GHOST CONDENSATE MODEL OF FLAT ROTATION CURVES

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An effective action of ghost condensate with higher derivatives creates a source of gravity and mimics a dark matter in spiral galaxies. We present a spherically symmetric static solution of Einstein–Hilbert equations with the ghost condensate at large distances, where flat rotation curves are reproduced in leading order over small ratio of two energy scales characterizing constant temporal and spatial derivatives of ghost field: μ_*^2 and $\mu_\star^2$, respectively, with a hierarchy $\mu_\star \ll \mu_*$. We assume that a mechanism of hierarchy is provided by a global monopole in the center of galaxy. An estimate based on the solution and observed velocities of rotations in the asymptotic region of flatness, gives $\mu_* \sim 10^{19}$ GeV and the monopole scale in a GUT range $\mu_\star \sim 10^{16}$ GeV, while a velocity of rotation v_0 is determined by the ratio: $\sqrt{2}\, v_0^2 = \mu_\star^2/\mu_*^2$. A critical acceleration is introduced and naturally evaluated of the order of Hubble rate, that represents the Milgrom's acceleration.

In addition to cosmological indirect indications of dark matter representing a nonbaryonic pressureless contribution to energy budget of Universe during evolution [1, 2], there are explicit observational evidences in favor of existence of dark matter. Firstly, rotation curves in spiral galaxies cannot be explained by Keplerian laws with visible distributions of luminous baryonic matter at large distances, where curves are becoming flat and reveal a $1/r^2$-profile of mass for the dark matter at large distances, if Newtonian dynamics remains valid. Secondly, gravitational lensing by galaxies corresponds to masses, which are significantly greater than those of visible matter. Thirdly, virial masses in clusters of galaxies witness for the dark matter, too. While the existence of dark matter is well established, its nature and origin are under question [3, 4].

The most straightforward opportunity is to assume an existence of weakly interacting massive particle, which could be experimentally observed in on-Earth-grounded facilities [4]. However, numerical simulations of N-body dynamics for the cold dark matter [5] give, firstly, a more rapid decay of mass density with distance ($1/r^3$ instead of $1/r^2$) and, secondly, a $1/r$-cusp in centers of galaxies. Yet both phenomena are in contradiction with observations, which prefer a core-like distribution with a constant density of dark matter in the center [6] and do not exhibit a falling down of rotation curves in spiral galaxies.

A second way suggests a modification of Newtonian dynamics (MOND) in the asymptotic regions of flat rotation curves. The most successful approach was offered by Milgrom in his MOND [7, 8, 9], which has many phenomenological advances. Milgrom supposed a phenomenon of critical acceleration a_0 below which the gravitational dynamics should be modified in order to reproduce the flat rotation curves, so that an actual acceleration is equal to $\sqrt{g_N a_0}$, where g_N is the acceleration generated by visible matter in galaxy. In the framework of MOND the rotation curves can be explained in terms of visible matter only! Moreover, the critical acceleration naturally leads to a strong correlation of asymptotic velocities with visible masses of galaxies: the Tully–Fisher law. Similar successes of MOND are reviewed in [10]. Certainly, the phenomenological evidence in favor of critical acceleration challenges the model of cold dark matter, where a regularity like the Tully–Fisher law seems quite occasional and could be some-how introduced as an effect of evolution only. Some theoretical shortcomings of primary MOND model [1] have been recently removed in a novelty

[1]For instance, one could mention superluminal velocities of graviscalar and insufficient gravitational lensing.

version of tensor-vector-scalar theory by Bekenstein [11]. However, a critical acceleration remains an *ad hoc* quantity in MOND paradigm as an indication of essential modification of general relativity in infrared.

Another example of modification is a nonsymmetric gravitation theory by Moffat [12], which involves several parameters, for example, a decay length of extraordinary force. The parameters can be also combined to compose a critical acceleration. A question is whether an introduction of nonsymmetric rank-2 tensor instead of metric is natural or rather exotic.

Finally, a possible explanation of flat rotation curves in terms of scalar fields was tried in several papers [13, 14, 15]. One found that relevant scalar fields should differ from both a scalar quintessence [16] responsible for a measured acceleration of Universe expansion [2] and a scalar inflaton governing an inflation in early Universe [17]. For example, Nucamendi, Salgado and Sudarsky (NSS) [14] have derived a metric consistent with flat rotation curves caused by a presence of perfect fluid given by a scalar field. Moreover, they have found that the scalar field should be represented by a triplet with an asymptotic behavior of global monopole at large distances. In addition, the NSS metric is consistent with gravitational lensing, too. Nevertheless, one still has not found a convincing relation of parameters in a scalar field dynamics with properties of rotation curves.

Let us focus an attention on the rotation curves. In present letter we introduce a ghost condensate model which dynamical parameters are deeply related with characteristics of rotation curves. Moreover, we find a natural way to get a critical acceleration in general relativity with the ghost condensate and estimate its value, which turns out to be of the order of Hubble rate at present day in agreement with phenomenological measurements.

The ghost condensate [18] is an analogue of Higgs mechanism. Indeed, a tachyon field σ with a negative square of mass can be stabilized by $\lambda\sigma^4$ term of its potential, which leads to a tachyon condensate, known as a Higgs mechanism in gauge theories. Similarly, a ghost field ϕ possessing an opposite sign of kinetic term can be stabilized by introduction of higher order terms leading to a ghost condensate. In contrast to tachyon condensation being a renormalizable and Lorentz-invariant procedure, an isotropic homogeneous ghost condensation gives a nonzero square of time derivative $\langle\dot{\phi}^2\rangle$, which breaks a Lorentz invariance, while higher derivative terms are acceptable in an effective theory in infrared, only. As for the breaking down the Lorentz invariance, it can simply imply appearing an arrow of time in a non-static isotropic homogeneous expanding Universe with ordinary Friedmann–Robertson–Walker metric. A modification of gravity in infrared by postulating a Goldstone nature of ghost in an effective theory was investigated in [18]. This model leads to instability of gravitational potential in a time exceeding the Universe age at least [19, 20]. We do not accept the Goldstone hypothesis, that allows us to avoid strict constraints on dimensional parameters of ghost action. A dilatonic ghost condensate as dark energy is considered in [21].

A leading term of lagrangian for the ghost field with invariance under a global translations $\phi \to \phi + c$ is given by

$$\mathcal{L}_X = P(X), \qquad X = \partial_\nu\phi\partial^\nu\phi, \tag{1}$$

in flat space-time with a metric signature $(+,-,-,-)$, so that $\mathcal{L}_X \to -\frac{1}{2}\,\partial_\nu\phi\partial^\nu\phi$ at $X \to 0$ reproduces the kinetic term with the negative sign, indicating instability which will be removed by ghost condensation. Indeed, expanding (1) near $X_0 = \mu_0^4$ by fixing

$$\phi = \mu_0^2\, t + \pi(x), \quad \partial_\nu\phi = (\mu_0^2 + \dot{\pi}, \boldsymbol{\nabla}\pi),$$

we get a quadratic approximation for small perturbations

$$\mathcal{L}_X^{(2)} = \dot{\pi}^2(P' + 2\mu_0^4\, P'') - (\boldsymbol{\nabla}\pi)^2\, P',$$

which is stable at $P' > 0$ and $P' + 2\mu_0^4\, P'' > 0$ at any suitable X_0. For definiteness, at relevant values of X we put a Higgs-like function

$$P(X) = -\frac{m_0^2}{2\eta^2}\, X + \frac{\lambda}{4\eta^4}\, X^2. \tag{2}$$

An expansion with the Friedmann-Robertson–Walker metric gives

$$\partial_t\left(a(t)^3\,P'\,\dot\phi\right)=0\quad\Rightarrow\quad P'\,\dot\phi=\frac{\text{const.}}{a^3}\to 0,$$

where $a(t)$ is a scale parameter of metric. So, the evolution drives to $P'\to 0$, since $\dot\phi=0$ is not a stable point by construction. Thus, a preferable choice is an extremum point $P'(X_0)=0$ with $P''>0$ [2]. We introduce a correction of the form

$$\Delta\mathcal{L}=-\frac{1}{2\eta^2}\,\partial_\alpha\partial_\beta\phi\,\partial^\alpha\partial^\beta\phi,\tag{3}$$

which does not destroy a stability, since in quadratic approximation it gives $\Delta\mathcal{L}^{(2)}\approx-\frac{1}{2\eta^2}\,(\boldsymbol{\nabla}^2\pi)^2$, leading to the following dispersion relation for perturbations π in momentum space: $\omega^2\approx\boldsymbol{k}^4/2m_0^2$. A scaling analysis performed in [18] has confirmed that the model is a correct effective theory in infrared.

Next, consider the ghost condensate in presence of global monopole [23]. Then we put *at large distances*

$$\phi=\mu_*^2\,t-\mu_\star^2\,r+\sigma(x),\tag{4}$$

with $\mu_*^2-\mu_\star^2=\mu_0^2$, $\kappa=\mu_\star/\mu_*\ll 1$, so $P'=0$, and we add a correction induced by monopole $\Delta\widetilde{\mathcal{L}}=-\varkappa^2\left(\boldsymbol{\nabla}\phi+\boldsymbol{n}\,\mu_\star\right)^2$, $\boldsymbol{n}=\boldsymbol{\nabla}r$, where $\mu_\star$ fixes an energy scale in dynamics of monopole, while $\varkappa^2>0$ guarantees a stability of monopole, and its rather large absolute value preserves a stability over perturbations [3], [4].

Neglecting perturbations, we study the ghost condensate in presence of monopole (4) as a source of gravity at large distances in spherically symmetric quasi-static limit. Then, the only source of energy-momentum tensor is the correction of (3), where we should replace partial derivatives by covariant ones [1] with the metric

$$\mathrm{d}s^2=\mathtt{f}(r)\,\mathrm{d}t^2-\frac{1}{\mathtt{h}(r)}\,\mathrm{d}r^2-r^2[\mathrm{d}\theta^2+\sin^2\theta\,\mathrm{d}\varphi^2],\tag{5}$$

so that due to a small parameter κ we can expand in it and find the following solution of corresponding Einstein–Hilbert equations in the leading order over κ [5]:

$$v_0^2=\kappa^2/\sqrt{2},\quad \mathtt{h}(r)=1-2v_0^2,\quad \mathtt{f}'(r)=\frac{2v_0^2}{r},\tag{6}$$

giving a $1/r^2$-profile of the curvature and a flat asymptotic behavior for a constant velocity of rotation v_0 [6], if $8\pi\,G\,\mu_*^4/\eta^2=1+\mathcal{O}(\kappa^4)$. In the leading order at $\mu_\star\ll\mu_*$ we have $\mu_*^4\approx m_0^2\eta^2/\lambda$, and, hence, $8\pi\,G\,m_0^2/\lambda\approx 1$. So, putting $\eta=m_0$ for a canonical normalization in (2) at $\lambda\sim 1$, we get

[2] It is easy to recognize that a substitution of $\partial_\nu\phi=\eta\,\mathcal{A}_\nu$ transforms lagrangian (1) to a potential of vector field $\mathcal{A}_\nu$, and the preference point is the extremum of potential for the vector field, representing the ghost condensate (see also [22]).

[3] In Minkowski space-time at large distances from a monopole center, one could compose a constant four vector $\mathcal{A}^\nu$ by the ghost field and monopole triplet-scalar [24], so that the temporal derivative of ghost $\dot\phi$ would be combined with the spatial triplet $\phi^a=\boldsymbol{n}$ in $\mathcal{A}^\nu=\frac{1}{\eta}\,\{\dot\phi,\mu_\star^2\boldsymbol{n}\}$, which take the form $\mathcal{A}^\nu=\frac{1}{\eta}\,\{\mu_*^2,\mu_\star^2,0,0\}$ in polar coordinates $\{t,r,\theta,\phi\}$ with the ghost $\phi=\mu_*^2\,t$. In Minkowski space-time we can simply put $\eta\,\mathcal{A}_\nu=\partial_\nu(\mu_*^2\,t-\mu_\star^2\,r)$, which is exact in this case, and we get a purely gauge vector field *composed by the ghost in presence of global monopole* (see (4)).

[4] Higgs-like fields as dark matter are treated in [25].

[1] A model extension to a curved space-time is the following: $\mathcal{A}^\nu=\frac{1}{\eta}\,\{\mu_*^2,\mu_\star^2,0,0\}$, $\quad\Delta\mathcal{L}=-\frac{1}{2}\,\nabla_\alpha\mathcal{A}^\nu\nabla^\alpha\mathcal{A}_\nu$, i.e. the constant covariant four-vector is reasonably motivated, though the specified $\mathcal{A}^\nu$ cannot be represented as a gradient function, since $\mathcal{A}_{t;r}-\mathcal{A}_{r;t}\neq 0$.

[5] We use an ordinary notation for the derivative with respect to the distance by the prime symbol $\partial_r f(r)=f'(r)$.

[6] Thus, we have found the NSS metric with a perfect fluid of ghost condensate.

$$8\pi\, G\, \mu_*^2 \sim 1, \tag{7}$$

and the ghost condensate scale is of the order of Planck mass: $\mu_* \sim 10^{18-19}$ GeV.

The solution leads to the temporal component of the energy-momentum tensor dominates and has the required profile with the distance [7]:

$$T_r^r \sim T_\varphi^\varphi \sim T_\theta^\theta \sim \mathcal{O}(v_0^2) \cdot T_t^t \sim \mathcal{O}\left(\frac{1}{r^2}\right). \tag{8}$$

Numerically at $v_0 \sim 100 - 200$ km/sec, we get

$$\kappa \sim 10^{-3} \quad \Rightarrow \quad \mu_\star \sim 10^{15-16}\,\mathrm{GeV}, \tag{9}$$

so, the characteristic scale in the dynamics of monopole is in the range of GUT. Thus, the small ratio of two natural energetic scales determines the rotation velocity in dark galactic halos.

Since we treat the ghost condensate as an external source in the Einstein–Hilbert equations, let us consider conditions providing that the corrections could be neglected.

Firstly, suppressing the dependence of ghost on the distance, in the Friedmann-Robertson–Walker metric we find that the covariant derivatives in (3) generate the correction, determined by the Hubble rate H (see [22]):

$$\delta\mathcal{L} = -\frac{3}{2\eta^2}\, H^2\, \dot{\phi}^2, \tag{10}$$

so that the temporal derivative acquires a slow variation with the time due to the displacement of stable point, since we can use an effective quantity $m_{\mathrm{eff}}^2 = m_0^2 + 3H^2$, and the dependence is really negligible, if the Hubble rate is much less than the Planck mass, $H \ll m_0 \sim m_{\mathrm{Pl}}$.

Secondly, if we take into account both the expansion and radial dependence, then in presence of monopole the covariant derivatives of ghost with respect to polar coordinates (r, θ, φ) (more accurately see [31])

$$\phi^{;r}_{;r} = H\,\dot{\phi}, \qquad \phi^{;\theta}_{;\theta} = \phi^{;\varphi}_{;\varphi} = -\frac{1}{r}\,\phi' + H\,\dot{\phi}, \tag{11}$$

induce the correction

$$\delta_\star\mathcal{L} = -\frac{1}{2\eta^2}\, H^2\, \dot{\phi} - \frac{1}{\eta^2}\left(-\frac{1}{r}\,\phi' + H\,\dot{\phi}\right)^2, \tag{12}$$

which can be neglected at large distances, only. Therefore, the 'cosmological limit' of ghost condensate is consistently reached, if

$$\frac{1}{r}\,\mu_\star^2 \ll H\,\mu_*^2. \tag{13}$$

The consideration above is disturbed because of (12) at distances less than r_0 defined by

$$\frac{1}{r_0}\,\mu_\star^2 = \varepsilon\, H\, \mu_*^2 \quad \Rightarrow \quad \frac{1}{r_0}\,\frac{\mu_\star^2}{\mu_*^2} = \varepsilon\, H_0, \tag{14}$$

where $H_0 = H(t_0)$ is the value of Hubble rate at present, and ε is a parameter of the order of $1 - 0.1$. Substituting $\mu_\star^2/\mu_*^2 = \sqrt{2}\, v_0^2$ into (14), we get $v_0^2/r_0 = \varepsilon\ H_0/\sqrt{2}$, while

$$a_0 = \frac{v_0^2}{r_0} \tag{15}$$

is a centripetal acceleration, and, then, the critical acceleration is determined by the Hubble rate,

$$a_0 = \frac{\varepsilon}{\sqrt{2}}\, H_0, \tag{16}$$

[7] The accretion of ghost to the center of gravity should be suppressed at $P' = 0$ (see [26]).

that is the acceleration below which the limit of flat rotation curves becomes justified. That is exactly a direct analogue of the critical acceleration introduced by Milgrom in the framework of MOND [7].

Further, we could suppose that in the case, when the gravitational acceleration produced by the visible matter in the galactic centers exceeds the critical value, we cannot reach the limit of flat rotation curves. Indeed, in that case the distance dependence cannot be excluded from the ghost condensate. The Newtonian acceleration at distance r_0 is equal to

$$a_0^* = \frac{G\mathcal{M}}{r_0^2}, \tag{17}$$

where $\mathcal{M}$ is a visible galactic mass. According to (16), the critical acceleration is a universal quantity slowly depending on the time, while (15) implies that the distance and velocity can be adjusted by variation in order to compose the universal a_0. Therefore, we should put

$$a_0^* = a_0, \tag{18}$$

which yields

$$v_0^4 = G\mathcal{M}a_0. \tag{19}$$

The galaxy mass is proportional to an H-band luminosity of the galaxy L_H, so that (19) reproduces the Tully–Fisher law $L_H \propto v_0^4$. Then, other successes of MOND can be easily incorporated in the framework under consideration, too.

Nevertheless, we could treat (18) as a coincidence. For instance, (19) leads to

$$\mu_\star^4 \sim \mathcal{M}H_0/G.$$

Therefore, if the flattening is observed in a spiral galaxy, the mass of galaxy should strongly correlate with the Hubble rate at present as well as the scale of monopole dynamics. This fact could be reflected in a correlation of rotation velocity with a mass of central body, a supermassive black hole, as observed empirically.

Thus, we have presented the working example of ghost condensate model in presence of monopole in order to get the description of flat rotation curves in spiral galaxies at large distances. There are two energy scales in the model. The scales are natural, and they represent the Planck mass and GUT scale. The critical acceleration determining the region of validity for the model has been estimated in general relativity with the ghost condensate.

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