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

Speakers: Sergio Sevillano-Munoz

Collection/Series: 50 Years of Horndeski Gravity: Exploring Modified Gravity

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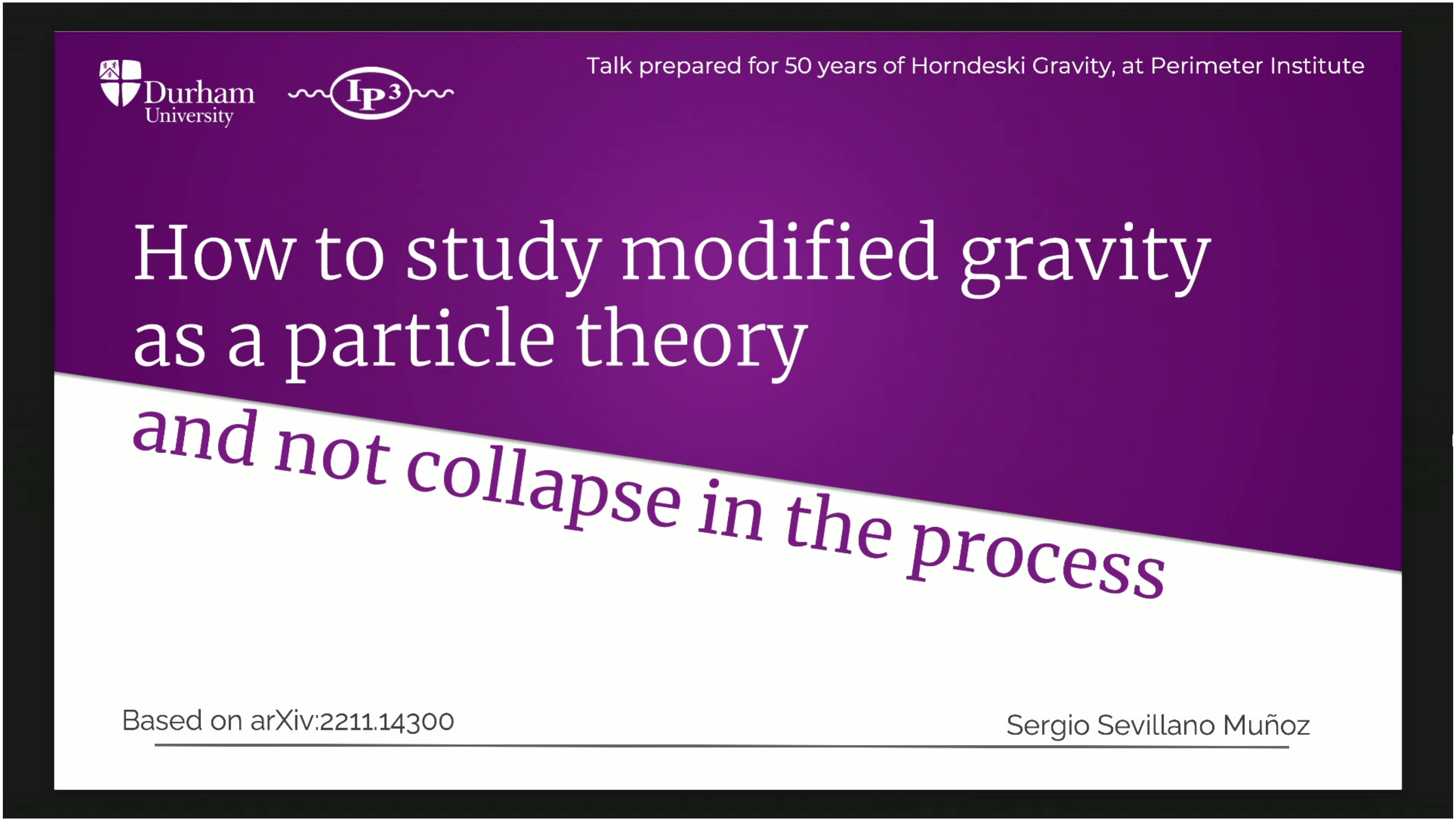
Abstract:

The ability to represent perturbative expansions of interacting quantum field theories in terms of simple diagrammatic rules has revolutionized calculations in particle physics. However, in the case of extended theories of gravity, deriving this set of rules requires linearization of gravity perturbation of the scalar fields and multiple field redefinitions making this process very time-consuming and model dependent. In this talk, I will motivate and present FeynMG, a Mathematica extension of FeynRules that automatizes this calculation allowing for the application of quantum field theory techniques to scalar-tensor theories.


Durham University
Talk prepared for 50 years of Horndeski Gravity, at Perimeter Institute
How to study modified gravity as a particle theory
and not collapse in the process
Based on arXiv:2211.14300
Sergio Sevillano Muñoz

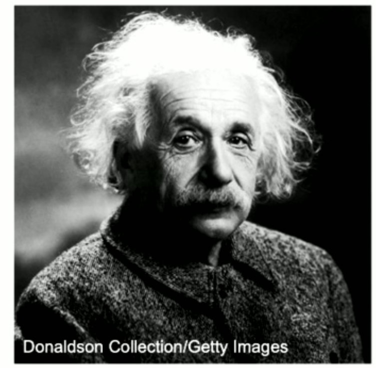
Why would we need to modify gravity?

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

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

Curvature

Matter action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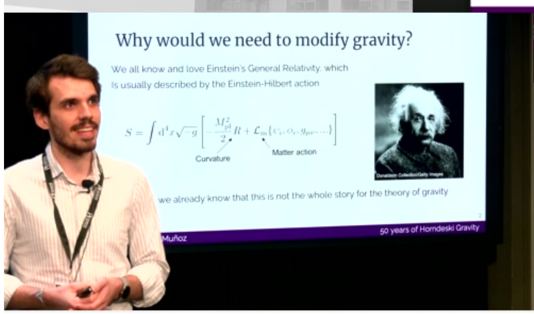
However, we already know that this is not the whole story for the theory of gravity



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

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

Non-minimal couplings to a scalar field

Scalar-Tensor theories -- Horndeski theories

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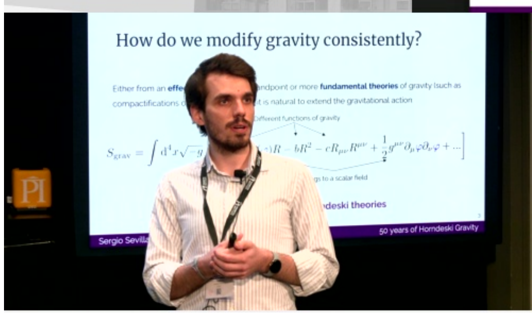

Bounds on Scalar-Tensor theories

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

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

-Cosmological scales (GWs) — Ezquiaga and Zumalacarregui 2017

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

-Atomic scales (Atom interferometry) — YT talk by Clare Burrage in “Cosmology Talks”

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Bounds on Scalar-Tensor theories

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

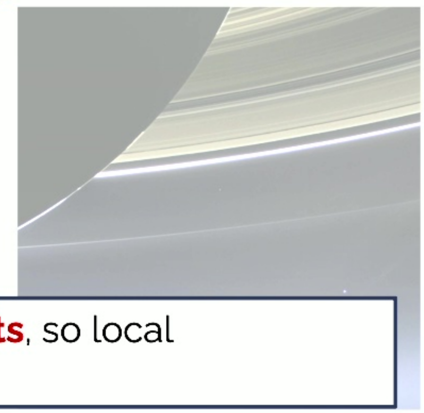
In most cases, they introduce new dynamics into the matter sector (**fifth forces**)

Screening mechanisms

-Cosmological scales (Gravitational waves) Bertotti et al. 2003

-Solar system scales (Cassini spacecraft) Avilez et al. 2013

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



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

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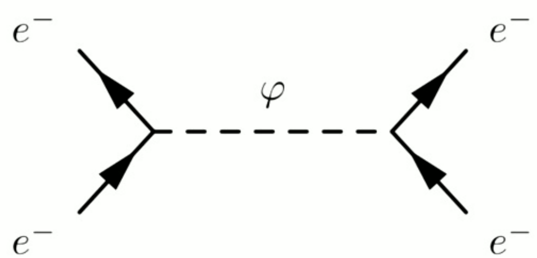
Particle physics

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

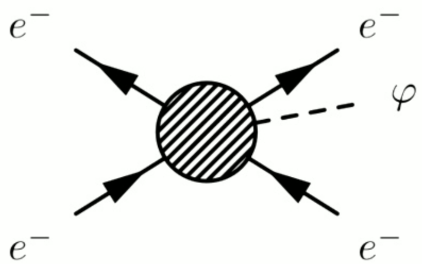
We can also study them on the subatomic scale using particle theory, unveiling the effect that the modification of gravity has in the Standard Model [Brax et al. (2016), Aaboud et al. 2019]

Modification as an internal propagator



Screened due to effective mass

``Missing energy" due to external state:



Not screened!

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

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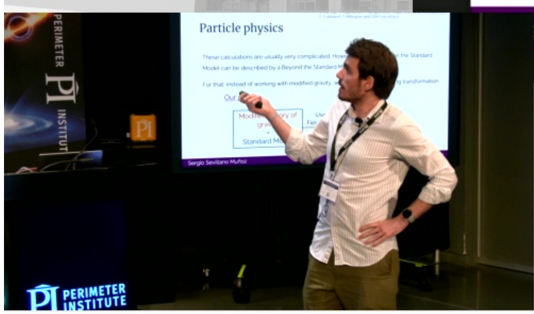

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Einstein frame:

The common way of solving this called Transforming to the Einstein frame
Make a conformal transformation such that gravity becomes canonical

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

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

Standard gravity

Beyond the Standard Model matter sector

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

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:

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

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

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

Graviton

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

Jordan frame:

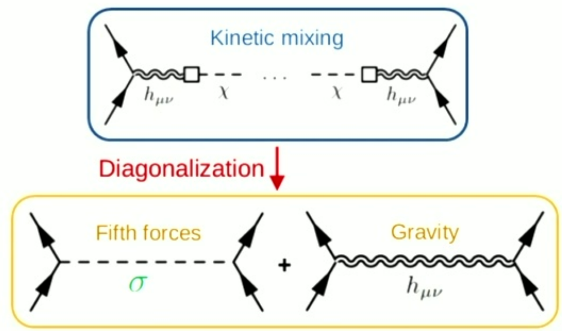
Fifth forces transmit through a kinetic mixing with gravity

The kinetic mixing can be diagonalized so that fields are canonical

Fifth forces

χ is a function of φ

Modified theory of gravity
+
Standard Model



General Relativity
+
Beyond the Standard Model

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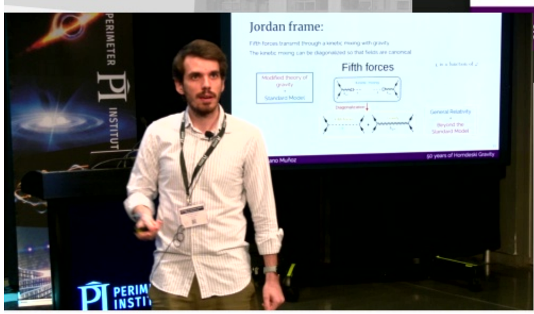


SSM, E. Copeland, P. Millington and Michael Spannowsky (2211.14300)

Beyond the Standard Model:

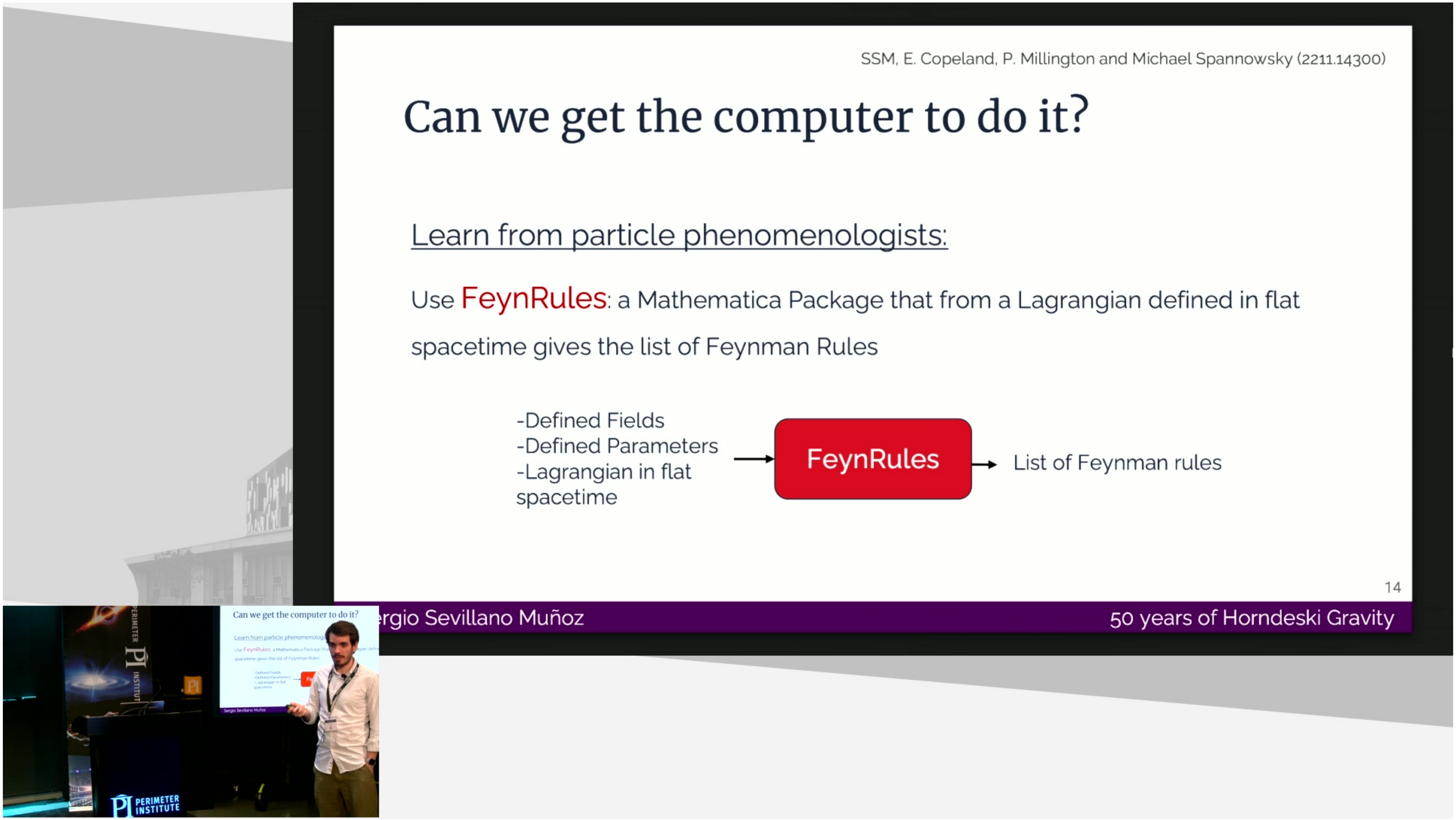
Once we have the Beyond Standard Model description, we can calculate from quantum corrections to scattering amplitudes!

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)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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
FeynRules
List of Feynman rules
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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!!!

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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
→ **FeynRules** → List of Feynman rules

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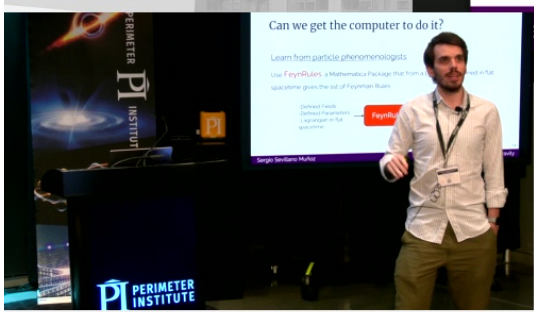

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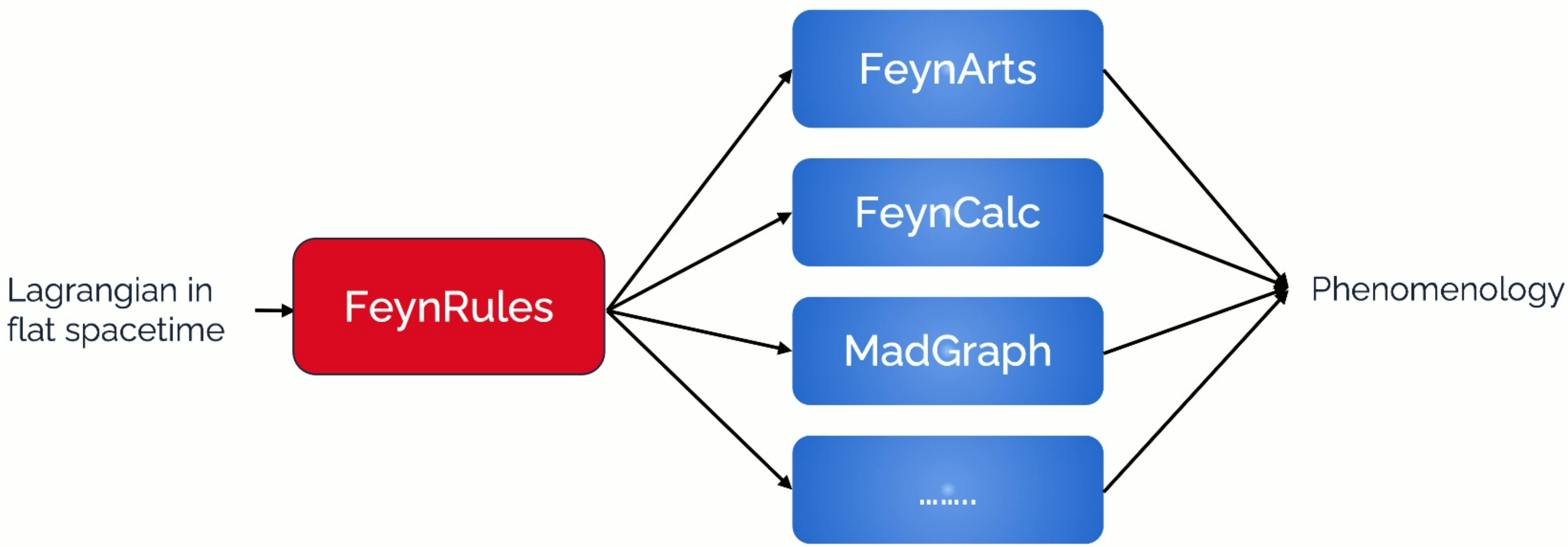
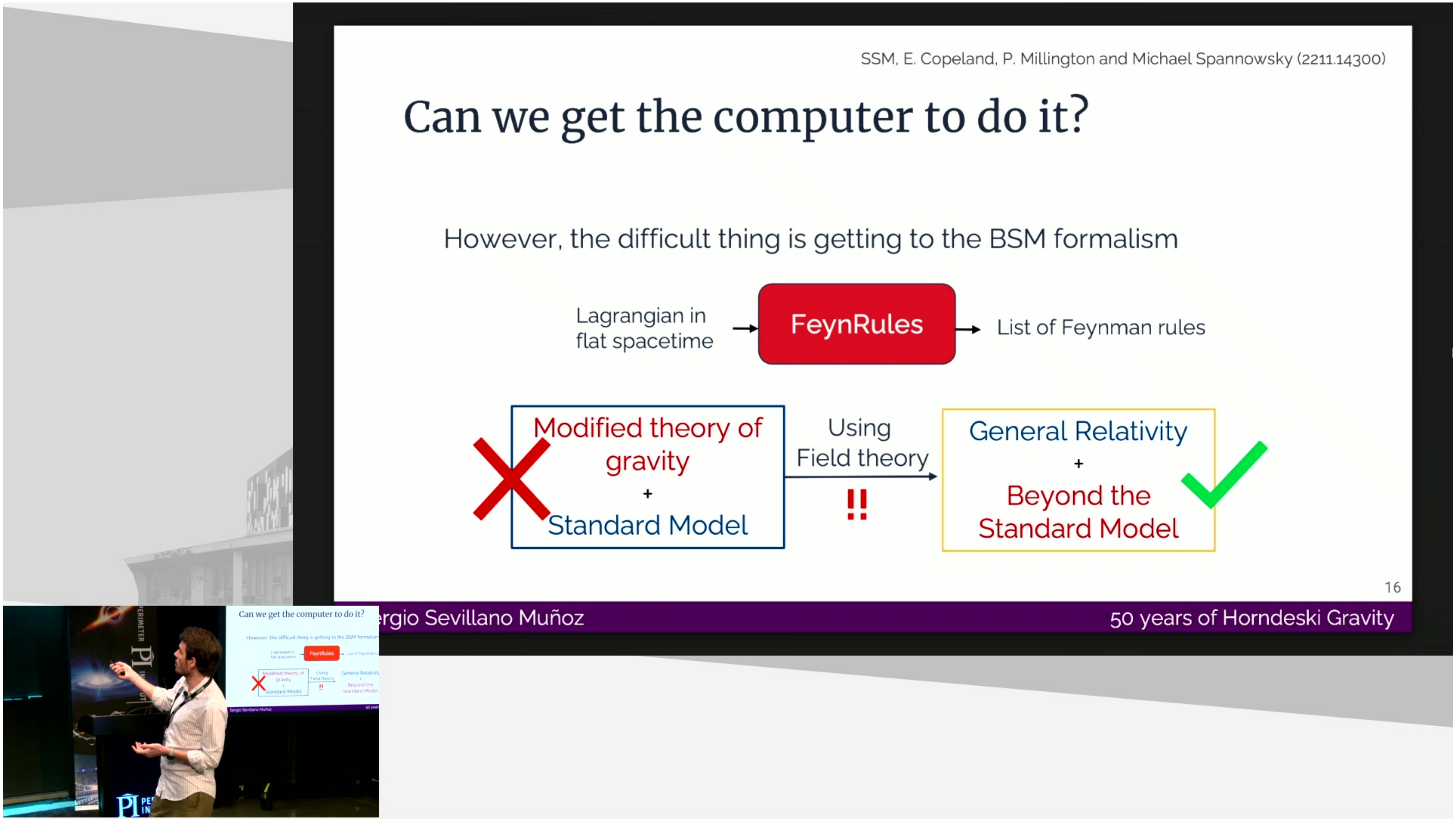
Can we get the computer to do it?

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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
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FeynMG!

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

Feyn MG

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]

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FeynMG:

Feyn MG

Lagrangian in flat spacetime → FeynRules → FeynArts / FeynCalc / MadGraph / .... → Pheno for Scalar-Tensor theories!

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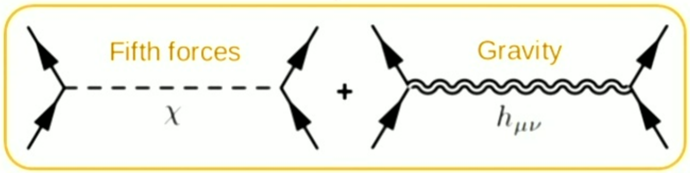
FeynMG:

A quick example to express my excitement:

Calculating by hand

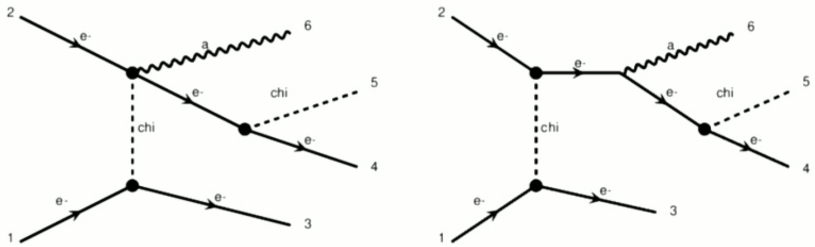
fifth forces for an electron



3-4 months of learning and mistakes in the process

vs

Using MadGraph:



It took x mins to generate the possible 344 diagrams

It can work with any scalar-tensor theory

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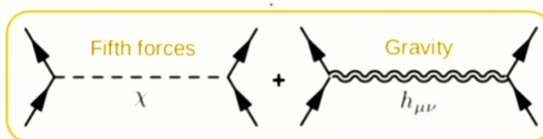
FeynMG:

A quick example to express my excitement:

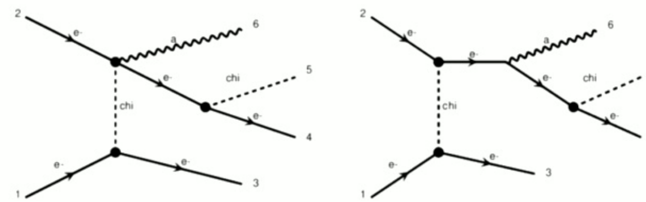
Calculating by hand
fifth forces for an electron



3-4 months of learning and mistakes
in the process

vs

Using MadGraph:



It took ~1min +0.45s to generate the
possible 344 diagrams
It can work with any scalar-tensor theory

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Conclusions

-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 from a particle's perspective

It is also very useful from a theoretical standpoint:

Quantum corrections
Screening from a field theory perspective (2407.08779)