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Dark glueballs and their ultralight axions

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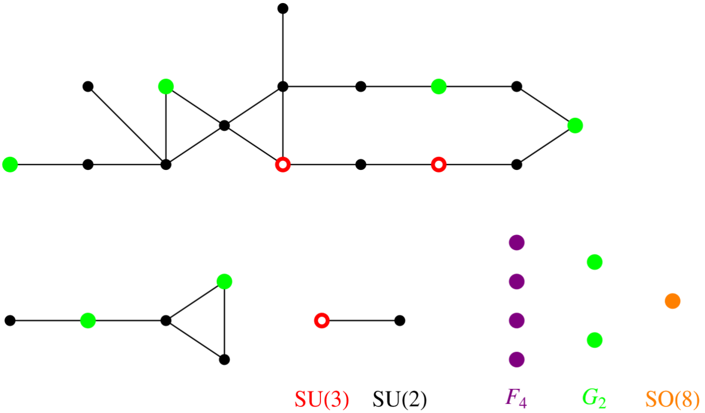
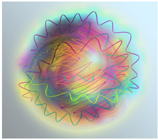
Hidden gauge sectors in string theory

- Generically, multiple disconnected gauge sectors arise in the low-energy theory [Halverson, Langacker (2018)].



Confinement in the dark sector

- We treat the simplest case of a pure Yang-Mills sector in the infrared:
  - Above the confinement scale Λ, it is composed of dark gluons.
  - Below Λ, the formation of dark glueballs occurs.

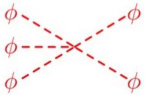


- Ultraviolet physics (e.g., moduli stabilization) sets the gauge couplings α_{UV}, generating a hierarchy of confinement scales.
- The glueballs contribute to the DM energy density; what is the relic density produced?

The glueball component

- Assuming that a dark sector gets reheated to a temperature $T'_{RH} > \Lambda$, it goes through the phase transition gluons $\rightarrow$ glueballs at $T' \sim \Lambda$.
- Once the glueball states are formed, they quickly decay to the lightest one (a scalar field ϕ), with mass $m_{gb} \gtrsim \Lambda$.
- Glueballs are self-interacting, and thus realize the self-interacting dark matter (SIDM). In special, 3 $\rightarrow$ 2 interactions, of the form

$$\mathcal{L} \supset \frac{1}{\Lambda}\frac{f}{5!}\phi^5 \,,$$



further deplete the energy density until decoupling at T'_d.

Dark glueball relic

- The glueball relic density is, then, found out to be

$$\boxed{\Omega_{gb} h^2 = \frac{\Lambda}{3.6\ \text{eV}\,\xi}\omega(\Lambda)}\ ,$$

with $\xi = s/s'$ being the visible-to-dark entropy ratio and $\omega(\Lambda)^{-1}$ being a $\mathcal{O}(1-100)$ slowly varying function, given by

$$\omega(\Lambda)^{-1} = \frac{5}{4} W\left[7.45 \times 10^{12} \frac{f^{6/5} g'^{4/5}}{\xi^{2/5}} \left(\frac{3.6\ \text{eV}}{\Lambda}\right)^{4/5}\right]\ ,$$

where W is the Lambert W-function.

- Therefore, the primary variables that determine Ω_{gb} are Λ and ξ, and Ω_{gb} is approximately linear in Λ.

Dependence on UV parameters

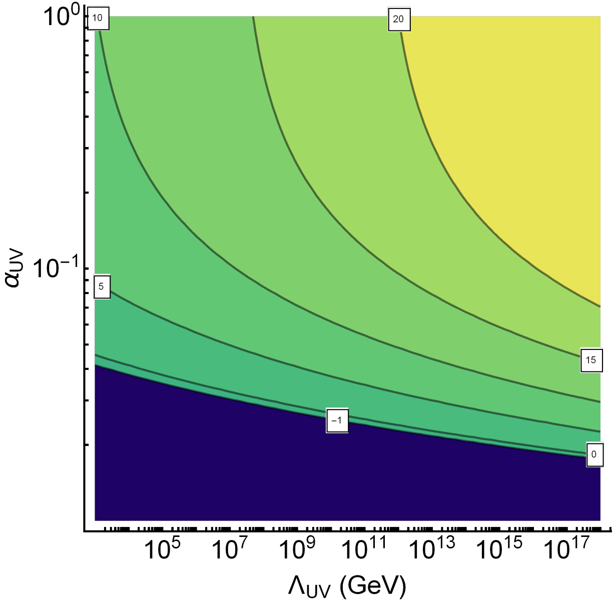
- The confinement scale is found from the running of the gauge coupling, with the assumption that the super Yang-Mills beta function holds all the way down to low scales,

$$\Lambda \equiv \Lambda_{IR} = \Lambda_{UV} \mathrm{e}^{-2\pi/3C_2(G)\alpha_{UV}} \ ,$$

where Λ_{UV} is the ultraviolet energy scale for which $\alpha = \alpha_{UV}$, Λ_{IR} is the scale in which the coupling diverges and $C_2(G)$ is the dual Coxeter number.

Thus, since $\Omega_{gb} \propto \Lambda$, the relic density of glueballs is exponentially sensitive to the UV coupling.

Relic density for $G = \mathrm{SU}(2)$, with $\xi = 1$



The dark glueball problem

[Halverson, Nelson & Ruehle, 2016]

- Glueballs exponentially oversaturate the relic density for much of the natural *UV* parameter space.
- An exponential fine-tuning is required for glueballs to produce (a fraction of) the observed DM density Ω_{dm}.
- For many hidden sectors, this problem appears to be unavoidable.
- This issue is present in *any* pure Yang-Mills sector, these appear very often in string theory.
- Possible way out:
  - Strong preferential reheating into the visible sector, i.e., $\xi \gg 1$.

Axions in string theory

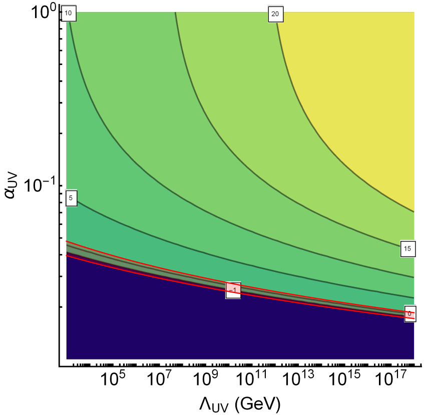
- String theory suggests the presence of many ultralight axions, with masses possibly spanning many orders of magnitude, all the way down to 10^{-33} eV.

  [Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell, 2009 ("Axiverse")]

- Each hidden gauge sector is associated to an axion field, and this will be a second ingredient in our pure Yang-Mills dark sector.

- Axion decay constants are $f_a \sim M_{Pl}/\tau$, with $\tau \sim \mathcal{O}(10-100)$ in many string compactification scenarios [Kachru, Kallosh, Linde, Trivedi, 2003], which leads to $f_a \sim 10^{16} - 10^{17}$ GeV.

- The non-perturbative effects that generate the axion mass are the usual Yang-Mills instantons, giving $\boxed{m_a = \Lambda^2/f_a}$.



The region shown in red corresponds to:

10^{-23} eV $< m_a < 10^{-21}$ eV

with $\Lambda = \sqrt{m_a f_a} \sim 100$ eV.

If the glueballs are only a fraction of the relic density, the associated ultralight axion is fuzzy!

Fuzzy dark matter

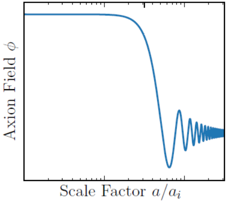
- A particle with mass $m \sim 10^{-22}$ eV and velocity $v \sim 10^{-3}$ (galactic dispersion) has a de Broglie wavelength of the order ~ 1 kpc.
- The Jeans scale is non-zero and of the order of de Broglie wavelength, uncertainty principle gives stability below this scale.
- Possible solution to the core-cusp and too big to fail problems, known as *fuzzy dark matter* (FDM) [Hu, Barkana & Gruzinov, 2000].

Ultralight axions are a concrete realization of FDM.

- Inflation makes the axion field homogeneous over cosmologically large distances.

- Initially, its evolution is overdamped by Hubble friction.

- Once $H \sim m_a \sim 10^{-22}$ eV, oscillations set in and the axion field evolves towards the minimum of its potential.



[Marsh, 2016]

- The axion relic density is

$$\Omega_a h^2 \sim 0.1 \left(\frac{m_a}{10^{-22}\ \text{eV}} \right)^{1/2} \left(\frac{f_a}{10^{17}\ \text{GeV}} \right)^2 .$$

Ultra-strongly self-interacting dark matter

- We expect the glueball self-interaction cross section to be of the order

$$\sigma_{gb} \sim \frac{4\pi}{\Lambda^2} \; .$$

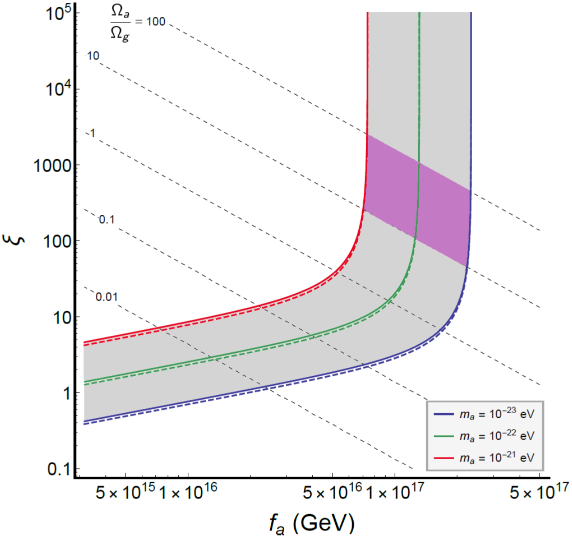
- This gives $\sigma_{gb}/m_{gb} \gg 1 \text{ cm}^2/\text{g}$. Experimental estimates for SIDM cross sections give

$$\frac{\sigma_{\text{SIDM}}}{m_{\text{SIDM}}} \sim 0.1 - 1 \text{ cm}^2/\text{g} \; .$$

- However, the experimental constraints allow for a fraction $f \lesssim 0.1$ of the dark matter with much stronger self-interactions, referred to as ultra-strongly self-interacting dark matter (uSIDM).

Observed relic density

- Therefore, we require that axions be the dominant component of the relic density, by at least one order of magnitude over the glueballs.



In the gray region, the axion mass is in our chosen range.

The purple region has the axion dominating the relic density, with

$$10 < \frac{\Omega_a}{\Omega_{gb}} \leq 100 \,.$$

Notice that $\xi \sim 10^3$ in the preferred region.

Reheating temperatures

- Assuming the entropy in each sector is conserved since reheating, we have

$$\xi = \frac{g_{MSSM}}{g'_{RH}} \left(\frac{T}{T'}\right)^3_{RH} \sim 10^3 \;\Rightarrow\; \left(\frac{T}{T'}\right)_{RH} \sim 1.6\, {g'_{RH}}^{1/3} \;,$$

  with g'_{RH} being the number of relativistic degrees of freedom in the hidden sector at the time of reheating.

- Thus, one needs only a mild temperature difference between the sectors.

Implications of a mixed model

- Of course, one can consider the simpler scenario of only the ultralight axion as DM. However, our mixed model brings further implications.
- A model of pure FDM is in strong tension with the Lyman-α forest measurements of the power spectrum.
  - Making FDM a fraction of the dark matter might relax these constraints.
- Observations of quasars at large redshift ($z \sim 7$) potentially contradict the cosmology of ΛCDM.
  - The presence of a uSIDM component of dark matter can form seeds that grow into a supermassive black holes at high redshifts. [Pollack, Spergel & Steinhardt, 2014]
- Therefore, even a small component of uSIDM might have significant implications for structure formation.

Conclusions

- We were able to construct a scenario of FDM mixed with SIDM, in which both the axions and the glueballs contribute significantly to the DM relic density.
- Preferential reheating is needed, but only a mild one.
- This scenario might avoid the tension between pure FDM and observations, while still being a solution to the small scale crises of cold dark matter.
- The glueball component might have interesting implications for structure formation.
- It arises naturally in the context of string theory, provided that there's a solution to the dark glueball problem.

Thank you!