GRAVITATIONAL NATURALIZATION OF EFFECTIVE FIELD THEORIES

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OUTLINE

THE PROBLEM

- Effective field theories, obtained by integrating-out high-energy quantum field fluctuations, are quantum theories of low-energy fields.

- Effective field theories flee the low-energy domain by the quadratic and quartic divergences in their bosonic sectors, including the anomalous gauge boson masses.

- Known mechanisms capable of neutralizing the quadratic and quartic divergences seem to have been sidelined by the LHC experiments; a new, viable mechanism is needed.

PROPOSED SOLUTION:

As will be discussed in this talk, gravity can emerge in a way

- restoring gauge symmetries,

- neutralizing the quadratic and quartic divergences, and

- introducing new particles that can cover various phenomena, including the dark matter.

INCLUDING QUADRATIC AND QUARTIC DIVERGENCES IN DIMENSIONAL REGULARIZATION

$$I_n = \int \frac{d^4p}{(2\pi)^4} \frac{1}{(p^2 - m^2 + i0)^n}$$

$$= \Lambda^{4-2n} \, \mu^{2n-D} \frac{1}{(2\pi)^{4-D}} \int \frac{d^Dp}{(2\pi)^D} \frac{1}{(p^2 - m^2 + i0)^n}$$

$$= \begin{cases} \dfrac{i\Lambda^4}{8\pi^4} & (n \to 0\,, D \to 0) \\[2ex] \dfrac{-i\Lambda^2}{16\pi^3} \log\dfrac{\mu^2}{m^2} & (n \to 1\,, D \to 2) \\[2ex] \dfrac{i}{16\pi^2} \log\dfrac{\mu^2}{m^2} & (n \to 2\,, D \to 4) \end{cases}$$

"Dimensional Regularization" is modified by introducing two scales:

- Λ for power-law divergences
- μ for logarithmic divergences

D.Demir, to be submitted (August 2021)

As equivalent of cut-off regularization, "Minimal Subtraction" is extended to "Power-Divergence Subtraction" by keeping all three divergences:

- $D = 0$ (quartic)
- $D = 2$ (quadratic)
- $D = 4$ (logarithmic)

D.B.Kaplan *et al.*, Phys. Lett. B424, 390 (1998)

EFFECTIVE FIELD THEORY

Once high-energy quantum fields are integrated out, the low-energy fields ψ_{LE} assume the effective action

$$S_{eff}(\psi_{LE}) = S(\psi_{LE}) + \delta S(\psi_{LE})$$

with the quantum correction (in power-divergence subtraction scheme)

$$\delta S = \int d^4x \sqrt{-\eta}\,\{-c_O\Lambda^4 - \sum_m c_m m^2\Lambda^2 \; - c_S\Lambda^2 S^\dagger S + c_V\Lambda^2\eta_{\alpha\beta}\mathrm{tr}[V^\alpha V^\beta] + \delta\ell(\eta, \log\mu\,, \psi_{LE})\}$$

- $\eta_{\alpha\beta} = \mathrm{diag.}(1, -1, -1, -1)_{\alpha\beta}$ is the flat Minkowski metric
- $c_O = c_O(\log\mu),\; c_m = c_m(\log\mu),\; c_S = c_S(\log\mu),\; c_V = c_V(\log\mu)$
- $\psi_{LE} = \{\text{scalars } S(x), \text{gauge bosons } V_i^\alpha(x), \text{fermions } f(x)\}$
- $\delta\ell(\eta, \log\mu\,, \psi) =$ logarithmic ($\log\mu$) corrections
- $c_O \propto n_B - n_F$ and at one loop $\sum_m c_m m^2 \propto \mathrm{str}[m^2]$

D.Demir, to be submitted (August 2021)

EXPLICIT BREAKING OF GAUGE SYMMETRIES

Gauge bosons in the QFT acquire anomalous mass terms:

$$\delta S_V(\eta, \Lambda) = \int d^4x \sqrt{-\eta}\; c_V \Lambda^2 \eta_{\alpha\beta} \mathrm{tr}[V^\alpha V^\beta]$$

These loop-induced hard mass terms lead to a complete destruction of the QFT because

- They violate electric and color charge conservations

  M.Peskin and D. Schroeder, Quantum Field Theory (1995); P. Chankowski *et al.*, Acta Phys. Pol. B48, 5 (2017)

- They push the W and Z masses outside the spontaneous electroweak breaking regime, with unavoidable changes in the weak mixing angle.

- They can in principle be avoided by using the Stueckelberg trick but that method leads to unphysical effects like the coupling of photons to neutrinos.

  H. Ruegg and M. Ruiz-Altaba, Int. J. Mod. Phys. A19, 3265 (2004).

RESTORATION OF GAUGE SYMMETRIES

Gauge symmetries broken explicitly by the anomalous masses

$$\delta S_V(\eta, \Lambda) = \int d^4x \sqrt{-\eta}\, c_V(\log \mu^2)\, \Lambda^2 \eta_{\alpha\beta} \mathrm{tr}[V^\alpha V^\beta]$$

can be restored as usual by introducing spurion fields:

R. Penco, An Introduction to Effective Field Theories, arXiv:2006.16285 (2020).

- $\mu \to \mu(x)$ spurion is forbidden by the equivalence principle.

- $\Lambda \to \Lambda(x)$ spurion is allowed because it pertains only to the quadratic and quartic divergences.

- What is needed is to determine if the $\Lambda(x)$ spurion can be given the requisite form to restore the gauge symmetries.

RESTORATION OF GAUGE SYMMETRIES

Consider these two kinetic structures:

$$I_V(\eta) = \int d^4x\sqrt{-\eta}\; c_V \mathrm{tr}[V^{\alpha\beta}V_{\alpha\beta}]$$

$$\tilde{I}_V(\eta) = \int d^4x\sqrt{-\eta}\; c_V \mathrm{tr}[V^{\alpha}(-D^2\eta_{\alpha\beta} + D_\alpha D_\beta + iV_{\alpha\beta})V^{\beta} + \partial_\alpha\left(V_\beta V^{\alpha\beta}\right)]$$

by-parts

- In flat spacetime:

  $-I_V(\eta) + \tilde{I}_V(\eta) = 0$

- In curved spacetime (general covariance: $\eta_{\alpha\beta} \rightarrow g_{\alpha\beta}$ and $\partial_\alpha \rightarrow \nabla_\alpha$):

  $-I_V(g) + \tilde{I}_V(g) = -\int d^4x\sqrt{-g}\; c_V \mathrm{tr}[V^{\alpha}R_{\alpha\beta}({}^{g}\Gamma)\mathrm{V}^{\beta}]$

- ∇_α = Levi-Civita connection with the coefficients

  ${}^{g}\Gamma^{\lambda}_{\alpha\beta} = \frac{1}{2}\, g^{\lambda\rho}\left(\partial_\alpha g_{\beta\rho} + \partial_\beta g_{\rho\alpha} - \partial_\rho g_{\alpha\beta}\right)$

D. Demir, Adv. High Energy Phys. 6727805 (2016)

D. Demir, Adv. High Energy Phys. 4652048 (2019)

D. Demir, Gen. Rel. Grav. 53, 22 (2021)

RESTORATION OF GAUGE SYMMETRIES

In flat spacetime:

$$\delta\hat{S}_V(\eta,\Lambda) = -I_V(\eta) + \tilde{I}_V(\eta) + S_V(\eta,\Lambda)$$

In curved spacetime:

$$\delta\hat{S}_V(g,\Lambda) = -I_V(g) + \tilde{I}_V(g) + S_V(g,\Lambda) = \int d^4x\sqrt{-g}\, c_V \mathrm{tr}[V^\alpha(\Lambda^2(x)\, g_{\alpha\beta} - R_{\alpha\beta}({}^g\Gamma))\mathrm{V}^\beta]$$

- $\Lambda(x)$ spurion lives in flat spacetime. It can have therefore no relationship to the spacetime Ricci curvature $R_{\alpha\beta}({}^g\Gamma)$.

- $\Lambda(x)$ spurion can have, however, a direct relationship to "affine curvature" $\mathbb{R}_{\alpha\beta}(\Gamma)$ because the affine connection $\Gamma^\lambda_{\alpha\beta}$ is independent of the spacetime metric and can live in flat spacetime as a rank-(1,2) tensor field ($\Gamma^\lambda_{\alpha\beta}$ is independent of the Levi-Civita connection ${}^g\Gamma^\lambda_{\alpha\beta}$).

- If the dynamics of affine connection $\Gamma^\lambda_{\alpha\beta}$ enables gauge symmetries can be restored by the definition

  $$\Lambda^2(x)\, g_{\alpha\beta}(x) = \mathbb{R}_{\alpha\beta}(\Gamma(x))$$

RESTORATION OF GAUGE SYMMETRIES

Identification of the $\Lambda(x)^2$ spurion with the affine curvature results in a metric-affine gravity theory

$$\delta\hat{S} = \int d^4x \sqrt{-g}\,\left\{-\frac{c_O}{16}\left(g^{\alpha\beta}\mathbb{R}_{\alpha\beta}(\Gamma)\right)^2 - \frac{1}{16\pi G_N}g^{\alpha\beta}\mathbb{R}_{\alpha\beta}(\Gamma) - \frac{c_S}{4}g^{\alpha\beta}\mathbb{R}_{\alpha\beta}(\Gamma)\left(S^\dagger S - \langle S^\dagger S\rangle\right) + \right.$$

which remains stationary against variations in the affine connection $\Gamma^\lambda_{\alpha\beta}$ provided that

$$^{\Gamma}\nabla_\lambda \mathrm{Q}_{\alpha\beta} = 0$$

in which $^{\Gamma}\nabla_\lambda$ is covariant derivative with respect to $\Gamma^\lambda_{\alpha\beta}$, and

$$Q_{\alpha\beta} = \left(\frac{1}{16\pi G_N} + \frac{c_S}{4}g^{\alpha\beta}S^\dagger S + \frac{c_O}{8}g^{\mu\nu}\mathbb{R}_{\mu\nu}(\Gamma)\right)g_{\alpha\beta} - c_V \mathrm{tr}[V_\alpha V_\beta]$$

with Newton's constant

$$G_N^{-1} = 4\pi\left(\sum_m c_m m^2 + c_S\langle S^\dagger S\rangle\right)\xrightarrow[\text{1-loop}]{} 4\pi\left(\mathrm{str}[m^2] + c_S\langle S^\dagger S\rangle\right)$$

RESTORATION OF GAUGE SYMMETRIES

The affine connection $\Gamma^{\lambda}_{\alpha\beta}$ has the general solution

$$\Gamma^{\lambda}_{\alpha\beta} = {}^{g}\Gamma^{\lambda}_{\alpha\beta} + \frac{1}{2}(Q^{-1})^{\lambda\rho}\left(\nabla_{\alpha}Q_{\beta\rho} + \nabla_{\beta}Q_{\rho\alpha} - \nabla_{\rho}Q_{\alpha\beta}\right)$$

which at the leading order gives rise to

$$\Gamma^{\lambda}_{\alpha\beta} = {}^{g}\Gamma^{\lambda}_{\alpha\beta} + 8\pi G_N\left(\nabla_{\alpha}Q^{\lambda}_{\beta} + \nabla_{\beta}Q^{\lambda}_{\alpha} - \nabla^{\lambda}Q_{\alpha\beta}\right) + \mathcal{O}(G_N^2)$$

and hence

$$\mathbb{R}_{\alpha\beta}(\Gamma) = R_{\alpha\beta}({}^{g}\Gamma) + 8\pi G_N\left(\nabla^{\mu}\nabla_{\alpha}\delta^{\nu}_{\beta} + \nabla^{\nu}\nabla_{\alpha}\delta^{\mu}_{\beta} - \Box\delta^{\mu}_{\alpha}\delta^{\nu}_{\beta} - \nabla_{\alpha}\nabla_{\beta}g^{\mu\nu} + (\alpha \leftrightarrow \beta)\right)Q_{\mu\nu} + \mathcal{O}(G_N^2)$$

derivatives of the scalars S and gauge fields V_i^{α}

RESTORATION OF GAUGE SYMMETRIES

Given the solution of the affine curvature, metric-affine curvature sector reduce to that of the metrical curvature scalar $R(g) = g^{\alpha\beta} R_{\alpha\beta}({}^{g}\Gamma)$:

GR emerges

- $\int d^4x \sqrt{-g}\left\{-\frac{1}{16\pi G_N} g^{\alpha\beta}\mathbb{R}_{\alpha\beta}(\Gamma)\right\} = \int d^4x \sqrt{-g}\left\{-\frac{R(g)}{16\pi G_N} + \mathcal{O}(G_N)\right\}$

gauge hierarchy problem reduces to logarithmic little hierarchy problem

- $\int d^4x \sqrt{-g}\{-c_S g^{\alpha\beta}\mathbb{R}_{\alpha\beta}(\Gamma) S^\dagger S\} = \int d^4x \sqrt{-g}\left\{-\frac{c_S}{4} R(g) S^\dagger S + \mathcal{O}(G_N)\right\}$

cosmological constant problem persists with logarithmic terms

- $\int d^4x \sqrt{-g}\left\{-\frac{c_O}{16}\left(g^{\alpha\beta}\mathbb{R}_{\alpha\beta}(\Gamma)\right)^2\right\} = \int d^4x \sqrt{-g}\left\{-\frac{c_O}{16}(R(g))^2 + \mathcal{O}(G_N)\right\}$

- $\int d^4x \sqrt{-g}\{c_V(\mathbb{R}_{\alpha\beta}(\Gamma) - R_{\alpha\beta}({}^{g}\Gamma))\,\mathrm{tr}[V^\alpha V^\beta]\} = \int d^4x \sqrt{-g}\{0 + \mathcal{O}(G_N)\}$

charge and color breaking are gone; gauge symmetries get restored!

EMERGENT GR + RENORMALIZED QFT

$$S_{QFT\cup GR} = S_c(g,\psi_{LE}) + \delta S_\ell(g, \log\mu, \psi_{LE}) + \int d^4x\, \sqrt{-g}\, \left\{ -\frac{R(g)}{16\pi G_N} - \frac{c_O}{16} R(g)^2 - \frac{c_S}{4} R(g)\left(S^\dagger S - \langle S^\dagger S\rangle\right) + \mathcal{O}(G_N) \right\}$$

QFT with

- dimensional-regularization,
- $\overline{\text{MS}}$-renormalization,
- RG running with $\log\mu$,
- loop-induced coefficients computed in the flat spacetime QFT

$R + R^2$ gravity with

- non-minimal coupling to scalars,
- $\mathcal{O}(G_N)$ derivative remainder involving scalars and gauge fields,
- loop-induced coefficients computed in the flat spacetime QFT.

symmetry-restoring emergent gravity = “symmergent gravity”

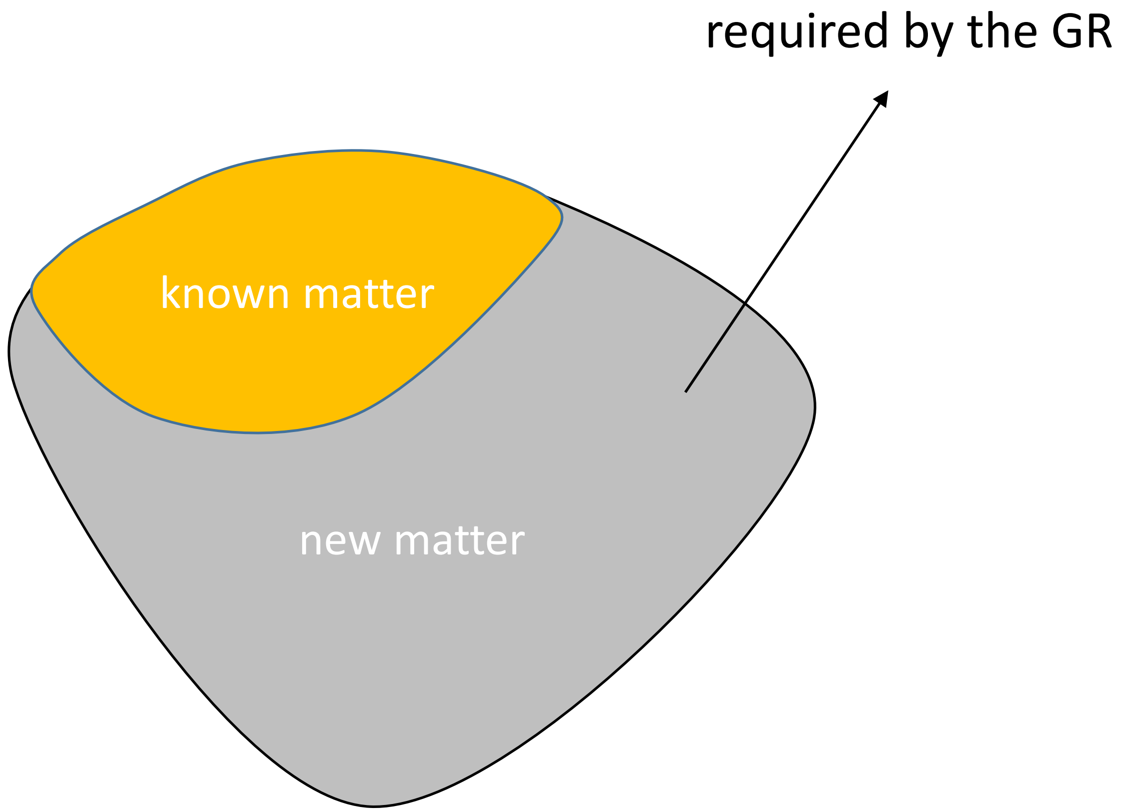
NEW PARTICLES ARE A NECESSITY

Newton's constant arises as

$$G_N^{-1} = 4\pi\left(\sum_m c_m m^2 + c_S\langle S^\dagger S\rangle\right)$$

quarks, leptons, W, Z and
Higgs cannot generate G_N

extra fields are a necessity;
gravity acquires right strength
only if there is matter beyond
the known ones!



D. Demir, Adv. High Energy Phys. 6727805 (2016)
D. Demir, Adv. High Energy Phys. 4652048 (2019)
D. Demir, Gen. Rel. Grav. 53, 22 (2021)

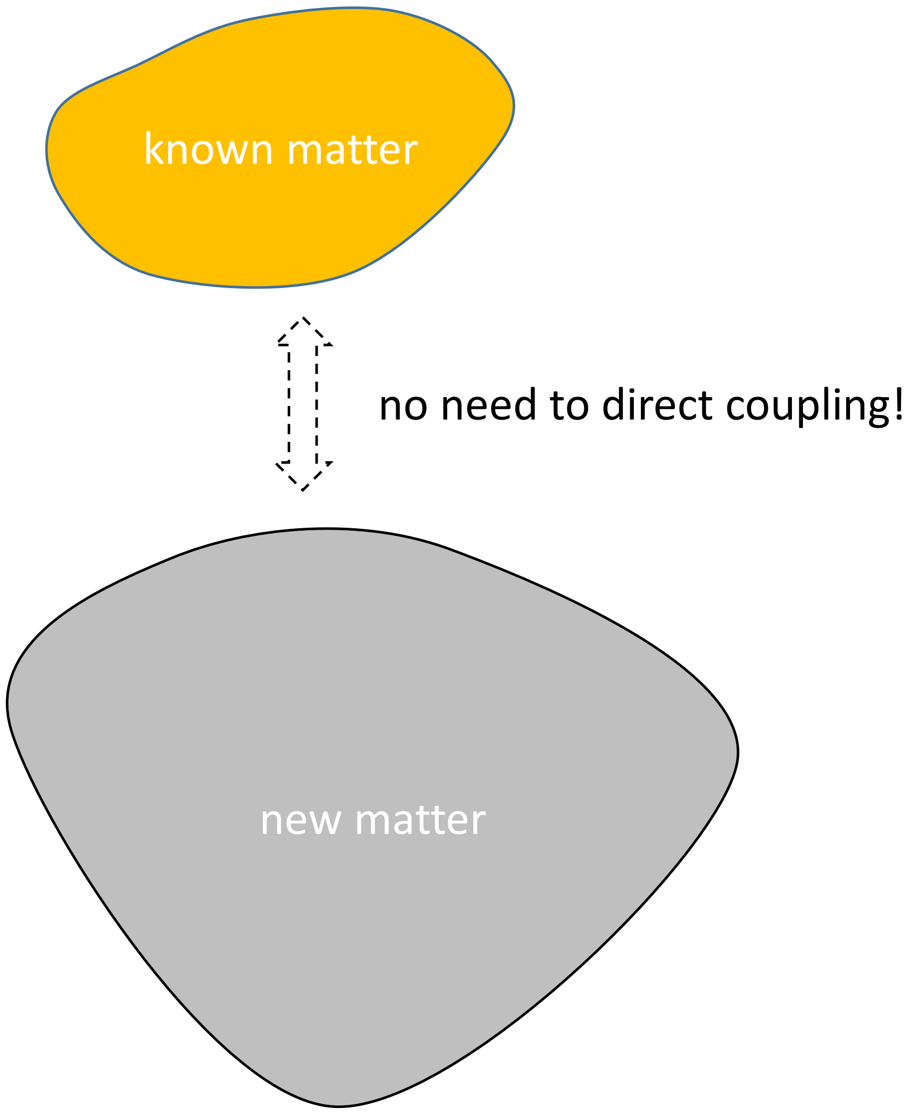
NEW PARTICLES DO NOT HAVE TO COUPLE TO KNOWN ONES

Newton’s constant takes shape as

$$G_N^{-1} = 4\pi \left(\sum_m c_m m^2 + c_S \langle S^\dagger S \rangle \right)$$

a weighted sum over
field mass-squareds

no specific coupling among fields
are required namely known and
unknown matter do not have to
couple to each other



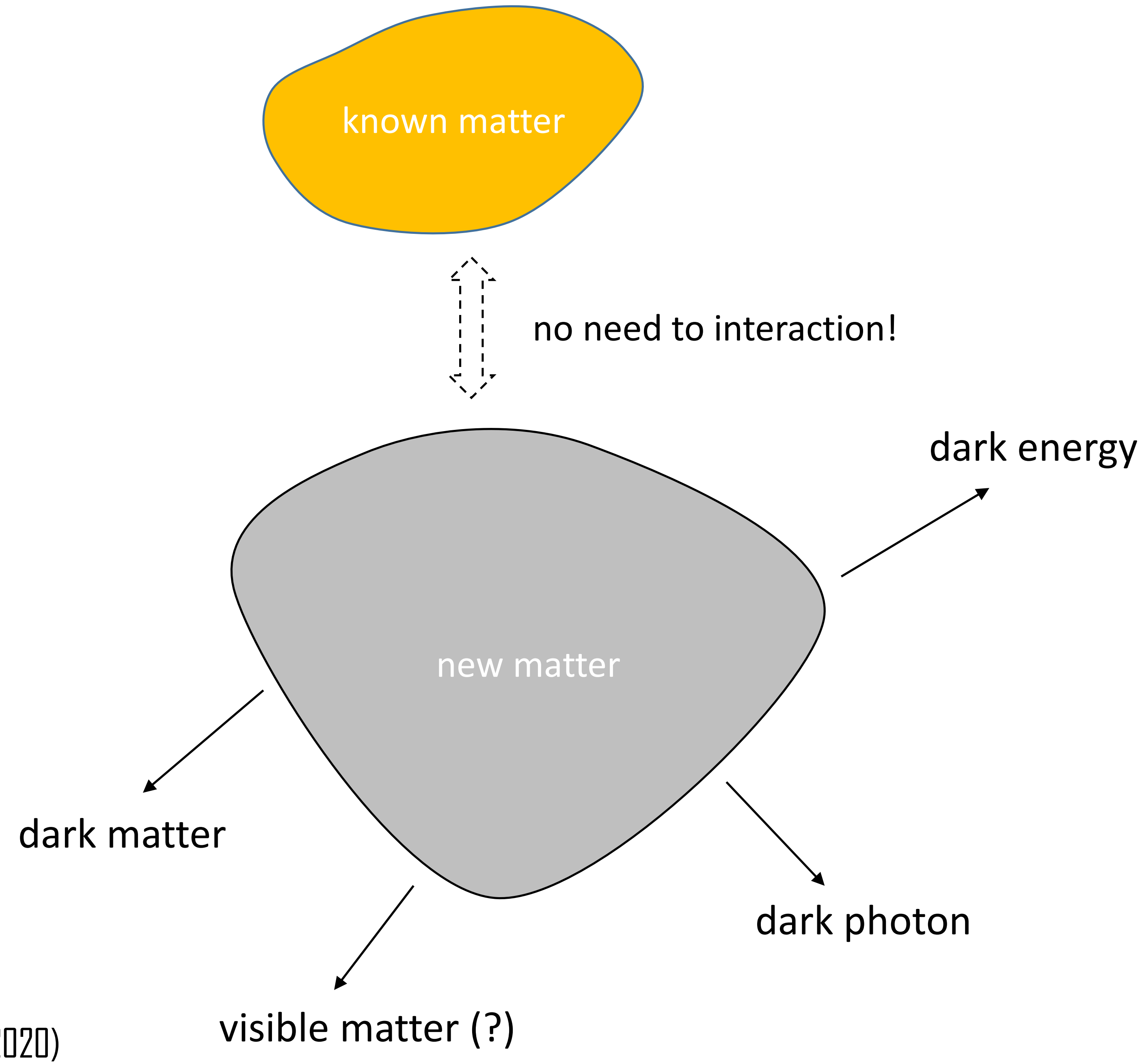
NEW PARTICLES CAN FORM A DARK SECTOR

- New fields can form a dark sector made up of dark matter and other dark stuff.

- Dark matter does not have to couple to the known matter.

  - Dark matter may have only gravitational couplings to known matter (in agreement with current observations)
    P. Peebles and A. Vilenkin, Phys. Rev. D60, 103506 (1999).

  - Dark matter may have naturally weak couplings to known matter and can be probed at high-luminosity experiments.
    K. Cankoçak *et al.*, Eur. Phys. J. C80, 1188 (2020)



CONCLUSION

We have shown that the GR emerges in a way

- restoring gauge symmetries,
- neutralizing the quadratic and quartic divergences, and
- bringing in new fields that can cover various phenomena, including the dark matter.

The resulting QFT + GR setup

- leads to quadratic-curvature gravity which can lead to various effects, including the Starobinsky inflation
  I. Çimdiker, Phys. Dark Universe 30, 100736 (2020)
- provides a dark sector that can lead to various phenomena, including the dark matter, dark energy, inflaton and the like, and
- consists of various fields which can give distinctive signals in high-luminosity colliders (LHC-HL and FCC),
- gives cause to various collider, astrophysical (DM, NS, BH, ..) and cosmological (inflation, DE,..) effects.

THANK YOU !