

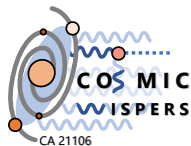
Santander, 29th May 2023

Glueball Dark Matter

Based on

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

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COST ACTION CA21106

COSMIC WISPers in the Dark Universe:

Theory, astrophysics and experiments



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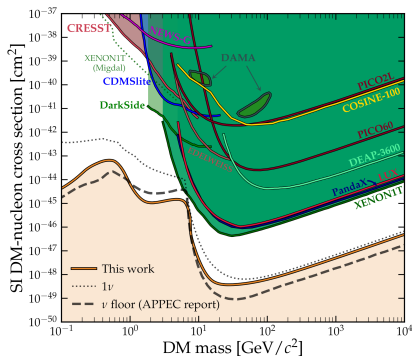
Some DM candidates: WIMPs

C. A. J. O'Hare, Phys. Rev. Lett. **127** (2021) no.25, 251802

The WIMP miracle...

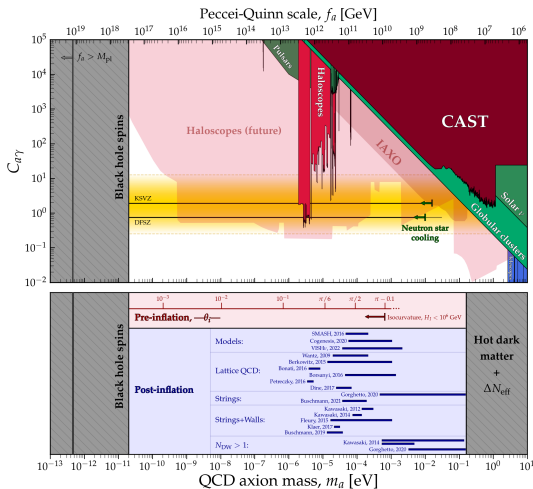
$$\Omega h^2 \simeq 0.12 \times \left(\frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle} \right)$$

... and the most optimistic status for WIMP searches



Some DM candidates: Axions

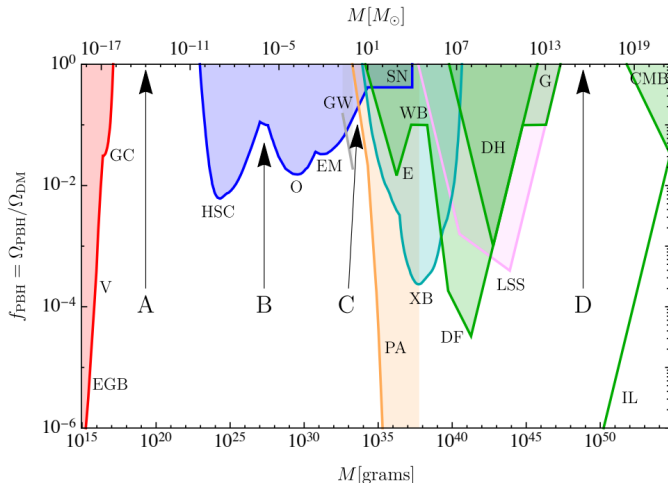
F. Chadha-Day *et al.*, *Sci. Adv.* **8** (2022) no.8, abj3618



Some DM candidates: primordial black holes

B. Carr and F. Kuhnel, SciPost Phys. Lect. Notes **48** (2022), 1

Lunar and Stupendously Large Black Holes are still allowed



Some DM candidates: Macro DM

Actually the only requirement to be dark is

$$\frac{\sigma}{m} \lesssim 1\text{cm}^2/\text{g}$$

so many big things can be DM

- ▶ strangelets
- ▶ (axion-)quark nuggets
- ▶ Q-Balls
- ▶ MACHOs

just in case... J. Singh Sidhu *et al.*, "Death and serious injury from dark matter," Phys. Lett. B **803** (2020), 135300

My definition of DM

The Thin Common Core Concept of Mainstream DM: A massive field with $\Omega h^2 \simeq 0.12$, responsible for certain gravity-mediated observables related to structure formation, clusters and galaxies. In case it is a particle, its mass is roughly between 10^{-22} and 10^{13} eV.

N. C. M. Martens, Found. Phys. **52** (2022) no.1, 16

Let's discuss of DM in 35 orders of magnitude in mass...

All the fields between spin 0 and 1 are very well explored except

non-abelian vector gauge bosons

Glueball Dark Matter:
another side of the spin-1 DM
candidate

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

Hidden gauge sectors: confining sectors

Many works on confining dark $SU(N)$

▶ **Self-interacting DM**

E. D. Carlson *et al.*, *Astrophys. J.* **398** (1992), 43-52

▶ **Glueball phenomenology**

A. Soni and Y. Zhang, *Phys. Rev. D* **93** (2016) no.11, 115025

▶ **The dark glueball problem**

J. Halverson *et al.*, *Phys. Rev. D* **95** (2017) no.4, 043527

▶ **The nightmare scenario**

R. Garani *et al.*, *JHEP* **12** (2021), 139

▶ **Thermal Squeezeout**

P. Asadi *et al.*, *Phys. Rev. D* **104** (2021) no.9, 095013

▶ **Gravitational waves from confinement**

W. C. Huang *et al.*, *Phys. Rev. D* **104** (2021) no.3, 035005

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?

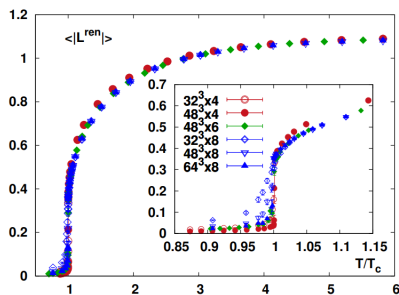
The Polyakov loop model

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

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

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

with A_0 time component vector potential



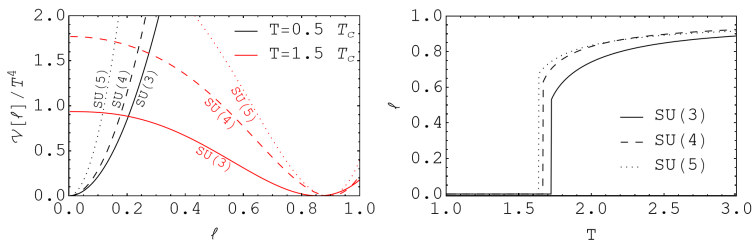
P. M. Lo *et al.*, Phys. Rev. D **88** (2013), 074502

Effective potential

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

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

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

The dark gluon-gluon Lagrangian

Putting the pieces together

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

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

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

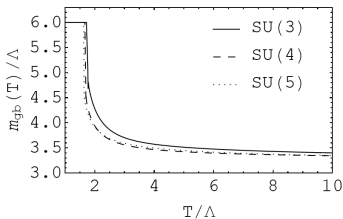
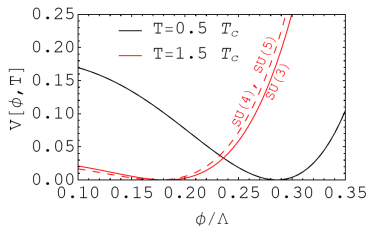
where $\mathcal{H} = 2^{-8} c^{-2} \phi^4$

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

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

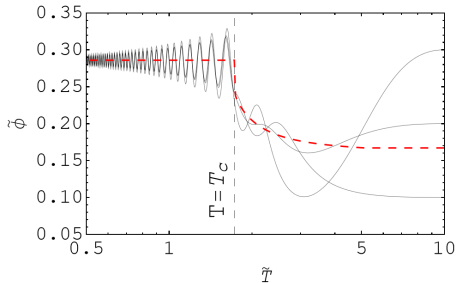
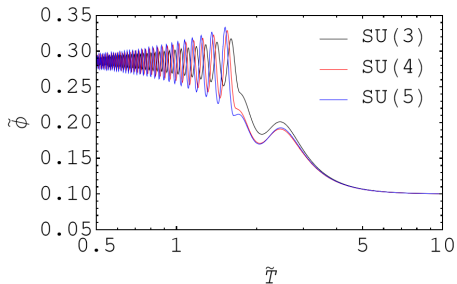
and the relic density is proportional to

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

Very similar to the misalignment mechanism!!

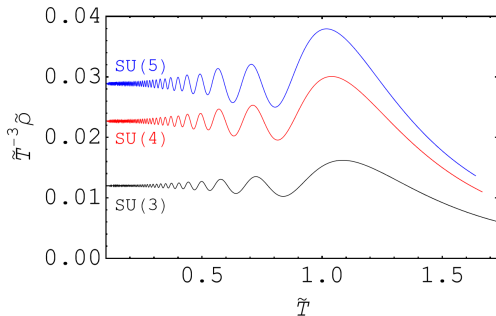
Results

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 unknown:

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

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

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

for decoupling soon after inflation or together with neutrinos.

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

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

Constraints on dark gluon abundance

Relativistic species in equilibrium until BBN/CMB epoch is not allowed

$$\Delta N_{\text{eff}} = \frac{4}{7} \left(\frac{11}{4} \right)^{4/3} g \zeta_T^{-4} \lesssim 0.35 \rightarrow \zeta_T^{-1} \lesssim 0.37$$

This constrains the temperature of dark gluons

Partially excluding the freeze-out window :(

Constraint on self-interactions

D. Eckert *et al.*, *Astron. Astrophys.* **666** (2022), A41

Glueballs undergo $\phi\phi \rightarrow \phi\phi$ scattering, constrained to be

$$\frac{\sigma}{m} \lesssim 0.19 \text{cm}^2/\text{g}$$

X-ray measurement constrain the shape of DM profiles in galaxy clusters

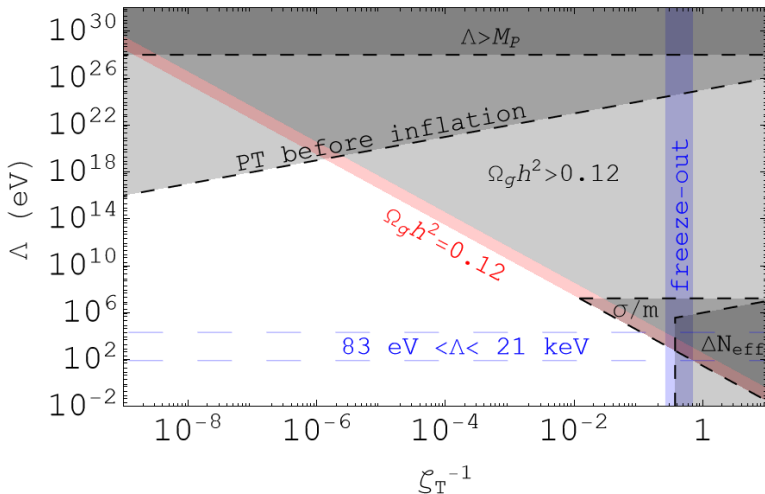
Excluding

$$\Lambda \lesssim 17 \text{ MeV}$$

Once more excluding the freeze-out window :(

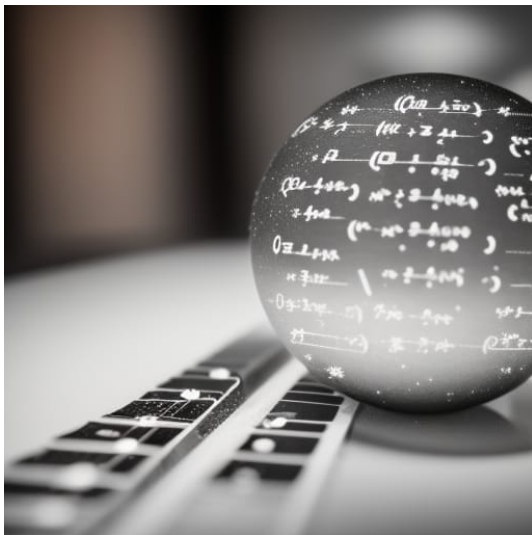
Glueball parameter space

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!!