Higgs Inflation and the Ambiguities of General Relativity

Sebastian Zell

Based on work[1] with

G. Karananas, C. Rigouzzo, M. Shaposhnikov, A. Shkerin and I. Timiryasov

École Polytechnique Fédérale de Lausanne

2nd June 2022

[1] M. S., A. S., I. T. and S. Z., *Higgs inflation in Einstein-Cartan gravity*, JCAP **02** (2021) 008 `arXiv:2007.14978`.
G. K., M. S., A. S., and S. Z., *Matter matters in Einstein-Cartan gravity*, Phys. Rev. D **104** (2021) 064036, `arXiv:2106.13811`.
C. R. and S. Z., *Coupling Metric-Affine Gravity to a Higgs-Like Scalar Field*, `arXiv:2204.03003`.

An Open Question in General Relativity

- Different formulations: metric, Einstein-Cartan, . . .

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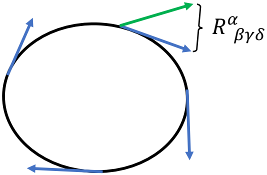
Which formulation should we use?

1. From Einstein-Cartan to Metric-Affine Gravity
2. Higgs Inflation

The Geometry of Gravity

Einstein: curvature

$$R^{\alpha}{}_{\beta\gamma\delta}$$



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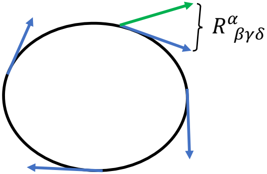
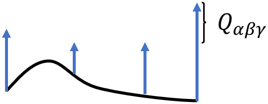


Weyl:[2] non-metricity

$$Q_{\alpha\beta\gamma} = \nabla_{\alpha} g_{\beta\gamma}$$



[2] H. Weyl, *Gravitation und Elektrizität*, Sitzungsber. Preuss. Akad. Wiss. (1918) 465.

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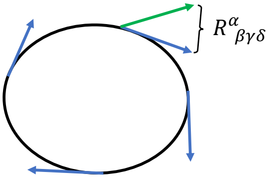

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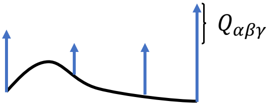
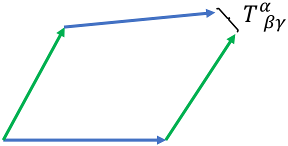


Cartan:[3] torsion

$$T^{\alpha}_{\beta\gamma} = \Gamma^{\alpha}_{\beta\gamma} - \Gamma^{\alpha}_{\gamma\beta}$$



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[3] É. Cartan, *Sur une généralisation de la notion de courbure de Riemann et les espaces à torsion*, Comptes Rendus, Ac. Sc. Paris **174** (1922) 593.

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- Question: Include curvature/torsion/non-metricity?

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  - $R^{\alpha}{}_{\beta\gamma\delta}$ and $T^{\alpha}_{\beta\gamma}$: Einstein-Cartan
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- General Einstein-Cartan

$$\mathcal{L} = \frac{1}{2} M_P^2 R + c_1 M_P^2 T_{\alpha}{}^{\beta\gamma} T^{\alpha}{}_{\beta\gamma} + \ldots$$

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$$\frac{\delta \mathcal{L}}{\delta \Gamma^{\alpha}_{\beta\gamma}} \sim T_{\alpha}{}^{\beta\gamma} \qquad \Rightarrow \qquad T_{\alpha}{}^{\beta\gamma} = 0$$

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- Torsion vanishes dynamically: equivalent to metric GR

Include Matter

- Palatini model

$$\mathcal{L} = \frac{1}{2} M_P^2 R - \frac{1}{2} (\partial_\mu h)^2 - V(h)$$

Include Matter

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$$\mathcal{L} = \frac{1}{2}\left(M_P^2 + \xi h^2\right) R - \frac{1}{2}(\partial_\mu h)^2 - V(h)$$

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- Many more non-minimal coupling constants
- No assumptions about geometry: metric-affine gravity

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$$\mathcal{L} = \frac{1}{2}\left(M_P^2 + \xi h^2\right) R - \frac{1}{2}(\partial_\mu h)^2 - V(h)$$

- Match amplitude of perturbations in CMB:
  metric: $\xi \sim 10^3$ Palatini: $\xi \sim 10^7$

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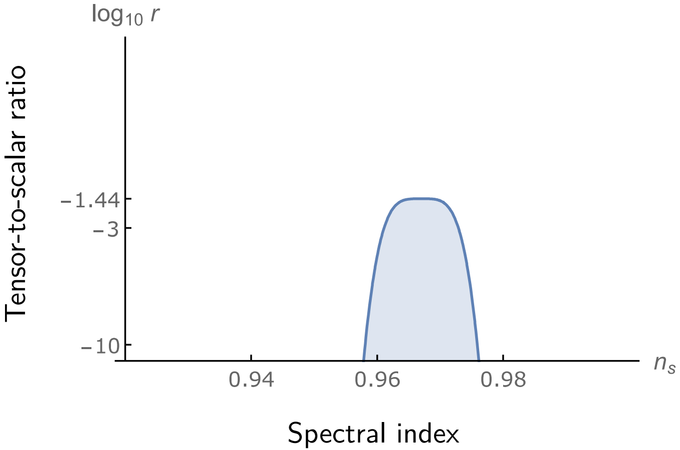
Review of Higgs Inflation



Planck Collaboration, *Planck 2018 results. I.*, `arXiv:1807.06205`.
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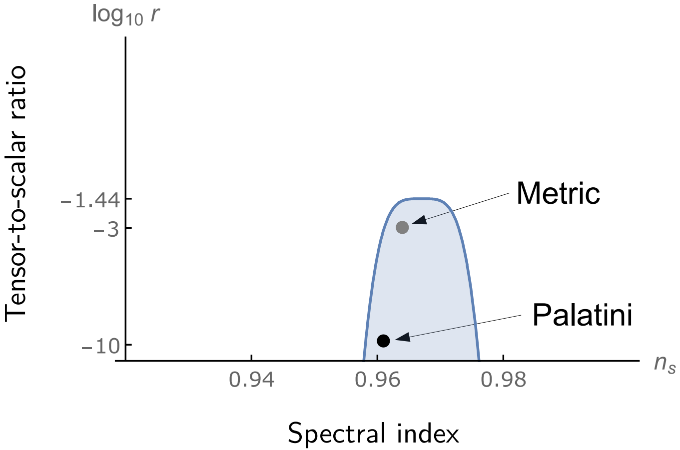

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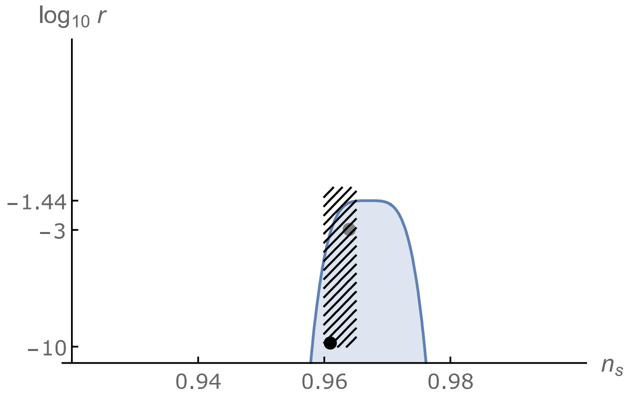

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- Consistent with observations for many choices of couplings
- Higgs inflation as probe of GR
- Quantum effects can distinguish:
  perturbative study of preheating not always possible

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Summary

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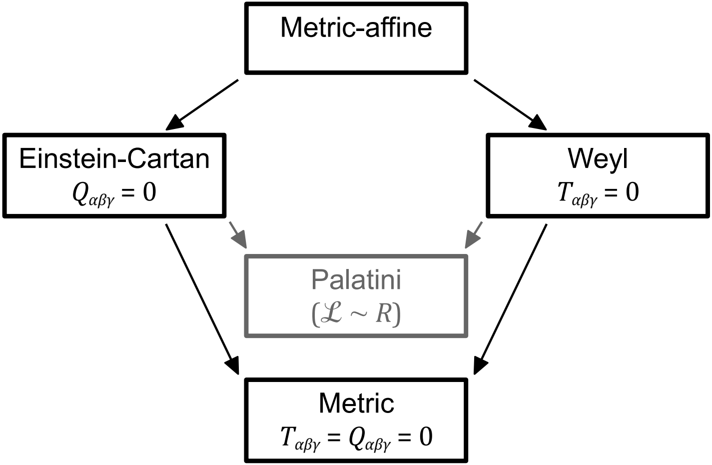
- Include matter: distinct observable predictions
- Important implications
  - Higgs inflation
  - Fermionic dark matter production[8]
  - ...

[8] M. Shaposhnikov, A. Shkerin, I. Timiryasov, S. Z., *Einstein-Cartan Portal to Dark Matter*, `arXiv:2008.11686`.

Additional Material

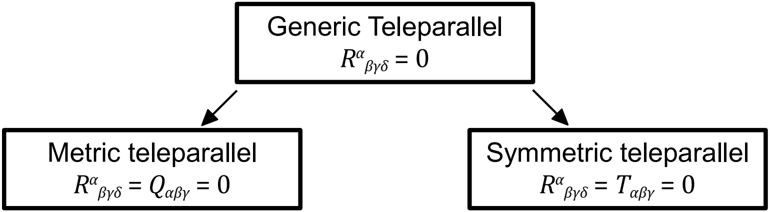
3. Seven Formulations of General Relativity
4. Full Action
5. Fermionic Dark Matter

Four Formulations with Curvature



Metric-affine gravity: avoid a priori assumption

Three formulations without curvature[9]



Equivalence to metric GR in pure gravity

$$\Downarrow$$

Generically no free parameters

[9] See J. Jiménez, L. Heisenberg, D. Iosifidis, A. Jiménez-Cano, T. Koivisto, *General Teleparallel Quadratic Gravity*, `arXiv:1909.09045`.

Decomposition

- Torsion
$$T^\alpha = g_{\mu\nu} T^{\mu\alpha\nu}$$
$$\hat{T}^\alpha = \epsilon^{\alpha\beta\mu\nu} T_{\beta\mu\nu} \ ,$$
$$t^{\alpha\beta\gamma} \text{ with } g_{\mu\nu} t^{\mu\alpha\nu} = 0 = \epsilon^{\alpha\beta\mu\nu} t_{\beta\mu\nu}$$
- Decomposition
$$T_{\alpha\beta\gamma} = -\frac{2}{3} g_{\alpha[\beta} T_{\gamma]} + \frac{1}{6} \epsilon_{\alpha\beta\gamma\nu} \hat{T}^\nu + t_{\alpha\beta\gamma}$$
- Non-metricity
$$Q^\gamma = g_{\alpha\beta} Q^{\gamma\alpha\beta}$$
$$\hat{Q}^\gamma = g_{\alpha\beta} Q^{\alpha\gamma\beta}$$
$$q^{\alpha\beta\gamma} \text{ with } g_{\alpha\beta} q^{\gamma\alpha\beta} = 0 = g_{\alpha\beta} q^{\alpha\gamma\beta}$$
- Decomposition
$$Q_{\alpha\beta\gamma} = \frac{1}{18}[g_{\beta\gamma}(5Q_\alpha - 2\hat{Q}_\alpha) + 2g_{\alpha(\beta}(4\hat{Q}_{\gamma)} - Q_{\gamma)})] + q_{\alpha\beta\gamma}$$

Full action

$$
\begin{aligned}
\mathcal{L} =& \frac{1}{2}\Omega^2(h)\mathring{R} - \frac{1}{2}\tilde{K}(h)g^{\alpha\beta}\partial_\alpha h \partial_\beta h - V(h) \\
&+ A_1(h)\mathring{\nabla}_\alpha \hat{T}^\alpha + A_2(h)\mathring{\nabla}_\alpha T^\alpha + A_3(h)\mathring{\nabla}_\alpha \hat{Q}^\alpha + A_4(h)\mathring{\nabla}_\alpha Q^\alpha \\
&+ B_1(h)Q_\alpha Q^\alpha + B_2(h)\hat{Q}_\alpha \hat{Q}^\alpha + B_3(h)Q_\alpha \hat{Q}^\alpha \\
&+ C_1(h)T_\alpha T^\alpha + C_2(h)\hat{T}_\alpha \hat{T}^\alpha + C_3(h)T_\alpha \hat{T}^\alpha \\
&+ D_1(h)\epsilon_{\alpha\beta\gamma\delta}t^{\alpha\beta\lambda}t^{\gamma\delta}{}_\lambda + D_2(h)\epsilon_{\alpha\beta\gamma\delta}q^{\alpha\beta\lambda}q^{\gamma\delta}{}_\lambda + D_3(h)\epsilon_{\alpha\beta\gamma\delta}q^{\alpha\beta\lambda}t^{\gamma\delta}{}_\lambda \\
&+ E_1(h)T_\alpha Q^\alpha + E_2(h)\hat{T}_\alpha Q^\alpha + E_3(h)T_\alpha \hat{Q}^\alpha + E_4(h)\hat{T}_\alpha \hat{Q}^\alpha \\
&+ B_4(h)q_{\alpha\beta\gamma}q^{\alpha\beta\gamma} + B_5(h)q_{\alpha\beta\gamma}q^{\beta\alpha\gamma} \\
&+ C_4(h)t_{\alpha\beta\gamma}t^{\alpha\beta\gamma} + E_5(h)t^{\alpha\beta\gamma}q_{\beta\alpha\gamma}
\end{aligned}
$$

Equivalent Metric Theory

$$\mathcal{L} = \frac{1}{2}\mathring{R} - \frac{1}{2}K(h)g^{\alpha\beta}\partial_\alpha h \partial_\beta h - \frac{V(h)}{\Omega^4}$$

- Full metric-affine theory

$$K(h) = \frac{1}{(1+\xi h^2)}\left[1 + \frac{h^2 \sum_{n=0}^{7} P_n h^{2n}}{M_P^2 (\sum_{m=0}^{4} O_m h^{2m})^2} + \frac{6\xi^2 h^2}{(1+\xi h^2)}\right]$$

- Einstein-Cartan formulation

$$K(h) = \frac{1}{(1+\xi h^2)}\left[1 + \frac{8h^2 \sum_{n=0}^{1} H_n h^{2n}}{M_P^2 \sum_{m=0}^{2} O_m h^{2m}} + \frac{6\xi^2 h^2}{(1+\xi h^2)}\right]$$

Include Fermions

- Coupling of fermion Ψ to torsion (or non-metricity)

$$\left(\xi_1 \partial^\mu h^2\right) T^{\nu}{}_{\mu\nu}$$

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$$\left(\xi_1 \partial^\mu h^2 + \zeta_1 \bar{\Psi}\gamma^\mu\Psi + \zeta_2 \bar{\Psi}\gamma_5\gamma^\mu\Psi\right) T^\nu{}_{\mu\nu}$$

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$$\mathcal{L} \supset \frac{1}{M_P^2}\left(\zeta_1 \, \bar{\Psi}\gamma^\mu \Psi + \zeta_2 \, \bar{\Psi}\gamma_5 \gamma^\mu \Psi\right)^2$$

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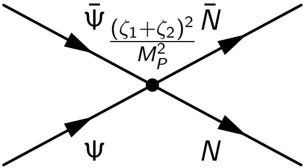
- Universal 4-fermion interaction

Dark Matter Production[10]

- Singlet fermion N in early Universe



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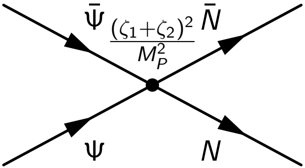

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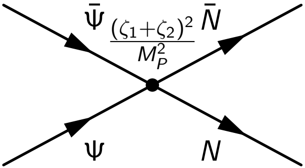

- Portal to dark matter
- Relative abundance

$$\frac{\Omega_N}{\Omega_{DM}} = 10^{-2}\frac{m_N}{10\,\text{keV}}(\zeta_1+\zeta_2)^4\frac{T^3}{M_P^3}$$

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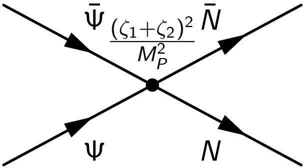

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- All of dark matter for

$$m_N = 10\,\text{keV}, \ldots, 10^8\,\text{GeV}$$

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Example: Warm Dark Matter

- Cutoff in Palatini Higgs inflation[11]

$$\Lambda \sim \frac{M_P}{\sqrt{\xi}}$$

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[11] F. Bauer and D. Demir, *Higgs-Palatini Inflation and Unitarity*, `arXiv:1012.2900`.

Example: Warm Dark Matter

- Cutoff in Palatini Higgs inflation[11]

$$\Lambda \sim \frac{M_P}{\sqrt{\xi}}$$

- Universal scales

$$\zeta_1 \sim \zeta_2 \sim \sqrt{\xi}$$

- Warm dark matter

$$\frac{\Omega_N}{\Omega_{DM}} = \frac{m_N}{10\text{keV}}$$

- Characteristic momentum distribution

[11] F. Bauer and D. Demir, *Higgs-Palatini Inflation and Unitarity*, arXiv:1012.2900.