An update on scalar singlet dark matter

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With: Jim Cline, Kimmo Kainulainen & Christoph Weniger

(arXiv:1305.xxxx)

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

What is the scalar singlet model?

- Ultra-minimal dark matter model (McDonald, PRD 1994)
- 1 new scalar particle S, SM gauge singlet

  → 4 new (renormalizable) Lagrangian terms not forbidden by any symmetries:

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

- Impose Z_2 symmetry to make S stable
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- Impose Z_2 symmetry to make S stable
  → 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 $\lambda_{hs}S^2H^\dagger H$ 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:

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

Introduces two new interaction vertices:

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

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

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, *most* very 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, low-mass direct detection are conceivable, but parameters are ruled out (as should become clear) – need supplemental physics

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

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Why the update?

Answers

- Include 125 GeV Higgs
- Add *Fermi* dwarf and CMB limits (best ID limits available)
- Update to new LHC limits
- Treat models with sub-dominant relic densities consistently
- Higgs-nucleon coupling now much better understood from lattice calculations

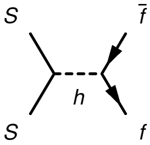
Outline

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

Annihilation Channels

$SS \to f\bar{f}$:

$$\langle \sigma v \rangle_{0,f\bar{f}} = \frac{3\lambda_{hs}^2 m_f^2 \left(m_S^2 - m_f^2\right)^{3/2}}{4\pi m_S^3 \left[(4m_S^2 - m_h^2)^2 + m_h^2 \Gamma_h^2\right]}$$



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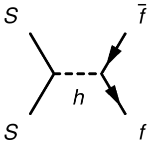
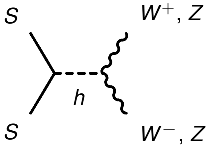


$SS \rightarrow V\bar{V}$ (with $\delta_W = 1, \delta_Z = 1/2$):

$$\langle \sigma v \rangle_{0,V\bar{V}} = \frac{\lambda_{hs}^2 \delta_V \left[2m_v^4 + (m_V^2 - 2m_S^2)^2\right] \left(m_S^2 - m_V^2\right)^{1/2}}{8\pi m_S^3 \left[(4m_S^2 - m_h^2)^2 + m_h^2 \Gamma_h^2\right]}$$



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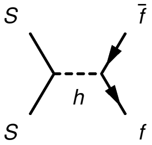

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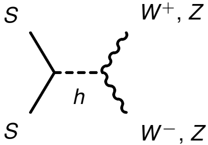

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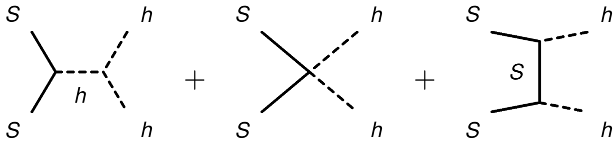

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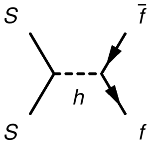

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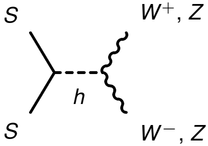
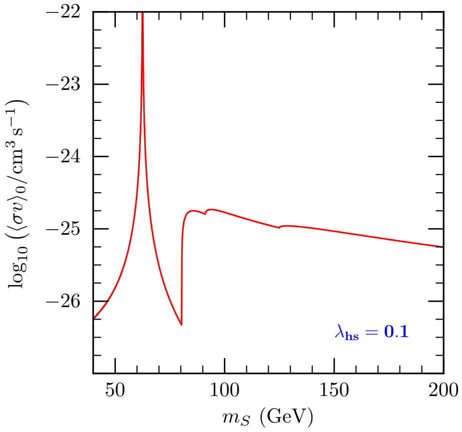


$SS \rightarrow hh$:

$$\langle\sigma v\rangle_{0,hh} = \left(\frac{\lambda_{hs}}{\lambda_h}\frac{\left[m_S^2 - \frac{1}{4}m_h^2\right]^2 m_h^2}{m_S^2 m_h^2 - 2m_S^4} + m_S^2 + \frac{m_h^2}{2}\right)^2 \frac{\lambda_{hs}^2 \left(m_S^2 - m_h^2\right)^{1/2}}{4\pi m_S^3 \left[(4m_S^2 - m_h^2)^2 + m_h^2\Gamma_h^2\right]}$$

Annihilation cross-section

Resulting $\langle \sigma v \rangle_0$:



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

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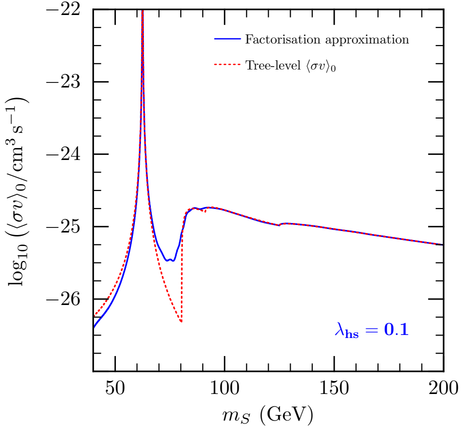
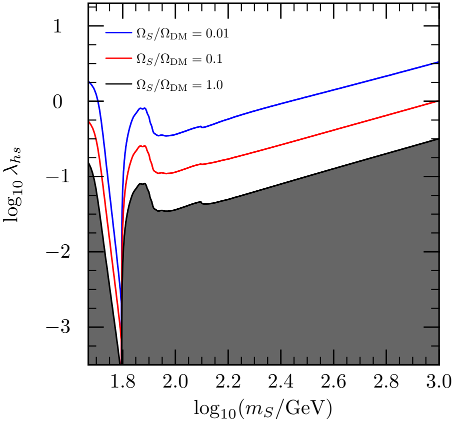


→ better to factor non-*hh* channels into *SSh* fusion part × full Higgs decay width Γ_h to all SM particles:

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

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 $\rightarrow$ relic density in this region from explicit freeze out calculation (just assuming instantaneous thermalisation – gives a conservative limit)

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)

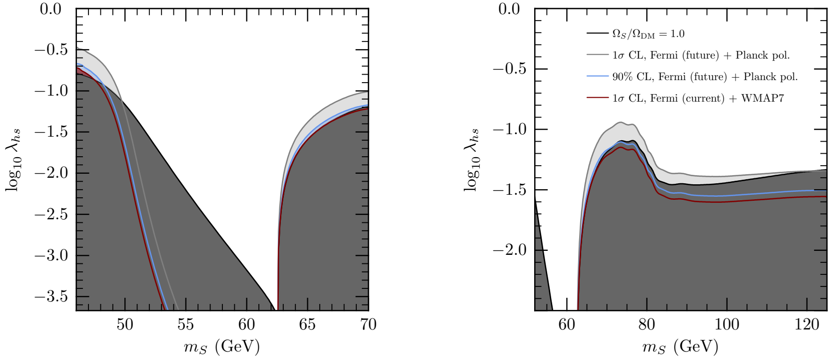
2. CMB constraints on energy injection (WMAP7 / Planck polarisation)

   - 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 as 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 + full Planck results) will exclude more at 90% CL; yet more will be in $\geq 1\sigma$ tension.

Indirect Detection Limits

Question

Return of the 4-body final state problem: how to get $\langle \sigma v \rangle_0$ 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 '$SS \to V^* \bar{V}^*$' channel for $m_S < m_V$
3. analytically extrapolate $SS \to V\bar{V}$ γ-ray spectra below m_V to estimate $SS \to V^* \bar{V}^* \to f\bar{f}\ f\bar{f}$ spectra

Indirect Detection Limits

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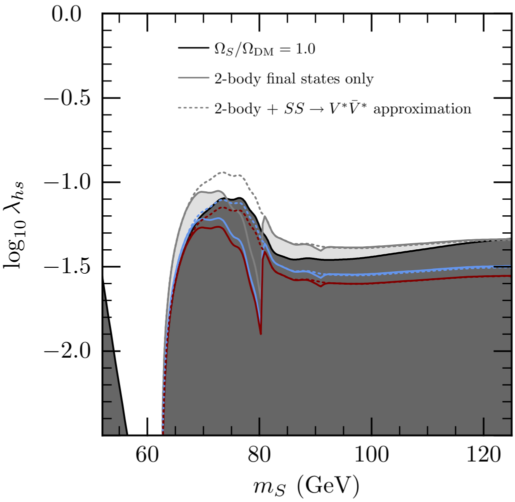

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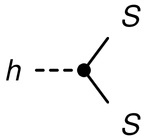
Dude, where's my Higgs?

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



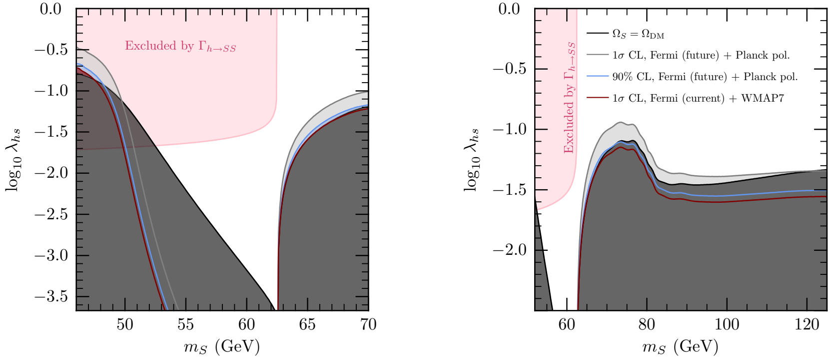
with rate:

$$\Gamma_{h\to SS} = \frac{\lambda_{hs}^2 v_0^2}{32\pi m_h^2}\left(m_h^2 - 4m_S^2\right)^{1/2} \tag{5}$$

- 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 $BF_{SS} < 23\%$ (Belanger et al. 1302.5694)

Constraints

Resulting LHC+Tevatron limits:



- Together with relic density, rules out all models with $m_S < 53\,\mathrm{GeV}$

$\Longrightarrow$ DAMA/CoGeNT/CRESST are not seeing scalar singlet DM

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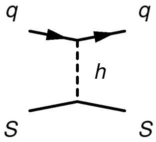
Higgs portal interactions give spin-independent nuclear scattering via *t*-channel Higgs exchange:

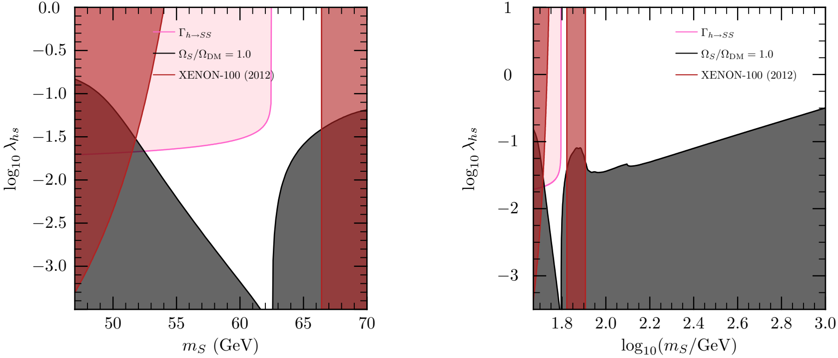


Cross-section in terms of S-N reduced mass μ_N is quite simple:

$$\sigma_{\mathrm{SI},N} = \frac{\lambda_{hs}^2 f_N^2 \mu_N^2 m_N^2}{4\pi m_h^4 m_S^2}. \tag{6}$$

- Pion nuclear sigma uncertainty recently reduced → strange quark content of nucleons now not as much of an issue → Higgs-N effective coupling now f_N ∼0.25–0.26
- Following results just use standard Maxwellian halo – see paper for others.

Resulting direct limits:



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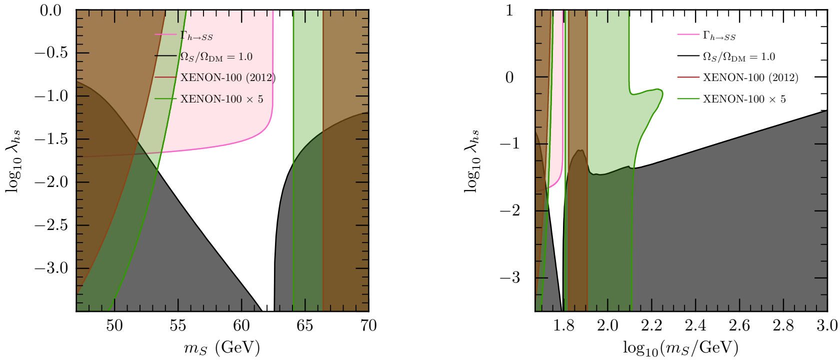

- Future direct detection experiments (LUX, XENON-1T, DARWIN) will probe most of the parameter space…
- …yet a small window at $m_S \sim 60\,\mathrm{GeV}$ will remain viable.

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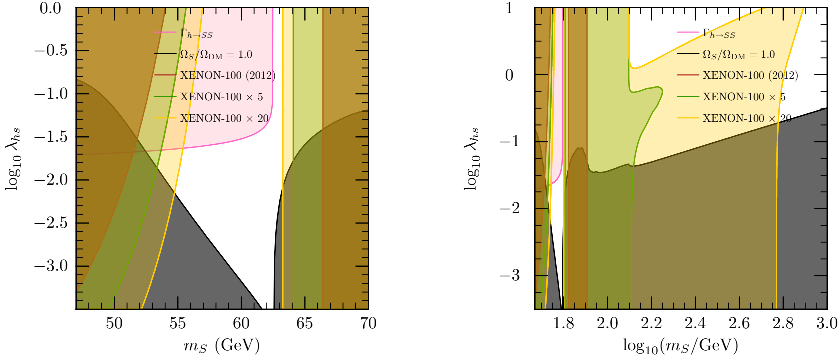

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- Signals expected in LHC, direct detection and indirect detection experiments
- Constraints on parameter space from DD, ID and LHC are highly complimentary
- Model is excluded as explanation for low-mass DM hints/anomalies
- Upcoming experiments (DD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