Rethinking Gravity: From Torsion and Nonmetricity to Black Holes and Cosmology

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Outline

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Why modify gravity from geometry?

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Conceptual motivations

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Guiding idea

General Relativity ties gravity to spacetime geometry, so changing the geometric structure is a direct route to new gravitational physics.

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- Then spacetime can carry curvature, torsion and nonmetricity as independent geometric structures.

Curvature, torsion and nonmetricity

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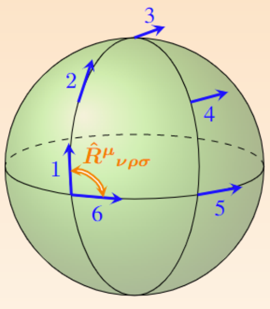
Curvature R



Directions change after transport around a loop.
96 independent components.

$$\tilde{R}^{\lambda}{}_{\rho\mu\nu} = 2\partial_{[\mu}\tilde{\Gamma}^{\lambda}{}_{|\rho|\nu]} + 2\tilde{\Gamma}^{\lambda}{}_{\sigma[\mu}\tilde{\Gamma}^{\sigma}{}_{|\rho|\nu]}$$

Curvature, torsion and nonmetricity

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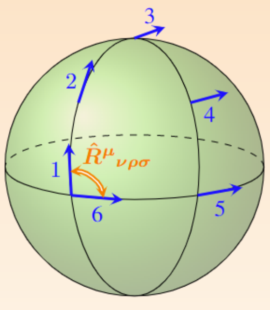

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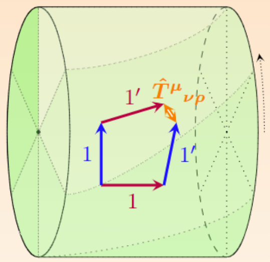
Torsion T



Infinitesimal parallelograms fail to close.
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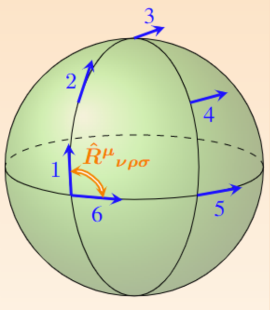

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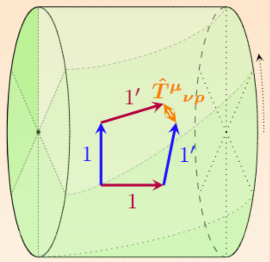

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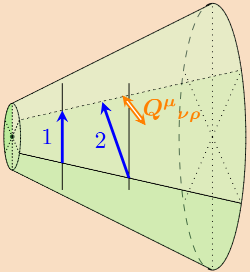
Nonmetricity Q



Lengths and angles change under transport.
40 independent components.
$Q_{\lambda\mu\nu} = \tilde{\nabla}_{\lambda} g_{\mu\nu}$

This talk focuses on geometries where R, T, and Q can participate in the dynamics.

Post-Riemannian decomposition

- It is useful to separate the connection as

$$\tilde{\Gamma}^{\lambda}{}_{\mu\nu} = \Gamma^{\lambda}{}_{\mu\nu} + N^{\lambda}{}_{\mu\nu}\,,$$

with

$$N^{\lambda}{}_{\mu\nu} = K^{\lambda}{}_{\mu\nu} + L^{\lambda}{}_{\mu\nu}\,,$$

where K is built from torsion and L from nonmetricity (linear combination).

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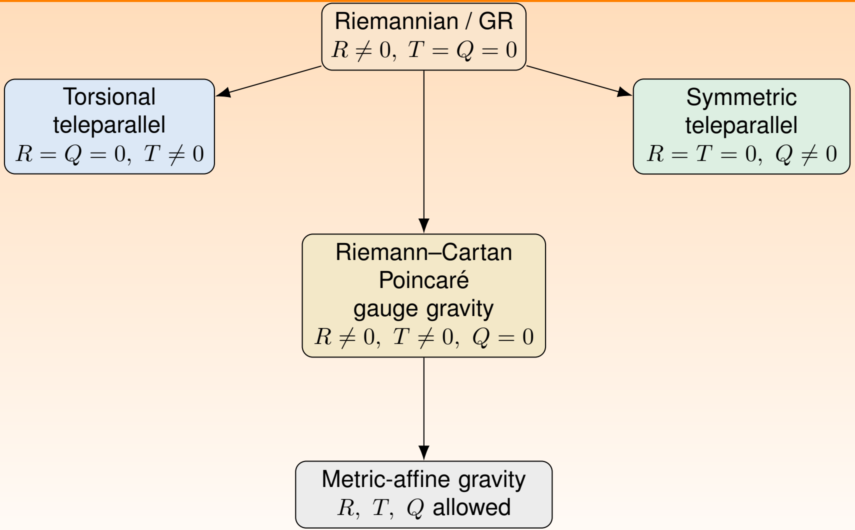
- Therefore modified gravity from geometry appears as extra terms in the connection itself.

Different extended geometries give different types of gravitational theories



S. Bahamonde, K. F. Dialektopoulos, C. Escamilla-Rivera, G. Farrugia, V. Gakis, M. Hendry, M. Hohmann, J. Levi Said, J. Mifsud and E. Di Valentino, Rep. Prog.

Poincaré gauge gravity and metric-affine gravity

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- Therefore MAG allows, in general:

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Dynamics in MAG gauge theories

- A broad class of theories has

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

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Quadratic Poincaré gauge theory - ghost issue

- The most general class of quadratic Poincaré gauge theory (parity preserving) is

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  2. Effectively 2 extra scalar fields+ torsional masses (degenerate vector theory): (Holst)

$$\mathcal{L}_2 = \frac{M_{\rm pl}^2}{2}\tilde{R} + \alpha(\varepsilon_{\rho\lambda\mu\nu}\tilde{R}^{\rho\lambda\mu\nu})^2 + C_1 T_{\rho\mu\nu}T^{\rho\mu\nu} + C_2 T_{\rho\mu\nu}T^{\nu\rho\mu} + C_3 T^{\rho}{}_{\rho\mu}T^{\lambda}{}_{\lambda}{}^{\mu}$$

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Relax some of the standard assumptions, for example:

1. Break Poincaré gauge approach and consider torsion more like ”EFT”: $(\nabla T)^2, R\nabla T...$
2. Consider Cubic Poincaré gauge gravity. (cubic in field strength tensors)

Cubic Poincaré gauge theory

- Torsion decomposes into vector, axial vector and tensor pieces:

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

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- Cubic parity preserving branch with mixing terms (26 h_i): (S. Bahamonde and J. Gigante Valcarcel, Phys. Rev. D **109** (2024) no.10, 10)

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

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- We showed that by including these Poincaré gauge invariants, ghost issue in the vector sector is solved!
- One can generalise it with nonmetricity as well (S. Bahamonde and J. Gigante Valcarcel, Phys. Rev. D **111** (2025) no.8, 084058)

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Take-home message

Once the connection becomes dynamical, geometry can carry new modes, new charges, and new observational signatures.

Outline

Riemann–Cartan background cosmology

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- These background torsion modes can modify the Friedmann equations and model:
  - non-singular bouncing cosmologies;
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  - inflationary scenarios, including Einstein–Cartan-Higgs models.
- The next step is perturbations for Cubic Poincare (extra massive spin-2 appears): extra geometry must propagate consistently.

Cosmology in MAG

- Let us assume that the metric, torsion and nonmetricity have the same cosmological symmetries (isotropy and homogeneity)
$$\mathcal{L}_\xi \bar{g}_{\mu\nu} = \mathcal{L}_\xi \bar{T}^\lambda{}_{\mu\nu} = \mathcal{L}_\xi \bar{Q}^\lambda{}_{\mu\nu} = 0\,.$$

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$$\mathcal{L}_\xi \bar{g}_{\mu\nu} = \mathcal{L}_\xi \bar{T}^\lambda{}_{\mu\nu} = \mathcal{L}_\xi \bar{Q}^\lambda{}_{\mu\nu} = 0\,.$$
- Solving these symmetry conditions gives the FLRW metric and the most general homogeneous and isotropic torsion and nonmetricity tensors:

$$\begin{aligned}
\bar{g} &= -\bar{n}_\mu \bar{n}_\nu \mathrm{d}x^\mu \otimes \mathrm{d}x^\nu + \bar{P}_{\mu\nu}\mathrm{d}x^\mu \otimes \mathrm{d}x^\nu = -N^2 \mathrm{d}t \otimes \mathrm{d}t + a^2 \gamma_{ij} \mathrm{d}x^i \otimes \mathrm{d}x^j\,,\\
\bar{T}^\lambda{}_{\mu\nu} &= 2T_1(t)\,\bar{n}_{[\mu}\bar{P}_{\nu]}{}^\lambda + 2T_2(t)\,\bar{\varepsilon}^\lambda{}_{\mu\nu\rho}\bar{n}^\rho\,,\\
\bar{Q}_{\lambda\mu\nu} &= 2Q_1(t)\bar{n}_\lambda \bar{n}_\mu \bar{n}_\nu + 2Q_2(t)\bar{n}_\lambda \bar{P}_{\mu\nu} + 2Q_3(t)\bar{P}_{\lambda(\mu}\bar{n}_{\nu)}\,,
\end{aligned}$$

where $\gamma_{ij}\mathrm{d}x^i \otimes \mathrm{d}x^j = \frac{\mathrm{d}r^2}{1-Kr^2} + r^2 \mathrm{d}\Omega^2$. Note that there are 5 independent functions coming from Post-Riemannian.

SVT decomposition around FLRW

- FLRW preserves spatial rotations, so perturbations are organised by spin and parity.

K. Aoki, S. Bahamonde, J. Gigante Valcárcel and M. A. Gorji, Phys. Rev. D **110**, 024050 (2024).

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$$\delta t_{\rho\mu\nu} \longrightarrow A_{ij}^{(\mathrm{TT},+)}, \qquad \mathcal{A}_{ij}^{(\mathrm{TT},-)} .$$

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- Nonmetricity is even richer:

$$\delta Q_{\lambda\mu\nu} \longrightarrow 0^{\pm}, 1^{\pm}, 2^{\pm}, 3^{+} .$$

K. Aoki, S. Bahamonde, J. Gigante Valcárcel and M. A. Gorji, Phys. Rev. D **110**, 024050 (2024).

Extra massive spin-2 mode in cubic Poincaré gauge gravity

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After SVT, isolate the torsional helicity-2 sector. The post-Riemannian theory reads:

$$\mathcal{L} = \frac{M_{\rm pl}^2}{2} R + \frac{\alpha}{2} R^2 + \frac{\beta}{2} W_{\mu\nu\rho\sigma} W^{\mu\nu\rho\sigma} + 2\beta R_{\mu\nu} \nabla_\rho t^{\mu\nu\rho} + \beta \nabla_\rho t^{\mu\nu\rho} \nabla^\sigma t_{\mu\nu\sigma} + (q_5 + \frac{1}{2} q_6) \nabla_\mu t^{\mu\nu\lambda} \nabla_\rho t^\rho{}_{\nu\lambda}$$
$$+ \frac{1}{2}\gamma\, {M_T}^2 t_{\mu\nu\rho} t^{\mu\nu\rho} - 2(b_1 - \beta) R^{\mu\rho\lambda\sigma} t_\mu{}^\nu{}_\lambda t_{\rho\nu\sigma} - 4(\beta - b_2) R^{\mu\sigma\lambda\rho} t_\mu{}^\nu{}_\lambda t_{\rho\nu\sigma} - 2(\beta - b_3) R_{\mu\nu} t_\lambda{}^\nu{}_\rho t^{\lambda\mu\rho}$$
$$+ b_4 R_{\mu\nu} t^\mu{}_{\lambda\rho} t^{\lambda\nu\rho} + \frac{1}{2}(b_5 + \alpha - \frac{1}{3}\beta) R t_{\mu\nu\lambda} t^{\mu\nu\lambda}.$$

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Around Minkowski, the torsional sector mixes with the Weyl-squared spin-2 mode and can remove the usual massive spin-2 ghost, leaving an additional healthy massive spin-2 excitation.

K. Aoki and S. Mukohyama, Phys. Rev. D **100**, 064061 (2019).

Quadratic Action for helicity-2 sector

- Following SVT as explained before, $\delta t_{\rho\mu\nu} \to A_{ij}, \mathcal{A}_{ij}$ and $\delta g_{\mu\nu} \to h_{ij}$.

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$$\mathcal{L}_T = f_R\left(h'_{ij}h'^{ij} - \partial_k h_{ij}\partial^k h^{ij}\right) + \beta\big(X'_{ij} - \frac{1}{2}D_- h_{ij}\big)^2 - X_{ij}X^{ij}\big(f_T + (c_1 - c_3 - \beta)\mathcal{H}' + (c_3-\beta)\mathcal{H}^2\big)$$
$$+ \beta\mathcal{H}X^{ij}(D_+ h_{ij}) + \partial^2 Y^{ij}\left[\beta\left(\frac{1}{4}\partial^2 Y_{ij} + \frac{1}{2}Dh_{ij} - \frac{1}{a}(aX_{ij})'\right) - \frac{1}{4}Y_{ij}\big(f_T + (c_1 - c_2 - 2\beta)\mathcal{H}' + c_2\mathcal{H}^2\big)\right].$$

with

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- No Ostrogradsky ghosts in Minkowski and additional massive spin-2.

arXiv:2026XXXX, Sebastian Bahamonde, Matteo Magi, Jorge Gigante Varcarcel.

Stability region and tensor sound speeds

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- The theory can be stable, but tensor propagation is very different from GR.

What effects can this extra spin-2 mode produce?

- The phenomenological question is: what happens when the graviton mixes with an extra massive tensor?

$$S = \frac{1}{2}\int \mathrm{d}^3x\mathrm{d}\tau\, a^2\left[(\gamma'_{ij})^2 - (\partial_i\gamma_{jk})^2\right]$$
$$+ \frac{1}{2}\int \mathrm{d}^3x\mathrm{d}\tau\, a^2 f^2\left[(t'_{ij})^2 - c_t^2(\partial_i t_{jk})^2 - m_t^2 t_{ij}^2\right]$$
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J. Garriga, M. A. Gorji, F. Hajkarim and M. Sasaki, arXiv:2508.08481.

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- This can produce oscillatory or scale-dependent features in the tensor power spectrum.

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- These intrinsic charges can survive in the exterior geometry.

Reissner–Nordström-like black holes

Exact static solution

In cubic metric-affine gravity with torsion and nonmetricity, one finds an exact static, spherically symmetric black-hole solution (S. Bahamonde and J. Gigante Valcarcel, Phys. Rev. D **111** (2025) 084058),

$$ds^2 = \Psi(r)\, dt^2 - \frac{dr^2}{\Psi(r)} - r^2 d\Omega^2, \qquad \Psi(r) = 1 - \frac{2m}{r} + \frac{\mathcal{Q}_{\rm geom}}{r^2}.$$

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Why it is interesting

The metric looks like Reissner–Nordström, but the extra $1/r^2$ term is not an electric charge. It comes from intrinsic geometric charges carried by torsion and nonmetricity,

$$\mathcal{Q}_{\rm geom} = H_1\kappa_{\rm s}^2 + H_2\kappa_{\rm d}^2 + H_3\kappa_{\rm sh}^2.$$

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Physical message

A familiar black-hole metric can therefore hide genuinely new geometric hair. For suitable signs of the constants H_i, one also finds a branch without an inner Cauchy horizon.

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Physical point

These charges are integration constants of the exterior geometry. GR has no direct analogue, because standard GR couples matter only through energy–momentum.

From atomic spin-orbit coupling to gravity

- In atomic systems, orbital motion couples to intrinsic spin and produces a spin-orbit interaction:

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- In Poincaré gravity, axial symmetry activates the full torsion sector, so an exact slowly rotating solution is highly non-trivial.
- The result is a gravitational analogue of spin-orbit coupling, but with a purely geometric origin.

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Exact slowly rotating solution

We found an **exact slowly rotating Kerr-like black-hole solution** with non-trivial dynamical torsion:

$$ds^2 = \Psi(r)dt^2 - \frac{dr^2}{\Psi(r)} - r^2 d\vartheta^2 - r^2 \sin^2\vartheta\, d\phi^2 + 2a\big(1 - \Psi(r)\big)\sin^2\vartheta\, dt\, d\phi, \qquad \Psi(r) = 1 - \frac{2m}{r}.$$

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New torsion-induced interaction

Schematically, the solution contains

$$\mathcal{L}_{\rm eff} = \underbrace{\frac{d_1 N_1^2 \kappa_{\rm s}^2}{8\pi r^4}}_{\text{static spin charge}} + \underbrace{\frac{d_1 N_1 a\kappa_{\rm s}}{2\pi} F(r,\vartheta)}_{\text{new } a\kappa_{\rm s} \text{ term}}.$$

Here the same function $F(r,\vartheta)$ that appears in the axial torsion controls the new interaction.

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The key new effect is a purely torsion-induced coupling between black-hole rotation a and intrinsic spin charge $\kappa_{\rm s}$: a gravitational spin–orbit interaction.

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Energy extraction without torsion: the Kerr reference case

- For a rotating black hole, the near-horizon frequency is shifted by the horizon angular velocity:

$$\tilde{\omega} = \omega - k\Omega_H, \qquad \Omega_H \simeq \frac{a}{2mr_h}.$$

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- For standard Dirac fermions in Kerr, there is no ordinary classical superradiance.
- Fermions do not give the usual bosonic amplification mechanism.
- The question is whether torsion can modify the near-horizon fermionic energy balance.

Dirac fermion with axial torsion

Adding torsion to the fermionic problem

To test whether torsion can modify the Kerr energy balance, we now consider a minimally coupled Dirac field. Only the axial torsion mode enters:

$$\gamma^\mu \nabla_\mu \psi - \frac{i}{4}\gamma^5 \gamma^\mu S_\mu \psi + i\mu\psi = 0.$$

Thus fermions couple to axial part of torsion S_μ, not the full torsion tensor. This change parity!

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Near-horizon data

Requiring separability fixes the angular structure of the axial mode,

$$F(r,\vartheta) = \frac{3-4\Psi(r)}{6r\Psi(r)}\cos\vartheta + \frac{f(r)}{r}.$$

The near-horizon splitting is therefore controlled by

$$\kappa_{\rm s}\ \text{(intrinsic spin)}, \qquad f(r_h)\ \text{(arbitrary function related to grav spin-orbit interaction)}.$$

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Chiral splitting and fermionic energy extraction

- Near the horizon, the two fermionic helicities see different effective frequencies:

$$\Omega_\pm = \omega - k\Omega_H \pm \Delta_T, \qquad \Omega_H \simeq \frac{a}{2mr_h},$$

with the torsion-induced splitting

$$\Delta_T = \frac{3}{r_h}\left(N_1\kappa_{\rm s} - \frac{a}{m}f(r_h)\right).$$

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- This gives a fermionic-superradiance-like effect: energy can be extracted, while the particle number flux remains positive,

$$\frac{dN}{dt} \approx \frac{1}{4}\left(|A_3|^2 + |A_2|^2\right) > 0.$$

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Axial torsion enables helicity-dependent fermionic energy extraction.

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Main conclusions

- Enlarging the geometry of spacetime gives a controlled way to go beyond GR:

$$\Gamma^{\lambda}{}_{\mu\nu} \longrightarrow \tilde{\Gamma}^{\lambda}{}_{\mu\nu}, \qquad R,\ T\,\text{torsion},\ Q\,\text{nonmetricity}.$$

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- Rotation plus torsion gives a new grav spin–orbit-type effect and can split the two fermionic helicity sectors near the horizon.

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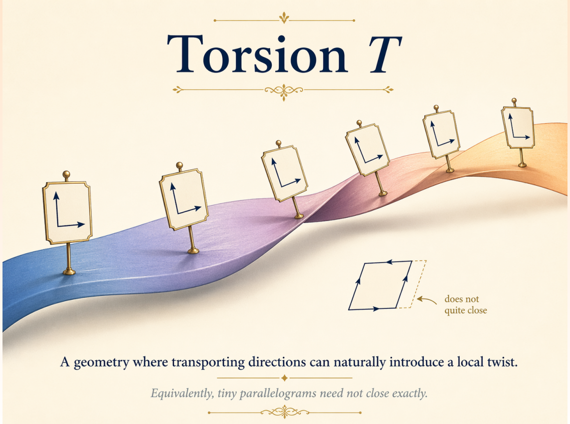

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