Integrable auxiliary field deformations of dimensionally reduced gravity

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DESY Theory Workshop: Synergies towards the future Standard Model

September 24, 2025

Based on [MC, A. Kleinschmidt, D.Osten, arXiv:2409.04523]
[MC, D.Osten, arXiv:2502.01750]

Plan of the talk

1. Integrability: what do we mean?

2. Auxiliary field deformations: KK reduction of $D = 4$ GR to $D = 2$

3. Conclusions

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In $D = 2$, $x^\mu = (t, x)$.

1. *Lax integrability*: the Euler-Lagrange equations are equivalent to the flatness of the *Lax connection* $\mathfrak{L}(t, x; z) = \mathfrak{L}_\mu(t, x; z) dx^\mu$,

$$\partial_t \mathfrak{L}_x(t, x; z) - \partial_x \mathfrak{L}_t(t, x; z) + [\mathfrak{L}_t(t, x; z), \mathfrak{L}_x(t, x; z)] = 0\,.$$

2. *Hamiltonian integrability*: one of the possible ways to show the involution of conserved charges is when [J.M. Maillet, '86]

$$\left\{\mathfrak{L}_{x,\underline{\mathbf{1}}}(x, z), \mathfrak{L}_{x,\underline{\mathbf{2}}}(x', z')\right\} = \left[r_{\underline{\mathbf{12}}}(z, z'), \mathfrak{L}_{x,\underline{\mathbf{1}}}(x, z)\right] - \left[r_{\underline{\mathbf{21}}}(z', z), \mathfrak{L}_{x,\underline{\mathbf{2}}}(x', z')\right]$$
$$- \left(r_{\underline{\mathbf{12}}}(z, z') + r_{\underline{\mathbf{21}}}(z', z)\right) \partial_x \delta(x - x')\,,$$

where

$$X_{\underline{\mathbf{1}}} \equiv X \otimes \mathbb{1} = X^A (T_A \otimes \mathbb{1}), \qquad X_{\underline{\mathbf{2}}} \equiv \mathbb{1} \otimes X = X^A (\mathbb{1} \otimes T_A),$$
$$r_{\underline{\mathbf{12}}} = r^{AB} T_A \otimes T_B\,, \qquad r_{\underline{\mathbf{21}}} = r^{BA} T_A \otimes T_B$$

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$D = 4$

Gravity with two space-like isometries

$D = 3$

$D = 2$

$D = 4$ Gravity with two space-like isometries

$\downarrow$ S^1

$D = 3$ $\mathbb{R}^+ \times \mathsf{SL}(1)$ symmetry + dualisation of KK vector

$\mathbb{R}^+ \times \mathsf{SL}(2)_{(\mathsf{E})}$ symmetry

$D = 2$

Dimensionally reduced GR

KK reduction of $D=4$ GR to $D=2$

$D=4$ Gravity with two space-like isometries

↓ S^1

$D=3$ $\mathbb{R}^+ \times \mathsf{SL}(1)$ symmetry + dualisation of KK vector

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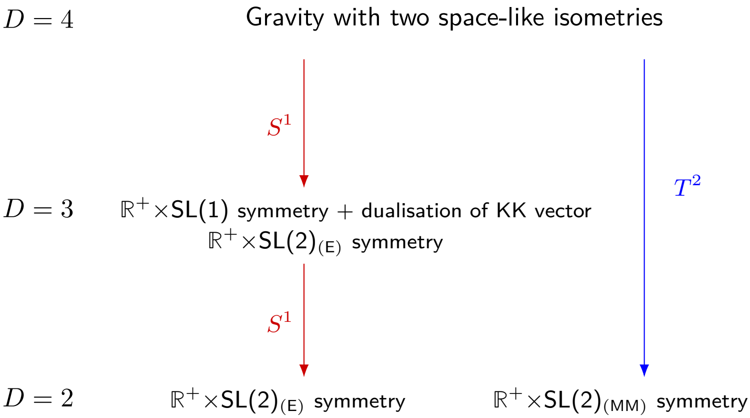
$D=2$ $\mathbb{R}^+ \times \mathsf{SL}(2)_{(\mathsf{E})}$ symmetry

Dimensionally reduced GR

KK reduction of $D = 4$ GR to $D = 2$



Dimensionally reduced GR

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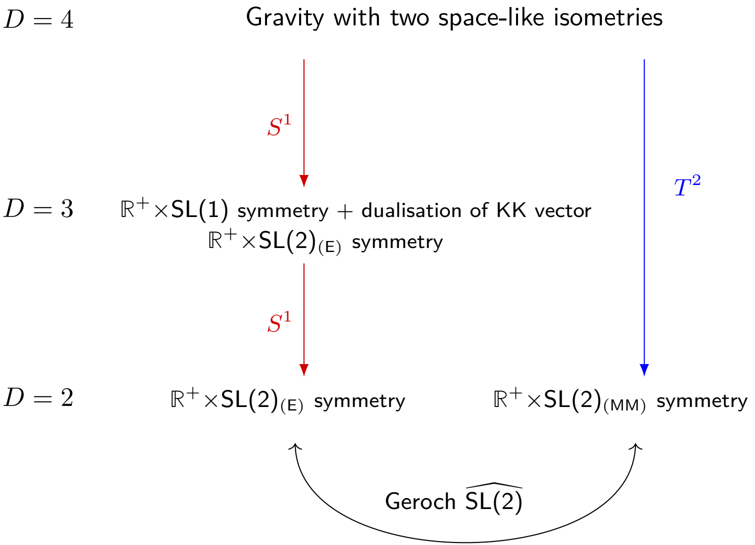

The Lagrangian in $D = 2$ after dimensional reduction is

$$\mathcal{L}_{D=2} = \partial_\mu \rho \partial^\mu \sigma - \frac{1}{2} \rho \mathsf{Tr}(P_\mu P^\mu) \,,$$

with

$$V^{-1} \partial_\mu V = P_\mu + Q_\mu \,, \quad V \in \mathsf{SL(2)}, \quad Q_\mu \in \mathfrak{so}_2 \,, \quad P_\mu \in \mathfrak{sl}_2 \ominus \mathfrak{so}_2 \,.$$

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Equations of motion:

$$\begin{aligned} & D_\mu (\rho P^\mu) = 0 \,, \\ & \Box \sigma + \frac{1}{2} \mathsf{Tr}(P_\mu P^\mu) = 0 \,, \\ & \Box \rho = 0 \,, \end{aligned}$$

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supplemented by Virasoro constraints

$$V_{\mu\nu} = \partial_\mu \rho \partial_\nu \sigma - \frac{1}{2} \partial_\nu \partial_\mu \rho - \frac{1}{2} \rho \mathsf{Tr}(P_\mu P_\nu) = 0 \, .$$

In [B. Julia, H. Nicolai, '96] was proven the existence of an even larger duality-symmetry,

$$\frac{\mathcal{W} \ltimes \widehat{\mathsf{SL}(2)}}{K\left(\mathcal{W}\right) \ltimes K\left(\widehat{\mathsf{SL}(2)}\right)}.$$

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For integrability, define

$$\hat{\mathcal{Y}} = \left(\hat{\mathcal{V}}(z) \cdot \mathbf{\Gamma},\, e^{\hat{\sigma}}\,\mathsf{K}\right) \in \frac{\mathcal{W} \ltimes \widehat{\mathsf{SL}(2)}}{K(\mathcal{W}) \ltimes K\left(\widehat{\mathsf{SL}(2)}\right)},$$

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with

$$\hat{\mathcal{V}}(z) \in \widehat{\mathsf{SL}(2)}, \quad \boldsymbol{\Gamma} \in \mathcal{W}.$$

The conformal factor is rescaled:

$$\hat{\sigma} = \sigma - \frac{1}{2}\ln(\partial_+\rho\partial_-\rho)\,,$$

so that transforms as a proper scalar under conformal transformations.

Generalised linear system + twisted self duality constraints:

$$\hat{\mathcal{Y}}^{-1}\partial_\mu\hat{\mathcal{Y}} = \left(\mathbf{\Gamma}^{-1}\hat{\mathcal{V}}^{-1}\partial_\mu\left(\hat{\mathcal{V}}\mathbf{\Gamma}\right),\ \left[\partial_\mu\hat{\sigma} - \Omega'(\hat{\mathcal{V}},\hat{\mathcal{V}}^{-1}\partial_\mu\hat{\mathcal{V}})\right]\mathsf{K}\right) \cong (\mathfrak{L}_\mu(z), 0),$$

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where

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Then

$$d\mathfrak{L} + \frac{1}{2}[\mathfrak{L}, \mathfrak{L}] = 0 \quad \Longleftrightarrow \quad \text{Euler-Larange field equations.}$$

Deform the Lagrangian through introduction of auxiliary fields [MC, D. Osten, '25]. An approach pioneered for the PCM by [C.Ferko, L. Smith, '24] and inspired by [E. Ivanov, B. Zupnik, '02].

$$
\begin{aligned}
\tilde{\mathcal{L}} = &-\partial_\mu \rho \partial^\mu \sigma - 2(\chi_{1\,\mu}\partial^\mu \rho + \chi_{2\,\mu}\partial^\mu \sigma + \chi_1^\mu \chi_{2\,\mu}) \\
&+ \rho \left(\mathrm{Tr}\left[\frac{1}{2}(P_\mu P^\mu) + 2P_\mu v^\mu + v_\mu v^\mu \right] \right) + E(\nu)\,,
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with

$$\nu = (\eta^{\alpha\beta}\eta^{\gamma\sigma} + \epsilon^{\alpha\beta}\epsilon^{\gamma\sigma}) \left(\chi_{1\,\alpha}\chi_{2\,\gamma} - \frac{\rho}{2}\mathrm{Tr}(v_\alpha v_\gamma) \right) \left(\chi_{1\,\beta}\chi_{2\,\sigma} - \frac{\rho}{2}\mathrm{Tr}(v_\beta v_\sigma) \right)\,.$$

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We define:

$$\mathcal{P}_\mu = -(P_\mu + 2v_\mu)\,, \quad \mathcal{R}_\mu = -(\partial_\mu \rho + 2\chi_{2\,\mu})\,, \quad \mathcal{S}_\mu = -(\partial_\mu \sigma + 2\chi_{1\,\mu})\,.$$

Equations of motion: dynamical for scalars , dynamical for conformal factor and algebraic ones ,

$$\begin{cases} \partial_\mu \mathcal{R}^\mu = 0\,, \\ D_\mu(\rho \mathcal{P}^\mu) = 0\,, \end{cases}$$

$$\begin{cases} \partial_\mu \mathcal{S}^\mu = \mathrm{Tr}\left[\frac{1}{2}(P_\mu P^\mu) + 2P_\mu v^\mu + v_\mu v^\mu\right] + K^{\mu\nu}(\chi_{1,2}, v, \rho)\,\mathrm{Tr}(v_\mu v_\nu)\,, \end{cases}$$

$$\begin{cases} P_\mu = -v_\mu + K_\mu{}^\nu(\chi_{1,2}, v, \rho) v_\nu, \\ \partial_\mu \sigma = -\chi_{1\,\mu} + K_\mu{}^\nu(\chi_{1,2}, v, \rho)\chi_{1\,\nu}\,, \\ \partial_\mu \rho = -\chi_{2\,\mu} + K_\mu{}^\nu(\chi_{1,2}, v, \rho)\chi_{2\,\nu}\,, \end{cases}$$

where

$$K_\mu{}^\nu(\chi_{1,2}, v, \rho) = E'(\nu)(\delta_\mu^\alpha \eta^{\gamma\nu} - \eta_{\mu\rho}\epsilon^{\rho\alpha}\epsilon^{\gamma\nu})\left(\chi_{1\,\alpha}\chi_{2\,\gamma} - \frac{\rho}{2}\mathrm{Tr}(v_\alpha v_\gamma)\right)$$

With the same parametrisations, the same twisted self-duality conditions, impose the generalised linear system:

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The flatness of this connection is equivalent to the EOMs [MC, D. Osten, ‘25].

Virasoro constraints stemming from the vanishing of the central term are

$$\tilde{\mathcal{S}}_\pm = -\frac{1}{2}\rho\,\mathrm{Tr}\left(\frac{v_\pm v_\pm}{\chi_{2\,\pm}} + \frac{K_\pm{}^\mp v_\mp v_\mp}{\chi_{2\,\mp}}\right)\,,$$

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On Hamiltonian integrability: we recover the same r-matrix of [D. Bernard, N.Regnault, '01].

Coda

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- Integrable deformations of the $D = 2$ reduction of GR along commuting isometries.

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- Chern-Simons embedding?