Symmergent Gravity

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Question

How to reconcile GR with the SM?

Way 1: quantized GR + the SM ☹

Way 2: classical GR + the SM ☹

Way 3: ?????? 😐

A Hint

What could be Way 3 ?

- EP is violated in quantum theory:

$$-\frac{\hbar^2}{2m_I}\frac{\partial^2}{\partial z^2}\psi(z,t) + m_G g z \psi(z,t) = i\hbar\frac{\partial}{\partial t}\psi(z,t)$$

- EP is revived after quantum fluctuations are integrated out:

$$m_I \frac{d^2}{dt^2}\langle z \rangle = -m_G g$$

An Answer

It is thus possible that:

Way 3 = “classical GR + effective QFT”

reveals UV sensitivity
(log, power-law)

involves long-wavelength fields
(quasi-classical field theory)

lives in experimental reach
(testable with data)

Scales and QFTs

Λ_{UV} — ultimate UV boundary ⟵ end of QFT (end of rigid flat ST) (ST elasticity scale)

⋮

SM + BSM ?

Experiment's scale $= \mathrm{TeV's}$ ⟵ LHC13

SM

Λ_{SM} — SM's UV limit $= 550\ \mathrm{GeV}$ ⟵ $\frac{\delta m_h^2}{m_h^2} \propto \frac{\Lambda_{SM}^2}{m_h^2} = 1$

SM

EW scale $= 250\ \mathrm{GeV}$

SM

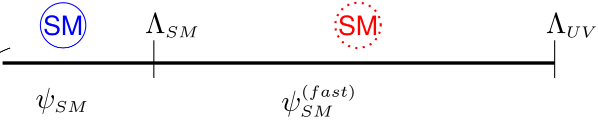
A Realistic Setup

In line with the status at the LHC experiments:

- The SM, which has already transcended Λ_{SM}, can be assumed to extend all the way up to Λ_{UV}.

  - Possible BSM physics can be revealed by physical consistency.

The SM Effective Action



$$e^{iS_{eff}(\eta,\psi_{SM})} = \int_{[\Lambda_{SM}]}^{[\Lambda_{UV}]} \mathcal{D}\psi_{SM}^{(fast)} e^{iS\left(\eta,\psi_{SM},\psi_{SM}^{(fast)}\right)}$$

flat metric $\eta_{\mu\nu}$

slow SM fields

The SM Effective Action

$$S_{eff} = \underbrace{S_{tree}\left(\psi_{SM}\right) + \delta S_{log}\left(\psi_{SM}, \Lambda_{SM} \log \frac{\Lambda_{SM}}{\Lambda_{UV}}\right)}_{\text{at the SM scale}}$$

$$+ \underbrace{\delta S_{power}\left(H, V_{\mu}, \Lambda_{UV}^2 - \Lambda_{SM}^2, \Lambda_{UV}^2 + \Lambda_{SM}^2\right)}_{\text{at the UV scale}}$$

$\Lambda_{UV}^2 + \Lambda_{SM}^2$
($\rightsquigarrow$ gravity)

$\frac{\Lambda_{UV}}{\Lambda_{SM}} =$ hierarchy

$\Lambda_{UV}^2 - \Lambda_{SM}^2$
($\rightsquigarrow$??????)

Power-Law UV Contributions

$$\delta S_{power} = \delta S_O + \delta S_H + \delta S_V$$

$$\int d^4x \sqrt{-\eta}\, c_V \left(\Lambda_{UV}^2 - \Lambda_{SM}^2\right) \mathrm{Tr}\left[V_\mu V^\mu\right]$$

$$-\int d^4x \sqrt{-\eta}\, c_H \left(\Lambda_{UV}^2 - \Lambda_{SM}^2\right) H^\dagger H$$

$$-\int d^4x \sqrt{-\eta}\, c_O \left(\Lambda_{UV}^4 - \Lambda_{SM}^4\right)$$

$$c_{O,H,V} = c_{O,H,V} \left(\frac{\Lambda_{SM}}{\Lambda_{UV}}\right)$$

Hierarchy Problems

$$\delta S_{power} = \delta S_O + \delta S_H + \delta S_V$$

$$\int d^4x \sqrt{-\eta}\, c_V \left(\Lambda_{UV}^2 - \Lambda_{SM}^2\right) \text{Tr}\left[V_\mu V^\mu\right]$$

$$-\int d^4x \sqrt{-\eta}\, c_H \left(\Lambda_{UV}^2 - \Lambda_{SM}^2\right) H^\dagger H$$

hard UV masses to all $U(1)_Y, SU(2)_L, SU(3)_C$ gauge bosons

☹

big hierarchy problem

☹

explicit breaking of $SU(3)_C$ **and** $U(1)_{EM}$

Curving Away Gauge Boson UV-Masses

$$\delta S_V = \delta S_V - \int d^4x \sqrt{-\eta}\, \frac{c_V}{2} \text{Tr}\Big[V_{\mu\nu} V^{\mu\nu}\Big] + \int d^4x \sqrt{-\eta}\, \frac{c_V}{2} \text{Tr}\Big[V_{\mu\nu} V^{\mu\nu}\Big]$$

$$= \int d^4x \sqrt{-\eta}\, c_V \left(\Lambda^2_{UV} - \Lambda^2_{SM}\right) \text{Tr}\Big[V_\mu V^\mu\Big]$$

$$- \int d^4x \sqrt{-\eta}\, \frac{c_V}{2} \text{Tr}\Big[V_{\mu\nu} V^{\mu\nu}\Big]$$

$$+ \int d^4x \sqrt{-\eta}\, c_V \text{Tr}\Big[V^\mu \Big(- D^2 \eta_{\mu\nu} + D_\mu D_\nu + V_{\mu\nu}\Big) V^\nu\Big]$$

$$+ \int d^4x \sqrt{-\eta}\, c_V \text{Tr}\Big[\partial_\nu (V_\mu V^{\mu\nu})\Big]$$

$$D_\mu = \partial_\mu - V_\mu$$

Curving Away Gauge Boson UV-Masses

$$\delta S_V \xrightarrow{\eta_{\mu\nu} \Longmapsto g_{\mu\nu}} \int d^4x \sqrt{-g}\, c_V \left(\Lambda_{UV}^2 - \Lambda_{SM}^2\right) \text{Tr}\left[V_\mu V^\mu\right]$$

$$- \int d^4x \sqrt{-g}\, \frac{c_V}{2} \text{Tr}\left[V_{\mu\nu} V^{\mu\nu}\right]$$

$$+ \int d^4x \sqrt{-g}\, c_V \text{Tr}\left[V^\mu \Big(- \mathcal{D}^2 g_{\mu\nu} + \mathcal{D}_\mu \mathcal{D}_\nu + V_{\mu\nu} \Big) V^\nu\right]$$

$$+ \int d^4x \sqrt{-g}\, c_V \text{Tr}\left[\nabla_\nu \left(V_\mu V^{\mu\nu}\right)\right]$$

$$\mathcal{D}_\mu = \nabla_\mu - V_\mu$$

Curving Away Gauge Boson UV-Masses

$$= -\int d^4x \sqrt{-g}\frac{c_V}{2}\text{Tr}\left[V_{\mu\nu}V^{\mu\nu}\right]$$

$$+\int d^4x \sqrt{-g} c_V \text{Tr}\left[V^{\mu}\left(-\mathcal{D}^2 g_{\mu\nu} + \mathcal{D}_\mu \mathcal{D}_\nu + V_{\mu\nu} + \left(\Lambda_{UV}^2 - \Lambda_{SM}^2\right) g_{\mu\nu}\right) V^{\nu}\right]$$

$$+\int d^4x \sqrt{-g} c_V \text{Tr}\left[\nabla_\nu (V_\mu V^{\mu\nu})\right]$$

What if this is a fixed value assigned to curvature?

$$(\Lambda_{UV}^2 - \Lambda_{SM}^2) g_{\mu\nu} \Longrightarrow R_{\mu\nu}(g)\,?$$

Curving Away Gauge Boson UV-Masses

$$\xrightarrow{(\Lambda_{UV}^2-\Lambda_{SM}^2)g_{\mu\nu} \Longmapsto R_{\mu\nu}(g)}$$

$$-\int d^4x\sqrt{-g}\frac{c_V}{2}\mathrm{Tr}\Big[V_{\mu\nu}V^{\mu\nu}\Big]$$

$$+\int d^4x\sqrt{-g}c_V\,\mathrm{Tr}\Big[V^{\mu}\Big(-\mathcal{D}^2 g_{\mu\nu}+\mathcal{D}_{\mu}\mathcal{D}_{\nu}+V_{\mu\nu}+R_{\mu\nu}(g)\Big)V^{\nu}\Big]$$

$$+\int d^4x\sqrt{-g}c_V\,\mathrm{Tr}\Big[\nabla_{\nu}(V_{\mu}V^{\mu\nu})\Big]$$

$$\xrightarrow{\text{if } c_V \text{ is held unaffected}}$$

$$-\int d^4x\sqrt{-g}\frac{c_V}{2}\mathrm{Tr}\Big[V_{\mu\nu}V^{\mu\nu}\Big]+\int d^4x\sqrt{-g}\frac{c_V}{2}\mathrm{Tr}\Big[V_{\mu\nu}V^{\mu\nu}\Big]$$

$$=0$$

→ massless photon, massless gluon!

→ log-UV corrections to W, Z masses!

SM/UV Hierarchy Is Preserved

While $(\Lambda^2_{UV} - \Lambda^2_{SM})g_{\mu\nu} \Longmapsto R_{\mu\nu}(g)$

- $c_V\left(\frac{\Lambda_{SM}}{\Lambda_{UV}}\right)$ is held unchanged
  - hence $\frac{\Lambda_{SM}}{\Lambda_{UV}}$
    - and so are $c_O\left(\frac{\Lambda_{SM}}{\Lambda_{UV}}\right)$ and $c_H\left(\frac{\Lambda_{SM}}{\Lambda_{UV}}\right)$

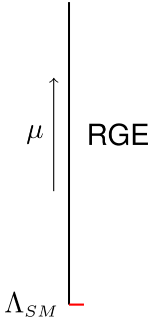
Log UV Contributions Are As Usual (Dim. Reg.)

While $(\Lambda_{UV}^2 - \Lambda_{SM}^2) g_{\mu\nu} \Longmapsto R_{\mu\nu}(g)$

- $\dfrac{\Lambda_{SM}}{\Lambda_{UV}}$ is held unchanged

- so is $\delta S_{log}\left(\psi_{SM}, \Lambda_{SM} \log \dfrac{\Lambda_{SM}}{\Lambda_{UV}}\right)$

- Dim. Reg.: $\log \dfrac{\Lambda_{SM}}{\Lambda_{UV}} \equiv -\dfrac{1}{\epsilon} - \log \dfrac{\mu}{\Lambda_{SM}}$



Power-Law UV Contributions Set Curvature Sector

$$\delta S_{power} \xrightarrow[c_O,\, c_H \text{ held unchanged}]{(\Lambda_{UV}^2 - \Lambda_{SM}^2) g_{\mu\nu} \Longmapsto R_{\mu\nu}(g)}$$

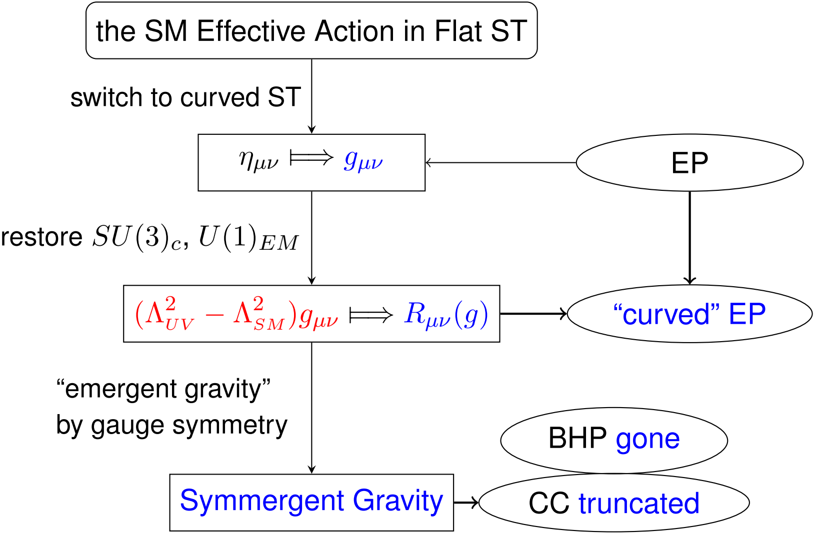
$$-\int d^4x \sqrt{-g}\, \underbrace{\frac{c_O}{4}\left(\Lambda_{UV}^2 + \Lambda_{SM}^2\right)}_{\frac{M_{Pl}^2}{2}} R(g)$$

☺ quartic contribution to vacuum energy turns into EH term !

$$-\int d^4x \sqrt{-g}\, \frac{c_H}{4} H^\dagger H\, R(g)$$

☺ big hierarchy problem is gone!

"Symmergent Gravity"



Symmergent Gravity vs. Induced Gravity

Table 1: Contrasting symmergent gravity with Sakharov's induced gravity for $M_{Pl} \cong \Lambda_{UV}$.

	Gravity Sector	Cosmological Constant	Higgs Mass
Induced Gravity	EH + HC	$\Lambda_{UV}^4/M_{Pl}^2 \cong M_{Pl}^2$	$\cong M_{Pl}$
Symmergent Gravity	EH	$\Lambda_{SM}^4/M_{Pl}^2 \cong m_\nu^2$	$\cong \Lambda_{SM}$

Alas! The SM Alone Can't Lead To Proper Gravity

In the SM (at one loop):

$$c_O \cong \frac{(n_b - n_f)}{64\pi^2} = \frac{-62}{64\pi^2}$$

not eligible for inducing gravity

introduce new fields
to make $c_O \gtrsim 1$
so that $\Lambda_{UV} \lesssim M_{Pl}$

A BSM Sector Is Required

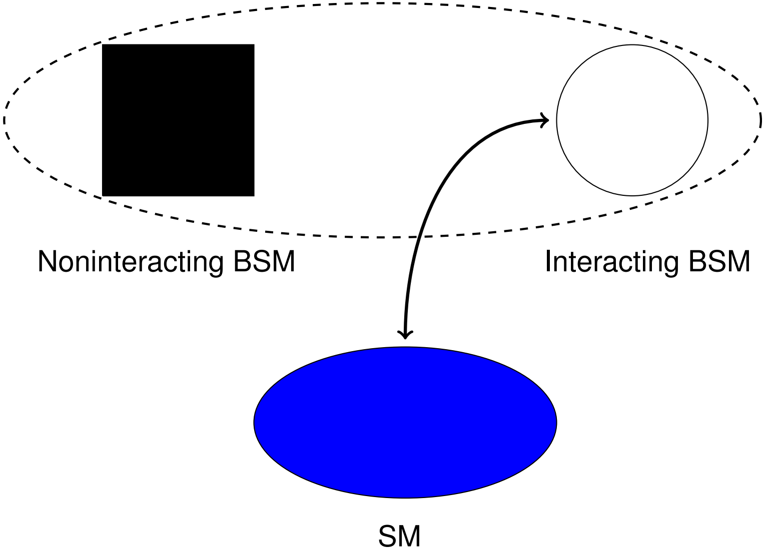
- In general, BSM does not have to interact with the SM but it can.

- All it has to do is to provide some

  $n_b^{BSM} - n_f^{BSM} \gtrsim 128\pi^2 + 62 \approx 1325$

  more bosons than fermions to insure $\Lambda_{UV} \lesssim M_{Pl}$.

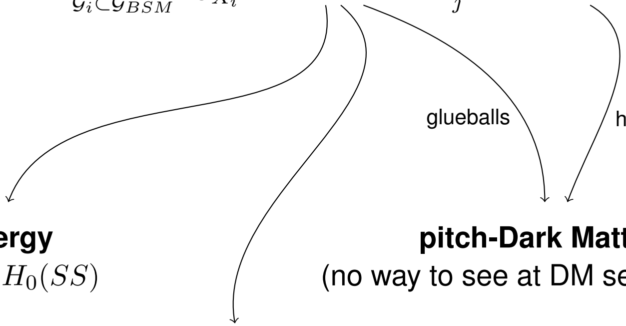
BSM Can Come In Two Types



Noninteracting BSM Is Sweet Home For "Dark Stuff"

Non-Abelian gauge theories like $\mathcal{G}_{BSM} = SO(51),\ SU(26),\ E(8)^3, \ldots$

$$S^{(ni)} = \int d^4x \sqrt{-\eta} \left\{ - \sum_{\mathcal{G}_i \subset \mathcal{G}_{BSM}} \frac{1}{2 g_{X_i}^2} \mathrm{Tr} \left\{ X^i_{\mu\nu} X_i^{\mu\nu} \right\} + \sum_j \overline{\chi}_j \left(i \not{D} - m_{\chi_j} \right) \chi_j \right\}$$



Dark Energy

$H_0(CMB)$ vs. $H_0(SS)$

pitch-Dark Matter

(no way to see at DM searches)

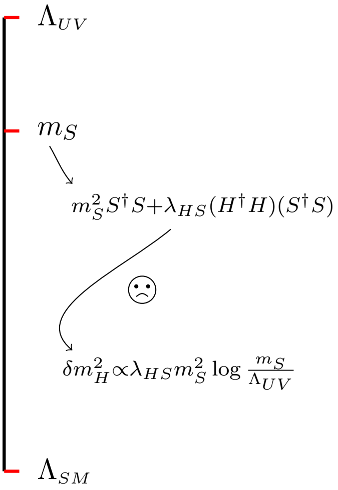
Inflaton?

Interacting BSM Is Needed

- No evidence for interacting BSM at LHC and DM searches.
- But it is necessary for Strong CP, Flavor, Baryogenesis, Inflation, . . . whose realizations can involve some heavy scalars S.
- δm_H^2 can be suppressed only if

  $$\lambda_{HS} \lesssim \Lambda_{SM}^2/m_S^2$$

  as obeyed by phenomena above. (SUSY, Xtra Dim, Comp. don't!)
- Majorana neutrinos: $\Lambda_{UV} = m_N$ (with a crowded noninteracting BSM)



IMPLICATION 1

SM+Gravity+Noninteracting-BSM:

$$S_{eff}^{(SM+BSM)} = \int d^4x\sqrt{-g}\left\{-\frac{1}{2}M_{Pl}^2 R(g) - \frac{c_H}{4} H^\dagger H R(g)\right\}$$

$$+ S_{tree}(\psi_{SM}) + \delta S_{log}\left(\psi_{SM}, \Lambda_{SM} \log\frac{\Lambda_{SM}}{\Lambda_{UV}}\right)$$

$$+ S_{tree}^{(BSM)}(\psi_{BSM}) + \delta S_{log}^{(BSM)}\left(\psi_{BSM}, \Lambda_{BSM} \log\frac{\Lambda_{BSM}}{\Lambda_{UV}}\right)$$

this setup can account for all of the available data and constraints except for one thing: CCP!

IMPLICATION 2

- The real challenge is to understand how CC can be reduced from Λ_{BSM}^4/M_{Pl}^2 down to H_0^2.

- Solution of the CCP can reveal structure of the BSM. $CC_{SM} + CC_{BSM} \cong H_0^2$ can put highly non-trivial constraints on BSM (coupling to SM is not a must).

- The CCP may well be a door to sought new physics. (BSM, if noninteracting, can lie at ...TeV's, GeV's, MeV's, ...)

IMPLICATION 3

- LHC or other colliders do not have to discover any new particle.

- If they discover any then BSM needs be structured accordingly.

In Conclusion

- We should analyze any given experimental signal without any theoretical prejudice.
- We should keep in mind that an experimental signal does not have to arise.
- We should focus on the CCP to reveal structure of the BSM.
- We should explore trans-UV physics in regard to SM+BSM setup.

Thank You For Your Attention

References:

- *Naturalizing Gravity of the Quantum Fields, and the Hierarchy Problem,* arXiv:1703.05733
- *Curvature-Restored Gauge Invariance and Ultraviolet Naturalness,* arXiv:1605.00377
- *A Mechanism of Ultraviolet Naturalness,* arXiv:1510.05570

Acknowledgement

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