

An update on scalar singlet dark matter

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With: Jim Cline, Kimmo Kainulainen & Christoph Weniger
(arXiv:1306.4710)

Slides available from <http://www.physics.mcgill.ca/~patscott>



What is the scalar singlet model?

- Ultra-minimal dark matter model (Silveira & Zee, PLB 1985)
- 1 new scalar particle S , SM gauge singlet
 - 4 new (renormalizable) Lagrangian terms not forbidden by any symmetries:

$$\mathcal{L}_S = -\frac{\mu_S^2}{2} S^2 - \frac{\lambda_{hs}}{2} S^2 H^\dagger H - \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{\lambda_S}{4} S^4 \quad (1)$$

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 - S^3 and $SH^\dagger H$ terms disallowed



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 - S^3 and $SH^\dagger H$ terms disallowed
- $\partial_\mu S \partial^\mu S = S$ kinetic term, $\lambda_S S^4 = S$ self-interaction
 - So long as $\lambda_S \lesssim 1$ (to remain perturbative), only $\mu_S^2 S^2$ and $\lambda_{hs} S^2 H^\dagger H$ matter for phenomenology



Consequences

After H gets a VEV v_0 during electroweak symmetry-breaking, $\lambda_{hs} S^2 H^\dagger H$ induces hSS and $hhSS$ terms:

$$\mathcal{L}_{S^2|H|^2} \rightarrow O_{hSS} + O_{hhSS} = -\frac{\lambda_{hs} v_0}{2} hSS - \frac{\lambda_{hs}}{4} hhSS \quad (2)$$

Introduces two new interaction vertices:



S gets mass contributions from bare term $\mu_S^2 S^2$ and new SS term also induced by $\lambda_{hs} S^2 H^\dagger H$:

$$m_S = \sqrt{\mu_S^2 + \frac{\lambda_{hs} v_0^2}{2}} \quad (3)$$



Advantages

Question

Why is the scalar singlet model attractive?

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Why is the scalar singlet model attractive?

Answers

- Occam's razor: super-simple, just one singlet scalar and a Z_2 symmetry
- 2 parameters only: λ_{hs} , m_S (or trade for μ_S if you prefer)
- All phenomenology fully calculable, some extremely straightforwardly
- Predictive and very testable



Advantages

Question

Can it solve the hierarchy problem / give me 130 GeV lines / low-mass DM / make my lunch?



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Answers

Not really. . .

- any hierarchy 'solution' would require fine-tuning and probably not hold at higher orders anyway
- 130 GeV line requires additional charged scalar
- Low-mass direct detection is conceivable, but parameters are ruled out (**more later**)
- Electroweak baryogenesis works, but not with S as all DM (**more later**)



Phenomenology

Plenty of phenomenological studies over the years. . .

- Pre-LHC investigations of collider and dark matter detection prospects

(e.g. McDonald hep-ph/0106249, Burgess et al. hep-ph/0011335, Patt & Wilczek hep-ph/0605188, Barger et al. 0706.4311, 1008.1796)

- As an explanation for DAMA/CoGeNT/CRESST

(Andreas et al. 0808.0255, 1003.2595, Tytgat 1012.0576)

- Indirect detection prospects

(Yaguna 0810.4267, Goudelis et al. 0909.2799, Arina & Tytgat 1007.2765)

- As a way to achieve baryogenesis

(Profumo et al. 0705.2425, Barger et al. 0811.0393, Cline & Kainulainen 1210.4196)

- Impacts of early LHC searches, XENON-100

(e.g. Mambrini 1108.0671, Djouadi et al. 1205.3169)



Phenomenology

Question

Why the update?



Phenomenology

Question

Why the update?

Answers

- Include 125 GeV Higgs
- Update to new LHC and XENON100 limits
- Add *Fermi* dwarf and CMB limits (best ID limits available)
- Treat models with sub-dominant relic densities consistently
- Higgs-nucleon coupling now much better understood from lattice calculations
- Use full thermal-average $\langle\sigma v\rangle$ for relic density
- Make predictions for CTA, XENON1T, LHC14 TeV



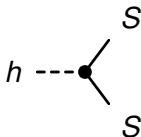
Outline

- 1 Background
- 2 Updated constraints + predictions
 - LHC: Invisible Higgs width
 - Relic density and indirect detection
 - Direct detection



Dude, where's my Higgs?

If S is light enough, the Higgs decay $h \rightarrow SS$ is kinematically allowed:



with rate:

$$\Gamma_{h \rightarrow SS} = \frac{\lambda_{hs}^2 v_0^2}{32\pi m_h^2} \left(m_h^2 - 4m_S^2 \right)^{1/2} \quad (4)$$

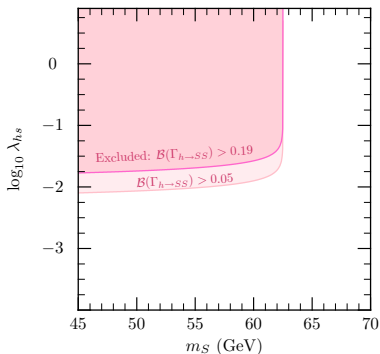
- Higgs production rates (e.g. via gg fusion, vector boson fusion) can be compared to observed h decay rates (e.g. $\gamma\gamma$, $b\bar{b}$, etc) to test for missing decays
- Latest 95% CL combined LHC+Tevatron limit across all production and decay channels is $BF_{SS} < 19\%$ (Belanger et al.

1306.2941)



Constraints

Resulting LHC+Tevatron limits:



300 fb⁻¹ 14 TeV LHC will manage BF limit of 5% (Peskin, arXiv:1207.2516)



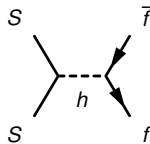
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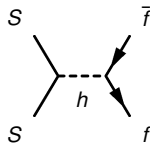
Annihilation Channels

$$SS \rightarrow f\bar{f}$$

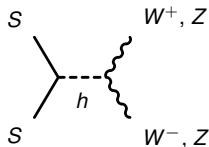


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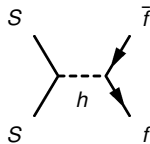


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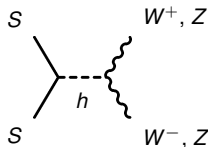


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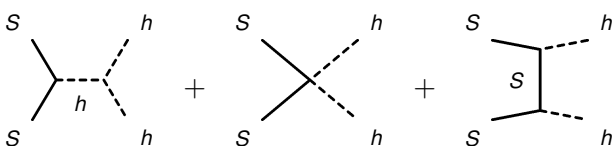
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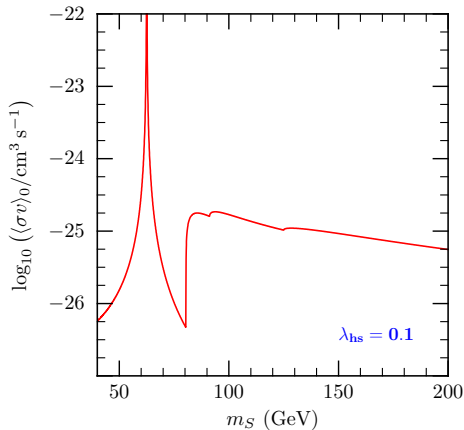


$$SS \rightarrow hh:$$



Annihilation cross-section

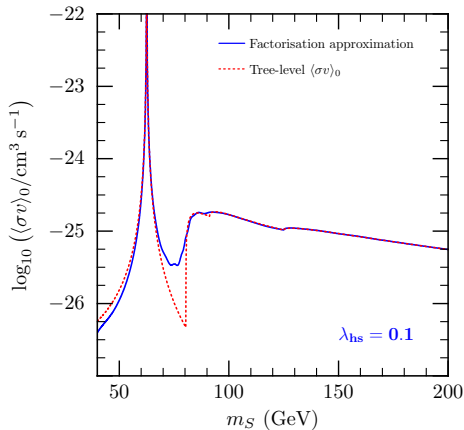
Resulting $\langle\sigma v\rangle_0$:



- Higgs resonance:
 $m_S \sim m_h/2 = 62.5$ GeV
- W, Z thresholds: 4-body final states from $SS \rightarrow V^* \bar{V}^* \rightarrow f\bar{f} f\bar{f}$ become significant just below $m_{W,Z}$



Annihilation cross-section

Resulting $\langle\sigma v\rangle_0$:

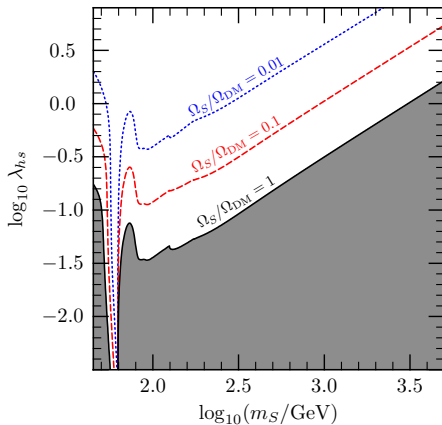
→ better to factor non- hh channels into SSh fusion part \times full Higgs decay width Γ_h to all SM particles:

$$\begin{aligned} \langle\sigma v\rangle_0 &= \langle\sigma v\rangle_{0,hh} + \langle\sigma v\rangle_{0,\text{others}} \\ &= \langle\sigma v\rangle_{0,hh} + \\ &\quad \frac{\lambda_{hs}^2 v_0^2 \Gamma_h}{m_S [(4m_S^2 - m_h^2)^2 + m_h^2 \Gamma_h^2]} \end{aligned} \quad (5)$$



Relic density

Resulting relic densities:



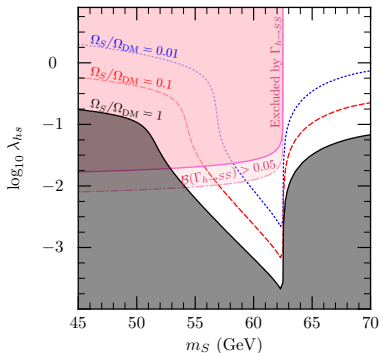
- When $m_S \gtrsim m_h/2$: OK to just get relic density estimate direct from $\langle\sigma v\rangle_0$
(a la Steigman et al. 1204.3622)
- When $m_S < h/2$: must include thermal effects
→ relic density in this region from explicit freeze out calculation (just assuming instantaneous thermalisation – gives a conservative limit)



Relic density

Together with Higgs invisible width, rules out all models with $m_S < 53$ GeV

\Rightarrow DAMA/CoGeNT/CRESST not seeing scalar singlet DM



Indirect Detection Limits

Question

Return of the 4-body final state problem: how does one get $\langle\sigma v\rangle_{0,4f}$ and γ/e spectra for 4-body channels?



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Answer

γ -ray yield per annihilation in WW and ZZ channels is very close to linear with mass (especially near $m_{W,Z}$), so...

- 1 use difference in factorised and tree-level annihilation cross-sections to estimate missing BFs
- 2 assign missing BF to ' $SS \rightarrow V^* \bar{V}^*$ ' channel for $m_S < m_V$
- 3 analytically extrapolate $SS \rightarrow V \bar{V}$ γ -ray spectra below m_V to estimate $SS \rightarrow V^* \bar{V}^* \rightarrow f\bar{f} f\bar{f}$ spectra



Indirect Detection Limits

1 *Fermi*-LAT 3-year combined dwarf gamma-ray limits

(Geringer-Sameth & Koushiappas 1108.2914, *Fermi*-LAT Collab 1108.3546)

- Implemented from *full set of CLs* on gamma-ray flux particle physics parameter Φ_{PP} (1108.2914; kindly provided by Alex Geringer-Sameth)

2 CMB constraints on energy injection (WMAP7 / Planck polarisation)

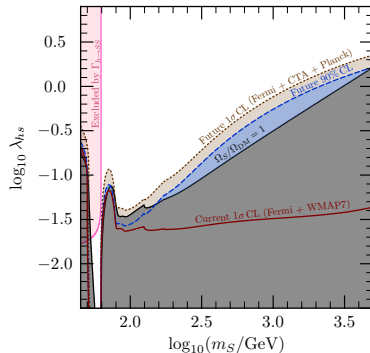
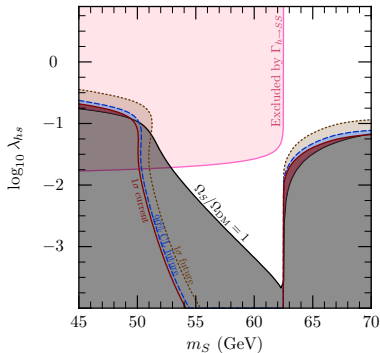
- Implemented with tabulated likelihoods for all SM final states (Cline & PS 1301.5908)

→ Model-by-model *Fermi* + CMB combination of limits from all final states, according to actual branching fractions at each $\{m_S, \lambda_{hs}\}$.



Indirect Detection Limits

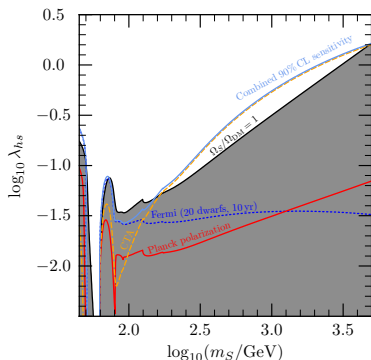
Resulting ID limits:



- Current ID reveals slight tension at $\geq 1\sigma$ level in small parts of parameter space, but not much better than that
- Future searches (*Fermi* 10 yr, 20 dwarfs + Planck pol. + CTA 500 hr GC) will exclude more at 90% CL; yet more will be in $\geq 1\sigma$ tension.



Contributions to ID limits



As expected, *Fermi* dominates at low masses, CTA at high masses – but making realistic CTA projections is a bit like predicting the weather. . . (systematics? *J* factors? observing strategy? observatory configuration??)

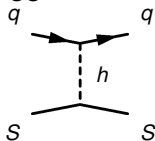


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Higgs portal interactions give spin-independent nuclear scattering via t -channel Higgs exchange:



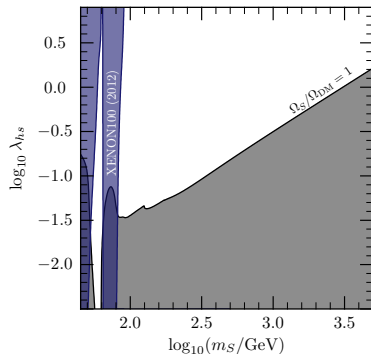
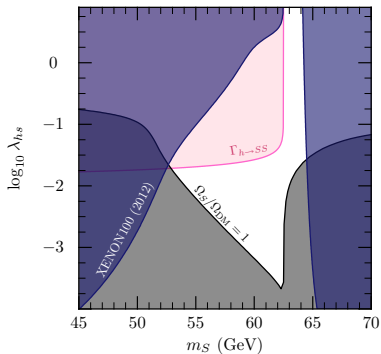
Cross-section in terms of S - N reduced mass μ_N is quite simple:

$$\sigma_{\text{SI},N} = \frac{\lambda_{hs}^2 f_N^2 \mu_N^2 m_N^2}{4\pi m_h^4 m_S^2}. \quad (6)$$

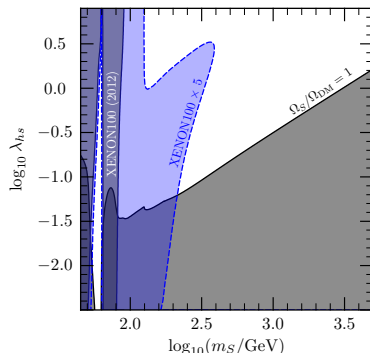
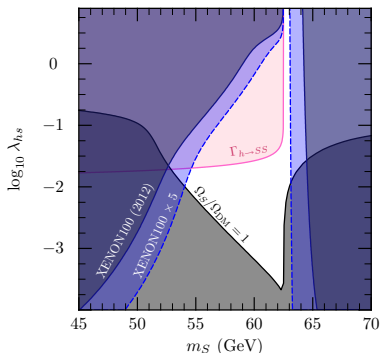
- Pion nuclear sigma uncertainty recently reduced (ChPT, lattice vals \uparrow to ~ 60 MeV – matches experiment)
 - strange quark content of nucleons now not as important
 - Higgs- N effective coupling now $f_N \sim 0.345 \pm 0.02$
- Following results just use standard Maxwellian halo.



Resulting direct limits:



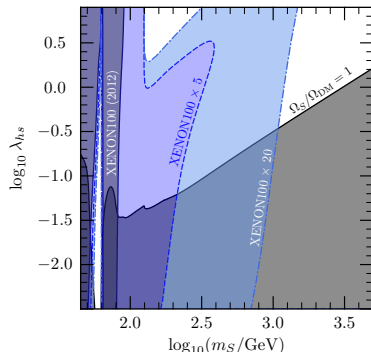
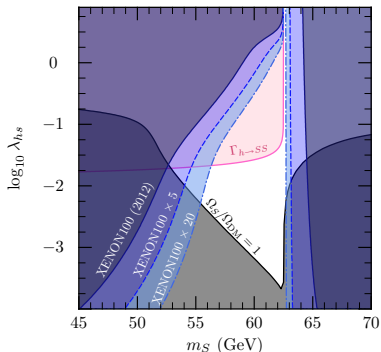
Resulting direct limits:



- Future direct detection experiments (LUX, XENON-1T, DARWIN) will probe most of the parameter space...
- ...yet a small window at $m_S \sim 60$ GeV will remain viable.



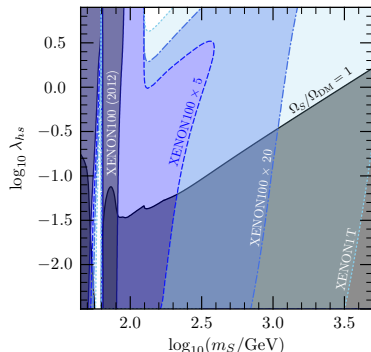
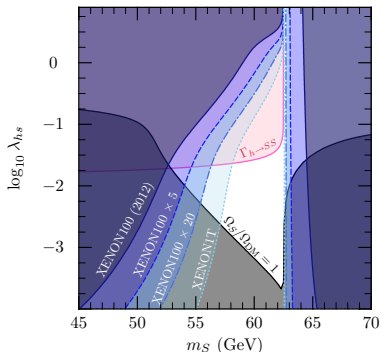
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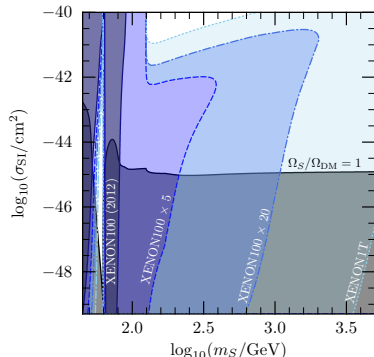
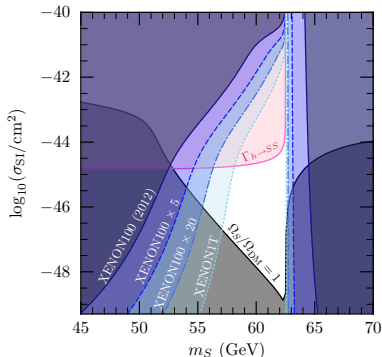
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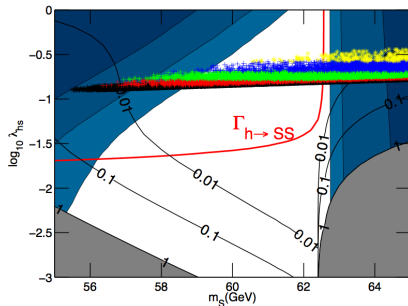
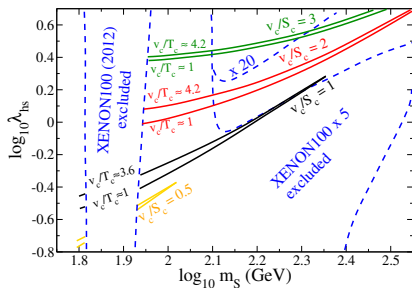
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Electroweak baryogenesis with S



- Electroweak baryogenesis (EWBG) is possible with singlet model, but not at the same time as $\Omega_S/\Omega_{DM} = 1$
- Future DD will squeeze the EWBG parameter space severely.



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- Signals expected in LHC, direct detection and indirect detection experiments
- Constraints on parameter space from DD, ID and LHC are highly complimentary
- Model is excluded as explanation for low-mass DM hints/anomalies
- Upcoming experiments (DD especially) will access large parts of the remaining parameter space



Backup Slides



Branching Fractions

