Composite dark matter axion-like particles: Glueball-ALPs

Based on

PC, R. Pasechnik, G. Salinas and Z. W. Wang, Phys. Rev. Lett. **129** (2022) no.26, 26

PC, T. Ferreira, R. Pasechnik and Z. W. Wang, Phys. Rev. D **108** (2023) no.12, 12

PC, R. Pasechnik and Z. W. Wang, Phys. Rev. Lett. **135** (2025) no.2, 021001

PC, R. Pasechnik and Z. W. Wang, 2411.11716

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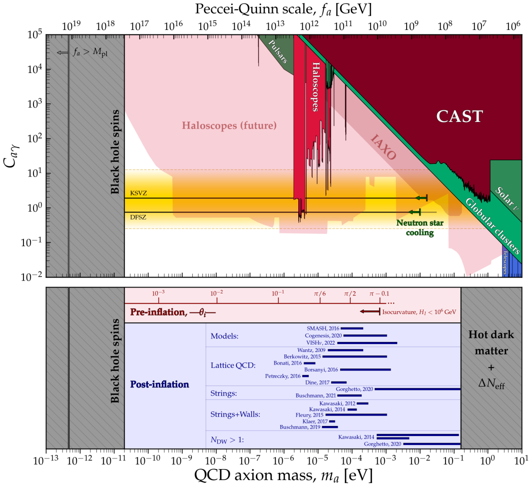
An interesting DM candidates: Axions

F. Chadha-Day *et al.*, Sci. Adv. **8** (2022) no.8, abj3618



Hidden Yang-Mills sector

Many works on confining dark $SU(N)$

$$\mathcal{L} = -\frac{1}{4} G^{\mu\nu\, a} G^{a}_{\mu\nu} \,,$$

- Glueballs are the stable states at low energy
- How many glueball types?
- Can they be DM?
- Can they be composite axion-like DM?

Confinement in QCD

H. D. Politzer, Phys. Rev. Lett. **30** (1973), 1346-1349

D. J. Gross and F. Wilczek, Phys. Rev. D **8** (1973), 3633-3652

The coupling g runs with the energy scale μ

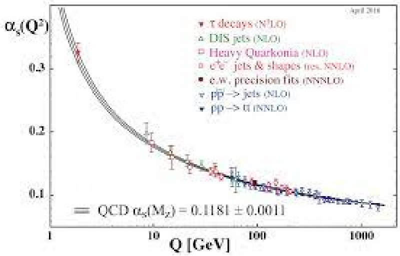
$$\frac{\partial g}{\partial \ln \mu} = \beta(g)$$

determined by the β function

In QCD

$$\beta(g) < 0$$

We observe confined states: hadrons



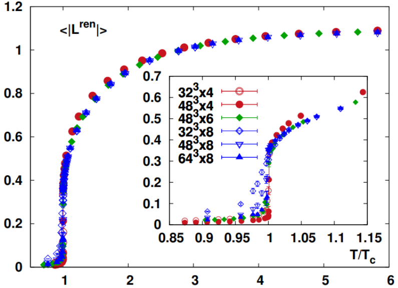
The Polyakov loop model

R. D. Pisarski, Phys. Rev. D **62** (2000), 111501

At temperature T, for $SU(N)$, we define

$$\ell(x) = \frac{1}{N}\mathrm{Tr}[\mathsf{L}] \equiv \frac{1}{N}\mathrm{Tr}\left[\mathcal{P}\exp\left[i\,g\int_0^{1/T} A_0(\tau,\mathsf{x})d\tau\right]\right]$$

with A_0 time component vector potential



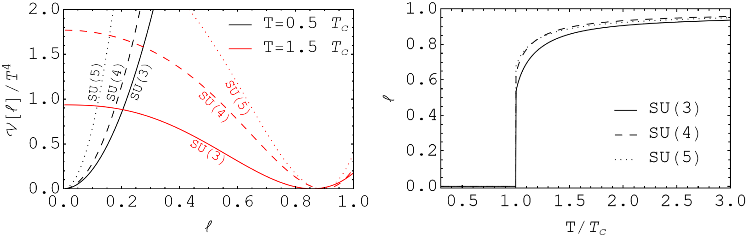
P. M. Lo *et al.*, Phys. Rev. D **88** (2013), 074502

Effective potential

The behaviour of ℓ is described as a field in an effective potential

$$\mathcal{V}[\ell] = T^4 \left(-\frac{b_2(T)}{2}|\ell|^2 + b_4|\ell|^4 - b_3\left(\ell^N + \ell^{*N}\right) + b_6|\ell|^6 + b_8|\ell|^8 \right)$$

determined by symmetry arguments



The glueball potential

J. Schechter, Phys. Rev. D **21** (1980), 3393-3400

Our theory is described by

$$\mathcal{L}_{\mathrm{SU(N)}} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \frac{\theta}{4} G^a_{\mu\nu} \tilde{G}^{\mu\nu a} ,$$

but in the confined phase gluons are not observable. Glueballs are

$$H^4 = -\frac{\beta(g)}{2g} G^a_{\mu\nu} G^{\mu\nu a} \qquad \mathrm{scalar} ,$$
$$A\, H^3 = G^a_{\mu\nu} \tilde{G}^{\mu\nu a} \qquad \mathrm{pseudoscalar} ,$$

we can write

$$\mathcal{L}_{\mathrm{eff}} = \frac{1}{2} \partial_\mu H \partial^\mu H + \frac{1}{2} \partial_\mu A \partial^\mu A - V(H, A) ,$$

where V gives a vev for H and A

The dark gluon-glueball Lagrangian

Putting the pieces together

$$\mathcal{L} = \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{1}{2}\partial_\mu A \partial^\mu A - V(H, A, \ell)$$
$$V(H, A, \ell) = V(H, A) + \kappa(H^4 + A^4)|\ell|^2 + T^4 \mathcal{V}[\ell]$$

With ℓ non-dynamical field, that can be integrated out

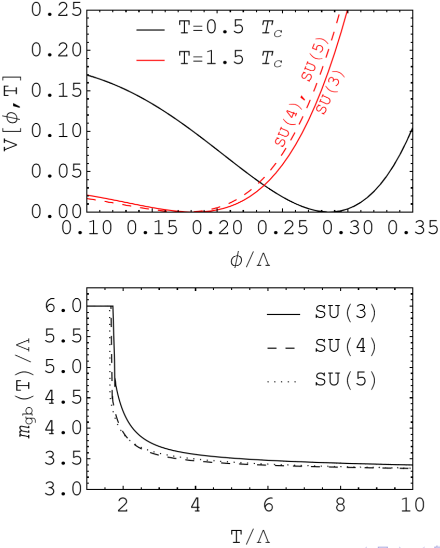
$$\frac{\partial}{\partial \ell} V(H, A, \ell) = 0$$

which allows us to integrate out $\ell = \ell(H, A, T)$

Dynamics of the dark gluon-glueball system

Equations of motion for the Polyakov loop

Let's consider the case with only scalar glueball, where $H = \phi/4\sqrt{c}$, integrating out the Polyakov loop...



Cosmological evolution of the (scalar) glueball field

Glueballs evolve in a FLRW metric as

$$\ddot{\phi} + 3H\dot{\phi} + \partial_\phi V[\phi, T] = 0$$

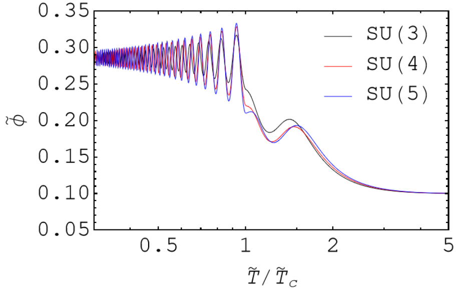
and the relic density is proportional to

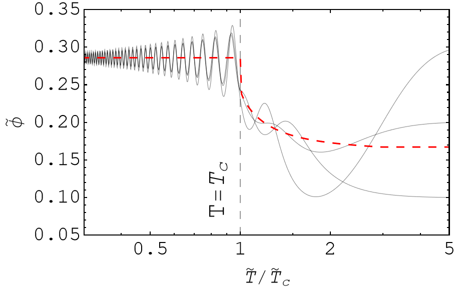
$$\rho = \frac{1}{2}(\dot{\phi})^2 + V[\phi, T]$$

Very similar to the misalignment mechanism!!

Results

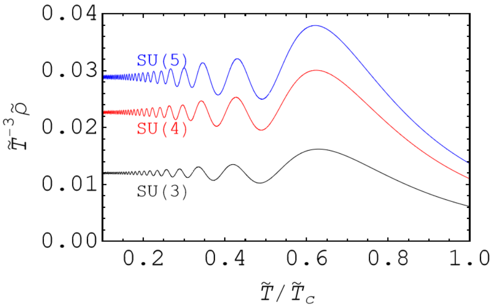
Weak dependence on the gauge group and on initial conditions





(Scalar) Glueball CDM today

Glueballs behaving like CDM, $\Omega_g h^2 = 0.12\zeta_T^{-3}\frac{\Lambda}{\Lambda_0}$



N	c_1	$100 \times \left\langle \frac{\tilde{\rho}}{\tilde{T}^3} \right\rangle_f$	Λ_0 (eV)
3	1.225 ± 0.19	$0.59^{+0.15}_{-0.14}$	133 ± 32
4	1.225 ± 0.8	$1.1^{+1.0}_{-0.9}$	204 ± 168
5	1.225 ± 0.8	$1.3^{+1.2}_{-1.0}$	139 ± 109

Temperature of the dark sector

There is an important unkown:

$$\zeta_T^{-1} = \frac{T}{T_\gamma}$$

which is determined by the thermalization of the dark sector

Do we need to know the visible-dark sector interaction? No

Thermal history of dark gluons

- Freeze-out: feeble interactions with SM particles bring dark gluons in equilibrium until T_d, then

$$\frac{T}{T_\gamma} = \zeta_T^{-1} = \left(\frac{g_{*,s}(T_\gamma)}{g_{*,s}(T_d)}\right)^{1/3} \to 0.26 \lesssim \zeta_T^{-1} \lesssim 0.71$$

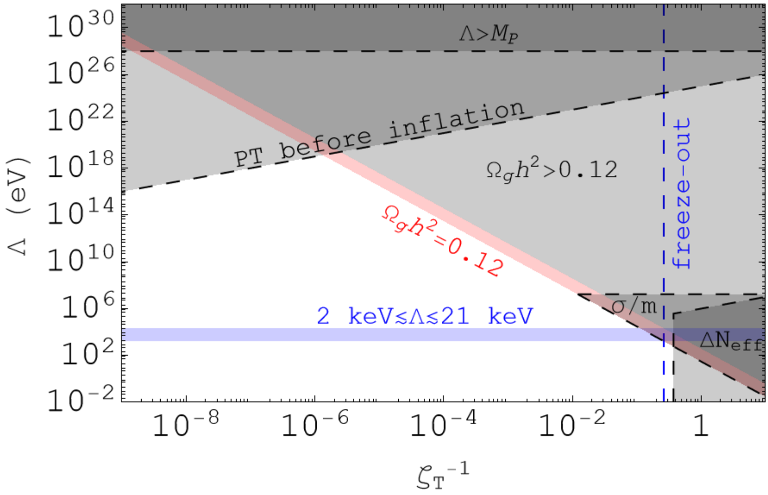
  for decoupling soon after inflation or together with neutrinos.

- Parent particle decay: inflaton decaying into dark gluons with a BR f leads to

$$\frac{T}{T_\gamma} = \zeta_T^{-1} = \left(\frac{g_{*,s}(T_\gamma)}{g_{*,s}(T_d)}\right)^{1/3} \left(\frac{f}{1-f}\right)^{1/4} \to ? \lesssim \zeta_T^{-1} \lesssim ?$$

Glueball DM parameter space

A large portion of the parameter space is viable



Cosmology with pseudoscalar glueballs

Expanding $H = h_0 + h$ and $A = a_0 + a$, glueball interactions are

$$V \simeq \frac{m_h^2}{2} h^2 + \frac{m_a^2}{2} a^2 + \lambda_{1,1} \Lambda^2 h\, a + \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \lambda_{i,j} \Lambda^{4-i-j} h^i a^j \Big|_{i+j \geq 3} ,$$

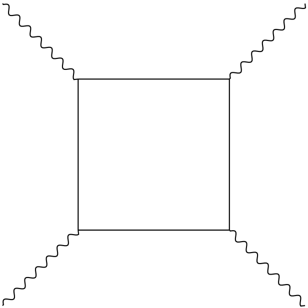
allowing for the very efficient decay $a \to hh$

- $m_a > 2m_h$: only h DM survives
  in this case $20\ \text{MeV} \lesssim \Lambda \lesssim 10^{10}\ \text{GeV}$.
- $m_a < 2m_h$: mixed a and h DM

Dark gluon interactions

A. E. Faraggi and M. Pospelov, Astropart. Phys. **16** (2002), 451-461

The simplest dark gluon-SM interaction is via heavy fermions



$$\mathcal{L}_{\rm eff} \supset \frac{\tau^2\alpha^2}{M_\Psi^4}\left[c_\gamma\, G^a_{\mu\nu}G^{\mu\nu a}F_{\alpha\beta}F^{\alpha\beta} + \tilde{c}_\gamma\, G^a_{\mu\nu}\tilde{G}^{\mu\nu a}F_{\alpha\beta}\tilde{F}^{\alpha\beta}\right], \,,$$

GALPS!

Considering the case of dark gluons interacting with photons

$$\mathcal{L}_{\rm eff} \supset \frac{\tau^2\alpha^2}{M_\Psi^4}\left[c_\gamma\, G^a_{\mu\nu} G^{\mu\nu a} F_{\alpha\beta} F^{\alpha\beta} + \tilde{c}_\gamma\, G^a_{\mu\nu} \tilde{G}^{\mu\nu a} F_{\alpha\beta} \tilde{F}^{\alpha\beta}\right],$$

$$\downarrow$$

$$\mathcal{L}_{\rm eff} \supset \frac{1}{4}\sum_{i=1,2}\left[g_{\phi_i\gamma}\,\phi_i F_{\alpha\beta} F^{\alpha\beta} + \tilde{g}_{\phi_i\gamma}\,\phi_i F_{\alpha\beta} \tilde{F}^{\alpha\beta}\right],$$

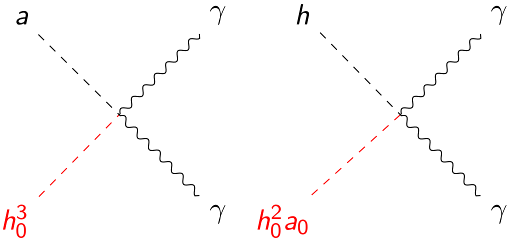
We get an axion-like particle and a scalar with CP violating interactions

GALP-photon interactions

ALP-like couplings:

$$g_{\mathrm{GALP}\gamma} = \kappa\, \alpha^2 \Lambda^{-1} \left[\frac{\Lambda}{M_\Psi}\right]^4$$

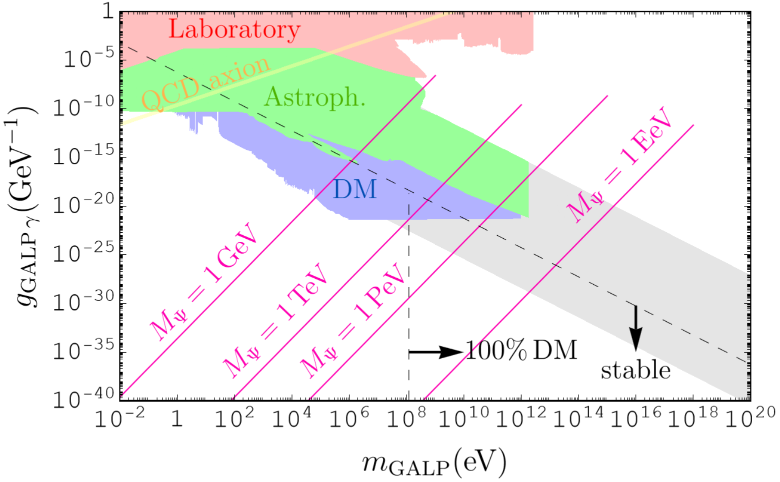
$$= 2.45 \times 10^{-7}\, \mathrm{GeV}^{-1}\, \kappa \left[\frac{m_{\mathrm{GALP}}}{\mathrm{GeV}}\right]^3 \left[\frac{M_\Psi}{\mathrm{GeV}}\right]^{-4} .$$



$$f_a \simeq 4.1 \times 10^3\ \mathrm{GeV}\, \kappa^{-1} \left[\frac{\Lambda}{\mathrm{GeV}}\right]^{-3} \left[\frac{M_\Psi}{\mathrm{GeV}}\right]^4 .$$

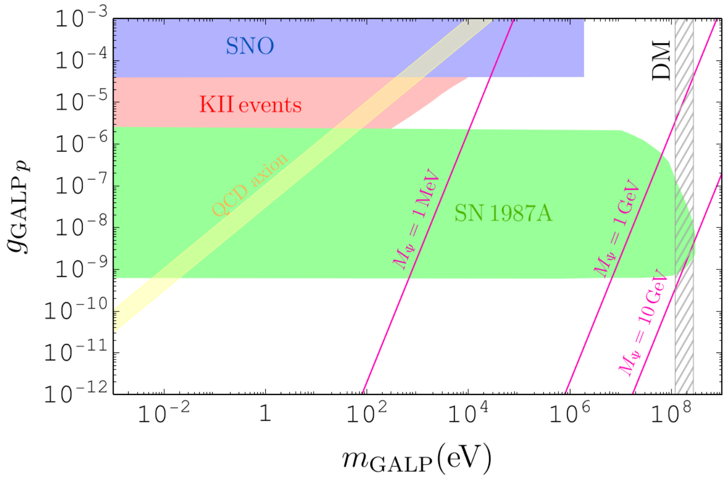
GALP parameter space

Here, $m_{\rm GALP} = 6\Lambda < M_\Psi$



QCD-GALPS!

$$g_{\mathrm{GALP}p} = -2 \times 10^{-3} \kappa \left(\frac{m_{\mathrm{GALP}}}{\mathrm{GeV}} \right)^3 \left(\frac{M_\Psi}{\mathrm{GeV}} \right)^{-4}$$



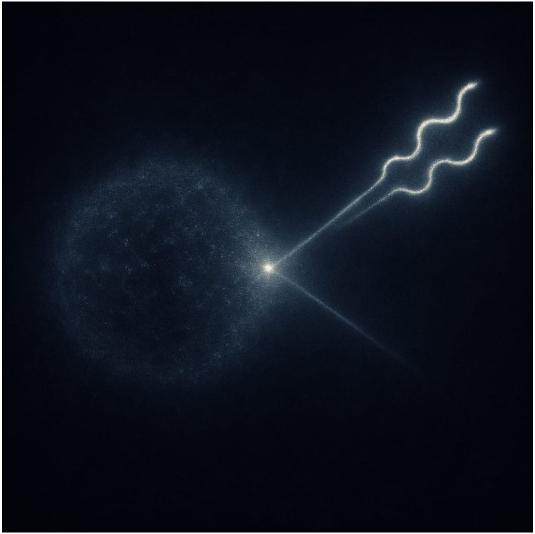
GALPs vs ALPs

- **Not a composite axion.** The proposed GALP model is not leading to a solution of the strong-CP problem, as done by composite axion models
- **No scale hierarchy problem.** No need for $f_a \sim (10^9 - 10^{10})$ GeV. The effective PQ scale f_a can even reach super-Planckian values for $M \gtrsim$ TeV
- **DM more massive than usual axion models.** The natural prediction for GALP DM with a mass $m_{\rm GALP} \gtrsim 180$ MeV lies in between the light axion DM paradigm and the GeV-scale traditional Weakly Massive Interacting Particles.

- **Intriguing phenomenology.** The GALP model requires to study the phenomenology of heavy and, possibly, strongly interacting ALPs that acquired interest in a model-independent fashion, but find a physical motivation in the GALP model.
- **An extended dark sector.** If the term GALP refers to the pseudoscalar glueball, any GALP model requires the existence of the scalar glueball which can be searched for in parallel with the GALP. A joint signal would be a strong hint towards this model.

AI concept of dark matter glueball

https://www.su.se/department-of-physics/news



Thanks for your attention!!