Higgs Portal interactions and BSM with Classical Scale Invariance and Dark Matter

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Necessity of New Physics beyond the Standard Model

The LHC Higgs discovery is the crowning achievement of the SM. At a more fundamental level it leaves key questions unanswered:

- SM accommodates $v = 246\ \mathrm{GeV}$ and $m_h \simeq 125\ \mathrm{GeV}$ as input par-s, but does not explain their origin & why $\ll M_{\mathrm{Pl}}$
- The SM Higgs potential is unstable at $\mu_{\mathrm{RG}} \gtrsim 10^{11}$ GeV
- There is no Dark Matter in the SM
- Generation of the matter-anti-matter asymmetry of the Universe (BAU) is impossible within the SM
- Particle physics implementation of Cosmological Inflation? Strong CP? Neutrino masses?

Non-minimal Higgs Sector

What constitutes a non-minimal Higgs sector?

1. Presence of additional scalar fields, such that
2. at least some of them develop VEVs or otherwise mix with the SM Higgs field

Example: mixing between the SM Higgs H and a SM singlet ϕ,

$$H^{\mathrm{T}}(x) = \frac{1}{\sqrt{2}}(0, v + h(x)) \quad \text{and} \quad \phi(x) = \langle\phi\rangle + \varphi(x)$$

via the Higgs portal interaction:

$$\mathcal{L}_{\text{int}} \ni \lambda_{\mathrm{P}} \, |H(x)|^2 \, \phi(x)^2 \; = \; 2\lambda_{\mathrm{P}} \, v \langle\phi\rangle \, h(x) \, \varphi(x) \, + \, \ldots$$

Generic types of models with extended Higgs sectors:

1. New scalar SM-singlets mixing with the Higgs –
   realised as simple Higgs portal models with $\mathcal{L}_{\rm int} \ni \lambda_{\rm P}\, |H|^2\, \phi^2$

2. Multi-flavour Higgs models (e.g. new SM scalar doublets) –
   Two-Higgs-Doublet Models (2HDM) are most common.

   $\ni$ SUSY models: MSSM is an example of 2HDM Type-II;
   NMSSM is a 2HDM + a Singlet;
   pMSSM is MSSM with 19 phenomenological parameters

3. Composite Higgs models –
   realised as EFTs with higher-dimensional operators, or as
   'microscopic theory examples'

4. Large extra dimensions, KK gravitons, AdS/non-CFT, etc –
   phenomenological models inspired by (but not derived from)
   string theory.

Concentrate on: Higgs mixing with SM Singlets $->$ Higgs Portals

Simplest extensions of the Standard Model, well-motivated and attractive thanks to minimality in number of assumptions.

- Can generate the Higgs VEV radiatively and explain the origin of the electroweak scale (CSI models)
- Can stabilise the SM Higgs potential (when the 2nd Higgs is heavier than the SM Higgs and/or when more singlets added with not too small portal couplings)
- New Singlets can serve as *mediators to Dark Sectors* and can provide Dark Matter candidates.

Generically lead to reduced Higgs couplings to SM vectors and fermions due to the Higgs mixing angle, $\kappa_V \sim \cos\alpha \sim \kappa_f$.

$$\kappa_V : \quad g_{HVV} = \kappa_V \frac{2M_V^2}{v} \quad \text{and} \quad \kappa_f : \quad g_{Hff} = \kappa_f \frac{m_f}{v}$$

Minimal BSM framework: Higgs Portals to New Physics

There is just a single occurrence of a non-dynamical scale in the Standard Model – the negative-valued $\mu^2_{\rm SM}$ parameter in:

$$V_{\rm cl}^{\rm SM}(H) = \mu^2_{\rm SM}\, H^\dagger H + \frac{\lambda_{\rm H}}{2} \left(H^\dagger H\right)^2$$

Remove $\mu^2_{\rm SM}$ by introducing a Higgs portal interaction with new ϕ:

$$V_{\rm cl}(H,\phi) = -\,\lambda_{\rm P}(H^\dagger H)|\phi|^2 + \frac{\lambda_{\rm H}}{2}(H^\dagger H)^2 + \frac{\lambda_\phi}{4!}|\phi|^4$$

$V_{\rm cl}$ is now scale-invariant. If the right value for $\langle\phi\rangle \ll M_{UV}$ can be generated quantum mechanically, it will trigger the EWSB:

$$\mu^2_{\rm SM} = -\,\lambda_{\rm P}|\langle\phi\rangle|^2 \quad = -\,\frac{1}{2}\, m_h^2 = -\,\frac{1}{2}\,\lambda_{\rm H}\, v^2$$

Minimal BSM framework: Higgs Portals to New Physics

Coleman-Weinberg mechanism 40 years ago: a massless scalar field ϕ coupled to a gauge field dynamically generates a non-trivial $\langle\phi\rangle$ via dimensional transmutation of the log-running couplings

$$\langle\phi\rangle \sim M_{UV} \times \exp\left[-\frac{\mathrm{const}}{g_{CW}^2}\right] \ll M_{UV}$$

g_{CW} is the gauge coupling of ϕ.

SM$\times$CW BSM theory

Classically scale-invariant with the Higgs portal $-\lambda_{\mathrm{P}}|H|^2|\phi|^2$

$\langle\phi\rangle$ is non-vanishing, calculable in a weakly-coupled theory, and is naturally small (exp. suppressed) relative to the UV cut-off. Then:

$$\mathrm{EWSB}: \quad v = \sqrt{\frac{2\lambda_{\mathrm{P}}}{\lambda_{\mathrm{H}}}}\,\langle\phi\rangle\,, \quad m_h = \sqrt{2\lambda_{\mathrm{P}}}\,\langle\phi\rangle$$

Minimal BSM framework: Higgs Portals to New Physics

The SM taken in isolation as a QFT has no problems with the Higgs mass (ignore super-Planckian Landau poles). It does not address key sub-Planckian issues (DM, Matter-anti-Matter asymmetry ...) so extend it.

SM×CW BSM theory

Classically scale-invariant: No input mass terms are allowed

In the course of UV renormalisation, the subtraction scheme is chosen to set the *renormalised masses* at the origin of the field space to zero

$$m^2|_{\phi=0} \;:=\; V''(\phi)\Big|_{\phi=0} = 0$$

In *dimensional regularisation* this masslessness eqn is automatic:

- No power-like dependences on the cutoff scale can appear;
- Since there are no explicit mass scales at the outset, no finite corrections to mass terms at the origin are genereated.

Dim reg preserves classical scale invariance, the theory as it stands is not fine-tuned.

Comments on classical scale-invariance:

- Classical scale invariance is not an exact symmetry. It is broken anomalously by logarithmically running couplings.
- This is precisely what generates dynamical scales $\langle\phi\rangle \ll M_{UV}$ and feeds to EWSB and other features.
- The scale invariance is broken by the anomaly in a controlled way – the order parameter is $\langle|\phi|^2\rangle$.
  Generic UV regularisation instead would introduce *large* effects $\sim \alpha\, M_{UV}^2$
  $$\alpha\, M_{UV}^2 \gg \langle|\phi|^2\rangle$$
  To maintain the anomalously broken scale invariance, one must choose a scale-invariance-preserving regularisation scheme – dimensional regularisation – Bardeen 1995.

Some references:

S. R. Coleman and E. J. Weinberg, Phys. Rev. D **7** (1973) 1888

SM$\times$U(1)$_{CW}$ model first appears in:

R. Hempfling, Phys. Lett. B **379** (1996) 153

The special role of dimensional regularisation:

W. A. Bardeen, FERMILAB-CONF-95-391-T

Classical scale invariance introduced in:

K. A. Meissner and H. Nicolai, Phys. Lett. B **648** (2007) 312

Our approach:

C. Englert, J. Jaeckel, VVK and M. Spannowsky, 1301.4224 – *Original*

VVK, C. McCabe and G. Ro, arXiv:1403.4953 – *Higgs Stab. and DM*

VVK and G. Ro, 1307.3764 – *Matter-anti-Matter via Leptogenesis*

VVK 1308.6338 – *Inflation in the Higgs Portal*

Classically Scale Invariant Extended Standard Model

SM $\times G_{CW}$ with a hidden gauge sector G_{CW} and no mass scales. The theory is classically scale-invariant. Classical scalar potential:

$$V_{\rm cl}(H,\Phi) = \lambda_\phi(\Phi\Phi^\dagger)^2 + \lambda_H(HH^\dagger)^2 - \lambda_{\rm P}(\Phi\Phi^\dagger)(HH^\dagger)$$

The Higgs Portal interaction $-\lambda_{\rm P}\langle\Phi\Phi^\dagger\rangle(HH^\dagger)$ generates the Higgs VEV $v = 246$ GeV and triggers EWSB in the SM.

Consider Abelian and non-Abelian choices for G_{CW}:

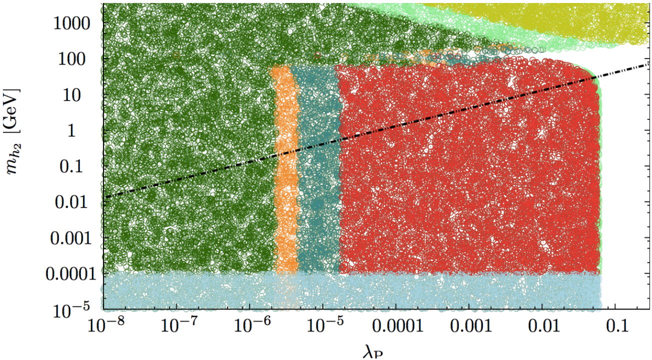
- Standard Model $\times$ $\mathrm{U(1)}_{\mathbf{CW}}$
- Standard Model $\times$ $\mathrm{U(1)}_{\mathbf{B-L}}$ => SM quarks and leptons charged under $\mathrm{U(1)}_{\mathbf{B-L}}$
- Standard Model $\times$ $\mathrm{SU(2)}_{\mathbf{CW}}$

Classically Scale Invariant Extended Standard Model

- Minimal CSI SM$\times$G$_{CW}$ models have only two free parameters, the portal coupling, $\lambda_{\rm P}$ and the hidden gauge coupling g_{CW}.
- H and Φ scalars mix, giving two higgs mass-eigenstates $m_{h_1} \simeq 125$ GeV and m_{h_2} (which can be $>$ or $< m_{h_1}$).
- There is always Z' with $M_{Z'} \gg m_{h_2}$. Both, m_{h_2} and $M_{Z'}$ can be determined in terms of $\lambda_{\rm P}$ and g_{CW}.
- If $m_{h_1} > 2m_{h_2}$ the SM Higgs can decay into two hidden Higgses which constrains $\lambda_{\rm P} \lesssim 10^{-5}$.
- For $m_{h_2} > m_{h_1}/2$ the coupling $\lambda_{\rm P}$ is much less constrained.
- Collider production of Z' possible if SM quarks couple to the hidden G_{CW} - as in the U$(1)_{B-L}$ example - but not otherwise.

Light h_2 states are highly constrained by large invisible Higgs decays $\Gamma_{h_1 \to h_2 h_2}$. More interested in heavier h_2.

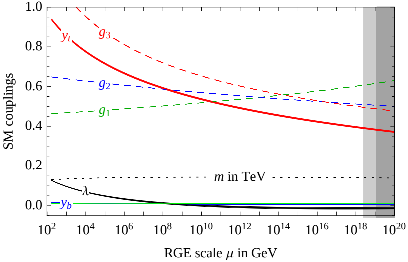
C. Englert, J. Jaeckel, V. V. Khoze and M. Spannowsky, 1301.4224

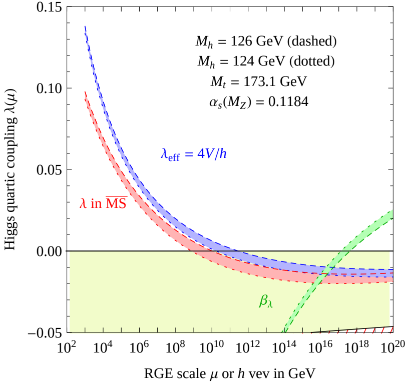


Scatter plot in the (λ_P, m_{h_2}) plane. Red region is excluded by current LHC measurements. The cyan region can be probed by HL LHC and orange region is a projection for a combination of a HL LHC with an LC. The allowed parameter points are depicted in green.

Stabilisation of the Higgs potential

The SM Higgs potential is unstable as the Higgs self-coupling λ_H turns < 0.





D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio and A. Strumia, 1307.3536

Stabilisation of the Higgs potential

A minimal and robust way to repair the EW vacuum stability is provided by the Higgs portal extension of the SM – just what we have in our theory.

Two effects to stabilise the vacuum:

1. When h_2 heavier than the SM Higgs h_1, the initial value of $\lambda_H > \lambda_{SM}$ $=>$ can be used in preventing $\lambda_H(\mu)$ from going negative at large μ.

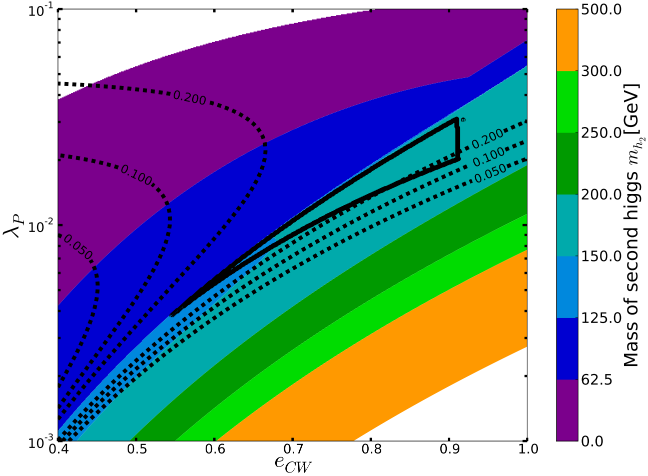
2. The portal coupling gives a positive contribution to the beta function of the Higgs quartic coupling, $\Delta\beta_{\lambda_H} \sim +\lambda_{\rm P}^2$.

   Hence we also consider extending the model by adding a real singlet:

   $$\text{CSI} \quad \text{SM} \times G_{CW} \oplus \text{singlet } s(x)$$

   The singlet gives the inflaton and the Dark Matter candidate plus helps with the Higgs vacuum stabilisation

VVK, C. McCabe and G. Ro, arXiv:1403.4953



U(1)$_{CW}$× SM: The Higgs potential is stabilised inside the wedge-shaped region. Contours of the Higgs mixing angle $\sin^2\alpha = 0.05$, 0.1 and 0.2 are shown and the mass of the 2nd scalar h_2 is colour-coded.

VVK, C. McCabe and G. Ro, arXiv:1403.4953

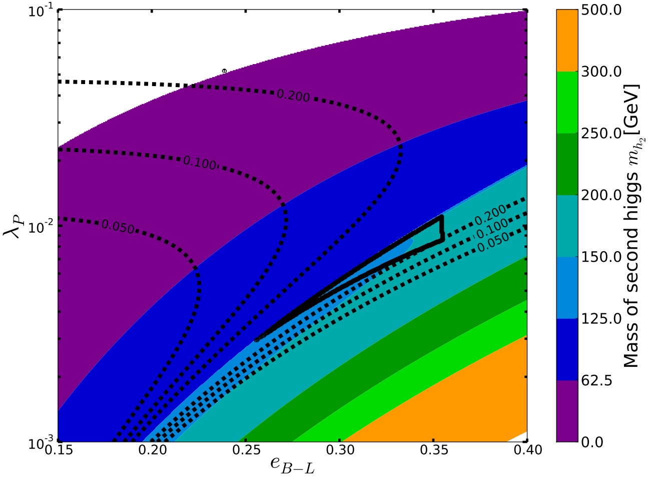


Figure : $\mathrm{U}(1)_{B-L} \times$ SM

VVK, C. McCabe and G. Ro, arXiv:1403.4953

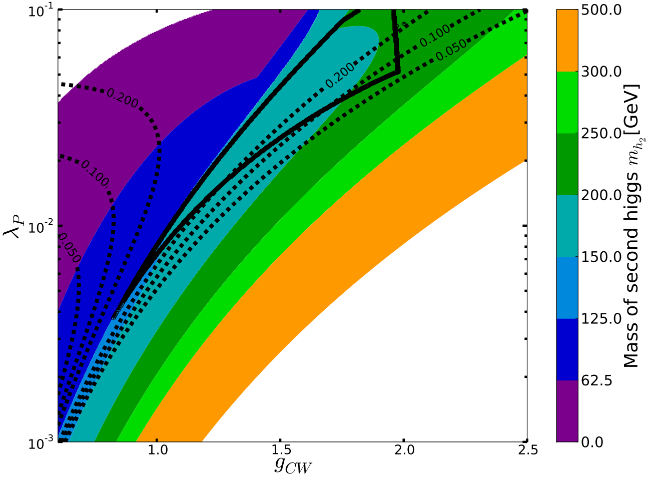


Figure : $SU(2)_{CW} \times SM$

CSI SM $\times G_{cw} \oplus$ singlet $s(x)$

Now consider adding a new singlet:

$$V_{\rm cl}(H,\phi,s) = \frac{\lambda_{Hs}}{2}|H|^2 s^2 + \frac{\lambda_{\phi s}}{2}|\Phi|^2 s^2 + \frac{\lambda_s}{4}s^4 + V_{\rm cl}(H,\Phi)$$

Since all portal couplings give positive contributions to the beta function of the Higgs quartic coupling, $\Delta\beta_{\lambda_H} \sim +\lambda_{Hs}^2$ =>

- Values of $\lambda_{Hs} \gtrsim 0.35$ are sufficient to stabilise the Higgs by this effect on its own. Don't need to be inside the wedge region.

VVK, C. McCabe and G. Ro, arXiv:1403.4953

Dark Matter

There are two DM candidates in the CSI models we have considered:

1. The $SU(2)_{CW}$ gauge bosons give vector DM. They are stable due to an SO(3) symmetry and no kinetic mixing

   T. Hambye 2008, T. Hambye and A. Strumia 1306.2329

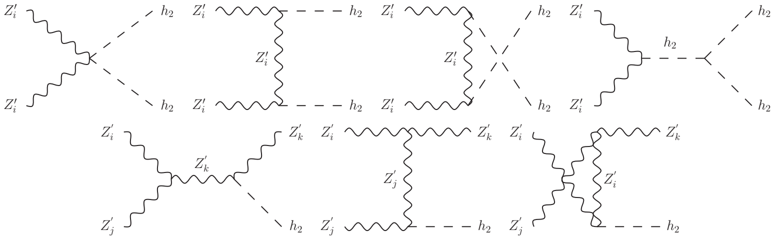
2. The singlet scalar $s(x)$, if present, is stable due to a Z_2 symmetry which is automatic due to CSI and gauge invariance

The origin of the dark matter scale is the same as the origin of the EW scale as $m_{DM} \sim \langle \Phi \rangle$. Relic abundance produced by standard freeze out mechanism.

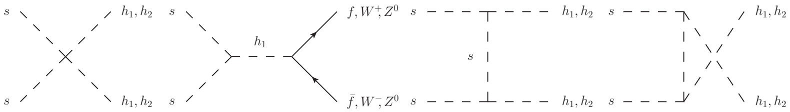
VVK, C. McCabe and G. Ro, arXiv:1403.4953

Dark Matter

1. $SU(2)_{CW}$ Vector Dark Matter annihilation and semi-annihilation:



2. Scalar Dark Matter annihilation diagrams include:



Vector Dark Matter

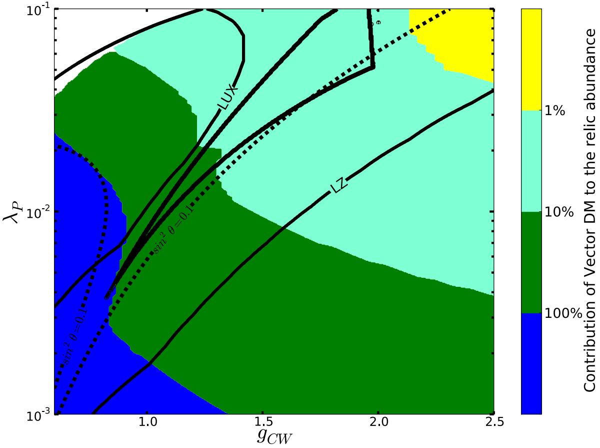


Figure : $\mathrm{SU(2)}_{CW}\times$ SM CSI model – $\lambda_{\rm P}$, g_{CW} plane.
For $\mathrm{SU(2)}_{CW}\times$ SM $\oplus$ singlet $s(x)$ – don't need to be inside the wedge.

Vector Dark Matter

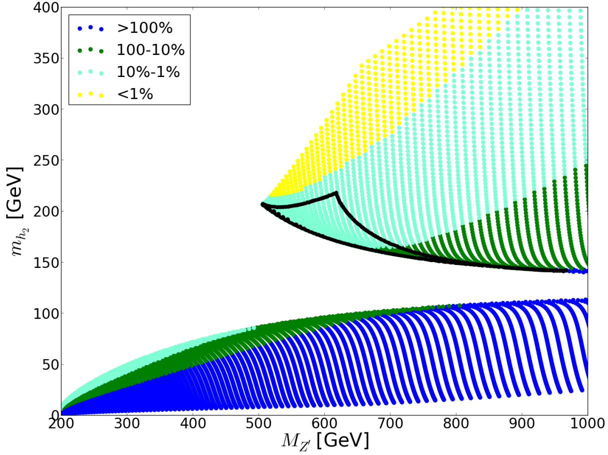


Figure : SU(2)$_{CW}\times$ SM CSI model: same plot – m_{h_2}, M_Z plane. When new singlet is added – don't need to be inside the wedge.

Scalar Dark Matter

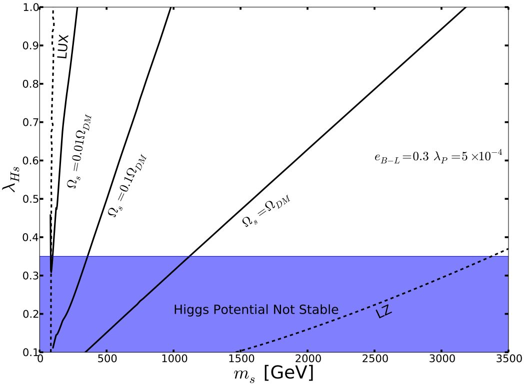


Figure : $U(1)_{B-L} \times$ SM $\oplus$ singlet CSI model

Vector and Scalar Dark Matter

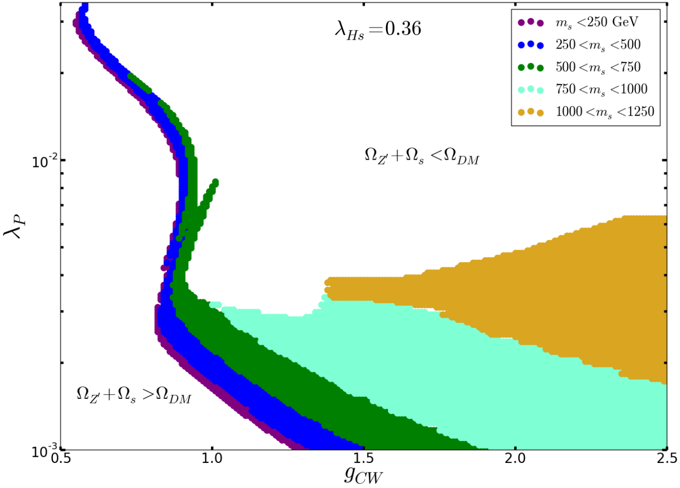


Figure : VDM and SDM making up the total DM density in the $SU(2)_{CW} \times$ SM $\oplus$ singlet CSI model

Summary

SM×G_{CW} classically scale-invariant Extended SM

All mass scales in the theory must be generated dynamically

A powerful principle for BSM model building. No vastly different scales can co-exist in such a theory:

1. Hard to generate a large hierarchy of scales from one $\langle \Phi \rangle$
2. Large new mass scales would ultimately couple to the Higgs and destabilise it mass

- Minimal, calculable and testable BSM models
- Address all the sub-Planckian shortcomings of the SM at once, without introducing scales higher than $\langle \phi \rangle$ which itself is not much higher the electroweak scale.
- Some open questions about physics at $E \gtrsim M_{\rm Pl}$ and gravity

Summary

1. CSI ESM examples:
   - Standard Model $\times$ $U(1)_{\mathrm{CW}}$
   - Standard Model $\times$ $U(1)_{\mathrm{B-L}}$
   - Standard Model $\times$ $SU(2)_{\mathrm{CW}}$
2. Stabilisation of the Higgs potential
   - Standard Model $\times$ G_{CW}
   - Standard Model $\times$ $G_{\mathrm{CW}} \oplus$ singlet
3. Vector and Scalar Dark Matter
   - Other DM species (fermions) and more involved DM models
   - Can also have Monopole & Vector DM and Dark radiation

Progress has also been made in addressing

4. Matter-anti-Matter asymmetry: Leptogenesis via sterile neutrino oscillations
5. Cosmological Inflation
6. Axions and axion-like particles