Dark Matter beyond (Simple) WIMPs

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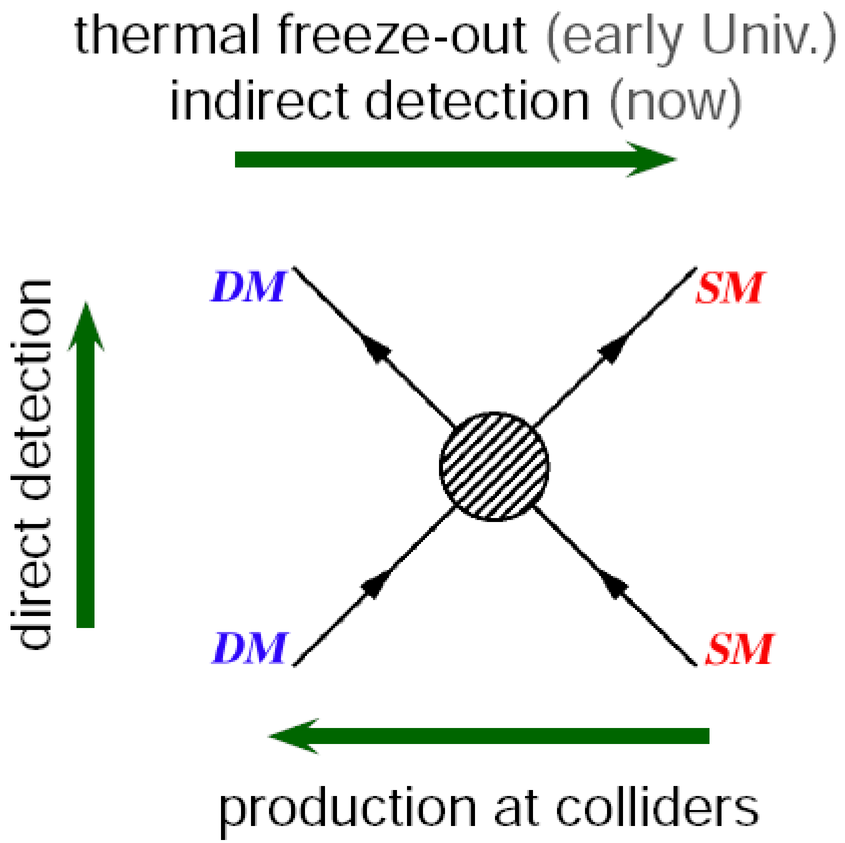
WIMP DM



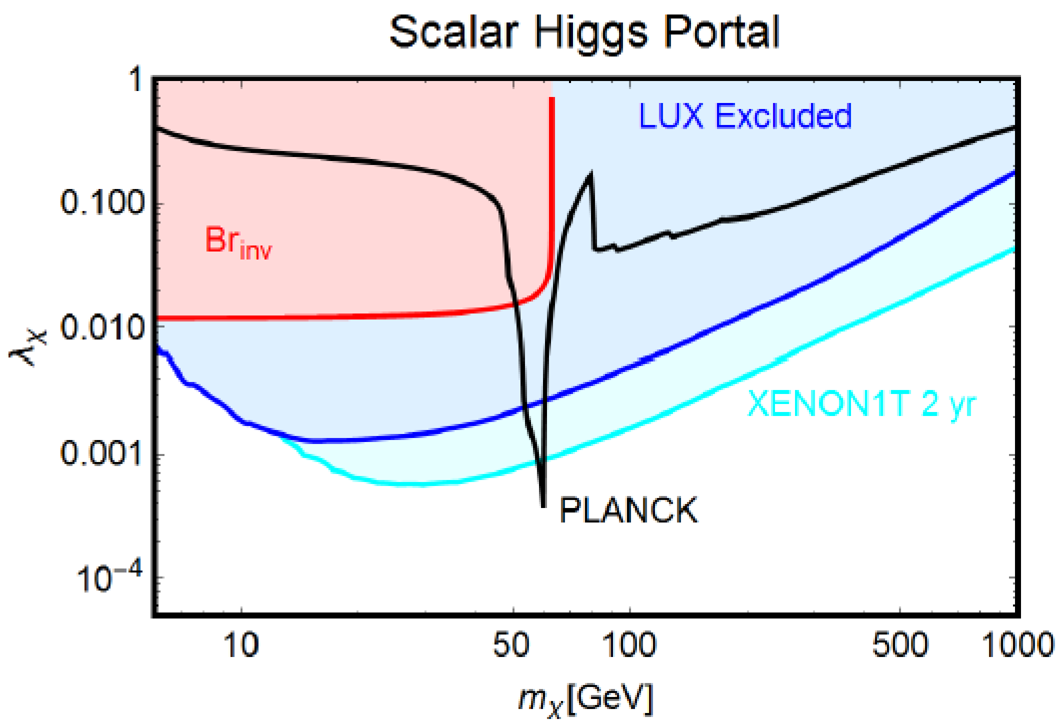
$$\Omega h^2 \simeq 0.12 \longrightarrow \langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

$$\downarrow$$

$$\langle \sigma v \rangle = f_1 \sigma_{\chi N}^{\mathrm{SI}} + f_2 \sigma_{\chi N}^{\mathrm{SD}}$$

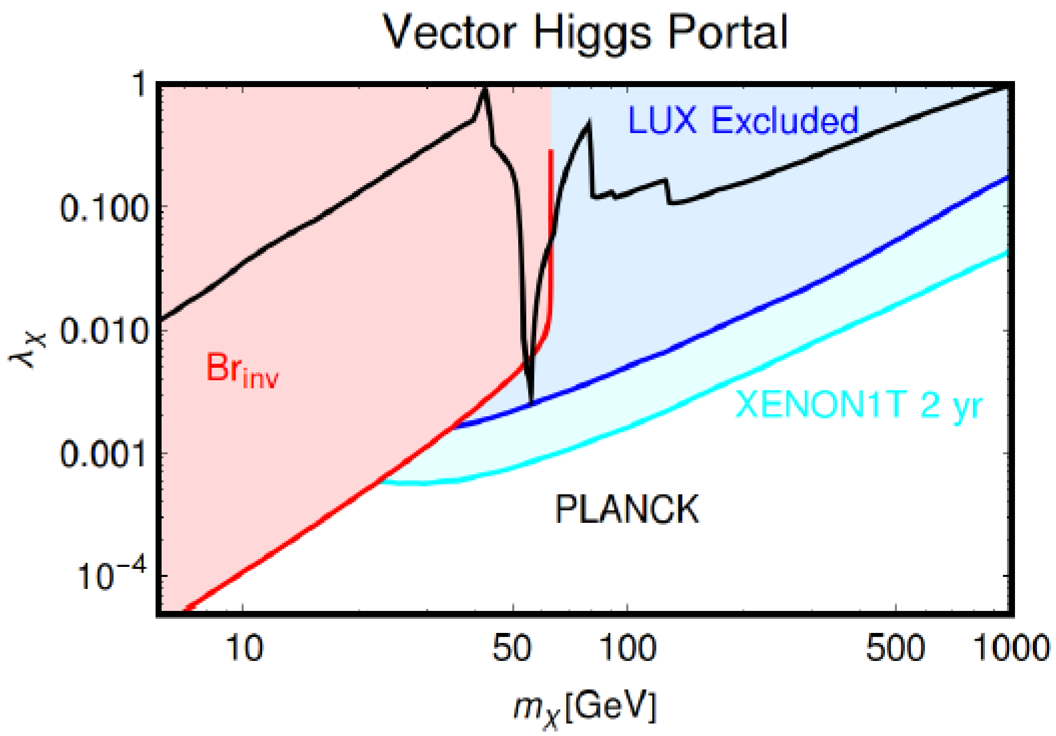
$$\downarrow$$

Too strong limits from Direct Detection would imply a too much suppressed annihilation cross-section and overabundant Dark Matter.



Simplest WIMP configurations are in increasing tensions with experimental constraints.

Many of them will be excluded by absence of signal at next generation detectors.



Motivation and summary

Possible way out:

- Consider setups with null/suppressed direct detection cross-section, e.g. pseudoscalar portal (Arina et al. 1406.5542) (not covered by this talk)

- Maybe we are considering too simple setups: break the strict relation between Direct Detection and annihilation cross-section: e.g. multicomponent DM
- Go beyond WIMPs

Multi-component DM

In single component dark portals the relic density depends, through inverse proportionality relation, only on pair annihilations into SM states.

In multi-component DM from hidden sector one have different possible processes:

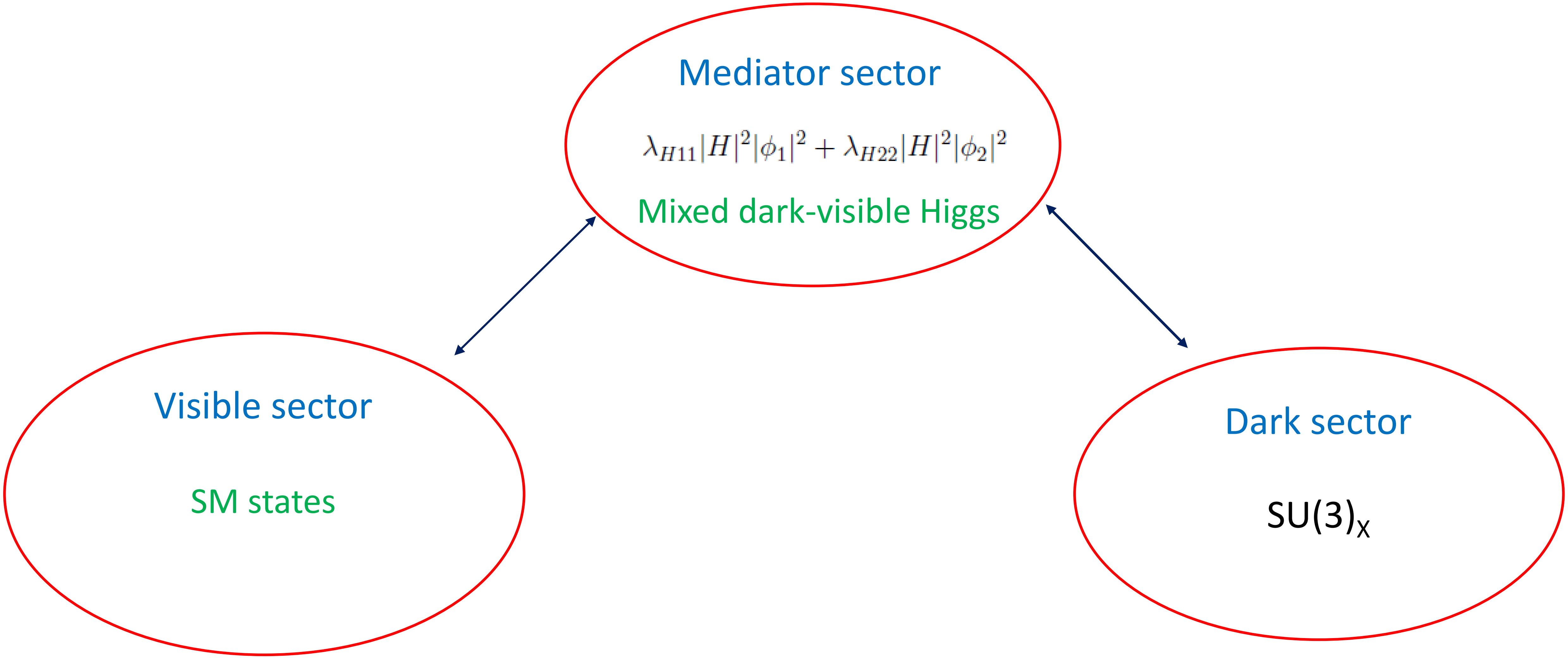
-pair annihilations of both components into SM states
-pair annihilations of the heavier DM component into the lightest one
-co-annihilations
-semi(co)-annihilations

Relation between relic density and DD is not trivial.

DD is a sum of different contributions weighted by different density fractions.

Explicit example:Hidden SU(3) model

C. Gross, O. Lebedev, Y. Mambrini, arXiv:1505.07480
G.A. , C. Gross, O. Lebedev, Y. Mambrini, S. Pokorski, T. Toma, arXiv:1611.00365



$$-\mathcal{L}_{\rm portal} = V_{\rm portal} = \lambda_{H11}\,|H|^2|\phi_1|^2 + \lambda_{H22}\,|H|^2|\phi_2|^2 - (\lambda_{H12}\,|H|^2\phi_1^\dagger\phi_2 + {\rm h.c.})$$

$$\mathcal{L}_{\rm hidden} = -\frac{1}{2}{\rm tr}\{G_{\mu\nu}G^{\mu\nu}\} + |D_\mu\phi_1|^2 + |D_\mu\phi_2|^2 - V_{\rm hidden}$$

$$G_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + i\tilde{g}[A_\mu, A_\nu] \qquad D_\mu\phi_i = \partial_\mu\phi_i + i\tilde{g}A_\mu\phi_i$$

$SU(3)_x \longrightarrow Z_2 x Z_2'$

The minimal way to break the dark gauge group is through two fields in the fundamental representation

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \\ v_1 + \varphi_1 \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 + \varphi_2 \\ (v_3 + \varphi_3) + i(\chi) \end{pmatrix}$$

gauge eigenstates	mass eigenstates	$\mathbb{Z}_2 \times \mathbb{Z}_2'$
h, φ_i, A_μ^7	$h_i, \tilde{h}_4, \tilde{A}_\mu^7$	$(+,+)$
A_μ^1, A_μ^4	A_μ^1, A_μ^4	$(-,-)$
A_μ^2, A_μ^5	A_μ^2, A_μ^5	$(-,+)$
$\chi, A_\mu^3, A_\mu^6, A_\mu^8$	$\tilde{\chi}, A_\mu'^3, \tilde{A}_\mu^6, A_\mu'^8$	$(+,-)$

Multi-component DM in general predicted

	Case I	Case II	Case III	Case IV
dark matter	$(A_\mu^1, A_\mu^2, \tilde{\chi})$	$(A_\mu^4, A_\mu^5, \tilde{\chi})$	$(A_\mu^1, A_\mu^2, A_\mu'^3)$	$(A_\mu^4, A_\mu^5, A_\mu'^3)$
parameter	$v_2/v_1 < 1$	$v_2/v_1 > 1$	$v_2/v_1 < 1$	$v_2/v_1 > 1$
choice	$\lambda_4 - \lambda_5 \ll 1$	$\lambda_4 - \lambda_5 \ll 1$	$\lambda_4 - \lambda_5 = \mathcal{O}(1)$	$\lambda_4 - \lambda_5 = \mathcal{O}(1)$

Simplified model $v_1 >> v_2 >> v_3$

$$\mathcal{L} \supset \frac{1}{2} m_A^2 \sum_{a=1,2} A_\mu^a A^{a\mu} + \frac{1}{2} m_{\tilde{\chi}}^2 \tilde{\chi}^2$$
$$+ \frac{\tilde{g}\, m_A}{2} (-h_1 \sin\theta + h_2 \cos\theta) \sum_{a=1,2} A_\mu^a A^{a\mu}$$
$$+ (1+r)\lambda_2 v_2 (-\sin\theta h_1 + \cos\theta h_2) + (1+r)\lambda_{H22}(\cos\theta h_1 + \sin\theta h_2)\tilde{\chi}^2$$

Case I can be reduced to a two component scalar portal

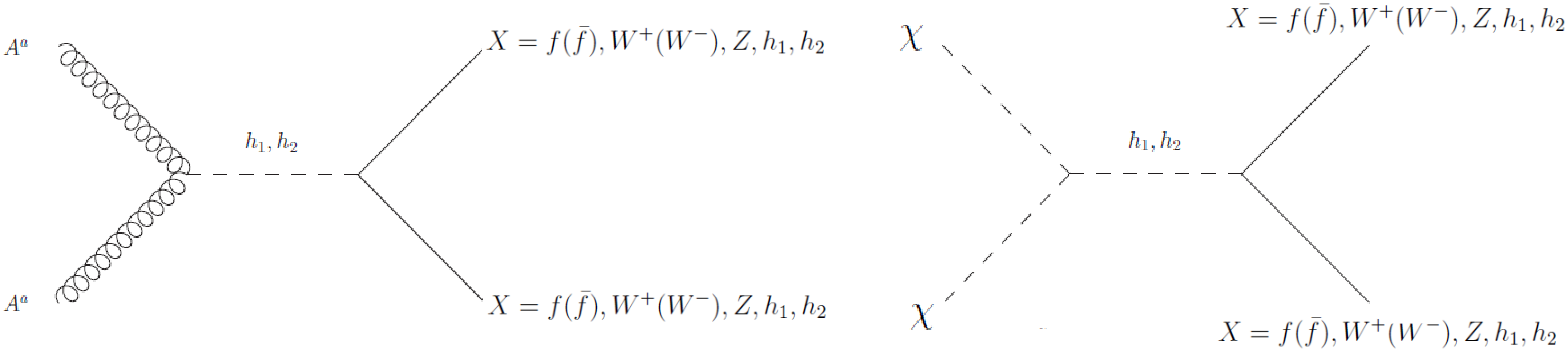
$$\lambda_2 = \frac{\cos\theta m_{h_2}^2 + \sin^2\theta m_{h_1}^2}{v_2^2} = \tilde{g}^2 \frac{\cos^2\theta m_{h_2}^2 + \sin^2\theta m_{h_1}^2}{4 m_A^2}$$
$$\lambda_{H22} = \frac{(m_{h_1}^2 - m_{h_2}^2)\sin\theta\cos\theta}{v v_2} = \tilde{g} \frac{(m_{h_1}^2 - m_{h_2}^2)\sin\theta\cos\theta}{2 v m_A}$$

The model has only one fundamental parameter, the « dark » gauge coupling.

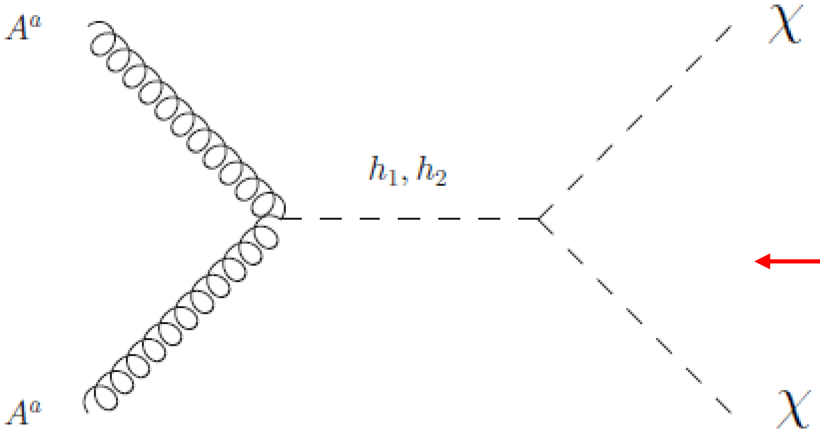
Boltzmann equation for simplified system

$$\frac{dY_A}{dx} = -\overline{\langle \sigma v \rangle}(AA \to XX)\left(Y_A^2 - Y_{A,\text{eq}}^2\right) - \overline{\langle \sigma v \rangle}(AA \to \chi\chi)\left(Y_A^2 - \frac{Y_{A,\text{eq}}^2}{Y_{\chi,\text{eq}}^2} Y_\chi^2\right)$$
$$- \overline{\langle \sigma v \rangle}(AA \to A^3 h_{1,2})\left(Y_A^2 - \frac{Y_\chi}{Y_{\chi,\text{eq}}} Y_{A,\text{eq}}^2\right)$$

$$\frac{dY_\chi}{dx} = -\overline{\langle \sigma v \rangle}(\chi\chi \to XX)\left(Y_\chi^2 - Y_{\chi,\text{eq}}^2\right) + \overline{\langle \sigma v \rangle}(AA \to \chi\chi)\left(Y_A^2 - \frac{Y_{A,\text{eq}}^2}{Y_{\chi,\text{eq}}^2} Y_\chi^2\right)$$
$$- \overline{\langle \sigma v \rangle}(AA^3 \to A h_{1,2}) Y_A Y_{A^3,\text{eq}}\left(\frac{Y_\chi}{Y_{\chi,\text{eq}}} - 1\right) + \overline{\langle \sigma v \rangle}(AA \to A^3 h_{1,3})\left(Y_A^2 - \frac{Y_\chi}{Y_{\chi,\text{eq}}} Y_{A,\text{eq}}^2\right)$$



Conventional pair annihilations



The relic density is mostly determined by pair annihilations.

Dark annihilation

Direct Detection

Both components feature a SI cross-section:

$$\sigma_{A_1 N} = \frac{\tilde{g}^2 \mu_{\mathrm{A_1 N}}^2}{4\pi} \sin^2\theta \cos^2\theta \left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2}\right)^2 \frac{\left[Z f_p + (A-Z) f_n\right]^2}{A^2}$$

Trilinear couplings of the scalar potential generate a null coupling in the not-relativistic limit (« blind spot »)

$$\lambda_2 v_2(-\sin\theta h_1 + \cos\theta h_2) + \lambda_{H22}(\cos\theta h_1 + \sin\theta h_2)\tilde{\chi}^2 = \frac{\tilde{g}}{4 m_A} \sin\theta\cos\theta\left(-h_1 m_{h_1}^2 \sin\theta + h_2 m_{h_2}^2 \cos\theta\right)$$

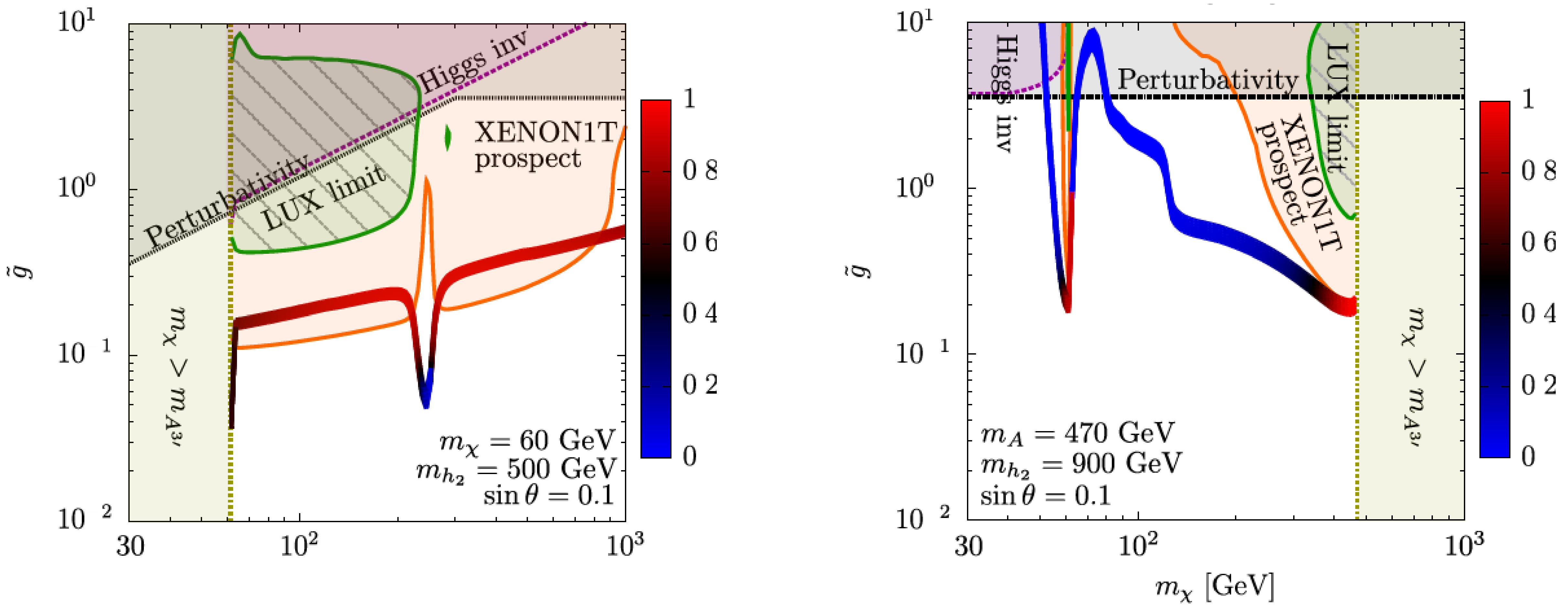
(see also 1406.0617)

Cross-section generated by scalar vector mixing

$$\sigma_{\chi N} = \frac{\mu_{\chi N}^2}{4\pi} \frac{m_\chi^2 m_A^2}{m_{A_6}^4} \sin^2\theta \cos^2\theta \left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2}\right)^2 \frac{\left[Z f_p + (A-Z) f_n\right]^2}{A^2} \longrightarrow 0$$

Simplified limit

Scalar component is « coy » with respect to direct detection. For vector component the SI cross-section is suppressed by a small mixing angle with respect to the main annihilation channel.



Going beyond WIMPs

Minimal model: SM+ Majorana fermion (DM candidate)+ Scalar field

$$L_{\rm eff} = \lambda_{\psi f} \, \bar{\psi} f \, \Sigma_f^{\dagger} + h.c.$$

$\Sigma_f =$ Scalar field, not trivially charged under the standard model gauge group

$\psi =$ Majorana field, Dark matter candidate

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

DM is never in thermal equilibrium in the Early Universe.

DM produced through the decays of the scalar field in thermal equilibrium (freeze-in/FIMP) and/or out-of-equilibrium (SuperWimp)

Less explored scenario. Possible peculiar signatures.

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

DM in thermal equilibrium in the Early Universe.

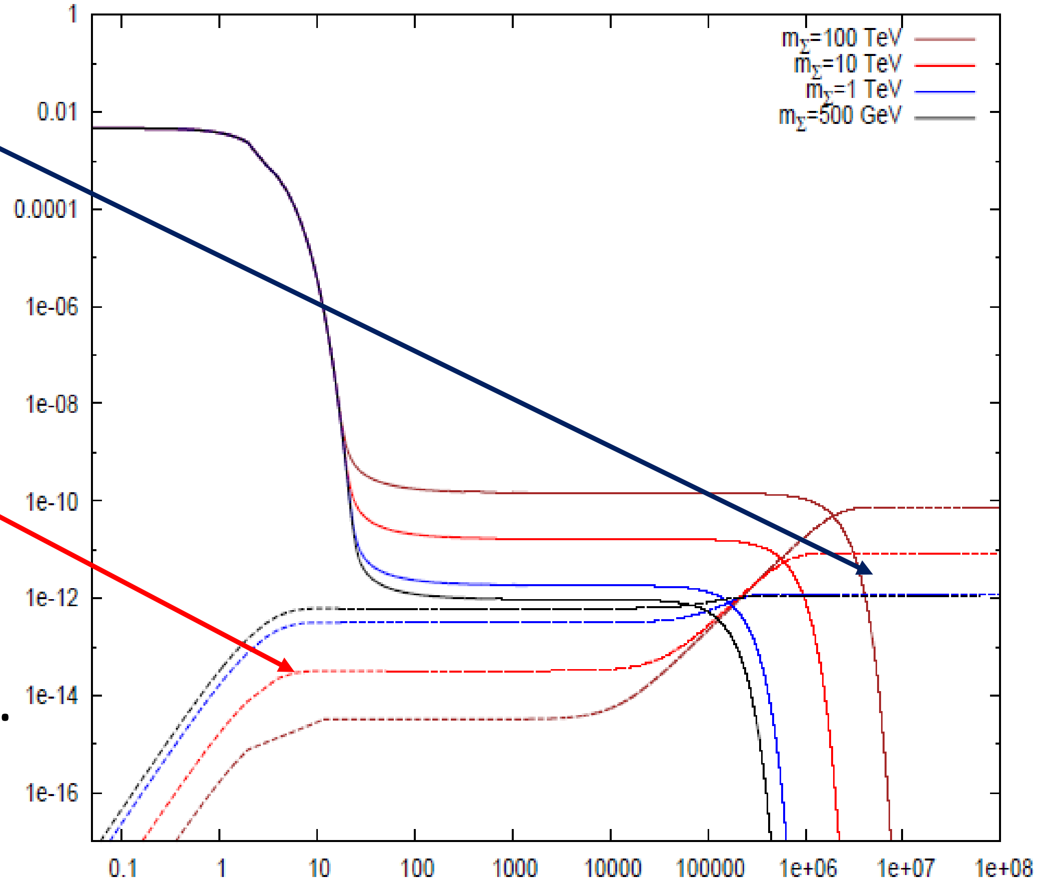
DM produced through freeze-out mechanism.

Very well known scenario.

SuperWimp

Freeze-in

$$Y = \frac{n}{s}$$



$$\omega = \frac{M_\Sigma}{T}$$

The two mechanism act on different time scales.
Relic density given by the sum of two contributions.

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

Hall et al, arXiv:0911.1120

$$\Omega_\psi^{SW} h^2 = x\, BR(\Sigma_f \to \psi f)\Omega_\Sigma h^2 \qquad x = m_\psi / m_{\Sigma_f}$$

No symmetry is imposed to stabilize the DM. The scalar field has analogous couplings with two SM fermions

Colored scalar field

$$L_{\text{eff}} = \lambda_{1q}\bar{d}\ell\Sigma_q + \lambda_{2q}\bar{q}_R^c d^c\Sigma_q + \lambda_{3q}u^c\ell\tilde{\Sigma}_q + h.c. \qquad \Sigma_q = (3,2,1/3)$$

$$L_{\text{eff}} = \lambda_{1u}\bar{d}d^c\Sigma_u^\dagger + \lambda_{2u}e^c d^c\Sigma_u^\dagger + \lambda_{3u}\bar{l}q_L\Sigma_u + h.c. \qquad \Sigma_u = (3,1,4/3)$$

$$L_{\text{eff}} = \lambda_{1d}\bar{l}^c q_L\Sigma_d^\dagger + \lambda_{2d}\bar{u}d^c\Sigma_d^\dagger + \lambda_{3d}\bar{e}_R u_L^c\Sigma_d^\dagger + \lambda_{4d}\bar{q}_R^c q_L\Sigma_d + h.c. \qquad \Sigma_u = (3,1,-2/3)$$

Scalar field only weakly interacting

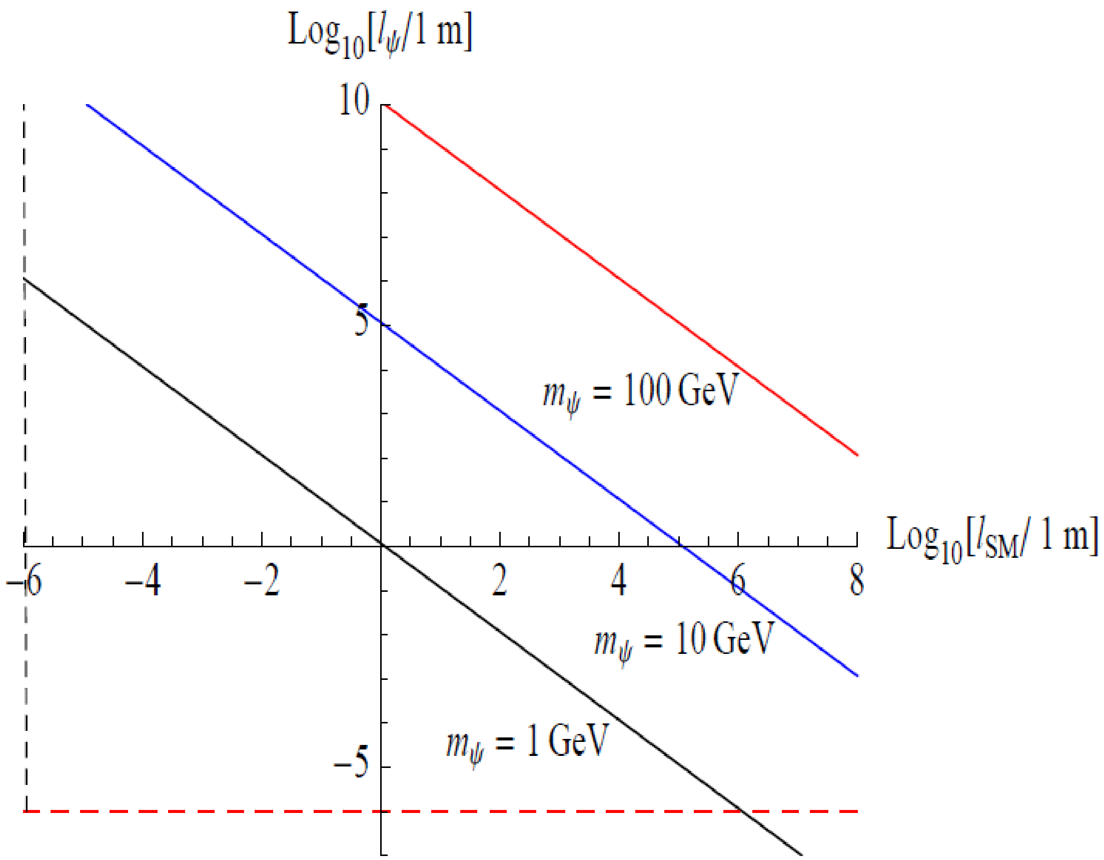
$$L_{\text{eff}} = \lambda_{1\ell}\bar{e}\ell\Sigma_\ell + \lambda_{2\ell}\bar{d}q\Sigma_\ell + \lambda_{3l}\bar{u}_R q_L\tilde{\Sigma}_l + h.c. \qquad \Sigma_l = (1,2,-1)$$

$$L_{\text{eff}} = \lambda_{1e}\bar{\ell}^c\ell\Sigma_e^\dagger + \lambda_{2e}\bar{d}_R u_L^c\Sigma_e + h.c. \qquad \Sigma_e = (1,1,-2)$$

Assumption: only a scalar field (single assignment of quantum numbers) and single operator considered per time.

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

DM lifetime related to the scalar field decay lenght

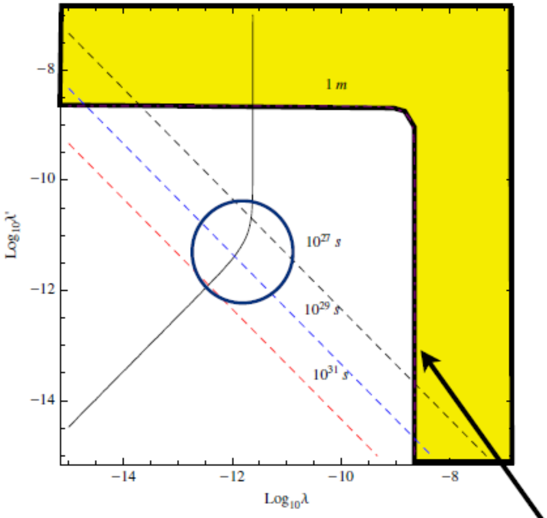


$$l_{\Sigma,DM} \simeq 1.17\,{\rm m} \left(\frac{m_{\Sigma_f}}{1{\rm TeV}}\right)^{-6} \left(\frac{m_\psi}{1{\rm GeV}}\right)^5 \left(\frac{l_{\Sigma,SM}}{1{\rm m}}\right)^{-1} \left(\frac{\tau_\psi}{10^{27}{\rm s}}\right)$$

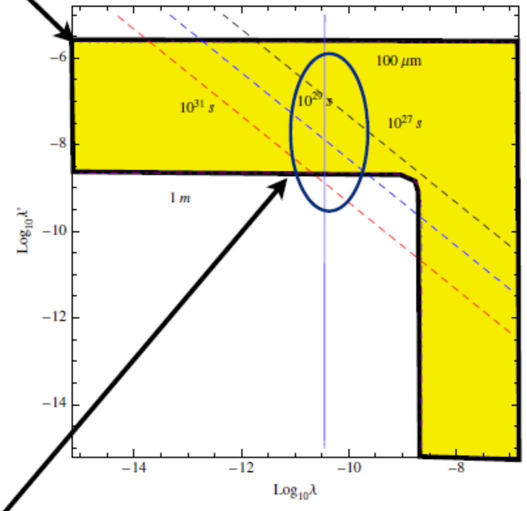
Possible scenario of detection of both decay channels together with ID of DM decay.

Only EW charged field

Displaced vertex



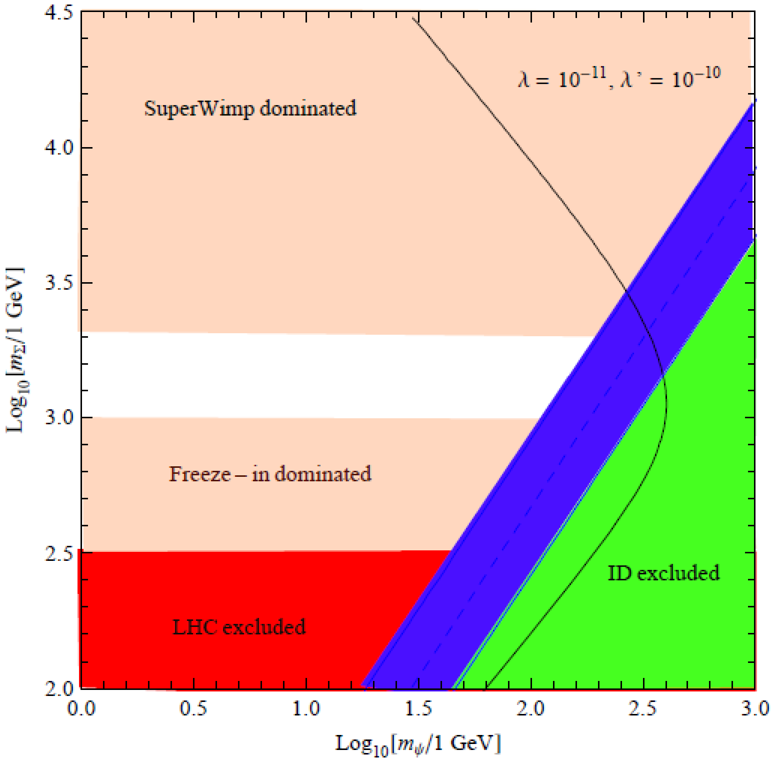
$x = 0.1$



$x = 0.001$

Scalar field decay length

(G.A. and L. Covi, arXiv:1305.6587)



More precise LHC study

CMS detector design: → 3 detector regions

-Pixel
-Tracker → Inner detector

Suited for displaced vertices

-Outside the detector region

Sensitive to detector stable particles (disappearing tracks)

Simulation of scalar pair production events with MadGraph5 at 14 TeV center of mass energy.

Three reference luminosities: 25, 300 (near future), 3000 (high luminosity upgrade) fb^(-1).

↓

Determination of the spatial distribution of the decay vertices of the scalar field in term of kinematical variables and lifetime.

(For details of the method see L. Covi and F. Dradi, 1403.4923)

Discovery (conservative) criterium: at least 10 decay events in one of the three detector regions.

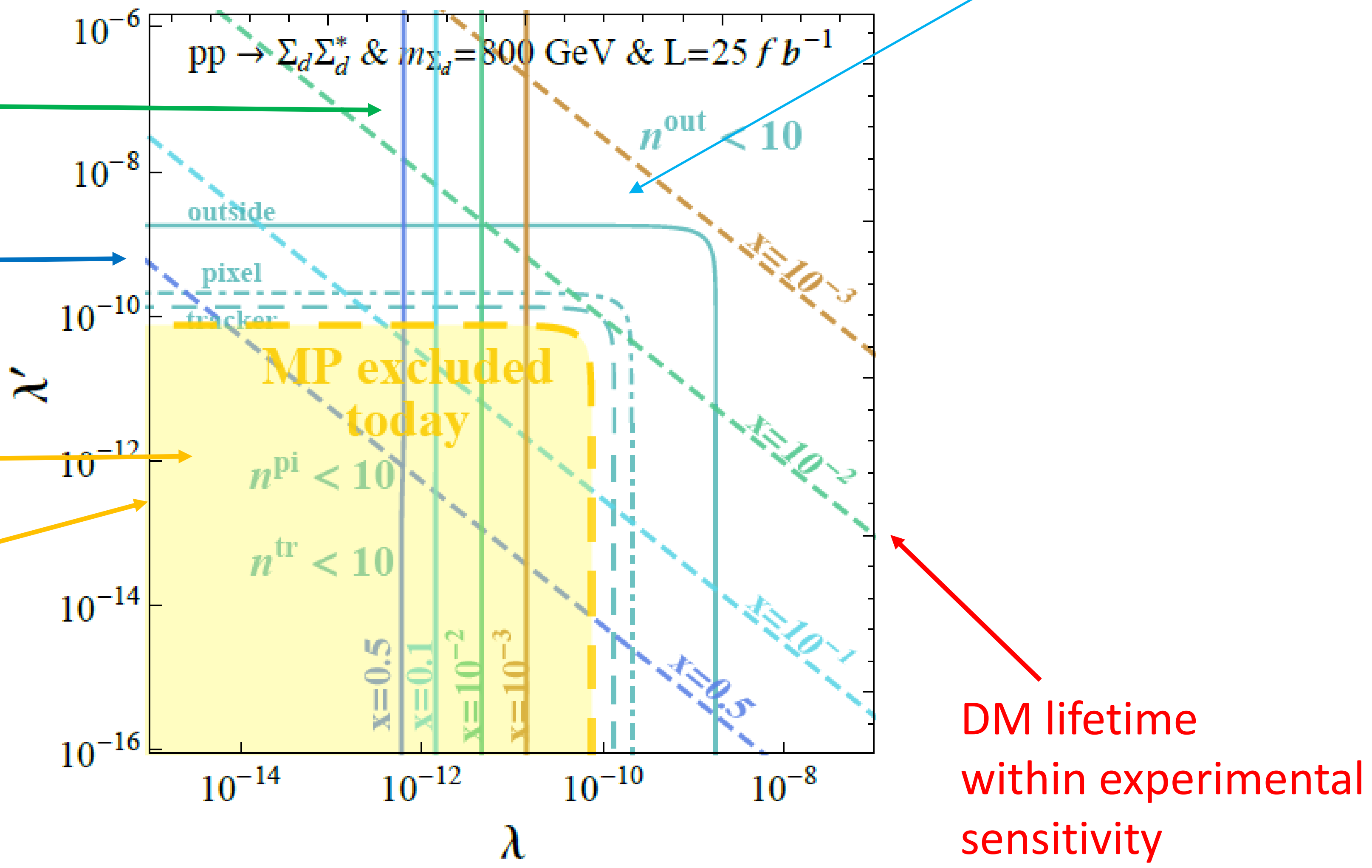
(Assumptions: no background and 100 percent detector efficiency)

DOUBLE LHC detection region: observation of 10 events in one of the inner detector regions and 10 events outside the detector.

Optimal determination of the scalar field lifetime and rejection of eventual backgrounds.

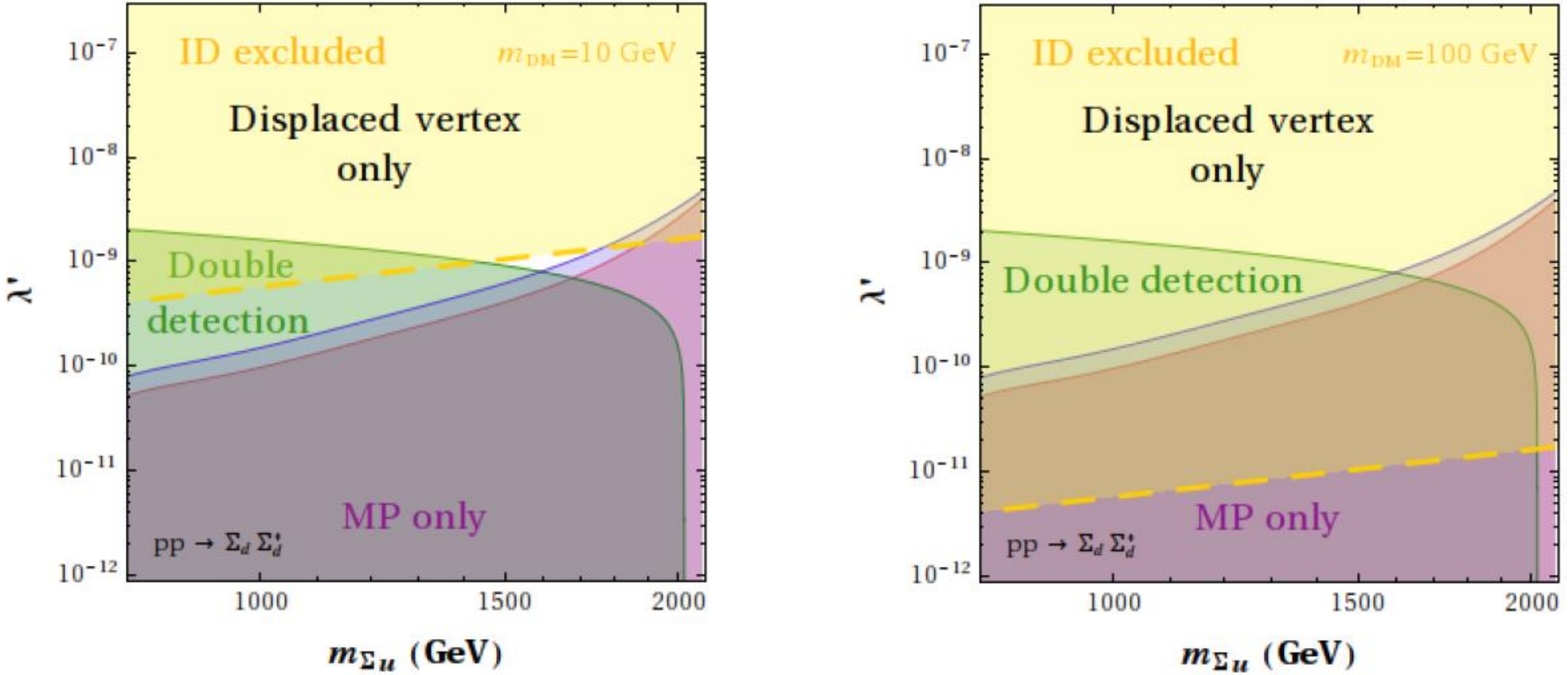
Optimal region of our scenario: double LHC detection of the decay of the scalar field accompanied by ID of decay of DM with the correct relic density.

Results



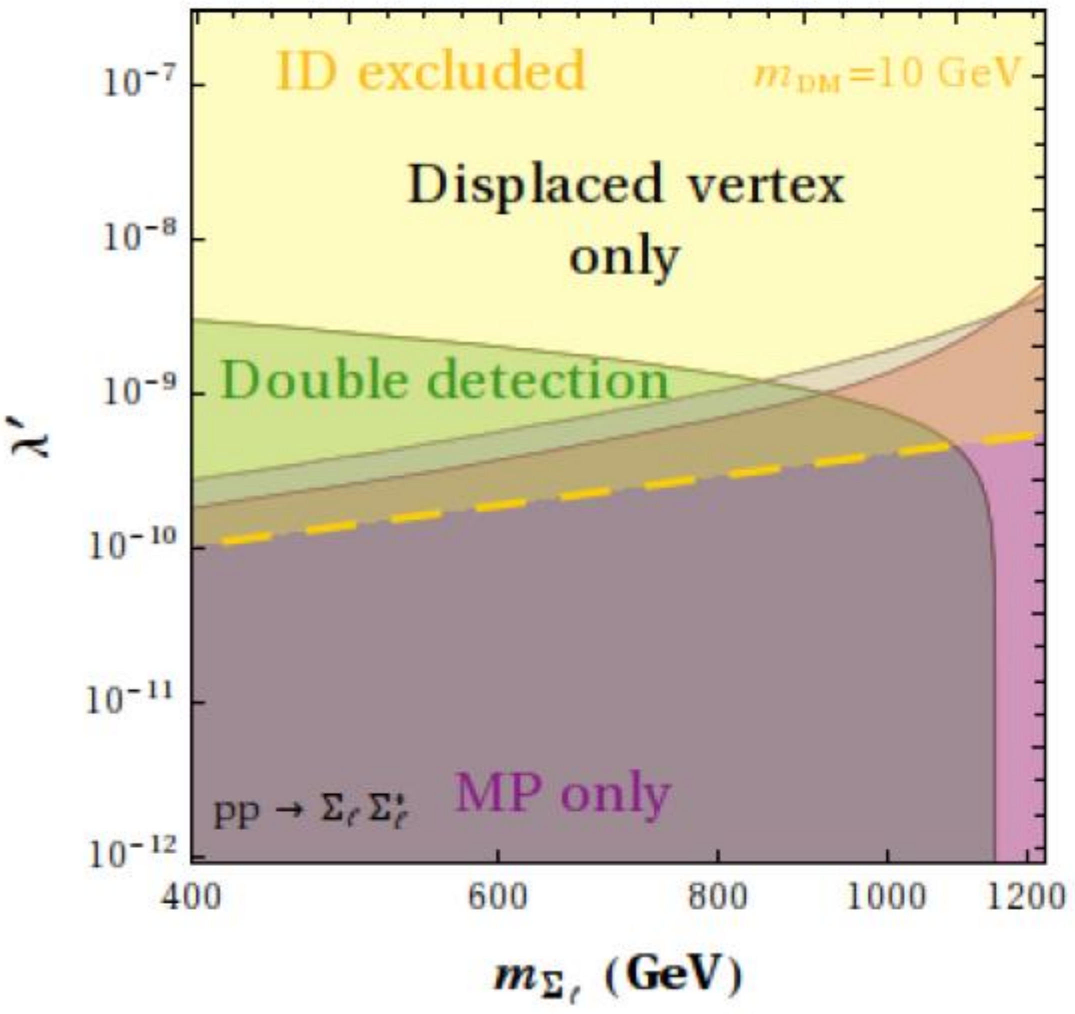
$pp \to \Sigma_d \Sigma_d^* \;\&\; m_{\Sigma_d}$=800 GeV & L=25 fb^{-1}
$n^{out} < 10$
outside
pixel
tracker
MP excluded today
$n^{pi} < 10$
$n^{tr} < 10$
x=0.5
x=0.1
x=10^{-2}
x=10^{-3}
x=10^{-3}
x=10^{-2}
x=10^{-1}
x=0.5
λ'
λ
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
Correct DM relic density
Double LHC Detection region
Detector stable state
Limit on metastable particles (irrelevant at higher masses)
Only displaced vertices
DM lifetime within experimental sensitivity

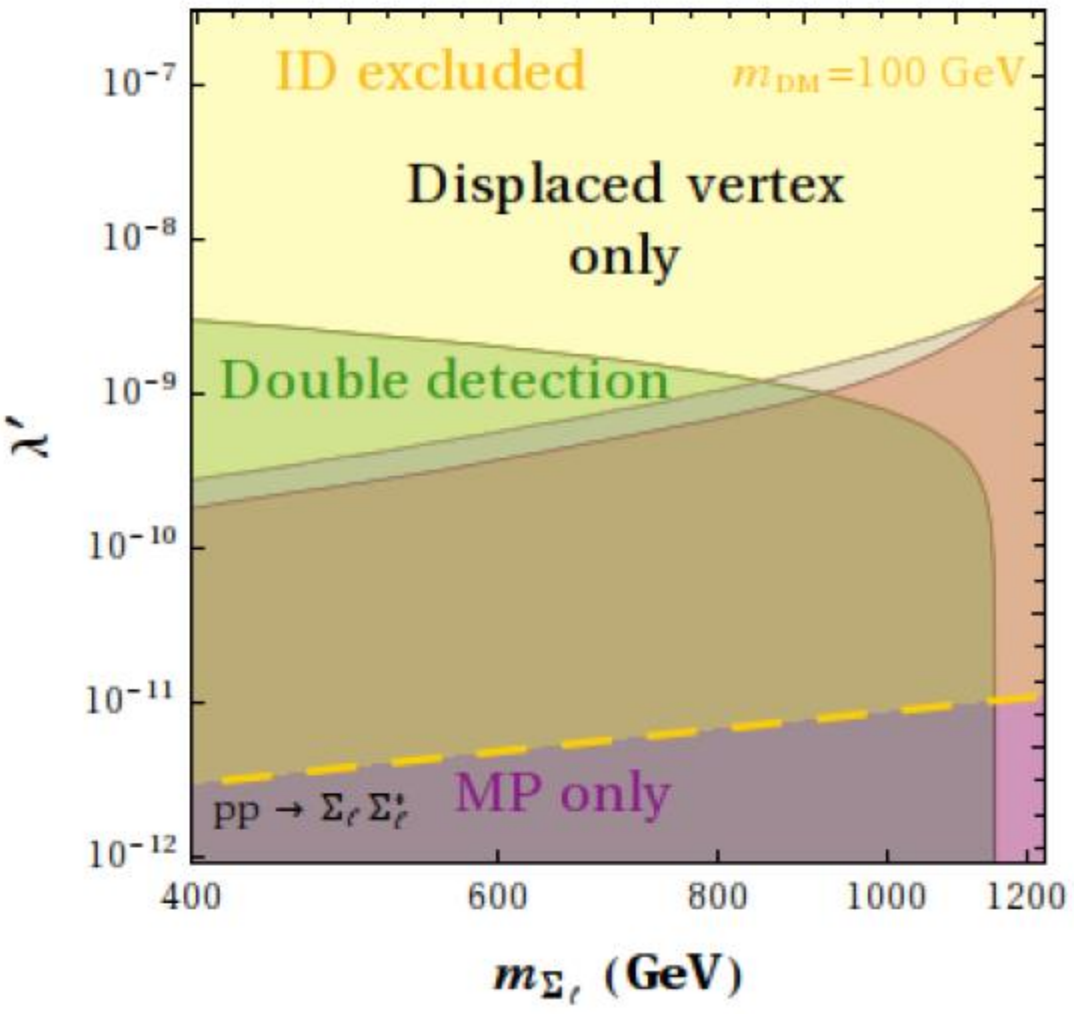
Summary colored scalar mediator



DM Indirect Detection disfavors the double LHC detection region for masses above 10 GeV

Summary EW scalar mediator





Conclusions

Simplest realizations of WIMPs are in increasing tension with experimental limits, especially from DM DD. Tensions can be relaxed by considering more complete setups.

Alternatively one can consider superweak interactions of the DM with SM states. Non-WIMP scenarios can be also probed by current experimetal facilities.