CHARGE CONSERVATION, GRAVITY AND DARK MATTER

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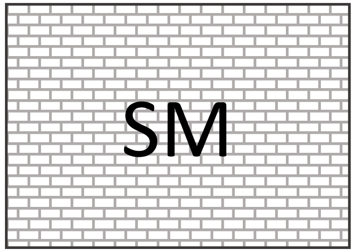
Physics Seminar @ MSGÜ (Dec. 5, 2019, İstanbul)

The Standard Model of elementary particles (SM) is the only known and verified QFT.

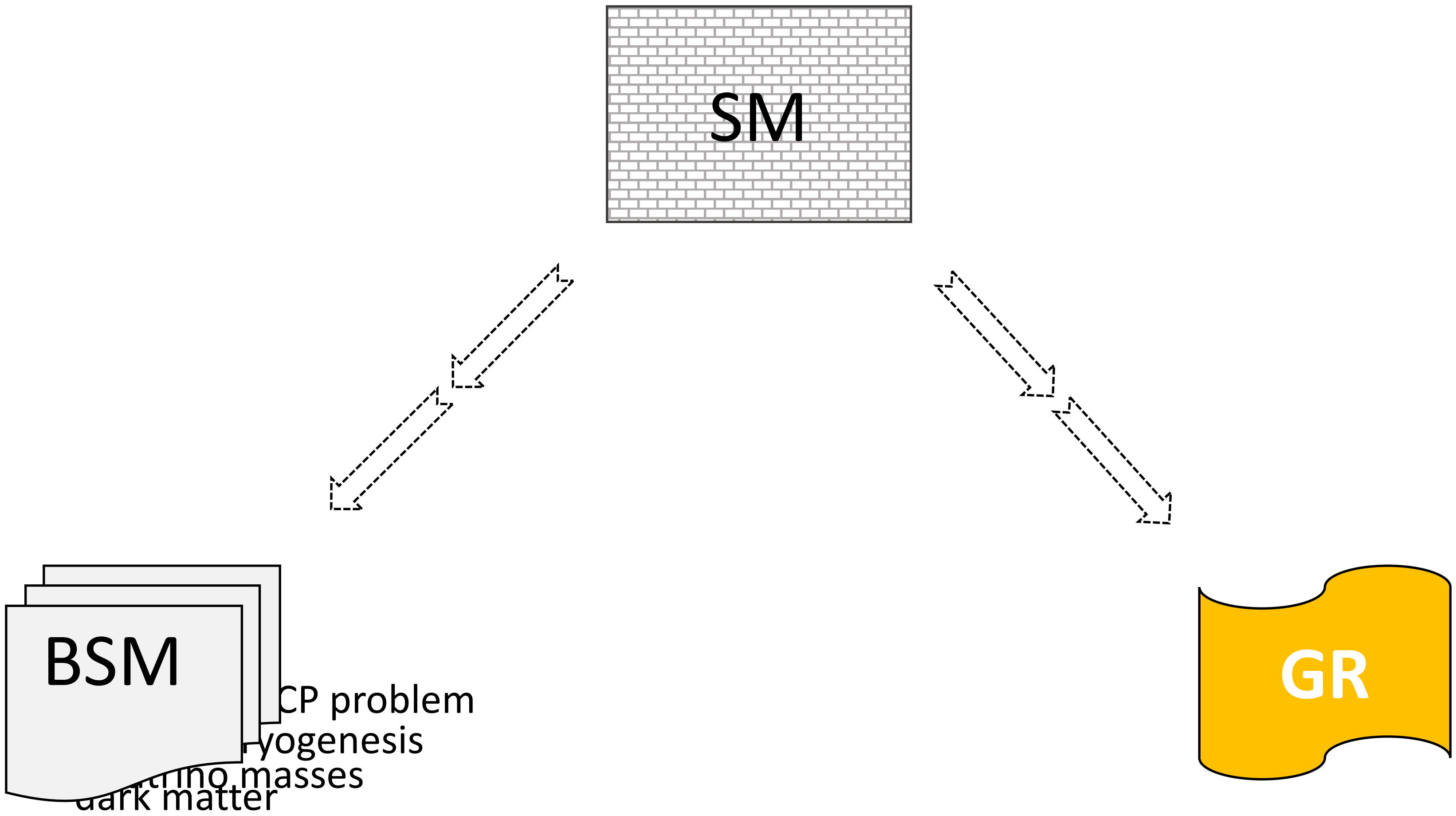


its particle spectrum, masses, couplings have all been fixed by the collider experiments

$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge theory with spontaneous $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$ symmetry breaking

a Poincare-invariant QFT in the flat spacetime of metric $\eta_{\mu\nu}$

There are phenomena which necessitate the SM to be extended/metamorphosed.



Each extension comes with its own scale and mechanism :

Experimental Fact	Extension of the SM	Mechanism
"neutrinos have mass"	Lepton # breaking at a scale $m_N < \infty$ leads to neutrino mass: $m_N \hookrightarrow m_\nu$	see-saw
"neutron EDM is small"	Peccei-Quinn breaking at a scale $f < \infty$ leads to axion mass: $f \hookrightarrow m_a$	relaxation

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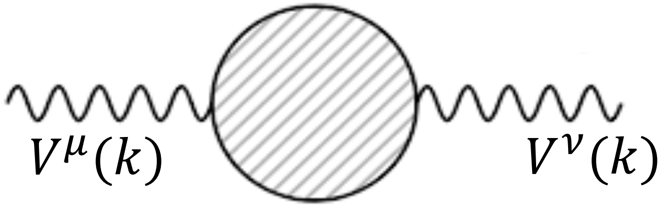
“neutron EDM is small”	Peccei-Quinn breaking at a scale $f < \infty$ leads to axion mass: $f \hookrightarrow m_a$	relaxation
“gravity exists”	**Poincare breaking at a scale $\Lambda_\wp < \infty$ leads to curvature:** $\Lambda_\wp^2 \hookrightarrow \mathbb{R}$	**equivalence**

- As a Poincare-invariant QFT, the SM ends at energies $\sim \Lambda_{\wp}$ (or distances $\sim 1/\Lambda_{\wp}$).

- All loop momenta are thus cut off at $\Lambda_{\wp}$.

- This hard UV cutoff gives $\mathcal{O}(\Lambda_{\wp})$ masses to all bosons, including the gauge bosons:



$$\equiv \quad \mathrm{V}^{\mu}(k)\{\Pi(k^2)\left(k_{\mu}k_{\nu} - k^2\,\eta_{\mu\nu}\right) + \boldsymbol{c_V \Lambda_{\wp}^2}\,\eta_{\mu\nu}\}V^{\nu}(k)$$

$$\delta S_V(\eta, \Lambda_{\wp}) = \int d^4x\,\sqrt{-\eta}\,\left\{\boldsymbol{c_V \Lambda_{\wp}^2} + 0\,.\log \Lambda_{\wp}\right\} \mathrm{tr}\left[\mathrm{V}_{\mu}\,\mathrm{V}^{\mu}\right]$$

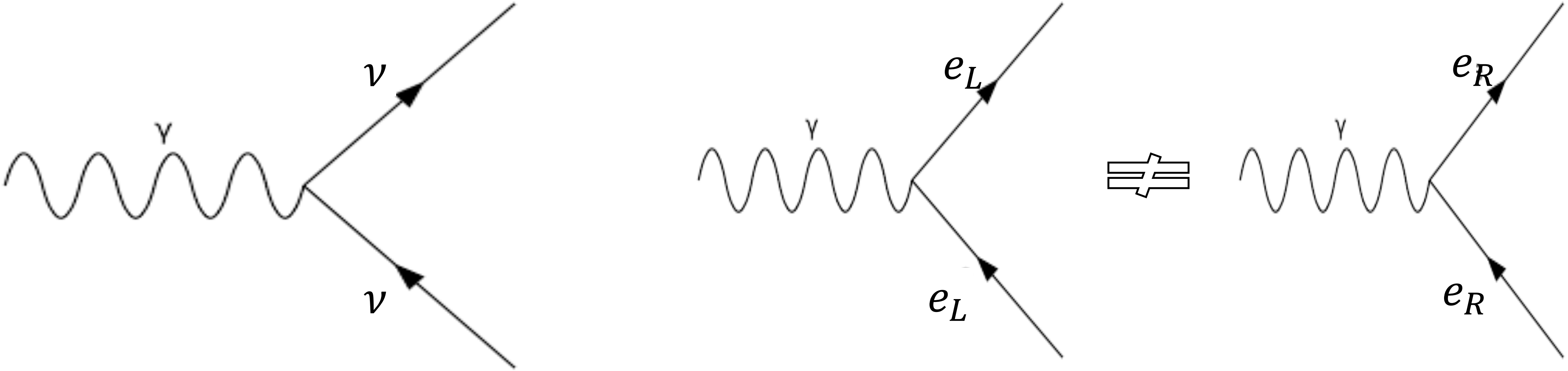
(D'Attanasio & Morris, hep-ph/9602156, '96; Peskin & Schroeder, '95)

The loop factor c_V changes from gauge group to gauge group. Its one-loop values are:

Gauge Boson (V^μ)	Loop Factor (c_V)	Broken Symmetry
$g_\mu^{a=1,\ldots,8}$	$c_g = \frac{21}{16\pi^2} g_s^2$	color
$W_\mu^{i=1,\ldots,3}$	$c_W = \frac{21}{16\pi^2} g_2^2$	isospin
B_μ	$c_B = \frac{39}{32\pi^2} g_Y^2$	hypercharge

- Color breaking demolishes confinement and destructs therefore all the hadronic structures.
- Isospin is broken explicitly and spontaneously (by $\langle H \rangle \neq 0$).
- Electromagnetism is broken explicitly by $c_W \neq 2\, c_B$:

$$\tan 2\tilde{\theta}_W = \frac{(g_2^2 - g_Y^2)\, \langle H \rangle^2}{(g_2^2 - g_Y^2)\langle H \rangle^2 + 2(c_W - 2\, c_B)\Lambda_{\wp}^2} \tan 2\theta_W \;\Longrightarrow\; \partial_\mu J^\mu_{EM} \neq 0$$



(L. Okun & M. Voloshin, '77; A. Ignatiev & G. Joshi, '96)

- How to prevent charge and color breaking (CCB)?
- How to insure spontaneity of electroweak breaking?
- In response, it proves efficacious to set the trivial identity

$$\delta S_V \equiv -I_V + \delta S_V + I_V$$

$$I_V(\eta) = \int d^4x \sqrt{-\eta} \, \frac{c_V}{2} \mathrm{tr}\left[\mathrm{V}_{\mu\nu}\mathrm{V}^{\mu\nu}\right]$$

(DD, arXiv:1901.07244, ’19; arXiv:1605.00377, ‘16)

- Keep " $-I_V$" untouched
- Integrate " $+ I_V$" by parts, and
- combine it with $\delta S_V(\eta, \Lambda_\wp)$ to get

$$\delta S_V(\eta, \Lambda_\wp) \equiv -I_V(\eta) + \int d^4x \sqrt{-\eta}\, c_V \mathrm{tr}[V^\mu(-D^2_{\mu\nu} + \Lambda^2_\wp\, \eta_{\mu\nu})V^\nu + \partial_\mu(V_\nu V^{\mu\nu})]$$

$$D^2_{\mu\nu} = D^2\eta_{\mu\nu} - D_\mu D_\nu - V_{\mu\nu}$$

$$D_\mu = \partial_\mu + ig\, V_\mu$$

- Incorporation of gravity starts with a (putatively curved) metric $g_{\mu\nu}$.

- In accordance with general covariance, let

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

which takes $\delta S_V(\eta, \Lambda_\wp)$ into curved geometry of $g_{\mu\nu}$:

$$\delta S_V(g, \Lambda_\wp) \equiv -I_V(g) + \int d^4x \sqrt{-g}\, c_V \mathrm{tr}[V^\mu(-\mathcal{D}^2_{\mu\nu} + \Lambda^2_\wp\, g_{\mu\nu})V^\nu + \nabla_\mu(V_\nu V^{\mu\nu})]$$

$$\mathcal{D}^2_{\mu\nu} = \mathcal{D}^2 g_{\mu\nu} - \mathcal{D}_\mu \mathcal{D}_\nu - V_{\mu\nu}$$

$$\mathcal{D}_\mu = \nabla_\mu + ig\, V_\mu$$

$${}^g\Gamma^\lambda_{\mu\nu} = \frac{1}{2}\, g^{\lambda\rho}(\partial_\mu g_{\nu\rho} + \partial_\nu g_{\rho\mu} - \partial_\rho g_{\nu\mu})$$

- By its nature, $\Lambda_{\wp}^2$ is to curvature whatever $\eta_{\mu\nu}$ is to $g_{\mu\nu}$.

- It is thus legitimate to introduce the «affine curvature map»

$$\Lambda_{\wp}^2\, g_{\mu\nu} \hookrightarrow \mathbb{R}_{\mu\nu}(\Gamma)$$

that takes $\delta S_V\left(g, \Lambda_{\wp}\right)$ into "metric-affine" geometry:

$$\delta S_V(g,\mathbb{R}) \equiv -I_V(g)\ + \int d^4x\,\sqrt{-g}\,\mathrm{c_V}\,\mathrm{tr}\left[V^{\mu}\left(-\mathcal{D}^2_{\mu\nu} + \mathbb{R}_{\mu\nu}(\Gamma)\ \right)V^{\nu} + \nabla_{\mu}(V_{\nu}V^{\mu\nu})\right]$$

$$= \int d^4x\,\sqrt{-g}\,c_V\mathrm{tr}\left[V^{\mu}\left(\mathbb{R}_{\mu\nu}(\Gamma)\ - R_{\mu\nu}({}^{g}\Gamma)\ \right)V^{\nu}\right]$$

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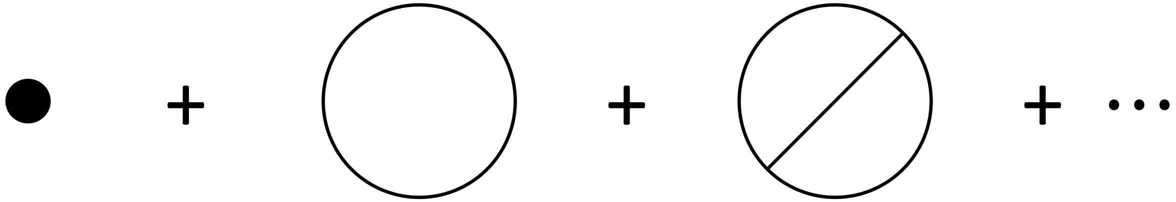
$$\ldots \left(\mathbb{R}_{\mu\nu}(\Gamma) - R_{\mu\nu}({}^g\Gamma)\right)V^\nu\Big]$$

CCB gets suppressed if $\mathbb{R}_{\mu\nu}(\Gamma) \rightarrow R_{\mu\nu}({}^g\Gamma)$, and this is decided by the dynamics of $\Gamma_{\mu\nu}^\lambda$.

(DD, arXiv:1901.07244, '19; arXiv:1605.00377, '16)

- Dynamics of $\Gamma^{\lambda}_{\mu\nu}$ is determined by curvature sector, and

- curvature sector stems from corrections to the vacuum and Higgs sectors:



$$\delta S_{OH}\left(\eta, \Lambda_{\wp}\right) = -\int d^4x \sqrt{-\eta}\, \{c_4\, \mathrm{str}[1]\Lambda_{\wp}^4 + c_m\, \mathrm{str}[m^2]\Lambda_{\wp}^2 + c_h\, \Lambda_{\wp}^2\, h^2\}$$

$$c_m = 2\, c_4 = \frac{1}{32\pi^2}$$

(cosmological constant problem)

$$c_h = \frac{1}{32\pi^2\Lambda_W^2}\,(2\, m_h^2 + \mathrm{str}[m^2])$$

(gauge hierarchy problem)

The metrical and curvature maps then lead to the curvature sector:

$$\delta S_{OH}(g,\mathbb{R}) = -\int d^4x\,\sqrt{-g}\,\{\frac{c_4}{16}\,\mathrm{str}[1](\mathbb{R}(g,\Gamma))^2+\frac{c_m}{4}\,\mathrm{str}[m^2]\mathbb{R}(g,\Gamma)+\frac{c_h}{4}\,\mathbb{R}(g,\Gamma)h^2\}$$

scalar affine curvature
$\mathbb{R}(g,\Gamma) = g^{\mu\nu}\,\mathbb{R}_{\mu\nu}(\Gamma)$

$m = \{m_h\ ,m_V\ ,m_f\ ,\cdots\}$

str[…] must lead to M_{Pl}^2!

Higgs-curvature coupling $\zeta = \frac{c_h}{2}$

The metrical and curvature maps then lead to the curvature sector:

$$\delta S_{OH}(g,\mathbb{R}) = -\int d^4x\,\sqrt{-g}\,\{\frac{c_4}{\ldots} \ldots \frac{c_m}{4}\,\mathrm{str}[m^2]\mathbb{R}(g,\Gamma) + \frac{c_h}{4}\,\mathbb{R}(g,\Gamma)h^2\}$$

M_{Pl}^2 comes out wrong

($\mathrm{str}[m^2] < 0$, $\mathrm{str}[m^2] \sim \Lambda_W^2$)

$\Longrightarrow$ BSM sector is necessary!

$m = \{m_h\ ,\, m_V\ ,\, m_f\ ,\cdots\}$

Higgs-curvature coupling $\zeta = \frac{c_h}{2}$

str[…] must lead to M_{Pl}^2

- BSM sector must contain massive fields (of masses $m' = \{m_{h'}\ , m_{V'}\ , m_{f'}\ , \cdots\}$)

- BSM sector must be bosonic or must contain heavy bosons (as heavy as M_{Pl})

- BSM fields do not have to interact with the SM fields (a vital feature of BSM!)

$$M_{Pl}^2 = \frac{1}{2}\left(c_m\, \mathrm{str}[m^2] + c_{m'}\, \mathrm{str}[m'^2]\right) \xrightarrow{\text{one-loop}} \frac{1}{64\pi^2}\, \mathrm{str}[\mathcal{M}^2]$$

$$\mathcal{M} = \{m_h\ , m_V\ , m_f , m_{h'}\ , m_{V'}\ , m_{f'}\ , \cdots\}$$

The complete curvature sector (with SM+BSM fields) takes the form:

$$\delta S(g,\mathbb{R}) = \int d^4x\,\sqrt{-g}\,\{-\mathrm{Q}^{\mu\nu}\mathbb{R}_{\mu\nu}(\Gamma) + \frac{c_4}{16}\,\mathrm{str}[1]\big(\mathbb{R}(g,\Gamma)\big)^2 - c_V R_{\mu\nu}({}^g\Gamma)\mathrm{tr}[\mathcal{V}^\mu\mathcal{V}^\nu]\}$$

$$Q^{\mu\nu} = \left(\frac{M_{Pl}^2}{2} + \frac{c_4}{8}\,\mathrm{str}[1]\mathbb{R}(g,\Gamma)\right)g^{\mu\nu} + \mathcal{K}^{\mu\nu}$$

$$\mathcal{K}^{\mu\nu} = \frac{c_{\mathcal{H}}}{4}\mathcal{H}^2 g^{\mu\nu} - c_{\mathcal{V}}\,\mathrm{tr}[\mathcal{V}^\mu\mathcal{V}^\nu]$$

$\Gamma^{\lambda}_{\mu\nu}$ obeys the equation of motion

$$^{\Gamma}\nabla_{\alpha}\, Q_{\mu\nu} = 0$$

with the solution

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

a non-linear PDE for $\Gamma^{\lambda}_{\mu\nu}$ because
$Q_{\mu\nu}$ involves the affine curvature
$\mathbb{R}(g,\Gamma) \sim \partial\Gamma + \Gamma\Gamma$

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GR is guaranteed if $\Gamma^{\lambda}_{\mu\nu}$ contains no «geometrical degrees of freedom» beyond ${}^{g}\Gamma^{\lambda}_{\mu\nu}$!

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… and this happens if

$str[1] = 0$

or equivalently if

$$n^{(b)}_{SM+BSM} = n^{(f)}_{SM+BSM}$$

… for $\Gamma^{\lambda}_{\mu\nu}$ because

…s the affine curvature

…) $\sim \partial\Gamma + \Gamma\Gamma$

With $\mathrm{str}[1] = 0$, the affine connection relates to Levi-Civita connection algebraically:

$$\Gamma^{\lambda}_{\mu\nu} = {}^{g}\Gamma^{\lambda}_{\mu\nu} + \frac{1}{2}\left(\left(\frac{M_{Pl}^2}{2} g + \mathcal{K}\right)^{-1}\right)^{\lambda\rho} \left(\nabla_\mu \mathcal{K}_{\nu\rho} + \nabla_\nu \mathcal{K}_{\rho\mu} - \nabla_\rho \mathcal{K}_{\mu\nu}\right)$$

$$= {}^{g}\Gamma^{\lambda}_{\mu\nu} + \frac{1}{M_{Pl}^2} \left(\nabla_\mu \mathcal{K}_{\nu\rho} + \nabla_\nu \mathcal{K}_{\rho\mu} - \nabla_\rho \mathcal{K}_{\mu\nu}\right) + \mathcal{O}\left(\frac{\nabla \mathcal{K}^2}{M_{Pl}^4}\right)$$

involves only the scalars $\mathcal{H}$ and gauge bosons $\mathcal{V}_\mu$ in SM+BSM!

The solution of the affine connection leads to the affine curvature

$$\mathbb{R}_{\mu\nu}(\Gamma) = R_{\mu\nu}({}^{g}\Gamma) + \mathcal{O}(\frac{\nabla^2\mathcal{K}}{M_{Pl}^2})$$

so that the notorious CCB gauge-boson mass action becomes

$$\delta S_V(g,\mathbb{R}) \equiv \int d^4x\,\sqrt{-g}\,c_V \mathrm{tr}\left[V^\mu\left(\mathbb{R}_{\mu\nu}(\Gamma) - R_{\mu\nu}({}^{g}\Gamma)\right)V^\nu\right] = 0 + \int d^4x\,\sqrt{-g}\,c_V\mathcal{O}(\frac{\nabla^2\mathcal{K}}{M_{Pl}^2})$$

no contribution to scalar
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gauge symmetry-restoring emergent gravity
or briefly
«symmergent gravity»

The solution of the affine curvature

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causes the complete curvature sector to reduce as

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$$= \int d^4x\,\sqrt{-g}\,\{-\frac{M_{Pl}^2}{2}\,R(g) - \frac{c_{\mathcal{H}}}{4}\,R(g)\,\mathcal{H}^2 + \mathcal{O}\left(\frac{\mathcal{K}\nabla^2\mathcal{K}}{M_{Pl}^2}\right)\}$$

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gauge hierarchy problem is gone!

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causes the complete curvature sector to

symmergent gravity is exact Einstein gravity!

$$\delta S(g, \mathbb{R}) = \int d^4 \cdots Q^{\mu\nu}\mathbb{R}_{\mu\nu}(\Gamma) + \frac{c_4}{16}\,\mathrm{str}[1]\big(\mathbb{R}(g,\Gamma)\big)^2 - c_V R_{\mu\nu}({}^{g}\Gamma)\mathrm{tr}[\mathcal{V}^{\mu}\mathcal{V}^{\nu}]\}$$

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SM+BSM might have a SUSY structure. Indeed, the constraint

$$\mathrm{str}[1] = 0$$

and the expression for the gravitational scale

$$M_{Pl}^2 = \frac{1}{64\pi^2}\,\mathrm{str}[\mathcal{M}^2]$$

might be taken to suggest that SM+BSM is a trans-Planckian SUSY broken around $M_{SUSY} \sim 16\, M_{Pl}$. This high-scale SUSY exists for enabling the GR and inducing the gravitational scale M_{Pl}. It is a «SUSY-for-GR» picture.

This high-scale SUSY is not realistic. It can be reconciled with the lightness and non-SUSY character of the SM if it exhibits a split-SUSY structure. This is a highly-fine tuned framework in that both $(\delta V)_{log}$ and $\left(\delta m_h^2\right)_{log}$ are suppressed by fine-tuning the model parameters up to some 121 digits.

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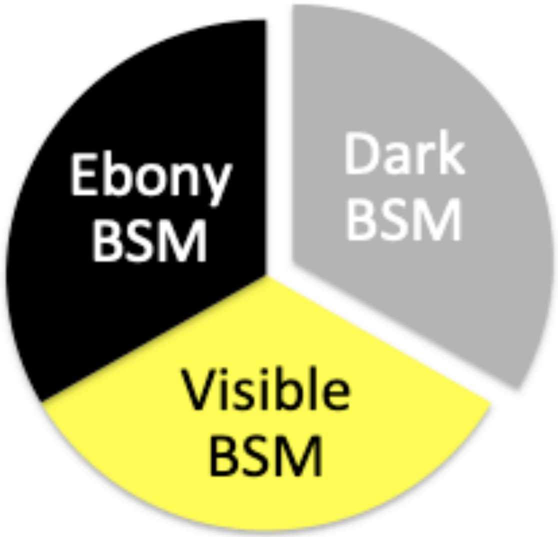
trans-Planckian SUSY is possible but it is extremely fine-tuned (split SUSY)!

A non-SUSY BSM seems much more viable! Indeed, the way M_{Pl} arises never require any coupling between the SM and the BSM fields. This is what differentiates symmergence from other known completions.

Symmergence:



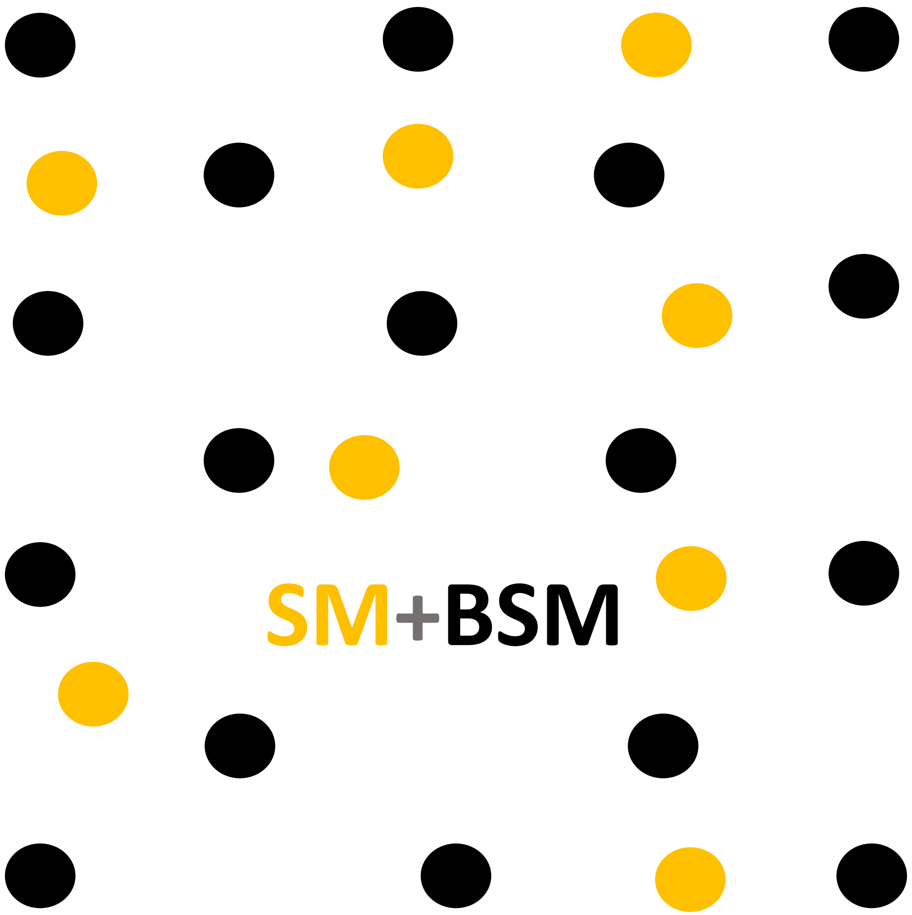
BSM can come in 3 types:

- BSM can be completely decoupled from the SM to form a pitch-dark **«ebony sector»**.
- BSM can couple to the SM as an SM-singlet sector and form a «dark sector».
- BSM can couple to the SM as an SM-charged sector and form «visible sector».

SUSY, Extra Dimensions, Technicolor:

The dark sector can be **ebony** (pitch-dark) in that it couples to the SM only gravitationally. It stabilizes electroweak scal with $\left(\delta m_h^2\right)_{log} = 0$ but can do nothing about the CCP since $(\delta V)_{log} \neq 0$

- It is a natural home to Dark Energy. (Could it be structured to solve the CCP?)
- It is a natural home also to «undetectable» Dark Matter (Isn't the current data pointing to an undetectable Dark Matter?)
- It can be produced by gravitational particle production at the end of inflation.



(P. Peebles and A. Vilenkin, arXiv:astro-ph/9904396)

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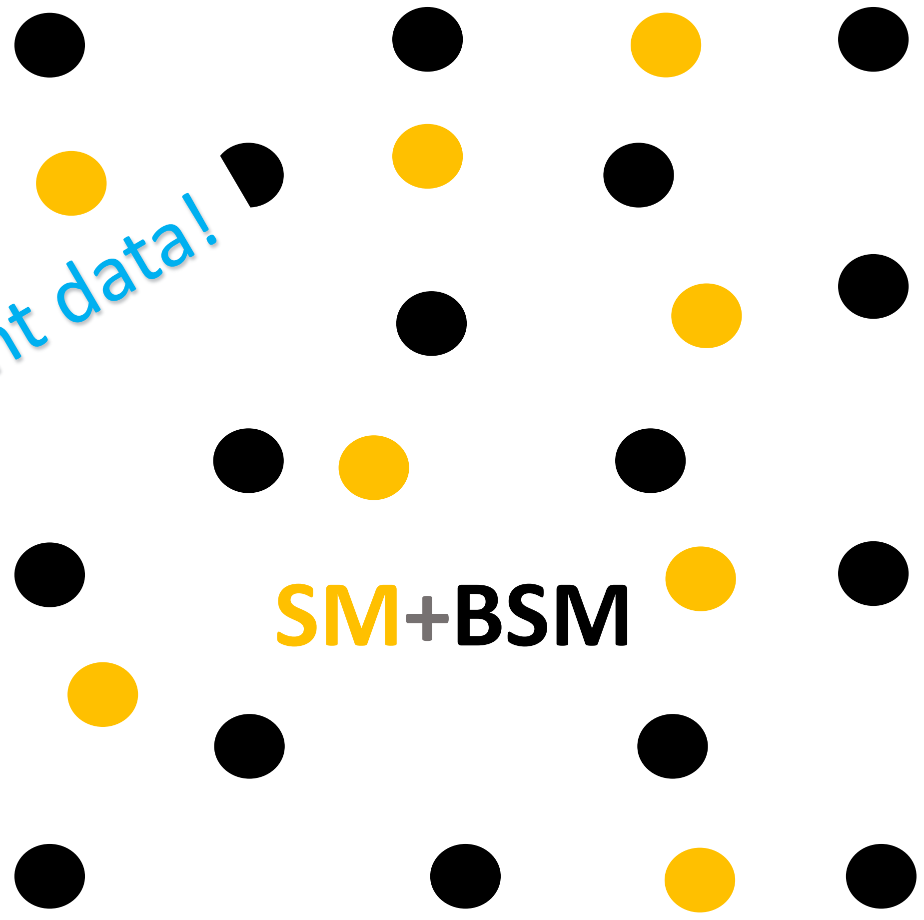
ebony BSM agrees with present data!



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Dark BSM is an SM-singlet sector. It can couple to the SM gravitationally as well as directly through the Higgs, Hypercharge, Lepton portals:

$$S_{int}(g) = \int d^4x \sqrt{-g}\, \{\lambda_{HH'}^2 (H^\dagger H)(H'^\dagger H') + \lambda_{BZ'}\, B^{\mu\nu} Z'_{\mu\nu} + (\lambda_{HN}\, \bar{L} H N + h.c.)$$

each of which gives rise to the aforementioned logarithmic shift $\left(\delta m_h^2\right)_{log}$ in the Higgs boson mass. The electroweak scale can be stabilized only if the SM-BSM couplings obey the bound

$$\lambda^2{}_{\psi\psi'} \lesssim \frac{m_h^2}{m_{\psi'}^2} \qquad\qquad (m_{\psi'} \geq m_h)$$

which sets a see-sawic relationship between the Higgs boson and BSM masses. Symmergence does not put any constraint on $\lambda_{\psi\psi'}$ so the see-sawic relationship above is physically allowed. In SUSY, extra dimensions and compositeness, however, $\lambda_{\psi\psi'}$ is tied to the SM couplings by symmetries so that a see-sawic relationship is never allowed! It is for this reason that the LHC has already started excluding them!)

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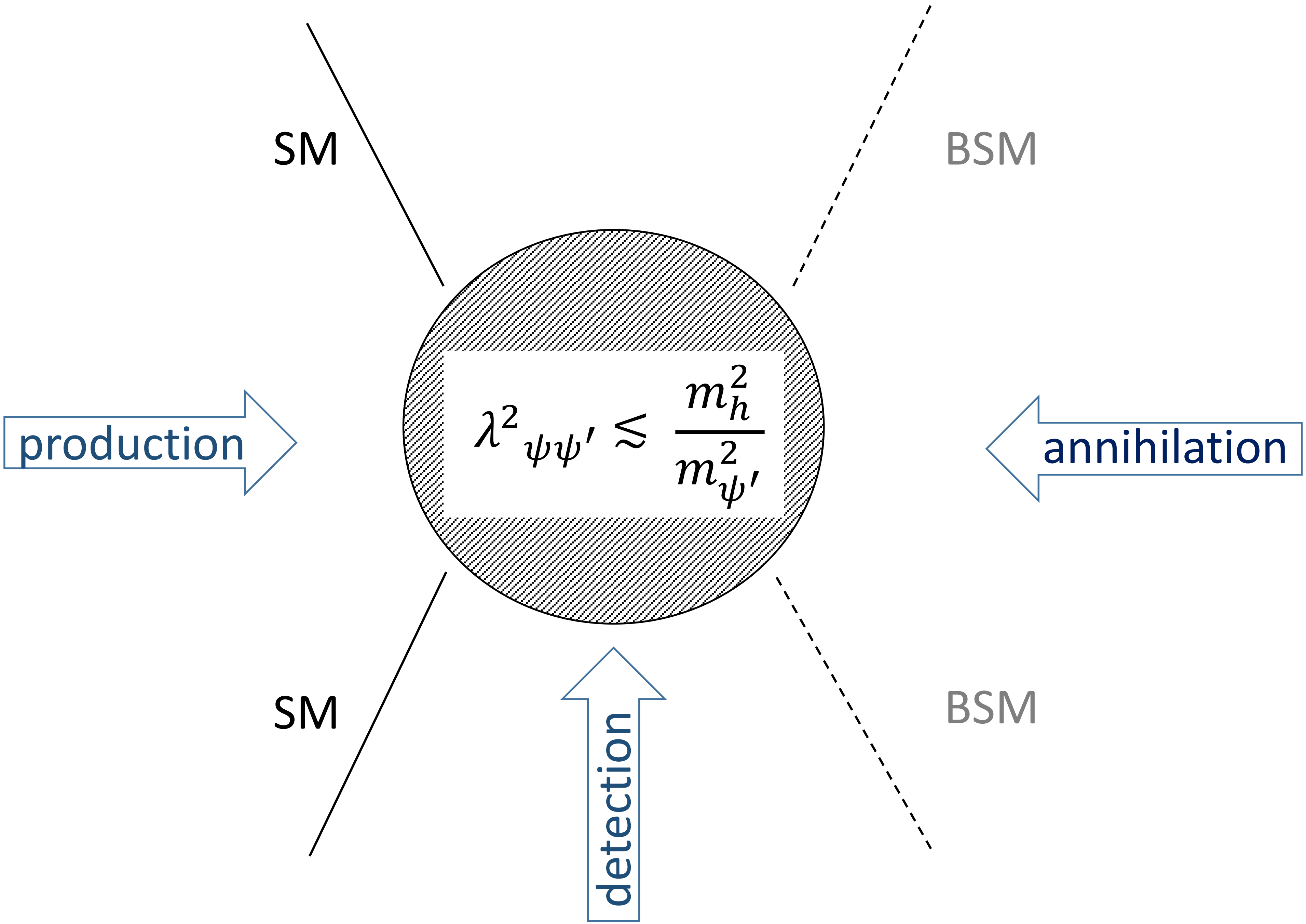
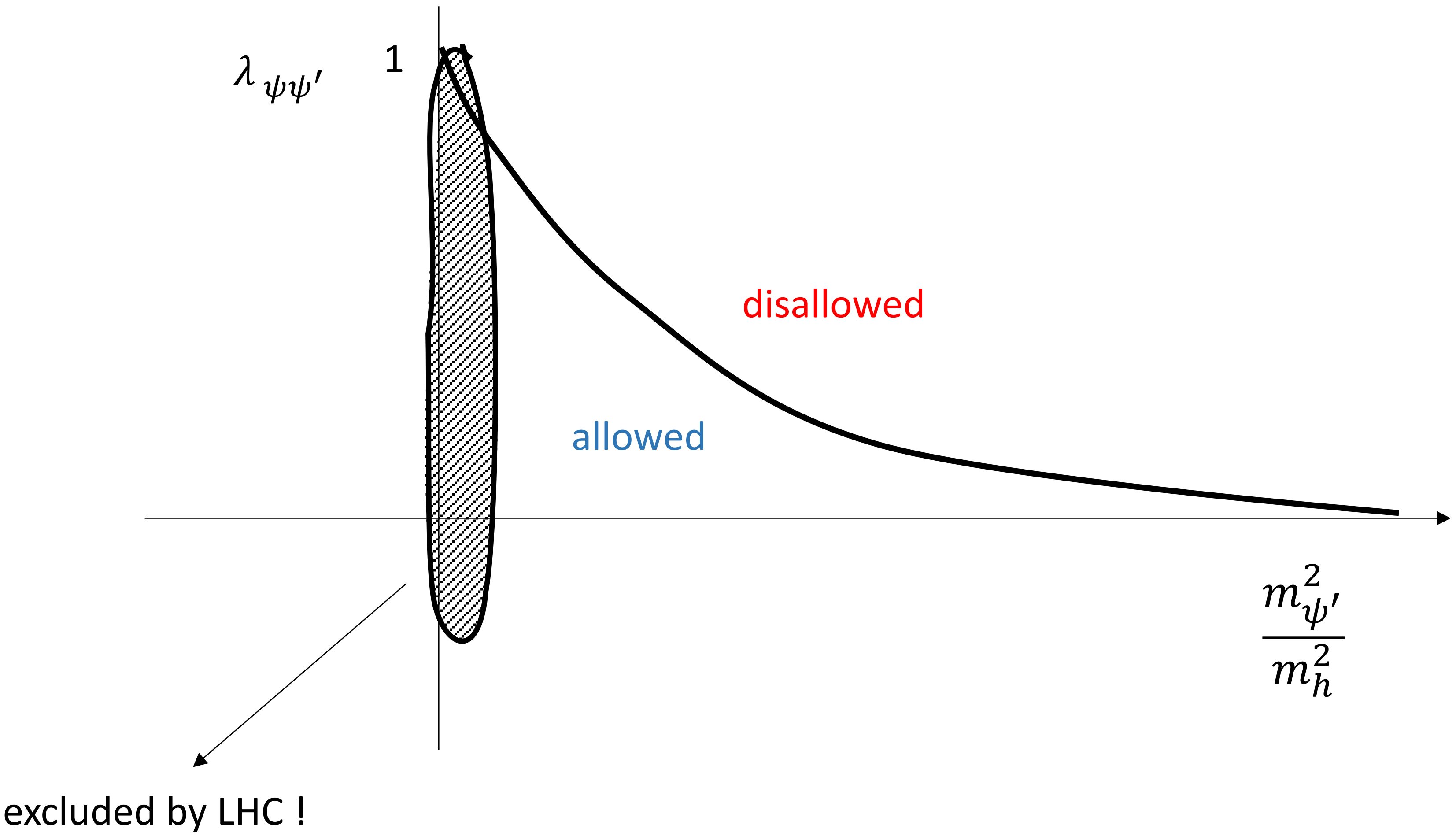
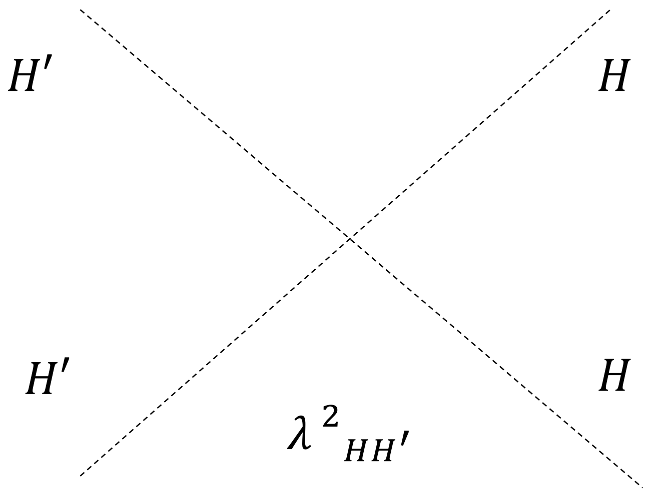
dark BSM possesses novel pheno and astro!


SM
BSM
production
$\lambda^2{}_{\psi\psi'} \lesssim \frac{m_h^2}{m_{\psi'}^2}$
annihilation
SM
detection
BSM

Dark BSM particles can be detected at mainly the high-luminosity colliders.



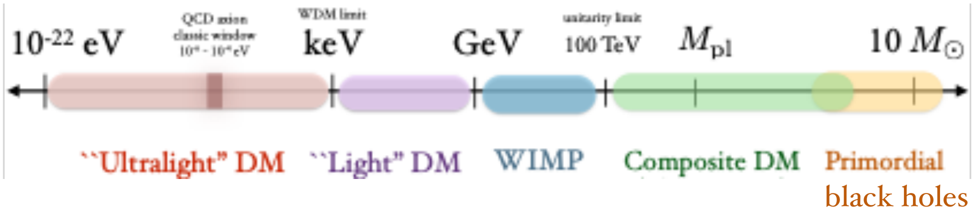
Scalar Dark mass is bounded from above:

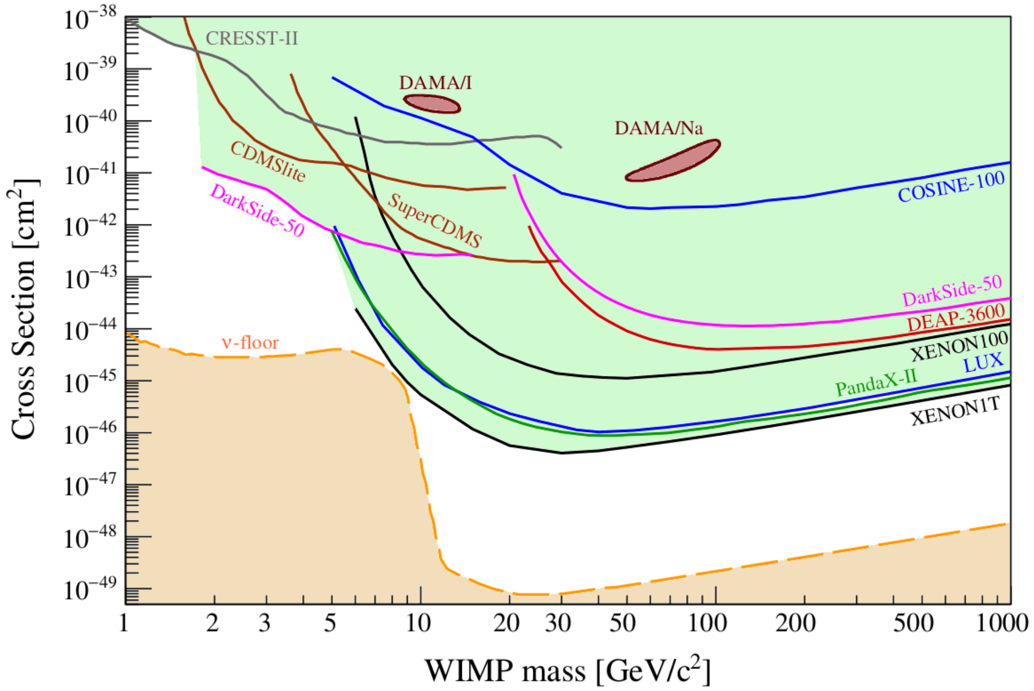


- H' remains stable if it ejoys a $\mathbb{Z}_2$ symmetry
- H' acquires correct relic density if $\lambda^2_{HH'} \simeq 2.1\times10^{-4}\,(\frac{m_{H'}}{\mathrm{GeV}})$
- and as a result, see-sawic structure imposes $m_h \lesssim m_{H'} \lesssim 3.38\, m_h \simeq 420$ GeV

→ a fairly light dark matter!

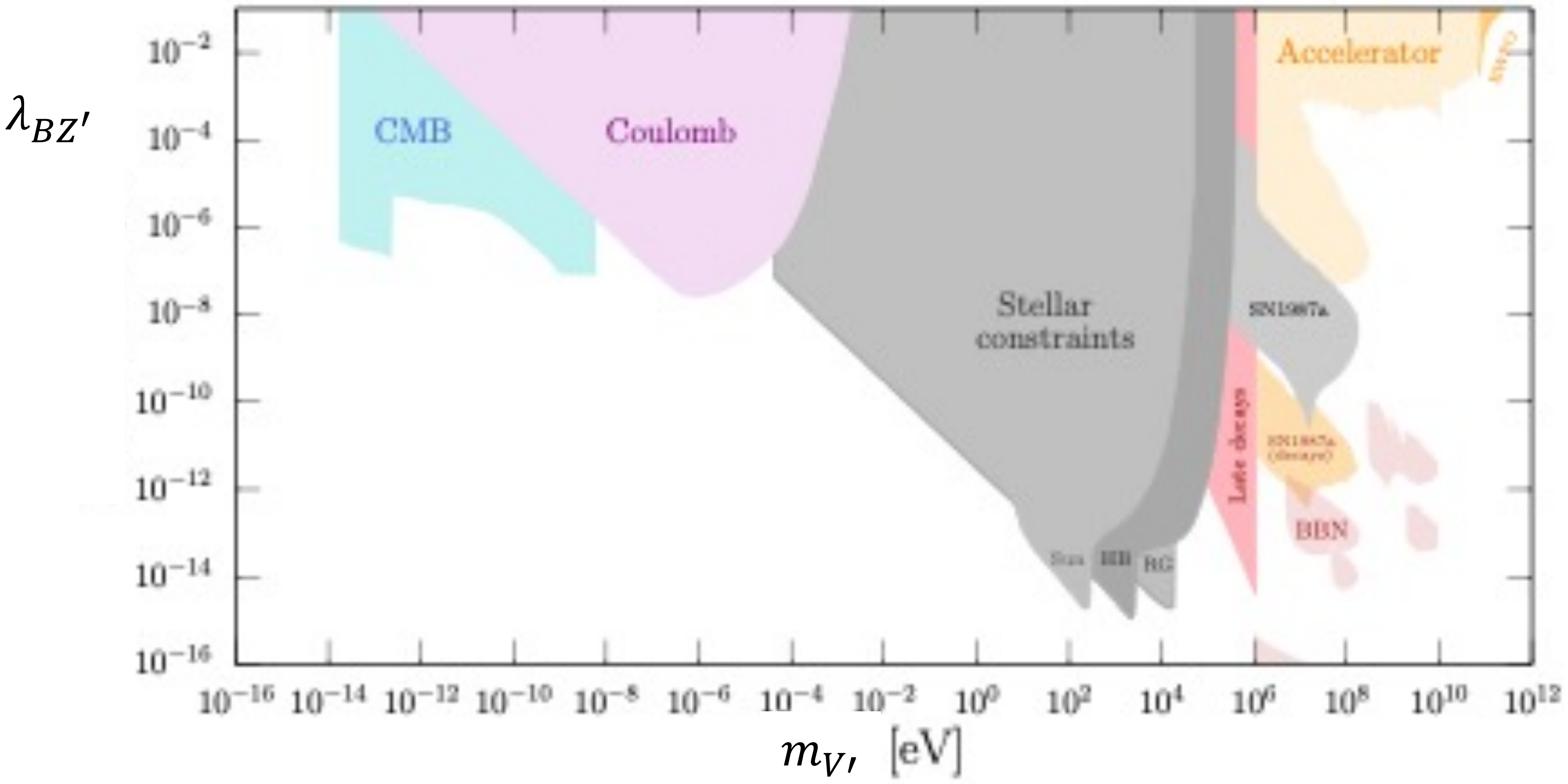
Dark matter comes in various types but detection cross-section is getting smaller and smaller at each new experiment:





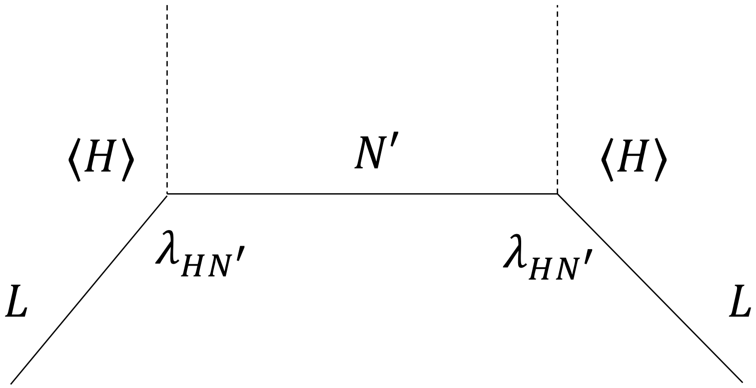
(T. Lin, arXiv:1904.07915)

Dark photon coupling well satisfies the see-sawic bound:



(T. Lin, arXiv:1904.07915)

Dark Neutrios must be relatively light:



- Active neutrinos acquire a mass $m_\nu = \lambda^2_{HN'} (\langle H \rangle / M_{N'})$

- and as a result, see-sawic structure imposes $m_{N'} \lesssim 1000\ \mathrm{TeV}$

a fairly light RH neutrino sector!

(F. Vissani, hep-ph/9709409, 1998)

- SM and GR are reconciled in a completely new way.
- GR emerges in a way restoring gauge symmetries and stabilizing the SM.
- There exists a rather wide/unconstrained BSM sector.
- There is a wide room to dark stuff (matter,energy,radiation).
- There are more …

- We have to understand gravity at «high curvature».
- We need a detailed collider analysis of «seeswic BSM» portals.
- We need a detailed dark matter/energy/photon analysis of «seesawic BSM».
- We need to understand if there is an underlying SUSY.
- We need to understand …

Thank You