Hidden Monopole Dark Matter via Axion Portal Coupling 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?

- **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

- **A magnetic monopole can arise when a non-abelian gauge symmetry is spontaneously broken via the Higgs mechanism.**

’t Hooft, Polyakov '74

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

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

$\times$ **: product in the group space**

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

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

hidden gauge coupling

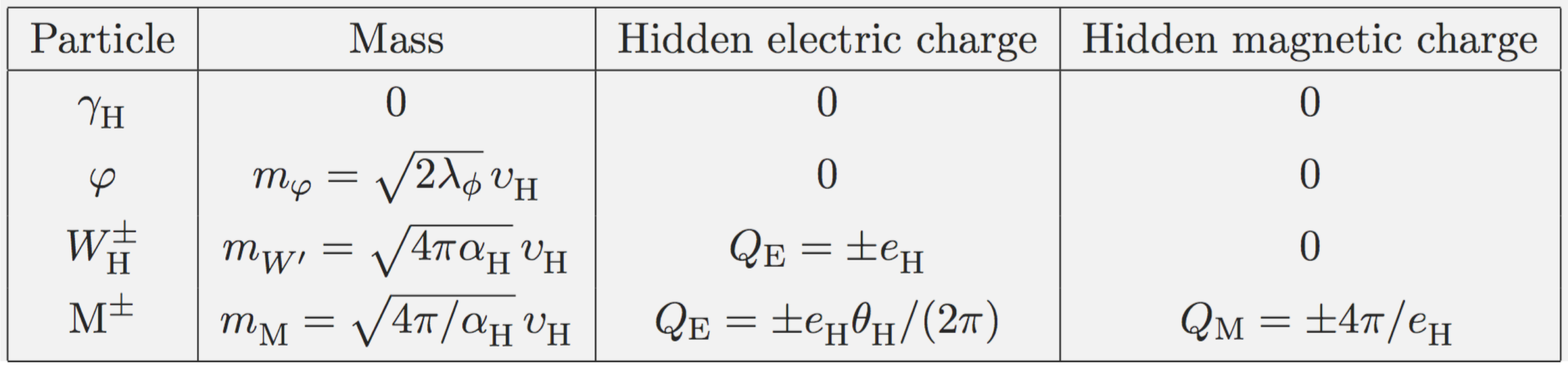
vev of the scalar field

’t Hooft-Polyakov monopole

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

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

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



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

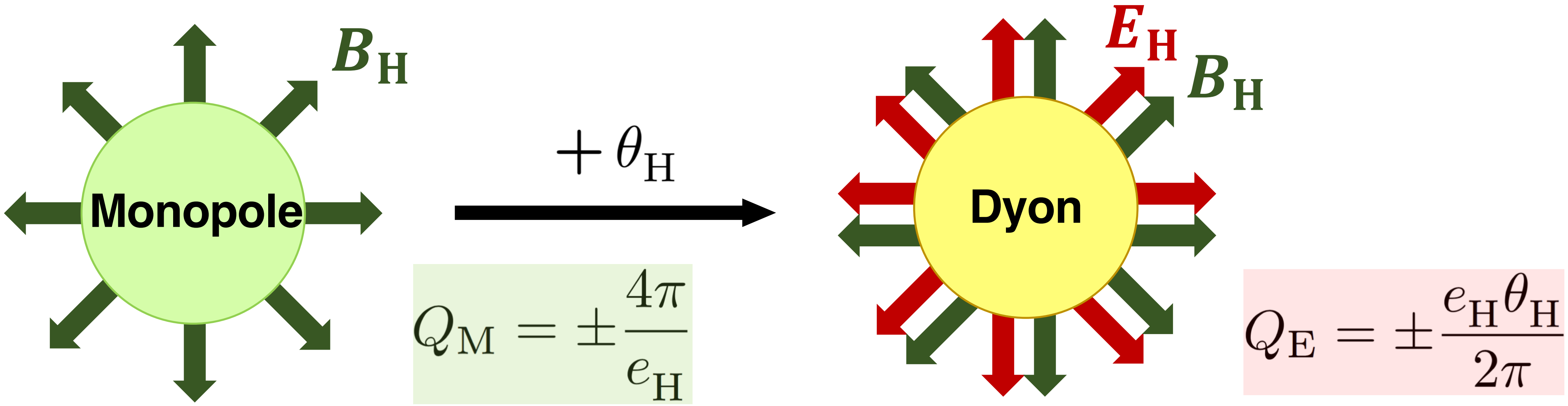
The Witten effect

Witten '79

- **The theta term of hidden U(1) 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 effect in the presence of the monopole.



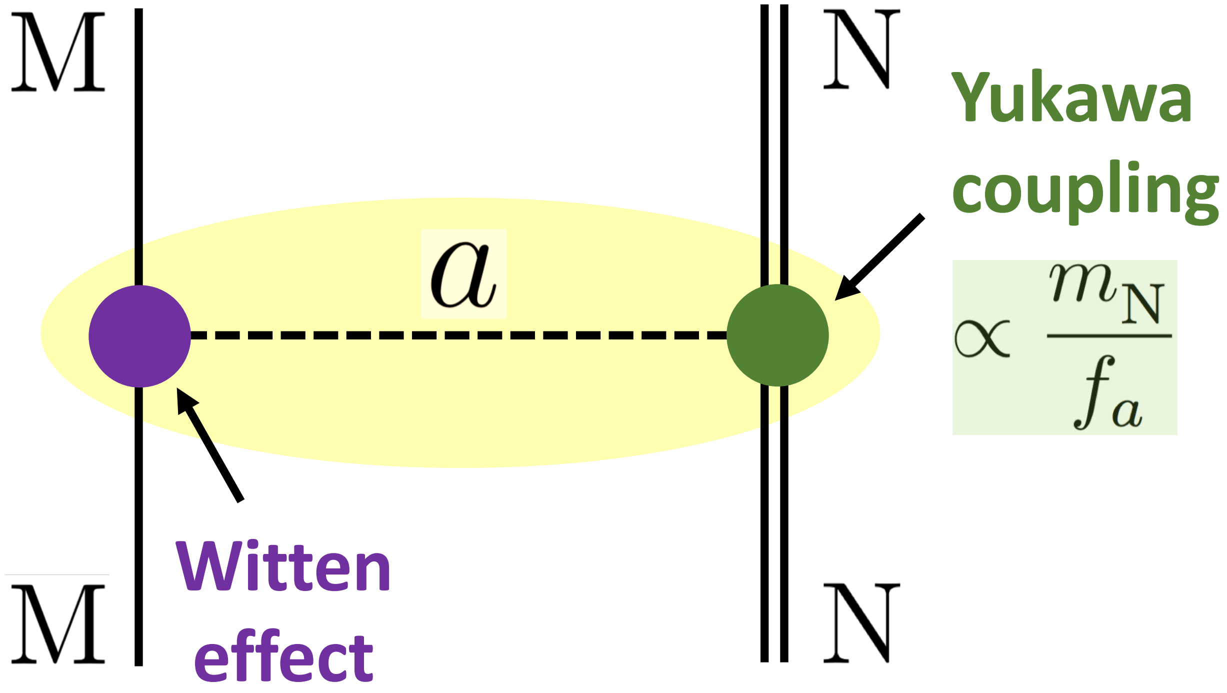
$$Q_\mathrm{M} = \pm \frac{4\pi}{e_\mathrm{H}}$$

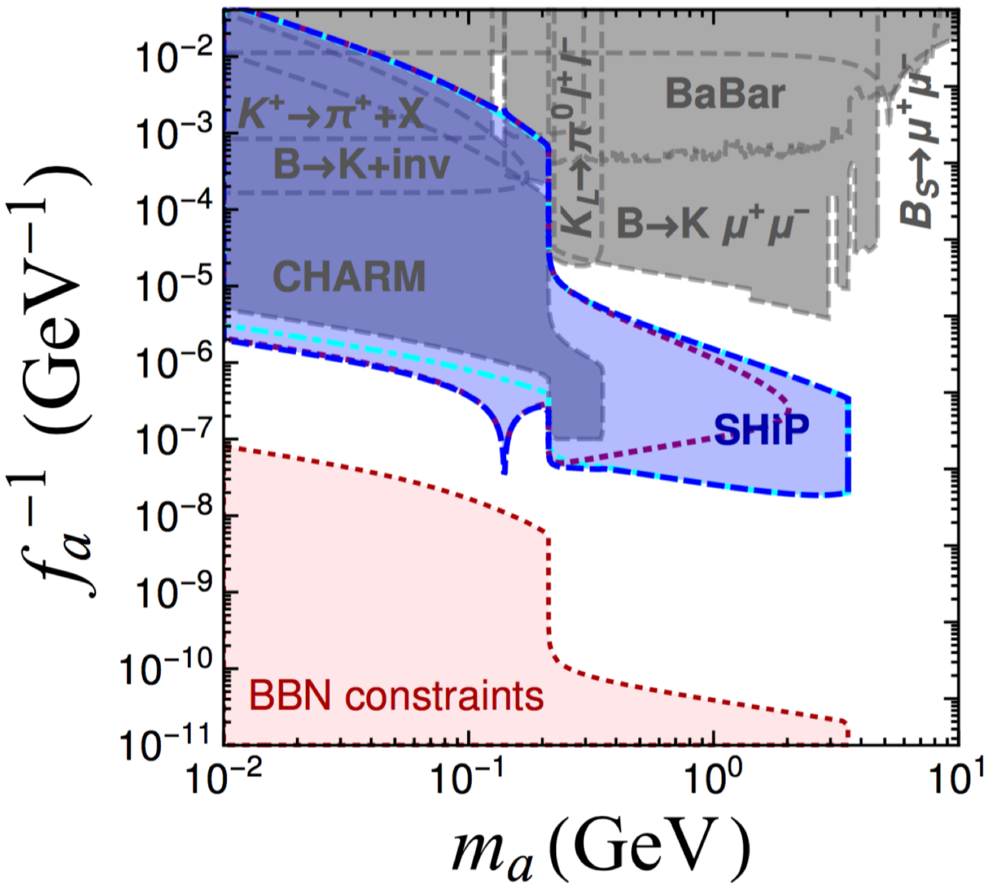
$$Q_\mathrm{E} = \pm \frac{e_\mathrm{H}\theta_\mathrm{H}}{2\pi}$$

What we did

- **Axion portal coupling** + **Yukawa interactions**

S. Alekhin et al. 16'





Direct search experiments

Beam-dump experiments

(See O. Lantwin's talk)

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')

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

- **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

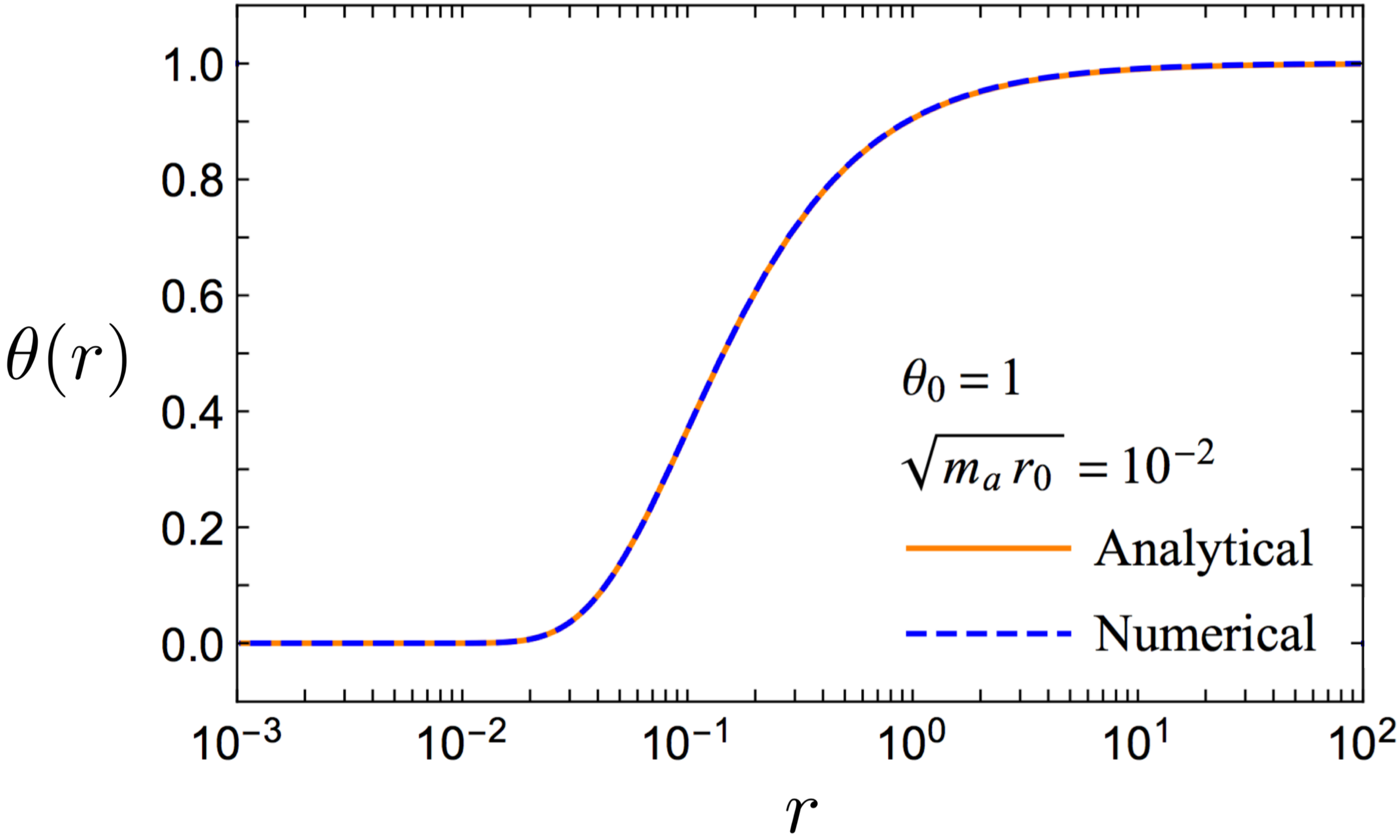
- **Equation of motion of the axion field**

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

  - **Boundary conditions :** $\theta(r \to 0) = 0 \,, \quad \theta(r \to \infty) = \theta_0$
  - **This differential equation can be solved approximately.**

$$\theta(r) \simeq \begin{cases} \theta_+(r) \equiv \theta_0 \left(\dfrac{1+\sqrt{m_a r_0}}{1+2\sqrt{m_a r_0}}\right) e^{-r_0/r+\sqrt{m_a r_0}} & \text{for} \quad r < \sqrt{r_0/m_a} \\ \\ \theta_-(r) \equiv \theta_0 \left(1 - \dfrac{r_0/r}{1+2\sqrt{m_a r_0}} e^{-m_a r+\sqrt{m_a r_0}}\right) & \text{for} \quad r > \sqrt{r_0/m_a} \end{cases}$$

Axion profile around the monopole



Hidden monopole-nucleon scattering

- Axion-nucleon interaction (Yukawa coupling)

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

- Scattering amplitude

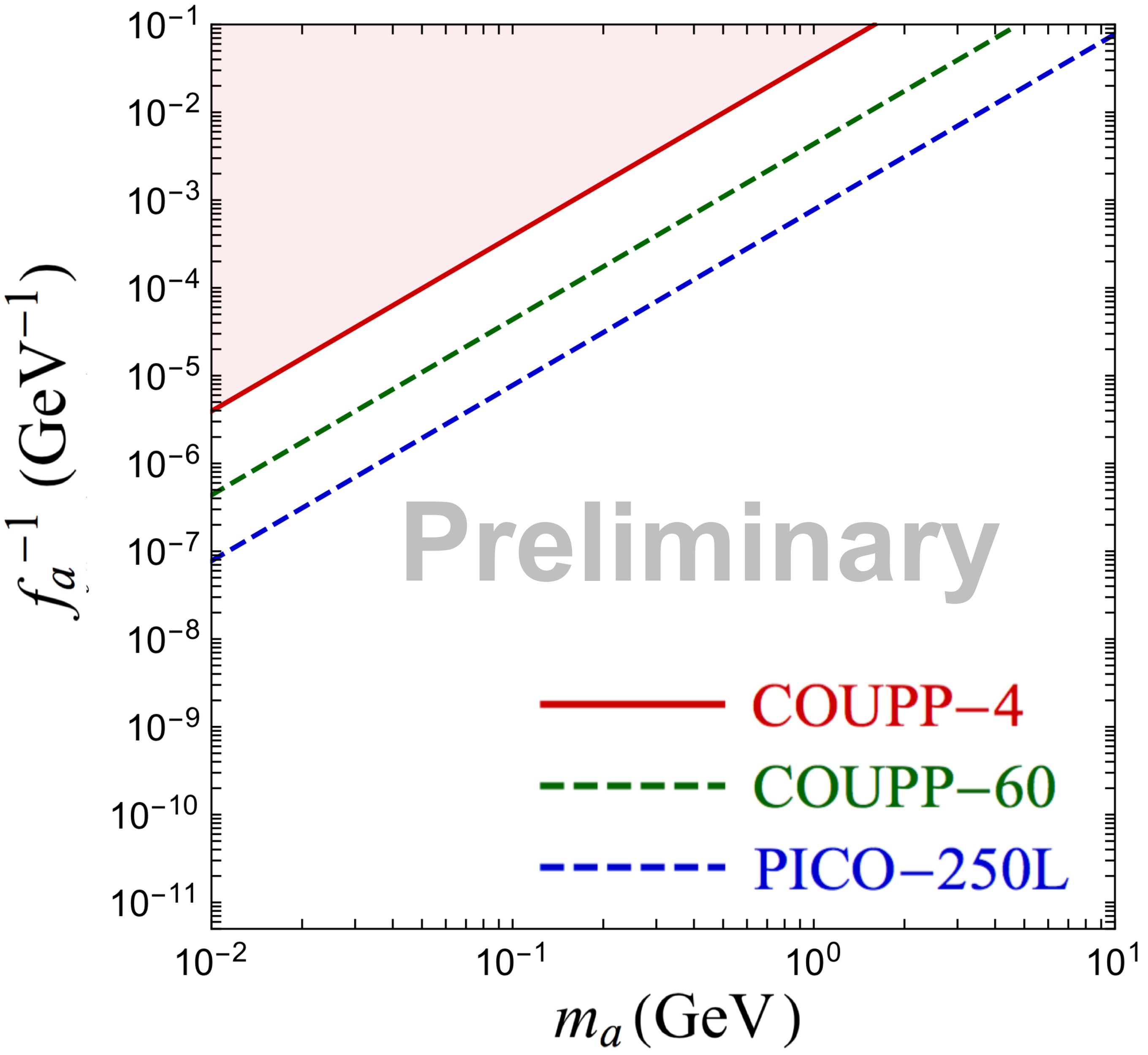
$$i\mathcal{M}_{\mathrm{M+N\to M+N}} = m_{\mathrm{N}}\,\overline{u}_{\mathrm{N}}(p_{\mathrm{out}})\gamma^5 u_{\mathrm{N}}(p_{\mathrm{in}})\int d^3x\,\theta(\mathbf{x})\,e^{-i\boldsymbol{q}\cdot\mathbf{x}}$$

- 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 : m_a vs f_a^{-1}



$\alpha_{\mathrm{H}} \simeq 0.73$

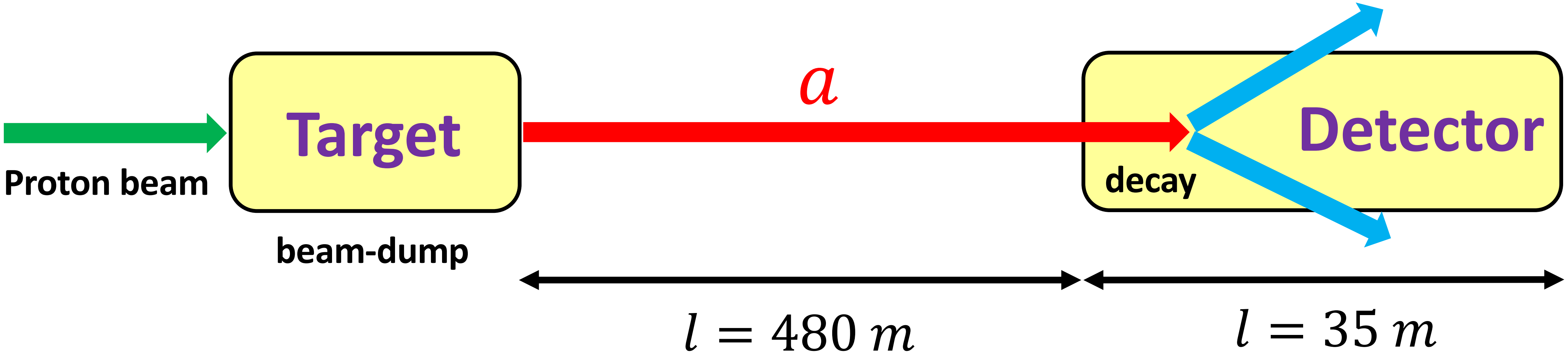
$m_{\mathrm{M}} \simeq 220\,\mathrm{TeV}$

Beam-dump experiments

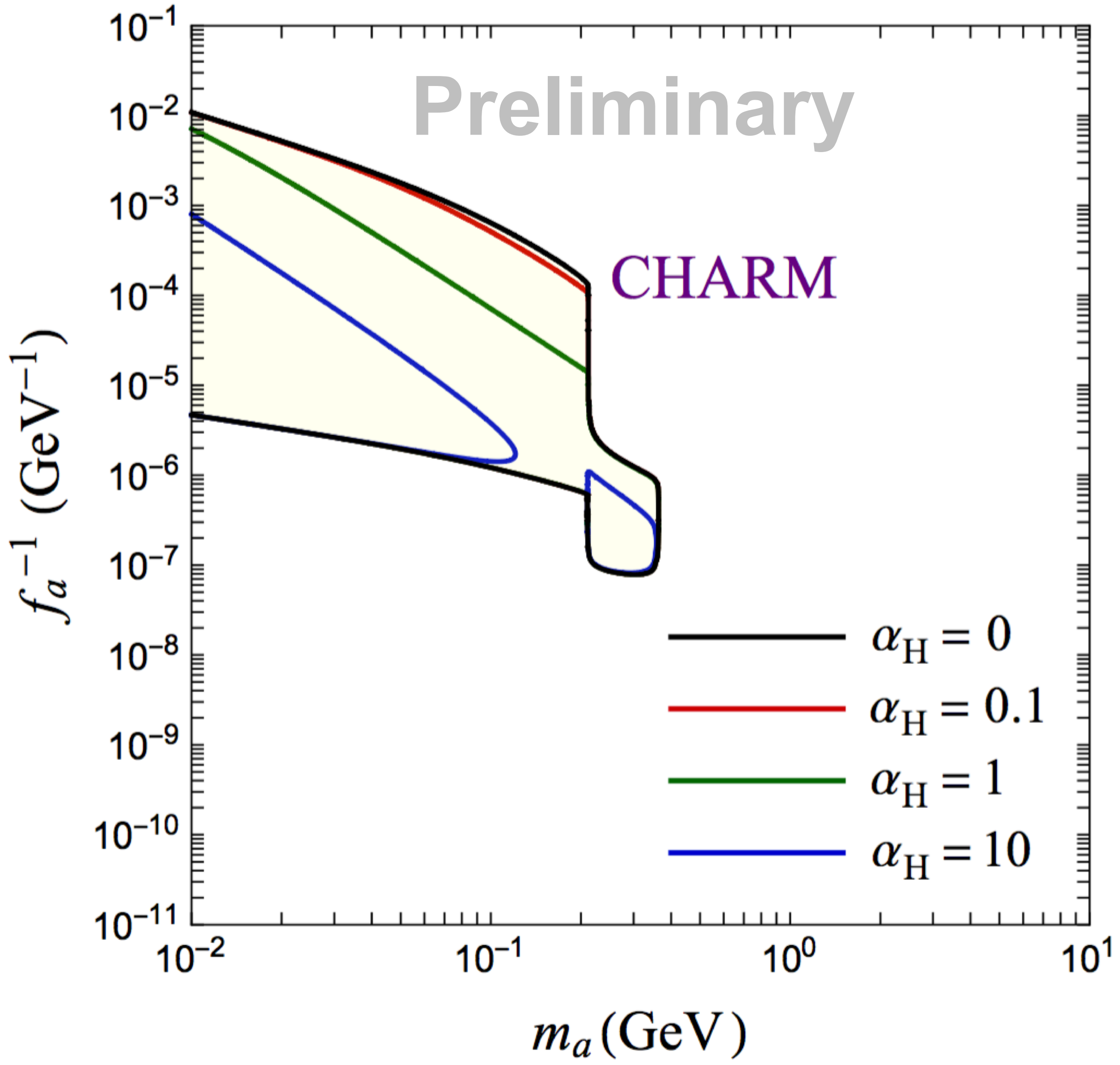
- **In our model, the axion can decay into the hidden photons.**

$$\mathcal{L} = \frac{\alpha_{\mathrm{H}}}{8\pi}\frac{a}{f_a}F_{\mathrm{H}}^{\mu\nu}\widetilde{F}_{\mathrm{H}\mu\nu} \quad \longrightarrow \quad \Gamma(a \to \gamma_{\mathrm{H}}\gamma_{\mathrm{H}}) = \frac{\alpha_{\mathrm{H}}^2 m_a^3}{256\pi^3 f_a^2}$$

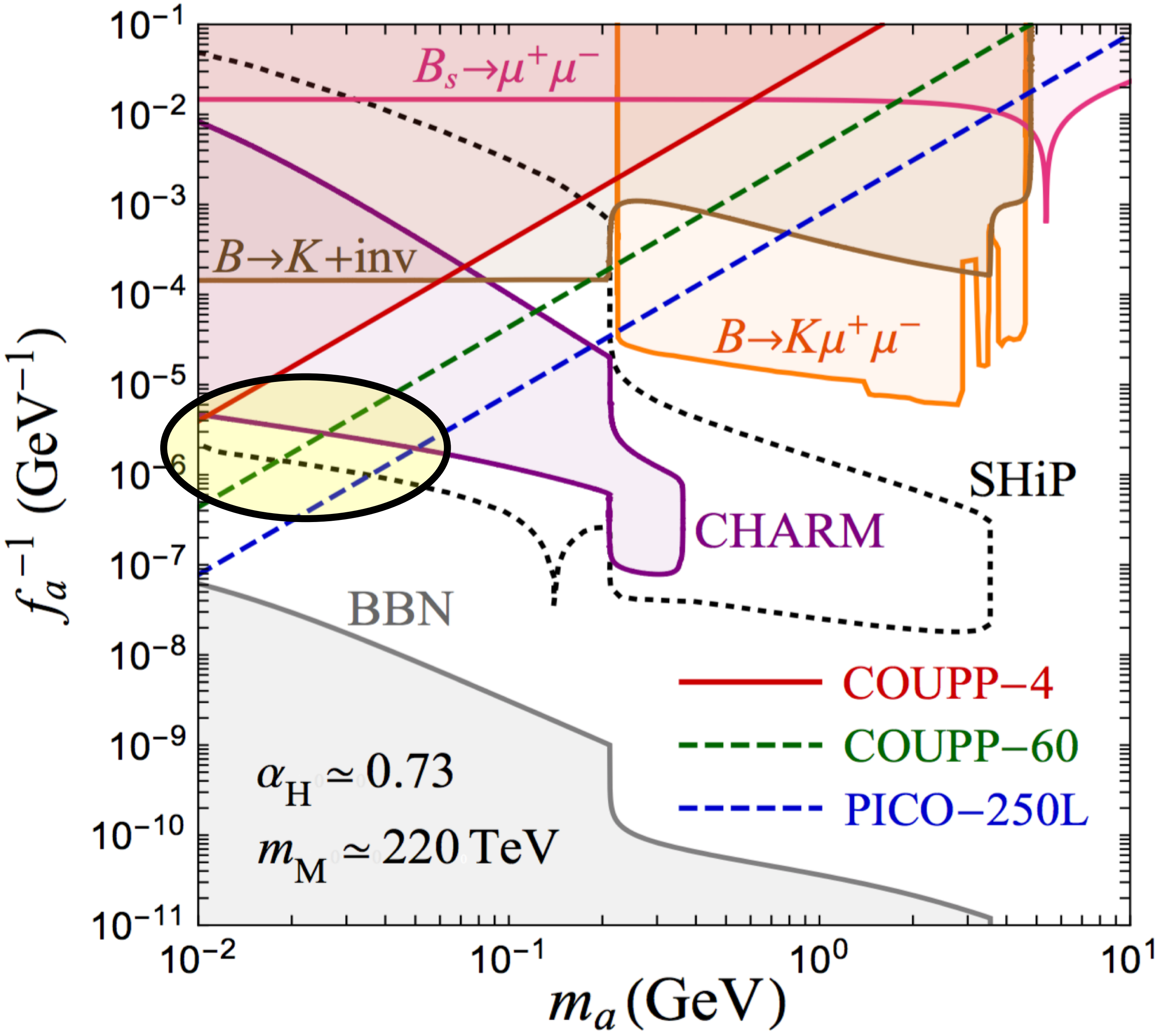
- **Experimental setup (CHARM)**



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



Combined result : m_a vs f_a^{-1}



$$m_a = \mathcal{O}(10)\,\mathrm{MeV}$$

$$f_a = \mathcal{O}(10^{5-6})\,\mathrm{GeV}$$

The parameter region where both the hidden monopole DM and the axion are within the reach of the direct search and beam-dump experiments.

Preliminary

Summary

- We have studied the hidden monopole DM via the axion portal.
- We have computed the spin-dependent cross-section of the hidden monopole DM scattering off a nucleon and compare it to the direct search experiments.
- We have found the parameter region where both the hidden monopole DM and the axion are within the reach of the direct search experiments & beam-dump experiments.