Patras Workshop- 22/09/2025

No Dark Matter Axion During Minimal Higgs Inflation

Claire Rigouzzo[1] and Sebastian Zell[2,3]

[1] *Theoretical Particle Physics and Cosmology, King's College London, WC2R 2LS, UK*

[2] *Arnold Sommerfeld Center, Ludwig-Maximilians-Universität,*

Theresienstrasse 37, 80333 Munchen, Germany

[3] *Max-Planck-Institut fur Physik, Boltzmannstr. 8, 85748 Garching b. Munchen, Germany*

- Observations : Dark Matter & Inflation
- What is the microscopic nature?
- Many proposed models

We need more constraints.

I. Review and Previous Argument

II. Fundamental Derivation

III. Conclusion

IV. * Way(s)-out?

I. REVIEW AND PREVIOUS ARGUMENT

A. QCD Axion

- θ term:

$$\mathcal{L} \supset \bar{\theta}\,\mathrm{Tr}\,G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- Axion solution to strong CP problem and dark matter [1,2] :

$$\bar{\theta} \to \theta \equiv a/f_a$$

- PQ-symmetry broken *before* inflation

[1] R. Peccei, H. Quinn, CP conservation in the presence of pseudoparticles, Phys. Rev. Lett. 38 (1977).

[2] Review: L. Di Luzio, M. Giannotti, E. Nardi, L. Visinelli, The landscape of QCD axion models, arXiv:2003.01100.

B. Isocurvature Perturbations

- Isocurvature perturbations:

$$\Delta_a \sim \mathcal{F}_{\rm DM}^a \frac{H_{\rm inf}}{f_a \theta}$$

- CMB observations constrain [3]

$$\Delta_a \lesssim 10^{-5}$$

- Constrain Hubble scale of inflation:

$$H_{\rm inf} \lesssim 10^{-5} f_a \frac{\theta}{\mathcal{F}_{\rm DM}^a} \sim 10^{-6} f_a \frac{1}{\mathcal{F}_{\rm DM}^{a\,1/2}} \left(\frac{10^{14}{\rm GeV}}{f_a}\right)^{7/12}$$

- Incompatible with some inflationary models (metric Higgs inflation, Starobinsky, alpha attractors etc)

[3] Y. Akrami et al. (Planck), Planck 2018 results. X. Constraints on inflation, Astron. Astrophys. 641, A10 (2020), arXiv:1807.06211 [astro-ph.CO]

C. Higgs inflation

- There exists a coupling from matter to gravity [4]: $\mathcal{L} = \frac{M_P^2}{2} \underbrace{\left(1 + \xi h^2\right)}_{\Omega^2} R - \frac{1}{2}\partial_\alpha h \partial^\alpha h - \frac{\lambda}{4} h^4$
- What is the value of ξ? Depends on the **formulation of gravity** [5]

[4] F. Bezrukov and M. Shaposhnikov, The Standard Model Higgs boson as the inflaton, arXiv:0710.3755. [5] Review: C. Rigouzzo, S. Z., Coupling metric-affine gravity to the standard model and dark matter fermions, arXiv:2306.13134.

I. REVIEW AND PREVIOUS ARGUMENT

C. Higgs inflation

- There exists a coupling from matter to gravity [4]: $\mathcal{L} = \frac{M_P^2}{2} \underbrace{\left(1 + \xi h^2\right)}_{\Omega^2} R - \frac{1}{2}\partial_\alpha h \partial^\alpha h - \frac{\lambda}{4} h^4$
- What is the value of ξ? Depends on the **formulation of gravity** [5]

Metric GR

- Degree of freedom : $g_{\mu\nu}$
- $\xi \sim 10^4$
- $H_{\rm inf} \sim 10^{13}$ GeV

Palatini GR

- Degree of freedom : $\{g_{\mu\nu}, \Gamma^\alpha{}_{\beta\gamma}\}$
- $\xi \sim 10^8$
- $H_{\rm inf} \sim 10^8$ GeV

[4] F. Bezrukov and M. Shaposhnikov, The Standard Model Higgs boson as the inflaton, arXiv:0710.3755.

[5] Review: C.R , S. Zell, Coupling metric-affine gravity to the standard model and dark matter fermions, arXiv:2306.13134.

D. Previous Argument

- Palatini Higgs inflation obeys isocurvature constraints [6]

$$H_{\rm inf} \sim 10^8 \text{GeV} \lesssim 10^{-6} f_a \quad \text{for } f_a \gtrsim 10^{14} \text{GeV}$$

All good!

[6] T. Tenkanen, L. Visinelli, Axion dark matter from Higgs inflation with an intermediate H*, arXiv:1906.11837.

D. Previous Argument

- Palatini Higgs inflation obeys isocurvature constraints [6]

$$H_{\rm inf} \sim 10^{8}{\rm GeV} \lesssim 10^{-6} f_a \quad \text{for } f_a \gtrsim 10^{14}{\rm GeV}$$

All good!

Or is it?

[6] T. Tenkanen, L. Visinelli, Axion dark matter from Higgs inflation with an intermediate H*, arXiv:1906.11837.

II. FUNDAMENTAL DERIVATION

A. Closer look at non-minimal coupling consequences [7]

- Fundamental theory

$$\mathcal{L} = \frac{M_P^2}{2}\Omega^2 R - \frac{1}{2}\partial_\alpha a \partial^\alpha a + \frac{a}{f_a} c_G \,\mathrm{Tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

[7] C. Rigouzzo, S. Zell , No Dark MAtter Axion During Minimal Higgs Inflation, arXiv:2504.02952.

A. Closer look at non-minimal coupling consequences [7]

- Fundamental theory

$$\mathcal{L} = \frac{M_P^2}{2}\Omega^2 R - \frac{1}{2}\partial_\alpha a \partial^\alpha a + \frac{a}{f_a} c_G \operatorname{Tr} G^{\mu\nu}\tilde{G}_{\mu\nu}$$

- Conformal transformation $g_{\mu\nu} \to \Omega^{-2} g_{\mu\nu}$

$$\mathcal{L} = \frac{M_P^2}{2} R - \frac{1}{2\Omega^2}\partial_\alpha a \partial^\alpha a + \frac{a}{f_a} c_G \operatorname{Tr} G^{\mu\nu}\tilde{G}_{\mu\nu}$$

[7] C. Rigouzzo, S. Zell , No Dark Matter Axion During Minimal Higgs Inflation, arXiv:2504.02952.

II. FUNDAMENTAL DERIVATION

A. Closer look at non-minimal coupling consequences [7]

- Fundamental theory

$$\mathcal{L} = \frac{M_P^2}{2}\Omega^2 R - \frac{1}{2}\partial_\alpha a \partial^\alpha a + \frac{a}{f_a} c_G \,\mathrm{Tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

- Conformal transformation $g_{\mu\nu} \to \Omega^{-2} g_{\mu\nu}$

$$\mathcal{L} = \frac{M_P^2}{2} R - \frac{1}{2\Omega^2}\partial_\alpha a \partial^\alpha a + \frac{a}{f_a} c_G \,\mathrm{Tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

- Approximately canonical axion $A = \frac{a}{\Omega}$

$$\mathcal{L} = \frac{M_P^2}{2} R - \frac{1}{2}\partial_\alpha A \partial^\alpha A + \frac{\Omega A}{f_a} c_G \,\mathrm{Tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

[7] C. Rigouzzo, S. Zell , No Dark MAtter Axion During Minimal Higgs Inflation, arXiv:2504.02952.

II. FUNDAMENTAL DERIVATION

A. Closer look at non-minimal coupling consequences [7]

- Fundamental theory

$$\mathcal{L} = \frac{M_P^2}{2}\Omega^2 R - \frac{1}{2}\partial_\alpha a \partial^\alpha a + \frac{a}{f_a} c_G \,\mathrm{Tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

- Conformal transformation $g_{\mu\nu} \to \Omega^{-2} g_{\mu\nu}$

$$\mathcal{L} = \frac{M_P^2}{2} R - \frac{1}{2\Omega^2}\partial_\alpha a \partial^\alpha a + \frac{a}{f_a} c_G \,\mathrm{Tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

- Approximately canonical axion $A = \frac{a}{\Omega}$

$$\mathcal{L} = \frac{M_P^2}{2} R - \frac{1}{2}\partial_\alpha A \partial^\alpha A + \frac{\Omega A}{f_a} c_G \,\mathrm{Tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

$$f_{a,\mathrm{inf}} = \frac{f_a}{\Omega}$$

[7] C. Rigouzzo, S. Zell , No Dark MAtter Axion During Minimal Higgs Inflation, arXiv:2504.02952.

B. Field-dependent decay constant

- Field-dependant decay constant

$$f_{a,\mathrm{inf}} = \frac{f_a}{\Omega} \sim 10^{-5} f_a$$

- Enhance isocurvature perturbations [1]

$$\sigma_\theta \sim \frac{H_{\mathrm{inf}}}{f_{a,\mathrm{inf}}} \sim 10^5 \frac{H_{\mathrm{inf}}}{f_a}$$

- Impact on isocurvature bound:

$$H_{\mathrm{inf}} \lesssim 10^{-6} f_a \frac{1}{\mathcal{F}_{\mathrm{DM}}^{a\ 1/2}} \left(\frac{10^{14}\mathrm{GeV}}{f_a} \right)^{7/12}$$

[1] Opposite case: M. Fairbairn, R. Hogan, D. Marsh, Unifying inflation and dark matter with the Peccei-Quinn field: observable axions and observable tensors, arXiv:1410.1752.
G. Ballesteros, J. Redondo, A. Ringwald, C. Tamarit, Standard Model-axion-seesaw- Higgs portal inflation. Five problems of particle physics and cosmology solved in one stroke, arXiv:1610.01639.

B. Field-dependent decay constant

- Field-dependant decay constant

$$f_{a,\text{inf}} = \frac{f_a}{\Omega} \sim 10^{-5} f_a$$

- Enhance isocurvature perturbations [1]

$$\sigma_\theta \sim \frac{H_{\text{inf}}}{f_{a,\text{inf}}} \sim 10^5 \frac{H_{\text{inf}}}{f_a}$$

- Impact on isocurvature bound:

$$H_{\text{inf}} \lesssim 10^{-6} f_{a,\text{inf}} \frac{1}{\mathcal{F}_{\text{DM}}^{a\ 1/2}} \left(\frac{10^{14}\text{GeV}}{f_a} \right)^{7/12}$$

[1] Opposite case: M. Fairbairn, R. Hogan, D. Marsh, Unifying inflation and dark matter with the Peccei-Quinn field: observable axions and observable tensors, arXiv:1410.1752.
G. Ballesteros, J. Redondo, A. Ringwald, C. Tamarit, Standard Model-axion-seesaw- Higgs portal inflation. Five problems of particle physics and cosmology solved in one stroke, arXiv:1610.01639.

III. CONCLUSION

No Dark Matter Axion During Higgs inflation

- Same applies to any model with non-minimal coupling : cannot ”save” models by changing formulation of gravity!

- Isocurvature bounds are **stronger than previously thought in all non-minimally coupled models**, in particular Starobinsky inflation and alpha-attractors.

IV. WAY(S)-OUT

- Include

$$\mathcal{L} \supset -\zeta f_a \partial_\alpha a T^\alpha \quad (T^\alpha = g_{\mu\nu} T^{\mu\alpha\nu}, \quad 2T^\mu_{\alpha\nu} \equiv \Gamma^\mu_{\alpha\nu} - \Gamma^\mu_{\nu\alpha})$$

- Integrate out torsion

$$\mathcal{L} \supset -\frac{1}{2\Omega^2}\left(1 - \frac{3\zeta^2 f_a^2}{2M_P^2\Omega^2}\right)\partial_\alpha a \partial^\alpha a$$

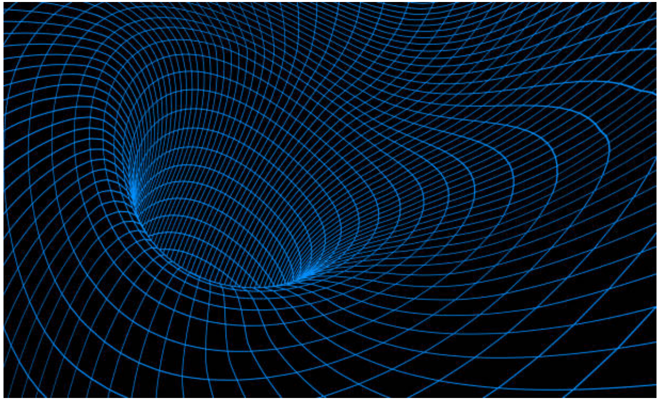
- Low-energy modification of decay constant

$$f_a \to f_{a,\mathrm{IR}}\left(f_a\right) = \sqrt{1 - \frac{3\zeta^2 f_a^2}{2M_P^2}}\, f_a$$

- Isocurvature bound lifted if $f_{a,\mathrm{IR}} \lesssim f_{a,\mathrm{inf}}$: strong finetuning!

V. APPENDIX

A. Metric Gravity



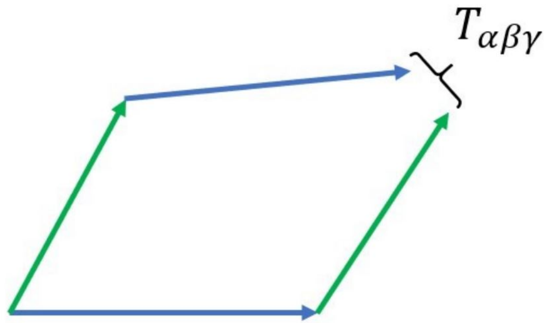
Degrees of freedom: $g_{\mu\nu}$

The connection is **uniquely** determined by the metric:

$$\mathring{\Gamma}^{\alpha}{}_{\beta\gamma} = \frac{1}{2} g^{\alpha\mu} \left(\partial_\beta g_{\mu\gamma} + \partial_\gamma g_{\mu\beta} - \partial_\mu g_{\beta\gamma} \right)$$

Degrees of freedom: $\{g_{\mu\nu}, \Gamma^{\alpha}{}_{(\beta\gamma)}\}$

The connection is no longer determined by the metric, they are **a priori** independent.

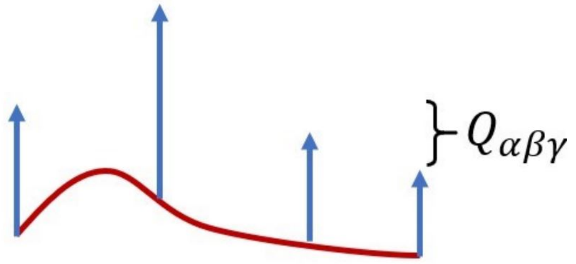


Degrees of freedom: $\{g_{\mu\nu}, \Gamma^{\alpha}{}_{\beta\gamma}\}$

$\Gamma^{\alpha}{}_{\beta\gamma}$ need not be symmetric in the last indices

$\Rightarrow$ **Torsion**:

$$T_{\alpha\beta\gamma} = \Gamma^{\alpha}{}_{[\beta\gamma]}$$



Degrees of freedom: $\{g_{\mu\nu}, \Gamma^{\alpha}{}_{\beta\gamma}\}$

Most general formulation of gravity

$\Rightarrow$ **Non-metricity**:

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

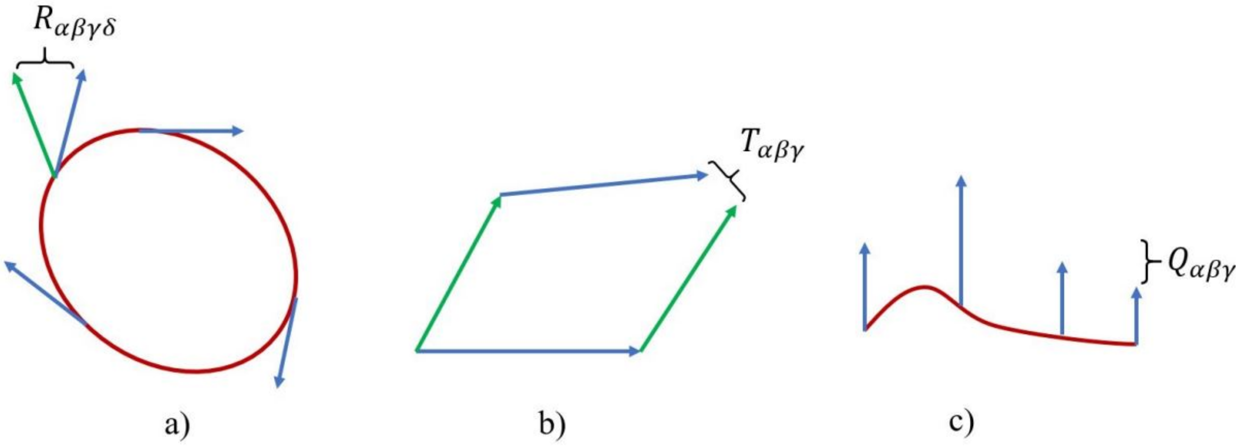


Figure 1: Schematic representation of the change of a vector under parallel transport due to the presence of: a) curvature b) torsion c) non-metricity.

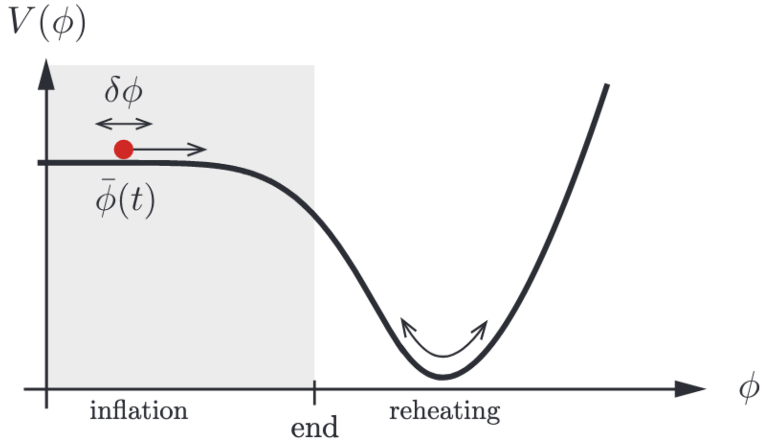
What are the benefits of one formulation over the other?

a. *Metric-Affine:* The most general formulation, minimal assumptions made.

b. *Einstein-Cartan:* It arises naturally when gauging the Poincare group. Torsion is also needed to couple directly fermions to gravity.

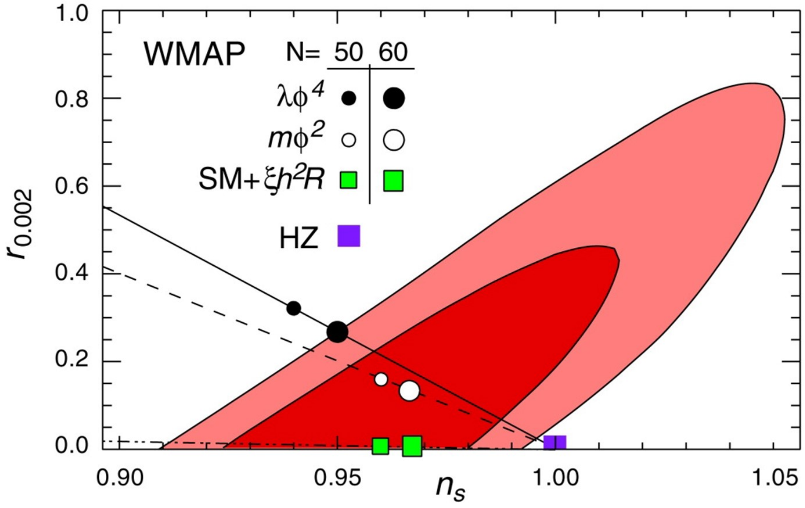
c. *Palatini:* Can make computation easier, expecially when one needs to perform a conformal transformation of the metric.

d. *Metric:* The most used one.



$$V(h) \simeq \frac{\lambda h^4}{4}$$

B. Recap of Higgs inflation



$$S \supset \int d^4x(1+\xi h^2)R$$

[3] F. Bezrukov, M. Shaposhnikov, The Standard Model Higgs boson as the inflaton, 0710.3755