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

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Outline

1. Modifying gravity from geometry
2. Black holes with torsion and nonmetricity
3. Cosmology with torsion and nonmetricity

Why modify gravity from geometry?

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Conceptual motivations

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Why modifying GR from geometry?

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

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- The metric tells us distances, clocks and light cones:

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

Curvature, torsion and nonmetricity

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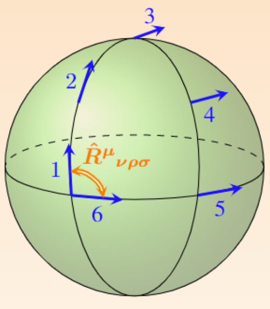
Curvature R



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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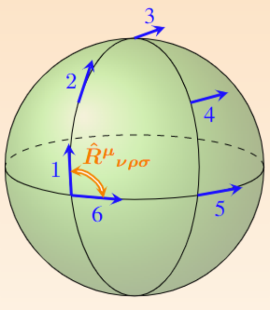

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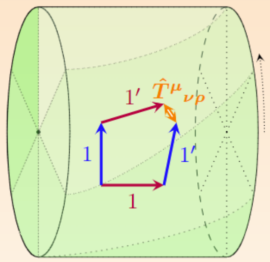
Torsion T



Infinitesimal parallelograms fail to close.
24 independent components.

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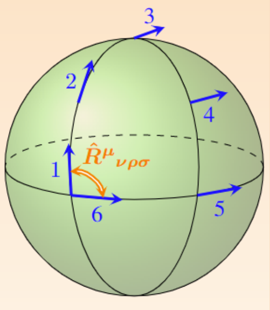

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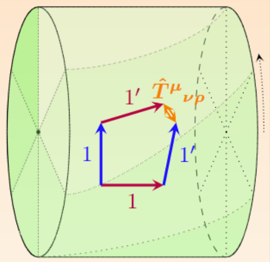

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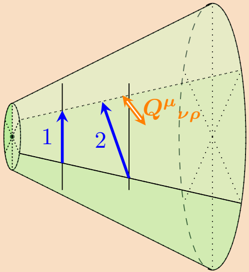
Nonmetricity Q



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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- General decomposition of the curvature tensor:

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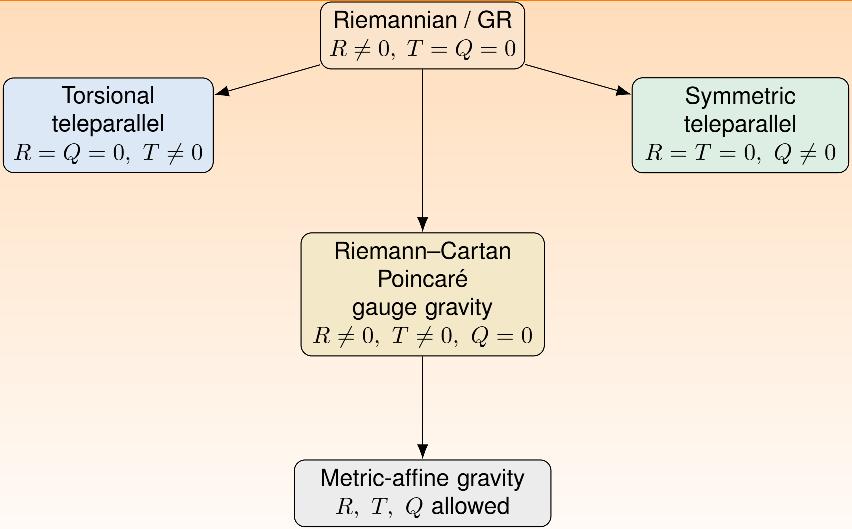
- Therefore modified gravity from geometry appears as extra terms in the connection itself.

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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spin | dilation | shear.
- 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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- Varying with respect to tetrads and spin connection gives the sources

$$\begin{aligned}
\frac{1}{\sqrt{-g}}\frac{\delta\left(\mathcal{L}_g\sqrt{-g}\right)}{\delta e^a{}_\nu} &= 16\pi\theta_a{}^\nu\,, \\
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3. **Intrinsic Shears** term ${}^{(\mathrm{sh})}\Delta_{(\mu\nu)\lambda}$: source of **traceless nonmetricity**

Quadratic Poincaré gauge theory - ghost issue

- The most general parity-preserving quadratic Poincaré gauge theory contains (schematically)

$$\mathcal{L}_{\rm Quad} = \frac{M_{\rm Pl}^2}{2}\tilde{R} + q_i\,\tilde{R}\tilde{R} + C_i\,TT\,,$$

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$$\mathcal{L} \sim \frac{M_{\rm Pl}^2}{2}\tilde{R} + q_1\tilde{R}^2 + q_2\left(\varepsilon_{\rho\lambda\mu\nu}\tilde{R}^{\rho\lambda\mu\nu}\right)^2 + C_iTT,$$

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Is it possible to activate tensor/vector modes without ghosts?

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Answer: not necessarily

The obstruction mainly applies to the most conservative quadratic Poincaré gauge setting. A healthier propagating torsion sector may still be obtained if one goes beyond these assumptions.

Relax some of the standard assumptions, for example:

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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:

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

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- One can generalise it with nonmetricity as well (S. Bahamonde and J. Gigante Valcarcel, Phys. Rev. D **111** (2025) no.8, 084058)
- Our construction can in principle allow additional dynamical torsion/nonmetricity sectors to be activated while remaining ghost-free.

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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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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,

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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.

Algebraic classification of geometric black-hole hair

- **Petrov classification in GR.** In four-dimensional Riemannian geometry,
$$20 = 10_{\mathrm{Weyl}} + 9_{\mathrm{Ricci}_0} + 1_R, \qquad R_{\mu\nu} = 0 \Rightarrow R_{\lambda\rho\mu\nu} = W_{\lambda\rho\mu\nu}.$$
Thus Petrov classification is the classification of the Weyl tensor by principal null directions. Kerr is Type D in vacuum; RN/Kerr–Newman are Weyl Type D in electrovac.

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- **What we classified.** Most irreducible blocks reduce to known algebraic problems:

10-component block: Petrov-type, 9-component blocks: Segre-type, 6-component blocks: two-form type.

The most non-trivial new part is the 30-component block

$${}^{(1)}\tilde{Z}_{\lambda\rho\mu\nu}, \qquad \#({}^{(1)}\tilde{Z}) = 30,$$

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- **Application to our black hole.** The metric can look Reissner–Nordström-like, but the full non-Riemannian curvature can be algebraically different:
$$\kappa_{\mathrm{sh}} \neq 0 \quad \Rightarrow \quad {}^{(1)}\tilde{Z}_{\lambda\rho\mu\nu} \text{ is not Type D, even in spherical symmetry.}$$

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.

A new exact slowly rotating solution with axial torsion

Exact slowly rotating solution

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

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

For the rotating solution, we focus on a branch with $H_i = 0$, so $\kappa_{\rm s}$ does not deform the Schwarzschild metric in the static spherical limit.

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New torsion-induced interaction

The 24 components of torsion are non-zero. Schematically, the solution contains a Lagrangian of the same form as spin-orbit interaction:

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

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

What is black-hole superradiance?

Physical idea

A rotating black hole can transfer part of its rotational energy to an incoming wave. If the wave enters the horizon carrying negative energy, the reflected wave comes out amplified.

For a mode with frequency ω and azimuthal number k, the frequency measured at the horizon is

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Bosonic superradiance

Amplification occurs when the horizon frequency is negative:

$$\tilde{\omega} < 0 \qquad \Longleftrightarrow \qquad 0 < \omega < k\Omega_H \,.$$

Kerr reference case: why fermions are special

Standard Kerr result

In the usual torsion-free Kerr background, standard Dirac fermions do not exhibit ordinary classical superradiant amplification.

W. G. Unruh, Phys. Rev. D **10** (1974) 3194.

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Fermions couple to gravity through the spin connection. In torsion-free GR, this coupling is completely fixed once the metric is fixed. In Poincaré gauge theory, torsion gives an additional gravitational coupling to fermionic spin.

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Can this extra torsional coupling modify the near-horizon fermionic energy flux?

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:

$$\gamma^\mu \nabla_\mu \psi - \underbrace{\frac{i}{4}\gamma^5 \gamma^\mu S_\mu \psi}_{\text{axial torsion coupling}} + i\mu\psi = 0.$$

Thus fermions couple to the axial part of torsion S_μ, not the full torsion tensor. This parity-sensitive coupling distinguishes the two helicity sectors.

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Separability ansatz for torsional part

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

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

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

Axial torsion enables helicity-dependent fermionic energy extraction.

S. Bahamonde and J. Gigante Valcárcel, “Black-hole superradiance in Poincaré gauge theory,” arXiv:2603.19140.

non-Riemannian FLRW cosmology

FLRW symmetry can be imposed not only on the metric, but also on torsion and nonmetricity:

$$\mathcal{L}_\xi \bar{g}_{\mu\nu} = \mathcal{L}_\xi \bar{T}^\lambda{}_{\mu\nu} = \mathcal{L}_\xi \bar{Q}_{\lambda\mu\nu} = 0.$$

The metric takes the usual FLRW form:

$$ds^2 = -N^2 dt^2 + a^2 \gamma_{ij} dx^i dx^j .$$

The most general homogeneous and isotropic torsion and nonmetricity tensors are:

$$\begin{aligned}
\bar{T}^\lambda{}_{\mu\nu} &= 2T_1(t)\bar{n}_{[\mu}\bar{P}_{\nu]}{}^\lambda + 2T_2(t)\bar{\varepsilon}^\lambda{}_{\mu\nu\rho}\bar{n}^\rho ,\\
\bar{Q}_{\lambda\mu\nu} &= 2Q_1(t)\bar{n}_\lambda\bar{n}_\mu\bar{n}_\nu + 2Q_2(t)\bar{n}_\lambda\bar{P}_{\mu\nu} + 2Q_3(t)\bar{P}_{\lambda(\mu}\bar{n}_{\nu)} .
\end{aligned}$$

Message

At the background level, FLRW allows two torsion functions and three nonmetricity functions. Riemann–Cartan cosmology is the subcase with $Q_i = 0$; this is the sector relevant for cubic Poincaré gravity.

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- In the cubic Poincaré model discussed below, we specialise to the Riemann–Cartan sector:

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- In this sector, the tensor part of torsion can propagate as an additional massive spin-2 mode on FLRW.

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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- The torsional helicity-2 pieces are:

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

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

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

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

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

Physical mechanism

The relevant structures are W^2, $R\nabla t$, $(\nabla t)^2$, and Rtt. Together, they make the metric spin-2 mode and the tensor part of torsion combine into a degenerate spin-2 system.

In the healthy branch, the usual Weyl-squared massive ghost is replaced by a massive spin-2 excitation carried by torsion.

This mechanism was already identified around Minkowski in K. Aoki and S. Mukohyama, Phys. Rev. D **100**, 064061 (2019).

Helicity-2 sector on FLRW

On an FLRW background, the tensor perturbations are

$$\delta g_{ij} \to h_{ij}\,, \qquad \delta t_{\rho\mu\nu} \to X_{ij}\,,\, Y_{ij}\,.$$

After using the degeneracy and solving the constraints, the helicity-2 sector reduces schematically to

$$q_\lambda = \begin{pmatrix} h_\lambda \\ \Xi_\lambda \end{pmatrix}, \qquad \mathcal{L}_\lambda = \frac{1}{2} {q'_\lambda}^T \mathcal{K} q'_\lambda + {q'_\lambda}^T \mathcal{M} q_\lambda - \frac{1}{2} q_\lambda^T \mathcal{U} q_\lambda\,.$$

- h_λ: tensor mode continuously connected with the GR graviton.

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Message

On FLRW, the usual graviton and the massive torsional spin-2 mode form a coupled two-tensor system.

Tensor phenomenology from two coupled spin-2 modes

The reduced system is analogous to an EFT of two coupled tensor fields:

$$\gamma_{ij} \quad \longleftrightarrow \quad t_{ij}.$$

$$\begin{aligned} S = &\frac{1}{2}\int \mathrm{d}^3x\mathrm{d}\tau\, a^2\left[(\gamma'_{ij})^2 - (\partial_i\gamma_{jk})^2\right] \\ &+ \frac{1}{2}\int \mathrm{d}^3x\mathrm{d}\tau\, a^2 f^2\left[(t'_{ij})^2 - c_t^2(\partial_i t_{jk})^2 - m_t^2 t_{ij}^2\right] \\ &+ \int \mathrm{d}^3x\mathrm{d}\tau\, a^2\gamma'_{ij}\left(\alpha\mathcal{H}t^{ij} + \kappa t'^{ij}\right). \end{aligned}$$

- The mixing allows the graviton to exchange amplitude and phase with the massive tensor.

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- The mixing allows the graviton to exchange amplitude and phase with the massive tensor.
- This can generate oscillatory or scale-dependent features in the tensor spectrum.

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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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- Torsion gives a new gravitational spin–orbit interaction and can split the two fermionic helicity sectors near the horizon.

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Questions?

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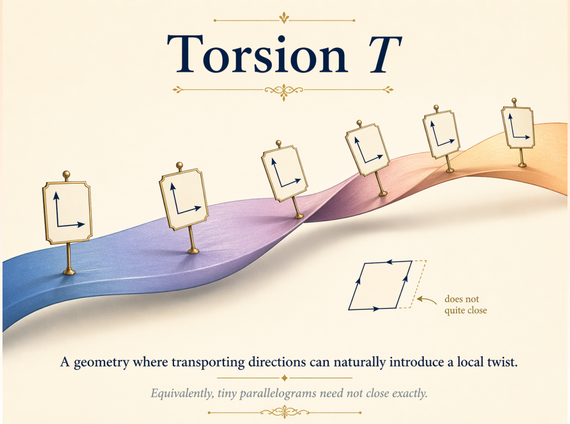

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