Spontaneous scalarization : asymmetron as dark matter

arXiv: 1508.01384 by P. Chen(LeCosPA), TS and J.Yokoyama(RESCEU)

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Oct 12th, 2015@CHICAGO

Spontaneous scalarization-induced dark matter and variation of the gravitational constant

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Dawn of a new era of gravitational physics

Experimental tests of GR in strong gravity regime become possible soon.

Stringent solar-system constraints do not mean GR is correct.

Is there any model where large deviation from GR occurs only in strong gravity regime?

Damour–Esposito–Farese(DEF) model (Damour&Esposito–Farese, 1993)

Simplest class of the ST theory

$$S = \int d^4x\sqrt{-g}\left(\frac{R}{16\pi G_N} - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{\mu^2}{2}\phi^2\right) + \int d^4x\sqrt{-\tilde{g}}\mathcal{L}_m(\tilde{g}, \psi_m),$$

$\tilde{g}_{\mu\nu} = A^2(\phi)g_{\mu\nu}$ is the Jordan–frame metric.

DEF model : $\mu = 0,\ A(\phi) = \exp(2\pi G_N \beta\phi^2)$

(Brans–Dicke : $\mu = 0,\ A(\phi) = \exp\left(\sqrt{\frac{4\pi G_N}{2\omega_{BD}+3}}\,\phi\right)$) ($\omega_{BD} \gtrsim 5\times 10^4$)

$\beta < 0$ is a (dimensionless) free parameter of this model (and supposed to be order unity).

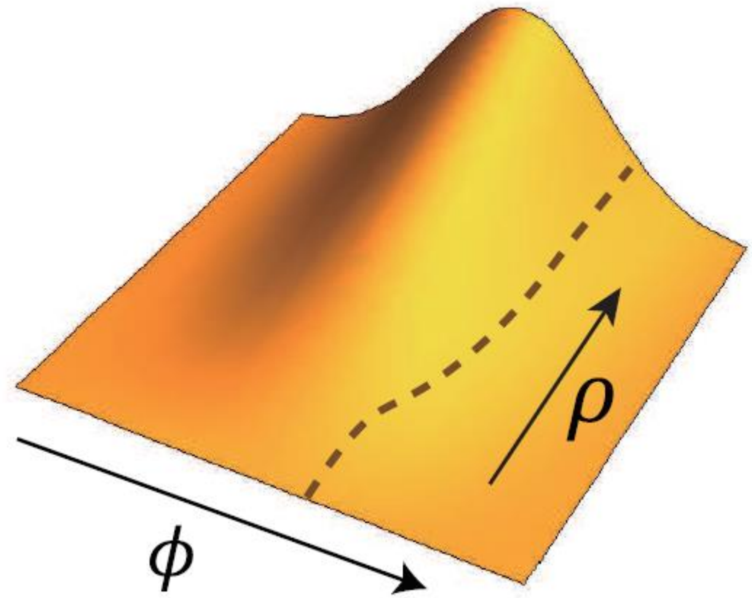
$\frac{d}{d\phi}\ln A(\phi)$, which measures the amount of deviation from GR, is proportional ϕ.
Thus the amount of deviation from GR depends on the background value of ϕ.

Stringent constraints from the solar–system experiments can be safely satisfied by choosing the value of ϕ to be sufficiently small.

Effective potential in the DEF model

$$\Box\phi - V_{\mathrm{eff},\phi} = 0.$$

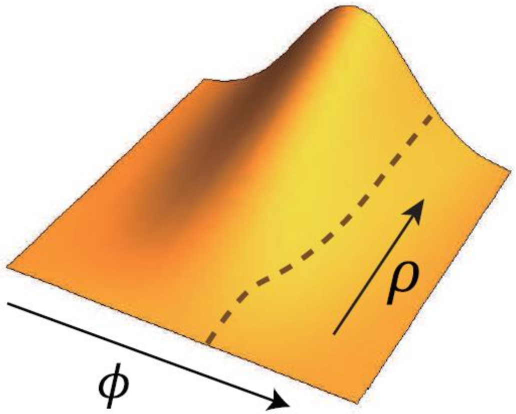
$$V_{\mathrm{eff}}(\phi) = \frac{\mu^2}{2}\phi^2 - \frac{1}{4}A^4(\phi)\tilde{T},$$



Even if the asymptotic value of ϕ satisfies the solar-system constraints, it is possible that significant deviation from GR appears at the vicinity and inside of the neutron star.

Many papers on this model.

Cosmology of the DEF model (e.g. Sampson et al, 2014)



GR limit corresponds to $\phi = 0$.

In the early Universe, the non-relativistic matter pushes ϕ away from the origin.

GR is not the cosmological attractor in the DEF model and fine-tuning of the initial value of ϕ is required to be consistent with the solar-system experiments.

Can we have a viable model?

Our new scalar-tensor model : Asymmetron

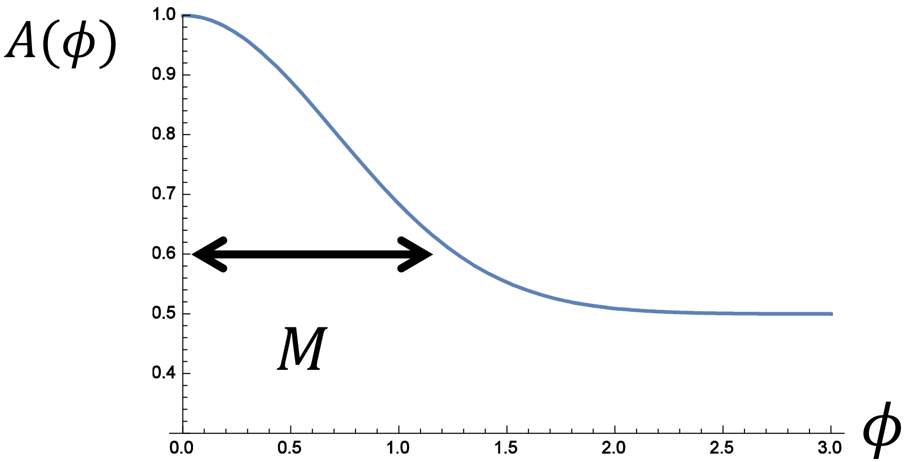
Two modifications

- Massive ϕ ($\mu \neq 0$)
- Decreasing function for $A(\phi)$

$$A^2(\phi) = 1 - \varepsilon + \varepsilon e^{-\frac{\phi^2}{2M^2}}$$

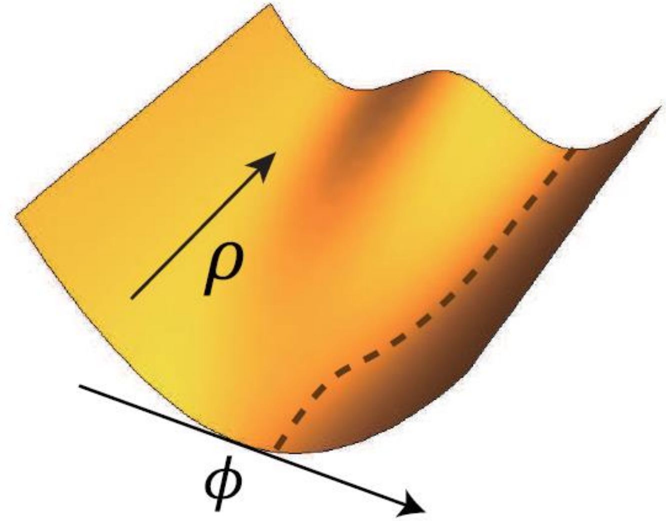
$$0 < \varepsilon < 1.$$

To derive quantitative results,
we use this form.



Our new model does not suffer from the issue present in the DEF model. Furthermore, ϕ becomes a natural candidate of dark matter.

Spontaneous scalarization



Taylor expansion around $\phi = 0$,

$$V_{\rm eff}(\phi) = \frac{1}{4}\tilde{\rho} + \frac{1}{2}\left(\mu^2 - \frac{\varepsilon\tilde{\rho}}{2M^2}\right)\phi^2 + \mathcal{O}(\phi^4)$$

$\phi = 0$ is stable for $\tilde{\rho} < \rho_{PT}$ and unstable otherwise.

$\rho_{PT} \equiv 2\mu^2 M^2/\varepsilon$ is the critical density.

If $\tilde{\rho}$ is above ρ_{PT}, spontaneous scalarization occurs and stable value $\bar{\phi}$ is given by

$$\frac{\bar{\phi}^2}{2M^2} = \ln f(\varepsilon, \rho_{\rm PT}/\tilde{\rho}), \qquad f(\varepsilon, \eta) \equiv \frac{2\varepsilon}{1-\varepsilon}\left(\sqrt{1 + \frac{4\varepsilon\eta}{(1-\varepsilon)^2}} - 1\right)^{-1}$$

Apart from the logarithmic factor, $\bar{\phi} \sim M$.

Symmetric phase ($\phi = 0$)

$$S = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi G_N} - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{\mu^2}{2} \phi^2 \right) + \int d^4x \sqrt{-\tilde{g}} \mathcal{L}_m(\tilde{g}, \psi_m),$$

$$A^2(\phi) = 1 - \varepsilon + \varepsilon e^{-\frac{\phi^2}{2M^2}}$$

There is no difference between the Jordan-frame and the Einstein-frame metrics.

Interaction at the leading order is given by $\sim \frac{\phi^2}{M^2} T$. For our case of interest, M is much larger than TeV scale. We do not expect detectable signal of the existence of the ϕ field from the terrestrial experiments.

$$G_{\mu\nu} = 8\pi G_N \left[- \left(\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \frac{\mu^2}{2} \phi^2 \right) g_{\mu\nu} + \partial_\mu \phi \partial_\nu \phi + A^2(\phi) \tilde{T}_{\mu\nu} \right]$$

$\phi = 0$

$$G_{\mu\nu} = 8\pi G_N \tilde{T}_{\mu\nu}$$

Laws of gravity are just GR.

Spontaneous scalarization phase

In the spontaneous scalarization phase, field eqs for gravity are modified.

$$G_{\mu\nu} = 8\pi G_N \left[- \left(\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \frac{\mu^2}{2} \phi^2 \right) g_{\mu\nu} + \partial_\mu \phi \partial_\nu \phi + A^2(\phi) \tilde{T}_{\mu\nu} \right]$$

Assuming no-excitation of the ϕ field,

$$\tilde{G}_{\mu\nu} + \Lambda_{\text{eff}} \tilde{g}_{\mu\nu} = 8\pi G_{\text{eff}} \tilde{T}_{\mu\nu},$$

Emergence of the effective cosmological constant (contrary to the Higgs mechanism)

Variation of the gravitational constant

$\widetilde{g_{\mu\nu}}$ obeys the Einstein equations with the effective C.C. given by $\Lambda_{eff} > 0$ and with the gravitational constant given by $G_{eff} < G_N$.

$$\Lambda_{\text{eff}} = 4\pi G_N \mu^2 \bar{\phi}^2 A^{-2}(\bar{\phi}) = 4\pi G_N \varepsilon \rho_{\text{PT}} \ln f(\varepsilon, \rho_{\text{PT}}/\tilde{\rho}) \left(1 - \varepsilon + \frac{\varepsilon}{f(\varepsilon, \rho_{\text{PT}}/\tilde{\rho})} \right)^{-1}$$

$$G_{\text{eff}} = A^2(\bar{\phi}) G_N = \left(1 - \varepsilon + \frac{\varepsilon}{f(\varepsilon, \rho_{\text{PT}}/\tilde{\rho})} \right) G_N.$$

Spontaneous scalarization phase

For $\tilde{\rho} \gg \rho_{PT}$, we have

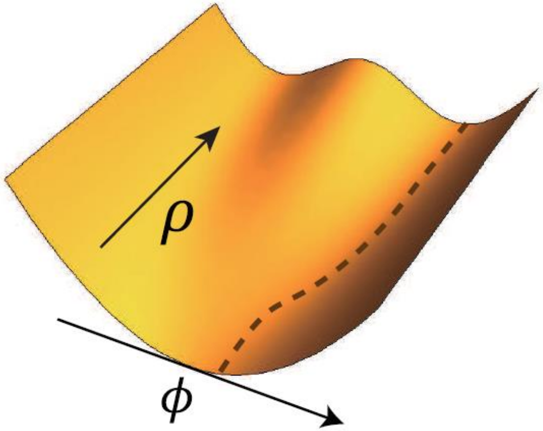
$$\Lambda_{\text{eff}} \approx 4\pi G_N \frac{\varepsilon}{1-\varepsilon} \rho_{\text{PT}} \ln\left((1-\varepsilon)\frac{\tilde{\rho}}{\rho_{\text{PT}}}\right), \qquad G_{\text{eff}} \approx (1-\varepsilon) G_N .$$

We find that Λ_{eff} is only logarithmically enhanced compared to ρ_{PT}. Thus, the effective cosmological constant does not play a significant role in deep scalarization phase.

The gravitational constant is reduced from the one measured in the laboratory by the factor ε.

In the deep scalarization phase, the scalar force is suppressed and the dominant modification is the weakening of gravity while keeping the structure of GR.

Spontaneous scalarization



What is the value of ρ_{PT}?

It is a free parameter of the model.

But we can restrict a possible range.

$$\rho_{PT} \gg \rho_{\oplus} \approx 5 \times 10^{-17} GeV^4$$

Interesting case is $\rho_{PT} < \rho_{NS} \approx 3 \times 10^{-3} GeV^4$. Then, spontaneous scalarization occurs inside the compact objects such as the neutron stars.

Spontaneous scalarization may be visible in the present Universe.

It is possible that ϕ field constitutes the whole DM for such case.

Screening Long-Range Forces through Local Symmetry Restoration

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(Received 19 February 2010; published 10 June 2010)

We present a screening mechanism that allows a scalar field to mediate a long-range (~ Mpc) force of gravitational strength in the cosmos while satisfying local tests of gravity. The mechanism hinges on local symmetry restoration in the presence of matter. In regions of sufficiently high matter density, the field is drawn towards $\phi = 0$ where its coupling to matter vanishes and the $\phi \to -\phi$ symmetry is restored. In regions of low density, however, the symmetry is spontaneously broken, and the field couples to matter with gravitational strength. We predict deviations from general relativity in the solar system that are within reach of next-generation experiments, as well as astrophysically observable violations of the equivalence principle. The model can be distinguished experimentally from Brans-Dicke gravity, chameleon theories and brane-world modifications of gravity.

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Why asymmetron?

Scalar fields are the simplest of fields. Light, gravitationally coupled scalars are generically predicted to exist by many theories of high energy physics. These scalars may play a crucial role in dark energy as quintessence fields, and generically arise in infrared-modified gravity theories [1–7]. Despite their apparent theoretical ubiquity, no sign of such a fundamental scalar field has ever been seen, despite many experimental tests designed to detect solar system effects or fifth forces that would naively be expected if such scalars existed [8,9].

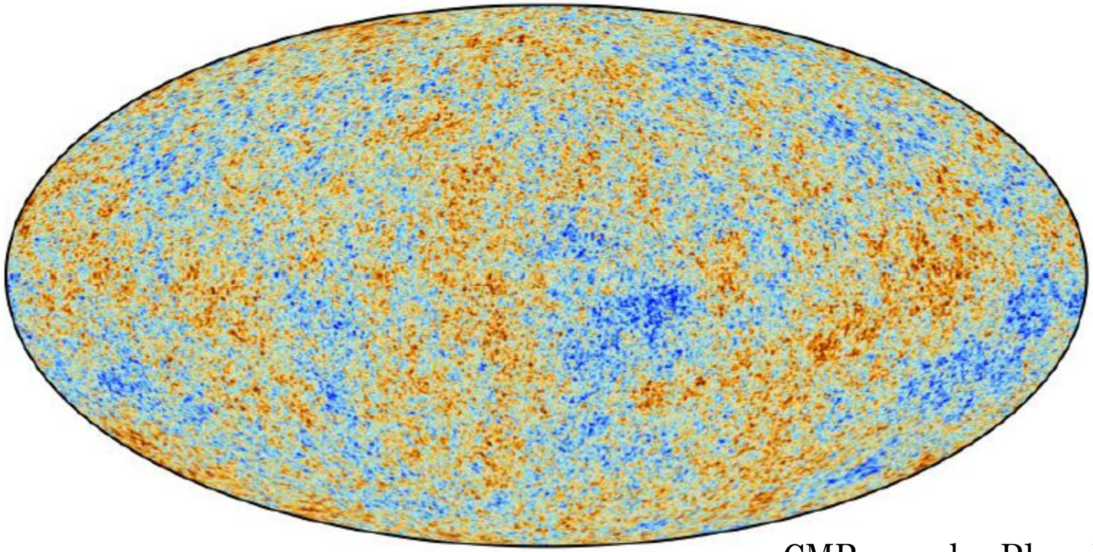
Several broad classes of theoretical mechanisms have been developed to explain why such light scalars, if they exist, may not be visible to experiments performed near the Earth. One such class, the chameleon mechanism [5,6], operates whenever the scalars are nonminimally coupled to matter in such a way that their effective mass depends on the local matter density. Deep in space, where the local mass density is low, the scalars would be light and would display their effects, but near Earth, where experiments are performed, and where the local mass density is high, they would acquire a mass, making their effects short range and mass density, becoming large in regions of low mass density, and small in regions of high mass density. In addition, the coupling of the scalar to matter is proportional to the VEV, so that the scalar couples with gravitational strength in regions of low density, but is decoupled and screened in regions of high density.

This is achieved through the interplay of a symmetry-breaking potential, $V(\phi) = -\mu^2\phi^2/2 + \lambda\phi^4/4$, and universal coupling to matter, $\phi^2\rho/2M^2$. In vacuum, the scalar acquires a VEV $\phi_0 = \mu/\sqrt{\lambda}$, which spontaneously breaks the $\mathbb{Z}_2$ symmetry $\phi \to -\phi$. In the presence of sufficiently high ambient density, however, the field is confined near $\phi = 0$, and the symmetry is restored. In turn, $\delta\phi$ fluctuations couple to matter as $(\phi_{\rm VEV}/M^2)\delta\phi\rho$, and so are weakly coupled in high density backgrounds and strongly coupled in low density backgrounds. Since the screening mechanism relies on the local restoration of a symmetry, we refer to the scalar as a *symmetron field*.

The model predicts a host of observational signatures. The solar light-deflection and time-delay deviations from general relativity (GR) are just below currents bound and

Asymmetron as dark matter

Asymmetron as dark matter



CMB map by Planck

Cosmic observations strongly suggest that there was an inflationary era in the very early Universe.

In the asymmetron scenario, $\phi = 0$ becomes unstable during inflation and the ϕ field is pushed away from the origin.

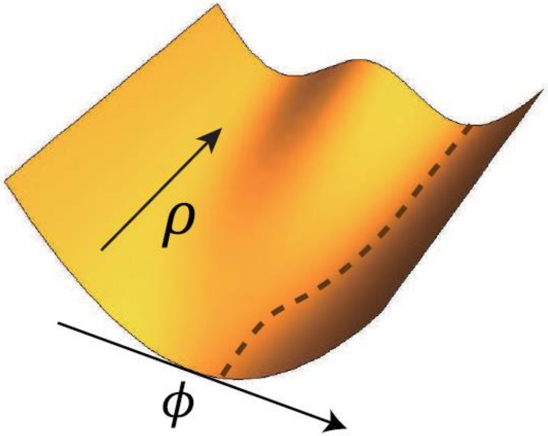
Dark matter is "seeded" during inflation.

Asymmetron as dark matter

In our model, the ϕ field universally couples to all the rest of the fields including the inflaton.

During inflation, we have $\tilde{T} \approx -4\widetilde{\rho_{inf}}$ and

$$V_{\rm eff}(\phi) = \frac{\mu^2}{2}\phi^2 + \left(1 - \varepsilon + \varepsilon e^{-\frac{\phi^2}{2M^2}}\right)^2 \tilde{\rho}_{\rm inf}$$



We are interested in the case where $\tilde{\rho}_{inf} > \rho_{PT}/4$.
Then $\phi = 0$ becomes unstable and the stable value is given by

$$\frac{\bar{\phi}^2}{2M^2} = \ln f(\varepsilon, \rho_{\rm PT}/(4\tilde{\rho}_{\rm inf}))$$

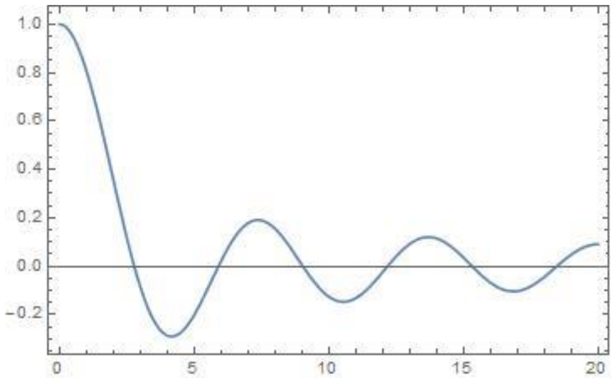
For definiteness, we assume field value during inflation is fixed to this value.

Asymmetron as dark matter

After inflation, the Universe is dominated by radiation as a result of the decay of the inflaton. Then, ϕ decouples from the matter since $\tilde{T} = 0$.

$$\ddot{\phi} + 3H\dot{\phi} + \mu^2\phi = 0$$

$\phi(t)/\phi(0)$



μt

After $H = \mu$, ϕ undergoes damped oscillations as $\phi \propto a^{-3/2}$

Since ϕ asymptotically approaches zero, GR is a cosmological attractor.

ϕ field behaves as non-relativistic matter.

ϕ field satisfies all the properties required for dark matter.

Asymmetron as dark matter

- Non-trivial two constraints

  1. Non-observation of the CDM isocurvature perturbation in the CMB.

  2. Non-observation of the fifth force.

Asymmetron as dark matter

1. Non-observation of the CDM isocurvature perturbation in the CMB.

Asymmetron DM contains uncorrelated CDM isocurvature perturbation.

Components: dark matter, baryons, radiations

Adiabatic perturbations: perturbations of all the components are the same

Isocurvature perturbations: perturbation of each components is independent

WMAP 9yr constraint

$$\frac{\mathcal{P}_{\rm CDM}}{\mathcal{P}_{\mathcal{R}}} < \frac{\alpha}{1-\alpha}, \qquad \alpha < 0.047 \quad (95\% \; CL)$$

Asymmetron as dark matter

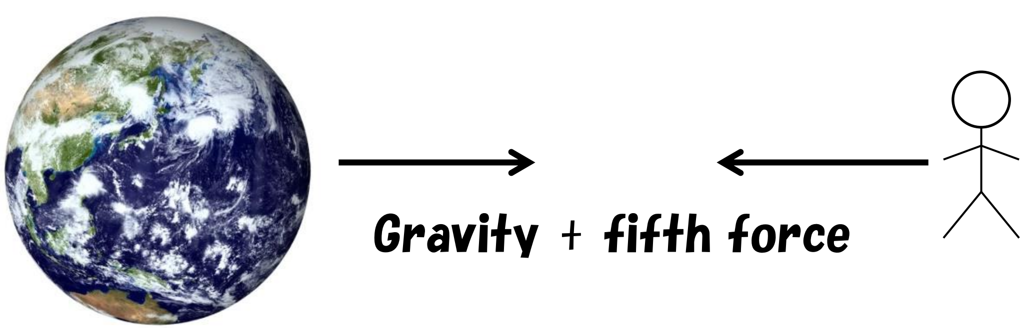
2. Non-observation of the fifth force.

Since ϕ field is still oscillating today, its has non-vanishing $<\phi^2>$.

$$\frac{1}{2}\mu^2 < \phi^2 > = \rho_{DM,local}$$

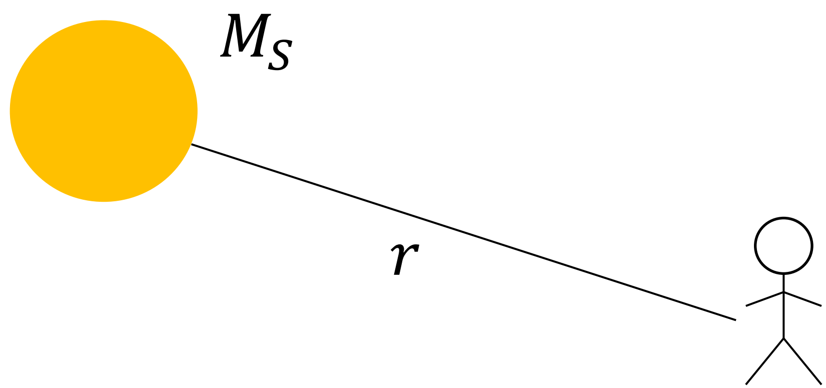
Since ϕ field has non-vanishing amplitude, it mediates fifth-force.
In particular, the strength of the fifth-force changes periodically in time.

$$\frac{2\pi}{\mu} \approx 4 \times 10^{-4}\ s \left(\frac{\mu}{10^{-11}\ \mathrm{eV}}\right)^{-1}$$



Asymmetron as dark matter

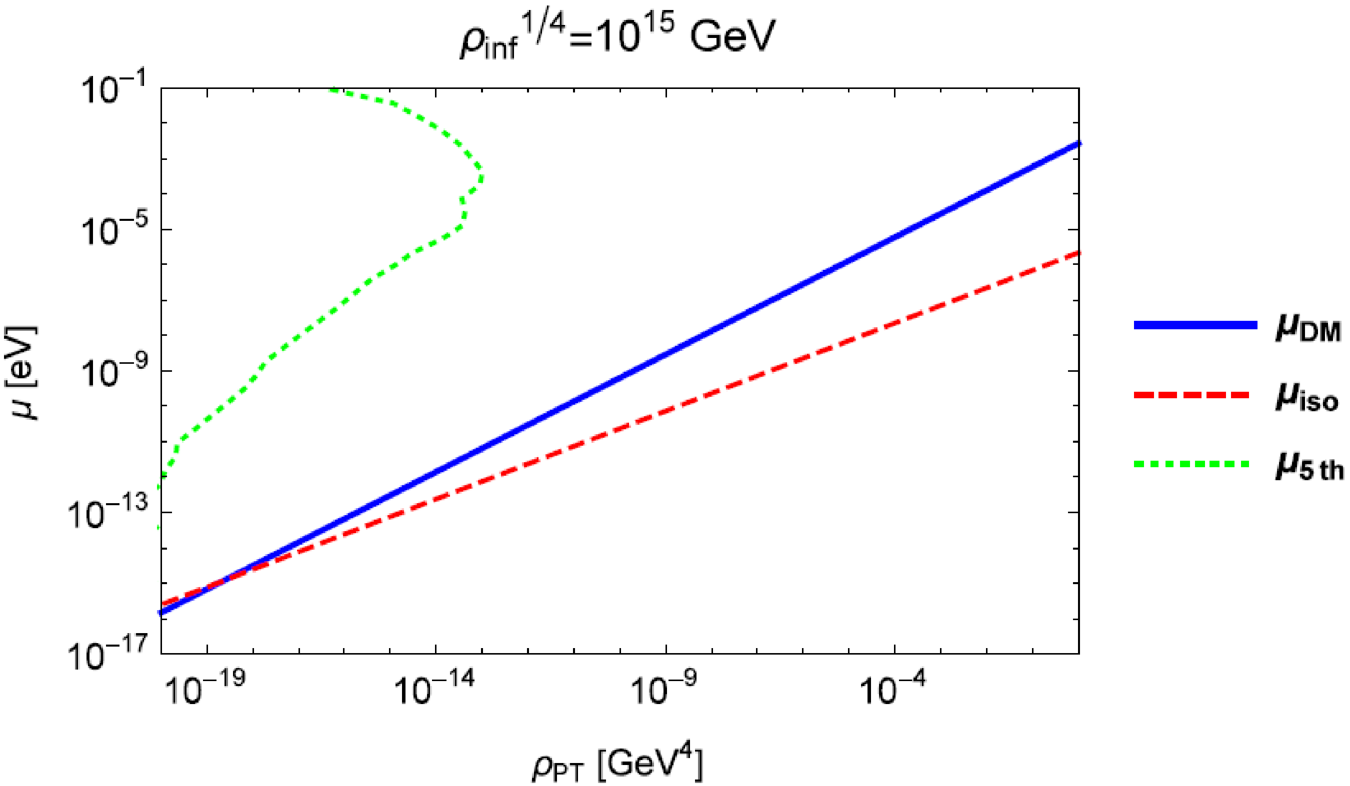
2. Non-observation of the fifth force.



$$\tilde{g}_{00} = -1 + \frac{2G_N M_s}{r} F(r)$$

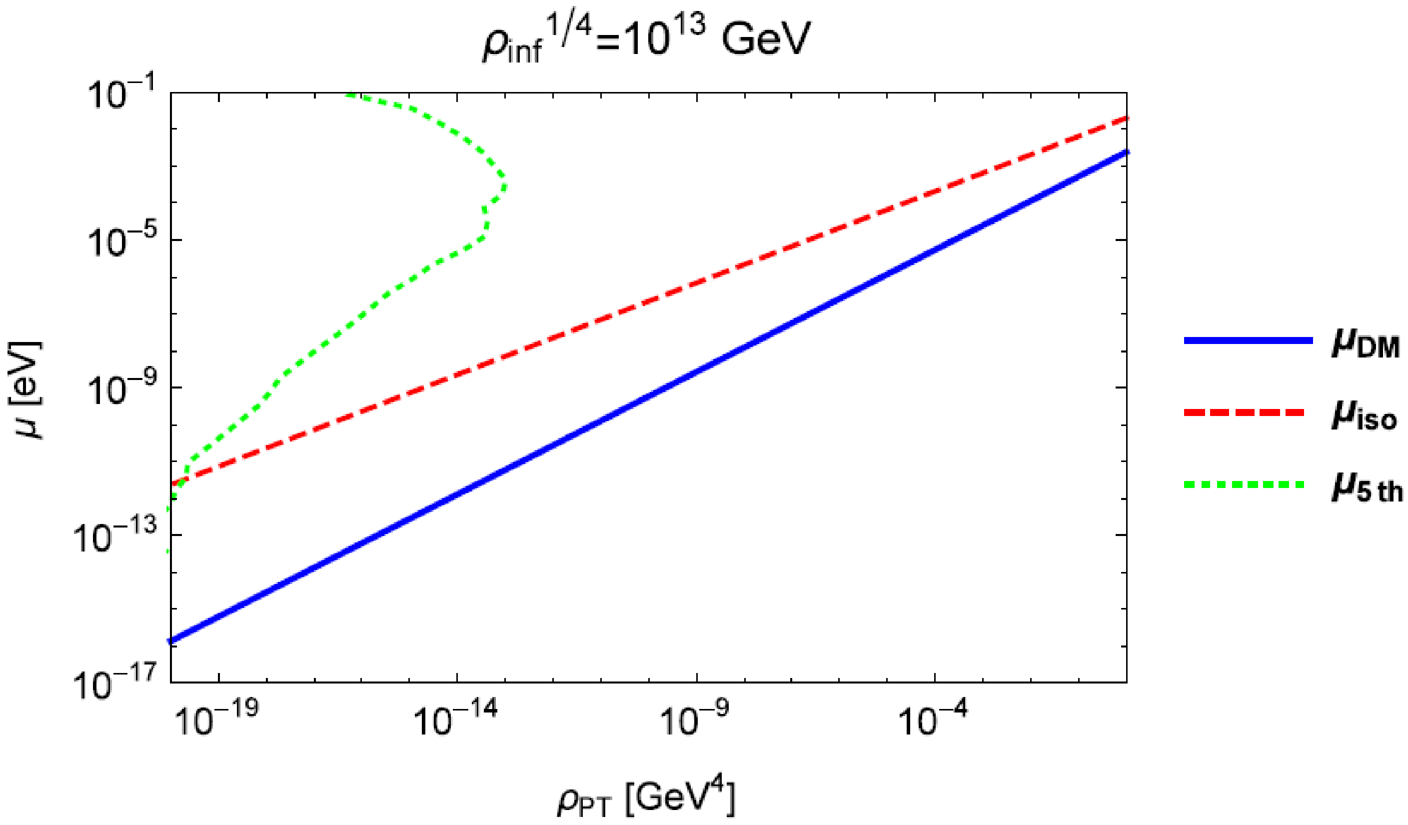
$$F(r) = 1 + \boxed{\frac{\mu^2}{4\pi G_N \varepsilon} \frac{\rho_{\rm DM}}{\rho_{\rm PT}^2} e^{-\mu r}}$$

Correction due to the fifth-force



Fifth-force from the asymmetron dark matter is much smaller than the upper limit set by the experiments.

However, constraint from the non-observation of CDM isocurvature perturbation is strong. Asymmetron as dark matter is inconsistent with inflation models with energy scale as large as $10^{15}GeV$.



Asymmetron as dark matter is consistent with inflation models with energy scale $10^{13} GeV$.

Low energy inflation is consistent with asymmetron being DM.

Summary

We have proposed a new scalar-tensor model in which the scalar field undergoes the spontaneous scalarization above the critical density.

The scalar field can be the DM. Spontaneous scalarization also provides the mechanism to generate the initial abundance of DM. (additional production mechanism is not needed)

The scalar field is only very weakly interacting with our matter (in the symmetric phase) and detecting such a field on the Earth is quite hard.

In the spontaneous scalarization phase, the gravitational constant gets weakened compared to the one measured in the laboratory. This may happen inside the compact objects.

Opening of GW observations will enable us to test this scenario and first "detection" of DM may come from such observations.

Issues to be investigated

Astrophysics of the spontaneous scalarization

- How is the structure of neutron star changed?
- What happens when scalarized object collapses into a BH?
- Dynamics of spontaneous scalarization. Process to reach into the stable state.
- What kind of observations are the most effective to test this model?