Discussing the UV structure of quantum unimodular gravity

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Outline of the talk

- The idea behind unimodular gravity, its implementation, and a diffeomorphism invariant formulation of it at the level of the action

- The study of the unimodular theory's UV completion within the Exact Renormalisation Group and Asymptotic Safety

- The similarity between its UV completion with that of General Relativity (GR), as well as the main differences of the two theories in this context

Introducing unimodular gravity

- General Relativity: A Diffeomorphism (Diff) invariant, and successful theory of gravity at solar and cosmological (?) scales

$$S = \int d^4x \sqrt{-g}\,\frac{R - 2\Lambda}{16\pi G} + S_{\text{matter}}$$

- **Motivation:** The cosmological constant problem, $|\Lambda + 8\pi G < \rho >_{\text{matter}} | \sim H_0^2$

- **The idea** of unimodular gravity: Change the status of the coupling Λ by decoupling it from the gravitational dynamics [1]

$$\frac{\delta}{\delta g_{\mu\nu}} \sqrt{-g} = 0 \qquad \text{Unimodularity condition}$$

- **The classical dynamics of unimodular gravity**:

$$\text{Bianchi identities:} \quad R - 8\pi G T^{\mu}{}_{\mu} = \text{const.} \equiv 4\lambda_0$$

$$\text{Field equations:} \quad G_{\mu\nu} + \lambda_0 g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- Bianchi identities are no longer identically satisfied due to the enforcement of the unimodularity condition

  Classical equations are equivalent with those of GR, but now the cosmological constant appears as a constant of integration

[1] The first one to introduce unimodular gravity was Einstein himself, but in a different context, A. Einstein, Annalen der Physik, vol. 354, 769?822 (1916)

Unimodular gravity and diffeomorphism symmetry

- The gauge symmmetry of the metric field in GR is the symmery under diffeomorphisms

$$g_{\alpha\beta} \to g_{\alpha\beta} + \delta g_{\alpha\beta} \equiv g_{\alpha\beta} + \nabla_\alpha \xi_\beta + \nabla_\beta \xi_\alpha \tag{1}$$

- Imposing the unimodularity condition, classically or quantum–mechanically, restricts the allowed variations of the metric field

$$\frac{\delta}{\delta g_{\mu\nu}} \sqrt{-g} = 0 \qquad \rightsquigarrow \quad \nabla_\mu \xi^\mu = 0 \;\; \text{(restricted symmetry:TDiff)} \tag{2}$$

- Classically, the unimodularity condition implies a modification of the Bianchi identities

- Different ways to impose unimodularity: Quantum mechanically, they lead to different quantisation procedures

- **This talk**: A quantisation of a fully-diffeomorphism unimodular action for gravity within the exact renormalisation group and asymptotic safety

A fully diffeomorphism-invariant action for unimodular gravity

- **Unimodularity in action:** The unimodularity condition can be implemented as an on–shell condition through a lagrange multiplier $\lambda(x)$ [2]

$$S = \int d^4x \left[\sqrt{-g}\,\frac{R}{16\pi G} - \lambda\left(\sqrt{-g} - \epsilon_0\right) \right] \tag{3}$$

- **Stückelberg-ing the action:** Introduce four Stückelberg fields $\phi^\alpha(x)$, following the pattern of a general coordinate transformation: $x^\alpha \to \phi^\alpha(x)$, $\alpha = 0, \ldots 3$ [3]

$$\int d^4x\lambda\left(\sqrt{-g} - \epsilon_0\right) \;\to\; \int d^4x\lambda\left(\sqrt{-g} - \epsilon_0\left|J^\alpha{}_\beta\right|\right) \equiv \int d^4x\sqrt{-g}\lambda\left(1 - \epsilon_0\psi\right) \tag{4}$$

$$\text{The Stückelberg Jacobian:}\quad \left|J^\alpha{}_\beta\right| \equiv \left|\frac{\partial\phi^\alpha(x)}{\partial x^\beta}\right| \quad \text{with}\quad \psi \equiv \frac{\left|J^\alpha{}_\beta\right|}{\sqrt{-g}},\quad \alpha,\beta = 0,\ldots,3 \tag{5}$$

- A generalised and **Diff-invariant** unimodular formulation of GR [4]

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \lambda f(\psi) - q(\psi)\right] \tag{6}$$

$\rightsquigarrow$ Its easy to see that the equations of motion for the fields λ and ψ **ensure the classical dynamics are the same as** those of GR

[2] W. Buchmuller and N. Dragon, Phys.Lett., vol. B223, p. 313 (1989).

[3] See also K. V. Kuchar PRD43, 3332?3344 (1991)

[4] A. Paddila and I. D. Saltas, arXiv:1409.3573 [gr–qc]

A fully diffeomorphism-invariant action for unimodular gravity

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \lambda f(\psi) - q(\psi)\right] + S_{\text{matter}} \qquad (7)$$

- The classical equations result from variation with respect to the metric ($g_{\mu\nu}$), Lagrange multipler (λ) and Stückelberg fields (ϕ^α) [5]

$$G_{\mu\nu} = 8\pi G\left[T_{\mu\nu} + g_{\mu\nu}\left(\lambda V(\psi) + U(\psi)\right)\right] \qquad (8)$$

$$f(\psi) = 0, \quad \partial_\alpha\left(\lambda f'(\psi) + q'(\psi)\right) = 0, \qquad (9)$$

$$\psi \equiv \frac{\left|\partial_\alpha\phi^\beta\right|}{\sqrt{-g}}, \quad V(\psi) \equiv \psi f'(\psi) - f(\psi), \quad U(\psi) \equiv \psi q'(\psi) - q(\psi)$$

- Classical dynamics of the theory are the same as in GR with a cosmological constant
- The new constraint equations ensure the Bianchi identities are satisfied

[5] A. Paddila and I. D. Saltas, arXiv:1409.3573 [gr–qc]

Unimodular gravity and asymptotic safety: A brief review of previous work

- A conceptually different approach has been followed before in the literature [6]
- The main key of the approach: Define a TDiff-invariant quantisation of the Einstein–Hilbert truncation (without a cosmological constant)

$$Z[J] = \int Dg_{\mu\nu}\; e^{iS[g_{\mu\nu}]+i\int J^{\alpha\beta}g_{\alpha\beta}+\Delta S_k}\;, \tag{10}$$

$$S[g_{\mu\nu}] = \int d^4x\sqrt{-g}\,\frac{R}{16\pi G} + S_{\text{TDiff-gauge fixing}} + S_{\text{TDiff-ghost}} \tag{11}$$

- Usual gauge fixing condition F_μ acted upon with a transverse projector

$$F_\mu \quad\rightarrow\quad F_\mu^{\text{TDiff}} \equiv P_\mu{}^\kappa F_\kappa, \qquad P_{\mu\nu} = \frac{1}{\bar\nabla^2}(g_{\mu\nu}\bar\nabla^2 - \bar\nabla_\mu\bar\nabla_\nu) \tag{12}$$

- Unimodularity condition imposed up to second order in expansion of the metric:

$$\delta_g^{(1)}\sqrt{g} = 0, \quad \delta_g^{(2)}\sqrt{g} = 0 \quad\rightarrow\quad \Gamma^{(2)}_{\text{TDiff}} \tag{13}$$

- Theory was found to be asymptotically safe with a UV fixed point $G_* = 2.65$ and eigenvalue $= -2.341$

[6] A. Eichhorn Class.Quant.Grav., vol. 30, p. 115016 (2013)

Setting up the calculation: Generating functional and gauge fixing

- The starting point is the generating functional, where **all fields of the theory are coupled to external sources**

$$Z[J] = \int Dg_{\mu\nu} D\phi^{\alpha} D\lambda \; e^{iS[\Phi_A]+i\int J_A \Phi_A + \Delta S_k} \,, \qquad \Phi_A = \{g_{\mu\nu}, \lambda, \phi^{\alpha}\} \tag{14}$$

$$S[\Phi_A] = \int d^4x \sqrt{-g}\left[\frac{R-2\Lambda}{16\pi G} + \lambda(x) f(\psi) + q(\psi)\right] + S_{\text{gauge fixing}} + S_{\text{ghost}}\,, \qquad \psi \equiv \frac{1}{\sqrt{g}}\left|\frac{\partial\phi^{\alpha}(x)}{\partial x^{\beta}}\right| \tag{15}$$

$$\Delta S_k = \frac{1}{2}\int d^4x \sqrt{-g}\; \Phi_A \; R_k^{AB}(-\Box)\; \Phi_B\,, \tag{16}$$

- The theory is Diff invariant, and the gauge fixing sector defines the de Donder gauge

$$S_{\text{gauge fixing}} = Z_G \int d^4x \sqrt{\bar{g}}\, \bar{g}^{\mu\nu} h_{\alpha\beta} \mathcal{F}_{\mu}^{\alpha\beta} \mathcal{F}_{\nu}^{\gamma\delta} h_{\gamma\delta}\,, \qquad \mathcal{F}_{\mu}^{\alpha\beta} \equiv \delta_{\mu}^{\beta} \bar{g}^{\alpha\gamma} \bar{\nabla}_{\gamma} - \tfrac{1}{2} \bar{g}^{\alpha\beta} \bar{\nabla}_{\mu} \tag{17}$$

- There are two ghost contributions: One from the gauge fixing and another from the Stückelberg sector

$$S^{\text{GF ghost}} = -\int d^4x \sqrt{\bar{g}}\; \bar{C}_{\mu}\left(-\delta_{\nu}^{\mu}\Box - \frac{1}{4}\delta_{\nu}^{\mu} R\right) C^{\nu} \qquad Z^{\text{GF ghost}} = 1 \tag{18}$$

$$S^{\text{Stück. ghost}} \equiv -\frac{1}{2}\int d^4x \sqrt{\bar{g}}\; \bar{\eta}(-\Box)\eta \qquad Z^{\text{Stück. ghost}} = 1 \tag{19}$$

- Why introduce the cosmological constant term in the action?

Setting up the calculation: Field expansion and background choice

- Our tool: **The Exact Renormalisation Group Equation (ERGE)** [7]

$$\partial_t \Gamma_k = \frac{1}{2}\mathrm{Tr}\left[\left(\mathbf{\Gamma}_k^{(2)} + \mathbf{R}_k\right)^{-1} k\partial_k \mathbf{R}_k\right],$$

$$\Gamma_k = -\int d^4x\sqrt{g}\left[Z_G(R-2\Lambda) - \lambda\, f(\psi) \;-\; q(\psi)\right] + S_{\text{ghosts}} + S_{\text{gauge fixing}} \tag{20}$$

- The metric, Lagrange multiplier and Stückelberg fields fluctuate as

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + G_0^{1/2}\hat{h}_{\mu\nu} + \tfrac{1}{4}G_0^{1/2}\bar{g}_{\mu\nu}h$$

$$\lambda = \bar{\lambda} + G_0^{-1/2}\delta\lambda$$

$$\phi^\alpha = \bar{\phi}^\alpha + G_0^{1/2}\delta\hat{\phi}^\alpha + G_0\bar{\nabla}^\alpha\delta\phi \tag{21}$$

- Background choice:

$$\bar{R}_{\alpha\beta\gamma\delta} = \tfrac{1}{12}\bar{R}\left(\bar{g}_{\alpha\gamma}\bar{g}_{\beta\delta} - \bar{g}_{\beta\gamma}\bar{g}_{\alpha\delta}\right), \qquad \bar{\phi}^\alpha = \epsilon x^\alpha, \qquad \psi \equiv \frac{|J^\alpha{}_\beta|}{\sqrt{-g}} = \frac{\epsilon^4}{\sqrt{\bar{g}}}$$

$$\bar{R} = const., \quad \bar{\lambda} = const. \tag{22}$$

[7] C. Wetterich Phys. Lett. **B 301**, 90 (1993) |T. R. Morris, Int. J. Mod. Phys. A 9 (1994) 2411.

Evaluating the exact RG equation

$$\Gamma_k[g_{\mu\nu},\lambda,\psi] = -\int d^4x\sqrt{g}\left[\frac{R-2\Lambda_k}{16\pi G_k} - \lambda f_k(\psi) - q_k(\psi)\right] + S_{\text{ghosts}} + S_{\text{gauge fixing}} \tag{23}$$

- A cosmological–constant type modification to the "Einstein–Hilbert" Hessians

$$\left[\Gamma^{(2)}_{(\hat{h}\hat{h})}\right]^{\mu\nu}_{\rho\sigma} = Z_{\hat{h}\hat{h}}\left[-\Box - 2\Lambda + \frac{2}{3}R - Z_G^{-1}\left(\lambda V(\psi) + U(\psi)\right)\right]\left(\delta^{\mu\nu}_{\rho\sigma} - \frac{1}{4}g^{\mu\nu}g_{\rho\sigma}\right), \tag{24}$$

$$\Gamma^{(2)}_{(hh)} = Z_{hh}\left[-\Box - 2\Lambda - Z_G^{-1}\left(\lambda V(\psi) + U(\psi)\right) - 2Z_G^{-1}\psi^2\left(\lambda f''(\psi) + q''(\psi)\right)\right] \tag{25}$$

$$Z_{\hat{h}\hat{h}} \equiv \frac{1}{32\pi}\frac{G_0}{G_k}, \quad Z_{hh} \equiv -\frac{1}{128\pi}\frac{G_0}{G_k}, \quad V(\psi) \equiv f(\psi) - \psi f'(\psi) \tag{26}$$

- New, non–trivial interactions in the scalar sector

$$\Gamma^{(2)}_{\phi\phi}[-\Box], \;\; \Gamma^{(2)}_{\phi\lambda}[-\Box], \;\; \Gamma^{(2)}_{h\phi}[-\Box] \tag{27}$$

- Stückelberg sector: Only longitudinal mode (ϕ) propagates, transverse one ($\hat{\phi}^\alpha$) is integrated out ($R_{\hat{\phi}\hat{\phi}} = 0$)

Solving the flow equation

$$\Gamma_k[g_{\mu\nu},\lambda,\psi] = -\int d^4x\sqrt{g}\left[Z_G(R-2\Lambda) - \lambda\, f(\psi)\; - \; q(\psi)\;\right] + S_{\text{ghosts}} + S_{\text{gauge fixing}}$$

- We choose a Type 1 cut–off, with $-\Box \to -\Box + R_k(-\Box)$, together with the optimised regulator R_k [8]

- The trace over momenta in the ERGE is evaluated asymptotically on S_4 using a heat kernel expansion. The flow equation takes schematically the form

$$\left(\tilde{Vol}\right)^{-1}\partial_t\Gamma_k = \partial_t\Gamma_k|_{\text{T}} + \partial_t\Gamma_k|_{\text{Scalar}} + \partial_t\Gamma_k|_{\text{Ghosts}} \equiv \partial_t\Gamma_k[G_k^{(0,1)}, \Lambda_k^{(0,1)}; f_k'^{(0,1)}, f_k''^{(0,1)}; f \leftrightarrow q], \tag{28}$$

- We solve the flow equation approximately through a polynomial ansatz in the Stückelberg sector

$$f(\psi) = \sum_{i=0}^{N_f} \tfrac{1}{i!}\rho_i\psi^i \qquad q(\psi) = \sum_{i=1}^{N_q} \tfrac{1}{i!}\sigma_i\psi^i \tag{29}$$

- The beta functions are derived by expanding w.r.t $\bar{\tilde{R}}, \bar{\psi}, \bar{\tilde{\lambda}}$ and projecting out similar operators on both sides

Einstein–Hilbert sector: $k\partial_k\tilde{\Lambda} = (-2+\eta_{\tilde{\Lambda}})\tilde{\Lambda}, \quad k\partial_k\tilde{G} = (2+\eta_{\tilde{G}})\tilde{G}$

Stückelberg sector: $k\partial_k\tilde{\rho}_i = (-2+\eta_{\tilde{\rho}_i})\tilde{\rho}_i, \quad k\partial_k\tilde{\sigma}_i = (-4+\eta_{\tilde{\sigma}_i})\tilde{\sigma}_i$

$[\tilde{c} \equiv c/k^d,\ \eta_c \equiv \frac{k\partial_k c}{c}]$

- The beta functions for $\widetilde{G}, \widetilde{\Lambda}$ receive contirbutions from $\tilde{\rho}, \tilde{\sigma}$ and vice versa: $\eta_i = \eta_i(\widetilde{G}, \widetilde{\Lambda}; \tilde{\rho}_j, \tilde{\sigma}_j)$

[8] D. F. Litim, Phys.Lett., B486, 92–99 (2000)

Fixed points and critical exponents: The minimal unimodular case

Fixed points: $\beta_{\tilde{c}_i}(\widetilde{G}, \widetilde{\Lambda}; \tilde{\rho}_j, \tilde{\sigma}_m) = 0$

Eigenvalues: $\partial_t \tilde{c}_i = \sum_j \left.\frac{\partial \beta_i(\tilde{c}_n)}{\partial \tilde{c}_j}\right|_{\tilde{c}_j = \tilde{c}_{j*}} \times (\tilde{c}_j - \tilde{c}_{j*})$

- The GR truncation: $f(\psi) = 0, \quad q(\psi) = 0, \quad \mathcal{L} = \sqrt{g} Z_G (R - 2\Lambda)$

  Fixed points: $(\tilde{\Lambda}, \tilde{G}) = (0.193, 0.707)$

  $$\text{Eigenvalues: } (\gamma_\Lambda, \gamma_G) \simeq (-1.99 \pm 3.829i)$$
  $$\tilde{G} \times \tilde{\Lambda} \simeq 0.136 \tag{30}$$

- The minimal unimodular case:
  $f(\psi) = \rho_0 + \rho_1 \psi, \quad q(\psi) = 0, \quad \mathcal{L} = \sqrt{g} Z_G (R - 2\Lambda) - \lambda(\sqrt{g} - |J^\alpha{}_\beta|)$

  Fixed points: $(\tilde{\Lambda}, \tilde{G}, \tilde{\rho}_0, \tilde{\rho}_1) = (0.206, 0.661, 0, 0)$

  $$\text{Eigenvalues: } (\gamma_{\tilde{\Lambda}, \tilde{G}}, \gamma_{\tilde{\rho}_0}, \gamma_{\tilde{\rho}_1}) = (-1.611 \pm 3.2446i, -6.066, -2)$$
  $$\tilde{G} \times \tilde{\Lambda} \simeq 0.136 \tag{31}$$

Higher order Stückelberg interactions

$$\mathcal{L} = \sqrt{g}\left[Z_G(R-2\Lambda) - \lambda\, f(\psi) \;-\; q(\psi)\right]$$

- Beyond the minimal unimodular ansatz

$$f(\psi) = \textstyle\sum_{i=0}^{4} \frac{1}{i!}\rho_i\psi^i \;, \qquad q(\psi) = \sum_{i=1}^{4} \frac{1}{i!}\sigma_i\psi^i \tag{32}$$

- Fixed point and attractive, complex eigen-values of $(\tilde{\Lambda}, \tilde{G})$ **persist and show good quantitative stability** as we increase the interations in the Stückelberg sector

- The Stückelberg couplings $\tilde{\rho}_i, \tilde{\sigma}_j$ **remain trivial** in the UV, while *the associated eigenvalues remain negative as we increase the truncation order*

- The effective actions for GR and the unimodular theory look similar in the UV

$$\Gamma^{\text{Unim.}}\Big|_{k/k_0 \gg 1} \simeq \Gamma^{\text{GR}}\Big|_{k/k_0 \gg 1} \tag{33}$$

$$\tilde{G}_*\tilde{\Lambda}_*\Big|_{\text{Unimod.}} \simeq \tilde{G}_*\tilde{\Lambda}_*\Big|_{\text{GR}} \simeq 0.13 \tag{34}$$

- The Diff-invariant unimodular theory and GR share **similar UV completions**

The full results: Fixed points and eigenvalues for up to fourth order Stückelberg sector

$\tilde{\Lambda}_*$	$\tilde{G}_*$	$\tilde{\rho}_{0*}$	$\tilde{\rho}_{1*}$	$\tilde{\rho}_{2*}$	$\tilde{\rho}_{3*}$	$\tilde{\rho}_{4*}$	$\tilde{\sigma}_{1*}$	$\tilde{\sigma}_{2*}$	$\tilde{\sigma}_{3*}$	$\tilde{\sigma}_{4*}$
0.193	0.707	–	–	–	–	–	–	–	–	–
0.206	0.661	0	0	–	–	–	–	–	–	–
0.206	0.661	0	0	0	–	–	–	–	–	–
0.206	0.661	0	0	0	0	–	–	–	–	–
0.206	0.661	0	0	0	0	0	–	–	–	–
0.201	0.674	–	–	–	–	–	–	0	–	–
0.202	0.670	–	–	–	–	–	–	0	0	–
0.203	0.666	–	–	–	–	–	–	0	0	0
0.206	0.661	0	0	–	–	–	0	–	–	–
0.206	0.661	0	0	–	–	–	0	0	–	–

$\gamma_{\tilde{\Lambda}}$	$\gamma_{\tilde{G}}$	$\gamma_{\tilde{\rho}_0}$	$\gamma_{\tilde{\rho}_1}$	$\gamma_{\tilde{\rho}_2}$	$\gamma_{\tilde{\rho}_3}$	$\gamma_{\tilde{\rho}_4}$	$\gamma_{\tilde{\sigma}_1}$	$\gamma_{\tilde{\sigma}_2}$	$\gamma_{\tilde{\sigma}_3}$	$\gamma_{\tilde{\sigma}_4}$
$-1.475 + 3.043i$	$-1.475 - 3.043i$	–	–	–	–	–	–	–	–	
$-1.611 + 3.244i$	$-1.611 - 3.244i$	-6.066	-2	–	–	–	–	–	–	
$-1.611 + 3.244i$	$-1.611 - 3.244i$	-6.066	-2	-0.780	–	–	–	–	–	
$-1.611 + 3.244i$	$-1.611 - 3.244i$	-6.066	-2	-0.780	-1.458	–	–	–	–	
$-1.611 + 3.244i$	$-1.611 - 3.244i$	-6.066	-2	-0.660	-1.458	-1.898	–	–	–	
$-1.644 + 3.119i$	$-1.644 - 3.119i$	–	–	–	–	–	–	-2.797	–	–
$-1.624 + 3.139i$	$-1.624 - 3.139i$	–	–	–	–	–	–	-3.131	-3.131	–
$-1.630 + 3.159i$	$-1.630 - 3.159i$	–	–	–	–	–	–	-3.465	-3.465	-3.465
$-1.611 + 3.244i$	$-1.611 - 3.244i$	-6.066	-2	–	–	–	-4	–	–	–
$-1.611 + 3.244i$	$-1.611 - 3.244i$	-6.066	-2	–	–	–	-4	-2.780	–	–

RG dynamics away from the UV fixed point

- Away from the fixed point regime, the RG flow will drive the Stückelberg sector of the Diff-invariant unimodular theory away from triviality: $f_k(\psi) \neq 0$, $q_k(\psi) \neq 0$

- The non–trivial Stückelberg interactions generated by the RG flow at lower energies imply that in principle

$$\Gamma^{\text{Unim.}} \neq \Gamma^{\text{GR}}, \quad \textit{away from the fixed point regime} \tag{35}$$

$\rightarrow$ The two theories are in principle not equivalent to each other quantum–mechanically (*Reminder*: The Lagrange multiplier and Stückelberg fields were coupled to external sources in the path integral!)

Predictivity of the theory in the UV

- *An apparent problem*: The number of relevant couplings in the Stückelberg sector increases with the order of truncation in ψ, as the anomalous dimension remains much smaller than the canonical one for $\tilde{\rho}$ $(= -2)$ and $\tilde{\sigma}$ $(= -4)$

- *Root of the problem*: The dimensionless nature of the field $\psi \equiv \dfrac{\left|\partial_\alpha \phi^\beta\right|}{\sqrt{-g}}$

  (In contrast with usual scalar field theories)

- Canonically normalising the field ψ,

$$\psi \to \psi / Z_\psi^{1/2}, \quad [Z_\psi] = 2 \tag{36}$$

  shifts all Stückelberg eigenvalues as

$$\gamma_{\tilde{\rho}_n} \to \gamma_{\tilde{\rho}_n} + n \tag{37}$$

- Shift produces a 'critical' eigenvalue after which couplings become irrelevant, while fixed point and eigenvalues for $\widetilde{G}, \widetilde{\Lambda}$ remain unaffected

The number of relevant eigenvalues appears to become finite, and the theory predictive

Summary

- A fully diffeomorphism-invariant unimodular theory was studied within the Wilsonian approach of the exact renormalisation group and asymptotic safety
- The effective action of the unimodular theory was shown to share a similar structure with that of GR in the UV, and the two theories shared similar UV completions within Asymptotic Safety
- The UV fixed-point and corresponding eigen-values for Newton's G and Λ were found to be similar with those of the Einstein–Hilbert truncation, and the unimodular theory appeared to be predictive
- Away from the UV-fixed point regime, the non–trivial (Stückelberg) interactions generated along the RG flow in principle make the unimodular theory to differ from its GR counterpart

Thank you!