Dark matter in models with extended scalar sector

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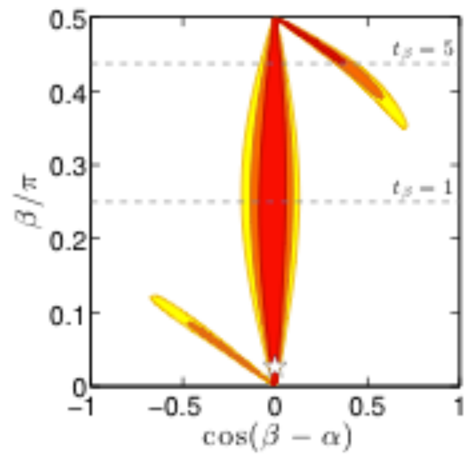
based on
G.B., K. Kannike, A. Pukhov, M. Raidal, JCAP (arXiv:1202.2962)
G.B., K. Kannike, A. Pukhov, M. Raidal, JCAP (arXiv:1211.1014)
G.B., K. Kannike, A. Pukhov, M. Raidal, in preparation

Introduction

- Neutralino in supersymmetry was put forward as ideal dark matter candidate - a solution to gauge hierarchy problem naturally explains dark matter
- However, no sign of SUSY or NP at LHC (yet), furthermore the minimal SUSY model requires some fine-tuning to explain m_h=125GeV (alleviate in NMSSM)
- While there is still room for SUSY discovery in the next LHC run, important to consider wide spectrum of possibilities for DM
- DM results
  - Precise determination of Ωh^2=0.1199+/-0.0027 (PLANCK)
  - Many searches both direct and indirect, no confirmed signal of DM (hints in DD)
- LHC discovery of new scalar : Higgs
  - natural extension : extended scalar sector

- Extended scalar sector generic in extensions of the SM
  - not LHC-friendly - no new coloured particles
- Models with extended scalar sector much studied from the Higgs point of view (e.g. two-Higgs-doublet model) compatible with all Higgs data



GB,Dumont, Ellwanger, Gunion, Kraml
1306.2941

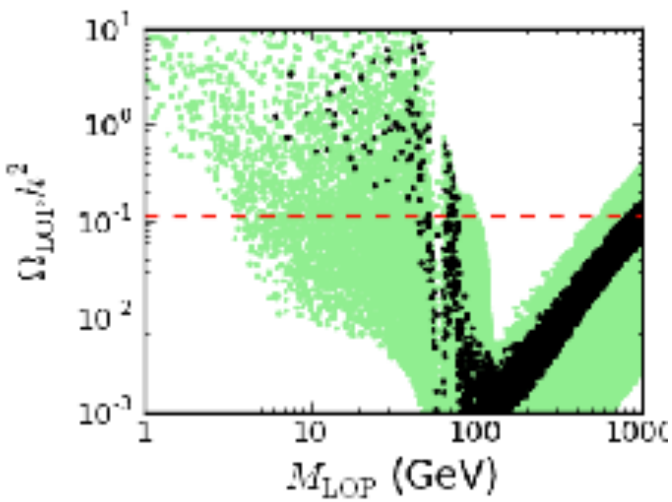
- To also provide a DM candidate - impose discrete symmetry to guarantee the stability of the lightest neutral particle from the 'dark' sector.
- Usually a Z_2 symmetry (R-parity in SUSY, KK-parity...)

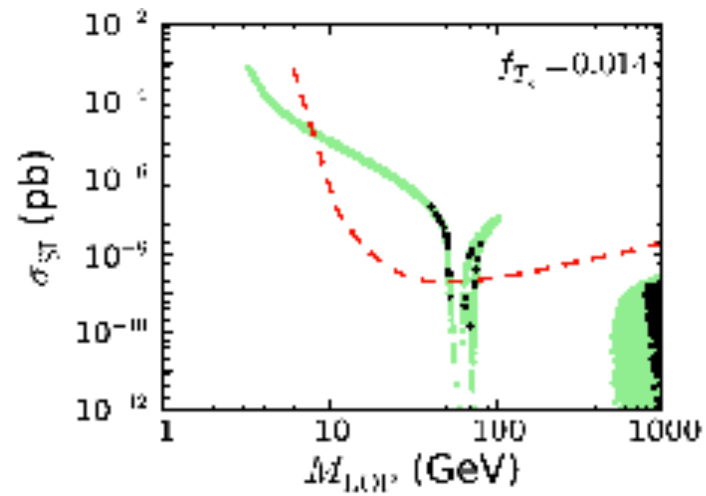
Inert doublet

- Two-Higgs doublet model with Z_2 symmetry
  - Deshpande, Ma, PRD18(1978) 2574; Barbieri, Hall, Rychkov, PRD74 (2006) 015007
  - Although suggested as alternative to light Higgs model (natural to have mh >>100 GeV) compatible with light Higgs and provide alternative to neutralino dark matter
  - Lopez Honorez, Nezri,Oliver, Tytgat, JCAP 0702(2007) 028; Arina et al (2009); Lopez Honorez ,Yaguna (2011); Goudelis et al (2013)
- SM + doublet
  - odd under Z_2 --> H or A stable
  - no coupling of H_2 to fermions

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2^2| + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + \text{h.c.}\right] ,$$

- Higgs constraints: stability, perturbativity, invisible Higgs, global Higgs fits
- DM properties





Goudelis, Herrmann, Stal 1303.3010

- Other extended scalar dark matter models
  - 1 doublet and singlet
    - Silveira, Zee (1985); J. McDonald PRD50(94) hep-ph/0702143; Burgess et al (2001); Barger et al (2008,2009,2010); Guo,Wu (2011), Biswas, Majumdar (2011) ....
  - 2 doublet and 1 singlet
- Discrete symmetry: discrete remnant of some broken gauge group, in general does not have to be Z_2 - consider Z_N
- Impact for dark matter :
  - semi-annihilation : processes involving different number of "odd particles" xx --> x* SM (Hambye, 0811.0172; D'Eramo,Thaler 1003.5912)
  - More than one DM candidate -> Assisted freeze-out/DM conversion : interaction between particles from different dark sectors (Liu,Wu,Zhao, 1101.4148; GB,Park)
    - » x_1x_1 <--> x_2x_2

- Consider minimal model with semi-annihilation: scalar dark matter model with inert scalar doublet + complex singlet
- Two cases : Z_3 and Z_4 symmetry
- Investigate consequences of semi-annihilation and (in the case of Z_4) of having two dark matter candidates.
- Note: discrete symmetries investigated to explain neutrino masses (e.g. Z_3, D_3, A_4) and in some cases also for dark matter
  - Adulpravitchai et al, 1103.3053

The Z_3 case : semi-annihilation

Semi-annihilation

- Number density   (x : dark sector   X: SM)

$$\frac{dn}{dt} = -v\sigma^{xx^*\to XX}\left(n^2 - \overline{n}^2\right) - \frac{1}{2}v\sigma^{xx\to x^*X}\left(n^2 - n\,\overline{n}\right) - 3Hn.$$

$$\sigma_v \equiv v\sigma^{xx^*\to XX} + \frac{1}{2}v\sigma^{xx\to x^*X} \quad \text{and} \quad \alpha = \frac{1}{2}\frac{\sigma_v^{xx\to x^*X}}{\sigma_v}$$

$$3H\frac{dY}{ds} = \sigma_v\left(Y^2 - \alpha Y\overline{Y} - (1-\alpha)\overline{Y}^2\right).$$

- Modified equation solved numerically ($Y=Y_{eq}+\Delta Y$) with usual micrOMEGAs procedure ΔY - >$\Delta Y/(1-\alpha/2)$

$$3H\frac{d\overline{Y}}{ds} = \sigma_v\overline{Y}\Delta Y\,(2-\alpha)$$

- Increase " DM annihilation" -> decrease relic density

The model

- Inert doublet + complex singlet (H_2, S, do not couple to quarks)

Field	$SU(3)$	$SU(2)_L$	T^3	$Y/2$	$Q = T^3 + Y/2$
$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}$	**1**	**2**	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$\frac{1}{2}$	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$
$H_2 = \begin{pmatrix} -iH^+ \\ \frac{H^0+iA^0}{\sqrt{2}} \end{pmatrix}$	**1**	**2**	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$\frac{1}{2}$	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$
$S = \frac{S_H+iS_A}{\sqrt{2}}$	**1**	**1**	0	0	0

- Scalar potential ($Z_3(H_1)$=0, $Z_3(S)$= $Z_3(H_2)$=1)

$$V_c = \mu_1^2|H_1|^2 + \lambda_1|H_1|^4 + \mu_2^2|H_2|^2 + \lambda_2|H_2|^4 + \mu_S^2|S|^2 + \lambda_S|S|^4 + \lambda_{S1}|S|^2|H_1|^2 + \lambda_{S2}|S|^2|H_2|^2 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4(H_1^\dagger H_2)(H_2^\dagger H_1).$$

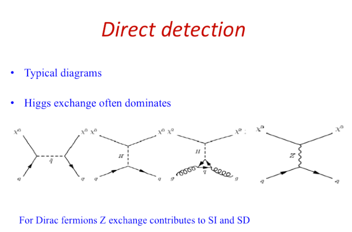
$$V_{Z_3} = V_c + \frac{\mu_S''}{2}(S^3 + S^{\dagger 3}) + \frac{\lambda_{S12}}{2}(S^2 H_1^\dagger H_2 + S^{\dagger 2} H_2^\dagger H_1) + \frac{\mu_{SH}}{2}(S H_2^\dagger H_1 + S^\dagger H_1^\dagger H_2),$$

- Mixing H_2- S

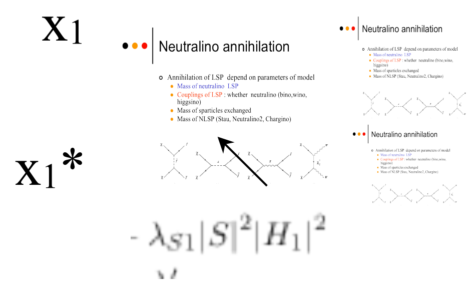
$$H_2 = \begin{pmatrix} -iH^+ \\ x_1 \sin\theta + x_2 \cos\theta \end{pmatrix}, \qquad S = x_1 \cos\theta - x_2 \sin\theta.$$

- Dark sector : complex x_1,x_2,H^+, Z_3 charge=1

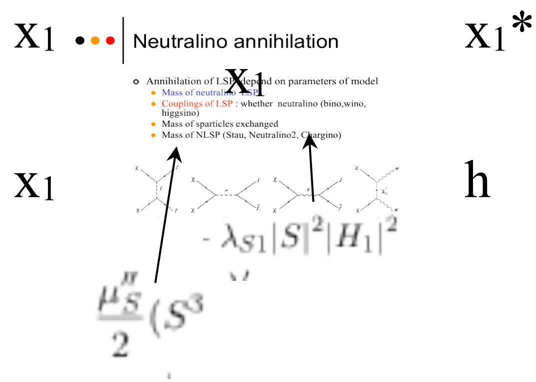
- Small mixing : otherwise large SI direct detection rate



- Annihilation

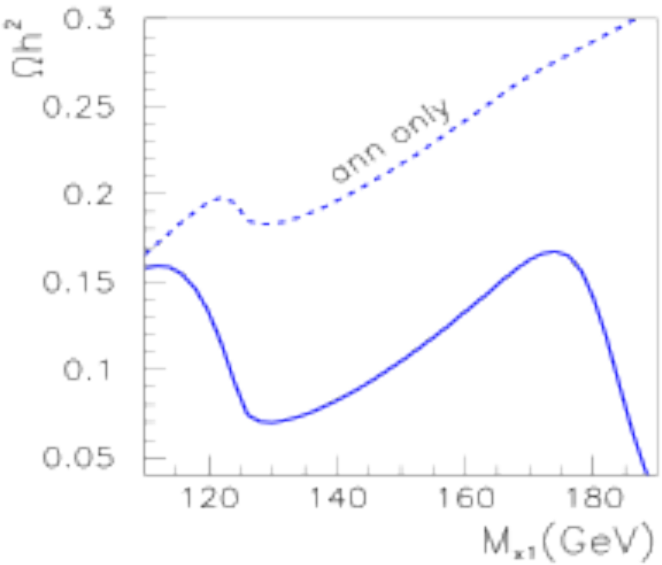


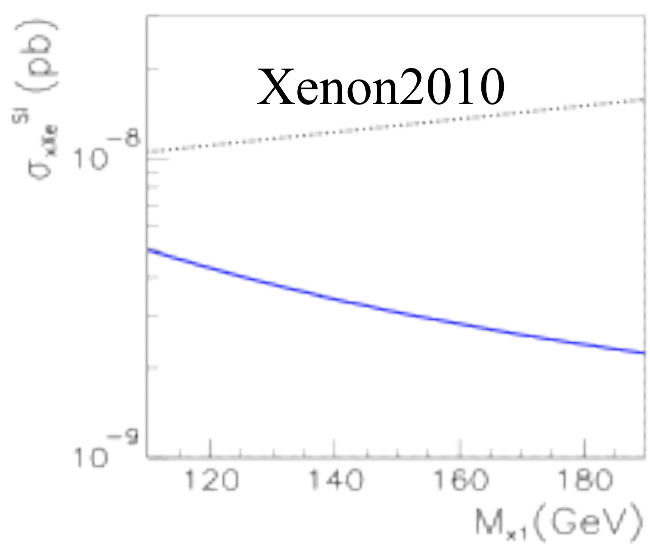
- Semi- annihilation



- also x_1x_1->x_1Z,x_2Z,x_2h,HW ;
- 'semi-co-annihilation' : x_1x_2->x_1Z,x_1h

Impact of semi-annihilation





- M_{x1}=110 GeV : semi-annihilation kinematically forbidden
- Decrease of relic density when semi-anni. contribute
- semi-annihilation enhanced when $M_{x1}=M_{x2}/2$

Theoretical constraints

- Perturbativity
  - all coefficients in vertices $< 4\pi$
- Unitarity of scalar-scalar scattering matrix

$$|\mathrm{Re}\mathcal{M}| < \frac{1}{2}.$$

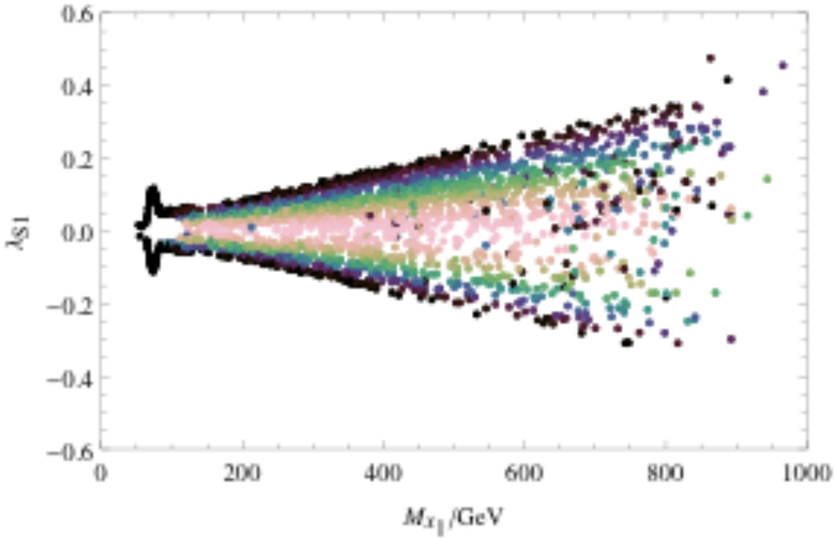
- Vacuum stability
  - scalar potential bounded from below
- Globality of Z_N vacuum
- Conditions on parameters of scalar potential

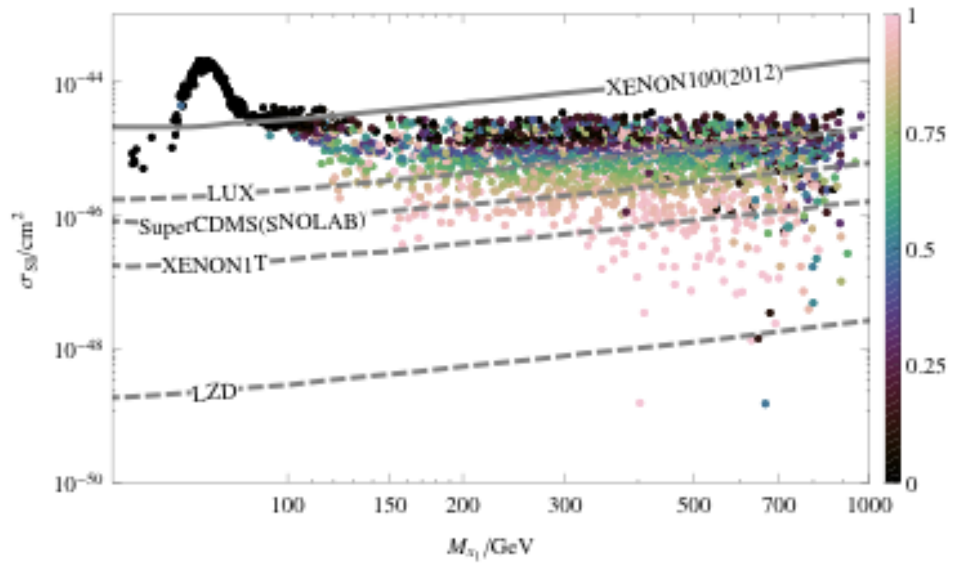
Experimental constraints

- Electroweak precision tests (corrections due to charged Higgs + singlet/doublet mixing for Z_3)
  - $S = 0.05 +/- 0.10$ $T = 0.08 +/- 0.07$

- LEP limits (Z invisible < 3MeV)
- LHC Higgs couplings + invisible width
  - $R_{\gamma\gamma} = 1.06 +/- 0.10$
  - $Br_{inv} < 0.24$ @95%CL
- Relic density (PLANCK)
  - $\Omega h^2 = 0.1199 +/- 0.0027$
- Direct detection (Xenon100 exclusion)

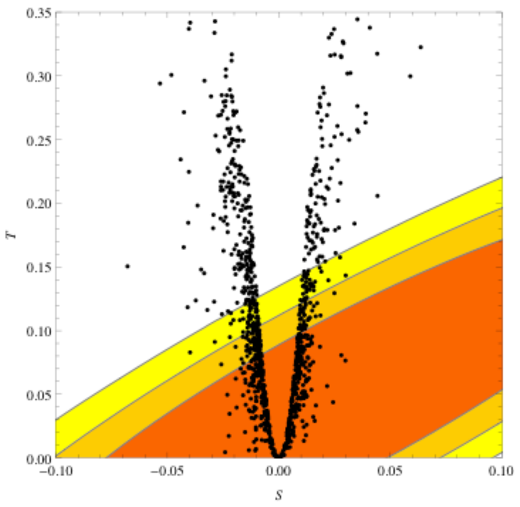
Results

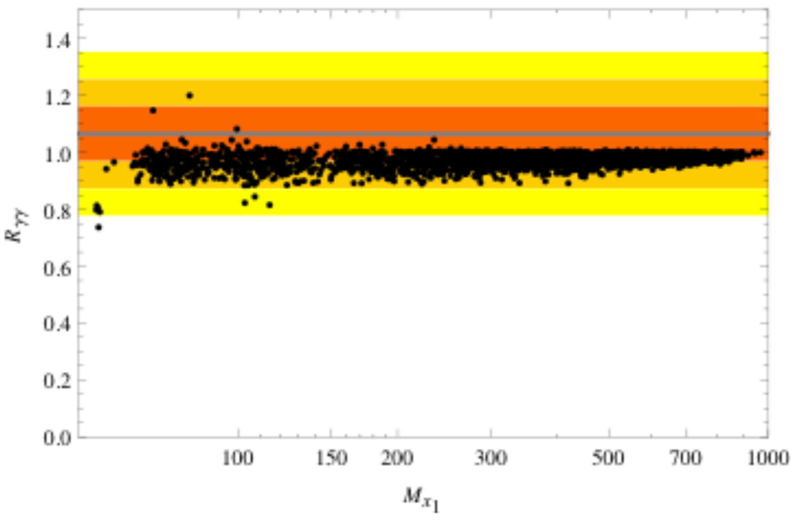




- Semi-annihilation --> changes relation between relic density and direct detection
- m_{DM}<50 GeV : constrained by Br_{inv}

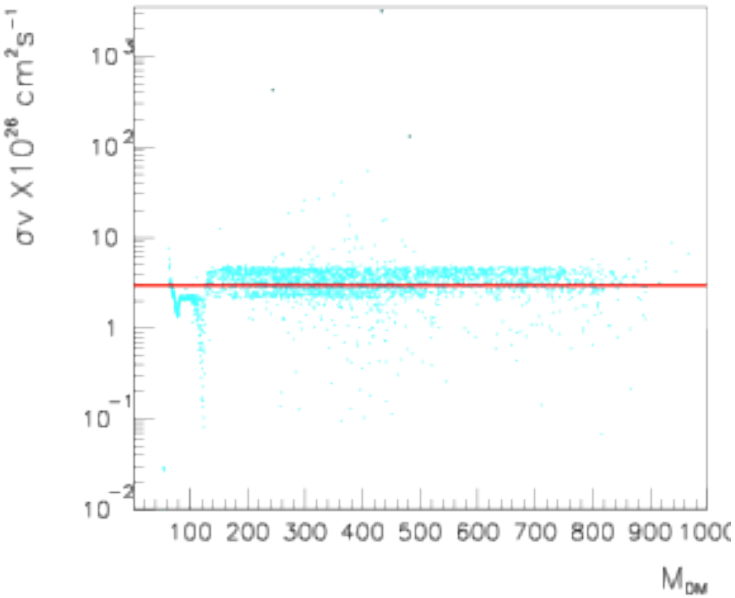
Results (2)





- EW constraints important - no direct correlation with DM properties
- No strong deviation of the Higgs-two photon coupling (after Hinv)

Indirect detection



- Main channels: bb,WW,ZZ,hh
- Semi-annihilation : --> x_1Z, x_1h
- Possibility of having large enhancement of sigma v --> resonance effect when $m_{x1} \sim m_{x2}/2$
- Constraints from PAMELA measurement of antiprotons

The Z_4 case : two DM candidates

The Z_4 case

- Z_4 potential, $Z(H_2)=2$, $Z(S)=1$, $Z(H_2)=0$

$$V^1_{Z_4} = V_c + \frac{\lambda'_S}{2}(S^4 + S^{\dagger 4}) + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + (H_2^\dagger H_1)^2\right]$$
$$+ \frac{\lambda_{S12}}{2}(S^2 H_1^\dagger H_2 + S^{\dagger 2} H_2^\dagger H_1) + \frac{\lambda_{S21}}{2}(S^2 H_2^\dagger H_1 + S^{\dagger 2} H_1^\dagger H_2).$$

- DM sector 1 : complex scalar S
- DM sector 2 : 3 real scalars H,A,H^+

$$H_2 = \begin{pmatrix} -iH^+ \\ H^0 + iA^0 \end{pmatrix}.$$

- lightest particle of charge 2 stable (A or H) if $M_{H,A}<2M_s$
- If $M_{H,A}>2M_S$ decay before freeze-out, -> case with one DM candidate

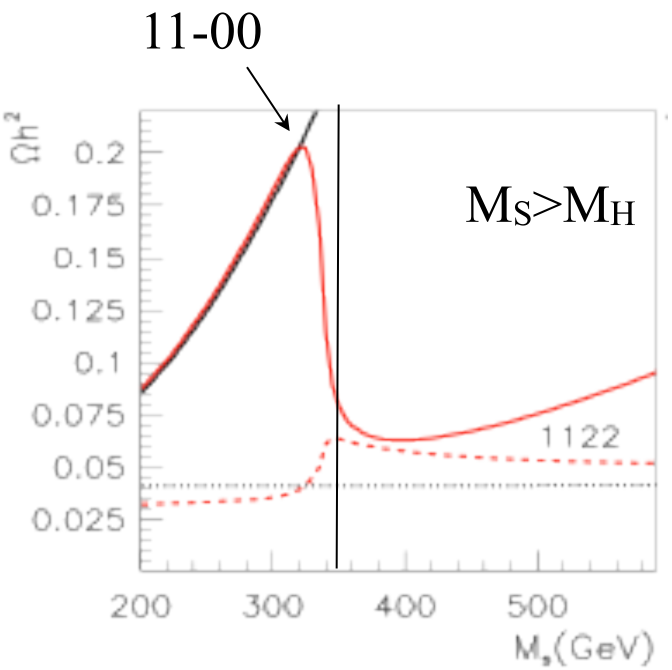
- Equations for number density

$$\frac{dn_1}{dt} = -\sigma_v^{1100}\left(n_1^2 - \bar{n}_1^2\right) - \sigma_v^{1120}\left(n_1^2 - \bar{n}_1^2\frac{n_2}{\bar{n}_2}\right) - \sigma_v^{1122}\left(n_1^2 - n_2^2\frac{\bar{n}_1^2}{\bar{n}_2^2}\right) - 3Hn_1$$

$$\frac{dn_2}{dt} = -\sigma_v^{2200}\left(n_2^2 - \bar{n}_2^2\right) + \frac{1}{2}\sigma_v^{1120}\left(n_1^2 - \bar{n}_1^2\frac{n_2}{\bar{n}_2}\right) - \frac{1}{2}\sigma_v^{1210}\left(n_1 n_2 - n_1\bar{n}_2\right) - \sigma_v^{2211}\left(n_2^2 - n_1^2\frac{\bar{n}_2^2}{\bar{n}_1^2}\right) - 3Hn_2,$$

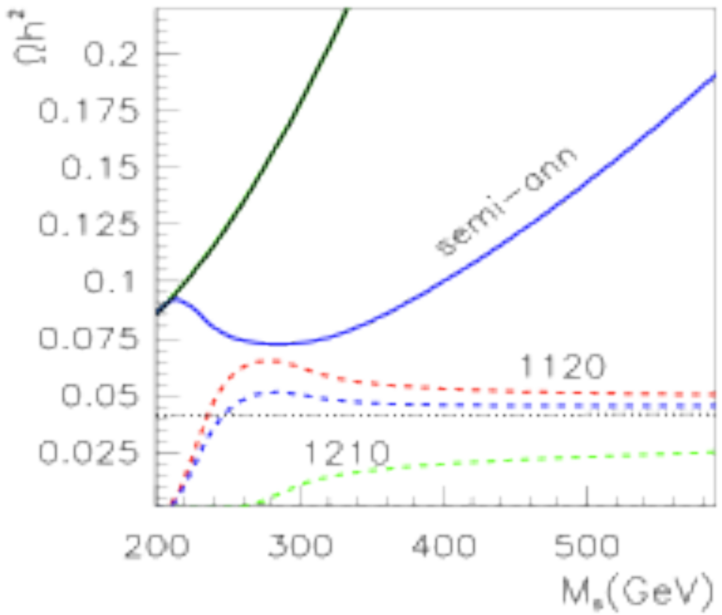
- DM annihilation : sector 1 : ss*-> hh
- sector 2 : similar Inert doublet, HH -> $WW^{(*)}$,ff
- Semi annihilation ss ->Hh (Ah)
- DM conversion HH -> ss*

DM conversion



- T_{fo} (heavy)> T_{fo}(light), at freeze-out of heavy component 22->ll adds to 22->00 and lead to decrease of heavy DM abundance
- interaction 22->ll increase abundance of light component
- Effect large when $M_S > M_H$ and 1122>>1100

Semi-annihilation

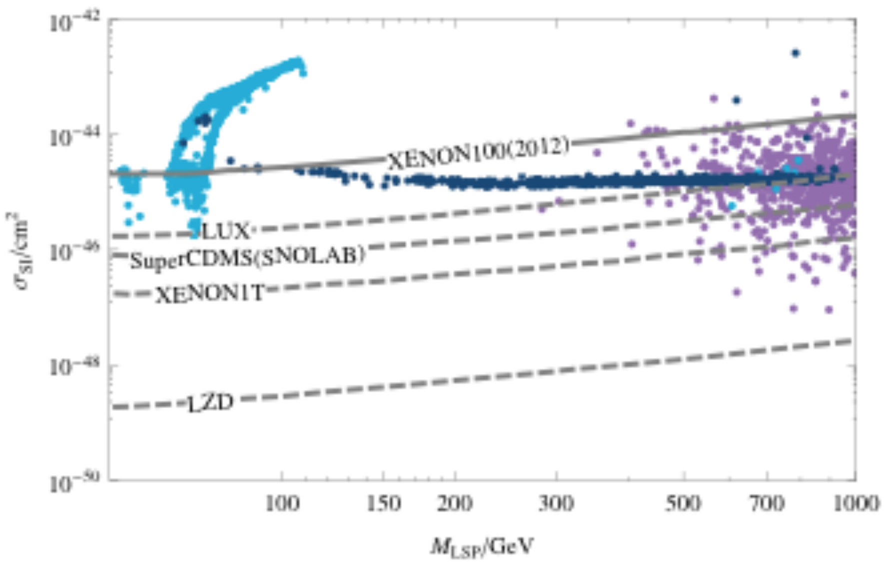


- Two types of semi-annihilation
  - sH->sh (1210) no effect on Ω_1, reduce Ω_2
  - ss*-> Hh (1120) reduce Ω_1, increase Ω_2
- Semi-annihilation dominant $M_S<M_H$, DM conversion important when $M_S>M_H$

Results

- General scan (theoretical and expt constraints as for the Z3 case) : usually one component dominates

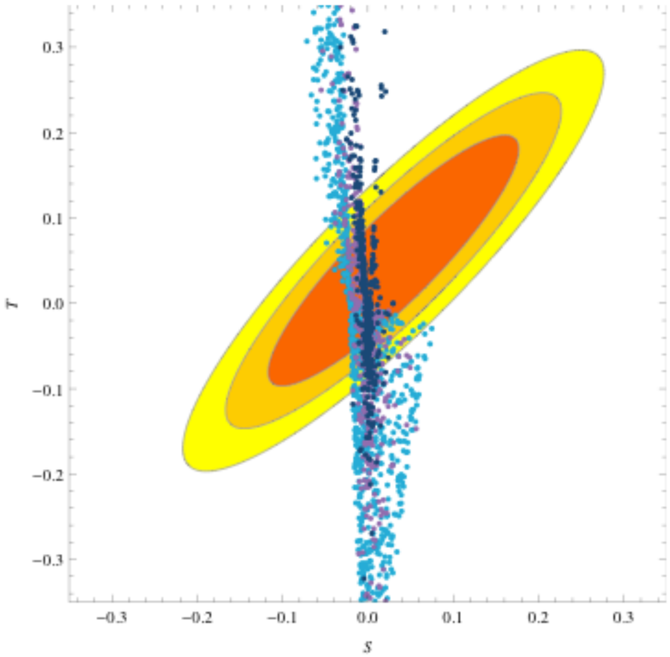
H,A: light,dominant S light, dominant

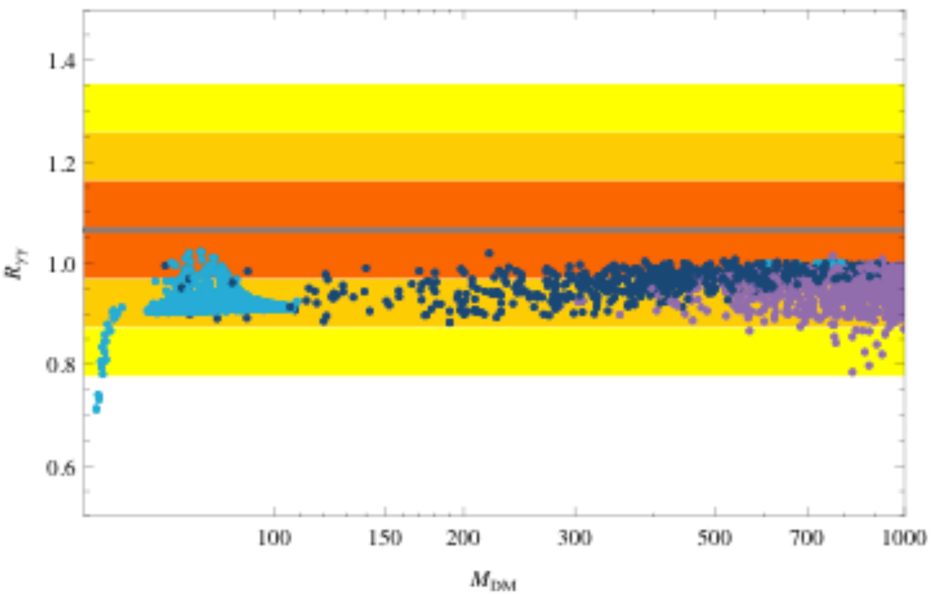


S heavy, dominant

- Indirect Signatures (in progress)

Results





- Strong constraints from t-parameter
- Few cases with suppressed Higgs couplings

CONCLUSION

- Extended scalar sectors+ discrete symmetry -> alternative DM candidates

- Larger discrete symmetry group lead to new mechanisms for relic density of dark matter and potentially suppressed signature in direct detection + possibility of more than one WIMP

- Still eagerly waiting for a confirmed DM signal in direct/ indirect detection and/or BSM signal at LHC