

# Black Holes in Metric-Affine Gravity and Gravitational Spin–Orbit Interaction

Sebastián Bahamonde

Senior Research Fellow at Institute for Basic Science, Daejeon, South Korea.  
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Jointly with Jorge Gigante Valcarcel

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- 1 Metric-Affine gravity and Gauge approach with Cubic interactions
- 2 Black holes with torsion and nonmetricity
  - Spherically symmetric black holes
  - Axially symmetric black holes
- 3 Conclusions

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- MAG extends GR to include more general geometric structures, enabling richer interactions with matter (e.g., spin, microstructure).

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- Curvatures and field strengths:

$$\begin{aligned} G_{ab\mu} &= \partial_\mu g_{ab} - g_{ac} \omega^c{}_{b\mu} - g_{bc} \omega^c{}_{a\mu} = g_{ac} g_{bd} e^{c\lambda} e^{d\rho} Q_{\mu\lambda\rho}, \\ F^a{}_{\mu\nu} &= \partial_\mu e^a{}_\nu - \partial_\nu e^a{}_\mu + \omega^a{}_{b\mu} e^b{}_\nu - \omega^a{}_{b\nu} e^b{}_\mu = e^a{}_\lambda T^\lambda{}_{\nu\mu}, \\ F^a{}_{b\mu\nu} &= \partial_\mu \omega^a{}_{b\nu} - \partial_\nu \omega^a{}_{b\mu} + \omega^a{}_{c\mu} \omega^c{}_{b\nu} - \omega^a{}_{c\nu} \omega^c{}_{b\mu} = g_{bc} e^a{}_\lambda e^{c\rho} \tilde{R}^\lambda{}_{\rho\mu\nu}. \end{aligned}$$

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- When nonmetricity is vanishing, the group becomes the Poincaré group  $\implies$  Poincaré gauge theories of gravity (PG).

# Dynamics in MAG gauge theories

- Gravitational action with dynamical torsion and nonmetricity

$$S = \int d^4x \sqrt{-g} \left[ \mathcal{L}_m - \frac{1}{16\pi} \mathcal{L}_g(\tilde{\mathcal{R}}, \mathcal{T}, \mathcal{Q}) \right].$$

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- Intrinsic Shears** term  ${}^{(sh)}\Delta_{(\mu\nu)\lambda}$ : source of **traceless nonmetricity**

# Quadratic Poincaré gauge theory - ghost issue

- Convenient to decompose torsion as

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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:

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

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- It is not possible to have a stable propagating torsion tensor with propagating vectors in quadratic Poincaré gauge theory for general backgrounds. Kinetic part of vectors  $T_\mu$  and  $S_\mu$  propagate a ghost.

# Cubic Poincaré gauge theory

- Cubic parity preserving branch with mixing terms: (S. Bahamonde and J. Gigante Valcarcel,

Phys. Rev. D **109** (2024) no.10, 10)

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

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

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

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

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- We showed that by including these Poincaré gauge invariants, ghost issue in the vector sector is solved!

# Spherically symmetric spacetimes

- Explicit symmetries on the metric and torsion tensors:

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

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- Static and spherically symmetric space-times:

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

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

$$\#40 \rightarrow \#12 \left\{ \begin{array}{ccc} Q_{ttt} & Q_{trr} & Q_{ttr} \\ Q_{t\vartheta\vartheta} & Q_{rtt} & Q_{rrr} \\ Q_{rtr} & Q_{r\vartheta\vartheta} & Q_{\vartheta t\vartheta} \\ Q_{\vartheta r\vartheta} & Q_{\vartheta t\varphi} & Q_{\vartheta r\varphi} \end{array} \right.$$

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## Spin-Orbit Interaction in Atomic Physics

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- Nuclear Physics: 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 focused on a degenerate model of cubic PG theory, which provides static and spherically symmetric solutions with a spin charge that does not affect the Schwarzschild geometry

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- The form of torsion contains 24 dof being non-zero.
- Is it possible to find a solution in the non-degenerate theory and find a modified Kerr metric with interactions between  $\kappa_s$  and  $a$  in the metric?

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- The arbitrary function  $G(r, \vartheta)$  is encoded solely in the axial mode of the torsion tensor of the solution.
- Therefore, trajectories of Dirac particles minimally coupled to torsion will accordingly experience deviations from the geodesic motion, which can already be measured in the semiclassical limit by an acceleration of the form:

$$u^\lambda \nabla_\lambda u_\mu = \frac{1}{4m_s} \hat{R}_{\lambda\rho\mu\nu} \bar{b}_0 \sigma^{\lambda\rho} b_0 u^\nu,$$

where  $u_\mu$  represents the four-velocity of the particle,  $b_0$  its normalised state,  $m_s$  its mass,  $\sigma^{\lambda\rho}$  the spin matrices and  $\hat{R}_{\lambda\rho\mu\nu}$  the part of the Riemann-Cartan curvature tensor that includes corrections from the axial mode alone.

# Conclusions

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# Conclusions

- **Gauge gravity** with propagating  $T$  and  $Q$  can be formulated **without known ghosts** via **Cubic** interactions in axial/vector sectors.
- **New black hole solutions** with all **intrinsic properties of matter** behaving as RN with the charges being related to the dynamical torsion and nonmetricity.
- In Cubic Poincaré: we found a slowly rotating Kerr-like BH with **gravitational spin-orbit interaction** that is the analogue version of the atomic physics spin-orbit interaction.