

Isospin-violating dark matter from a double portal

RPP 2014, Strasbourg

Work in collaboration with G. Belanger, J.-C. Park, A. Pukhov

arXiv:1311.0022, to appear in JCAP

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Outline

- The magnificent world of direct dark matter detection
- ...small clouds and blobs...
- Isospin-violating dark matter and a double portal
- Conclusions

Direct detection of dark matter

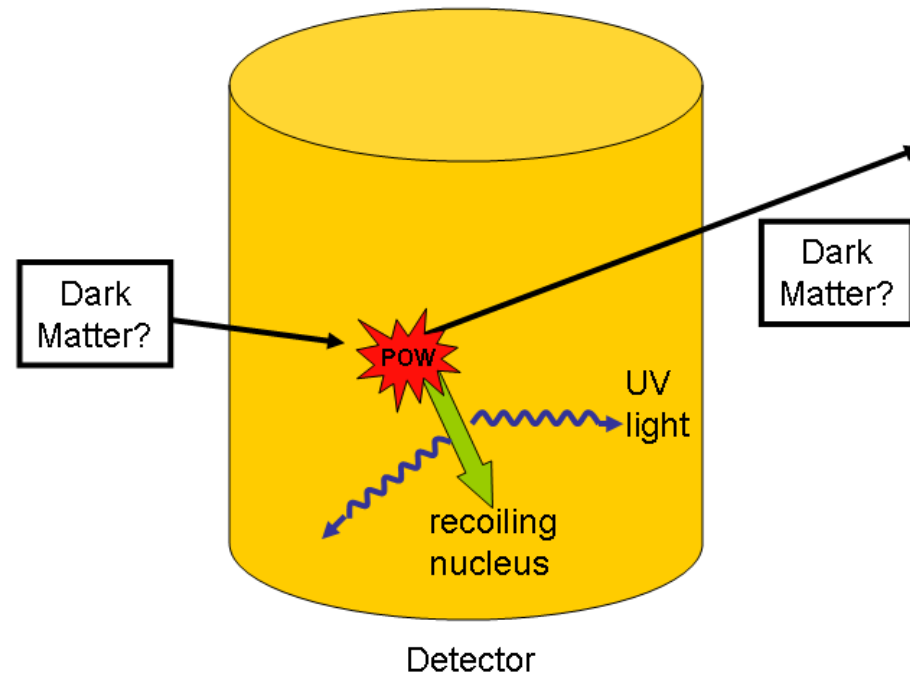
The whole idea of direct dark matter detection starts from a pretty simple hypothesis :

Dark matter could (hopefully) interact with ordinary matter.

NB : If that's true, it probably does so quite weakly, but with a large enough detector, we might stand a chance!

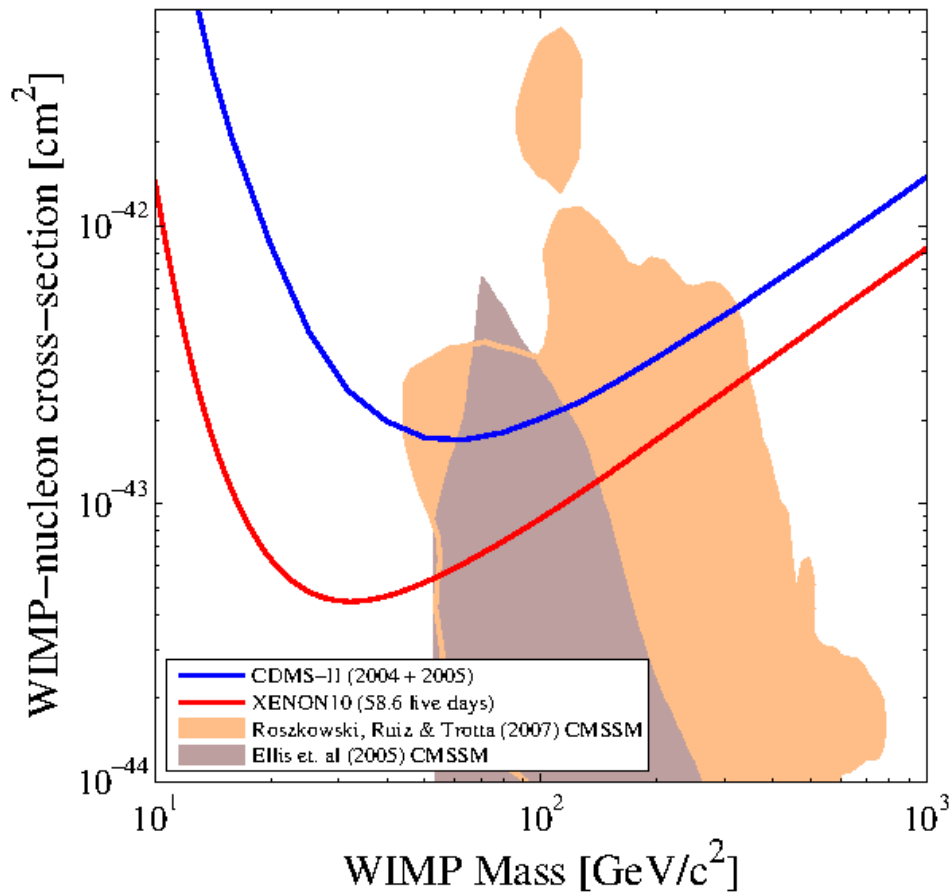
So, let's build large detectors and place them underground, where the bkg is small and just wait...

Goodman, Witten, (1986)

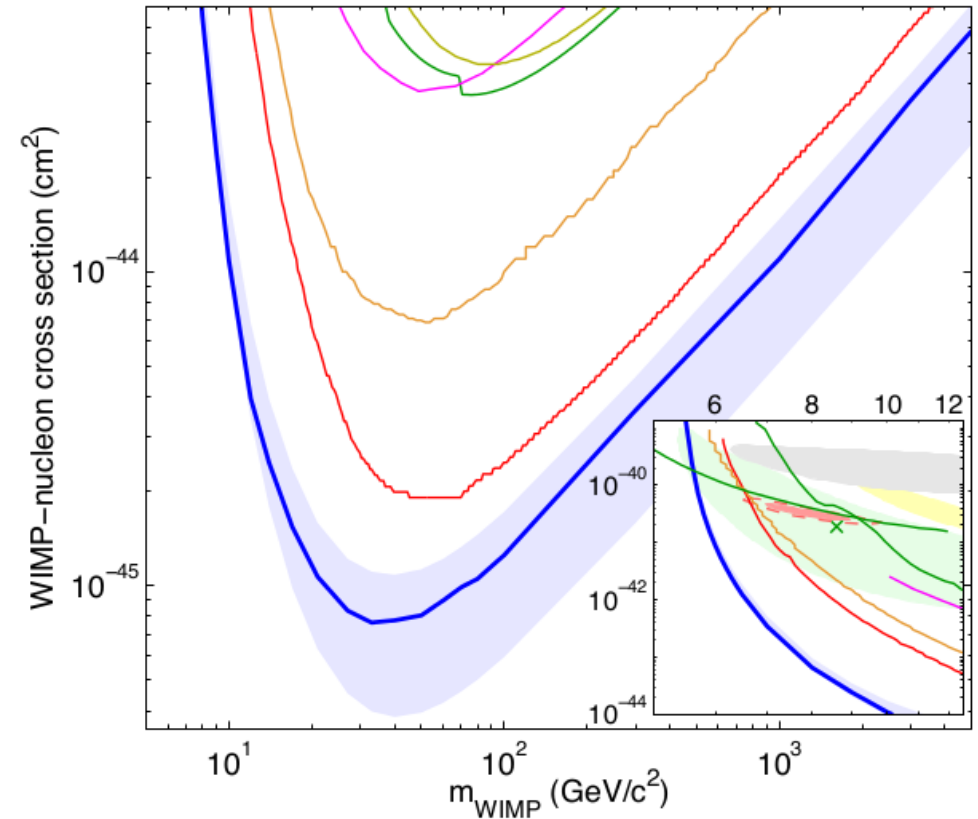


Experiments have kept busy...

Since quite a few years, direct detection experiments have done an amazing job!



Xenon 10, 06/2007



LUX, 10/2013

For $m_x = 40 \text{ GeV}$, we have ~ 2 orders of magnitude improvement!

A concrete example

The Inert Doublet model, “an archetype for dark matter”

Desphande, Ma (1978)

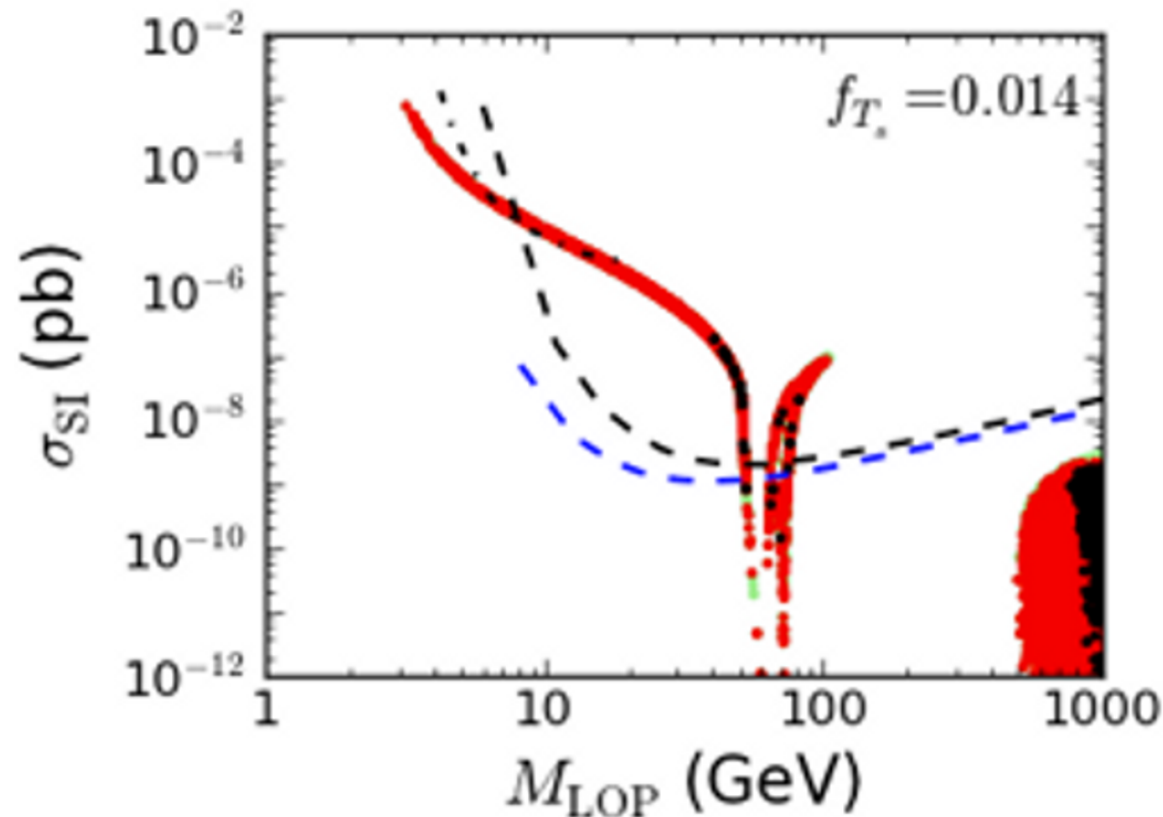
Ma (2006)

Barbieri, Hall, Rychkov(2006)

Honorez, Nezri, Oliver, Tytgat (2006)

A.G., Herrmann, Stal (2013)

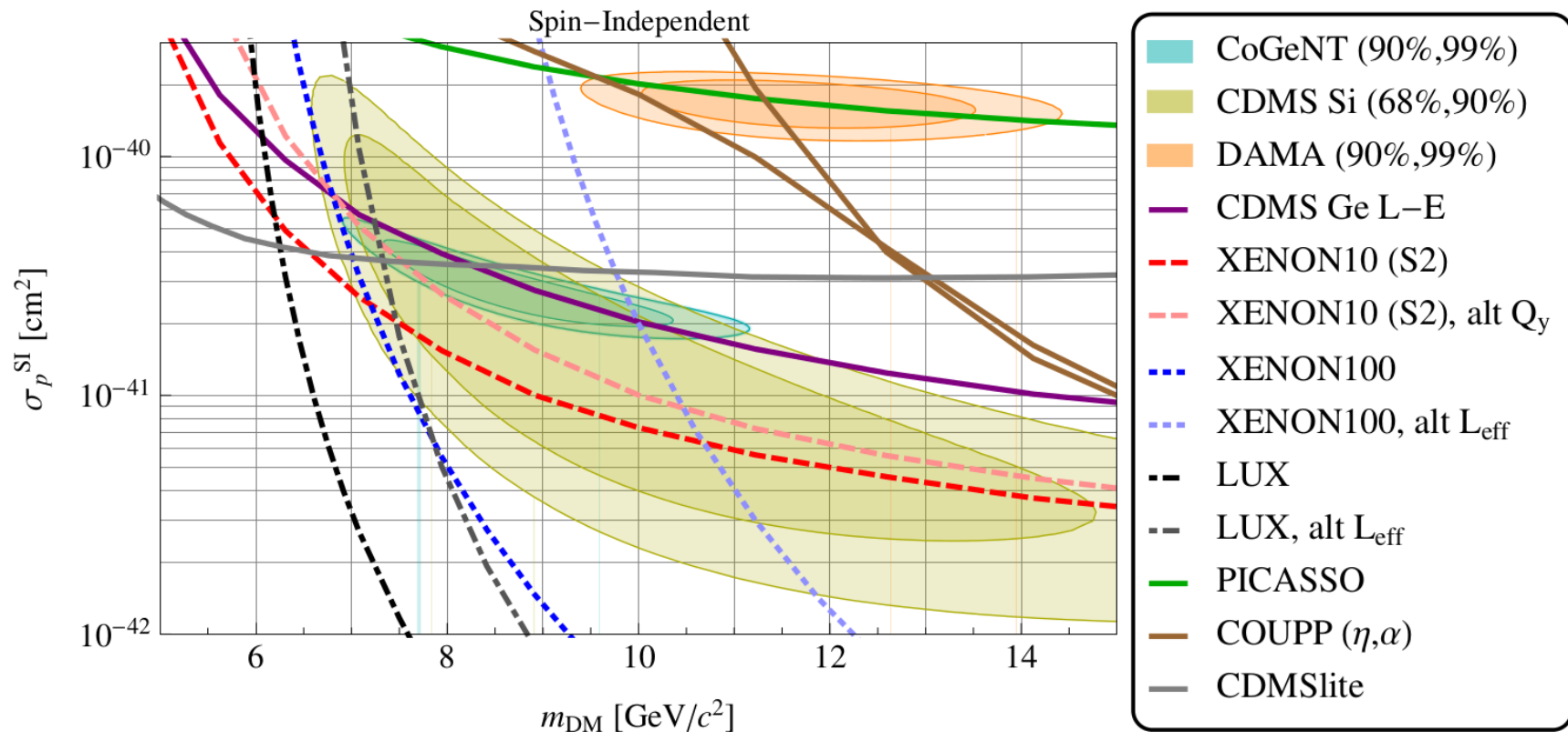
...



**The WIMP-y regime is currently being excluded
(at least for moderate masses)**

...however...

Something is rotten in the kingdom of low-mass DM : weird excesses!



Gresham, Zurek (2013)

- Some unidentified background?
- Something wrong with Xenon response for low DM masses (the L_{eff} wars)?
- Some sort of non-standard DM interaction : IVDM, anapole, dipole, inelastic ...?

Isospin-violating dark matter ?

The cross-section for scattering off a point-like nucleus is

$$\sigma_{\psi Nuc}^0 = \frac{4\mu^2}{\pi} (Z f_p + (A - Z) f_n)^2$$

All experimental results published in the literature assume $f_p = f_n$.

However, if $f_n/f_p = -Z/(A-Z)$, then the two amplitudes interfere destructively and the cross-section can vanish!

Feng, Kumar, Marfatia, Sanford (2011)

E.g. for Xenon, this happens when $f_n/f_p \sim -0.7$.

Note that the cross-section can strictly vanish for *a single* (Z,A) combination.

- Different cross-sections could be expected at experiments using different materials.
- The existence of different isotopes makes it that the cross-section doesn't formally vanish in any experiment.

But how...?

A model for IVDM

Few concrete examples of IVDM exist in the literature.

Fransen, Kahlhoefer, Sarkar, Schmidt-Hoberg (2011)
He, Tandean (2013)

Let's assume a “double portal” extension of the SM by :

- A $U(1)_X$ gauge group.
- A dirac fermion, uncharged under the SM gauge group.
- A real singlet scalar field, giving mass to the extra fermion.

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{SM} &- \frac{1}{2} \sin \epsilon \hat{B}_{\mu\nu} \hat{X}^{\mu\nu} - \frac{1}{4} \hat{X}_{\mu\nu} \hat{X}^{\mu\nu} + \frac{1}{2} m_{\hat{X}}^2 \hat{X}^2 + y_{\psi} S \bar{\psi} \psi + g_X \hat{X}_{\mu} \bar{\psi} \gamma^{\mu} \psi \\ &- \lambda_{SH} S^{\dagger} S H^{\dagger} H + \frac{1}{2} \mu_S^2 S^{\dagger} S - \frac{1}{4} \lambda_S (S^{\dagger} S)^2 + \frac{1}{2} \mu_H^2 H^{\dagger} H - \frac{1}{4} \lambda_H (H^{\dagger} H)^2\end{aligned}$$

→ Further assume some DM asymmetry in the early universe, so that DM is completely dominant over anti-DM.

The IV mechanism

The elastic scattering cross-section is given by

$$\sigma_{\psi Nuc}^0 = \frac{4\mu^2}{\pi} [c(Zf_p + (A - Z)f_n)^2 + \bar{c}(Z\bar{f}_p + (A - Z)\bar{f}_n)^2]$$

where the nucleon amplitudes receive two contributions :

$$f_N = f_N^h \pm f_N^V$$

So, by properly choosing the vector and scalar couplings, we can achieve the IV limit. For simplicity, we'll stick to fully asymmetric DM.

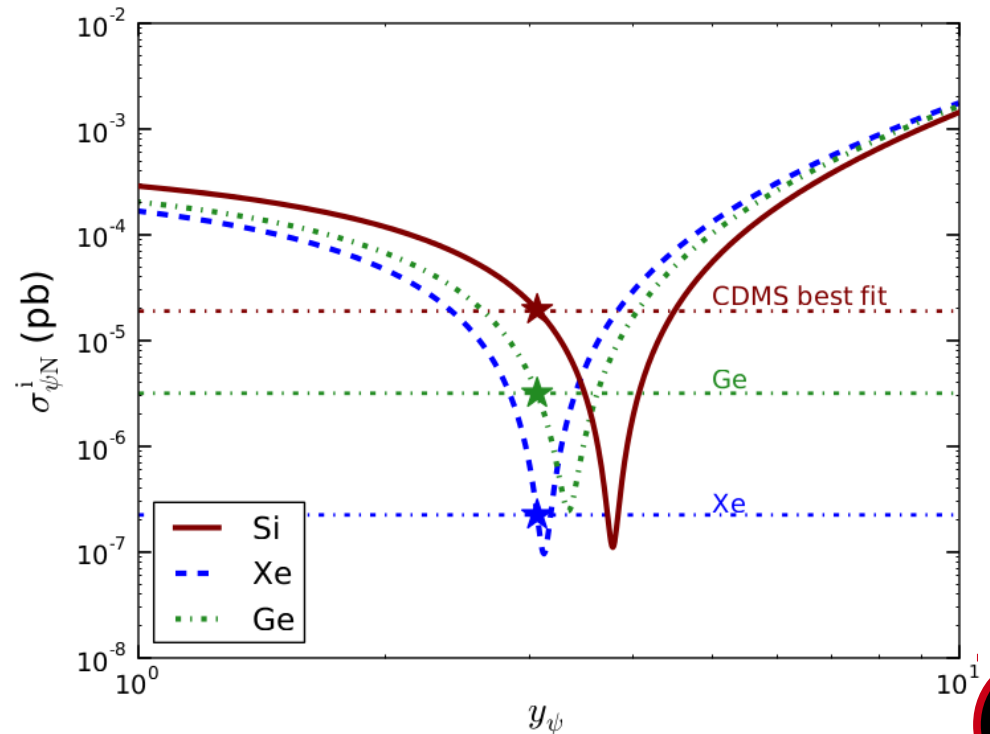
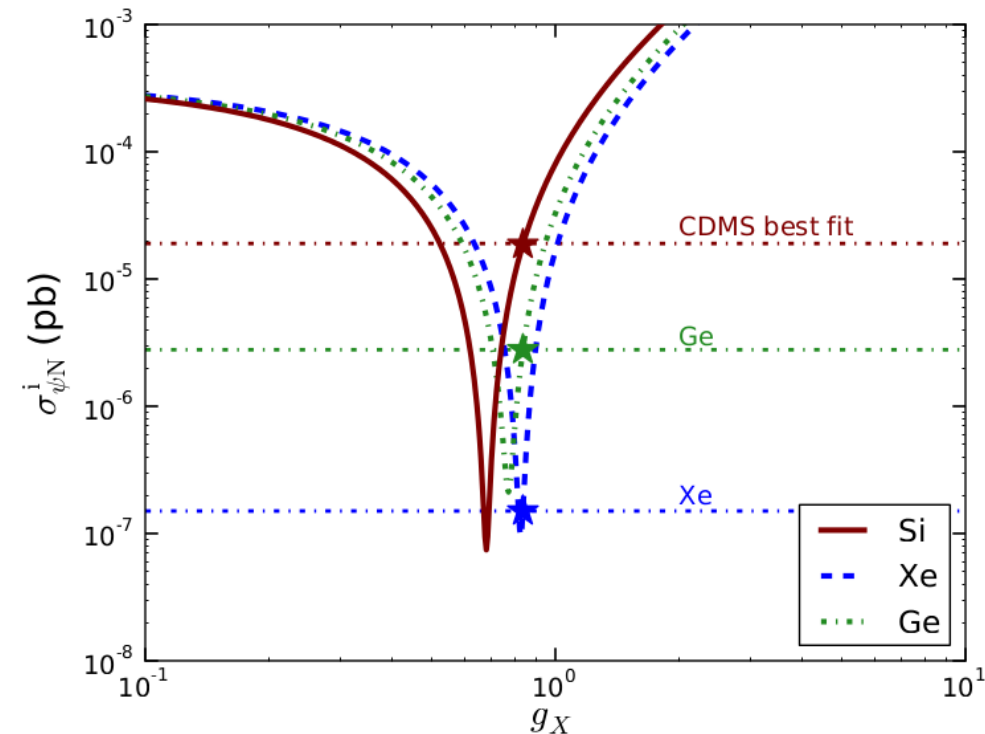
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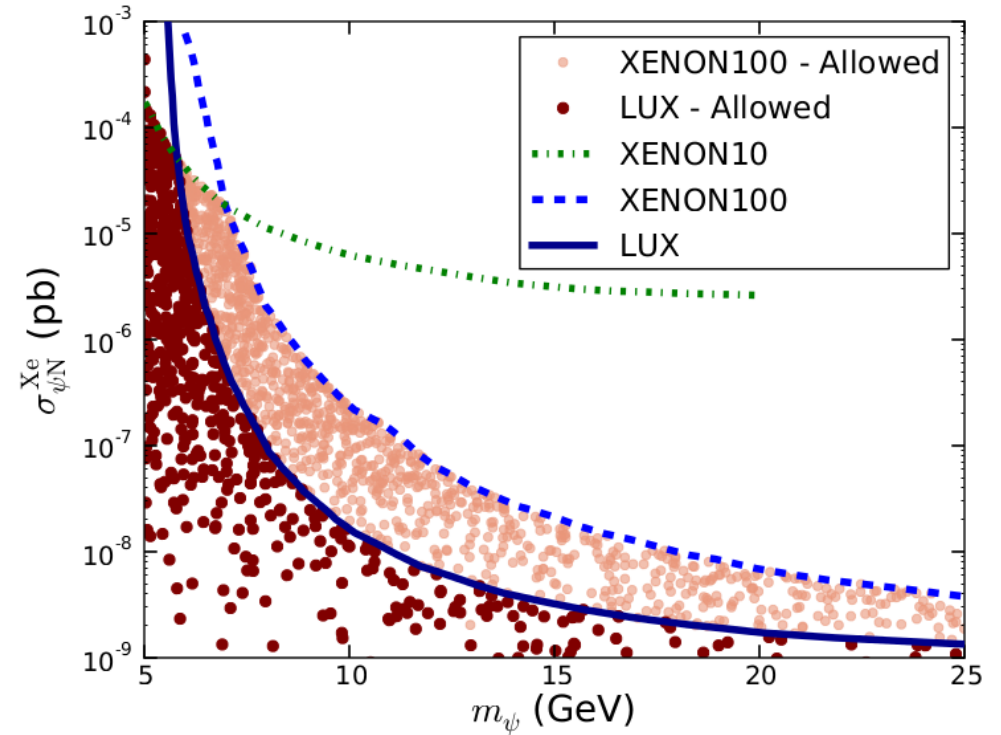
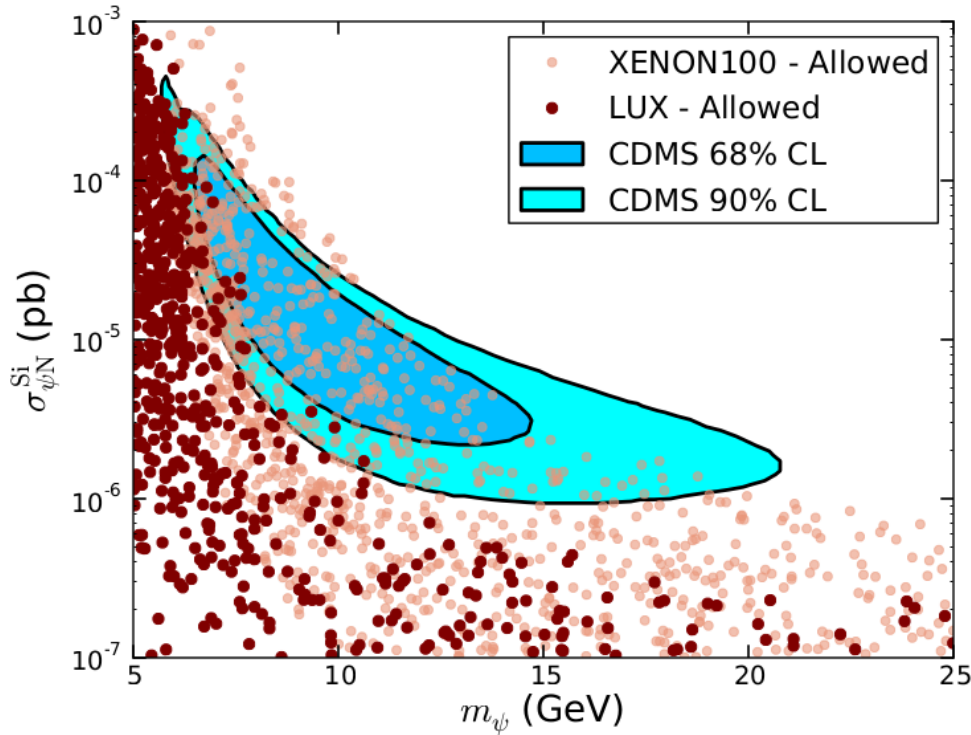
$$\sigma_{\psi N_{uc}}^0 = \frac{4\mu^2}{\pi} [c(Zf_p + (A - Z)f_n)^2 + \bar{c}(Z\bar{f}_p + (A - Z)\bar{f}_n)^2]$$

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CDMS vs XENON/LUX



- Before the LUX results, there was essentially no tension between the two experiments assuming IV interactions.
- It was even possible to reconcile CDMS and CoGeNT (to some extent). Not any more. DAMA is hopeless in this framework.
- LUX puts severe pressure on the IVDM explanation of low mass excesses.

What to keep from this story

- The low DM mass excesses made us realize (or remember) that the assumption $f_p = f_n$ is not necessarily true. Direct detection results, invaluable as they are, *do come with assumptions* and must be read with caution!
- We have shown this in a simple model that only incorporates pretty standard model-building ingredients.
- The only point that's a bit hard to buy is the asymmetry (although asymmetric DM models can have interesting connexions to baryogenesis).
- What the low DM mass excesses are is unclear. It's highly probable that they're unrelated to DM, and LUX will probably more or less fully test them shortly.

However...

- The IVDM picture extends well beyond the low-mass regime! It's something that *appears* in models, for any value of the DM mass, and can act in all directions.
- It is important to look for DM through different techniques and with different materials: LUX will dominate for the next few years. What about a large lighter element detector?

Thank you!

Constraints

- EWPTs

$$\left(\frac{\tan \epsilon}{0.1}\right)^2 \left(\frac{250 \text{ GeV}}{m_{Z_X}}\right)^2 \leq 1$$

- Z invisible width

$$\Gamma(Z \rightarrow \psi\bar{\psi}) < 3 \times 0.0015 \text{ GeV}$$

- Higgs invisible BR

$$BR(h \rightarrow inv) \lesssim 0.3$$

- Flavor : basically $B \rightarrow K\mu\mu$

- Relic density : Planck + WMAP + BAO + High L

- Direct detection : the most tricky point, since *all* cross-sections are suppressed to some extent!

NB : Isotopic composition of elements properly accounted for.



Parameter space *to explain CDMS-Si*

$$91.1813 < m_Z < 91.1939$$

$$80.340 < m_W < 80.430$$

$$0.9992 < \rho < 1.0016$$

$$0.003 < \epsilon < 0.04$$

$$5 < m_\psi < 25$$

$$2m_\psi - 7 < m_{Z_X} < 2m_\psi + 7$$

$$0.005 < y_\psi < 10$$

$$0.1 < g_X < 10$$

$$123 < m_{h_2} < 129$$

$$0.2 < m_{h_1} < 5$$

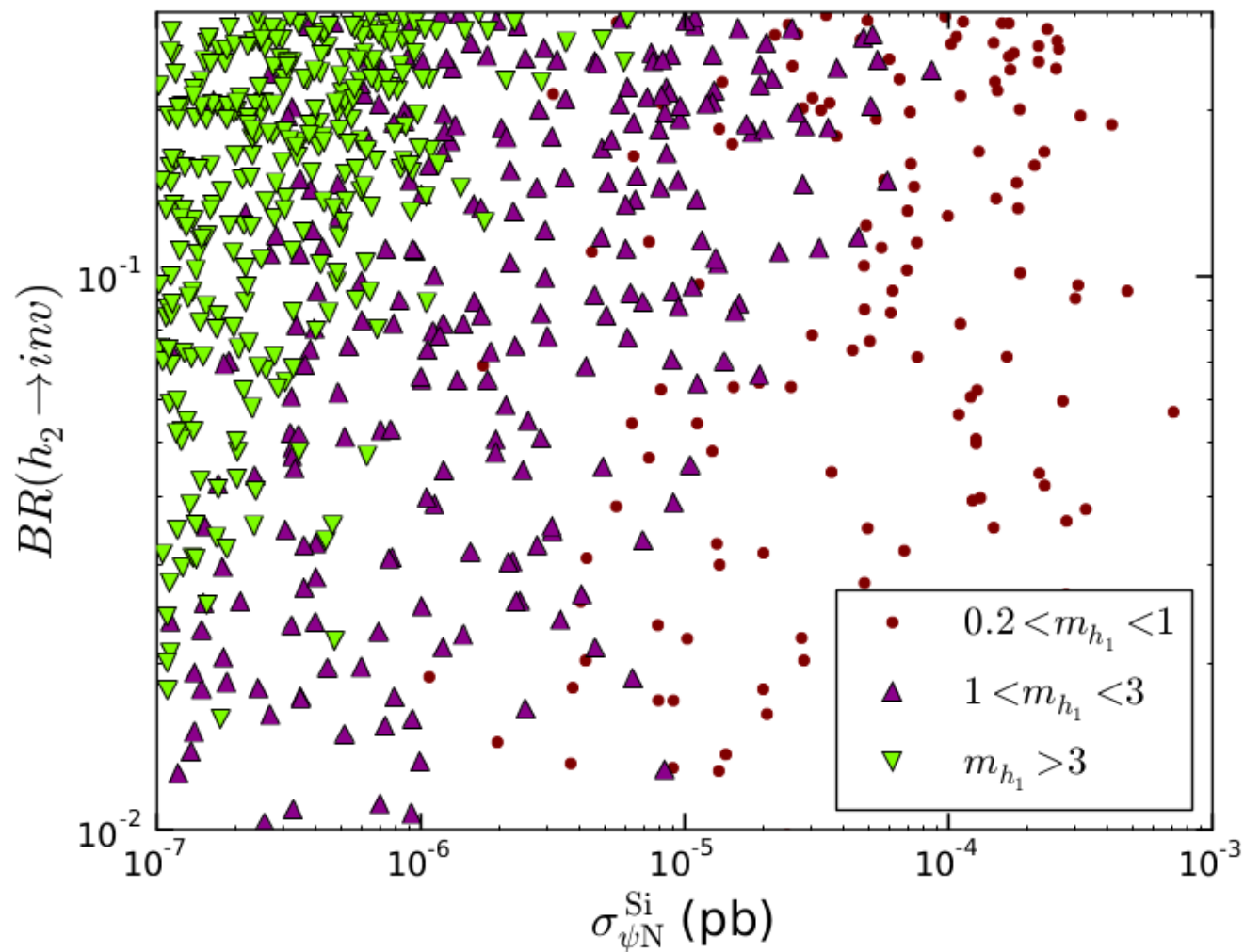
$$1 \times 10^{-4} < \alpha < 5 \times 10^{-3}$$

- Very light scalar: needed to achieve large scattering cross-sections without having problems with the Higgs width and flavor

- Vector mass: to eliminate the symmetric DM phase \rightarrow abundance fixed by asymmetry.



The Higgs decays

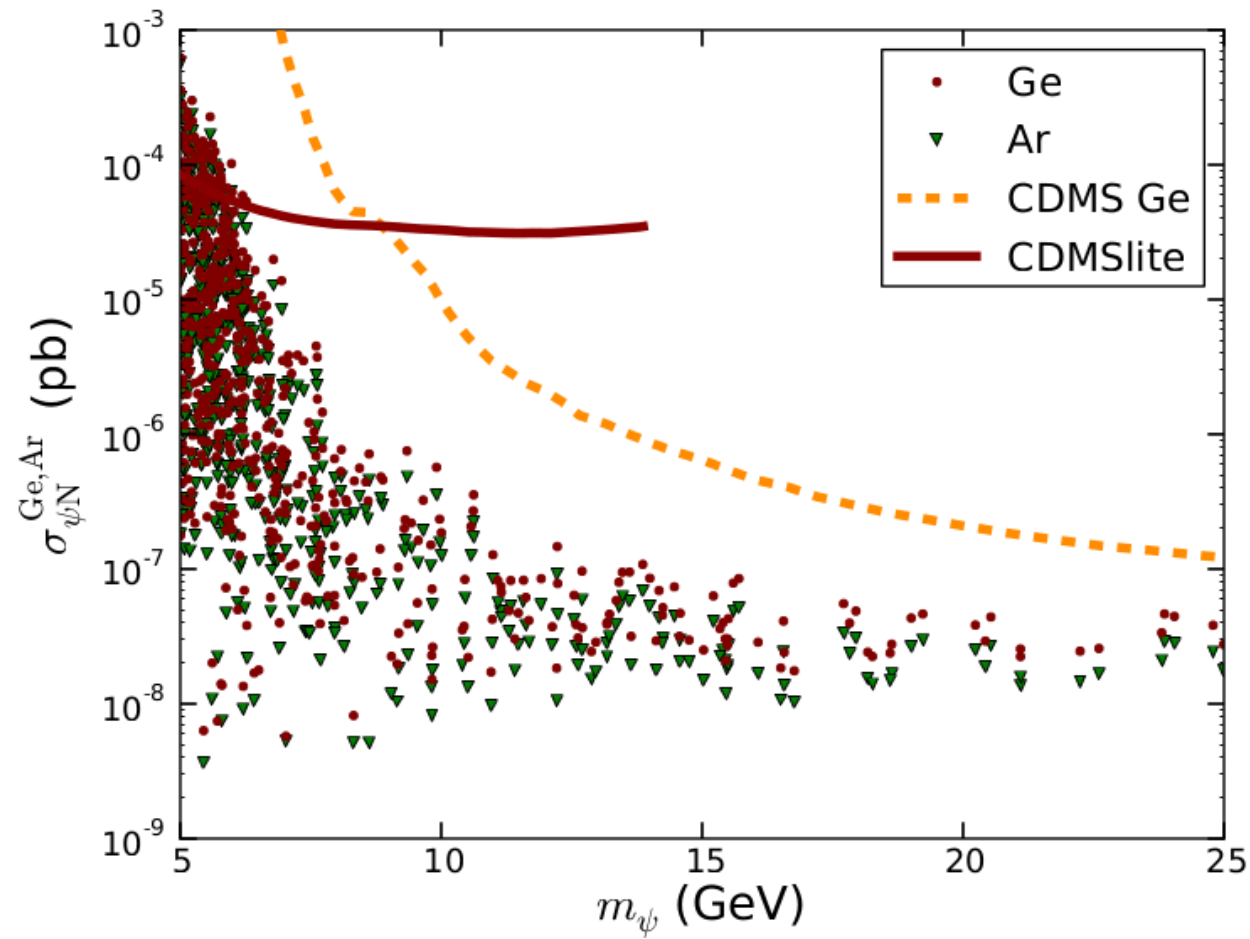


- **Major** constraint! The basic reason we had to resort to very light scalars in the first place.

- Not necessarily the case if we don't care about CDMS-Si though!



Other elements



More on the analytical explanation

We consider scenarios with

$$f_p^V \gg f_n^V$$

$$f_p^{h_i} \simeq f_n^{h_i}$$

So the neutron amplitude is Higgs-dominated

$$f_n \simeq f_n^{h_i} + f_n^{Z_X} \approx f_p^{h_i}$$

whereas the proton amplitude is sensitive to both contributions.

So, by choosing the couplings such that

$$f_p^{h_i} \approx -0.4 f_p^{Z_X}$$

we can get

$$f_n/f_p \approx f_p^{h_i} / (f_p^{h_i} + f_p^{Z_X}) \approx -0.7$$



A useful definition

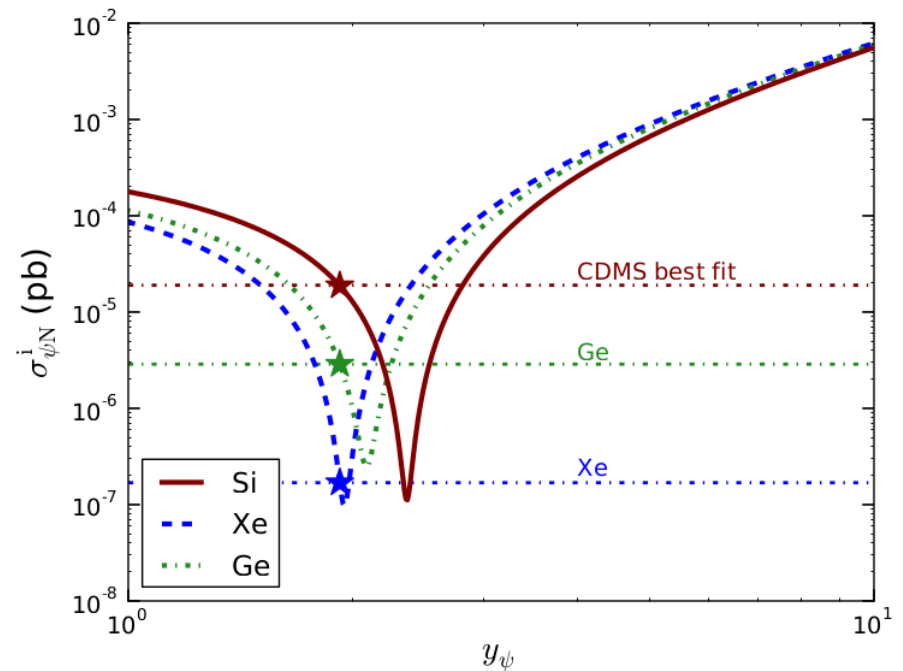
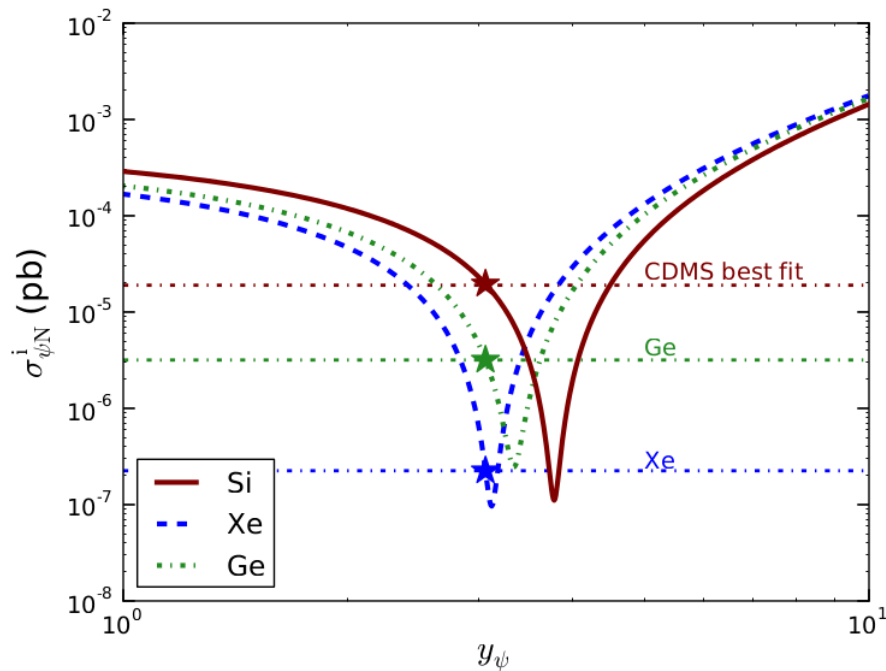
In the case of IVDM, the relevant quantity to be computed is the “normalized-to-nucleon” scattering cross-section *for each element*

$$\sigma_{\psi N^Z} = \sigma_{\psi p} \left[c \frac{\sum \eta_i \mu_{A_i}^2 (f_p Z + f_n (A^i - Z))^2}{\sum \eta_i \mu_{A_i}^2 f_p^2} + \bar{c} \frac{\sum \eta_i \mu_{A_i}^2 (\bar{f}_p Z + \bar{f}_n (A^i - Z))^2}{\sum \eta_i \mu_{A_i}^2 \bar{f}_p^2} \right]$$



Hadronic uncertainties

Already at leading order in the chiral expansion, there are uncertainties tied to the quark content of the nucleon



Moreover, chiral NLO corrections can be sizeable (and nucleus-dependent).

Cirigliano, Graesser, Ovanesyan (2012)

Cirigliano, Graesser, Ovanesyan, Shoemaker (2013)

→ The exact parameter values for which the effect takes place may be subject to modifications.

(although calculation so far performed only for scalar-mediated interactions!)

