Gravity Beyond a Single Metric

Consistency and Uniqueness of Ghost-Free Spin-2 Interactions

Joakim Flinckman

with Fawad Hassan

Stockholm University

Oskar Klein centre

GeomGravX – Tartu 2026

MASSLESS SPIN-2 THEORY!

Could gravity be part of a **larger spin-2 structure** similar to how electromagnetism is part of electroweak theory?

Success of General Relativity

- General Relativity: theoretically & empirically **successful**

Success of General Relativity

- General Relativity: theoretically & empirically **successful**
- **Open Questions**: DM, DE, Hubble tension, Inflation, QG? $\Longrightarrow$ Modify gravity?

Success of General Relativity

- General Relativity: theoretically & empirically **successful**
- **Open Questions**: DM, DE, Hubble tension, Inflation, QG? $\Longrightarrow$ Modify gravity?
    - Viable modifications are **highly constrained** (theoretically and observationally)

Success of General Relativity

- General Relativity: theoretically & empirically **successful**
- **Open Questions**: DM, DE, Hubble tension, Inflation, QG? $\Longrightarrow$ Modify gravity?
  - Viable modifications are **highly constrained** (theoretically and observationally)
  - A different route: **Theoretical consistency first!**

Theoretical Consistency as a Guide

CLASSICAL!

- Lorentzian field theory: (mass, spin) + Consistency conditions:

Theoretical Consistency as a Guide

Classical!

- Lorentzian field theory: (mass, spin) + Consistency conditions:
  - Fix structure of field equations

Theoretical Consistency as a Guide

CLASSICAL!

- Lorentzian field theory: (mass, spin) + Consistency conditions:
  - Fix structure of field equations
  - Ghost-Freedom: $\mathcal{L} = -\dot{\phi}^2 + \ldots$ ✗ $\mathcal{L} = \dot{\phi}^2 + \ldots$ ✔

Theoretical Consistency as a Guide

Classical!

- Lorentzian field theory: (mass, spin) + Consistency conditions:
    - Fix structure of field equations
    - Ghost-Freedom: $\mathcal{L} = -\dot{\phi}^2 + \ldots$ ✗ $\mathcal{L} = \dot{\phi}^2 + \ldots$ ✔
- Provides essentially **unique** theories:

Theoretical Consistency as a Guide

CLASSICAL!

- Lorentzian field theory: (mass, spin) + Consistency conditions:
  - Fix structure of field equations
  - Ghost-Freedom: $\mathcal{L} = -\dot{\phi}^2 + \ldots$ ✗ $\mathcal{L} = \dot{\phi}^2 + \ldots$ ✔
- Provides essentially **unique** theories:
  - s < 2: building blocks of SM: KG, Dirac, YM (well-known)

Theoretical Consistency as a Guide

CLASSICAL!

- Lorentzian field theory: (mass, spin) + Consistency conditions:
  - Fix structure of field equations
  - Ghost-Freedom: $\mathcal{L} = -\dot{\phi}^2 + \dots$ ✗ $\mathcal{L} = \dot{\phi}^2 + \dots$ ✔
- Provides essentially **unique** theories:
  - s < 2: building blocks of SM: KG, Dirac, YM (well-known)
  - s > 2: Not possible*

Theoretical Consistency as a Guide

CLASSICAL!

- Lorentzian field theory: (mass, spin) + Consistency conditions:
  - Fix structure of field equations
  - Ghost-Freedom: $\mathcal{L} = -\dot{\phi}^2 + \ldots$ ✗ $\mathcal{L} = \dot{\phi}^2 + \ldots$ ✔
- Provides essentially **unique** theories:
  - s < 2: building blocks of SM: KG, Dirac, YM (well-known)
  - s > 2: Not possible*
  - s = 2: Last part of parameter space!

Theoretical Consistency as a Guide

CLASSICAL!

- Lorentzian field theory: (mass, spin) + Consistency conditions:
  - Fix structure of field equations
  - Ghost-Freedom: $\mathcal{L} = -\dot{\phi}^2 + \ldots$ ✗ $\mathcal{L} = \dot{\phi}^2 + \ldots$ ✔
- Provides essentially **unique** theories:
  - s < 2: building blocks of SM: KG, Dirac, YM (well-known)
  - s > 2: Not possible*
  - s = 2: Last part of parameter space!
    - General Relativity (m=0, Lovelock), but beyond one field essentially **unknown.**

Theoretical Consistency as a Guide

Example

- Massless spin-1 field: $A_\mu(x)$

Theoretical Consistency as a Guide

Example

- Massless spin-1 field: $A_\mu(x)$
  - Ostrogradsky:

EOM AT MOST 2ND ORDER IN TIME!

Theoretical Consistency as a Guide

Example

EOM AT MOST 2ND ORDER IN TIME!

- Massless spin-1 field: $A_\mu(x)$
  - Ostrogradsky:

$$\mathcal{L} = a\partial_\mu A_\nu \partial^\mu A^\nu + b\partial_\mu A_\nu \partial^\nu A^\mu + \text{BT \& tadpoles}$$

Theoretical Consistency as a Guide

Example

EOM AT MOST 2ND ORDER IN TIME!

- Massless spin-1 field: $A_\mu(x)$
  - Ostrogradsky:

$$\mathcal{L} = a\partial_\mu A_\nu \partial^\mu A^\nu + b\partial_\mu A_\nu \partial^\nu A^\mu + \text{BT \& tadpoles}$$

$$A_\mu = A_\mu^T + \partial_\mu \chi$$

Theoretical Consistency as a Guide

Example

EOM AT MOST 2ND ORDER IN TIME!

- Massless spin-1 field: $A_\mu(x)$
  - Ostrogradsky:

$$\mathcal{L} = a\partial_\mu A_\nu \partial^\mu A^\nu + b\partial_\mu A_\nu \partial^\nu A^\mu + \text{BT \& tadpoles}$$

$$A_\mu = A_\mu^T + \partial_\mu \chi \quad \Longrightarrow \quad \mathcal{L} = (a+b)\ddot{\chi}^2 + \ldots \quad ✗$$

EOM: $\ddot{\ddot{\chi}} + \ldots = 0$

Theoretical Consistency as a Guide

Example

EOM AT MOST 2ND ORDER IN TIME!

- Massless spin-1 field: $A_\mu(x)$
  - Ostrogradsky:

$$\mathcal{L} = a\partial_\mu A_\nu \partial^\mu A^\nu + b\partial_\mu A_\nu \partial^\nu A^\mu + \text{BT \& tadpoles}$$

$$A_\mu = A_\mu^T + \partial_\mu \chi \quad \Longrightarrow \quad \mathcal{L} = (a+b)\ddot{\chi}^2 + \ldots \quad ✗$$

$$a + b = 0 \quad \Longrightarrow \quad \text{Gauge Sym.} \quad A_\mu \mapsto A_\mu + \partial_\mu \theta$$

Theoretical Consistency as a Guide

Example

- Massless spin-1 field: $A_\mu(x)$
  - Ostrogradsky: ← EOM AT MOST 2ND ORDER IN TIME!

$$\mathcal{L} = a\partial_\mu A_\nu \partial^\mu A^\nu + b\partial_\mu A_\nu \partial^\nu A^\mu + \text{BT \& tadpoles}$$

$$A_\mu = A_\mu^T + \partial_\mu \chi \quad \Longrightarrow \quad \mathcal{L} = (a+b)\ddot{\chi}^2 + \ldots \quad ✗$$

$$a + b = 0 \quad \Longrightarrow \quad \text{Gauge Sym.} \quad A_\mu \mapsto A_\mu + \partial_\mu \theta$$

$$a = -\tfrac{1}{2} \quad \Longrightarrow \quad \mathcal{L} = -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

MAXWELL!

Multi-Gravity

Labels species

- Beyond 1 field: $g^{I}_{\mu\nu}$ $(I = 1, \ldots, \mathcal{N})$

Multi-Gravity

- Beyond 1 field: $g^I_{\mu\nu} \qquad (I = 1, \ldots, \mathcal{N})$

$$\mathcal{S} = \int \mathrm{d}^4x \sum_{I=1}^{\mathcal{N}} m_I^2 \sqrt{-g_I} R_I$$

PROVIDE KINETIC TERMS FOR
6 COMPONENTS OF THE METRIC

Multi-Gravity

- Beyond 1 field: $g^I_{\mu\nu}$ $(I = 1, \ldots, \mathcal{N})$

$$\mathcal{S} = \int \mathrm{d}^4 x \left[\sum_{I=1}^{\mathcal{N}} m_I^2 \sqrt{-g_I} R_I - V(g_1, \ldots, g_{\mathcal{N}}) \right]$$

NON-DERIVATIVE!

PROVIDE KINETIC TERMS FOR 6 COMPONENTS OF THE METRIC

Multi-Gravity

- Beyond 1 field: $g^{I}_{\mu\nu} \qquad (I = 1, \ldots, \mathcal{N})$

NON-DERIVATIVE!

$$\mathcal{S} = \int \mathrm{d}^4 x \left[\sum_{I=1}^{\mathcal{N}} m_I^2 \sqrt{-g_I} R_I - V(g_1, \ldots, g_{\mathcal{N}}) \right] + \sum_{I=1}^{\mathcal{N}} \mathcal{S}_m[g^I, \psi^a]$$

PROVIDE KINETIC TERMS FOR
6 COMPONENTS OF THE METRIC

Multi-Gravity

- Beyond 1 field: $g^{I}_{\mu\nu} \qquad (I = 1, \ldots, \mathcal{N})$

$$\mathcal{S} = \int \mathrm{d}^4 x \left[\sum_{I=1}^{\mathcal{N}} m_I^2 \sqrt{-g_I} R_I - V(g_1, \ldots, g_{\mathcal{N}}) \right] + \sum_{I=1}^{\mathcal{N}} \mathcal{S}_m[g^I, \psi^a]$$

  - Quadratic spectrum: 1 **massless** & multiple **massive** spin-2 fields

Multi-Gravity

- Beyond 1 field: $g^{I}_{\mu\nu} \qquad (I = 1, \dots, \mathcal{N})$

$$\mathcal{S} = \int \mathrm{d}^4x \left[\sum_{I=1}^{\mathcal{N}} m_I^2 \sqrt{-g_I} R_I - V(g_1, \dots, g_{\mathcal{N}}) \right] + \sum_{I=1}^{\mathcal{N}} \mathcal{S}_m[g^I, \psi^a]$$

- Quadratic spectrum: 1 **massless** & multiple **massive** spin-2 fields
- Generically propagate extra **ghostly scalar modes** ✗

Multi-Gravity

- Beyond 1 field: $g^I_{\mu\nu} \qquad (I = 1, \ldots, \mathcal{N})$

$$\mathcal{S} = \int \mathrm{d}^4x \left[\sum_{I=1}^{\mathcal{N}} m_I^2 \sqrt{-g_I} R_I - V(g_1, \ldots, g_{\mathcal{N}}) \right] + \sum_{I=1}^{\mathcal{N}} \mathcal{S}_m[g^I, \psi^a]$$

- Quadratic spectrum: 1 **massless** & multiple **massive** spin-2 fields
- Generically propagate extra **ghostly scalar modes** ✗
- Ghost-freedom is **extremely restrictive!**

How can adding a non-derivative term to Einstein–Hilbert generate a dynamical ghost?

Where is the ghost?

- Einstein–Hilbert ghost?

Where is the ghost?

- Einstein–Hilbert ghost?
  - Ghost-isolating Ansatz: $g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = -N^2(t)\mathrm{d}t^2 + f^2(\phi(t))\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j$

LAPSE

Where is the ghost?

- Einstein–Hilbert ghost?
  - Ghost-isolating Ansatz: $g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = -N^2(t)\mathrm{d}t^2 + f^2(\phi(t))\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j$

$$\mathcal{S}_{\mathrm{EH}} = -\int \mathrm{d}t \frac{\dot{\phi}^2}{2N} \qquad \left(f(\phi) = \left(\tfrac{3}{16}\right)^{1/3}\phi^{2/3}\right)$$

Smart choice!

Where is the ghost?

- Einstein–Hilbert ghost?
  - Ghost-isolating Ansatz: $g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = -N^2(t)\mathrm{d}t^2 + f^2(\phi(t))\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j$

$$\mathcal{S}_{\mathrm{EH}} = -\int \mathrm{d}t \frac{\dot{\phi}^2}{2N} = \int \mathrm{d}t \big[\pi\dot{\phi} + \underbrace{\tfrac{N}{2}\pi^2}_{-H}\big]$$

Where is the ghost?

- Einstein–Hilbert ghost?
  - Ghost-isolating Ansatz: $g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = -N^2(t)\mathrm{d}t^2 + f^2(\phi(t))\delta_{ij}\mathrm{d}x^i \mathrm{d}x^j$

$$\mathcal{S}_{\mathrm{EH}} = -\int \mathrm{d}t \frac{\dot{\phi}^2}{2N} = \int \mathrm{d}t \left[\pi\dot{\phi} + \underbrace{\tfrac{N}{2}\pi^2}_{-H}\right]$$

$$\frac{\delta \mathcal{S}_{\mathrm{EH}}}{\delta N} = \frac{\pi^2}{2} = 0$$ (Non-dynamical)

Where is the ghost?

- Einstein–Hilbert ghost?
  - Ghost-isolating Ansatz: $g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = -N^2(t)\mathrm{d}t^2 + f^2(\phi(t))\delta_{ij}\mathrm{d}x^i \mathrm{d}x^j$

$$\mathcal{S}_{\mathrm{EH}} = -\int \mathrm{d}t \frac{\dot{\phi}^2}{2N} = \int \mathrm{d}t \left[\pi\dot{\phi} + \underbrace{\tfrac{N}{2}\pi^2}_{-H}\right]$$

$$\frac{\delta \mathcal{S}_{\mathrm{EH}}}{\delta N} = \frac{\pi^2}{2} = 0$$ (Non-dynamical)

This constraint must survive!

Where is the ghost?

- Multi-gravity: $$\mathcal{S} = \int \mathrm{d}^4x \left[\sum_{I=1}^{\mathcal{N}} m_I^2 \sqrt{-g_I} R_I - V(g_1, \ldots, g_{\mathcal{N}}) \right]$$

Where is the ghost?

- Multi-gravity: $$\mathcal{S} = \int \mathrm{d}^4x \left[\sum_{I=1}^{\mathcal{N}} m_I^2 \sqrt{-g_I} R_I - V(g_1, \ldots, g_{\mathcal{N}}) \right]$$

$$\mathcal{S} = \int \mathrm{d}t \left[\sum_I \pi_I \dot{\phi}_I - \Big(- \sum_I \tfrac{N_I}{2} \pi_I^2 + V(\phi, N) \Big) \right]$$

Where is the ghost?

- Multi-gravity: $$\mathcal{S} = \int \mathrm{d}^4x \left[\sum_{I=1}^{\mathcal{N}} m_I^2 \sqrt{-g_I} R_I - V(g_1, \ldots, g_{\mathcal{N}}) \right]$$

$$\mathcal{S} = \int \mathrm{d}t \left[\sum_I \pi_I \dot{\phi}_I - \left(-\sum_I \tfrac{N_I}{2} \pi_I^2 + V(\phi, N) \right) \right]$$

$$\frac{\delta \mathcal{S}}{\delta N_I} = \frac{\pi_I^2}{2} - \frac{\partial V}{\partial N_I} = 0$$

Determines Lapses!

Where is the ghost?

- Multi-gravity: $$\mathcal{S} = \int \mathrm{d}^4x \left[\sum_{I=1}^{\mathcal{N}} m_I^2 \sqrt{-g_I} R_I - V(g_1, \ldots, g_{\mathcal{N}}) \right]$$

$$\mathcal{S} = \int \mathrm{d}t \left[\sum_I \pi_I \dot{\phi}_I - \left(- \sum_I \tfrac{N_I}{2} \pi_I^2 + V(\phi, N) \right) \right]$$

$$\frac{\delta \mathcal{S}}{\delta N_I} = \frac{\pi_I^2}{2} - \frac{\partial V}{\partial N_I} = 0$$

DETERMINES LAPSES!

Necessary condition: $$\frac{\partial^2 V}{\partial N_I \partial N_J} = 0$$

[Flinckman, Hassan, 26xx.xxxxx]

Uniqueness of Multi-gravity

- Vielbein formulation: $g^I_{\mu\nu} = e^a_{I\ \mu} \eta_{ab} e^b_{I\ \nu}$

$$e^a_{I\,0} \propto N_I$$

$$g^I_{00} \propto -N_I^2$$

Uniqueness of Multi-gravity

- Vielbein formulation: $g^I_{\mu\nu} = e^a_{I\ \mu}\eta_{ab}e^b_{I\ \nu}$

$e^a_{I\,0} \propto N_I$

$g^I_{00} \propto -N_I^2$

- **Unique** Covariant + Linear in Lapses:

Uniqueness of Multi-gravity

- Vielbein formulation: $g^{I}_{\mu\nu} = e^{a}_{I\ \mu}\eta_{ab}e^{b}_{I\ \nu}$

$e^{a}_{I\,0} \propto N_I$

$g^{I}_{00} \propto -N_I^2$

- **Unique** Covariant + Linear in Lapses:

$$V = \sum_{IJKL} \beta^{IJKL}\epsilon_{abcd}\epsilon^{\alpha\beta\gamma\delta}e^{a}_{I\ \alpha}e^{b}_{J\ \beta}e^{c}_{K\ \gamma}e^{d}_{K\ \delta}$$

FREE CONSTANT PARAMETERS

[Flinckman, Hassan, 26xx.xxxxx]
([Hinterbichler, Rosen, 1203.5783])

Uniqueness of Multi-gravity

- Vielbein formulation: $g^I_{\mu\nu} = e^a_{I\ \mu}\eta_{ab}e^b_{I\ \nu}$

$e^a_{I\,0} \propto N_I$

$g^I_{00} \propto -N_I^2$

- **Unique** Covariant + Linear in Lapses:

$$V = \sum_{IJKL} \beta^{IJKL}\epsilon_{abcd}\epsilon^{\alpha\beta\gamma\delta}e^a_{I\ \alpha}e^b_{J\ \beta}e^c_{K\ \gamma}e^d_{K\ \delta}$$ ✗

[Flinckman, Hassan, 26xx.xxxxx]

([Hinterbichler, Rosen, 1203.5783])

Uniqueness of Multi-gravity

- Vielbein formulation: $g^I_{\mu\nu} = e^a_{I\ \mu}\eta_{ab}e^b_{I\ \nu}$ $e^a_{I\,0} \propto N_I$ $g^I_{00} \propto -N_I^2$
- **Unique** Covariant + Linear in Lapses:

$$V = \sum_{IJKL} \beta^{IJKL}\epsilon_{abcd}\epsilon^{\alpha\beta\gamma\delta}e^a_{I\ \alpha}e^b_{J\ \beta}e^c_{K\ \gamma}e^d_{K\ \delta}$$ ✗

[Flinckman, Hassan, 26xx.xxxxx]
([Hinterbichler, Rosen, 1203.5783])

- **Necessary** condition (multi-interaction):

Uniqueness of Multi-gravity

- Vielbein formulation: $g^I_{\mu\nu} = e^a_{I\ \mu}\eta_{ab}e^b_{I\ \nu}$ $e^a_{I\,0} \propto N_I$ $g^I_{00} \propto -N_I^2$
- **Unique** Covariant + Linear in Lapses:

$$V = \sum_{IJKL} \beta^{IJKL}\epsilon_{abcd}\epsilon^{\alpha\beta\gamma\delta}e^a_{I\ \alpha}e^b_{J\ \beta}e^c_{K\ \gamma}e^d_{K\ \delta}$$ ✗

[Flinckman, Hassan, 26xx.xxxxx] ([Hinterbichler, Rosen, 1203.5783])

- **Necessary** condition (multi-interaction):

$$\beta^{IJKL} = \beta^I\beta^J\beta^K\beta^L$$

ELSE:
EOM OF THE LORENTZ DOF
RUIN THE LINEARITY

[Flinckman, Hassan, 2604.07625]

Uniqueness of Multi-gravity

- Vielbein formulation: $g^I_{\mu\nu} = e^a_{I\ \mu}\eta_{ab}e^b_{I\ \nu}$ $e^a_{I\,0} \propto N_I$ $g^I_{00} \propto -N_I^2$
- **Unique** Covariant + Linear in Lapses:

$$V = \sum_{IJKL} \beta^{IJKL}\epsilon_{abcd}\epsilon^{\alpha\beta\gamma\delta}e^a_{I\ \alpha}e^b_{J\ \beta}e^c_{K\ \gamma}e^d_{K\ \delta} \quad ✗$$

[Flinckman, Hassan, 26xx.xxxxx]
([Hinterbichler, Rosen, 1203.5783])

- **Necessary** condition (multi-interaction):

$$\beta^{IJKL} = \beta^I\beta^J\beta^K\beta^L \quad \Longrightarrow \quad V = 2m^4 \det\left(\sum_I \beta^I e_I\right)$$

[Flinckman, Hassan, 2604.07625], [Hassan, Schmidt-May, 1804.09723]

Ghost-free Multi-Gravity

- Full theory: $$\mathcal{S} = \sum_I \mathcal{S}_{\rm EH}[g_I] - 2m^4 \int \mathrm{d}^4x \det\left(\sum_I \beta^I e_I\right) + \sum_I \mathcal{S}_m[g_I, \psi^a]$$

WE COUPLE TO ONLY ONE METRIC

Ghost-free Multi-Gravity

- Full theory: $$\mathcal{S} = \sum_I \mathcal{S}_{\mathrm{EH}}[g_I] - 2m^4 \int \mathrm{d}^4x \det\left(\sum_I \beta^I e_I\right) + \sum_I \mathcal{S}_m[g_I, \psi^a]$$

$$G^I_{\mu\nu} + \Lambda_I g^I_{\mu\nu} + V^I_{\mu\nu} = \frac{1}{2m_I^2} T^I_{\mu\nu}$$

Ghost-free Multi-Gravity

- Full theory: $$\mathcal{S} = \sum_I \mathcal{S}_{\rm EH}[g_I] - 2m^4 \int \mathrm{d}^4x \det\left(\sum_I \beta^I e_I\right) + \sum_I \mathcal{S}_m[g_I, \psi^a]$$

$$G^I_{\mu\nu} + \Lambda_I g^I_{\mu\nu} + V^I_{\mu\nu} = \frac{1}{2m_I^2} T^I_{\mu\nu}$$

- Free of Ghosts - Full, non-linear Hamiltonian constraint analysis 😮‍💨
- Healthy mass spectrum: 1 massless + multiple massive spin-2 fields

[Flinckman, Hassan, 2510.03014]

[Flinckman, Hassan, 2410.09439]

Ghost-free Multi-Gravity

- Full theory: $$\mathcal{S} = \sum_I \mathcal{S}_{\text{EH}}[g_I] - 2m^4 \int \mathrm{d}^4x \det\left(\sum_I \beta^I e_I\right) + \sum_I \mathcal{S}_m[g_I, \psi^a]$$

$$G^I_{\mu\nu} + \Lambda_I g^I_{\mu\nu} + V^I_{\mu\nu} = \frac{1}{2m_I^2} T^I_{\mu\nu}$$

- Free of Ghosts - Full, non-linear Hamiltonian constraint analysis 😮‍💨 [Flinckman, Hassan, 2510.03014]
- Healthy mass spectrum: 1 massless + multiple massive spin-2 fields [Flinckman, Hassan, 2410.09439]

Ghost-freedom essentially imposes a unique class of spin-2 interaction!

Multi-Gravity Cosmology

SCALE FACTORS

- Multi-Gravity FLRW: $H^2 = H_0^2\left[\Omega_\rho(a) + \Omega_\Lambda + \Omega_k(a)\right] + V_{\text{eff}}(a_I), \qquad \mathcal{P}_I(a_J) = 0$

"PHYSICAL" SCALE FACTOR

Multi-Gravity Cosmology

SCALE FACTORS

- Multi-Gravity FLRW: $H^2 = H_0^2\left[\Omega_\rho(a) + \Omega_\Lambda + \Omega_k(a)\right] + V_{\text{eff}}(a_I), \qquad \mathcal{P}_I(a_J) = 0$
  - $V_{\text{eff}}(a_I)$ contains terms behaving as dynamical dark energy

Multi-Gravity Cosmology

SCALE FACTORS

- Multi-Gravity FLRW: $H^2 = H_0^2\left[\Omega_\rho(a) + \Omega_\Lambda + \Omega_k(a)\right] + V_{\text{eff}}(a_I), \qquad \mathcal{P}_I(a_J) = 0$
  - $V_{\text{eff}}(a_I)$ contains terms behaving as dynamical dark energy
  - Massive spin-2 modes provide natural DM candidates

Multi-Gravity Cosmology

SCALE FACTORS

- Multi-Gravity FLRW: $H^2 = H_0^2\left[\Omega_\rho(a) + \Omega_\Lambda + \Omega_k(a)\right] + V_{\text{eff}}(a_I), \qquad \mathcal{P}_I(a_J) = 0$
  - $V_{\text{eff}}(a_I)$ contains terms behaving as dynamical dark energy
  - Massive spin-2 modes provide natural DM candidates
- $N > 2$: Largely unexplored, but bimetric theory ($N = 2$) is well studied

Multi-Gravity Cosmology

SCALE FACTORS

- Multi-Gravity FLRW: $H^2 = H_0^2\left[\Omega_\rho(a) + \Omega_\Lambda + \Omega_k(a)\right] + V_{\text{eff}}(a_I), \qquad \mathcal{P}_I(a_J) = 0$
  - $V_{\text{eff}}(a_I)$ contains terms behaving as dynamical dark energy
  - Massive spin-2 modes provide natural DM candidates
- $N > 2$: Largely unexplored, but bimetric theory ($N = 2$) is well studied
  - Rich set of cosmologies: standard, self-accelerating, bouncing, etc.

Multi-Gravity Cosmology

SCALE FACTORS

- Multi-Gravity FLRW: $H^2 = H_0^2\left[\Omega_\rho(a) + \Omega_\Lambda + \Omega_k(a)\right] + V_{\text{eff}}(a_I), \qquad \mathcal{P}_I(a_J) = 0$
  - $V_{\text{eff}}(a_I)$ contains terms behaving as dynamical dark energy
  - Massive spin-2 modes provide natural DM candidates
- $N > 2$: Largely unexplored, but bimetric theory ($N = 2$) is well studied
  - Rich set of cosmologies: standard, self-accelerating, bouncing, etc.
  - Competitive with $w_0 w_a$CDM while alleviating Hubble tension

[Högås, Mörtsell, 2507.03743]

Thank you for listening!
Questions?

Stockholm University

Oskar Klein centre

Multi-Gravity Phenomenology

- Cosmology
  - Dark Energy
  - Dark Matter
- Gravitational Waves
  - Graviton mixing
  - GW echoes
  - Waveform inversion
- Black Holes
  - No Birkhoff's theorem! $\Rightarrow$ New types of BH solutions