The Higgs-portal for vector Dark Matter and the Effective Field Theory approach: a reappraisal

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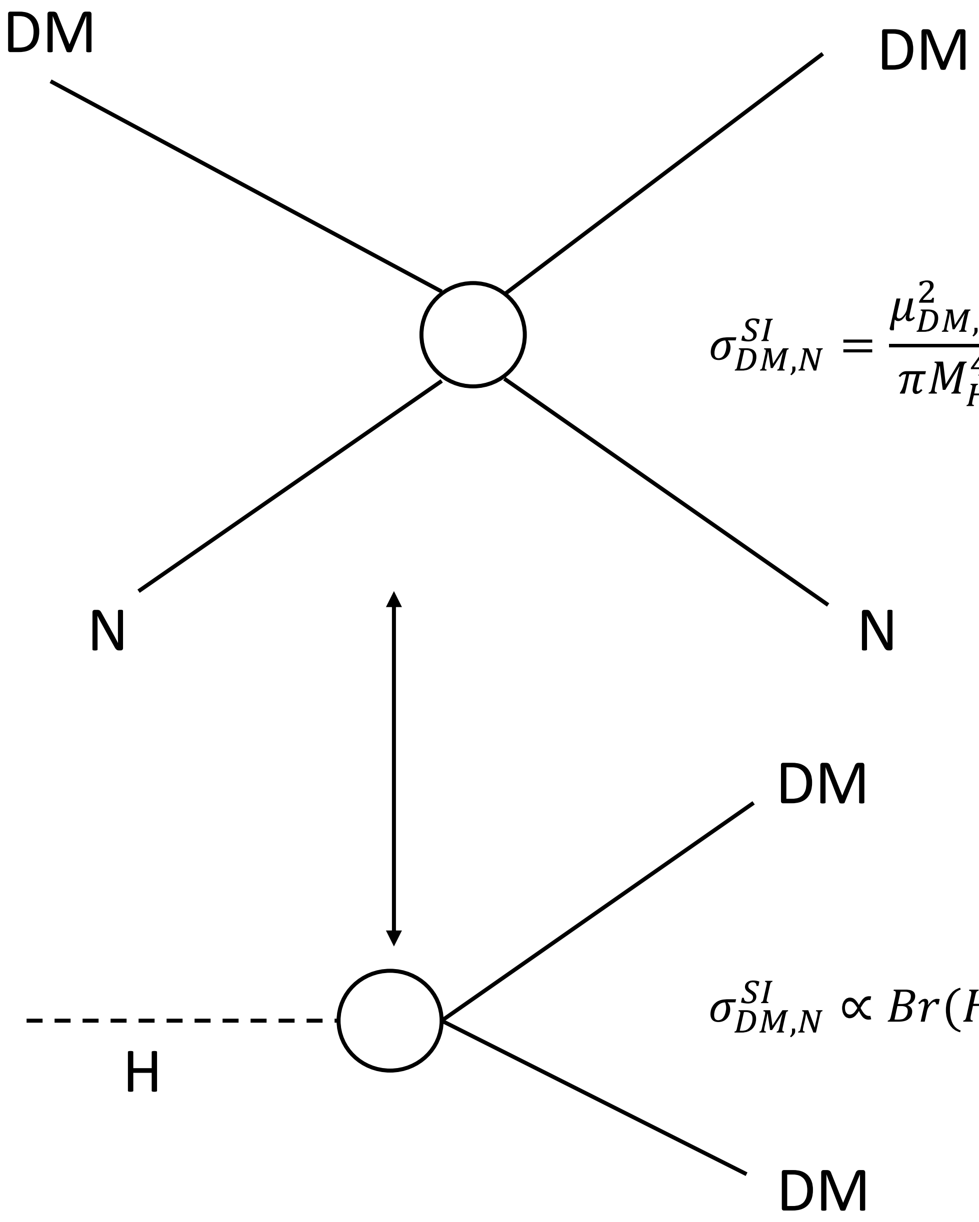
“Portals“

Solution to Dark Matter Puzzle from Particle Physics is a widely accepted conjecture.

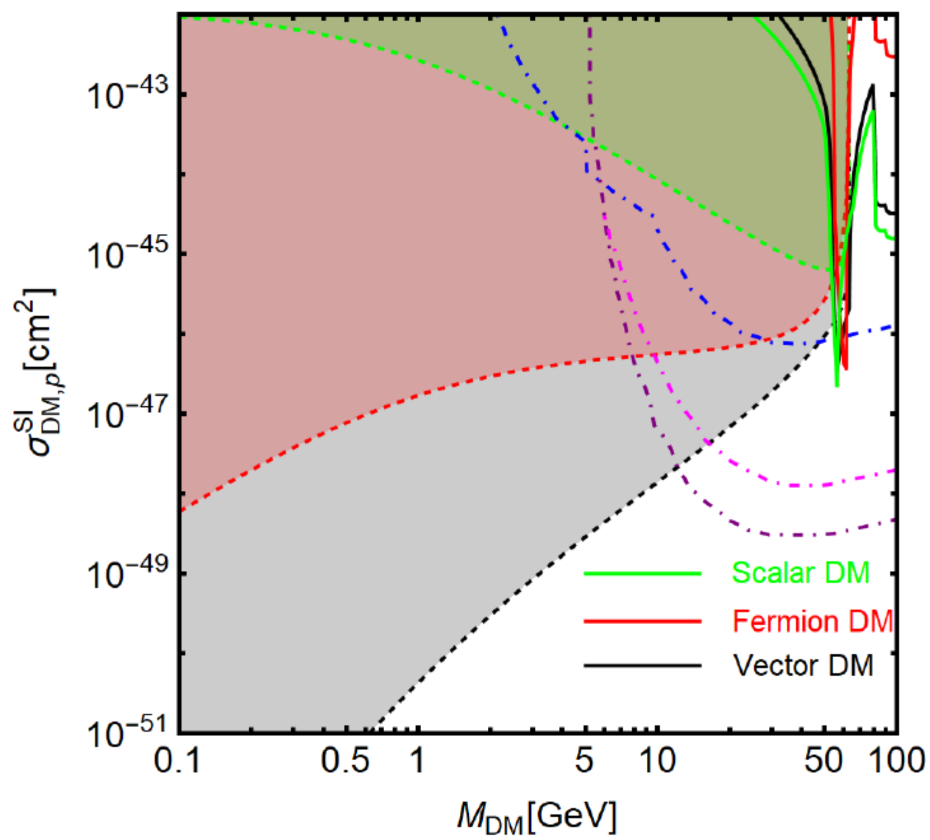
Particle DM is searched through a very broad experimental program.
An efficient theory interface is needed to maximally profit of the various experimental outcomes.

LHC DD vs Invisible H width correlation plot



$$\sigma^{SI}_{DM,N} = \frac{\mu^2_{DM,p}}{\pi M_H^4} \lambda^2_{HDMDM} \lambda^2_{HNN}$$

$$\sigma^{SI}_{DM,N} \propto Br(H \to DMDM)$$



See e.g. also ATLAS, JHEP 11 (2015) 206
CMS Eur. Phys. J. C74 (2014) 2980

The LHC correlation plot appears to be very powerful….

Some relevant questions arise:

- Is the picture full theoretically consistent?
- Can it also describe more complete models?
- Which is the impact of requiring the correct relic density?

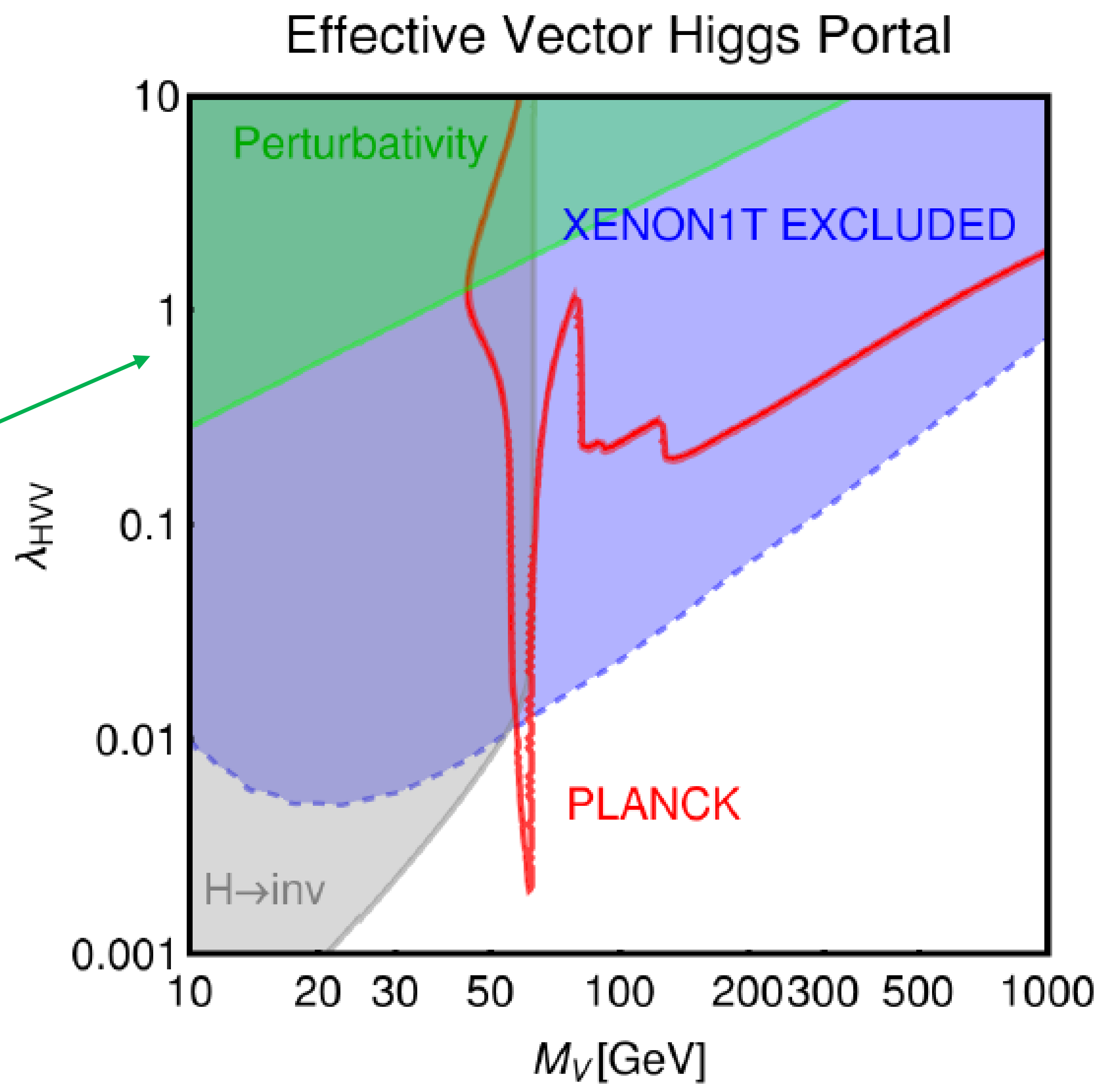
Effective Higgs Portal: $L_V \subset M_V^2 V^\mu V_\mu + \frac{1}{4}\lambda_V (V^\mu V_\mu)^2 + \frac{1}{4}\lambda_{HVV} H^\dagger H V^\mu V_\mu$

Case of study: Vector Dark Matter

Perturbative unitarity

$$M_V \geq \frac{\lambda_{HVV} v}{\sqrt{8\pi}}$$

O. Lebedev, Y. M. Lee, Y. Mambrini
Phys.Lett.B 707 (2012) 570-576



Besides experimental constraints, thermal DM is not viable below around 45 GeV.

Vector DM from gauge symmetry

Is Effective Higgs portal an appropriate benchmark? Let's compare it with more concrete models.

$\sum_i \lambda_{H\phi_i} |H|^2 |\phi_i|^2$

Portal through mixing between SM and dark Higgs

SM (Visible Sector)

Dark Sector. SM vector boson of a dark gauge symmetry

Dark U(1)

$$L_{DM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + (D_\mu\phi)(D^\mu\phi) + V(\phi) \qquad D_\mu = \partial_\mu + i\tilde{g}V_\mu$$

$$H = \frac{1}{\sqrt{2}}(0 \quad v+h)^T \quad \phi = \frac{1}{\sqrt{2}}(\tilde{v}+\rho)$$

$U(1)$ spontaneosuly broken by $\tilde{v}$. A relic Z_2 symmetry remains.

$$L_{portal} = \lambda_{H\phi}|H|^2|\phi|^2$$

Portal couplings induces mass mixing.

$$\rho = -H_1 sin\theta + H_2 cos\theta$$

$$h = H_1 cos\theta + H_2 sin\theta$$

Bounds from Higgs signal strength require $sin\theta < 0.3$. H_1 is identified with the 125 GeV SM-like Higgs.

$$L_{physical} = \frac{(H_1 cos\theta + H_2 sin\theta)}{v}\left(2M_W^2 W^\mu W_\mu + M_Z^2 Z^\mu Z_\mu - m_f \bar{f} f\right) + \frac{\tilde{g}M_V}{2}(-H_1 sin\theta + H_2 cos\theta)V^\mu V_\mu + trilinear\ scalar\ couplings$$

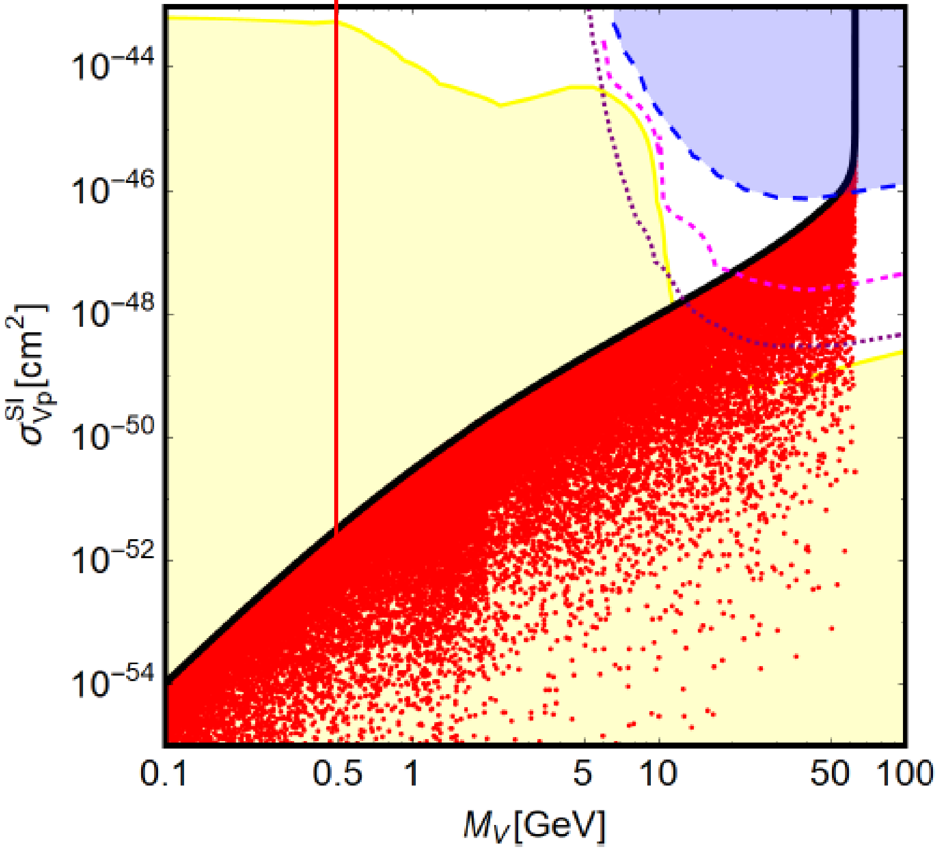
In general the extra degree of freedom spoils the correlation plot

$$\sigma_{Vp}^{SI}\Big|_{U(1)} = 32\cos^2\theta\,\mu_{Vp}^2 \frac{M_V^2}{M_{H_1}^3}\frac{Br(H\to VV)\Gamma_{H_1}^{tot}}{\beta_{VH_1}}\left(\frac{1}{M_{H_2}^2}-\frac{1}{M_{H_1}^2}\right)^2\frac{m_p^2}{v^2}|f_p|^2$$

The effective Higgs portal might represent a limit case

$$\sigma_{Vp}^{SI}\Big|_{EFT} = 32\mu_{Vp}^2\frac{M_V^2}{M_H^3}\frac{Br(H\to VV)\Gamma_H^{tot}}{\beta_{VH}}\frac{1}{M_H^4}\frac{m_p^2}{v^2}|f_p|^2$$

$$r = \frac{\sigma_{U(1)}^{SI}}{\sigma_{EFT}^{SI}} = 1 \longrightarrow \cos^2\theta\left(\frac{1}{M_{H_2}^2}-\frac{1}{M_{H_1}^2}\right)\approx 1$$



Is the effective limit theoretically consistent?...

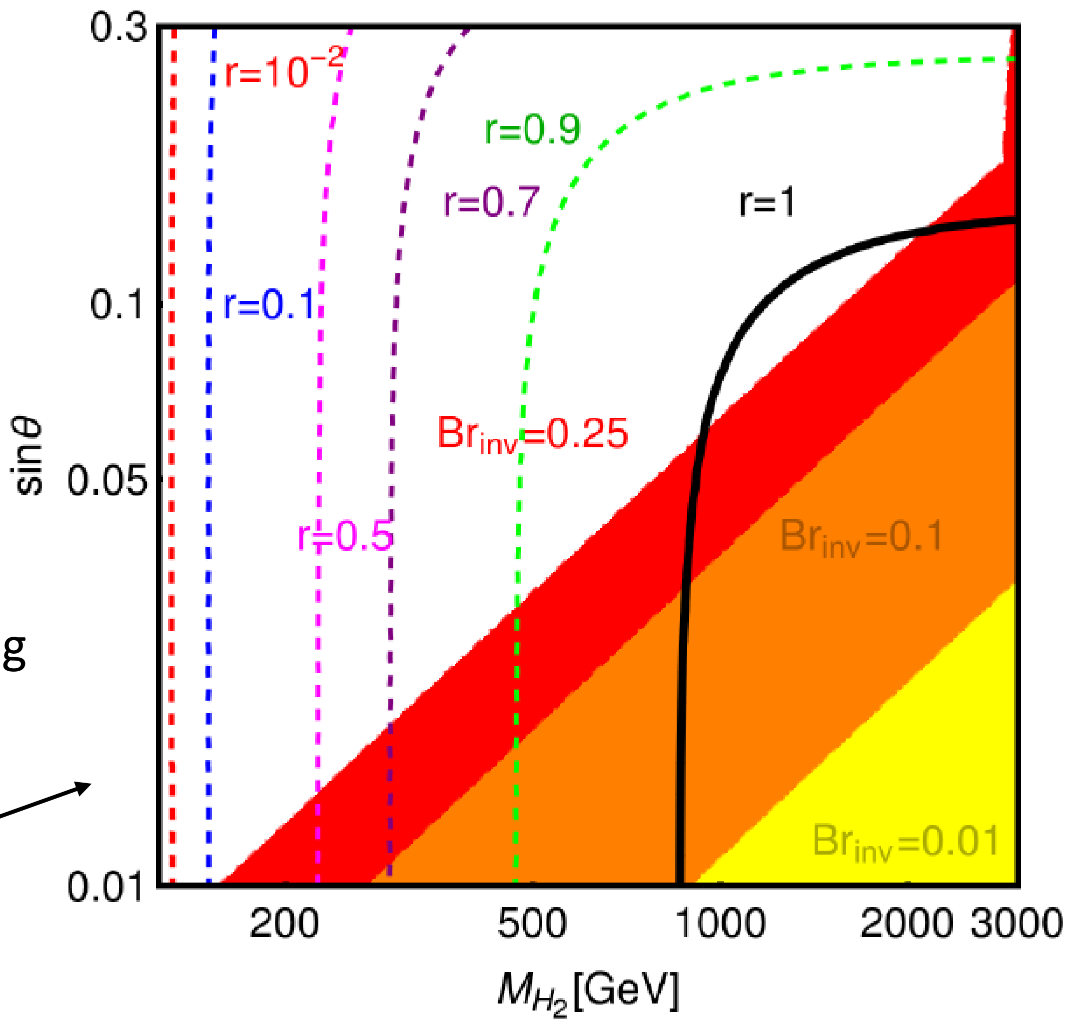
... yes provided that some conditions hold.

$$\lambda_{HS} \leq \frac{4\pi}{3} \Longrightarrow \text{BR}(H_1 \to VV) \lesssim 0.25 \left(\frac{3\,\text{TeV}}{M_{H_2}}\right)^4,$$
$$\lambda_S \quad \leq \frac{4\pi}{3} \Longrightarrow \text{BR}(H_1 \to VV) \lesssim 0.35 \left(\frac{\sin\theta}{0.1}\right)^2 \left(\frac{3\,\text{TeV}}{M_{H_2}}\right)^2$$

Theoretical consistency gives a limit on the invisible branching fraction.

Current strong constraints are compatible with EFT limit.

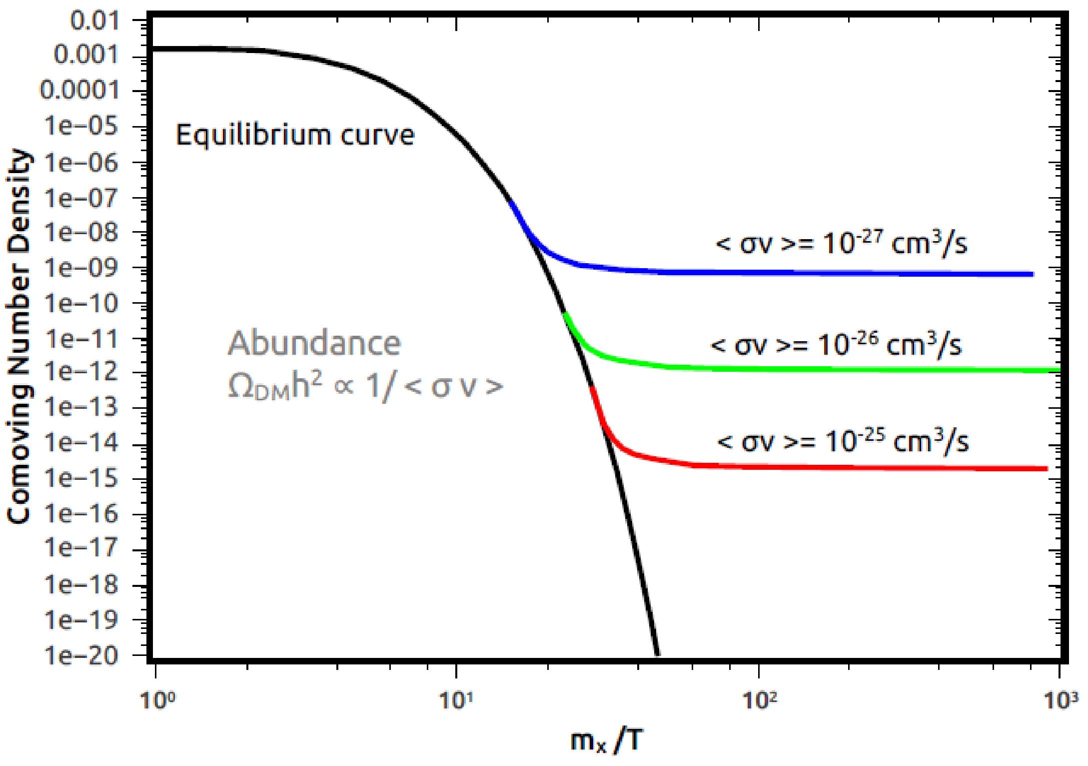
$$r = \frac{\sigma^{SI}_{U(1)}}{\sigma^{SI}_{EFT}}$$



G. Arcadi, A. Djouadi, M. Kado
Phys.Lett.B 805 (2020) 135427

Include DM relic density

We assume the freeze-out paradigm:

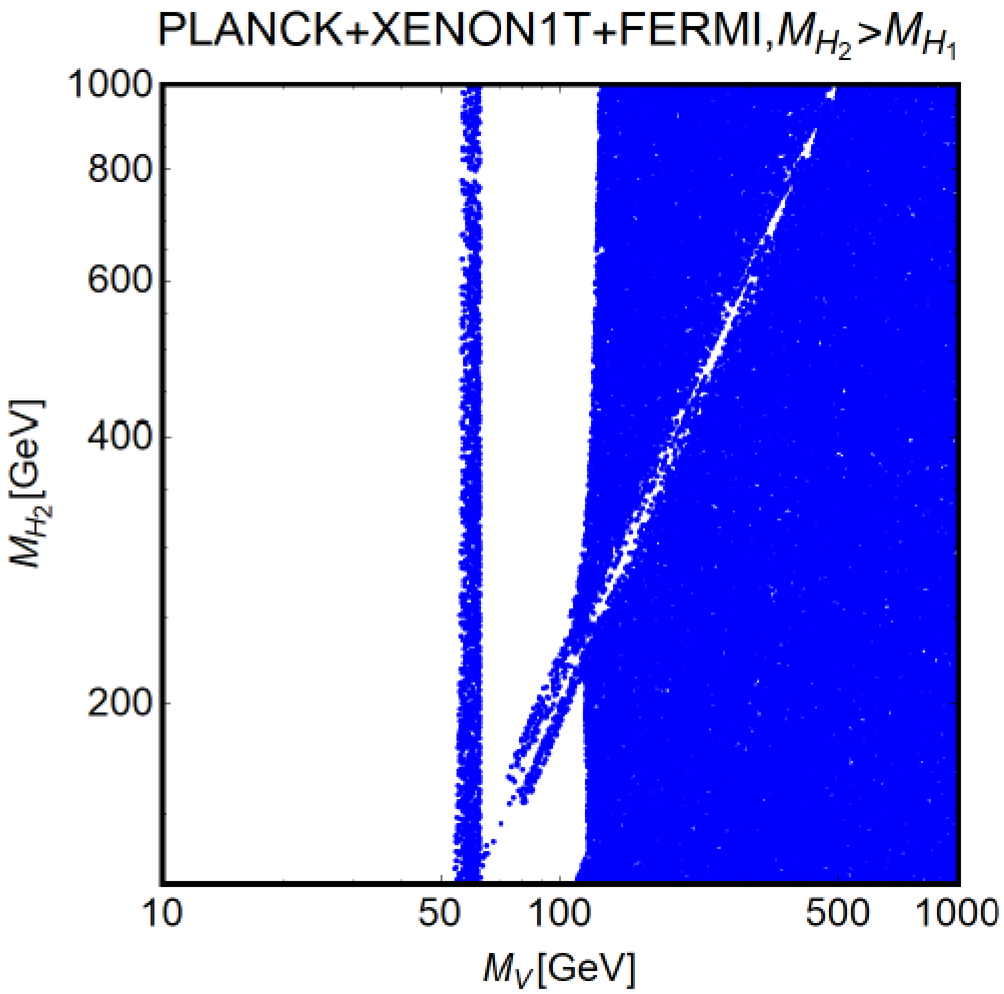


$$\frac{dn_{DM}}{dt} + 3Hn_{DM} = -\langle\sigma v\rangle\left(n_{DM}^2 - n_{DM,eq}^2\right)$$

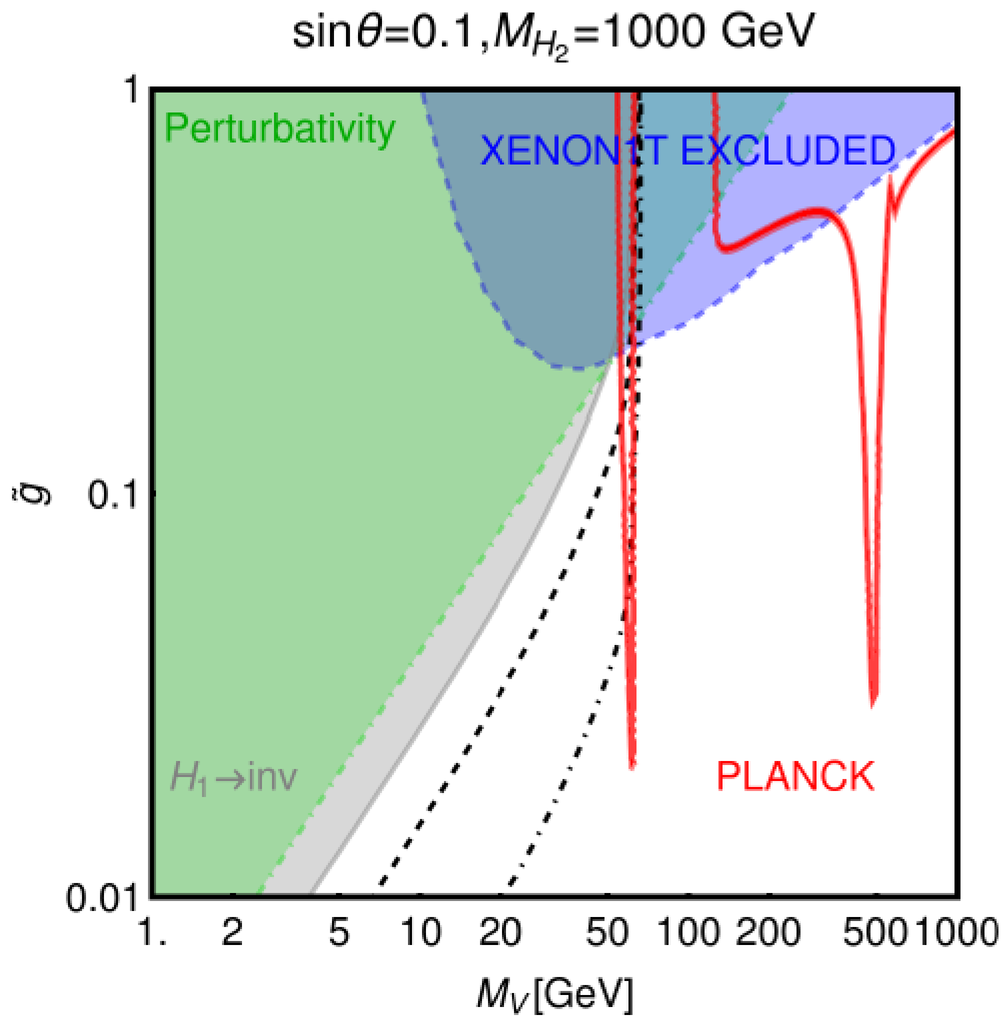
$$\langle\sigma v\rangle = \frac{1}{8\, m_{DM}^4 T\, K_2\left(\frac{m_{DM}}{T}\right)^2}\int_{4\, m_{DM}^2}^{\infty} ds\, \sqrt{s}\,(s - 4\, m_{DM}^2)\sigma(s)K_1\left(\frac{\sqrt{s}}{T}\right)$$

$$\Omega_{DM}h^2 \approx 8.76\times 10^{-11} GeV^{-2}\left[\int_{T_0}^{T_{f.o.}} g_*^{\frac{1}{2}}\langle\sigma v\rangle \frac{dT}{m_{DM}}\right]^{-1}$$

Relic density depends on a single particle physics input

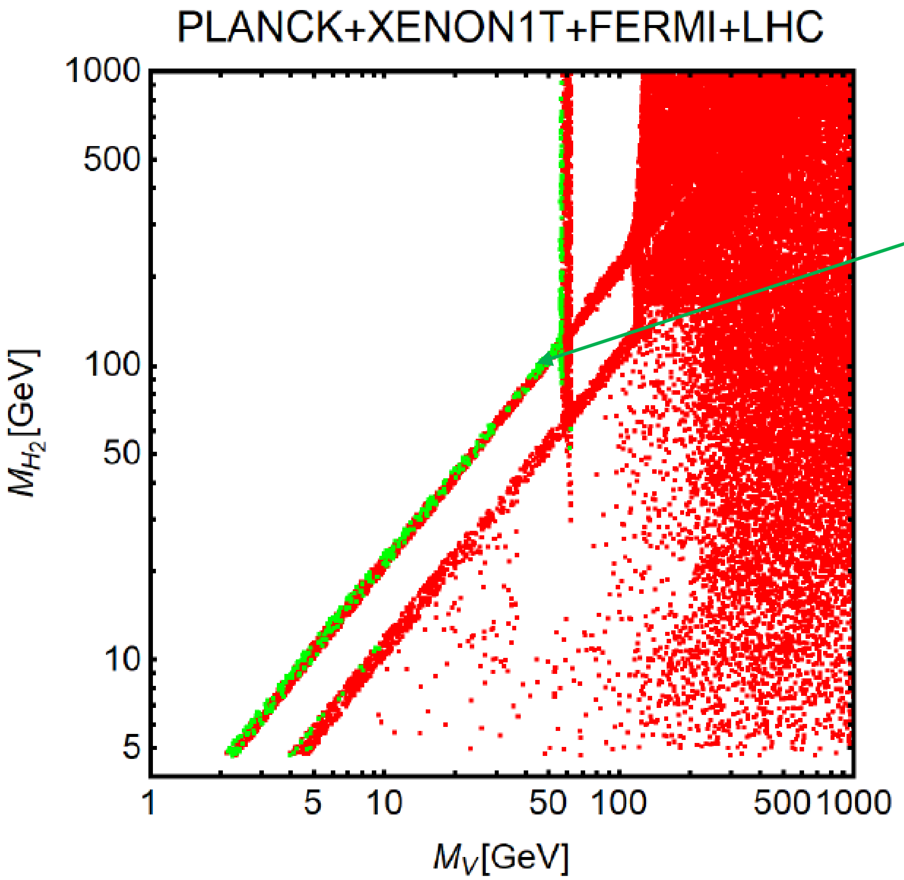


PLANCK+XENON1T+FERMI,$M_{H_2}>M_{H_1}$
M_{H_2}[GeV]
M_V[GeV]



sinθ=0.1,M_{H_2}=1000 GeV
Perturbativity
XENON1T EXCLUDED
$H_1\to$inv
PLANCK
$\tilde{g}$
M_V[GeV]

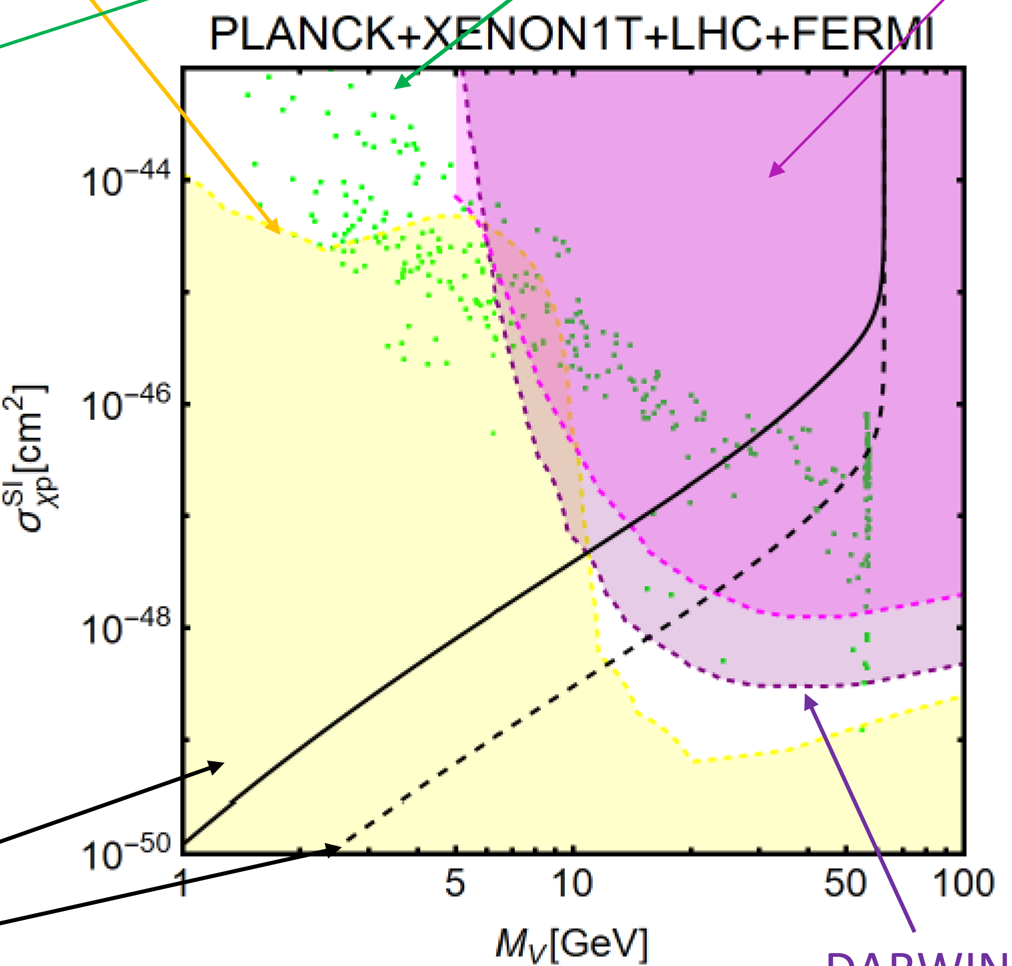
Light viable DM requires extra light degrees of freedom at the scale of the SM-like Higgs or below.



ν-floor

$2.5\% \leq Br(H \rightarrow inv) \leq 11\%$

XENONnT



EFT Portal

DARWIN

Dark SU(3) dark symmetry

$$\mathcal{L}_{\text{Higgs}} = -\frac{\lambda_H}{2}|\phi|^4 - m_H^2|\phi|^2$$

$$\mathcal{L}_{\text{portal}} = -\lambda_{H11}|\phi|^2\phi_1^2 - \lambda_{H22}|\phi|^2\phi_2^2 + \left(|\phi|^2\phi_1^\dagger\phi_2 + \text{h.c}\right)$$

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \\ v_1 + h_1 \end{pmatrix}$$

$$\phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 + h_2 \\ v_3 + h_3 + i\left(v_4 + h_4\right) \end{pmatrix}$$

$$\mathcal{L}_{\text{hidden}} = -\frac{1}{2}\text{Tr}\left\{V_{\mu\nu}V^{\mu\nu}\right\} + |D_\mu\phi_1|^2 + |D_\mu\phi_2|^2 - V_{\text{hidden}}$$

SU(3) completely broken by two Higgses in the fundamental representation

$$V_{\text{hidden}} = m_{11}^2|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2\left(\phi_1^\dagger\phi_2 + \text{h.c.}\right) + \left[\frac{\lambda_5}{2}\left(\phi_1^\dagger\phi_2\right)^2 + \lambda_6|\phi_1|^2\left(\phi_1^\dagger\phi_2\right) + \lambda_7|\phi_2|^2\left(\phi_1^\dagger\phi_2\right) + \text{h.c.}\right]$$
$$+ \frac{\lambda_1}{2}|\phi_1|^4 + \frac{\lambda_2}{2}|\phi_2|^4 + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2$$

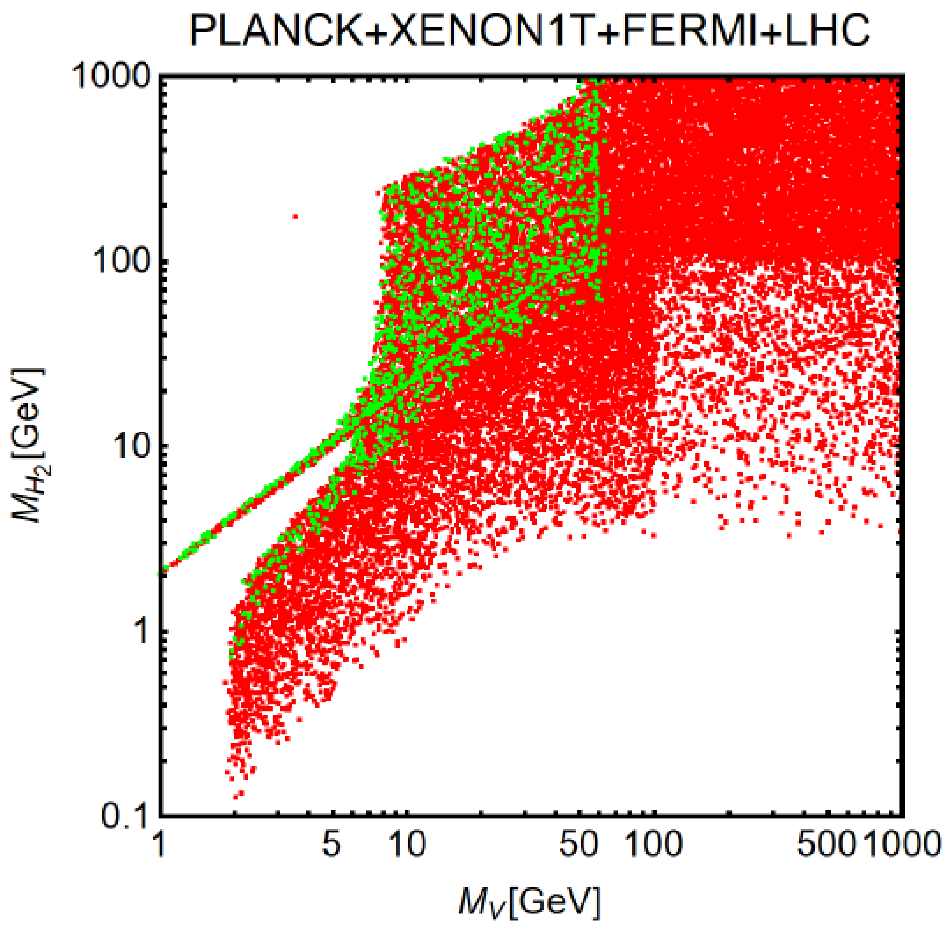
Higgs Portal Embedding in Dark SU(3)

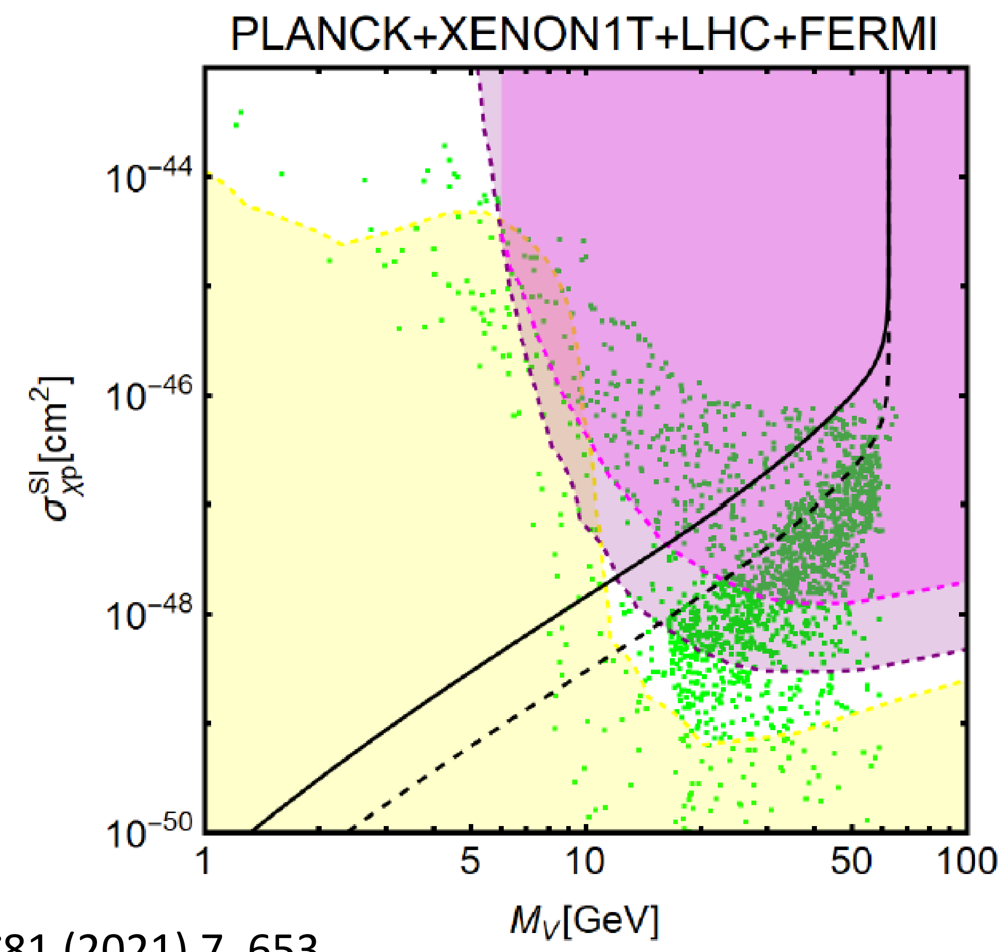
We can reduce the model to an extended Higgs portal in the limit:

$$v_3 \ll v_2 \ll v_1$$

$$\begin{aligned}
\mathcal{L} &= \frac{\tilde{g} M_V}{2} \left(-\sin\theta H_1 + \cos\theta H_2\right) \left(\sum_{a=1,2} V_\mu^a V^{\mu\, a} + \left(\cos\alpha - \frac{\sin\alpha}{\sqrt{3}}\right)^2 V_\mu^3 V^{\mu\, 3} \right) \\
&+ \tilde{g} \cos\alpha \sum_{a,b,c} \epsilon_{abc} \partial_\mu V_\nu V_\nu^a V^{b\,\mu} V^{c\,\nu} - \frac{\tilde{g}^2}{2} \cos^2\alpha \sum_{a=1,2} \left(V_\mu^a V^{a\,\mu} V_\nu^3 V^{3\,\nu} - \left(V_\mu^a V^{a\,\mu}\right)^2 \right) \\
&- \frac{1}{2} m_\psi^2 \psi^2 + \left[\frac{\tilde{g}}{2 M_V} \left(-\sin\theta H_1 + \cos\theta H_2\right) - \frac{1}{4} \left(\lambda_{\psi\psi 11} H_1^2 + 2 \lambda_{\psi\psi 12} H_1 H_2 + \lambda_{\psi\psi 22} H_2^2 \right) \right] \psi^2 \\
&- \frac{k_{111}}{2} v H_1^3 - \frac{k_{112}}{2} H_1^2 H_2 v \sin\theta - \frac{\kappa_{221}}{2} H_1 H_2^2 v \cos\theta - \frac{\kappa_{222}}{2} H_2^3 v \\
&+ \frac{H_1 \cos\theta + H_2 \sin\theta}{v} \left(2 M_W^2 W_\mu^+ W^{\mu -} + M_Z^2 Z_\mu Z^\mu - m_f \bar{f} f \right)
\end{aligned}$$

V DM plus metastable V^3





G.A., A. Djouadi, M. Kado, EPJ C81 (2021) 7, 653

$VV \rightarrow V^3 V^3$ annihilation allow correct relic density for very heavy H_2. We can recover the EFT limit.

Conclusions

We have compared EFT Higgs portals with more realistic models in light of the LHC Invisible width/Direct Detection correlation plot.

The interpretation of LHC results in terms of EFT Higgs portal is theoretically consistent.

The requirement of the correct DM relic density, if thermal freeze-out is assumed, calls, however, for additional light degrees of freedom requiring a recasting of the correlation plot.