Electroweak Axion Portal to Dark Matter

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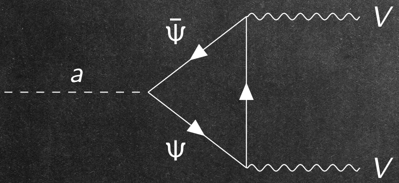
Motivation

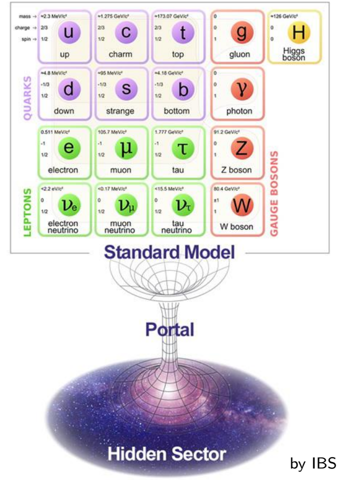
- The low-mass pseudo-Goldstone bosons, which arise from the breaking of an anomalous (chiral) global symmetry are referred as axion-like particles (ALPs).
- ALPs can be found in many models of physics beyond the SM such as supersymmetric theories and string theory.
- ALPs can couple to the gauge fields in a manner proportional to the gauge field.



$$\mathcal{L}_{\mathrm{gauge-ALP}} = -\frac{g_{aV}}{4}\, a V_{\mu\nu} \tilde{V}^{\mu\nu} \quad (1)$$

Motivation

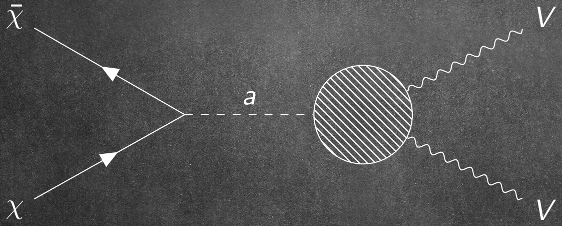
- ALPs can naturally have any mass, which arise from explicit symmetry breaking.
- The coupling strength of the ALP is inversely proportional to the scale of spontaneous symmetry breaking ($g_{aV} \sim 1/f$)
- ALPs are ideal candidates to act as mediators to the hidden sector via the so-called "axion portal."



by IBS

Model: Mediator EFT

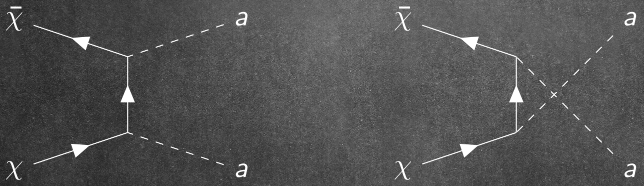
$$\mathcal{L}_{\text{gauge}-\text{ALP}} = -\frac{C_{aB}}{4} aB_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{C_{aW}}{4} aW^b_{\mu\nu}\tilde{W}^{b\mu\nu} \quad (2)$$



$$\mathcal{L}_{\text{DM}-\text{ALP}} = -\frac{1}{2f}\partial_\mu a\,\bar{\chi}\gamma^\mu\gamma^5\chi \quad (3)$$

Model: Mediator EFT

$$\mathcal{L}_{\rm gauge-ALP} = -\frac{C_{aB}}{4} aB_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{C_{aW}}{4} aW^b_{\mu\nu}\tilde{W}^{b\mu\nu} \quad (2)$$



$$\mathcal{L}_{\rm DM-ALP} = -\frac{1}{2f}\partial_\mu a\,\bar{\chi}\gamma^\mu\gamma^5\chi \quad (3)$$

Benchmark

Goals: concrete predictions between indirect detection, colliders, and relic abundance (thermal freeze-out and freeze-in).

$$(1) : C_{aW} = 0,\; C_{aB} = \frac{\alpha_Y Q_Y^2}{\pi f} \qquad \leftarrow \text{Hypercharge}$$

$$(2) : C_{aW} = \frac{\alpha_W T(R)}{\pi f},\; C_{aB} = 0 \qquad \leftarrow \text{SU(2)}$$

	Small coupling	Large coupling
Q_Y	1	10
$T(R)$	1/2	110

Thermal dark matter abundance

	Secluded ($M_a < M_\chi$)	Annhilation to SM ($M_a \geq M_\chi$)
Dominant mode	$\chi\bar{\chi} \to aa$	$\chi\bar{\chi} \to \gamma\gamma$ (or other EW pairs)
Resonance	NA	$M_a \sim 2M_\chi$

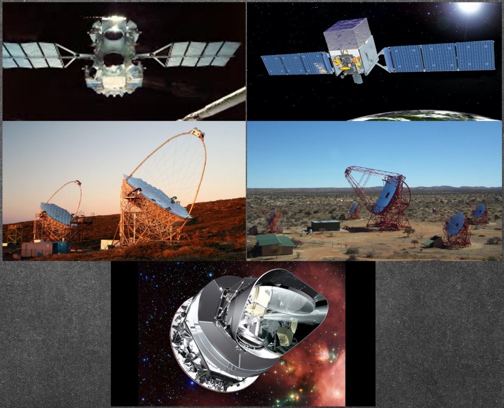
Propagator analytical approximation near resonance:

$$\frac{1}{(s - M_a^2)^2 + M_a^2\Gamma_a^2} \to \frac{\pi}{M_a\Gamma_a}\delta(s - M_a^2) \tag{4}$$

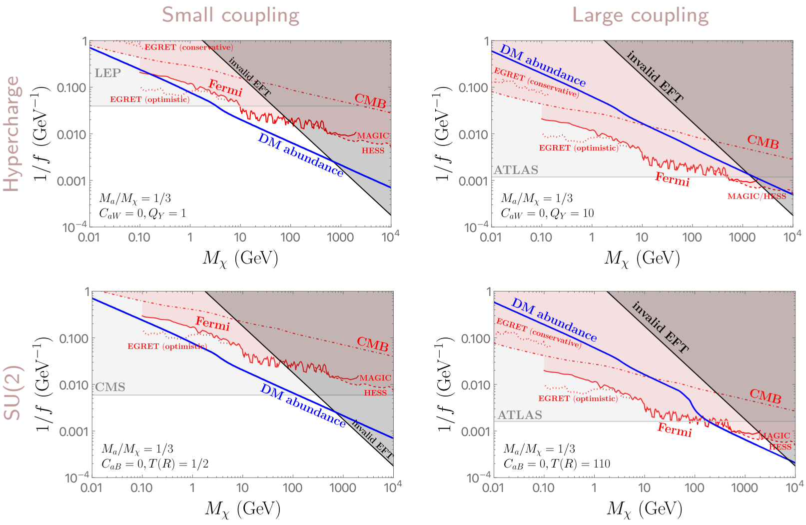
FeynRules $\longrightarrow$ micrOMEGAs $\longrightarrow$ DM thermal relic
(except at resonance)

Results: Indirect Detection

- Gamma-ray line searches:
  - ERGET
  - Fermi LAT
  - MAGIC
  - HESS
- Diffusive CMB:
  - Planck Satellite

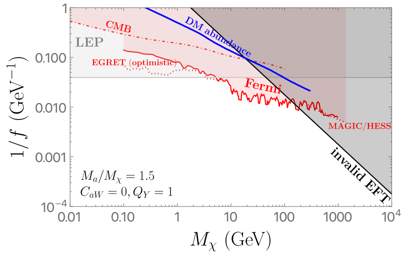


Results: Indirect Detection ($M_a < M_\chi$)



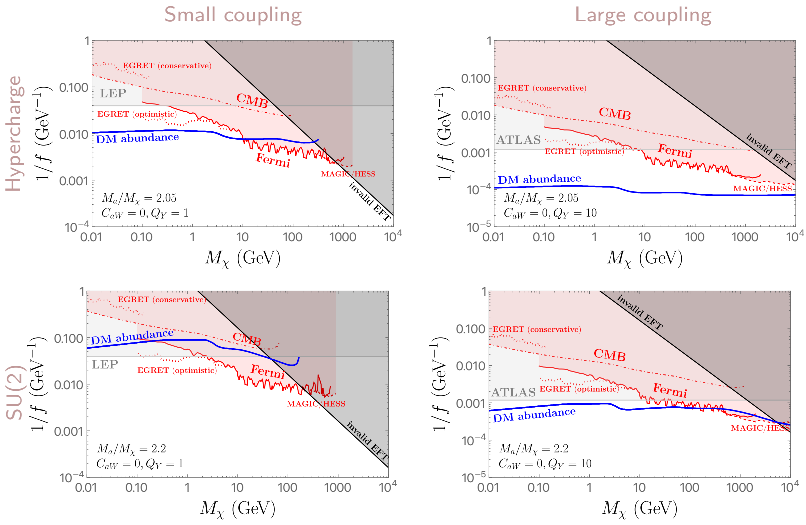
Results: Indirect Detection ($M_a > M_\chi$)

Small hypercharge coupling

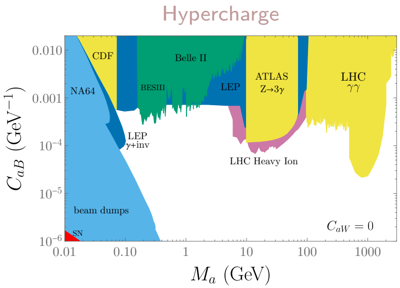


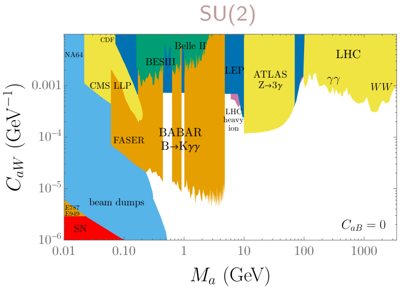
Other cases are comparable.

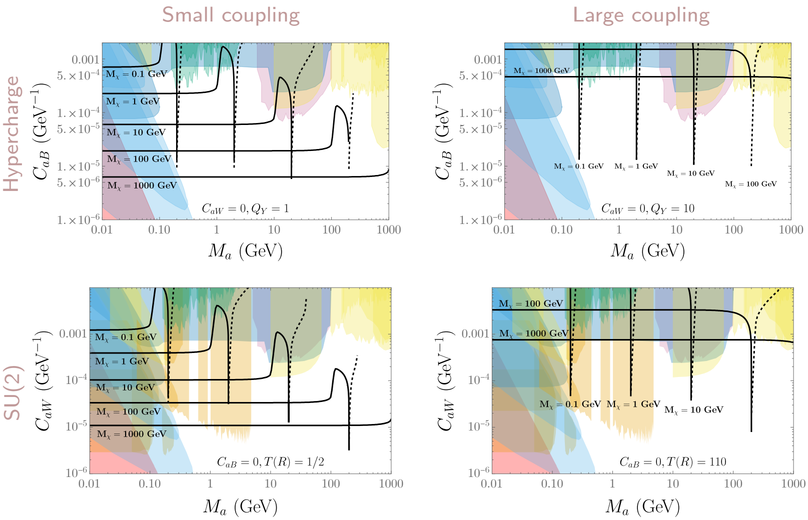
Results: Indirect Detection ($M_a \sim 2M_\chi$)



Results: Accelerator and collider searches for ALPs

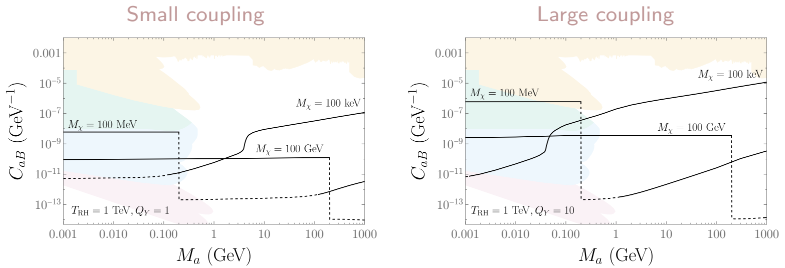





Small coupling
Large coupling
Hypercharge
SU(2)
C_{aB} (GeV^{-1})
C_{aW} (GeV^{-1})
M_a (GeV)
M_χ = 0.1 GeV
M_χ = 1 GeV
M_χ = 10 GeV
M_χ = 100 GeV
M_χ = 1000 GeV
$C_{aW} = 0, Q_Y = 1$
$C_{aW} = 0, Q_Y = 10$
$C_{aB} = 0, T(R) = 1/2$
$C_{aB} = 0, T(R) = 110$

Freeze-in

- Instantaneous reheating; $M_a, M_\chi \leq T_{\mathrm{RH}}$
- DM production: $\gamma\gamma \to \bar{\chi}\chi$, $a \to \bar{\chi}\chi$, and $aa \to \bar{\chi}\chi$
- ALPs production: $\gamma\gamma \to a$, $\bar{f}f \to \gamma a$, $f\gamma \to fa$, and $\bar{f}\gamma \to \bar{f}a$



Conclusion

- We have systematically studied the cosmology and phenomenology of electroweak ALP portal DM
  - Substantial thermal parameter space was constrainted and the remain will also be probed by future experiments
  - Meaningful constraint for freeze-in scenario for ALP below 100 MeV
- Future study beyond EFT model can extend the parameter space and search for new phenomena

Conclusion

Thank you

Back-up Slides: EW mixing

$$
\begin{aligned}
\mathcal{L}_{\mathrm{gauge-ALP}} =& -\frac{g_{a\gamma\gamma}}{4}\, aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{aZZ}}{4}\, aZ_{\mu\nu}\tilde{Z}^{\mu\nu} \\
& - \frac{g_{a\gamma Z}}{2}\, aF_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{2}\, aW^{+}_{\mu\nu}\tilde{W}^{-\mu\nu} \\
g_{a\gamma\gamma} =& C_{aB}\cos^2\theta_{\mathrm{W}} + C_{aW}\sin^2\theta_{\mathrm{W}}, \\
g_{aZZ} =& C_{aB}\sin^2\theta_{\mathrm{W}} + C_{aW}\cos^2\theta_{\mathrm{W}}, \\
g_{a\gamma Z} =& (C_{aW} - C_{aB})\sin\theta_{\mathrm{W}}\cos\theta_{\mathrm{W}}, \\
g_{aWW} =& C_{aW}
\end{aligned}
$$

Back-up Slides: Freeze-out Boltzmann Equation

$$\frac{dY_\chi}{dx} = -\frac{s\langle\sigma_{\bar{\chi}\chi\to\gamma\gamma}v\rangle^{\mathrm{sub}}(Y_\chi^{\mathrm{eq}})^2}{xH(x)}\left[\frac{Y_\chi^2}{(Y_\chi^{\mathrm{eq}})^2}-1\right] - \frac{s\langle\sigma_{\bar{\chi}\chi\to aa}v\rangle(Y_\chi^{\mathrm{eq}})^2}{xH(x)}\left[\frac{Y_\chi^2}{(Y_\chi^{\mathrm{eq}})^2}-1\right] - \frac{\langle\Gamma_a\rangle Y_a^{\mathrm{eq}}}{xH(x)}\mathrm{BF}(a\to\bar{\chi}\chi)\left[\frac{Y_\chi^2}{(Y_\chi^{\mathrm{eq}})^2}-1\right]. \tag{5}$$

$$\langle\sigma_{\bar{\chi}\chi\to\gamma\gamma}v\rangle^{\mathrm{sub}} = \langle\sigma_{\bar{\chi}\chi\to\gamma\gamma}v\rangle - \frac{Y_a^{\mathrm{eq}}}{s(Y_\chi^{\mathrm{eq}})^2}\langle\Gamma_a\rangle\mathrm{BF}(a\to\bar{\chi}\chi)\mathrm{BF}(a\to\gamma\gamma) \tag{6}$$

Back-up Slides: Freeze-in Boltzmann Equations

$$\begin{aligned}\frac{dY_a}{dx} =& -\frac{\langle\Gamma_a\rangle Y_a^{\rm eq}}{xH(x)}\mathrm{BF}(a\to\gamma\gamma)\left(\frac{Y_a}{Y_a^{\rm eq}}-1\right)\\ &-\frac{\langle\Gamma_a\rangle Y_a^{\rm eq}}{xH(x)}\mathrm{BF}(a\to\bar\chi\chi)\left[\frac{Y_a}{Y_a^{\rm eq}}-\frac{Y_\chi^2}{(Y_\chi^{\rm eq})^2}\right]\\ &+\frac{2s\langle\sigma_{\bar\chi\chi\to aa}v\rangle(Y_\chi^{\rm eq})^2}{xH(x)}\left[\frac{Y_\chi^2}{(Y_\chi^{\rm eq})^2}-\frac{Y_a^2}{(Y_a^{\rm eq})^2}\right]\\ &-\frac{s\langle\sigma_{\mathrm{SM}\,a\to\mathrm{SM}\,\mathrm{SM}}v\rangle Y_{\rm SM}^{\rm eq}Y_a^{\rm eq}}{xH(x)}\left(\frac{Y_a}{Y_a^{\rm eq}}-1\right),\end{aligned} \tag{7}$$

Back-up Slides: Freeze-in Boltzmann Equations

$$\frac{dY_\chi}{dx} = -\frac{s\langle\sigma_{\bar{\chi}\chi\to\gamma\gamma}v\rangle(Y_\chi^{\mathrm{eq}})^2}{xH(x)}\left[\frac{Y_\chi^2}{(Y_\chi^{\mathrm{eq}})^2}-1\right]$$
$$-\frac{s\langle\sigma_{\bar{\chi}\chi\to aa}v\rangle(Y_\chi^{\mathrm{eq}})^2}{xH(x)}\left[\frac{Y_\chi^2}{(Y_\chi^{\mathrm{eq}})^2}-\frac{Y_a^2}{(Y_a^{\mathrm{eq}})^2}\right]$$
$$-\frac{\langle\Gamma_a\rangle Y_a^{\mathrm{eq}}}{xH(x)}\mathrm{BF}(a\to\bar{\chi}\chi)\left[\frac{Y_\chi^2}{(Y_\chi^{\mathrm{eq}})^2}-\frac{Y_a}{Y_a^{\mathrm{eq}}}\right] \quad (8)$$