Higgs-portal Dark Matter: EFT vs UV-complete models

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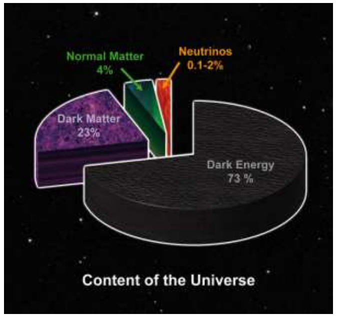
Higgs-portal Dark Matter
Phenomenology and complementarity
The case of vector DM: the U(1)$_X$ option
Discussion and Conclusion

with Giorgio Arcadi and Marumi Kado, arXiv:2001.10750 and work to appear

The Higgs portal to dark matter

Dark Matter: a crucial hint for physics beyond the SM.

DM makes:
25% of energy budget of Universe
80% of total matter of Universe



PLANCK: $\Omega_{\rm DM} h^2 = 0.119 \pm 0.001$

- **WIMPs are the best candidates and need to be searched for.**
- **Easiest and most minimal way to implement them in practice:**
  - **a singlet particle but of any spin i.e. a scalar, vector or fermion;**
  - **QED neutral + isosinglet, no SU(2)xU(1) charge: no Z couplings;**
  - **Z_2 parity for stability: no couplings or mixing with fermions.**

Hence, only couplings with the Higgs bosons ⇒ Higgs portal DM:

- **annihilates into SM particles via s-channel Higgs exchange;**
- **interacts with fermionic matter only through Higgs exchange;**
- **can be produced in pairs via Higgs boson exchange or decays.**

Occam razor (again): assume only the SM-like Higgs boson.

The Higgs portal to dark matter

Use a rather simple effective field theory (EFT) approach:

$$\Delta\mathcal{L}_s = -\frac{1}{2}M_s^2 s^2 - \frac{1}{4}\lambda_s s^4 - \frac{1}{4}\lambda_{Hss}\Phi^\dagger\Phi s^2$$
$$\Delta\mathcal{L}_v = \frac{1}{2}M_v^2 v_\mu v^\mu + \frac{1}{4}\lambda_v (v_\mu v^\mu)^2 + \frac{1}{4}\lambda_{Hvv}\Phi^\dagger\Phi v_\mu v^\mu$$
$$\Delta\mathcal{L}_\chi = -\frac{1}{2}M_\chi \bar\chi\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\bar\chi\chi$$

In principle, the terms $\lambda_s s^4$ and $\lambda_v (v_\mu v^\mu)^2$ do not matter to us.
After EWSB, the Φ field becomes $\Phi \to \frac{1}{\sqrt{2}}(v+H)$ with v=246 GeV,
and the various mass terms in the three spin cases will become:

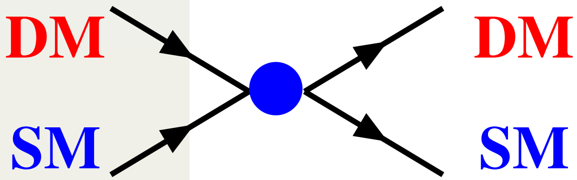
$$m_x^2 = M_x^2 + \frac{1}{4}\lambda_{Hxx} v^2$$

Two free parameters: DM mass m_x and DM-Higgs coupling λ_{Hxx},

$\Rightarrow$ very simple, model–independent and rather convenient approach,
$\Rightarrow$ often used as a benchmark in theoretical/experimental analyses
(despite that it is effective and even non-renormalisable in some cases).

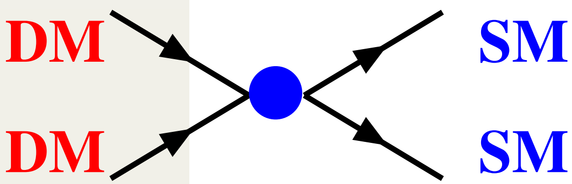
Phenomenology and complementarity

Direct Detection:



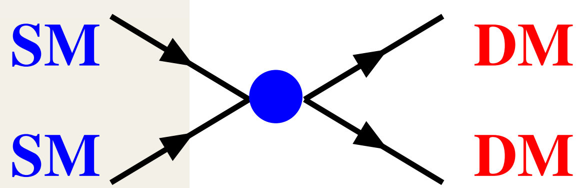
scattering on nucl. target:
XENON $\Rightarrow$ LZ,DARWIN

Indirect Detection:

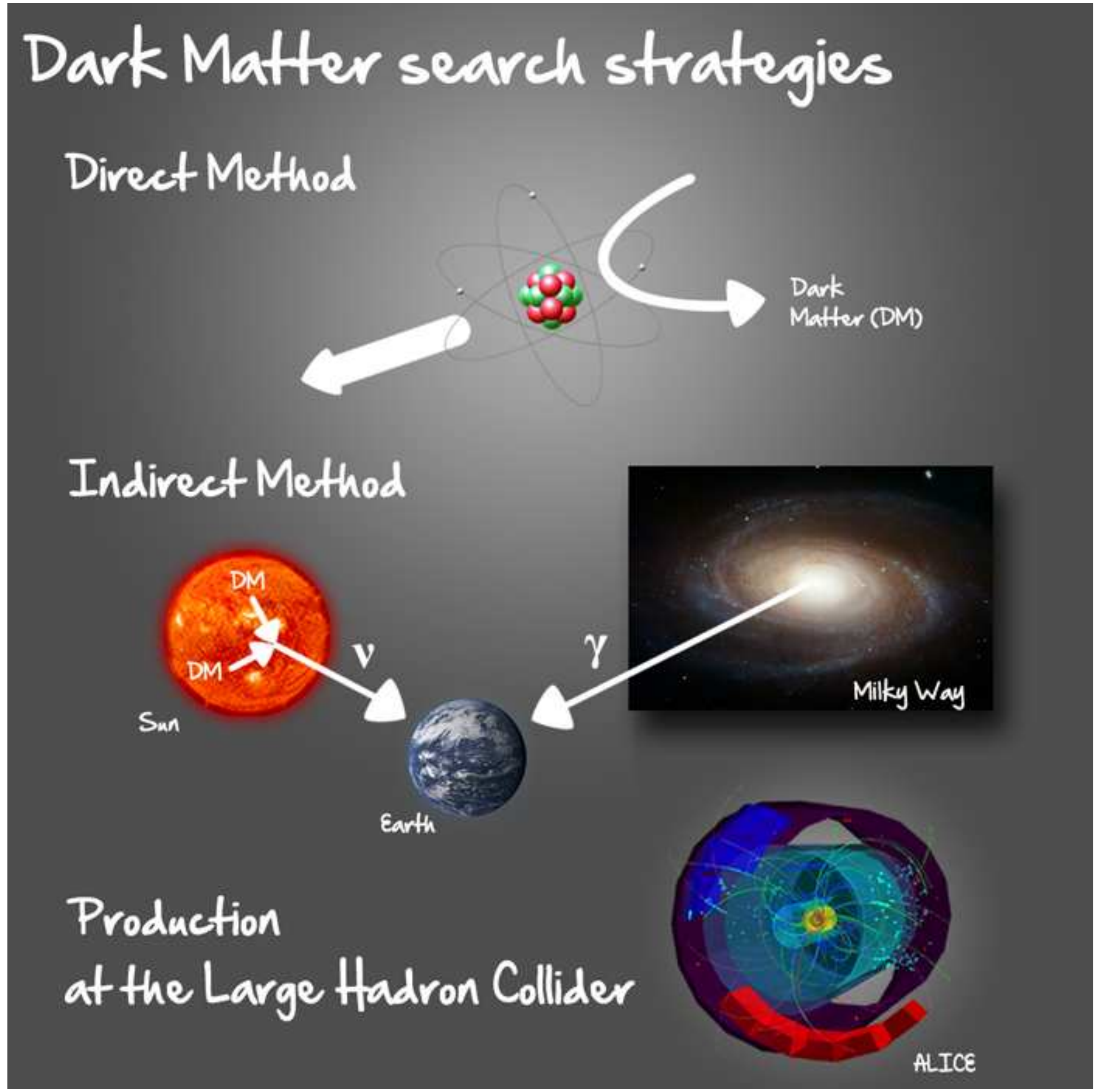


annihilation products:γ, ν
HESS,Fermi$\Rightarrow$ CTA, ...

Detection at colliders:



missing energy signature
LHC $\Rightarrow$ HL-LHC,e^+e^-,pp



Phenomenology and complementarity

- **Collider searches in invisible Higgs decays into DM, very simple:**

$$\Gamma_{\rm inv}(H\to ss) = \frac{\lambda_{Hss}^2 v^2 \beta_s}{64\pi M_H}$$

$$\Gamma_{\rm inv}(H\to vv) = \frac{\lambda_{Hvv}^2 v^2 M_H^3 \beta_v}{256\pi M_v^4}\left(1-\frac{4M_v^2}{M_H^2}+\frac{12M_v^4}{M_H^4}\right)$$

$$\Gamma_{\rm inv}(H\to ff) = \frac{\lambda_{Hff}^2 v^2 M_H \beta_f^3}{32\pi \Lambda^2}$$

BR(H→inv) measured through $\Gamma_H, g_{Hff}+g_{HVV}$ or $pp\to X+E_T^{mis}$.

- **Spin–independent direct detection, simple for s, v, f DM states:**

$$\sigma_{x-N}^{SI} = \frac{\lambda_{Hxx}^2}{16\pi M_H^4}\frac{m_N^4 f_N^2}{(m_x+m_N)^2}\delta_x', \quad \text{with } \delta_s=\delta_v=1, \delta_f=\frac{4}{\Lambda^2}$$

Nice complementarity between collider and direct detection searches:

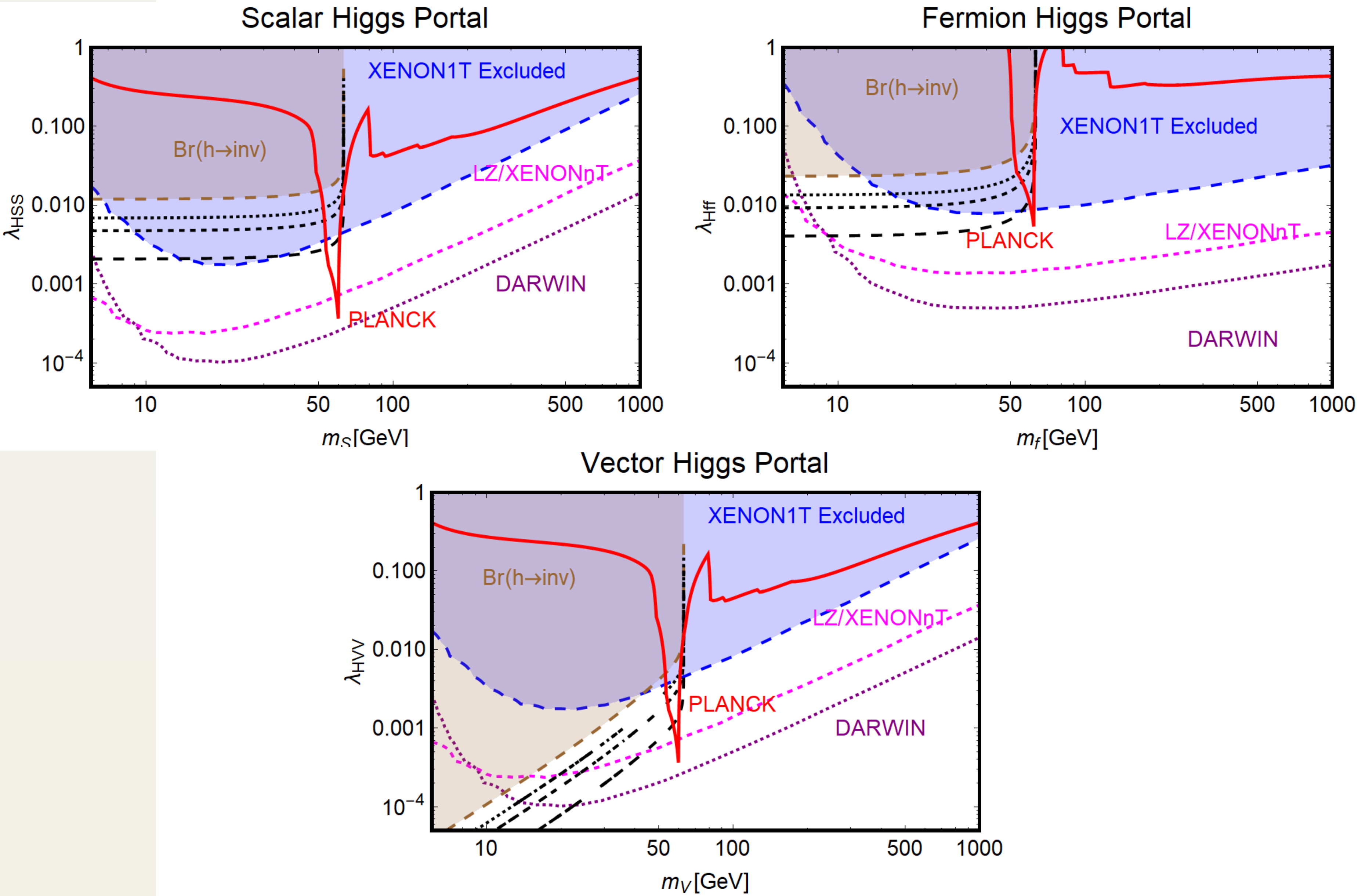
$$BR(H\to inv) = \frac{\Gamma(H\to xx)}{\Gamma_H^{SM}+\Gamma(H\to xx)} = \frac{\sigma_{xp}^{SI}}{\Gamma_H^{tot}/r_x+\sigma_{xp}^{SI}};\ r_x=\frac{\Gamma_{\rm inv}}{\sigma_{xp}^{SI}}=f(m_x,\lambda_{Hxx})$$

In principle needs to fit the Planck value: $\Omega_{DM}h^2=0.119\pm0.001$

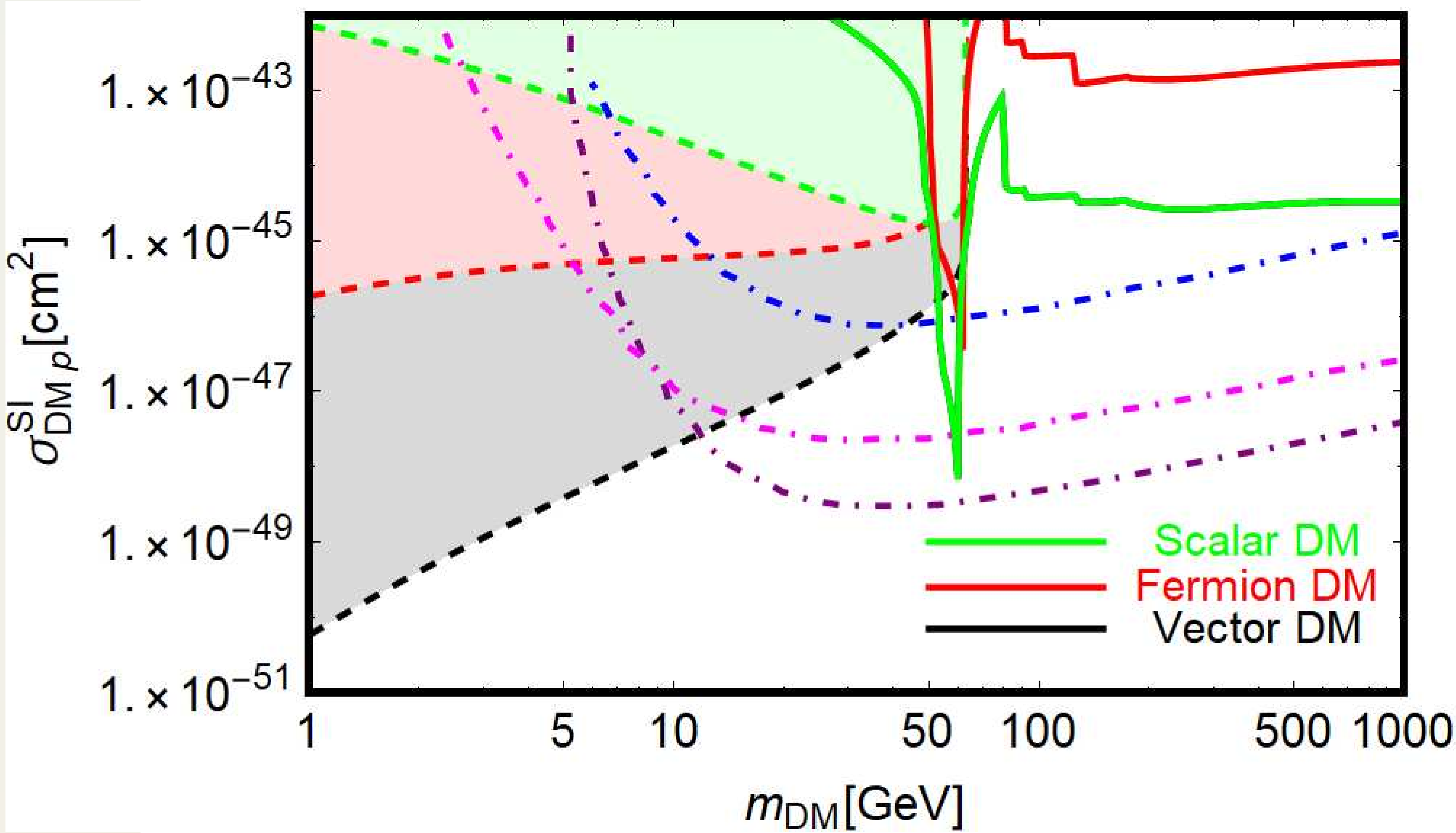
- **Relic density $\propto 1/\langle\sigma(xx\to H\to f\bar{f})v_r\rangle$ annihilation rate.**

but maybe no, X not all DM and/or Ωh^2 obtained via other means...

Phenomenology and complementarity



Phenomenology and complementarity



Arcadi, AD, Raidal

Phenomenology and complementarity

ut there is a problem: EFT approach might break down too early...

$\Delta\mathcal{L}_s = -\frac{1}{2}M_s^2 s^2 - \frac{1}{4}\lambda_{Hss}\Phi^\dagger\Phi s^2$ $\Rightarrow$ **OK in principle;**

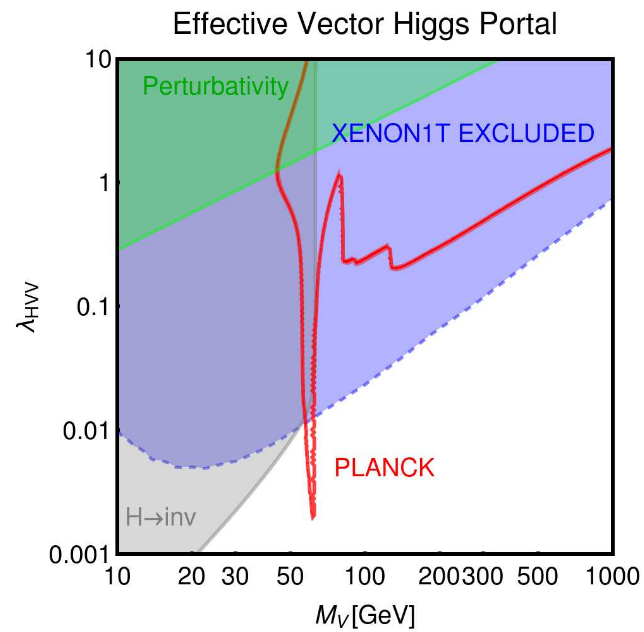
$\Delta\mathcal{L}_\chi = -\frac{1}{2}M_\chi\bar\chi\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\bar\chi\chi$ $\Rightarrow$ **non renor.** $\Lambda \gtrsim$ **a few TeV;**

$\Delta\mathcal{L}_v = \frac{1}{2}M_v^2 v_\mu v^\mu + \frac{1}{4}\lambda_{Hvv}\Phi^\dagger\Phi v_\mu v^\mu$ $\Rightarrow$ **severe pbs with unitarity.**

Consider processes like $vv \to H \to vv$**,**
in order to maintain unitarity, needs:

$$M_v \geq \lambda_{Hvv} v/\sqrt{16\pi}$$

$\Rightarrow$ **low** M_v **for large** λ_{Hvv} **forbidden.**
Needs a more realistic (UV?) theory:
- **introduces light degrees of freedom**
- **affects significantly DM phenomenology**
- **spoils collider/DD complementarity!**



Vector DM case removed from recent ATLAS+CMS H_{inv} **analyses.**

Can we circumvent problem? Vector DM UV-complete U(1) theory.

Case of vector DM: the $U(1)_X$ option

Simplest UV scenario, introduce new singlet S which mixes with Φ:

$$V_{\Phi,S} = \frac{\lambda_H}{4}\Phi^4 + \frac{\lambda_{HS}}{4}\Phi^2 S^2 + \frac{\lambda_S}{4} S^4 + \frac{1}{2}\mu_H^2 \Phi^2 + \frac{1}{2}\mu_S^2 S^2$$

Both fields develops vevs: $v^2 \equiv \frac{2\lambda_{HS}\mu_S^2 - 4\lambda_S \mu_H^2}{4\lambda_H\lambda_S - \lambda_{HS}^2}, \quad \omega^2 \equiv \frac{2\lambda_{HS}\mu_H^2 - 4\lambda_H\mu_S^2}{4\lambda_H\lambda_S - \lambda_{HS}^2}$

There are two Higgs states H_1, H_2 with mixing θ and masses:

$$M^2_{H_1,H_2} = \lambda_H v^2 + \lambda_S \omega^2 \mp (\lambda_S\omega^2 - \lambda_H v^2)/\cos 2\theta$$

Interactions of Higgs, with fermions/bosons and self-interactions:

$$L_S^{SM} = (H_1 c_\theta + H_2 s_\theta)\left(2M_W^2 W_\mu^+ W^{-\mu} + M_Z^2 Z_\mu Z^\mu - m_f \bar{f} f\right)/v$$

$$L_S^{tril} = -(\kappa_{111}H_1^3 + \kappa_{112}H_1^2 H_2 s_\theta + \kappa_{221}H_1 H_2^2 \cos_\theta + \kappa_{222}H_2^3)v/2$$

DM introduced as dark gauge boson of $U(1)_X$ broken by field S:

$$L_X = -\frac{1}{4}v_{\mu\nu}v^{\mu\nu} + (D^\mu S)^\dagger (D_\mu S) - V(H,S)\,, D_\mu = \partial_\mu + i\tilde{g}v_\mu$$

$$\frac{1}{2}\tilde{g}M_v\,(H_2 c_\theta - H_1 s_\theta)\,v_\mu v^\mu + \frac{1}{8}\tilde{g}^2\,(H_1^2 s_\theta^2 - 2H_1H_2 s_\theta c_\theta + H_2^2 c_\theta^2)\,v_\mu v^\mu \ldots$$

$M_v = \frac{1}{2}\tilde{g}\omega$; the free parameters are: $[M_V, \tilde{g}, \sin\theta, M_{H_2}]$; $H_1 \equiv H$.

Case of vector DM: the U(1)$_X$ option

Phenomenology of DM vector boson in EFT and U(1)$_X$ scenario.

Idea in mind: can EFT be good limit of UV model and when/where?

Invisible Higgs decays@LHC:

$$\Gamma_{\rm inv}|_{\rm EFT} = \frac{\lambda^2_{\rm HVV} v^2 M_H^3}{128\pi M_V^4}\beta_{\rm VH}$$

$$\Gamma_{\rm inv}|_{\rm U(1)} = \frac{\tilde{g}^2 \sin^2\theta}{32\pi}\frac{M^3_{H_1}}{M_V^2}\beta_{\rm VH_1}$$

Solving above, express SI cross section $\sigma^{\rm SI}_{\rm Vp}$ in terms of BR$(\rm H \to inv)$

$$\sigma^{\rm SI}_{\rm Vp}|_{\rm EFT} = 8\mu^2_{\rm Vp}\frac{M_V^2}{M_H^3}\frac{{\rm BR(H\to VV)}\Gamma^{\rm tot}_{\rm H}}{\beta_{\rm VH}}\frac{1}{M_H^4}\frac{m_p^2}{v^2}|f_p|^2$$

$$\sigma^{\rm SI}_{\rm Vp}|_{\rm U(1)} = 8\cos^2\theta\mu^2_{\rm Vp}\frac{M_V^2}{M^3_{H_1}}\frac{{\rm BR(H_1\to VV)}\Gamma^{\rm tot}_{\rm H_1}}{\beta_{\rm VH_1}}\left(\frac{1}{M^2_{H_2}}-\frac{1}{M^2_{H_1}}\right)^2\frac{m_p^2}{v^2}|f_p|^2$$

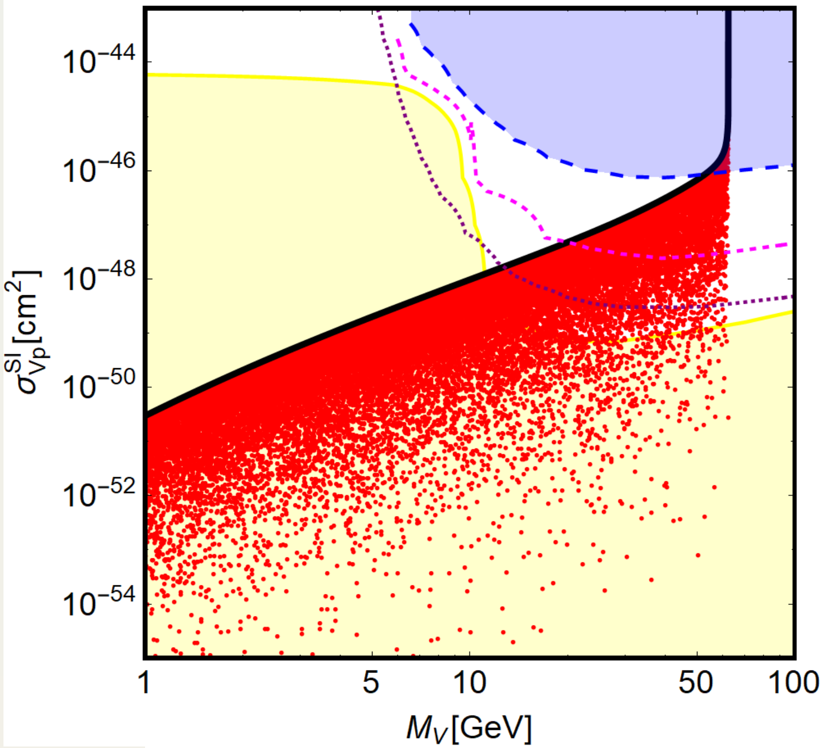
So, when does EFT give the same results as the complete model?

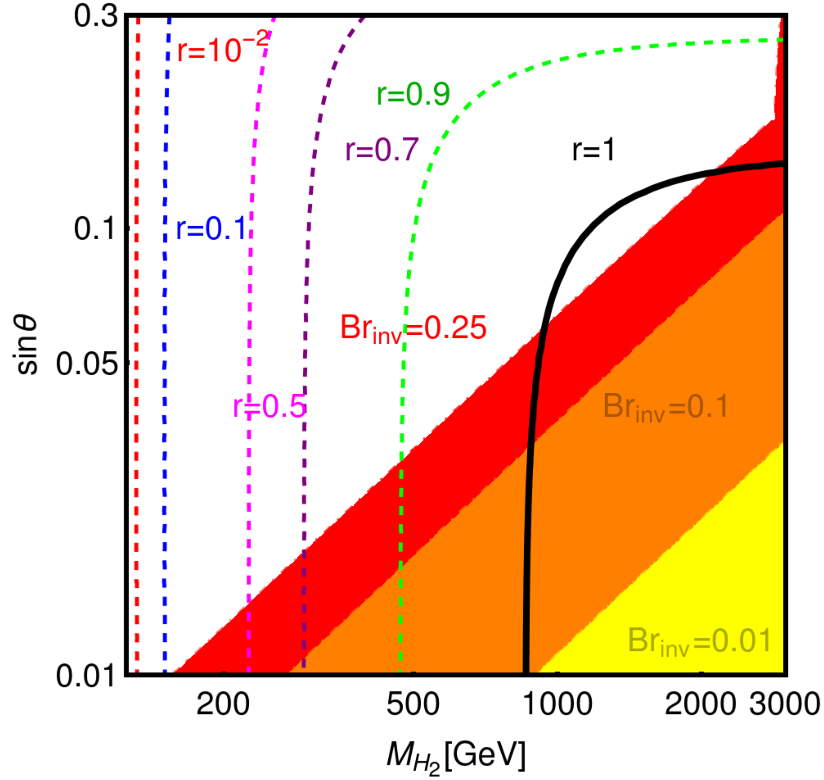
$$\cos^2\theta\, M_H^4\left(1/M^2_{H_2}-1/M^2_{H_1}\right)^2 \approx 1.$$

To see where/when it happens, full scan in U(1) parameter space:

$$\sin\theta \in [10^{-3}, 0.3]\,,\ M_V \in [10^{-2}, 62.5]\ {\rm GeV},\ M_{H_2} \in [125, 1000]\ {\rm GeV}.$$

Case of vector DM: the $U(1)_X$ option





$\mathbf{BR(H \to inv) = 0.25}$ **$\mathbf{BR_{inv}}$ and r fixed**

Arcadi, AD, Kado

EFT can be recovered as a limit, even when unitarity is enforced if:

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

$$\lambda_S \leq 4\pi/3 \Longrightarrow \mathrm{BR(H_1 \to VV)} \lesssim 0.35(\sin\theta/0.1)^2(3\,\mathrm{TeV}/\mathrm{M_{H_2}})^2$$

Discussion and Conclusions

EFT is indeed a good limit of an UV–complete theory for vector DM,
'light' degrees of freedom do not spoil LHC and DD complementarity.
This has been proven inthe simplest possible U(1) model of vector DM:
$\Rightarrow$ analyses of vector DM at the LHC are possible and should be back;
$\Rightarrow$ re-implementation discussed by LHC–DM WG and is on the way.

However, requirement that vector DM gives good Ωh^2 not enforced!
We tried in U(1) and failed: works only if $M_V \approx \frac{1}{2} M_H$. Possible cures:
– give up thermal DM paradigm and invoke modified cosmology;
– look at more complicated/enlarged DM sectors and scenarios.
We tried the more involved cases of $SU(2)_X$ and $SU(3)_X$ DM models
and yes, EFT with good relic can be recovered under some conditions.

Arcadi, AD, Kado (in preparation)

In fact, discussion can be generalized to fermionic and scalar cases.
It is under way; I hope to have the chance to tell you about it soon....

Muchas Gracias!