Gravitational effects on the Higgs field

Franco D. Albareti

PhD student
under the supervision of

Prof. Antonio L. Maroto and Prof. Francisco Prada

Instituto de Física Teórica UAM/CSIC

30th October 2015

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To be honest...

this talk is about classical gravity

Does gravity affect the Higgs VEV?

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Quantum frequencies

Higgs boson ~ 125 GeV

Higgs field ~ 250 GeV
VEV

Quantum frequencies

Higgs boson ~ 125 GeV

Higgs field ~ 250 GeV
VEV

Gravitacional frequencies

Solar System ~ 10^{-25} GeV

Cosmology ~ 10^{-39} GeV

Ok,

this is all about classical gravity

Ok,

this is all about classical gravity

but…with quantum fields

QFT in curved spacetimes

(Birrel & Davies ‘82)

Outline

- **Introduction**

- **Modes**

- **Results**

- **Observational effects**

- **Conclusions**

Introduction

KG eq.

$$\Box\,\phi + \boldsymbol{V'}(\phi) \;=\; \mathbf{0}$$

Introduction

KG eq.

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

Quantum operator

Introduction

KG eq.

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

Quantum operator

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

Background field

Quantum perturbation

Introduction

KG eq.

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

Quantum operator

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

Background field

Quantum perturbation

where...

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

Introduction

$$\Box\,\phi + \boldsymbol{V'}(\phi) \;=\; \mathbf{0}$$

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

Introduction

$$\Box\,\phi + \boldsymbol{V'}(\phi) = \mathbf{0}$$

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

Take $\langle 0 | \ldots | 0 \rangle$

Introduction

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

Take $\langle 0|\ldots|0\rangle$

Introduction

$$\Box\,\hat{\phi} + \boldsymbol{V'}_{\mathbf{eff}}\left(\hat{\phi}\right) = \mathbf{0}$$

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

- Quantum fluctuations (1-loop)

Take $\langle 0|\ldots|0\rangle$

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Introduction

$$\Box\,\hat{\phi} + \underbrace{\boldsymbol{V'}_{\text{eff}}}_{\boldsymbol{V'}(\hat{\phi}) \,+\, \frac{1}{2}\boldsymbol{V'''}(\hat{\phi})\,\langle \boldsymbol{\delta\phi}^2 \rangle \,+\, \dots}\left(\hat{\phi}\right) \;=\; 0$$

Introduction

$$\Box\,\hat{\phi} + \boldsymbol{V'}_{\mathbf{eff}}\left(\hat{\phi}\right) = \mathbf{0}$$

$$\overbrace{\underbrace{\boldsymbol{V'}(\hat{\phi}) + \frac{1}{2}\boldsymbol{V'''}(\hat{\phi})\left\langle \boldsymbol{\delta}\phi^2 \right\rangle}_{\boldsymbol{V'}^{\circ}_{\mathbf{eff}}\left(\hat{\phi}\right)} + \ldots}$$

1-loop effective potential for $\hat{\phi}$

Introduction

Constant solution $\hat{\phi}_c$

Instead of

$$V'(\hat{\phi}_c) = 0$$

one solves

$$V'^{\circ}_{\text{eff}}(\hat{\phi}_c) = 0$$

1-loop

Introduction

Flat space-time

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

Vaccum energy of quantum fluctuations

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Introduction

Flat space-time

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

Vaccum energy of quantum fluctuations $\frac{1}{2}\hbar\omega$

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

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

Introduction

Flat FRW

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

Vaccum energy of quantum fluctuations $\frac{1}{2}\hbar\omega$

$$V^{\circ}_{\text{eff}} = V + \frac{\hbar}{64\pi^2} m^4 \log\left(\frac{m^2}{(\mu/a)^2}\right)$$

Introduction

Flat FRW

$$V^{\circ}_{\text{eff}} = V + \frac{\hbar}{2}\int \frac{\mathrm{d}^3(k/a)}{(2\pi)^3}\sqrt{(k/a)^2 + m^2}$$

Momentum and energy
get redshifted

$$V^{\circ}_{\text{eff}} = V + \frac{\hbar}{64\pi^2} m^4 \log\left(\frac{m^2}{(\mu/a)^2}\right)$$

Physical renormalization scale μ_{ph}

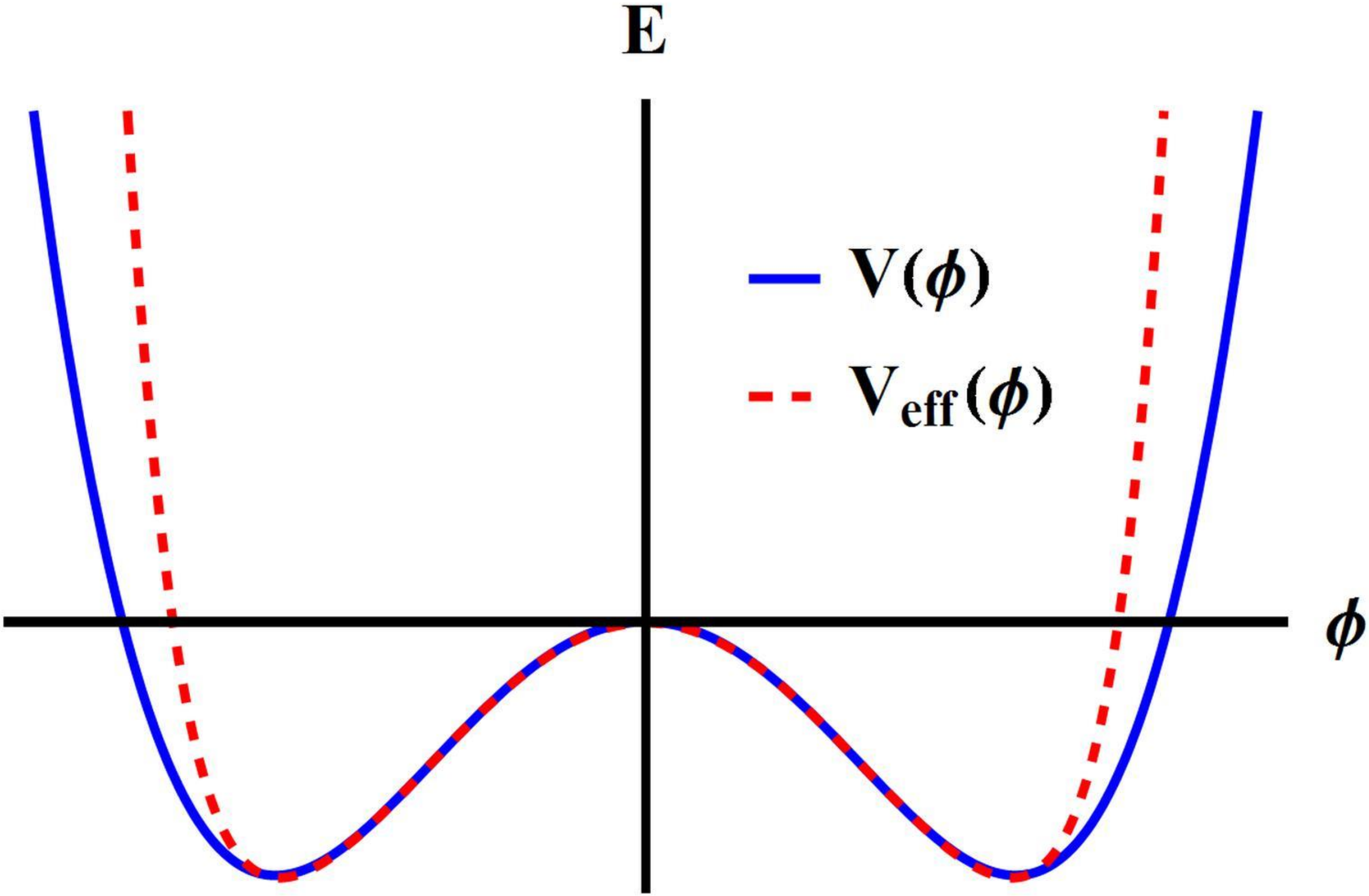
Introduction

Flat space-time

Flat FRW

Homogeneous effect

Does gravity affect the
Higgs VEV in a non-trivial way?



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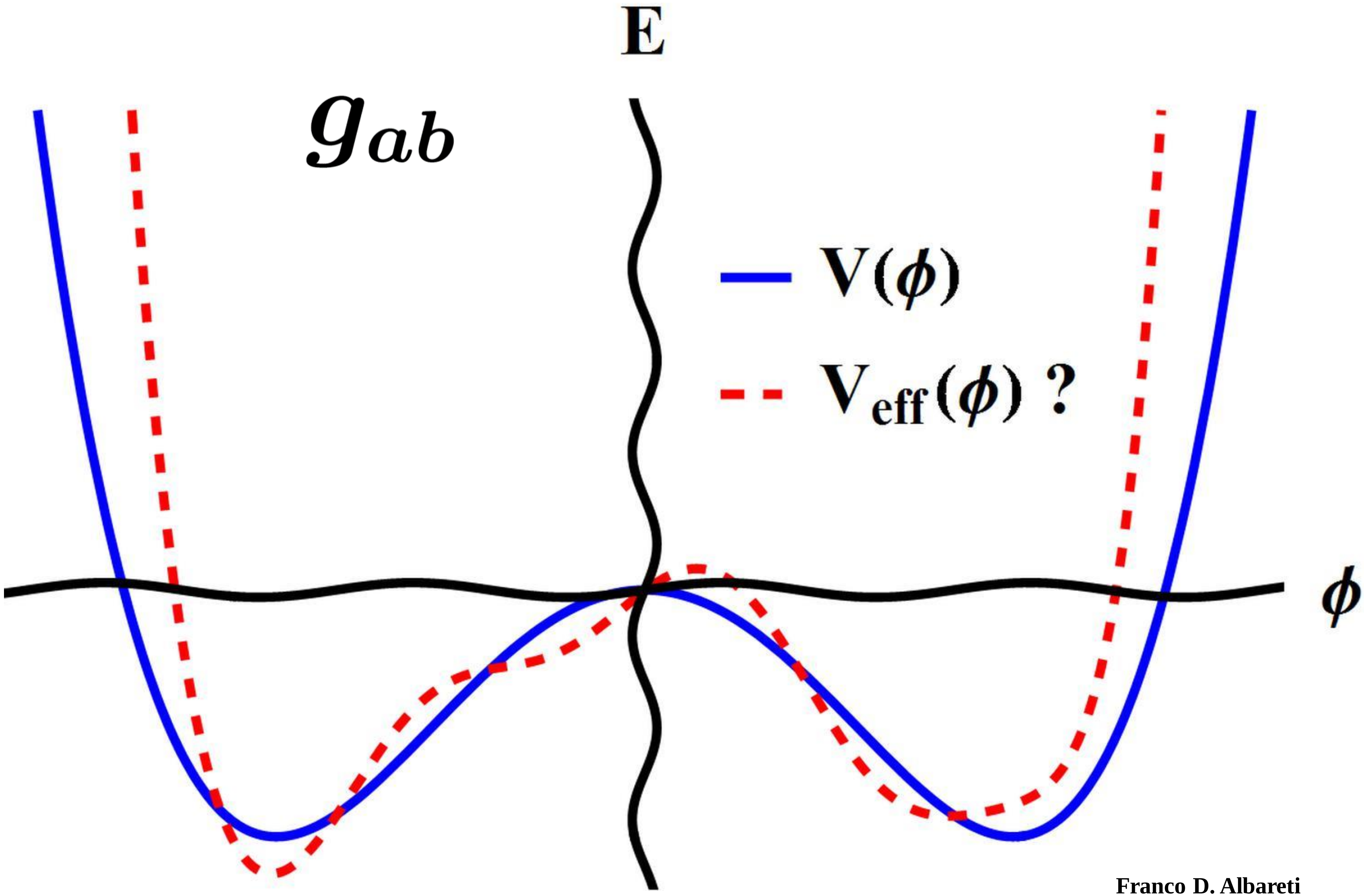
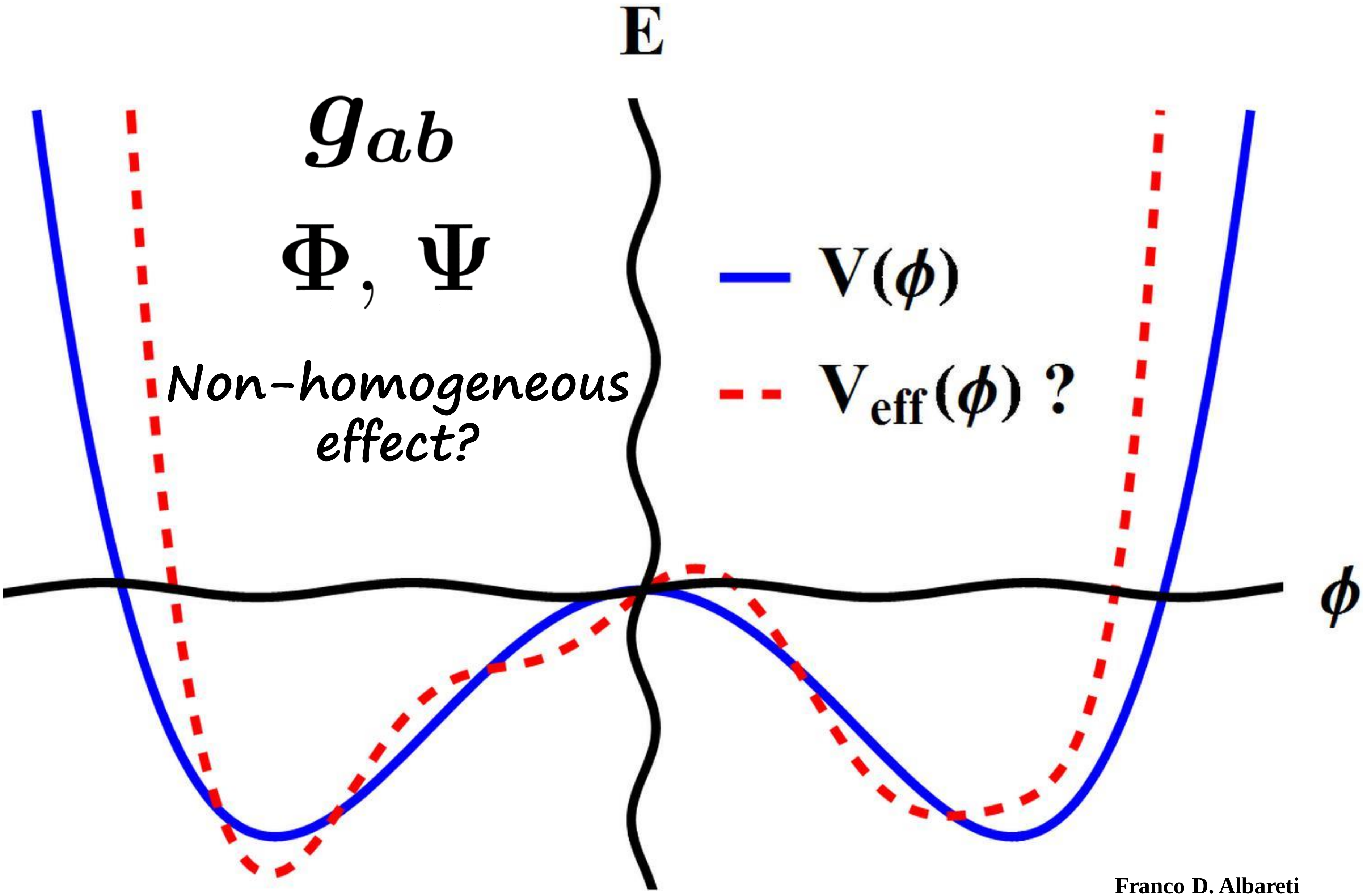

E
g_{ab}
$V(\phi)$
$V_{eff}(\phi)$?
ϕ



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Scenarios

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

$$\Phi, \ \Psi$$

Static weak gravitational field (Solar System…)

Cosmological effects due to the LSS

Outline

- **Introduction** ✓
- **Modes**
- **Results**
- **Observational effects**
- **Conclusions**

Outline

- Introduction ✓
- Modes
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Modes

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

$$V'^{\circ}_{\mathrm{eff}} = V' + \frac{1}{2} V''' \langle \delta\phi^2 \rangle$$

Modes

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

$$V'^{\circ}_{\text{eff}} = V' + \frac{1}{2} V''' \langle \delta\phi^2 \rangle$$

$$V^{\circ}_{\text{eff}} = V + \frac{1}{2} \int_0^{m^2(\hat{\phi})} \mathrm{d}m^2 \, \langle \delta\phi^2 \rangle$$

$$\bigcirc = \langle \delta\phi^2 \rangle = \langle 0 | \delta\phi^2 | 0 \rangle$$

Quantum loops

Modes

1) Quantize the fluctuations canonically

$$\delta\phi = \int \frac{\mathrm{d}k^3}{(2\pi)^3}\left(a_k\,\delta\phi_k + a_k^\dagger\,\delta\phi_k^*\right)$$

2) Find the modes

- Solve KG to first order (field, metric...)
- Using a WKB ansatz

$$\delta\phi_k = f_k\, e^{i\,\theta_k}$$

$$\omega \gg \mathcal{H},\, \nabla \;\; (\Phi, \Psi)$$

Modes

1) Quantize the fluctuations canonically

$$\delta\phi = \int \frac{\mathrm{d}\boldsymbol{k}^3}{(2\pi)^3}\left(a_{\boldsymbol{k}}\,\delta\phi_{\boldsymbol{k}} + a^\dagger_{\boldsymbol{k}}\,\delta\phi^*_{\boldsymbol{k}}\right)$$

2) Find the modes

- Solve KG to first order (field, metric...)
- Using a WKB ansatz
- Boundary conditions

  Match the perturbed modes to the unperturbed ones at $\eta = 0$

  (adiabatic vacuum)

Modes

1) Quantize the fluctuations canonically

$$\delta\phi = \int \frac{\mathrm{d}\boldsymbol{k}^3}{(2\pi)^3} \left(a_{\boldsymbol{k}}\, \delta\phi_{\boldsymbol{k}} + a^\dagger_{\boldsymbol{k}}\, \delta\phi^*_{\boldsymbol{k}} \right)$$

2) Find the modes

$$\delta\phi_{\boldsymbol{k}} = f_{\boldsymbol{k}}\, e^{i\,\theta_{\boldsymbol{k}}}$$

3) Compute

$$\langle 0|\delta\phi^2|0\rangle$$

4) Regularize & Renormalize

Modes

4) Regularize & Renormalize

$$\langle 0|\delta\phi^2|0\rangle$$

- Fourier space
- Expand in powers of p
- Dimensional regularization for the integration over quantum modes k

Renormalization?

- The same UV behaviour than in flat space-time
- Contributions from Φ, Ψ to the V°_{eff} are finite!!

Outline

- **Introduction** ✓
- **Modes** ✓
- **Results**
- **Observational effects**
- **Conclusions**

Outline

- **Introduction** ✓
- **Modes** ✓
- **Results**
- **Observational effects**
- **Conclusions**

Results

$$\boldsymbol{V}^{\circ}_{\mathbf{eff}} = \underbrace{\boldsymbol{V} + \frac{\hbar}{64\pi^2}\boldsymbol{m}^4 \log\left(\frac{\boldsymbol{m}^2}{\boldsymbol{\mu}^2_{\mathbf{ph}}}\right)}_{\text{same as before}} + \underbrace{\frac{\hbar}{16\pi^2}\boldsymbol{m}^4 \left(\boldsymbol{H}_{\boldsymbol{\Phi}} + \boldsymbol{H}_{\boldsymbol{\Psi}}\right)}_{\text{correction due to the potentials}}$$

Results

$$V^{\circ}_{\text{eff}} = \underbrace{V + \frac{\hbar}{64\pi^2} m^4 \log\left(\frac{m^2}{\mu^2_{\text{ph}}}\right)}_{\text{same as before}} + \underbrace{\frac{\hbar}{16\pi^2} m^4 \left(H_\Phi + H_\Psi\right)}_{\text{correction due to the potentials}}$$

Remarks

- Non-homogeneous effect, the field value which minimizes the potential is different for each point of spacetime.
- $\Phi \approx \Psi \Rightarrow H_{\Phi+\Psi} \gg H_{\Phi-\Psi}$
- $H_\Phi,\ H_\Psi$ in Fourier space.

Outline

- Introduction ✓
- Modes ✓
- Results ✓
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Outline

- Introduction ✓
- Modes ✓
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Observational effects

Higgs VEV

$$v_{\mathrm{G}}(t,x) = v + \Delta v(t,x)$$

Homogeneous

Spacetime dependent

Observational effects

Higgs VEV

$$v_{\mathrm{G}}(t,x) = v + \Delta v(t,x)$$

Homogeneous

Spacetime dependent

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

$$\frac{\Delta m_e}{m_e} \qquad \frac{\Delta G_F}{G_F} \qquad \frac{\Delta \mu}{\mu}$$

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Observational effects

Solar System (momentum space)

$$H_{\Phi+\Psi} = \left(\frac{\sin(p\,t)}{p\,t} - \cos(p\,t)\right)\left(\frac{\Phi(p) + \Psi(p)}{2}\right)$$

$$H_{\Phi-\Psi} = \left(\frac{\sin(p\,t)}{p\,t} - 1\right)\left(\frac{\Phi(p) - \Psi(p)}{2}\right)$$

Observational effects

Solar System (momentum space)

$$H_{\Phi+\Psi} = \left(\frac{\sin(p\,t)}{p\,t} - \cos(p\,t)\right)\left(\frac{\Phi(p)+\Psi(p)}{2}\right)$$

$$H_{\Phi-\Psi} = \left(\frac{\sin(p\,t)}{p\,t} - 1\right)\left(\frac{\Phi(p)-\Psi(p)}{2}\right)$$

$$H_{\Phi+\Psi}, H_{\Phi-\Psi} \xrightarrow{p\to 0} 0$$

There is no shift in the spacetime mean value of Higgs VEV

Observational effects

Newtonian potential

Solar System (momentum space)

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$$H_{\Phi+\Psi}, H_{\Phi-\Psi} \xrightarrow{p\to 0} 0$$

There is no shift in the spacetime mean value of Higgs VEV

Observational effects

Solar System (real space, momentum space)

- Newtonian potential

$$\Phi_N(r) = -\frac{1}{r} G M \longleftrightarrow \Phi_N(p) = -\frac{4\pi}{p^2} G M$$

Observational effects

Solar System *(real space)*

$$
\left.\begin{aligned}
H^N_{\Phi+\Psi} &= \left(\frac{r}{t}\right)\,\Phi_N \\[2em]
H^N_{\Phi-\Psi} &= \frac{1}{2}\left(\frac{r}{t}-1\right)\,\Phi_N\,(1-\underbrace{\gamma}_{\text{Eddington parameter}})
\end{aligned}\right\} \times\ \theta(t^2-r^2)
$$

Observational effects

Solar System (real space)

$$\left.\begin{array}{l} H^{N}_{\Phi+\Psi} = \left(\dfrac{r}{t}\right)\, \Phi_N \\[2ex] H^{N}_{\Phi-\Psi} = \dfrac{1}{2}\left(\dfrac{r}{t} - 1\right)\, \Phi_N\,(1 - \underbrace{\gamma}_{\text{Eddington parameter}}) \end{array}\right\} \times \underbrace{\theta(t^2 - r^2)}_{\text{Causality}}$$

Observational effects

Solar System (real space)

$$\left.\begin{aligned} H^N_{\Phi+\Psi} &= \left(\frac{r}{t}\right)\Phi_N \\ H^N_{\Phi-\Psi} &= \frac{1}{2}\left(\frac{r}{t}-1\right)\Phi_N\,(1-\gamma) \end{aligned}\right\} \times \underbrace{\theta(t^2-r^2)}_{\text{Causality}}$$

Remarks

- $\frac{r}{t}$ → Boundary effects from the bc's of the modes

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Observational effects

Solar System (real space)

$$\left.\begin{aligned} H^{N}_{\Phi+\Psi} &= \cancel{\left(\frac{r}{t}\right)}\,\Phi_N \\ H^{N}_{\Phi-\Psi} &= \frac{1}{2}\left(\cancel{\frac{r}{t}} - 1\right)\Phi_N\,(1-\gamma) \end{aligned}\right\} \times \underline{\theta(t^2 - r^2)}$$

Causality

Remarks

- $\dfrac{r}{t}$ → Boundary effects from the bc's of the modes

$$\underline{t \to \infty}$$

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Observational effects

Solar System (real space)

$$H^{N}_{\Phi+\Psi} = 0$$

$$H^{N}_{\Phi-\Psi} = -\frac{1}{2}\Phi_N\left(1 - \underbrace{\gamma}_{\text{Eddington parameter}}\right)$$

Remarks

- $\frac{r}{t}$ → Boundary effects from the bc's of the modes

$$\underline{t \to \infty}$$

Observational effects

Solar System (real space)

$$H^{N}_{\Phi+\Psi} = 0$$

$$H^{N}_{\Phi-\Psi} = -\frac{1}{2}\Phi_N\left(1-\underbrace{\gamma}_{\text{Eddington parameter}}\right)$$

Remarks

- $\gamma = \dfrac{\Psi}{\Phi}$ $\rightarrow$ In GR $\gamma = 1$

  no effect in GR

Observational effects

Solar System (real space, momentum space)

- Newtonian potential

$$\Phi_N(r) = -\frac{1}{r} G\, M \longleftrightarrow \Phi_N(p) = -\frac{4\pi}{p^2} G\, M$$

Observational effects

Solar System (real space, momentum space)

- Newtonian potential

$$\Phi_N(r) = -\frac{1}{r} G\, M \longleftrightarrow \Phi_N(p) = -\frac{4\pi}{p^2} G\, M$$

- General potential

$$\Phi(r) = -\frac{1}{r} \sum_{l=0}^{\infty} \sum_{m=l}^{l} \frac{Q_{lm}}{r^l} \sqrt{\frac{4\pi}{2l+1}} Y_{lm}(\theta, \phi)$$

$$\updownarrow$$

$$\Phi(p) = -\frac{4\pi}{p^2} \sum_{l=0}^{\infty} i^l \sum_{m=l}^{l} \frac{Q_{lm}}{(2p)^l} \sqrt{\frac{4\pi}{2l+1}} Y_{lm}(\theta_p, \phi_p)$$

Observational effects

Solar System (real space) Newtonian results

$$H^N_{\Phi+\Psi} = 0$$

$$H^N_{\Phi-\Psi} = -\frac{1}{2}\Phi_N\left(1-\underbrace{\gamma}_{\text{Eddington parameter}}\right)$$

Remarks

- $\gamma = \dfrac{\Psi}{\Phi}$ → In GR $\gamma = 1$

no effect in GR

Observational effects

Solar System (real space)

General results

$$H^{\cancel{N}}_{\Phi+\Psi} = 0$$

$$H^{\cancel{N}}_{\Phi-\Psi} = -\frac{1}{2}\Phi_{\cancel{N}}(1-\underbrace{\gamma}_{\text{Eddington parameter}})$$

Remarks

- $\gamma = \dfrac{\Psi}{\Phi}$ $\rightarrow$ In GR $\gamma = 1$

  no effect in GR

Observational effects

Solar System (real space)

Eddington parameter

$$\Delta_{\text{Higgs}} = \frac{3\lambda}{8\pi^2}\,\underbrace{\Delta\Phi}_{\text{Gravitational potential}}\,(1-\gamma)$$

$\lambda \simeq 1/8$

Gravitational potential

Observational effects

Solar System (real space)

$$\Delta_{\text{Higgs}} = \frac{3\lambda}{8\pi^2} \Delta\Phi \left(1 - \gamma\right)$$

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

Proton-to-electron mass ratio

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

Atomic clocks on Earth

Huntemann, et al. 2014

Observational effects

Solar System (real space)

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

Cassini bound,

Bertotti, et al. 2003

$$\Delta_{\text{Higgs}} = \frac{3\lambda}{8\pi^2}\Delta\Phi\,(1-\gamma)$$

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

on Earth

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

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

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

around the Sun

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

Proton-to-electron mass ratio

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

Atomic clocks on Earth

Huntemann, et al. 2014

Observational effects

Solar System (real space)

$$\Delta^{i}{}_{\mathrm{Higgs}} \approx \frac{3\lambda}{8\pi^2}\,\Delta\Phi\,(1-\gamma)$$

- Higgs self-interactions
- Vector bosons
- Top quark

Observational effects

Solar System (real space)

$$\Delta^{i}_{\mathrm{Higgs}} \approx \frac{3\lambda}{8\pi^2}\,\Delta\Phi\,(1-\gamma)\;\times\; n_{\mathrm{eff}}\;\times$$

$\downarrow$

Bosons,
Fermions

- Higgs self-interactions
- Vector bosons
- Top quark

Observational effects

Solar System (real space)

$$\Delta^{i}{}_{\mathrm{Higgs}} \approx \frac{3\lambda}{8\pi^2}\,\Delta\Phi\,(1-\gamma) \times n_{\mathrm{eff}} \times \left(\frac{g_i}{\lambda}\right) \times \left(\frac{m_i}{m_{\mathrm{Higgs}}}\right)^4$$

Bosons, Fermions

Mass/coupling factors

- Higgs self-interactions
- Vector bosons
- Top quark

Work in progress...

Outline

- Introduction ✓
- Modes ✓
- Results ✓
- Observational effects ✓
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Outline

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Conclusions

Yes!

- Metric perturbations induce a space-time dependent Higgs VEV which translates into variations on the masses of all the elementary particles.
- Competitive constraints on the Eddington parameter can be obtained from measurements of the proton-to-electron mass ratio within the Solar System.