Cosmological constant, inflaton, and dark matter all naturally originated from Poincaré gauge gravity

Hongchao Zhang,[1,*] Tao Zhu,[1,†] and Anzhong Wang[2,‡]

[1]*Institute for Theoretical Physics and Cosmology, Zhejiang University of Technology, Hangzhou, 310023, China, and United Center for Gravitational Wave Physics (UCGWP), Zhejiang University of Technology, Hangzhou, 310023, China*

[2]*GCAP-CASPER, Physics Department, Baylor University, Waco, Texas 76798-7316, USA*

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We propose a cosmological model in the framework of Poincaré gauge gravity, in which the cosmological constant, the inflaton, and the dark matter candidate all naturally originate. The cosmological constant originates in the process of breaking of the Poincaré symmetries down to the Lorentz symmetries. We select a gauge Lagrangian without any additional matter fields, which can be regarded as a minimum extension of general relativity with two more massive modes from the Lorentz connection. Numerical analysis shows that the scalar dominates a slow-rolling inflation and the pseudoscalar behaves as a dark matter candidate.

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I. INTRODUCTION

Cosmic inflation, dark matter, and late-time acceleration are three main tensions between modern cosmology based on Einstein's general relativity (GR) and observations [1–4]. In recent decades, a series of models based on the extension of the standard model of particle physics and/or the modification of GR have been proposed to address these tensions. Some of these models have been ruled out by observational data, while others are still undergoing further rigorous tests from both theory and observation [5–8]. So far, the optimal models for inflation, dark matter, and late-time acceleration in line with observations are slow-rolling inflation dominated by a single scalar field, cold dark matter particles, and cosmological constant, respectively. However, explaining these three phenomena within a unified theoretical framework that is compatible with both the standard model and gravitational theory remains a long-term and challenging task. In the standard model, $U(1) \times SU(2) \times SU(3)$ gauge theories describe the generations of electromagnetic, weak, and strong interactions, respectively. Spontaneous symmetry breaking combined with the Higgs mechanism explains the source of the masses of gauge bosons. From this perspective, gravity theories by gauging spacetime groups have more advantages in compatibility with the standard model than GR. The Poincaré group is the maximum isometric group in Minkowski spacetime, and also the representation group of elementary particles. Localization of this group leads us to the Poincaré gauge theory of gravity (PGG) [9–12]. Because of the fact that the Poincaré group involves the translations between different points in spacetime (which leads to the Poincaré group being external), we cannot simply define gauge transformation as vertical automorphism along fiber, as in those gauge theories of internal groups, but rather introduce automorphisms between fibers in a nonlinear way [13–16]. Coincidentally, nonlinear representation is not only an appropriate approach to describe the gauge theories of spacetime groups, but also introduces the natural description of spontaneous symmetry breaking [17–21]. Then, by introducing the appropriate Higgs mechanisms, the story of gravity will naturally develop in the same direction as the standard model.

The goal of this paper is to introduce a cosmological scenario in which the cosmological constant, inflaton, and (cold) dark matter candidate naturally originate in the framework of PGG.

II. ORIGINATION OF COSMOLOGICAL CONSTANT FROM THE BREAKDOWN OF THE POINCARÉ SYMMETRIES TO THE LORENTZ SYMMETRIES

From the perspective of gauge field theory, a Poincaré (P) observer (base) at point x can be expressed by a binary tuple $\{e\ \ v\}_x$, with e a Lorentz (L) observer and v a base for measuring "internal coordinates" [20]. By introducing a five dimensional matrix representation [13,21], a P transformation on a P observer can be performed in the following way:

*zhanghongchao852@live.com
†zhut05@zjut.edu.cn
‡anzhong_wang@baylor.edu

$$\{\tilde{e} \quad \tilde{v}\}_x = \{e \quad v\}_x \begin{pmatrix} \Lambda & \xi \\ 0 & 1 \end{pmatrix}, \tag{1}$$

where Λ is an element of the L group, and $\xi \in \mathbb{R}^4$ is an element of the translational group. A P field of matter (referred to the definition of a matter field in fiber bundle terminology—a section in the fiber bundle associated to principal fiber bundle) is an equivalence class with respect to P observer given by

$$\Psi = \left(\{e \quad v\}, \begin{pmatrix} \psi & y \\ 0 & 1 \end{pmatrix}\right) \Big/ \sim, \tag{2}$$

where ψ is an L field in a certain representation, and y is the corresponding internal coordinates measured by v. The localization of the P symmetries leads to the introduction of P-gauge field (connection) and the P-covariant derivative,

$$\lozenge \equiv \begin{pmatrix} \boldsymbol{\mathcal{D}} & \boldsymbol{B} \\ 0 & 0 \end{pmatrix}, \tag{3}$$

where $\boldsymbol{\mathcal{D}} \equiv \boldsymbol{d} + \boldsymbol{A}$ is the L-covariant derivative with respect to the L-connection $\boldsymbol{A}$. According to the transformation properties [14,21], $\boldsymbol{B}$ is a connection-like P vector. The action of $\lozenge$ on a P field, i.e. P velocity of a P field is

$$\lozenge \begin{pmatrix} \psi & y \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} \boldsymbol{\mathcal{D}}\psi & \boldsymbol{\theta} \\ 0 & 0 \end{pmatrix}, \tag{4}$$

where $\boldsymbol{\theta} \equiv \boldsymbol{\mathcal{D}}y + \boldsymbol{B}$ is the so-called canonical one-form, which is an L vector according to the transformation properties. The P-gauge strength can be obtained by twice actions of $\lozenge$:

$$\lozenge \wedge \lozenge \equiv \begin{pmatrix} \boldsymbol{R} & \boldsymbol{S} \\ 0 & 0 \end{pmatrix}, \tag{5}$$

where $\boldsymbol{R}$ is curvature, and $\boldsymbol{S}$ is a gauge strengthlike P vector. Furthermore, the action of (5) on a P field reads

$$\lozenge \wedge \lozenge \begin{pmatrix} \psi & y \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} \boldsymbol{R}\psi & \boldsymbol{T} \\ 0 & 0 \end{pmatrix}, \tag{6}$$

where $\boldsymbol{T} \equiv \boldsymbol{R}y + \boldsymbol{S}$ is torsion—an L vector.

In order to construct the Lagrangian of a P field, including the kinetic energy term and the interaction with P-gauge field, a common approach is

$$L_M = \lozenge \begin{pmatrix} \psi & y \\ 0 & 1 \end{pmatrix} \cdot \lozenge \begin{pmatrix} \psi & y \\ 0 & 1 \end{pmatrix}. \tag{7}$$

However, because P algebra is not semisimple, it is impossible to define such an inner product "$\cdot$" [21], so the expression in (7) is invalid. However, there exists a Killing-Cartan metric, i.e. the so-called Minkowski metric η in L algebra, so that the inner product between L vectors can be defined. It so happens that the two components $\boldsymbol{\mathcal{D}}\psi$ and $\boldsymbol{\theta}$ in the rhs of P velocity (4) are quantities with L representation. Therefore, the Lagrangian in (7) can be modified to

$$L_M = \eta(\boldsymbol{\mathcal{D}}\psi, \boldsymbol{\mathcal{D}}\psi) + \eta(\boldsymbol{\theta}, \boldsymbol{\theta}). \tag{8}$$

The first term in the rhs of (8) is the kinetic energy term of L field, including the interaction with L-gauge field. While the second term can be rewritten in [17,21] (release all hidden indices),

$$\eta(\boldsymbol{\theta}, \boldsymbol{\theta}) = g^{\mu\nu} e_\mu{}^a e_\nu{}^b \eta_{ab} = 4, \tag{9}$$

with $e_\mu{}^a = \partial_\mu \lrcorner \boldsymbol{\theta}^a$ referred to the tetrad or vielbein field. This means that in the process of breaking the P symmetries down to the L symmetries, a constant term naturally originates in the Lagrangian of matter.

On the other hand, the Lagrangian four-form of the P-gauge field would be

$$L_G = \begin{pmatrix} \boldsymbol{R} & \boldsymbol{S} \\ 0 & 0 \end{pmatrix} \wedge^* \begin{pmatrix} \boldsymbol{R} & \boldsymbol{S} \\ 0 & 0 \end{pmatrix}. \tag{10}$$

But due to the same reason as above, expression (10) is invalid. By means of L-metric η, it can be modified in

$$L_G = \boldsymbol{R} \wedge^* \boldsymbol{R} + \boldsymbol{T} \wedge^* \boldsymbol{T} \tag{11}$$

according to (6), which is the general form of the Yang-Mills (YM) type gauge Lagrangian for "Poincaré" gauge gravity that we are familiar with. Obviously, both $\boldsymbol{R}$ and $\boldsymbol{T}$ are L tensors, thus (11) is the expression after the breaking of the P symmetries down to the L symmetries.

To summarize this section, in the framework of PGG, the action including the matter field and the gauge field should take the following form:

$$s = s_M + s_G = \int dx^4 e(\mathcal{D}_\mu \psi \mathcal{D}^\mu \psi + \lambda) + \int dx^4 e\left[\frac{1}{2\kappa}(R + T^2) + R^2\right], \tag{12}$$

with $e \equiv \det(e_\mu{}^a)$ and λ a constant plugging (9) in and $\kappa \sim m_{\rm Pl}^{-2}$ the coupling constant of gravity. In the gauge action, in addition to the quadratic terms of the field strengthes, we also consider the linear curvature term, namely the Einstein-Hilbert (EH) term. For simplicity, we only consider the parity-conserving terms.

III. A MINIMUM MODEL

Generally speaking, the quadratic terms in the gauge Lagrangian can be decomposed into several inequivalent and irreducible pieces [22], and the system may contain ghosts and tachyons. According to [23–30], the most general ghost- and tachyon-free YM type Lagrangian of PGG contains up to eight kinds of *possible* modes in terms of the $SO(3)$ spin-parity decomposition: two massless and six massive. However, except for one massless spin-0^+ mode and two massive spin-$0^\pm$ modes, none of them are of concern to us in the following cosmological context. Fortunately, those modes can be suppressed by selecting appropriate combinations of Lagrangian parameters. As a result, we selected a minimum ghost- and tachyon-free parity-conserving EH-YM type Lagrangian based on [31,32] as follows:

$$\begin{aligned} L_G = {} & b_0 R + \frac{b_0}{3} T_{\mu\nu\rho}(T^{\mu\nu\rho} + T^{\rho\nu\mu} - g^{\mu\rho}T^{\nu}) \\ & + \frac{2A_1}{3} T_\mu T^\mu + \frac{A_2}{12} T_{\mu\nu\rho}(2T^{\rho\nu\mu} - T^{\mu\nu\rho}) \\ & + \frac{B_1}{9}\left(R_{\mu\nu}R^{\nu\mu} - \frac{1}{4}R_{\mu\nu\rho\sigma}R^{\rho\sigma\mu\nu}\right) \\ & + \frac{B_2}{9} R_{\mu\nu\rho\sigma}\left(R^{\mu\rho\nu\sigma} - \frac{1}{4}R^{\mu\nu\rho\sigma} - \frac{1}{4}R^{\rho\sigma\mu\nu}\right), \end{aligned} \tag{13}$$

where b_0, A_1, A_2 are parameters in the unit of quadratic Planck mass, i.e. m_{Pl}^2, and B_1, B_2 are dimensionless. All parameters are nonzero positive. The combination of terms in (13) not only guarantees that there are no ghosts and tachyons, but also no extra modes, such as spin-$1^\pm$, spin-2^-, and massive spin-2^+, up to the linear perturbed order. It should be emphasized that this Lagrangian still keeps a massless spin-2^+ mode with the same propagator as the conversant gravitational waves in GR. Therefore, the Lagrangian (13) can be regarded as a minimum extension of GR within the framework of PGG from the perspective of "particles." See Fig. 1 for a more intuitive display. For studies of the similar Lagrangian and their cosmological applications in various scenarios, please see [33–35].

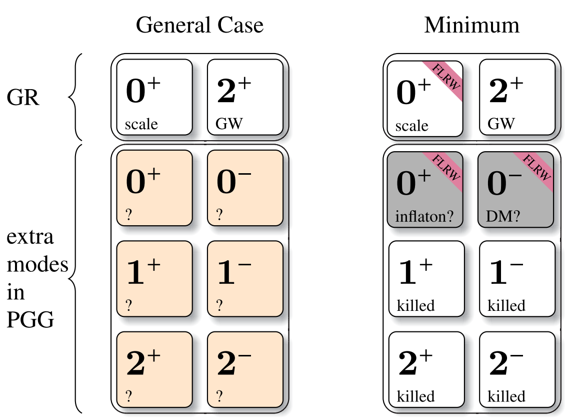

FIG. 1. Particle spectrum of PGG in the general case (left panel) and in our minimum case (right panel). "?" indicates that the mode may exist, depending on the Lagrangian parameters. "Killed" means the mode has been suppressed. There are three modes remaining on the FLRW background in the minimum case, where two of them are massive.

IV. COSMIC DYNAMICS

Under the spatially homogeneous and isotropic reduction, spacetime possesses six *global* symmetries: three spatial translations and three rotations. Besides, symmetries referred to the temporal direction are *local*. Six global Killing fields, additionally trivial assumption of spatial topology, lead to that the tetrad field residues one degree of freedom (d.o.f.),

$$e_0{}^{\hat{0}} = 1, \qquad e_i{}^{\hat{j}} = a(t)\delta_{ij}, \tag{14}$$

i.e. the scale factor $a(t)$, where t is the cosmic time corresponding to the zeroth component, and i, j, $k = 1$, 2, 3 are spatial indices. The hatted indices are decomposed from the Latin alphabet. Meanwhile, the L-connection residues two d.o.f.s [36,37]:

$$A_i{}^{\hat{j}\hat{0}} = a(t)\phi_h(t)\delta_{ij}, \qquad A_i{}^{\hat{j}\hat{k}} = -a(t)\phi_f(t)\epsilon_{ijk}, \tag{15}$$

i.e. a scalar field $\phi_h(t)$ and a pseudoscalar field $\phi_f(t)$, corresponding to the spin-0^+ and the spin-0^- modes in Fig. 1, respectively. Ansatz (14) and (15) define the so-called Friedmann-Lemaître-Robertson-Walker (FLRW) background. On the FLRW background, the gauge action consisting of the minimum Lagrangian (13) reduces to

$$s_G^0 = \int dt dx^3 a^3 L_G^0 \tag{16}$$

$$\begin{aligned} L_G^0 = {} & -6b_0(\dot{\phi}_h + H\phi_h - \phi_h^2 + \phi_f^2) - 6A_1(\phi_h + H)^2 \\ & - 6A_2\phi_f^2 + B_1\Big[(\dot{\phi}_h + H\phi_h)^2 \\ & - \frac{4}{3}(\dot{\phi}_h + H\phi_h)(\phi_h^2 - \phi_f^2) \\ & - \frac{4}{3}(\dot{\phi}_f + H\phi_f)\phi_h\phi_f + (\phi_h^2 - \phi_f^2)^2\Big] \\ & + B_2(\dot{\phi}_f + H\phi_f - 2\phi_h\phi_f)^2, \end{aligned} \tag{17}$$

where the dot denotes the derivative with respect to t, and $H \equiv \dot{a}/a$ is the Hubble rate. It can be read from (17) that the Proca masses for ϕ_h and ϕ_f occur in the forms $\frac{1}{2}m_h^2\phi_h^2$, $\frac{1}{2}m_f^2\phi_f^2$ with

$$m_h = 2\sqrt{3(A_1 - b_0)}, \qquad m_f = 2\sqrt{3(A_2 + b_0)} \tag{18}$$

as their masses, respectively.

The cosmic dynamic equations corresponding to Lagrangian (13) take the form of the ϕ-sourced and A_1-rescaled Friedmann equations

$$H^2 = \frac{1}{3A_1}\rho_\phi, \tag{19}$$

$$2\dot{H} + 3H^2 = -\frac{1}{A_1}p_\phi, \tag{20}$$

and two Klein-Gordon (KG) equations of ϕ_h and ϕ_f:

$$\ddot{\phi}_h + 3H\dot{\phi}_h - \frac{m_h^2}{4A_1}\phi_h(\dot{\phi}_h + H\phi_h) + 2\frac{B_1+B_2}{B_1}\phi_f(\dot{\phi}_f + H\phi_f) + \frac{1}{2A_1}\phi_h\left(\frac{m_h^2}{2}\phi_h^2 + \frac{m_f^2}{2}\phi_f^2\right) + \frac{1}{2B_1}\frac{\partial V_\phi}{\partial \phi_h} + \frac{m_h^2}{2B_1}H = 0, \tag{21}$$

$$\ddot{\phi}_f + 3H\dot{\phi}_f - \frac{m_h^2}{4A_1}\phi_f(\dot{\phi}_h + H\phi_h) - 2\frac{B_1+B_2}{B_2}\phi_f(\dot{\phi}_h + H\phi_h) + \frac{1}{2A_1}\phi_f\left(\frac{m_h^2}{2}\phi_h^2 + \frac{m_f^2}{2}\phi_f^2\right) + \frac{1}{2B_2}\frac{\partial V_\phi}{\partial \phi_f} = 0. \tag{22}$$

The energy density, the pressure, and the potential of ϕs is given by

$$\rho_\phi = \frac{B_1}{2}(\dot{\phi}_h + H\phi_h)^2 + \frac{B_2}{2}(\dot{\phi}_f + H\phi_f)^2 + \frac{1}{2}V_\phi, \tag{23}$$

$$p_\phi = \frac{1}{3}\left[\rho_\phi + \frac{m_h^2}{2}(\dot{\phi}_h + H\phi_h - \phi_h^2) - \frac{m_f^2}{2}\phi_f^2\right], \tag{24}$$

$$V_\phi = \frac{m_h^2}{2}\phi_h^2 + \frac{m_f^2}{2}\phi_f^2 - B_1(\phi_h^2 - \phi_f^2)^2 - 4B_2\phi_h^2\phi_f^2. \tag{25}$$

In addition, it can be checked that the energy density (23) and the pressure (24) satisfy the following conservation law:

$$\dot{\rho_\phi} = -3H(\rho_\phi + p_\phi). \tag{26}$$

We do the calculations with the help of XACT [38] and integrate our calculations in a Wolfram package PGC [39], which is available on Github.

It is worth mentioning that although we did not add additional material terms to the Lagrangian (13), the material composition constructed by ϕ_h and ϕ_f appears on the right side of the Friedmann equations. From the potential (25) and equations of motion (21) and (22), it can be seen that there is interaction and momentum exchange between the two fields, with the intensity related to the values of B_1, B_2. Both fields are up to quartic order in the potential. Because of B_1 being positive, the quartic coefficients are negative. It means that the potential has an inverted Mexican-hat shape, which causes the system to suffer from vacuum instability problem. Fortunately, the fourth terms in (21) and (22) contribute ϕ_h^3 and ϕ_f^3 terms (i.e. external forces) to the KG equations, respectively, and correspond to two additional quartic terms to the potential. Therefore, if the coefficients of the additional quartic terms are greater than the original absolute values, then the system would be stable, which leads to the following constraint conditions on parameters:

$$m_h^2 > 8A_1, \qquad m_f^2 > 8A_1\frac{B_1}{B_2}. \tag{27}$$

V. INFLATON AND DARK MATTER CANDIDATE

To understand the system intuitively, we tend to do numerical analysis by choosing appropriate values of parameters and initial conditions. The modern hot big bang theory and the power spectrum of cosmic microwave background (CMB) radiation observation have provided some requirements on models of the very early universe:

(1) the energy density of inflaton should be on -12 orders of magnitude during inflation in terms of Planck mass ($m_{\rm Pl}^4$),
(2) the energy density ratio of dark matter is diluted to the order of -20 at the end of inflation and approaches 1 after reheating,
(3) the e-folds during inflation are about 60, and the reheating process goes through about 20 e-folds.

There are totally five parameters in our system. We fix B_1 and B_2 because they can be rescaled from the action (16). We believe that the initial kinetic energy of the universe is on the Planck scale, so it is reasonable to set the initial values of the fields to 0 and the initial velocities to 1, in terms of Planck mass, see (23). Now we only have three mass-related parameter values to choose in (18). To meet the previous requirements, we choose the following parameter values:

$$\begin{aligned} A_1 &= 5.0\times10^{-7}m_{\rm Pl}^2, \qquad & b_0 &= 1.5\times10^{-8}m_{\rm Pl}^2,\\ A_2 &= 5.0\times10^{-6}m_{\rm Pl}^2, \qquad & B_1 &= B_2 = 1, \end{aligned} \tag{28}$$

and initial conditions at Planck time $t_0 = 1m_{\rm Pl}^{-1}$,

$$\phi_h(t_0) = \phi_f(t_0) = 0m_{\rm Pl}, \quad \dot{\phi}_h(t_0) = \dot{\phi}_f(t_0) = 1m_{\rm Pl}^2, \tag{29}$$

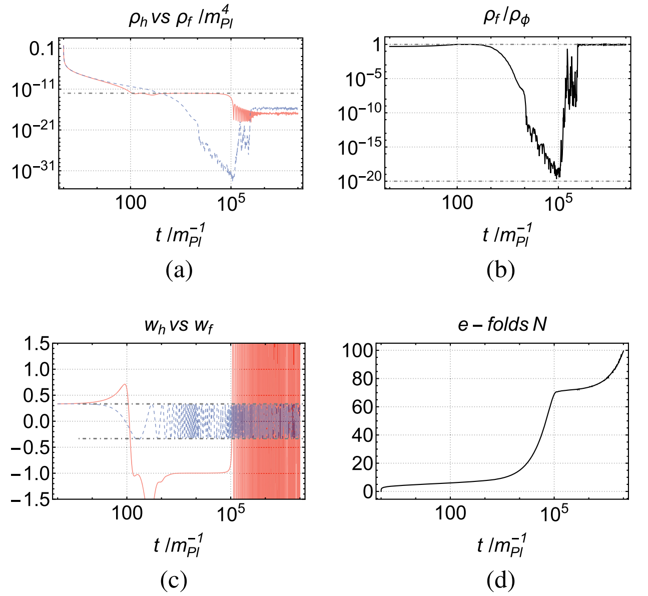

FIG. 2. (a) Evolution of ρ_h (red solid) and ρ_f (blue dash). The gray dot dashed line marks 10^{-12}. (b) Ratio of ρ_f to ρ_ϕ (black solid). The upper gray dot dashed line marks 1 and the lower marks 10^{-20}. (c) Evolution of w_h (red solid) and w_f (blue dash). The two gray dot dashed lines mark $\pm 1/3$. (d) Evolution of e-folds N.

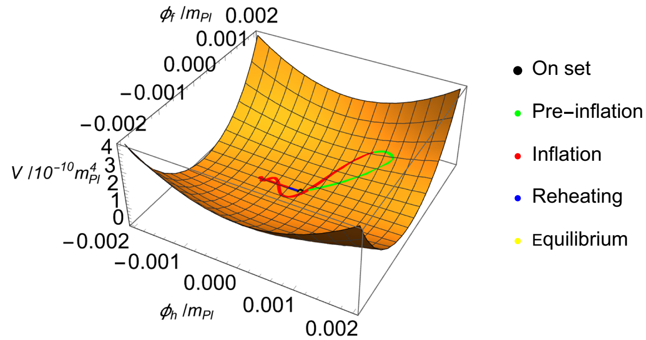

FIG. 3. Evolution phase diagram of ϕ_h and ϕ_f in the effective potential. The evolution trajectory is divided into four stages.

then, the corresponding visualizations are shown in Fig. 2. In fact, these three parameter values can fluctuate within certain ranges, and the above choice is a set that we believe meets the requirements quite well. The accurate constraints should be obtained by comparing the primordial power spectrum with the actual observation from CMB radiation, which is our subsequent work.

According to the numerical analysis, the interaction between ϕ_h and ϕ_f is significantly small, so we can ignore the interaction terms in potential (25) and separate the total energy density ρ_ϕ (23) into two parts: ρ_h and ρ_f, and plot them in Fig. 2(a). It is obvious that the whole evolution process can be divided into four periods:

(i) preinflation, $1 m_{\rm Pl}^{-1} \sim 100 m_{\rm Pl}^{-1}$,

(ii) slow-rolling inflation, $\sim 100 m_{\rm Pl}^{-1} \sim 10^5 m_{\rm Pl}^{-1}$,

(iii) reheating, $\sim 10^5 m_{\rm Pl}^{-1} \sim 10^6 m_{\rm Pl}^{-1}$,

(iv) equilibrium, $> 10^6 m_{\rm Pl}^{-1}$,

where ϕ_h dominates the slow-rolling inflationary period, and spontaneously decays to the reheating period. During inflation, ρ_h is about -12 orders of magnitude, which meets requirement (1). Meanwhile, ρ_f is sharply diluted by more than 20 orders of magnitude, then due to the interaction between ϕ_f and ϕ_h in the KG equations, ϕ_h decays partly to ϕ_f, causing ρ_f to rebound until it exceeds ρ_h in the equilibrium period. The ratio of ρ_f to ρ_ϕ in Fig. 2(b) shows clearly that the requirement (2) is also met. The equation of state defined as $w \equiv p/\rho$ is an important quantity that characterizes the properties of cosmic components. $w < -1/3$ is a necessary condition for causing an accelerating expansion of the universe and $w = 0$ marks pressureless nonrelativistic matter. We plot w_h and w_f in Fig. 2(c). It shows that w_h is approximately -1 during inflation, indicating that ϕ_h is indeed an inflaton. w_f oscillates rapidly between $\pm 1/3$ with a period significantly shorter than the dynamical scale we concerned, i.e. its average value is about 0. So far, although we are not yet clear about the specific properties of dark matter particles, to become a candidate, some general limitations need to be met. For example, they must be stable enough on the cosmic timescale so that they can still exist today. In addition, they cannot have strong or electromagnetic interaction. It has been known that an alternative cold dark matter candidate is a coherently oscillating scalar field, the archetypal example being axion dark matter. Such coherent scalar fields are therefore a well developed alternative to the weakly interacting massive particle paradigm [40,41]. w_f shows that ϕ_f behaves like pressureless axion matter, and is indistinguishable from traditional cold dark matter candidates on the background level. We plot e-folds $N \equiv \int H dt$ in Fig. 2(d) which meets requirement (3).

At the end of the Sec. IV, we have pointed out the relationship between the shape of potential and the stability of the system, as well as the restrictions on parameters. To visually show the stability, we draw the evolution phase diagram of the fields in the effective potential, namely, the potential compensated by the additional terms from KG equations, see Fig. 3. From the shape of the effective potential, the system is stable.

VI. CONCLUSION AND DISCUSSION

In this paper, we introduce a cosmological model in the framework of PGG, in which cosmological constant, inflaton, and dark matter candidate all naturally originate. First, according to previous studies, in the process of breaking of the P symmetries down to the L symmetries, the cosmological constant originates in the Lagrangian of matter. Then we select a ghost- and tachyon-free parity-conserving EH-YM type gauge Lagrangian, which is a minimum extension of GR with two additional massive modes. By considering the cosmological reduction, the tetrad field residues the scale factor a, and the L connection residues a scalar field ϕ_h and a pseudoscalar field ϕ_f. The cosmic dynamic is given by the ϕs-sourced and A_1-rescaled Friedmann equations. Numerical analysis shows that ϕ_h dominates a slow-rolling inflation and ϕ_f behaves as a dark matter candidate.

From the perspective of GR cosmology, ϕ_h and ϕ_f defined in (15) are related to the vector and axial vector components of torsion tensor, respectively,

$$T_{i0}{}^{j} = (\phi_h + H)\delta_{ij}, \qquad T_{ij}{}^{k} = -2a\phi_f \epsilon_{ijk}. \tag{30}$$

These propagating components of torsion can be regarded as the geometric "substances" on the background. "Torsion cannot propagate" is a misunderstanding brought to us by Einstein-Cartan theory, which is the minimum extension of GR in Riemann-Cartan spacetime with respect to the EH action [42]. Based on our previous analysis, it can be seen that the missing torsion in most modern theories of gravity plays an important role in the very early universe and the formation of large-scale structures. From the perspective of gauge theory, ϕ_h and ϕ_f are just "gauge bosons of gravity." They are similar to the two polarizations of photons, the difference being that photons have no extra d.o.f. in the direction of propagation, so photons are massless [43], while in the direction of cosmic evolution, scale factor a plays the role of a Goldstone d.o.f., which "gives" the two gravity bosons masses.

In the subsequent work, we will continue: (1) to obtain the primordial power spectrum of the model through perturbation, so that to constrain the parameters by comparing with observation of CMB radiation; (2) to consider the interactions with standard model particles. More general cosmology based on gauge theories of gravity beyond the P group will also be studied in the future.

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