Black holes with torsion

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Outline

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- Definition of the torsion tensor (contains 24 dof):

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$$\tilde{R}^{\lambda}{}_{[\mu\nu\rho]} = \tilde{\nabla}_{[\mu}T^{\lambda}{}_{\rho\nu]} + T^{\sigma}{}_{[\mu\rho}T^{\lambda}{}_{\nu]\sigma}\,,$$
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- Just one independent trace, the generalised Ricci tensor

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- Unique scalar and pseudoscalar curvatures:

$$\tilde{R} = g^{\mu\nu}\tilde{R}_{\mu\nu}\,, \quad *\tilde{R} = \varepsilon^{\lambda\rho\mu\nu}\tilde{R}_{\lambda\rho\mu\nu}\,.$$

Dynamics in theories with torsion

- One can write down an action of the form

$$S = \int d^4x \sqrt{-g} \Big[\mathcal{L}_m - \frac{1}{2\kappa^2} \mathcal{L}_g(\tilde{\mathcal{R}}, \mathcal{T}) \Big].$$

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- Correspondence between geometry and matter:

$$\frac{1}{\sqrt{-g}} \frac{\delta \left(\mathcal{L}_g \sqrt{-g} \right)}{\delta e^a{}_\nu} = 2\kappa^2 \theta_a{}^\nu,$$

$$\frac{1}{\sqrt{-g}} \frac{\delta \left(\mathcal{L}_g \sqrt{-g} \right)}{\delta \omega^a{}_{b\nu}} = 2\kappa^2 \Delta_a{}^{b\nu},$$

  where we have two matter sources:

$$\theta_\mu{}^\nu = \frac{e^a{}_\mu}{\sqrt{-g}} \frac{\delta \left(\sqrt{-g} \mathcal{L}_m \right)}{\delta e^a{}_\nu},$$

$$\Delta^{\lambda\mu\nu} = \frac{e^{a\lambda} e_b{}^\mu}{\sqrt{-g}} \frac{\delta \left(\sqrt{-g} \mathcal{L}_m \right)}{\delta \omega^a{}_{b\nu}}.$$

Poincaré gauge theory

- $ISO(1,3) = T^4 \rtimes SO(1,3)$ gauge connection[1]:

$$A_\mu = e^a{}_\mu P_a + \omega^a{}_{b\mu} J_a{}^b, \quad g_{\mu\nu} = e^a{}_\mu e^b{}_\nu \eta_{ab},$$

where

$$\omega^a{}_{b\mu} = e^a{}_\lambda e_b{}^\rho \tilde\Gamma^\lambda{}_{\rho\mu} + e^a{}_\lambda \partial_\mu e_b{}^\lambda.$$

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- Generators of the Poincaré group $ISO(1,3)$:

$$[P_a, P_b] = 0 \,, \quad [P_a, J_{bc}] = i\, \eta_{a[b} P_{c]} \,,$$

$$[J_{ab}, J_{cd}] = \frac{i}{2} \left(\eta_{ad} J_{bc} + \eta_{cb} J_{ad} - \eta_{db} J_{ac} - \eta_{ac} J_{bd} \right) \,.$$

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- $ISO(1,3)$ translational and rotational field strength tensors:

$$F_{\mu\nu} = F^a{}_{\mu\nu} P_a + F^a{}_{b\mu\nu} J_a{}^b,$$

where

$$F^a{}_{\mu\nu} = \partial_\mu e^a{}_\nu - \partial_\nu e^a{}_\mu + \omega^a{}_{b\mu} e^b{}_\nu - \omega^a{}_{b\nu} e^b{}_\mu,$$

$$F^a{}_{b\mu\nu} = \partial_\mu \omega^a{}_{b\nu} - \partial_\nu \omega^a{}_{b\mu} + \omega^a{}_{c\mu} \omega^c{}_{b\nu} - \omega^a{}_{c\nu} \omega^c{}_{b\mu}.$$

Quadratic Poincaré gauge theory - ghost issue

- Convenient to decompose torsion as

$$T^\lambda{}_{\mu\nu} = \frac{1}{3}\left(\delta^\lambda{}_\nu T_\mu - \delta^\lambda{}_\mu T_\nu\right) + \frac{1}{6}\varepsilon^\lambda{}_{\rho\mu\nu}S^\rho + t^\lambda{}_{\mu\nu}\,.$$

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- The most general class of quadratic Poincaré gauge models that are reduced to General Relativity in the absence of torsion is:

$$S_g = \frac{1}{16\pi}\int\Big[-R + c_2\tilde{R}_{\lambda\rho\mu\nu}\tilde{R}^{\lambda\mu\rho\nu} - \frac{1}{2}\left(2c_1+c_2\right)\tilde{R}_{\lambda\rho\mu\nu}\tilde{R}^{\mu\nu\lambda\rho} + c_1\tilde{R}_{\lambda\rho\mu\nu}\tilde{R}^{\lambda\rho\mu\nu}$$
$$+ d_1\tilde{R}_{\mu\nu}\big(\tilde{R}^{\mu\nu} - \tilde{R}^{\nu\mu}\big) + \frac{1}{2}\big(m_T^2 T_\mu T^\mu + m_S^2 S_\mu S^\mu + m_t^2 t_{\lambda\mu\nu}t^{\lambda\mu\nu}\big)\Big]\sqrt{-g}\,d^4x\,.$$

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$$\left. + d_1\tilde{R}_{\mu\nu}\left(\tilde{R}^{\mu\nu} - \tilde{R}^{\nu\mu}\right) + \frac{1}{2}\left(m_T^2 T_\mu T^\mu + m_S^2 S_\mu S^\mu + m_t^2 t_{\lambda\mu\nu}t^{\lambda\mu\nu}\right)\right]\sqrt{-g}\,d^4x\,.$$

- It is not possible to have a stable propagating torsion tensor in quadratic Poincaré gauge theory for general backgrounds. Kinetic part of vectors T_μ and S_μ propagate a ghost.

Cubic Poincaré gauge theory

- Cubic parity preserving branch with mixing terms:[2]

$$\mathcal{L}_{\text{curv-tors}}^{(3)} = \mathcal{L}_{\tilde{R}TT}^{(3)} + \mathcal{L}_{\tilde{R}SS}^{(3)} + \mathcal{L}_{\tilde{R}tt}^{(3)} + \mathcal{L}_{\tilde{R}TS}^{(3)} + \mathcal{L}_{\tilde{R}Tt}^{(3)} + \mathcal{L}_{\tilde{R}St}^{(3)},$$

$$\mathcal{L}_{\tilde{R}TT}^{(3)} = h_1 \tilde{R}_{\mu\nu} T^\mu T^\nu + h_2 \tilde{R} T_\mu T^\mu, \quad \mathcal{L}_{\tilde{R}SS}^{(3)} = h_3 \tilde{R}_{\mu\nu} S^\mu S^\nu + h_4 \tilde{R} S_\mu S^\mu,$$

$$\mathcal{L}_{\tilde{R}tt}^{(3)} = h_5 \tilde{R}_{\lambda\rho\mu\nu} t_\sigma{}^{\lambda\rho} t^{\sigma\mu\nu} + h_6 \tilde{R}_{\lambda\rho\mu\nu} t_\sigma{}^{\lambda\mu} t^{\sigma\rho\nu} + h_7 \tilde{R}_{\lambda\rho\mu\nu} t^{\lambda\rho}{}_\sigma t^{\sigma\mu\nu}$$
$$+ h_8 \tilde{R}_{\lambda\rho\mu\nu} t^{\lambda\mu}{}_\sigma t^{\sigma\rho\nu} + h_9 \tilde{R}_{\lambda\rho\mu\nu} t^{\lambda\mu}{}_\sigma t^{\rho\nu\sigma} + h_{10} \tilde{R}_{\lambda\rho} t_{\mu\nu}{}^\lambda t^{\rho\mu\nu}$$
$$+ h_{11} \tilde{R}_{\lambda\rho} t_{\mu\nu}{}^\lambda t^{\mu\nu\rho} + h_{12} \tilde{R} t_{\lambda\rho\mu} t^{\lambda\rho\mu},$$

$$\mathcal{L}_{\tilde{R}TS}^{(3)} = h_{13} \varepsilon^{\lambda\rho\mu\nu} \tilde{R}_{\lambda\rho\mu\nu} T_\sigma S^\sigma + h_{14} \varepsilon_\nu{}^{\lambda\rho\sigma} \tilde{R}_{\lambda\rho\mu\sigma} T^\mu S^\nu + h_{15} \varepsilon^{\lambda\rho\mu\nu} \tilde{R}_{\lambda\rho} T_\mu S_\nu,$$

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$$\mathcal{L}_{\tilde{R}St}^{(3)} = h_{20} \varepsilon_{\alpha\rho\mu\nu} \tilde{R}_\tau{}^{\rho\mu\nu} S^\gamma t^{\alpha\tau}{}_\gamma + h_{21} \varepsilon_{\alpha\rho\mu\nu} \tilde{R}_\tau{}^{\rho\mu\nu} S^\gamma t_\gamma{}^{\alpha\tau}$$
$$+ h_{22} \varepsilon_{\alpha\rho}{}^{\mu\nu} \tilde{R}^\rho{}_{\mu\tau\nu} S^\gamma t_\gamma{}^{\alpha\tau} + h_{23} \varepsilon_{\alpha\rho}{}^{\mu\nu} \tilde{R}_{\gamma\mu\tau\nu} S^\alpha t^{\gamma\rho\tau}$$
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[2] S. Bahamonde and J. Gigante Valcarcel, Phys. Rev. D **109** (2024) no.10, 10

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- We showed that by including these Poincare gauge invariants, ghost issue is solved!

Spherically symmetric black holes

- Explicit symmetries on the metric, torsion and nonmetricity tensors:

$$\mathcal{L}_\xi g_{\mu\nu} = \mathcal{L}_\xi T^\lambda{}_{\mu\nu} = 0 \implies \mathcal{L}_\xi \tilde{R}^\lambda{}_{\rho\mu\nu} = 0\,.$$

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- Static and spherically symmetric space-times:

$$\#10 \to \#2 \left\{ ds^2 = \Psi_1(r)\, dt^2 - \frac{dr^2}{\Psi_2(r)} - r^2 \left(d\vartheta^2 + \sin^2\vartheta d\varphi^2 \right) \,;\right.$$

$$\#24 \to \#8 \left\{ \begin{array}{lll} T^t{}_{tr} & T^r{}_{tr} & T^\vartheta{}_{t\vartheta} \\ T^\vartheta{}_{r\vartheta} & T^\vartheta{}_{t\varphi} & T^\vartheta{}_{r\varphi} \\ T^t{}_{\vartheta\varphi} & T^r{}_{\vartheta\varphi} & \end{array} \right.$$

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- First one needs to solve the connection eqs (8 eqs+8 dof of torsion) and then the metric eqs (2 eqs+2 dof).

- By solving the equations in Cubic Poincare we find and exact BH solution:

$$T^t{}_{tr} = \frac{\Psi'(r)}{2\Psi(r)} + \frac{wr}{\Psi(r)}, \quad T^r{}_{tr} = T^t{}_{tr}\Psi(r),$$

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$$T^t{}_{\vartheta\varphi} = \frac{N_2\kappa_s r}{\Psi(r)}\sin\vartheta, \quad T^r{}_{\vartheta\varphi} = T^t{}_{\vartheta\varphi}\Psi(r),$$

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Reissner-Nordström-like black holes in Cubic Poincare

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$$\Psi = 1 - \frac{2m}{r} + (2N_1 - N_2)(N_1 + N_2)\left[\frac{2N_1 + N_2}{4N_1 + N_2}d_1 + 2h_{25}\right]\frac{\kappa_{\rm s}^2}{3r^2}.$$

Reissner-Nordström-like black holes in Cubic Poincare

- By solving the equations in Cubic Poincare we find and exact BH solution:

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- This solution has a dynamical torsion with its spin-2 part being massive and is related to the constant w.

Electrodynamics coupled with torsion

- Let us consider a theory with couplings between the electromagnetic field strength $F_{\mu\nu} = \partial_{[\mu}A_{\nu]}$ and $\tilde{R}^{\lambda}{}_{\rho\mu\nu}$:

$$\mathcal{L} = -R - 4k_1 F_{\mu\nu}F^{\mu\nu} + k_2 \tilde{R}^2 + k_3 F^{\mu\nu}\tilde{R}_{\mu\nu}.$$

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- With the following metric and electric potential

$$\Psi(r) = 1 - \frac{2m}{r} + \frac{k_1 q^2}{r^2} - \frac{k_3 \kappa_s q}{4r^2} - \frac{k_3^2 q^2}{128 k_2 r^2},$$

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- Different charges would give rise to different phenomenology.

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4. We expect that the spin charge might be important in certain astrophysical scenarios such as: highly magnetized neutron stars; supermassive black holes with endowed spin.

Axially symmetric black holes

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- In spherical symmetry we obtained RN, but in axial symmetry we expect to have an extension of Kerr-Newman with new interactions between κ_s (intrinsic spin) and macroscropic spin a.

Axially symmetric black holes - spin orbit interaction

Spin-Orbit Interaction in Atomic Physics

The spin-orbit interaction is a fundamental quantum mechanical effect that describes how an electron's intrinsic spin interacts with its orbital motion around the nucleus. This interaction leads to energy level splitting in atoms, particularly noticeable in heavy elements.

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- The spin-orbit interaction increases the energy gap between certain nuclear energy levels, making nuclei with magic numbers more stable.

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- We just found a solution of the 24 connection equations in the non-dynamical sector with $F_1(r)$
- We are now trying to find the dynamical part as well.

Conclusions

- It is possible to construct a Gauge approach of gravity that includes torsion and the invariants are restricted to be invariant under the Poincare group.

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- Quadratic Poincare gauge gravity contains ghosts but we cure this issue with cubic interactions of the form $\tilde{R}TT$.

- We found new exact spherically symmetric solutions with dynamical torsion with a charge (intrinsic spin) that enters the metric as RN.

- We are now investigating axial symmetry where we observe the emergence of a potentially new physical interaction within our theory: a gravitational spin-orbit coupling $a\kappa_s$.

Thank You for Listening!

Questions? Comments?