The QCD Nature of Dark Energy Signatures and Applications

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Abstract

The infrared sector of QCD contains all the necessary ingredients, once laid onto a time-dependent, curved background, to cater for the much needed cosmological vacuum energy. This is achieved through the fields that describe the impact of the long-range interactions of QCD, the Veneziano ghost and its dipolar partner. Although technically extremely challenging, the physics is well understood and the estimated dark energy density is of the correct order of magnitude. A further tantalising application of this proposal is the ability of generating cosmological magnetic fields via a Standard Model anomalous coupling between the ghost and photons. As a spin-off it is possible to show that the QCD vacuum possesses a Casimir-like energy density if enclosed in a non-trivial compact manifold.

GENERALITIES

This poster, prepared for the COSMO/CosPA 2010 Conference, presents two proposals for a Standard Model (SM) based solution of the wearisome cosmological vacuum energy problem, which find their common denominator in the infrared sector of QCD, and in particular make use of the highly peculiar properties of the so-called Veneziano ghost. The Veneziano ghost, despite being unphysical, it nevertheless can contribute to the vacuum energy of the system if the latter is embedded in a manifold with non-trivial topology, or if we consider an expanding universe. Our description in terms of the auxiliary ghost fields is a matter of convenience: it allows us to deal with complicated physics hidden in non-trivial boundary conditions accounting for the existence of the θ-vacua.

THE VENEZIANO GHOST

The Veneziano ghost was introduced by Gabriele Veneziano in 1979 in order to reconcile the two sides of the large-N_c limit anomalous axial $U(1)$ Ward Identity (WI)

$$\chi \equiv i \int \mathrm{d}x \langle 0|T\{Q(x), Q(0)\}|0\rangle = m_q \langle \bar{q} q\rangle + O(m_q^2)\,. \tag{1}$$

The standard Witten-Veneziano solution of the $U(1)_A$ problem is based on the assumption (confirmed by numerous lattice computations) that the topological susceptibility χ does not vanish in pure gluodynamics despite of the fact that Q is a total derivative. It implies that there is an unphysical pole at zero momentum in the correlation function of K_μ, similar to the Kogut-Susskind (KS) ghost in the Schwinger model.

The relevant part of the effective Lagrangian in 2d and 4d is exactly the same:

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_0 + \frac{1}{2}\partial_\mu \hat{\phi}\partial^\mu \hat{\phi} + \frac{1}{2}\partial_\mu \phi_2 \partial^\mu \phi_2 - \frac{1}{2}\partial_\mu \phi_1 \partial^\mu \phi_1 \\
&- \frac{1}{2} m_{\eta'}^2 \hat{\phi}^2 + N_f m_q |\langle \bar{q} q \rangle| \cos\left[\frac{\hat{\phi} + \phi_2 - \phi_1}{f_{\eta'}} + \frac{\theta}{N_f}\right] ,
\end{aligned} \tag{2}
$$

This Lagrangian (2) is that part of QCD which describes long distance physics in our context. There are no new fields or coupling constants beyond the standard model. Once appropriate auxiliary conditions on the physical Hilbert space are imposed (similarly to the Gupta-Bleuler Lorentz-invariant quantisation of QED), the unphysical degrees of freedom ϕ_1 and ϕ_2 drop out of every gauge-invariant matrix element, leaving the theory well defined. This contribution is essential when we compute the mass of the η' meson, which would conflict with experiment otherwise.

The Veneziano ghost is needed from an experimental point of view, it is already in the Standard Model!

NON-TRIVIAL TOPOLOGY – CASIMIR ENERGY

Due to the existence of the Veneziano ghost, when the system is embedded in a non-trivial manifold, such as a torus, the corrections due to the very large but finite size L of the manifold are small, but not exponentially small, $\exp(-L)$, as one could anticipate for any QFT where all physical degrees of freedom are massive (i.e., QCD). This correction can be exactly computed in 2d, and gives us information about the vacuum energy of the system through

$$\chi = -\frac{\partial^2 \epsilon_{vac}(\theta)}{\partial \theta^2}|_{\theta=0} \,. \qquad (3)$$

In this case, we can show that the first correction to the tomological susceptibility is **linear**, and, for estimation purposes, and also because we know it must be so, we can choose a manifold of size $L \sim 1/H_0$: this leads at once to

$$\Delta\chi \simeq c \cdot \frac{H_0}{m_{\eta'}} \cdot |m_q \langle \bar{q} q \rangle| \,. \qquad (4)$$

The value of the corresponding vacuum energy therefore becomes

$$\rho_\Lambda \equiv \Delta\epsilon_{vac} = c \cdot \frac{H_0}{m_{\eta'}} \cdot |m_q \langle \bar{q} q \rangle| \sim c(3.6 \cdot 10^{-3}\mathrm{eV})^4 \,, \tag{5}$$

to be compared with the observational value $\rho_\Lambda = (2.3 \cdot 10^{-3}\mathrm{eV})^4$. It is important to notice that the non-vanishing result for ρ_Λ is parametrically proportional to m_q, and only occurs if the θ-dependence is non-trivial.

This effect could be looked for in the CMB sky, where, in the simplest example of an effective $\mathbb{T}^1$-universe, would imply

$$L = \frac{1}{cH_0} \approx 17 H_0^{-1} \approx 74\mathrm{Gpc}\,. \tag{6}$$

This effect is entirely due to the ghost, and only much smaller corrections arise from all other QCD fields!

EXPANDING UNIVERSE – DYNAMICS

Now let's consider an expanding Universe. The Lagrangian in the same (made covariant), but, unlike Minkowski space, we can not force the Gupta-Bleuler conditions globally as time is not a killing vector of the spacetime. Hence:

$$\langle \mathcal{H}_{\rm phys} | \mathrm{H} | \mathcal{H}_{\rm phys} \rangle \neq 0, \quad \Rightarrow \quad \langle 0 | \mathrm{H} | 0 \rangle \neq 0\,. \tag{7}$$

Therefore, we consider the expectation value for energy-momentum tensor: we expect to obtain an extra (in comparison with Minkowski space) time-dependent vacuum energy density for the mode k from the fact that

$$\langle 0 | \mathrm{H}_k | 0 \rangle = \omega_k \sum_l (|\beta_{kl}|^2 + |\beta'_{kl}|^2)\,, \tag{8}$$

where the β_{kl} coefficients are the so-called Bogolubov coefficients.

No cancellation occurs in this case!

It is known that, in a FLRW Universe, the β_{kl} are of order one for $\omega_k \simeq H$, whereas higher frequency modes are exponentially suppressed. Accordingly then this contribution would be of the form

$$\rho_\Lambda \simeq \Lambda^3_{\mathrm{QCD}} H_0 \cdot f\left(a(t), H(t)\right) \,, \tag{9}$$

where Λ_{QCD} is the scale of confinement (typically around 100 MeV).

The precise form of such vacuum energy is not known analytically, and we can not predict the time evolution of this Dark Energy component, but we can assume that at late times the function f will tend to unity, and spacetime will tend to deSitter, in which case one finds again that the magnitude of the vacuum energy is of the right order of magnitude, than is, $\Lambda^3_{\mathrm{QCD}} H_0$.

This effect is entirely related to the dynamical background coupled to the Veneziano ghost!

DARK ENERGY AND MAGNETIC FIELDS

This "ghost condensate" is not destined to manifest itself only in the vacuum energy of the theory. Indeed, as is the case for pions and η' mesons, the ghost dipole in the SM is coupled to the electromagnetic field via the anomalous term

$$\mathcal{L}_{(\phi_2-\phi_1)\gamma\gamma} = \frac{\alpha}{4\pi} N_c \mathrm{Tr}(I_3 Q_i^2) \left(\frac{\phi_2 - \phi_1}{f_{\eta'}} \right) F_{\mu\nu} \tilde{F}^{\mu\nu} \,. \tag{10}$$

In Minkowski space this interaction term would be entirely irrelevant, as it will automatically disappear as a consequence of the Gupta-Bleuler conditions imposed on the ghost dipole. In curved space, however, it gives rise to the possibility of energy transfer from the ghost to the electromagnetic (in the end, only magnetic) field, with a rate and coupling constant uniquely determined within the SM.

The resulting magnetic field can be easily roughly estimated if we notice that the process described by (10) is never in equilibrium in our expanding Universe: it can be shown that it takes circa $\alpha/4\pi$ Hubble times to have one scattering process, and that in each single scattering the energy transferred is $\alpha/4\pi\rho_\Lambda$, so that:

$$B \;\simeq\; \left(\frac{\alpha}{2\pi} N_c \sum Q_i^2\right)^2 \cdot c \cdot \rho_{DE} \sim \mathrm{nG}\,. \tag{11}$$

This is correlated on scales of order $1/H$, and is of the same order of magnitude of the fields observed in galaxies, clusters, and possibly superclusters, and entirely expressed in terms of known SM physics. In this description, the cosmological magnetic fields are a direct manifestation of the underlying dark energy component, and comes to prominence now, not in the distant past.

Therefore, the observed magnetic fields are a consequence of the existence of Dark Energy and its coupling to Electromagnetism!

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