Extended scalar sectors and dark matter

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Outline

- Scalars as dark matter
- Scalars as mediators

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· Scalars as dark matter

· Scalars as mediators

Basically some notes to start a discussion. For a good part, what I'll discuss is subject to the craftsmanship of the model-builder.

In other words, models can be complicated and constraints can be evaded, that's part of what we do for a living!

How relevant are ESS's to the DM problem ?

There is no *a priori* reason why answering the dark matter question should involve invoking an extended scalar sector. But:

· Dark matter could be a scalar.

· If dark matter is comprised of particles (in the particle physics sense), it should get its mass from somewhere. An extended scalar sector could be involved.

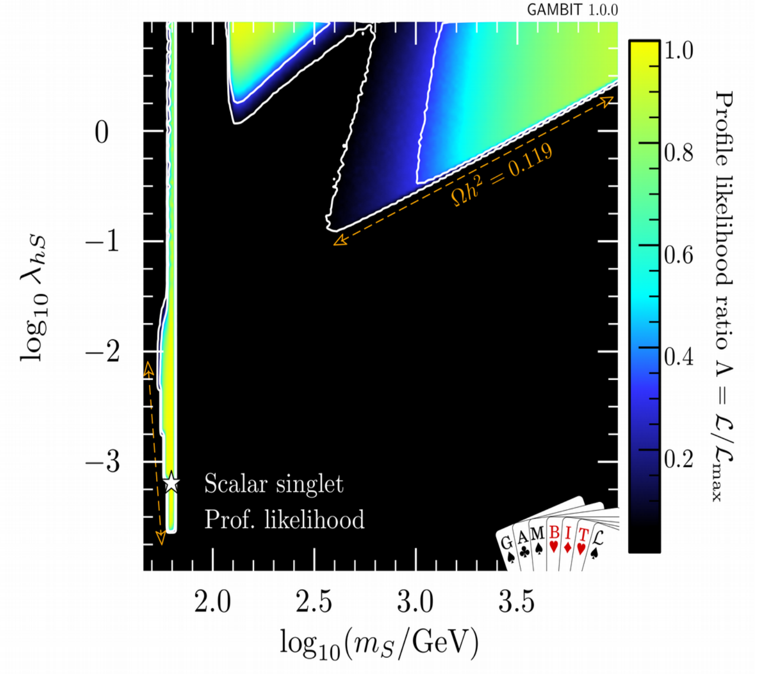
· New scalar degrees of freedom could mediate the dark matter interactions with the Standard Model.

· New scalar degrees of freedom could decay into dark matter particles, thus giving rise to their observed abundance (freeze-in).

Simple scalar DM models - 1

The simplest dark matter model: SM + a real singlet Z_2-odd scalar

GAMBIT, arXiv:1705.07931



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\left(\partial_\mu s\right)\left(\partial^\mu s\right) - \frac{\mu_s^2}{2}s^2 + \frac{\lambda_s}{4}s^4 + \lambda_{Hs}H^\dagger H s^2$$

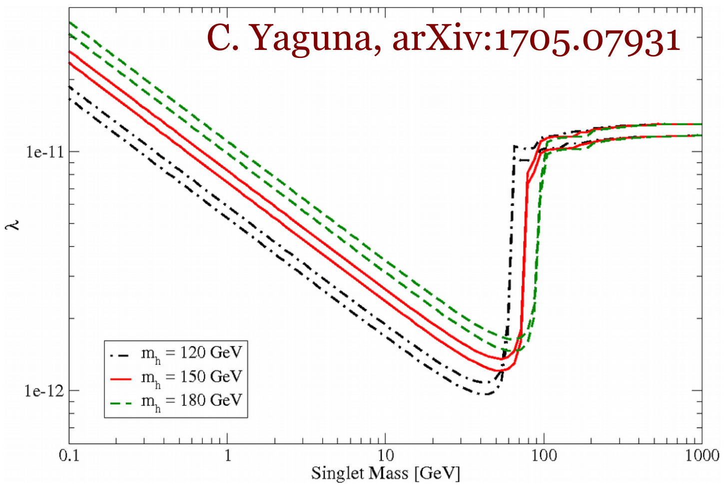
· Need to fine-tune or move to large DM masses.

Mostly driven by Higgs invisible width + direct detection

Will the Higgs funnel always evade detection?

This picture involves strong enough couplings → thermal equilibrium. For very small couplings, rather in the freeze-in regime.

C. Yaguna, arXiv:1705.07931



· All constraints can be evaded within this framework.

· Possible to achieve large self-interactions → solve short-scale issues of ΛCDM.

But issue almost factorisable, modulo remarks in arXiv:1501.08527

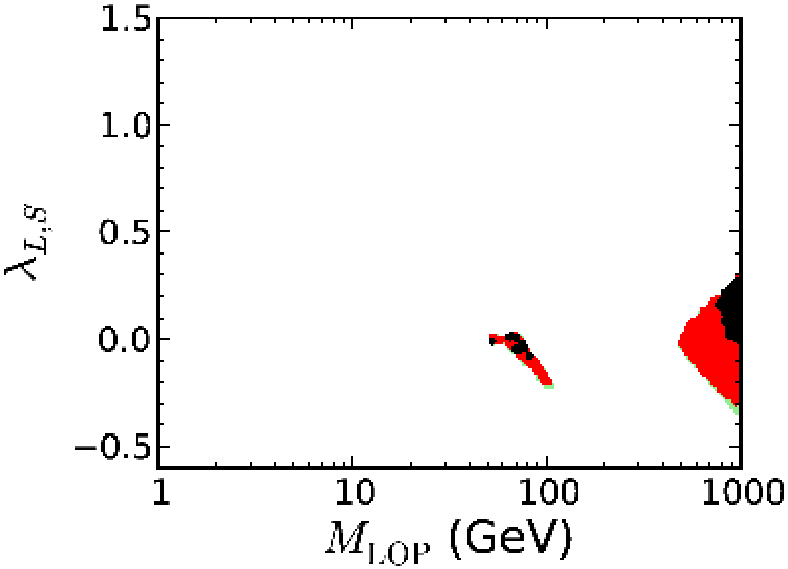
Can we test this scenario?

Simple scalar DM models - 2

Slightly more involved: The Inert Doublet Model (SM + a Z_2-odd complex scalar doublet)

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

A.G., B. Herrmann, O. Stal, arXiv:1303.3010



· More recent constraints from LUX continue along the same lines.

For more updated analyses *cf*
A. Ilnicka, M. Krawczyk, T. Robens arXiv:1508.01671
B. Eiteneuer, A. G., J. Heisig, arXiv:1705.01458

· LHC searches for dileptons + MET and dijets+MET may probe funnel region but not high mass one.

E. Dolle et al, arXiv:0909.3094, G. Bélanger *et al*, arXiv:1503.07367,
P. Poulose, S. Sahoo, K. Sridhar arXiv:1604.03045

· As of (roughly) now, the inclusion of NLO EW corrections to the WIMP-nucleon scattering cross-section becomes necessary for direct detection.

M. Klasen, C. E. Yaguna, J. D. Ruiz-Alvarez, arXiv:1302.1657

$\boxed{\text{Invoking freeze-in is impossible}}$

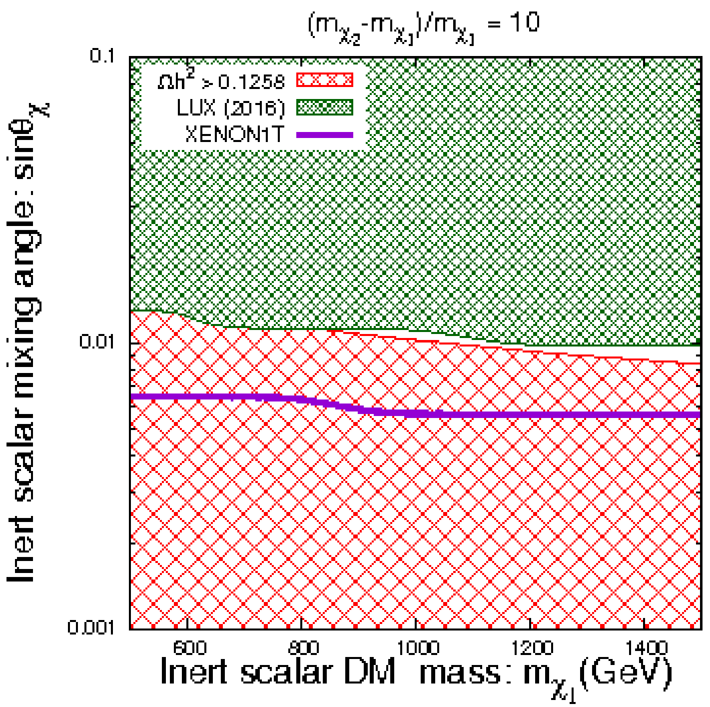
EW interactions too strong

Simple scalar DM models - 3

And a bit more: Doublet-Singlet Scalar complex scalar DM

"Sneutrino-like"

$$V = \mu_H^2 (H^\dagger H) + \frac{\lambda_1}{2}(H^\dagger H)^2 + \mu_\eta^2(\eta^\dagger \eta) + \frac{\lambda_2}{2}(\eta^\dagger\eta)^2 + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) + \lambda_4 (H^\dagger \eta)(\eta^\dagger H)$$
$$+ \mu_s^2 (s^* s) + \frac{\lambda_s}{2}(s^* s)^2 + \lambda_{Hs}(H^\dagger H)(s^* s) + \lambda_{\eta s}(\eta^\dagger \eta)(s^* s) + A(\eta^\dagger H s + \text{h.c.}),$$



M. Kakizaki et al, arXiv:1609.06555

· Lower masses strongly constrained by direct detection, although exact lower χ_1 mass limit depends on heavier scalar mass. For very low masses, additional constraints from h/Z invisible width.

· (not seen) Additional viable region exists around $m_h/2$ → small mixing angle.

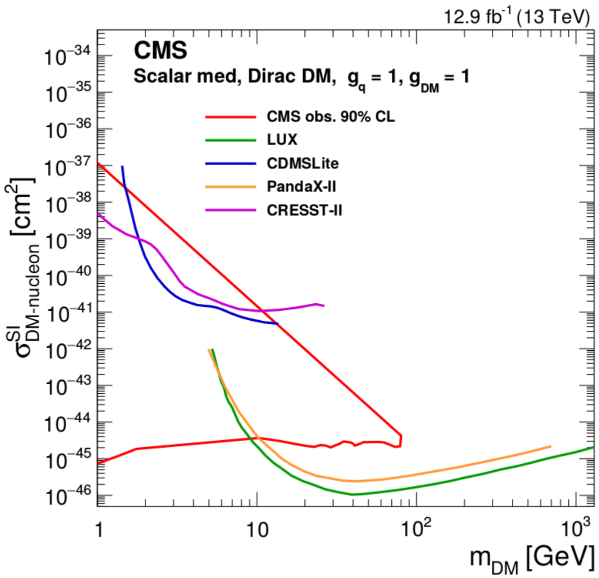
· Eventually, constraints from searches for the heavy partners.

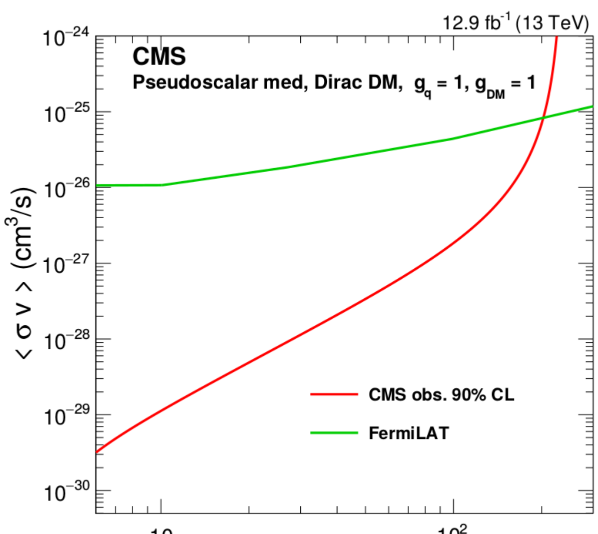
Direct detection severely challenges these scenarios

But freeze-in possible

Scalars as mediators

Scalars could also mediate the interactions of (whatever spin) dark matter with the Standard Model. Until recently, LHC collaborations relied on simplified models:





CMS, arXiv:1703.01651

· Until now, dark matter has mostly been looked for in the mono-X channels.

· Colliders are mostly sensitive to dark matter with masses below $m_{med}/2$.

But DM phenomenology doesn't depend strongly on this condition.

· They don't care much the CP properties of the mediator.

But they are *crucial* for DM phenomenology!

· When direct detection works, it *works*. It doesn't work:

- For light dark matter.

But: C. Kouvaris, J. Pradler arXiv:1607.01789
Or : ask Tien-Tien

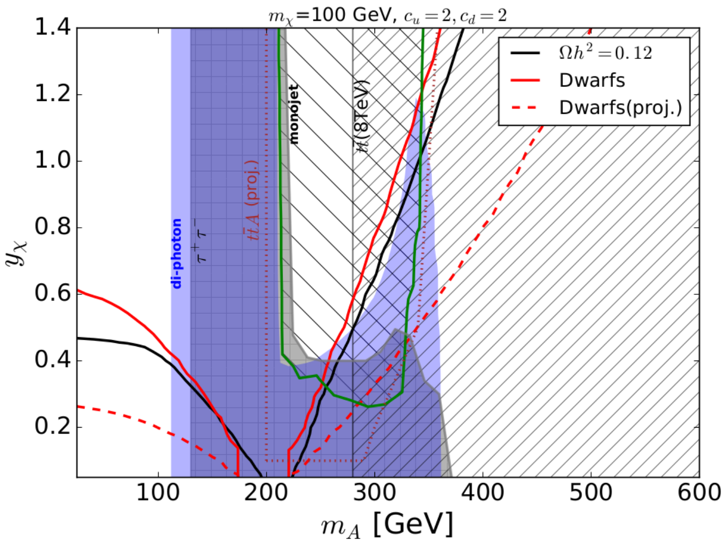
- For pseudoscalar mediators.

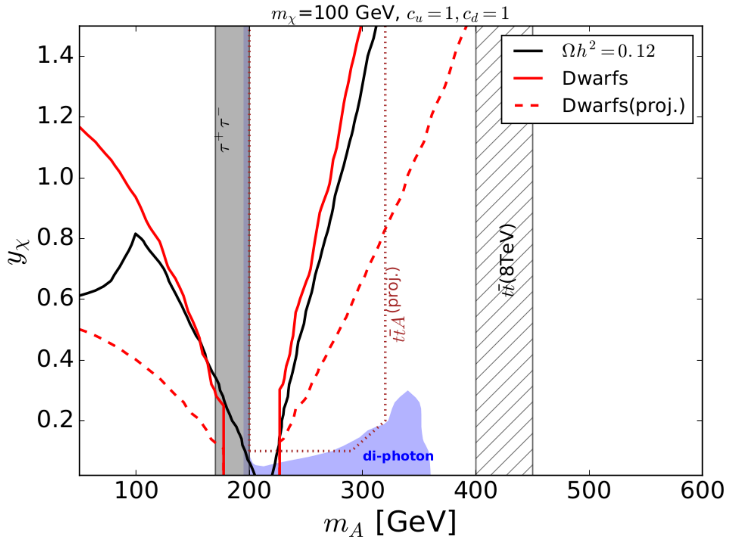
What about the off-shell regime?

Pseudoscalars and the off-shell regime

In the off-shell regime, and for sufficiently high masses, one can look for the mediator itself. And there are many channels one can use!

e.g. M. Chala *et al*, arXiv:1503.05916





S. Banerjee *et al*, arXiv:1705.02327

· Consider Lagrangian as

$$\mathcal{L}_{\rm DS} = \frac{1}{2}(\partial^\mu A)(\partial_\mu A) - \frac{m_A^2}{2}A^2 + \frac{1}{2}\bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi - i\frac{y_\chi}{2}A\bar{\chi}\gamma_5\chi$$

$$\mathcal{L}_{\rm f} = -i\sum_{f_u} c_u \frac{m_{f_u}}{v} A\bar{f}_u\gamma_5 f_u - i\sum_{f_d} c_d \frac{m_{f_d}}{v} A\bar{f}_d\gamma_5 f_d$$

· Would be really useful to provide results also for lower mass scalars.

· So the LHC does seem to say things about dark matter.

But how realistic is this picture in actual models?

e.g. M. Bauer *et al*, arXiv:1701.07427