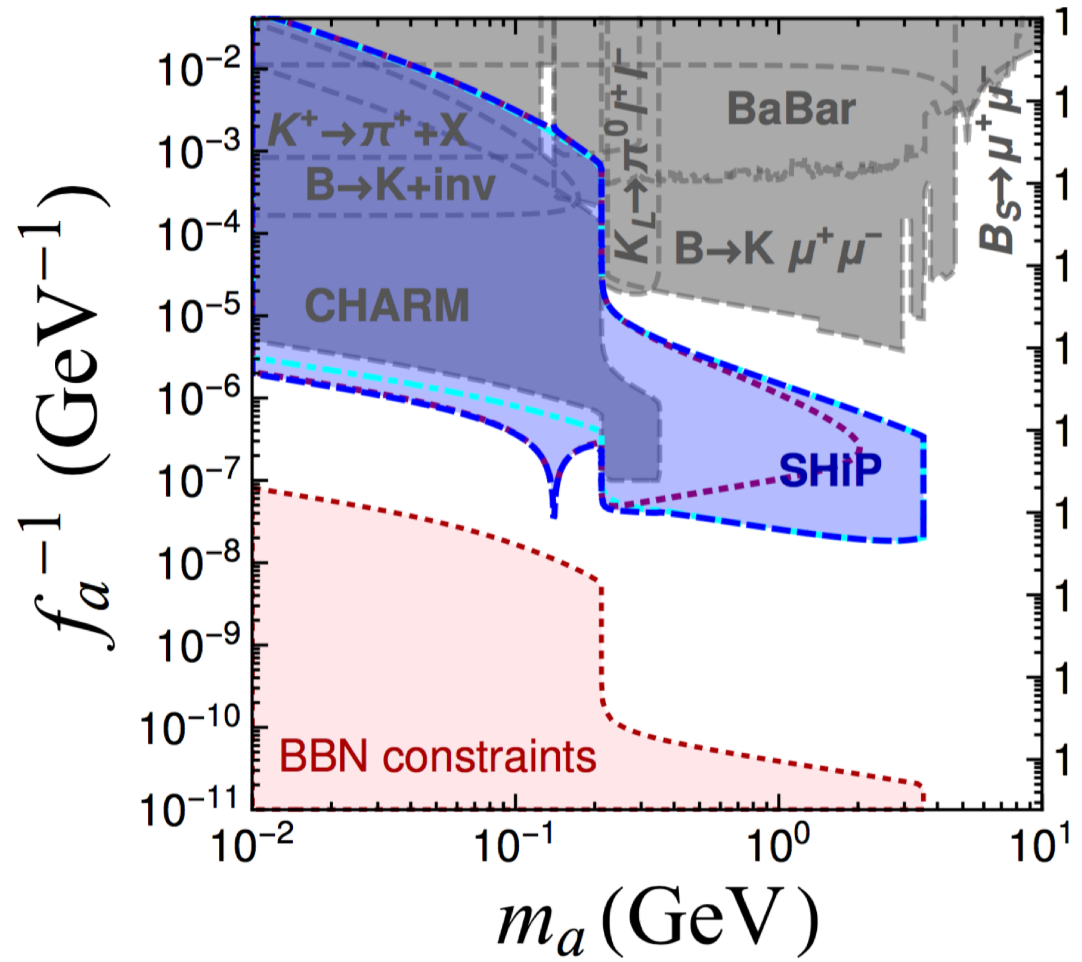
What we did

- **Axion portal coupling + Yukawa interactions**



Direct search experiments

S. Alekhin et al. 16'



Beam-dump experiments

Axion portal coupling

Lagrangian density

$$\mathcal{L} = -\frac{1}{4}F_{\mathrm{H}}^{\mu\nu}F_{\mathrm{H}\mu\nu} + \frac{1}{2}f_a^2\partial^\mu\theta\partial_\mu\theta - \frac{1}{2}m_a^2 f_a^2(\theta-\theta_0)^2 + \theta\frac{e_{\mathrm{H}}^2}{32\pi^2}F_{\mathrm{H}}^{\mu\nu}\widetilde{F}_{\mathrm{H}\mu\nu}$$

(c.f. W. Fischler & J. Preskill 83')

$$F_{\mathrm{H}}^{\mu\nu} = \partial^\mu A_{\mathrm{H3}}^\nu - \partial^\nu A_{\mathrm{H3}}^\mu \qquad \theta \equiv a/f_a + \theta_{\mathrm{H}}$$

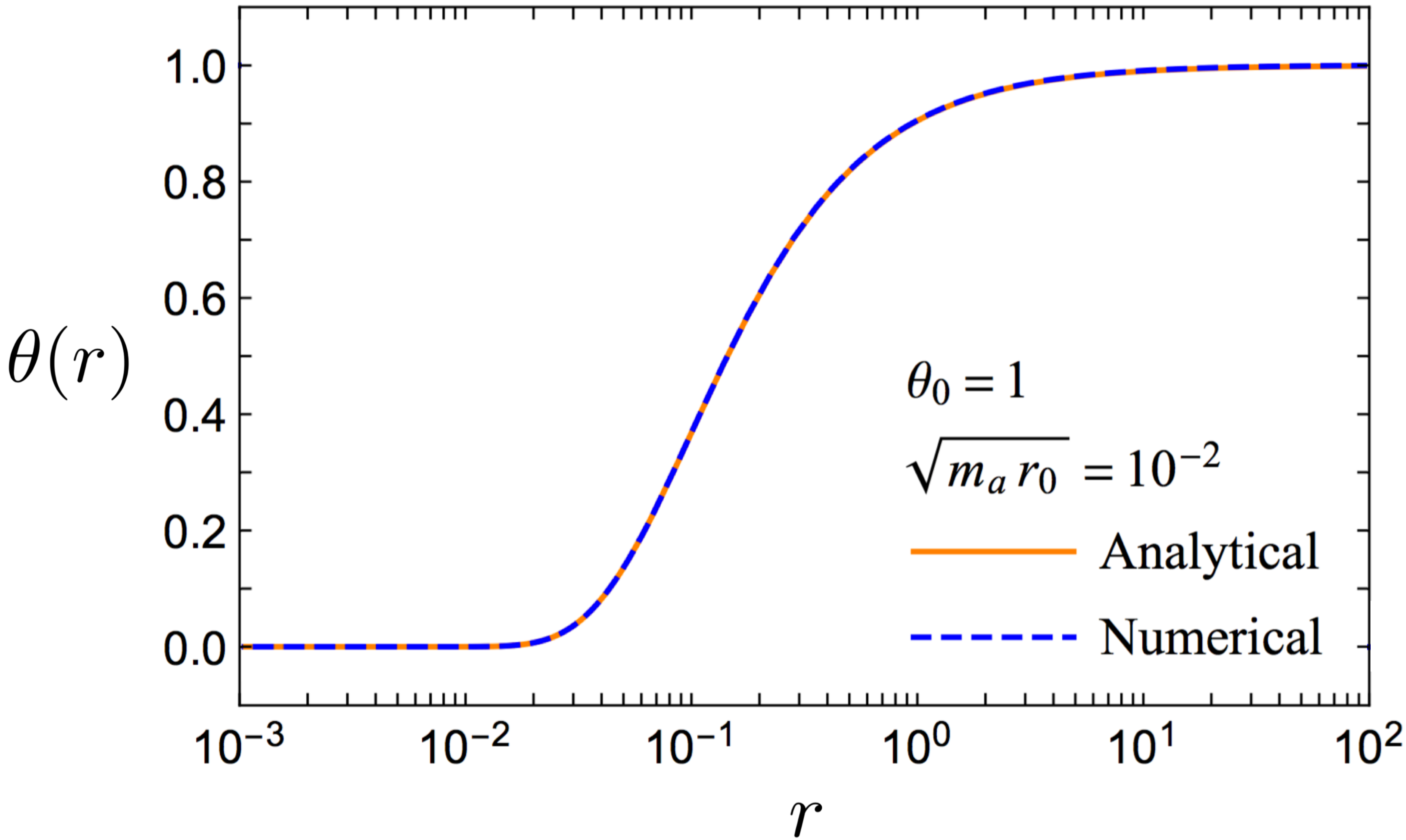
Equation of motion of the axion field

$$\frac{d^2\theta}{dr^2} + \frac{2}{r}\frac{d\theta}{dr} - \left(m_a^2 + \frac{r_0^2}{r^4}\right)\theta + m_a^2\theta_0 = 0 \qquad r_0 = \frac{e_{\mathrm{H}}}{8\pi^2 f_a}$$

Boundary conditions : $\theta(r\to 0) = 0\ , \quad \theta(r\to\infty) = \theta_0$

The total energy density of the axion-monopole system must be finite.

Axion profile around the monopole



Hidden monopole-nucleon scattering

- **Axion-nucleon interaction (Yukawa coupling)**

$$H_{a-\mathrm{N}} = i\frac{m_{\mathrm{N}}}{f_a}\int d^3x\left[a(x)\overline{\psi}_{\mathrm{N}}(x)\gamma^5\psi_{\mathrm{N}}(x)\right]$$

- **Amplitude of the hidden monopole-nucleon scattering**

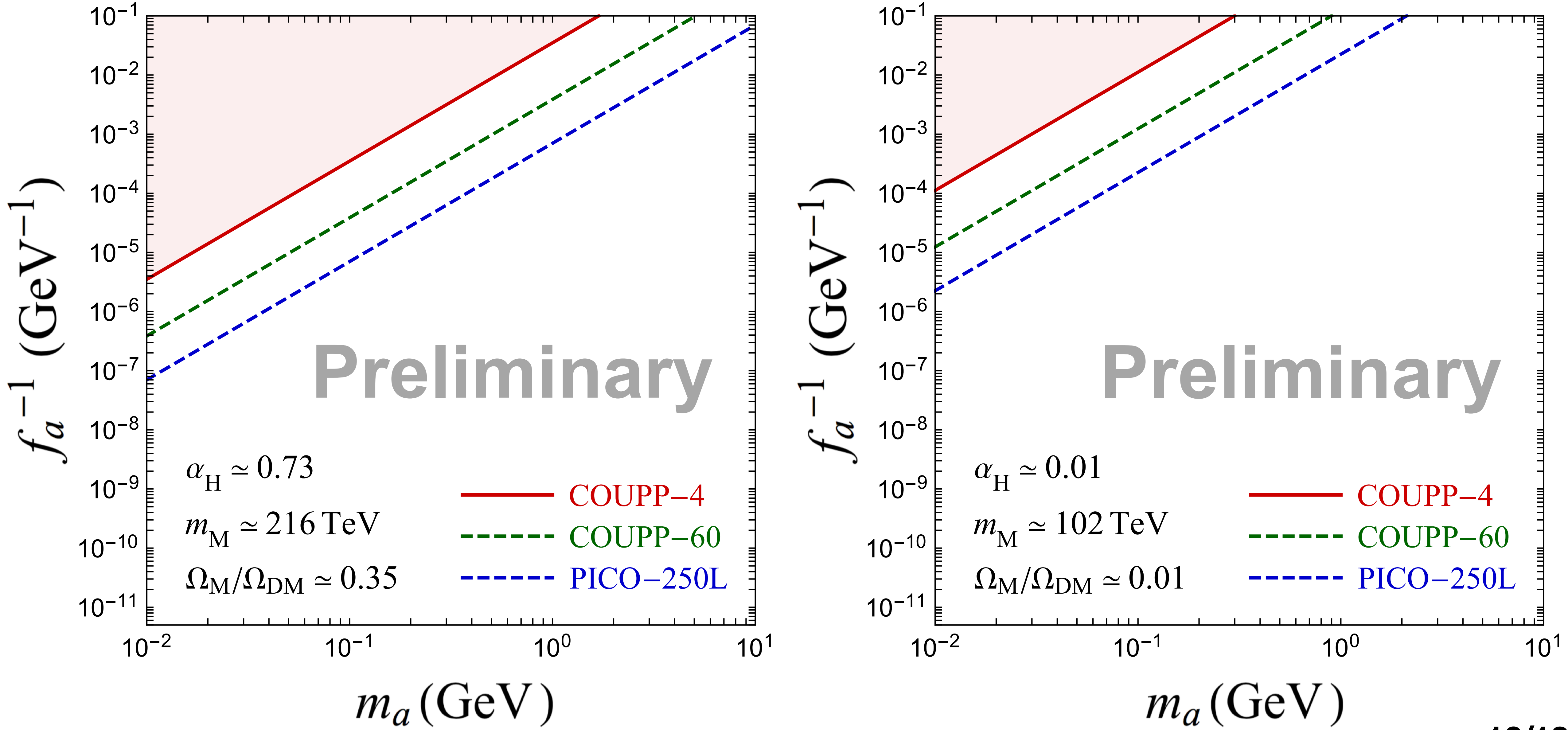
$$i\mathcal{M}_{\mathrm{M+N\to M+N}} = m_{\mathrm{N}}\,\overline{u}_{\mathrm{N}}(p_{\mathrm{out}})\gamma^5 u_{\mathrm{N}}(p_{\mathrm{in}})\int d^3x\,\theta(\mathbf{x})\,e^{-i\boldsymbol{q}\cdot\mathbf{x}}$$

- **Spin-dependent cross-section**

$$\boxed{\frac{d\sigma_{\mathrm{M+N\to M+N}}}{d\Omega} \simeq \frac{\alpha_{\mathrm{H}}\theta_0^2}{16\pi^3}\frac{m_{\mathrm{N}}^2}{m_a^4 f_a^2}|\boldsymbol{q}|^2}$$

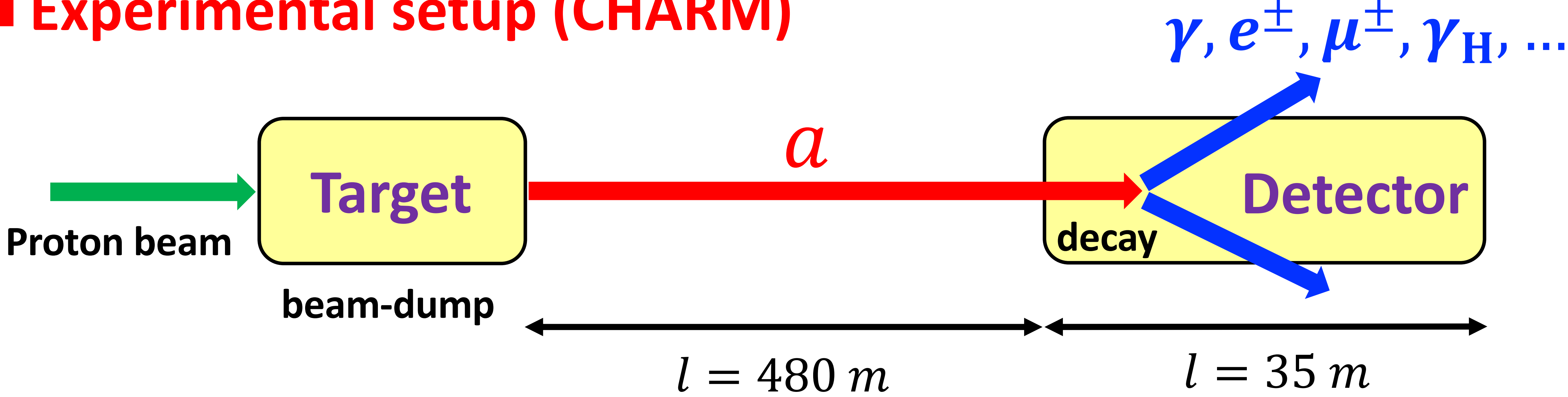
$$\boldsymbol{q} = \boldsymbol{p}_{\mathrm{out}} - \boldsymbol{p}_{\mathrm{in}}$$

Direct search exps. : m_a vs f_a^{-1}



Beam-dump experiments

■ Experimental setup (CHARM)

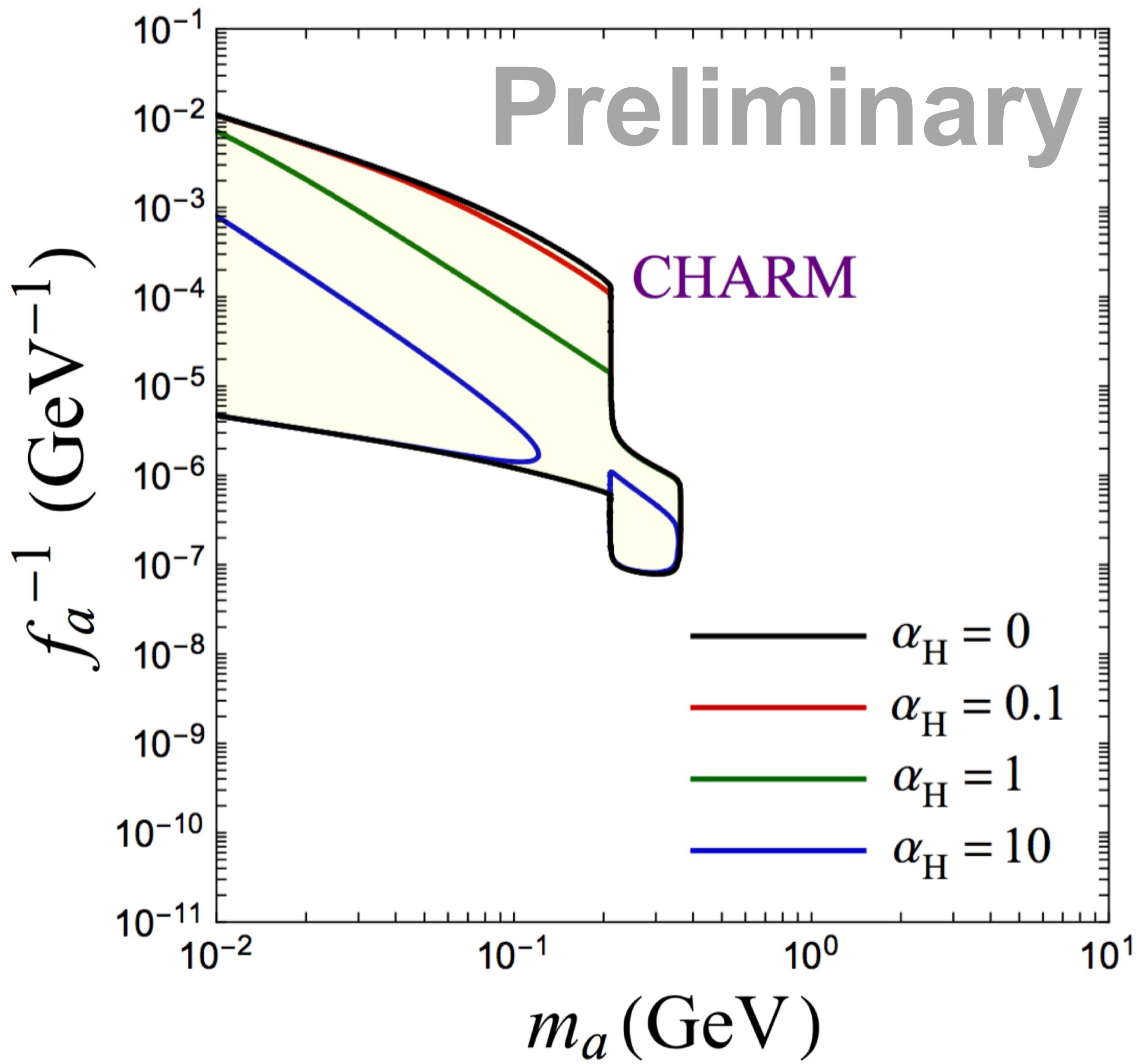


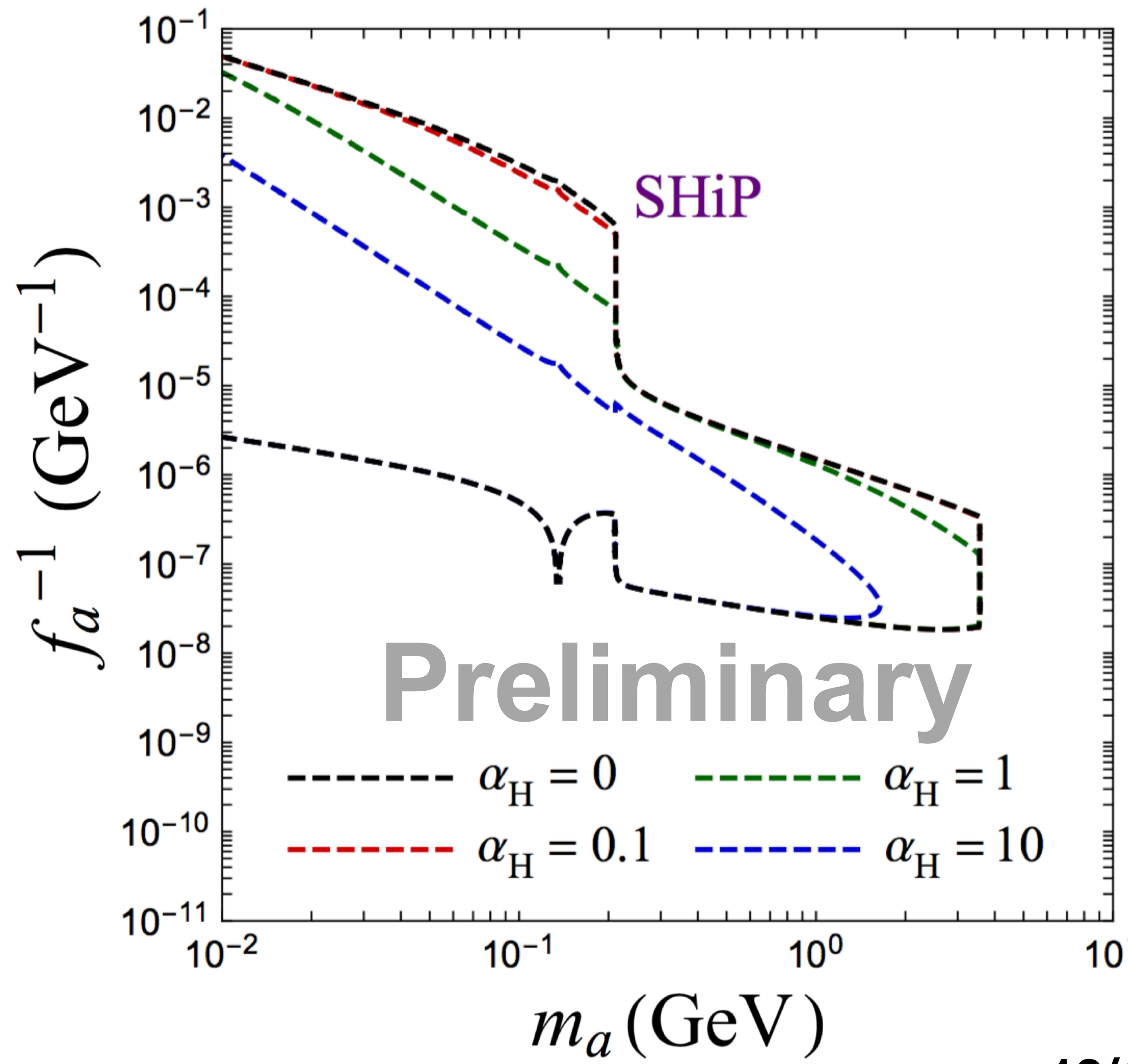
J.D. Clarke et al. 2014

$$N_{\mathrm{det}} \approx N_a \exp\left(-\frac{480\,\mathrm{m}}{\gamma_a \beta_a c\, \tau_a}\right)\left[1 - \exp\left(-\frac{35\,\mathrm{m}}{\gamma_a \beta_a c\, \tau_a}\right)\right] \sum_{X=e,\,\mu,\gamma} \mathcal{B}(a \to X\bar{X}) < 2.3$$

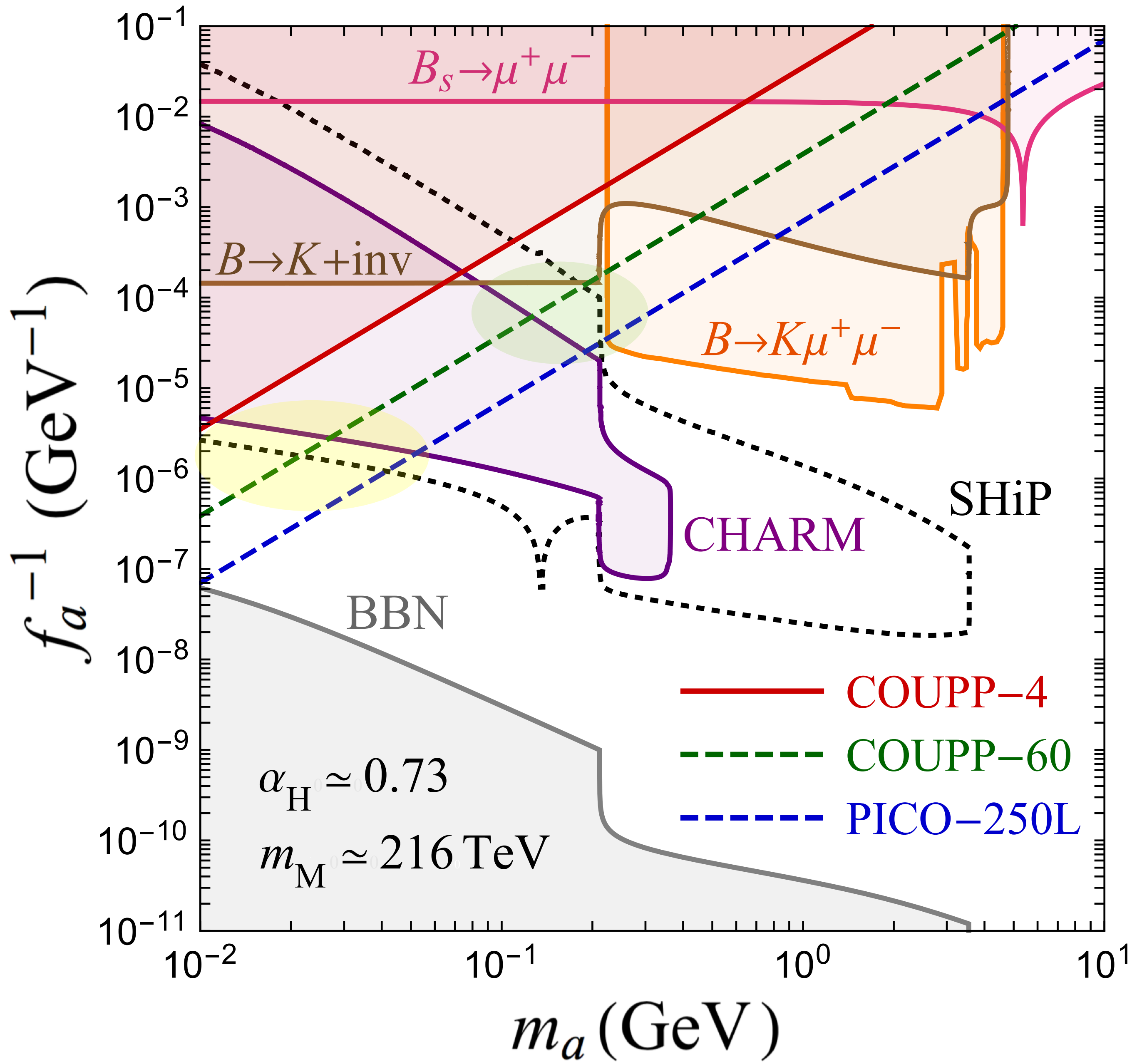
$$\gamma_a = (1-\beta_a^2)^{-1/2} \approx 10\,\mathrm{GeV}/m_a \qquad \tau_a = \frac{1}{\Gamma_a} = \frac{1}{\Gamma(a \to \gamma_{\mathrm{H}}\gamma_{\mathrm{H}}) + \Gamma(a \to \mathrm{vis})}$$

Beam-dump exps. : m_a vs f_a^{-1}





Combined result : m_a vs f_a^{-1}



$$m_a = \mathcal{O}(10)\,\mathrm{MeV}$$
$$f_a = \mathcal{O}(10^5)\,\mathrm{GeV}$$

$$m_a = \mathcal{O}(100)\,\mathrm{MeV}$$
$$f_a = \mathcal{O}(10^4)\,\mathrm{GeV}$$

We find two parameter regions where both the hidden monopole DM and the axion are within the reach of the direct search and beam-dump experiments.

Preliminary

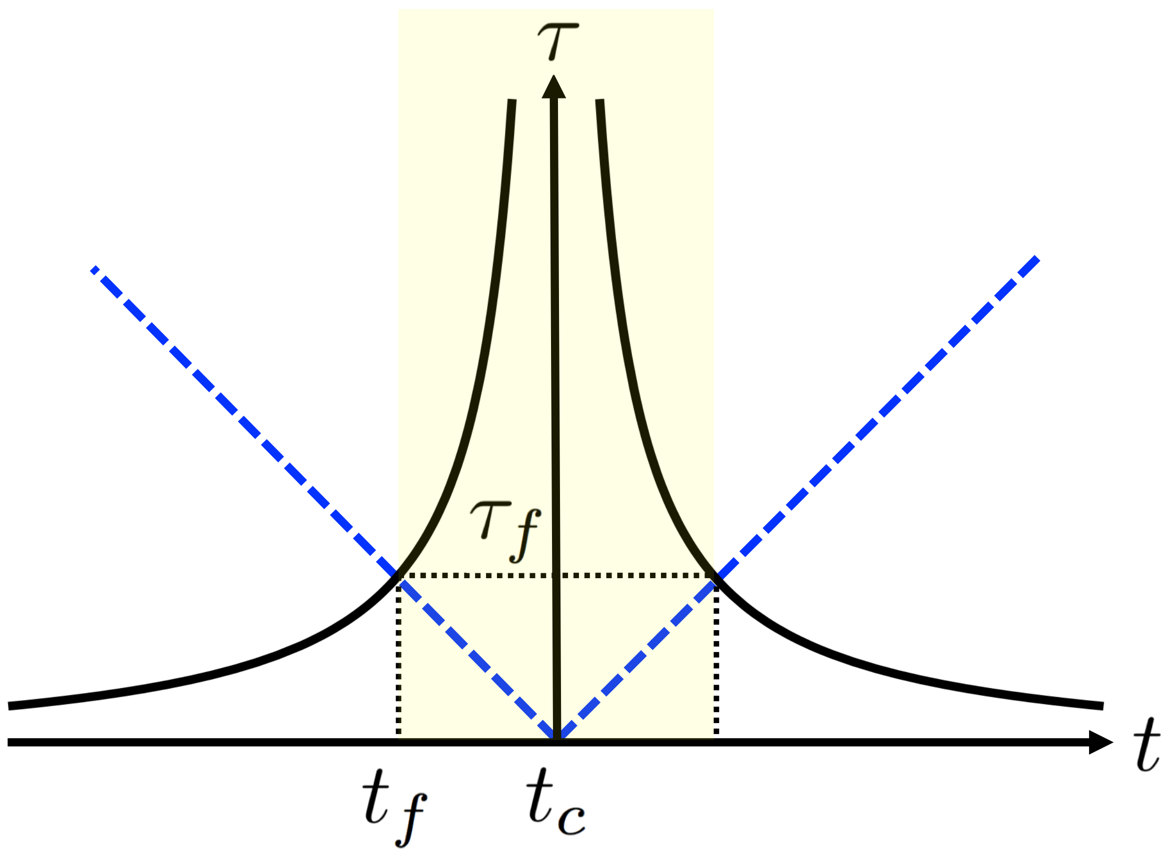
Back up

Kibble-Zurek mechanism

■ Second-order phase transition

$$\zeta = \zeta_0 |\epsilon|^{-\nu}, \quad \tau = \tau_0 |\epsilon|^{-\mu}, \quad \epsilon \equiv \frac{T - T_c}{T_c}$$

Correlation length **Relaxation time**



Frozen : $t_f - t_c = \tau_f$

$$|\epsilon_f| = \left[\tau_0 H(t_c)\right]^{1/(1+\mu)}$$

$$\zeta_f = \zeta_0 \left[\tau_0 H(t_c)\right]^{-\nu/(1+\mu)}$$

$$n_{\mathrm{M}} \simeq \zeta_f^{-3}$$