Glueball Dark Matter

Roman Pasechnik
Lund U.

In collaboration with:
G. Salinas, P. Carenza, Z.-W. Wang

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Why gauge fields are interesting:

- Important physical examples of gauge fields are realised in Nature (QCD and electroweak interactions)

- Non-perturbative QCD phenomena are far from being understood (e.g. quark confinement, mass gap, QCD phase transitions, hot/dense QCD phenomena etc)

- Non-abelian gauge (Yang-Mills) fields are present in most of UV completions of the Standard Model (e.g. GUTs, string/EDs compactifications etc)

- Confining dark Yang-Mills sectors are often considered as a possible source of Dark Matter in the Universe (e.g. dark glueballs)

- Relic abundance of dark glueballs, ubiquitous in string theory, overcloses the Universe for confining sectors with critical temperature above the eV-scale (a big problem for phenomenology!)

- Confining Yang-Mills theories are well studied by lattice simulations, and the robust results are available

main motivation for our analysis!

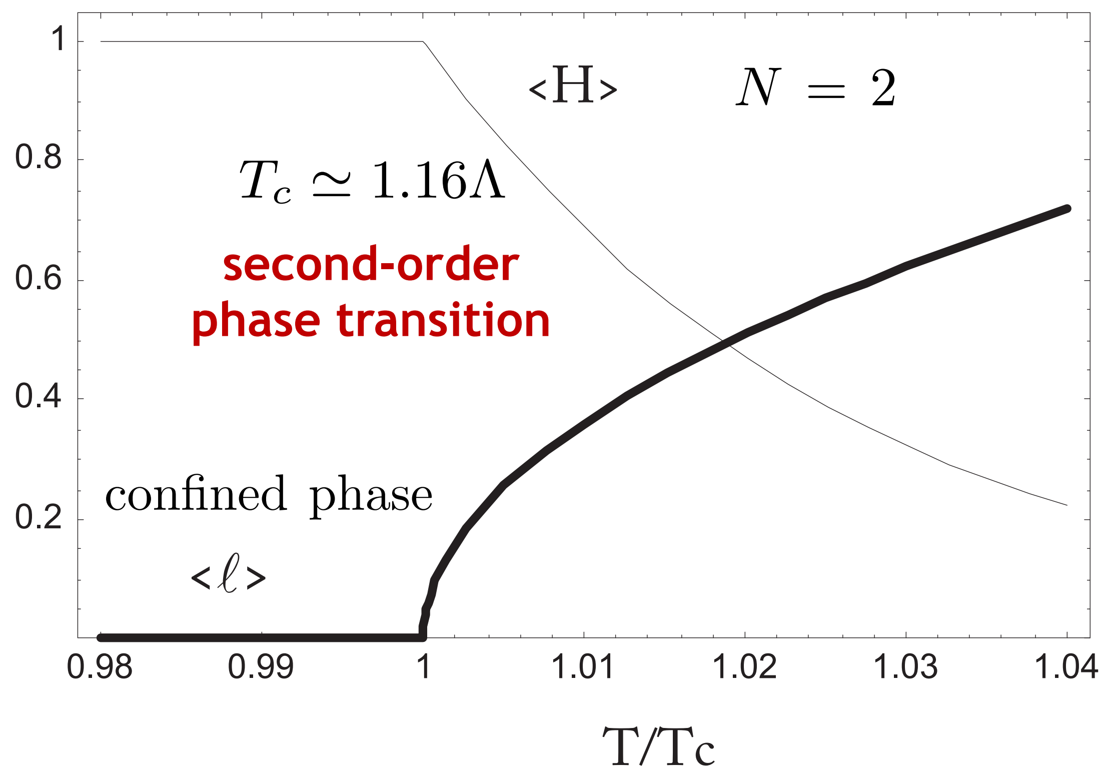
Dark glueball in effective field theory at finite T:

- **Polyakov loop operator charged under the center of SU(N):**

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

$$\ell \;\rightarrow\; z\ell \qquad\qquad z \in \mathbb{Z}_N \qquad\qquad N \geq 2$$

- **Polyakov loop VEV is an order parameter of confinement phase transition:**



F. Sannino, *Polyakov loops versus hadronic states*, *Phys. Rev. D* **66** (2002) 034013 [hep-ph/0204174].

$$\mathcal{L} = \frac{c}{2}\frac{\partial_\mu \mathcal{H}\partial^\mu \mathcal{H}}{\mathcal{H}^{3/2}} - V[\mathcal{H},\ell]$$

$$V\,[\mathcal{H},\ell] = \frac{\mathcal{H}}{2}\ln\left[\frac{\mathcal{H}}{\Lambda^4}\right] + T^4\mathcal{V}\,[\ell] + \mathcal{H}\mathcal{P}[\ell] + V_T\,[\mathcal{H}]$$

$$c = \frac{1}{2\sqrt{e}}\left(\frac{\Lambda}{m_{\mathrm{gb}}}\right)^2$$

PLM well captures essential thermodynamical observables predicted by lattice simulations

Thermal evolution of the glueball-dark gluon system:

- Introducing canonically normalised field $\mathcal{H} = 2^{-8}c^{-2}\phi^4$
  the effective Lagrangian reads:

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

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

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

$$\mathcal{V}[\ell] = -\frac{b_2(T)}{2}|\ell|^2 + b_4|\ell|^4 - b_3(\ell^3 + (\ell^*)^3)\,,$$

$$b_2(T) = \sum_{i=0}^{4} a_i\left(\frac{T_c}{T}\right)^i\,,$$

- Fits to lattice results for observables provide:

a_0	a_1	a_2	a_3	a_4	b_3	b_4
3.72	−5.73	8.49	−9.29	0.27	2.40	4.53

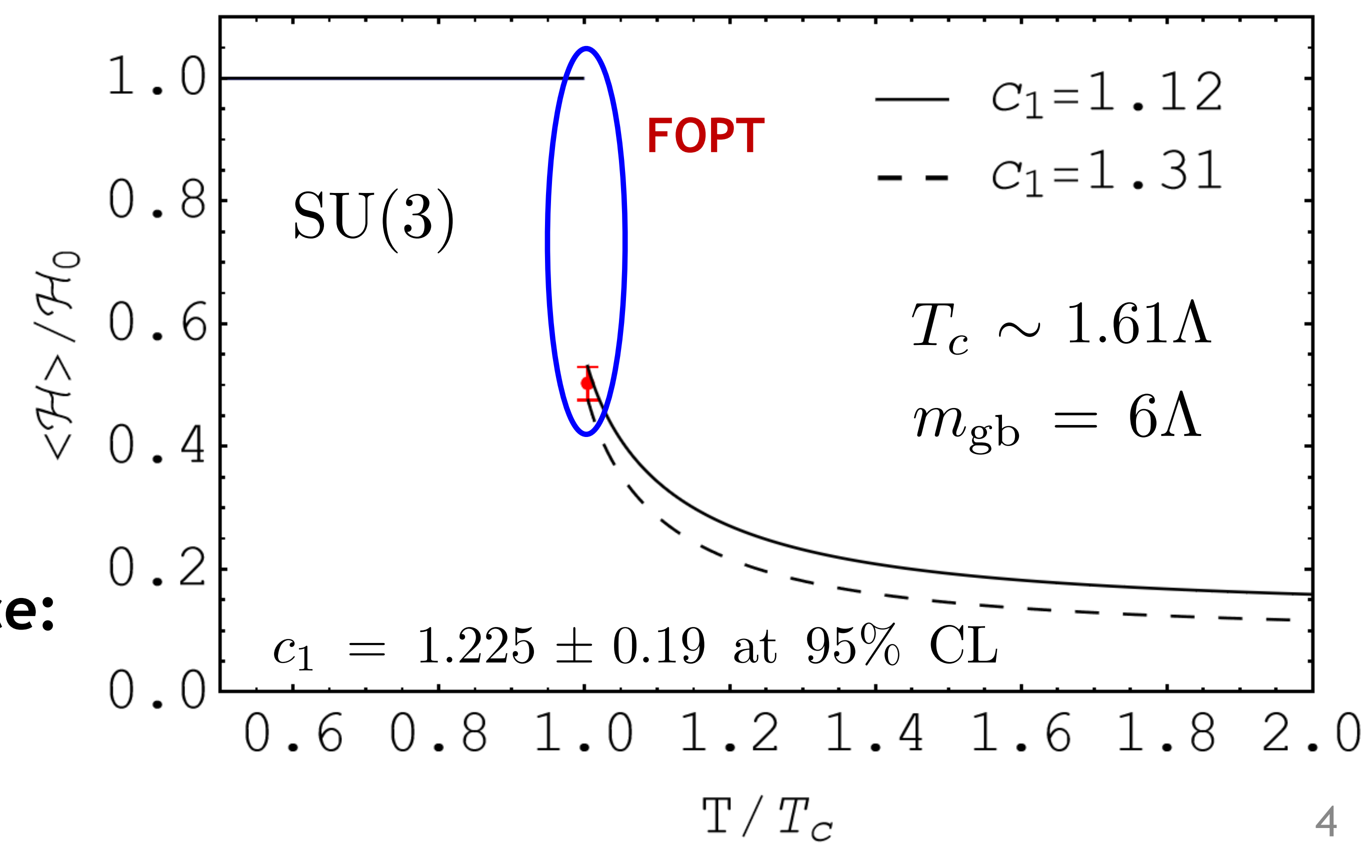
W.-C. Huang, M. Reichert, F. Sannino and Z.-W. Wang, *Testing the dark SU(N) Yang-Mills theory confined landscape: From the lattice to gravitational waves*, *Phys. Rev. D* **104** (2021) 035005 [2012.11614]

- Integrating out the Polyakov loop in the high-T phase provides

$$V[\phi,T] = V[\phi,\ell(\phi,T)]$$

matching the size of discontinuity to lattice:

M. D'Elia, A. Di Giacomo and E. Meggiolaro, *Gauge invariant field strength correlators in pure Yang-Mills and full QCD at finite temperature*, *Phys. Rev. D* **67** (2003) 114504 [hep-lat/0205018].



Cosmological evolution of the dark glueball field:

- Since quantum effects are embedded into the effective Lagrangian, the evolution can be treated as if it were classical

- The glueball field is considered homogeneous and evolves in expanding FLRW Universe, with the Klein-Gordon e.o.m.

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

- If there are no interactions with the SM, the dark sector is colder than the SM thermal bath, with the visible-to-dark sector temperature ratio ξ_T

- Time variable is found in terms of the photon temperature:

$$t = \frac{1}{2}\sqrt{\frac{45}{4\pi^3 g_{*,\rho}(T_\gamma)}}\frac{m_P}{T_\gamma^2} \qquad T_\gamma = \xi_T T$$

- E.o.m. in terms of the dark sector temperature:

$$\boxed{\frac{4\pi^3 g_{*,\rho}}{45 m_P^2}\xi_T^4 T^6 \frac{d^2\phi}{dT^2} + \frac{2\pi^3}{45 m_P^2}\frac{dg_{*,\rho}}{dT}\xi_T^4 T^6 \frac{d\phi}{dT} + \partial_\phi V[\phi, T] = 0\,,} \qquad g_{*,\rho} = 100$$

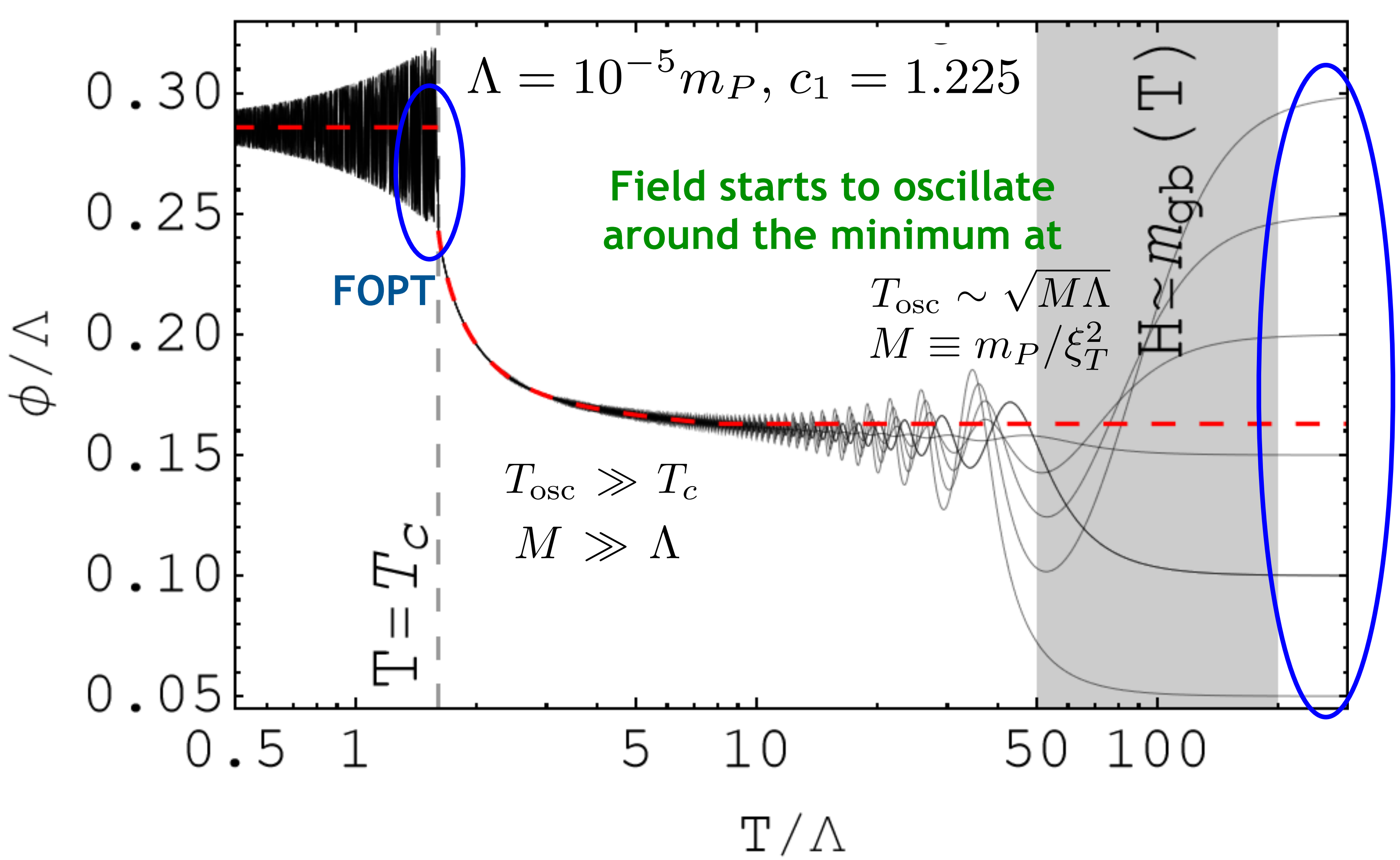
encodes non-perturbative dynamics of the glueball field!

Cosmological evolution of the dark glueball field:

- After the phase transition, we assume that the energy stored in the glueball fields gives rise to the Dark Matter relic density (no further decays implied)

- Due to the interaction term, dark glueballs are formed from dark gluons populating the Universe in the deconfined regime

- Higher-order non-linear interaction terms among glueballs are important for large amplitudes of glueball field oscillations around the minimum (particularly relevant for phase transition)



In early times in deconfined regime, for different initial conditions the field evolution is dominated by Hubble friction (slow evolution)

Oscillations have long time to decay regardless of the initial condition (field follows the minimum)

FOPT washes out any dependence on initial conditions

Glueball relic density:

- In the confined phase, due to large oscillations, annihilation of n glueballs into m<n glueballs is possible due to (n+m)-interaction term

- As the glueball number density decreases, only 3->2 processes remain efficient and determine the relic abundance when $\Gamma_{3\to 2} < H$

- The evolution of the glueball field is that of a dumped harmonic oscillator in a non-linear potential, with oscillations about the minimum $\phi_{\rm min} \approx 0.28\Lambda$

- Energy stored in those oscillations gives rise to the relic DM abundance:

$$\Omega h^2 = \rho/\rho_c \qquad \rho_c = 1.05\times 10^4\,{\rm eV\,cm^{-3}}$$

$$\rho = \frac{2\pi^3}{45} g_{*,\rho}(T)\frac{T^6}{M^2}\left(\frac{d\phi}{dT}\right)^2 + V[\phi] \ \sim T^3$$

after decoupling of 3->2 transitions, the density scales as that of Cold Dark Matter

- Below freeze-out temperature, the relic abundance

$$\boxed{0.12\zeta_T^{-3}\frac{\Lambda}{137.9\,{\rm eV}} \lesssim \Omega h^2 \lesssim 0.12\zeta_T^{-3}\frac{\Lambda}{82.7\,{\rm eV}}}$$

$$\Lambda \lesssim 0.1\,M$$

$$1.035 < c_1 < 1.415$$

Comparison with early studies:

- We confirm the existence of the glueball overabundance problem for high-scale confinement previously found in the literature due to the linear scaling

$$\Omega h^2 \sim \Lambda$$

- Our prediction is an order of magnitude smaller than the existing glueball abundance results in the literature

$$\Omega h^2 \quad \sim \quad 0.12\, \zeta_T^{-3} \Lambda / 5.45\, \mathrm{eV}$$

E. D. Carlson, M. E. Machacek and L. J. Hall, *Self-interacting dark matter*, *Astrophys. J.* **398** (1992) 43.

Two main differences

the energy density of dark gluons for temperatures right above the critical one strongly deviates (reduced by a factor ~ 50) from that of an ideal gas, in agreement with lattice results

glueballs do not redshift as CDM immediately after the phase transition but dilute slower than dust, going through a phase with equation of state $-1 \lesssim p/\rho \lesssim 0$

- Thermal corrections to the glueball potential are expected to increase the glueball relic density by up to 80%, due to displacing the high-temperature minimum of a ~10% farther from the low-temperature minimum (in progress)

- Contribution of dark gluons to the effective number of relativistic species, is constrained to be

$\Delta N_{\rm eff} < 0.35$ $\qquad$ $\zeta_T \gtrsim 2$ **is enough to avoid this constraint**

Summary:

- We developed a new approach based upon the well-established thermal EFT and the existing lattice results to calculate the glueball CDM relic density incorporating confinement effects and non-perturbative self-interactions

- While in the present work we considered only SU(3), due its generality, our approach can be easily applied to different gauge groups

- A dark gauge sector interacting only via gravitational interactions with the SM and a confinement scale at the eV scale might explain the DM abundance without spoiling other cosmological observables

- Our method is suitable for investigations of the glueball formation in modified cosmological histories, requiring only a simple modification of the main evolution equation