Direct Detection of Hidden Monopole Dark Matter via Axion Portal Coupling

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Outline

- Hidden monopole dark matter
- Model Setup : ’t Hooft-Polyakov monopole + ALP
- The Witten effect
- Axion-portal and axion profile around the monopole
- Direct detection searches
- Beam-dump experiments
- Summary

Hidden monopole dark matter

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(1 PeV = 1000 TeV)

Murayama & Shu 2010

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- The stability of the hidden monopole dark matter is guaranteed by its topological nature.

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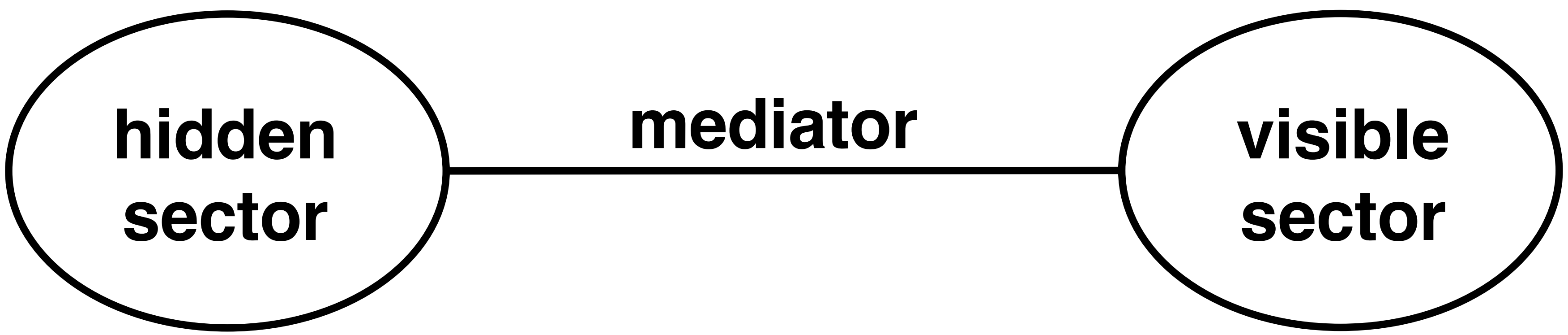
- There are lots of underground experiments for searching dark matter, e.g. LUX, XENON, COUPP, PICO, etc.
  - **Q** : Can we detect the hidden monopole dark matter by these experiments?
  - **A** : No, at least in the minimum setup. One has to introduce certain couplings with the standard model (SM) sector.



Hidden monopole DM-SM interactions

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

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

't Hooft-Polyakov monopole

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

't Hooft, Polyakov '74

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

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

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

$\times$: products in the
$\cdot$ group space

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

hidden gauge coupling

vev of the scalar field

’t Hooft-Polyakov monopole

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

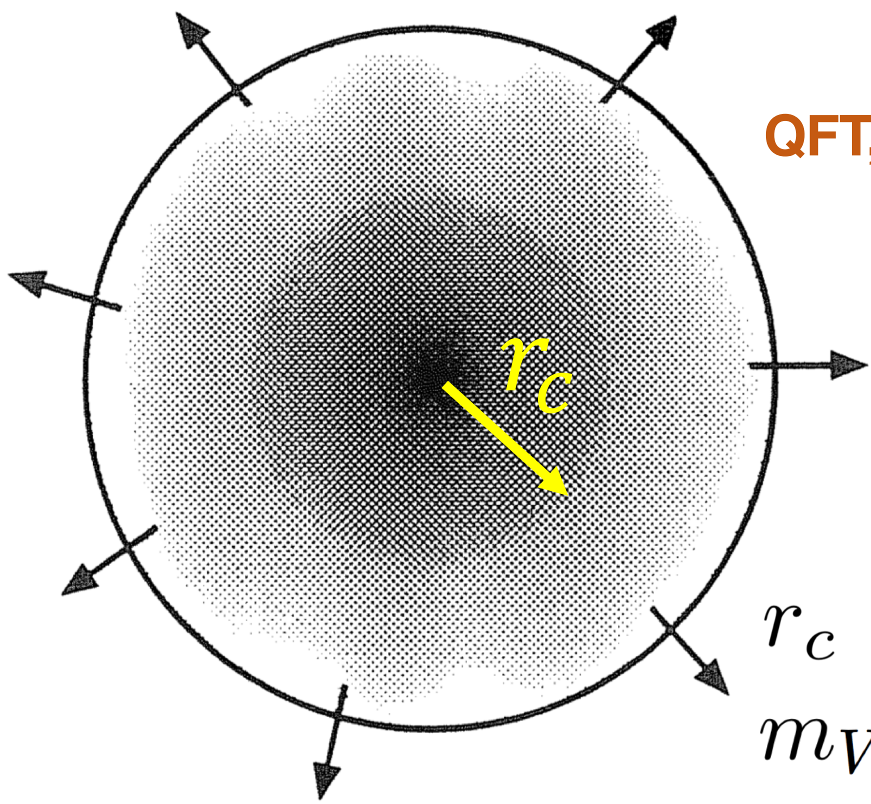
$$\phi \to \phi + \langle \phi \rangle \qquad \langle \phi \rangle = (0, 0, v_{\mathrm{H}})$$

  - **One massless hidden photon :** γ_{H}
  - **One massive hidden scalar field :** φ
  - **Two massive hidden gauge bosons :** $W^{\pm}_{\mathrm{H}}$

$$\mathrm{SU}(2)_{\mathrm{H}} \xrightarrow{\langle \phi \rangle} \mathrm{U}(1)_{\mathrm{H}}$$

't Hooft-Polyakov monopole

- **Magnetic Monopole**
  - **Static solution : time-independent solution +** $A_{\mathrm{H}}^{0} = 0$
  - **Finite-energy field configuration :** $|\phi(r \to \infty)| \to v_{\mathrm{H}}$



QFT, Ryder

$$r_c \simeq m_{W'}^{-1}$$
$$m_{W'} = e_{\mathrm{H}} v_{\mathrm{H}}$$

Asymptotic forms

$$\boldsymbol{B}_{\mathrm{H}}(r \to \infty) = \frac{\hat{\boldsymbol{r}}}{e_{\mathrm{H}} r^2}$$

$$\boldsymbol{\phi}(r \to \infty) = v_{\mathrm{H}} \frac{\boldsymbol{r}}{r}$$

$$\mathcal{D}_{\mu} \boldsymbol{\phi}(r \to \infty) = 0$$

't Hooft-Polyakov monopole

- **Mass and Charge**
  - **Bogomol'nyi bound :**

$$m_{\rm M} \geq m_{W'}/\alpha_{\rm H} f(\lambda_\phi/\alpha_{\rm H})$$

$$f(0) = 1$$

$$f(\infty) \simeq 1.787$$

E. B. Bogomolny '76

$$\alpha_{\rm H} = e_{\rm H}^2/(4\pi)$$

  - **Bogomol'nyi limit :** $\lambda_\phi \to 0$

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
$\rm M(\overline{M})$	$m_{\rm M} = \sqrt{4\pi/\alpha_{\rm H}}\, v_{\rm H}$	$Q_{\rm E} = \pm e_{\rm H}\theta_{\rm H}/(2\pi)$	$Q_{\rm M} = \pm 4\pi/e_{\rm H}$

The Witten effect

Witten '79

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

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

  - This term usually has no effect since it is a total derivative.

The Witten effect

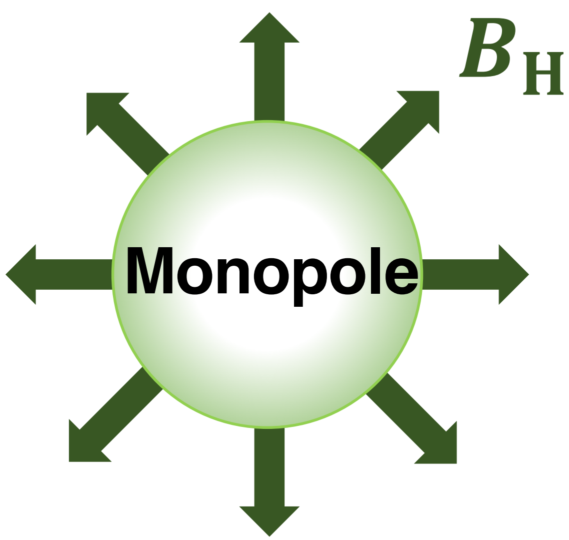
Witten '79

- **Hidden Maxwell's equation**

$F_{\rm H}^{j0} = E_{\rm H}^j \quad F_{\rm H}^{jk} = -\epsilon_{jkl} B_{\rm H}^l$

$$\partial_\mu F_{\rm H}^{\mu\nu} = \frac{e_{\rm H}^2}{8\pi^2}\partial_\mu\left(\theta_{\rm H}\widetilde{F}_{\rm H}^{\mu\nu}\right) \longrightarrow \nabla\cdot\boldsymbol{E}_{\rm H} = \frac{e_{\rm H}^2}{8\pi^2}\nabla\cdot\left(\theta_{\rm H}\boldsymbol{B}_{\rm H}\right)$$

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



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

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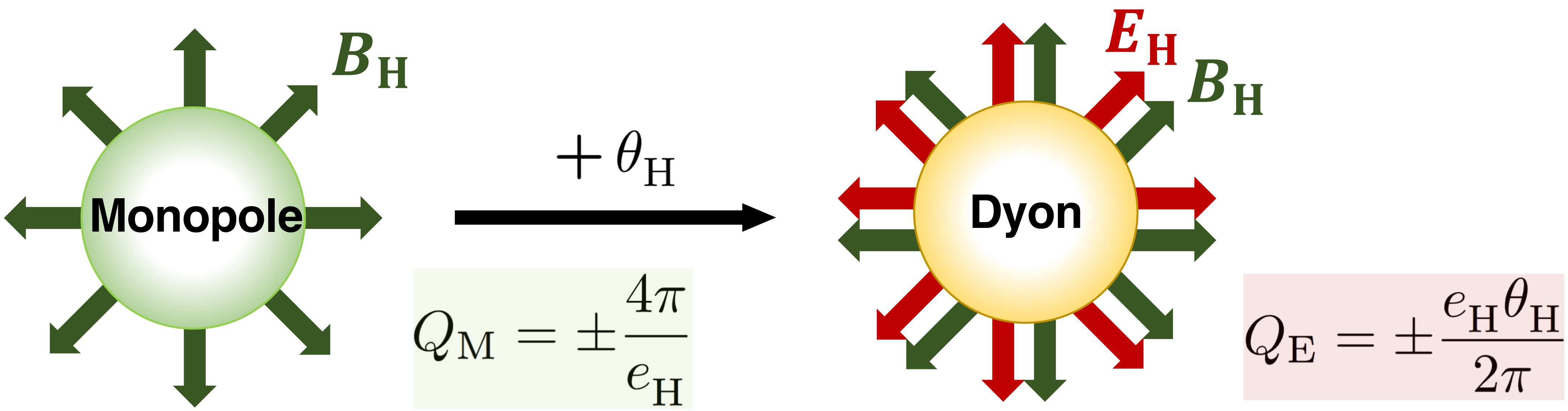
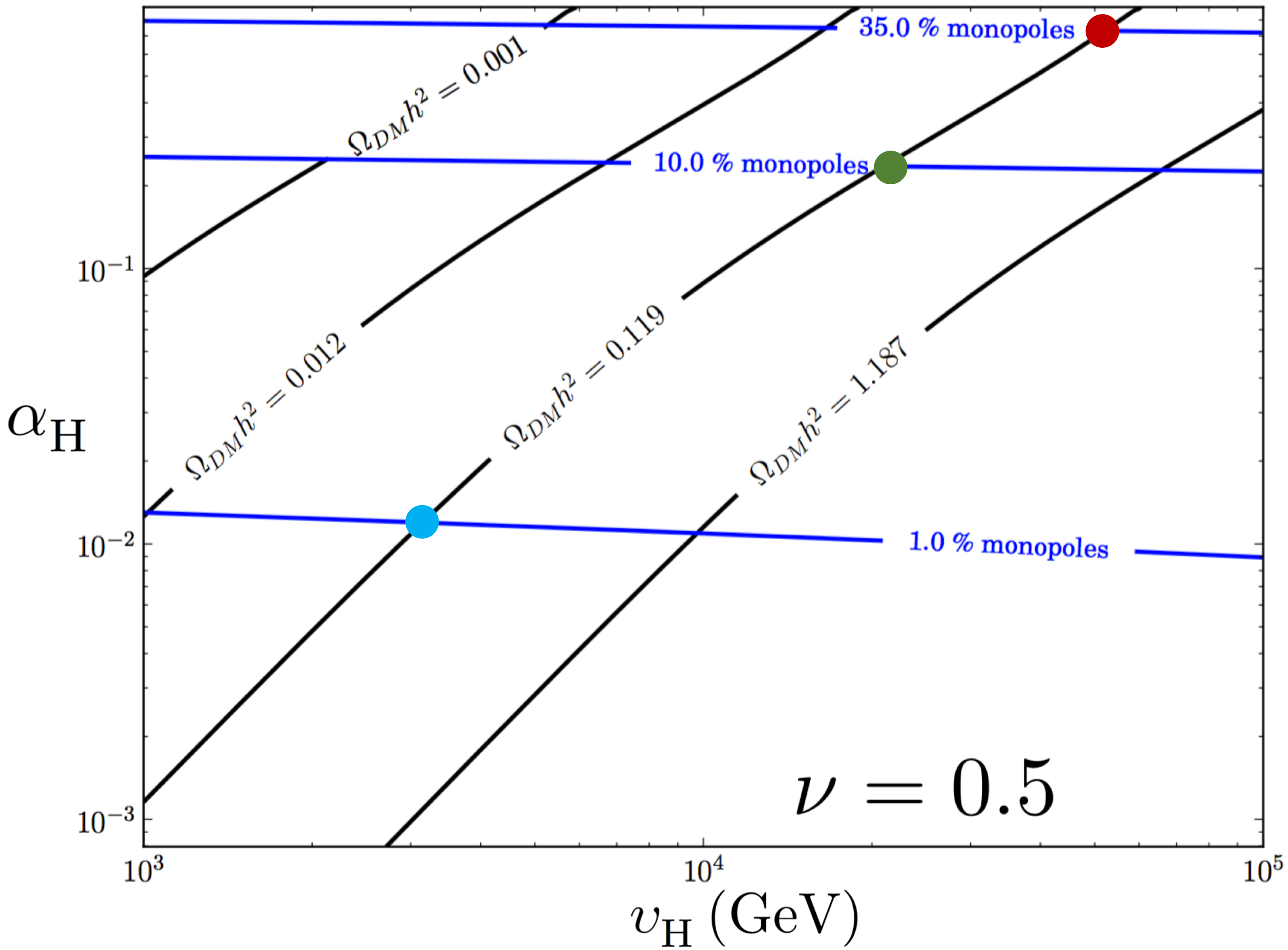


Benchmark point

■ Combined relic abundance of DM

Khoze & Ro 2014



$$m_{\rm M} = \sqrt{4\pi/\alpha_{\rm H}}\, v_{\rm H}$$

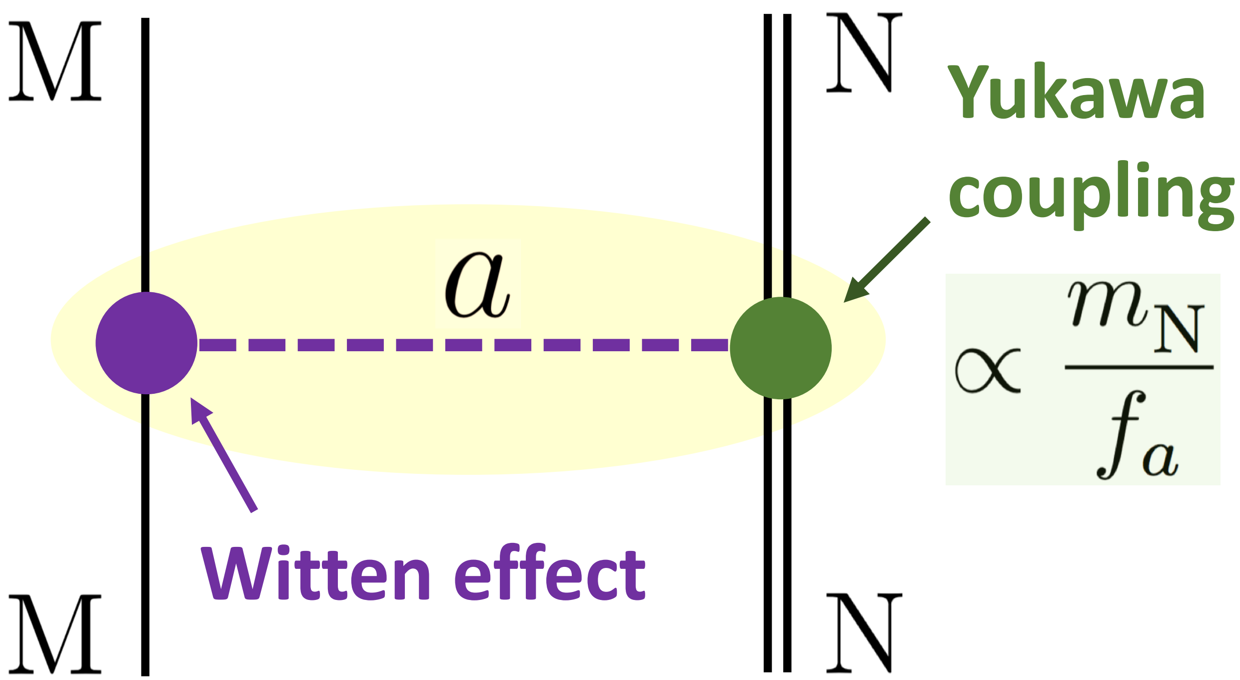
- ● ~ 2.2*10^5 GeV
- ● ~ 1.5*10^5 GeV
- ● ~ 1.0*10^5 GeV

35% hidden monopole DM

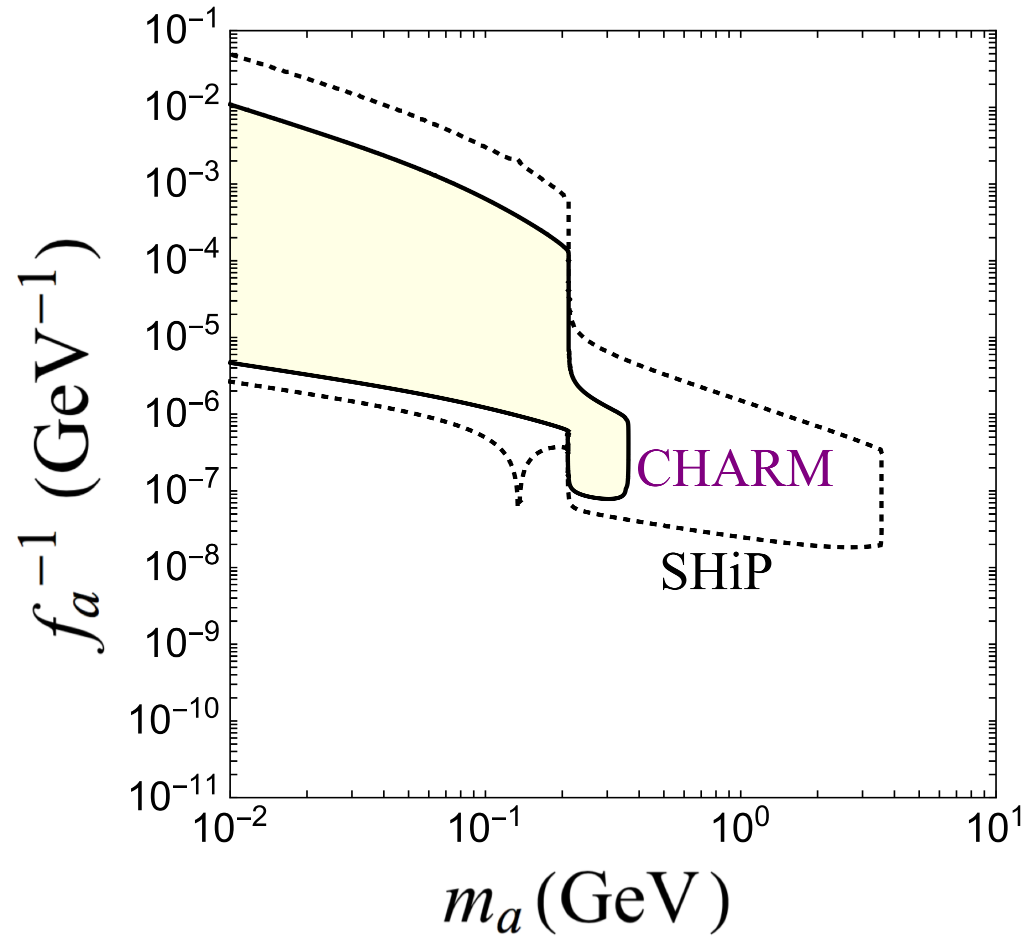
$$\alpha_{\rm H} \simeq 0.73$$
$$m_{\rm M} \simeq 216\ {\rm TeV}$$

What we did

- **Axion portal coupling + Yukawa interaction**



Direct detection searches



Beam-dump experiments

Axion portal coupling

Lagrangian density

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

- **Field strength of the hidden photon :** $F_{\rm H}^{\mu\nu} = \partial^\mu A_{\rm H3}^\nu - \partial^\nu A_{\rm H3}^\mu$
- **Axion decay constant (PQ breaking scale) :** $f_{\rm H}$
- **Normalized axion field :** $\theta \equiv a/f_a$
- **Axion mass :** m_a
  - ✓ **E.g.** $\big(\theta - \theta_0\big)G_{\rm H'}\widetilde{G}_{\rm H'}$

Axion-monopole system

- **In the case of the axion coupling to the hidden photons**

$$\boldsymbol{E}_{\rm H}(r) = \frac{Q_{\rm E}(r)}{4\pi}\frac{\hat{\boldsymbol{r}}}{r^2} \qquad Q_{\rm E}(r) = \pm\frac{e_{\rm H}}{2\pi}\theta_{\rm H}(r)$$

  - **The hidden electric charge is spread out in space by the axion field.**

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- **Hamiltonian of the axion-monopole system**

$$\begin{aligned} H_{a-\mathrm{M}} &= \int d^3x\left[\frac{1}{2}\dot{\theta}^2 + \frac{1}{2}f_{\mathrm{H}}^2(\nabla\theta)^2 + \frac{1}{2}m_a^2 f_{\mathrm{H}}^2(\theta-\theta_0)^2 + \frac{1}{2}|\boldsymbol{E}_{\mathrm{H}}|^2 + \frac{1}{2}|\boldsymbol{B}_{\mathrm{H}}|^2\right] \\ &= 2\pi f_{\mathrm{H}}^2\int_{r_c}^{\infty} dr\left[\left(r\frac{d\theta(r)}{dr}\right)^2 + m_a^2 r^2\left(\theta(r)-\theta_0\right)^2 + \frac{r_0^2}{r^2}\theta(r)^2\right] + \mathrm{const.} \end{aligned}$$

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

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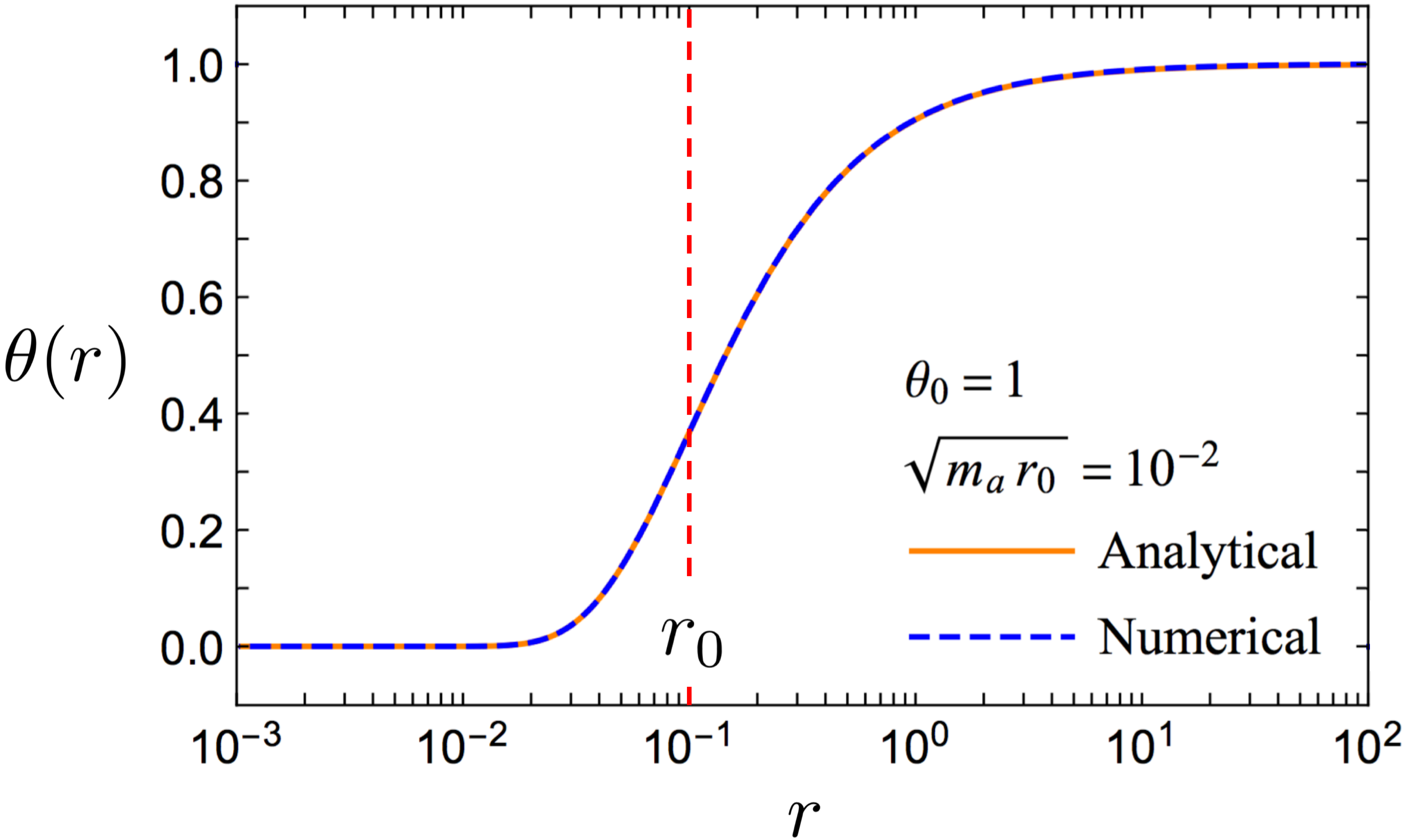
- **Boundary conditions :** $\theta(r \to 0) = 0 \,, \quad \theta(r \to \infty) = \theta_0$
- **This differential equation can be solved asymptotically.**

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

$$z = r_0/r$$

Axion profile around the monopole



Hidden monopole-nucleon scattering

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

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

QFT, Peskin

$$H_I = \int d^3x \, e\bar{\psi}\gamma^\mu\psi \, A_\mu$$

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

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

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Axion profile

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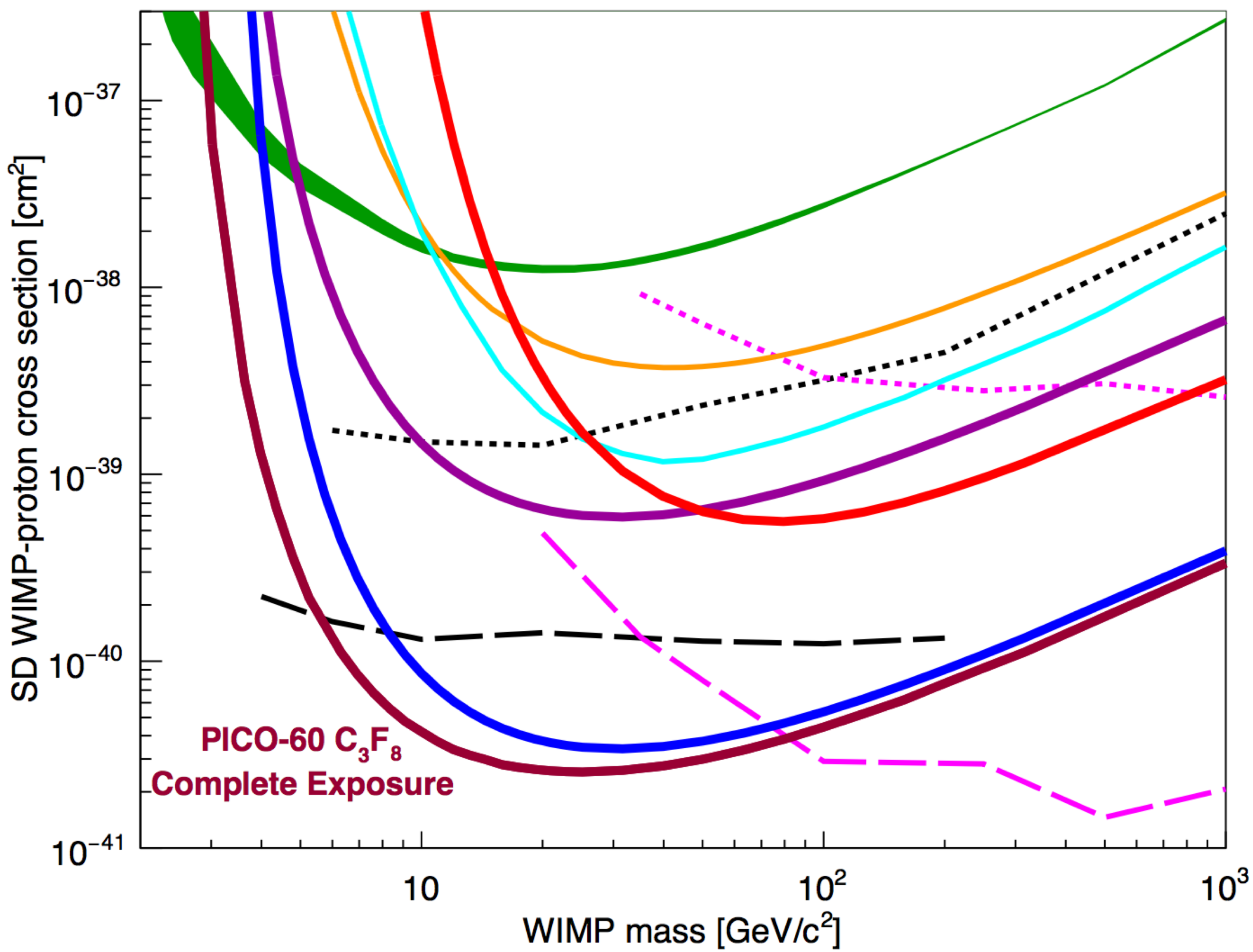
Axion profile

- **Spin-dependent cross-section**

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

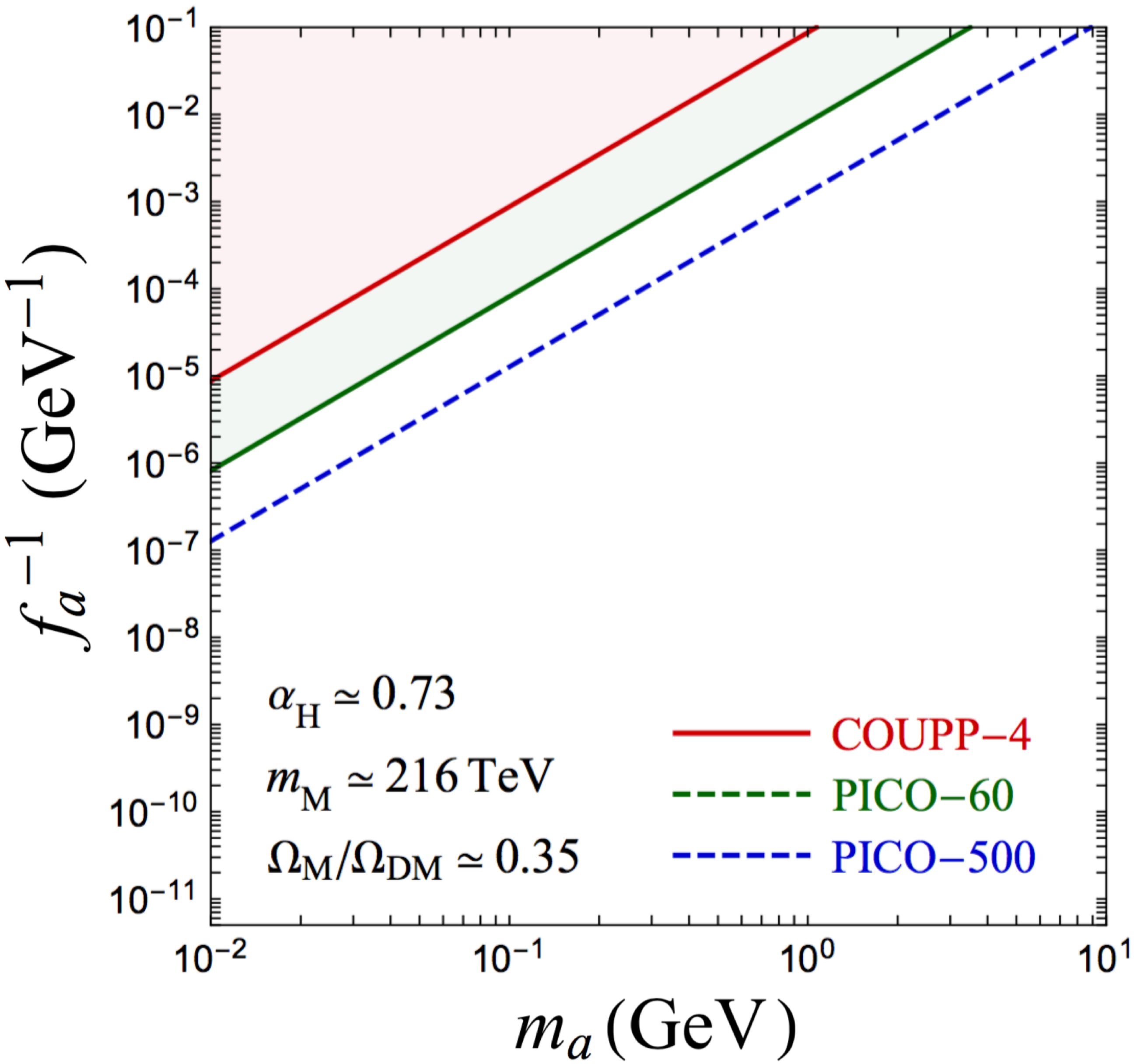
$$\boldsymbol{q} = \boldsymbol{p}' - \boldsymbol{p}$$

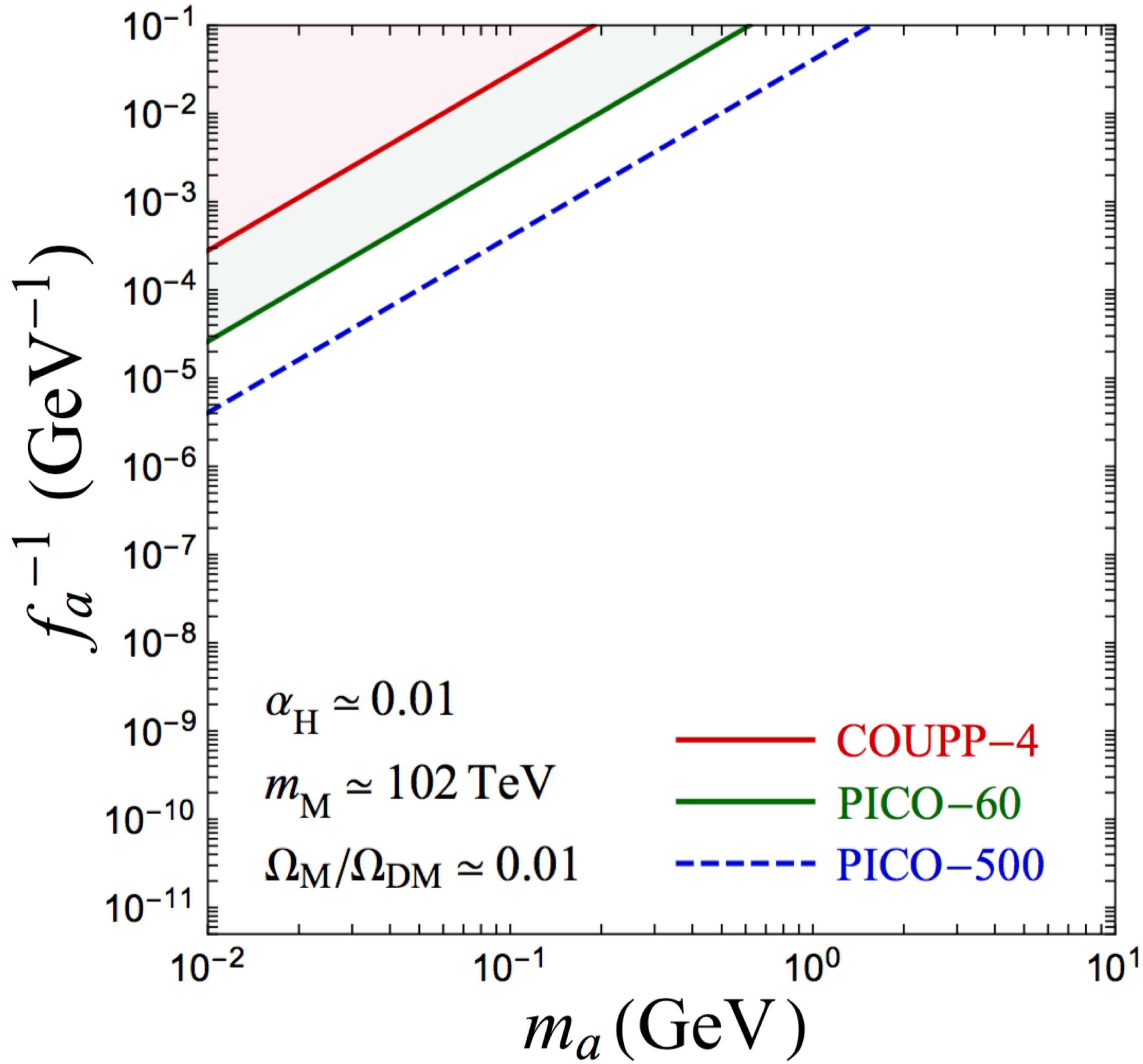
Direct detection experiments



arXiv:1902.04031

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





Axion decay channels

Hidden photon decay channel

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

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

Fermion & photon decay channels

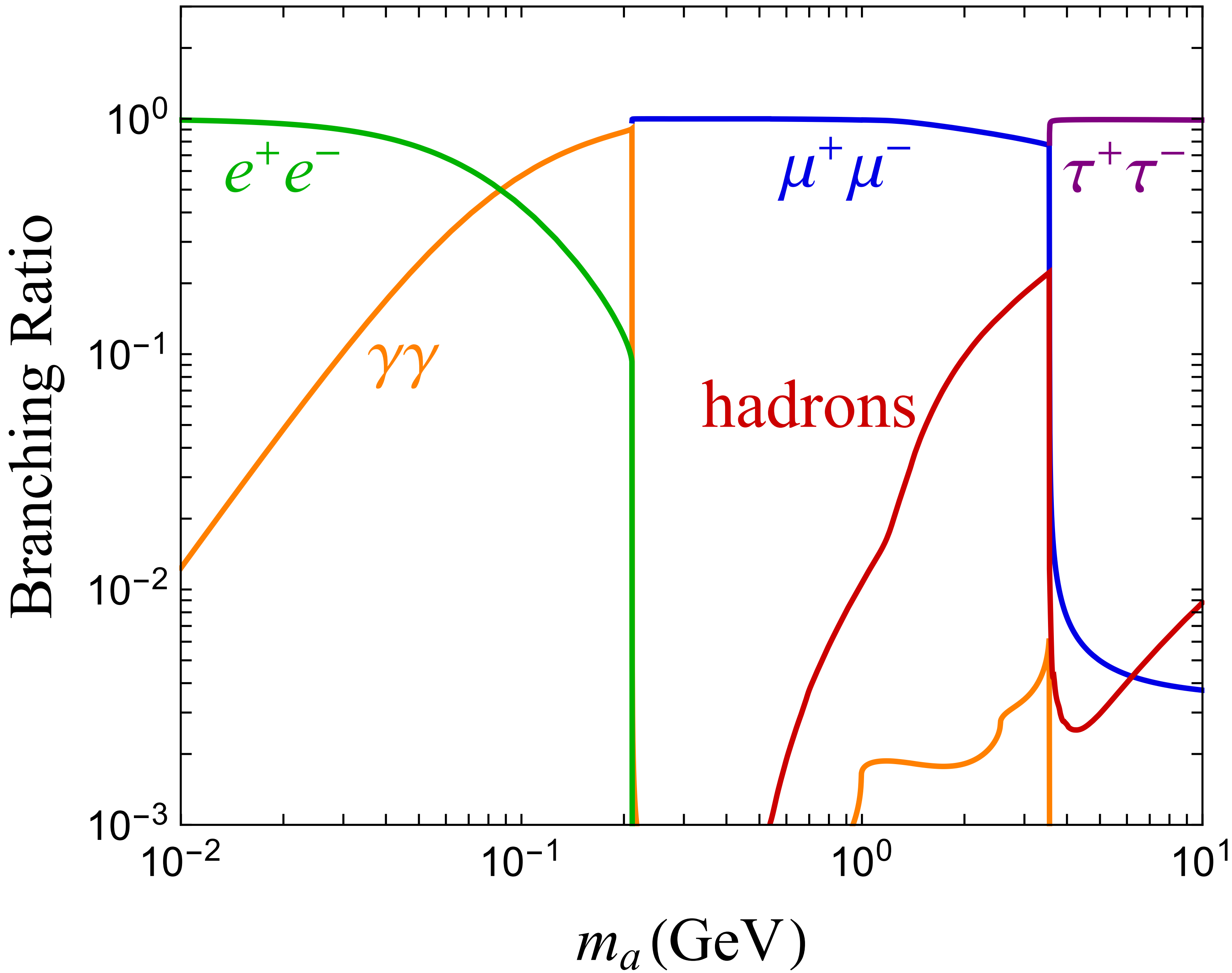
- We assume Yukawa-like coupling for the axion

$$\mathcal{L} = \sum_f \frac{m_f}{f_a} a\bar{f} i\gamma^5 f \longrightarrow$$

$$\Gamma(a \to f^+ f^-) = \frac{m_a m_f^2}{8\pi f_a^2}\sqrt{1 - \frac{4m_f^2}{m_a^2}}$$

$$\Gamma(a \to \gamma\gamma) \simeq \frac{\alpha^2 m_a^3}{256\pi^3 f_a^2}$$

Axion decay channels without γ_H

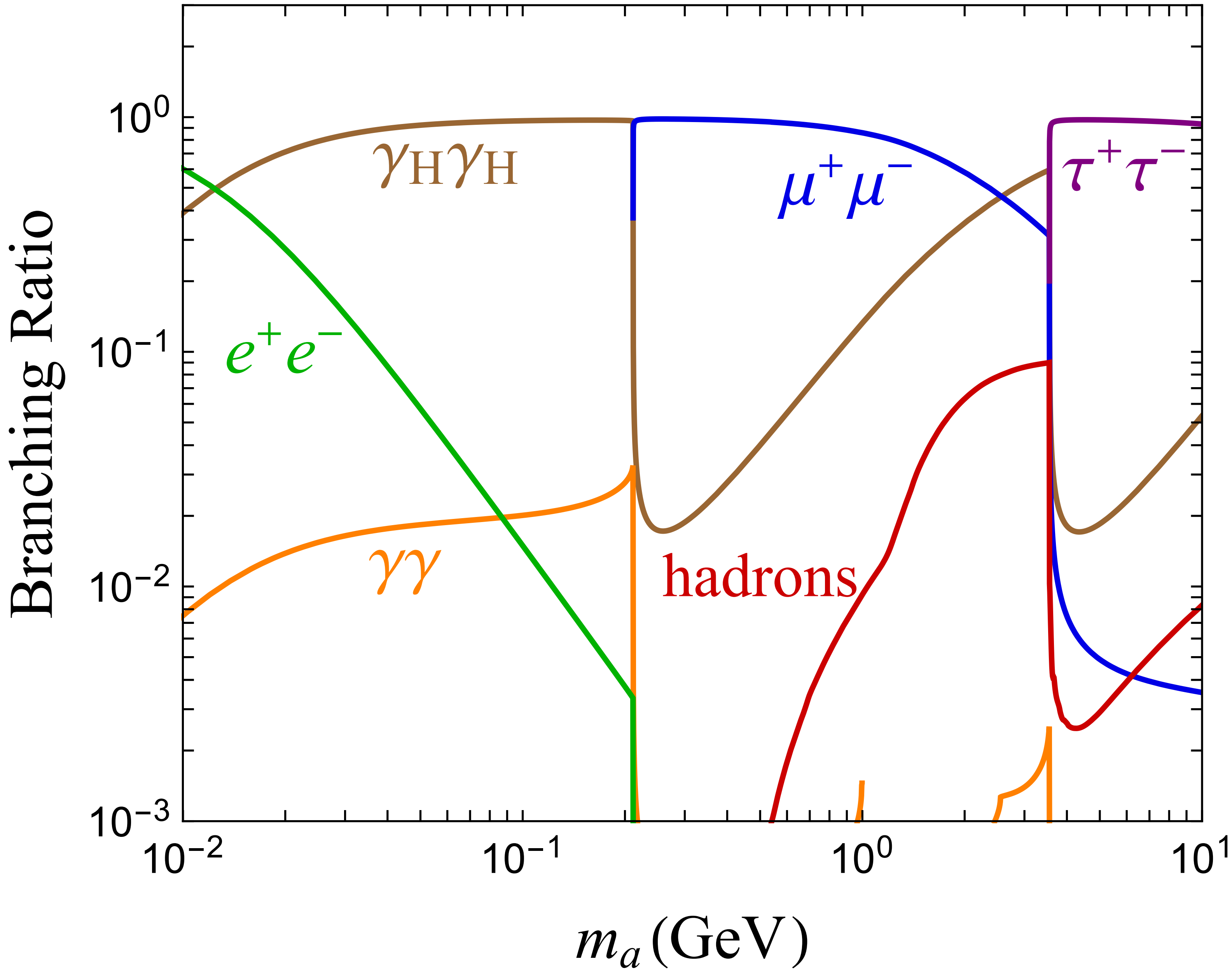


S.Y. Ho & F. Takahashi

M. Dolan et al. 2015

Axion decay channels with γ_H

S.Y. Ho & F. Takahashi

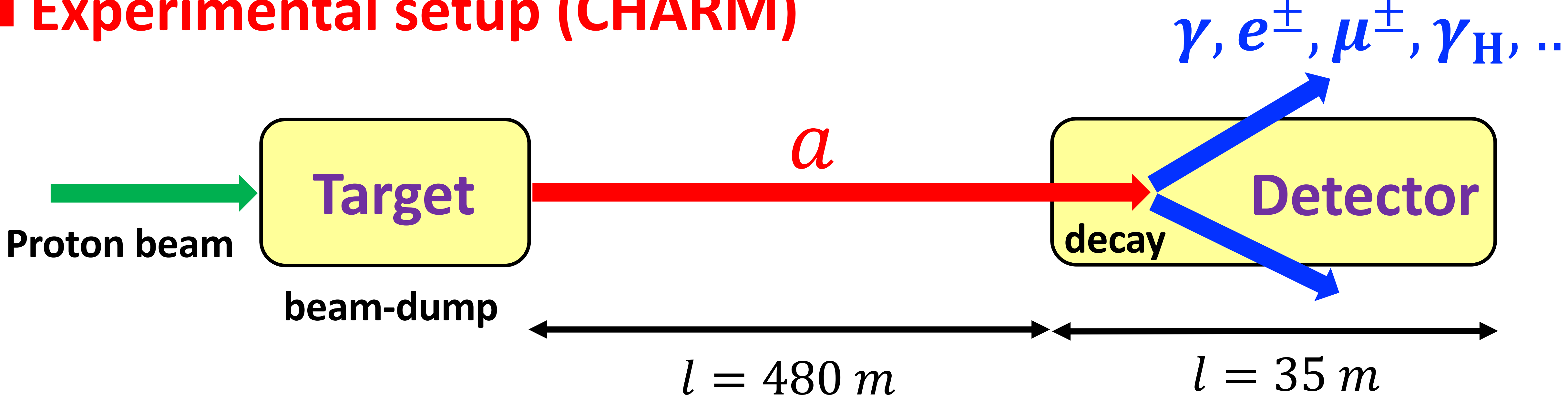


$$f_H = f_a$$

$$\alpha_H \simeq 0.73$$

Beam-dump experiments

■ Experimental setup (CHARM)

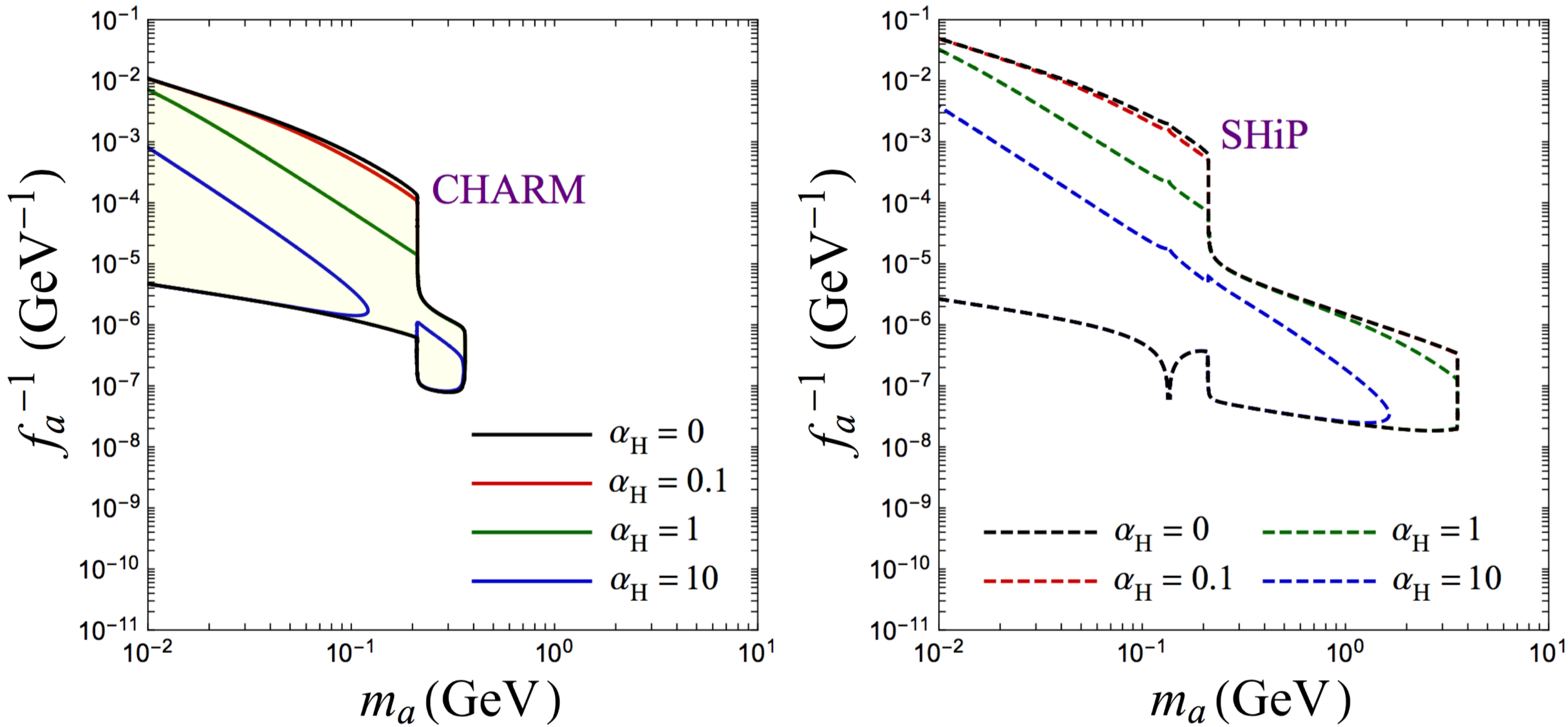


J.D. Clarke et al. 2014

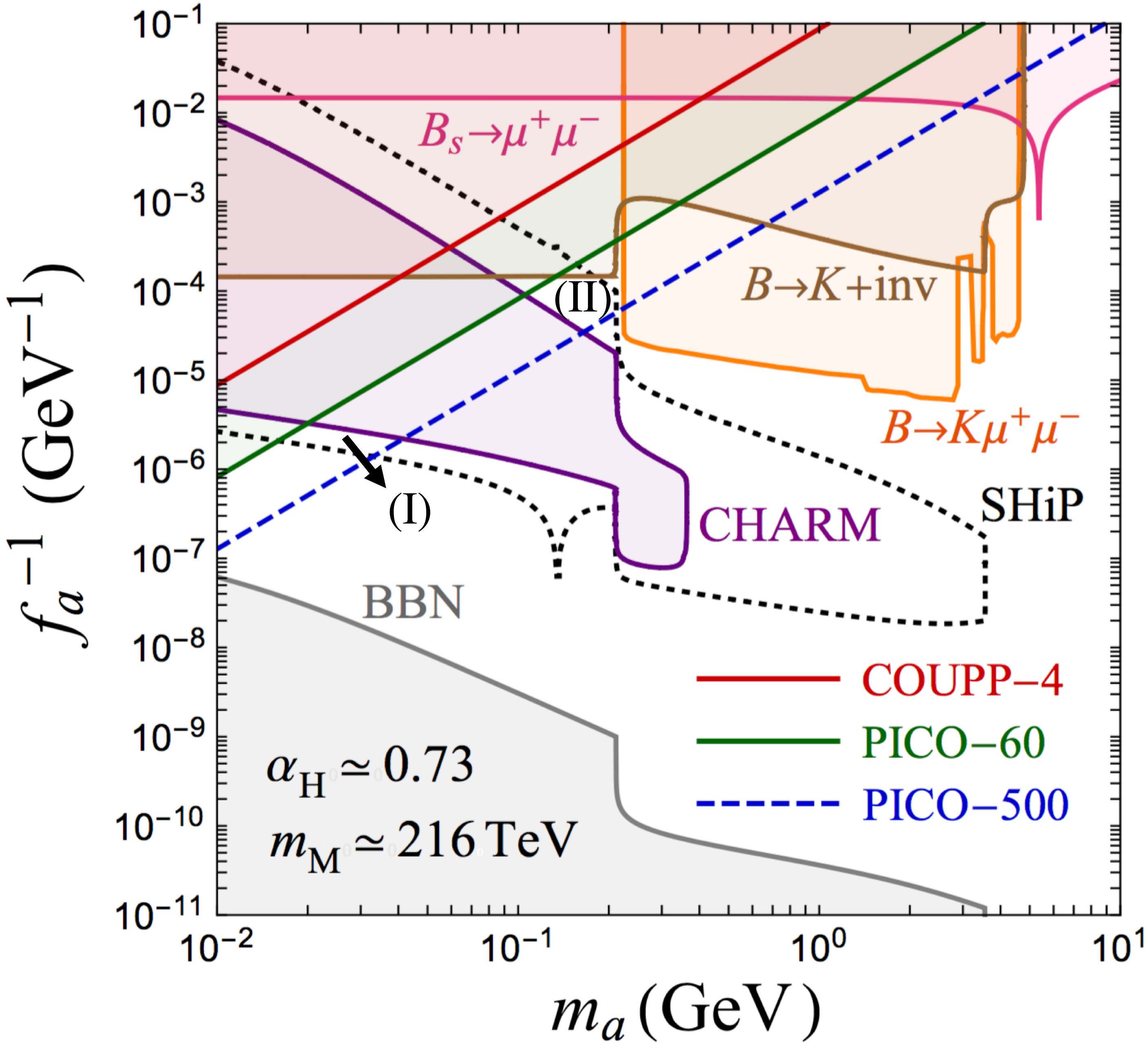
$$N_{\rm det} \approx N_a \exp\left(-\frac{480\,{\rm m}}{\gamma_a \beta_a c\, \tau_a}\right)\left[1 - \exp\left(-\frac{35\,{\rm m}}{\gamma_a \beta_a c\, \tau_a}\right)\right] \sum_{X=e,\,\mu,\gamma} \mathcal{B}(a \to X\bar{X}) < 2.3$$

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

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



Combined result : m_a vs f_a^{-1}



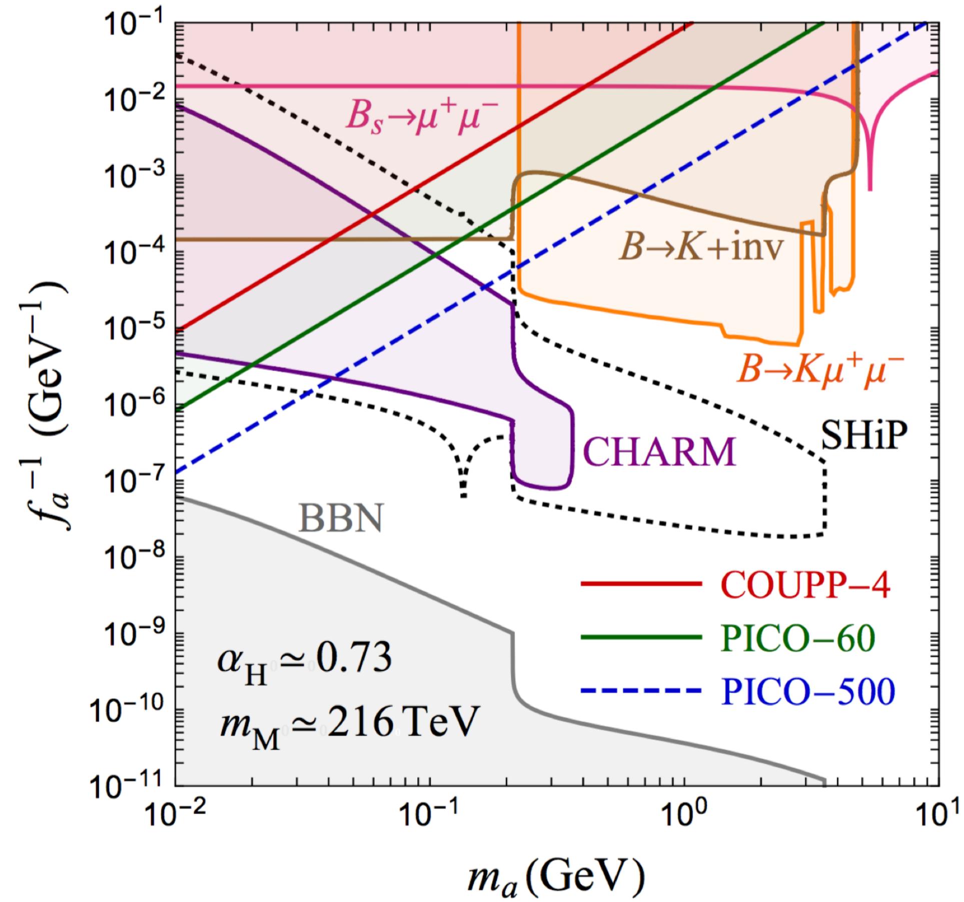
(I) $m_a = \mathcal{O}(10)$ MeV, $f_a = \mathcal{O}(10^5)$ GeV

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

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



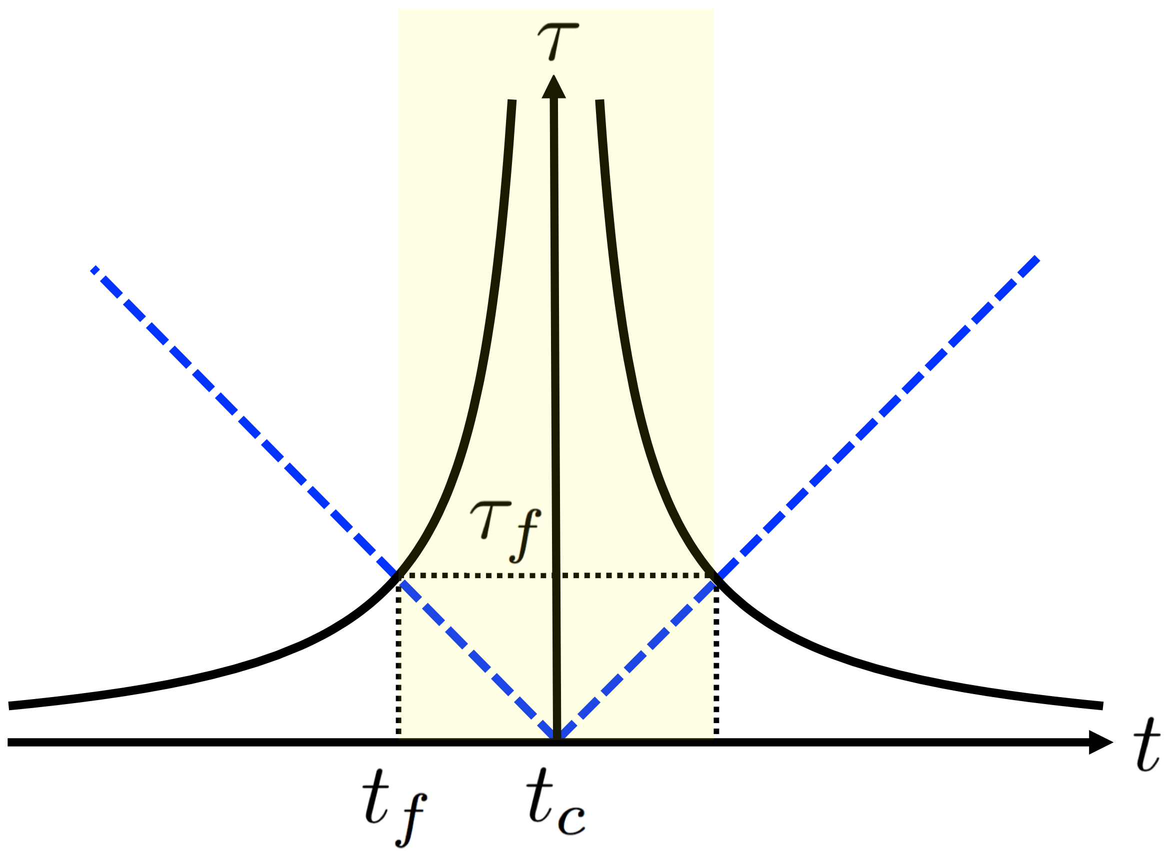
Back up

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 : $t_f - t_c = \tau_f$

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

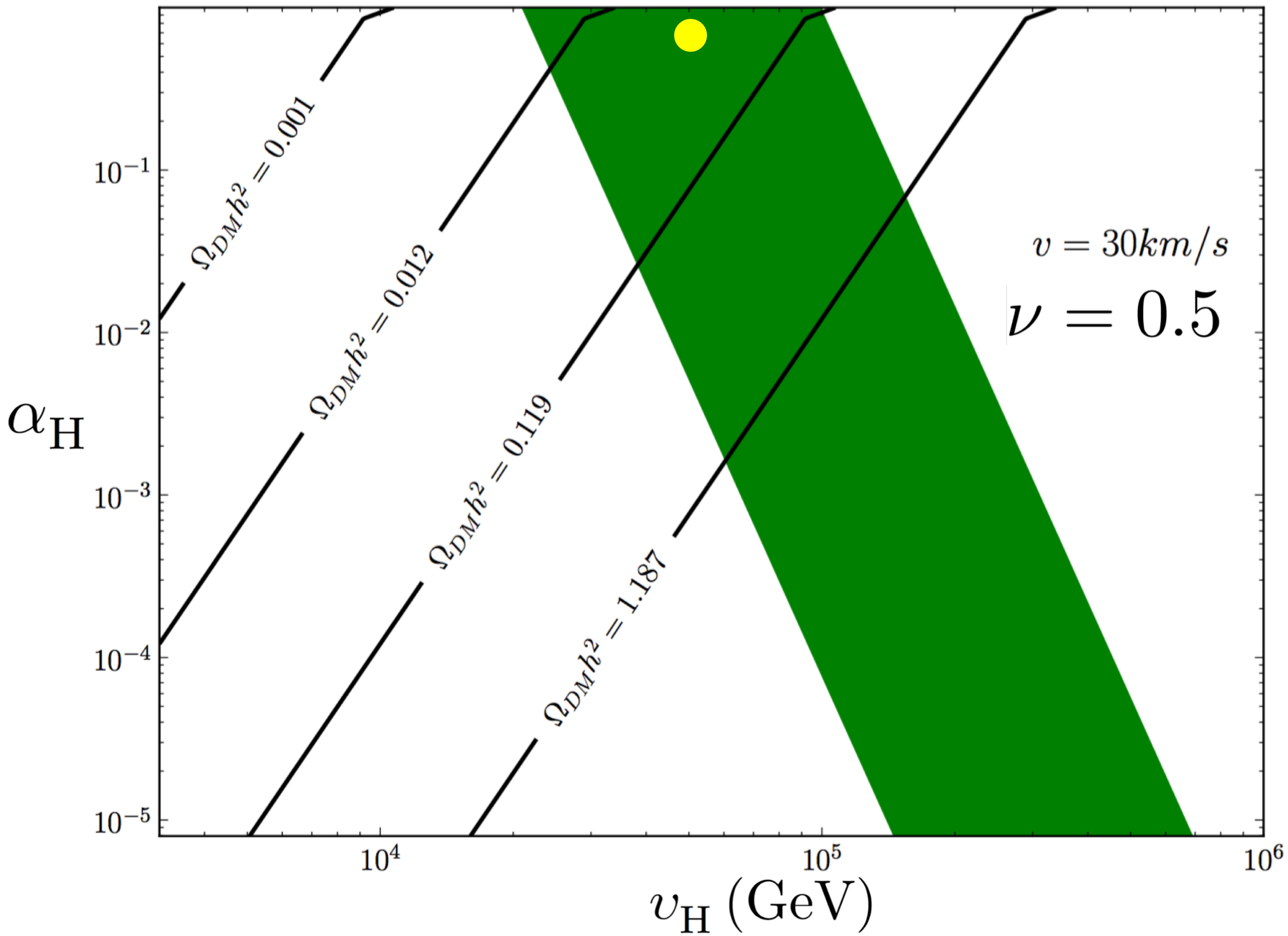
$$\zeta_f = \zeta_0 \left[\tau_0 H(t_c)\right]^{-\nu/(1+\mu)}$$

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

Benchmark point

■ Self-interacting DM : Hidden monopole

Khoze & Ro 2014



Green region

$$0.1\ \frac{\rm cm^2}{\rm g} < \frac{\sigma_{\rm T}}{m_{\rm DM}} < 10\ \frac{\rm cm^2}{\rm g}$$

$$v_{\rm DM} \simeq 30\ \frac{\rm km}{\rm s}$$

35% hidden monopole DM

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

$$m_{\rm M} \simeq 216\ {\rm TeV}$$