

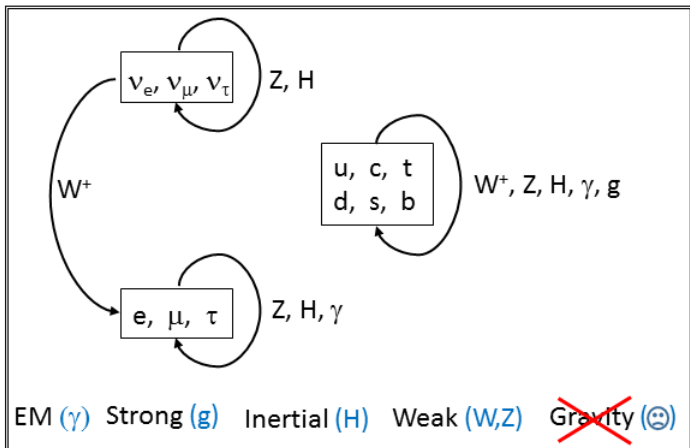
# Symmergent Gravity and Ultraviolet Physics

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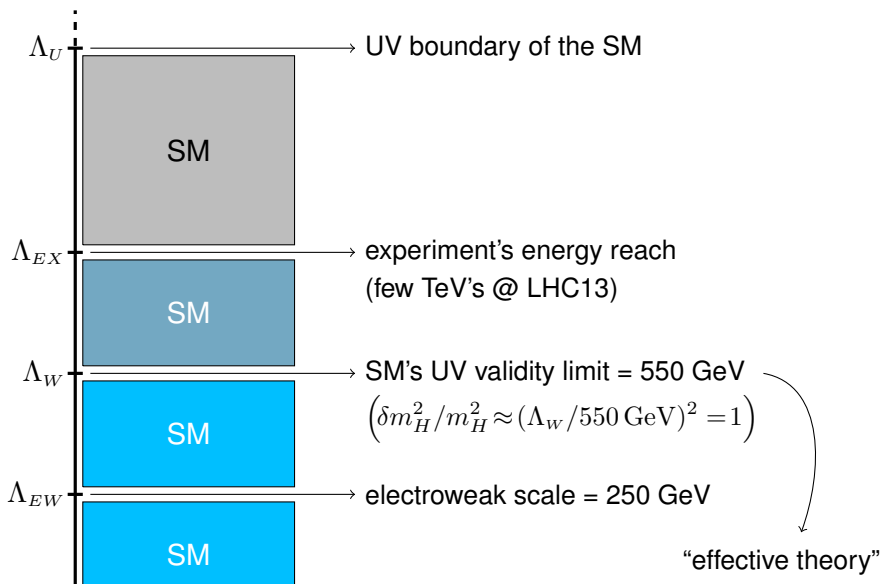
QDIS (April 23, 2018), İstanbul, Turkey

# The Standard Model

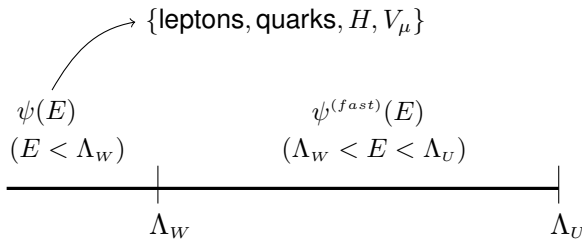


«a spontaneously broken,  
renormalizable QFT  
in flat spacetime»

# SM's UV Overextension



# Effective SM



The diagram shows a horizontal line representing energy scales. Two vertical tick marks are labeled  $\Lambda_W$  and  $\Lambda_U$ . Above the line, the energy range  $(E < \Lambda_W)$  is associated with  $\psi(E)$ , and the range  $(\Lambda_W < E < \Lambda_U)$  is associated with  $\psi^{(fast)}(E)$ . An arrow points from the text  $\{\text{leptons, quarks, } H, V_\mu\}$  to the  $\psi(E)$  region. Another arrow points from the text "flat metric  $\eta_{\mu\nu}$ " to the  $\psi^{(fast)}(E)$  region.

$\psi(E)$   
 $(E < \Lambda_W)$

$\psi^{(fast)}(E)$   
 $(\Lambda_W < E < \Lambda_U)$

$\Lambda_W$   $\Lambda_U$

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

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

$$e^{iS_{eff}(\eta, \psi)} = \int_{[\Lambda_W]}^{[\Lambda_U]} \mathcal{D}\psi^{(fast)} e^{iS(\eta, \psi, \psi^{(fast)})}$$

$$\begin{aligned} S_{eff}\left(\eta, \psi, \frac{\Lambda_W}{\Lambda_U}, \Lambda_U^2 - \Lambda_W^2\right) &= S_{tree}(\eta, \psi) \\ &+ \delta S_{log}\left(\eta, \psi, \Lambda_W^2 \log \frac{\Lambda_W}{\Lambda_U}\right) \\ &+ \delta S_{pow}\left(\eta, H, V_\mu, \Lambda_U^2 - \Lambda_W^2, \Lambda_U^2 + \Lambda_W^2\right) \end{aligned}$$

# UV Sensitive Parts

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

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

$$-\int d^4x \sqrt{-\eta} c_H (\Lambda_U^2 - \Lambda_W^2) H^\dagger H$$

$$-\int d^4x \sqrt{-\eta} \{ c_O (\Lambda_U^4 - \Lambda_W^4) + c_m (\Lambda_U^2 - \Lambda_W^2) m_H^2 \}$$

# UV-Induced Problems

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

cosmological  
constant problem  
in curved ST

explicit breaking of  
Color & EM & Weak

big  
hierarchy  
problem

Poincare breaking  
(switch to curved geometry?)

# How Not To Go To Curved Geometry

$$S_{eff}\left(\eta, \psi, \frac{\Lambda_W}{\Lambda_U}, \Lambda_U^2 - \Lambda_W^2\right)$$



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

$$S_{eff}\left(g, \psi, \frac{\Lambda_W}{\Lambda_U}, \Lambda_U^2 - \Lambda_W^2\right)$$



add curvature by hand

$$S_{eff}\left(g, \psi, \frac{\Lambda_W}{\Lambda_U}, \Lambda_U^2 - \Lambda_W^2\right) - \int d^4x \sqrt{-g} \left\{ M'^2 R(g) + a' R(g)^2 + \dots \right\}$$

**incalculable**, arbitrary terms  
since all loops are used up



# A Gauge Route To Curvature

$$\delta S_V = \delta S_V + I_V(\eta) - I_V(\eta)$$

The diagram illustrates the decomposition of the variation of the action  $\delta S_V$  into two terms. The original expression is  $\delta S_V = \delta S_V + I_V(\eta) - I_V(\eta)$ . The term  $I_V(\eta)$  is shown in green and is defined as  $\int d^4x \sqrt{-\eta} \frac{c_V}{2} \text{Tr}[V_{\mu\nu} V^{\mu\nu}]$ . The term  $\delta S_V$  is shown in black and is defined as  $\int d^4x \sqrt{-\eta} c_V (\Lambda_U^2 - \Lambda_W^2) \text{Tr}[V_\mu V^\mu]$ . Arrows indicate the mapping from the original expression to these two terms.

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

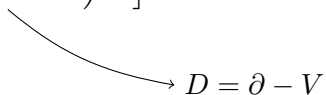
# A Gauge Route To Curvature

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

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

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

$$- I_V(\eta)$$


$$D = \partial - V$$

# A Gauge Route To Curvature

$$\xrightarrow{\eta_{\mu\nu} \leftrightarrow g_{\mu\nu}}$$

“Equivalence Principle”

$$\int d^4x \sqrt{-g} c_V (\Lambda_U^2 - \Lambda_W^2) \text{Tr}[V_\mu V^\mu]$$

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

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

$$- I_V(g)$$

$${}^g\mathcal{D} = {}^g\nabla - V \equiv \partial + {}^g\Gamma - V$$

$${}^g\Gamma_{\mu\nu}^\lambda = \frac{1}{2} g^{\lambda\iota} (\partial_\nu g_{\mu\iota} + \partial_\mu g_{\iota\nu} - \partial_\iota g_{\mu\nu})$$

# A Gauge Route To Curvature

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

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

$$- I_V(g)$$

what if  $(\Lambda_U^2 - \Lambda_W^2)g_{\mu\nu} \hookrightarrow R_{\mu\nu}(\Gamma)$  ?

affine connection  $\Gamma_{\mu\nu}^\lambda \neq {}^g\Gamma_{\mu\nu}^\lambda$   
affine curvature  $R_{\mu\nu}(\Gamma) \neq R_{\mu\nu}({}^g\Gamma)$

# A Gauge Route To Curvature

$$\frac{(\eta_{\mu\nu} \leftrightarrow g_{\mu\nu}) \& (\Lambda_U^2 - \Lambda_W^2) g_{\mu\nu} \leftrightarrow R_{\mu\nu}(\Gamma)}{\text{"Curved Equivalence Principle" (?)}} \rightarrow$$

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

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

$$- I_V(g)$$

would combine to give  $I_V(g)$   
if it were  $R_{\mu\nu}({}^g\Gamma)$  not  $R_{\mu\nu}(\Gamma)$

# A Gauge Route To Curvature

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

possible if  $c_V$  is held unaffected while  $(\Lambda_U^2 - \Lambda_W^2)g_{\mu\nu} \leftrightarrow R_{\mu\nu}(\Gamma)$

the EW/UV hierarchy  $\frac{\Lambda_W}{\Lambda_U}$  is preserved

# Effective SM Gets To Metric-Affine Geometry

$$S_{eff}\left(g, \psi, \frac{\Lambda_W}{\Lambda_U}, R(\Gamma)\right) = S_{tree}(g, \psi) + S_{log}\left(g, \psi, \Lambda_W^2 \log \frac{\Lambda_W}{\Lambda_U}\right)$$

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

$$- \int d^4x \sqrt{-g} \frac{c_H}{4} H^\dagger H g^{\mu\nu} R_{\mu\nu}(\Gamma)$$

big hierarchy  
problem is gone

$$- \int d^4x \sqrt{-g} \left\{ \underbrace{\left( \frac{c_O}{2} \Lambda_W^2 + \frac{c_m}{4} m_H^2 \right)}_{\frac{M_{Pl}^2}{2}} g^{\mu\nu} R_{\mu\nu}(\Gamma) + \frac{c_O}{16} \left( g^{\mu\nu} R_{\mu\nu}(\Gamma) \right)^2 \right\}$$

UV end of CCP is gone

# Gravitational Constant

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

does not have to  
interact with the  
SM fields

**BSM**  
 $(H', V'_\mu, f')$

must contain  
 $n_b - n_f \simeq 10^{35}$   
fields to render  
 $c_O \simeq 10^{32}$

must have  
masses  
 $m_{BSM} \lesssim \Lambda_W$



# Effective (SM + BSM) Reconciles With MAG

$$\begin{aligned} S_{eff}(g, \psi, \psi', R(\Gamma)) \supset & - \sum_{\phi=H, H'} \int d^4x \sqrt{-g} \frac{c_\phi}{4} \phi^\dagger \phi g^{\mu\nu} R_{\mu\nu}(\Gamma) \\ & + \sum_{\nu=V, V'} \int d^4x \sqrt{-g} c_\nu \text{Tr}[\mathcal{V}^\mu (R_{\mu\nu}(\Gamma) - R_{\mu\nu}({}^g\Gamma)) \mathcal{V}^\nu] \\ & - \int d^4x \sqrt{-g} \left\{ \frac{M_{Pl}^2}{2} g^{\mu\nu} R_{\mu\nu}(\Gamma) + \frac{(c_O)_{tot}}{16} (g^{\mu\nu} R_{\mu\nu}(\Gamma))^2 \right\} \end{aligned}$$

$(c_O)_{tot} = (c_O)_{SM} + (c_O)_{BSM} \simeq 10^{32}$

# Affine Connection

$$\frac{M_{Pl}^2}{2} g_{\mu\nu} + \frac{c_\phi}{4} \phi^\dagger \phi g_{\mu\nu} - c_\nu \text{Tr}[\mathcal{V}_\mu \mathcal{V}_\nu] + \frac{(c_O)_{tot}}{8} R_{\mu\nu}(\Gamma)$$

$$\nabla_\lambda^\Gamma (\sqrt{-g} Q_{\mu\nu}) = 0$$

$$\Gamma_{\mu\nu}^\lambda = {}^g\Gamma_{\mu\nu}^\lambda + \frac{1}{2} (Q^{-1})^{\lambda\gamma} ({}^g\nabla_\mu Q_{\nu\gamma} + {}^g\nabla_\nu Q_{\gamma\mu} - {}^g\nabla_\gamma Q_{\mu\nu})$$

$${}^g\Gamma_{\mu\nu}^\lambda + \mathcal{O}\left(\frac{\Lambda_W^3}{M_{Pl}^2}\right) \quad \text{if } |g^{\mu\nu} R_{\mu\nu}(\Gamma)| \ll \Lambda_W^2 \text{ (low curvature)}$$

$${}^g\Gamma_{\mu\nu}^\lambda + ? \quad \text{if } |g^{\mu\nu} R_{\mu\nu}(\Gamma)| \gg \Lambda_W^2 \text{ (high curvature)}$$

# Low-Curvature MAG Is Nearly GR

$$\int d^4x \sqrt{-g} \frac{M_{Pl}^2}{2} g^{\mu\nu} R_{\mu\nu}(\Gamma) \rightsquigarrow \int d^4x \sqrt{-g} \frac{M_{Pl}^2}{2} g^{\mu\nu} R_{\mu\nu}({}^g\Gamma) + \mathcal{O}\left(\frac{\Lambda_W^6}{M_{Pl}^2}\right)$$

$$\int d^4x \sqrt{-g} \phi^\dagger \phi g^{\mu\nu} R_{\mu\nu}(\Gamma) \rightsquigarrow \int d^4x \sqrt{-g} \phi^\dagger \phi g^{\mu\nu} R_{\mu\nu}({}^g\Gamma) + \mathcal{O}\left(\frac{\Lambda_W^6}{M_{Pl}^2}\right)$$

$$\int d^4x \sqrt{-g} \text{Tr}[\mathcal{V}^\mu (R_{\mu\nu}(\Gamma) - R_{\mu\nu}({}^g\Gamma)) \mathcal{V}^\nu] \rightsquigarrow \mathbf{0} + \mathcal{O}\left(\frac{\Lambda_W^6}{M_{Pl}^2}\right)$$

# Low-Curvature MAG Yields The “Usual”

$$S_{eff}(g, \psi, \psi', R(\Gamma)) \supset$$

$$- \int d^4x \sqrt{-g} \frac{M_{Pl}^2}{2} g^{\mu\nu} R_{\mu\nu}(^g\Gamma)$$

$$- \sum_{\phi=H, H'} \int d^4x \sqrt{-g} \frac{c_\phi}{4} \phi^\dagger \phi g^{\mu\nu} R_{\mu\nu}(^g\Gamma)$$

$$+ \mathcal{O}\left(\frac{\Lambda_W^6}{M_{Pl}^2}\right)$$

explicit gauge breaking  
is now Planck-suppressed  
(Color & EM ✓)  
(EW breaking is spontaneous ✓)

# “Symmergent Gravity”

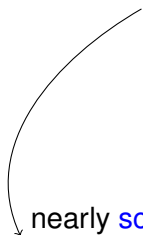
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“gravity is a gauge **symmetry**-restoring, **emergent** phenomenon”

# High-Curvature MAG Is Scale-Invariant

$$S_{eff}(g, \psi, \psi', R(\Gamma)) = - \int d^4x \sqrt{-g} \frac{(CO)_{tot}}{16} \left( g^{\mu\nu} R_{\mu\nu}(\Gamma) \right)^2$$

+ subleading contributions from EH & matter



nearly **scale-invariant**  
nearly **geometrical**

# Symmergent Gravity Results In Dim. Reg.

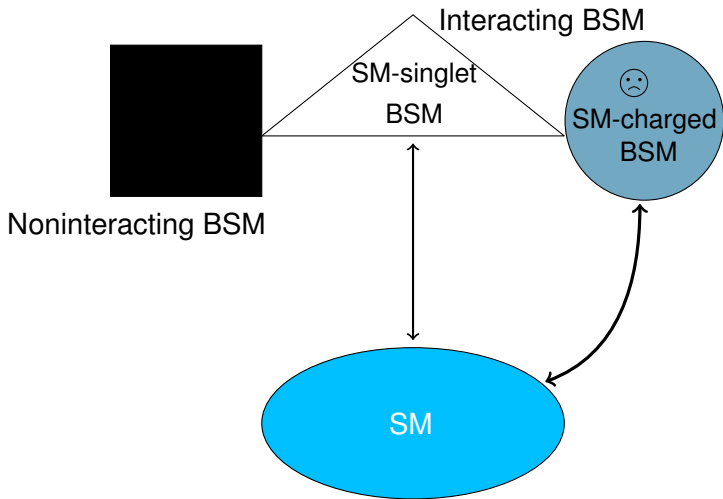
Holding  $\log \frac{\Lambda_W}{\Lambda_U}$  unaffected while  $(\Lambda_U^2 - \Lambda_W^2)g_{\mu\nu} \iff R_{\mu\nu}(g)$

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

$$\delta S_{\log} \left( \psi, \log \frac{\Lambda_W}{\Lambda_U} \right) \rightsquigarrow \text{Dim. Reg.}$$

the usual RGEs

# BSM Comes In Two Types

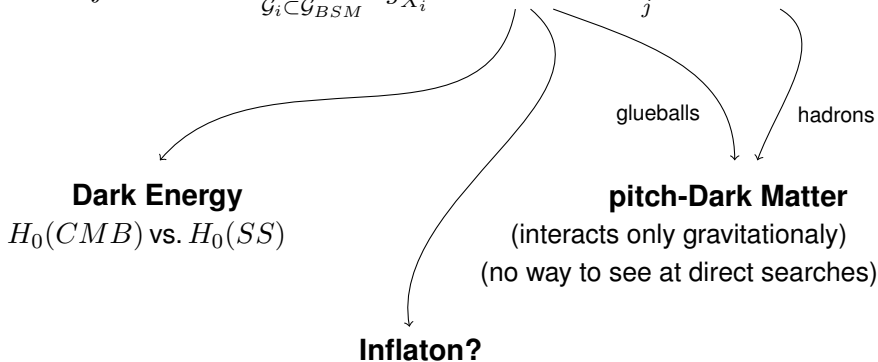




# NonInt-BSM Is Sweet Home For “Dark Stuff”

- ▶ It can span only SM-singlet **non-Abelian gauge fields** and **fermions**.
- ▶ It can be structured with large gauge groups  $\mathcal{G}_{BSM}$
- ▶ It is described by the action:

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



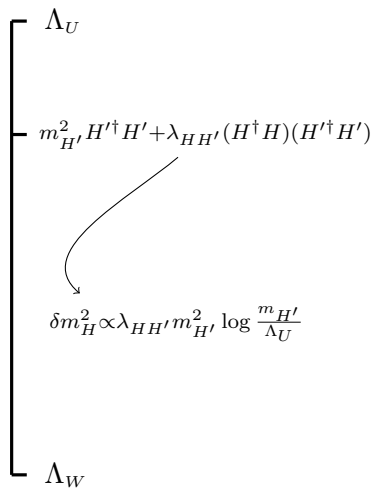
# SM-Singlet Int-BSM Must Couple Seesawly

- ▶ **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  $S$ .

- ▶  $\delta m_H^2$  can be suppressed only if

$$\lambda_{HH'} \lesssim \Lambda_W^2 / m_{H'}^2$$

- ▶  $\delta \lambda_{HH'} \propto \lambda_{HH'} \implies \lambda_{HH'}$  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.
- ▶  $\delta m_H^2$  can be suppressed only if

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

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

A vertical bracket on the left side of the diagram spans from the top scale  $\Lambda_U$  to the bottom scale  $\Lambda_W$ . The top of the bracket is labeled  $\Lambda_U$  and the bottom is labeled  $\Lambda_W$ . In the middle of the bracket, the Lagrangian term  $m_{Z'}^2 Z'_\mu Z'^\mu + \lambda_{BZ'} B^{\mu\nu} Z'_{\mu\nu}$  is written. A curved arrow originates from this term and points downwards towards the equation  $\delta m_H^2 \propto \lambda_{BZ'}^2 m_{Z'}^2 \log \frac{m_{Z'}}{\Lambda_U}$ .

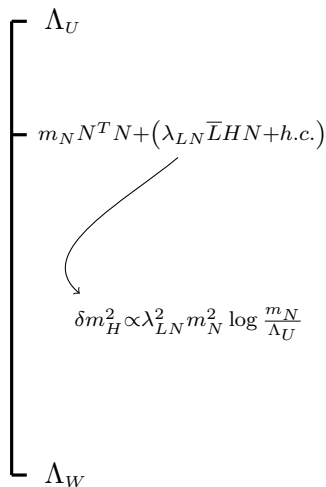
$$\delta m_H^2 \propto \lambda_{BZ'}^2 m_{Z'}^2 \log \frac{m_{Z'}}{\Lambda_U}$$

# SM-Singlet Int-BSM Must Couple Seesawly

- ▶ Interacting BSM can contain a heavy right-handed neutrino  $N$ .
- ▶ It induces active neutrino masses
- ▶  $\delta m_H^2$  can be suppressed only if

$$\lambda_{LN}^2 \lesssim \Lambda_W^2 / m_N^2$$

- ▶  $m_N \lesssim 1000 \text{ TeV}$



# It Is OK Even If LHC Discovers Nothing New

Symmergent gravity necessitates “no new interacting particles”:

- ▶ No new particle needs be **detected** at the LHC and others.
- ▶ No new particle needs be **detected** in DM searches.
- ▶ “SM + Noninteracting BSM” can **account for** present data.

# CCP Is “The” Problem

- ▶ The real **challenge** is to understand how CC can be reduced from  $\Lambda_w^4/M_{Pl}^2$  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, ... modulo the bounds from BBN and others)

# MAG Has To Be Elucidated

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- ▶ It seems highly involved but the affine connection  $\Gamma$  needs be solved.
  
- ▶ BH and other objects need be restudied in view of scale-invariance at high curvatures.

# Thank You For Your Attention

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## 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](#)



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