WISPy dark matter from the top down

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Introduction

- Reminder of the motivations for WISPs
- Misalignment production of WISPy dark matter
- Cosmological constraints
- Motivation for WISPs in string theory
- What properties we might expect ...

Axions, ALPs, and Hidden Photons

Axions/ALPs:

- Periodic fields: $\phi_i \sim \phi_i + 2\pi f_i$
- Pseudo-Nambu Goldstone bosons of some symmetry
- Most important couplings are to QCD (for axion), photons and electrons

$$\mathcal{L} \supset -\frac{a}{f_a}\frac{g_3^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{C_{i\gamma\gamma}}{f_i}\frac{e^2}{32\pi^2}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{C_{ei}}{2f_i}\bar{e}\gamma^\mu\gamma_5 e\partial_\mu\phi_i$$

- Constrained $f_a \gtrsim 10^9$ GeV, upper bound of 10^{12} GeV in absence of dark matter dilution mechanism

Hidden photons:

- Extend the (MS)SM by at least one $U(1)$ gauge (super)field:

$$\mathcal{L} \supset \frac{\chi_{ab}}{2}F_{a\,\mu\nu}F_b^{\mu\nu} - \frac{\theta^M}{8\pi^2}F_{a\,\mu\nu}\tilde{F}_b^{\mu\nu} + (i\tilde{\chi}_{ab}\lambda_a\sigma^\mu\partial_\mu\bar{\lambda}_b + \text{h.c.})$$

Bottom-up motivation for WISPs

For anyone who was asleep yesterday and/or has wandered in to the wrong meeting – many different experiments:

- Haloscopes
- Helioscopes
- Dish antennae
- Beam dumps – e.g. the SHiP experiment!
- Light shining through walls
- Molecular interferometry

and of course cosmic searches such as isocurvature and tensor modes, rotation of CMB polarisation, ...

- Opportunity to probe weak couplings or very high energy scales!

ALPs

ALPs: Bottom-up motivation

$$\mathcal{L} \supset -\frac{g_3^2}{32\pi^2}\frac{a\,C_{a3}}{f_a}F^b_{3,\mu\nu}\tilde{F}_3^{b,\mu\nu} - \frac{e^2}{32\pi^2}\frac{C_{i\gamma}}{f_{a_i}}a_i\,F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{C_{ie}}{2f_{a_i}}\bar{e}\gamma^\mu\gamma_5 e\,\partial_\mu a_i\,,$$

- Axion as solution to strong CP problem!
- Misalignment dark matter!
- For a light ALP($< 10^{-9}$ eV) anomalous transparency of the universe for VHE gamma rays
$$f_i/C_{i\gamma} \sim 10^8 \text{ GeV}$$
- ... and for same value of $f_i/C_{i\gamma}$, steps is power spectrum at critical energy of 100 GeV, hinting at $m_{\mathrm{ALP}} \sim 10^{-9} \div 10^{-10}$ eV.
- X-ray hint of ALPs from the Coma cluster (Conlon, Marsh, Powell, ...)
$$\frac{f_a}{C_{a\gamma}} \lesssim 10^{10}\text{GeV}\sqrt{0.5/\Delta N_{eff}}$$
- (Now in doubt) solution to non-standard energy loss of white dwarfs
$$f_i/C_{ie} \simeq (0.2 \div 2.6) \times 10^9 \text{ GeV}$$
- These are compatible (need $C_{i\gamma}/C_{ie} \gtrsim 10$) and could be searched for in future experiments!!

Misalignment dark matter

- An axion or ALP is a periodic field: it can take any initial value in $[0, 2\pi f_a]$ since the potential energy in the field is negligible compared to energies in early universe.
- During inflation any scalar field will undergo quantum fluctuations of magnitude $\frac{H_I}{2\pi} \to \sigma_\Theta = \frac{H_I}{2\pi f_a}$
- At later times, the scalar field behaves classically with equation of motion

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

- While $3H > m$, the field is damped and retains its initial vev.
- When $3H = m$, it starts to oscillate and will behave like a bath of particles; the energy stored in the field is $\frac{1}{2}m^2\phi_0^2 \sim \frac{1}{2}m_a^2 f_a^2 \theta^2$ which starts to red-shift like matter $\propto a^{-3}$.
- One complication: for the QCD axion, the mass decreases rapidly as the temperature increases; instanton calculations give

$$V_{\mathrm{inst}} \sim \frac{m_u m_d m_s \Lambda_{QCD}^9}{(\pi T)^8} \to m_a \sim T^{-4}$$

ALP vs axion dm

- So for the QCD axion we find

$$\frac{\Omega_a h^2}{0.112} \simeq 6 \times \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{7/6} \left(\frac{\theta_a}{\pi}\right)^2$$

- While for an ALP we find

$$\frac{\Omega_a h^2}{0.112} \simeq 1.4 \times \left(\frac{m_{a_i}}{\mathrm{eV}}\right)^{1/2} \times \left(\frac{f_{a_i}}{10^{11}\mathrm{GeV}}\right)^2 \left(\frac{\theta_a}{\pi}\right)^2$$

This means that the parameter space can be very different:

- For the QCD axion we are restricted by dark matter at high f_a
- The QCD axion always mixes with pions and therefore has restrictions coming from nucleon couplings
- It will always have a minimal coupling to electrons and photons coming from this too (more later) which bound $f_a \gtrsim 10^9$ GeV.
- For an ALP, we have no such restrictions except that it should not couple strongly to QCD!
- In fact we have a “maximum” allowed coupling to the photon:

$$g_{i\gamma} \equiv \frac{\alpha}{2\pi}\frac{C_{a_i}}{f_{a_i}} \lesssim \frac{\alpha}{2\pi f_{a_i}}$$

- Gives the lifetime of

$$\tau_{a_i} = \frac{64\pi}{g_{i\gamma}^2 m_{a_i}^3} \simeq 1.3 \times 10^{25}\,s \left(\frac{g_{i\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^{-2} \left(\frac{m_{a_i}}{\mathrm{eV}}\right)^{-3}$$

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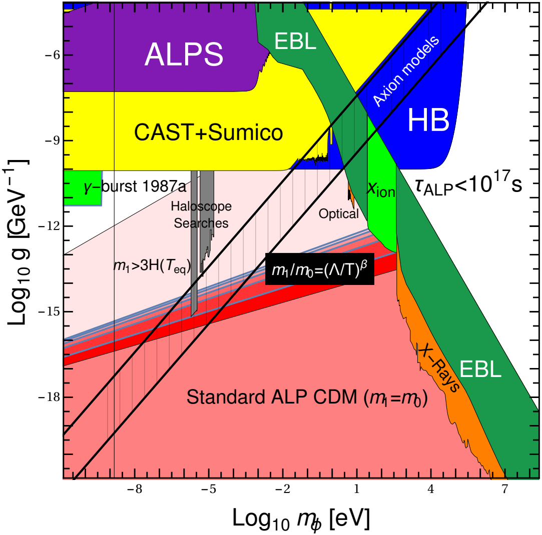
DM constraints



Cosmological constraints

There are important cosmological constraints:

- Black hole superradiance $m_a > 3 \times 10^{-11}$eV (or $\lesssim 10^{-21}$eV) ([Arvanitaki, Dubovsky '10])
- Isocurvature – since the axion is effectively massless during inflation its fluctuations correspond to isocurvature, and there are strong constraints: $\beta_{iso} = \frac{P_{II}}{P_{RR}+P_{II}} < 0.035$ (Planck 2015)
- We know that $P_{RR} = 2.196^{+0.051}_{-0.060}$ is the amount of primordial fluctuations

$$
\begin{aligned}
P_{II} \simeq & \frac{4\sigma_\theta^2}{P_{RR}\theta^2}\left(\frac{\Omega_{a_i}}{\Omega_m}\right)^2 \\
\to H_I < & 2.8 \times 10^{-5}\left(\frac{\Omega_m}{\Omega_{a_i}}\right)^2 \theta f_{a_i} \\
\to H_I < & 0.9 \times 10^7 \text{ GeV}\left(\frac{f_a}{10^{11}}\right)^{0.408} \qquad \text{QCD axion}
\end{aligned}
$$

- Also have the constraint from non-observation of tensor modes that $r = P_{TT}/P_{RR} < 0.11$ and $P_{TT} = \frac{2H_I^2}{\pi^2 M_P^2}$ giving

$$
H_I < 8.3 \times 10^{13} \text{ GeV}
$$

ALPs in IIB strings

$$S \supset -\left(dc_\alpha + \frac{M_P}{\pi} A_i q_{i\alpha}\right) \frac{\mathcal{K}_{\alpha\beta}}{8} \wedge \star \left(dc_\beta + \frac{M_P}{\pi} A_j q_{j\beta}\right)$$
$$+ \frac{1}{4\pi M_P} r^{i\alpha} c_\alpha \mathrm{tr}(F \wedge F) - \frac{r^{i\alpha}\tau_\alpha}{4\pi M_P} \mathrm{tr}(F_i \wedge \star F_i).$$

- Axions periodic fields, $c_\alpha \to c_\alpha + M_P, T_\alpha = \tau_\alpha + ic_\alpha \sim T_\alpha + iM_P$
- Decay constants determined by diagonalising $(\mathcal{K}_0)_{\alpha\beta} \equiv \frac{\partial^2(-2\log\mathcal{V})}{\partial_{\tau_\alpha}\partial_{\tau_\beta}}$:

$$f_\alpha \equiv \frac{M_P}{4\pi}\sqrt{\lambda_\alpha}, a_\alpha \sim a_\alpha + 2\pi f_\alpha$$

- Canonically normalise the axion fields

$$c_\alpha = 2\,a_\gamma \mathcal{C}_{\beta\alpha}, \quad \mathcal{C}_{\gamma'\alpha}\mathcal{K}_{\alpha\beta}\mathcal{C}^T_{\beta\delta'} = \delta_{\gamma'\delta'}, \quad \mathcal{C}_{\gamma'\alpha}\mathcal{C}^T_{\alpha\delta'} = \lambda^{-1}_{\gamma'}\delta_{\gamma'\delta'},$$

- Read off couplings to gauge groups:

$$\frac{f_{a_j}}{C_{ji}} = \frac{1}{8\pi}\frac{M_P}{r^{j\alpha}\mathcal{C}^T_{\alpha i}} \times \begin{cases} 1/2 & U(1) \\ 1 & SU(N) \end{cases}.$$

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The LARGE Volume Scenario

- Type IIB string theory, Complex structure moduli stabilised at SUSY value by three-form fluxes, gives superpotential W_0
- Volume of Calabi-Yau in "swiss-cheese" form

$$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2} - h(\tau_i)$$

- Or K3-fibration:

$$\mathcal{V} = \tau_{b'}^{1/2}\tau_b - \tau_s^{3/2} - h(\tau_i)$$

- $\rightarrow$ Instanton/gaugino condensate generate contribution to superpotential $W \supset Ae^{-a\tau_s}$, but typically only need one or two! (c.f. KKLT)
- Kähler potential with α' corrections $K \supset -2\log\left[\Re(\tau_b)^{3/2} + \xi/2\right]$, needs $h^{2,1} > h^{1,1}$
- Volume, τ_b stabilised at exponentially large value: $\mathcal{V} \sim 10^6$ for GUT, $\sim 10^{14}$ for intermediate scale strings, $\sim 10^{30}$ for TeV strings
- Small cycle τ_s stabilised at $a\tau_s \sim \log\mathcal{V}$
- AdS vacuum with $\cancel{SUSY}$, small uplift required to dS by anti-branes, D-terms, F-terms, instantons at quivers ...
- (MS)SM realised on $D7$ branes on collapsed cycles $\tau_a \sim 0$ (Quiver locus) or $\gtrsim 1$ (Geometric regime)

The LVS axiverse

- For LARGE volume scenario (LVS) need

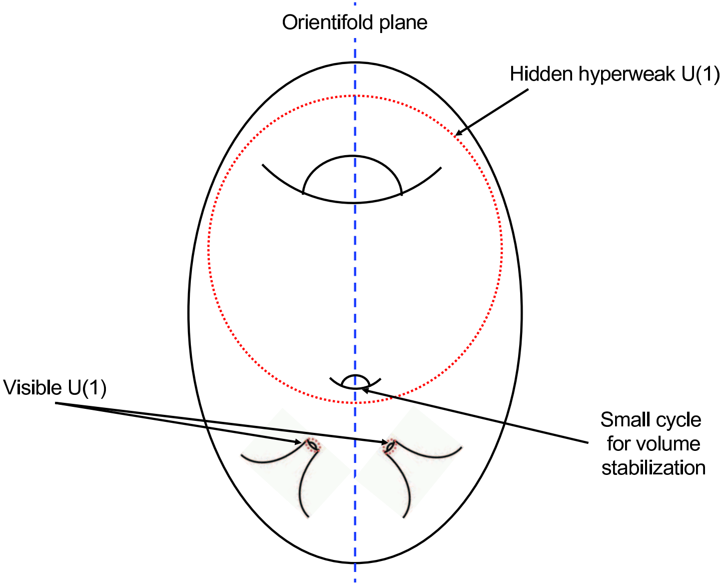
$$W = W_0 + A e^{-a\tau_{\mathrm{dP}}}, \qquad W_0 \sim 1$$

- τ_{dP} is a diagonal del Pezzo blow-up $\rightarrow$ removes issue of chirality.
- Do not need other NP effects: others can be fixed by D-terms, α' and g_s effects - open ($V \sim \frac{W_0^2}{\mathcal{V}^3}$) and closed ($V \sim \frac{W_0^2}{\mathcal{V}^4}$) string loops.
- Non-vanishing D-terms are dangerous ($V \sim \mathcal{V}^{-2}$) but are useful for stabilising cycles relative to each other

$$\xi_a = \frac{1}{4\pi\mathcal{V}} q_{aj} t^j = 0 \rightarrow \text{linear combination fixed}$$

- Each NP term in superpotential and each linearly independent D-term eats one axion
- In scenario where LARGE cycle unwrapped/no D-term, have at least $n_{\mathrm{ax}} = h^{1,1} - 1 - d \geqslant 1$ light axions
- Generically this number may be large, particularly if many unwrapped cycles.
- Since further single instanton/gaugino condensate contributions may not be generic $\rightarrow$ very light axions $\rightarrow$ ALPs.

Swiss cheeses



Decay constants

We expect

$$f_\alpha \sim \begin{cases} M_P/\tau_\alpha & \text{non}-\text{local axion} \\ M_s \sim M_P/\sqrt{\mathcal{V}} & \text{local axion} \end{cases}$$

e.g. for $\mathcal{V} = \frac{1}{9\sqrt{2}}\left(\tau_b^{3/2} - \tau_s^{3/2}\right)$ we have $4\pi g_b^{-2} = \tau_b \sim \mathcal{V}^{2/3}$ and

$$\mathcal{K}_0 \sim \begin{pmatrix} \mathcal{V}^{-4/3} & \mathcal{V}^{-5/3} \\ \mathcal{V}^{-5/3} & \mathcal{V}^{-1} \end{pmatrix}$$

Have $f_{a_b} = \frac{\sqrt{3}}{4\pi}\frac{M_P}{\tau_b} \simeq \frac{M_P}{4\pi\mathcal{V}^{2/3}}$, $f_{a_s} = \frac{1}{\sqrt{6}(2\tau_s)^{1/4}}\frac{M_P}{4\pi\sqrt{\mathcal{V}}} \simeq \frac{M_s}{\sqrt{4\pi}\tau_s^{1/4}}$.

$$\begin{aligned} \mathcal{L} \supset & \frac{c_b}{M_P} g_b^2 \,\mathrm{tr}(F_b \wedge F_b) + \frac{c_s}{M_P} g_s^2 \,\mathrm{tr}(F_s \wedge F_s) \\ \simeq & \left[\mathcal{O}\left(\frac{1}{M_P}\right) a_b + \mathcal{O}\left(\frac{\tau_s^{3/4}}{\mathcal{V}^{1/2} M_P}\right) a_s\right] \mathrm{tr}(F_b \wedge F_b) \\ & + \left[\mathcal{O}\left(\frac{1}{M_P}\right) a_b + \mathcal{O}\left(\frac{1}{\tau_s^{3/4} M_s}\right) a_s\right] \mathrm{tr}(F_s \wedge F_s). \end{aligned}$$

- Non-local ALPs can have small decay constants, e.g. $\frac{M_P}{\mathcal{V}^{2/3}}$, but the couplings to matter are always $\gtrsim M_P$ suppressed
- If we want ALPs in the classic axion window, they need to be “local,” and have an intermediate string scale: $f_i \sim M_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}$, $\mathcal{V} \sim 10^{15}$.
- To have an axion and ALP, need several intersecting local cycles

Matter couplings

In global SUSY, derive matter couplings from

$$\int d^4\theta\, \Phi\overline{\Phi}\left(T_\alpha + \overline{T}_\alpha\right) \supset (\psi\sigma^\mu\overline{\psi})\partial_\mu c_\alpha\,.$$

In SUGRA find

$$\mathcal{L} \supset \partial_{T_\alpha}\left(\log[e^{-\frac{K_0}{2}}\hat{K}_i]\right)(\psi^i\sigma^\mu\overline{\psi}^{\bar{i}})\partial_\mu c_\alpha.$$

nb this is different to moduli couplings!
We then translate these into ALP-matter couplings (to axions ρ_i''):

$$\frac{\hat{X}^i_\psi}{f_i} = \frac{1}{3M_P}C_{\beta\alpha}\begin{cases} \frac{t_\alpha}{2\mathcal{V}} + \frac{1}{t_{ab}}r^{ai}r^{bj}k_{ijk}K^{k\alpha} & \text{Matter on curve } t_{ab} \\ \frac{t_\alpha}{2\mathcal{V}} + \frac{r^{a\alpha}}{\tau_a} & \text{Matter on cycle } a \\ \frac{t_\alpha}{2\mathcal{V}} & \text{Matter at a singularity} \end{cases}$$

- Dependent on conjectures for Kähler metrics
- Loop corrections should be important for quiver locus, $\frac{t_\alpha}{2\mathcal{V}} = 0$ or $\sim \mathcal{V}^{-2/3}$.

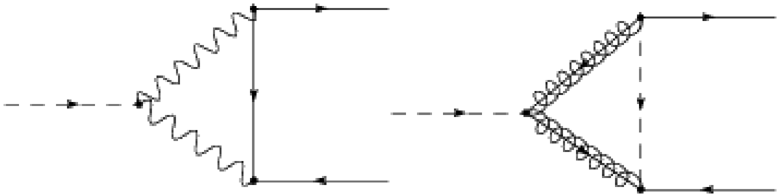
Loop couplings to matter fields

Couplings to electrons is most important:

$$\mathcal{L} \supset \frac{C^A_{ie}}{2f_i}\bar{e}\gamma^\mu\gamma_5 e\partial_\mu\phi_i + \frac{C^V_{ie}}{2f_i}\bar{e}\gamma^\mu e\partial_\mu\phi_i,$$
$$C^{A,V}_{ie} = \hat{X}^{A,Vj}_e + \Delta_{i\gamma\gamma}[C^{A,V}_{ie}] + \delta_{ai}\Delta_{QCD}[C^A_{ae}], \quad (1)$$

where $\hat{X}^{A,Vj}_e \equiv \frac{1}{2}(\tilde{X}^j_{e_R} \pm \tilde{X}^j_{e_L})$ and $\Delta_{QCD}[C^A_{ae}] = \frac{3\alpha^2}{4\pi}\Delta C_{a\gamma\gamma}\log(\Lambda_{QCD}/m_a)$
In SUSY theories, loops involve gauginos as well as photons:

$$\mathcal{L} \supset -\int d^2\theta\ (i\phi_i)\frac{g_{a\gamma}}{4}W^\alpha W_\alpha \supset \frac{1}{4}g_{i\gamma}\phi_i F_{em,\mu\nu}\tilde{F}^{\mu\nu}_{em} + \frac{1}{2}g_{i\gamma}\partial_\mu\phi_i\lambda^\alpha\sigma^\mu\bar{\lambda}, \quad (2)$$



Loop couplings cont'd

To a rough approximation we can take

$$\begin{aligned}\Delta_{i\gamma\gamma}[C^A_{ie}] \approx& \frac{3\alpha^2}{4\pi^2} C_{i\gamma} \log(M_{\rm SUSY}/m_e) + \frac{2\alpha^2}{4\pi^2} C_{i\gamma} \log(\Lambda/M_{SUSY}),\\ \Delta_{i\gamma\gamma}[C^V_{ie}] \approx& \frac{2\alpha^2}{4\pi^2} C_{i\gamma} \log(\Lambda/M_{\rm SUSY}),\end{aligned} \tag{3}$$

where $M_{\rm SUSY}$ is the scale of superpartner masses, and Λ the cutoff of the theory, of the order of the string scale.

Couplings summary

Bottom line:

- For quiver locus, matter couplings to most axions dominated by loops:

$$C_{i\gamma}/C_{ie} \sim \frac{4\pi^2}{2\alpha^2 \log \Lambda/M_{SUSY}} \sim 10^4 \div 10^5$$

- For geometric regime,

$$C_{i\gamma}/C_{ie} \sim \frac{8\pi}{3}\tau_i \sim 10 \div 100 \qquad \text{local cycle}$$

i.e. this geometric regime ratio is exactly what we want to explain the astrophysical anomalies!

Masses

May have higher superpotential corrections to masses, and also Kähler potential corrections [Conlon, '06]

$$V_{\delta W} = \frac{-2\pi n \tau_i W_0}{\mathcal{V}^2} e^{-2\pi n \tau_i} \cos 2\pi n c_i$$
$$V_{\delta K} \sim \frac{W_0^2}{\mathcal{V}^3} e^{-2\pi n \tau_i} \cos 2\pi n c_i \tag{4}$$

T_s axion has a mass $\sim M_P/\mathcal{V}$, but "local" axions with masses from Kähler corrections have

$$m_{\text{local}} \sim e^{-n\pi\tau_{\text{local}}} \times \begin{cases} M_P & \text{Superpotential terms or QCD-like masses} \\ m_{3/2} & \text{Kähler potential terms} \end{cases}$$

Can be $\sim 10^{-11}$ eV for SM cycle sizes, or less.
Non-local axions get negligible masses: $e^{-\pi\tau_b} < 10^{600}$ for $\mathcal{V} = 10^4, \tau_b \simeq V^{2/3}$.

ALPs: remarks

Closed strings:

- In string theory it is hard to escape from the constraint $f_a/C_{a\gamma} < M_s$ for closed string ALPs.
- The coupling to electrons can, however, be significantly suppressed.
- There should generically be an "axiverse" of ALPs, most with couplings $\lesssim M_P^{-1}$ and logarithmically distributed masses.
- Finding acceptable models of inflation and soft masses for intermediate-scale strings is problematic.
- ... detection of appreciable r would be almost certainly incompatible with intermediate-scale closed-string ALPs.

Open strings, that I haven't discussed:

- Non-universal, essentially field theory/Sugra models
- Tempting to try to identify the intermediate scale with the SUSY-breaking scale.
- Very model-dependent and need to understand the matter spectrum first too.
- But should be compatible with GUTs and high-scale inflation: implies the matter spectrum is not just MSSM.

Non-standard cosmology

Another important point for stringy model is often have non-standard cosmology:

- The lightest modulus will decay at late times after dominating energy density of universe
- In typical SUGRA scenarios have "cosmological moduli problem": $Gamma_\tau \sim m_\tau^3/M_P^2 = H(MeV) \to m_\tau \sim$ 30 TeV.
- For the LVS in the sequestered regime with a string scale $\sim 10^{14}$ GeV compatible with GUTs, the soft masses are $\sim M_P/\mathcal{V}^2$ but the heavy modulus mass is $M_P/\mathcal{V}^{3/2} \sim 10^6$ GeV
- The heavy modulus decays to ALPs and Higgs bosons before BBN
- It induces reheating at $T \sim$ GeV.
- This can dilute axion or other dark matter if the reheating is after it has been formed (e.g. below Λ_{QCD}).
- This can widen the classic axion window to 10^{14} GeV!

Hidden photons

Vector dark matter

Almost exclusively people consider dark matter to be comprised of fermions or scalars:

- WIMPs
- axion/ALPs,
- FIMPs
- SIMPs
- etc etc.

However, why not consider a new massive vector?

Stability

Typically the obstruction to a vector dark matter particle is the need for stability on the age of the universe:

- For a WIMP, we could invoke a new symmetry to protect it, e.g. $\mathbb{Z}_2$ of [Lebedev, Lee, Mambrini, 1111.4482]: $X_\mu \to -X_\mu$.
- $\rightarrow$ Such a symmetry prevents kinetic mixing with the hypercharge, and also classic gauge currents $\rightarrow$ the interactions must therefore seem "exotic" or just be effective.
- Alternatively, we should produce the vectors via a different mechanism $\rightarrow$ then we can make the interactions sufficiently weak!

In the following I shall consider classic abelian "hidden photons" which interact through kinetic mixing only (so not a Z')

Decays of hidden photons

Recall

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{m_{\gamma'}^2}{2}X_\mu X^\mu - \frac{\chi}{2}F_{\mu\nu}X^{\mu\nu} + J^\mu A_\mu$$

$$\underbrace{T=0}\longrightarrow -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{m_{\gamma'}^2}{2}X_\mu X^\mu + J^\mu(A_\mu - \chi X_\mu)$$

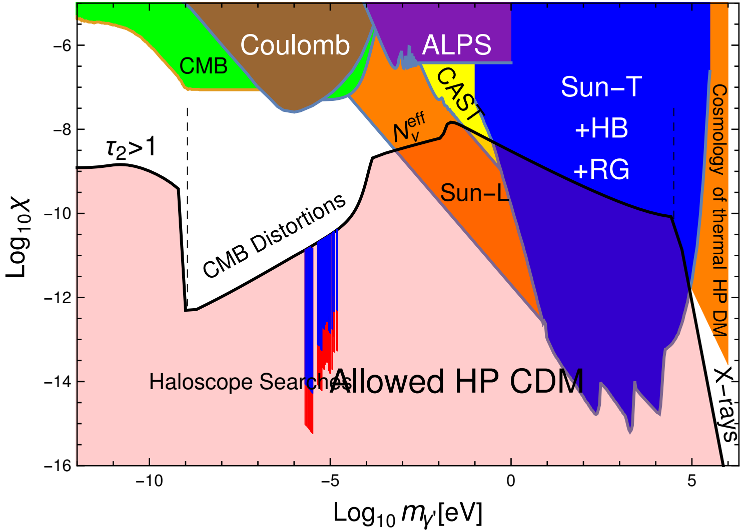
Once we have produced hidden photon dark matter, it must survive to the present time:

- If $m_{\gamma'} > 2m_e$ then the decay to two electrons will be very fast since $\Gamma \sim \chi^2 m_{\gamma'}$ for large $m_{\gamma'}$ so would need $m \lesssim 10^{-40}\chi^{-2}\text{GeV}$
- Even below this threshold have $\gamma' \to 3\gamma$
- Also must carefully take care of resonance effects since for finite T we have non-zero photon mass m_γ:

$$\chi_{\text{eff}}^2 \simeq \frac{\chi^2 m_{\gamma'}^4}{(m_\gamma^2 - m_{\gamma'}^2)^2 + \mu^4} \qquad (\mu \equiv \max\{\chi m_{\gamma'}^2, m_{\gamma'}\Gamma\})$$

- Effects characterised by $\tau_2 \sim \frac{\chi^2 m_{\gamma'}}{H_{\text{res}}}$ which controls amount of energy lost by condensate into the photon bath.

Parameter space



Misalignment production

- Above we only considered survival of an initial abundance of hidden photons.
- For such weakly interacting an light particles misalignment production would seem appropriate!
- However, since it is a vector the transverse modes redshift; $X^{\mu}X_{\mu} = -\frac{1}{a^2}X\cdot X$ for $g_{\mu\nu} = \mathrm{diag}(1, -a^2, -a^2, -a^2)$
- Then $\rho \sim \frac{m_{\gamma'}^2}{a^2}X\cdot X \to$ we would require an enormous initial energy density
- One solution is to add a non-minimal coupling to gravity

$$\mathcal{L}_{\mathrm{grav}} = \frac{\kappa}{12}RX_{\mu}X^{\mu}$$

- This term is also introduced in vector inflation models!
- If $\kappa = 1$ we can redefine $\overline{X}_i = X_i/a$ and find

$$\ddot{\overline{X}}_i + 3H\dot{\overline{X}}_i + m_{\gamma'}^2\overline{X}_i = 0$$

- Then we recover the usual case of misalignment dark matter!
- Unfortunately such a term does not seem to be present with the correct magnitude in string theory.

Longitudinal modes

A very new result by [Graham, Mardon, Rajendran, 1504.02102]:

- Consider a standard coupling of hidden photon with Stückelberg mass to gravity.
- During inflation, the longitudinal mode couples much more strongly to the inflaton than the transverse modes
- A relic abundance of vectors is produced with

$$\Omega_{\gamma'} = \Omega_{\text{cdm}} \times \sqrt{\frac{m_{\gamma'}}{6 \times 10^{-6}\ \text{eV}}} \left(\frac{H_I}{10^{14}\text{GeV}} \right)^2$$

- Unlike ALP misalignment production, the fluctuations are sharply peaked around

$$1/k_* \sim 3.2 \times 10^{-10}\text{Mpc} \sqrt{\frac{10^{-5}\text{eV}}{m_{\gamma'}}}$$

- ... hence isocurvature fluctuations from the dark matter produced this way are never observable in the CMB.

Hidden photons from string theory

So can we motivate such a hidden photon parameter space?

- R-R $U(1)$s
- D-branes carry $U(N) = SU(N) \times U(1)$ gauge group
- Several stacks of D-branes to realise (MS)SM

$\rightarrow$Generically several $U(1)$s (most anomalous)

- Some non-anomalous $U(1)$s massive via Stückelberg mechanism
- May have hidden branes for global consistency of model
- τ_b provides potential hyperweak U(1) with $g \sim g_{YM} \mathcal{V}^{-1/3}$ [Burgess, Conlon, Hung, Kom, Maharana, Quevedo 2008] or possibly even weaker for $K3$ fibrations, up to $g \sim g_{YM} \mathcal{V}^{-1/2}$
- May have hidden anti-$D3$ branes for uplifting to dS, or uplifting by hidden D-term
- $\rightarrow$ hidden $U(1)$s

What are the masses and mixings?

Kinetic Mixing in SUSY Theories

- For supersymmetric configurations, kinetic mixing is a holomorphic quantity:

$$\mathcal{L} \supset \int d^2\theta \left\{ \frac{1}{4(g^h_a)^2} W_a W_a + \frac{1}{4(g^h_b)^2} W_b W_b - \frac{1}{2}\chi^h_{ab} W_a W_b \right\}$$

- Runs/is generated only at one loop
- SUSY operator contains mixing of gauge bosons, gauginos and D-terms:

$$\int d^2\theta - \frac{1}{2}\chi^h_{ab} W_a W_b + \text{c.c.} \supset -\frac{\chi_{ab}}{2} F_{a\,\mu\nu} F^{\mu\nu}_b + (i\tilde{\chi}_{ab}\lambda_a \sigma^\mu \partial_\mu \bar{\lambda}_b + \text{h.c.}) - \chi_{ab} D_a D_b$$

Kinetic Mixing in SUSY Theories II

- Can show that physical mixing obeys a Kaplunovsky-Louis type formula

$$\frac{\chi_{ab}}{g_a g_b} = \Re(\chi^h_{ab}) + \frac{1}{8\pi^2}\mathrm{tr}\Big(Q_a Q_b \log Z\Big) - \frac{1}{16\pi^2}\kappa^2 K \sum_r n_r Q_a Q_b (r)$$

- Only Kähler potentials from light fields charged under both contribute $\rightarrow$ does not run below messenger scale (except for gauge running)
- "Natural" size given by one-loop formula, assuming $\mathrm{tr}(Q_a Q_b) = 0$:

$$\chi^h_{ab} = -\frac{1}{8\pi^2}\mathrm{tr}\Big(Q_a Q_b \log \mathcal{M}/\Lambda\Big)$$
$$\rightarrow \chi_{ab} = -\frac{g_a g_b}{16\pi^2}\mathrm{tr}\Big(Q_a Q_b \log |\mathcal{M}|^2\Big) \sim -\frac{g_a g_b}{16\pi^2}$$

- Depends only on the holomorphic quantities!

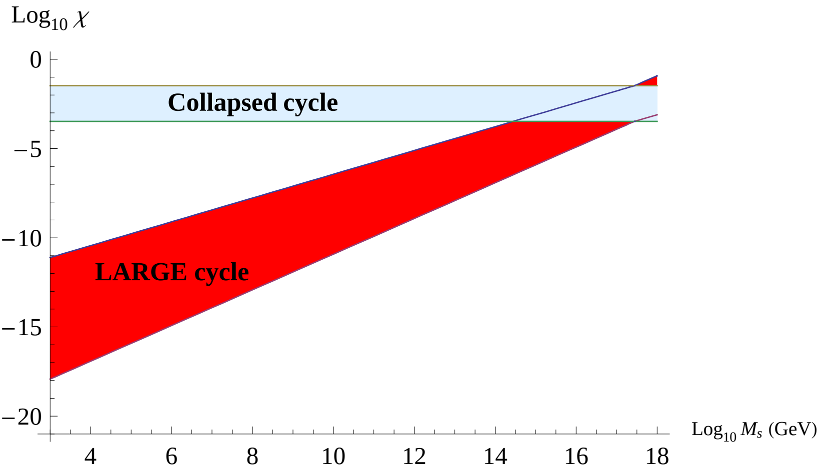
Kinetic Mixing and LARGE Volumes

- Holomorphic kinetic mixing parameter depends only on complex structure and open moduli:

$$\chi^h_{ab} = \chi^{1-\text{loop}}_{ab}(z_i, y_i) + \chi^{\text{non-perturbative}}_{ab}(z_i, e^{-T_j}, y_i)$$

- For separated branes, no light states $\rightarrow$ no volume dependence from Kähler potential
- Fluxes do not break supersymmetry
- Complex structure moduli typically $\mathcal{O}(1)$, or small in warped throats
- Expect typical $\chi^h_{ab} \sim \mathcal{O}(1/16\pi^2)$
- Find $\chi_{ab} \sim g_a g_b / 16\pi^2$
- Hyperweak brane leads to mixing $\chi_{ab} \sim 10^{-3}\mathcal{V}^{-1/3}$ (swiss cheese) or $\chi_{ab} \sim 10^{-3}\mathcal{V}^{-1/2}$ (K3 fibre)

Kinetic Mixing vs String Scale

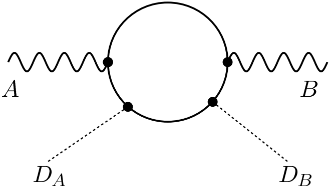


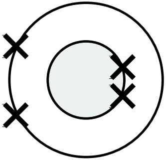
Kinetic Mixing with $\cancel{\text{SUSY}}$

- If mixing cancels, may still be induced by SUSY breaking effects
- Look for operators at one loop:

$$\Delta\mathcal{L} \supset \int d^4\theta W^a W^b \left(\frac{\Xi + \overline{\Xi}}{M^2} + \frac{D^2(\overline{\Xi} + \Xi)^2}{M^4} \mathrm{c.c.} \right) + W^a W^b \frac{\overline{W}^c \overline{W}^c}{M^4},$$

- Can show that first and second are zero if SUSY kinetic mixing cancels
- Second has different gauge structure, but non-zero only for hypercharge D term $W^3 W'$
- Find (from toroidal calculation) $M^{-4} \approx (4\pi^5 M_s^4)^{-1} \mathcal{V}^{-2/3} \sim (M_s R)^{-4}$:





$$\chi_{Y\gamma'} \sim \frac{g_Y^2}{4} \frac{f(t^i)}{\mathcal{V}} \frac{g_{\gamma'} g_Y}{4\pi^5} \left(\frac{v}{M_s}\right)^4 \cos^2 2\beta$$

- $M_s \sim 10^{15}\,GeV$ have $\chi \sim \chi \sim 10^{-59}$, $M_s \sim 1\,TeV$ find 10^{-27}.
- Mixing with hidden D-term 10^{-33}, 10^{-25} respectively $\rightarrow$ maybe good dark matter candidate

Stückelberg Mechanism

- Massless modes of axions generate $U(1)$ masses:

$$S \supset -\left(dc_\alpha + \frac{M_P}{\pi} A_i q_{i\alpha}\right) \frac{\mathcal{K}_{\alpha\beta}}{8} \wedge \star \left(dc_\beta + \frac{M_P}{\pi} A_j q_{j\beta}\right) + \frac{1}{4\pi M_P} r^{i\alpha} c_\alpha \mathrm{tr}(F \wedge F) - \frac{r^{i\alpha}\tau_\alpha}{4\pi M_P} \mathrm{tr}(F_i \wedge \star F_i).$$

- Sensitive only to Kähler moduli $\rightarrow$ masses are diluted by volumes in compact space, and the gauge couplings:

$$m_{ab}^2 = g_a g_b \frac{M_P^2}{4\pi^2} q_{a\alpha} (\mathcal{K}_0)_{\alpha\beta} q_{b\beta}$$

- $1\mathrm{meV}$ possible for TeV scale strings
- NB KK modes of axions generate kinetic mixing.

Isotropic masses

- Consider isotropic swiss cheese, with volume form

$$\mathcal{V} = \frac{1}{6}\int_{CY} J \wedge J \wedge J = \frac{1}{6}\left(3t_1^2 t_2 + 18 t_1 t_2^2 + 36 t_2^3\right) = \frac{1}{9\sqrt{2}}\left(\tau_b^{3/2} - \tau_s^{3/2}\right)$$

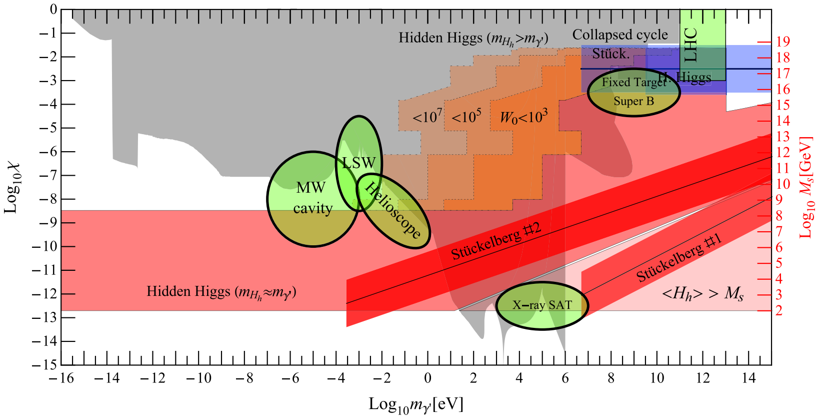
- Get the matrix ($\epsilon \equiv \sqrt{\tau_s/\tau_b} \ll 1$)

$$\mathcal{K}_0 = \frac{3}{2\tau_b^2}\begin{pmatrix} \epsilon^{-1} & -3\epsilon \\ -3\epsilon & 2 \end{pmatrix} \quad \text{and} \quad \mathcal{K}_0^{-1} = \frac{2\tau_b^2}{3}\begin{pmatrix} \epsilon & 3\epsilon^2/2 \\ 3\,\epsilon^2/2 & 1/2 \end{pmatrix}.$$

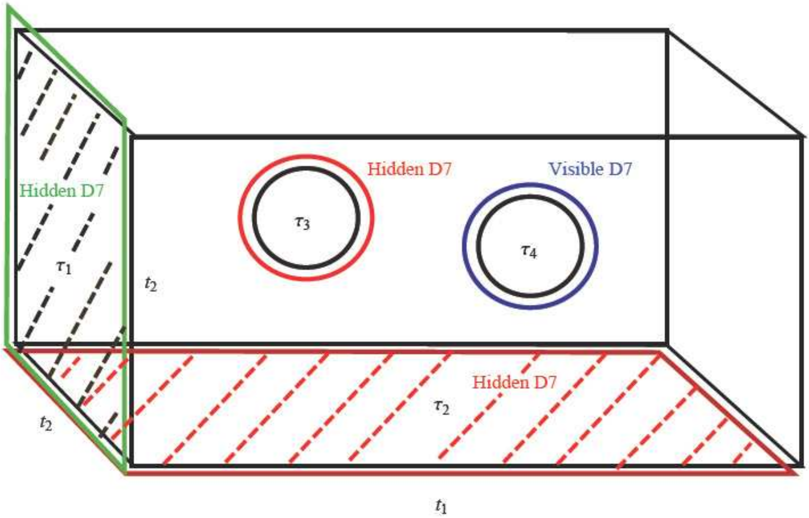
- $\tau_b \sim \mathcal{V}^{2/3}$, $g_b \sim \tau_b^{1/2}$ so get for $U(1)$ wrapping the large cycle

$$m \sim \frac{M_P}{\mathcal{V}}$$

Predictions



Anisotropic branes



Anisotropic masses

- If we instead have two dimensions very large, then $t \sim \mathcal{V}$, can get small masses <u>without small gauge couplings</u>, since the two-forms can propagate orthogonally to the brane
- K3 fibrations are ideal:

$$\mathcal{V} = t_1 t_2^2 + \frac{2}{3} t_2^3 = \frac{1}{2}\sqrt{\tau_1}\left(\tau_2 - \frac{2}{3}\tau_1\right)$$

- $\tau_1 = t_1^2, \tau_2 = 2t_1 t_2$ with t_2 large
- Metric and inverse:

$$\mathcal{K}_0 = \begin{pmatrix} \tau_1^{-2} & 0 \\ 0 & 2\tau_2^{-2} \end{pmatrix}, \quad \text{and} \quad \mathcal{K}_0^{-1} = \begin{pmatrix} \tau_1^2 & 0 \\ 0 & \tau_2^2/2 \end{pmatrix}$$

- Now wrap a brane on τ_1 and put a gauge flux on t_1; have

$$\chi \sim \frac{10^{-2}}{\sqrt{\tau_1}}, \qquad m_{\gamma'} \sim \frac{M_P}{\mathcal{V}}$$

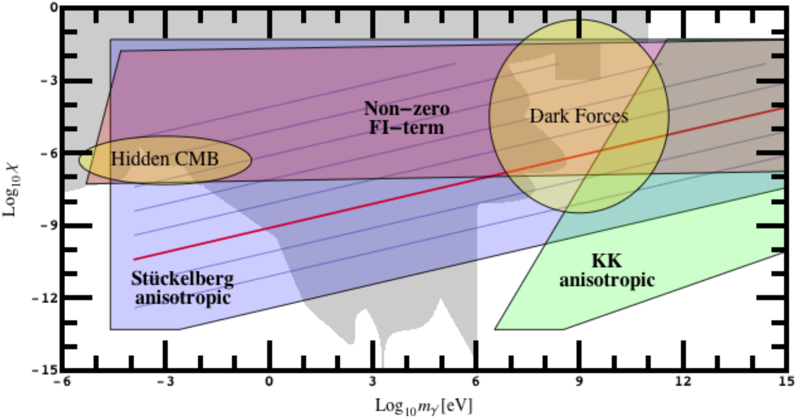
- Can realise $\chi \sim 10^{-6}$ and $m_{\gamma'} \sim$ meV
- In this case also have “Dark Force” KK modes!!
- Can obtain this scenario with stabilised moduli by adding extra blow-up mode

$$\mathcal{V} = t_1 t_2 (t_2 + t_3) = \sqrt{\tau_1 \tau_3 (\tau_2 - \tau_3)}$$

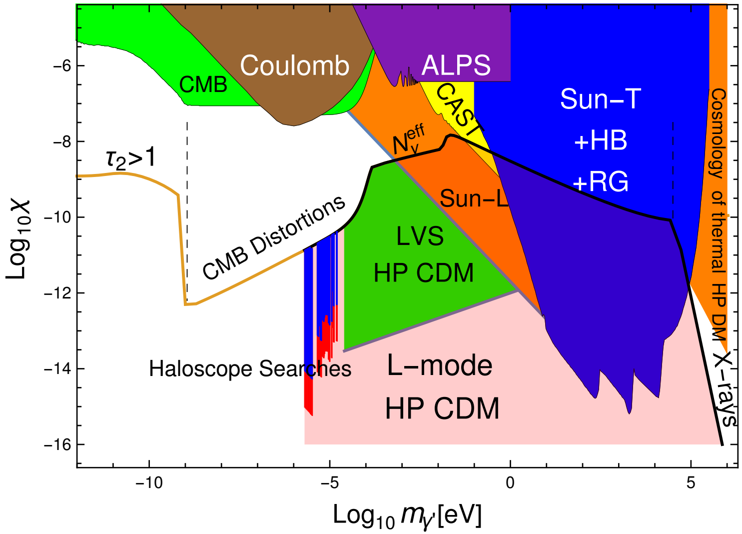
Hidden KK Modes

- For large hidden dimensions may detect KK modes of hidden gauge boson in beam dump experiments $\rightarrow$ effectively have massive hidden gauge bosons even though gauge group unbroken!
- Visible sector wraps small cycle $\rightarrow$ does not have KK modes
- In swiss cheese model, TeV strings ($\mathcal{V} \sim 10^{30}$) give masses $\mathcal{O}(10)$ MeV and mixing $\chi \sim 10^{-12}$
- Beam dumps sensitive up to $\mathcal{O}(100)$ MeV at $\chi \sim 10^{-7}$, but now have lots of KK modes!
- $\chi_{eff} \propto \chi \times \sqrt{N_K K}$
- For swiss cheese with TeV strings, $\chi_{eff} \sim 10^{-10} \rightarrow$ may be accessible with increased luminosity
- Actually can get much more realistic values if we allow for one large dimension...

Anisotropic predictions



Dark matter parameter space



Connection with other WISPs

Hints of an intermediate scale

Recall the several hints of an intermediate scale:

- Classical axion window of $10^9 - 10^{12}$ GeV.
- X-ray hint of ALPs from the Coma cluster (talks by Marsh, Powell, ...)

$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{1}{4}\frac{\alpha_{em}}{2\pi}\frac{C_{a\gamma}}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$g_{a\gamma} \gtrsim 10^{-13}\mathrm{GeV}^{-1}\sqrt{0.5/\Delta N_{eff}} \rightarrow \frac{f_a}{C_{a\gamma}} \lesssim 10^{10}\mathrm{GeV}\sqrt{0.5/\Delta N_{eff}}$$

- And the anomalous transparency of the universe – $\frac{f_a}{C_{a\gamma}} \lesssim 10^9\mathrm{GeV}$, cooling of White dwarfs etc.

Sterile neutrinos

- Idea of [Cicoli, Conlon, Marsh, Rummel]: dark matter decays to an ALP.
- Corresponds very well with galaxy simulations which suggest fermionic Warm Dark Matter (they have been predicting $1-2$ keV for several years! E.g. de Vega, Sanchez 1304.0759] as one example).
- So they suggest a sterile neutrino with coupling to an ALP:

$$\frac{\partial_\mu a}{\Lambda} \overline{N} \gamma^\mu \gamma_5 \nu \leftrightarrow \frac{m_N}{\Lambda} a \overline{N} \gamma_5 \nu, \qquad \Lambda \simeq 10^{17} \mathrm{GeV}$$

- In LVS, for direct couplings, we have

$$\Lambda \simeq \begin{cases} M_s/g^2 & \text{SM in geometric regime} \\ \gg M_P & \text{Sequestered} \end{cases}$$

- This does not seem to fit well; however, we can instead couple via the Majorana mass:

$$\mathcal{L} \supset -e^{-T} N N \rightarrow -m_N \frac{a}{f_a} \overline{N} \gamma_5 N \rightarrow -m_N \frac{\sin\theta_N}{f_a} a \overline{N} \gamma_5 \nu$$

- This implies $\sin\theta_N \sim f_a/10^{17}\mathrm{GeV}$ but we also have $\theta_N \gtrsim 10^{-6}$ to generate enough dark matter through non-resonant production $\rightarrow$ we are right at the border of this, but corresponds very well!

Two possibilities

ALPs are closed strings $\rightarrow$ intermediate string scale:

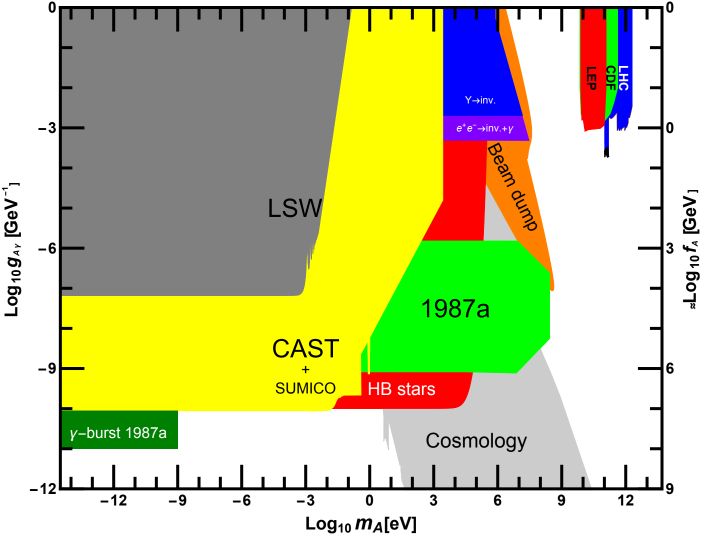
- Natural scale for axions and TeV SUSY
- Requirement to eat the axion on the large cycle in the LVS may lead to a hidden photon with mass greater than $\mathcal{O}(\mathrm{GeV})$.
- Problems with unification, inflation and cosmological moduli.

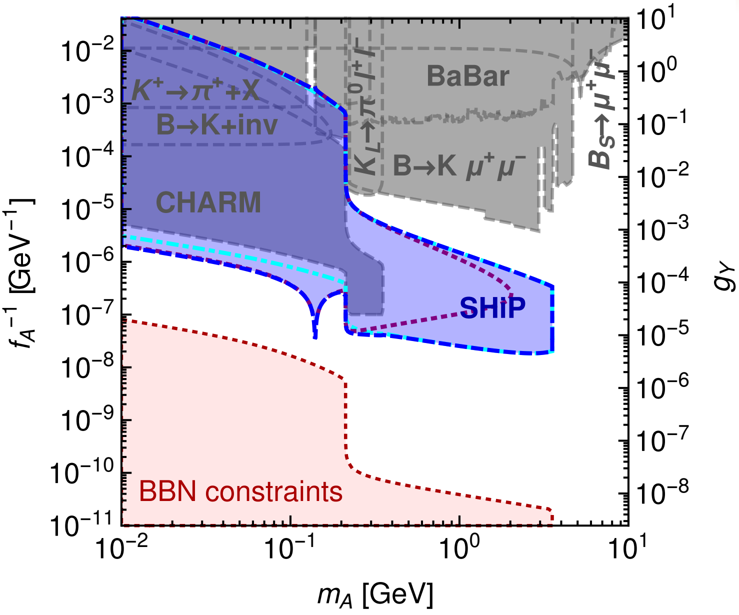
ALPs are open strings:

- Some new physics at the intermediate scale to break the approximate global symmetries.
- If we allow unification of gauge couplings, and take $\mathcal{V} \lesssim 10^8$ in string units, have high gravitino mass $\gtrsim 10^{10}$ GeV.
- Either need sequestering of masses, high scale SUSY, or something else.

Searching elsewhere for ALPs

The SHiP experiment is an interesting place to search for all kinds of new physics – including ALPs.




$K^+ \to \pi^+ + X$
B→K+inv
CHARM
BaBar
$K_L \to \pi^0 l^+ l^-$
B→K $\mu^+\mu^-$
$B_S \to \mu^+\mu^-$
SHiP
BBN constraints
f_A^{-1} [GeV^{-1}]
g_Y
m_A [GeV]