Light scalar dark matter coupled to a trace of energy-momentum tensor

[ArXiv:1812.04065]

Aleksandr Belokon, Anna Tokareva

M.V. Lomonosov Moscow State University, Faculty of Physics
Institute for Nuclear Research of Russian Academy of Sciences

Moscow International School of Physics 2020

Contents

Overview

Overview

- Dark Matter

Overview

- Dark Matter
- Scalar field

Overview

- Dark Matter
- Scalar field
- Interaction with the ordinary matter

Overview

- Dark Matter
- Scalar field
- Interaction with the ordinary matter
- Its influence on the SM

Overview

- Dark Matter
- Scalar field
- Interaction with the ordinary matter
- Its influence on the SM
- Constraints to reproduce observable Universe

Overview

- Dark Matter
- Scalar field
- Interaction with the ordinary matter
- Its influence on the SM
- Constraints to reproduce observable Universe
- Cross-check with other observations

Motivation for Ultralight DM

- Most ultralight scalar dark matter theories suppose only gravitational interaction, i.e. this type of DM is invisible for detection in experiments and observations.
  On the contrary, this theory gives a trace to observe signatures left in Early Universe

Motivation for Ultralight DM

- Most ultralight scalar dark matter theories suppose only gravitational interaction, i.e. this type of DM is invisible for detection in experiments and observations.
  On the contrary, this theory gives a trace to observe signatures left in Early Universe
- All large scale predictions are the same as in ΛCDM model

Motivation for Ultralight DM

- Most ultralight scalar dark matter theories suppose only gravitational interaction, i.e. this type of DM is invisible for detection in experiments and observations.
  On the contrary, this theory gives a trace to observe signatures left in Early Universe
- All large scale predictions are the same as in ΛCDM model
- For the fields with masses in range of about $10^{-22} - 10^{-21}$ eV the particle large de Broglie wavelength suppresses small-scale structure (the scale of dwarf galaxies of about 10 kpc)

Motivation for Ultralight DM

- Most ultralight scalar dark matter theories suppose only gravitational interaction, i.e. this type of DM is invisible for detection in experiments and observations.
  On the contrary, this theory gives a trace to observe signatures left in Early Universe
- All large scale predictions are the same as in ΛCDM model
- For the fields with masses in range of about $10^{-22} - 10^{-21}$ eV the particle large de Broglie wavelength suppresses small-scale structure (the scale of dwarf galaxies of about 10 kpc)
- All theory's signatures are consistent with many inflation theories

Motivation for Ultralight DM

- Most ultralight scalar dark matter theories suppose only gravitational interaction, i.e. this type of DM is invisible for detection in experiments and observations.
  On the contrary, this theory gives a trace to observe signatures left in Early Universe
- All large scale predictions are the same as in ΛCDM model
- For the fields with masses in range of about $10^{-22} - 10^{-21}$ eV the particle large de Broglie wavelength suppresses small-scale structure (the scale of dwarf galaxies of about 10 kpc)
- All theory's signatures are consistent with many inflation theories
- Motivation from other theories (QCD Axion, String theories)

Action and symmetries

- Model action:

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \left(\frac{m^2}{2}\phi^2 + \frac{\phi^2}{\Lambda^2}T^\mu_\mu\right)\right]. \tag{1}$$

Action and symmetries

- Model action:

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \left(\frac{m^2}{2}\phi^2 + \frac{\phi^2}{\Lambda^2}T^\mu_\mu\right)\right]. \tag{1}$$

- Model symmetries:
  - $\mathbb{Z}_2$-symmetry $\phi \to -\phi$ that excludes odd-term interaction

Action and symmetries

- Model action:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \left(\frac{m^2}{2}\phi^2 + \frac{\phi^2}{\Lambda^2}T^\mu_\mu\right)\right]. \tag{1}$$

- Model symmetries:
  - $\mathbb{Z}_2$-symmetry $\phi \to -\phi$ that excludes odd-term interaction
  - Shift symmetry $\phi \to \phi + const$ that took place before the phase transition

Equation of motion

- The effective mass of the field at Early Universe is

$$m_{eff}^2 = m^2 + \frac{T_\mu^\mu}{\Lambda^2}. \tag{2}$$

Equation of motion

- The effective mass of the field at Early Universe is

$$m_{eff}^2 = m^2 + \frac{T_\mu^\mu}{\Lambda^2}. \tag{2}$$

- At later time the second term in the right hand side of the relation can be neglected

Equation of motion

- The effective mass of the field at Early Universe is

$$m_{eff}^2 = m^2 + \frac{T_\mu^\mu}{\Lambda^2}. \tag{2}$$

- At later time the second term in the right hand side of the relation can be neglected
- Equation of motion for the action (1) in the case of a spatial homogeneous scalar field is

$$\partial_t^2 \phi + 3\frac{\dot{a}(t)}{a(t)}\phi + m_{eff}^2(t)\phi = 0. \tag{3}$$

Equation of motion

- The trace of a macroscopic energy-momentum tensor is given by the relation:

$$T^{\mu}_{\mu}(T) = \rho(T) - 3p(T). \tag{4}$$

Equation of motion

- The trace of a macroscopic energy-momentum tensor is given by the relation:

$$T^{\mu}_{\mu}(T) = \rho(T) - 3p(T). \tag{4}$$

- Using known formulas for energy density and pressure one can obtain:

$$T^{\mu}_{\mu}(T) = \sum_{i = all\, SM\, particles} \frac{g_i m_i^2}{2\pi^2} \int_{m_i}^{\infty} \frac{\sqrt{E^2 - m_i^2}}{\exp(E/T) \pm 1} \mathrm{d}E. \tag{5}$$

Equation of motion

- The trace of a macroscopic energy-momentum tensor is given by the relation:

$$T^{\mu}_{\mu}(T) = \rho(T) - 3p(T). \tag{4}$$

- Using known formulas for energy density and pressure one can obtain:

$$T^{\mu}_{\mu}(T) = \sum_{i=\text{all SM particles}} \frac{g_i m_i^2}{2\pi^2} \int_{m_i}^{\infty} \frac{\sqrt{E^2 - m_i^2}}{\exp(E/T) \pm 1} \mathrm{d}E. \tag{5}$$

- Note that T^{μ}_{μ} is a function of temperature. Therefore, it makes sense to rewrite equation of motion in terms of temperature.

Equation of motion

- Using Friedmann equations one can get the following equation:

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}T^2} + \left(3H(T)\frac{\mathrm{d}t}{\mathrm{d}T} - \frac{\mathrm{d}^2t}{\mathrm{d}T^2}\Big/\frac{\mathrm{d}t}{\mathrm{d}T}\right)\frac{\mathrm{d}\phi}{\mathrm{d}T} + \left(m^2 + \frac{T^\mu_\mu(T)}{\Lambda^2}\right)\phi = 0. \quad (6)$$

Equation of motion

- Using Friedmann equations one can get the following equation:

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}T^2} + \left(3H(T)\frac{\mathrm{d}t}{\mathrm{d}T} - \frac{\mathrm{d}^2 t}{\mathrm{d}T^2}\Big/\frac{\mathrm{d}t}{\mathrm{d}T}\right)\frac{\mathrm{d}\phi}{\mathrm{d}T} + \left(m^2 + \frac{T^\mu_\mu(T)}{\Lambda^2}\right)\phi = 0. \quad (6)$$

- This is the equation to be numerically solved in order to understand the evolution of the scalar field

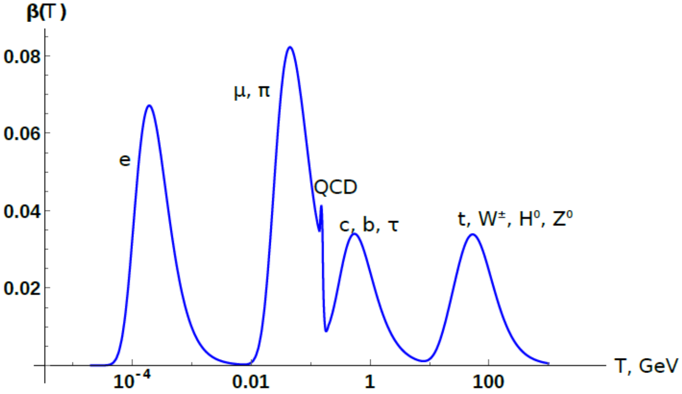
Equation of motion

- Using Friedmann equations one can get the following equation:

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}T^2} + \left(3H(T)\frac{\mathrm{d}t}{\mathrm{d}T} - \frac{\mathrm{d}^2 t}{\mathrm{d}T^2} \Big/ \frac{\mathrm{d}t}{\mathrm{d}T}\right)\frac{\mathrm{d}\phi}{\mathrm{d}T} + \left(m^2 + \frac{T^\mu_\mu(T)}{\Lambda^2}\right)\phi = 0. \quad (6)$$

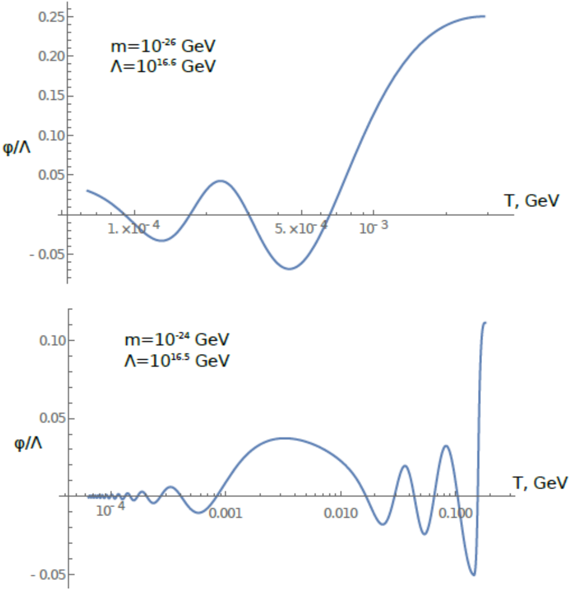
- This is the equation to be numerically solved in order to understand the evolution of the scalar field
- We also have to consider all particle species that influence the energy-momentum tensor behaviour

Equation of motion

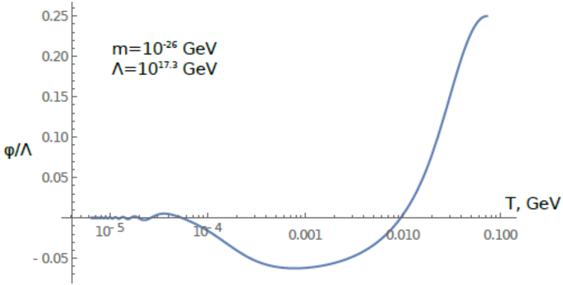


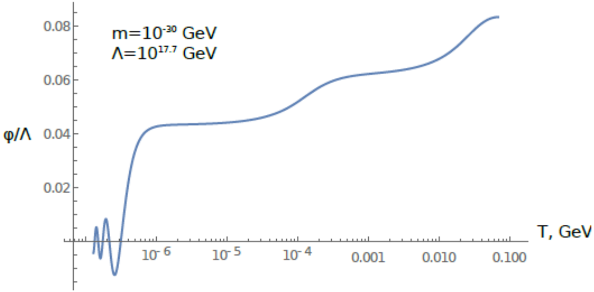
This figure shows the function $\beta(T) = T^{\mu}_{\mu}/\rho$ as a function of temperature. β deviates from zero when the temperature falls below the mass of a particle that is in thermal equilibrium with the radiation bath. It includes contributions from all the SM-particles

Field equation solutions



Field equation solutions





The changes of the fundamental constants

The coupling with the scalar leads to the shifts of [Campbell et al., 1995; Leutwyler H., Gasser J., 1982]

- electron mass:

$$m_e = m_e^0 \left(1 + \frac{\phi^2}{\Lambda^2}\right), \tag{7}$$

The changes of the fundamental constants

The coupling with the scalar leads to the shifts of [Campbell et al., 1995; Leutwyler H., Gasser J., 1982]

- electron mass:

$$m_e = m_e^0 \left(1 + \frac{\phi^2}{\Lambda^2}\right), \tag{7}$$

- quark masses (in the same way)

The changes of the fundamental constants

The coupling with the scalar leads to the shifts of [Campbell et al., 1995; Leutwyler H., Gasser J., 1982]

- electron mass:

$$m_e = m_e^0 \left(1 + \frac{\phi^2}{\Lambda^2}\right), \tag{7}$$

- quark masses (in the same way)
- QCD strong coupling scale:

$$\Lambda_{QCD} = \Lambda_{QCD}^0 \left(1 - \frac{14}{27}\frac{\phi^2}{\Lambda^2}\right), \tag{8}$$

The changes of the fundamental constants

The coupling with the scalar leads to the shifts of [Campbell et al., 1995; Leutwyler H., Gasser J., 1982]

- electron mass:

$$m_e = m_e^0 \left(1 + \frac{\phi^2}{\Lambda^2}\right), \quad (7)$$

- quark masses (in the same way)
- QCD strong coupling scale:

$$\Lambda_{QCD} = \Lambda_{QCD}^0 \left(1 - \frac{14}{27}\frac{\phi^2}{\Lambda^2}\right), \quad (8)$$

- neutron-to-proton mass difference:

$$\Delta m_{np} \equiv m_n - m_p = (m_n - m_p)_0 \left(1 + 0.82\frac{\phi^2}{\Lambda^2}\right), \quad (9)$$

The changes of the fundamental constants

The coupling with the scalar leads to the shifts of [Campbell et al., 1995; Leutwyler H., Gasser J., 1982]

- electron mass:

$$m_e = m_e^0 \left(1 + \frac{\phi^2}{\Lambda^2}\right), \tag{7}$$

- quark masses (in the same way)
- QCD strong coupling scale:

$$\Lambda_{QCD} = \Lambda_{QCD}^0 \left(1 - \frac{14}{27}\frac{\phi^2}{\Lambda^2}\right), \tag{8}$$

- neutron-to-proton mass difference:

$$\Delta m_{np} \equiv m_n - m_p = (m_n - m_p)_0 \left(1 + 0.82\frac{\phi^2}{\Lambda^2}\right), \tag{9}$$

- neutron life-time:

$$\tau_n = \tau_n^0 \left(1 + \frac{\phi^2}{\Lambda^2}\right). \tag{10}$$

BBN and DM constraints

- If Δm_{np} and τ_n differ from their SM values the dynamics of BBN is affected

BBN and DM constraints

- If Δm_{np} and τ_n differ from their SM values the dynamics of BBN is affected
- We know from the observations that the ^{4}He fraction produced during BBN is bounded by the Planck data as [Planck, 2018]

$$0.2464 \leq \mathrm{X}_{^4\mathrm{He}} \leq 0.2505. \tag{11}$$

BBN and DM constraints

- If Δm_{np} and τ_n differ from their SM values the dynamics of BBN is affected
- We know from the observations that the ^{4}He fraction produced during BBN is bounded by the Planck data as [Planck, 2018]

$$0.2464 \leq X_{^4\mathrm{He}} \leq 0.2505. \tag{11}$$

- The current dark matter energy density is characterized by the density parameter $\Omega_{DM} \equiv \rho_{DM}/\rho_{crit} = 0.2581$ [Planck, 2018]

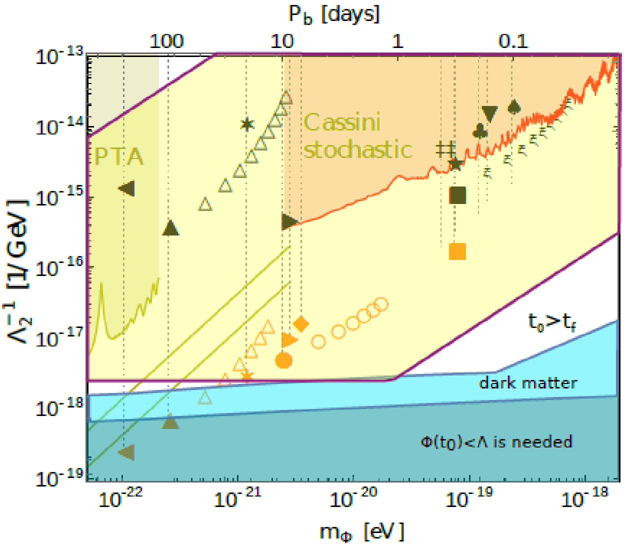
BBN and DM constraints

- If Δm_{np} and τ_n differ from their SM values the dynamics of BBN is affected
- We know from the observations that the ^{4}He fraction produced during BBN is bounded by the Planck data as [Planck, 2018]

$$0.2464 \leq X_{^4\mathrm{He}} \leq 0.2505. \tag{11}$$

- The current dark matter energy density is characterized by the density parameter $\Omega_{DM} \equiv \rho_{DM}/\rho_{crit} = 0.2581$ [Planck, 2018]
- Considering all these constraints we have to calculate the allowed parameter space to reproduce observable Universe

BBN and DM constraints & Observations of binary pulsars



Conclusions

- We examined the universal coupling of DM to matter which is quadratic in the field

Conclusions

- We examined the universal coupling of DM to matter which is quadratic in the field
- We found that at Early Universe the average value of T^{μ}_{μ} might be larger than the mass term providing with the drastic change of the fundamental constants before the oscillation period

Conclusions

- We examined the universal coupling of DM to matter which is quadratic in the field
- We found that at Early Universe the average value of T^{μ}_{μ} might be larger than the mass term providing with the drastic change of the fundamental constants before the oscillation period
- We obtained accurate bounds on the mass and coupling to matter that allows for the field to be DM

Conclusions

- We examined the universal coupling of DM to matter which is quadratic in the field
- We found that at Early Universe the average value of T_μ^μ might be larger than the mass term providing with the drastic change of the fundamental constants before the oscillation period
- We obtained accurate bounds on the mass and coupling to matter that allows for the field to be DM
- We found that if the field is initiated before BBN the allowed region is far from those which can be probed within the observations of binary pulsars

Thank you for your attention

This research was supported by the Russian Science Foundation Grant № $16-12-10494$