Stockholm, 23^{th} October 2023

Glueball Dark Matter

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,
2306.09510

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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

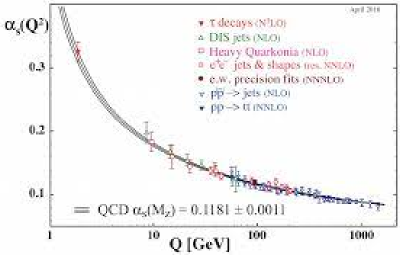
The coupling g runs with the energy scale μ

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

determined by the β function
In QCD

$$\beta(g) < 0$$

We observe confined states: hadrons



One step back to focus the problem

- Do we need to describe the cosmological evolution of the dark gluon gas?
- How do glueball form from dark gluons?
- Is there any constraint on glueball self-interactions?
- Is there a reliable estimate of the glueball relic density?

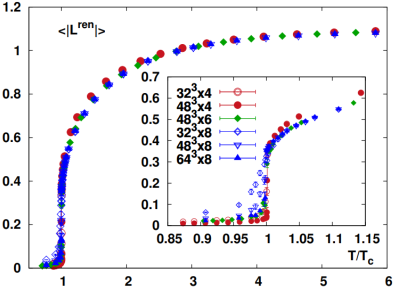
The Polyakov loop model

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

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

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

with A_0 time component vector potential



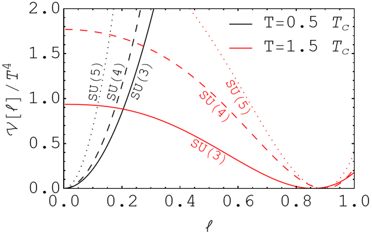
P. M. Lo *et al.*, Phys. Rev. D **88** (2013), 074502

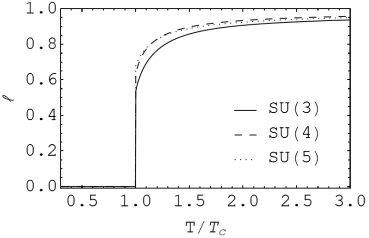
Effective potential

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

The scalar glueball field is defined as

$$\mathcal{H} = \text{tr}\, G^{\mu\nu} G_{\mu\nu}$$

and it corresponds to the dilatation anomaly

$$\theta^\mu_\mu = \partial_\mu D^\mu = -\frac{\beta(g)}{2g}\mathcal{H}$$

The following Lagrangian encodes this property

$$\mathcal{L} = \frac{c}{2}\frac{\partial_\mu \mathcal{H} \partial^\mu \mathcal{H}}{\mathcal{H}^{3/2}} - \frac{\mathcal{H}}{2} \ln\left[\frac{\mathcal{H}}{\Lambda^4}\right]$$

where $c = (\Lambda/m_{\rm gb})^2/2\sqrt{e}$

The dark gluon-glueball Lagrangian

Putting the pieces together

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V[\phi,\ell]$$

$$V[\phi,\ell] = \frac{\phi^4}{2^8c^2}\left[2\ln\left(\frac{\phi}{\Lambda}\right) - 4\ln 2 - \ln c\right] + \frac{\phi^4}{2^8c^2}\mathcal{P}[\ell] + T^4\mathcal{V}[\ell]$$

$$\mathcal{P}[\ell] = c_1|\ell|^2$$

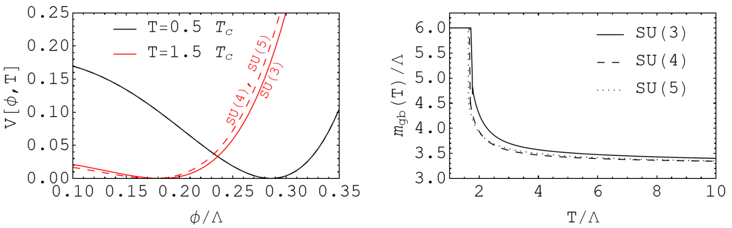
where $\mathcal{H} = 2^{-8}c^{-2}\phi^4$

Equations of motion for the Polyakov loop

Being a non-dynamical field, the EoM is

$$\frac{\partial}{\partial \ell} V[\phi, \ell] = 0$$

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



Cosmological evolution of the glueball field

Glueballs evolve in a FLRW metric as

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

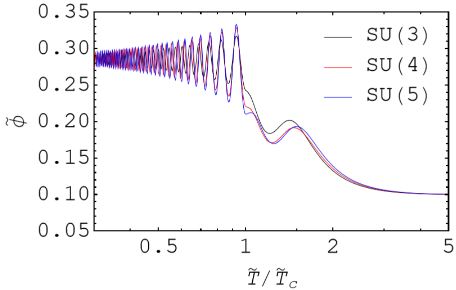
and the relic density is proportional to

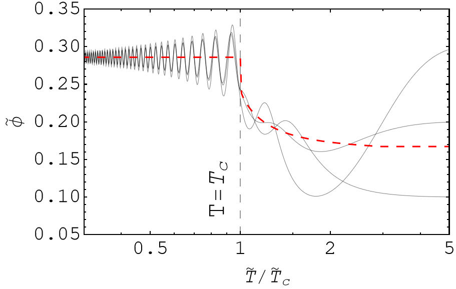
$$\rho = \frac{1}{2}(\dot{\phi})^2 + V[\phi, T]$$

Very similar to the misalignment mechanism!!

Results

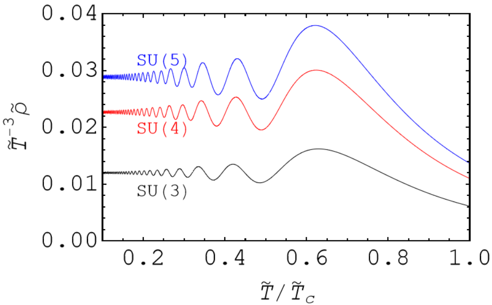
Weak dependence on the gauge group and on initial conditions





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

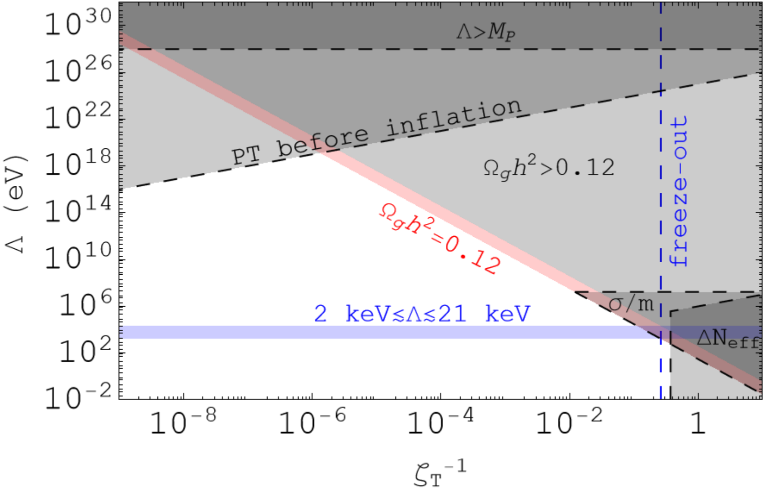
$$\frac{T}{T_\gamma} = \zeta_T^{-1} = \left(\frac{g_{*,s}(T_\gamma)}{g_{*,s}(T_d)}\right)^{1/3} \to 0.26 \lesssim \zeta_T^{-1} \lesssim 0.71$$

  for decoupling soon after inflation or together with neutrinos.
- Parent particle decay: inflaton decaying into dark gluons with a BR f leads to

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

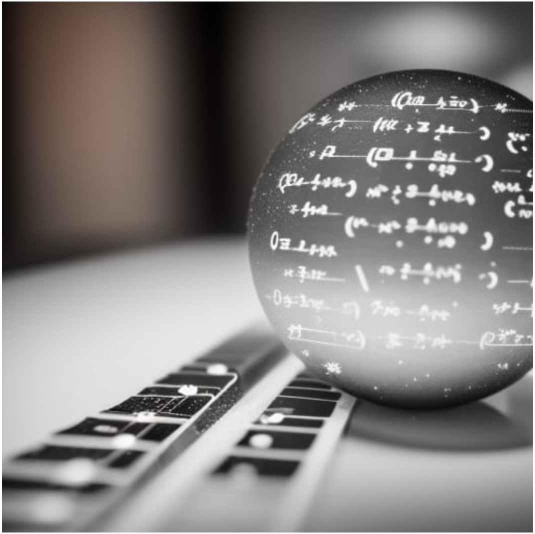
Glueball parameter space

This discussion can be summarized in the ζ_T^{-1} vs Λ plane



AI concept of dark matter glueball

https://creator.nightcafe.studio



Thanks for your attention!!