Symmergent Gravity and Ultraviolet Stability

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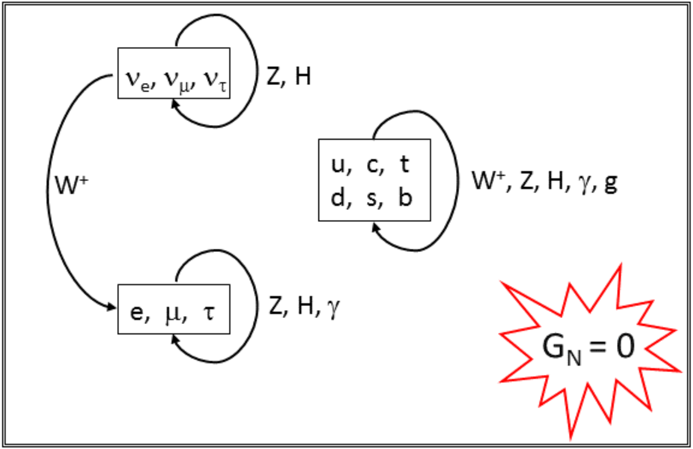
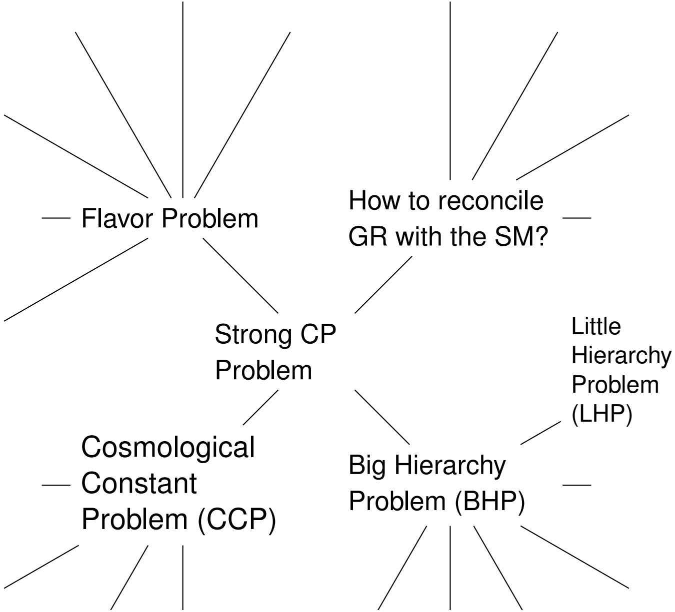
Working Model



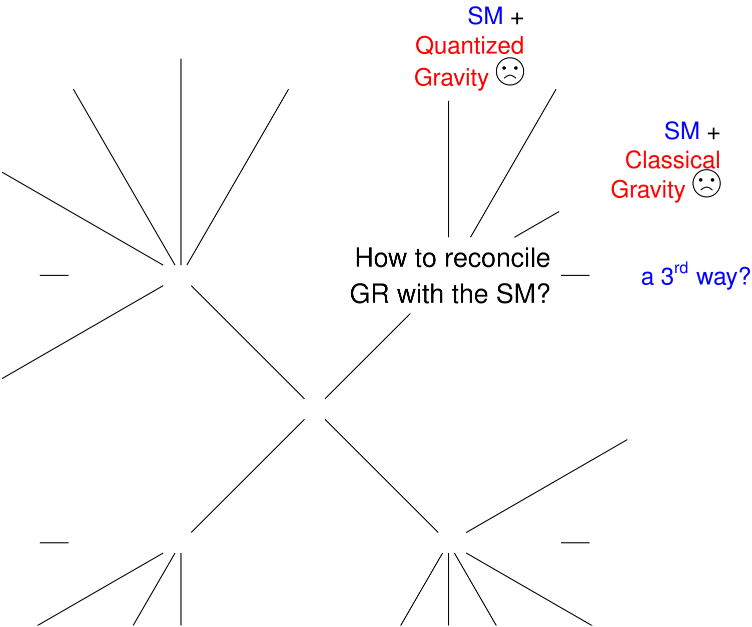
Standard Model = a renormalizable QFT of the

EM (γ) + Weak (W,Z,H) + Strong (g)

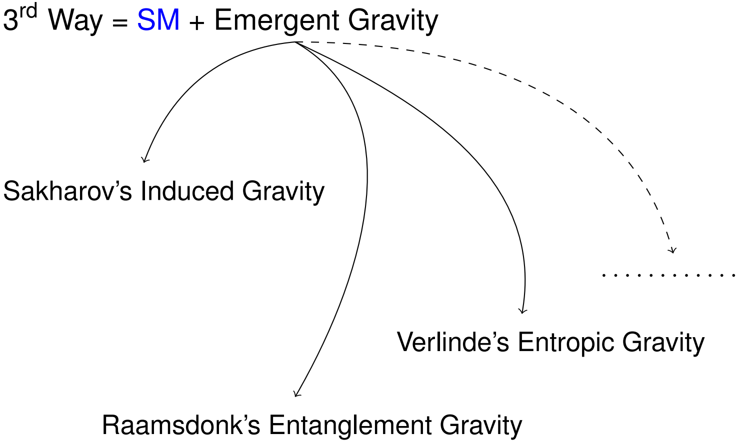
Gordian Knots In The SM



Gravity Knot

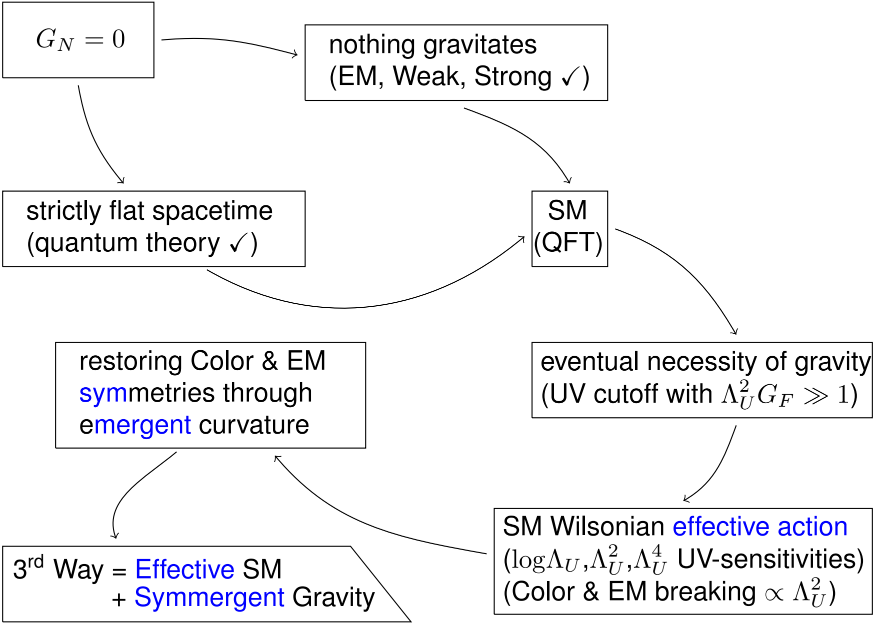


3^{rd} Way

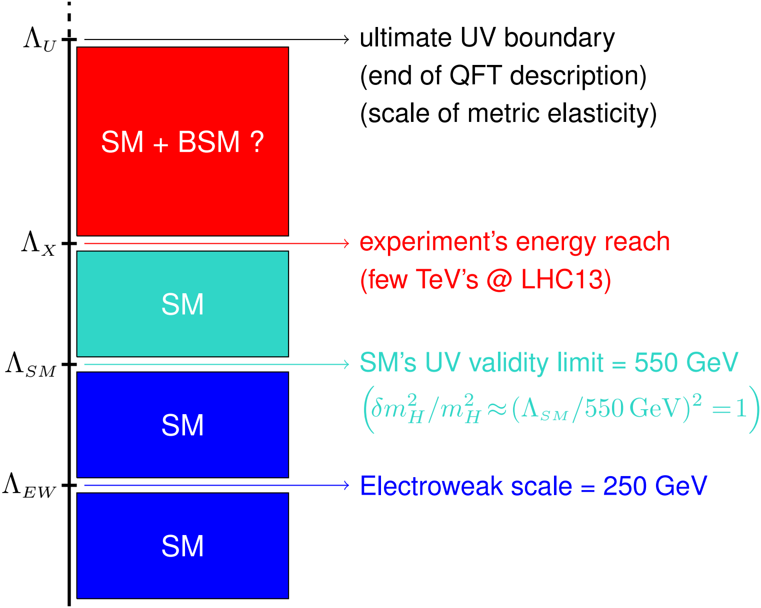


- Some of these can be in tension with Weinberg-Witten theorem !

3rd Way – A New Kind



Scales & QFTs



Λ_U
ultimate UV boundary
(end of QFT description)
(scale of metric elasticity)
SM + BSM ?
Λ_X
experiment's energy reach
(few TeV's @ LHC13)
SM
Λ_{SM}
SM's UV validity limit = 550 GeV
$\left(\delta m_H^2/m_H^2 \approx (\Lambda_{SM}/550\,\mathrm{GeV})^2 = 1\right)$
SM
Λ_{EW}
Electroweak scale = 250 GeV
SM

A Prudent QFT Setup

- Assume that the SM, which has already crossed Λ_{SM}, holds good all the way up to Λ_U.
- Determine then possible BSM physics by physical consistency.

SM Effective Action

$\{$leptons, quarks, $H, V_\mu\}$

$\psi_{SM}(E)$

$(E < \Lambda_X)$

$\psi_{SM}^{(fast)}(E)$

$(\Lambda_X < E < \Lambda_U)$

Λ_X Λ_U

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

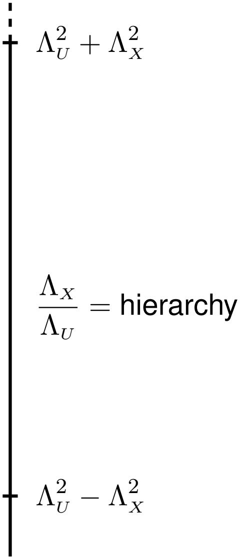
$$e^{iS_{eff}(\eta,\psi_{SM})} = \int_{[\Lambda_X]}^{[\Lambda_U]} \mathcal{D}\psi_{SM}^{(fast)} e^{iS\left(\eta,\psi_{SM},\psi_{SM}^{(fast)}\right)}$$

SM Effective Action

$$S_{eff} = S_{\color{blue}{tree}}\left(\eta, \psi_{SM}\right)$$

$$+\ \underbrace{\delta S_{\color{blue}{log}}\left(\eta, \psi_{SM}, \log\frac{\Lambda_X}{\Lambda_U}\right)}_{\color{blue}{\text{at the SM scale}}}$$

$$+\ \underbrace{\delta S_{\color{red}{power}}\left(\eta, H, V_\mu, \Lambda_U^2 - \Lambda_X^2, \Lambda_U^2 + \Lambda_X^2\right)}_{\color{red}{\text{at the UV scale}}}$$



UV-Born Parts

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

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

$$-\int d^4x\sqrt{-\eta}\, c_H\left(\frac{\Lambda_X}{\Lambda_U}\right)(\Lambda_U^2 - \Lambda_X^2)\,H^\dagger H$$

$$-\int d^4x\sqrt{-\eta}\, c_O\left(\frac{\Lambda_X}{\Lambda_U}\right)(\Lambda_U^4 - \Lambda_X^4)$$

UV-Caused Knots

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

no problem in flat ST

big hierarchy problem ☹

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

explicit breaking of Color & EM ☹

- How to untangle these knots?

How To Incorporate Gravity Into SM Effective Action?

$$S_{eff}\left(\eta, \psi_{SM}, \Lambda_X, \Lambda_U\right)$$

$\eta_{\mu\nu} \Longmapsto g_{\mu\nu}$

$$S_{eff}\left(g, \psi_{SM}, \Lambda_X, \Lambda_U\right)$$

"curvature" can be added by hand

$$S_{eff}\left(g, \psi_{SM}, \Lambda_X, \Lambda_U\right) - \int d^4x\sqrt{-g}\,\left(\tilde{M}^2 R(g) + \tilde{V} + \cdots\right)$$

incalculable, arbitrary constants ☹
(loops have already been used up)

How To Incorporate Gravity Into SM Effective Action?

$$S_{eff}\left(\eta, \psi_{SM}, \Lambda_X, \Lambda_U\right)$$

$$\eta_{\mu\nu} \Longmapsto g_{\mu\nu}$$

$$S_{eff}\left(g, \psi_{SM}, \Lambda_X, \Lambda_U\right)$$

$$? \Longmapsto R_{\mu\nu}(g)$$

"curvature" must be emergent!

$\ldots\ldots$

- ? = what? Is it Λ_X? or Λ_U? or some other scale?

Gauge Invariance & Emergent Curvature

It proves efficacious to start with the trivial identity:

$$\delta S_V = \delta S_V + I_V - {\color{green} I_V}$$

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

$$\delta S_V \rightarrow \int d^4x \sqrt{-\eta} c_V \,{\color{red} (\Lambda_U^2 - \Lambda_X^2)}\, \text{Tr}\Big[V_\mu V^\mu\Big]$$

Gauge Invariance & Emergent Curvature

$$= \int d^4x \sqrt{-\eta} c_V \, (\Lambda_U^2 - \Lambda_X^2) \text{Tr}\Big[V_\mu V^\mu\Big]$$

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

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

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

surface term

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

Gauge Invariance & Emergent Curvature

$$\xrightarrow[\text{“Equivalence Principle”}]{\eta_{\mu\nu} \Longmapsto g_{\mu\nu}}$$

$$\int d^4x \sqrt{-g}\, c_V \left(\Lambda_U^2 - \Lambda_X^2\right) \mathrm{Tr}\left[V_\mu V^\mu\right]$$

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

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

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

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

surface term

Gauge Invariance & Emergent Curvature

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

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

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

↓

What if this is a fixed value assigned to curvature?

↓

What if curvature emerges as $(\Lambda_U^2 - \Lambda_X^2)g_{\mu\nu} \Longmapsto R_{\mu\nu}(g)$?

Gauge Invariance & Emergent Curvature

$$\xrightarrow[\text{“Curved Equivalence Principle”}]{(\eta_{\mu\nu}\Longmapsto g_{\mu\nu})\&\left((\Lambda_U^2-\Lambda_X^2)g_{\mu\nu}\Longmapsto R_{\mu\nu}(g)\right)}$$

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

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

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

$$=\int d^4x\sqrt{-g}\frac{c_V}{2}\mathrm{Tr}\Big[V_{\mu\nu}V^{\mu\nu}\Big]-\int d^4x\sqrt{-g}\frac{c_V}{2}\mathrm{Tr}\Big[V_{\mu\nu}V^{\mu\nu}\Big]\equiv 0 \quad ☺$$

if c_V is held unaffected

Gauge Invariance & Emergent Curvature

In summary:

$$\delta S_V = \delta S_V + I_V - I_V \xrightarrow[(\Lambda_U^2 - \Lambda_X^2) g_{\mu\nu} \Longmapsto R_{\mu\nu}(g)]{\eta_{\mu\nu} \Rightarrow g_{\mu\nu}} 0$$

$\delta M^2_{W,Z}$ are logarithmic

↓

EWB remains spontaneous!

photon and gluon are both massless

↓

Color & EM are restored!

SM/UV Hierarchy Is Preserved

Holding $c_V\left(\frac{\Lambda_X}{\Lambda_U}\right)$ unaffected while $(\Lambda_{UV}^2 - \Lambda_{SM}^2)g_{\mu\nu} \Longmapsto R_{\mu\nu}(g)$

$\downarrow$

the hierarchy $\frac{\Lambda_X}{\Lambda_U}$ is preserved

$c_O\left(\frac{\Lambda_X}{\Lambda_U}\right) \quad \swarrow \quad \searrow \quad c_H\left(\frac{\Lambda_X}{\Lambda_U}\right)$

Power-Law UV Contributions Set Curvature Sector

$$\delta S_{power} \xrightarrow[c_O, c_H \text{ held unchanged}]{(\Lambda_U^2 - \Lambda_X^2) g_{\mu\nu} \Longrightarrow R_{\mu\nu}(g)}$$

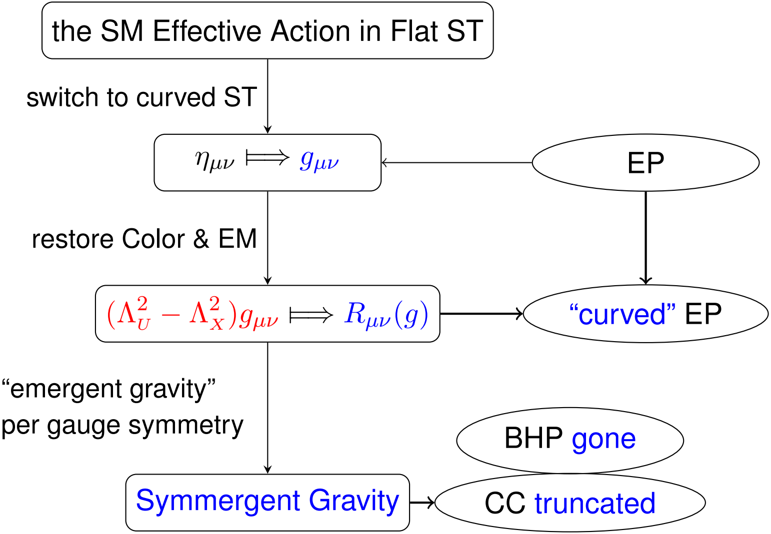
$$-\int d^4x \sqrt{-g}\, \underbrace{\frac{c_O}{4} \left(\Lambda_U^2 + \Lambda_X^2\right)}_{\frac{M_{Pl}^2}{2}} R(g)$$

☺ 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 $M_{Pl} \cong \Lambda_U$.

	Gravity Sector	Cosmological Constant	Higgs Mass	Color & EM
Induced Gravity	EH + HC	$\Lambda_U^4/M_{Pl}^2 \simeq M_{Pl}^2$	$\simeq M_{Pl}$	Broken
Symmergent Gravity	EH	$\Lambda_{EW}^4/M_{Pl}^2 \simeq m_\nu^2$	$\simeq \Lambda_{EW}$	Exact

Symmergent Gravity Results In Dim. Reg.

Holding $\log \frac{\Lambda_X}{\Lambda_U}$ unaffected while $(\Lambda_{UV}^2 - \Lambda_{SM}^2) g_{\mu\nu} \Longrightarrow R_{\mu\nu}(g)$

$\downarrow$

$$\log \frac{\Lambda_X}{\Lambda_U} \rightsquigarrow -\frac{1}{\epsilon} - \log \frac{\mu}{\Lambda_X}$$

$\downarrow$

$$\delta S_{log}\left(\psi_{SM}, \log \frac{\Lambda_X}{\Lambda_U}\right) \rightsquigarrow \text{Dim. Reg.}$$

$\downarrow$

the usual RGEs

Symmergent Gravity Entails Dim. Reg. In The IR

Λ_X

$$S_{eff}\left(g, \psi_{SM}, \frac{\Lambda_X}{\Lambda_U}, R(g), M_{Pl}^2\right)$$

$\downarrow$

in Dim. Reg.

$\downarrow$

all ψ_{SM} loops must be in Dim. Reg.

Symmergent Gravity Is Only Feebly Quantum

Λ_X

$$S_{eff}\left(g, \psi_{SM}, \frac{\Lambda_X}{\Lambda_U}, R(g), M_{Pl}^2\right)$$

$$\delta\psi_{SM} \rightsquigarrow \delta g_{\mu\nu}$$

tiny quantum gravity effects

Alas! 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 $\Lambda_U \lesssim M_{Pl}$

A BSM Sector Is Required

- All it has to do is to provide some

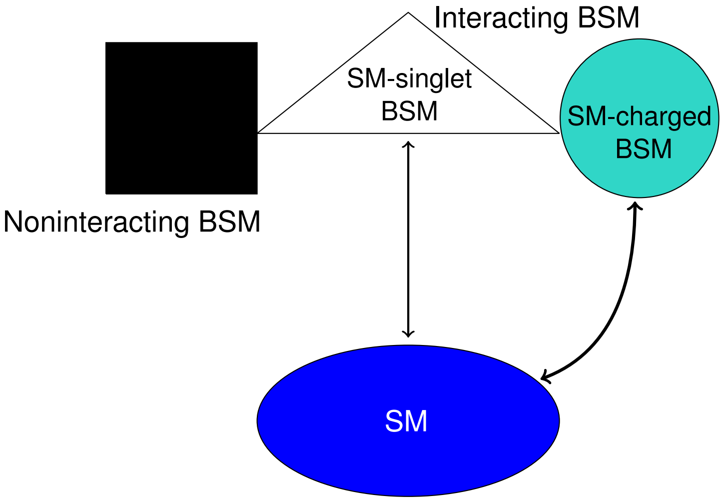
  $$n_b^{BSM} - n_f^{BSM} \gtrsim 128\pi^2 + 62 \approx 1325$$

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

- Smaller the Λ_U/M_{Pl} more crowded the BSM.

- It does not have to interact with the SM but it can.

BSM Comes In Two Types



NonInt-BSM Is Sweet Home For "Dark Stuff"

- It can span only SM-singlet non-Abelian gauge fields and fermions.
- It enjoys gauge groups like $\mathcal{G}_{BSM} = SO(51),\ SU(26),\ E(8)^3, \ldots$
- It is described by the action:

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

glueballs

hadrons

Dark Energy

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

pitch-Dark Matter

(interacts only gravitationaly)

(no way to see at direct searches)

Inflaton?

SM-Charged Int-BSM Seems Nonexistent

- No evidence for interacting BSM at the LHC and DM searches.

- Interacting BSM fields with SM charges, if any, must weigh near Λ_{EW} since their loop contributions to Higgs boson mass

$$\delta m_H^2 \propto m_{BSM}^2 \log \frac{m_{BSM}}{\Lambda_U}$$

  can be unacceptably large unless $m_{BSM} \cong \Lambda_{EW}$. But, this domain has already been scanned by the LHC and DM searches only to find nothing.

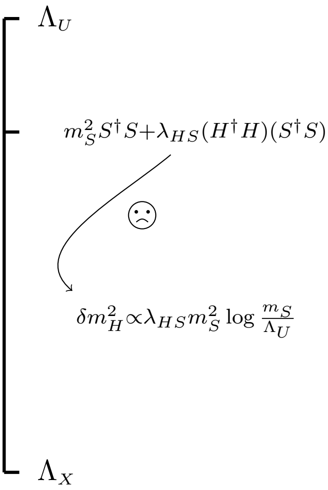
- It is for this reason that SUSY, Extra Dimensions, Compositeness and their various derivatives are disfavored by the data!

SM-Singlet Int-BSM Must Couple Seesawly

- No evidence for interacting BSM at the LHC and DM searches.
- But, it is required at least for Flavor, Strong CP, Baryogenesis, Inflation, whose models can contain scalars S.
- δm_H^2 can be suppressed only if

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

- $\delta\lambda_{HS} \propto \lambda_{HS} \Longrightarrow \lambda_{HS}$ is natural

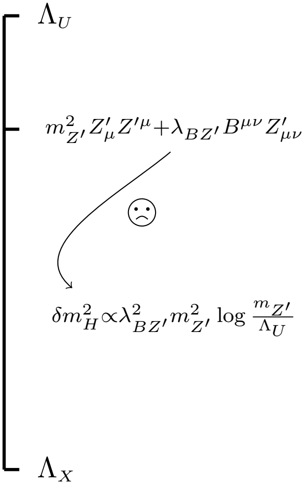


SM-Singlet Int-BSM Must Couple Seesawly

- Interacting BSM can contain a massive Z' gauge boson.
- It can mix with hypercharge gauge boson B kinetically.
- δm_H^2 can be suppressed only if

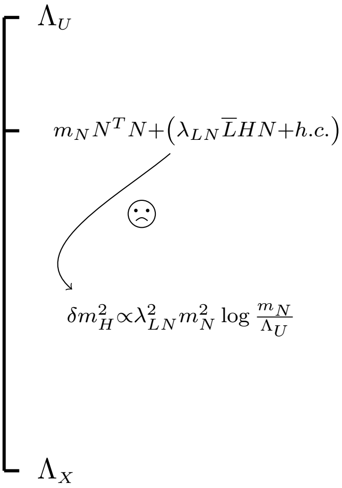
$$\lambda_{BZ'}^2 \lesssim \Lambda_{EW}^2 / m_{Z'}^2$$

- $\delta\lambda_{BZ'} \propto \lambda_{BZ'} \Longrightarrow \lambda_{BZ'}$ is natural



SM-Singlet Int-BSM Must Couple Seesawly

- Neutrinos can be Dirac or Majorana.
- Dirac neutrinos do not destabilize the Higgs sector.
- Majorana neutrinos do destabilize with RH neutrinos N of mass m_N.
- A crowded noninteracting BSM can set $\Lambda_U = m_N$ and stabilize the Higgs.

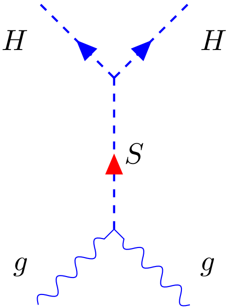


It Is OK Even If LHC Discovers Nothing New

Symmergent gravity necessitates “no new interacting particles”:

- No new particle has to be detected at the LHC and others.
- No new particle has to be detected in DM searches.
- “SM+Noninteracting BSM” can account for all the data.

Heavier The BSM Higher The Luminosity Needed



Discovering a scalar S of width Γ_S and mass m_S requires a collider of center-of-mass energy $\sqrt{s} \simeq m_S$ and integrated luminosity $\simeq \left(\frac{m_S}{m_H}\right)^4$

$$\#\text{extra events} \simeq \frac{m_H^2}{m_S^2} \times \frac{m_H^2}{\Gamma_S^2} \times \#\text{SM events}$$

CCP Is “The” Problem

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

- Solution of the CCP can reveal the BSM since

$$CC_{SM} + CC_{BSM} \cong H_0^2$$

can necessitate strong correlations with the SM.

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

We should ...

- investigate signals with no theoretical prejudice.
- keep in mind that we can end up with no signal.
- focus on the CCP to reveal structure of the BSM.
- 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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