Axion-Higgs Portal

The minimal Axion Model

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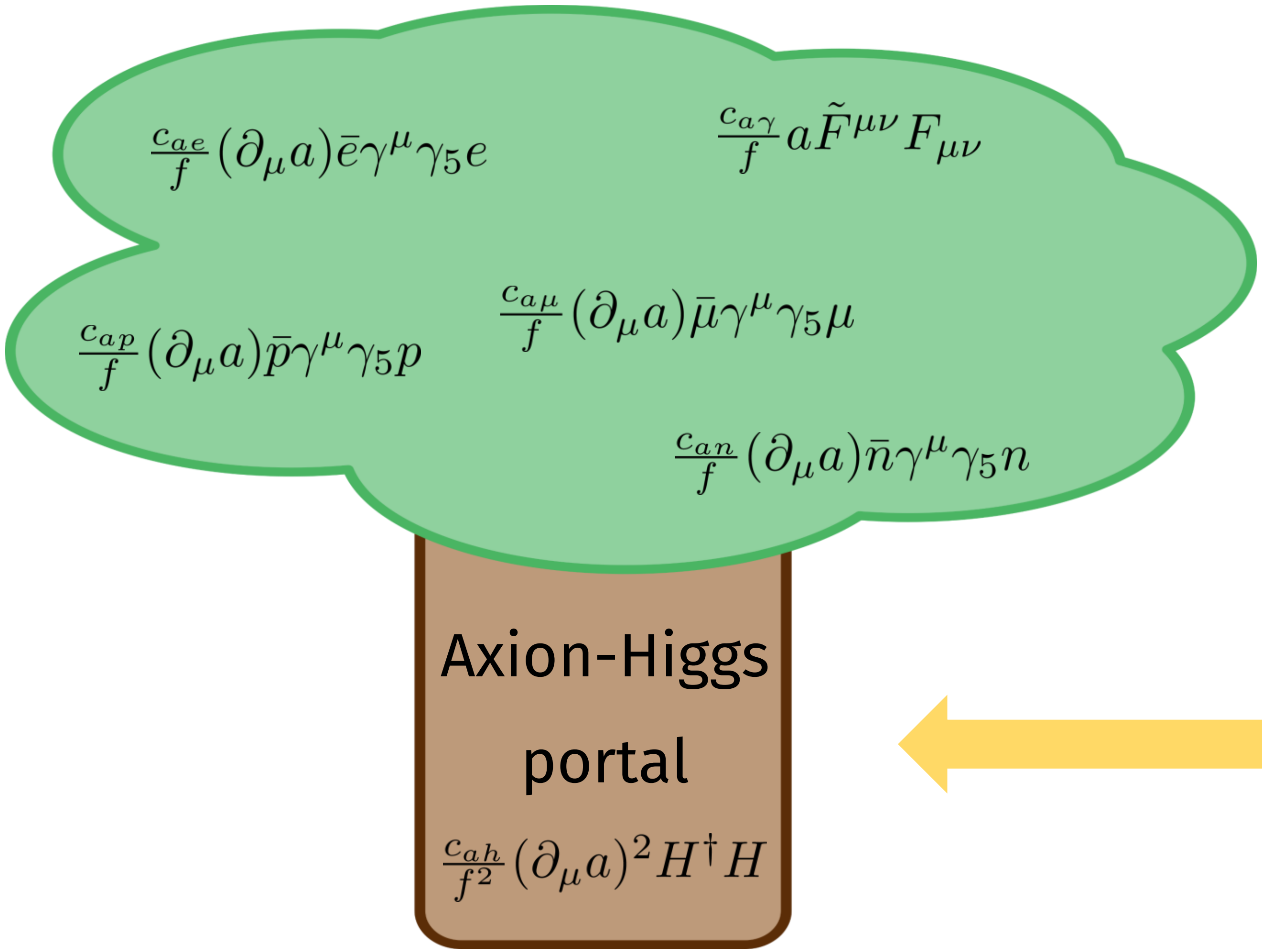
based on hep-ph/2207.05672
with Martin Bauer and Guillaume Rostagni

Axion Models as Trees

$a \to a + f\alpha$

- Axion = **Goldstone boson** of a spontaneously broken global symmetry



Special properties of the Axion-Higgs portal

- Z_2 symmetry $a \to -a$
- Dimension-6 operator

Higgs portal

$c_{sh} s^2 H^\dagger H$

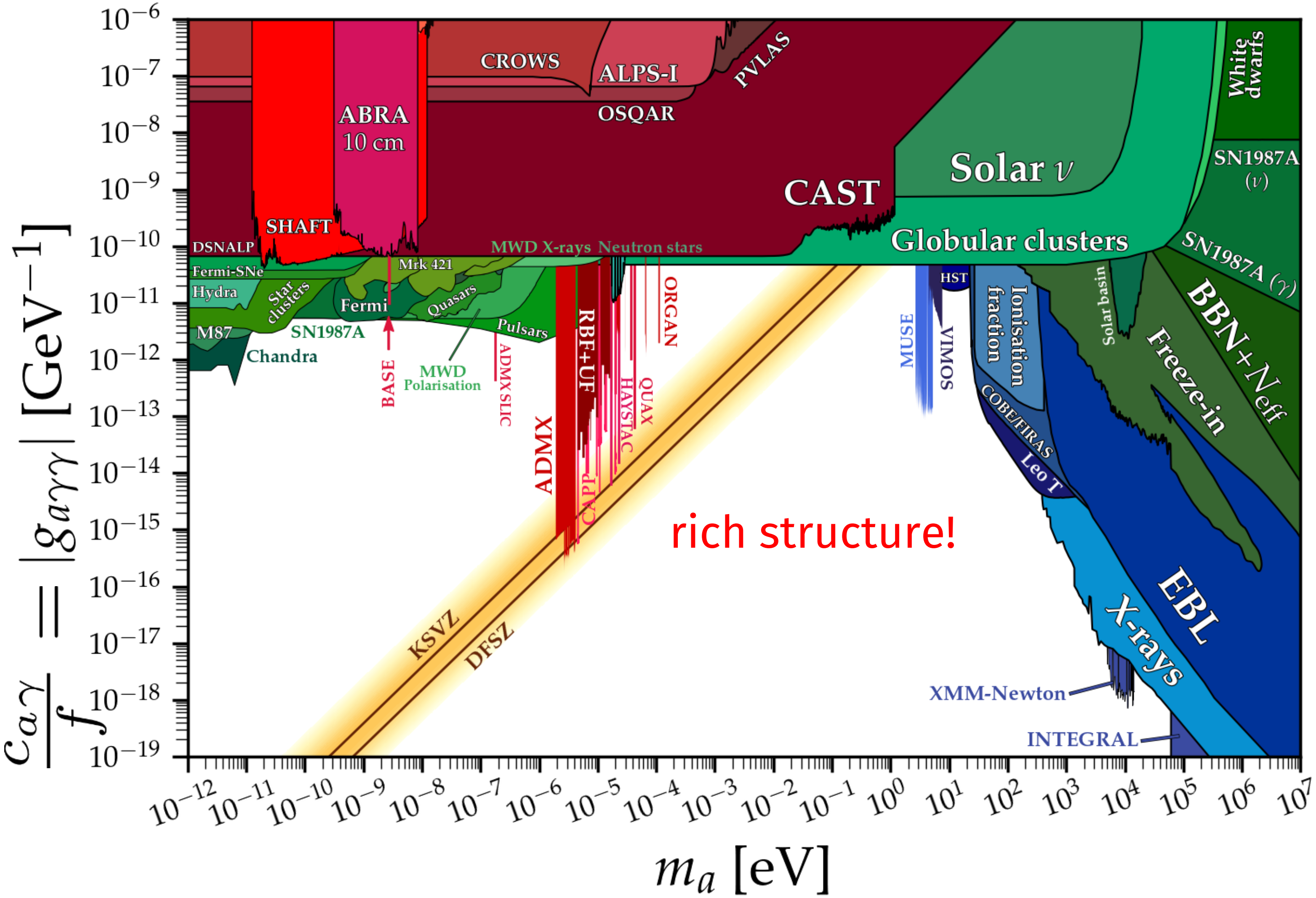
Outline

$$\mathscr{L} \supset \frac{c_{ah}}{f^2}(\partial_\mu a)^2 H^\dagger H$$

- Experimental constraints
- Dark matter from Freeze-In production
- Compare with other axion models and the Higgs portal

Constraints on the Axion-Photon Coupling

$$\mathscr{L} \supset \frac{c_{a\gamma}}{f} a \tilde{F}^{\mu\nu} F_{\mu\nu}$$

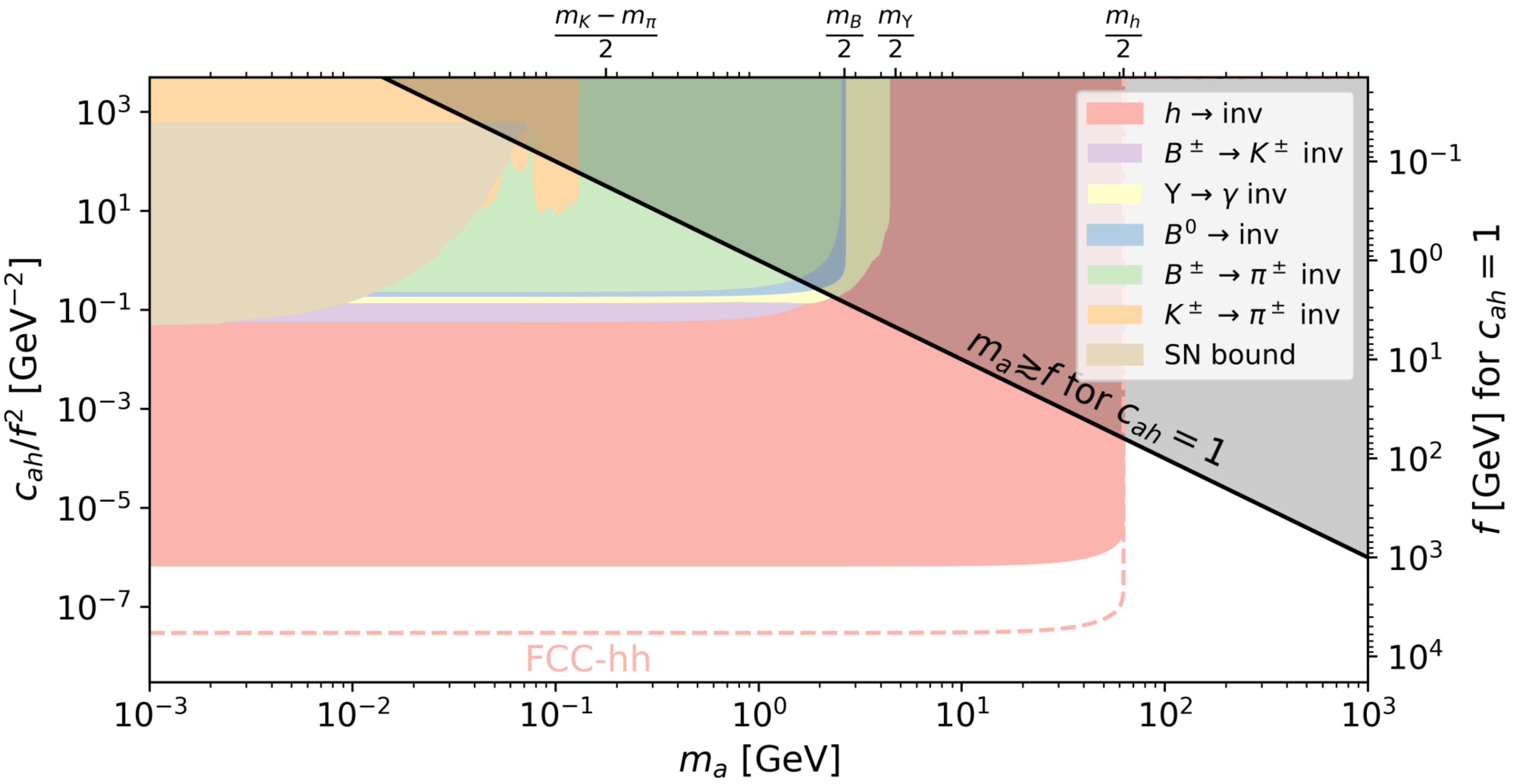


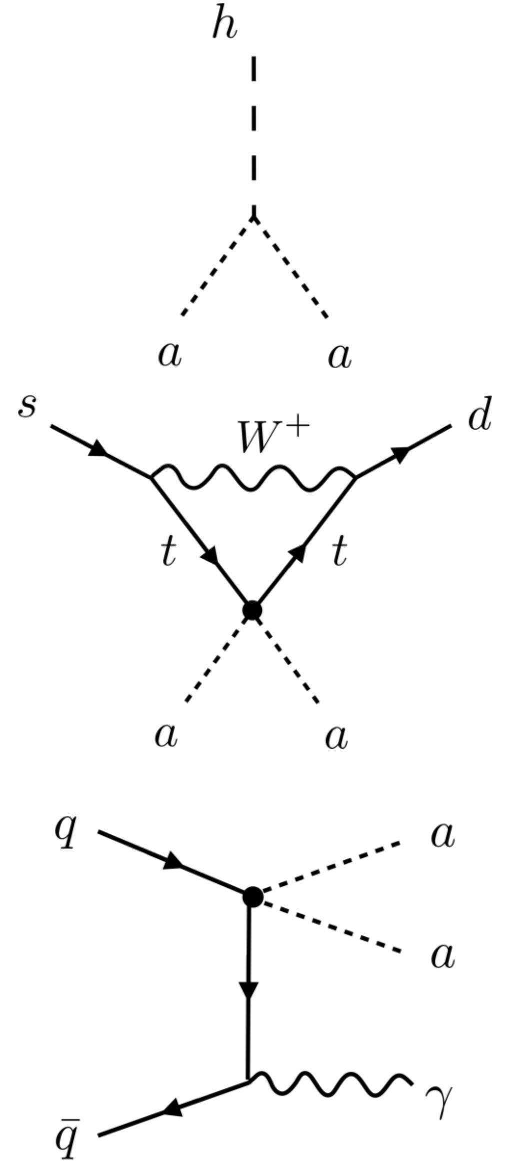
$\rightarrow f \gtrsim 10^{10}\,\text{GeV}$

github.com/cajohare/AxionLimits

Constraints on the Axion-Higgs Portal

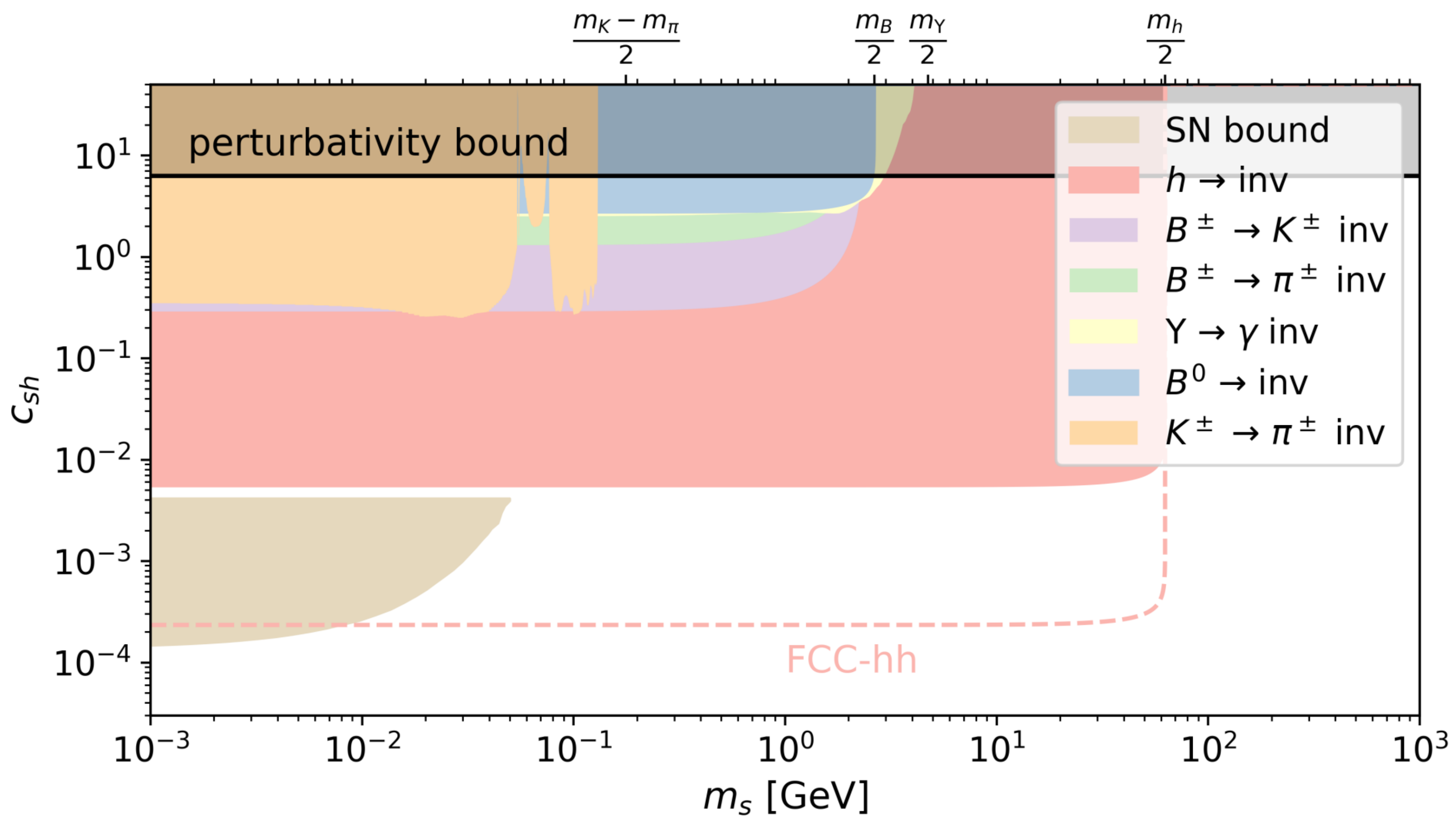
$$\mathscr{L} \supset \frac{c_{ah}}{f^2}(\partial_\mu a)^2 H^\dagger H$$

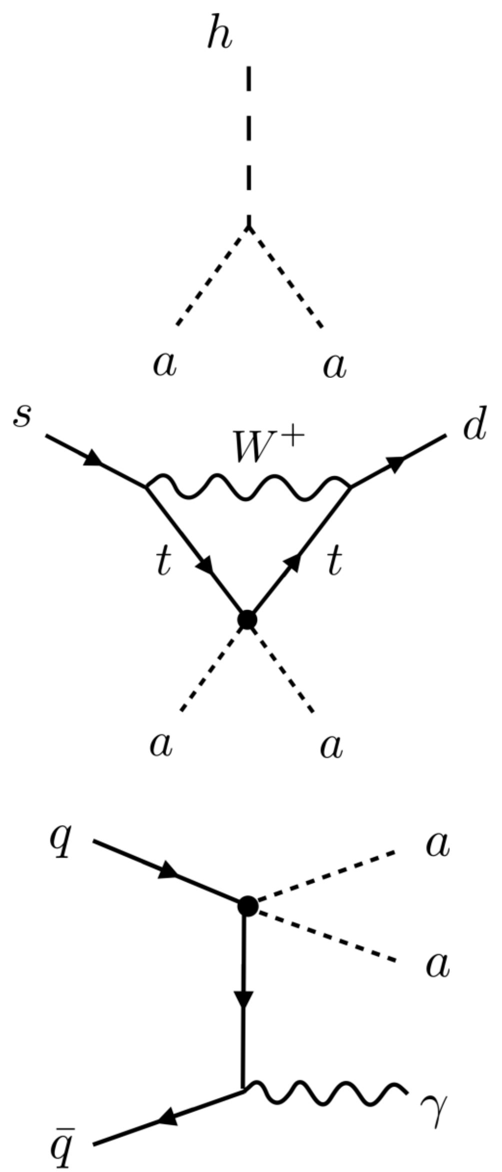




Constraints on the Higgs Portal

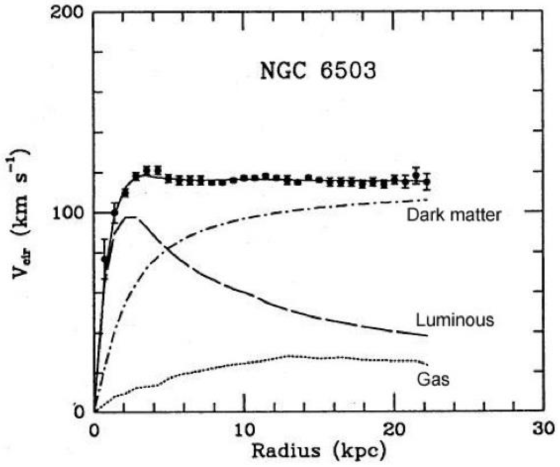
$$\mathscr{L} \supset c_{sh} s^2 H^\dagger H$$

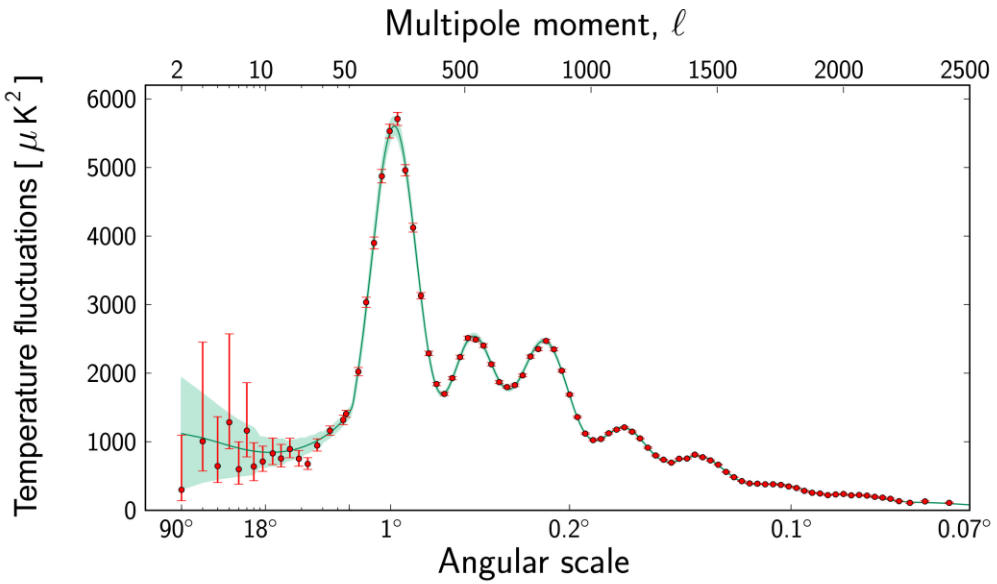




Dark Matter?

Evidence:





Production mechanisms:

DM coupling

Vacuum misalignment
„normal“ axion models

Freeze-In
e.g. Higgs portal,
Axion-Higgs portal

Freeze-Out
e.g. WIMPs

2→2 Freeze-In Production

- Consider a dimension-n operator $\mathscr{L} \supset \frac{1}{\Lambda^{n-4}}\mathcal{O}_n$
- At large temperature, cross section scales as $\sigma \propto \frac{1}{\Lambda^{2(n-4)}}T^{2(n-5)}$
- Dark Matter production scales as

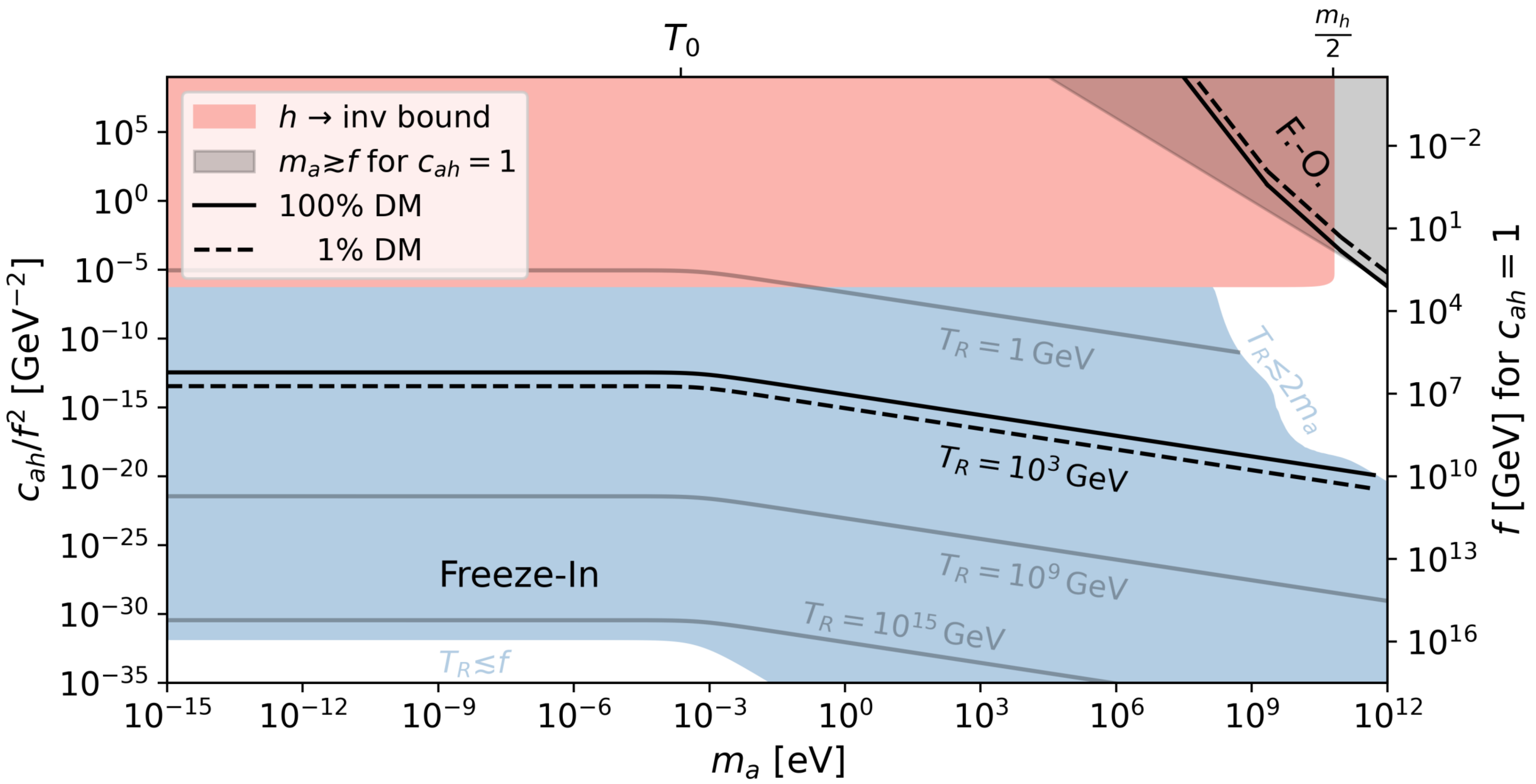
$$\Omega h^2 \propto \int_{T_0}^{T_R} dT\sigma \propto \begin{cases} {T_0}^{-1} & n=4 \\ {T_R}^{2(n-4)-1} & n>4 \end{cases}$$

T_0 : Temperature of the universe today

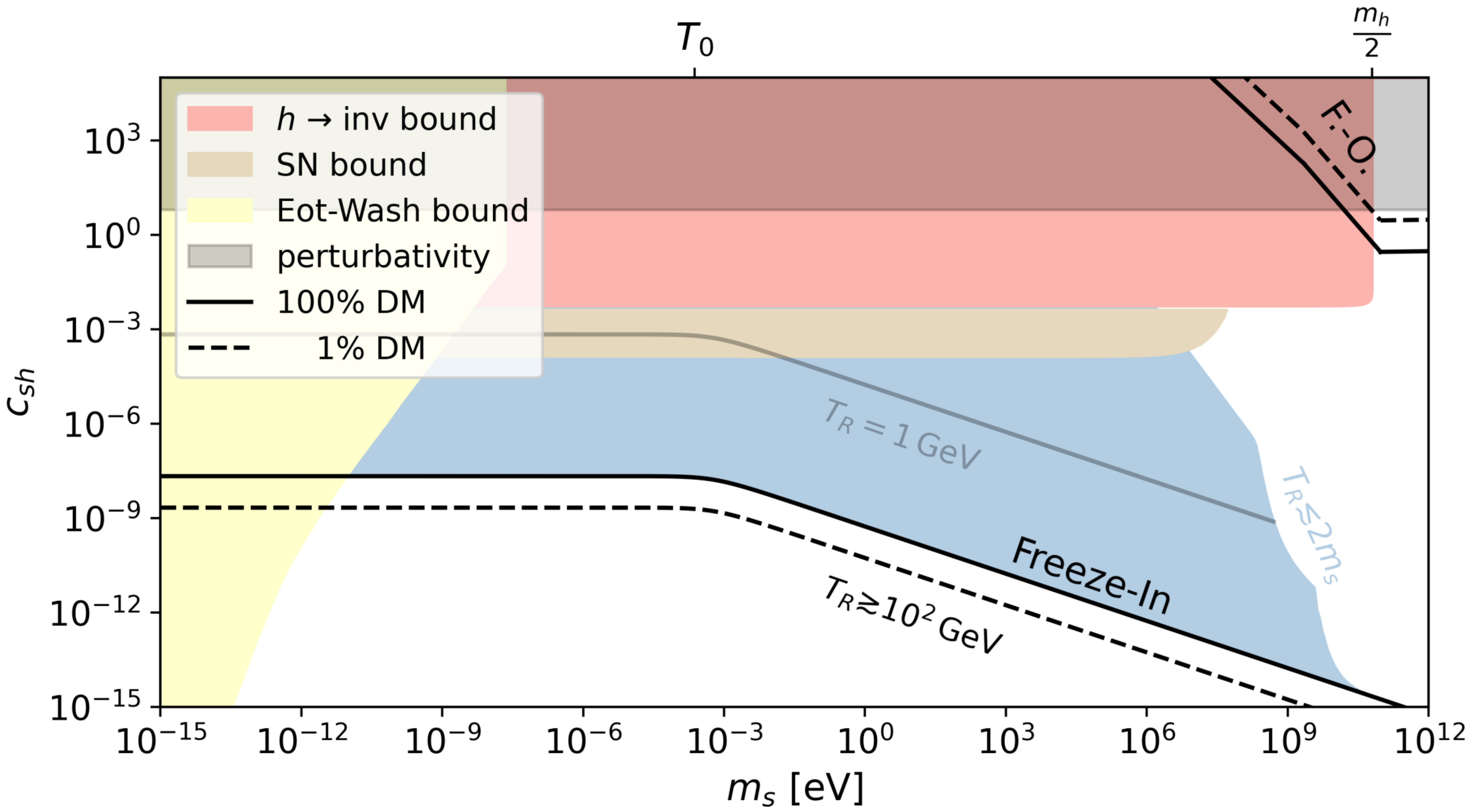
T_R : Cutoff temperature

Freeze-In via non-renormalizable operators is sensitive to the cutoff temperature T_R

Dark Matter from the Axion-Higgs Portal



Dark Matter from the Higgs Portal

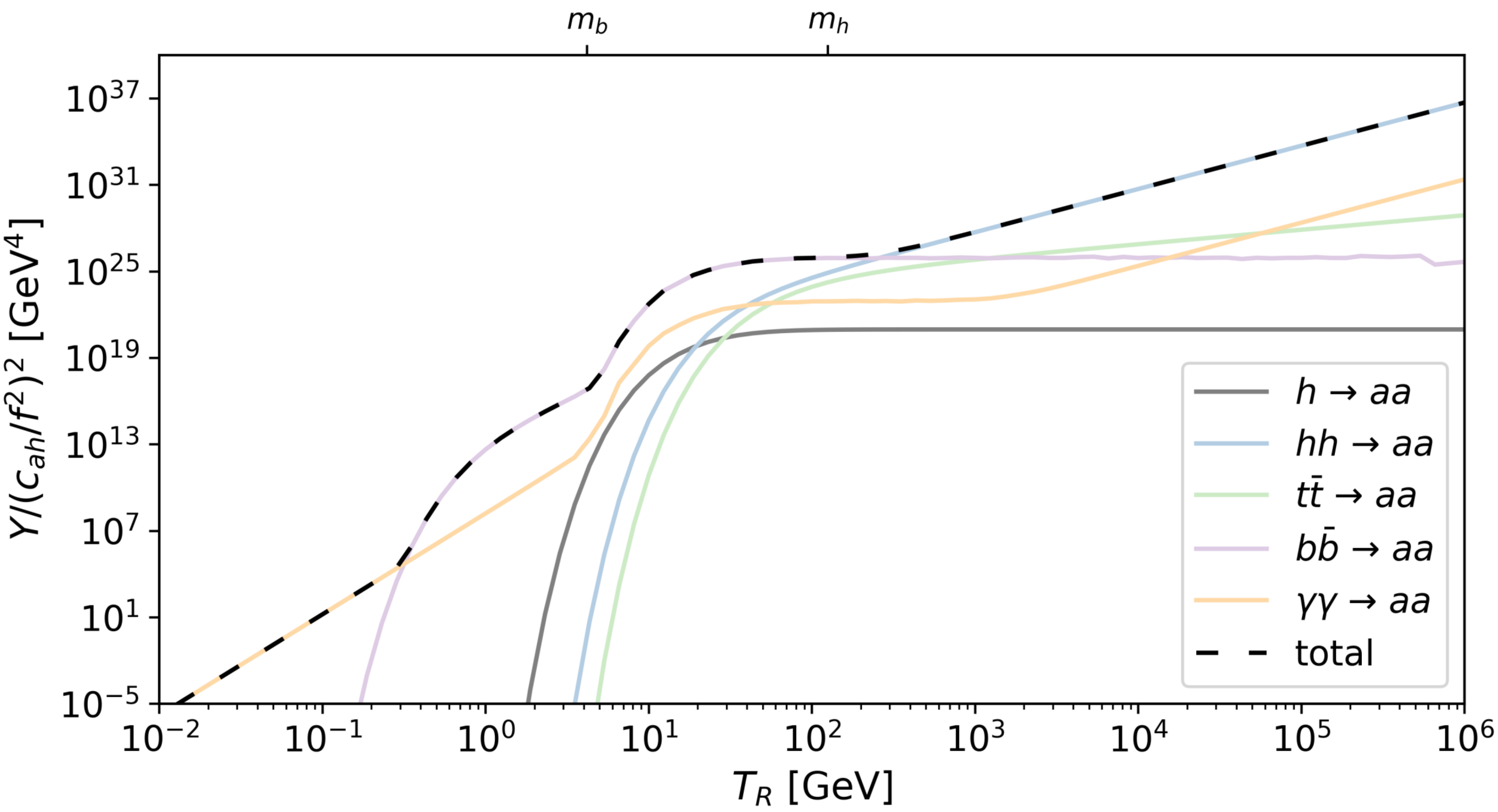


Results

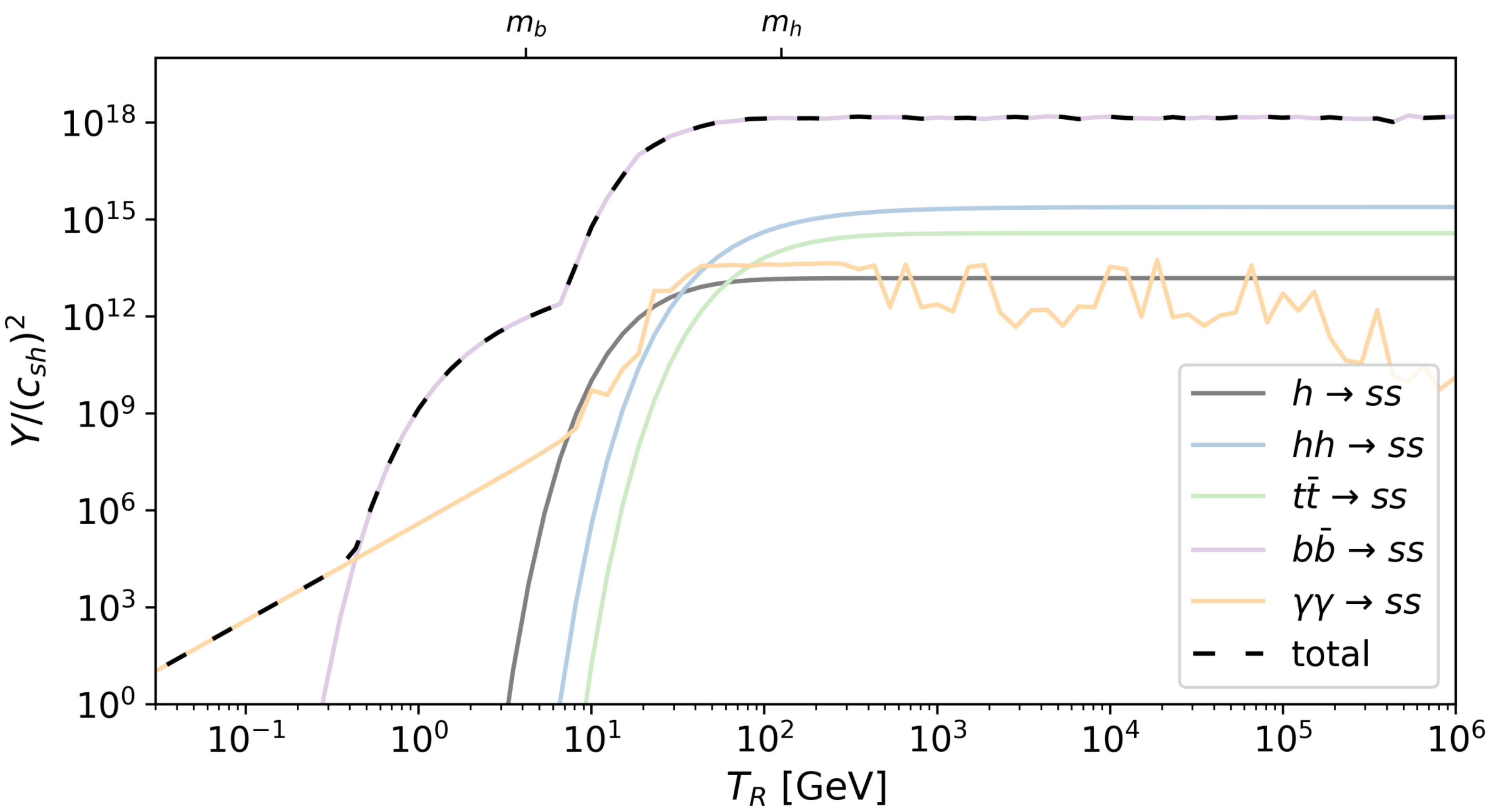
- The Axion-Higgs portal is the **minimal** axion model
- An Axion-Higgs portal particle is **naturally light**, while a Higgs portal particle is **naturally heavy**
- Need to look for **invisible Higgs** decays to find the Axion-Higgs portal
- Lots of parameter space for **Freeze-In Dark Matter** from Axion-Higgs portal

Backup

Axion-Higgs portal Freeze-In Channels



Higgs portal Freeze-In Channels



A Simple UV Completion

$$\mathscr{L} = \mathscr{L}_{\rm SM} + (\partial_\mu S)^\dagger(\partial^\mu S) + \mu_S^2 S^\dagger S - \lambda_S (S^\dagger S)^2 + g(S^\dagger S)H^\dagger H$$

1. SSB $S = \frac{f+s}{\sqrt{2}} e^{ia/f}$ $\quad \Rightarrow \quad$ $\mathscr{L} \supset \frac{1}{2f^2}(f+s)^2(\partial_\mu a)^2 - \frac{m_s^2}{2}s^2 - \frac{m_h^2}{2}h^2 - gfvsh$

$\langle h \rangle = v$

$\langle s \rangle = f$

2. Mass diagonalization $\begin{pmatrix} s \\ h \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{s} \\ \tilde{h} \end{pmatrix}$ with $\tan 2\theta = \frac{2gfv}{m_s^2 - m_h^2}$

SM Higgs Boson

3. Integrate out $\tilde{s}$ $\quad \Rightarrow \quad$ $\mathscr{L} \supset \frac{1}{2f^2}(f - \sin\theta \tilde{h})^2(\partial_\mu a)^2 \supset -\frac{\sin\theta}{f}\tilde{h}(\partial_\mu a)^2 \subset -\frac{\sin\theta}{fv}\tilde{H}^\dagger \tilde{H}(\partial_\mu a)^2$

$$\Rightarrow \quad c_{ah} = -\sin\theta \frac{f}{v} \sim -g\frac{f^2}{m_s^2} \sim 1$$

Axion-Higgs Portal Couplings

$$\mathscr{L}(\mu \lesssim f) \supset \frac{c_{ah} v}{f^2} h (\partial_\mu a)^2$$

$$\mathscr{L}(\mu \lesssim v) \supset -\sum_{i,j} \frac{c_{ah} c_{ij}}{f^2 m_h^2} (\partial_\mu a)^2 \bar{f}_i \Big(m_i P_L + m_j P_R \Big) f_j + \text{h.c.}$$

$$+ \frac{c_{ah} c_\gamma}{f^2 m_h^2} (\partial_\mu a)^2 F_{\mu\nu} F^{\mu\nu} + \frac{c_{ah} c_G}{f^2 m_h^2} (\partial_\mu a)^2 G_{\mu\nu} G^{\mu\nu}$$

EW physics integrated out

$$c_\gamma = -\frac{\alpha}{4\pi}\frac{47}{18} \qquad c_G = \frac{\alpha}{4\pi}\frac{1}{3} \qquad c_{ii} = 1$$

$$c_{ij} = \frac{3}{32\pi^2} \sum_u V_{ui}^* V_{uj} \frac{m_u^2}{v^2} \left\{ 1 - \frac{m_h^2}{m_W^2} \Delta\left(\frac{m_u^2}{m_W^2} \right) \right\}$$

$$\Delta(x) = \frac{x(2-x)}{3(1-x)^3} \log x + \frac{3-x}{6(1-x)^2}$$

Analytic Results for Axion-Higgs portal Freeze-In

$$\Omega h^2 = \frac{sh^2}{\rho_c}\frac{\rho}{n}Y = \frac{sh^2}{\rho_c}Y \times \begin{cases} m_a\,, & m_a \gg T_0 \\ \frac{\pi^4}{30\zeta_3}T_0\,, & m_a \ll T_0 \end{cases}$$

Approximate expressions for the dominant channels:

$$hh \to aa: \quad Y = \frac{2160}{\pi}\sqrt{\frac{10}{g_* g_{s*}}}\frac{c_{ah}^2 m_{\mathrm{Pl}} T_R^3}{f^4}$$

$$b\bar{b} \to aa: \quad Y = \frac{135}{4}\sqrt{\frac{10}{g_* g_{s*}^2}}\frac{c_{ah}^2 m_b^2 m_h^2 m_{\mathrm{Pl}}}{f^4 \Gamma_h}\int_{m_h/T_R}^{\infty} dx x^3 K_1(x)$$

$$\gamma\gamma \to aa: \quad Y = \frac{49766400}{7\pi}\sqrt{\frac{10}{g_* g_{s*}^2}}\frac{c_{ah}^2 c_\gamma^2 m_{\mathrm{Pl}} T_R^7}{f^4 m_h^4}$$