Semi-Annihilating Scalar Dark Matter

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2 $\mathbb{Z}_2$ and Beyond

- Why is WIMP dark matter stable?
- The simplest symmetry – parity $\mathbb{Z}_2$
- But also possible: $\mathbb{Z}_3$, $\mathbb{Z}_4$, …

3 New Phenomena for $\mathbb{Z}_N$, $N > 2$

For several species of dark matter x_i:

- Semi-annihilation $x_i\, x_j \to x_k\, X$,
  d'Eramo & Thaler 1003.5912,
  Hambye 0811.0172,
  Hambye & Tytgat 0907.1007
- Dark matter conversion $x_2 x_2 \leftrightarrow x_1 x_1$
  Liu, Wu & Zhou 1101.4148, Bélanger & Park 1112.4491,
  Adulpravitchai, Batell & Pradler 1103.3053

4 $\mathbb{Z}_N$ Symmetries

Field φ with charge X_φ transforms under $\mathbb{Z}_N$ as

$$\varphi \to e^{i \frac{X_\varphi}{N} 2\pi} \varphi$$

- Addition modulo N
- Discrete charges $X = 0, 1, \ldots, N-1$

5 $\mathbb{Z}_N$ Symmetries

- $SO(10) \supset U(1)_X \to \mathbb{Z}_N$ by a GUT Higgs with $X = N$
- Different assignments of charges can give the same low evergy potential
- Limited number of Lagrangian terms due to renormalisability
- For higher N, the $U(1)_X$ symmetric part plus one or two terms

6 Scalar Dark Matter

- Scalars – simplest dark matter
- May be seen via the Higgs portal
- New scalars can improve vacuum stability of the SM Higgs potential

7 Simplest Scalar Dark Matter

- Standard Model Higgs H
- Singlet S
- $\langle \mathrm{H} \rangle = \frac{v}{\sqrt{2}}, \langle S \rangle = 0$

8 $\mathbb{Z}_3$ Invariant Potential

$$V_{\mathbb{Z}_3} = \mu_H^2|H|^2 + \lambda_H|H|^4 + \mu_S^2|S|^2 + \lambda_S|S|^4 + \lambda_{SH}|S|^2|H|^2 + \frac{\mu_3}{2}(S^3 + S^{\dagger 3})$$

with $X_H = 0, X_S = 1$

Bélanger, K. K., Pukhov, Raidal, 1211.1014

Ma, 0708.3371

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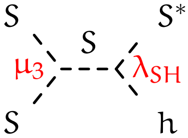
Semi-annihilation



9 Bound on μ_3

Too large μ_3 would break $\mathbb{Z}_3$, yielding the bound

$$\max \mu_3 \approx 2\sqrt{2}\sqrt{\frac{\lambda_S}{\delta}} M_S,$$

where $0 \leqslant \delta \leqslant 2$

- $\delta = 2$ gives absolute stability
- $\delta < 2$ gives metastability

Adams, hep-ph/9302321

Higgs boson hints at vacuum bubble apocalypse

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Wed, 20 Feb 2013 1:21p.m.

The calculation rests on the mass of the particle believed to be the Higgs boson (file pic)

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Tags

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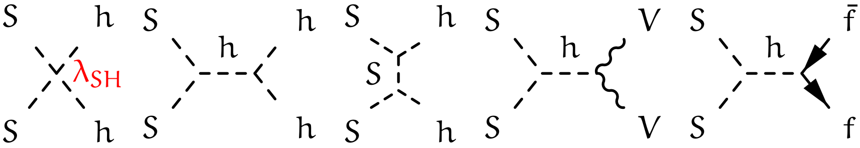
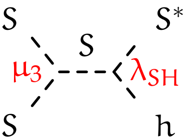
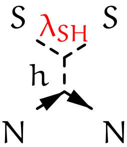
11 Relic Density & Direct Detection



Annihilation



Semi-annihilation



Direct detection

12 Relic Density

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

- Fraction of semi-annihilation

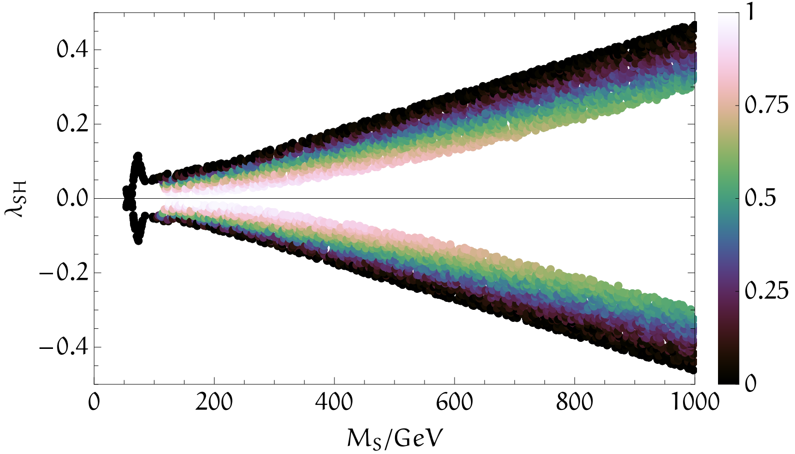
$$\alpha = \frac{1}{2}\frac{v\sigma^{SS\to S^*X}}{v\sigma^{SS^*\to XX} + \frac{1}{2}v\sigma^{SS\to S^*X}}$$

Parameter Space

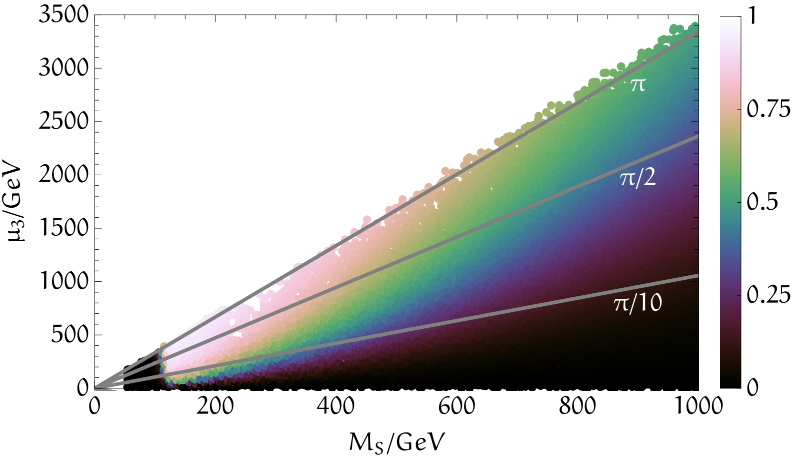
- $1\ \text{GeV} \leqslant M_S \leqslant 1000\ \text{GeV}$
- $0\ \text{GeV} \leqslant \mu_3 \leqslant 4000\ \text{GeV}$
- $0 \leqslant \lambda_S \leqslant \pi$
- $-2\pi \leqslant \lambda_{SH} \leqslant 2\pi$
- The WMAP 3σ range

$$\Omega h^2 = 0.1009 \pm 0.0056$$

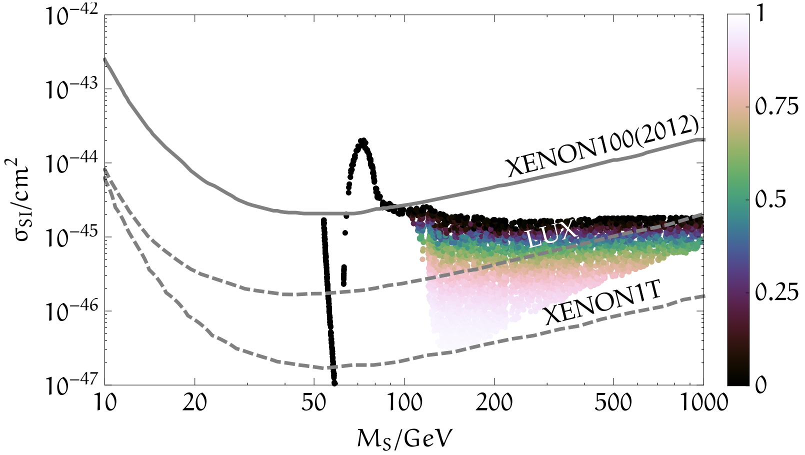
$|S|^2|H|^2$ Coupling λ_{SH} *vs.* M_S



Cubic Coupling μ_3 *vs.* M_S



Direct Detection



17 Scale of New Physics

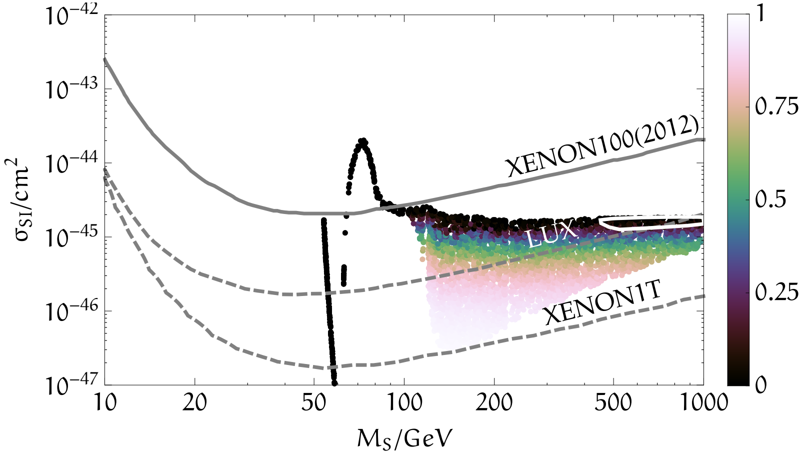
What is the scale of validity from

- perturbativity,
- vacuum stability?

In RGE running to higher energies,

- $\lambda_{SH} > 0$ stabilises the scalar potential
- Large λ_S blows up perturbativity

Direct Detection



$\mathbb{Z}_3$ Singlet & Inert Doublet

- Standard Model Higgs H_1
- Inert doublet H_2
- Complex singlet S
- S and H_2^0 mix into $x_1 \approx S$ and $x_2 \approx H_2^0$ with $M_{x_1} < M_{x_2}$

20 $\mathbb{Z}_3$ Invariant Potential

Quartic semi-annihilation coupling

$$V_{\mathbb{Z}_3} \supset \frac{\lambda_{S12}}{2}\left(S^2 H_1^\dagger H_2 + S^{\dagger 2} H_2^\dagger H_1\right)$$

$\mathbb{Z}_3$ Processes

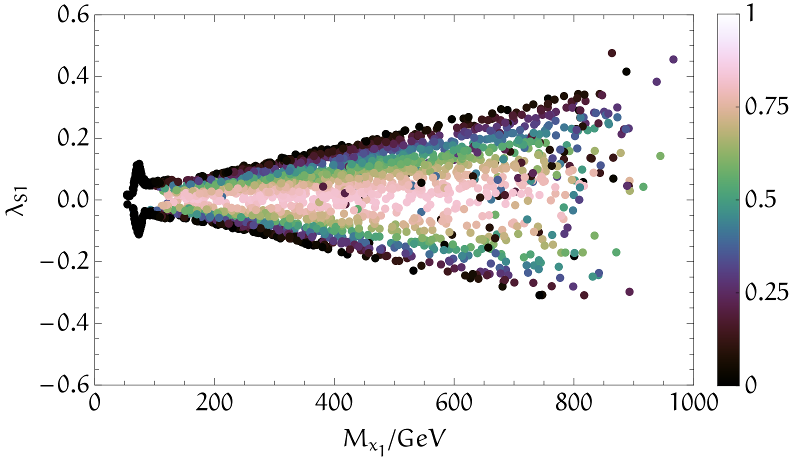
Annihilation

$$x_1 x_1^* \to XX$$

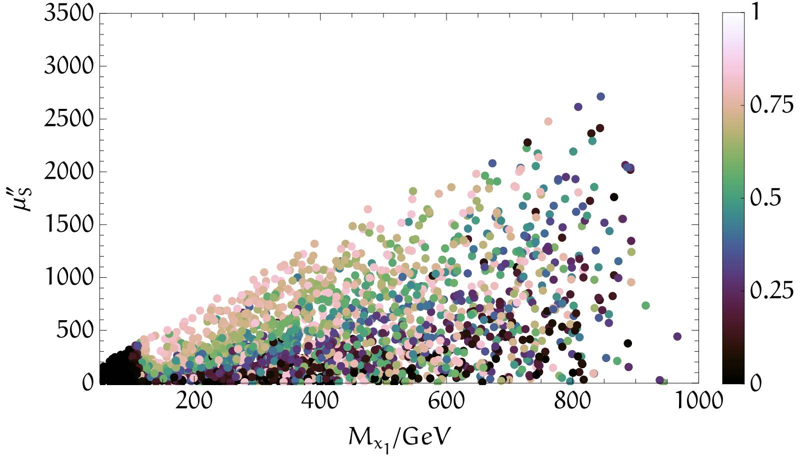
Semi-annihilation

$$x_1 x_1 \to x_2 X$$

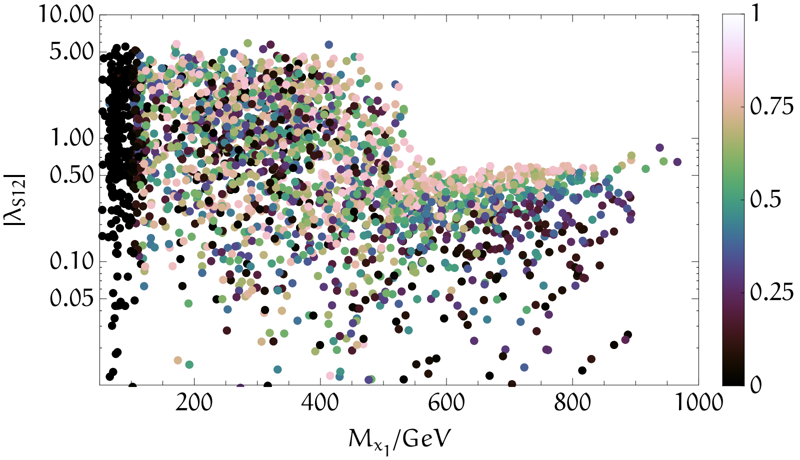
$|S|^2|H_1|^2$ Coupling λ_{S1} *vs.* M_{χ_1}



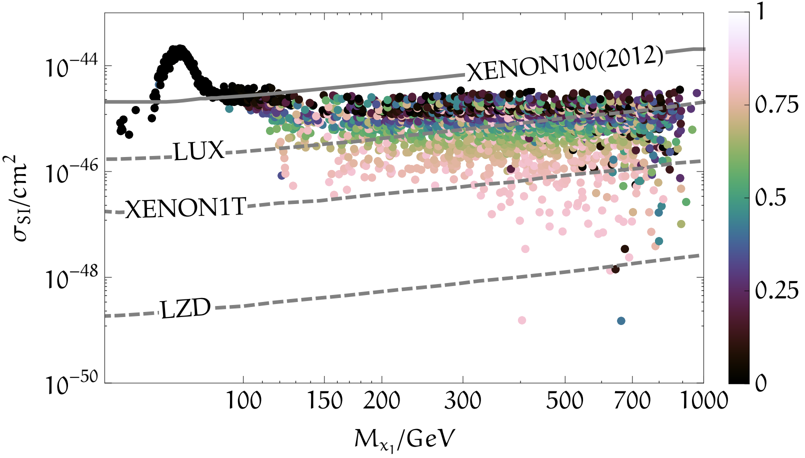
Cubic Coupling μ_S'' *vs.* M_{χ_1}



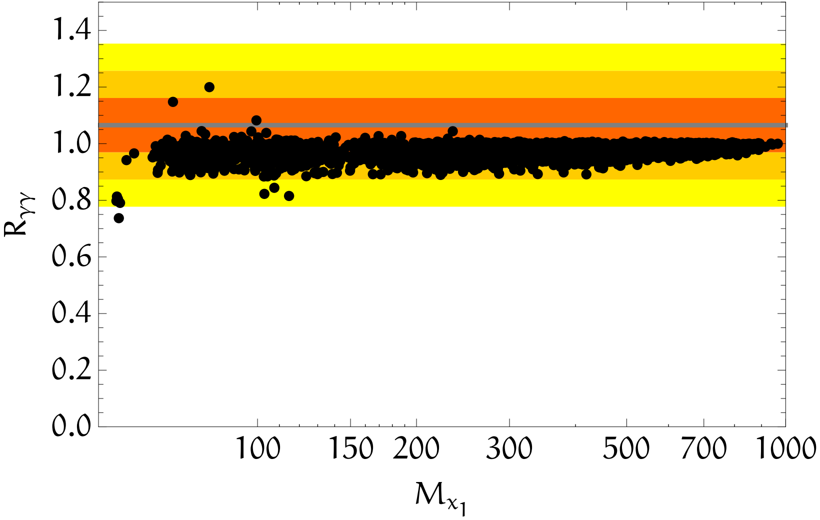
$\lambda_{S12} S^2 H_1^\dagger H_2$ Coupling *vs.* M_{χ_1}



Direct Detection



$h \to \gamma\gamma$ at LHC



Conclusions

- *The* simplest model with semi-annihilation: $\mathbb{Z}_3$ scalar singlet dark matter
- Semi-annihilation yields lower σ_{SI} for a given Ω
- Large semi-annihilation needs TeV-scale new physics
- Models with H_1, H_2, S have quartic semi-annihilation terms for $\mathbb{Z}_N$, $N > 2$
- Work in progress: Z_4 model with two-component DM