VILA DO CONDE, PORTUGAL, 29-31 MARCH, 2016

11th Iberian Cosmology Meeting

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SERIES OF MEETINGS WHICH AIM TO ENCOURAGE INTERACTIONS AND COLLABORATIONS BETWEEN RESEARCHERS WORKING IN COSMOLOGY AND RELATED AREAS IN PORTUGAL AND SPAIN.

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Inflation from String field theory

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Based on arXiv:1604.XXXX in collaboration with Alexey S. Koshelev and Paulo Vargas Moniz

PD F
PROGRAMAS DE DOUTORAMENTO FCT

Constraints on inflation

Spectral index Vs tensor scalar ratio

- The current bounds $n_s = 0.968 \pm 0.006$ and $r < 0.08$ at 95% CL from BKP severely constrain many inflationary scenarios.
- The perturbation spectrum imprinted in the CMB is Gaussian to a high degree, imposing severe constraints on the bispectrum amplitudes: $f_{NL}^{loc} = 0.8 \pm 5.0$, $f_{NL}^{eq} = -4 \pm 43$ and $f_{NL}^{ortho} = -26 \pm 21$ at the 68% confidence level.
- Small running $dn_s/d\ln k = -0.003 \pm 0.007$.
- All these so far not evidently deviated from single field inflation. Assuming a negligible non-Gaussianity Starobinsky and Higgs inflationary models are consistent and occupies a privileged position in the $n_s - r$ plane

$$n_s = 1 - \frac{2}{N} \quad , \quad r = \frac{12}{N^2}$$

Starobinsky (like) Inflation

- The flat potentials are most successful in single field inflationary cosmology

$$V \sim \left(1 - e^{-\sqrt{2/3B}\varphi}\right)^{2n}$$

- With an additional parameter " B " introduced gives Universal predictions with any value of $r < 0.1$

$$n_s = 1 - \frac{2}{N} \quad , \quad r = \frac{12B}{N^2}$$

- " B " which regulates the value of r has different origins in different inflationary models. Aiming towards UV completion there are models proposed with different constructions of $\mathcal{N} = 1$ SUGRA. For example,
- $\alpha-$attractor models, $B = \alpha$ which is the curvature of Kähler geometry. Kallosh and Linde (2013) ,No scale models , where B is related to the $\#$ of moduli fields, Ellis, Nanopolous and Olive (2013) , Axionic Starobinsky like inflation in String theory Ralph Blumenhagen et al (2015) etc.,.

String Field Theory

Strings at GUT scale

- Given the present observational data, value of the Hubble parameter during inflation can be as large as 10^{15} Gev suggesting the scale of inflation $M_I > 10^{15}$Gev.
- These energy scales are acceptable in string theory and strings were argued to play a crucial role indeed. M. Cicoli and A. Mazumdar (2011).
- Accounting strings as a key player in the inflationary model building one must account also the string field theory (SFT) which is crucial in building the potentials of string excitations I. Y. Arefeva et al (2001).
- In generic words SFT is an off-shell description of interacting strings. It describes a string by means of a string field Ψ and Non locality is an essential feature of SFT.

Tachyon condensation

Considering the field theory of open strings, the subject of tachyons is most crucial and as per the conjectures of Ashoke Sen (1999) *tachyon of open strings cause the decay of unstable D-branes or D-brane-anti-D-brane pairs. The phenomenon is known as tachyon condensation which prescribes the depth of the tachyon potential minimum is exactly the tension of an unstable brane to which the string is attached to.*

- We naturally assume that the string scale and energies of a brane decay (tachyon condensation) are higher than the scale of inflation.
- In our SFT scenario we consider open and closed strings low mass-level Lagrangians coupled through metric and dilaton. We show that the open string tachyon upon coupling to the massless sector of closed strings generates an interesting inflationary model. In other words, we obtain the inflation as the aftermath of an unstable brane (or pair of branes, i.e. brane-anti- brane) decay.

Closed string dilaton

To obtain a consistent infation based on SFT , we start with the following effective action of closed string dilaton and an open string tachyon ($\Phi = e^{-\phi}$)

$$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} \left(\Phi^2 R + 4\partial_\mu \Phi \partial^\mu \Phi \right) - \frac{T}{2} \Phi \sum_{n=0} \Phi^n v_n(\Box, \mathcal{T}) \right] .$$

- $n = 0$ case which corresponds to Linear dilaton supports only Minkowski solution, therefore such a case is not suitable for inflation.
- The above action supports a de Sitter phase (first requirement for inflation) at

$$\Phi = 1, \ \mathcal{T} = \mathcal{T}_0, \ g_{\mu\nu} \text{ is dS with } R = R_0 = 2\frac{T}{M_P^2} \sum_n v_{n,0} .$$

SFT Inflation

- We compute a quadratic variation of the previous action for scalar modes around the dS background. The scalar modes are $\varphi = \delta\Phi$, trace of the metric perturbations h (we define $\delta g_{\mu\nu} = h_{\mu\nu}$, $h = h^{\mu}_{\nu}$) and $\tau = \delta\mathcal{T}$.
- Eliminating τ and h using EoM , we arrive at

$$\delta^{(2)}S = \frac{1}{2}\int d^4x\,\sqrt{-g}\varphi\mathcal{F}(\Box)\varphi$$

- Here $\mathcal{F}(\Box)$ is a non-local operator which arise due to the coupling of dilaton and open string tachyon.
- To generate the inflation we must accompany our model with an appropriate potential. The linearization and corresponding analysis do not shed light on the form of the potential. However, choice of potential is arbitrary. Most important point to note here is the non-local operator which can give rise to interesting inflationary scenarios.

SFT Inflation

- With a general operator function $\mathcal{F}(\Box)$ one cannot extract physics of it easily.
- In general $\mathcal{F}(z)$ is an algebraic function that may have many roots. Following the Weierstrass factorization

$$\mathcal{F}(z) = e^{\gamma(z)} \prod_j (z - z_j)^{m_j}$$

We can write a locally equivalent action for the previous one with $\varphi = \sum \varphi_j$ (A. S. Koshelev (2007))

$$S_{local} = \frac{1}{2} \int d^4x \sqrt{-g} \sum_j \mathcal{F}'(z_j) \varphi_j (\Box - z_j) \varphi_j$$

- One real root z_1 is a simplest situation. In this case we have just a Lagrangian for a massive scalar. It is an acceptable one if $\mathcal{F}'(z_1) > 0$ in order to evade a ghost in the spectrum.

Attractor Inflation from SFT

Let us consider the following effective model

$$S_1 = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}\tilde{\Phi}^2 R - \frac{A}{2}\partial\tilde{\Phi}^2 - V(\tilde{\Phi})\right] .$$

- The model is equivalent to previously mentioned model of SFT with one real root $\mathcal{F}(z_1)$
- We can achieve this by matching quadratic variation of the action $\delta^2 S_1$ around dS. From this process we can identify

$$\begin{aligned}\mathcal{F}'(z_1) &\to 6M_P^2 + A \\ \mathcal{F}'(z_1)z_1 &\to 3M_P^2 R_0 - V''\left(\tilde{\Phi}_0\right) .\end{aligned} \tag{1}$$

In an inflating Universe the gravity part $M_P^2 R_0$ dominates over V''. As such we see that SFT produces an inflation and dictates $\mathcal{F}'(z_1)z_1$ to be $3M_P^2 R_0$.

Attractor Inflation from SFT

- We consider a potential $V_J\left(\tilde{\Phi}\right) = V_0\left(-\tilde{\Phi}^2 + \tilde{\Phi}^4\right)^2$ in the previous action, which corresponds to an Einstein frame potential in terms of canonically normalized field $\left(\tilde{\phi}\right)$

$$V_E = \tilde{V}_0\left(1 - e^{-\sqrt{\frac{2}{3B}}\tilde{\phi}}\right)^2 ,$$

where $B = 1 + A/6$. The inflationary predictions corresponding to the potential are well known to be

$$n_s = 1 - \frac{2}{N} \quad , \quad r = \frac{12B}{N^2} .$$

We therefore conclude that provided the non-local operator $\mathcal{F}(\Box)$ originating from the string field theory contains one real root it gives a successful inflation with a universal attractor predictions of $n_s = 0.967$ and any the value of the tensor to scalar ratio $r < 0.1$. The value of r can be regulated to any value by varying the slope of the non-local function $\mathcal{F}'(z_1)$ at the position of the root z_1.

Conformal invariance from SFT

- Considering such a pair of complex conjugate roots for $\mathcal{F}(\Box)$ we generate a two field model with one of them as ghost $\varphi_1 = \chi + i\sigma$, $z_1 = \alpha + i\beta$, $\mathcal{F}'(z_1) = f_1 + if_2$ one gets

$$S_{pair} = \int d^4x\sqrt{-g}[\chi(f_1\Box - f_1\alpha + f_2\beta)\chi - \sigma(f_1\Box - f_1\alpha + f_2\beta)\sigma - 2\chi(f_2\Box - f_2\alpha - f_1\beta)\sigma]$$

- The corresponding effective model can be written as

$$S_2 = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}[\tilde{\alpha}\tilde{\Phi}_1^2 - \tilde{\alpha}\tilde{\Phi}_2^2 - 2\tilde{\beta}\tilde{\Phi}_1\tilde{\Phi}_2]f\left(\frac{\tilde{\Phi}_2}{\tilde{\Phi}_1}\right)R + \frac{A}{2}[\tilde{\alpha}\partial\tilde{\Phi}_1^2 - \tilde{\alpha}\partial\tilde{\Phi}_2^2 - 2\tilde{\beta}\partial_\mu\tilde{\Phi}_1\partial^\mu\tilde{\Phi}_2]f\left(\frac{\tilde{\Phi}_2}{\tilde{\Phi}_1}\right) - V\left(\tilde{\Phi}_1, \tilde{\Phi}_2\right)\right]$$

- If $A = 6$ the above action would be conformally invariant and by gauge fixing the field $\Phi_1 = \sqrt{6}M_P$, the above model leads to Starobinsky inflation with an additional feature of a tiny uplift of potential at the minimum (Vacuum energy).

Thanks for listening

This research work is supported by the grants SFRH/BD/51980/2012 from Portuguese Agency Fundação para a Ciência e Tecnologia. UID/MAT/00212/2013.

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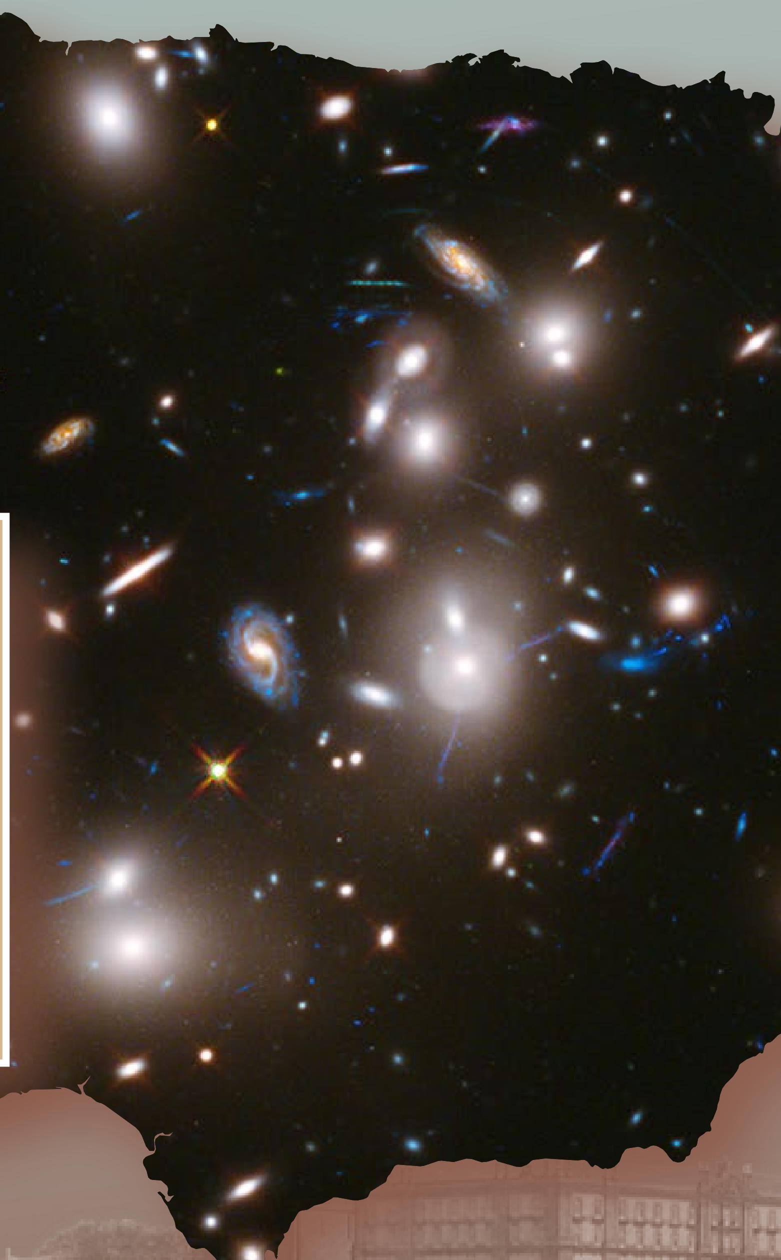

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Higgs effective potential on curved spacetimes

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29th March 2016

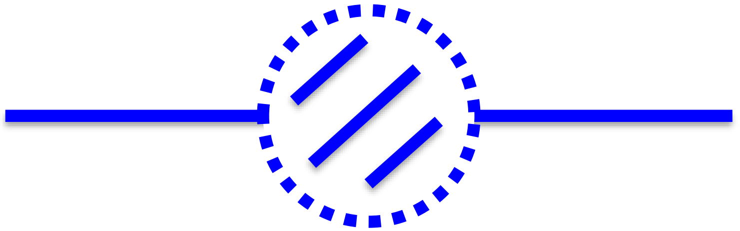
Acknowledgements

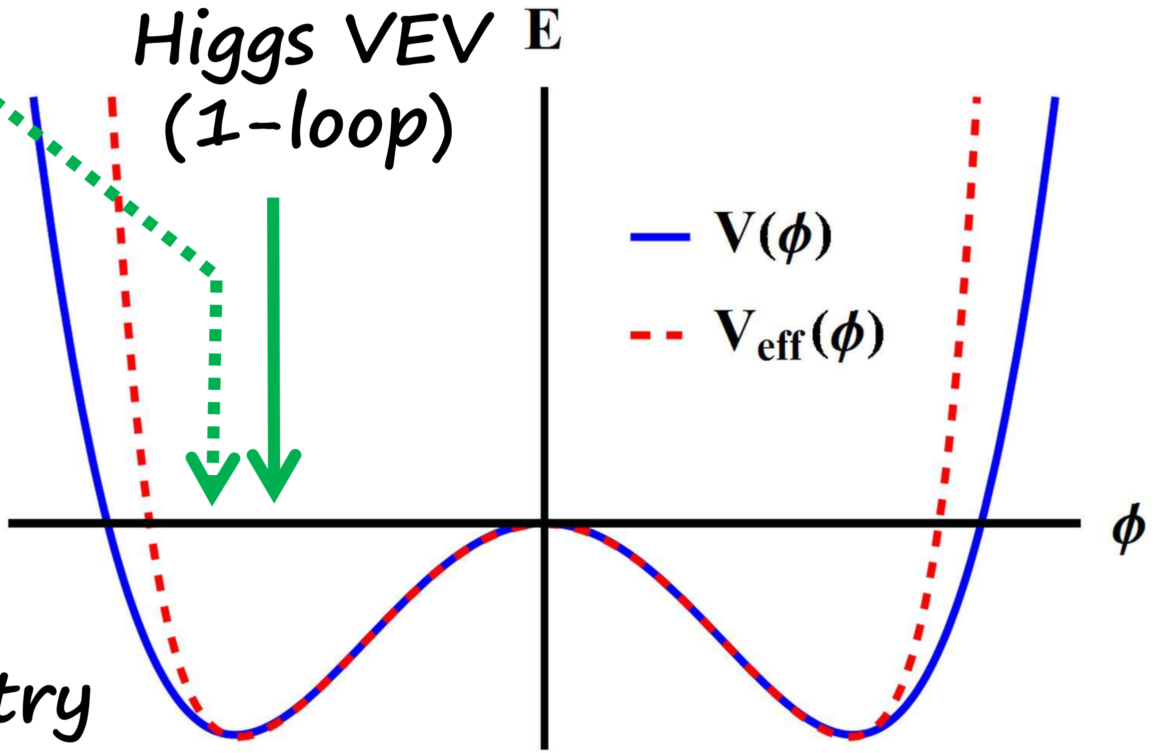
Obra Social
Fundación "la Caixa"

Higss effective potential

$$V(\hat{\phi}) = V_0 + \frac{1}{2}M^2\hat{\phi}^2 + \frac{1}{4}\lambda\hat{\phi}^4$$

Quantum corrections





- due to the Higgs interactions
- sensitive to the space-time geometry

In this work:

- Higgs self-interactions λ, M
- $a^2(\eta)\left\{[1+2\Phi(\eta,x)]\,\mathrm{d}\eta^2 - [1-2\Psi(\eta,x)]\,\mathrm{d}x^2\right\}$

Φ, Ψ

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Minkowski and Flat FRW space-time

$$V_{\text{eff}} = V + \underbrace{\frac{\hbar}{2}\int \frac{\mathrm{d}^3 \boldsymbol{k}}{(2\pi)^3}\sqrt{\boldsymbol{k}^2 + \boldsymbol{m}^2}}_{\frac{1}{2}\hbar\omega}$$

After renormalization...

$$V_{\text{eff}} = V + \frac{\hbar}{64\pi^2}\boldsymbol{m}^4 \log\left(\frac{\boldsymbol{m}^2}{\boldsymbol{\mu}^2}\right)$$

Homogeneous effect

Perturbations?

Coleman & Weinberg '73
Including W, Z and top contributions

At the level of the equations of motion

$$\Box\,\phi + V'(\phi) = 0$$

$$\hat{\phi} + \delta\phi$$

$$\hat{\phi} = \langle 0|\, \hat{\phi} + \delta\phi\, |0\rangle$$

$$\Box\,\hat{\phi} + V'_{\rm eff}\,(\hat{\phi}) = 0$$

$$V'(\hat{\phi}) + V''(\hat{\phi})\,\langle\delta\phi\rangle + \frac{1}{2}V'''(\hat{\phi})\,\langle\delta\phi^2\rangle + \ldots$$

Quantum fluctuations (1-loop)

$$V^{(1)}(\hat{\phi}) = \frac{1}{2}\int_0^{m^2(\hat{\phi})} {\rm d}m^2\,\langle 0|\delta\phi^2|0\rangle$$

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At the level of the equations of motion

$$\Box\,\phi + V'(\phi) = 0$$

$$\hat{\phi} + \delta\phi$$

$\delta\phi$ is a free field

$$\Box\,\delta\phi + m^2(\hat{\phi})\,\delta\phi = 0$$

Well-defined procedure:

- Solve the KG eq.
  - WKB ansatz
    1) First order in metric perturbations $\Phi,\ \Psi$
    2) Zero order in the adiabatic expansion $o\,(\mathcal{H}/\omega)^2$
  - Boundary conditions (adiabatic vacuum)
- Write $\langle 0|\delta\phi^2|0\rangle$ as a mode summation
- Renormalize
  - Dimensional regularization (Birrell & Davies '82)

At the level of the **action**

$$W = S + \frac{i}{2}\mathrm{Tr}\ln\left[-\left(\Box_x + m^2\right)\frac{\delta(x,y)}{\sqrt{g}}\right]$$

$W^{(1)}$

Quantum fluctuations (1-loop)

$$\frac{\mathrm{d}W^{(1)}}{\mathrm{d}m^2} = -\frac{i}{2}\,\mathrm{Tr}\,G_F = -\frac{1}{2}\int \mathrm{d}x\,\sqrt{g}\,\langle 0|\delta\phi^2|0\rangle$$

- $i\,G_F = \langle 0|T\left[\delta\phi(x)\,\delta\phi(y)\right]|0\rangle$
- $\left(\Box + m^2\right)\,G_F = -\frac{\delta}{\sqrt{g}}$

$$L^{(1)}_{\mathrm{eff}} = -\frac{1}{2}\int_0^{m^2(\hat{\phi})}\mathrm{d}m^2\,\langle 0|\delta\phi^2|0\rangle = -V^{(1)}_{\mathrm{eff}}$$

Effective lagrangian

$$\phi = \hat{\phi} + \delta\phi$$

$$L_{\rm eff} = -V_{\rm eff} + \ldots\, (\partial\hat{\phi})^2 + \ldots\, (\partial g_{ab})^2 + \ldots$$

Higgs boson ~ 125 GeV

Solar System ~ 10^{-25} GeV

Cosmology ~ 10^{-39} GeV

$$\left(\text{Gravitacional frequencies} \,/\, \text{Quantum frequencies}\right)^2 \times o\left(V_{\rm eff}\right)$$

$$\mathcal{H}^2,\ \nabla^2(\Phi,\Psi) \ll \omega^2$$

This is consistent with solving the EOM for the fluctuation at zero order in the adiabatix expansion $o\left(\mathcal{H}/\omega\right)^2$

$$V'_{\rm eff}\left(\hat{\phi}\right) \simeq 0$$

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Result

$$V_{\text{eff}} = V + \underbrace{\frac{\hbar}{64\pi^2} m^4 \log\left(\frac{m^2}{\mu^2}\right)}_{\text{Homogeneous contribution}} + \underbrace{\frac{\hbar}{16\pi^2} m^4 \overbrace{(H_\Phi + H_\Psi)}^{o(\Phi,\Psi)}}_{\text{Non-homogeneous contribution}}$$

Homogeneous contribution

- Divergent part
  - Local
  - Independent of $|0\rangle$
  - Covariant (curvature tensors)
  - Schwinger-De Witt/ Heat kernel

Non-homogeneous contribution

- Finite part
  - Non-local
  - Depends on $|0\rangle$
  - Not manifestly covariant
  - "Brute force" (mode summation)

Renormalized physical quantities

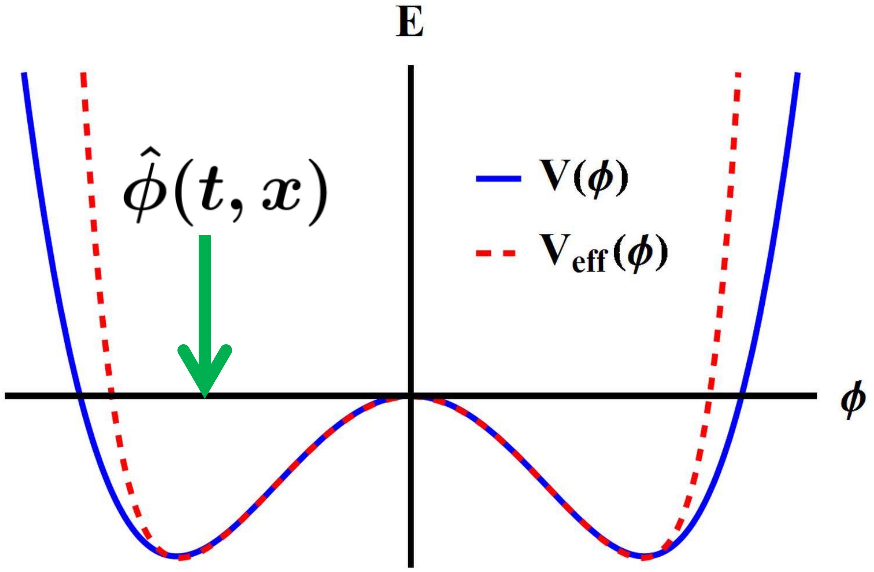
(Birrell & Davies '82)

Higgs VEV

Homogeneous

Space-time dependent

$$\hat{\phi}(t,x) = \hat{\phi}_0 + \Delta\hat{\phi}(t,x)$$



$$\Delta_{\text{Higgs}} = \frac{\Delta\hat{\phi}}{\hat{\phi}_0} = -\frac{3\lambda}{4\pi^2}(H_\Phi + H_\Psi)$$

No free parameter

$$\frac{\Delta m_e}{m_e} \qquad \frac{\Delta G_F}{G_F} \qquad \frac{\Delta \mu}{\mu} = -\Delta_{\text{Higgs}}$$

Proton-to-electron mass ratio

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Solar System (Static weak gravitational fields)

Eddignton parameter

$$H_\Phi + H_\Psi = -\frac{1}{2}(\Phi - \Psi) = -\frac{1}{2}\Phi(1-\gamma)$$

$$\gamma = \frac{\Psi}{\Phi} = 1$$

In GR

$$\frac{\Delta\mu}{\mu} = -\Delta_{\text{Higgs}} = \frac{3\lambda}{4\pi^2}(H_\Phi + H_\Psi)$$

$\frac{3\lambda}{4\pi^2}$: 10^{-2}

$(H_\Phi + H_\Psi)$: $\Delta\Phi_\oplus \approx 10^{-10}$

Atomic clocks on Earth

$$\frac{\Delta\mu}{\mu} < 10^{-16}$$

Huntemann, et al. 2014

$|\gamma - 1| < 10^{-4}$

$|\gamma - 1| < 10^{-8}$

(prospect)

on Earth

$\Delta\Phi_\oplus \approx 10^{-10}$

around the Sun

$\Delta\Phi_\odot \approx 10^{-6}$

$|\gamma - 1| < 10^{-5}$

Cassini bound,

Bertotti, et al. 2003

Cosmological scales

Power spectrum of Higgs fluctuations

$$\mathcal{P}_{\rm Higgs} = \frac{p^3}{2\pi^2}|\Delta_{\rm Higgs}|^2 = \left(\frac{3\lambda}{4\pi^2}\right)^2 c_{\rm Higgs}\,\mathcal{P}_\Phi\ (\times T)$$

$$\left(\frac{3\lambda}{4\pi^2}\right)^2 \to 10^{-4}, \quad c_{\rm Higgs} \to 1, \quad \mathcal{P}_\Phi \Rightarrow \left(\frac{3}{5}\right)^2 \mathcal{P}_{\mathcal{R}}, \quad \left(\frac{3}{5}\right)^2 \to 10^{-1}, \quad \mathcal{P}_{\mathcal{R}} \Rightarrow A_s\left(\frac{p}{p_*}\right)^{n_s-1}, \quad A_s \to 10^{-9}$$

Fluctuations

$$\frac{\Delta\mu}{\mu} \sim 10^{-7}$$

$$\left(\frac{\Delta\mu}{\mu}\right)_{\rm low\ z} = (-0.24 \pm 0.09) \times 10^{-6}$$

$$\left(\frac{\Delta\mu}{\mu}\right)_{\rm high\ z} = (3.4 \pm 2.0) \times 10^{-6}$$

Ferreira & Martins, 2015

- Higgs self-interactions ✓
- Vector bosons ?
- Top quark ?

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Conclusions

- Metric perturbations contribute to the finite part of the Higgs 1-loop effective action/potential.
- This leads to a space-time dependent Higgs VEV.
- In the Solar System, constraints on the Eddington parameter can be obtained from measurements of the proton-to-electron mass ratio.
- On Cosmological scales, it suggests fluctuations on the proton-to-electron mass ratio at the level of $10^{-6} - 10^{-7}$

More details: F.D.A., A.L. Maroto, F. Prada 1602.02776; 1602.03290.

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