Curved Equivalence Principle and the Hierarchy Problem

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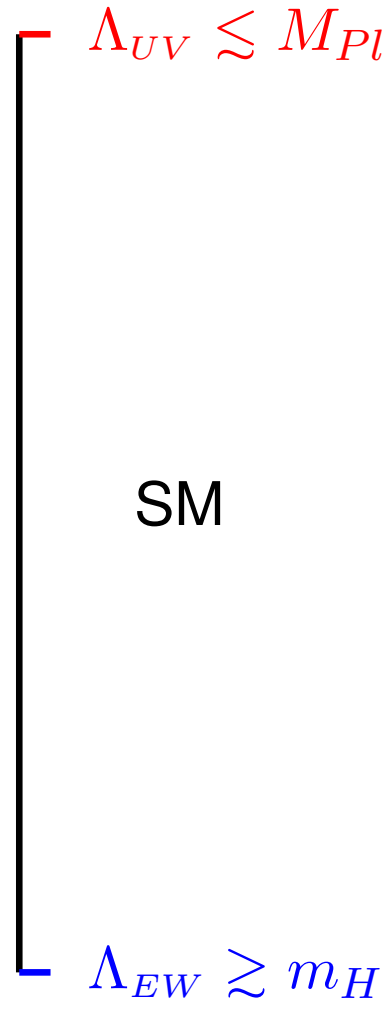
May 26, 2017 – PPC17, Corpus Christi,TX

The Problem

How is it possible that the SM is able to

describe physics at the Fermi scale

without any new fields at the LHC?



The SM Effective Action

$$S_{eff} = \underbrace{S_{tree}\left(\psi_{SM}\right) + \delta S_{log}\left(\psi_{SM}, \Lambda_{EW} \log \frac{\Lambda_{EW}}{\Lambda_{UV}}\right)}_{\text{EW scale}} + \overbrace{\delta S_{power}\left(H, V_{\mu}, \Lambda_{UV}\right)}^{\text{UV scale}}$$

Power-Law UV Contributions

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

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

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

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

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

Hierarchy Problems

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

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

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

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

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

big hierarchy problem

Curving Away Gauge Boson UV-Masses

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

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

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

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

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

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

Curving Away Gauge Boson UV-Masses

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

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

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

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

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

Curving Away Gauge Boson UV-Masses

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

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

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

constant value
assigned to curvature?

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

Curving Away Gauge Boson UV-Masses

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

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

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

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

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

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

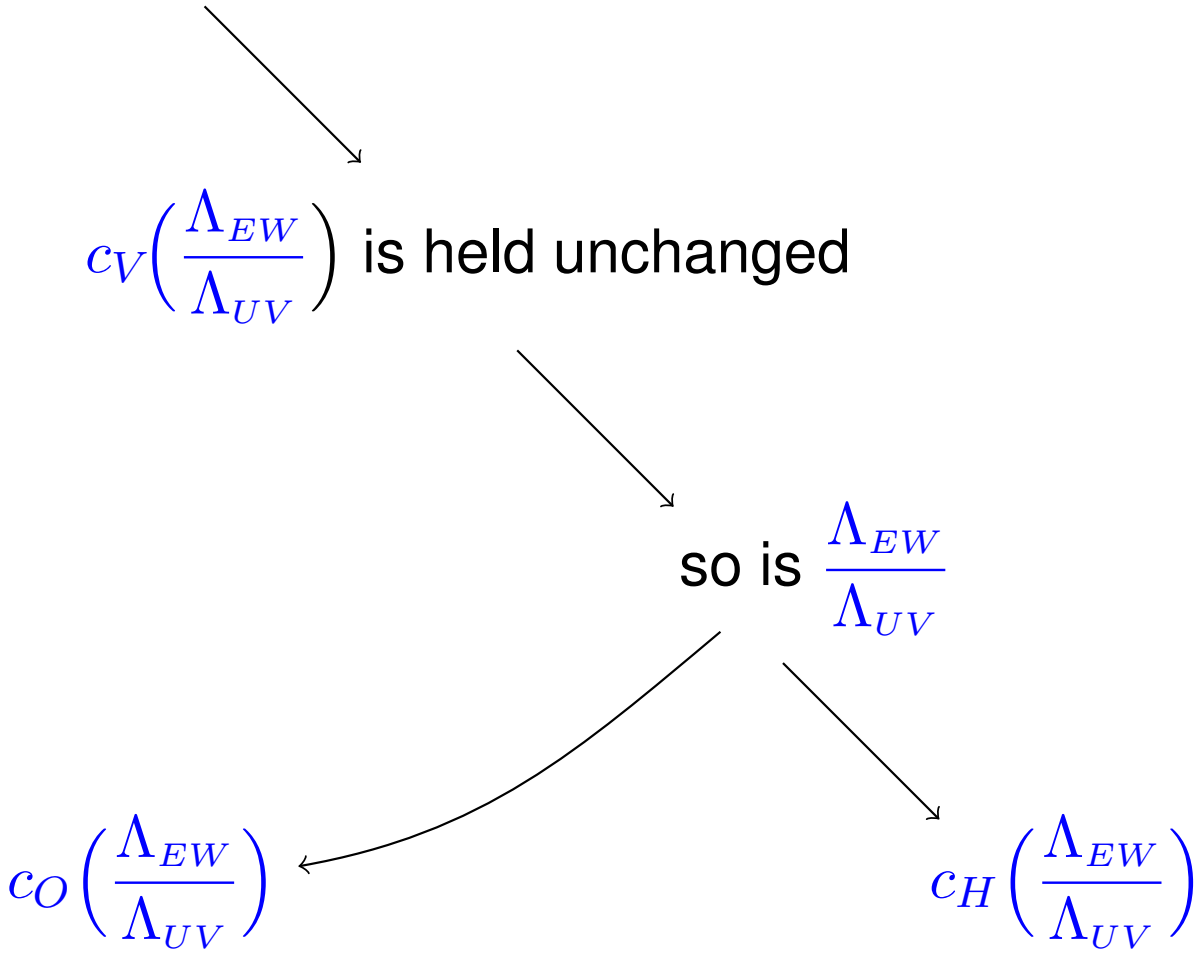
$$= 0$$

→ massless photon, massless gluon!

→ mere log-UV corrections to W, Z masses!

UV/IR Hierarchy Is Preserved

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



Log UV Contributions Read As Usual

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

$\frac{\Lambda_{EW}}{\Lambda_{UV}}$ is held unchanged

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

$$\log \frac{\Lambda_{EW}}{M_{Pl}} \equiv -\frac{1}{\epsilon} - \log \frac{\mu}{\Lambda_{EW}}$$

$\mu -$ independence results in RGEs

Power-Law UV Contributions Set Curvature Sector

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

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

Λ_{UV}^4 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 eliminated!

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

In the SM (at one loop):

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

ineligible to induce gravity

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

Include A “Secluded New Physics” Sector

- The NP must form a secluded sector so that

  the SM can continue to hold good up to Λ_{UV}.

- The NP must have

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

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

- This spectrum can arise from gauge theories like

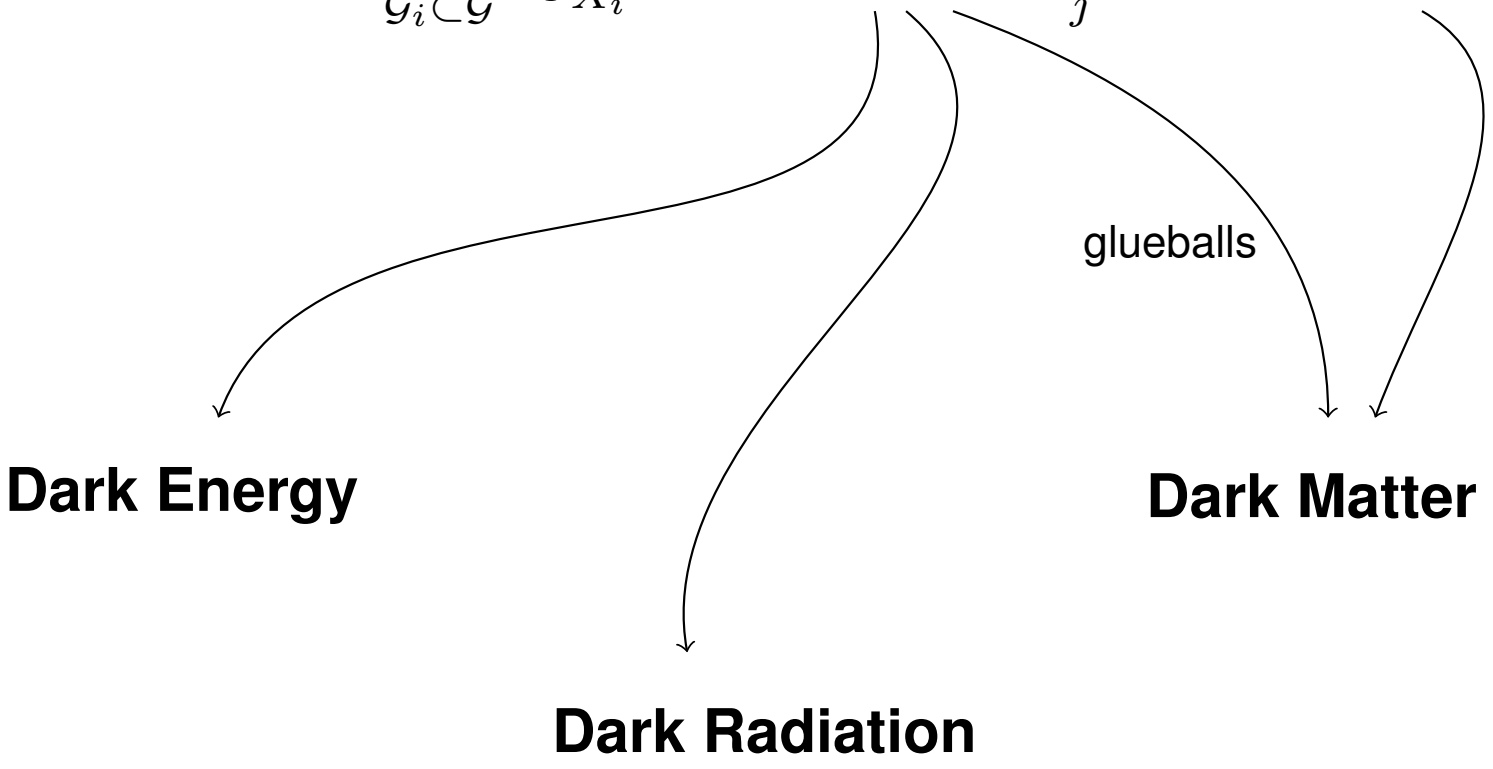
  $\mathcal{G}_{NP} = SO(51),\ SU(26),\ E(8)^3,\ SU(3)^{83},\ SU(5)^{26},\ \ldots$

  though it does not have to.

Secluded NP Is Sweet Home For “Dark Stuff”

Non-Abelian gauge theories are examples of secluded NPs:

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



SM + NP + Gravity: A Predictive Setup

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

$$+ S_{tree}^{(NP)}(\psi_{NP}) + \delta S_{log}^{(NP)}\left(\psi_{NP}, \Lambda_{NP}\log\frac{\Lambda_{NP}}{M_{Pl}}\right)$$

$$+ S_{tree}^{(SM)}(\psi_{SM}) + \delta S_{log}^{(SM)}\left(\psi_{SM}, \Lambda_{EW}\log\frac{\Lambda_{EW}}{M_{Pl}}\right)$$

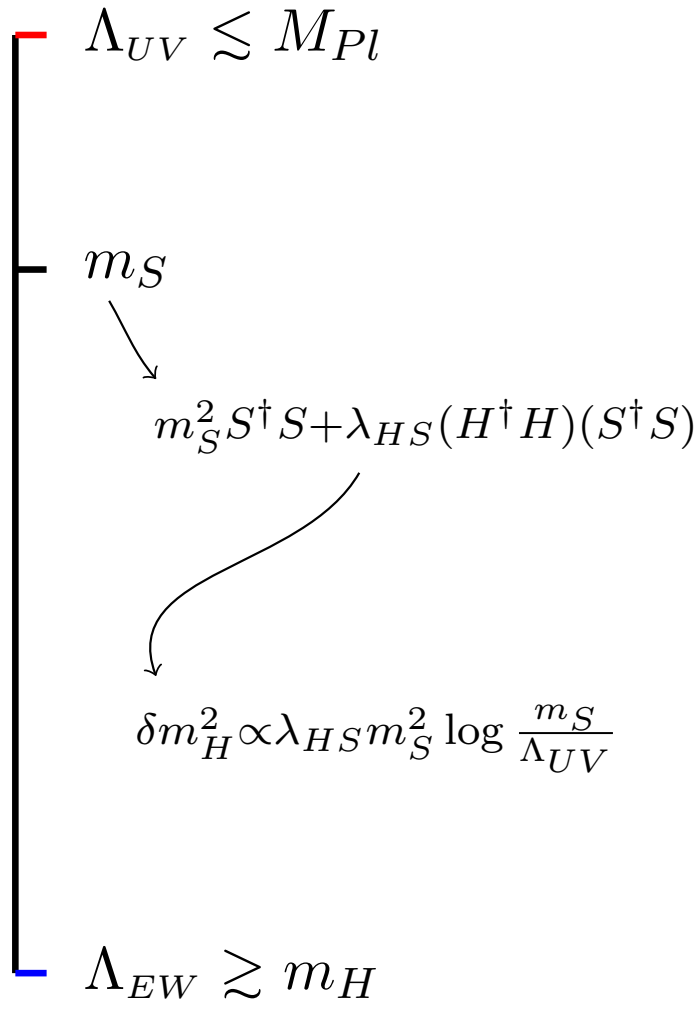
no new parameters beyond

those present in the flat ST

effective action !

SM $\rightarrow$ SM + BSM Is Welcome

- Strong CP, Flavor, Baryogenesis, Inflation, . . . are mostly modeled with heavy scalars S.
- $\langle S \rangle$ and $\langle H \rangle$ stay split as desired if $\lambda_{HS} \lesssim \Lambda_{EW}^2/m_S^2$, and this ensures stability of the Higgs boson.
- Interacting DM like axions arise.
- Majorana neutrinos are included by setting $\Lambda_{UV} = m_N$ with a crowded enough secluded NP sector.



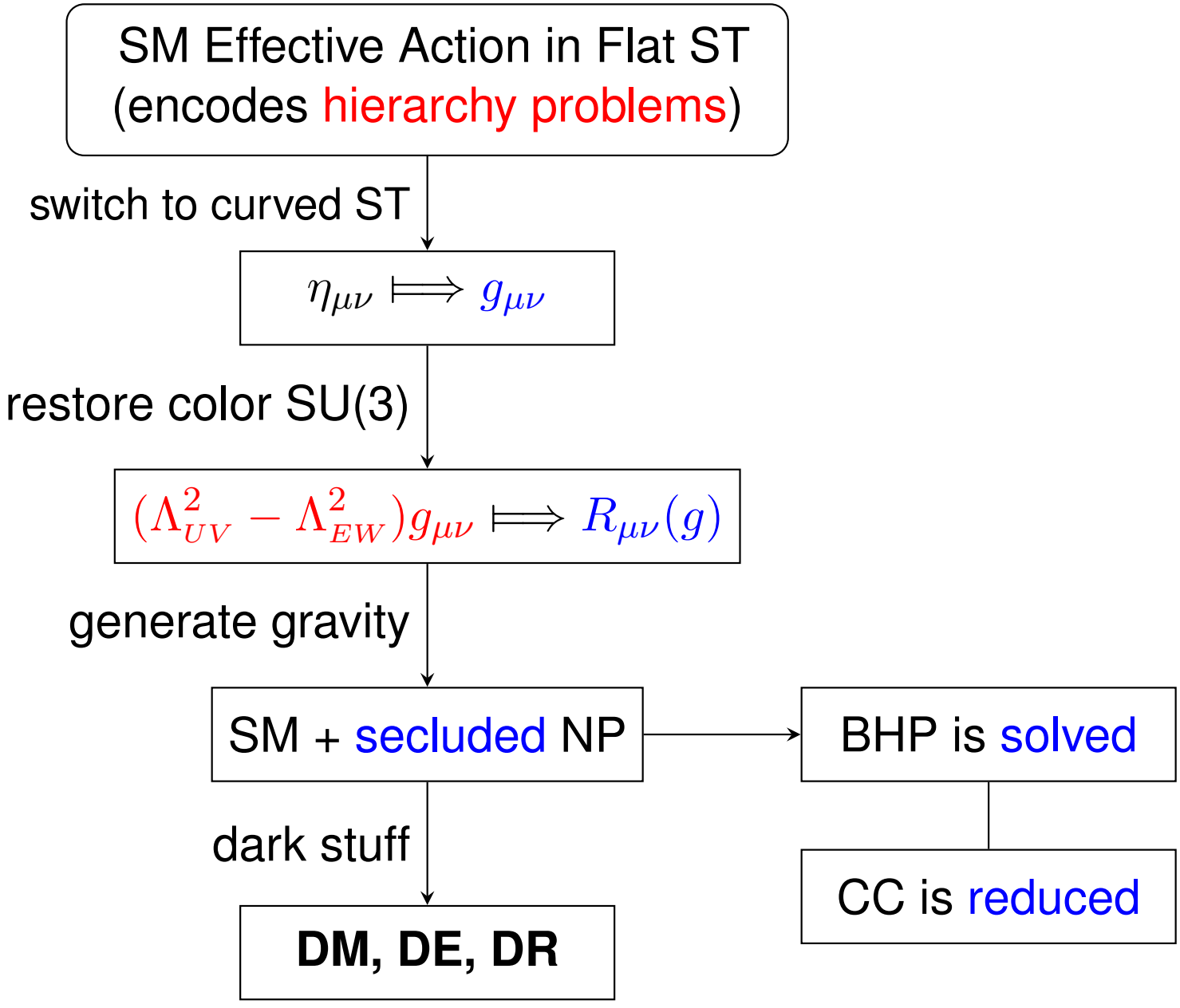
Basic Question, A Likely Answer

How to reconcile QFT to Curved Geometry?

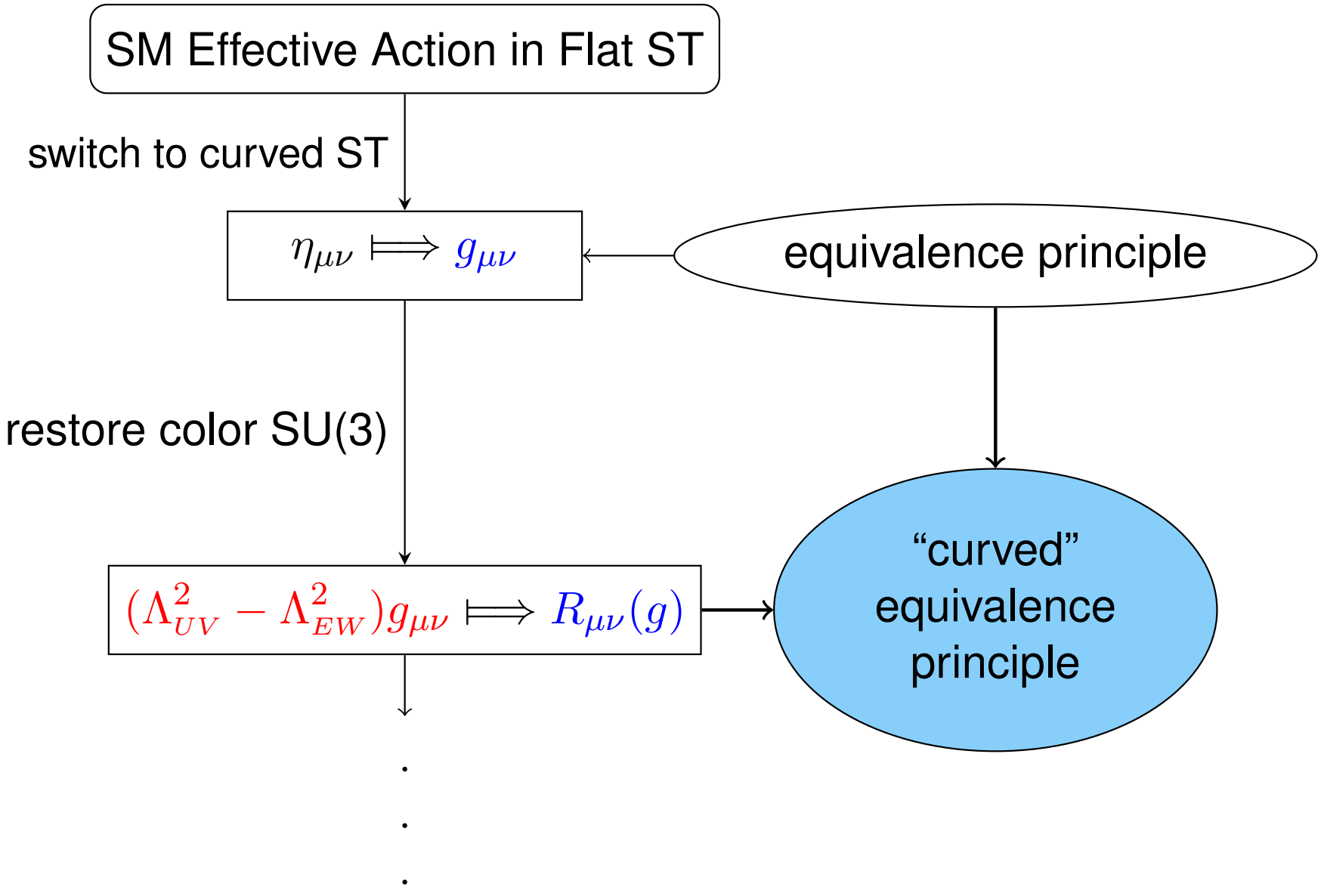
- Quantize geometry (yes, but QG is distant if not non-existent)

- Use effective QFT (essentially "classical FT" based on loop-corrected masses and couplings.)

Realization Of The Answer



Principle Behind



New Heavy Particles Are Not A Necessity

The mechanism does not rely on new fields interacting with the SM.

- It is thus fundamentally different than SUSY, Compositeness, Extra Dimensions, and their hybrids/variants.
- It does not need new heavy particles be discovered at the LHC or other high-energy colliders.
- It can accommodate new particles as BSM fields, though.

The CCP Is The Challenge

- The real challenge is to understand how CC can be reduced from $\Lambda^4_{EW,NP}/M^2_{Pl}$ down to H^2_0.

- Sub-Fermi energies, now populated by the NP fields, gains importance.

- The secluded NP can have something to do with (or can be blamed on ?) the CCP.

A Lot Of Work To Do

- Is ”seclusion” rigid? What NP-SM interactions can be tolerated?
- What models are eligible for the NP? GUTs? Strings?
- What NP can resolve the CCP? Symmetries?
- What BSM phenomena prefer what model? A detailed study?

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

This work is supported through TUBITAK grant 115212.