Beyond ΛCDM: Teleparallel Gravity
CosmoVerseSchool@Sofia 2026

Vasiliki Karanasou
University of Tartu

Sofia, 25–29 May 2026

Metric affine theories of gravity

[1] 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, Rept. Prog. Phys. **86**, no.2, 026901 (2023)

Metric affine theories of gravity

Metric $g_{\mu\nu}$ and affine connection $\Gamma^{\rho}{}_{\mu\nu}$ [1]

[1] 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, Rept. Prog. Phys. **86**, no.2, 026901 (2023)

Metric affine theories of gravity

Metric $g_{\mu\nu}$ and affine connection $\Gamma^{\rho}{}_{\mu\nu}$ [1]

Curvature

$$R^{\mu}_{\nu\rho\sigma} = \partial_\rho \Gamma^{\mu}_{\nu\sigma} - \partial_\sigma \Gamma^{\mu}_{\nu\rho} + \Gamma^{\mu}_{\tau\rho}\Gamma^{\tau}_{\nu\sigma} - \Gamma^{\mu}_{\tau\sigma}\Gamma^{\tau}_{\nu\rho} \tag{1}$$

[1] 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, Rept. Prog. Phys. **86**, no.2, 026901 (2023)

Metric affine theories of gravity

Metric $g_{\mu\nu}$ and affine connection $\Gamma^{\rho}{}_{\mu\nu}$ [1]

Curvature

$$R^{\mu}{}_{\nu\rho\sigma} = \partial_\rho \Gamma^{\mu}{}_{\nu\sigma} - \partial_\sigma \Gamma^{\mu}{}_{\nu\rho} + \Gamma^{\mu}{}_{\tau\rho}\Gamma^{\tau}{}_{\nu\sigma} - \Gamma^{\mu}{}_{\tau\sigma}\Gamma^{\tau}{}_{\nu\rho} \tag{1}$$

Torsion

$$T^{\mu}{}_{\nu\rho} = \Gamma^{\mu}{}_{\nu\rho} - \Gamma^{\mu}{}_{\rho\nu} \tag{2}$$

[1] 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, Rept. Prog. Phys. **86**, no.2, 026901 (2023)

Metric affine theories of gravity

Metric $g_{\mu\nu}$ and affine connection $\Gamma^{\rho}{}_{\mu\nu}$ [1]

Curvature

$$R^{\mu}{}_{\nu\rho\sigma} = \partial_\rho \Gamma^{\mu}{}_{\nu\sigma} - \partial_\sigma \Gamma^{\mu}{}_{\nu\rho} + \Gamma^{\mu}{}_{\tau\rho}\Gamma^{\tau}{}_{\nu\sigma} - \Gamma^{\mu}{}_{\tau\sigma}\Gamma^{\tau}{}_{\nu\rho} \tag{1}$$

Torsion

$$T^{\mu}{}_{\nu\rho} = \Gamma^{\mu}{}_{\nu\rho} - \Gamma^{\mu}{}_{\rho\nu} \tag{2}$$

Non-metricity

$$Q_{\mu\nu\rho} = \nabla_\mu g_{\nu\rho} = \partial_\mu g_{\nu\rho} - \Gamma^{\sigma}{}_{\nu\mu} g_{\sigma\rho} - \Gamma^{\sigma}{}_{\rho\mu} g_{\nu\sigma} \tag{3}$$

[1] 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, Rept. Prog. Phys. **86**, no.2, 026901 (2023)

Metric $g_{\mu\nu}$ and affine connection $\Gamma^{\rho}{}_{\mu\nu}$ [1]

Curvature

$$R^{\mu}_{\nu\rho\sigma} = \partial_\rho \Gamma^{\mu}_{\nu\sigma} - \partial_\sigma \Gamma^{\mu}_{\nu\rho} + \Gamma^{\mu}_{\tau\rho}\Gamma^{\tau}_{\nu\sigma} - \Gamma^{\mu}_{\tau\sigma}\Gamma^{\tau}_{\nu\rho} \tag{1}$$

Torsion

$$T^{\mu}_{\nu\rho} = \Gamma^{\mu}_{\nu\rho} - \Gamma^{\mu}_{\rho\nu} \tag{2}$$

Non-metricity

$$Q_{\mu\nu\rho} = \nabla_\mu g_{\nu\rho} = \partial_\mu g_{\nu\rho} - \Gamma^{\sigma}_{\nu\mu} g_{\sigma\rho} - \Gamma^{\sigma}_{\rho\mu} g_{\nu\sigma} \tag{3}$$

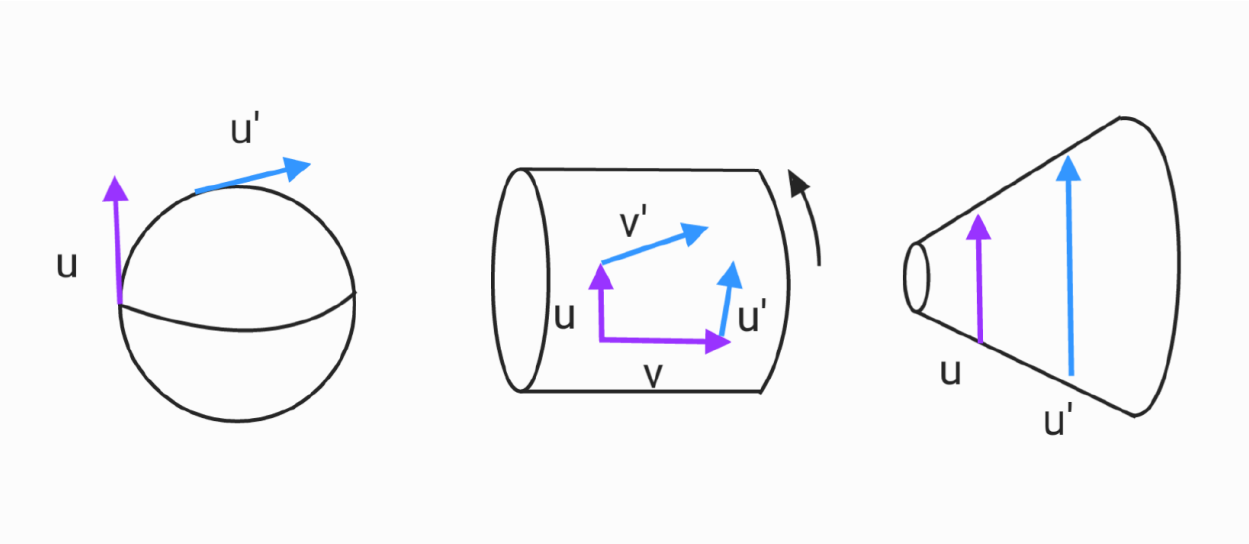

Figure 1: The effect of different geometric quantities.

[1] 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, Rept. Prog. Phys. **86**, no.2, 026901 (2023)

[2] J. Beltrán Jiménez, L. Heisenberg and T. S. Koivisto, Universe 5, no.7, 173 (2019)

Completely equivalent theories [2]:

[2] J. Beltrán Jiménez, L. Heisenberg and T. S. Koivisto, Universe 5, no.7, 173 (2019)

Completely equivalent theories [2]:

General Relativity

$$S_{GR} = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g}\, \mathring{R} \tag{4}$$

[2] J. Beltrán Jiménez, L. Heisenberg and T. S. Koivisto, Universe 5, no.7, 173 (2019)

Completely equivalent theories [2]:

General Relativity

$$S_{GR} = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g}\, \mathring{R} \tag{4}$$

Teleparallel equivalent of GR (TEGR)

$$S_{TEGR} = -\frac{1}{2\kappa^2} \int d^4x \sqrt{-g}\, T \tag{5}$$

[2] J. Beltrán Jiménez, L. Heisenberg and T. S. Koivisto, Universe 5, no.7, 173 (2019)

Completely equivalent theories [2]:

General Relativity

$$S_{GR} = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g}\, \mathring{R} \tag{4}$$

Teleparallel equivalent of GR (TEGR)

$$S_{TEGR} = -\frac{1}{2\kappa^2} \int d^4x \sqrt{-g}\, T \tag{5}$$

Symmetric teleparallel equivalent of GR (STEGR)

$$S_{STEGR} = -\frac{1}{2\kappa^2} \int d^4x \sqrt{-g}\, Q \tag{6}$$

[2] J. Beltrán Jiménez, L. Heisenberg and T. S. Koivisto, Universe 5, no.7, 173 (2019)

What are the effects of modified gravity?

[3] H. Asuküla, M. Hohmann, V. Karanasou, S.Bahamonde, C. Pfeifer and J. L.Rosa, Phys. Rev. D **109**, no.6, 064027 (2024)

[4] M. Hohmann and V. Karanasou, Phys. Rev. D **111**,no.6, 064057 (2025)

What are the effects of modified gravity?

- Exact solutions

[3] H. Asuküla, M. Hohmann, V. Karanasou, S.Bahamonde, C. Pfeifer and J. L.Rosa, Phys. Rev. D **109**, no.6, 064027 (2024)

[4] M. Hohmann and V. Karanasou, Phys. Rev. D **111**,no.6, 064057 (2025)

What are the effects of modified gravity?

- Exact solutions

  Modified black hole solutions [3] or even more exotic objects [4]

[3] H. Asuküla, M. Hohmann, V. Karanasou, S.Bahamonde, C. Pfeifer and J. L.Rosa, Phys. Rev. D **109**, no.6, 064027 (2024)

[4] M. Hohmann and V. Karanasou, Phys. Rev. D **111**,no.6, 064057 (2025)

What are the effects of modified gravity?

- Exact solutions

  Modified black hole solutions [3] or even more exotic objects [4]

  Exotic objects might be identified from the gravitational wave signal

[3] H. Asuküla, M. Hohmann, V. Karanasou, S.Bahamonde, C. Pfeifer and J. L.Rosa, Phys. Rev. D **109**, no.6, 064027 (2024)

[4] M. Hohmann and V. Karanasou, Phys. Rev. D **111**,no.6, 064057 (2025)

What are the effects of modified gravity?

- Exact solutions

  Modified black hole solutions [3] or even more exotic objects [4]

  Exotic objects might be identified from the gravitational wave signal

- Cosmology

[3] H. Asuküla, M. Hohmann, V. Karanasou, S.Bahamonde, C. Pfeifer and J. L.Rosa, Phys. Rev. D **109**, no.6, 064027 (2024)

[4] M. Hohmann and V. Karanasou, Phys. Rev. D **111**,no.6, 064057 (2025)

What are the effects of modified gravity?

- Exact solutions

  Modified black hole solutions [3] or even more exotic objects [4]

  Exotic objects might be identified from the gravitational wave signal

- Cosmology

  Dynamical system analysis: Avoidance of Big Bang singularity and alternative cosmological scenarios

[3] H. Asuküla, M. Hohmann, V. Karanasou, S.Bahamonde, C. Pfeifer and J. L.Rosa, Phys. Rev. D **109**, no.6, 064027 (2024)

[4] M. Hohmann and V. Karanasou, Phys. Rev. D **111**,no.6, 064057 (2025)

What are the effects of modified gravity?

- Exact solutions

  Modified black hole solutions [3] or even more exotic objects [4]

  Exotic objects might be identified from the gravitational wave signal

- Cosmology

  Dynamical system analysis: Avoidance of Big Bang singularity and alternative cosmological scenarios

  Role of cosmological constant and dark energy.

[3] H. Asuküla, M. Hohmann, V. Karanasou, S.Bahamonde, C. Pfeifer and J. L.Rosa, Phys. Rev. D **109**, no.6, 064027 (2024)

[4] M. Hohmann and V. Karanasou, Phys. Rev. D **111**,no.6, 064057 (2025)

What are the effects of modified gravity?

- Exact solutions

  Modified black hole solutions [3] or even more exotic objects [4]

  Exotic objects might be identified from the gravitational wave signal

- Cosmology

  Dynamical system analysis: Avoidance of Big Bang singularity and alternative cosmological scenarios

  Role of cosmological constant and dark energy.

  Alleviation of cosmological tensions

[3] H. Asuküla, M. Hohmann, V. Karanasou, S.Bahamonde, C. Pfeifer and J. L.Rosa, Phys. Rev. D **109**, no.6, 064027 (2024)

[4] M. Hohmann and V. Karanasou, Phys. Rev. D **111**,no.6, 064057 (2025)

What are the effects of modified gravity?

- Exact solutions

  Modified black hole solutions [3] or even more exotic objects [4]

  Exotic objects might be identified from the gravitational wave signal

- Cosmology

  Dynamical system analysis: Avoidance of Big Bang singularity and alternative cosmological scenarios

  Role of cosmological constant and dark energy.

  Alleviation of cosmological tensions

THANK YOU!

[3] H. Asuküla, M. Hohmann, V. Karanasou, S.Bahamonde, C. Pfeifer and J. L.Rosa, Phys. Rev. D **109**, no.6, 064027 (2024)

[4] M. Hohmann and V. Karanasou, Phys. Rev. D **111**,no.6, 064057 (2025)