General relativity as diffusive equilibrium of scalar-tensor gravity

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Based on arXiv:2604.16094 (with Laur Järv)

PASCOS 2026, JUNE 25

Outline

- First-order thermodynamics of Brans–Dicke theories
- Frame-dependence of thermodynamical quantities
- Frame-agnostic formulation of scalar-tensor theories
- Frame-invariant diffusive equilibrium

Outline of the outline

- First-order thermodynamics of Brans–Dicke theories
  - **The established approach**
- Frame-dependence of thermodynamical quantities
  - **The problem (and why it's an actual problem)**
- Frame-agnostic formulation of scalar-tensor theories
  - **The right toolset for the job**
- Frame-invariant diffusive equilibrium
  - **The solution (and future work)**

- Gravity and thermodynamics have a deep relationship
  - laws of black hole thermodynamics can be derived from the Einstein field equations
  - Einstein field equations can be derived from thermodynamical considerations of entropy and horizon area (Jacobson, 1995)
- Many motivations to study modified gravity, but scalar-tensor theories in particular are both elegant in their simplicity and rich in their features
- Effective energy-momentum tensor description of scalar-tensor theories provides a natural starting point for a thermodynamical description

Thermodynamics of Brans–Dicke Theories

- We examine the class of **Brans–Dicke theories**, specified by the action

$$S_{\text{BD}} = \frac{1}{2}\int d^4x\sqrt{-g}\left[\phi R - \frac{\omega(\phi)}{\phi}\nabla^\mu\phi\nabla_\mu\phi - V(\phi)\right] + S^{(\mathrm{m})}$$

- With the usual variational methods, the equations of motion are

$$G_{\mu\nu} = \frac{T^{(\mathrm{m})}_{\mu\nu}}{\phi} + \frac{\omega}{\phi^2}\left[\nabla_\mu\phi\nabla_\nu\phi - \frac{g_{\mu\nu}}{2}(\nabla\phi)^2\right] + \frac{1}{\phi}(\nabla_\mu\nabla_\nu\phi - g_{\mu\nu}\Box\phi) - \frac{g_{\mu\nu}}{\phi}\frac{V}{2}$$

$$\Box\phi = \frac{1}{2\omega+3}\left[T^{(\mathrm{m})} + \phi V' - 2V - \omega'(\nabla\phi)^2\right]$$

- Complicated, but with the correct definition of the effective **energy-momentum tensor** they can be put in a very simple form

$$G_{\mu\nu} = \frac{T^{(\mathrm{m})}_{\mu\nu}}{\phi} + T^{(\phi)}_{\mu\nu}$$

- The effective energy-momentum tensor is

$$T_{\mu\nu}^{(\phi)} = \frac{\omega}{\phi^2}\left[\nabla_\mu\phi\nabla_\nu\phi - \frac{g_{\mu\nu}}{2}(\nabla\phi)^2\right] + \frac{1}{\phi}(\nabla_\mu\nabla_\nu\phi - g_{\mu\nu}\Box\phi) - \frac{g_{\mu\nu}}{\phi}\frac{V}{2}$$

- This energy-momentum tensor can be *interpreted* as that of a **imperfect fluid** (only assumption necessary is timelike and future-oriented $\partial_\mu\phi$)
- Endows spacetime with **induced metric**

$$h_{\mu\nu} \equiv g_{\mu\nu} + u_\mu u_\nu .$$

- Velocity is $u_\mu \equiv \frac{\partial_\mu\phi}{\sqrt{-\nabla^\rho\phi\nabla_\rho\phi}}$
- Can define four-acceleration (with τ proper time defined along flow lines)

$$a^\mu \equiv \frac{du^\mu}{d\tau} = u^\nu\nabla_\nu u^\mu ,$$

- Using projection operator ${h_\mu}^\nu$, we can define other kinematic quantities like the expansion scalar, the shear scalar, the vorticity tensor, and the symmetric traceless shear tensor

- Can also define mechanical quantities e.g. energy density and pressure: hence, we decompose the energy-momentum tensor in the usual **imperfect fluid** form

$$T_{\mu\nu} = \rho u_\mu u_\nu + p h_{\mu\nu} + q_\mu u_\nu + u_\mu q_\nu + \pi_{\mu\nu}$$

- We have the comoving effective energy density ρ, the isotropic pressure p, the heat flux q_μ, and the anisotropic stress $\pi_{\mu\nu}$

- But how to connect to thermodynamics?

- Eckart's first-order relativistic thermodynamics (though supplanted by the Israel–Stewart formalism) can be used to write down constitutive laws between dissipative quantities (which are responsible for entropy production) and mechanical/kinetic fluid quantities

$$\begin{aligned} p_{\text{visc}} &= -\zeta\theta, \\ q_\mu &= -K(h_{\mu\nu}\nabla^\nu T + Ta_\mu), \\ \pi_{\mu\nu} &= -2\eta\sigma_{\mu\nu}. \end{aligned}$$

- Properties of the medium are encoded in the bulk viscosity ζ, the thermal conductivity K, and the shear viscosity η, whereas T is the temperature
- *A priori*, there really is no reason why a scalar-tensor theory should follow a thermodynamical law
- However, if the constitutive equations are satisfied by the effective fluid, then we have a *thermodynamical interpretation* of the theory

- And they do! Constructing the normalized velocity out of the only vector as $u_\mu \equiv \frac{\nabla_\mu \phi}{\sqrt{-\nabla_\rho \phi \nabla^\rho \phi}}$, the acceleration and the heat flux are:

$$a_\mu = \frac{(\nabla^\nu \phi)}{(-\nabla^\rho \phi \nabla_\rho \phi)^2} \left[(-\nabla^\rho \phi \nabla_\rho \phi)(\nabla_\mu \nabla_\nu \phi) + (\nabla^\sigma \phi)(\nabla_\sigma \nabla_\nu \phi)(\nabla_\mu \phi) \right]$$

$$q_\mu = \frac{(\nabla^\rho \phi)(\nabla^\sigma \phi)}{\phi(-\nabla^\nu \phi \nabla_\nu \phi)^{3/2}} \left[(\nabla_\sigma \phi)(\nabla_\rho \nabla_\mu \phi) - (\nabla_\mu \phi)(\nabla_\rho \nabla_\sigma \phi) \right]$$

- Comparing to $q_\mu = -K(h_{\mu\nu} \nabla^\nu T + T a_\mu)$ and, since in the comoving frame the spatial temperature gradient vanishes, we have

$$\boxed{KT = \frac{1}{\phi} \sqrt{-\nabla^\mu \phi \nabla_\mu \phi}}$$

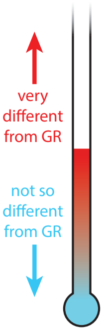
Thermodynamics of Brans–Dicke Theories

- A "hot" theory is therefore far away from GR, whereas a "cold" theory is closer to GR, and GR is at absolute zero

- For Brans–Dicke theories, GR emerges as a *thermal attractor* [Faraoni *et al.* '21]

$$\frac{d(KT)}{d\tau} = (KT)^2 - \theta KT + \frac{\Box\phi}{\phi}$$

- A free theory $\Box\phi = 0$ will therefore "cool down" or "warm up" depending on the expansion of spacetime: the critical line is $\theta = KT$, controlling whether the theory deviates from or converges to GR



The temperature frame problem

- Scalar-tensor theories can be written in different **frames** through a conformal transformation followed by a field reparametrization

$$g_{\mu\nu} \mapsto \hat{g}_{\mu\nu} = \Omega(\phi)^2 g_{\mu\nu}$$
$$\phi \mapsto \hat{\phi} = f(\phi)$$

- Frame transformations do not affect the physics (at least classically): they essentially correspond to **local unit transformations** [Dicke, '62], leaving unchanged
  - inflationary observables (n_s, r, etc.)
  - solar system predictions from PPN parameters
  - black hole entropy
  - radiative corrections [Vilkovisky & De Witt '81, '84], [Pilaftsis & SK '17, '19]
- So we would hope that temperature, which is an intensive property, is uniquely defined

The temperature frame problem

- We can go from one Brans–Dicke representation to another with $g_{\mu\nu} \to \hat{g}_{\mu\nu} = \Omega(\phi)^2 g_{\mu\nu}$ and $\hat{\phi} = \Omega(\phi)^{-2}\phi$

$$S_{\mathsf{BD}} = \frac{1}{2}\int d^4x\sqrt{-g}\left[\phi R - \frac{\omega(\phi)}{\phi}g^{\mu\nu}(\partial_\mu\phi)(\partial_\nu\phi)\right] + \dots$$

$$S_{\mathsf{BD}} = \frac{1}{2}\int d^4x\sqrt{-\hat{g}}\left[\hat{\phi}\hat{R} - \frac{\hat{\omega}(\hat{\phi})}{\hat{\phi}}\hat{g}^{\mu\nu}(\partial_\mu\hat{\phi})(\partial_\nu\hat{\phi})\right] + \dots$$

- Temperature transforms as

$$KT \to K\hat{T} = \frac{\Omega(\phi) - 2\phi\Omega'(\phi)}{\Omega(\phi)^2}KT$$

- So we can tune the temperature <u>arbitrarily</u> by choosing the function $\Omega(\phi)$

The temperature frame problem

- Is this a problem? Does temperature have to be the same in all frames?
- Not necessarily: e.g. for Lorentz frames, mass is a useful concept, but we usually refer to the rest mass
- Similarly, to get useful information regarding temperature, we must then pick a frame to measure it in
- In a sense, the "rest frame" of a scalar-tensor theory is the Einstein frame, where equations of motion take on a simpler form, so we may be tempted to define the "proper temperature" of the theory in the Einstein frame

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- However, we quickly find out that the temperature is identically zero in the Einstein frame with $\Omega^2 = \phi$:

$$K\hat{T} = \frac{\Omega(\phi) - 2\phi\Omega'(\phi)}{\Omega(\phi)^2} KT = \mathbf{0}$$

- Intuitive, since the effective fluid is now **perfect**, which means that all dissipative quantities vanish.

The temperature frame problem

- The proper temperature of a scalar-tensor theory makes about as much sense as the "proper velocity" of a test mass: it is unambiguously defined and invariant, but it's <u>identically zero</u> and <u>offers no physical information</u>
- In the Einstein frame, we can actually trade the temperature description for the diffusive description
- Instead of Fourier's law of thermal conduction and temperature, we have Fick's law of particle diffusion and the chemical potential μ

$$Q_\rho = -D(h_{\rho\sigma}\nabla^\sigma \mu + \mu a_\rho)$$

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- ...but it is a bit strange that our approach must depend on the representation of a theory. There must be some quantities that are *independent* of the frame the theory is expressed in
- **So how do we find them?**

- The different frames of a theory are none other than different **representations**: therefore, any quantity that parametrizes the physics of a theory should be **frame-invariant**

- A frame transformation can be interpreted as a local unit transformation: e.g. in both cases, all length scales are locally rescaled by a scale factor

$$\mathbf{ds^2} = g_{\mu\nu}dx^\mu dx^\nu \to \Omega^2 g_{\mu\nu}dx^\mu dx^\nu = \Omega^2\mathbf{ds^2}$$

- Whether the physics is affected by the rescaling of some mass/length scale depends on whether dimensionless ratios π are affected:

$$\pi = \frac{Q}{M_P^D} \to \frac{\Omega^{-D}Q}{M_P^D} = \Omega^{-D}\pi \qquad \text{(physics changes)}$$

$$\pi = \frac{Q}{M_P^D} \to \frac{\Omega^{-D}Q}{(\Omega^{-1}M_P)^D} = \pi \qquad \text{(physics doesn't change)}$$

The frame-invariant formalism: the why

- Unit transformations are not physical precisely because they leave all dimensionless ratios π invariant, leading to the Buckingham-π theorem: all laws of physics can be expressed in terms of dimensionless ratios

$$f(\pi_1, \pi_2, \ldots) = 0$$

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- **Conformal invariance** implies invariance of the action and is a statement about how the theory behaves at different scales

- **Frame invariance** implies form invariance of the action and is a statement about which features of a theory are independent of the choice of conformal frame

The frame-invariant formalism: the why

general covariance	frame covariance
trajectory	theory
observer/coordinate system	frame
equations of motion	action
coordinate transformation	frame transformation
relative quantities	frame-dependent quantities
absolute quantities	frame-independent quantities
rest frame	Einstein frame
moving frame	Jordan frame

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- ...but a covariant formalism does help us figure out what properties of an action are <u>artifacts of its representation</u> and which are <u>intrinsic</u> to the theory it specifies

- We consider a general scalar-tensor action, with three model functions

$$S_{ST} = \frac{1}{2}\int d^4x\sqrt{-g}\left[A(\phi)R - B(\phi)(\nabla\phi)^2 - 2V(\phi)\right]$$

- Given a frame transformation, we have the transformation rules:

$$\begin{aligned}\hat{A} &= \Omega^{-2}A,\\ \hat{B} &= \Omega^{-2}\left[f'^{-2}B - 6A(\ln\Omega)'^2 + 6A'(\ln\Omega)'\right],\\ \hat{V} &= \Omega^{-4}V,\end{aligned}$$

- Thus we have the frame-invariant metric, which can be used to compare physical lengths even between different frames

$$\mathfrak{g}_{\mu\nu} = Ag_{\mu\nu}$$

- We can also define the usual curvature tensors, now invariant:

$$\begin{aligned}\digamma^{\rho}_{\mu\nu} &\equiv \frac{\mathfrak{g}^{\rho\sigma}}{2}\left(D_\mu\mathfrak{g}_{\sigma\nu} + D_\nu\mathfrak{g}_{\mu\sigma} - D_\sigma\mathfrak{g}_{\mu\nu}\right).\\ \mathfrak{R}^{\rho}{}_{\sigma\mu\nu} &= D_\mu\digamma^{\rho}{}_{\nu\sigma} - D_\nu\digamma^{\rho}{}_{\mu\sigma} + \digamma^{\rho}{}_{\mu\lambda}\digamma^{\lambda}{}_{\nu\sigma} - \digamma^{\rho}{}_{\nu\lambda}\digamma^{\lambda}{}_{\mu\sigma},\\ \mathfrak{R}_{\mu\nu} &= \mathfrak{R}^{\rho}{}_{\mu\rho\nu},\\ \mathcal{R} &= \mathfrak{g}^{\mu\nu}\mathfrak{R}_{\mu\nu}.\end{aligned}$$

The frame-invariant formalism: the how

- Using the model functions, there exist two independent frame-invariant quantities: the invariant field and the invariant potential

$$\Phi \equiv \pm \int d\phi \sqrt{\frac{B(\phi)}{A(\phi)} + \frac{3}{2}\left[\frac{A'(\phi)}{A(\phi)}\right]^2} \qquad \mathfrak{U}(\Phi) \equiv \frac{V(\phi(\Phi))}{A(\phi(\Phi))^2}$$

- Much like selecting a basis for a vector space, there are infinitely many choices of invariant quantities, but we can have at most two independent ones

- Along with invariant metric $\mathfrak{g}_{\mu\nu} \equiv A g_{\mu\nu}$ and the associated invariant scalar curvature $\mathfrak{R}$, we can write the **invariant action**

$$S = \frac{1}{2}\int d^4x \sqrt{-\mathfrak{g}}\left[\mathfrak{R} - \mathfrak{g}^{\mu\nu}(\partial_\mu\Phi)(\partial_\nu\Phi) - 2\mathfrak{U}\right]$$

- <u>Any quantities extracted from this action will also be invariant!</u>

Frame-invariant diffusive equilibrium

- Again we write out the kinematic quantities, except now they are frame-invariant, e.g. fluid velocity and acceleration:

$$\mathfrak{u}^\mu \equiv \frac{\partial^\mu \Phi}{\sqrt{-\mathfrak{g}^{\rho\sigma}\partial_\rho \Phi \partial_\sigma \Phi}} \equiv \frac{\partial^\mu \Phi}{\sqrt{2\mathfrak{X}}}$$

$$\mathfrak{a}^\mu \equiv \mathfrak{u}^\nu \nabla_\nu^{(\mathfrak{g})} \mathfrak{u}^\mu ,$$

- Since the invariant action features minimal coupling, we can use the standard expressions for the mechanical quantities along with the particle density and the chemical potential

$$\varrho \equiv \mathfrak{X} + \mathfrak{U} \qquad \mathfrak{p} \equiv \mathfrak{X} - \mathfrak{U}$$

$$\mathfrak{n} \equiv \sqrt{2\mathfrak{X}} \qquad \boxed{\mathfrak{M} \equiv \frac{\varrho + \mathfrak{p}}{\sqrt{2\mathfrak{X}}}}$$

Frame-invariant diffusive equilibrium

- But is the constitutive equation (Fick's law of diffusion) satisfied for this fluid, just like Fourier's law of thermal conduction is satisfied for the nonminimally coupled equations of motion?

$$\mathfrak{Q}^{\mu} = -D(\mathfrak{h}^{\mu\nu}\nabla^{(\mathfrak{g})}_{\nu}\mathfrak{M} + \mathfrak{M}\mathfrak{a}^{\mu}),$$

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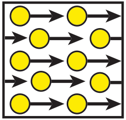
- As a result, we can again *read off* the (invariant, as promised!) chemical potential (which coincides with the particle number density)

$$\boxed{\mathfrak{M} = \mathfrak{n} \equiv \sqrt{-\left[B(\phi) + \frac{3}{2}\frac{A'(\phi)^2}{A(\phi)}\right] g^{\mu\nu}\,(\partial_{\mu}\phi)\,(\partial_{\nu}\phi)}}$$

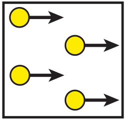
Frame-invariant diffusive equilibrium

fluid quantity	**frame-invariant quantity**
energy density ρ	$\mathfrak{X} + \mathfrak{U}$
pressure p	$\mathfrak{X} - \mathfrak{U}$
number density n	$\sqrt{2\mathfrak{X}}$
chemical potential μ	$\sqrt{2\mathfrak{X}}$
temperature T	0
entropy density s	indeterminate

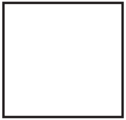
- We now see that particle density/chemical potential controls whether a theory is "close to" or "far away from" GR
- Depending on the details of the theory, the theory will either "dilute" (towards GR) or "condense" (away from GR)



very different from GR



closer to GR



GR

Frame-invariant diffusive equilibrium

- The EoM (which is the frame-invariant generalized Klein–Gordon equation $\Box^{(\mathfrak{g})}\Phi + \mathfrak{U}_{,\Phi} = 0$) is simply a consequence of the invariant continuity equation ($\mathfrak{t}$ now is the invariant proper time)

$$\frac{d\varrho}{d\mathfrak{t}} + (\varrho + \mathfrak{p})\Theta = 0$$

- The field equation can therefore be written in a very condensed way

$$\frac{d^2\Phi}{d\mathfrak{t}^2} + \Theta\frac{d\Phi}{d\mathfrak{t}} + \mathfrak{U}_{,\Phi} = 0$$

- Differentiating, we finally find the "diffusive attractor" equation

$$\boxed{\frac{d\mathfrak{M}}{d\mathfrak{t}} = -\mathfrak{M}\Theta + \Box^{(\mathfrak{g})}\Phi,}$$

- For a free theory, a monotonically expanding or contracting universe implies that GR is either asymptotically recovered or that the theory diverges from GR, respectively

Conclusions

- State-of-the-art thermodynamical description of scalar-tensor theories features an ambiguous definition of temperature
- Frame-invariant approach resolves this ambiguity, and offers an alternative diffusive interpretation valid for all theories
- Questions:
  - What insights can the invariant diffusive approach offer when dealing with application of scalar-tensor theories (e.g. inflation, black holes, etc.)?
  - Is there a mapping between the thermodynamical and diffusive pictures? And how sensitive is it to the presence of matter?
  - Theories beyond scalar-tensor?

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- Stay tuned...