Higgs field in cosmology

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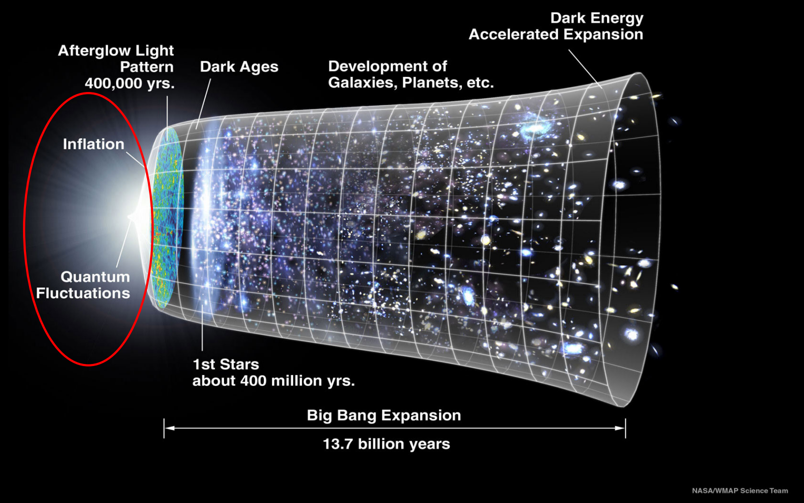
Albert-Ludwigs-Universität Freiburg

678th Wilhelm and Else Heraeus Seminar:

Hundred Years of Gauge Theory,

Bad Honnef, 02.08.2018

Cosmic history



The Friedmann universe on one slide

Cosmological principle: universe homogeneous and isotropic on large scales

Line element of a flat FLRW universe with scale factor $a(t)$:

$$\mathrm{d}s^2 = g_{\mu\nu}(x)\mathrm{d}x^\mu \mathrm{d}x^\nu = -\mathrm{d}t^2 + a^2(t)\left[\mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2\right]$$

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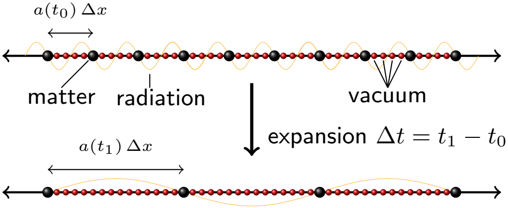
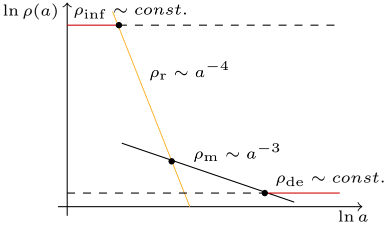
Friedmann equations for EM tensor of a perfect fluid and equation of state:

$$\left.\begin{aligned} H^2 = \left(\frac{\dot a}{a}\right)^2 &= \frac{\kappa}{3}\,\rho \\ \dot\rho &= -3H\,(\rho + p) \\ p &= \omega\,\rho \end{aligned}\right\}\ \rho \propto a^{-3\,(\omega+1)}$$

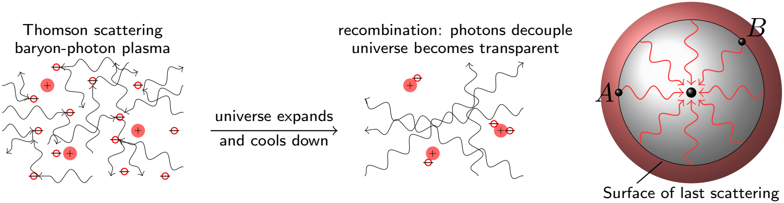
epoch	ω	$\rho(a)$	$a(t)$
matter	0	a^{-3}	$t^{2/3}$
radiation	$1/3$	a^{-4}	$t^{1/2}$
vacuum	-1	const.	e^{Ht}





Isotropic cosmic microwave background (CMB)

Surface of last scattering: CMB photons were released



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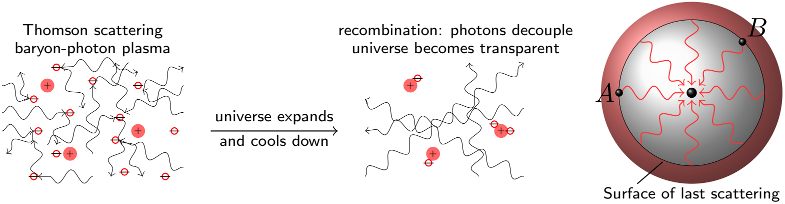
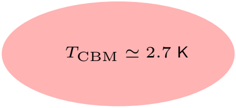
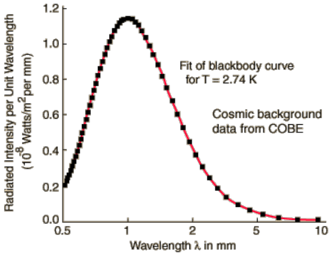


Isotropic microwave radiation: perfect black body spectrum

Projection of the sphere



Discovered by Penzias & Wilson, 1964

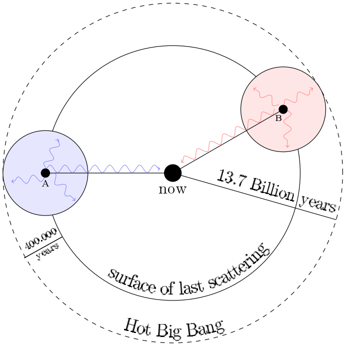


COBE collaboration

Horizon problem and inflation

Why do we observe the same CMB temperature from all directions in the sky?

Causal patches at recombination could have never been in causal contact



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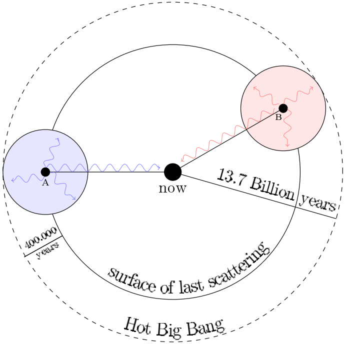

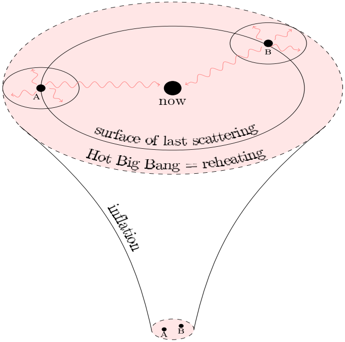

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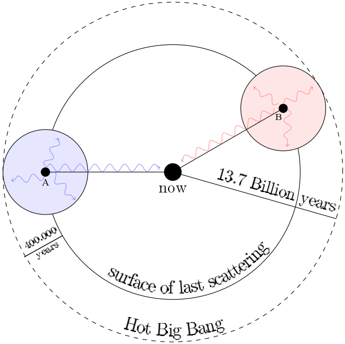

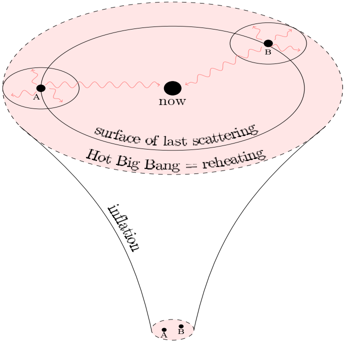

Inflation: CMB radiation observed today originates from the same causal patch.

Accelerated expansion $\ddot{a}/a = -\frac{\kappa\rho}{6}(1+3\omega) > 0$ requires $\omega \leq -1/3$

Cosmological constant $(\omega = -1) \rightarrow$ exponential expansion $a(t) = e^{Ht}$

Scalar field inflation

How is inflation realized? What is the mechanism behind inflation?

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Dynamical mechanism: scalar "inflaton" field φ drives inflation

$$S[\varphi, g] = \int \mathrm{d}^4x \sqrt{-g} \left[-\frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi - V(\varphi) \right], \quad \omega_\varphi = \frac{\frac{1}{2}\dot{\varphi}^2 - V(\varphi)}{\frac{1}{2}\dot{\varphi}^2 + V(\varphi)}$$

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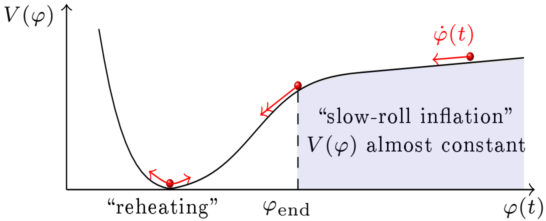
During inflation φ slowly rolls ($\dot{\varphi}^2 \ll V$) down the the potential $\omega_\varphi \approx -1$



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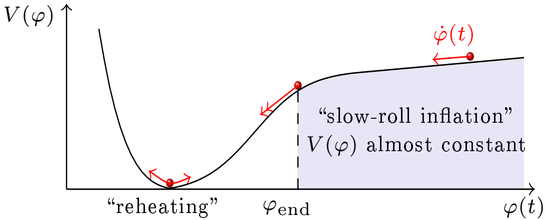
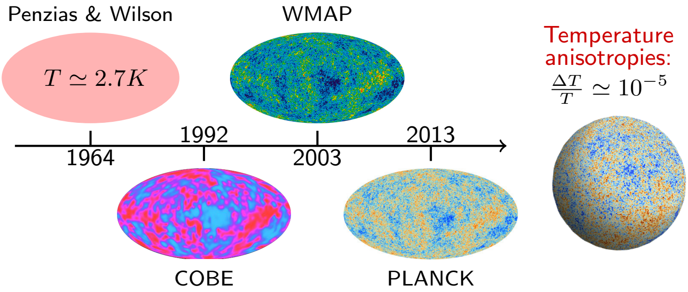


Quantify deviation from DeSitter space ($V =$ const.) by slow-roll parameters

$$\varepsilon_V = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2, \qquad \eta_V = M_P^2\frac{V''}{V}$$

CMB anisotropies and perturbations



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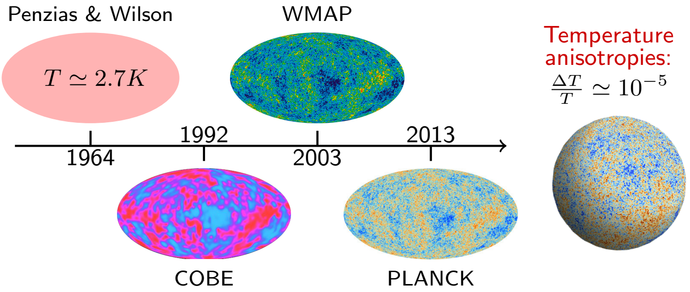

Tiny temperature anisotropies originate from quantum fluctuations

$$\varphi(x,t) = \bar{\varphi}(t) + \delta\varphi(x,t), \qquad g_{\mu\nu}(x,t) = \bar{g}_{\mu\nu}(t) + \delta g_{\mu\nu}(x,t)$$

single field Inflation: adiabatic fluctuations with almost scale-invariant spectrum

$$\mathcal{P}_{\rm s}(k) = A_{\rm s}(k_*)\left(\frac{k}{k_*}\right)^{n_{\rm s}-1+\ldots}, \quad \mathcal{P}_t(k) = A_{\rm t}(k_*)\left(\frac{k}{k_*}\right)^{n_{\rm t}+\ldots}, \quad r := \frac{A_{\rm t}}{A_{\rm s}}$$

Confronting predictions with observations

Slow-roll observables only depend on the inflaton potential (V, V' and V'')

$$A_\mathrm{s} = \frac{2}{24\pi^2\varepsilon_V}\frac{V}{M_\mathrm{P}^4}, \qquad \ln\left(10^{10}A_\mathrm{s}\right) = 2.975 \pm 0.056 \quad 68\%\ \text{CL}$$

$$n_\mathrm{s} = 1 + 2\eta_V - 6\varepsilon_V, \qquad r = 16\varepsilon_V$$

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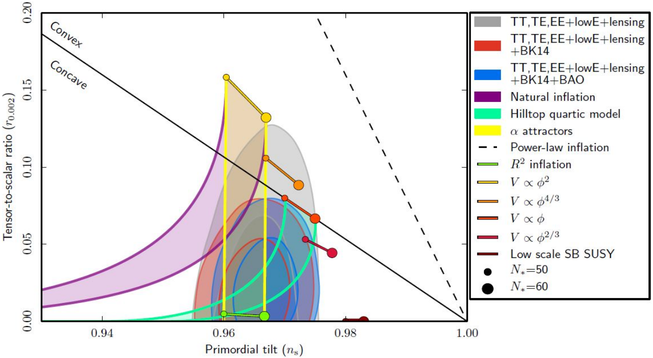

Planck 2018 results, arXiv:1807.06211

Confronting predictions with observations

Main observables: primordial power spectra of scalar and tensor perturbations

$$\mathcal{P}_{\mathrm{s}}(k) =: A_{\mathrm{s}}(k_*) \left(\frac{k}{k_*}\right)^{n_{\mathrm{s}}-1+\ldots}, \quad \mathcal{P}_t(k) =: A_{\mathrm{t}}(k_*) \left(\frac{k}{k_*}\right)^{n_{\mathrm{t}}+\ldots}, \quad r := \frac{A_{\mathrm{t}}}{A_{\mathrm{s}}}$$

Slow-roll inflation: observables depend on the inflaton potential V

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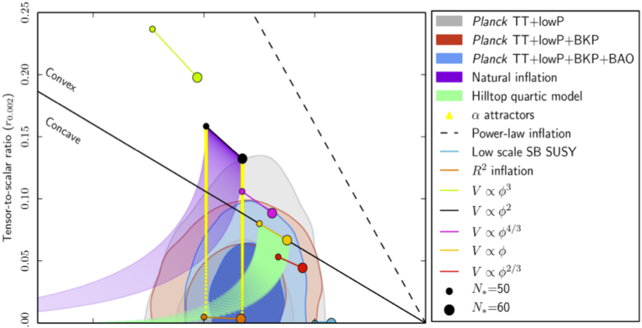
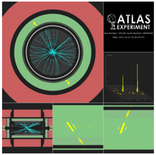
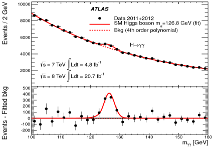
What is the fundamental nature of the inflaton field?



Standard Model Higgs boson = inflaton

A fundamental scalar particle has been observed: the SM Higgs boson





credit: ATLAS collaboration

$M_{\rm H} = 125.09 \pm 0.24$ GeV

(ATLAS/CMS)

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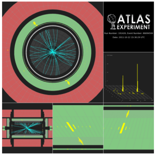

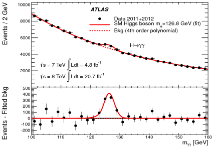

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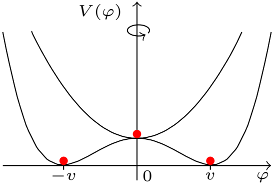
Standard Model Higgs potential:

$$V(\varphi^2) = \frac{\lambda}{4}(\varphi^2 - v^2)^2$$



BEH mechanism: φ develops nonzero vev $v \simeq 246$ GeV

Minimal vs. non-minimal Higgs inflation

Natural approach: Higgs boson minimally coupled to gravity (SM+gravity)

$$S[g,\varphi] = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_\mathrm{P}^2}{2}R - \frac{1}{2}(\partial\varphi)^2 - V(\varphi)\right], \quad V = \frac{\lambda}{4}\left(\varphi^2 - v^2\right)^2$$

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Does not work: CMB normalization incompatible with Higgs mass

CMB: $10^{-9} \simeq A_{\mathrm{s}} \propto 10^4\lambda \Rightarrow \lambda \simeq 10^{-13}$, SM: $M_{\mathrm{H}} \propto \sqrt{\lambda}v \sim 10^{-5}$ GeV

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Include lowest order of EFT expansion: add non-minimal coupling ξ term

[Bezrukov, Shaposhnikov (2008)]

$$S[g,\varphi] = \int \mathrm{d}^4x\sqrt{-g}\left[U(\varphi)R - \frac{1}{2}(\partial\varphi)^2 - V(\varphi)\right], \quad U = \frac{1}{2}\left(M_\mathrm{P}^2 + \xi\varphi^2\right)$$

Tree-level Higgs inflation: Einstein frame and large ξ

Transformation to Einstein frame: $\hat{g}_{\mu\nu} = \frac{2\,U}{M_{\rm P}^2} g_{\mu\nu}, \quad \left(\frac{\partial\hat{\varphi}}{\partial\varphi}\right)^2 = \frac{M_{\rm P}^2}{2U}\left(1 + 3\frac{U'^2}{U}\right)$

$$\hat{S}[\hat{g},\hat{\varphi}] = \int \mathrm{d}^4x\sqrt{-\hat{g}}\left[\frac{M_{\rm P}^2}{2}\,R(\hat{g}) - \frac{1}{2}\,(\partial\hat{\varphi})^2 - \hat{V}\right]$$

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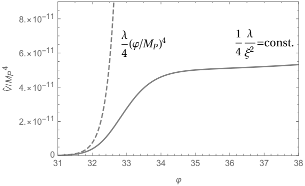
Einstein frame potential $\hat{V}$ flattens out for large field values $\varphi \gg M_{\rm P}/\sqrt{\xi}$



$$\frac{\hat{V}}{M_{\rm P}^4} = \frac{V}{4U^2}$$

$$= \frac{\lambda}{4}\frac{\left(\varphi^2 - v^2\right)^2}{\left(M_{\rm P}^2 + \xi\varphi^2\right)^2} \simeq \frac{1}{4}\frac{\lambda}{\xi^2}$$

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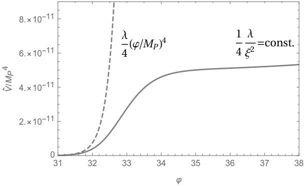

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For $\xi \simeq 10^3 - 10^4$ and $\lambda \simeq 0.1$ CMB and Higgs constraints can be satisfied:

$$A_\mathrm{s} \propto \frac{\lambda}{\xi^2} \simeq 10^{-9}, \qquad M_\mathrm{H} \simeq \sqrt{\lambda}v \simeq 125 \text{ GeV}$$

Inflationary observables in excellent agreement with observations

$$n_\mathrm{s} \simeq 0.967, \qquad r \simeq 0.003$$

Quantum corrections and renormalization group flow

Quantum contributions of heavy SM particles to effective potential important

[Barvinsky, Kamenshchik, Starobinksy (2008)]

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Energy scales of Standard Model and inflation separated by $E_{\rm inf}/v \simeq 10^{14}$

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Renormalization group flow: evaluate running couplings at E_{inf}

[Bezrukov, Shaposhnikov (2009)], [De Simone, Hertzberg, Wilczek (2009)],

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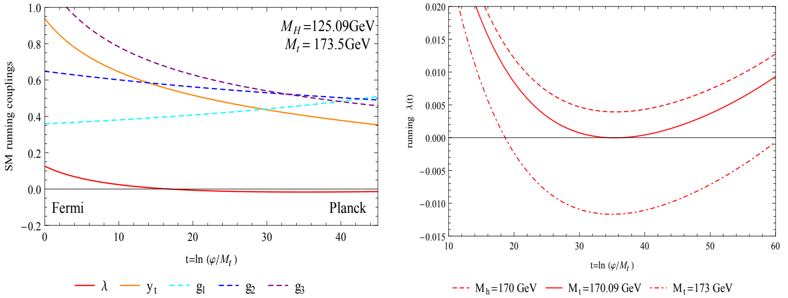
$\lambda(t)$ flows to very small values at high energies and can even become negative



Implications of a light Higgs: status of the model

Different scenarios for positive λ:

1.) Universal: $n_{\rm s}$, r almost insensitive to $M_{\rm H}$ and M_t (typically $\xi \sim 10^3$)

2.) Critical: $n_{\rm s}$, r very sensitive to $M_{\rm H}$ and M_t (typically $\xi \sim 10$, large r)

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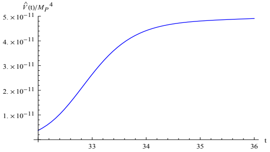
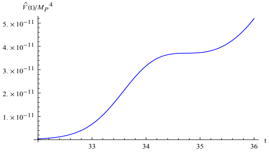


2.)



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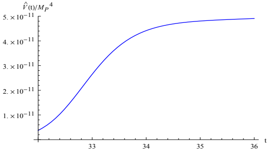

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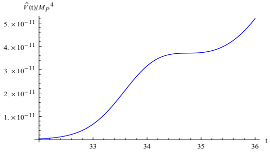
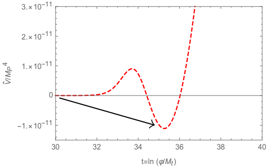
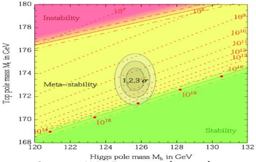


Electroweak vacuum becomes unstable for negative λ:

Tunnelling: EW vacuum metastable if lifetime $\tau_{EW} \sim \Gamma^{-1}_{\rm tunnel} > \tau_{\rm universe}$





from: JHEP 1312 (2013) 089

Instability sign of new physics or SM+gravity valid up to $M_{\rm P}$?

$f(R)$ gravity and quantum parametrization dependence

$f(R)$ gravity and Starobinsky inflation

Geometrical modification of Einstein's theory — $f(R)$ gravity:

$$S[g] = \int \mathrm{d}^4x \sqrt{-g} f(R)$$

Propagates in addition to spin-two graviton a massive spin-zero "scalaron"
[Stelle (1977)]

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[Starobinsky (1980)]

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[Starobinsky (1980)]

$$f(R) = \frac{M_{\mathrm{P}}^2}{2} \left(R + \frac{1}{6M^2} R^2 \right)$$

Same inflationary predictions as Higgs inflation for $M_{\mathrm{P}}^2/3M^2 = \lambda = \xi \simeq 10^4$

[Barvinsky, Kamenshchik and Starobinsky (2008)], [Bezrukov, Gorbunov (2012)] [Kehagias, Dizgah, Riotto (2014)]

$$n_{\mathrm{s}} = 1 - \frac{N}{2}, \qquad r = \frac{12}{N^2}$$

Equivalence of $f(R)$ gravity and scalar-tensor theories

Manifestation of a more general classical equivalence: $\hat{S}^{\mathrm{EF}}[\hat{g}, \hat{\varphi}] \Leftrightarrow S^f[g]$

$$\hat{S}^{\mathrm{EF}}[\hat{g}, \hat{\varphi}] = \int \mathrm{d}^4x \sqrt{-\hat{g}} \left[\frac{M_{\mathrm{P}}^2}{2} \hat{R} - \frac{1}{2} (\partial\hat{\varphi})^2 - \hat{V}(\hat{\varphi}) \right]$$

$$\updownarrow \quad \hat{g}_{\mu\nu} = \frac{f_1}{U_0} g_{\mu\nu}, \quad \hat{\varphi} = \sqrt{\frac{3}{2}} M_{\mathrm{P}} \ln f_1, \quad \hat{V} = \frac{M_{\mathrm{P}}^4}{4} \frac{f_1 R - f}{(f_1)^2} \quad \updownarrow$$

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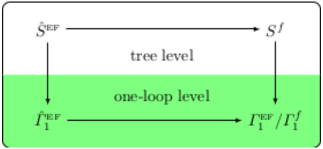
Does the equivalence extend to the quantum level?



Perturbative calculations in theories of gravity (on a general background)

['t Hooft and Veltman (1974)], [Christensen and Duff (1980)], [Fradkin and Tseytlin (1982)], [Avramidi and Barvinksy (1983)] ,[Goroff and Sagnotti (1985)], [van de Ven (1992)]

One-loop calculations in modified theories of gravity

One-loop divergences for a scalar-tensor theory, $\hat{\mathcal{G}} = (\hat{R}_{\mu\nu\rho\sigma})^2 - 4(\hat{R}_{\mu\nu})^2 + \hat{R}^2$

[Barvinksy, Karmazin, Kamenshchik (1993)], [Shapiro and Takata (1995)], [Kamenshchik and CS (2011)]

$$\hat{\Gamma}_1^{\mathsf{EF}}\Big|^{\rm div} = \frac{1}{32\,\pi^2\varepsilon}\int \mathrm{d}^4x\,\hat{g}^{1/2}\Bigg\{ -\frac{71}{60}\hat{\mathcal{G}} - \frac{43}{60}\hat{R}_{\mu\nu}\hat{R}^{\mu\nu} - \frac{1}{40}\hat{R}^2 + \frac{1}{6}\hat{R}\hat{V}_2 - \frac{1}{2}\left(\hat{V}_2\right)^2$$
$$+ U_0^{-1}\left[\frac{13}{3}\hat{R}\,\hat{V} + \frac{1}{3}\hat{R}\,(\partial_\mu\hat{\varphi}\partial^\mu\hat{\varphi}) + 2\left(\hat{V}_1\right)^2 + 2\,\hat{V}_2\,(\partial_\mu\hat{\varphi}\partial^\mu\hat{\varphi})\right]$$
$$- U_0^{-2}\left[5\,\hat{V}^2 + \hat{V}\,(\partial_\mu\hat{\varphi}\partial^\mu\hat{\varphi}) + \frac{5}{4}(\partial_\mu\hat{\varphi}\partial^\mu\hat{\varphi})^2\right]\Bigg\}$$

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One-loop divergences for $f(R)$ gravity, $(E_{\mu\nu} = f_1^{-1}\delta S^f/\delta g^{\mu\nu},\ E = g^{\mu\nu}E_{\mu\nu})$

[Ruf and CS (2018a)]

$$\Gamma_1^f\Big|^{\mathrm{div}} = \frac{1}{32\pi^2\varepsilon}\int \mathrm{d}^4x\,g^{1/2}\Bigg[-\frac{71}{60}\mathcal{G} - \frac{609}{80}R_{\mu\nu}R^{\mu\nu} + \frac{1}{3}\frac{f}{f_2} - \frac{115}{288}\left(\frac{f}{f_1}\right)^2$$
$$-\frac{1}{18}\left(\frac{f_1}{f_2}\right)^2 - \frac{15}{64}\frac{f}{f_1}R + \frac{3919}{1440}R^2 + \frac{15}{64}R\,\Delta\ln f_1 + E\left(\frac{55}{108}E\right.$$
$$\left.-\frac{419}{432}\frac{f}{f_1} + \frac{2933}{864}R + \frac{221}{288}\Delta\ln f_1\right) - E_{\mu\nu}\left(\frac{403}{96}E^{\mu\nu} + \frac{2987}{288}R^{\mu\nu}\right)\Bigg]$$

Off-shell dependence and observables in cosmology

Comparison: off-shell quantum parametrization dependence

[Ruf and CS (2018b)]

$$\Gamma_1^f\Big|^{\mathrm{div}} - \Gamma_1^{\mathsf{EF}}\Big|^{\mathrm{div}} = \frac{1}{32\pi^2\varepsilon}\int \mathrm{d}^4x\, g^{1/2} E_{\mu\nu}\Bigg[-\frac{3}{4}E^{\mu\nu} - \frac{1}{36}R^{\mu\nu} + \left(\frac{91}{108}E + \frac{53}{54}R - \frac{421}{216}\frac{f}{f_1} - \frac{1}{18}\frac{f_1}{f_2} - \frac{26}{9}\Delta\ln f_1\right)g^{\mu\nu}\Bigg] \neq 0$$

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On-shell ($E_{\mu\nu} = E = 0$) the equivalence is restored $\Gamma_1^f\Big|^{\mathrm{div}} - \Gamma_1^{\mathsf{EF}}\Big|^{\mathrm{div}} = 0$

Similar result for quantum equivalence between Jordan and Einstein frame

[Kamenshchik and CS (2014)], [Kamenshchik and CS (2015)]

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Beta functions are derived from off-shell divergences: running couplings inherit parametrization (and gauge) dependence in naïve RG improvement

Manifest gauge and parametrization independent observables in cosmology? Geometric ("unique") effective action?

[Vilkovisky (1984)], [DeWitt 1985)],[Kamenshchik and CS (2014)], [Kamenshchik and CS (2015)], [Moss (2014)], [Bounakis and Moss (2018)]

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Need for unambiguous quantum observables in cosmology