Dark matter in models with a Z_N discrete symmetry

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based on
G.B., K. Kannike, A. Pukhov, M. Raidal, JCAP (arXiv:1202.2962)
G.B., J.C.Park, JCAP 1203 (2012) 038.

- Introduction
- Z3 : model and results
- Z4 : model and results

Introduction

- In extensions of the SM, a discrete symmetry guarantees the stability of lightest “odd” particle->DM candidate if neutral
- Usually a Z_2 symmetry (R-parity in SUSY, KK-parity...)
- Discrete remnant of some broken gauge group, in general does not have to be Z_2 - consider Z_N
- Impact for dark matter :
  - New processes
    - semi-annihilation : processes involving different number of “odd particles” $xx \rightarrow x^* SM$
  - More than one DM candidate
    - Assisted freeze-out/DM conversion : interaction between particles from different dark sectors
      - » $x_1 x_1 \leftrightarrow x_2 x_2$

- Impact of these new processes on DM properties
  - semi-annihilation (D'Eramo, Thaler 1003.5912)
  - Assisted/DM conversion (Liu,Wu,Zhao, 1101.4148)
- No sign of SUSY or NP at LHC (yet)- no confirmed signal of DM in astroparticle; important to consider wide spectrum of possibilities for DM
- Consider minimal model: scalar dark matter model with inert scalar doublet + complex singlet
- Two cases :
  - Z_3 symmetry
  - Z_4 symmetry

The Z_3 case : semi-annihilation

The Z_3 case

- 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 - >$\Delta Y/(1-\alpha/2)$

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

The model

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

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

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

$$
\begin{aligned}
V_{\rm c} = {} & \mu_1^2|H_1|^2 + \lambda_1|H_1|^4 + \mu_2^2|H_2|^2 + \lambda_2|H_2|^4 + \mu_S^2|S|^2 + \lambda_S|S|^4 \\
& + \lambda_{S1}|S|^2|H_1|^2 + \lambda_{S2}|S|^2|H_2|^2 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4(H_1^\dagger H_2)(H_2^\dagger H_1).
\end{aligned}
$$

$$
\begin{aligned}
V_{Z_3} = {} & V_{\rm c} + \frac{\mu_S''}{2}(S^3 + S^{\dagger 3}) + \frac{\lambda_{S12}}{2}(S^2 H_1^\dagger H_2 + S^{\dagger 2} H_2^\dagger H_1) \\
& + \frac{\mu_{SH}}{2}(S H_2^\dagger H_1 + S^\dagger H_1^\dagger H_2),
\end{aligned}
$$

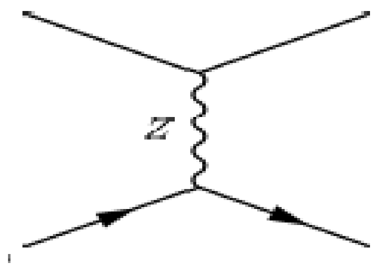
- Mixing H_2- S

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

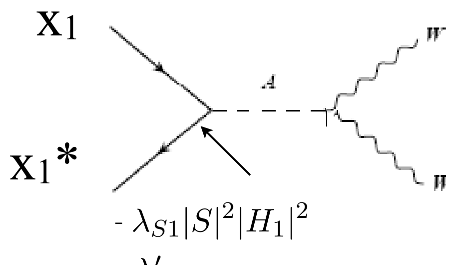
- Dark sector : complex x_1,x_2,H^+, Z_3 charge=1
- Free parameters:

λ_2	0.1	λ_S	0.2	λ_{S21}	0.1	M_{x_1}	150 GeV
λ_3	0.1	λ_{S1}	0.05	M_h	125 GeV	M_{x_2}	400 GeV
λ_4	0.1	λ_{S2}	0.1	μ''_S	80 GeV	$\sin\theta$	0.025

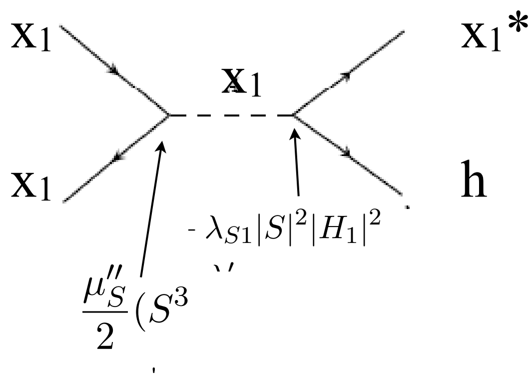
- Small mixing : otherwise large SI direct detection rate



- Annihilation

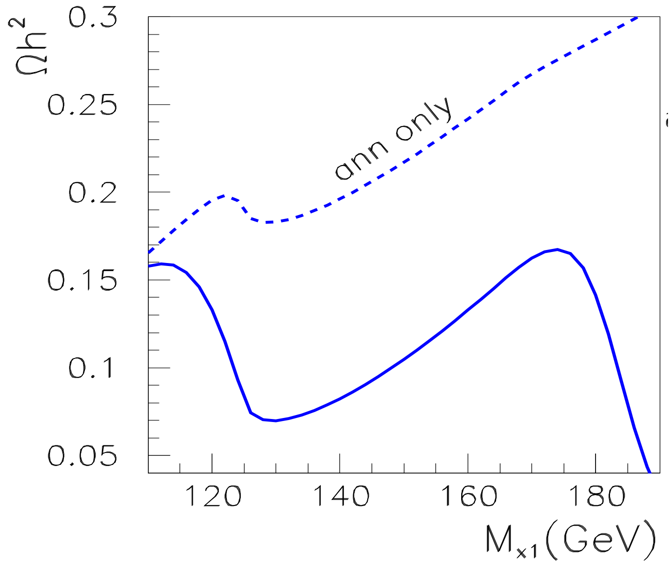


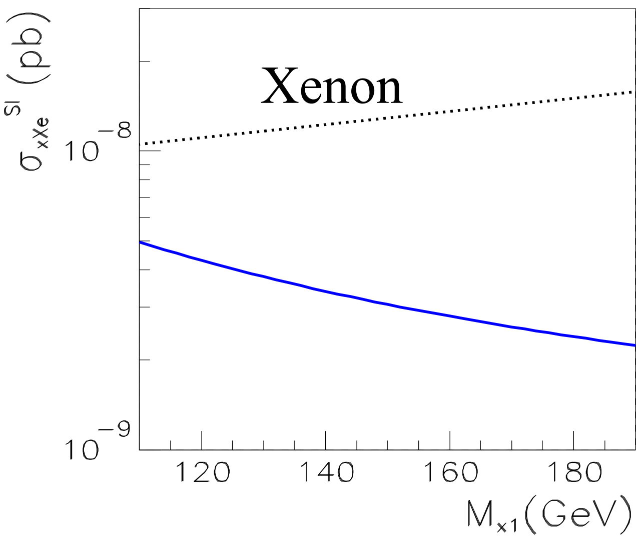
- Semi- annihilation



- Benchmark: Ωh^2=0.105 (54% from semi-annihilation)

Impact of semi-annihilation





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

The Z_4 case : two DM candidates

The Z_4 case

- Z_4 charge : 0,1,2
- Assume charge 0 for SM particle
- lightest particle of charge 1 : stable
- lightest particle of charge 2 stable if $M_2<2M_1$
- If $M_2>2M_1$ decay into charge 1 before freeze-out, usual case with only 1 DM candidate
- Equations for number density

$$\begin{aligned}
\frac{dn_1}{dt} &= -\sigma_v^{1100}\left(n_1^2-\bar{n}_1^2\right)-\sigma_v^{1120}\left(n_1^2-\bar{n}_1^2\frac{n_2}{\bar{n}_2}\right)-\sigma_v^{1122}\left(n_1^2-n_2^2\frac{\bar{n}_1^2}{\bar{n}_2^2}\right)-3Hn_1\\
\frac{dn_2}{dt} &= -\sigma_v^{2200}\left(n_2^2-\bar{n}_2^2\right)+\frac{1}{2}\sigma_v^{1120}\left(n_1^2-\bar{n}_1^2\frac{n_2}{\bar{n}_2}\right)-\frac{1}{2}\sigma_v^{1210}\left(n_1n_2-n_1\bar{n}_2\right)\\
&\quad -\sigma_v^{2211}\left(n_2^2-n_1^2\frac{\bar{n}_2^2}{\bar{n}_1^2}\right)-3Hn_2,
\end{aligned}$$

- All annihilation+ coannihilation included
- semi annihilation 11->20, 12->10
- DM conversion: 22 <->11
- Equations to solve

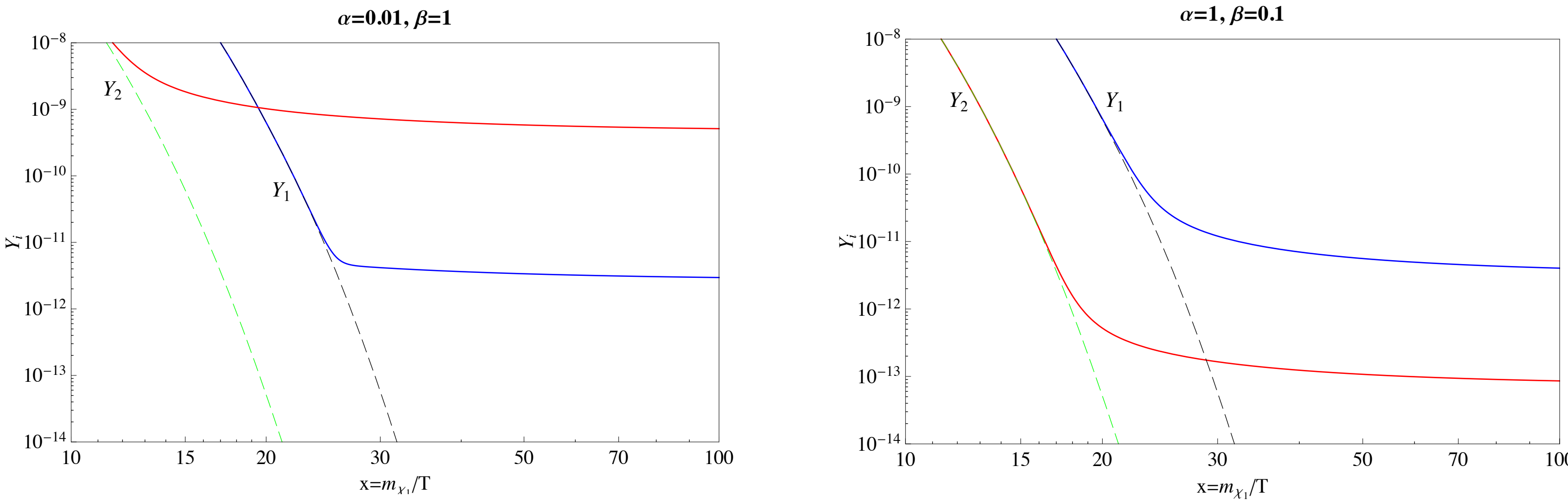
$$3H\frac{\Delta Y_i}{ds} = -C_i + A_{ij}(T)\Delta Y_j + Q_{ijk}(T)\Delta Y_j \Delta Y_k$$

$$\begin{aligned}
C_i &= 3H\frac{d\overline{Y}_i}{ds}, \\
A &= \begin{pmatrix} 2(\sigma_v^{1100} + \sigma_v^{1122} + \sigma_v^{1120})\overline{Y}_1 & -(\sigma_v^{1120} + 2\sigma_v^{1122})\frac{\overline{Y}_1^2}{\overline{Y}_2} \\ -\sigma_v^{1120}\overline{Y}_1 - 2\sigma_v^{1122}\overline{Y}_1 & 2(\sigma_v^{2200} + \sigma_v^{2211})\overline{Y}_2 + 0.5(\sigma_v^{1210} + \sigma_v^{1120}\frac{\overline{Y}_1}{\overline{Y}_2})\overline{Y}_1 \end{pmatrix} \\
Q_1 &= \begin{pmatrix} \sigma_v^{1100} + \sigma_v^{1122} + \sigma_v^{1120} & 0 \\ 0 & -\sigma_v^{2211} \end{pmatrix}, \\
Q_2 &= \begin{pmatrix} -\sigma_v^{1120} - \sigma_v^{1122} & \frac{1}{2}\sigma_v^{1210} \\ 0 & \sigma_v^{2200} + \sigma_v^{2211} \end{pmatrix}.
\end{aligned}$$

- To solve, neglect Q term at large T and solve for ΔY
- Relic density $\Omega\, h^2 = \Omega_1\, h^2 + \Omega_2 h^2$

Assisted freeze-out

- Simpler case : Z_2XZ_2 only interactions x_2x_2-x_1x_1 (α) and x_1x_1-SM,SM (β) - assume no x_2x_2->SM,SM
- When 22-11 interactions stronger than 11-00, Y_2 much reduced DM dominated Y_1



GB, Park,J.C., JCAP1203(2012) 038

Inert doublet+singlet model

- 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^+

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

- sector 1 : SS*-> hh
- sector 2 similar Inert doublet, DM either A,H
  - annihilation WW,WW*,ffbar, co-annihilation

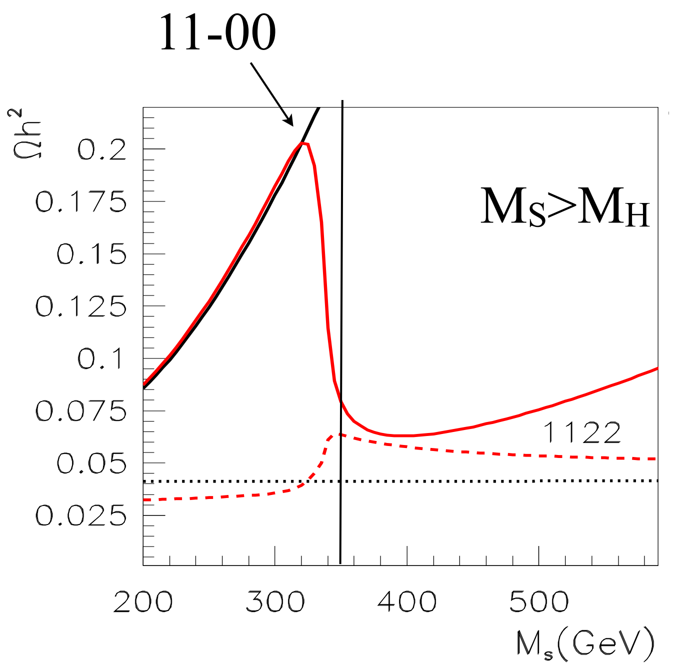
- Benchmark

λ_2	0.1	λ_{S1}	0.1	λ'_S	0.1	M_A	341 GeV
λ_3	0.1	λ_{S2}	0.3	μ_S	100 GeV	M_H	339 GeV
λ_4	0.01	λ_{S12}	0.13	M_h	125 GeV	M_S	350 GeV
λ_S	0.1	λ_{S21}	0.13				

- Two DM candidates with comparable contribution to relic density + semi-ann important + DM conversion

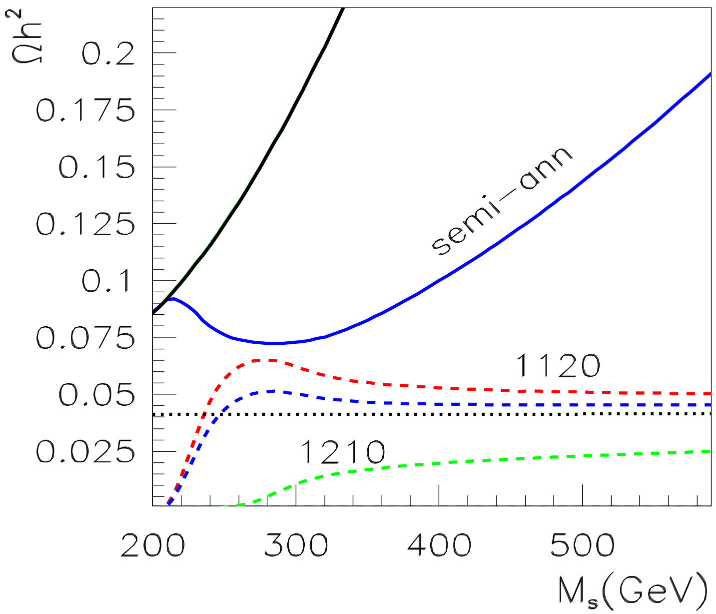
- $\Omega\, h^2 = \Omega_1\, h^2 + \Omega_2 h^2 = 0.1$
- Weak interaction of sector 1 (S) with SM particles

DM conversion



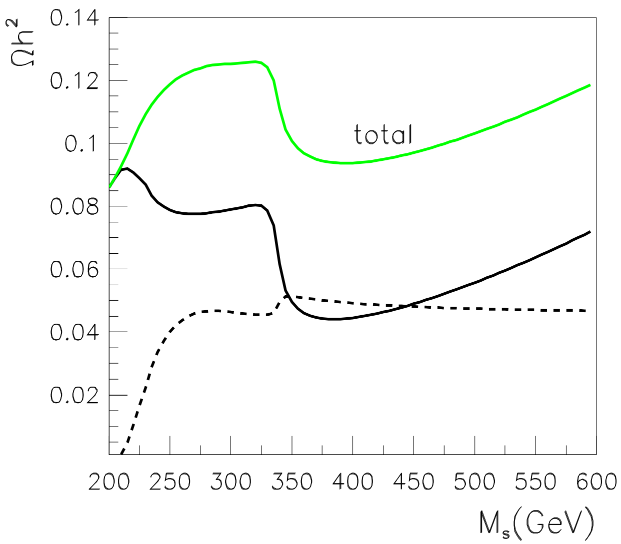
- T_{fo} (heavy)> T_{fo}(light), at freeze-out of heavy component hh->ll adds to hh->00 and lead to decrease of heavy DM abundance
- interaction hh->ll increase abundance of light component
- Effect large when $M_S>M_H$ since 1122>>1100

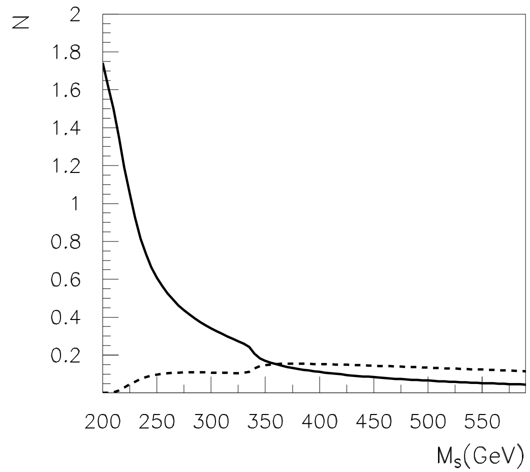
Semi-annihilation



- 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

All interactions





Expected number of events in Xenon100 with 1171 kg-day

- Semi-annihilation dominant $M_S < M_H$, assisted freeze-out important when $M_S > M_H$

CONCLUSION

- Larger discrete symmetry group lead to new mechanisms for relic density of dark matter
- Illustrate with Doublet + singlet DM model and Z_3,Z_4 symmetry
- More complete investigation of DM properties in Z_3, Z_4 models including direct/indirect signatures (in progress)