The Higgs field and gravity

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under the supervision of

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Instituto de Física Teórica UAM/CSIC

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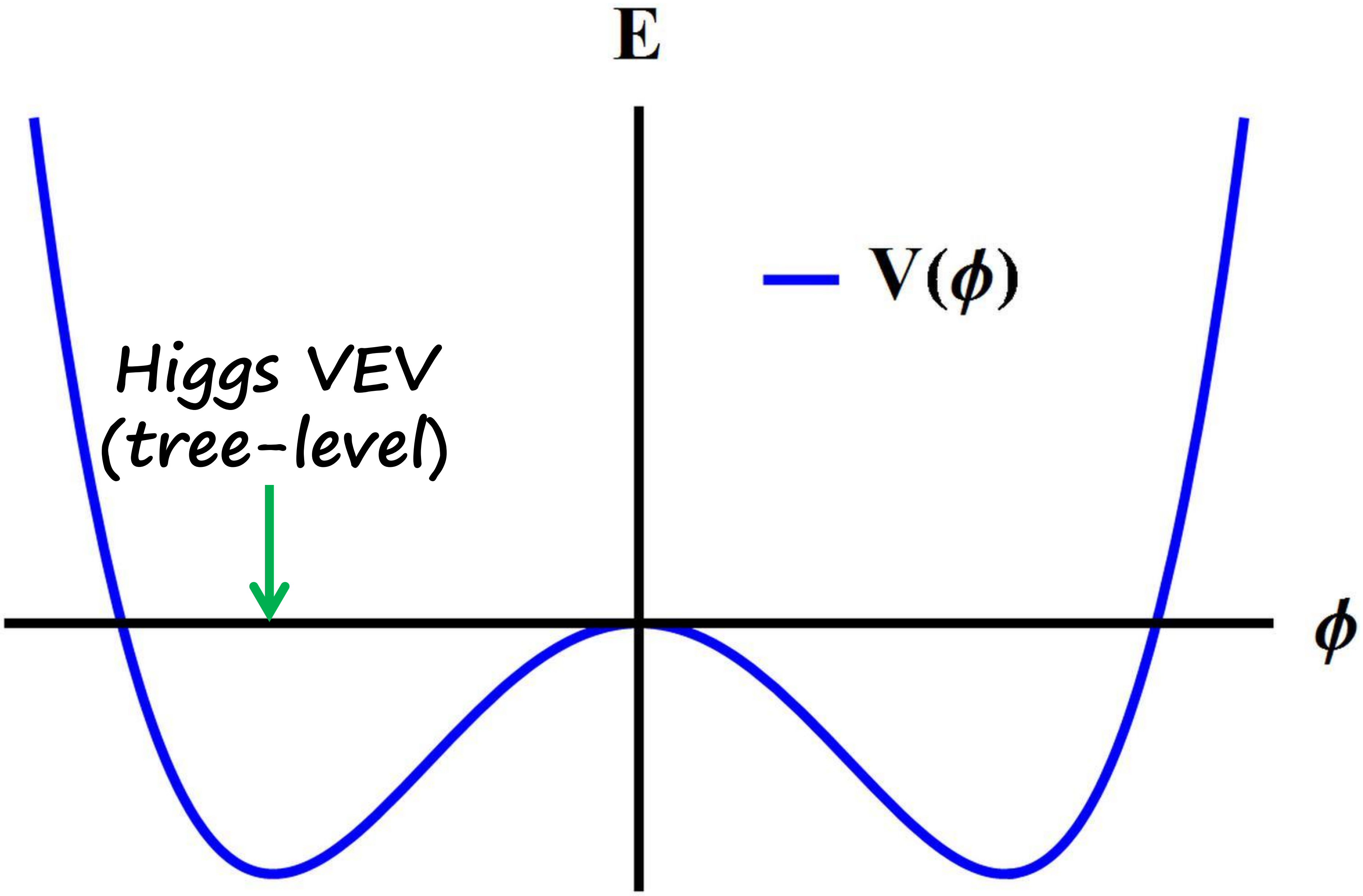

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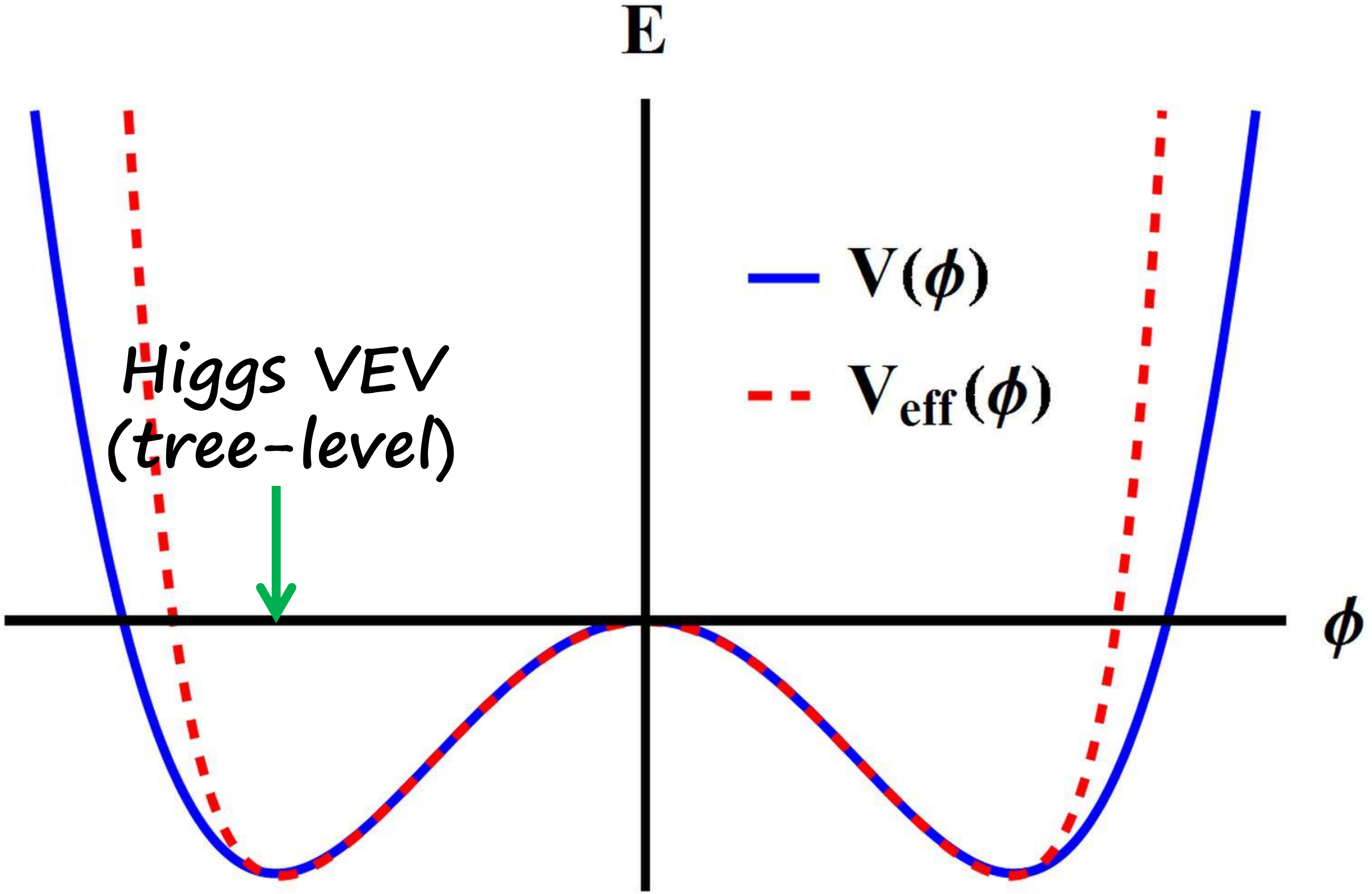
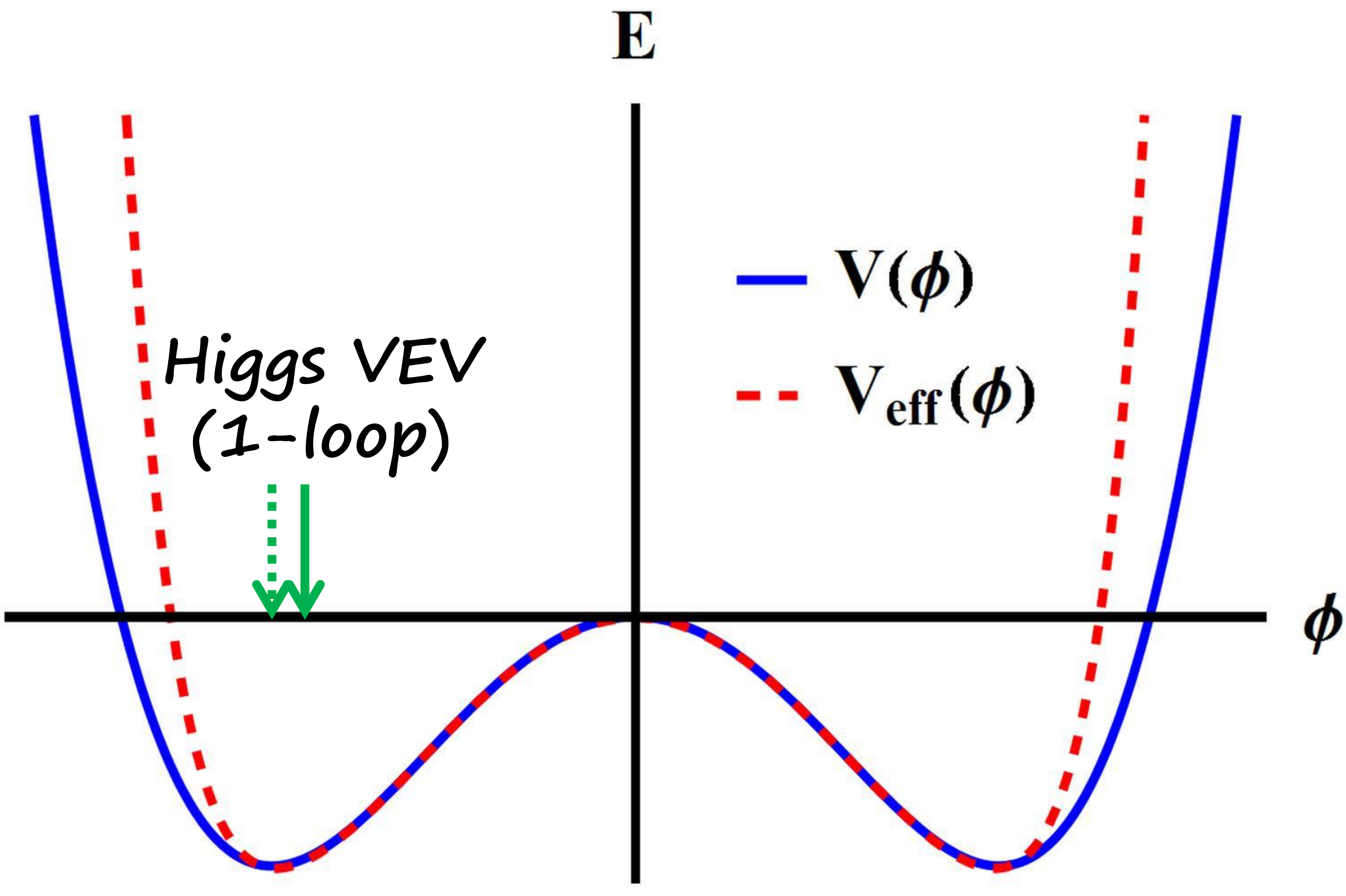

E
$V(\phi)$
$V_{eff}(\phi)$
Higgs VEV
(tree-level)
ϕ



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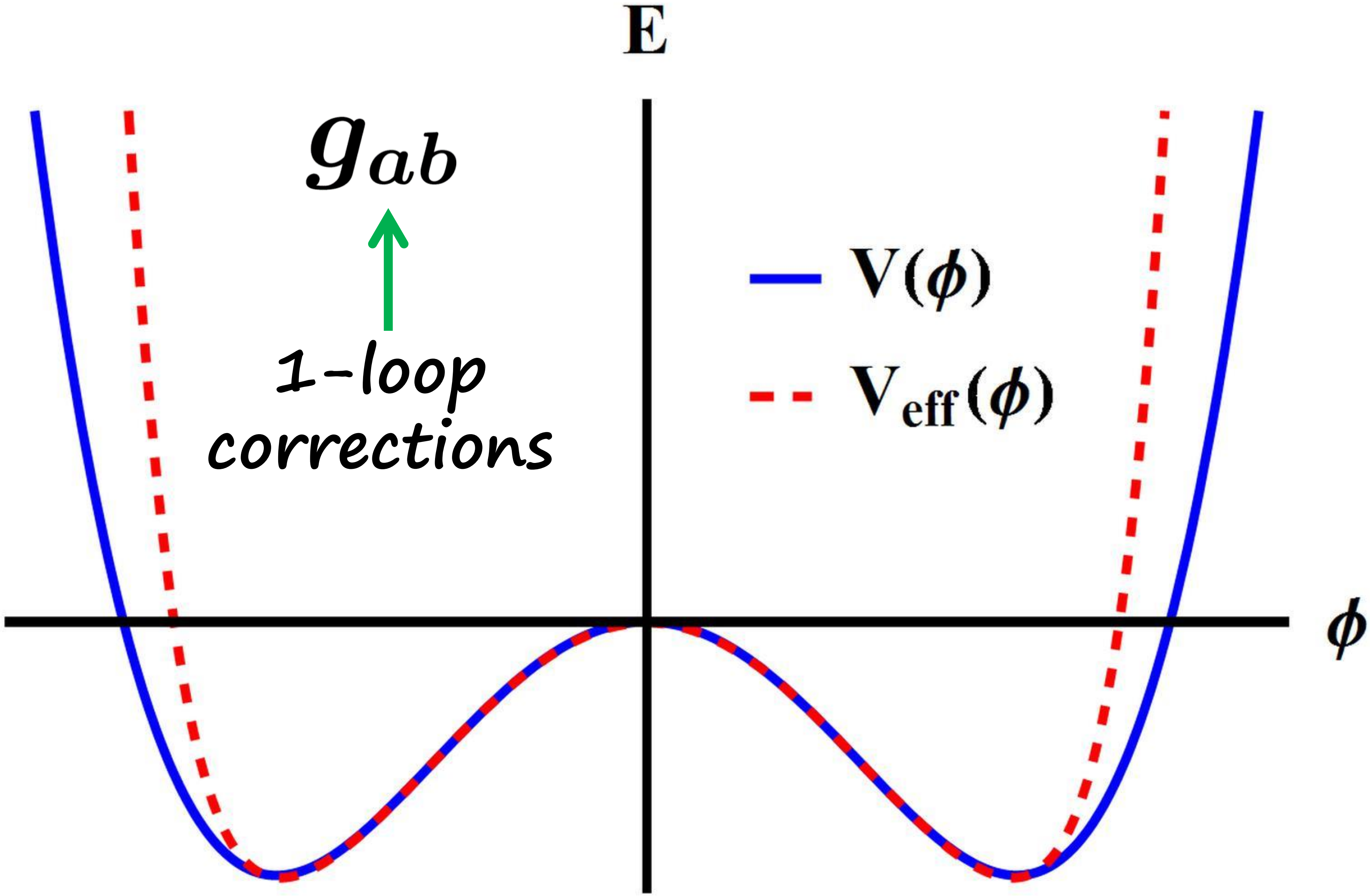
E
g_{ab}
1-loop corrections
$V(\phi)$
$V_{eff}(\phi)$
ϕ

Outline

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

Introduction

KG eq.

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

Introduction

KG eq.

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

Quantum operator

Introduction

KG eq.

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

Quantum operator

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

Background field

Quantum perturbation

Introduction

KG eq.

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

$$\overbrace{\hat{\phi} + \delta\phi}^{\text{Quantum operator}}$$

Background field

Quantum perturbation

where...

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

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

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

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

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

Background field

Introduction

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

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

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

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

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

Bare potential

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

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Introduction

Background field

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

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

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Bare potential

Quantum fluctuations
(1-loop)

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

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Introduction

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

$$\boldsymbol{V}^{\circ}_{\mathbf{eff}}(\hat{\phi}) = \boldsymbol{V}(\hat{\phi}) + \boldsymbol{V}^{\circ}(\hat{\phi})$$

Introduction

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

$$V^{\circ}_{\mathrm{eff}}(\hat{\phi}) = V(\hat{\phi}) + V^{\circ}(\hat{\phi})$$

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

Introduction

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

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

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

Quadratic operator

Introduction

Flat space-time

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

Vaccum energy of quantum fluctuations

Introduction

Flat space-time

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

Vaccum energy of quantum fluctuations

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

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

Introduction

Flat FRW

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

Vaccum energy of quantum fluctuations

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

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Introduction

Flat FRW

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

Comoving scales get
redshifted

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

Physical renormalization scale

Introduction

Flat space-time

Flat FRW

Homogeneous effect

Non-homogeneus effect?

Introduction

Perturbations

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

$$\Phi,\ \Psi$$

Static weak gravitational field (Solar System...)

Cosmological effects due to the LSS

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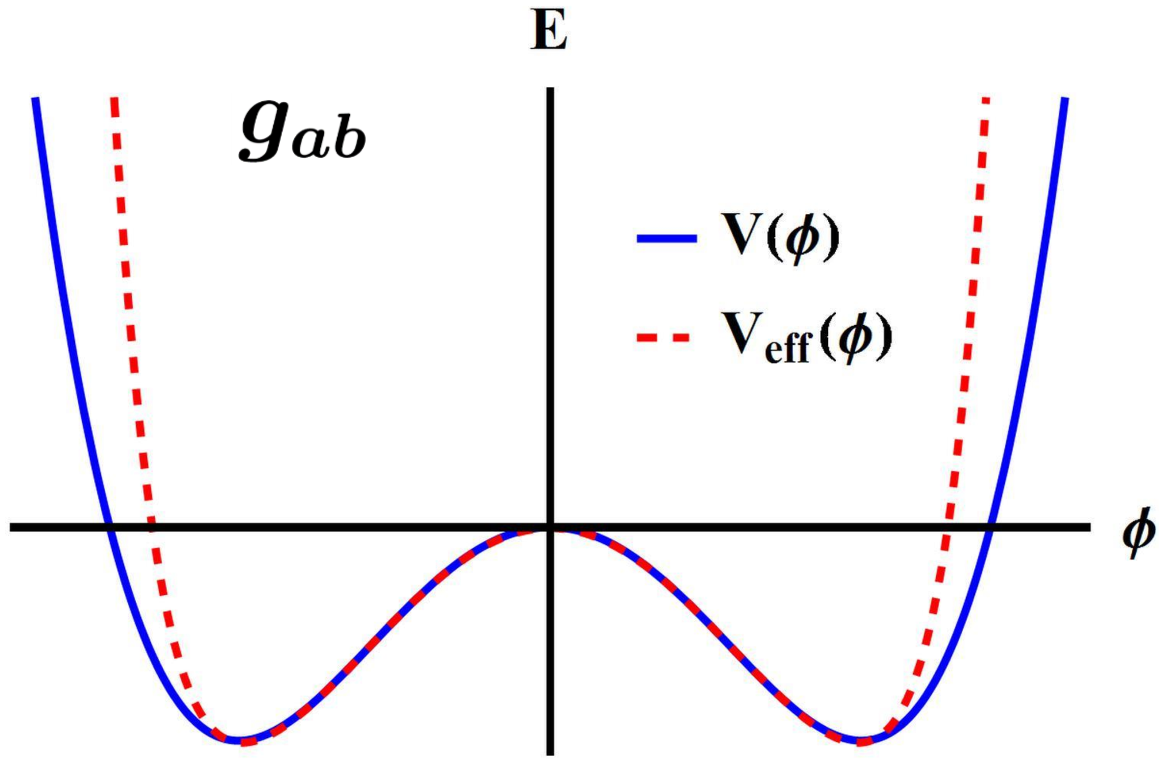
So…



1-loop corrections

due to the interactions with particles of the SM

sensitive to the space-time geometry

$\Phi, \ \Psi$

In this work, Higgs self-interactions

Outline

- **Introduction** ✓
- **Modes**
- **Results**
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Modes

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

$$V^{\circ}_{\text{eff}}(\hat{\phi}) = V(\hat{\phi}) + V^{\circ}(\hat{\phi})$$

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

Quadratic operator

Modes

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

- Divergent part
  - Local
  - Independent of $|0\rangle$
  - Covariant (curvature tensors)
  - Schwinger-de Witt
- Finite part
  - Non-local
  - Depends on $|0\rangle$
  - Not manifestly covariant
  - "Brute force" (mode summation)

Renormalized physical quantities

Modes

Classical gravity

with quantum fields

QFT in curved spacetimes

(Birrel & Davies '82)

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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 (in metric perturbations...)
- Using a WKB ansatz

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

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

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 (in metric perturbations...)
- 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

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

2) Find the modes

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

3) Compute

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

4) Regularize & Renormalize

Outline

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

Outline

- Introduction ✓
- Modes ✓
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Results

$$\boldsymbol{V}^{\circ}_{\mathbf{eff}} = \boldsymbol{V} + \frac{\hbar}{64\pi^2}\boldsymbol{m}^4 \log\left(\frac{\boldsymbol{m}^2}{\boldsymbol{\mu}^2}\right) + \frac{\hbar}{16\pi^2}\boldsymbol{m}^4\left(\boldsymbol{H}_{\boldsymbol{\Phi}} + \boldsymbol{H}_{\boldsymbol{\Psi}}\right)$$

Results

$$V^{\circ}_{\mathbf{eff}} = \boldsymbol{V} + \underbrace{\frac{\hbar}{64\pi^2}\boldsymbol{m}^4 \log\left(\frac{\boldsymbol{m}^2}{\boldsymbol{\mu}^2}\right)}_{\text{Homogeneous contribution}} + \frac{\hbar}{16\pi^2}\boldsymbol{m}^4\left(\boldsymbol{H}_{\boldsymbol{\Phi}} + \boldsymbol{H}_{\boldsymbol{\Psi}}\right)$$

- Divergent
- Does not depend on geometry to this order

Results

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

Homogeneous contribution

- Divergent
- Does not depend on geometry to this order

Non-homogeneous contribution

- Finite
- Non-local

Results

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

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Results

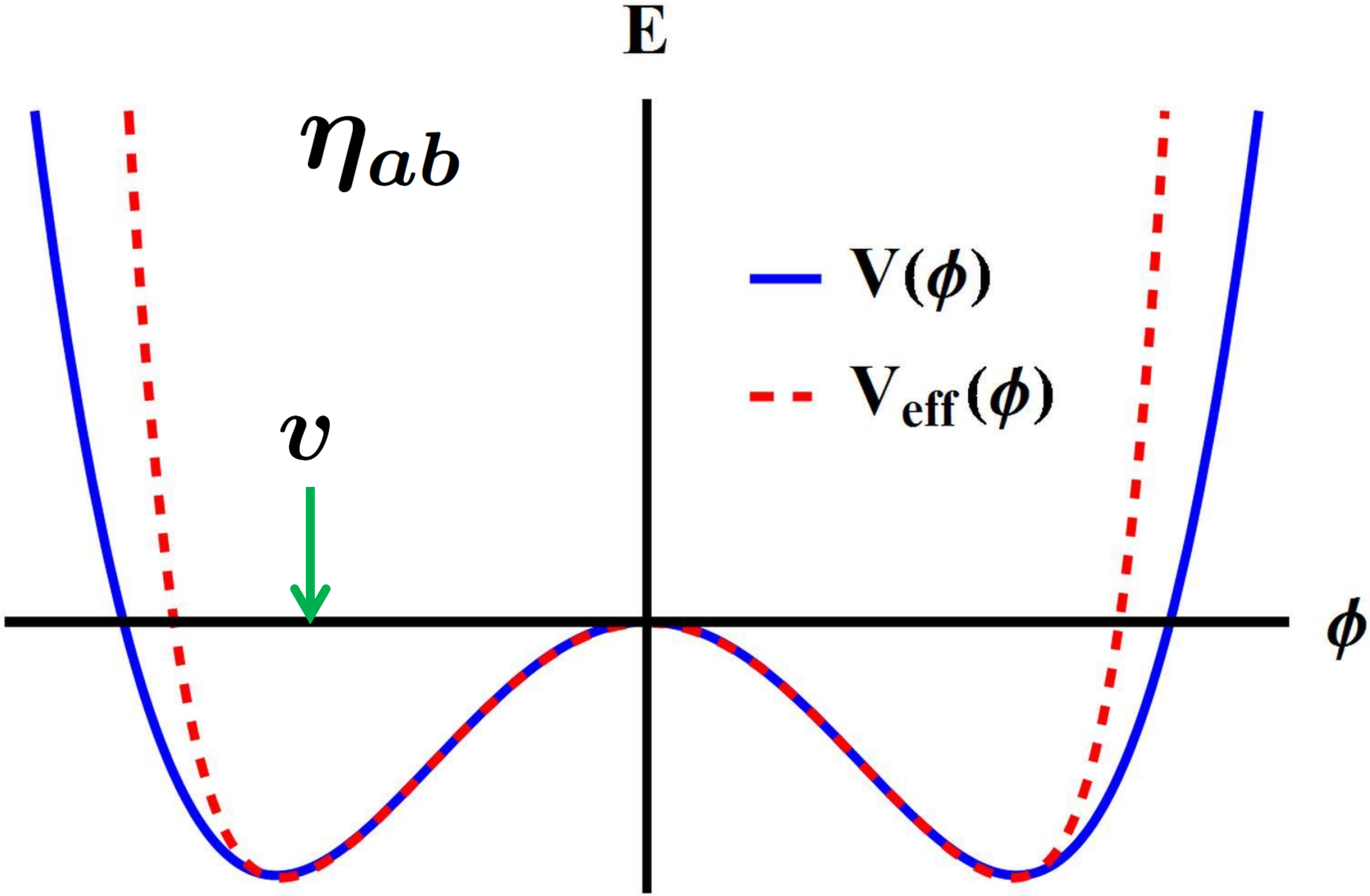
$$V(\hat{\phi}) = V_0 + \frac{1}{2}M^2\hat{\phi}^2 + \frac{1}{4}\lambda\hat{\phi}^4$$

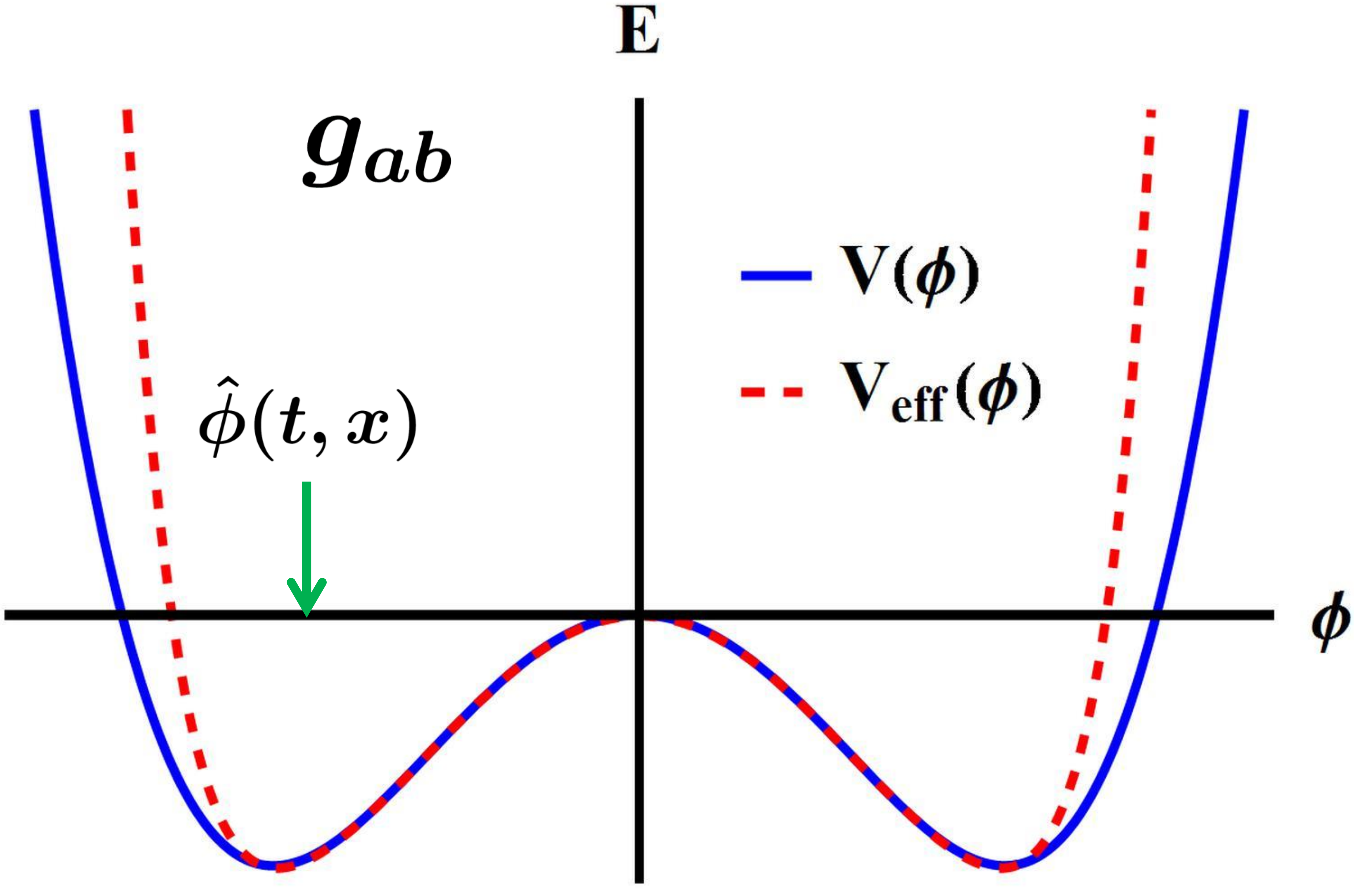
Results

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

$$\underline{M^2(\eta, x)} = M^2\left(1 + \frac{3\lambda}{4\pi^2}\left[H_\Phi(\eta, x) + H_\Psi(\eta, x)\right]\right)$$

$$\underline{\lambda(\eta, x)} = \lambda\left(1 + \frac{9\lambda}{4\pi^2}\left[H_\Phi(\eta, x) + H_\Psi(\eta, x)\right]\right)$$


E
η_{ab}
$V(\phi)$
$V_{eff}(\phi)$
v
ϕ


E
g_{ab}
V(ϕ)
$V_{eff}(\phi)$
$\hat{\phi}(t, x)$
ϕ

Results

Higgs VEV

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

Homogeneous

Space-time dependent

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

- Non-homogeneous effect, the field value which minimizes the potential is different for each point of spacetime.

Results

Perturbations

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

$\Phi,\ \Psi$

Static weak gravitational field (Solar System...)

Cosmological effects due to the LSS

Results

Perturbations

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

$$\Phi,\ \Psi$$

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Results

Solar System (momentum space)

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

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

Results

Solar System (momentum space)

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

The corrections tend to zero for large modes

Results

Newtonian potential

Solar System (momentum space)

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

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

The corrections tend to zero for large modes

Results

Solar System (real space, momentum space)

- Newtonian potential

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

Results

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

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

  no effect in GR

Results

Solar System (real space, momentum space)

- Newtonian potential

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

Results

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

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

$$\updownarrow$$

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

Results

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

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Results

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

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

  no effect in GR

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Observational effects

$$\Delta_{\text{Higgs}}$$

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

Observational effects

$$\Delta_{\mathrm{Higgs}}$$

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

Observational effects

Solar System

Eddington parameter

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

$\lambda \simeq 1/8$

Gravitational potential

Observational effects

Solar System

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

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

Proton-to-electron mass ratio

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

Atomic clocks on Earth

Huntemann, et al. 2014

Observational effects

Solar System

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

Cassini bound,
Bertotti, et al. 2003

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

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

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

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

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

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

- Higgs self-interactions
- Vector bosons
- Top quark

Observational effects

Solar System

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

$\downarrow$

Bosons,
Fermions

- Higgs self-interactions
- Vector bosons
- Top quark

Observational effects

Solar System

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

Bosons, Fermions

Mass/coupling factors

- Higgs self-interactions
- Vector bosons
- Top quark

Work in progress...

Outline

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

Outline

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Conclusions

- Metric perturbations contribute to the finite part of the Higgs 1-loop effective potential
- This leads to a space-time dependent Higgs VEV
- which suggests variations on the masses of all the elementary particles.
- Within the Solar System, constraints on the Eddington parameter can be obtained from measurements of the proton-to-electron mass ratio.

Backslides

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.

Results

Why not effective action?

$$\Gamma_Q = \int \mathrm{d}^4x \, (-V_{\text{eff}}) + \ldots (\partial\phi)^2 + \ldots$$

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

Quantum frequencies

Higgs boson mass ~ 125 GeV

Gravitacional frequencies

Solar System ~ 10^{-25} GeV

Cosmology ~ 10^{-39} GeV

Results

Solar System (real space)

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

Results

Solar System (real space)

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

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Results

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

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

Results

Solar System (real space)

$$H^{N}_{\Phi+\Psi} = \cancel{\left(\frac{r}{t}\right)}\, \Phi_N$$

$$H^{N}_{\Phi-\Psi} = \frac{1}{2}\left(\cancel{\frac{r}{t}} - 1\right) \Phi_N \,(1-\gamma)$$

$$\times\ \theta(t^2 - r^2)$$

Causality

Remarks

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

$$t \to \infty$$

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Results

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

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

$$t \to \infty$$