A scalar potential from gauge condensation and its implications

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Based on arXiv:1911.01050, with Prof. Eung Jin Chun (KIAS)

The importance of fundamental scalars

- Higgs: triggering electroweak symmetry breaking, giving mass to W/Z bosons as well as fermions
- Inflaton: driving expansion of early universe, solving the flatness and horizon problems, seeding the fluctuations in CMB
- A light scalar could also play a role of dark matter(fuzzy dark matter)
- A fundamental scalar may also be needed for Peccei-Quinn symmetry breaking or explaining the dark energy (quintessence)

Scalar interactions with gauge fields

Scalar interactions with gauge fields are widely considered:

E.g. with gluon fields $\frac{\phi}{M} G^{a\mu\nu} G^{a}_{\mu\nu}$ rich phenomenologies

- Leading to scalar-nucleus interactions

$$\frac{\phi}{M} G^{a\mu\nu} G^{a}_{\mu\nu} \Rightarrow \frac{c_N}{M} \phi \bar{N} N$$

↓ New force between matters

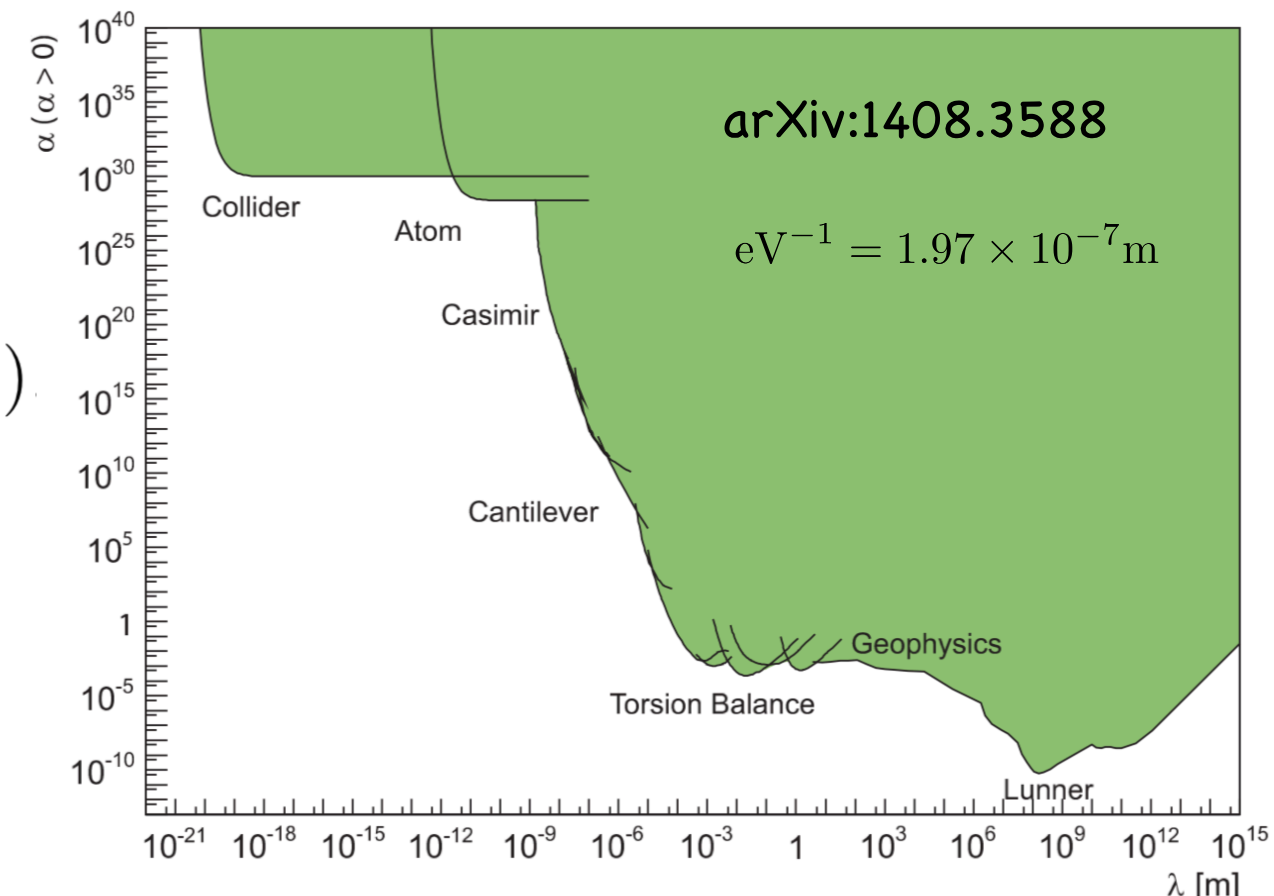
$$V_{Yukawa}(r) = -G_{\infty} \frac{Mm}{r} (1 + \alpha e^{-r/\lambda}) \qquad \alpha \sim M_P^2 \left(\frac{c_N}{M}\right)^2$$

Scalar interactions with gauge fields

- Motivating low energy experiments

$$V_{Yukawa}(r) = -G_{\infty}\frac{Mm}{r}(1+\alpha e^{-r/\lambda})$$

$$\alpha \sim M_P^2\left(\frac{c_N}{M}\right)^2$$



Fifth force searches

- Affecting star cooling process

Edward Hardy, Robert Lasenby, arXiv:1611.05852

Scalar interactions with gauge fields

- Leading the first order QCD phase transition

Robert D. Pisarski, Frank Wilczek 1984

The phase transition restoring chiral symmetry at finite temperatures is considered in a linear σ model. For three or more massless flavors, the perturbative ε expansion predicts the phase transition is of first order. At high temperatures, the UA(1)

(u, d, s) $\qquad m_s \sim 100 \text{ MeV} \quad \Lambda_{\text{QCD}} \sim 200 \text{ MeV}$

Seyda Ipek, Tim Tait,
Early Cosmological Period of QCD Confinement,
arXiv:1811.00559(PRL)

$$-\frac{1}{4g^2}\left(1-\frac{\langle\phi\rangle}{M}\right) G^{a\mu\nu}G^a_{\mu\nu}$$

$$\frac{1}{g^2} \to \frac{1}{g'^2} = \frac{1}{g^2}\left(1-\frac{\langle\phi\rangle}{M}\right)$$

Sebastian Ellis, Seyda Ipek, Graham White,
Electroweak Baryogenesis from Temperature-Varying Couplings
arXiv:1905.11994

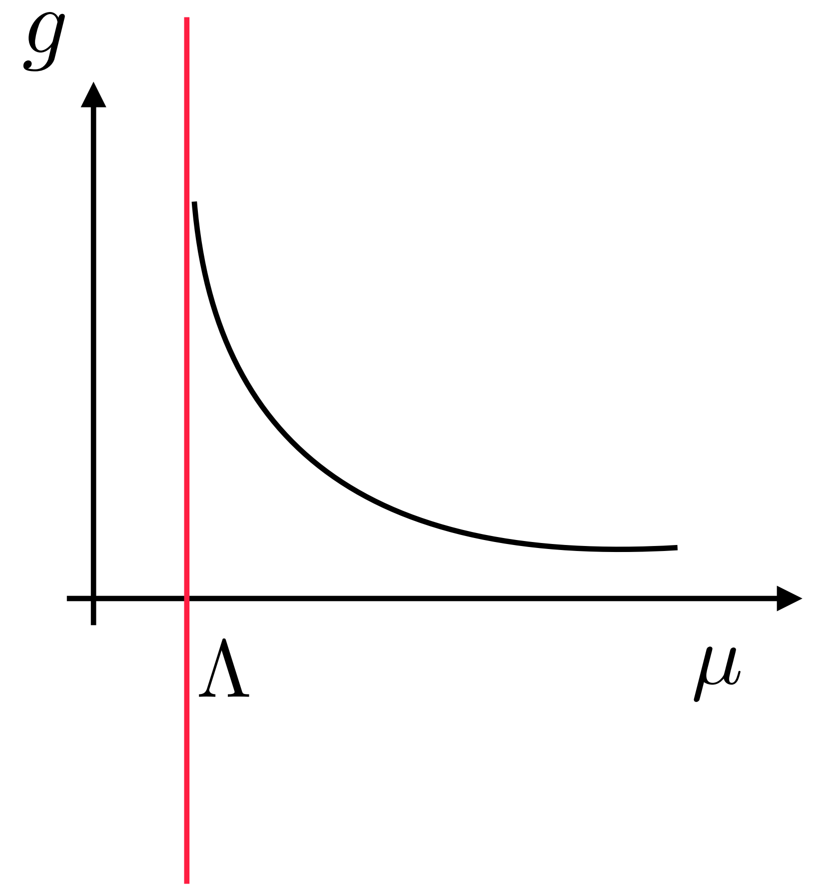
Djuna Croon, Jessica N. Howard, Seyda Ipek, Timothy M.P. Tait
QCD Baryogenesis, arXiv:1911.01432

Scalar interactions with gauge fields

- Considering a QCD-like SU(N),

$$\mathcal{L} \supset -\frac{1}{4g^2}\left(1 - c\frac{\phi}{M}\frac{\beta}{2g}\right) G^{\mu\nu}G_{\mu\nu}$$

Confinement at low energy scale



$$\frac{dg}{d\ln\mu} \equiv \beta = -\beta_0 \frac{g^3}{16\pi^2} \qquad \beta_0 = (\frac{11}{3}N - \frac{2}{3}n_f)$$

$$\frac{1}{g^2_{\rm eff}(M)} - \frac{1}{g^2(\mu)} = \frac{\beta_0}{8\pi^2}\ln\frac{M}{\mu}$$

$$\frac{1}{g^2(\Lambda)} \to 0 \qquad \Lambda = M\exp(-\frac{8\pi^2}{g^2_{\rm eff}\beta_0})$$

$$\frac{1}{g^2_{\rm eff}} = \frac{1}{g^2}(1 - c\frac{\langle\phi\rangle}{M}\frac{\beta}{2g}) \longrightarrow \Lambda = M\exp(-\frac{8\pi^2}{g^2\beta_0} - \frac{c}{4}\frac{\langle\phi\rangle}{M})$$

Scalar interactions with gauge fields

Like QCD, gauge fields condensates

$$\langle \frac{\alpha}{\pi} G^{\mu\nu} G_{\mu\nu} \rangle = \Lambda^4$$

M. A. Shifman, A.I. Vainshtein, V. I. Zakharov, 1979

The vacuum energy has phi dependence:

$$V_{vac} = \frac{1}{4}\langle T^{\mu}_{\mu} \rangle = \langle \frac{\beta}{8g_s} G^{\mu\nu} G_{\mu\nu} \rangle + \frac{1}{4} m_f \langle \bar{f} f \rangle$$

$$\simeq -\frac{\beta_0}{32}\Lambda^4 = -\frac{\beta_0}{32}\Lambda_0^4 \exp(-c\frac{\phi}{M}) \qquad |c\frac{\phi}{M}| \lesssim \mathcal{O}(1)$$

Scalar interactions with gauge fields

The new potential provide a dimensionful term for the scalar field, sourcing a new scale $\langle\phi\rangle$

$$\mathcal{L} \supset -\frac{\lambda}{4}\phi^4 - \frac{1}{4g^2}\left(1 - \frac{\phi}{M}\frac{\beta}{2g}\right) G^{\mu\nu}G_{\mu\nu}$$

$$V = \frac{\lambda}{4}\phi^4 - \Lambda_0^4 \exp(-\frac{\phi}{M})$$

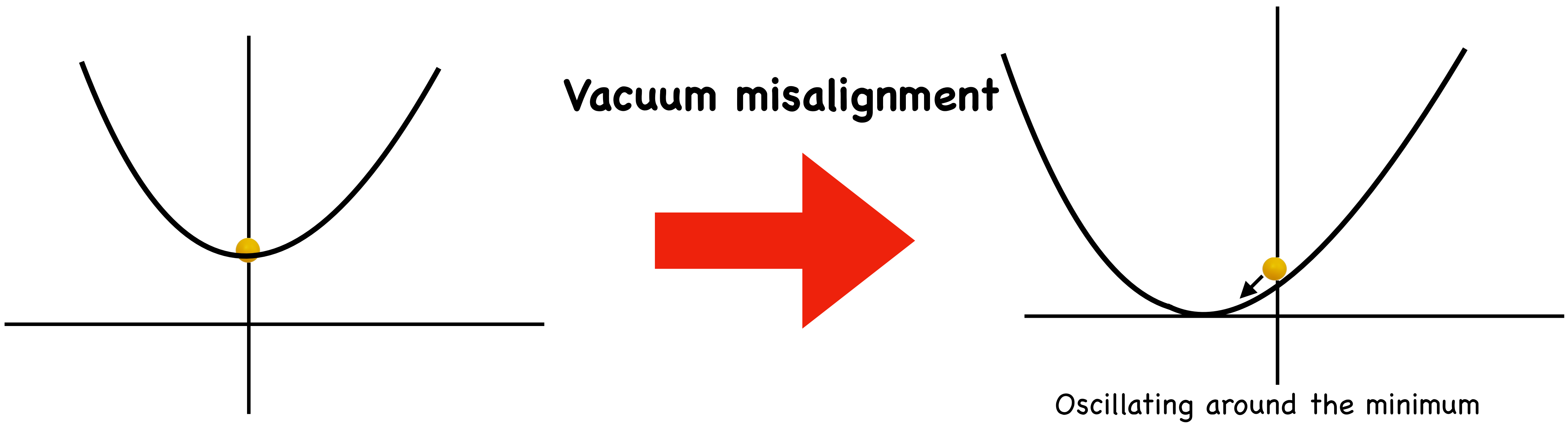
The minimum of potential locates at

$$\langle\phi\rangle \simeq -\lambda^{-1/3}\Lambda_0 \left(\frac{\Lambda_0}{M}\right)^{1/3}$$

$$m_\phi^2 = 3\lambda\langle\phi\rangle^2 - \frac{\Lambda_0^4}{M^2} \qquad \lambda > \frac{1}{27}(\frac{\Lambda_0}{M})^4$$

Vacuum misalignment

Before phase transition | After phase transition



$$V = \frac{\lambda}{4}\phi^4$$

$$\langle\phi\rangle \simeq 0$$

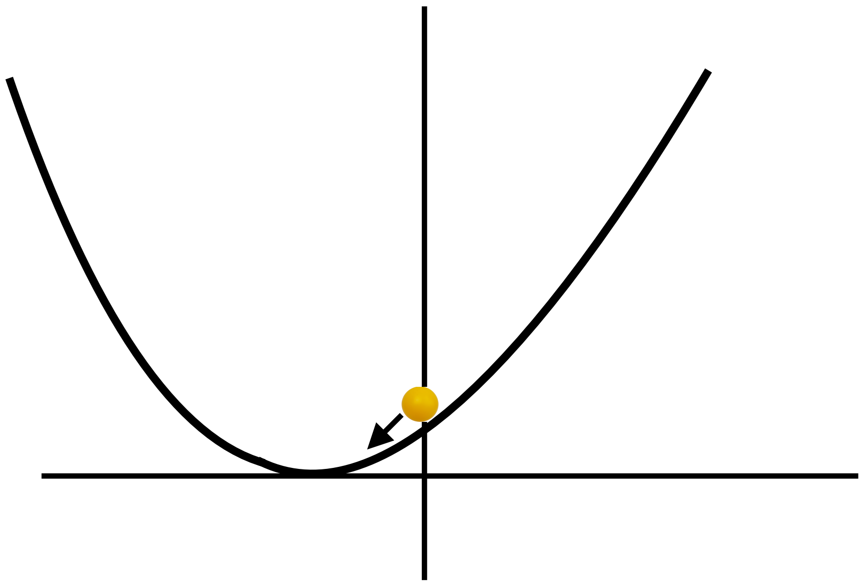
$$V = \frac{\lambda}{4}\phi^4 - \Lambda_0^4 \exp(-\frac{\phi}{M})$$

$$\langle\phi\rangle \simeq -\lambda^{-1/3}\Lambda_0\left(\frac{\Lambda_0}{M}\right)^{1/3}$$

(Ignore the radiative corrections)

No thermal corrections, no thermal equilibrium

Oscillating scalar field



Oscillating around the minimum

- Lifetime is short: similar to preheating, as a matter component and later release the entropy and reheat the universe

(Maybe interesting to study)

- Lifetime is long enough: dark matter candidate

(like axion dark matter)

$$\rho_\phi \times \left(\frac{T_{eq}}{T_{osc}}\right)^3 \frac{g_*(T_{eq})}{g_*(T_{osc})} \simeq 0.4\ (\mathrm{eV})^4$$

$$\rho_\phi \simeq \frac{3}{4}\lambda\langle\phi\rangle^4 \text{ and } T_{eq} \simeq 0.8\ \mathrm{eV}$$

Minimal model for scalar dark matter

Scalar couples to QCD sector

$$\mathcal{L} \supset -\frac{\lambda}{4}\phi^4 - \frac{1}{4g_s^2}\left(1 - \frac{\phi}{M}\frac{\beta_s}{2g_s}\right) G_s^{a\mu\nu} G^a_{s\mu\nu}$$

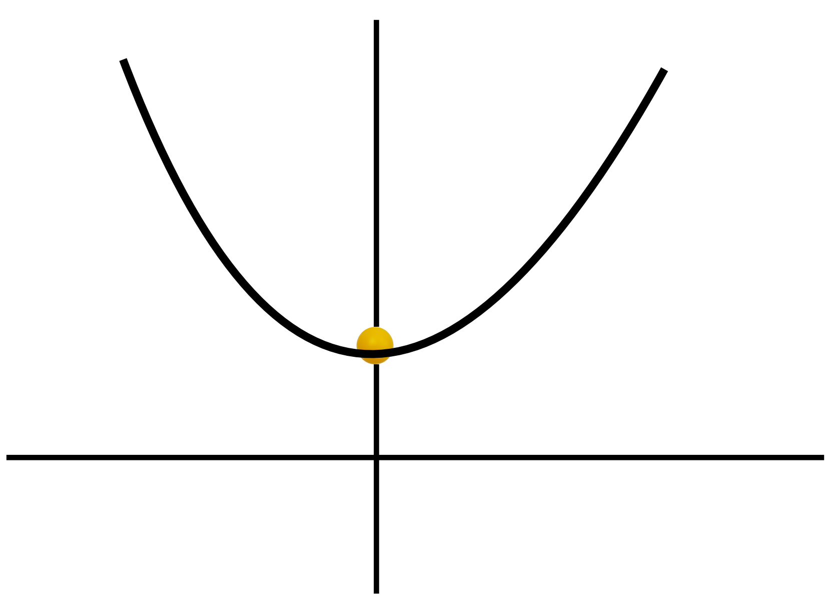
$$V = \frac{\lambda}{4}\phi^4 - \Lambda_{\rm QCD}^4 \exp(-\frac{\phi}{M})$$

→

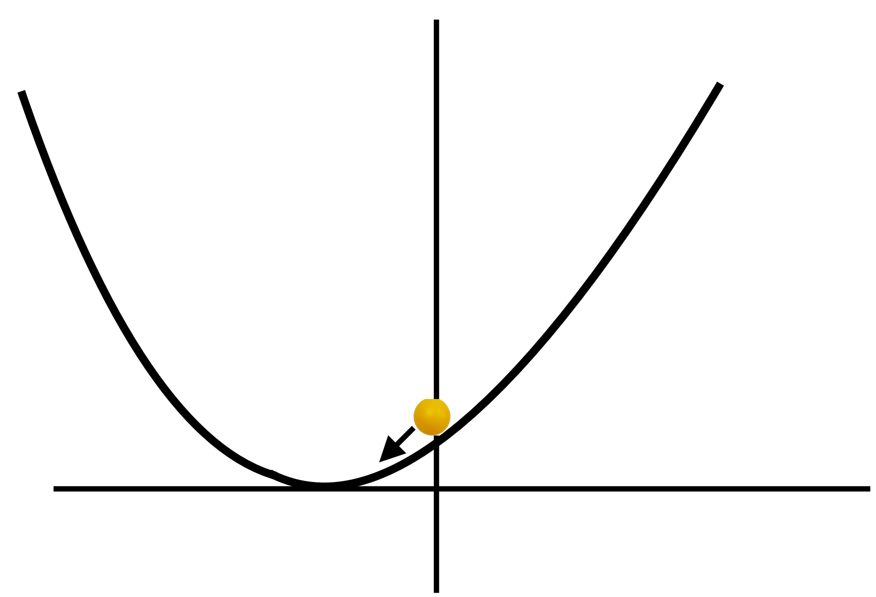
$$\langle\phi\rangle \simeq -\lambda^{-1/3}\Lambda_{\rm QCD}\left(\frac{\Lambda_{\rm QCD}}{M}\right)^{1/3}$$

$$m_\phi^2 = 3\lambda\langle\phi\rangle^2 - \frac{\Lambda_0^4}{M^2}$$

$T > \Lambda_{\rm QCD}$



$T < \Lambda_{\rm QCD}$



Oscillating around the minimum

Lifetime of the scalar field

Scalar decaying into di-photon

$$\frac{\phi}{M}\frac{\beta_s}{2g_s}G^{a\mu\nu}G^a_{\mu\nu} \Rightarrow \gamma_m \frac{m_f}{M}\phi\bar{f}f \Rightarrow C\frac{\phi}{M}F_{\mu\nu}F^{\mu\nu}$$

$$\Gamma_{\phi\to\gamma\gamma} \approx \sum_q \frac{1}{\pi}\left(\frac{\alpha}{4\pi}\right)^2 \alpha_s^2 Q_q^4 \frac{m_\phi^3}{M^2}$$

$$\tau_{\phi\to\gamma\gamma} \approx 5\times 10^{17}\text{sec}\left(\frac{3\text{ keV}}{m_\phi}\right)^5$$

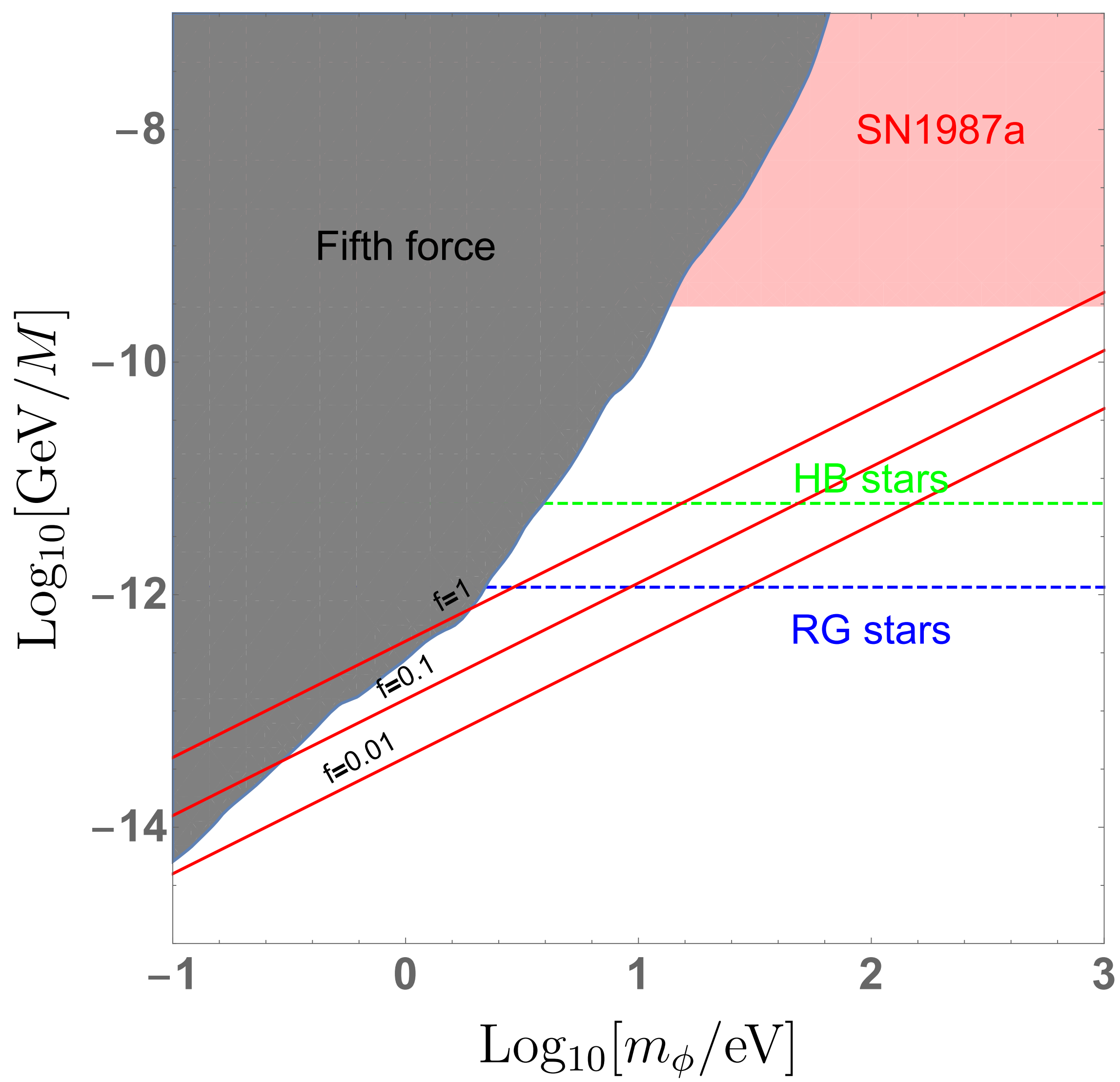
Scalar mass less than 3 keV lifetime longer than our universe

Scalar couplings with nucleus

$$\frac{\phi}{M}\frac{\beta}{2g}G^{a\mu\nu}G^{a}_{\mu\nu} \Rightarrow \mathcal{O}(1)\frac{\phi}{M}m_N\bar{N}N$$

- Fifth force measurement
- Star cooling process

Results for the minimal model



Very limited region, only mass around eV is allowed

larger parameter space with a fraction of dark matter

Additional SU(N)

Same coefficient for simplicity

$$\mathcal{L} \supset -\frac{1}{4}\lambda\phi^4 - \frac{1}{4g_N^2}\left(1 - \frac{\phi}{M}\frac{\beta_N}{2g_N}\right)G_N^2 - \frac{1}{4g_s^2}\left(1 - \frac{\phi}{M}\frac{\beta_s}{2g_s}\right)G_s^2$$

$$V = \frac{1}{4}\lambda\phi^4 - \Lambda_N^4 \exp(-\frac{\phi}{M}) - \Lambda_{\rm QCD}^4 \exp(-\frac{\phi}{M})$$

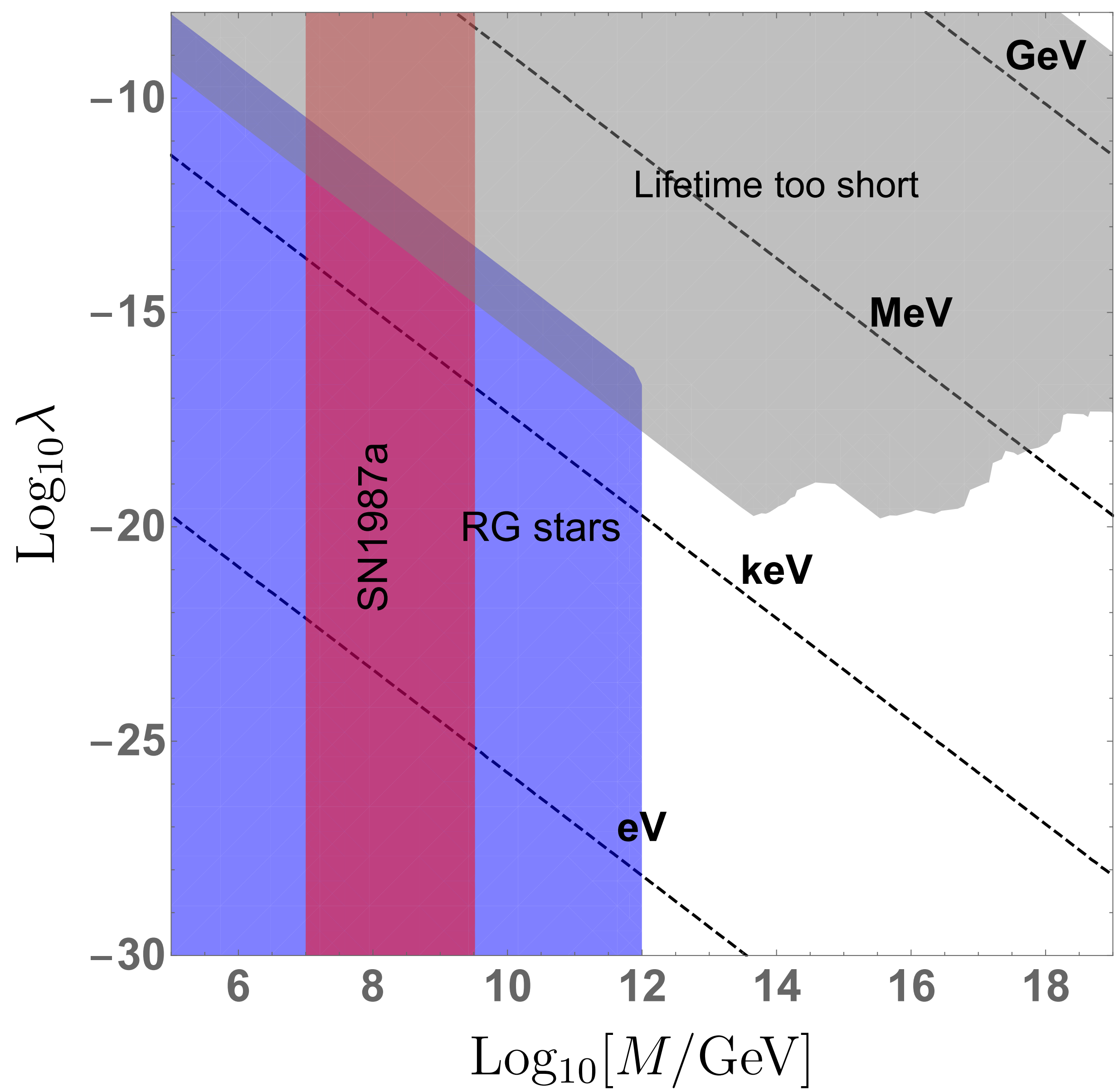
$$\Lambda_N \gg \Lambda_{\rm QCD}$$

$$\langle\phi\rangle \simeq -\lambda^{-1/3}\Lambda_N\left(\frac{\Lambda_N}{M}\right)^{1/3}$$

$$m_\phi^2 = 3\lambda\langle\phi\rangle^2 - \frac{\Lambda_0^4}{M^2}$$

Mass can be a free parameter

Additional SU(N)



- Dark matter mass (eV- MeV)
- Limit can be weaker for smaller coupling in QCD sector
- Some fermions is needed to make two sector same temperature in the very early universe

Scalar potential for symmetry breaking

Assuming phi carries additional charge

$$\mathcal{L} \supset -\frac{\lambda}{4}(\phi^\dagger\phi)^2 - \frac{1}{4g^2}\left(1 - c\frac{\phi^\dagger\phi}{M^2}\frac{\beta}{2g}\right)G^{\mu\nu}G_{\mu\nu}$$

↓

$$\begin{aligned} V &= \frac{\lambda}{4}(\phi^\dagger\phi)^2 - \Lambda_0^4 \exp(-c\frac{\phi^\dagger\phi}{M^2}) \\ &= \frac{\lambda}{4}(\phi^\dagger\phi)^2 - \Lambda_0^4 + c\frac{\Lambda_0^4}{M^2}\phi^\dagger\phi + \cdots \end{aligned}$$

$c > 0$ Only contributes the mass terms

$c < 0$ Symmetry breaking $\langle\phi\rangle \simeq (-\frac{2c}{\lambda})^{1/2}\frac{\Lambda_0^2}{M}$

For PQ-symmetry breaking 10^{11} GeV $\Lambda_0 \sim 10^{15}$ GeV

Origin of the Higgs potential

$$\mathcal{L} \supset -\lambda(H^\dagger H)^2 - \frac{1}{4g^2}\left(1 + \frac{H^\dagger H}{M^2}\frac{\beta}{2g}\right) G^{\mu\nu}G_{\mu\nu}$$

$$\begin{aligned} V &= \lambda(H^\dagger H)^2 - \Lambda_0^4 \exp(\frac{H^\dagger H}{M^2}) \\ &\approx -\frac{\Lambda_0^4}{M^2} H^\dagger H + (\lambda + \frac{1}{2}\frac{H^\dagger H}{M^2})(H^\dagger H)^2 - \frac{1}{6}\frac{\Lambda_0^4}{M^6}(H^\dagger H)^3 + \cdots . \end{aligned}$$

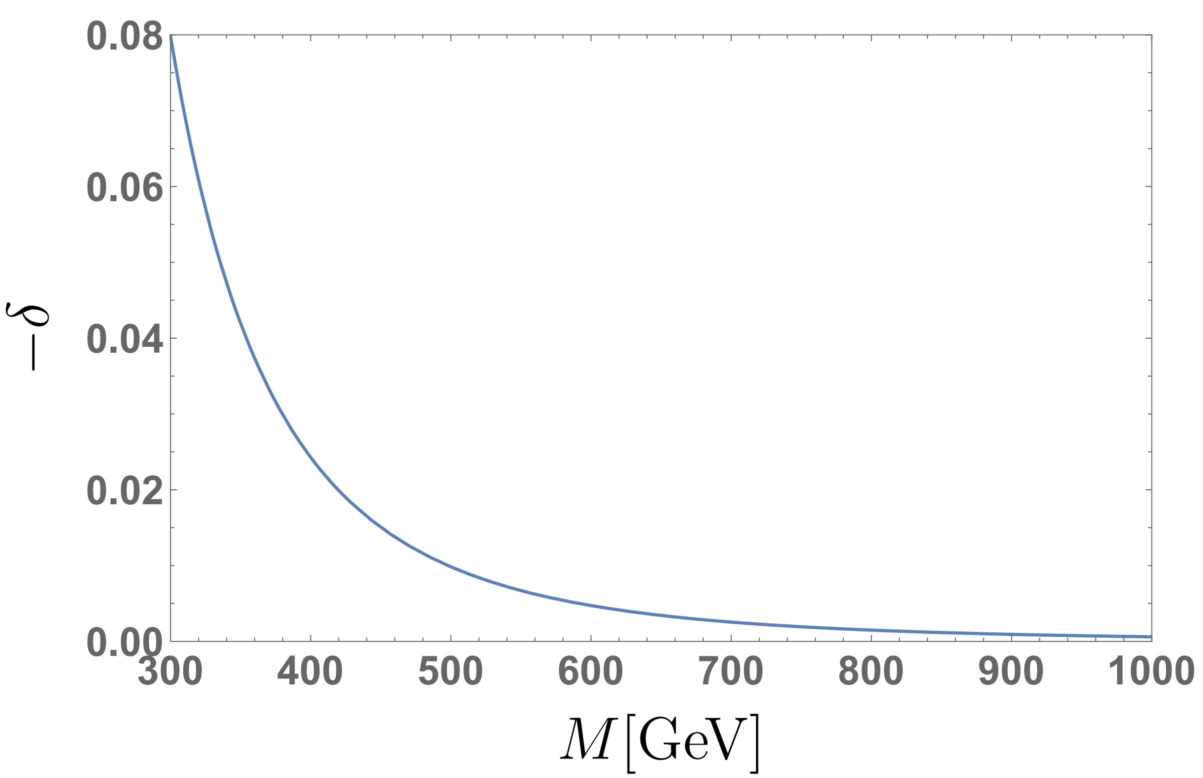
$$H = (0, (h+v)/\sqrt{2})^T \quad v = 246 \text{ GeV} \quad m_h = 125 \text{ GeV}$$

$$\Lambda_0 = \sqrt{2} M \left(\frac{m_h^2}{8M^2 - v^4/M^2}\right)^{1/4}$$

Origin of the Higgs potential

$$
\begin{aligned}
V &= \lambda(H^\dagger H)^2 - \Lambda_0^4 \exp(\frac{H^\dagger H}{M^2}) \\
&\approx -\frac{\Lambda_0^4}{M^2} H^\dagger H + (\lambda + \frac{1}{2}\frac{H^\dagger H}{M^2})(H^\dagger H)^2 - \frac{1}{6}\frac{\Lambda_0^4}{M^6}(H^\dagger H)^3 + \cdots .
\end{aligned}
$$

$$\delta \equiv (\lambda_{hhh}/\lambda_{hhh}^{SM}) - 1 \qquad \delta = -\frac{4v^4}{24M^4 - 3v^4} \simeq -\frac{1}{6}(\frac{v}{M})^4$$



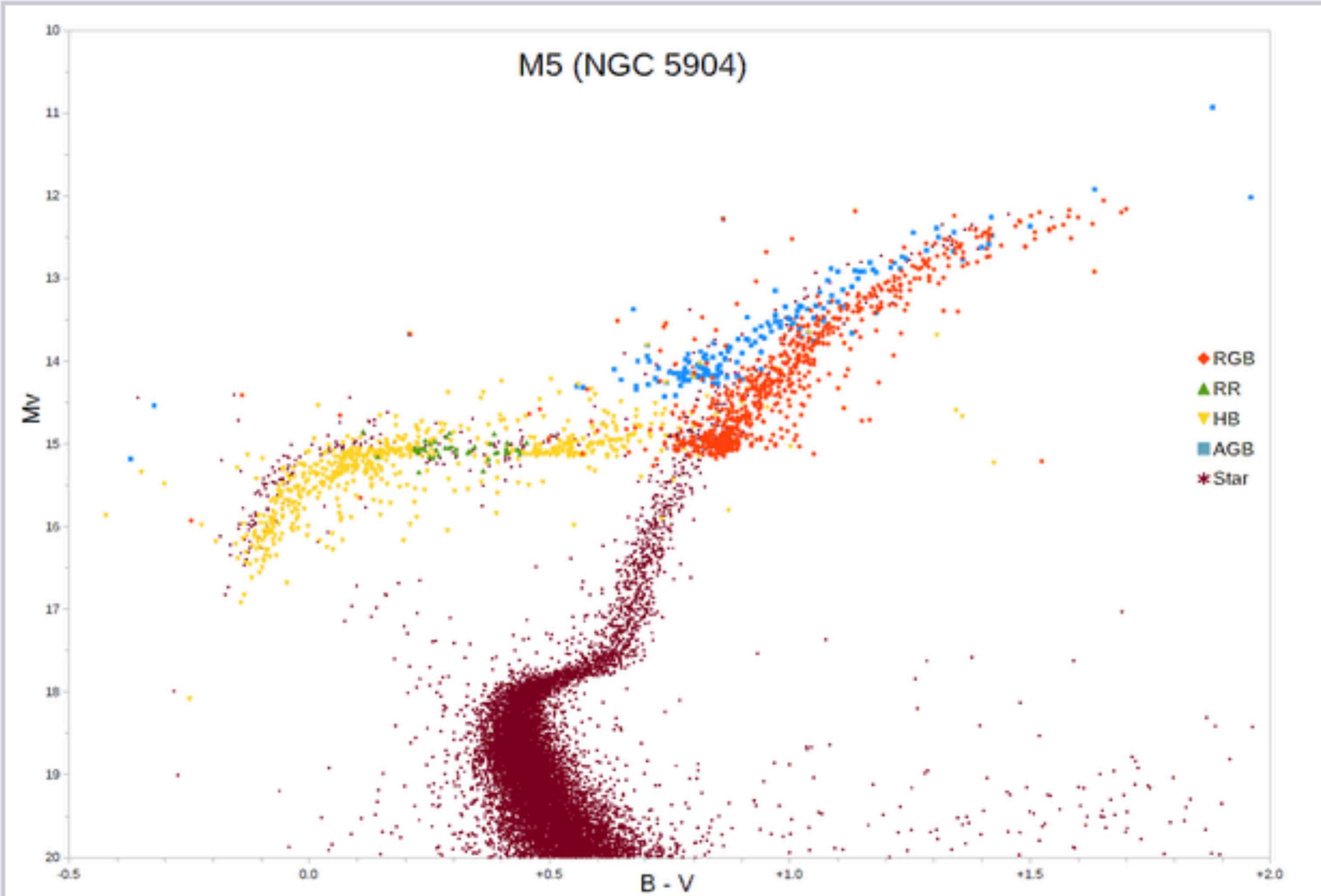
Summary

- If a scalar coupling to a kinetic term of a gauge field, after the confinement, it induces an exponential potential for the scalar field.

- It help us understand the origin of dark matter.

- It can also provide an origin of symmetry breaking, e.g. electroweak symmetry breaking

Back up



Hertzsprung–Russell diagram for globular cluster M5, with the horizontal branch marked in yellow, RR Lyrae stars in green, and some of the more luminous red giant branch stars in red