Heavy dark matter through the dilaton portal

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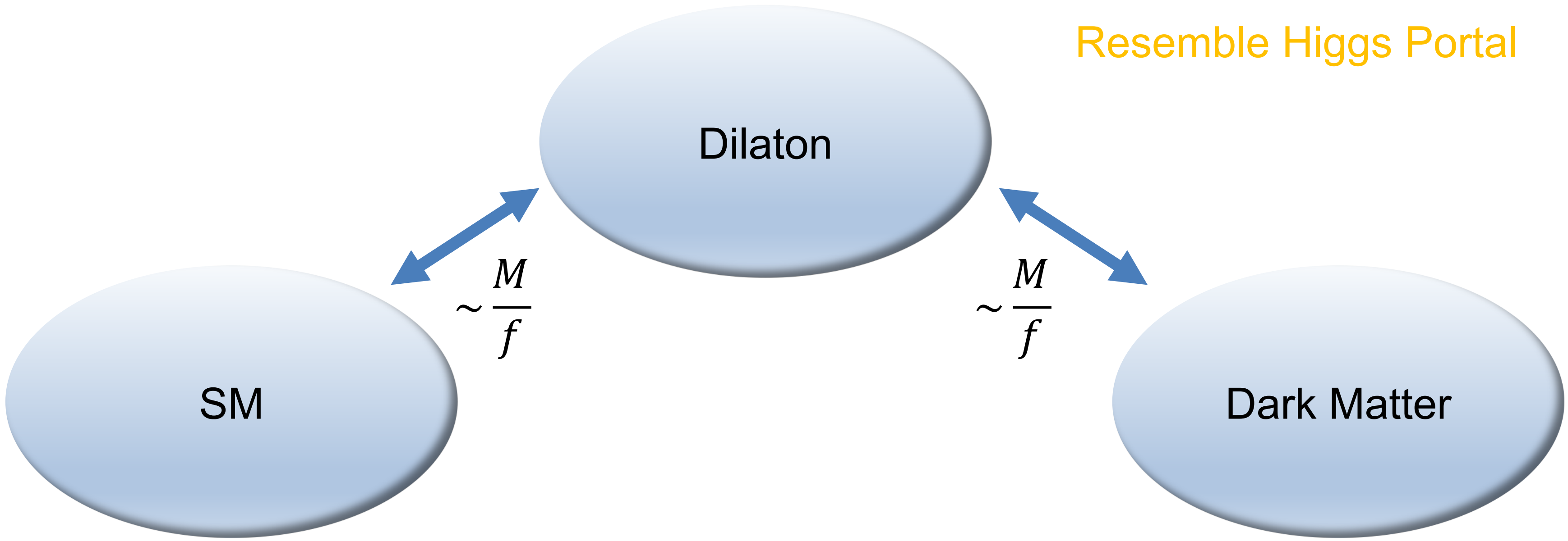
Contents

The dilaton portal to dark matter

Bai, Careba, Lykken 09'
Agashe, Blum, Lee, Perez 09'

- Embedding the SM partially or completely in a composite sector can solve the hierarchy problem, by making Higgs boson composite.
- Often such a composite sector arises as the low-energy limit of an approximately scale invariant theory, where scale invariance is broken somewhere above the weak scale.
- If the breaking of scale invariance is spontaneous, then it is accompanied by a dilaton (corresponding GB) that couples to the fields in the composite sector through $-\frac{\sigma}{f} Tr\, T$

The dilaton portal to dark matter



In the minimal set-up, basically three parameters determine the dynamics of thermal freeze-out in the early universe: f, m_χ, m_σ
+ mixing angle α between SM higgs and dilaton

Theoretical framework

Consider a generic Lagrangian

$$\mathcal{L}_0 = \sum_i g_i(\mu)\mathcal{O}_i(x)\,.$$

Scale transformation

$$x^\mu \to e^\lambda x^\mu\,, \quad \mathcal{O}_i(x) \to e^{\lambda d_i}\mathcal{O}_i(e^\lambda x)\,, \quad \mu \to e^{-\lambda}\mu\,.$$

$$\delta\mathcal{L} = \sum_i \left[(d_i - 4)\mathcal{O}_i - \mu\frac{\partial g_i}{\partial \mu}\right] = T^\mu{}_\mu\,.$$

$$d_i = [\mathcal{O}_i]$$

Scale invariance can then be established by introducing a conformal co mpensator field $\chi(x) \to e^\lambda \chi(e^\lambda x)\,.$
And by enforcing the replacement of the coupling $g_i(\mu) \quad \to \quad g_i\left(\mu\frac{\chi}{f}\right)\left(\frac{\chi}{f}\right)^{4-d_i} .$

$$\chi(x) = f + \sigma(x)\,.$$

$$\begin{aligned}\mathcal{L} &= \sum_i g_i\Big(\mu(1+\sigma(x)/f)\Big)\,\Big(1+\sigma(x)/f\Big)^{4-d_i}\mathcal{O}_i(x)\\ &= \mathcal{L}_0 + \sum_i \frac{\sigma(x)}{f}\Big[g_i(\mu)(4-d_i)\mathcal{O}_i(x) + \beta(g_i)\mathcal{O}_i(x)\Big]\\ &\quad + \frac{\sigma^2(x)}{2f^2}\sum_i\Big[(4-d_i)(3-d_i)g_i(\mu)\mathcal{O}_i(x)\Big] + \dots\,,\end{aligned}$$

Theoretical framework

- After EWSB, the interaction terms of the dilaton with the SM sector are given (dim 6 or below)

$$\mathcal{L}_\sigma = \frac{\sigma}{f}\Big[2m_W^2 W_\mu^+ W^{-\mu} + m_Z^2 Z_\mu Z^\mu - m_h^2 h^2 - \sum_\psi m_\psi \bar{\psi}\psi - \frac{m_h^2}{2v}\left[h^3 + hG^0G^0 + 2hG^+G^-\right]$$
$$+ \frac{gv}{2}\left[\partial^\mu G^- W_\mu^+ + \partial^\mu G^+ W_\mu^- + \frac{1}{c_W}\partial^\mu G^0 Z_\mu\right] + g m_W h W_\mu^+ W^{\mu-} + \frac{g}{2c_W} m_Z h Z_\mu Z^\mu$$
$$+ i g' m_W \left(G^- W_\mu^+ - G^+ W_\mu^-\right)\left(c_W A^\mu - s_W Z^\mu\right) + \frac{11\alpha_{\rm EM}}{24\pi} F_{\mu\nu}F^{\mu\nu} - \frac{7\alpha_s}{8\pi} G^a_{\mu\nu} G^{a\mu\nu}\Big]$$
$$+ \frac{\sigma^2}{2f^2}\left[2m_W^2 W_\mu^+ W^{-\mu} + m_Z^2 Z_\mu Z^\mu - m_h^2 h^2\right],$$

- The interaction of the dilaton with the dark matter candidates

$$\mathcal{L}_\sigma^{\rm DM} = \begin{cases} -\dfrac{\sigma}{2f} m_\Psi \overline{\Psi}_X \Psi_X & \text{(Majorana fermion)}, \\ \boxed{\left(\dfrac{\sigma}{f} + \dfrac{\sigma^2}{2f^2}\right) m_V^2 X_\mu X^\mu \quad \text{(vector boson)},} \end{cases}$$

- The dilaton kinetic term and potential term

$$\mathcal{L}_\sigma^{\rm self} = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{m_\sigma^2}{2}\sigma^2 - \frac{5}{6}\frac{m_\sigma^2}{f}\sigma^3 - \frac{11}{24}\frac{m_\sigma^2}{f^2}\sigma^4 + \dots,$$

Higgs-dilaton mixing

- When two physical neutral scalars are present in the theory, they could in principle mix, unless it is forbidden by some symmetry.

$$\begin{pmatrix} h \\ \sigma \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_0 \\ \sigma_0 \end{pmatrix} \equiv \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_0 \\ \sigma_0 \end{pmatrix}$$

- After relabel our scalar states,

$$r_f = v/f :$$

$$\mathcal{L}_\sigma^\psi = \sum_\psi \frac{m_\psi}{v}\Big(h_0 + r_f\sigma_0\Big)\bar{\psi}\psi = \sum_\psi \frac{m_\psi}{v}\Big[(c_\alpha + r_f s_\alpha)h + (r_f c_\alpha - s_\alpha)\sigma\Big]\,\bar{\psi}\psi\,.$$

$$\mathcal{L}_\sigma^V = \Big[(c_\alpha + r_f s_\alpha)h + (r_f c_\alpha - s_\alpha)\sigma\Big]\left[\frac{2m_W^2}{v}W_\mu^+ W^{-\mu} + \frac{m_Z^2}{v}Z_\mu Z^\mu\right].$$

$$\mathcal{L}_\sigma^{\rm DM} = -\frac{m_\Psi}{2f}s_\alpha h\overline{\Psi}_X\Psi_X - \frac{m_\Psi}{2f}c_\alpha\sigma\overline{\Psi}_X\Psi_X \qquad \text{(Majorana fermion)}\,,$$

$$\mathcal{L}_\sigma^{\rm DM} = \frac{m_V^2}{f}(s_\alpha h + c_\alpha\sigma)X_\mu X^\mu + \frac{m_V^2}{2f^2}(s_\alpha h + c_\alpha\sigma)^2 X_\mu X^\mu \qquad \text{(vector boson)}\,,$$

Higgs-dilaton mixing

- The trilinear couplings are phenomenologically very important, because they allow the dilaton to decay into a pair of Higgs bosons. Unfortunately, in our model they are not uniquely defined.

$$\mathcal{L}_{\phi^3} = -\frac{1}{2v} m_{h,0}^2 h_0^3 - \xi \frac{m_{\sigma,0}^2}{f} \sigma_0^3 - \frac{m_{h_0}^2}{f} h_0^2 \sigma_0 \,.$$

$$\mathcal{L}_{\phi^2} = -\frac{1}{2} m_{h,0}^2 h_0^2 - \frac{1}{2} m_{\sigma,0}^2 \sigma_0^2 - m_{h\sigma}^2 h_0 \sigma_0$$

(minimal mixing)

- However, it is clear that if it is present, then the full Lagrangian of the theory cannot be written in a gauge-invariant way
- We must write the SM degrees of freedom in terms of a doublet H

$$\mathcal{L} \supset -\frac{m_{h\sigma}^2}{v} \sigma |H|^2 \supset -m_{h\sigma}^2 h_0 \sigma_0 - \frac{1}{2} \frac{m_{h\sigma}^2}{v} h_0^2 \sigma_0$$

(gauge invariant mixing)

- This new trilinear coupling has dramatic consequences for the phenomenology: it allows for unsuppressed decays of the dilaton into two Higgs bosons. Therefore we will investigate bo th scenarios: the “minimal mixing scenario” and the “gauge invariant mixing scenario”

DM through the dilaton portal

Since our dilaton must be rather heavy and couples to all the SM particles including the Higgs boson, we could consider it as generating effective Higgs portal interactions.

$$\mathcal{L}_{eff} = \frac{1}{2f^2 m_\sigma^2}\left[\sum_\psi m_\psi \bar{\psi}\psi - m_V^2 X_\mu X^\mu - m_Z^2 Z_\mu Z^\mu - 2m_W^2 W_\mu^+ W^{-\mu} + m_h^2 h^2\right]^2$$

$$\Gamma(\sigma \to XX) = \frac{m_\sigma^3}{32\pi f^2}\left[1 - 4\frac{m_V^2}{m_\sigma^2} + 3\frac{m_V^4}{m_\sigma^4}\right]\sqrt{1 - \frac{4m_V^2}{m_\sigma^2}}$$

$$\underset{m_\sigma \gg m_V}{\rightarrow} \frac{m_\sigma^3}{32\pi f^2}$$

$$\boxed{\Gamma \underset{m_\sigma \gg m_V}{\simeq} \frac{m_\sigma^3}{8\pi f^2}}$$

$$BR(\sigma \to XX) \underset{m_\sigma \gg m_V}{\approx} 25\%$$

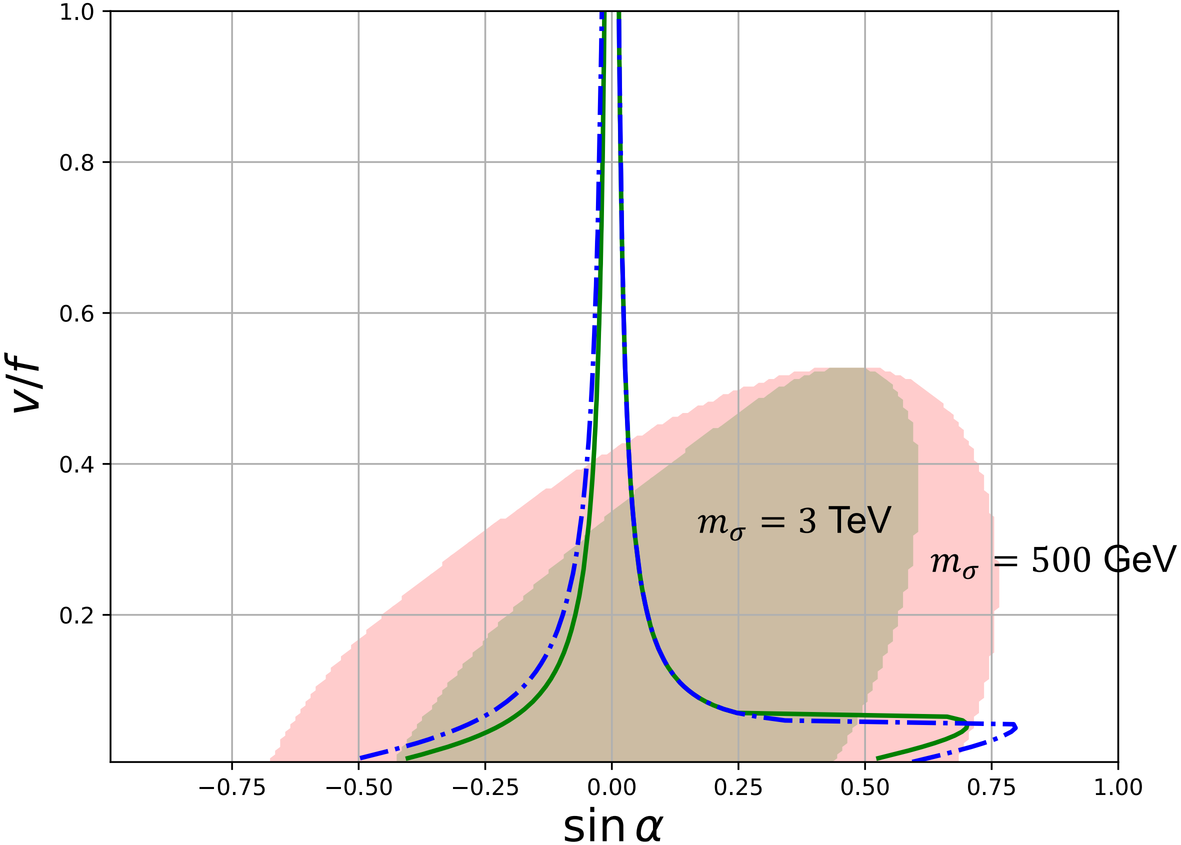
Higgs portal VDM

$$\mathcal{L}_{VHPDM} = \frac{\lambda_{hv}}{8} h^2 X_\mu X^\mu + \frac{1}{2} m_V^2 X_\mu X^\mu + \frac{\lambda}{4}(X_\mu X^\mu)^2$$

$$\Gamma(h \to XX) = \frac{\lambda_{hv}^2}{128\pi}\frac{v_h^2 m_h^3}{m_V^4}\left(1 - \frac{4m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right)\sqrt{1 - \frac{4m_V^2}{m_h^2}}$$

Constraints on Higgs-dilaton mixing

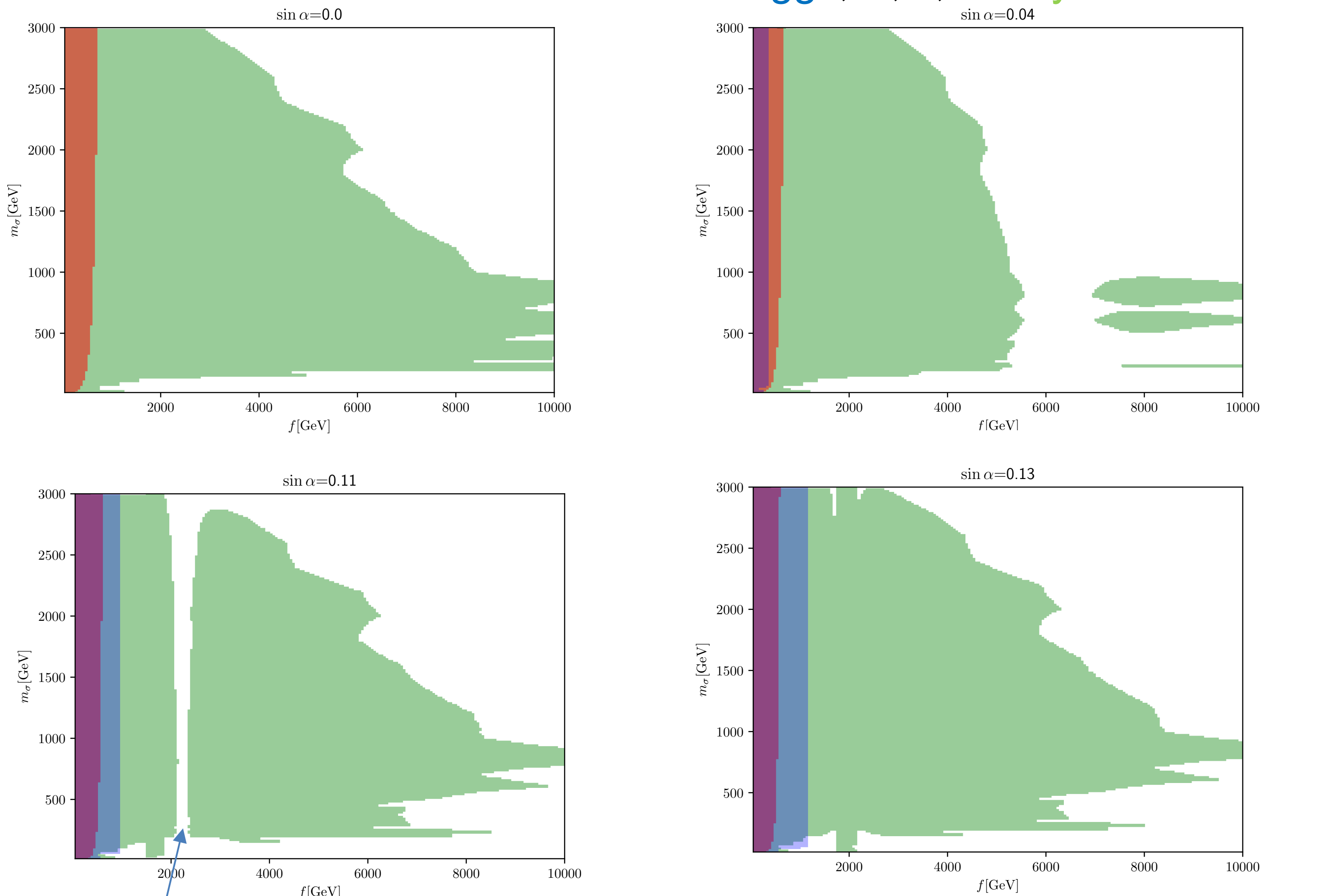
- Experimental Higgs-boson measurements
- Heavy scalar searches
- Peskin-Takeuchi parameters S and T



Constraints on Higgs-dilaton mixing

- Minimal mixing scenario

Higgs, S, T, heavy scalar search



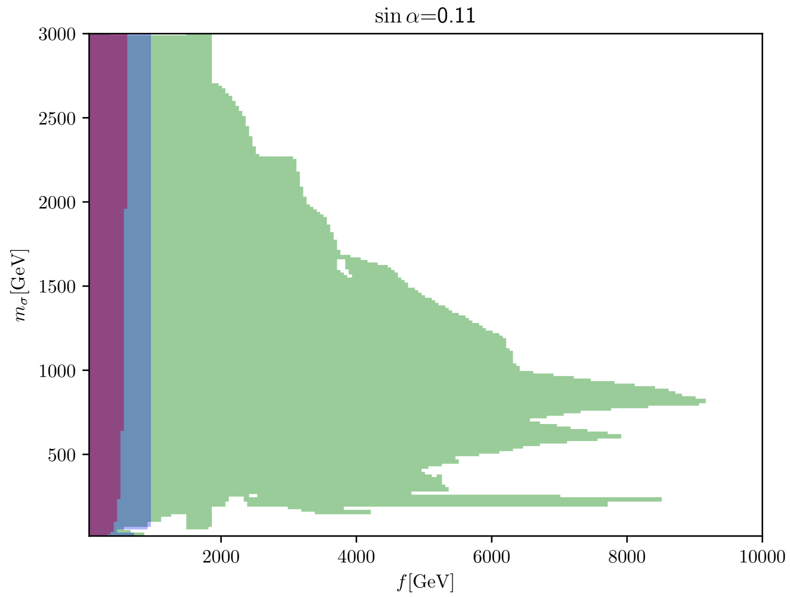
Magic window

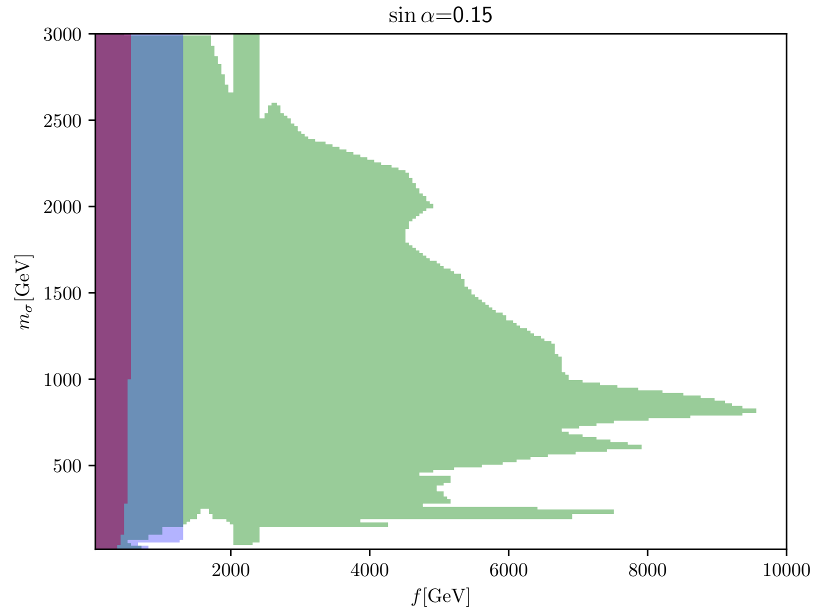
$r_f = \tan\alpha$

Constraints on Higgs-dilaton mixing

- Gauge invariant mixing scenario

Higgs, S, T, heavy scalar search





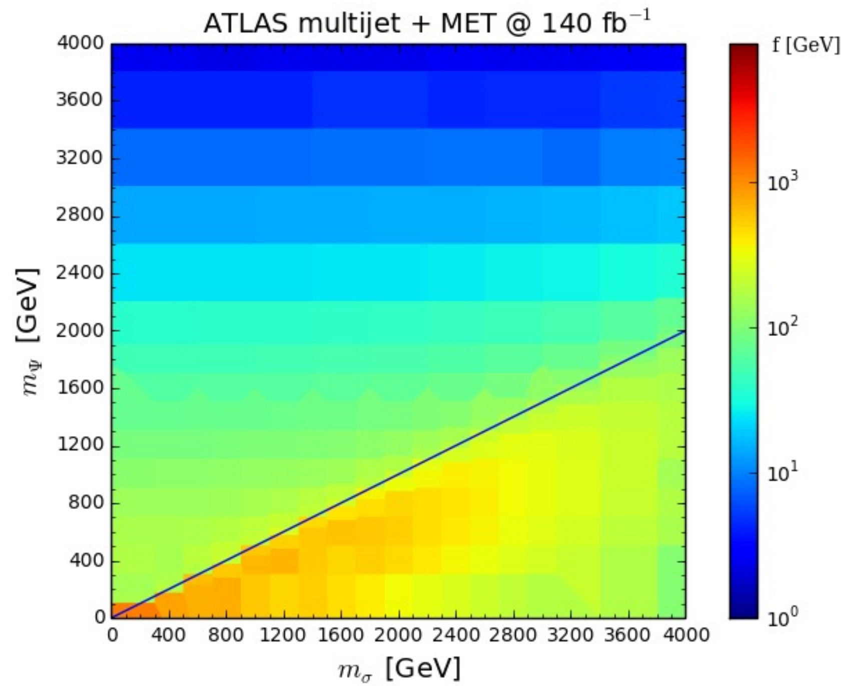
$\sigma \to hh$ dramatically enhanced

Magic window is disappeared

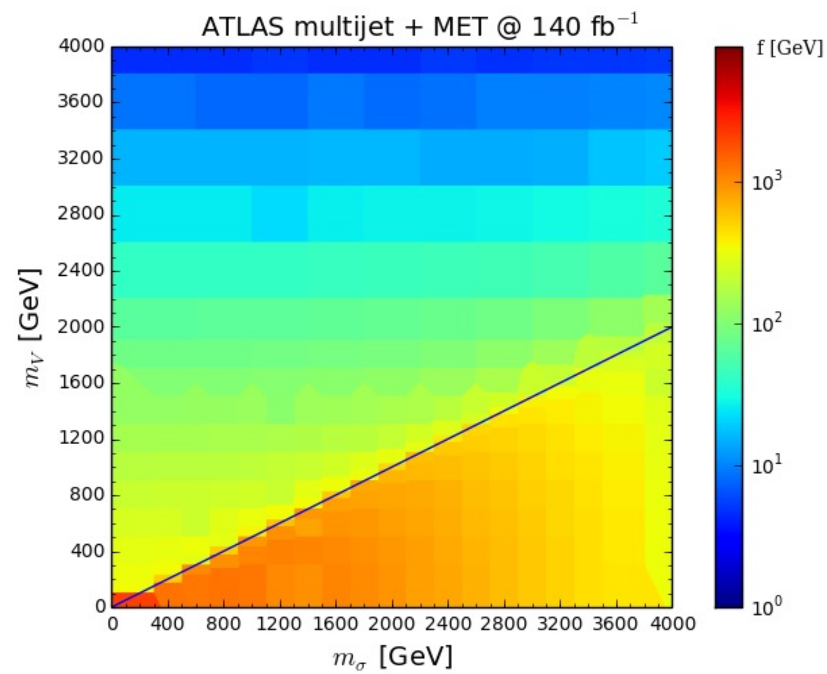
Collider constraint

- ATLAS multijet + MET search @ 140 fb^-1

Fermion DM



Vector DM

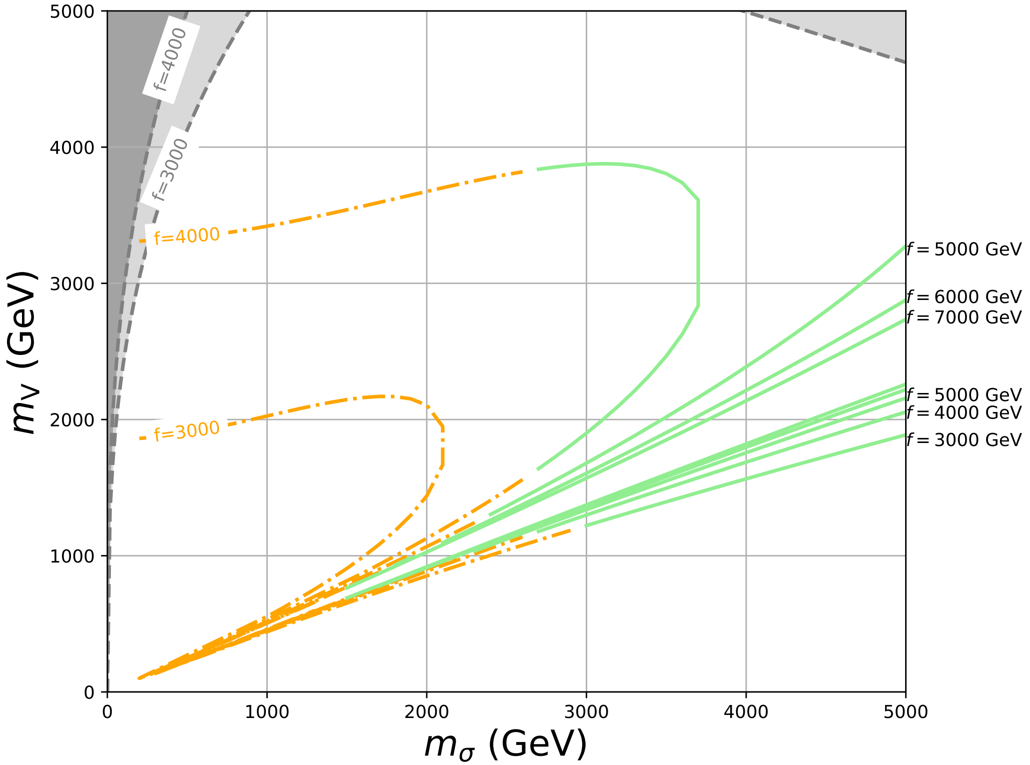


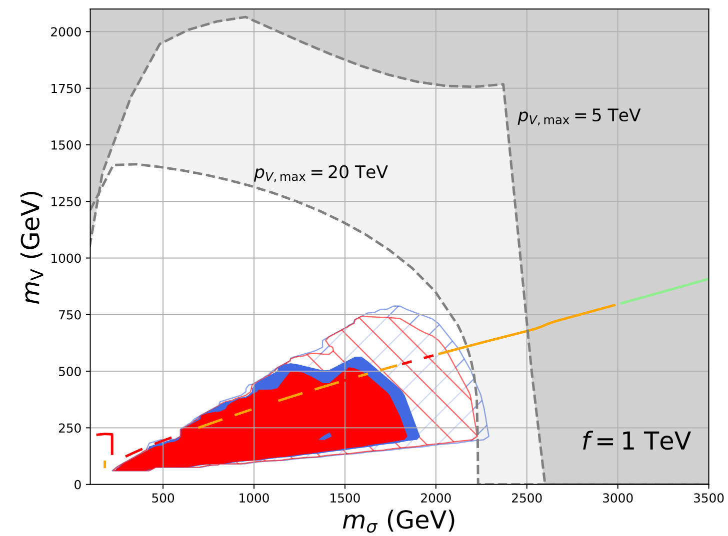
LHC has no sensitivity for $2m_X \gtrsim m_\sigma$

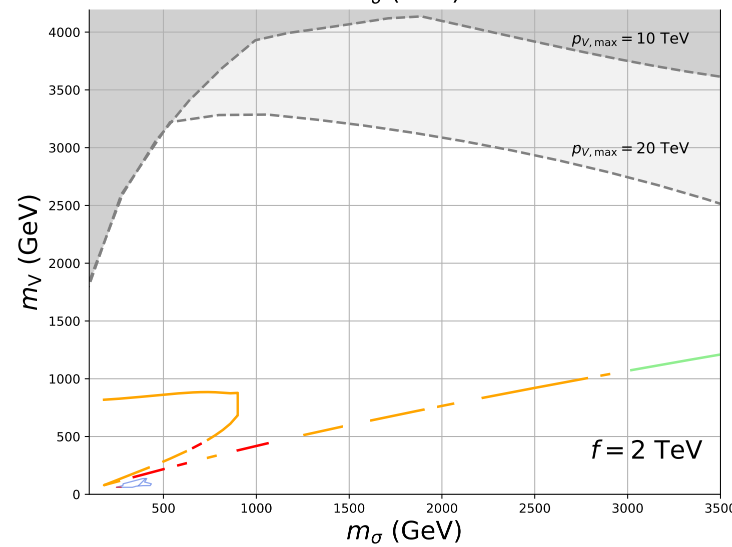
Relic abundance & perturbative unitarity

- Zero mixing scenario

LHC, HL-LHC, heavy scalar search, heavy scalar search, unitarity







Combined constraints

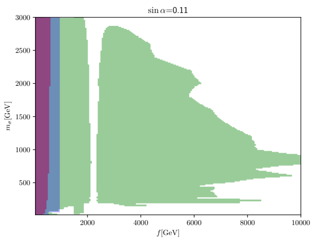
- Minimal mixing scenario

LHC, HL-LHC, heavy scalar search,
Direct detection, relic abundance

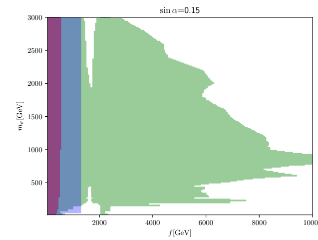
$\sin\alpha = 0.11$

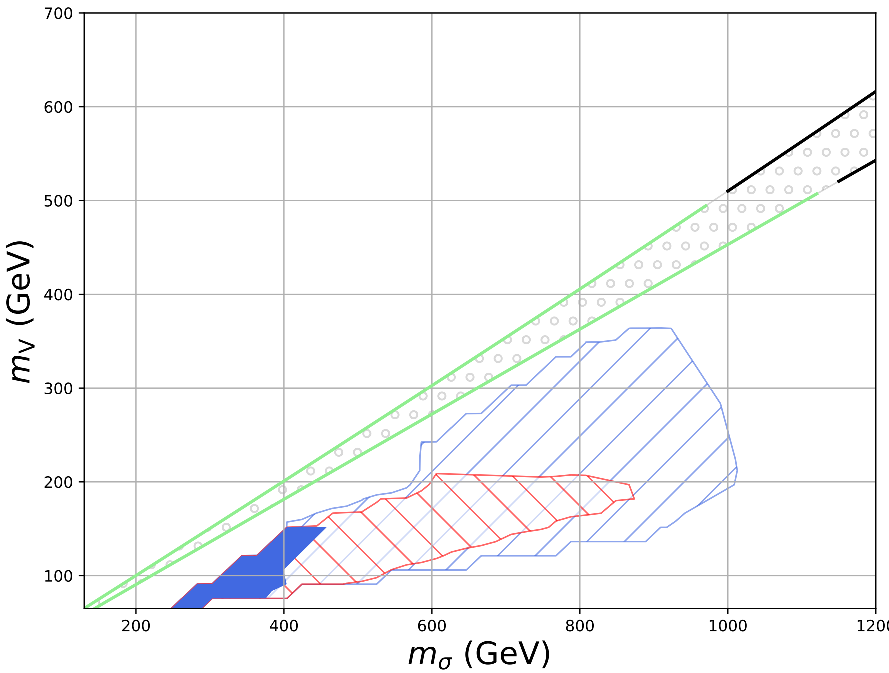
$\frac{v}{f} = \tan\alpha$

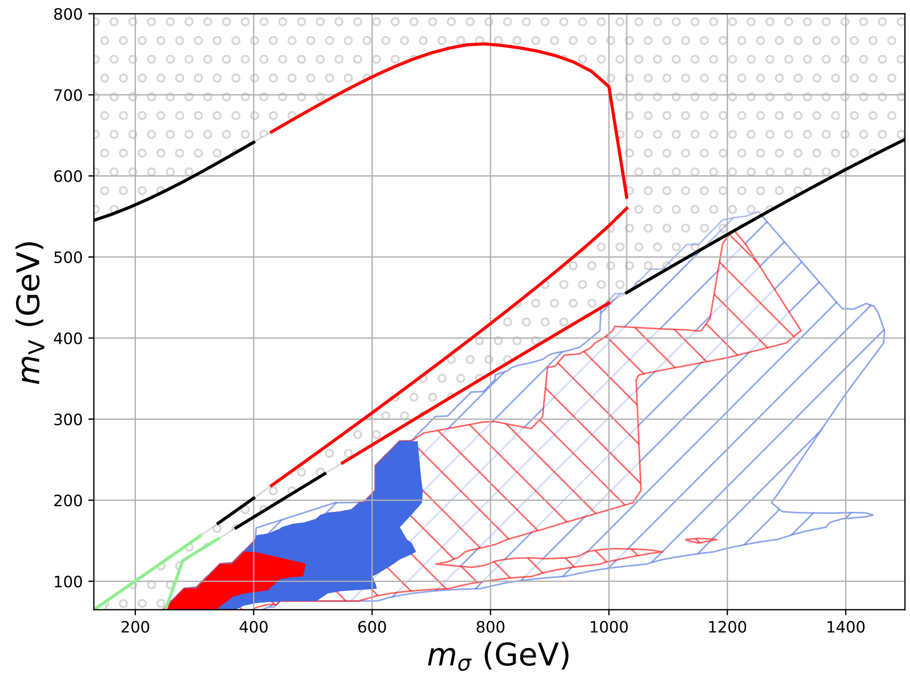
f = 2.2 TeV



$\sin\alpha = 0.15$





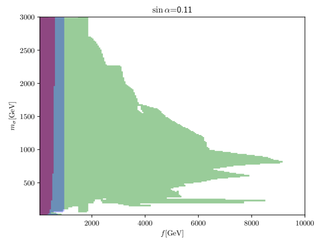


Combined constraints

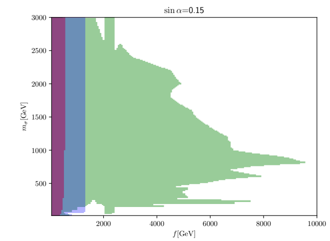
- Gauge invariant mixing scenario

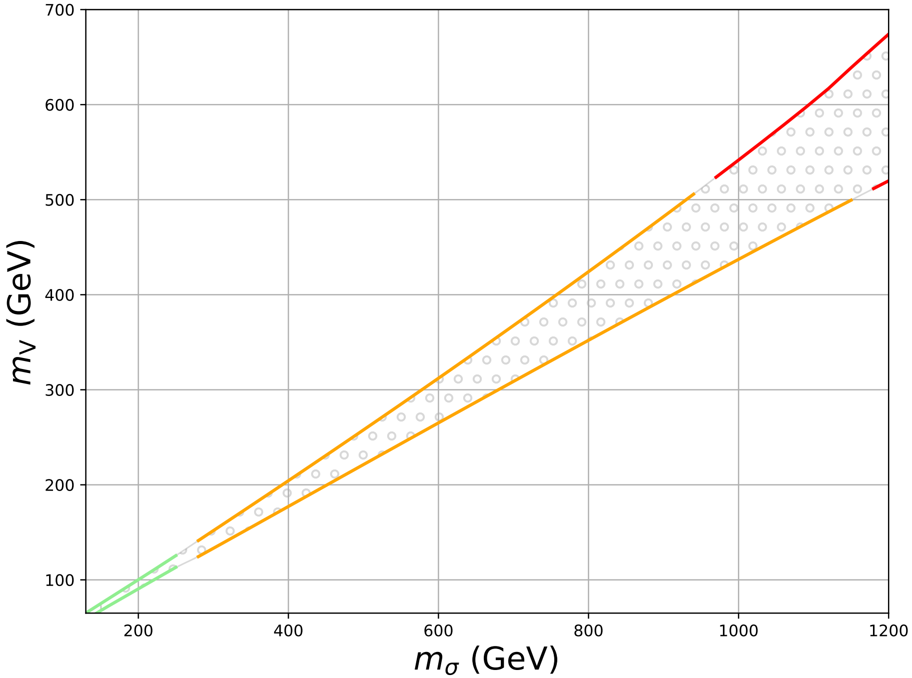
LHC, HL-LHC, heavy scalar search, heavy scalar search, Direct detection, relic abundance

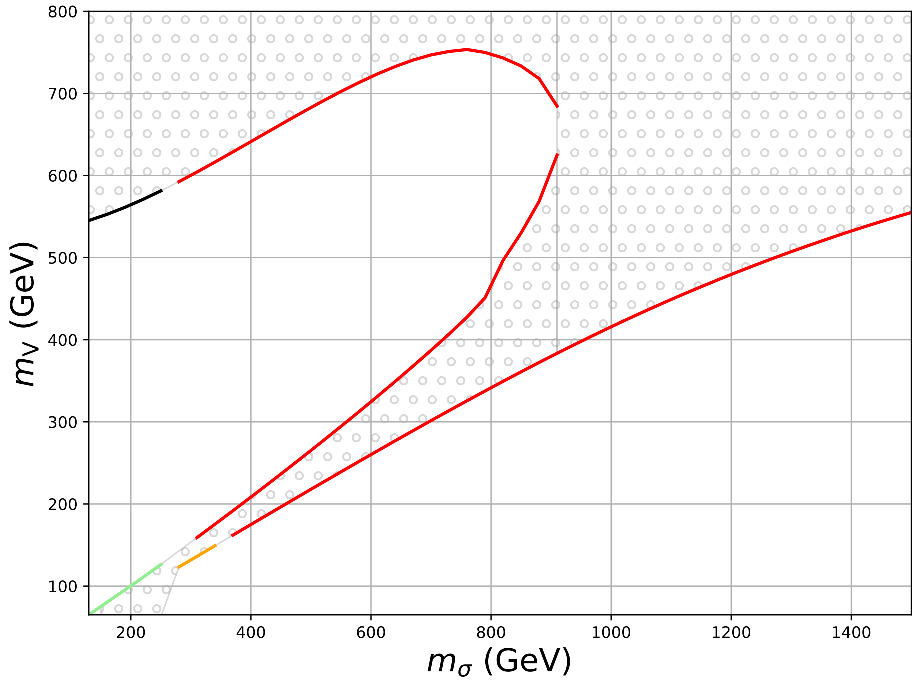
$$\sin\alpha = 0.11$$
$$\frac{v}{f} = \tan\alpha$$



$$\sin\alpha = 0.15$$

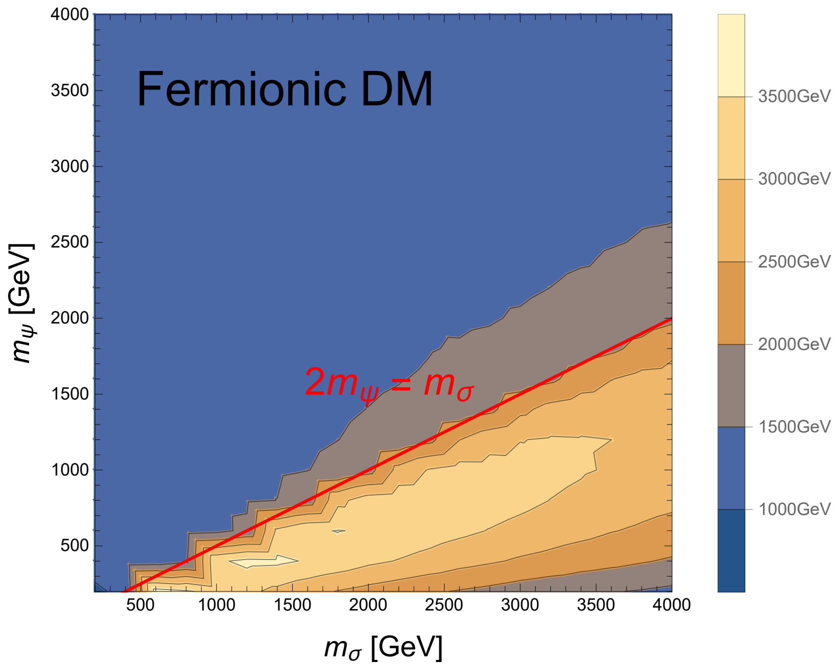


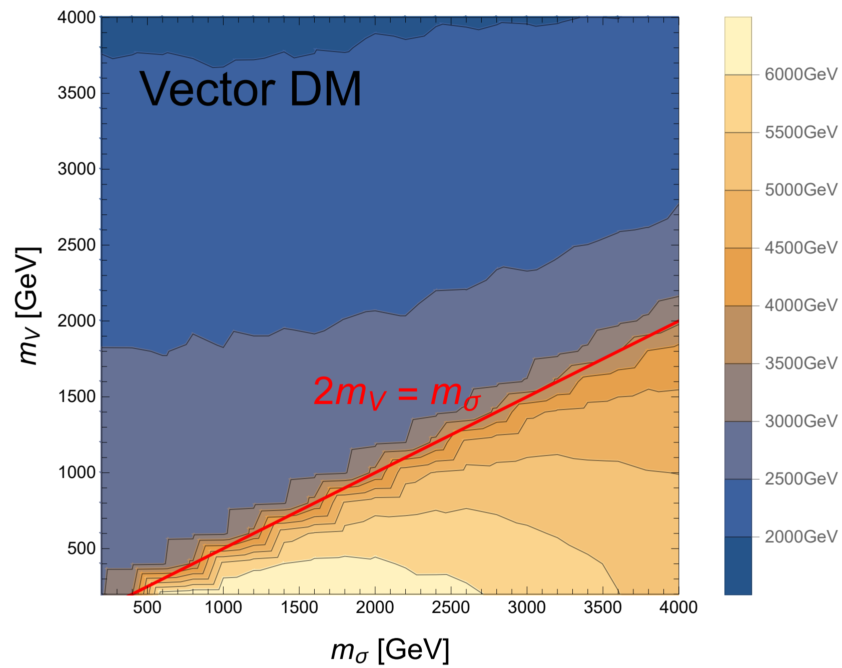




Future collider prospects

- Monojet and multijet + MET collider probes at a future 100 TeV collider with 3 ab^{-1} luminosity.





Summary

- We have presented a comprehensive up-to-date set of current and future constraints on the heavy dilaton-portal dark matter models.
- We paying attention to the Higgs-dilaton mixing with two scenarios; minimal mixing scenario and gauge invariant scenario.
- While heavy scalar and unitarity constraints push the model to large masses and weak couplings, to the extent that the direct dark matter production at the LHC can only probe a light dilaton, and not reach a ny viable parameter above 300 GeV.
- For minimal mixing case, thanks to the magic window, the DM and dilaton below 1 TeV is allowed.
- A future collider would potentially be sensitive. It would be interestin g to examine future projections for heavy scalar and dark matter sea rches

Thank You