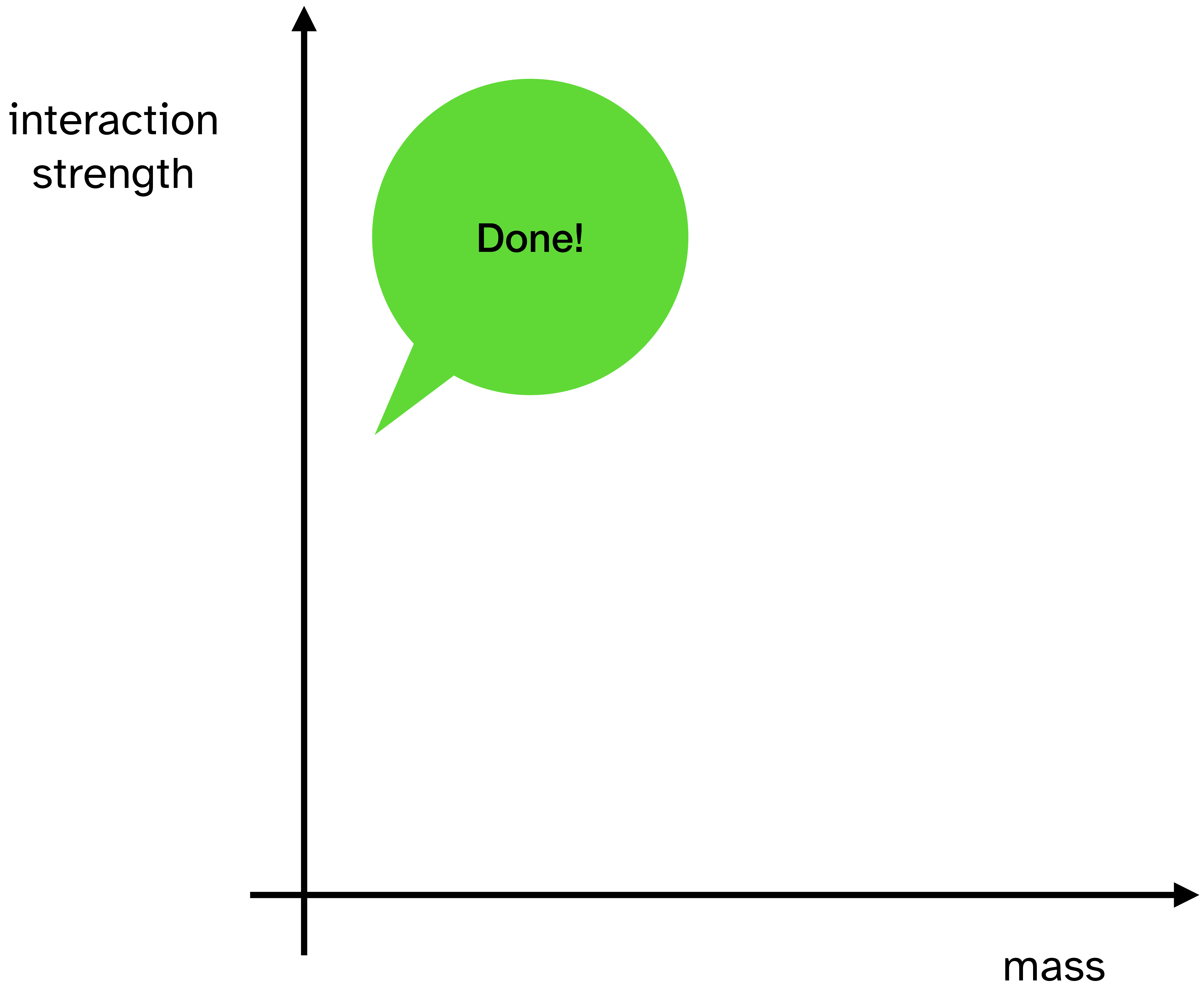
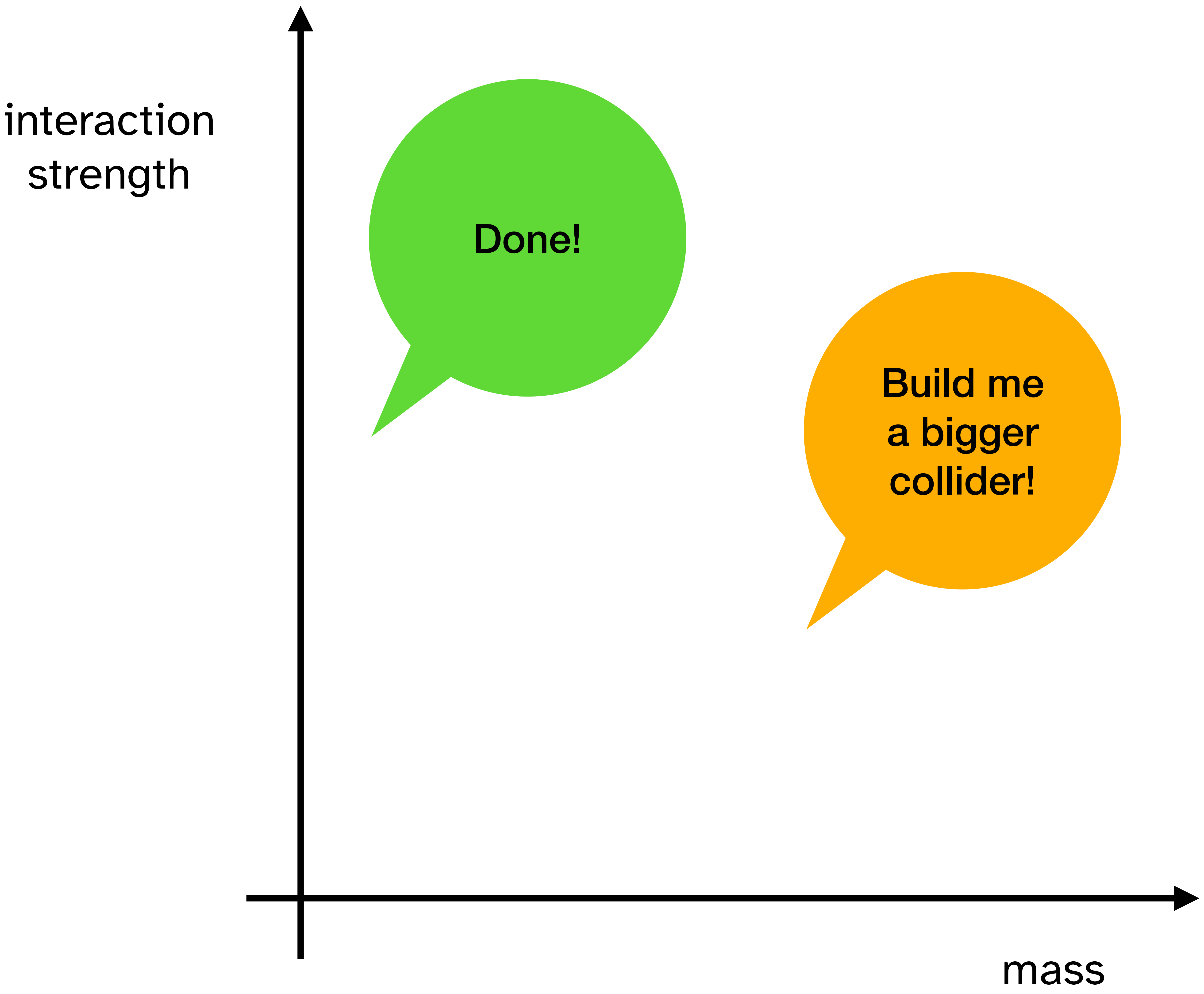
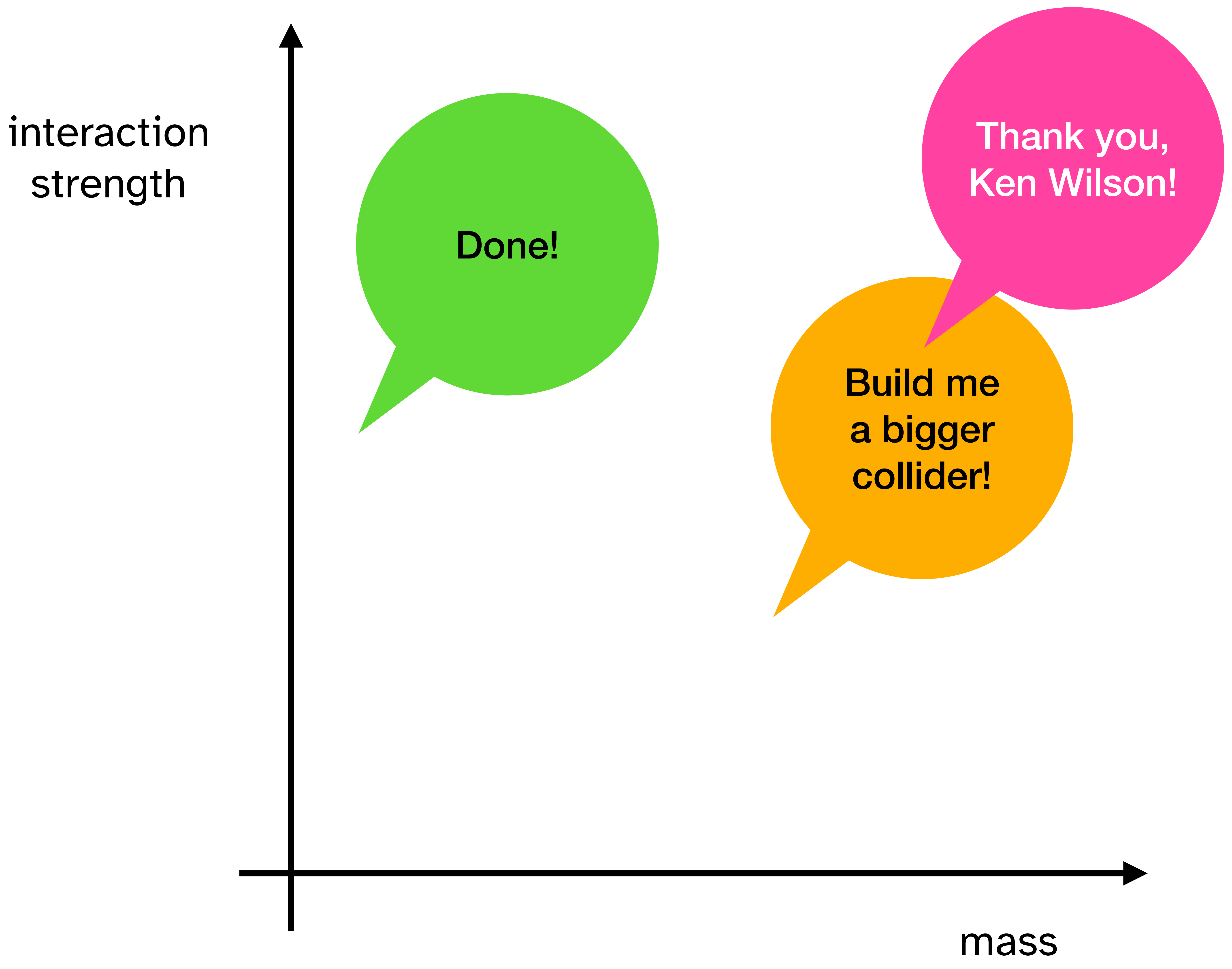
Recasting scalar-tensor theories of gravity for colliders

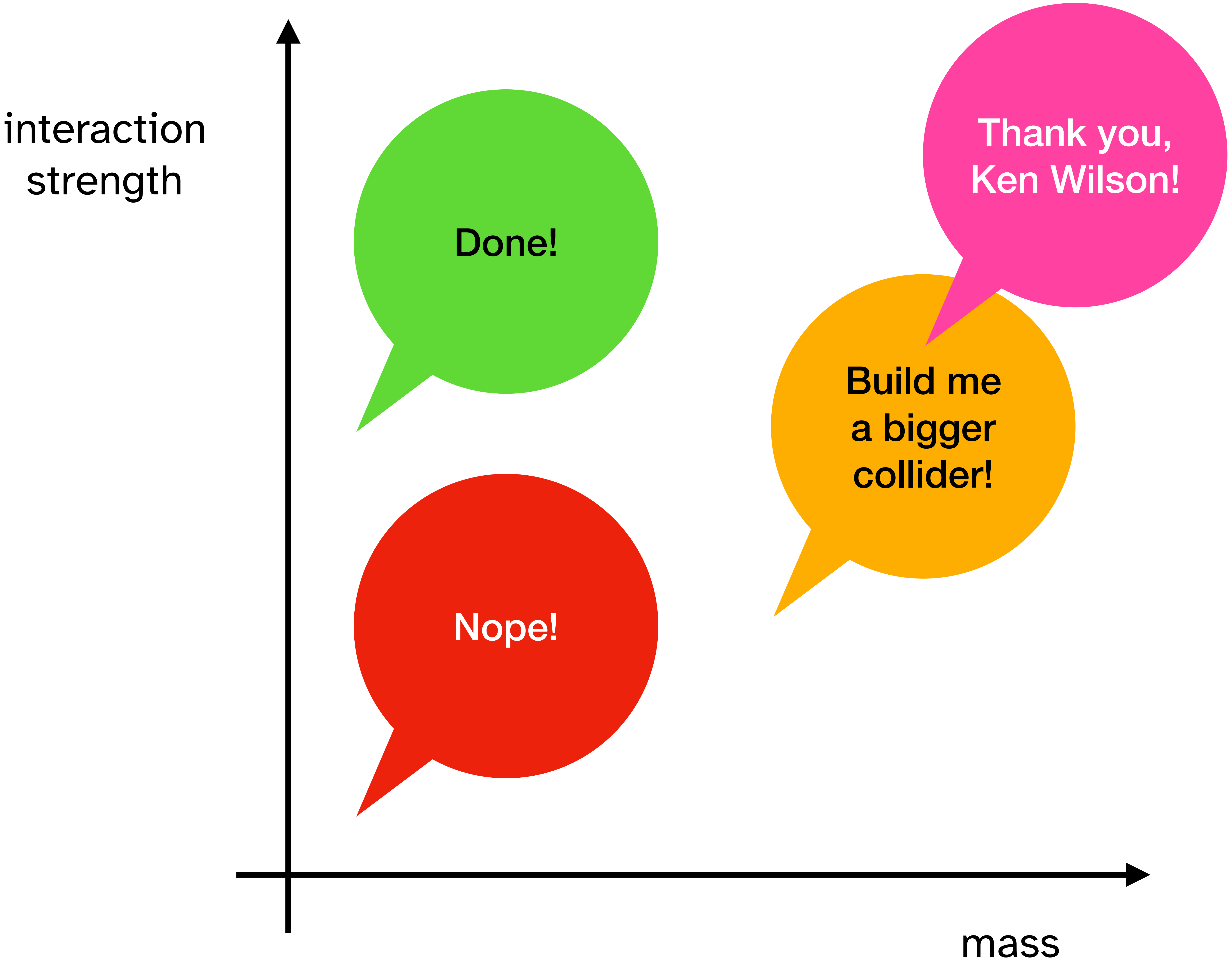
Based on work with: Clare Burrage (Nottingham), Edmund Copeland (Nottingham), Christoph Englert (Glasgow), Andrei Lazanu (Manchester), **Sergio Sevillano Muñoz (IPPP, Durham)**, Michael Spannowsky (IPPP, Durham)

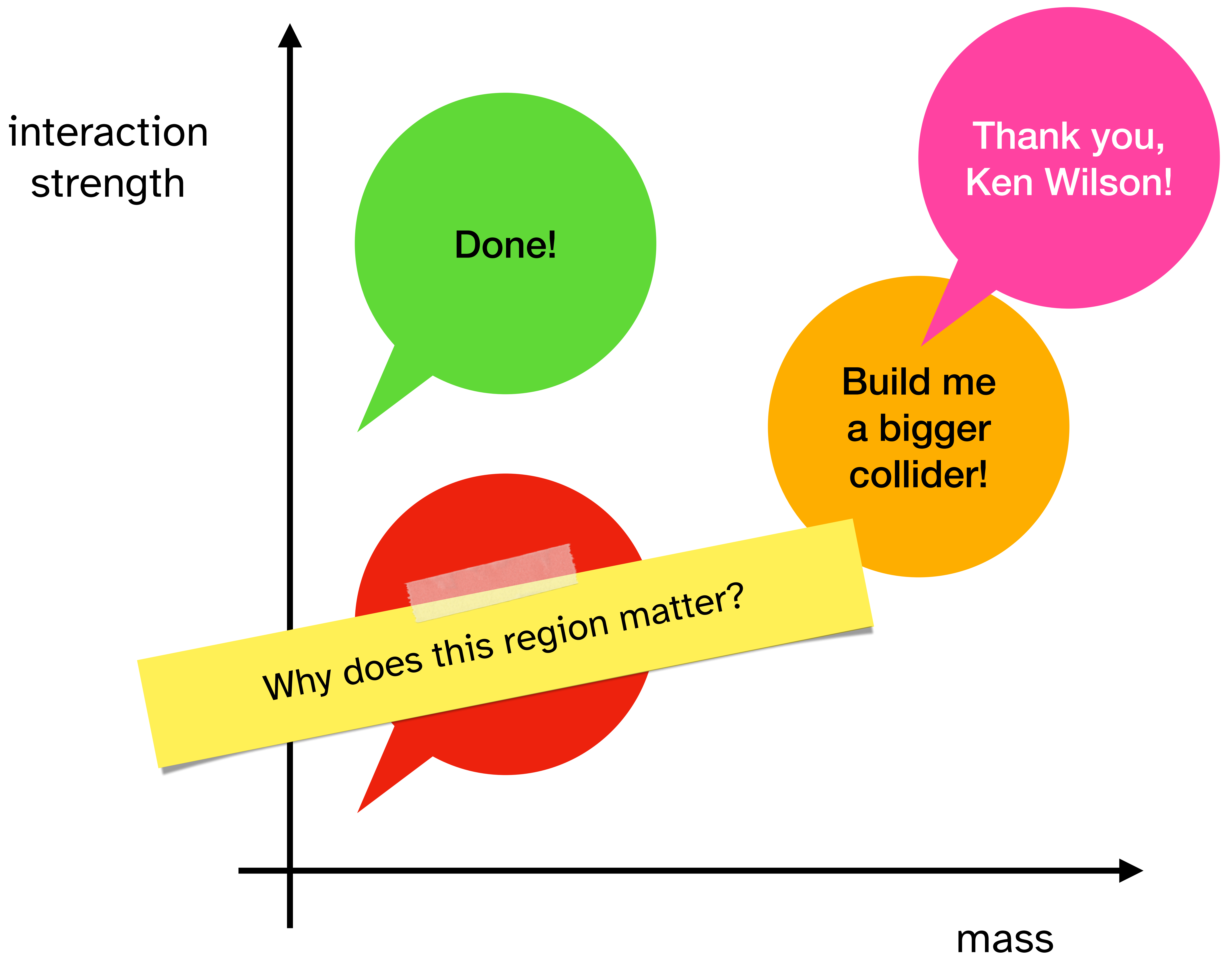
Peter Millington (UKRI Future Leaders Fellow, Particle Theory Group, University of Manchester)
peter.millington@manchester.ac.uk
ICHEP 2024, Prague, 18 July 2024


interaction
strength
Done!
mass

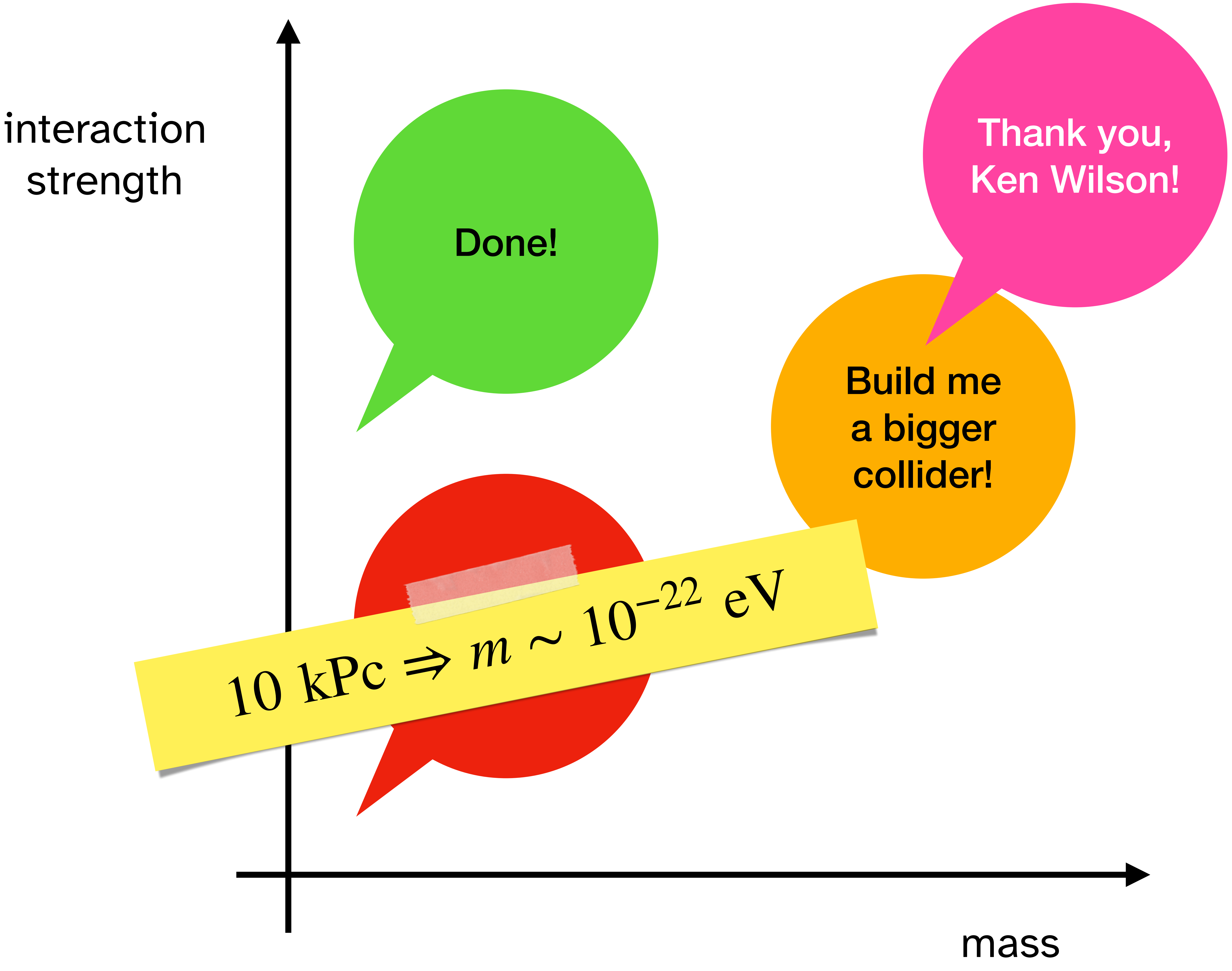

interaction strength
Done!
Build me a bigger collider!
mass


interaction strength
Done!
Thank you, Ken Wilson!
Build me a bigger collider!
mass

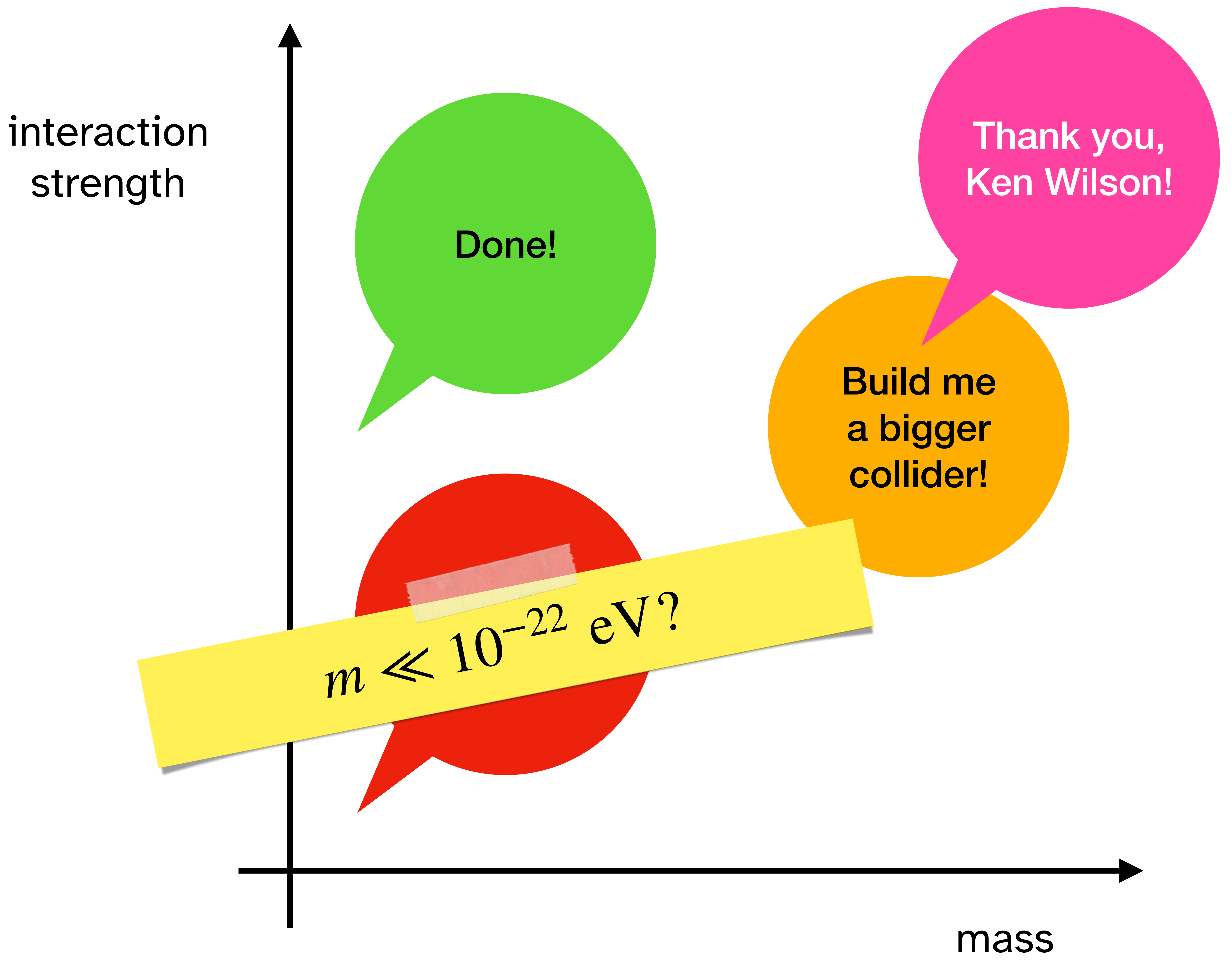

interaction strength
Done!
Thank you, Ken Wilson!
Build me a bigger collider!
Nope!
mass



see also Zimmermann et al. 2024 arXiv:2405.20374 [link]



see also Zimmermann et al. 2024, arXiv:2405.20374 [link]


interaction strength
Done!
Thank you, Ken Wilson!
Build me a bigger collider!
$m \ll 10^{-22}$ eV?
mass

Lovelock's theorem

a local gravity action in (3+1)D containing only 2nd-order derivatives of the metric $g_{\mu\nu}$ necessarily leads to the **Einstein field equations**

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + g_{\mu\nu}\Lambda = \kappa T_{\mu\nu}$$

Einstein Tensor   CC   SM

Lovelock 1971, J. Math. Phys. 12, 498 [link]

The Einstein–Hilbert action + CC + SM

$$S = \int \mathrm{d}^4x \sqrt{-g}\, \frac{M_{\mathrm{Pl}}^2}{2} (R - 2\Lambda) + S_{\mathrm{SM}} = S^\dagger$$

The Einstein–Hilbert action + CC + SM

gives
Newton's coupling

$$S = \int \mathrm{d}^4 x \, \sqrt{-g} \, \frac{M_{\mathrm{Pl}}^2}{2} \, (R - 2\Lambda) + S_{\mathrm{SM}} = S^{\dagger}$$

The Einstein–Hilbert action + CC + SM

gives
Newton's coupling

$$S = \underbrace{\int \mathrm{d}^4 x \sqrt{-g}}_{\text{spacetime volume element}} \frac{M_{\mathrm{Pl}}^2}{2} (R - 2\Lambda) + S_{\mathrm{SM}} = S^{\dagger}$$

spacetime
volume element

The Einstein–Hilbert action + CC + SM

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spacetime
volume element

Ricci scalar

The Einstein–Hilbert action + CC + SM

gives
Newton's coupling

CC

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spacetime
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spacetime
volume element

Ricci scalar

SM action

Going beyond ...

$$S = \int \mathrm{d}^4x \sqrt{-g}\, \frac{M_{\mathrm{Pl}}^2}{2} (R - 2\Lambda) + S_{\mathrm{SM}} = S^\dagger$$

see, e.g., Clifton, Ferreira, Padilla, Skordis 2012, Phys. Rept. 513, 1 [link]

Going beyond ...

make the Planck mass dynamical

$$S = \int \mathrm{d}^4x \sqrt{-g}\, \frac{M_{\rm Pl}^2}{2} (R - 2\Lambda) + S_{\rm SM} = S^\dagger$$

see, e.g., Clifton, Ferreira, Padilla, Skordis 2012, Phys. Rept. 513, 1 [link]

Going beyond …

make the Planck mass dynamical

$$S = \underbrace{\int \mathrm{d}^4x \sqrt{-g}}_{\text{add extra dimensions}} \frac{M_{\mathrm{Pl}}^2}{2} (R - 2\Lambda) + S_{\mathrm{SM}} = S^\dagger$$

add extra dimensions

see, e.g., Clifton, Ferreira, Padilla, Skordis 2012, Phys. Rept. 513, 1 [link]

Going beyond ...

make the Planck mass dynamical

CC

$$S = \int \underbrace{\mathrm{d}^4x \sqrt{-g}} \frac{M_{\mathrm{Pl}}^2}{2} (R - 2\Lambda) + S_{\mathrm{SM}} = S^\dagger$$

add extra dimensions

see, e.g., Clifton, Ferreira, Padilla, Skordis 2012, Phys. Rept. 513, 1 [link]

Going beyond ...

change the underlying symmetries

make the Planck mass dynamical

CC

$$S = \int \mathrm{d}^4x \sqrt{-g} \, \frac{M_{\mathrm{Pl}}^2}{2} (R - 2\Lambda) + S_{\mathrm{SM}} = S^\dagger$$

add extra dimensions

see, e.g., Clifton, Ferreira, Padilla, Skordis 2012, Phys. Rept. 513, 1 [link]

Going beyond ...

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make the Planck mass dynamical

CC

$$S = \int \mathrm{d}^4x \sqrt{-g}\, \frac{M_{\mathrm{Pl}}^2}{2} (R - 2\Lambda) + S_{\mathrm{SM}} = S^{\dagger}$$

add extra dimensions

add other curvature terms

see, e.g., Clifton, Ferreira, Padilla, Skordis 2012, Phys. Rept. 513, 1 [link]

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$$S = \int \mathrm{d}^4x \sqrt{-g}\, \frac{M_{\mathrm{Pl}}^2}{2} (R - 2\Lambda) + S_{\mathrm{SM}} = S^{\dagger}$$

add extra dimensions

add other curvature terms

add new degrees of freedom

add terms with higher derivatives or abandon locality

see, e.g., Clifton, Ferreira, Padilla, Skordis 2012, Phys. Rept. 513, 1 [link]

Going beyond ...

change the underlying symmetries

make the Planck mass dynamical

CC

$$S = \int \mathrm{d}^4x \sqrt{-g}\, \frac{M_{\mathrm{Pl}}^2}{2} (R - 2\Lambda) + S_{\mathrm{SM}} = S^\dagger$$

abandon Hermiticity or unitarity

add extra dimensions

add other curvature terms

add new degrees of freedom

add terms with higher derivatives or abandon locality

see, e.g., Clifton, Ferreira, Padilla, Skordis 2012, Phys. Rept. 513, 1 [link]

Going beyond ...

change the underlying symmetries

make the Planck mass dynamical

CC

abandon the action principle

$$S = \int \mathrm{d}^4x \, \sqrt{-g} \, \frac{M_{\mathrm{Pl}}^2}{2} \left(R - 2\Lambda\right) + S_{\mathrm{SM}} = S^\dagger$$

abandon Hermiticity or unitarity

add extra dimensions

add other curvature terms

add new degrees of freedom

add terms with higher derivatives or abandon locality

see, e.g., Clifton, Ferreira, Padilla, Skordis 2012, Phys. Rept. 513, 1 [link]

Going beyond ...

change the underlying symmetries

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CC

abandon the action principle

$$S = \int \mathrm{d}^4x \, \sqrt{-g} \, \frac{M_{\mathrm{Pl}}^2}{2} \left(R - 2\Lambda\right) + S_{\mathrm{SM}} = S^{\dagger}$$

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add extra dimensions

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add terms with higher derivatives or abandon locality

see, e.g., Clifton, Ferreira, Padilla, Skordis 2012, Phys. Rept. 513, 1 [link]

Geodesic equation

connection encodes the geometry

↓

$$\frac{\mathrm{d}^2 x^\mu}{\mathrm{d}\lambda^2} + \Gamma^\mu_{\alpha\beta} \frac{\mathrm{d}x^\alpha}{\mathrm{d}\lambda} \frac{\mathrm{d}x^\beta}{\mathrm{d}\lambda} = 0$$

$g_{\alpha\beta} \dfrac{\mathrm{d}x^\alpha}{\mathrm{d}\lambda} \dfrac{\mathrm{d}x^\beta}{\mathrm{d}\lambda}$ can be **timelike**, **spacelike** or **null** (i.e., zero)

Weyl rescaling

$$g_{\mu\nu} \to \Omega^2(x) g_{\mu\nu} \qquad \text{and} \qquad \frac{\mathrm{d}}{\mathrm{d}\lambda} \to \Omega^{-2}(x) \frac{\mathrm{d}}{\mathrm{d}\lambda}$$

$$\frac{\mathrm{d}^2 x^\mu}{\mathrm{d}\lambda^2} + \Gamma^\mu_{\alpha\beta} \frac{\mathrm{d}x^\alpha}{\mathrm{d}\lambda} \frac{\mathrm{d}x^\beta}{\mathrm{d}\lambda} - g_{\alpha\beta} \frac{\mathrm{d}x^\alpha}{\mathrm{d}\lambda} \frac{\mathrm{d}x^\beta}{\mathrm{d}\lambda} \frac{\partial}{\partial x_\mu} \ln \Omega = 0$$

geodesic motion

"fifth force"

Jordan versus Einstein frame

Jordan frame

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{F(\phi)}{2}R - \frac{Z^{\mu\nu}(\phi, \partial\phi, \ldots)}{2}\partial_\mu\phi\partial_\nu\phi - V(\phi) + \mathscr{L}_{\mathrm{SM}}(g_{\alpha\beta})\right]$$

Einstein frame, via $g_{\mu\nu} = M_{\mathrm{Pl}}^2 F^{-1}(\phi)\tilde{g}_{\mu\nu} = M_{\mathrm{Pl}}^2 A^2(\tilde{\phi})\tilde{g}_{\mu\nu}$

$$S = \int \mathrm{d}^4x\sqrt{-\tilde{g}}\left[\frac{M_{\mathrm{Pl}}^2}{2}\tilde{R} - \frac{\tilde{Z}^{\mu\nu}(\tilde{\phi}, \partial\tilde{\phi}, \ldots)}{2}\partial_\mu\tilde{\phi}\partial_\nu\tilde{\phi} - \tilde{V}(\tilde{\phi}) + \mathscr{L}_{\mathrm{SM}}(A^2(\tilde{\phi})\tilde{g}_{\alpha\beta})\right]$$

see also Finn, Karamitsos 2020, Pilaftsis Phys. Rev. D 102, 045014

Einstein frame

$$S_{\rm SM}[A^2(\tilde{\phi})\tilde{g}_{\mu\nu}, \{\psi\}] = S_{\rm SM}[\tilde{g}_{\mu\nu}, \{\psi\}] + \frac{1}{2}[A^2(\tilde{\phi}) - 1]\tilde{T}_{\rm SM} + \ldots$$

↑

"universal" coupling to SM

Test particle experiences a **fifth force**: $\overrightarrow{F}/m = -\overrightarrow{\nabla}\ln A(\tilde{\phi})$

Screening

$$\tilde{U}(r) \supset -\frac{1}{\tilde{Z}(\tilde{\varphi})c_s^2(\tilde{\varphi})}\left[\frac{\mathrm{d}A(\tilde{\varphi})}{\mathrm{d}\tilde{\varphi}}\right]^2 \frac{1}{4\pi r}\exp\left[-\frac{m(\tilde{\varphi})r}{\tilde{Z}^{1/2}(\tilde{\varphi})c_s(\tilde{\varphi})}\right]\mathscr{M}$$

Screening

increase the
effective mass

$$\tilde{U}(r) \supset -\frac{1}{\tilde{Z}(\tilde{\varphi})c_s^2(\tilde{\varphi})}\left[\frac{\mathrm{d}A(\tilde{\varphi})}{\mathrm{d}\tilde{\varphi}}\right]^2 \frac{1}{4\pi r}\exp\left[-\frac{m(\tilde{\varphi})r}{\tilde{Z}^{1/2}(\tilde{\varphi})c_s(\tilde{\varphi})}\right]\mathscr{M}$$

Khoury, Weltman 2004, Phys. Rev. Lett. 93, 171104 [link]

Screening

chameleon

increase the effective mass

$$\tilde{U}(r) \supset -\frac{1}{\tilde{Z}(\tilde{\varphi})c_s^2(\tilde{\varphi})}\left[\frac{\mathrm{d}A(\tilde{\varphi})}{\mathrm{d}\tilde{\varphi}}\right]^2 \frac{1}{4\pi r}\exp\left[-\frac{m(\tilde{\varphi})r}{\tilde{Z}^{1/2}(\tilde{\varphi})c_s(\tilde{\varphi})}\right]\mathscr{M}$$

Khoury, Weltman 2004, Phys. Rev. Lett. 93, 171104 [link]

Screening

chameleon

decrease the coupling strength

increase the effective mass

$$\tilde{U}(r) \supset -\frac{1}{\tilde{Z}(\tilde{\varphi})c_s^2(\tilde{\varphi})}\left[\frac{\mathrm{d}A(\tilde{\varphi})}{\mathrm{d}\tilde{\varphi}}\right]^2 \frac{1}{4\pi r}\exp\left[-\frac{m(\tilde{\varphi})r}{\tilde{Z}^{1/2}(\tilde{\varphi})c_s(\tilde{\varphi})}\right]\mathscr{M}$$

Khoury, Weltman 2004, Phys. Rev. Lett. 93, 171104 [link]

Screening

see e.g., Gessner 1992, Astrophys. Space Sci. 196, 1 [link]; Damour, Polyakov 1994, Nucl. Phys. B 423, 532 [link]; Hinterbichler, Khoury 2010, Phys. Rev. Lett. 104, 213301 [link]

symmetron/Damour–Polyakov

decrease the coupling strength

chameleon

increase the effective mass

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increase the effective sound speed

decrease the effective sound speed

Screening

Khoury, Weltman 2004, Phys. Rev. Lett. 93, 171104 [link]

see e.g., Gessner 1992, Astrophys. Space Sci. 196, 1 [link]; Damour, Polyakov 1994, Nucl. Phys. B 423, 532 [link]; Hinterbichler, Khoury 2010, Phys. Rev. Lett. 104, 213301 [link]

symmetron/Damour–Polyakov

decrease the coupling strength

chameleon

increase the effective mass

$$\tilde{U}(r) \supset -\frac{1}{\tilde{Z}(\tilde{\varphi})c_s^2(\tilde{\varphi})}\left[\frac{\mathrm{d}A(\tilde{\varphi})}{\mathrm{d}\tilde{\varphi}}\right]^2 \frac{1}{4\pi r}\exp\left[-\frac{m(\tilde{\varphi})r}{\tilde{Z}^{1/2}(\tilde{\varphi})c_s(\tilde{\varphi})}\right]\mathscr{M}$$

increase the effective sound speed

decrease the effective sound speed

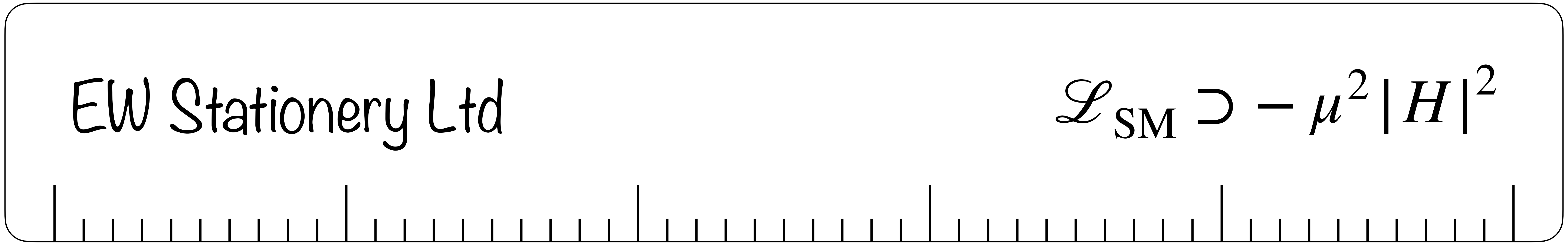
Vainshtein-like

Vainshtein 1972, Phys. Lett. B 39, 393 [link]

Weyl invariance

This is not the full story …

The SM Lagrangian is **scale invariant** with the **exception** of the **quadratic term** in the **Higgs potential**.



Beyond GR or Beyond SM?

scalar-tensor extension of GR

↓

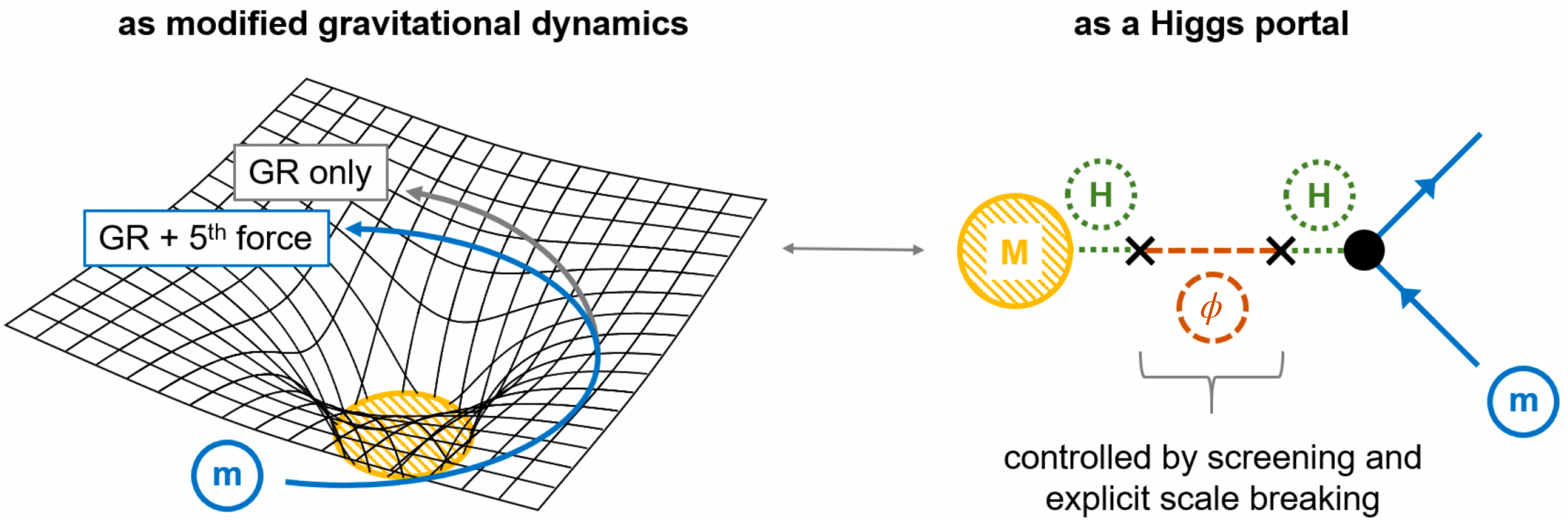
$\phi^2 R$ versus $\phi^2 |H|^2$

↑

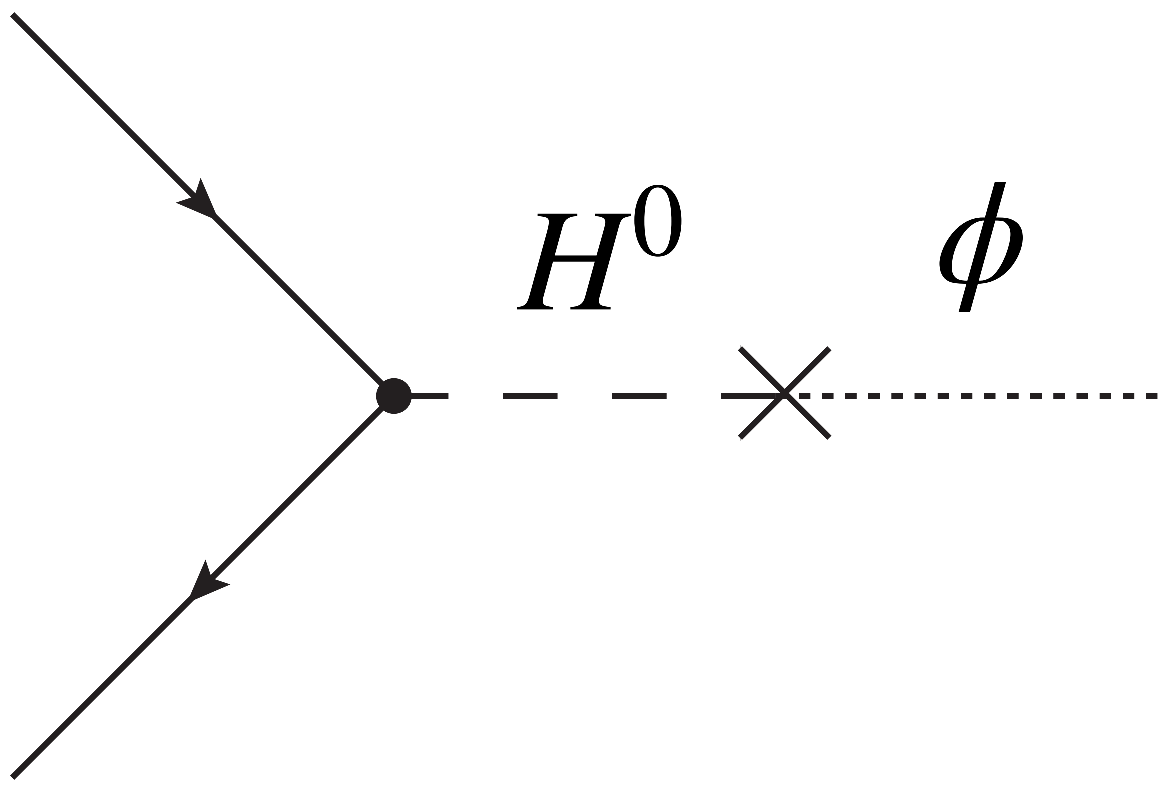
Higgs-portal extension of the SM

Burrage, Copeland, PM, Spannowsky 2018, JHEP11(2018)036 [link]

Beyond GR or Beyond SM?



Coupling to leptons



$$H^0 = \frac{h}{\sqrt{2}} + \frac{v}{\sqrt{2}}\frac{\zeta}{M}$$

$$\mathscr{L}_{\text{eff}} \supset -\frac{2\mu^2}{m_H^2}\frac{m_L}{M}\bar{\psi}_L\zeta\psi_L$$ where $$\frac{2\mu^2}{m_H^2} = 1$$ for the SM

Burrage, Copeland, PM, Spannowsky 2018, JHEP11(2018)036 [link]

Scale symmetry breaking

Fifth forces from $F(\phi)R$ terms depend on the origin of **scale breaking** in the electroweak and QCD sectors (and the origin of neutrino masses).

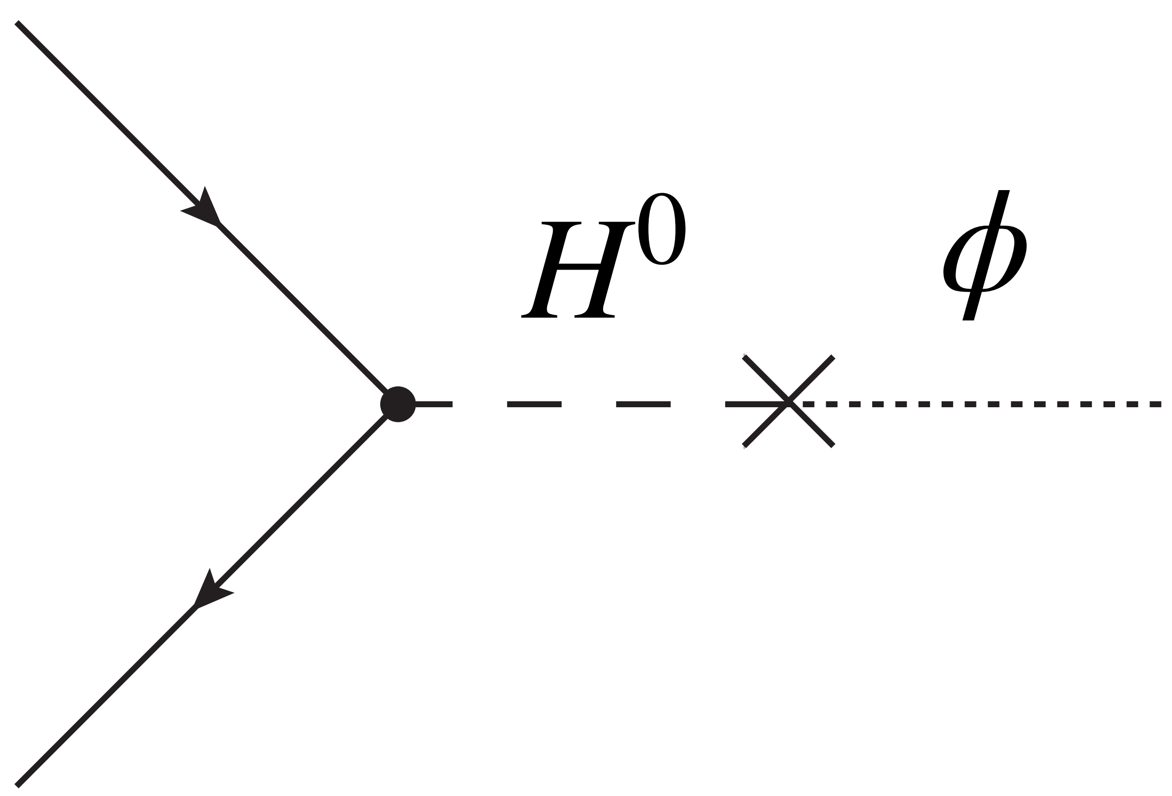
explicit scale breaking ⇒ fifth force coupling

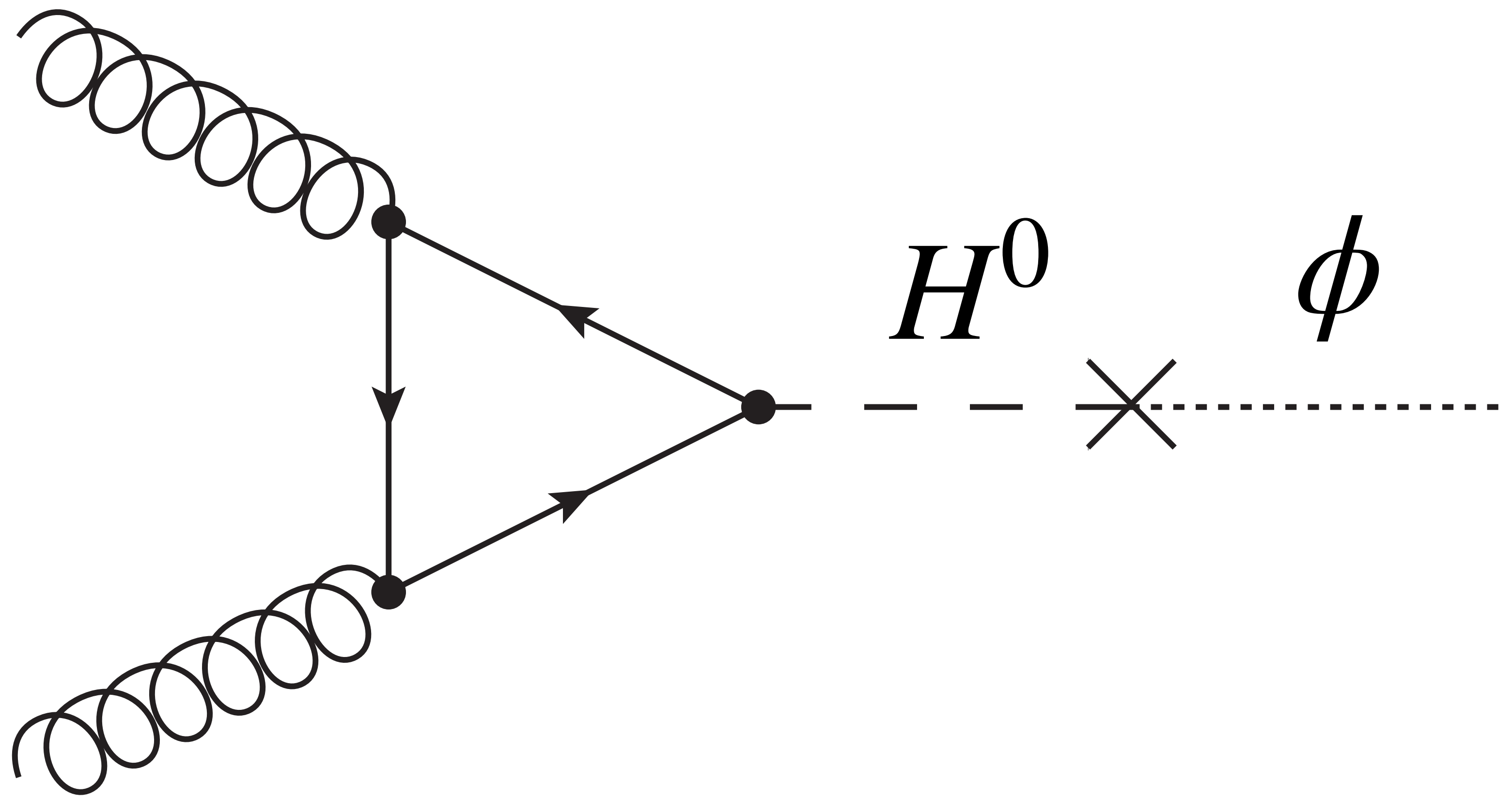
dynamical scale breaking ⇒ **no** fifth force coupling

But **beware**, fine tuning.

see e.g. Higgs-Dilaton theories: Shaposhnikov, Zenhäusern 2009, Phys. Lett. B 671, 187 [link]; see also Brax, Davis 2014, JCAP05(2014)019 [link]; Ferreira, Hill, Ross 2017, Pays. Rev. D 95, 064038 [link]; Burrage, Copeland, PM, Spannowsky 2018, JHEP11(2018)036 [link]

Coupling to hadrons (for the SM)





$$H^0 = \frac{h}{\sqrt{2}} + \frac{v}{\sqrt{2}}\frac{\zeta}{M}$$

heavy quarks

$$\mathscr{L}_{\text{eff}} \supset -\eta \frac{m_N}{M}\bar{\psi}_N \zeta \psi_N \quad \text{with} \quad \eta \equiv \frac{2N_H}{3B} + \sum_{q\in\{u,d,s\}} f_{Tq}^N \left(1 - \frac{2N_H}{3B}\right) < 1$$

light quarks

Burrage, Copeland, PM, Spannowsky 2018, JHEP11(2018)036 [link]

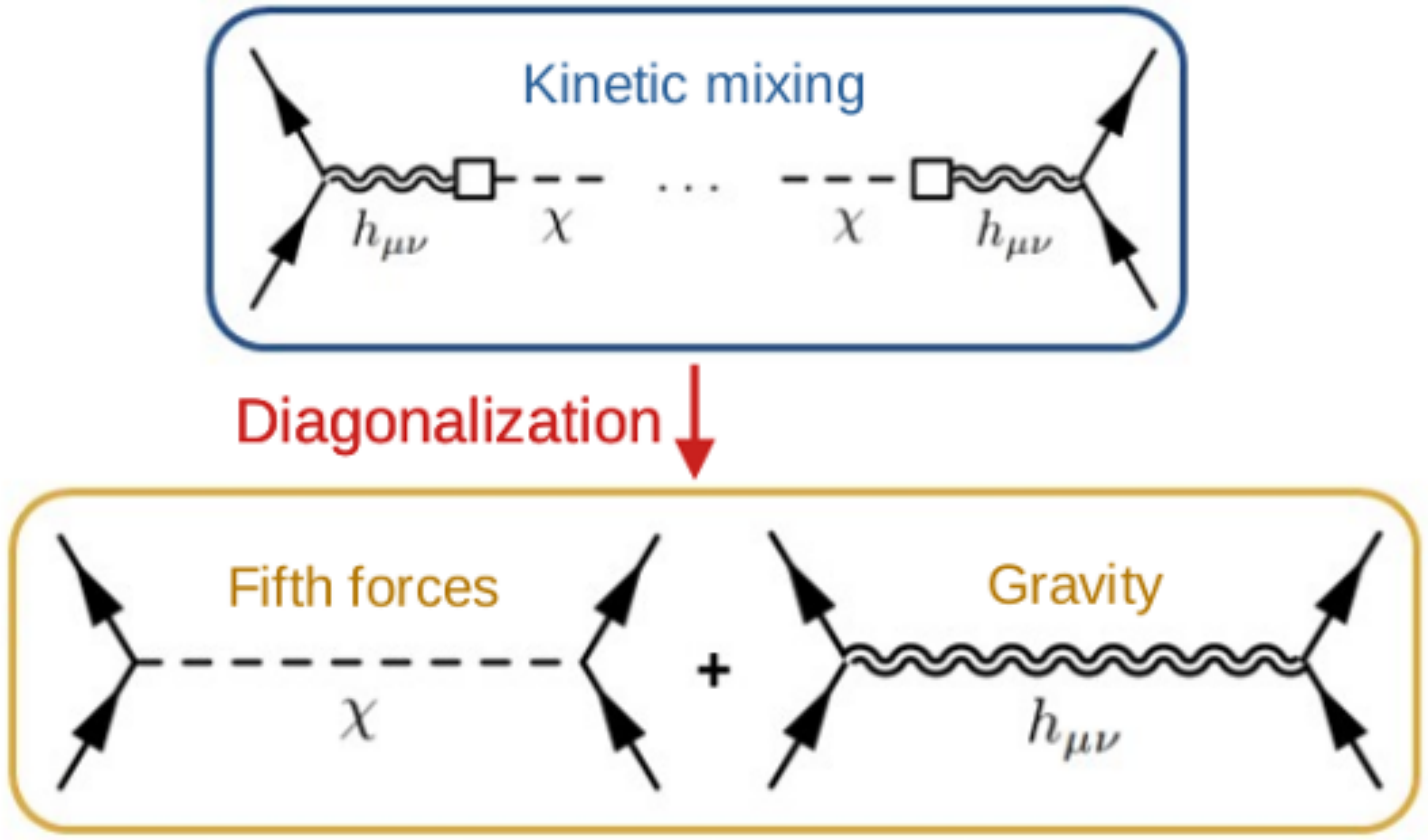
Fifth forces in the Jordan frame

Fifth forces in the Jordan frame arise via mixing with the graviton ($g \to \eta + g$):

$$\mathscr{L} = \frac{F(\phi)}{4}\left[\frac{1}{4}\partial_\mu g \partial^\mu g - \frac{1}{2}\partial_\rho g_{\mu\nu}\partial^\rho g^{\mu\nu}\right] + \frac{F'(\phi)}{4}\eta^{\mu\nu}\partial_\mu g \partial_\nu \phi$$

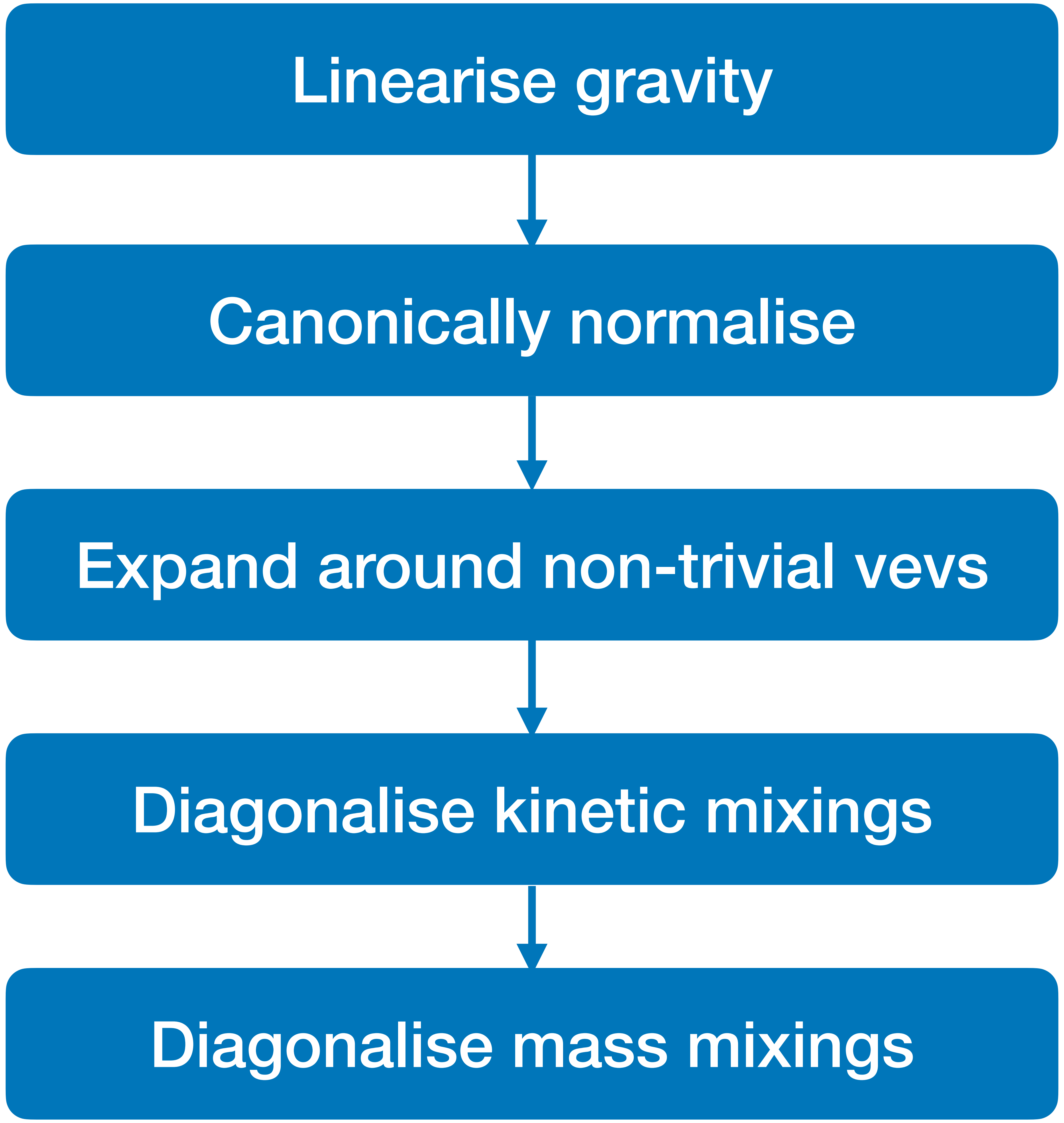
$$- \frac{1}{2}\left[Z(\phi) + \frac{[F'(\phi)]^2}{2F(\phi)}\right]\eta^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)$$

$$+ \frac{1}{2}g^{\mu\nu}T_{\mu\nu} + \mathscr{L}_{\rm SM}(\eta, \{\psi\})$$



Copeland, PM, Sevillano Muñoz 2111.06357; graphic by Sergio Sevillano Muñoz

Procedure



Sevillano Muñoz, Copeland, PM, Spannowsky 2211.14300; based on slide by Sergio Sevillano Muñoz

Automation — FeynMG

Feyn MG

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

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

[a] *School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, UK*

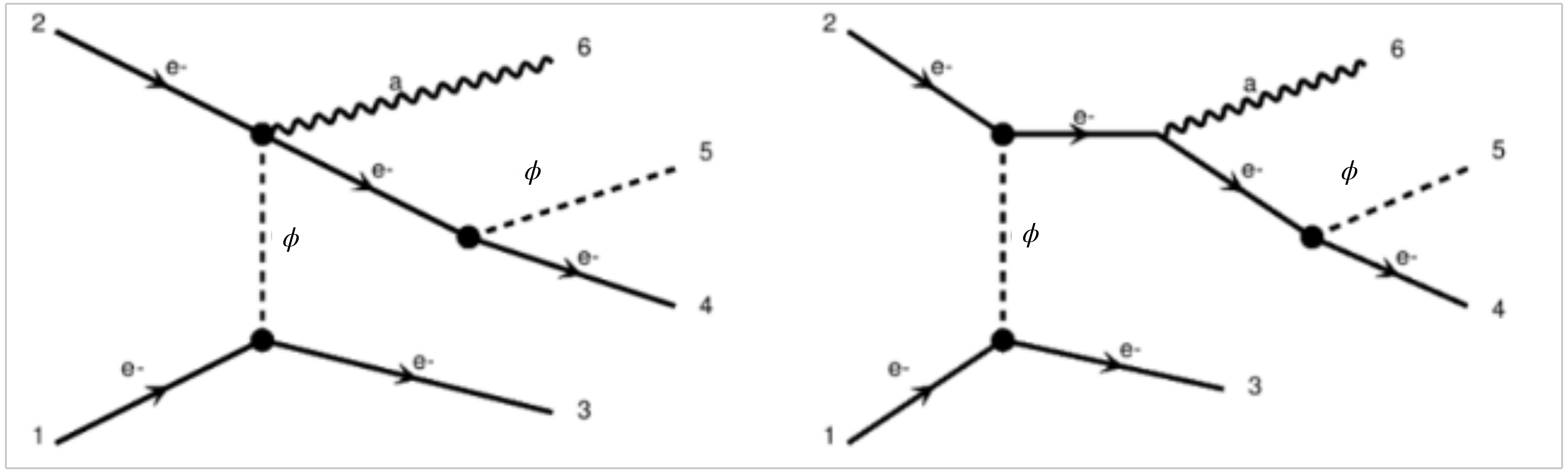
[b] *Department of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, UK*

[c] *Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham, DH1 3LE, UK*

SCAN ME

Sevillano Muñoz, Copeland, PM, Spannowsky 2211.14300; based on slide by Sergio Sevillano Muñoz

FeynMG



MadGraph Output

1. Load **FeynRules** and **FeynMG** into **Mathematica**.
2. Load a FeynRules Model File, say for the full SM.
3. Use FeynMG to append a (modified) gravitational sector and condition the Lagrangian into a form for FeynRules to process.
4. Generate Feynman rules or export to existing analysis pipelines (e.g., **MadGraph**).

Sevillano Muñoz, Copeland, PM, Spannowsky 2211.14300; based on slide by Sergio Sevillano Muñoz
FeynRules: https://feynrules.irmp.ucl.ac.be/; MadGraph: http://madgraph.phys.ucl.ac.be/index.html

An example: off-shell coupling

Consider the coupling

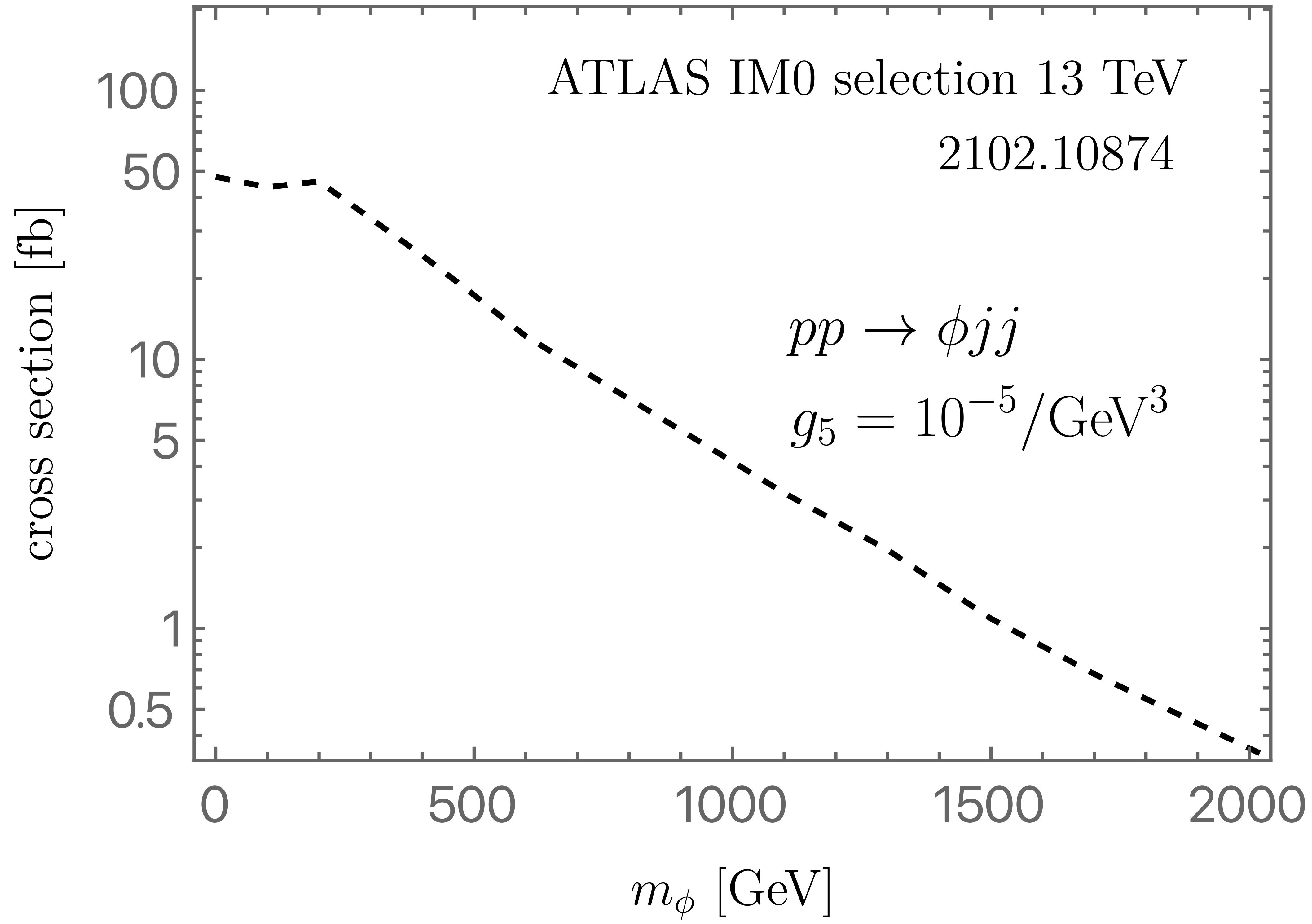
$$\mathscr{L} \supset \frac{C}{M^3} T_{\mu\nu} \partial^\mu \partial^\nu \phi$$

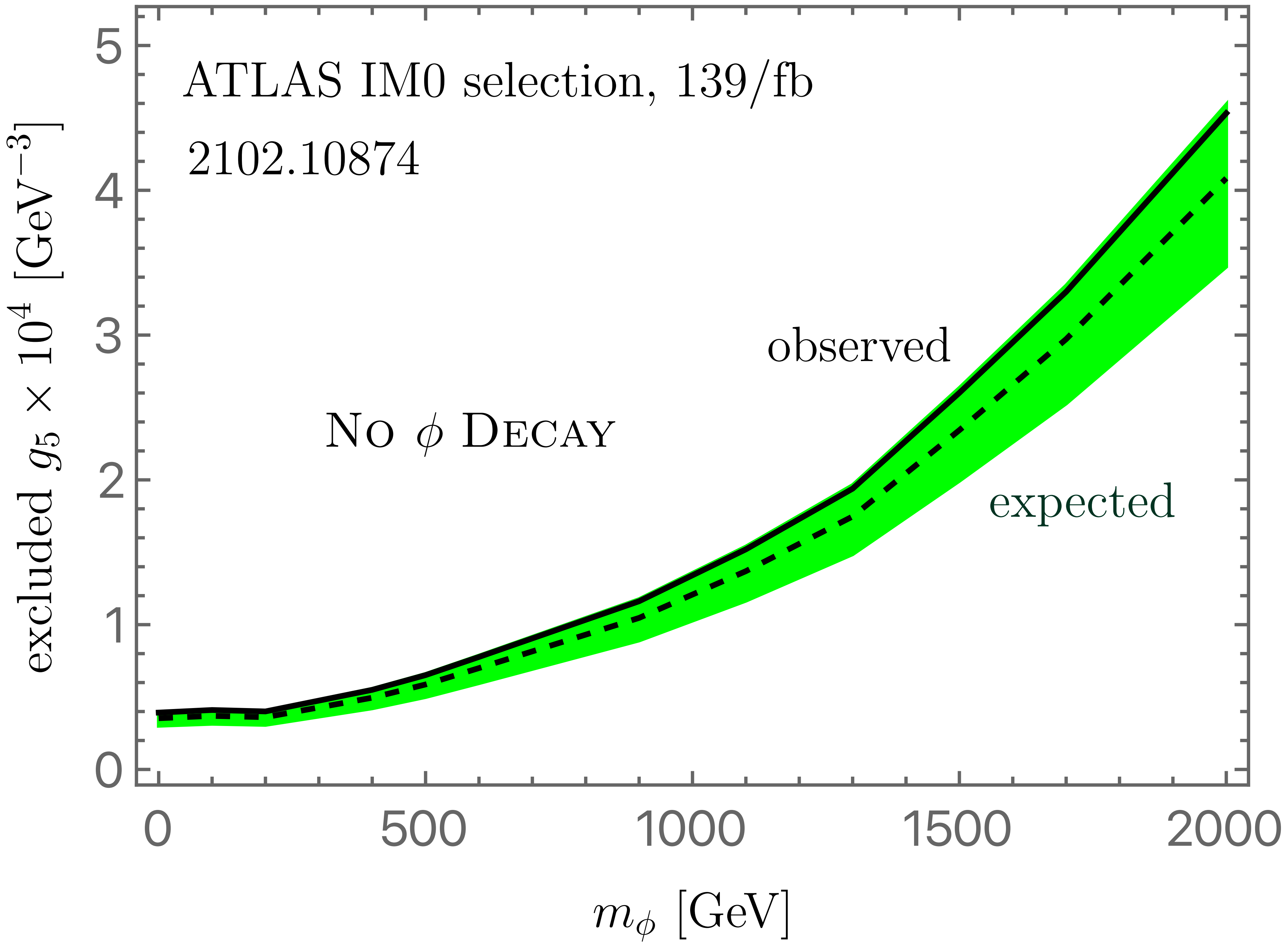
The energy-momentum tensor $T_{\mu\nu}$ of an on-shell state has vanishing divergence, so ϕ will couple only to off-shell states.

First deviations for 2 to 3 processes or at the loop level …

Englert, Lazanu, Millington 2024 (to appear)

An example: off-shell coupling





Left: Cross-section for ϕ plus two jets for the ATLAS IM0 selection before the ϕ decay.

Right: Translation of this into exclusion contours assuming ϕ is stable.

Englert, Lazanu, Millington 2024 (to appear)

Summary

QFT prevents us from disentangling **scalar extensions of GR** from **scalar extensions of the SM**.

Screened fifth forces have rich phenomenology due to their environmental dependence.

Parallels between scalar-tensor theories of gravity and: **axion-like models**, **ultra-light dark matter models**, **Higgs-portal theories**, …

Particle physics of a broad class of models can be automated … with **FeynMG** … with novel collider signatures.

Fifth force

Classical equation of motion for perturbations $\delta\tilde{\varphi} = \left\langle \tilde{\phi} \right\rangle - \tilde{\varphi}$:

$$\tilde{Z}(\tilde{\varphi})(\delta\ddot{\tilde{\varphi}} - c_s^2(\tilde{\varphi})\,\nabla^2\delta\tilde{\varphi}) + m^2(\tilde{\varphi})\delta\tilde{\varphi} = -\frac{1}{2}\frac{\mathrm{d}A^2(\tilde{\varphi})}{\mathrm{d}\tilde{\varphi}}\tilde{T}_{\mathrm{SM}}$$

Yukawa potential around a point source $\tilde{T} = -A^{-1}(\tilde{\varphi})\mathscr{M}\delta^3(\mathbf{x})$:

$$\tilde{U}(r) \supset -\frac{1}{\tilde{Z}(\tilde{\varphi})c_s^2(\tilde{\varphi})}\left[\frac{\mathrm{d}A(\tilde{\varphi})}{\mathrm{d}\tilde{\varphi}}\right]^2\frac{1}{4\pi r}\exp\left[-\frac{m(\tilde{\varphi})r}{\tilde{Z}^{1/2}(\tilde{\varphi})c_s(\tilde{\varphi})}\right]\mathscr{M}$$

Joyce, Jain, Khoury, Trodden 2015, Phys. Rept. 568, 1 [link]

Higgs-Dilaton

$$M_{\rm Pl}^2 R \to (\xi_H H^2 + \xi_\phi \phi^2)R \quad \text{and} \quad -\mu^2 H^2 + \frac{\lambda}{4}H^4 \to \frac{\lambda}{4}\left(H^2 - \frac{\beta}{\lambda}\phi^2\right)^2$$

There is a **conserved dilatation current**, and a **massless Goldstone mode**

$$\sigma \propto \ln\left[(6\xi_\phi + 1)\phi^2 + (6\xi_H + 1)H^2\right]$$

with at most derivative couplings to the Higgs boson ⇒ **no fifth forces**.

e.g., Shaposhnikov, Zenhäusern 2009, Phys. Lett. B 671, 187 [link]; Brax, Davis 2014, JCAP05(2014)019 [link];
Ferreira, Hill, Ross 2017, Pays. Rev. D 95, 064038 [link]; Burrage, Copeland, PM, Spannowsky 2018, JHEP11(2018)036 [link]