Minimal decaying Dark Matter and the LHC

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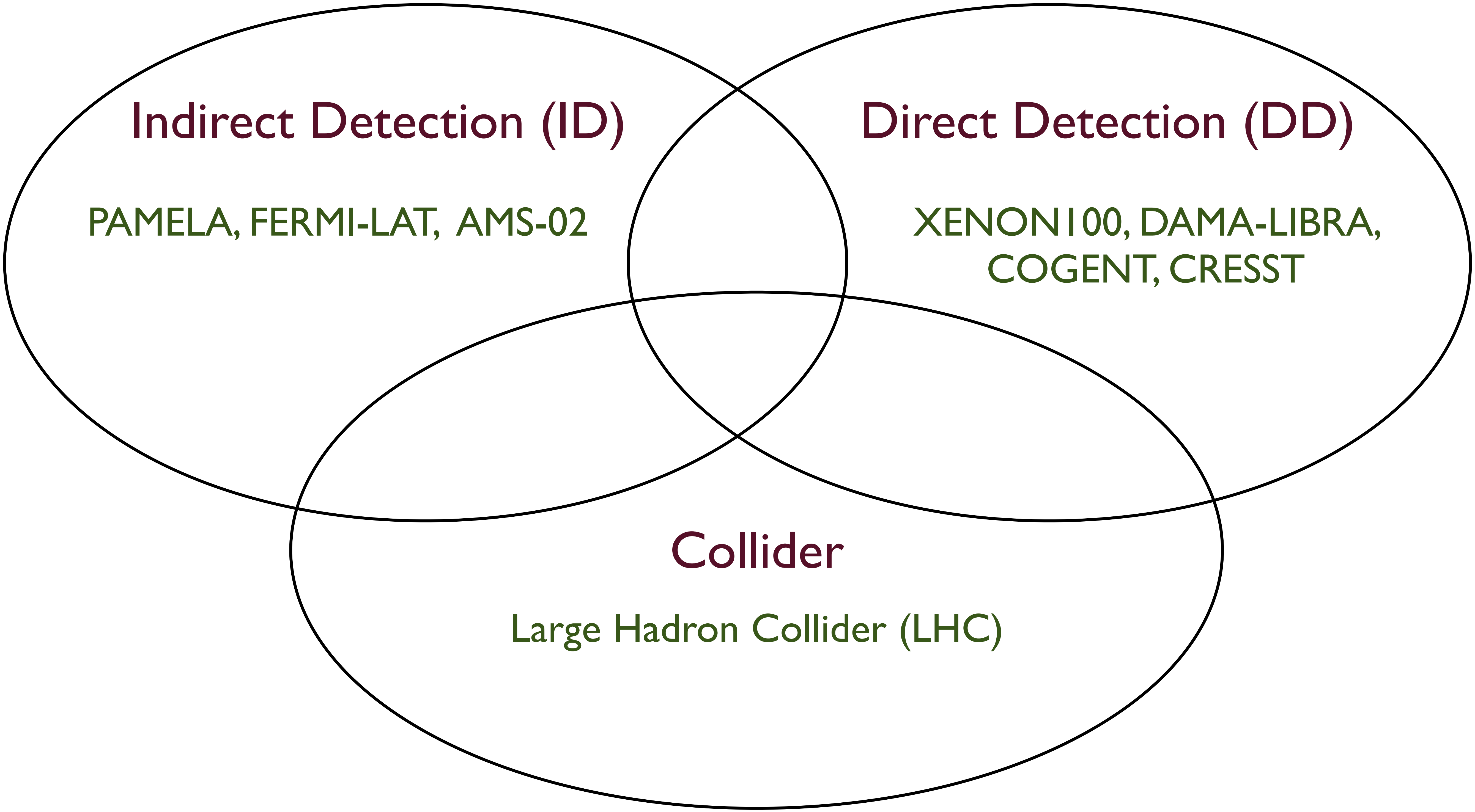
based on G.Arcadi and L. Covi, JCAP 1308 (2013) 005
arXiv: 1305.6587

$[q,p]=i\hbar$

invisibles
neutrinos, dark matter & dark energy physics

DM searches

Three (possibly) complementary search strategies



Outline of the talk

Correlation of ID and collider DM detection for decaying Dark Matter:

- Case of study: SM + DM Majorana Fermion+Scalar field (partially) charged under SM group.

Similar setup proposed in Garny et al. 1011.3786, 1112.5155, 1205.6783, 1207.1431

- Identification of cosmological viable regions.

- Investigation of regions of parameter space accessible to contemporary ID and collider detection.

Definition of the model

Minimal model: SM+Maiorana fermion+scalar field

$$L_{\text{eff}} = \lambda_{\psi f L} \bar{\psi} f_L \Sigma_f^\dagger + \lambda_{\psi f R} \bar{\psi} f_R \Sigma_f^\dagger + h.c.$$

Additional interactions of the scalar field:

$$L_{\text{eff}} = \lambda'_{qL} \bar{l}^c_R q_L \Sigma_d^\dagger + \lambda''_{qR} \bar{u}_R d^c_L \Sigma_d^\dagger + h.c.$$

$$L_{\text{eff}} = \lambda''_{qR} \bar{d}_R d^c_L \Sigma_u^\dagger + h.c.$$

$$L_{\text{eff}} = \lambda' \bar{d}_R l_L \Sigma_q + h.c.$$

Hadronic realizations

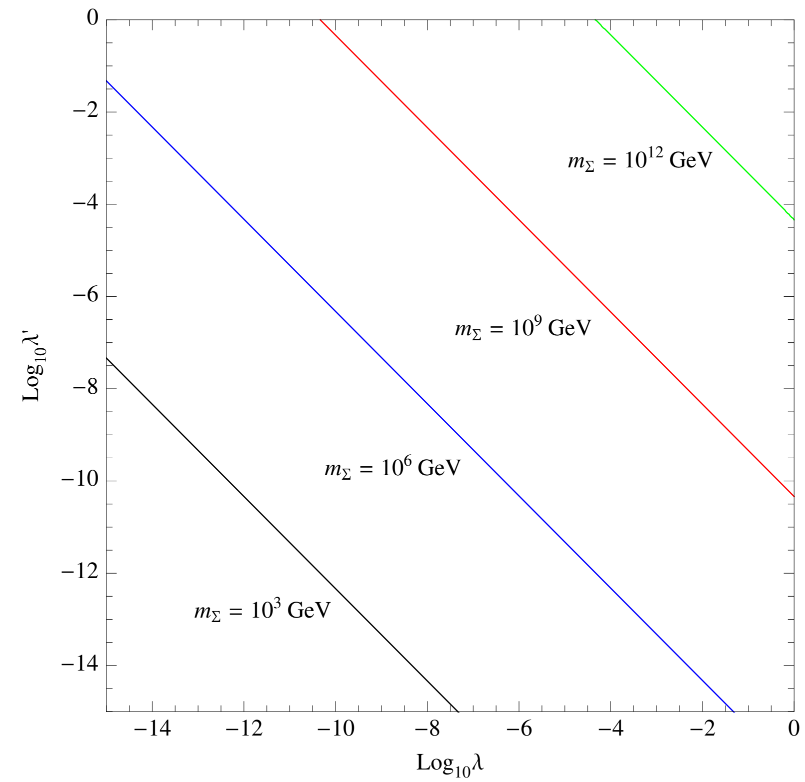
$$L_{\text{eff}} = \lambda_{lL} \bar{\nu}^c_L l_L \Sigma_e^\dagger + h.c.$$

$$L_{\text{eff}} = \lambda_l \bar{e}_R l_L \Sigma_l + \lambda'_l \bar{d}_R q_L \Sigma_l + h.c.$$

Leptonic realizations

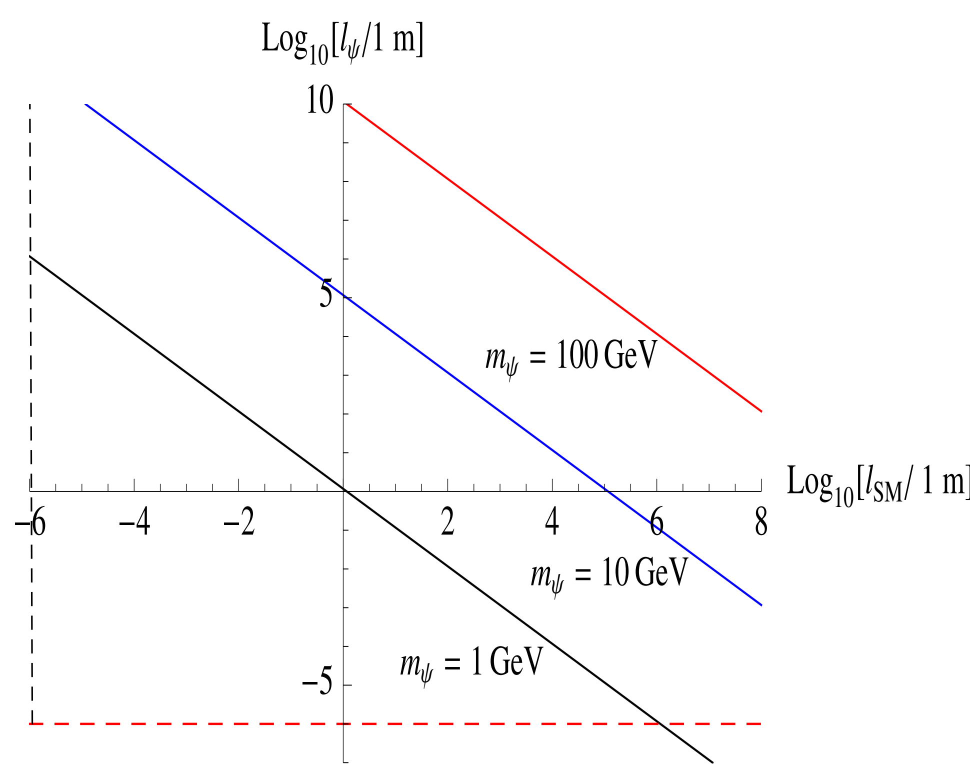
Correlation between collider and ID

$$\Gamma_{\rm DM} = \frac{\lambda^2_{\psi f}\lambda'^{\,2}}{128(2\pi)^3}\frac{m_\psi^5}{m^4_{\Sigma_f}}$$



DM lifetime related to scalar field decay lenght.

$$l_{\Sigma,DM} \simeq 1.17\,\mathrm{m}\left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-6}\left(\frac{m_\psi}{1\mathrm{GeV}}\right)^{5}\left(\frac{l_{\Sigma,SM}}{1\mathrm{m}}\right)^{-1}\left(\frac{\tau_\psi}{10^{27}\mathrm{s}}\right)$$



Possible scenario of detection of both decay channels together with ID of DM decay.

Study within a four parameter model: DM and scalar masses and couplings λ and λ'.

Our strategy

Identification of the regions accounting for the correct DM relic density. ⟷ Requirement of observable decay of DM, i.e. lifetime close to a reference sensitivity.

↘ ↙

Information of the coupling of DM with fermions.

Requirement of LHC production of the scalar field (compatibly with current limits). ⟶ Determination of decay lenght and possible distinctive signatures.

Distinctive collider signature of our framework is the detection of two kinds of decay channels of the scalar, i.e. SM+DM and SM only.

Cosmology

We distinguish two opposite scenarios:

$$\lambda \lesssim 10^{-7}$$

DM never in thermal equilibrium in the Early Universe.

Production through freeze-in or non thermal (SuperWimp)

Less explored scenario, possible peculiar signatures.

$$1 \lesssim \lambda \leq 4\pi$$

DM in thermal equilibrium in the Early Universe.

Production through Freeze-out mechanism.

Well known scenario, already strongly constrained in case of hadronic realizations.

DM relic density

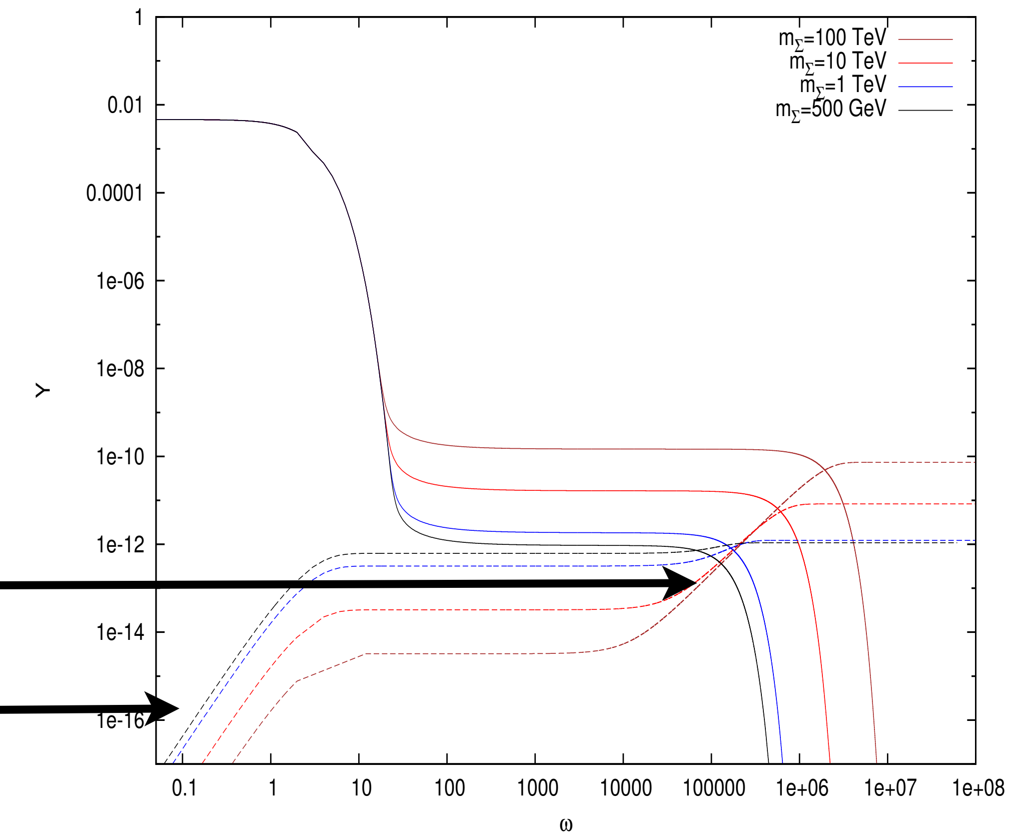
Two mechanisms for DM generation:

- Freeze-in: DM produced by scalar decay still in equilibrium.
Relic density depends on decay rate into dark matter.

- SuperWimp: DM produced by decay of scalar after its chemical decoupling.
Relic density depends on scalar field abundance and branching ratio of decay into DM.

SuperWimp contribution

Freeze-in contribution



The two mechanisms act on two different time scales. Relic density analytically computable as sum of two contributions.

Freeze-in

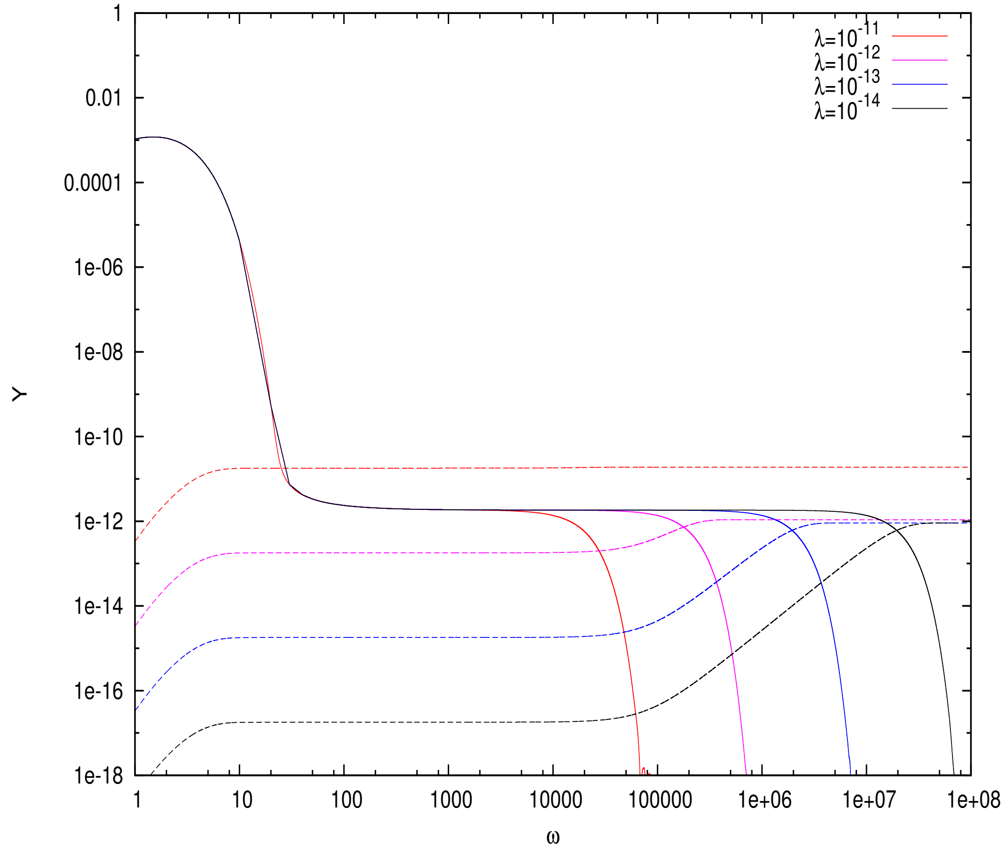
$$\Omega^{FI} h^2 = \frac{1.09 \times 10^{27} g_\Sigma}{g_*^{3/2}} \frac{m_\psi \Gamma(\Sigma_f \to \psi f)}{m^2_{\Sigma_f}}$$

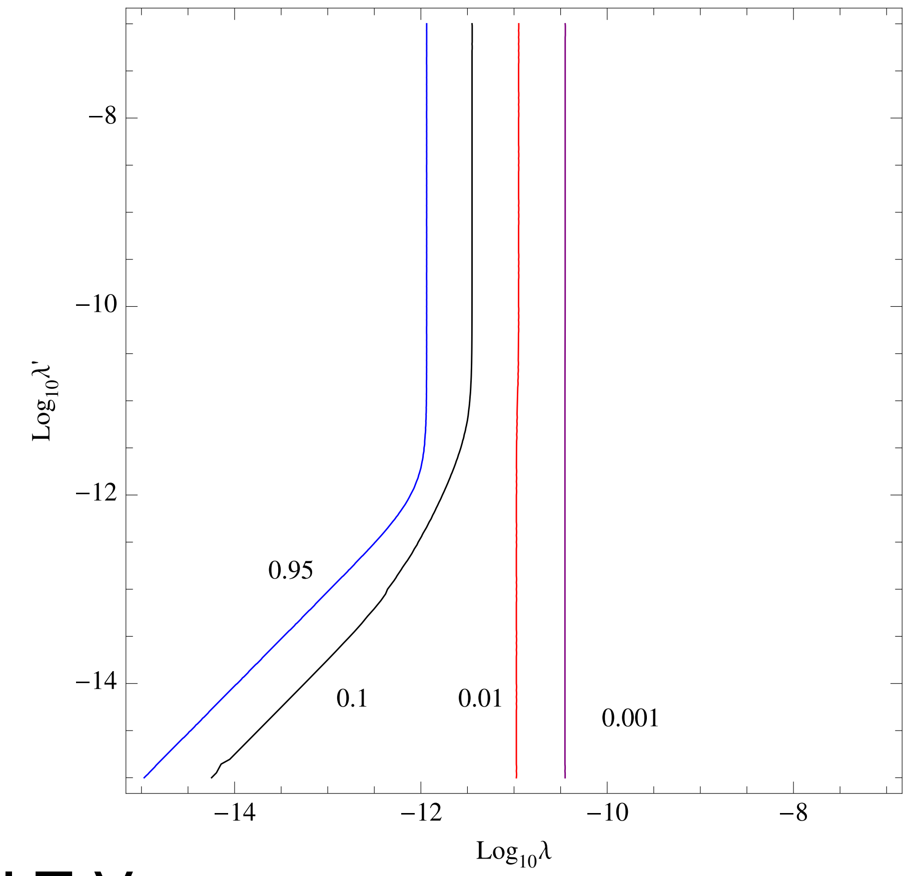
Hall et al. 0911.1120

SuperWimp

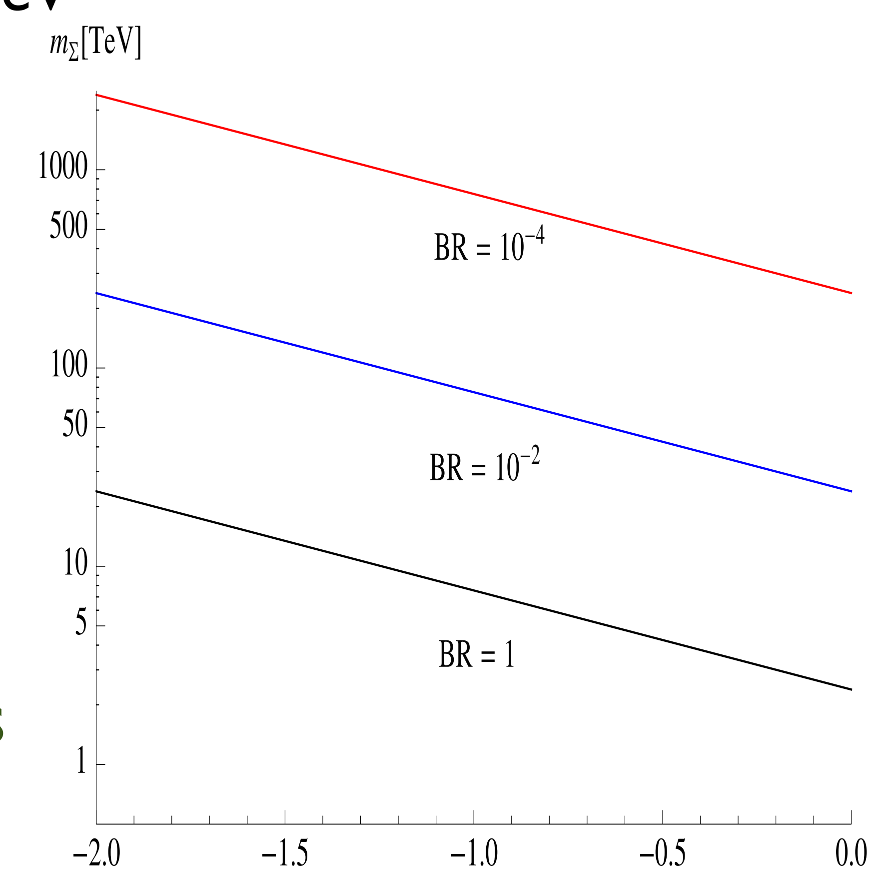
$$\Omega_\psi^{SW} h^2 = x\, Br(\Sigma_f \to \psi + SM) \Omega_\Sigma h^2$$

$$x = m_\psi / m_{\Sigma_f}$$





Mass of the scalar fixed at 1 TeV

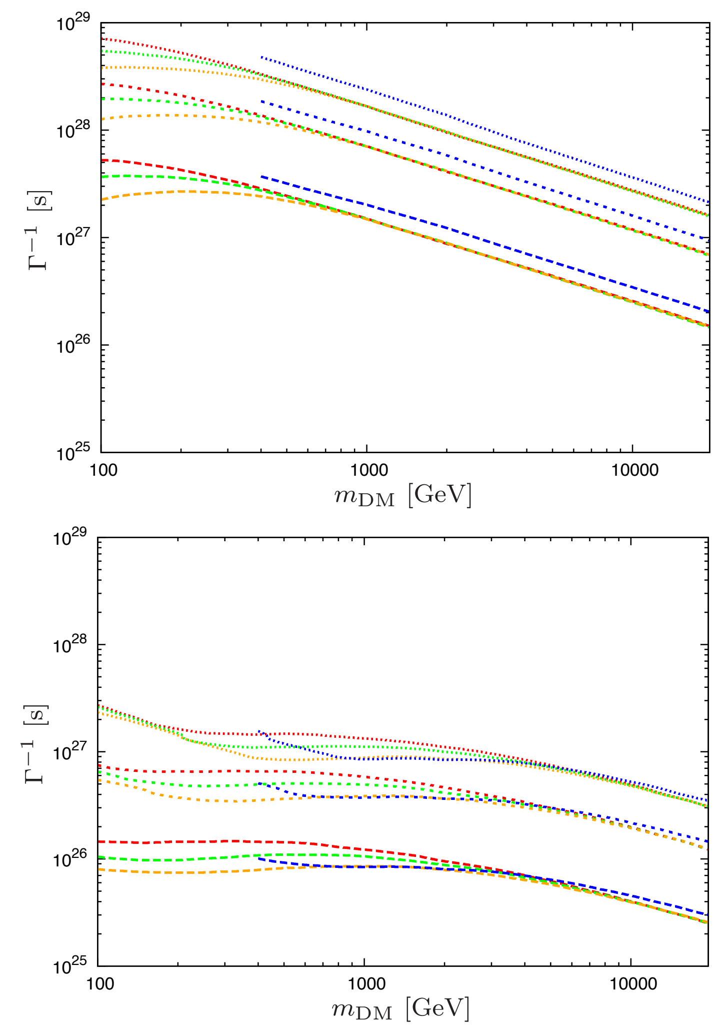


Scalar field features ordinary gauge interactions. Its relic density at chemical decoupling is typically very low.

SuperWimp mechanism can be relevant at high values of the mass of the scalar. This requirement is less stringent in case of only weak interactions.

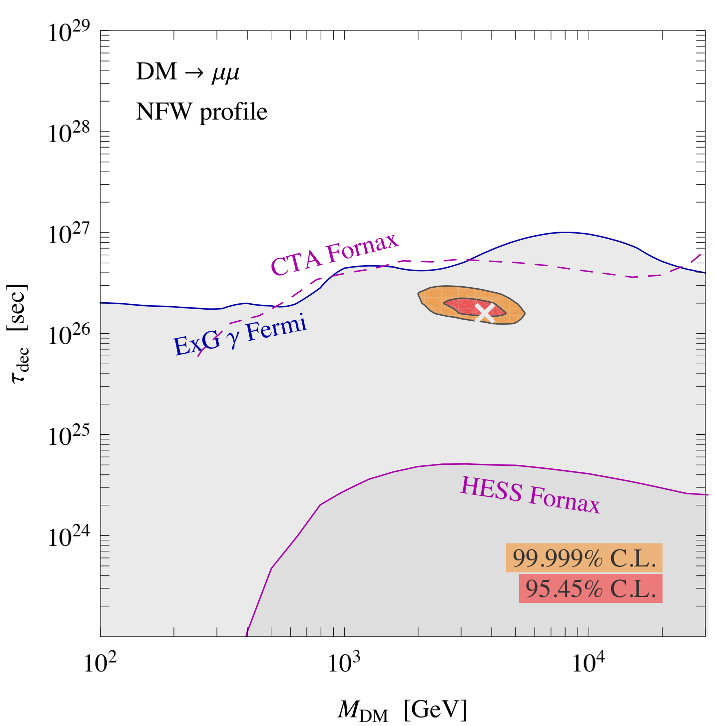
ID constraints

The DM decays at three level into three fermions.



Limits on decays into quark pair plus neutrino

Garny et al. 1205.6783



Cirelli et al. 1205.5283

Hadronic realizations are constrained by antiprotons

Strongest limits on decay into leptons come from gamma-rays

LHC prospects

In our framework collider phenomenology relies on production and decay of the scalar field.

Prediction of the decay lenght of the scalar field within the four parameter model compatible with cosmological and ID constraints.

Possible scenarios:

- Prompt decay

Case 1: Domination of coupling with DM

⟶ Dijet (Dileptons) events +Missing energy. Masses of the scalar excluded up to 800 (300) GeV

Case 2: Domination of coupling with only SM states. Lower amounts of missing energy. Limits from Leptoquark searches of 600-800 GeV. Some realizations weakly constrained.

- Displaced vertex

Very few searches employed. Yet unexplored scenario. Amount of missing energy again determined by the dominant coupling.
(see e.g. ATLAS-CONF-2013-092)

- Detector stable particle

Limits from detection of charged tracks of 300-400 GeV for only EW interacting particles, of above 1 TeV for color interacting particles. Alternative detection strategies under investigation.
(see e.g. ATLAS-CONF-2013-069; JHEP07(2013)122)

Definite example: hadronic models

ID and relic density constraints identify the ranges of the couplings as function of the masses.

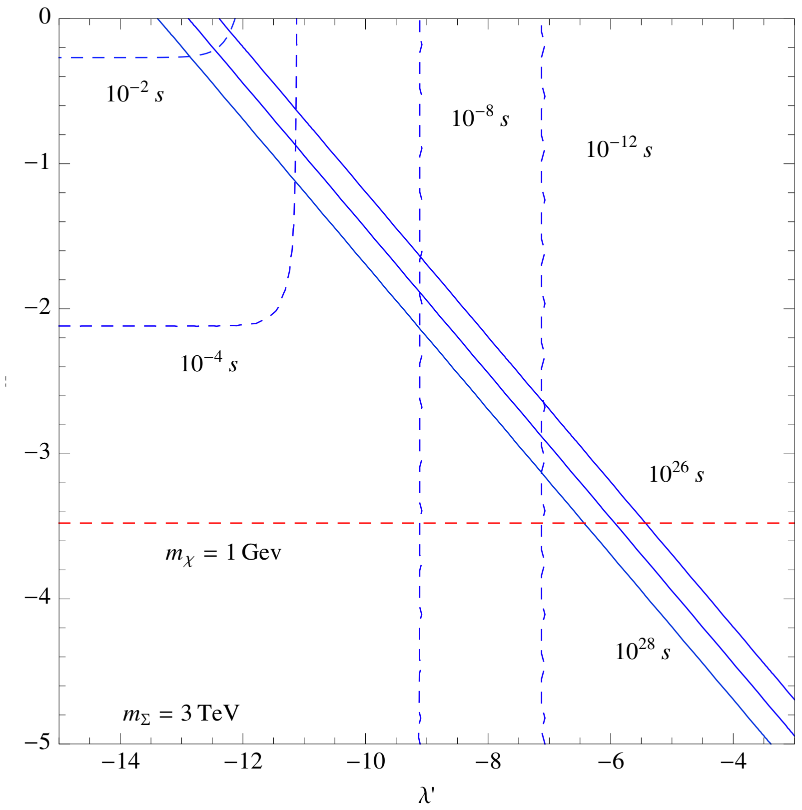
$\longrightarrow$ We can get a prediction of the collider decay lenght of the scalar field.

Hadronic models are dominated by the FIMP mechanism, a rather precise determination of the coupling is achieved.

$$\lambda \simeq 1.59 \times 10^{-12} \left(\frac{1}{x}\right)^{1/2} \left(\frac{g_*}{100}\right)^{3/2} g_\Sigma^{-1/2}$$

$$\lambda' \simeq 9.1 \times 10^{-13} x^{-2} \left(\frac{g_*}{100}\right)^{-3/4} \left(\frac{m_{\Sigma_{q,u,d}}}{1\text{TeV}}\right)^{-1/2} g_\Sigma^{1/2} \left(\frac{\tau_\psi}{10^{27}\text{s}}\right)^{-1/2}$$

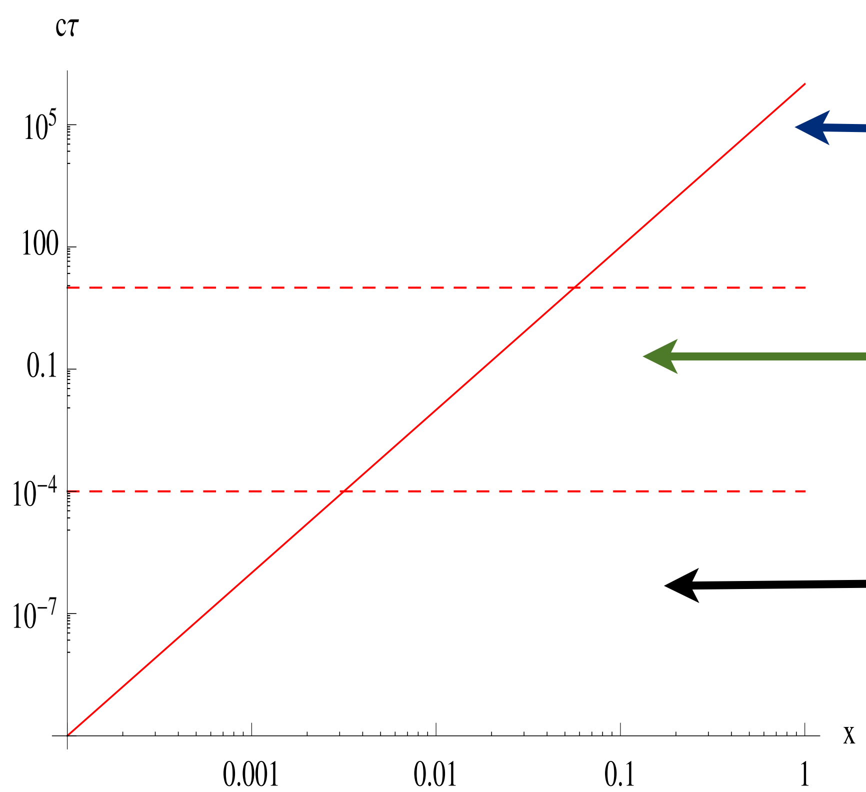
$$l_{\Sigma,SM} \simeq 55\,\text{m} \frac{1}{g_\Sigma} \left(\frac{m_{\Sigma_f}}{1\text{TeV}}\right)^{-4} \left(\frac{m_\psi}{10\text{GeV}}\right)^{4} \left(\frac{\tau_\psi}{10^{27}\text{s}}\right) \left(\frac{\Omega_{CDM}h^2}{0.11}\right)$$



DM lifetime. λ fixed by relic density

$$\frac{l_{\Sigma,DM}}{l_{\Sigma,SM}} \equiv \frac{BR(\Sigma_f \to SM)}{BR(\Sigma_f \to \psi f)} \simeq 38\, g_\Sigma^2 \left(\frac{x}{0.01}\right)^{-3} \left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-1} \left(\frac{\tau_\psi}{10^{27}\mathrm{s}}\right)^{-1} \left(\frac{\Omega_{CDM} h^2}{0.11}\right)^{-2} \left(\frac{g_*}{100}\right)^{-3}$$

Scalar field preferably decaying into SM only.



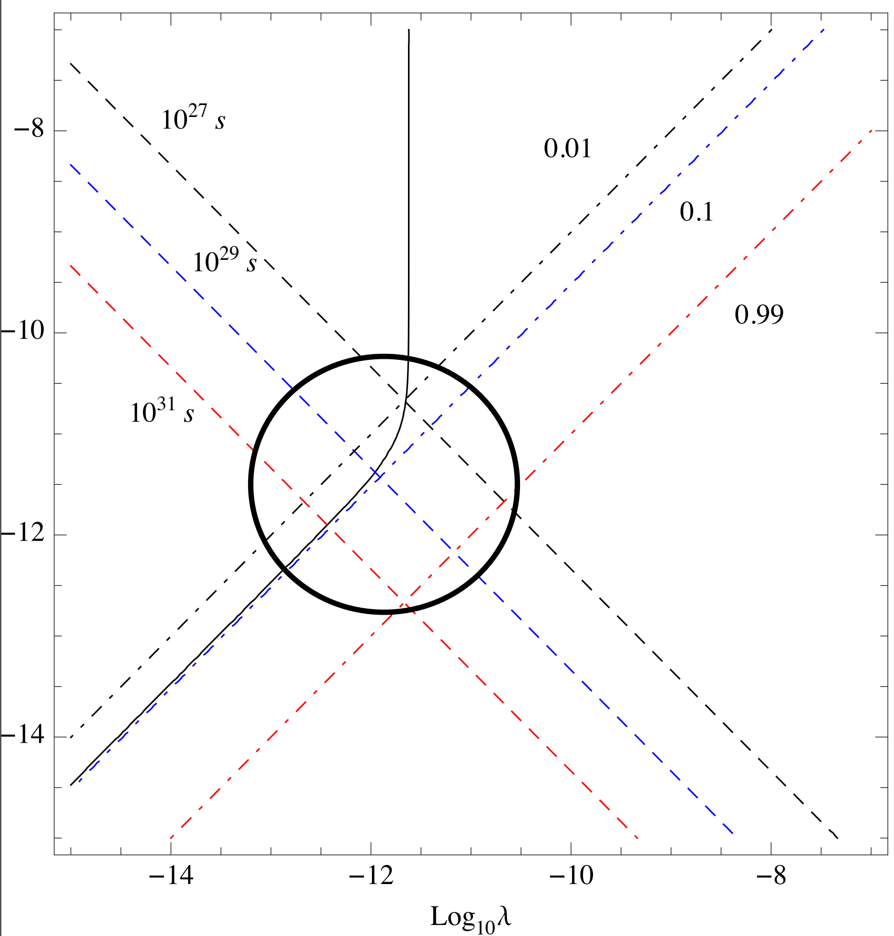
Detector stable particle

Displaced vertex

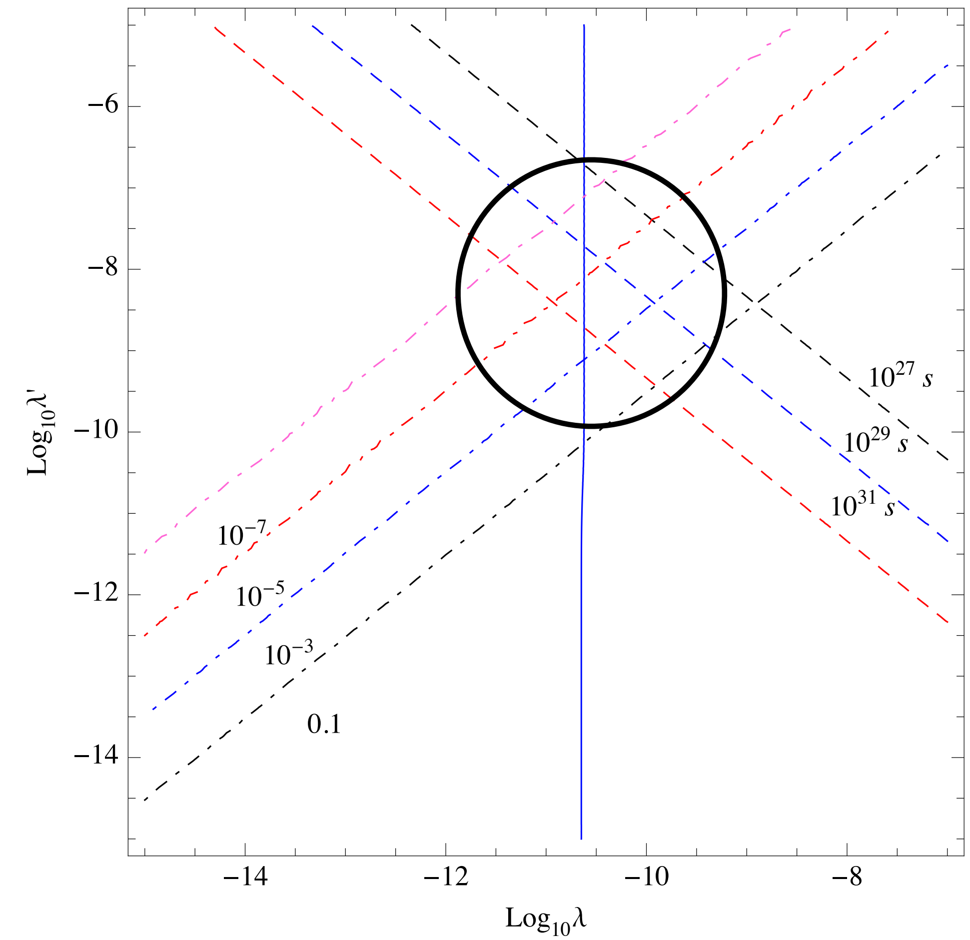
Prompt decays

Leptonic models

SuperWimp mechanism can be realized in leptonic models because of the lower annihilation rate of the scalar field.



$$BR(\Sigma_f \to \psi + SM)$$



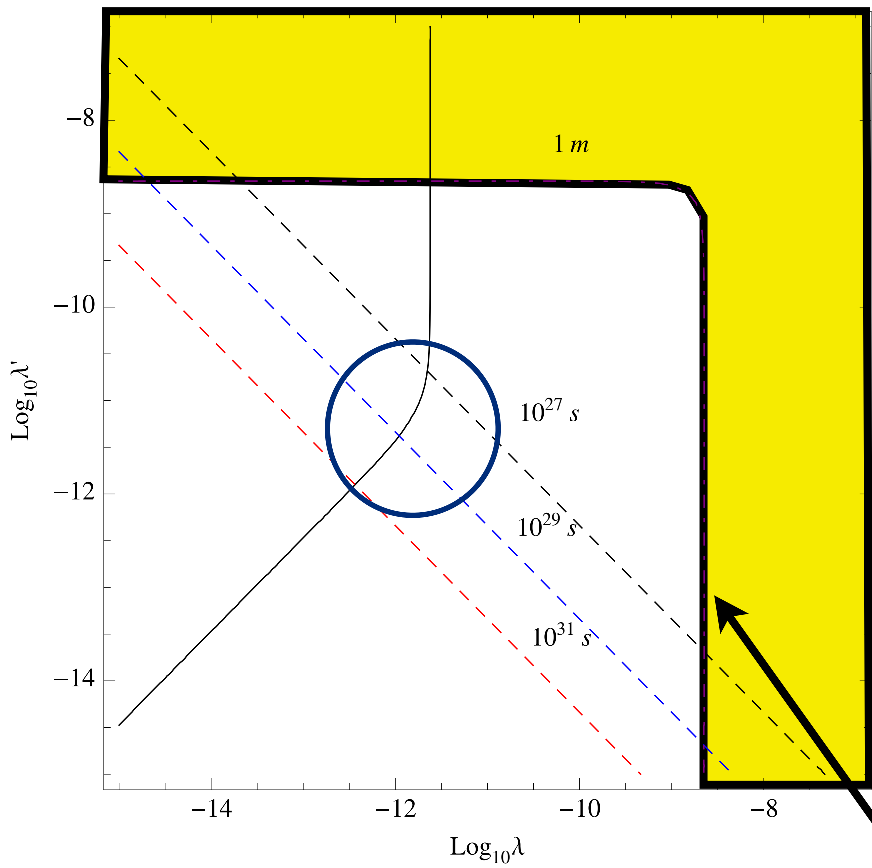
x=0.1

x=0.001

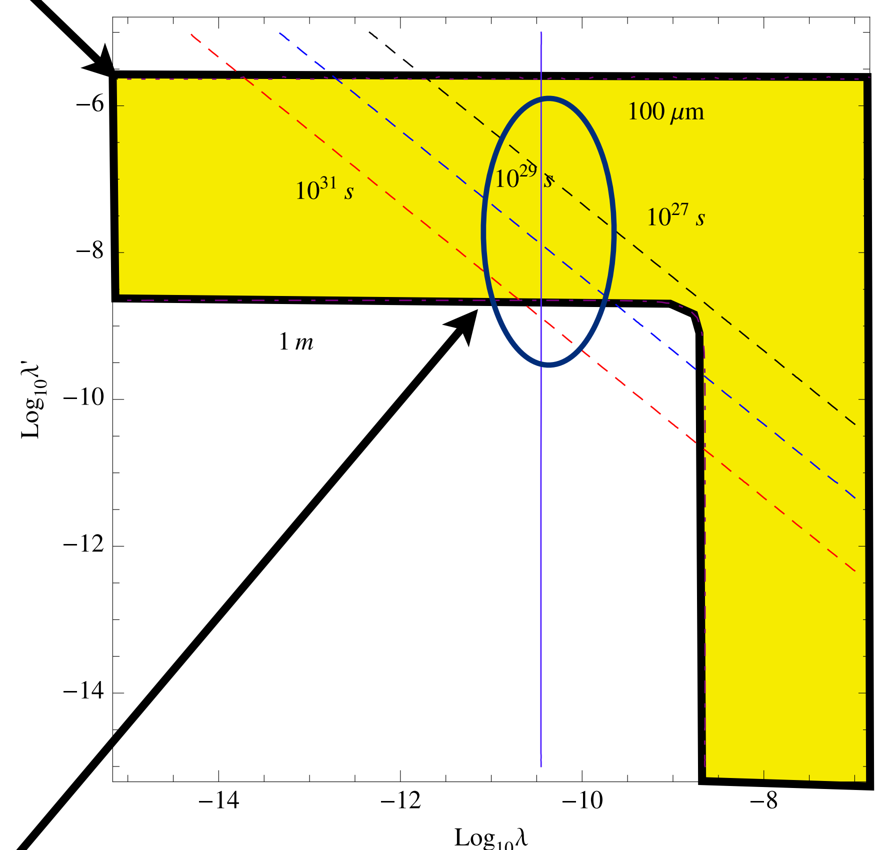
It occurs for moderate hierarchy between the DM and the scalar field and for comparable values of the coupling.

LHC detection of leptonic models

Displaced vertex



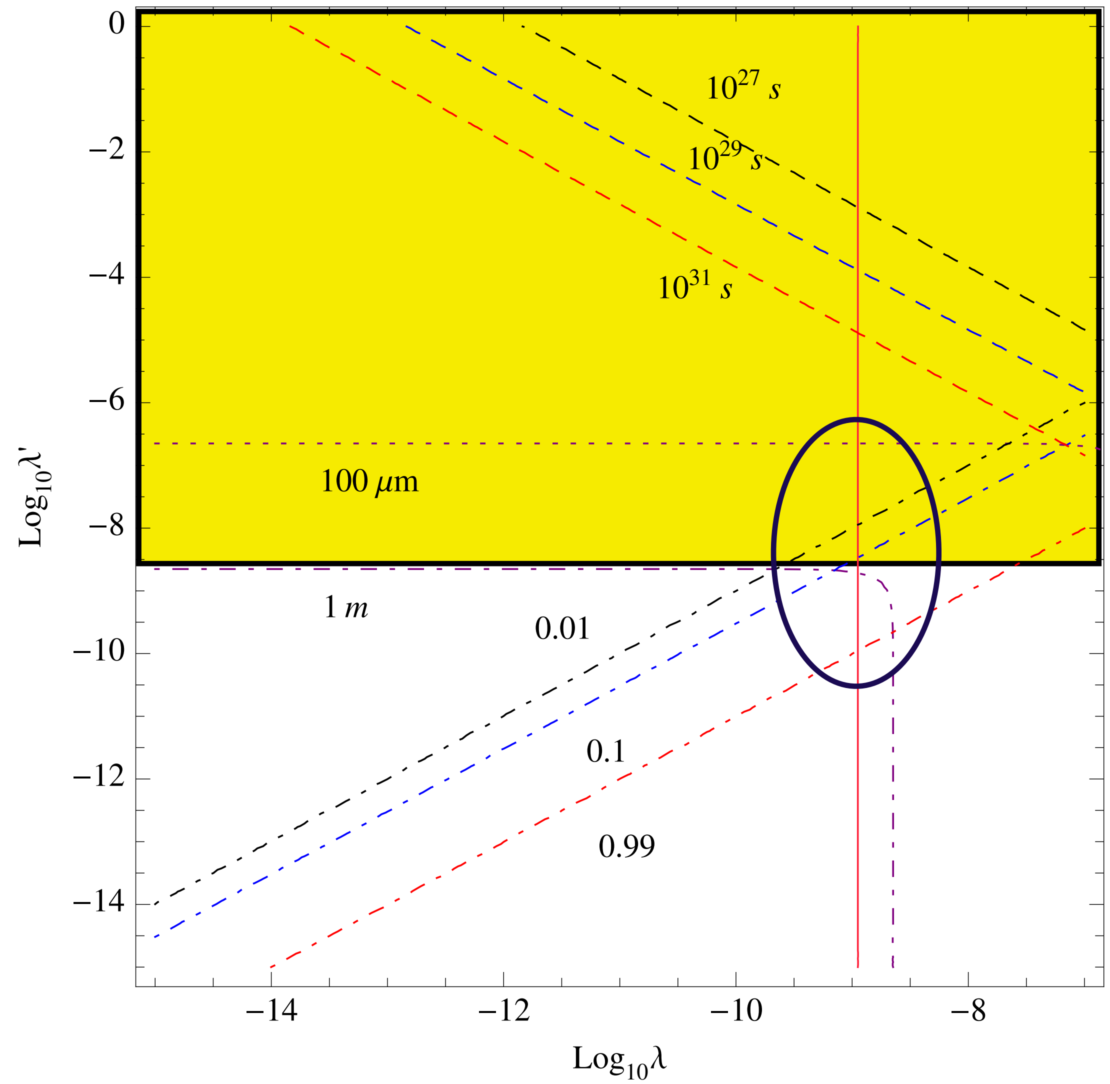
$x = 0.1$



$x = 0.001$

Scalar field decay length

Combined detection of decay into DM and only SM fields is achievable at very low masses, i.e. lower than 1 MeV.



$$x = 10^{-6}$$

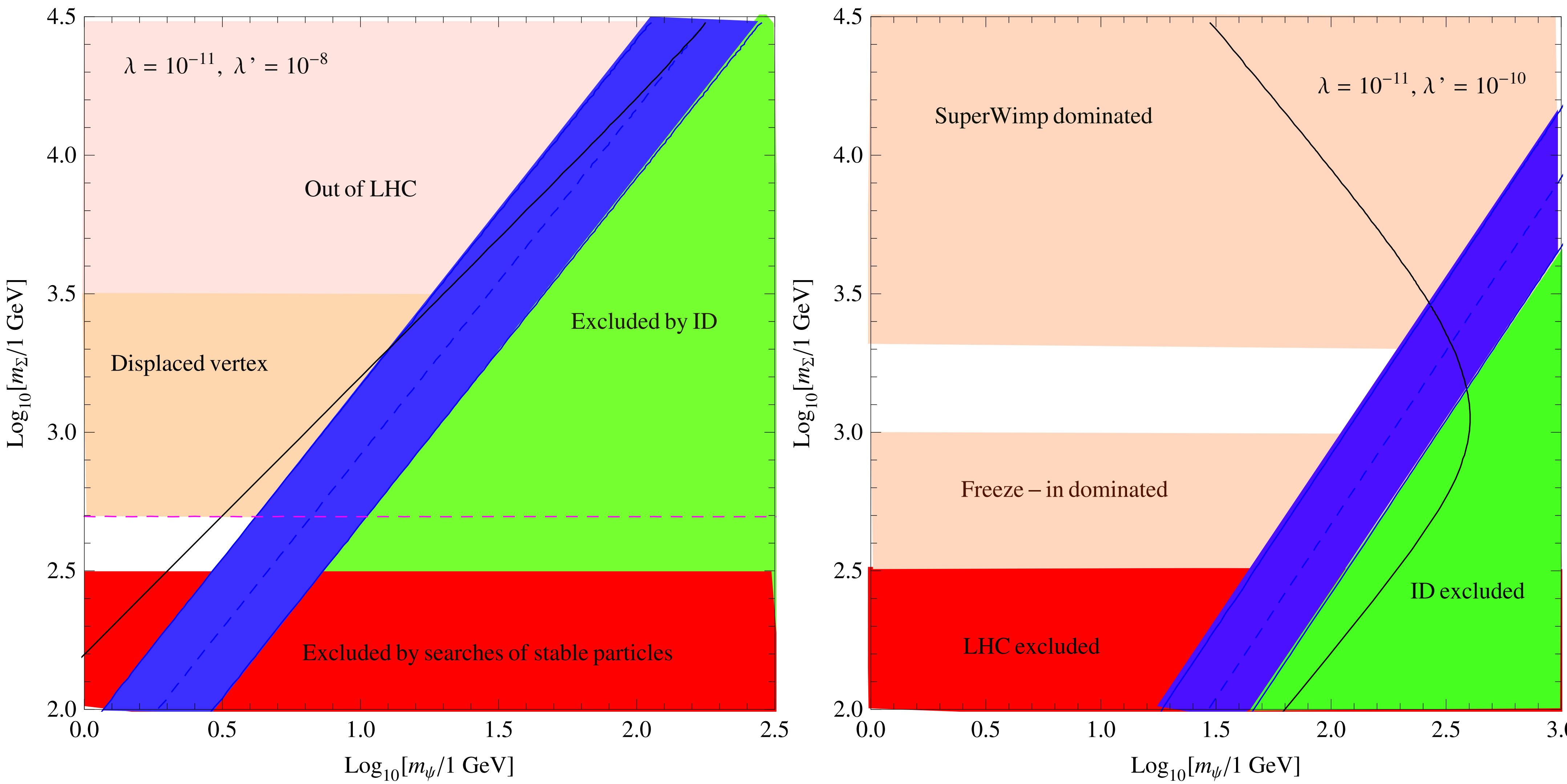
Loop induced decay into gamma and neutrino

But DM lifetime too high.

Summary of Fimp/SuperWimp scenario

In the Freeze-in/SuperWimp scenario the coupling between the scalar field and only SM particles dominates collider phenomenology over most of the parameter space.

Detection of DM decay is associated to observation of displaced vertices of detector stable particles.



Conclusions

We have explored the correlation among ID and collider detection in a simple scenario.

We have identified the regions accessible by contemporary ID and LHC detection.
Freeze-in/SuperWimp is promosing scenario not yet fully explored at the LHC.

Unlikely only one coupling seems accessible at collider compatibly with observable DM lifetime.
This statement requires however a detailed study of the detector response.

→ WORK IN PROGRESS ...