Talk prepared for IPPP, 8th of December

How to study modified gravity as a particle theory

and not collapse in the process

Based on arXiv:2211.14300

Sergio Sevillano Muñoz

Durham University

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How t gravity
as a pa
and not


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FeynMG: Automating particle physics calculations in scalar-tensor theories

Sergio Sevillano Muñoz

Supervised by
Prof. Edmund J. Copeland
Dr. Peter Millington

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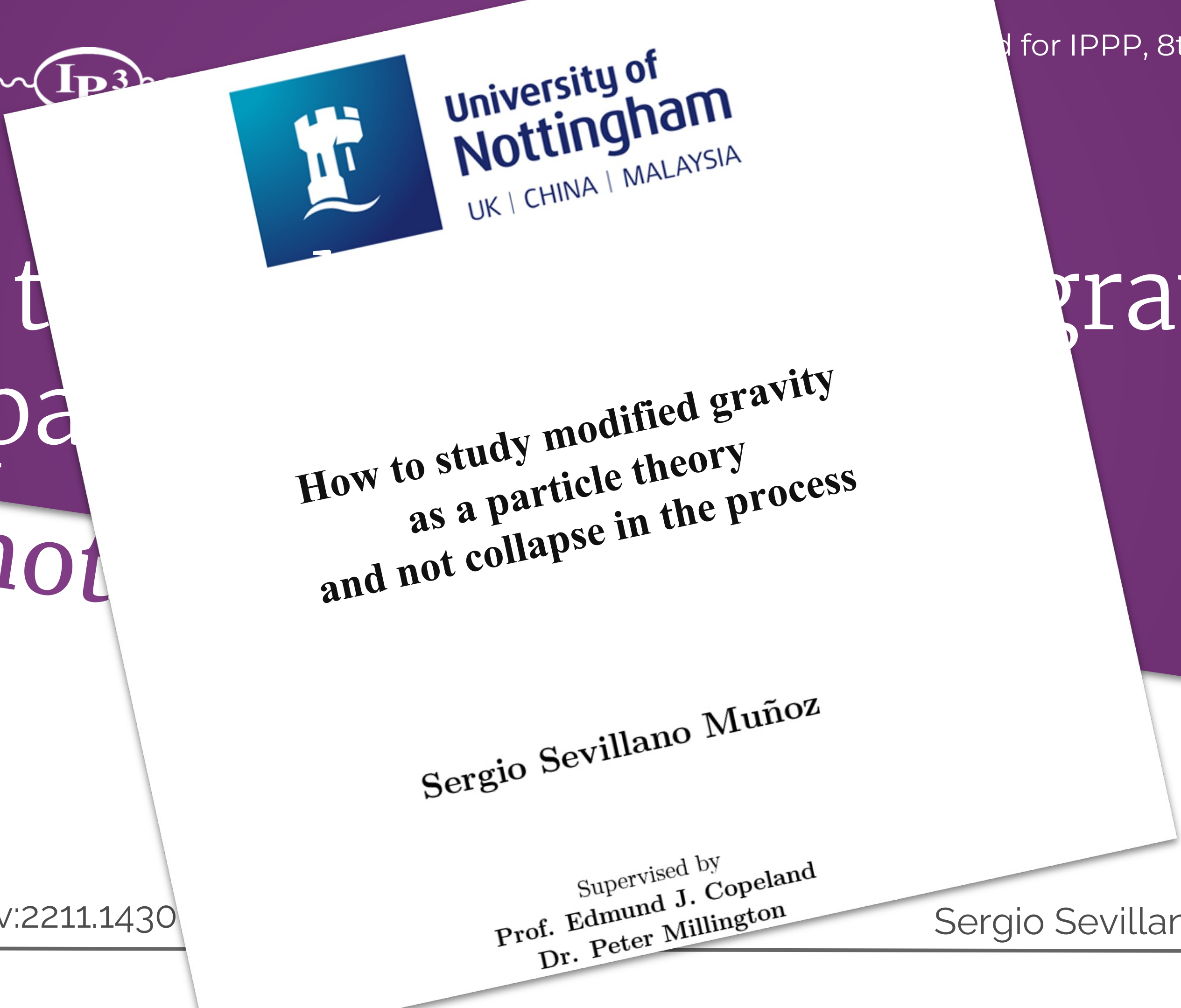
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How to study modified gravity as a particle theory and not collapse in the process

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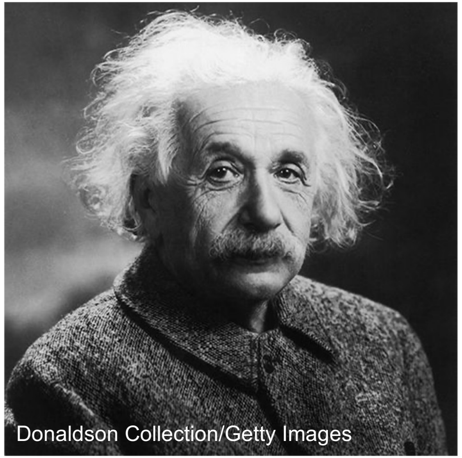
Why would we need to modify gravity?

We all know and love Einstein's General Relativity, which
Is usually described by the Einstein-Hilbert action

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[-\underbrace{\frac{M_{\rm pl}^2}{2}R}_{\text{Curvature}} + \underbrace{\mathcal{L}_{\rm m}\{\psi_i, \phi_i, g_{\mu\nu}, \ldots\}}_{\text{Matter action}}\right]$$


Donaldson Collection/Getty Images

However, we already know that this is not the whole story to the theory of gravity

Why would we need to modify gravity?

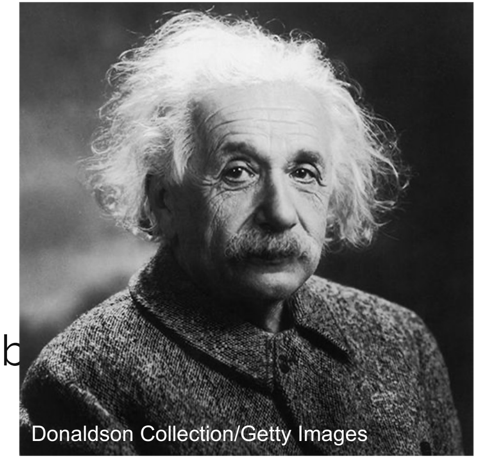
There are many problems to choose from with GR and the Standard Model

-The cosmological constant.

-What is dark matter.

-The early universe (Inflation, phase transitions)

-The coincidence problem, Hubble tension, Strong CP prob mass



Pick your favourite!

Why would we need to modify gravity?

Some of these problems require a extension of the Standard Model:

Standard Model $\longrightarrow$ **Beyond the Standard Model theories (BSM)**

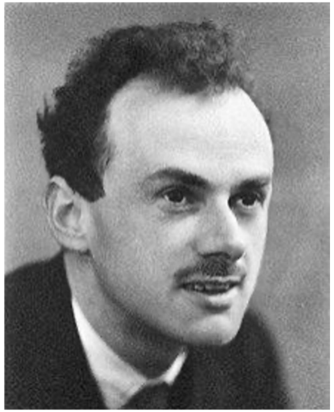
Axion, inflation, quintessence…

But in this talk we will focus on theories that instead modify the gravitational action

Standard Einstein-Hilbert action $\longrightarrow$ **New Modified gravity (?)**

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{M_{\rm pl}^2}{2}R + \mathcal{L}_{\rm m}\{\psi_i, \phi_i, g_{\mu\nu}, \ldots\}\right]$$

An example:



One of the first motivations for modified gravity started with Dirac, and its **large number hypothesis**

He noticed that both dimensionless ratios were of the same order

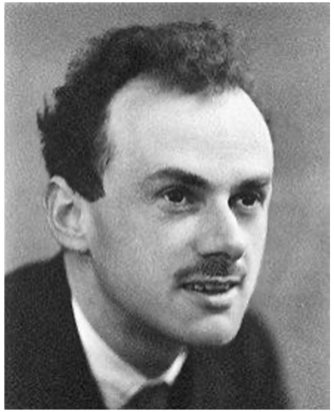
$$\frac{c\,t}{r_{\mathrm{e}}} \approx 3.47 \cdot 10^{41} \approx 10^{42} \qquad \frac{e^2}{4\pi\epsilon_0 G m_{\mathrm{p}} m_{\mathrm{e}}} \approx 10^{40}$$

From which he hypothesised that the strength of gravity might be changing with time!

$$G \sim \frac{1}{t}$$

An example:

Time-dependent gravitational constant? Quite crazy... $G \sim \frac{1}{t}$



However, of course, we cannot just insert some function of time as:

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[-\frac{M_{\mathrm{pl}}(t)^2}{2} R + \mathcal{L}_{\mathrm{m}}\{\psi_i, \phi_i, g_{\mu\nu}, \ldots\} \right]$$

Types of modified gravity:

Work within General Relativity
and choose different action

Ignore General Relativity
and change some classical mechanic definitions

Modified gravity
is not exclusively MOND

We'll choose theories within General Relativity but have a non-canonical gravitational action

How do we modify gravity consistently?

How *general* is the Einstein–Hilbert action?

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{M_{\mathrm{pl}}^2}{2}R + \mathcal{L}_{\mathrm{m}}\{\psi_i, \phi_i, g_{\mu\nu}, ...\}\right]$$

or the Einstein equation:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{2}{M_{\mathrm{pl}}^2}T_{\mu\nu}$$

<u>Can we build any new modified gravity action?</u>

How do we modify gravity consistently?

Lovelock's theorem:

In 4-D the only divergence-free rank-2 tensor constructed from only the metric and its derivatives up to second order, and preserving diffeomorphism invariance, is the Einstein tensor with a cosmological constant term.

How do we modify gravity consistently?

Lovelock's theorem:

In 4-D the only divergence-free rank-2 tensor constructed from only the metric and its derivatives up to second order, and preserving diffeomorphism invariance, is the Einstein tensor with a cosmological constant term.

Fancy words saying that if we have a rank-2 tensor L satisfying

$$\text{i)}\quad L^{\mu\nu} = L^{\mu\nu}(g_{\alpha\beta}, \partial_\sigma g_{\alpha\beta}, \partial_\sigma \partial_\rho g_{\alpha\beta});$$

$$\text{ii)}\quad \nabla_\mu L^{\mu\nu} = 0,$$

$$\longrightarrow \quad L_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R$$

How do we modify gravity consistently?

Therefore, it will necessary satisfy the Einstein equation

$$L_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \qquad\qquad R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{2}{M_{\rm pl}^2} T_{\mu\nu}$$

and come from the Einstein-Hilbert action

$$S = \int \mathrm{d}^4 x \sqrt{-g} \left[-\frac{M_{\rm pl}^2}{2} R + \mathcal{L}_{\rm m}\{\psi_i, \phi_i, g_{\mu\nu}, ...\} \right]$$

Implies that THIS is the most general action for such requirements

How can we modify gravity?

How do we modify gravity consistently?

Just break Lovelock's theorem:

In 4-D the only divergence-free rank-2 tensor constructed from only the metric and its derivatives up to second order, and preserving diffeomorphism invariance, is the Einstein tensor with a cosmological constant term.

We will choose a theory that allows for couplings to a scalar field.

How do we modify gravity consistently?

Either from an **effective field theory** standpoint or more **fundamental theories** of gravity (such as compactifications of extra dimensions) it is natural to extend the gravitational action:

Different functions of gravity

$$S_{\mathrm{grav}} = \int \mathrm{d}^4x\sqrt{-g}\left[-aR - F(\varphi)R - bR^2 - cR_{\mu\nu}R^{\mu\nu} + \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi + \ldots\right]$$

Non-minimal couplings to a scalar field

These extensions of gravity are called **Scalar-Tensor theories**

How do we modify gravity consistently?

Horndeski theory:

$$S_{\mathrm{H}} = \int \mathrm{d}^4x \sqrt{-g}\,[\mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5]$$

$$\mathcal{L}_2 = G_2(\varphi, X)$$

$$\mathcal{L}_3 = G_3(\varphi, X)\Box\varphi$$

$$\mathcal{L}_4 = G_4(\varphi, X)R + G_{4,X}(\varphi, X)\left[(\Box\varphi)^2 - (\nabla_\mu\nabla_\nu\varphi)^2\right]$$

$$\mathcal{L}_5 = G_5(\varphi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\varphi - \frac{1}{6}G_{5,X}(\varphi, X)\left[(\Box\varphi)^3 - 3\Box\varphi(\nabla_\mu\nabla_\nu\varphi)^2 + 2(\nabla_\mu\nabla_\nu\varphi)^3\right]$$

$$G^{\mu\nu} = R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu}R$$

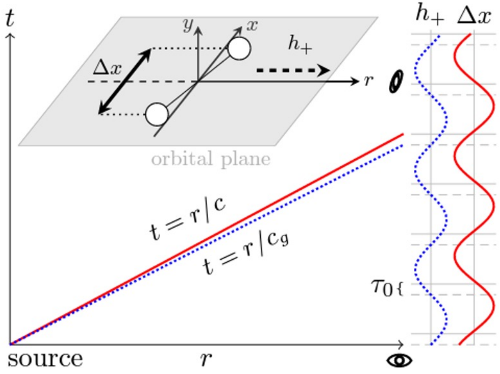
$$X = \tfrac{1}{2}\partial_\mu\varphi\partial^\mu\varphi$$

Bounds on Scalar-Tensor theories

Speed of gravitational waves:

$$\boxed{-3 \cdot 10^{-15} \leq c_T/c - 1 \leq 7 \cdot 10^{-16}}$$

$$\frac{c_T^2}{c^2} = \frac{G_4 - XG_{5,\varphi} - \ddot{\varphi}G_{5,\varphi}}{G_4 - 2XG_{4,\varphi} + XG_{5,\varphi} - \dot{\varphi}HXG_{5,X}}$$



Bettoni, Ezquiaga et al. 2017

Horndeski theory can be simplified to

$$\mathcal{L}_{\mathrm{H}}^{(c)} = G_4(\varphi)R + G_2(\varphi, X) - G_3(\varphi, X)\Box\varphi$$

Bounds on Scalar-Tensor theories

However, Brans, Dicke and Jordan had already been thinking about something similar, but using a scalar field

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{F(\varphi)}{2}R + \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - U(\varphi) + \mathcal{L}_\mathrm{m}\{\psi_i, \phi_i, g_{\mu\nu}, \ldots\}\right]$$

Such that at late times, when the scalar stabilizes

$$F(v_\varphi) \equiv M_\mathrm{pl}^2$$

This is a consistent theory with changing gravitational force!

Bounds on Scalar-Tensor theories

$$S=\int \mathrm{d}^4x\sqrt{-g}\left[-\frac{F(\varphi)}{2}R+\frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi-U(\varphi)+\mathcal{L}_\mathrm{m}\{\psi_i,\phi_i,g_{\mu\nu},...\}\right]$$

In most cases, they introduce new dynamics into the matter sector (**fifth forces**)

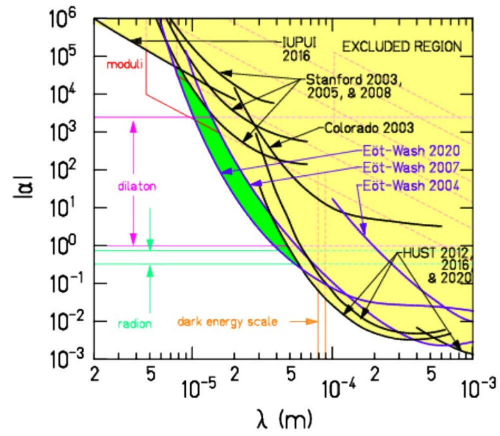
The tightest constraints come from large scales:

-Solar system scales (Cassini spacecraft) Bertotti et al. 2003

-Atomic scales (Atom interferometry) YT talk by Clare Burrage in "Cosmology Talks"

Bounds on Scalar-Tensor theories

$$S=\int \mathrm{d}^4x\sqrt{-g}\left[-\frac{F(\varphi)}{2}R+\frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi-U(\varphi)+\mathcal{L}_\mathrm{m}\{\psi_i,\phi_i,g_{\mu\nu},\ldots\}\right]$$



$$V(r)=\frac{Gm_1m_2}{r}\left(1+\alpha e^{-r/\lambda}\right)$$

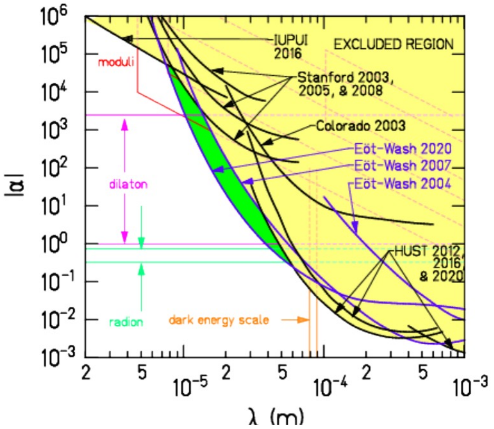
Screening mechanisms

They give an **effective mass** to the new scalar in **high-density environments**, so local effects are **exponentially suppressed**

$$V_5(r) = -\frac{1}{4\pi r}\frac{M^2}{M_{\rm Pl}^2}e^{-\hat{m}(\rho)r}$$

$$\hat{m}_\varphi^2(\rho)^2 = n(n+2)^{\frac{1}{n}}\frac{\rho^{\frac{n+1}{n}}}{(2\Lambda^{n+4})^{\frac{n+1}{n}}}$$

$$V(r) = \frac{Gm_1m_2}{r}\left(1+\alpha e^{-r/\lambda}\right)$$

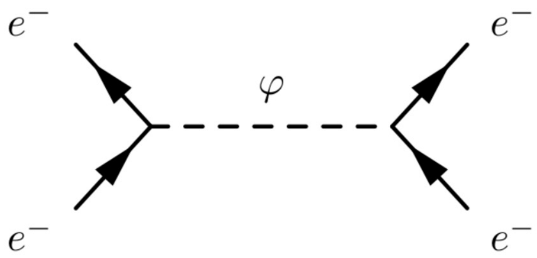


Particle physics

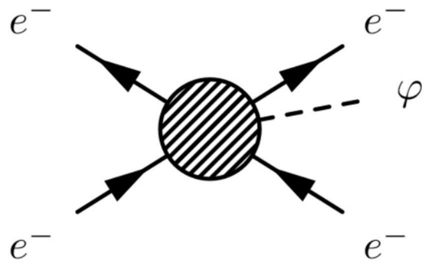
There is a way of getting around these screening mechanisms: using particle theory.

We can also study them on the subatomic scale using particle theory, unveiling the effect that the modification of gravity has in the Standard Model [Brax et al. (2016),Aaboud et al. 2019]

Modification as an internal propagator



``Missing energy'' due to external state:



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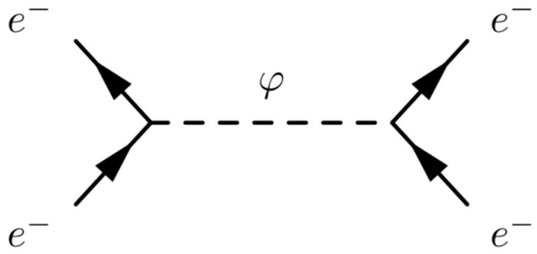
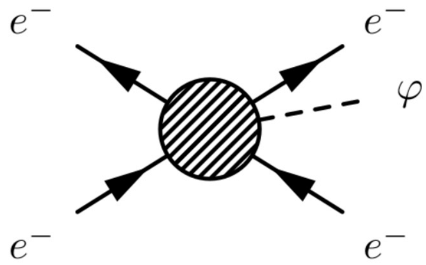


Screened due to effective mass

``Missing energy'' due to external state:



Not screened!

IPPP/16/31, DCPT/16/62

LHC Signatures Of Scalar Dark Energy

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W… hat

the modification of gravity has in the Standard Model [Brax et al. (2016), Aaboud et al. 2019]

Constraints on mediator-based dark matter and scalar dark energy models using $\sqrt{s} = 13$ TeV pp collision data collected by the ATLAS detector

The ATLAS Collaboration

C. Burrage, E. Copeland, P. Millington and M. Spannowsky (arXiv:1804.07180)
E. Copeland, P. Millington and SSM (2111.06357)

Particle physics

These calculations are usually very complicated. However, modifications on the Standard Model can be described by a Beyond the Standard Model theory.

For that, instead of working with modified gravity, we will make the following transformation

Our plan:

Modified theory of gravity
+
Standard Model

$\xrightarrow{\text{Using Field theory}}$

General Relativity
+
Beyond the Standard Model

Modified Gravity=BSM?

As an example, let's study the simplest modified theory of gravity

Brans-Dicke Action:

Matter action

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{F(\varphi)}{2}R + \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - U(\varphi) + \mathcal{L}_{\mathrm{m}}\{\psi_i, \phi_i, g_{\mu\nu}, \ldots\}\right]$$

To satisfy constraints, we need at late times:

$$F(v_\varphi) \equiv M_{\mathrm{pl}}^2$$

C. Burrage, E. Copeland, P. Millington and M. Spannowsky (arXiv:1804.07180)
E. Copeland, P. Millington and SSM (2111.06357)

Einstein frame:

The common way of solving this called [Transforming to the Einstein frame]

Make a conformal transformation such that gravity becomes canonical

$$g_{\mu\nu} \to \frac{\tilde{M}_{\rm Pl}^2}{F(X)} \tilde{g}_{\mu\nu}, \qquad g^{\mu\nu} \to \frac{F(X)}{\tilde{M}_{\rm Pl}^2} \tilde{g}^{\mu\nu},$$

$$S_{\rm EF} = \int {\rm d}^4 x \sqrt{-\tilde{g}} \left[\underbrace{- \frac{\tilde{M}_{\rm pl}{}^2}{2} \tilde{R}}_{\text{Standard gravity}} + \frac{\tilde{M}_{\rm pl}^2}{2} \left[\frac{1}{F(\varphi)} + \frac{3F'(\varphi)^2}{2F(\varphi)^2} \right] \tilde{g}^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi \right.$$
$$\left. - \frac{\tilde{M}_{\rm pl}{}^4}{F(\varphi)^2} U(\varphi) + \underbrace{\mathcal{L}_{\rm m}\{\psi_i, \phi_i, \varphi, \tilde{g}_{\mu\nu}, \ldots\}}_{\text{Beyond the Standard Model matter sector}} \right]$$

C. Burrage, E. Copeland, P. Millington and M. Spannowsky (arXiv:1804.07180)
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Jordan frame:

If the gravitational action is very complicated, there is no such transformation of the metric that takes us to the Einstein frame, then we are stuck in the Jordan frame

It is complicated even for the simplest Brans-Dicke case:

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{F(\varphi)}{2}R + \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - U(\varphi) + \mathcal{L}_{\mathrm{m}}\{\psi_i, \phi_i, g_{\mu\nu}, \ldots\}\right]$$

The best way of understanding that there is a BSM equivalent is by studying the **equations of motion**

Based on arXiv:2211.14300

Jordan frame:

$$\boxed{R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{2}{M_{\rm pl}^2}T_{\mu\nu}}$$

$$G^{\mu\nu} = R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu}R$$

Modified Gravity:

$$\frac{1}{2}F(\varphi)G_{\mu\nu} + \nabla_\mu\nabla_\nu F(\varphi) - g_{\mu\nu}\Box F(\varphi) = \frac{1}{2}T^{(\rm m)}_{\mu\nu} + \frac{1}{2}T^{(\varphi)}_{\mu\nu}$$

$$Z(\varphi)\Box\varphi + \frac{1}{2}Z'(\varphi)\partial_\mu\varphi\partial_\nu\varphi + U'(\varphi) + \frac{F'(\varphi)}{2}R = 0,$$

BSM in two steps:

Based on arXiv:2211.14300

Jordan frame:

$$\boxed{R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{2}{M_{\rm pl}^2}T_{\mu\nu}}$$

$$G^{\mu\nu} = R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu}R$$

Modified Gravity:

$$\frac{1}{2}F(\varphi)G_{\mu\nu} + \nabla_\mu\nabla_\nu F(\varphi) - g_{\mu\nu}\Box F(\varphi) = \frac{1}{2}T^{(\rm m)}_{\mu\nu} + \frac{1}{2}T^{(\varphi)}_{\mu\nu}$$

$$Z(\varphi)\Box\varphi + \frac{1}{2}Z'(\varphi)\partial_\mu\varphi\partial_\nu\varphi + U'(\varphi) + \frac{F'(\varphi)}{2}R = 0,$$

BSM in two steps:

1) $$G_{\mu\nu} = \frac{2}{F(\varphi)}\left(\frac{1}{2}T^{(\rm m)}_{\mu\nu} + \frac{1}{2}T^{(\varphi)}_{\mu\nu} - \nabla_\mu\nabla_\nu F(\varphi) + g_{\mu\nu}\Box F(\varphi)\right)$$

Based on arXiv:2211.14300

Jordan frame:

$$\boxed{R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{2}{M_{\rm pl}^2}T_{\mu\nu}}$$

$$G^{\mu\nu} = R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu}R$$

Modified Gravity:

$$\frac{1}{2}F(\varphi)G_{\mu\nu} + \nabla_\mu\nabla_\nu F(\varphi) - g_{\mu\nu}\Box F(\varphi) = \frac{1}{2}T^{(\rm m)}_{\mu\nu} + \frac{1}{2}T^{(\varphi)}_{\mu\nu}$$

$$Z(\varphi)\Box\varphi + \frac{1}{2}Z'(\varphi)\partial_\mu\varphi\partial_\nu\varphi + U'(\varphi) + \frac{F'(\varphi)}{2}R = 0,$$

BSM in two steps:

1) $$G_{\mu\nu} = \frac{2}{F(\varphi)}\left(\frac{1}{2}T^{(\rm m)}_{\mu\nu} + \frac{1}{2}T^{(\varphi)}_{\mu\nu} - \nabla_\mu\nabla_\nu F(\varphi) + g_{\mu\nu}\Box F(\varphi)\right)$$

2) $$Z(\varphi)\Box\varphi + \frac{1}{2}Z'(\varphi)\partial_\mu\varphi\partial^\mu\varphi - U'(\varphi) + \frac{F'(\varphi)}{F(\varphi)}\left(T^{\mu\,(\rm m)}_{\mu} + T^{\mu\,(\varphi)}_{\mu} + 3\Box F(\varphi)\right) = 0$$

Based on arXiv:2211.14300

Jordan frame:

$$\boxed{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{2}{M_{\rm pl}^2} T_{\mu\nu}}$$

$$G^{\mu\nu} = R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R$$

Modified Gravity:

$$\frac{1}{2} F(\varphi) G_{\mu\nu} + \nabla_\mu \nabla_\nu F(\varphi) - g_{\mu\nu} \Box F(\varphi) = \frac{1}{2} T_{\mu\nu}^{(\rm m)} + \frac{1}{2} T_{\mu\nu}^{(\varphi)}$$

$$Z(\varphi) \Box \varphi + \frac{1}{2} Z'(\varphi) \partial_\mu \varphi \partial_\nu \varphi + U'(\varphi) + \frac{F'(\varphi)}{2} R = 0,$$

BSM in two steps:

$$1) \quad G_{\mu\nu} = \frac{2}{F(\varphi)} \left(\frac{1}{2} T_{\mu\nu}^{(\rm m)} + \frac{1}{2} T_{\mu\nu}^{(\varphi)} - \nabla_\mu \nabla_\nu F(\varphi) + g_{\mu\nu} \Box F(\varphi) \right)$$

Standard gravity

Beyond the Standard Model matter sector

$$2) \quad Z(\varphi) \Box \varphi + \frac{1}{2} Z'(\varphi) \partial_\mu \varphi \partial^\mu \varphi - U'(\varphi) + \frac{F'(\varphi)}{F(\varphi)} \left(T_\mu^{\mu (\rm m)} + T_\mu^{\mu (\varphi)} + 3 \Box F(\varphi) \right) = 0$$

Jordan frame:

However, if we are going to study the particle phenomenology, we have to use QFT

$$S=\int \mathrm{d}^4x\sqrt{-g}\left[-\frac{F(X)}{2}R+\frac{1}{2}g^{\mu\nu}\partial_\mu X\partial_\nu X-U(X)+\mathcal{L}_\mathrm{m}\{\psi_i,\phi_i,g_{\mu\nu},\ldots\}\right]$$

In the Jordan frame, gravity will be the source of Fifth forces. For that, we will need to linearize gravity

$$g_{\mu\nu}=\eta_{\mu\nu}+h_{\mu\nu},$$

$$g^{\mu\nu}=\eta^{\mu\nu}-h^{\mu\nu}+\ldots,$$

Graviton

Jordan frame:

If linearizing gravity is difficult, just imagine how modified gravity is…

As an example, let's see how this affects a QED+Higgs singlet model in flat space-time:

Before linearizing gravity

$$S_{\rm m} = \int \mathrm{d}^4x \Big[\overbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}^{\text{Photon}} + \overbrace{\frac{1}{2}\partial_\mu\phi\partial^\mu\phi}^{\text{Higgs}} \\ + \underbrace{i\bar{\psi}\gamma^\mu D_\mu\psi - y\bar{\psi}\phi\psi}_{\text{Electron}} + \underbrace{\frac{1}{2}\mu^2\phi^2 - \frac{\lambda}{4!}\phi^4 - \frac{3\mu^4}{2\lambda}}_{\text{Higgs}} \Big]$$

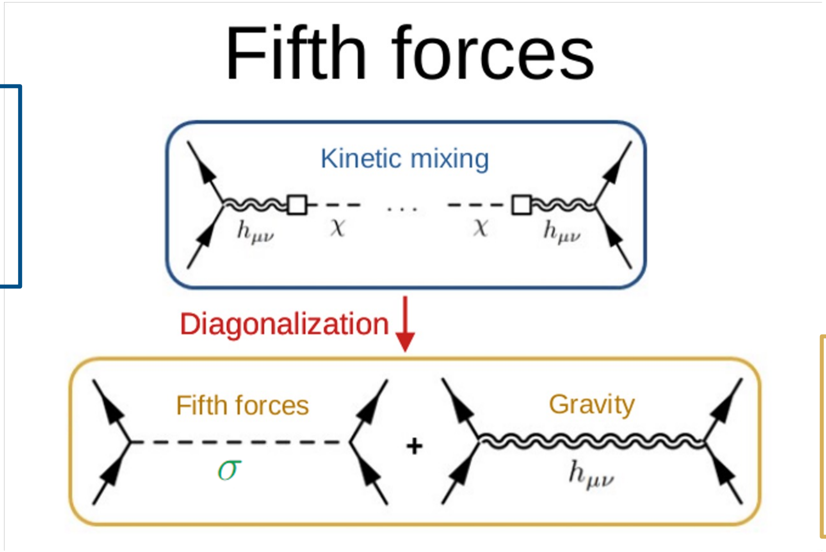
We will see which BSM is equivalent to Modified Gravity for this theory.

Jordan frame:

Fifth forces transmit through a kinetic mixing with gravity

The kinetic mixing can be diagonalized so that fields are canonical

Modified theory of gravity
+
Standard Model



χ is a function of φ

General Relativity
+
Beyond the Standard Model

Jordan frame:

χ is a function of φ

We finally find:

Photon

$$
\begin{aligned}
\mathcal{L} =& \frac{1}{4}\partial_\mu h \partial^\mu h - \frac{1}{2}\partial_\rho h_{\mu\nu}\partial^\rho h^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
& + i\bar{\psi}\gamma^\mu\partial_\mu\psi - q\bar{\psi}\gamma^\mu A_\mu\psi - y\bar{\psi}\phi\psi - \hat{U}(\chi(\sigma) + v_\chi) \\
& + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}\mu^2\phi^2 - \frac{\lambda}{4!}\phi^4 - \frac{3\mu^4}{2\lambda} \\
& + \frac{1}{M_{\rm pl}}h_{\mu\nu}T^{\mu\nu} + \frac{1}{2M_{\rm pl}}\frac{\hat{F}'(v_\chi)}{\sqrt{M_{\rm pl}^2 + \hat{F}'(v_\chi)^2}}\sigma T^\mu_\mu + \cdots ,
\end{aligned}
$$

Electron

Higgs

Standard Model

Fifth forces! (BSM)

E. Copeland, P. Millington and SSM (2111.06357)

LHC Signatures Of Scalar Da

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[4]Institute for Particle Physics Phenomenol
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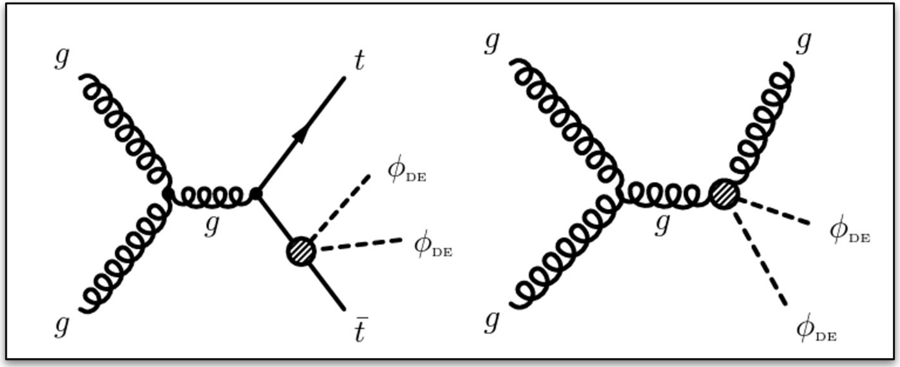
Constraints on mediator-based dark matter and scalar dark energy models using $\sqrt{s}$ = 13 TeV pp collision data collected by the ATLAS detector

The ATLAS Collaboration

$$\mathcal{L}_1 = \frac{\partial_\mu \phi_{\rm DE} \partial^\mu \phi_{\rm DE}}{M_1^4} T^\nu_\nu$$

$$\mathcal{L}_2 = \frac{\partial_\mu \phi_{\rm DE} \partial_\nu \phi_{\rm DE}}{M_2^4} T^{\mu\nu}$$



Beyond the Standard Model:

Once we have the Beyond Standard Model description, we can calculate from quantum corrections to scattering amplitudes!

The takeaway message is that these calculations are very tedious and model-dependent

Simplest Jordan frame calculation

Insertion of minimal couplings
Expansion of gravity
Canonical normalization
Expansion around non-trivial vevs
Kinetic mixings to graviton
Mass/kinetic mixings

(even for the Einstein frame)

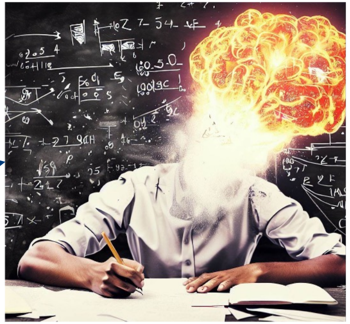
Beyond the Standard Model:

Once we have the Beyond Standard Model description, we can calculate from quantum corrections to scattering amplitudes!

The takeaway message is that these calculations are very tedious and model-dependent

Simplest Jordan frame calculation

(Graphic representation of your collapse)



Stable Diffusion

Almost impossible to study scalar-tensor theories beyond toy models!!!

5 stages of grief

1. Denial: It's not that difficult...

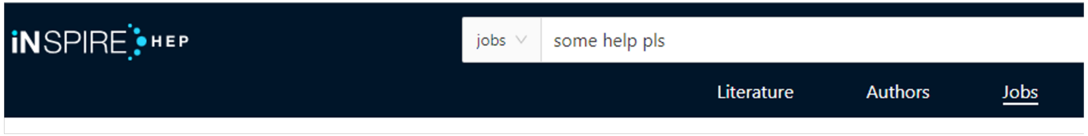
5 stages of grief

1. Denial: It's not that difficult…

2. Anger: I'm not doing that!

5 stages of grief

1. Denial: It's not that difficult…
2. Anger: I'm not doing that!
3. Bargaining: I'll get a graduate student to do it

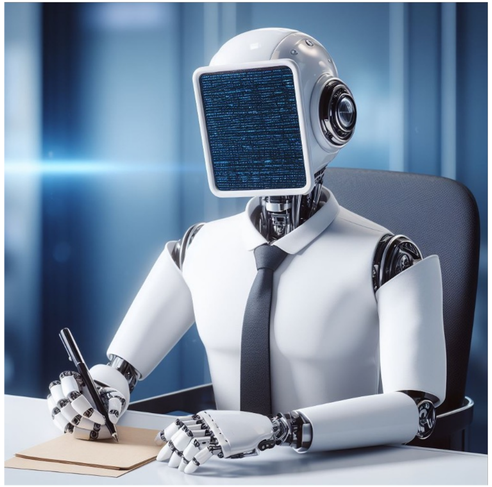


5 stages of grief

1. Denial: It's not that difficult…
2. Anger: I'm not doing that!
3. Bargaining: I'll get a graduate student to do it
4. Depression: It's very expensive…

5 stages of grief

1. Denial: It's not that difficult…
2. Anger: I'm not doing that!
3. Bargaining: I'll get a graduate student to do it
4. Depression: It's very expensive…
5. Acceptance: Maybe I can get a computer to do it!



Based on arXiv:2211.14300

Can we get the computer to do it?

Learn from particle phenomenologists:

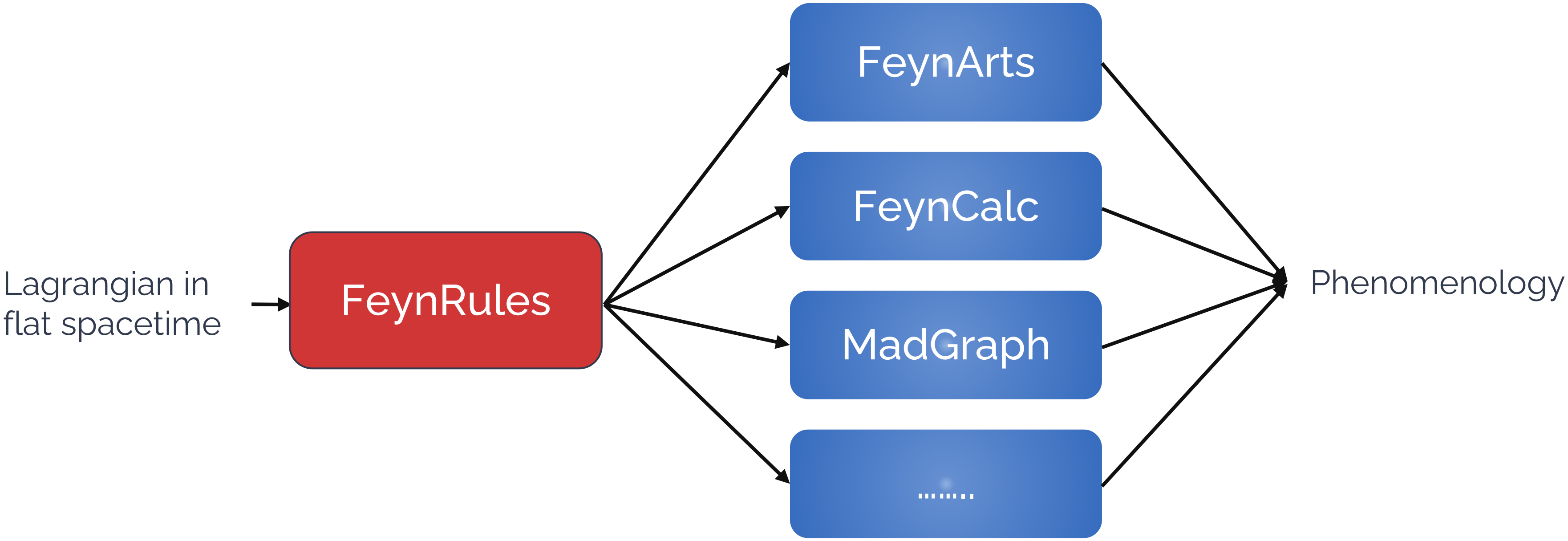
Use FeynRules: a Mathematica Package that from a Lagrangian defined in flat spacetime gives the list of Feynman Rules

-Defined Fields
-Defined Parameters
-Lagrangian in flat spacetime

$\rightarrow$ FeynRules $\rightarrow$ List of Feynman rules

Based on arXiv:2211.14300

Can we get the computer to do it?



Can we get the computer to do it?

However, the difficult thing is getting to the BSM formalism

Lagrangian in flat spacetime → **FeynRules** → List of Feynman rules

Modified theory of gravity
+
Standard Model

Using Field theory →
!!

General Relativity
+
Beyond the Standard Model

FeynMG!

We developed **FeynMG** to help through the process

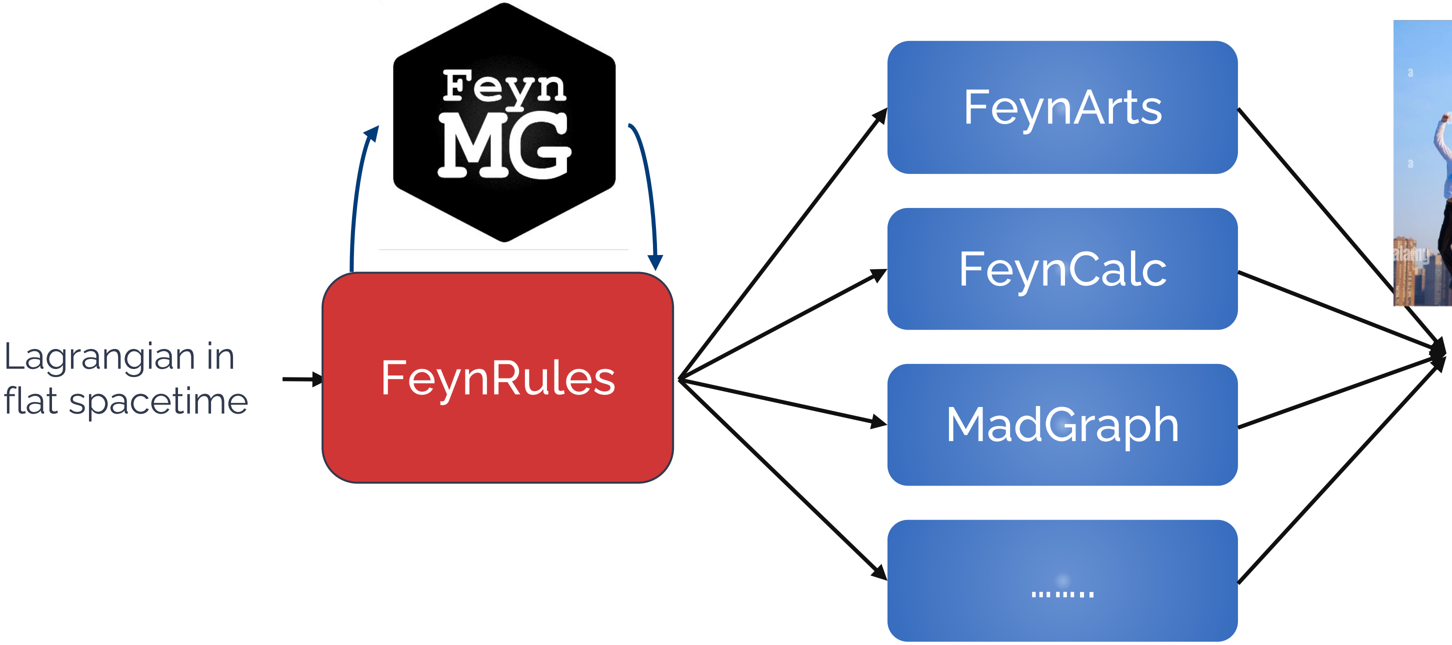
Subpackage for FeynRules

FeynMG: a FeynRules extension for scalar-tensor theories of gravity

Sergio Sevillano Muñoz[a,*], Edmund J. Copeland[a], Peter Millington[b], Michael Spannowsky[c]

Based on arXiv:2211.14300

FeynMG:



Pheno for Scalar-Tensor theories!

FeynMG:

-Allows the user to insert new scalar degrees of freedom and any gravitational theory

-Perform all the necessary operations to calculate the Beyond the Standard Model description

Simplest Jordan frame calculation

Insertion of minimal couplings `InsertCurv`

Expansion of gravity `LinearizeGravity`

`CanonScalar` Canonical normalization

`VevExpand` Expansion around non-trivial vevs

Kinetic mixings to graviton `GravKinMixing`

Mass/kinetic mixings `MassDiagMG`

Test Scalar-Tensor theories in colliders!

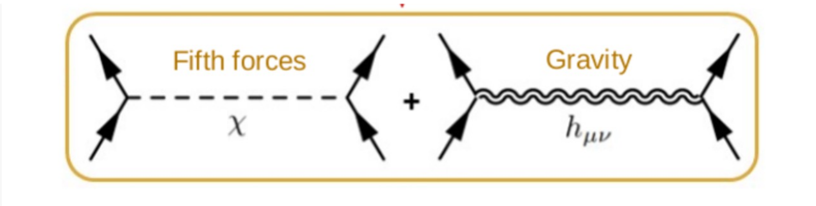
Based on arXiv:2211.14300

FeynMG:

A quick example to express my excitement:

Calculating by hand

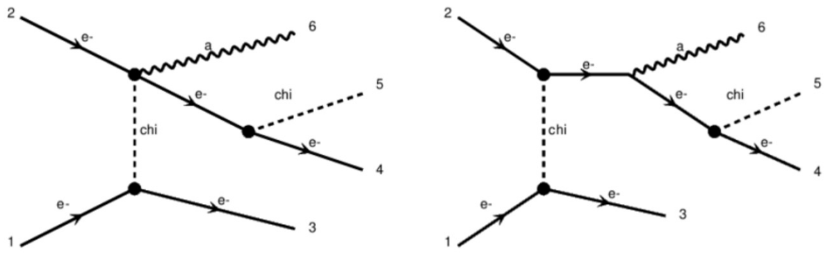
fifth forces for an electron



3-4 months of learning and mistakes in the process

vs

Using MadGraph:



It took x min. to generate the possible 344 diagrams

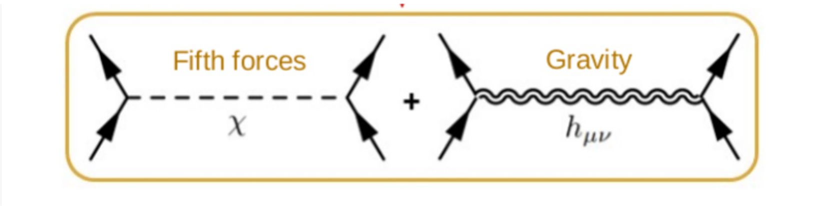
It can work with any scalar-tensor theory

FeynMG:

A quick example to express my excitement:

Calculating by hand

fifth forces for an electron



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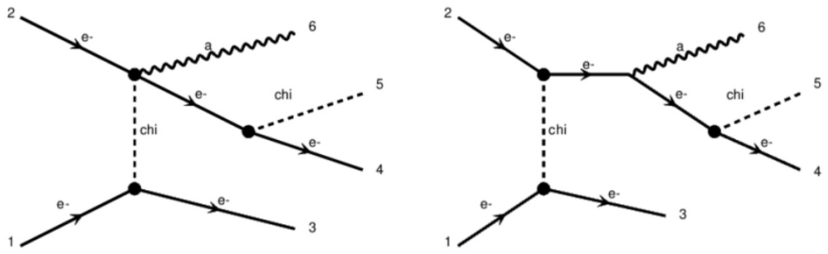
Using MadGraph:



It took ~1min +0.45s to generate the possible 344 diagrams

It can work with any scalar-tensor theory

Conclusions

-Modified theories of gravity are a natural extension of the standard model that must be considered.

-Scalar-tensor theories can be studied as a particle theory through a Beyond Standard Model description

-FeynMG help us through the calculation, making it possible to work with the whole Standard Model

-Being inside FeynRules, we can use all the compatible packages to do pheno studies!

FeynMG allows to consistently test Scalar-tensor theories of gravity at colliders

Based on arXiv:2211.14300

Thank you for your attention

SCAN ME

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https://gitlab.com/feynmg/FeynMG

Feyn MG