# Affine Gravitational Scenario for Dark Matter Decays

Hemza Azri

Department of Physics, UAEU

5th International Workshop on "Higgs as a Probe of New Physics" 25-27 March 2021, Osaka University, Japan

A talk based on:

H. Azri, A. Jueid, C. Karahan, and S. Nasri, Phys. Rev. D102. 8, 084036 (2020)

# Gravity: Metrical or affine?

- GR is based on the metric tensor which is only of secondary importance: measurements of distances and angles…etc !
- Gravity is a "manifestation" of spacetime curvature, hence, what is needed is the property of parallel displacements of tensors. This is achieved by introducing the concept of connection.
- The SM interactions are written in the framework of gauge field theory where the gauge fields are described by connections (arising through gauge invariance…)
- ✓ Affine spacetime, with its geodesics and no prior concept of metric, provides a very simple and possibly viable description for gravity !

# Affine space structure

- Affine space is endowed with an affine connection from which we construct covariant derivatives:

$$\nabla_\mu A^\alpha = \partial_\mu A^\alpha + \Gamma^\alpha_{\mu\beta} A^\beta$$

- It vanishes locally,

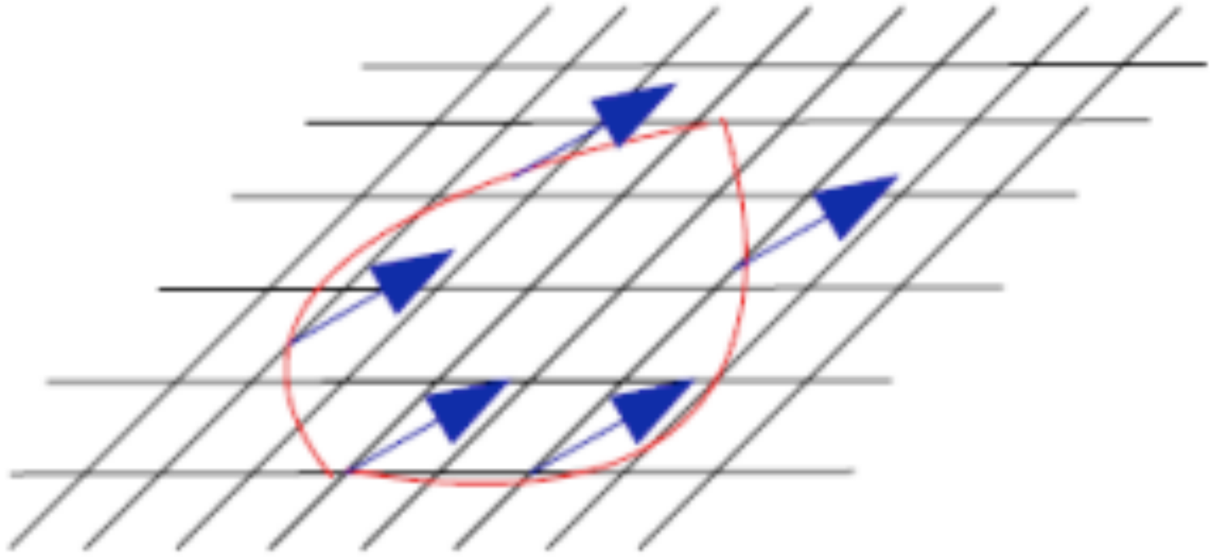
$$\Gamma^\alpha_{\mu\beta}(P) = 0$$

- It transforms as

$$\hat{\Gamma}^\alpha_{\lambda\mu} = \frac{\partial \hat{x}^\alpha}{\partial x^\beta}\frac{\partial x^\sigma}{\partial \hat{x}^\lambda}\frac{\partial x^\tau}{\partial \hat{x}^\mu}\Gamma^\beta_{\sigma\tau} + \frac{\partial^2 x^\beta}{\partial \hat{x}^\lambda \partial \hat{x}^\mu}\frac{\partial \hat{x}^\alpha}{\partial x^\beta}$$

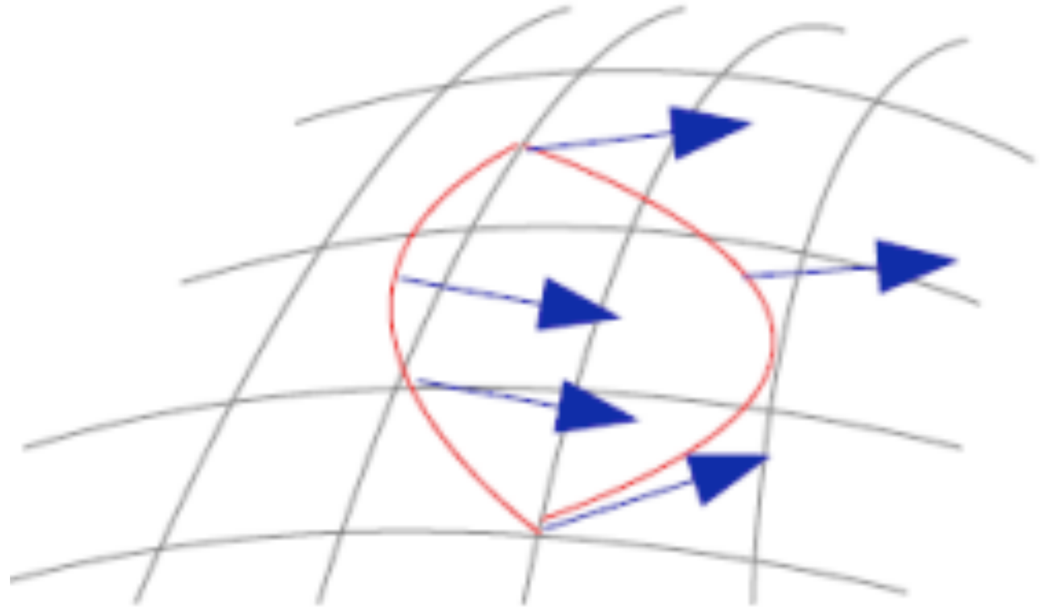
- Curvature can be defined from the "failure" of the commutativity: $[\nabla_\mu, \nabla_\nu]A^\alpha = R^\alpha_{\beta\mu\nu}(\Gamma)A^\beta$

When $\Gamma$ is symmetric



$$\partial_\mu \partial_\nu A^\alpha - \partial_\nu \partial_\mu A^\alpha = 0$$

Flat background



$$\nabla_\mu \nabla_\nu A^\alpha - \nabla_\nu \nabla_\mu A^\alpha \neq 0$$

Curved background

- Gravitational action with the SM fields:
  - This involves Einstein-Hilbert action and the SM Lagrangian

$$S = \int d^4x \sqrt{|g|} \left\{ \frac{M_{Pl}^2}{2} g^{\mu\nu} R_{\mu\nu}(g) + L[g, \mathrm{SM}] \right\}$$

  - The SM Lagrangian is written by simply replacing the flat metric by the general curved metric

$$L[g, \mathrm{SM}] = -g^{\mu\nu}(D_\mu H)^\dagger (D_\nu H) - V(H) - i\bar{\psi} g^{\mu\nu} \gamma_\mu \nabla_\nu \psi - \frac{1}{4} g^{\mu\nu} g^{\alpha\beta} F^a_{\mu\alpha} F^a_{\nu\beta}$$

Higgs Fermions Gauge bosons

- How about dark matter?

Its existence is revealed only through its gravitational influence! → The way it couples to gravity must be very crucial!

- Decoupling dark matter from the metric:

Unlike the SM particle fields, DM may couple only to the spacetime connection!

→ In this case, how to decouple it from the metric?

- From Palatini to purely affine action:

Take the following metric-affine model in which metric and connection are independent fields!

$$\mathscr{L}[\mathscr{I}] = \sqrt{|g|}\left\{\frac{M^2}{2}g^{\mu\nu}R_{\mu\nu}(\Gamma) - \frac{1}{2}g^{\mu\nu}X_{\mu\nu} - U(\mathscr{I})\right\}$$

Kinetic terms!

$$X_{\mu\nu}(\mathcal{I}) = \begin{cases} \nabla_\mu\phi\nabla_\nu\phi & \text{for scalar DM} \\ \bar{\chi}\gamma_\mu\boldsymbol{\nabla}_\nu\chi & \text{for fermionic DM} \\ \frac{1}{2}g^{\alpha\beta}\mathbb{F}_{\alpha\mu}\mathbb{F}_{\beta\nu} & \text{for vector DM} \end{cases}$$

Fermions and vector fields involve metric in their kinetic terms. Scalars do not!

- From Palatini to purely affine action:

Field equations arise from variation with respect to the (non-dynamical) metric

$$\mathscr{L}[\mathscr{I}] = \sqrt{|g|}\left\{\frac{M^2}{2}g^{\mu\nu}R_{\mu\nu}(\Gamma) - \frac{1}{2}g^{\mu\nu}X_{\mu\nu} - U(\mathscr{I})\right\}$$

For scalar DM → $M^2 R_{\mu\nu}(\Gamma) = \nabla_\mu \phi \nabla_\nu \phi + U(\mathscr{I}) g_{\mu\nu}$

Metric arises only through the potential term!

Hence, for nonzero potential, the metric can be easily integrated out!

$$g_{\mu\nu} = \frac{M^2 R_{\mu\nu}(\Gamma) - X_{\mu\nu}(\phi)}{U(\phi)}$$

→ The Scalar DM Lagrangian can be written in terms of the connection and its curvature only! ✓

- If dark matter is to decouple totally from the metric, it can simply be a scalar

$$\mathscr{L}[\Gamma, \mathrm{DM}] = \frac{\sqrt{\left| M^2 R_{\mu\nu}(\Gamma) - \nabla_\mu \phi \nabla_\nu \phi \right|}}{U(\phi)}$$

1. The model describes DM in curved spacetime interacting only with the connection (notice the absence of metric!)

2. Gravitational field equation are obtained by variation w.r.t the connection

This action can also be constructed based only on general covariance consideration!

$$\nabla_\alpha \left\{ \underbrace{\frac{\sqrt{|M^2 R_{\mu\nu}(\Gamma) - \nabla_\mu \phi \nabla_\nu \phi|}}{U(\phi)} \left( [M^2 R(\Gamma) - \nabla\phi\nabla\phi]^{-1} \right)^{\mu\nu}}_{\sqrt{|g|}\, g^{\mu\nu}} \right\} = 0$$

$$M^2 R_{\mu\nu}(\Gamma) = \nabla_\mu \phi \nabla_\nu \phi + U(\mathscr{I}) g_{\mu\nu}$$

Einstein's field equations!

- Nonminimal couplings
  (DM_Curvature interaction)

1. The $Z_2$ symmetry enjoyed by the previous action is broken by an interaction between DM and the affine curvature like $\xi\phi R_{\mu\nu}(\Gamma)$
2. Fields that enjoy a complete structure in purely affine spacetime are scalars, hence, the model can be extended by including the SM-Higgs potential

$$\mathscr{L}[\Gamma, \mathrm{DM}] = \frac{\sqrt{\left| M^2 R_{\mu\nu}(\Gamma) - \nabla_\mu \phi \nabla_\nu \phi + \xi M \phi R_{\mu\nu}(\Gamma) \right|}}{V(\phi, H)}$$

Where $V(\phi, H) \supset U(\phi) + m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$ .

Notice that there is No DM-SM coupling!

- Dark matter decays through the Higgs portal

  - The affine gravitational sector is recast to its canonical form as

$$\mathscr{L}[\Gamma, \mathrm{DM}] = \frac{\sqrt{\left| M^2 R_{\mu\nu}(\Gamma) - \alpha^{-1}(\phi)\nabla_\mu\phi\nabla_\nu\phi \right|}}{\alpha^{-2}(\phi)V(\phi, H)}$$

With the dimensionless parameter $\alpha(\phi) = 1 + \xi\phi/M$

  - As a result, the first order $Z_2$-symmetry breaking term implies DM decays to SM-Higgs through the induced interactions $\alpha^{-2}(\phi)V(\phi, H)$

➡ The interactions are a direct effects of the nonminimal coupling to affine gravity even in the absence of any explicit coupling of DM with SM particles within the potential !

- The resulting Decay modes

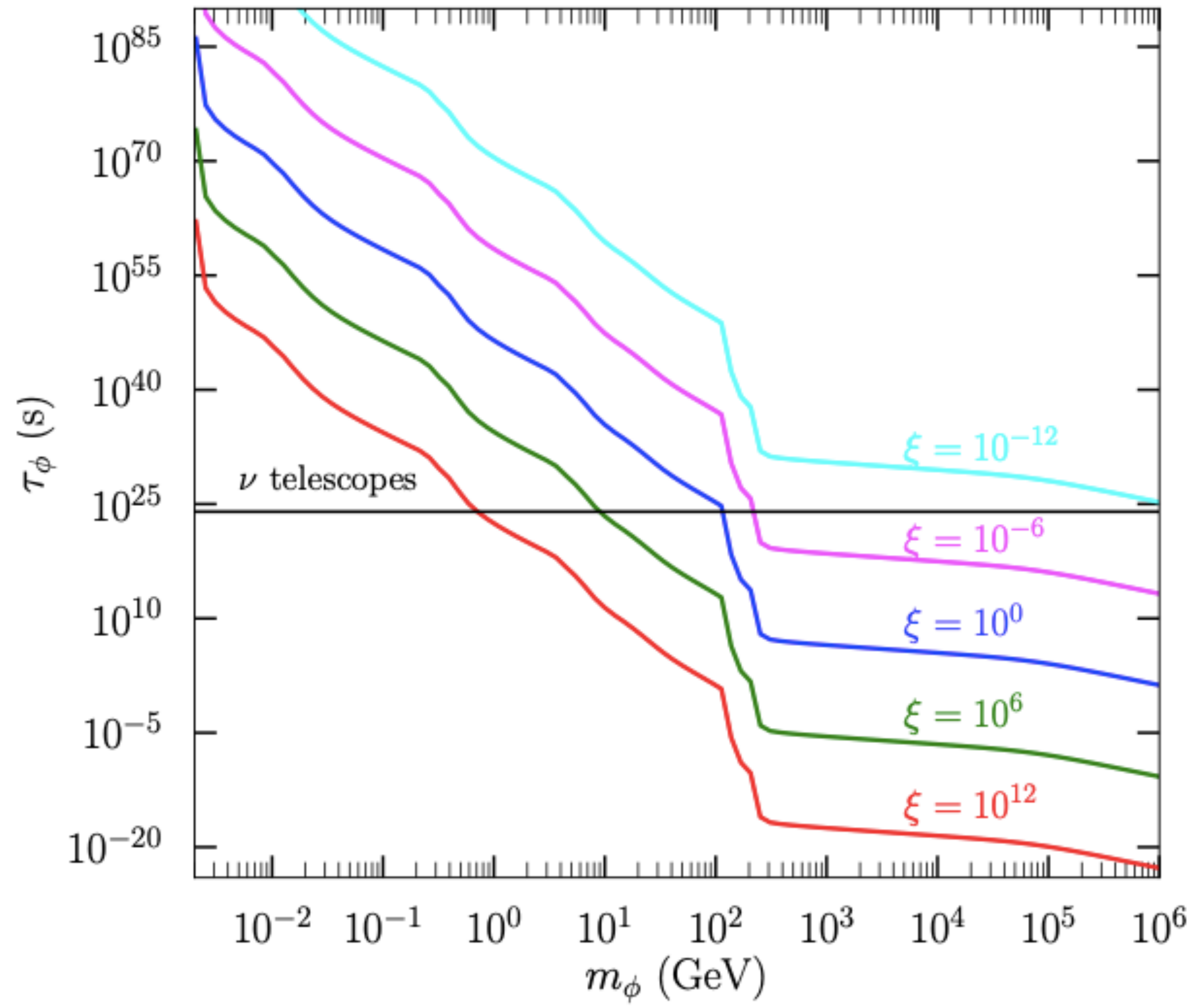
$$\phi \to hh$$

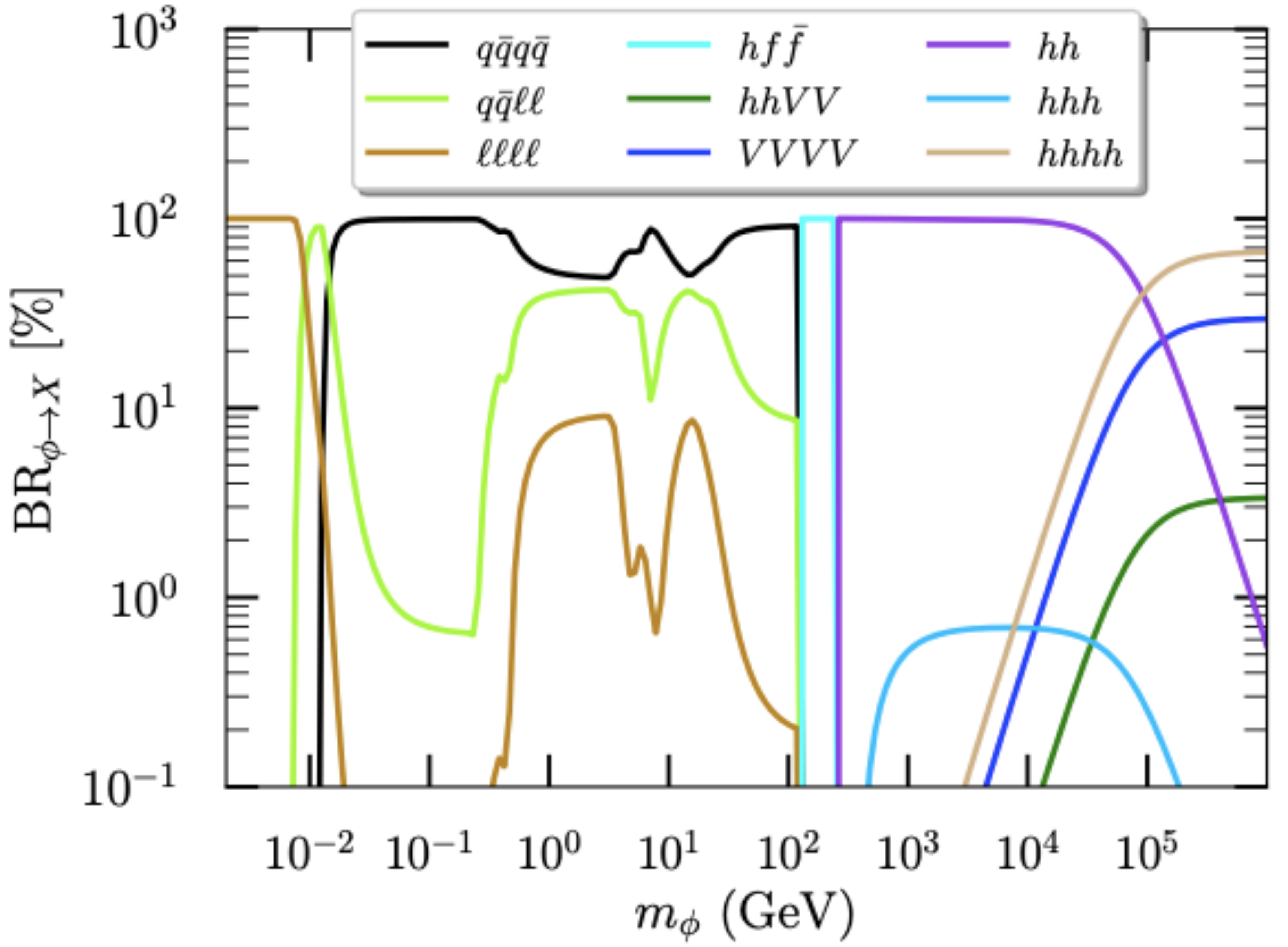
$$\phi \to hh^* \to hf\bar{f}, fVV, hhh$$ Where $V = W^\pm/Z$

$$\phi \to h^*h^* \to VVVV, VVf\bar{f}, VVhh, f\bar{f}f'\bar{f}', f\bar{f}hh, hhhh$$

The decay rates are suppressed by the factor $\xi^2/M^2$, leading to a large enough life time when $M = M_{Pl}$ !

- Relevant DM Mass ranges:
  - $m_\phi \sim 10^{-3} - 125\ GeV$
  - $m_\phi \sim 125 - 250\ GeV$
  - $m_\phi \sim 250 - 10^6\ GeV$



# Conclusion

- We have investigated the possibility that, unlike ordinary matter, DM interacts to gravity through only the affine connection of spacetime!
- We saw that DM decays, automatically, into the SM Higgs via a nonminimal coupling to gravity that breaks the $Z_2$-symmetry! This decay occurs without imposing any prior coupling between the two!
- The present scenario for DM decay is fully gravitational and it stands on a formulation of gravity, different from GR. It is expected to reveal more interesting features of the physics of DM!

# Thank you