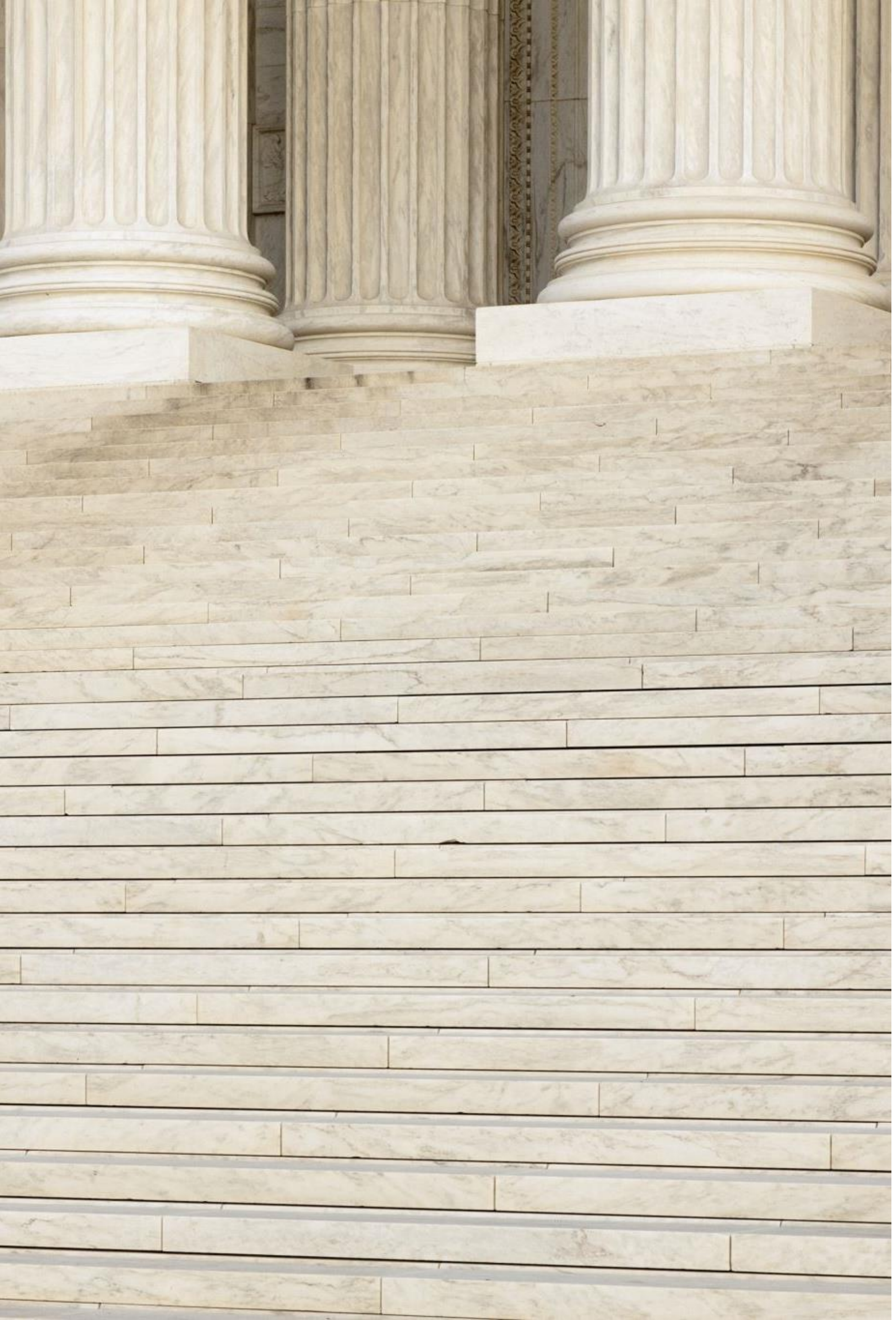

Collider prospects for vector Dark Matter coupled with the Higgs

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Based on G.A., A. Djouadi, M. Kado 2001.10750

plus work in preparation

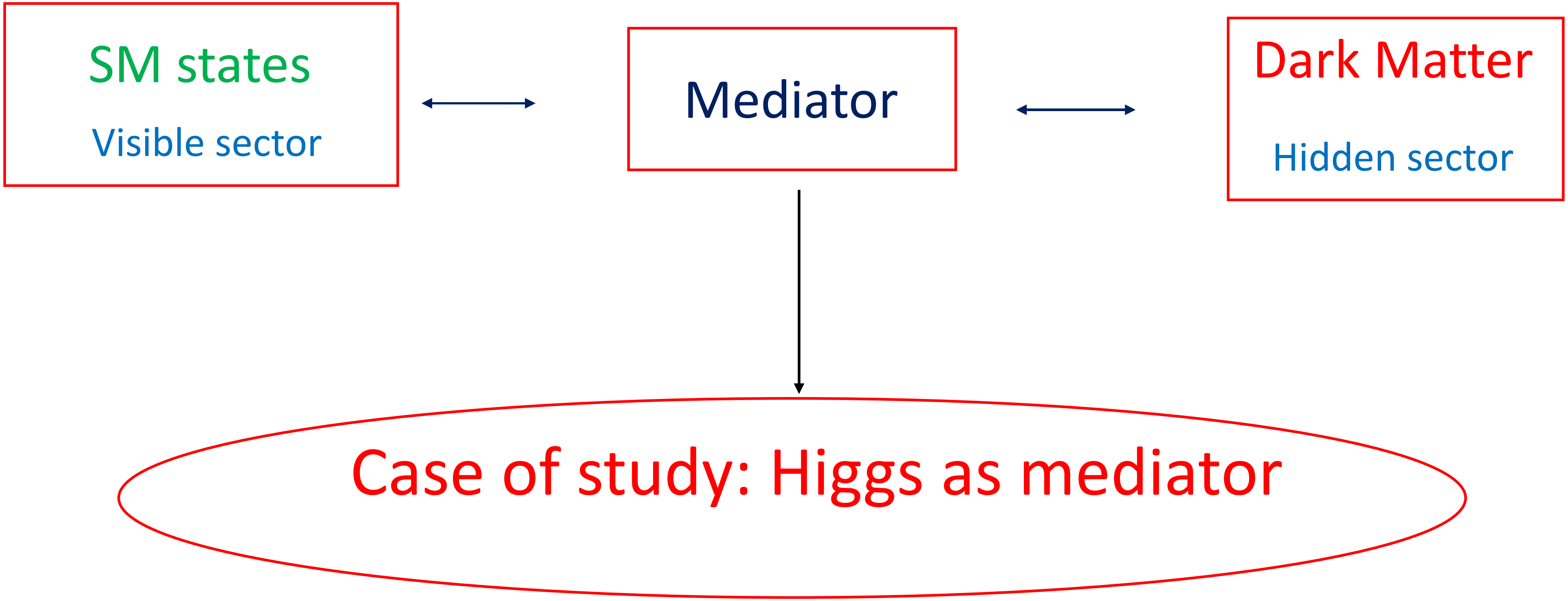
PARTICLE DM

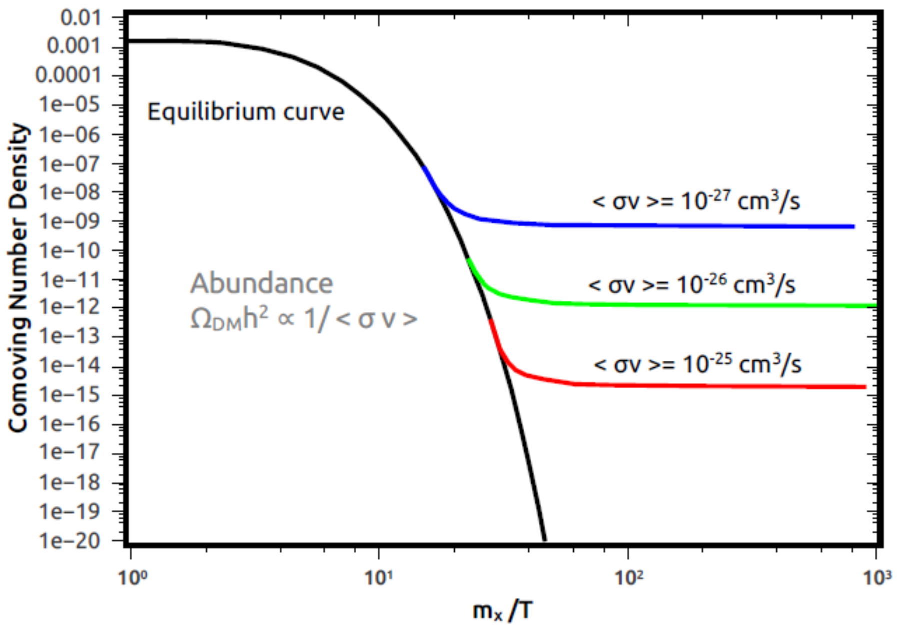
Dark Matter is one of the building blocks of the Standard Cosmological model.
Provides most of the matter contribution to the energy budget of the Universe.
Evidences from astrophysics and cosmology.

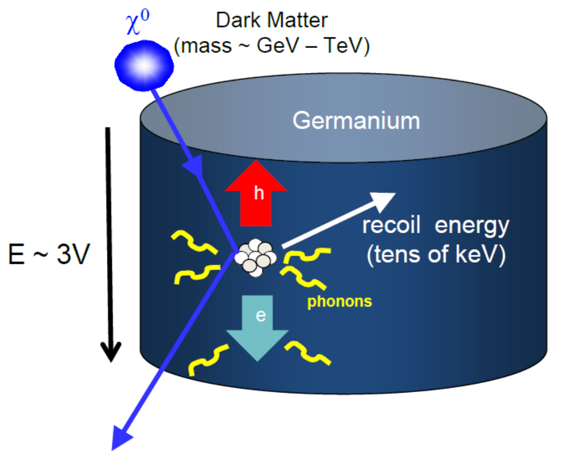
Stable on cosmological scales.
Weakly or SuperWeakly interacting with ordinary matter, photons.
Cold (up to warm) as opposed to hot.

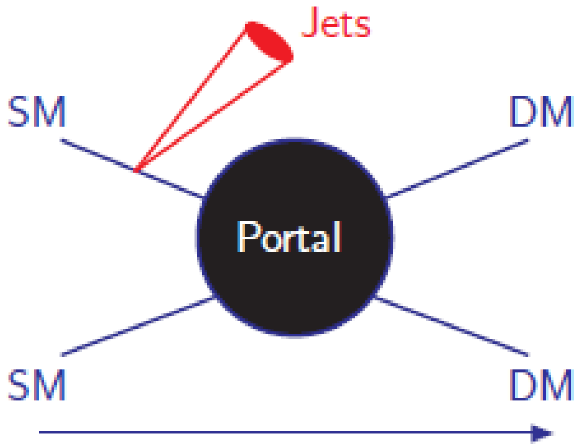
No (confirmed) detection so far.

"Portals"

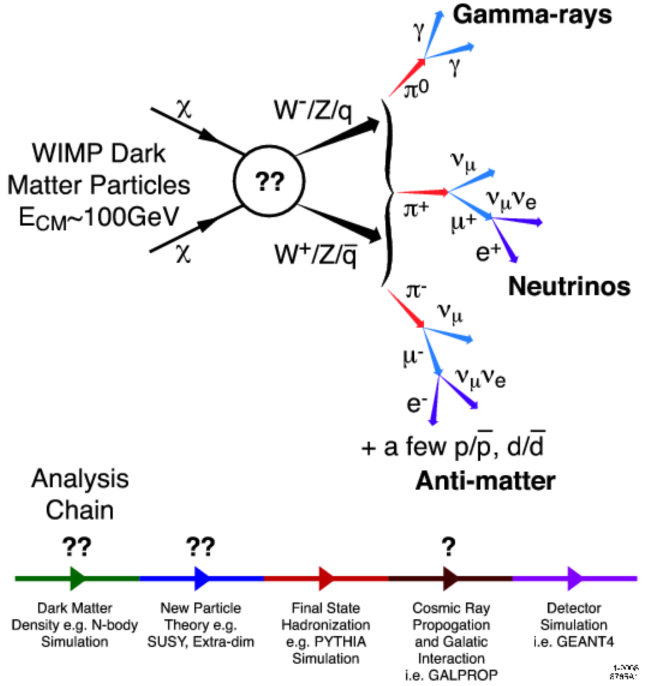

SM states
Visible sector
Mediator
Dark Matter
Hidden sector
Case of study: Higgs as mediator

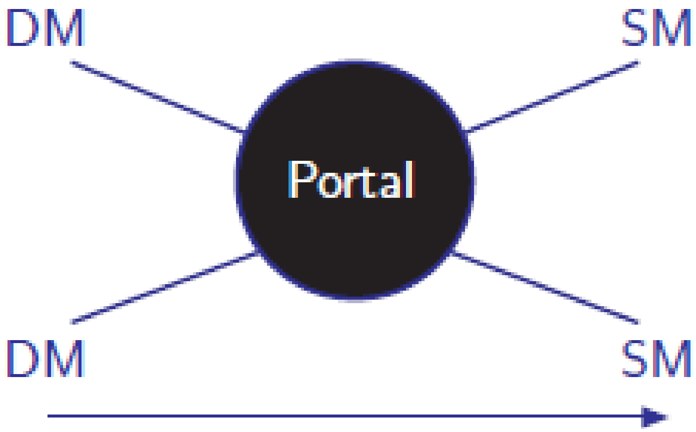




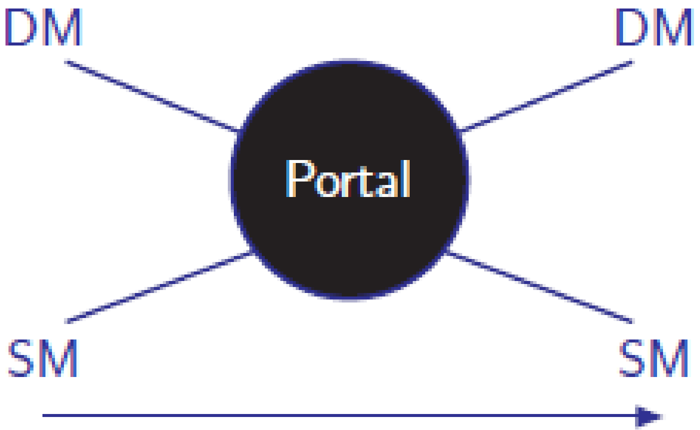


(c) Collider Detection





$\Omega h^2 \approx 0.12$
$\langle \sigma v \rangle \approx 3 \times 10^{-26}\, cm^3\, s^{-1}$



Relic Density

$$\langle \sigma v \rangle \approx \frac{\lambda_{DM}^2 \lambda_{SM}^2 m_{DM}^2}{(4\, m_{DM}^2 - m_{Portal}^2)^2}\left(a + \frac{b}{x}\right) \approx \frac{\lambda_{DM}^2 \lambda_{SM}^2 m_{DM}^2}{(4\, m_{DM}^2 - m_{Portal}^2)^2}\left(a + \frac{1}{2} b v_{f.o.}^2\right) \longleftrightarrow \sigma_{\chi N} \approx \frac{\mu_{\chi N}^2 \lambda_{DM}^2}{\pi m_{Portal}^4} f(\lambda_q)$$

s-wave

p-wave

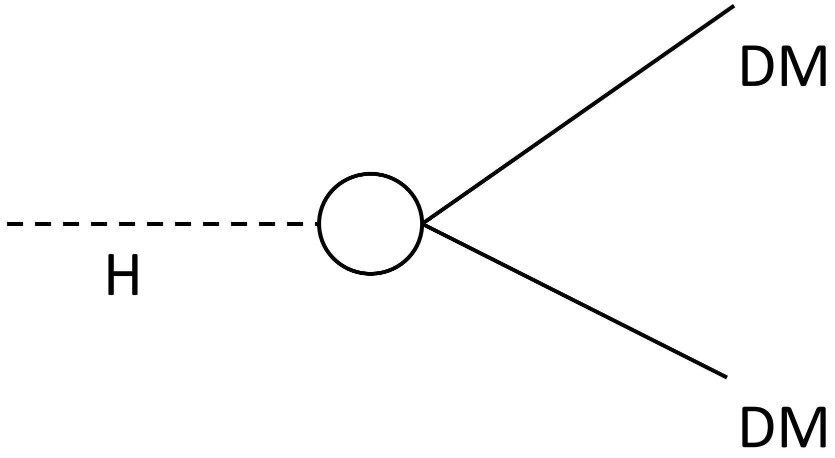
$v_{f.o.} \sim 0.3$

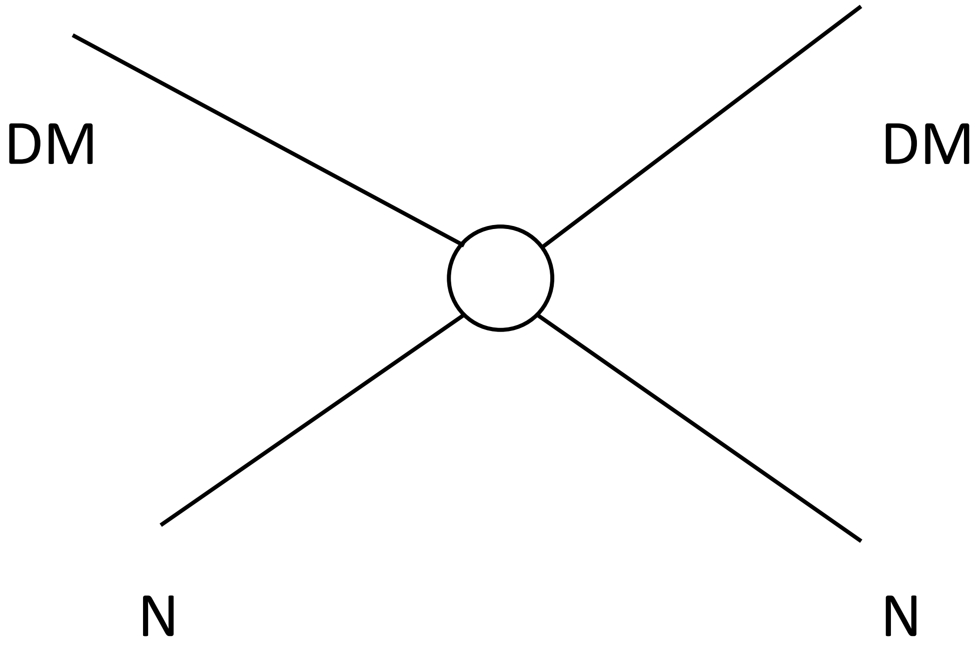
Indirect Detection

$$\langle \sigma v \rangle \approx \frac{\lambda_{DM}^2 \lambda_{SM}^2 m_{DM}^2}{(4\, m_{DM}^2 - m_{Portal}^2)^2}\left(a + \frac{1}{2} b v_{now}^2\right)$$

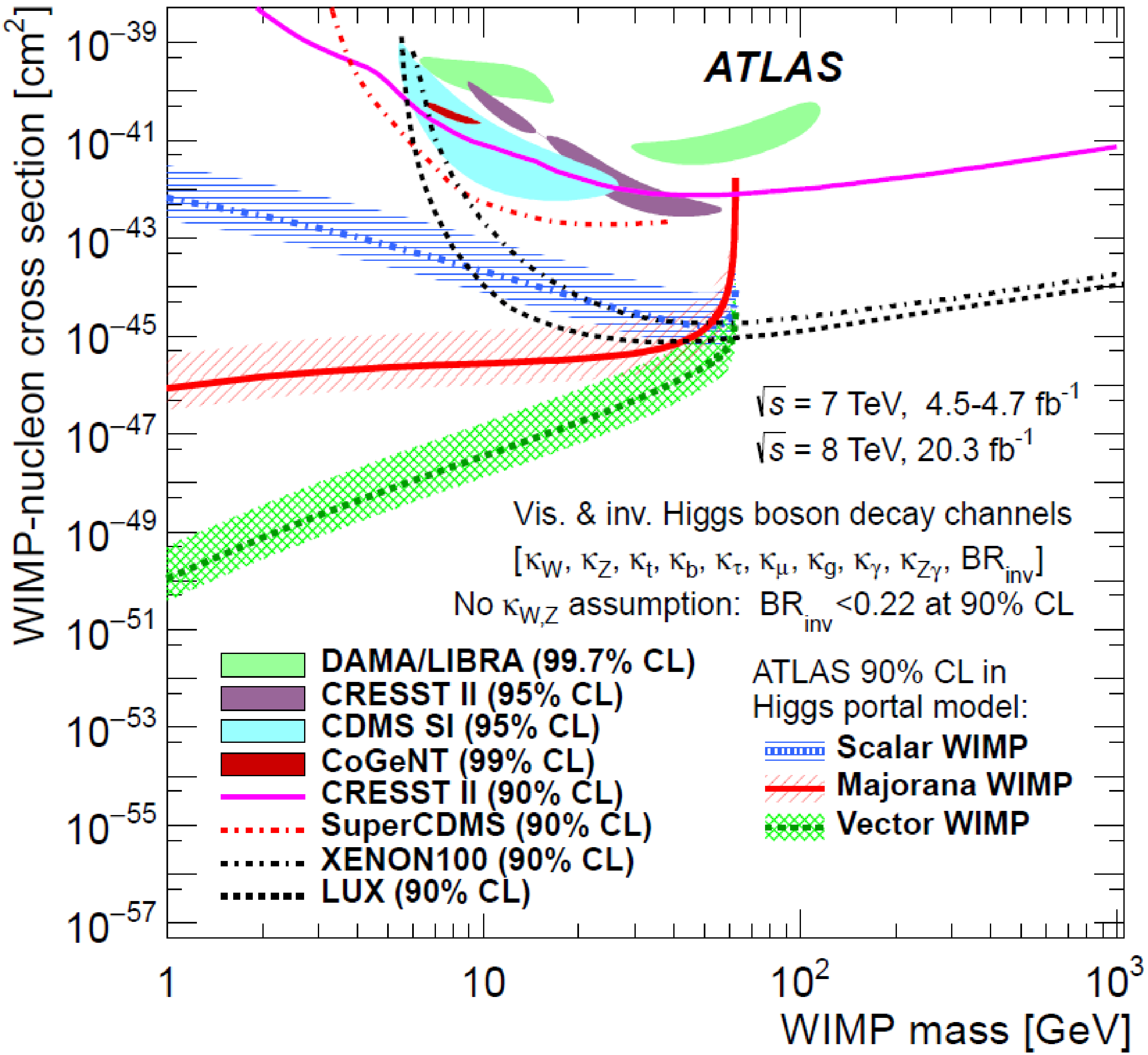
$v_{now} \sim 10^{-3}$

Invisible H decay vs Direct Detection





$$\sigma^{SI}_{DM,N} = \frac{\mu^2_{DM,p}}{\pi M_H^4} \lambda^2_{HDMDM} \lambda^2_{HNN} \quad \rightarrow \quad \sigma^{SI}_{DM,N} \propto Br(H \rightarrow DMDM)$$


ATLAS
WIMP-nucleon cross section [cm^2]
WIMP mass [GeV]
$\sqrt{s}$ = 7 TeV, 4.5-4.7 fb^{-1}
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Vis. & inv. Higgs boson decay channels
[κ_W, κ_Z, κ_t, κ_b, κ_τ, κ_μ, κ_g, κ_γ, $\kappa_{Z\gamma}$, BR_{inv}]
No $\kappa_{W,Z}$ assumption: BR_{inv}<0.22 at 90% CL
DAMA/LIBRA (99.7% CL)
CRESST II (95% CL)
CDMS SI (95% CL)
CoGeNT (99% CL)
CRESST II (90% CL)
SuperCDMS (90% CL)
XENON100 (90% CL)
LUX (90% CL)
ATLAS 90% CL in
Higgs portal model:
Scalar WIMP
Majorana WIMP
Vector WIMP

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

D=4, but potential issues of perturbative unitarity

$$\Delta\mathcal{L}_S = -\frac{1}{2}M_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HSS}\Phi^\dagger\Phi S^2 \,,$$

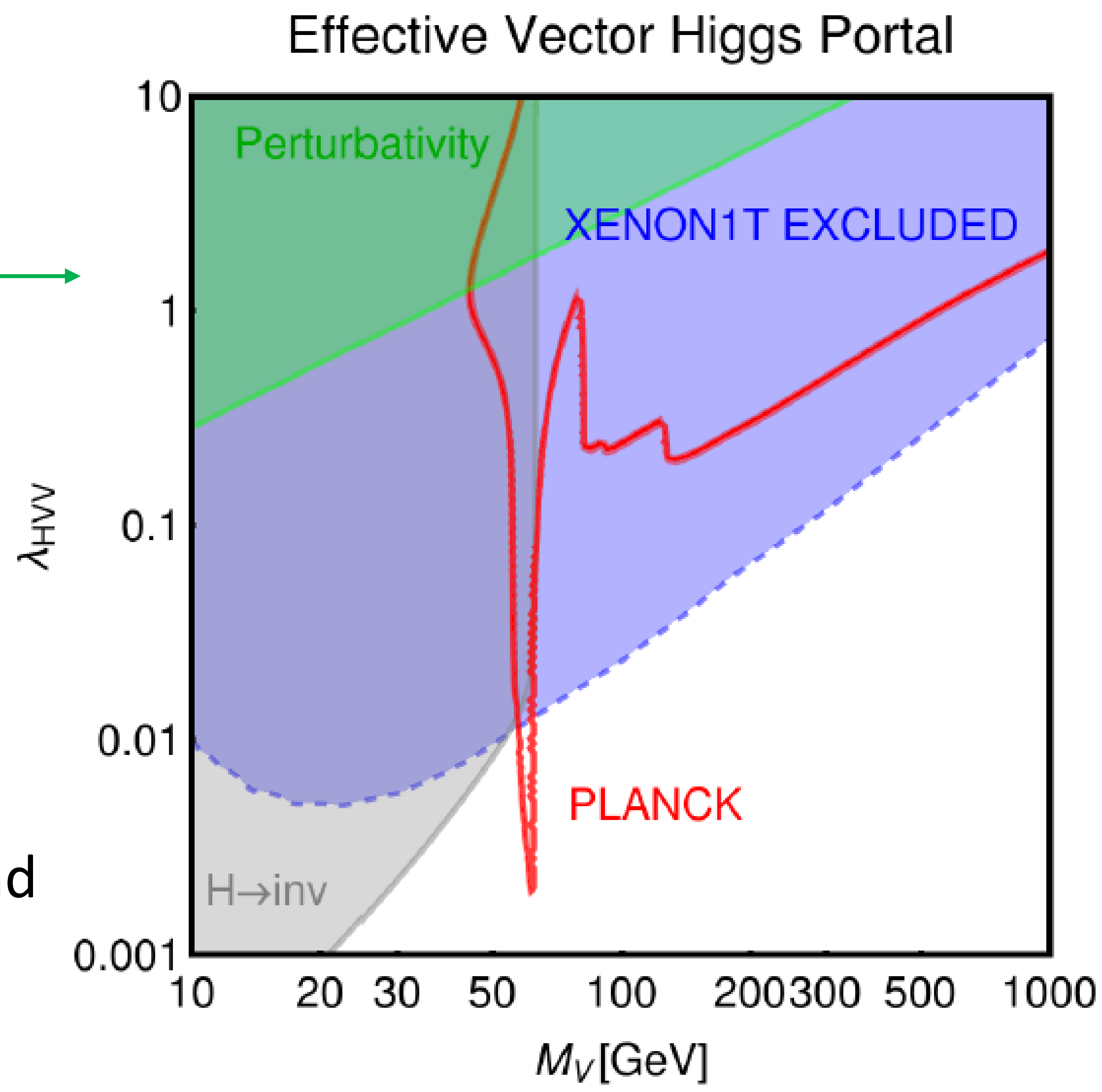
$$\Delta\mathcal{L}_V = \frac{1}{2}M_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{HVV}\Phi^\dagger\Phi V_\mu V^\mu$$

$$\Delta\mathcal{L}_\chi = -\frac{1}{2}M_\chi \bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\bar{\chi}\chi \,.$$

Explicitly $D \geq 4$. Depends on a NP scale Λ.

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.

Dark U(1)

Let's compare the effective vector Higgs portal with a more complete model.

$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu\phi)^\dagger D^\mu\phi - V(\phi)$$

U(1) spontaneosly broken ⟶ $A_\mu \to -A_\mu$

$$\mathcal{L}_{\rm portal} = -\lambda_{h\phi}|H|^2|\phi|^2$$

Spontaneous breaking leaves a residual Z_2 symmetry

$$\rho = -h_1 \sin\theta + h_2 \cos\theta$$
$$h = h_1 \cos\theta + h_2 \sin\theta\ ,$$

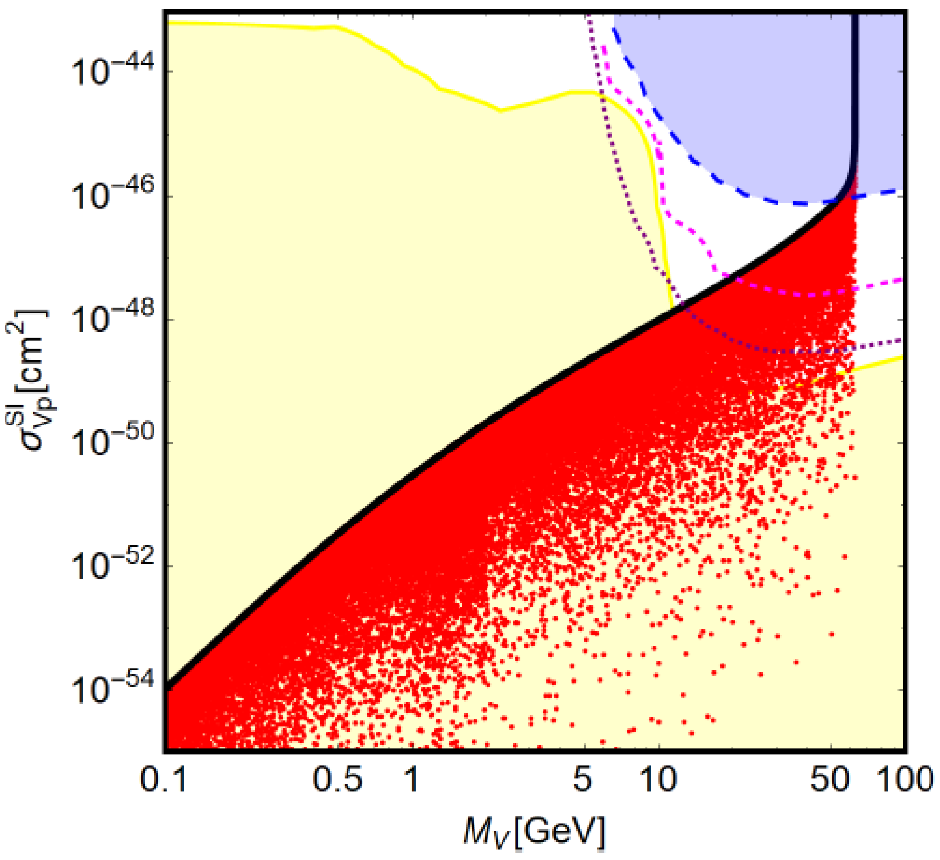
$$\Delta\mathcal{L}_{\rm s-g} = \frac{\tilde{g}^2}{4}\tilde{v}\rho\, A_\mu A^\mu + \frac{\tilde{g}^2}{8}\rho^2\, A_\mu A^\mu$$

As can be imagined, for $M_{H_2} \gg M_{H_1}$

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

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

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

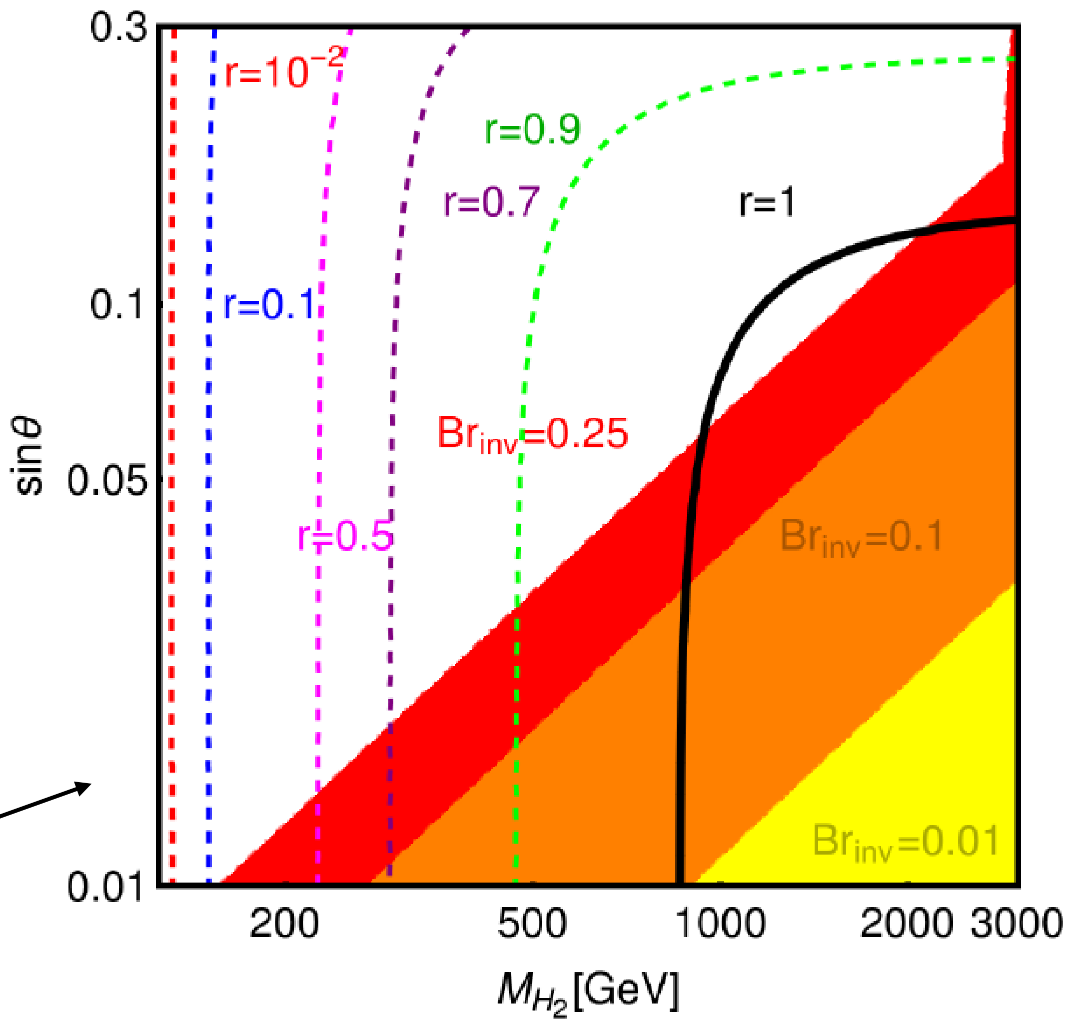


Perturbative Unitarity

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

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

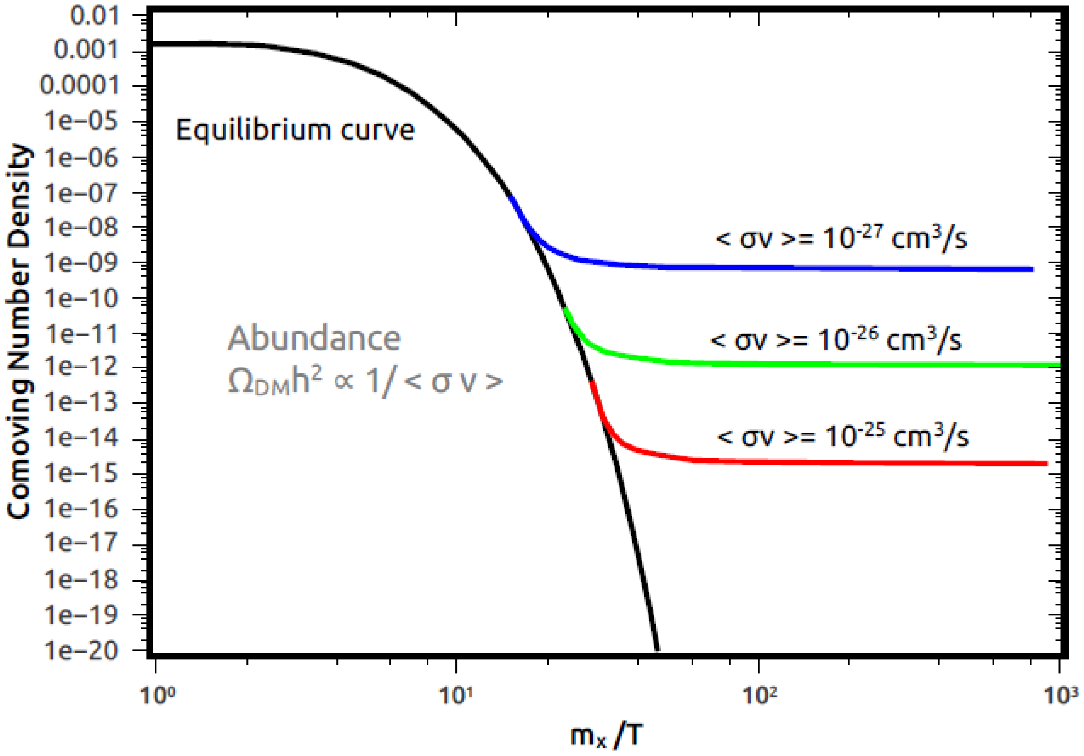
$$r = \frac{\sigma^{SI}_{U(1)}}{\sigma^{SI}_{EFT}}$$



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

Include DM relic density

We assume the freeze-out paradigm:



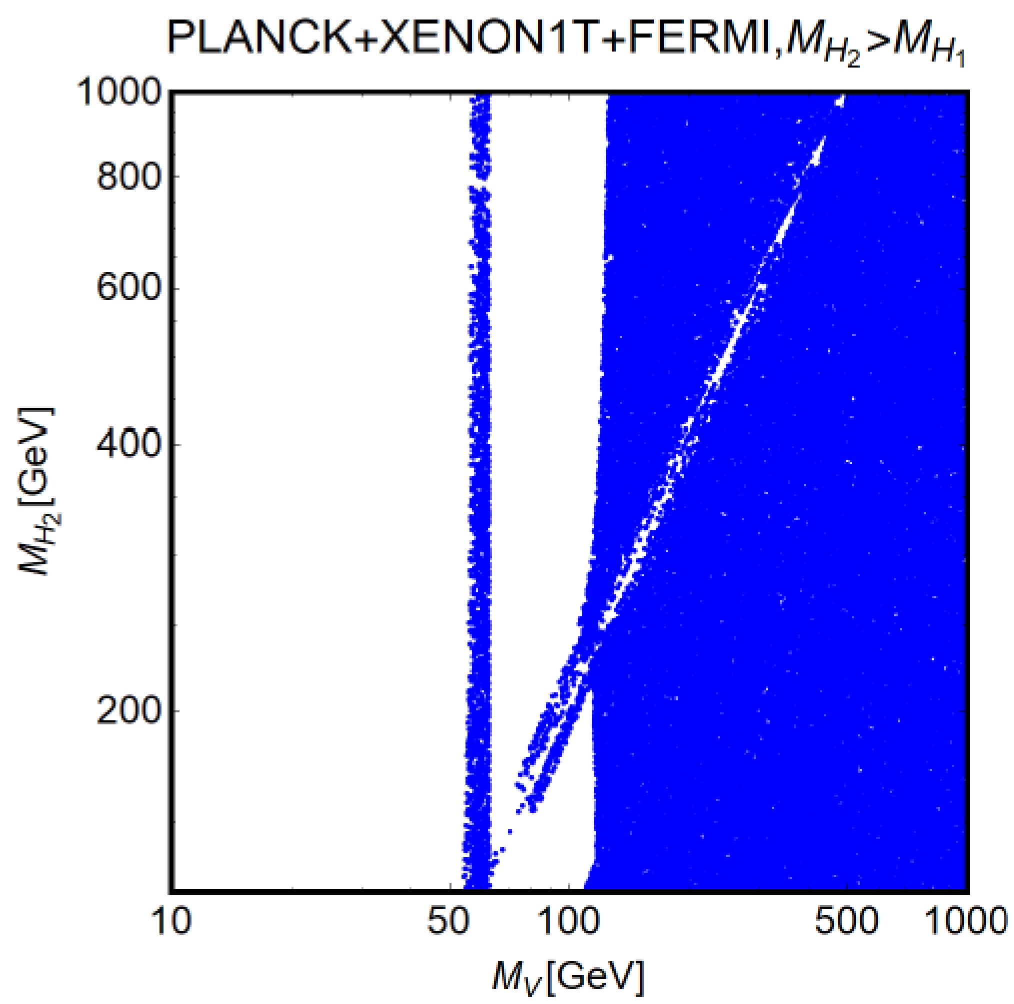
$$\frac{dn_{DM}}{dt} + 3Hn_{DM} = -\langle \sigma v \rangle \left(n_{DM}^2 - n_{DM,eq}^2 \right)$$

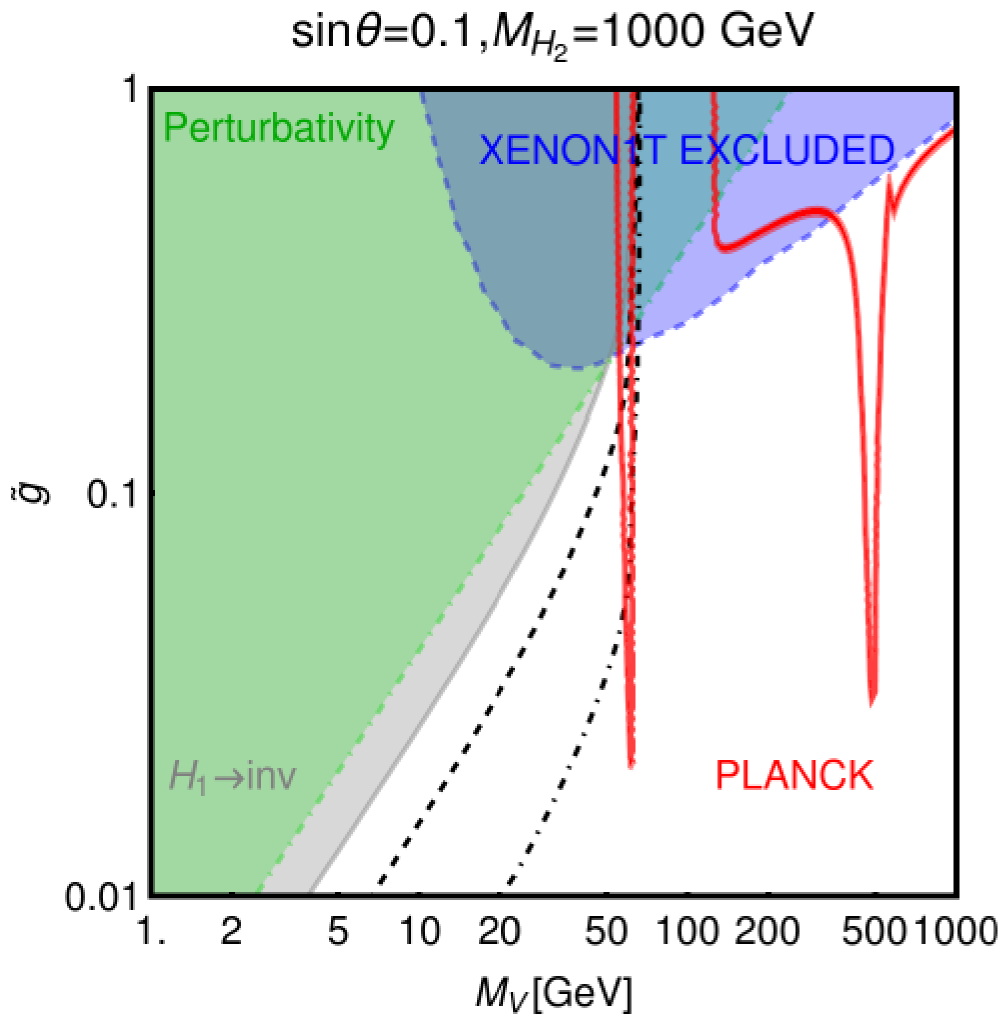
$$\langle \sigma v \rangle = \frac{1}{8\, m_{DM}^4 T\, K_2 \left(\frac{m_{DM}}{T} \right)^2} \int_{4\, m_{DM}^2}^{\infty} ds\, \sqrt{s}\, (s - 4\, m_{DM}^2) \sigma(s) K_1 \left(\frac{\sqrt{s}}{T} \right)$$

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

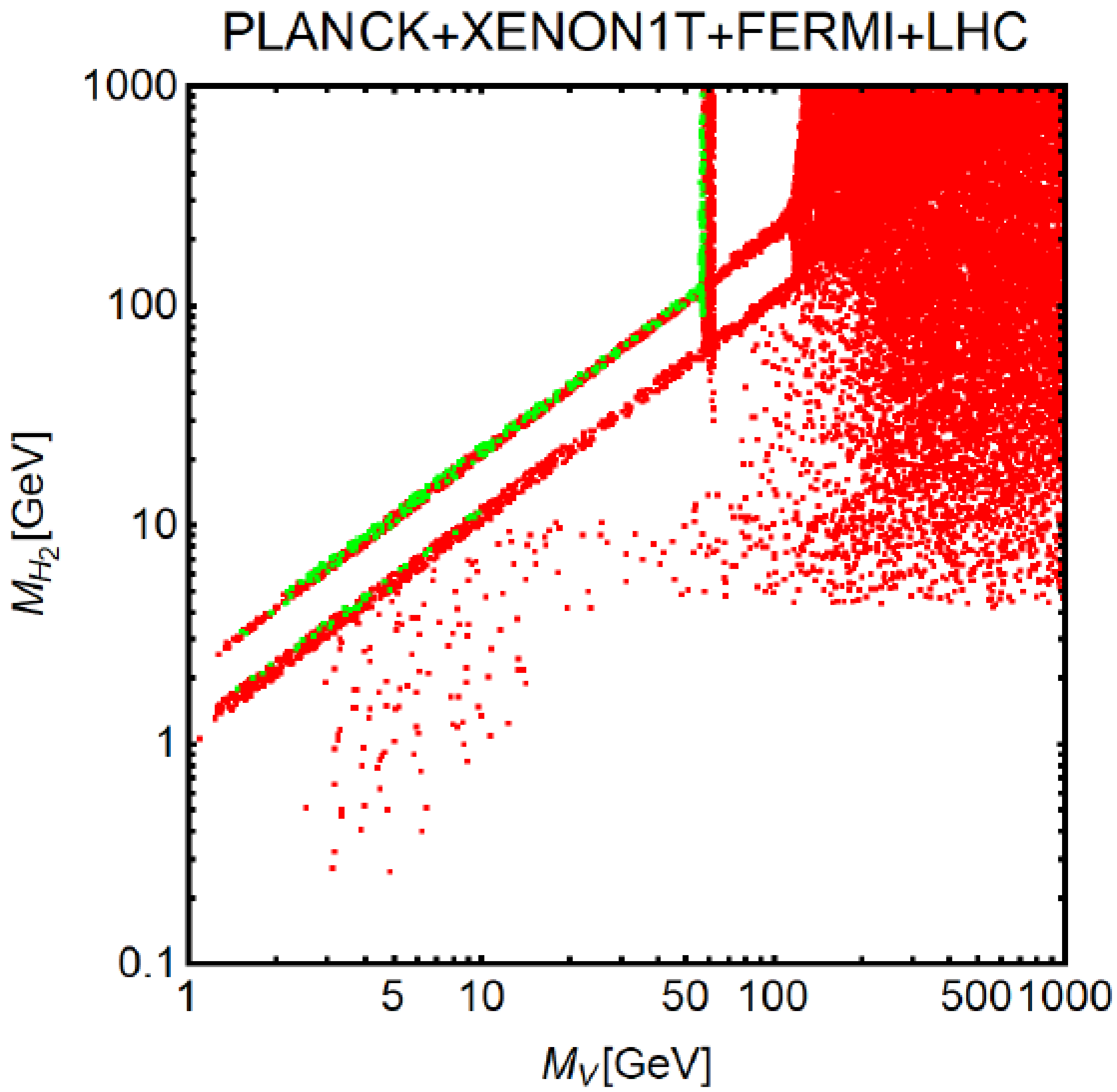
Relic density depends on a single particle physics input

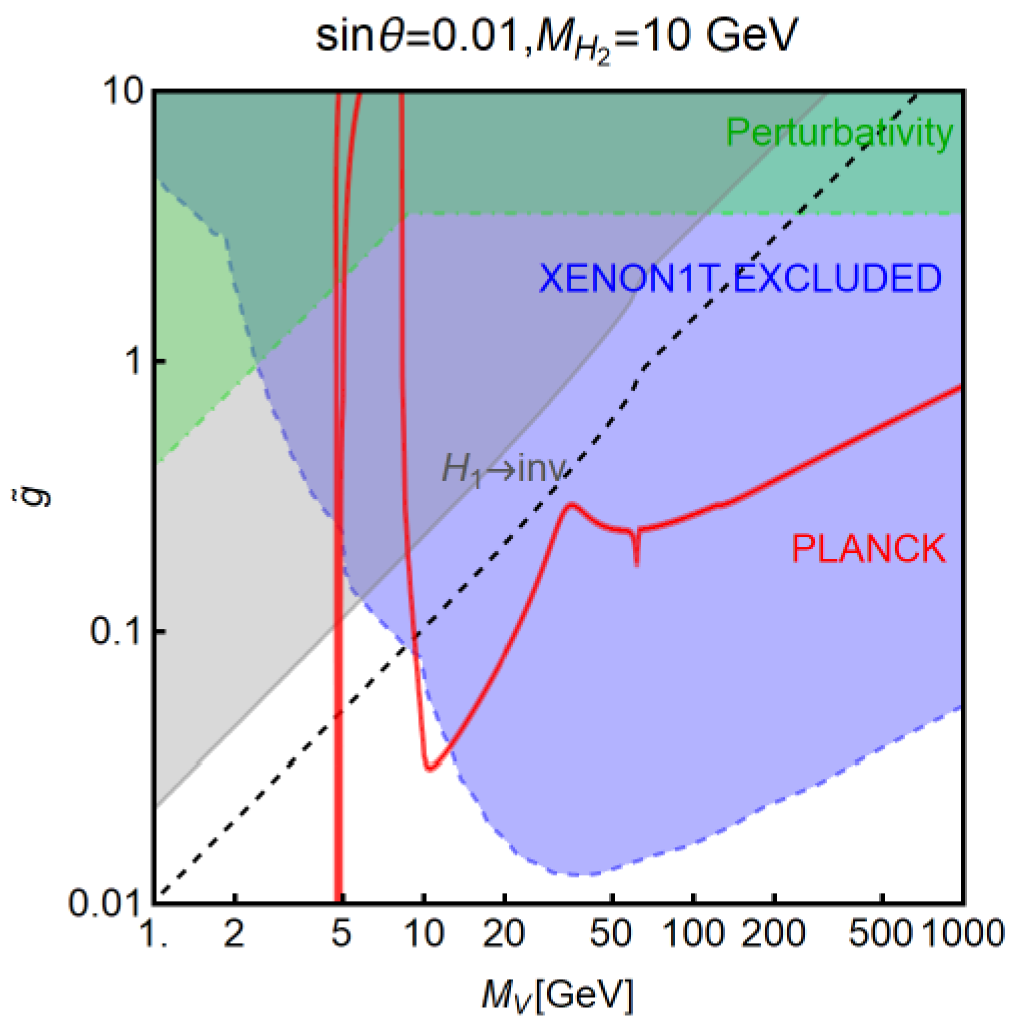
In the ‘decoupled’ regime we cannot have viable relic density within the kinematical reach of invisible Higgs decays.



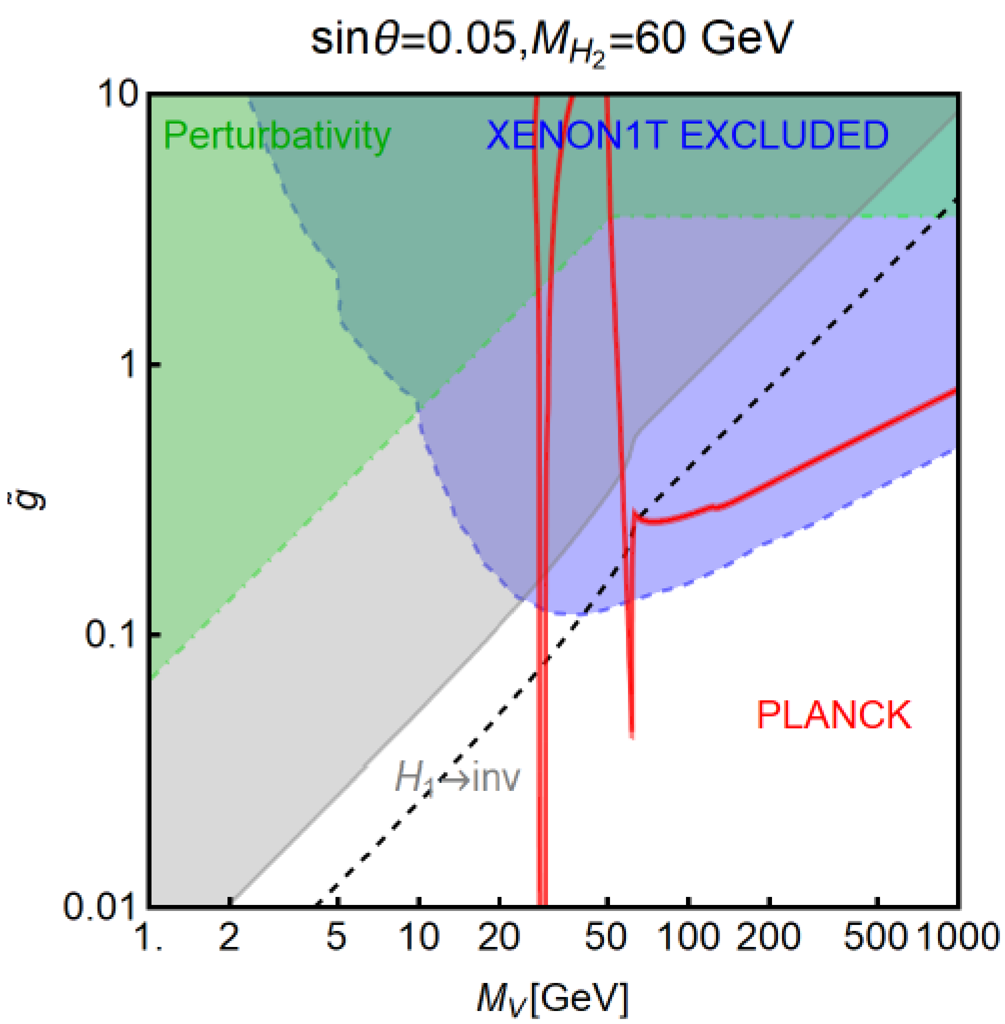


Light viable DM requires extra light degrees of freedom at the scale of the SM-like Higgs or below.

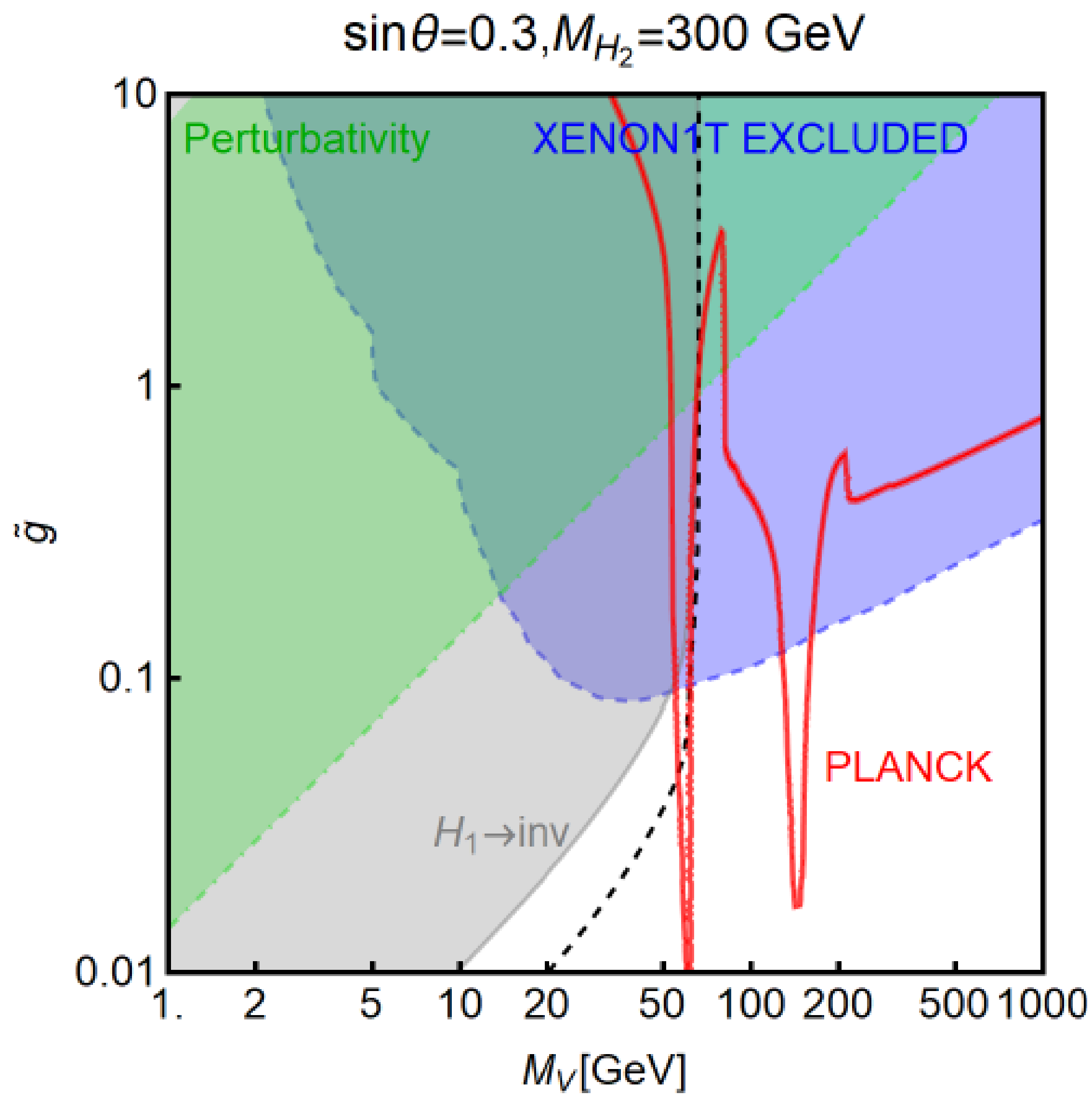


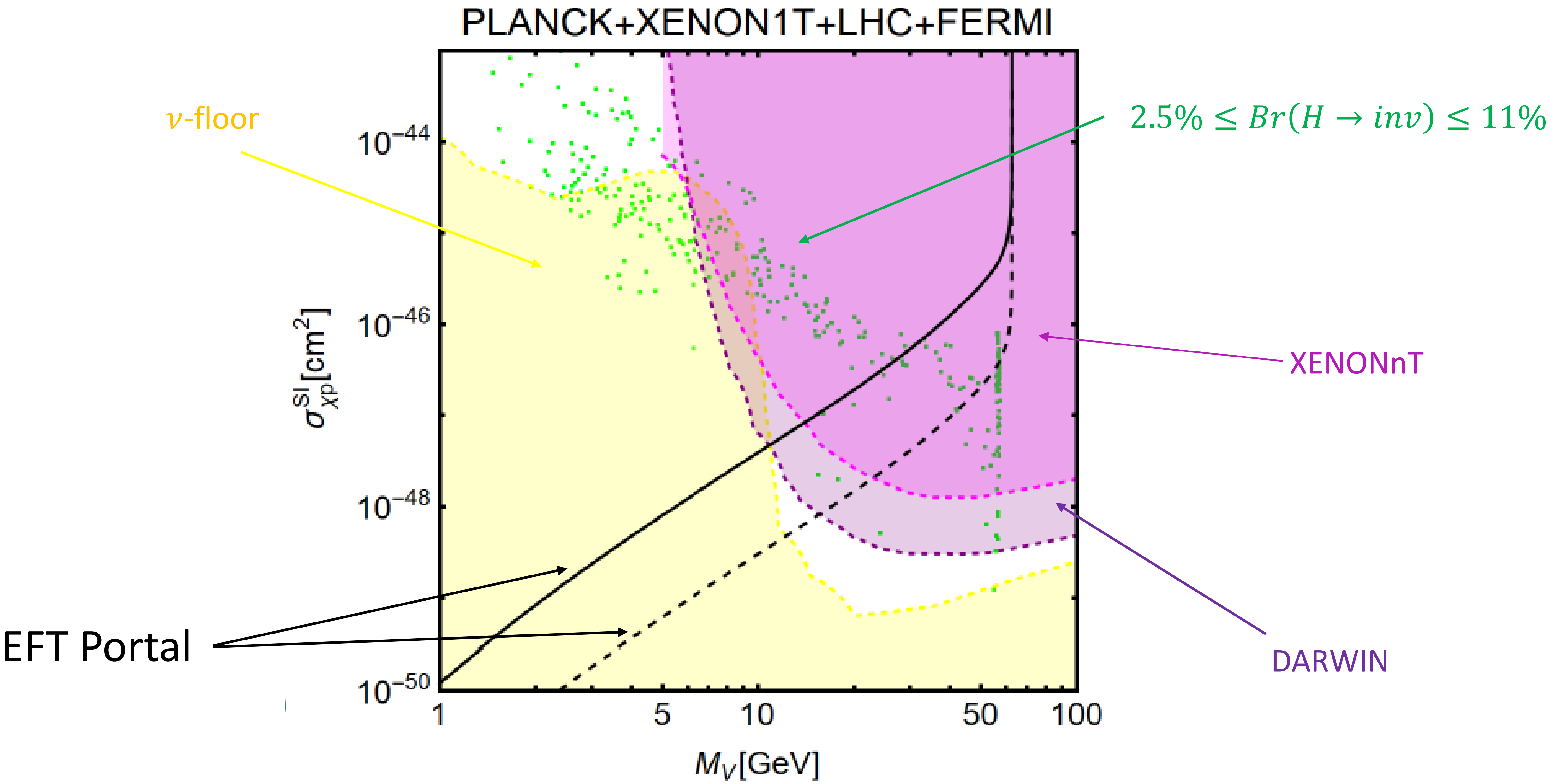


sinθ=0.01,M_{H_2}=10 GeV
Perturbativity
XENON1T EXCLUDED
H_1→inv
PLANCK
$\tilde{g}$
M_V[GeV]
10
1
0.1
0.01
1.
2
5
10
20
50
100
200
500
1000



sinθ=0.05,M_{H_2}=60 GeV
Perturbativity
XENON1T EXCLUDED
PLANCK
H_1→inv
$\tilde{g}$
M_V[GeV]
10
1
0.1
0.01
1.
2
5
10
20
50
100
200
500
1000


sinθ=0.3,M_{H_2}=300 GeV
Perturbativity
XENON1T EXCLUDED
PLANCK
H_1→inv
$\tilde{g}$
10
1
0.1
0.01
1.
2
5
10
20
50
100
200
500
1000
M_V[GeV]



PLANCK+XENON1T+LHC+FERMI
ν-floor
$2.5\% \leq Br(H \to inv) \leq 11\%$
XENONnT
DARWIN
EFT Portal
10^{-44}
10^{-46}
10^{-48}
10^{-50}
$\sigma^{SI}_{\chi p}[cm^2]$
1
5
10
50
100
M_V[GeV]

Conclusions

The LHC vs DD correlation plot is a powerful tool to highlight the complementarity between different DM search stratiegies.

The Vector Higgs portal is a theoretically consistent benchmark for the interpretation of the experimental outcome.

However the correlation plot does not properly described candidates achieving the correct relic density through the conventional freeze-out.