Mapping the landscape of gravity theories

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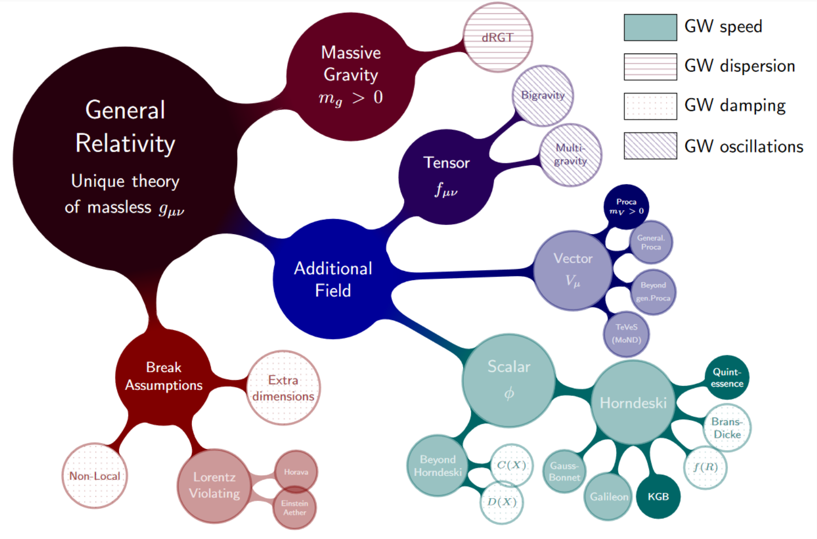
(A portion of) the landscape



Source: [1]

[1] J. M. Ezquiaga, M. Zumalacarregui, Front. Astron. Space Sci. 5:44 (2018) - arXiv:1807.09241

Big-picture goal

Explore generalisations of GR

$\Downarrow$

Understand GR as a special case in a broader framework

$\Downarrow$

Attempt to overcome limitations of GR (and learn about universe in the process)

Thermodynamics and gravity

- Thermodynamics $\Leftrightarrow$ gravity?
- GR $\Leftrightarrow$ thermodynamical equilibrium [2]
  Modified gravity $\Leftrightarrow$ non-equilibrium [3]
- "Thermodynamics of gravitational theories"
- Question: what exactly is the dissipative process leading to equilibrium from non-equilibrium?
- Question: what is the order parameter measuring closeness to equilibrium?

[2] T. Jacobson, PRL 75 (1995) - arXiv:gr-qc/9504004
[3] C. Eling, R. Guedens, T. Jacobson, PRL 96 (2006) - arXiv:gr-qc/0602001

The plan

- Take scalar-tensor gravity, containing $f(\mathcal{R})$ as subclass [4]
- Model scalar contribution as effective dissipative fluid [5]
- Apply irreversible non-equilibrium thermodynamical description, such as Eckart's [6]
- Extract thermodynamical quantities such as temperature and viscosity
- Understand dissipative process

[4] T. Sotiriou & V. Faraoni, Rev. Mod. Phys 82 (2010) - arXiv:0805.1726
[5] V. Faraoni & J. Coté, PRD 98 (2018) - arXiv:1808.02427
[6] C. Eckart, Phys. Rev. 58 (1940)

Imperfect fluid description of modified gravity

- Brans-Dicke scalar-tensor action (Jordan frame) ($G_{\text{eff}} = 1/\phi$)

$$S_{\text{ST}} = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left[\phi \mathcal{R} - \frac{\omega(\phi)}{\phi} \nabla^c \phi \nabla_c \phi - V(\phi) \right] + S^{(\text{m})}$$

- Effective Einstein equations

$$G_{ab} = 8\pi G_{\text{eff}} T^{(m)}_{ab} + 8\pi T^{(\phi)}_{ab}$$

- Study thermodynamics of imperfect fluid
  $T^{(\phi)}_{ab} = \rho^{(\phi)} u_a u_b + q^{(\phi)}_a u_b + q^{(\phi)}_b u_a + \Pi^{(\phi)}_{ab}$

- $\nabla_a \phi$ timelike + future-oriented $\Rightarrow$ natural fluid interpretation

- 4-velocity $u^a = \dfrac{\nabla^a \phi}{\sqrt{-\nabla^e \phi \nabla_e \phi}}$ with $u^a u_a = -1$

Eckart's thermodynamics

$$P^{(\phi)}_{\text{vis}} = -\zeta\,\theta$$

$$q^{(\phi)}_a = -\mathcal{K}\left(h_{ab}\nabla^b\mathcal{T} + \mathcal{T}\dot{u}_a\right)$$

$$\pi^{(\phi)}_{ab} = -2\eta\,\sigma_{ab}$$

- Non-equilibrium (irreversible) thermodynamics
- "1st order": simplest (linear) assumptions to satisfy $S^{\alpha}_{;\alpha} \geq 0$
- Relativistic generalisations of Stokes' law, Fourier's law and Newton's law of viscosity

Temperature and viscosity of ϕ-fluid

- Comparing $\dot{u}_a$ and $q_a^{(\phi)}$

$$q_a^{(\phi)} = -\frac{\sqrt{-\nabla^c\phi\nabla_c\phi}}{8\pi\phi}\dot{u}_a \quad \Rightarrow \quad \mathcal{K}\mathcal{T} = \frac{\sqrt{-\nabla^c\phi\nabla_c\phi}}{8\pi\phi} \geq 0$$

- Temperature ”of scalar-tensor gravity”, relative to GR [7]

- GR limit: $\mathcal{K}\mathcal{T} \to 0$ when $\phi = \text{const.} \Rightarrow G_{\text{eff}} = G_{\text{N}}$, no ϕ-fluid

[7] V. Faraoni, A. Giusti, PRD 103 (2021) - arXiv:2103.05389

Fixed points of dissipation equation

- Approach to equilibrium governed by effective heat equation for ϕ-fluid

$$\frac{d(\mathcal{K}\mathcal{T})}{d\tau} = 8\pi(\mathcal{K}\mathcal{T})^2 - \theta\mathcal{K}\mathcal{T} + \frac{\Box\phi}{8\pi\phi}$$

↙ ↘

$\mathcal{K}\mathcal{T} = 0$ | $\mathcal{K}\mathcal{T} = \text{const.}$

GR + theories with non-dynamical ϕ [8]

Scalar-tensor stealth solutions[9]

- GR seems to be the only stable equilibrium!

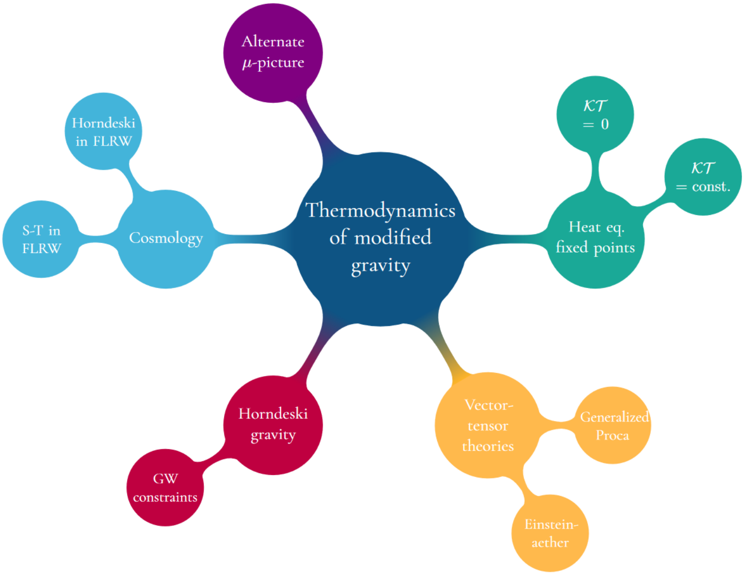
[8] V. Faraoni, A. Giusti, S. Jose, S. Giardino, PRD 106 (2022) - arXiv:2206.02046
[9] S. Giardino, A. Giusti, V. Faraoni - arXiv:2302.08550

Mapping the landscape

- Thermodynamical analogy $\Rightarrow$ map of gravity theories landscape
- GR: special role as the only stable equilibrium at $\mathcal{KT} = 0$
- Modified theories with additional dynamical degrees of freedom always have $\mathcal{KT} > 0$
- Nordström gravity with less degrees of freedom than GR has $\mathcal{KT} < 0$ (pathological)
- Dissipative relaxation process to GR in most cases, but not guaranteed

Intuitive picture

Further developments



Summary

- Connection between thermodynamics and gravity
- Jacobson's idea: GR equilibrium state, modified gravity non-equilibrium $\Rightarrow$ open questions
- New perspective: effective fluid approach to S-T theories + Eckart's non-equilibrium thermodynamics $\rightarrow \mathcal{T}$ of modified gravity, relative to GR
- Mapping the landscape of gravity theories with goal of understanding GR in more general framework
- $\mathcal{K}\mathcal{T} > 0$ whenever additional dynamical dof
- GR special as the only stable equilibrium state!

Thank you for your attention!