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Cosmological perturbations of the Higgs vacuum

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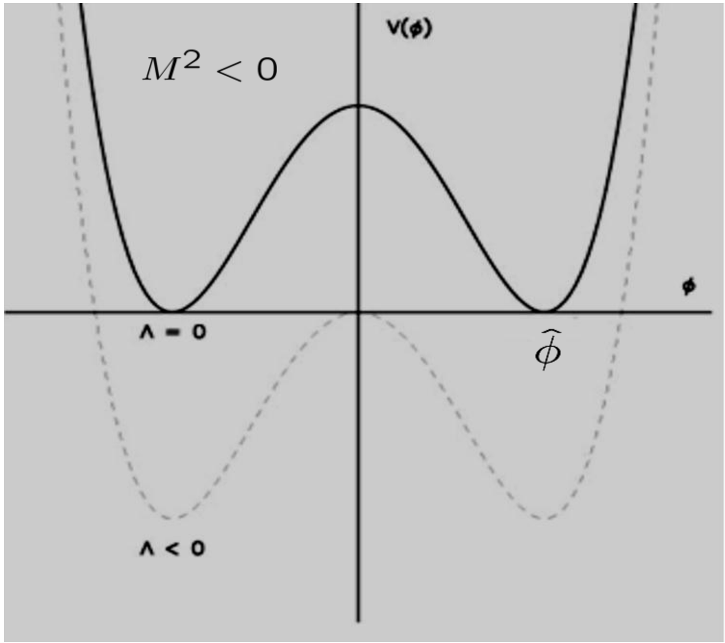
Introduction

- The **Higgs boson** found at the LHC with $m_H \approx 125$ GeV compatible with the Standard Model Symmetry Breaking Sector (SBS)

- But the SM also predicts the existence of a Higgs field, i.e. a constant field (in time and space) with $\hat{\phi} \approx 250$ GeV (no independent observational confirmation yet).

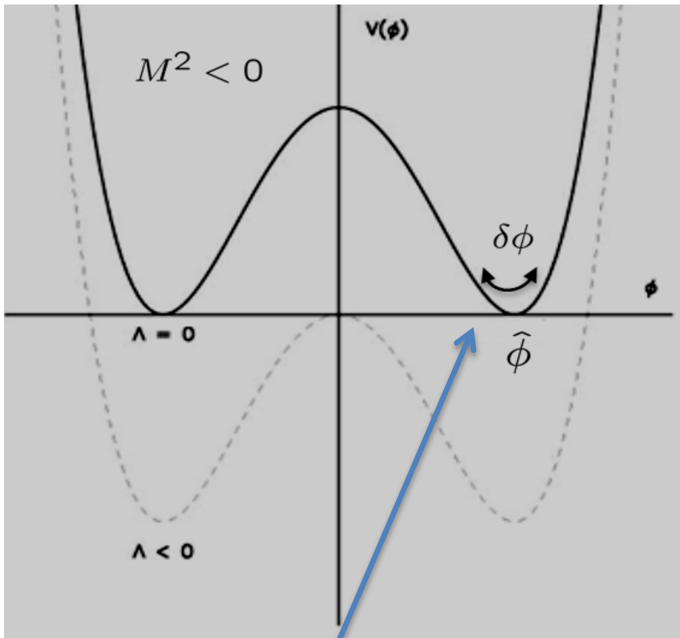
Classical potential

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



Effective potential in flat space-time

$$\phi(t, \mathbf{x}) = \hat{\phi} + \delta\phi(t, \mathbf{x})$$



$$m^2(\hat{\phi}) = V''(\hat{\phi})$$

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

$$\langle \delta\phi \rangle = 0$$

Quantum corrected equation of motion

$$\Box\hat{\phi} + \underbrace{V'(\hat{\phi}) + \frac{1}{2}V'''(\hat{\phi})\langle\delta\phi^2\rangle}_{V'_{eff}(\hat{\phi})} = 0\,.$$

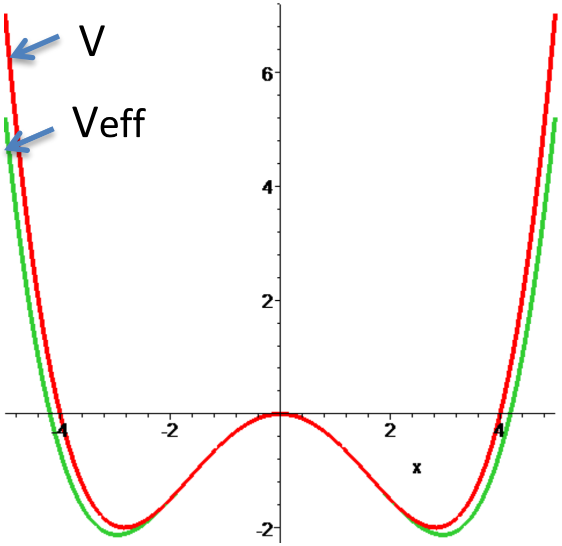
V_{eff} effective potential

Effective potential in flat space-time

$$V_{eff}(\hat{\phi}) = V(\hat{\phi}) + \underbrace{\frac{1}{2}\int \frac{d^3k}{(2\pi)^3}\sqrt{k^2 + m^2(\hat{\phi})}}_{V_1(\hat{\phi}) = \rho_{vac}(\hat{\phi})}$$

$$V_{eff}(\hat{\phi}) \;=\; V_0 + \frac{1}{2}M^2\hat{\phi}^2 + \frac{\lambda}{4}\hat{\phi}^4 + \frac{m^4(\hat{\phi})}{64\pi^2}\left(\ln\left(\frac{m^2(\hat{\phi})}{\mu^2}\right) + C\right)$$

Coleman-Weinberg, (1973)
Includes W, Z and top quark contributions



Equations in perturbed Robertson-Walker background

Spatially flat RW longitudinal gauge

$$\mathrm{d}s^2 = a^2(\eta)\left\{[1+2\Phi(\eta,\mathbf{x})]\,\mathrm{d}\eta^2 - [1-2\Psi(\eta,\mathbf{x})]\,\mathrm{d}\mathbf{x}^2\right\}$$

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

$$\phi(\eta,\mathbf{x}) = \hat{\phi}(\eta,\mathbf{x}) + \delta\phi(\eta,\mathbf{x})$$

Quantum fluctuations equation

$$\delta\phi'' + (2\mathcal{H} - \Phi' - 3\Psi')\delta\phi' - (1 + 2(\Phi+\Psi))\nabla^2\delta\phi - \vec{\nabla}\delta\phi\cdot\vec{\nabla}(\Phi-\Psi) + a^2(1+2\Phi)V''(\hat{\phi})\delta\phi = 0\,.$$

Quantization

For slowly varying background fields compared to the frequency of quantum fluctuations. i.e $\omega^2 \gg \mathcal{H}^2$ and $\omega^2 \gg \{\nabla^2\Phi,\ \nabla^2\Psi\}$ we can work in the adiabatic approximation

Adiabatic expansion

$$\delta\phi_k(\eta, \mathbf{x}) = f_k(\eta, \mathbf{x})\, e^{i\theta_k(\eta,\mathbf{x})}$$

slowly varying amplitude.

fast varying phase

Canonical quantization

$$\delta\phi(\eta, \mathbf{x}) = \int \mathrm{d}^3\mathbf{k} \left(a_{\mathbf{k}} \delta\phi_k(\eta, \mathbf{x}) + a^\dagger_{\mathbf{k}} \delta\phi^*_k(\eta, \mathbf{x}) \right)$$

Effective potential in perturbed RW background

$$V_1 = \frac{1}{2}\int dm^2 \langle 0|\delta\phi^2(\eta,\mathbf{x})|0\rangle$$

In **dimensional regularization**:

- Same divergences as in flat space-time
- Metric perturbations only contribute to the finite (non-local) part

$$V_{eff}(\hat{\phi}) = V(\hat{\phi}) + \frac{m^4(\hat{\phi})}{64\pi^2}\ln\left(\frac{m^2(\hat{\phi})}{\mu^2}\right) + \frac{m^4(\hat{\phi})}{16\pi^2}(H_\Phi(\eta,\mathbf{x}) + H_\Psi(\eta,\mathbf{x}))$$

Static background

$$H_\Phi(\eta,\mathbf{p}) = -\left(\frac{1}{2} + \frac{1}{2}\cos(p\eta) - \frac{\sin(p\eta)}{p\eta}\right)\Phi(\mathbf{p}) \quad \to 0$$

$$H_\Psi(\eta,\mathbf{p}) = \left(\frac{1}{2} - \frac{1}{2}\cos(p\eta)\right)\Psi(\mathbf{p}) \quad \to 0$$

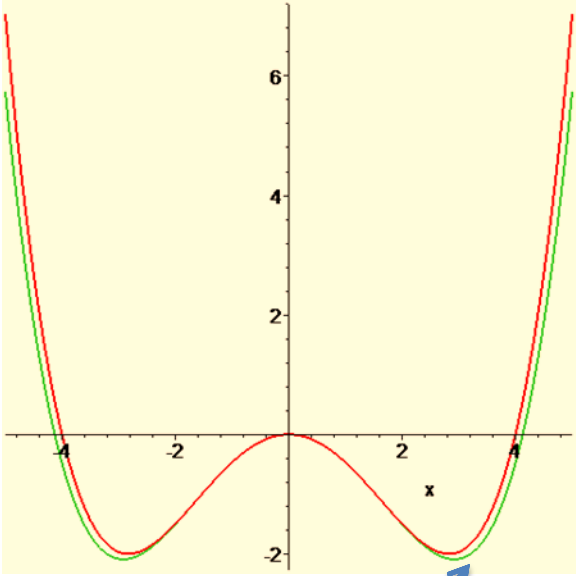
$p\eta \to 0$

Higgs vacuum expectation value

$$\hat{\phi}_{vac}(\eta, \mathbf{x}) = \hat{\phi}_0 + \Delta\hat{\phi}(\eta, \mathbf{x})$$

Homogeneous VEV

Perturbations contribution



$$\Delta(\eta, \mathbf{x}) = \frac{\Delta\hat{\phi}}{\hat{\phi}_0} = -\frac{3\lambda}{4\pi^2}(H_\Phi(\eta, \mathbf{x}) + H_\Psi(\eta, \mathbf{x}))$$

$$\lambda \simeq \frac{1}{8}$$

$$\hat{\phi}_{vac}(\eta, \mathbf{x})$$

Space-time dependent VEV

Higgs perturbations power spectrum

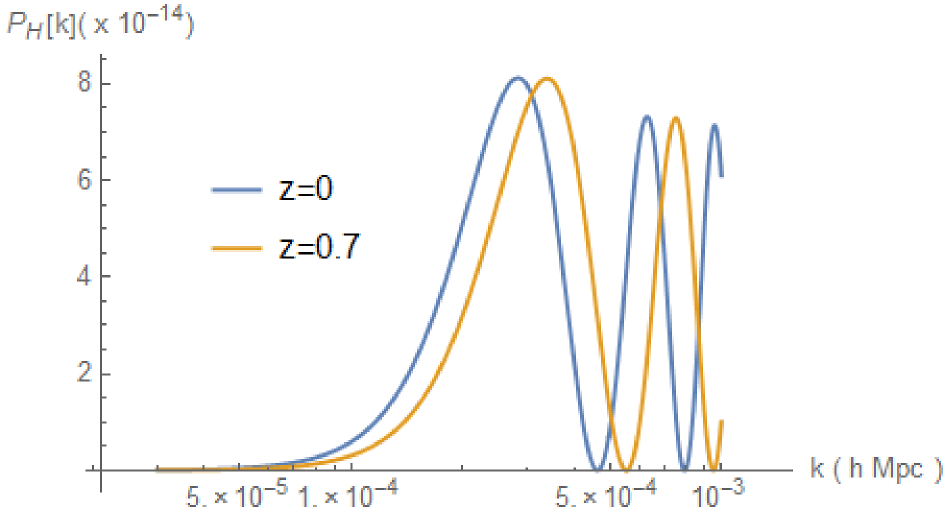
$$\langle \Delta(\eta, \mathbf{x})\ \Delta(\eta, \mathbf{x}+\mathbf{y}) \rangle = \frac{1}{(2\pi)^3} \int d^3p\, \mathcal{P}_H(p, \eta)\ e^{i\mathbf{p}\cdot\mathbf{x}}$$

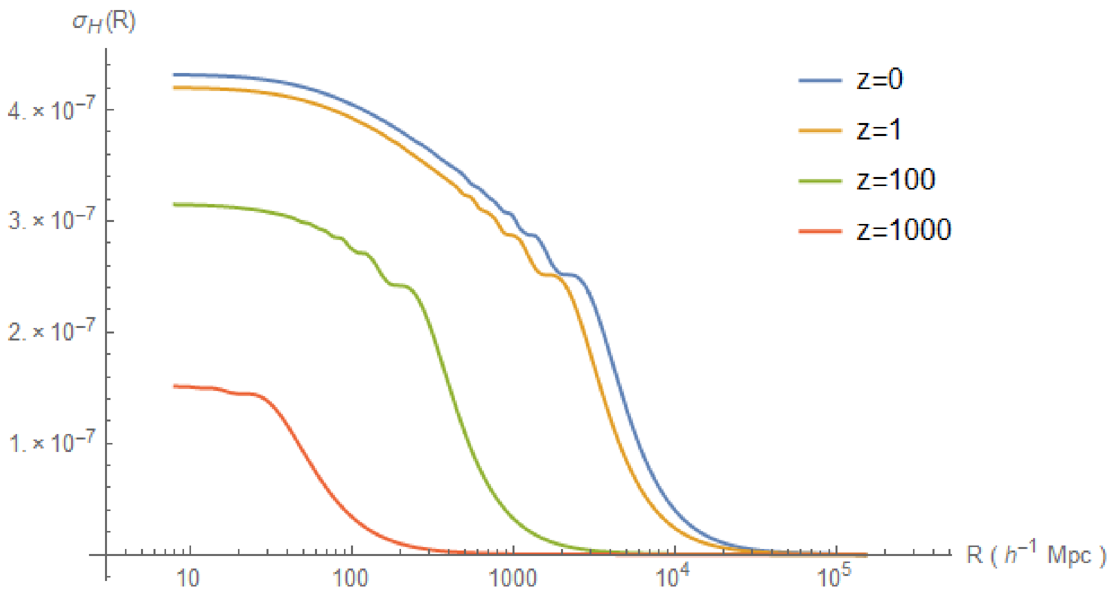
Higgs fluctuations power spectrum and dispersion

Power spectrum

$$\mathcal{P}_H(k,\eta) = \left(\frac{9}{160\pi^2}\right)^2 \mathcal{P}_R(k) T_H^2(k,\eta)$$

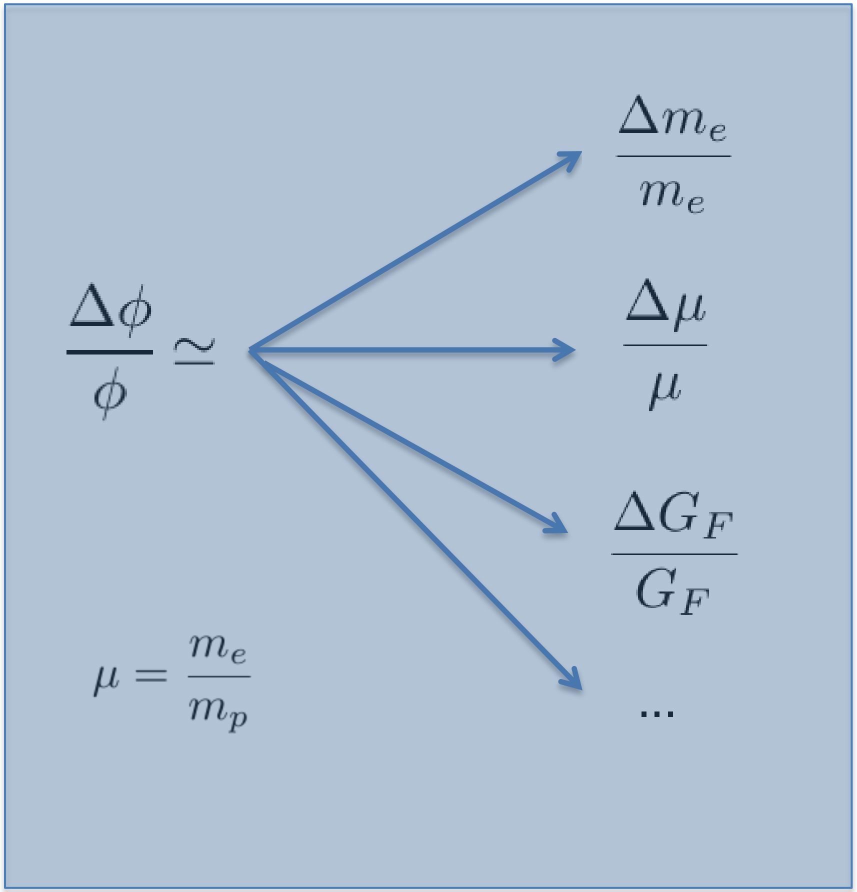
$$k < k_{eq}$$





RMS Higgs fluctuation

Phenomenological consequences



Astrophysical and cosmological constraints

- Quasar absorption spectra $\lesssim 10^{-6}$
- CMB $\lesssim 10^{-2}$
- BBN $\lesssim 10^{-3}$

Local constraints

- Atomic clocks on Earth $\lesssim 10^{-16}$
- Milky Way molecular clouds $\lesssim 10^{-8}$

Uzan, 2010

Limits on variations of the electron to proton mass ratio
spectroscopy with molecular absorption lines

x 10^{-6}

Object	z	$\Delta\mu/\mu$	Method	Ref.
B0218+357	0.685	0.74 ± 0.89	$NH_3/HCO^+/HCN$	[34]
B0218+357	0.685	-0.35 ± 0.12	$NH_3/CS/H_2CO$	[35]
PKS1830−211	0.886	0.08 ± 0.47	NH_3/HC_3N	[36]
PKS1830−211	0.886	-1.2 ± 4.5	CH_3NH_2	[37]
PKS1830−211	0.886	-2.04 ± 0.74	NH_3	[38]
PKS1830−211	0.886	-0.10 ± 0.13	CH_3OH	[39]
J2123−005	2.059	8.5 ± 4.2	H_2/HD (VLT)	[40]
J2123−005	2.059	5.6 ± 6.2	H_2/HD (Keck)	[41]
HE0027−1836	2.402	-7.6 ± 10.2	H_2	[7]
Q2348−011	2.426	-6.8 ± 27.8	H_2	[42]
Q0405−443	2.597	10.1 ± 6.2	H_2	[43]
J0643−504	2.659	7.4 ± 6.7	H_2	[12]
Q0528−250	2.811	0.3 ± 3.7	H_2/HD	[44]
Q0347−383	3.025	2.1 ± 6.0	H_2	[45]
J1443+2724	4.224	-9.5 ± 7.6	H_2	[13]

$$\left(\frac{\Delta\mu}{\mu}\right)_{Low,wm} = -0.24 \pm 0.09$$

x 10^{-6}

$$\left(\frac{\Delta\mu}{\mu}\right)_{High,wm} = 3.4 \pm 2.0\,,$$

M.C. Ferreira and C.J.A.P. Martins, arXiv:1506.0355

Conclusions

- We have calculated the Higgs one-loop effective potential in a perturbed Robertson-Walker background using the adiabatic vacuum of comoving observers

- Using dimensional regularization we have obtained the contribution from metric perturbations to the finite part of the effective potential.

- Space-time variations in the Higgs VEV are generated on sub-Hubble scales with amplitudes in the range $\Delta\phi/\phi \approx 10^{-7}$.

- Variations in the Higgs VEV imply variations in the electron to proton mass ratio, just below the present sensitivity range of spectroscopic observations of redshifted molecular lines.