

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

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Motivation:

- It is nearly impossible to detect the light scalar dark matter interacting with SM only gravitationally
- If the scalar is coupled to the SM particles the chances to detect are rising.
- The **universal** coupling between the dark matter scalar and SM particles can be written as

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

Here we assume the symmetry $\phi \rightarrow -\phi$ which forbids linear interactions. We concentrate on the lowest masses:

$m = 10^{-16} \div 10^{-21}$ eV correspond to the DM which starts to oscillate between the BBN and recombination.

Varying constants

What is the possible effect of such DM?

Fermion mass term ($E \ll v_h$):

$$T_\mu^\mu(f) = m_f \bar{\psi} \psi$$

The electron mass is affected by the scalar field

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

Variation of the gauge coupling:

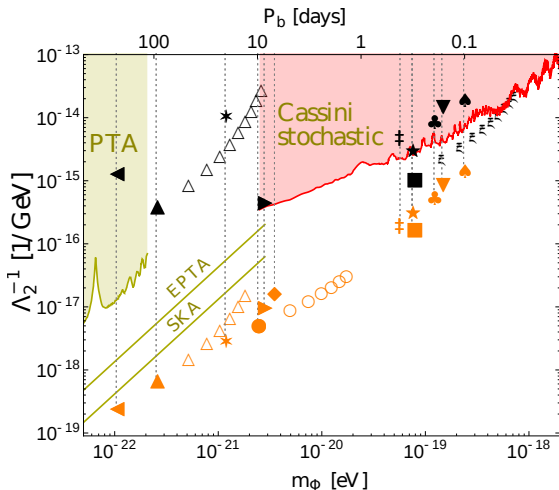
$$L = -\frac{1}{4g^2} F_{\mu\nu} F^{\mu\nu} + \frac{\phi^2}{\Lambda^2} \frac{b}{16\pi^2} F_{\mu\nu} F^{\mu\nu}$$

$\beta(g) = bg^3/16\pi^2$, for QCD $b = 7$.

The dark matter oscillations affect the electron, proton and neutron masses and gauge couplings.

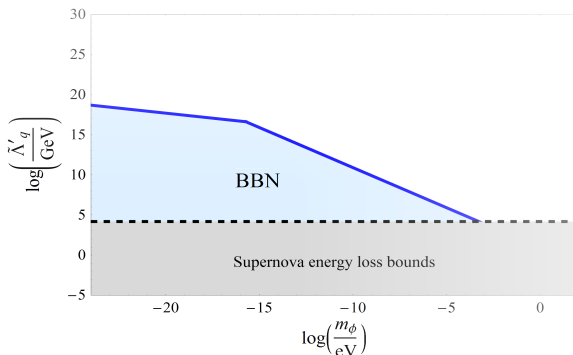
Constraints on the dark matter with quadratic coupling

Binary pulsars (Blas, Nacir, Sibiryakov, 1612.06789)



Constraints on the dark matter with quadratic coupling

Big Bang Nucleosynthesis (Stadnik, Flambaum, 1504.01798)



Not included: for low masses the interaction term with T_μ^μ can be relevant

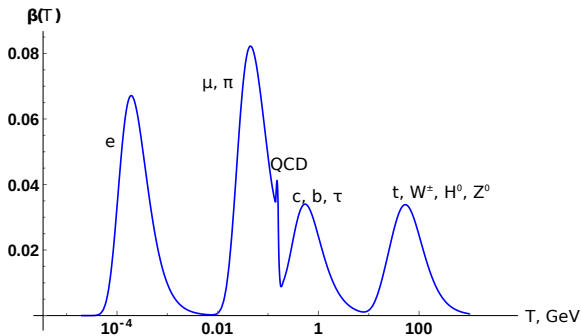
Dynamics of the scalar can be affected.

Trace of the energy-momentum tensor during the RD stage

$$T_{\mu}^{\mu} = \sum_i \frac{g_i}{2\pi^2} m_i^2 T^2 \int_{m_i/T}^{\infty} \frac{\sqrt{u^2 - (m_i/T)^2}}{\exp(u) \pm 1} du,$$

QCD anomaly is relevant for $T > 100$ GeV

$$T_{\mu}^{\mu} = \kappa \rho, \quad \kappa \sim 10^{-3}$$



Equation of motion for the scalar field in a hot Universe

Let us take $\kappa = 10^{-3}$ for analytical estimates.

$$t^2 \ddot{\phi} + \frac{3}{2} t \dot{\phi} + (m^2 t^2 + \alpha^2) \phi = 0$$

$$\alpha = \frac{3\beta M_{Pl}^2}{2\Lambda^2}$$

Initial conditions: $\phi(t_0) \sim \Lambda$

The leading solution before the oscillating regime ($mt \ll 1$):

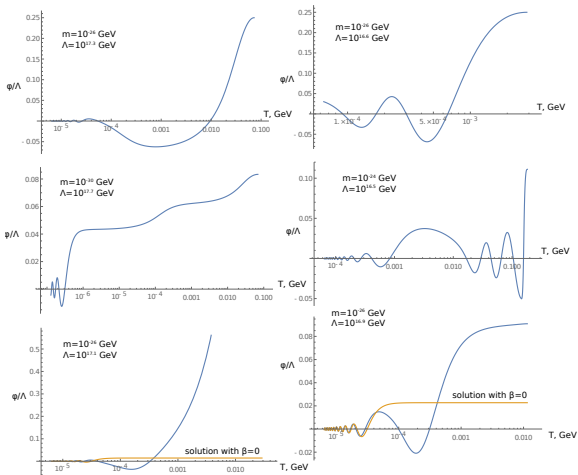
$$\phi(t) \approx \Lambda \left(\frac{t_0}{t} \right)^{\frac{1}{4}(1-\sqrt{1-16\alpha^2})}, \quad \alpha < 1/4$$

$$\phi(t) \approx \Lambda \left(\frac{t_0}{t} \right)^{1/4} \sin \left(\gamma \ln \left(\frac{mt}{2} + \text{const} \right) \right) \simeq \Lambda \left(\frac{t_0}{t} \right)^{1/4},$$

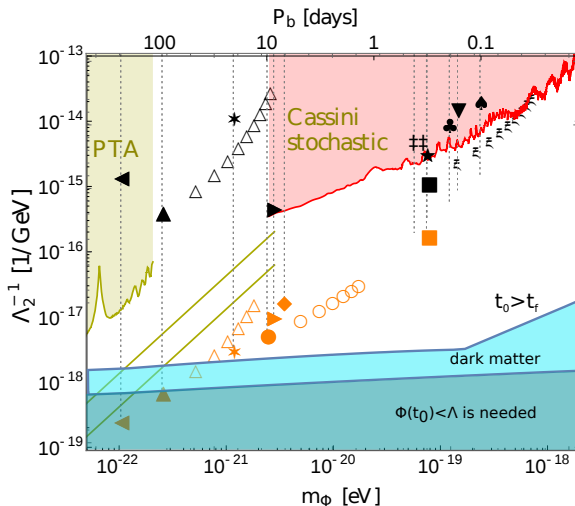
$$\alpha > 1/4, \quad \gamma = \frac{1}{4} \sqrt{16\alpha^2 - 1}$$

New effect: the field is falling for $mt \ll 1$ instead of being constant

Variety of solutions for the realistic T_{μ}^{μ}



Constraints from the dark matter production



Big Bang Nucleosynthesis with varying constants

The Planck data on the Helium fraction gives

$$0.2464 \leq X_{4He} \leq 0.2505.$$

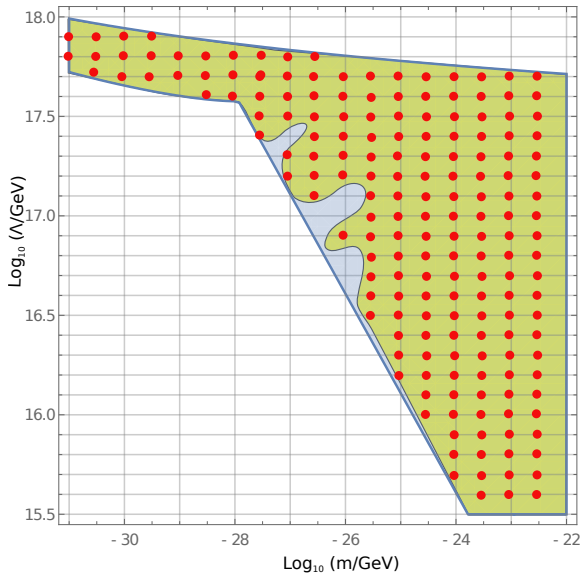
The Helium production is affected through the neutron-proton mass difference:

$$m_n - m_p = (m_n - m_p)_0 \left(1 + w \frac{\phi^2}{\Lambda^2} \right), \quad w \approx 0.82$$

The neutron lifetime is

$$\tau_n \sim G_F^2 m_e^5, \quad \tau_n = \tau_n^0 \left(1 + \frac{\phi^2}{\Lambda^2} \right)$$

Constraints from BBN and DM production



Is it possible to avoid the constraint?

Can we have the dark matter with **detectable** Λ which can be still produced and does not spoil BBN?

What do we need for that?

- During BBN the fundamental constants take SM values
- The variations start to appear after BBN

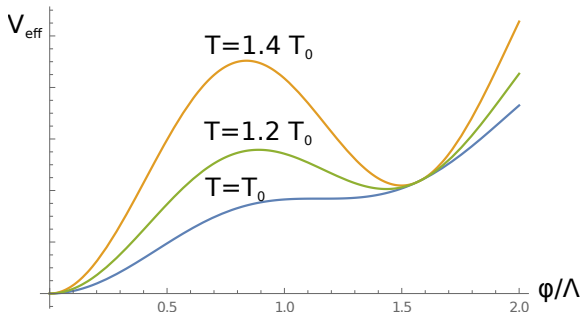
The model:

$$V(\phi) = m^2 \Lambda^2 \left(1 - \cos \left(\frac{\phi}{\Lambda} \right) \right).$$

$$L_{int}(\phi, T) = \kappa T_{\mu}^{\mu}(T) \left(1 - \cos \left(\frac{4\phi}{\Lambda} \right) \right).$$

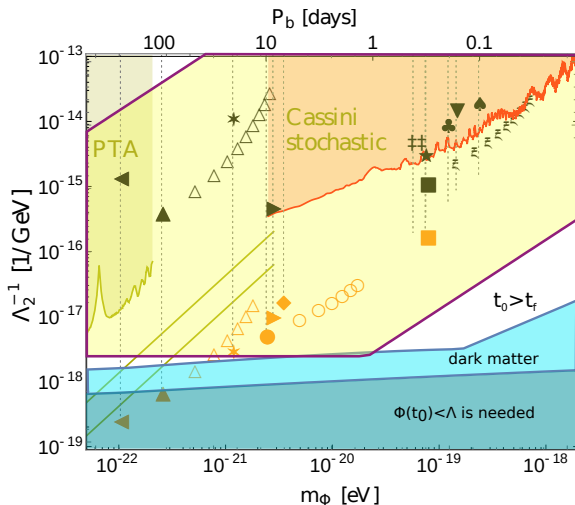
In the late Universe $\phi_{min} = 0$ but for large T $\phi_{min}/\Lambda \simeq \pi/2$.

The potential at different temperatures



Constraints for the cosine model

- $T_0 < 1$ keV
- $\kappa < 1$ — no strong coupling



- The dark matter with quadratic coupling to the trace of EMT is less constrained than those with linear coupling
- For the low mass range the impact of T_{μ}^{mu} on the classical field evolution before the oscillations is crucial.
- The most interesting (from the observational point of view) range of m and Λ is problematic. It should have started to evolve after BBN, to make all the dark matter. We need a complete model, in order to describe BBN. **It is not impossible!**
- We present an example of such a model which shows that the BBN (and production) constraints do not make the late time searches for the scalar DM unmotivated.



Thanks for your attention!