Isospin-violating dark matter from a double portal

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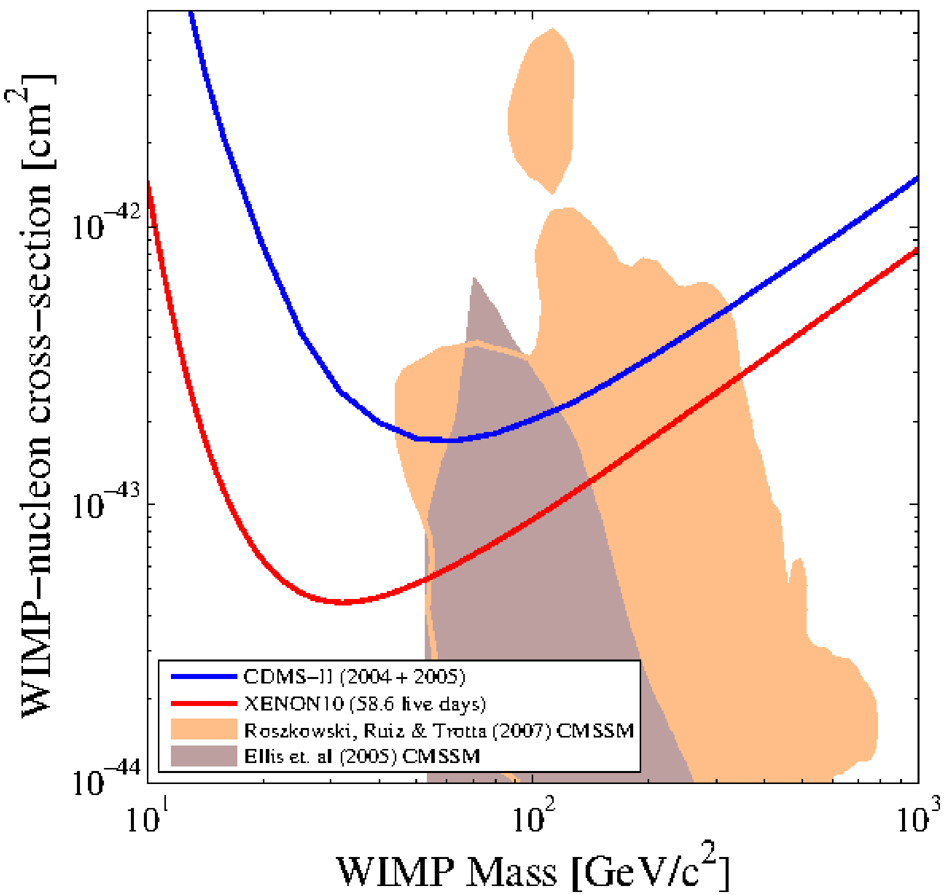
Outline

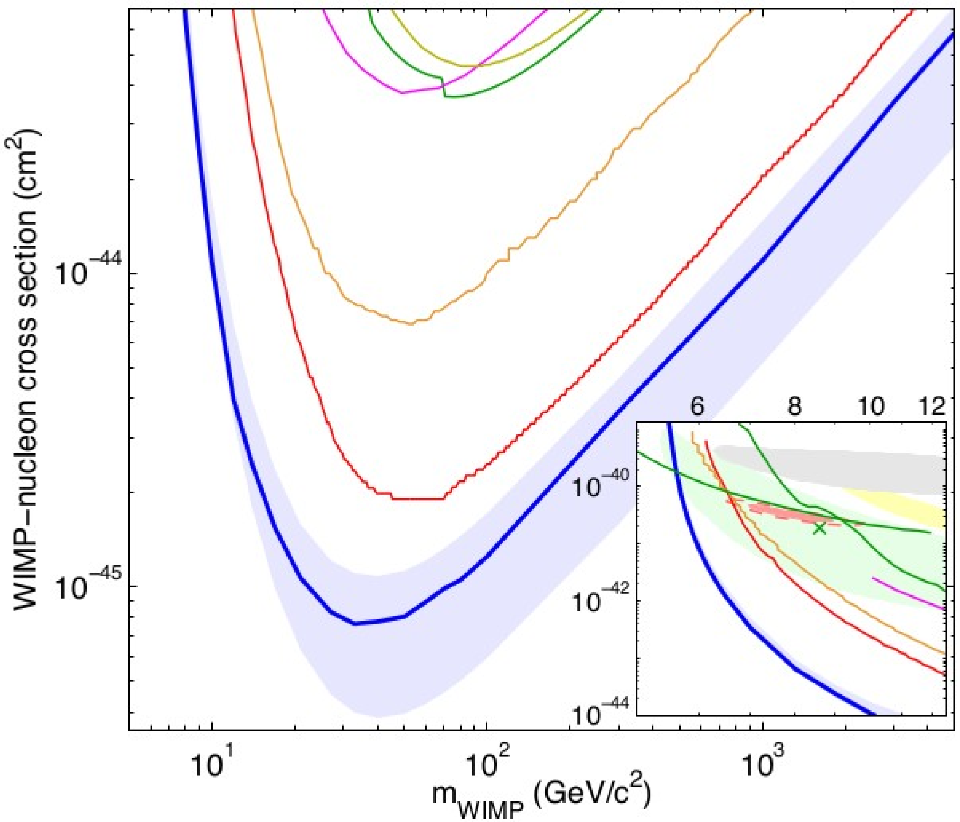
- The magnificent world of direct dark matter detection
- ...small clouds and blobs...
- Isospin-violating dark matter and a double portal
- Conclusions

DD experiments have kept busy...

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



Xenon 10, 06/2007

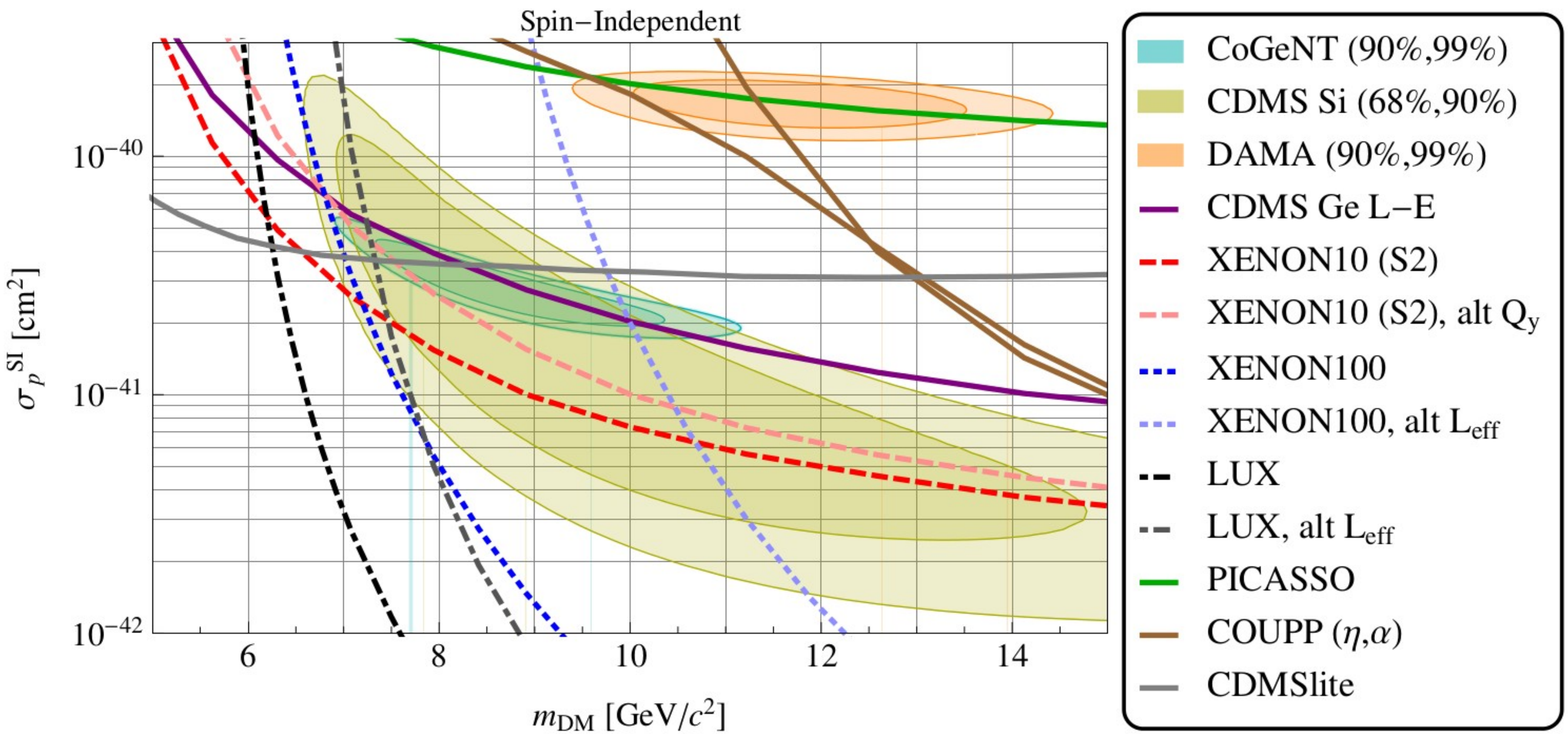


LUX, 10/2013

For m_x = 40 GeV, we have ~2 orders of magnitude improvement!

...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 (dipole, anapole, IVDM...)?

Isospin-violating dark matter ?

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

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

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 → The existence of different isotopes makes it that the cross-section doesn't formally vanish in real-life experiments.

→ Different cross-sections could be expected at experiments using different materials.

But how...?

A model for isospin-violating DM

Few concrete examples of IVDM exist in the literature.

Fransen, Kahlhoefer, Sarkar, Schmidt-Hoberg (2011)
He, Tandean (2013)
Bélanger, AG, Park, Pukhov (2013)
Hamaguchi, Liew, Moroi, Yamamoto (2014)

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.

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

→ 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

$$\sigma^0_{\psi Nuc} = \frac{4\mu^2}{\pi}\left[c(Zf_p + (A-Z)f_n)^2\right]$$

The nucleon amplitudes receive two contributions :

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

Consider scenarios with: $f_p^V \gg f_n^V \qquad f_p^{h_i} \simeq f_n^{h_i}$

so that the neutron amplitude is Higgs-dominated whereas the proton one is sensitive to both. Then, if we choose

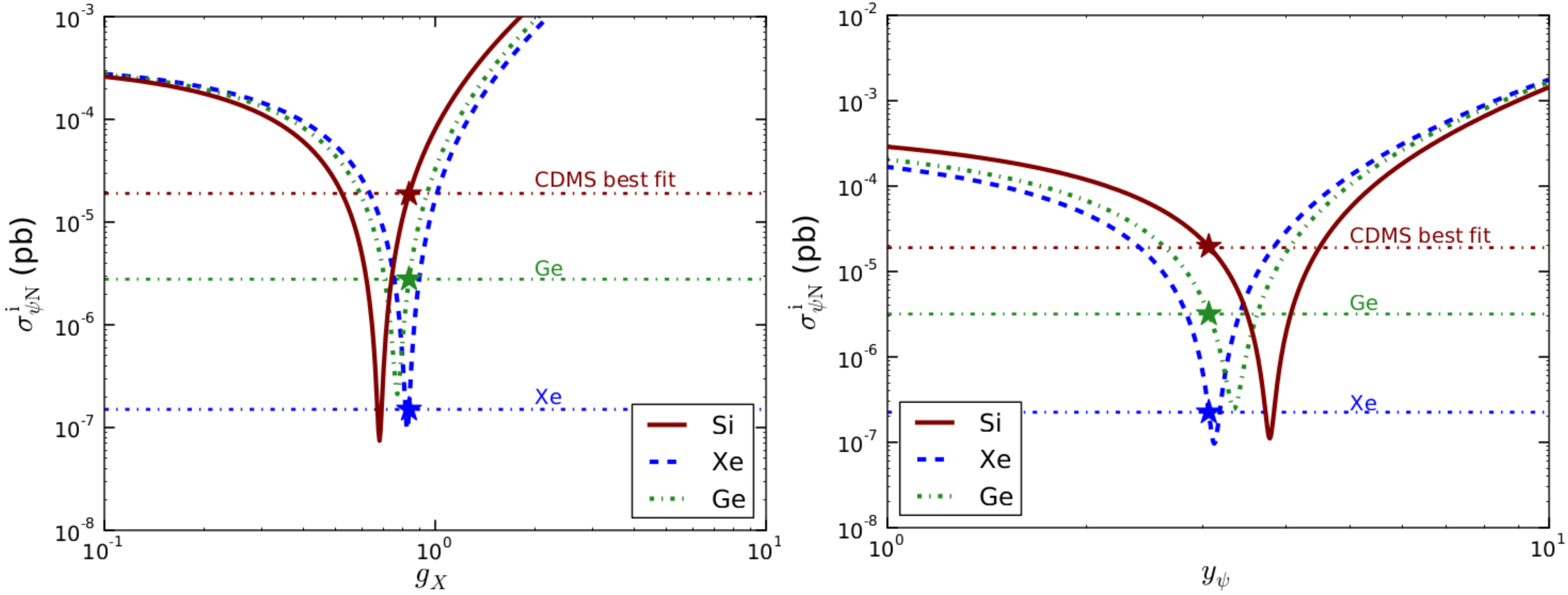
$$f_p^{h_i} \approx -0.4 f_p^{Z_X}$$

we can get the desired

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

The IV mechanism at play

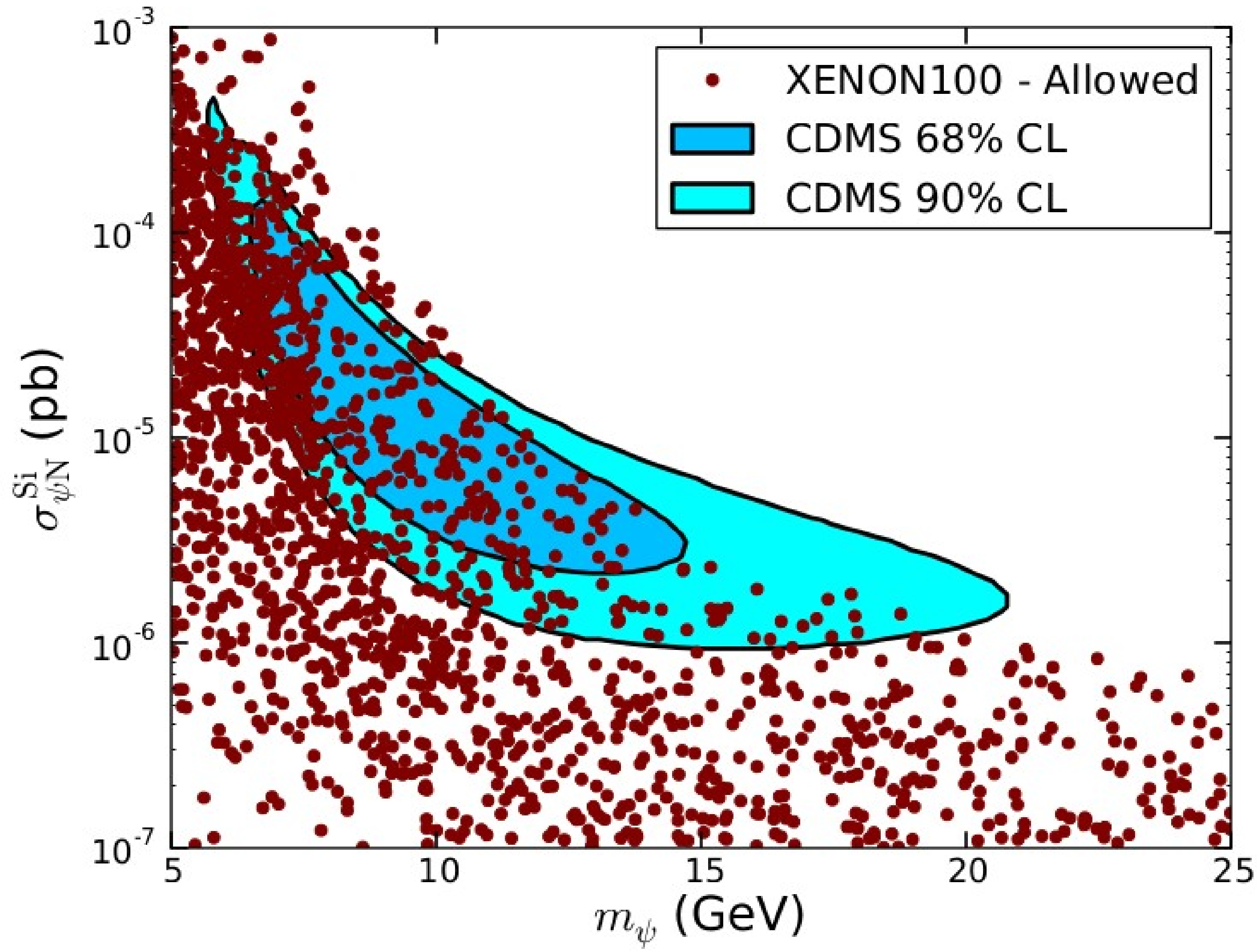
Here's an example reproducing the CDMS-Si “excess” and satisfying all experimental constraints, modulo LUX and superCDMS.



→ So, what's the impact of LUX and superCDMS?

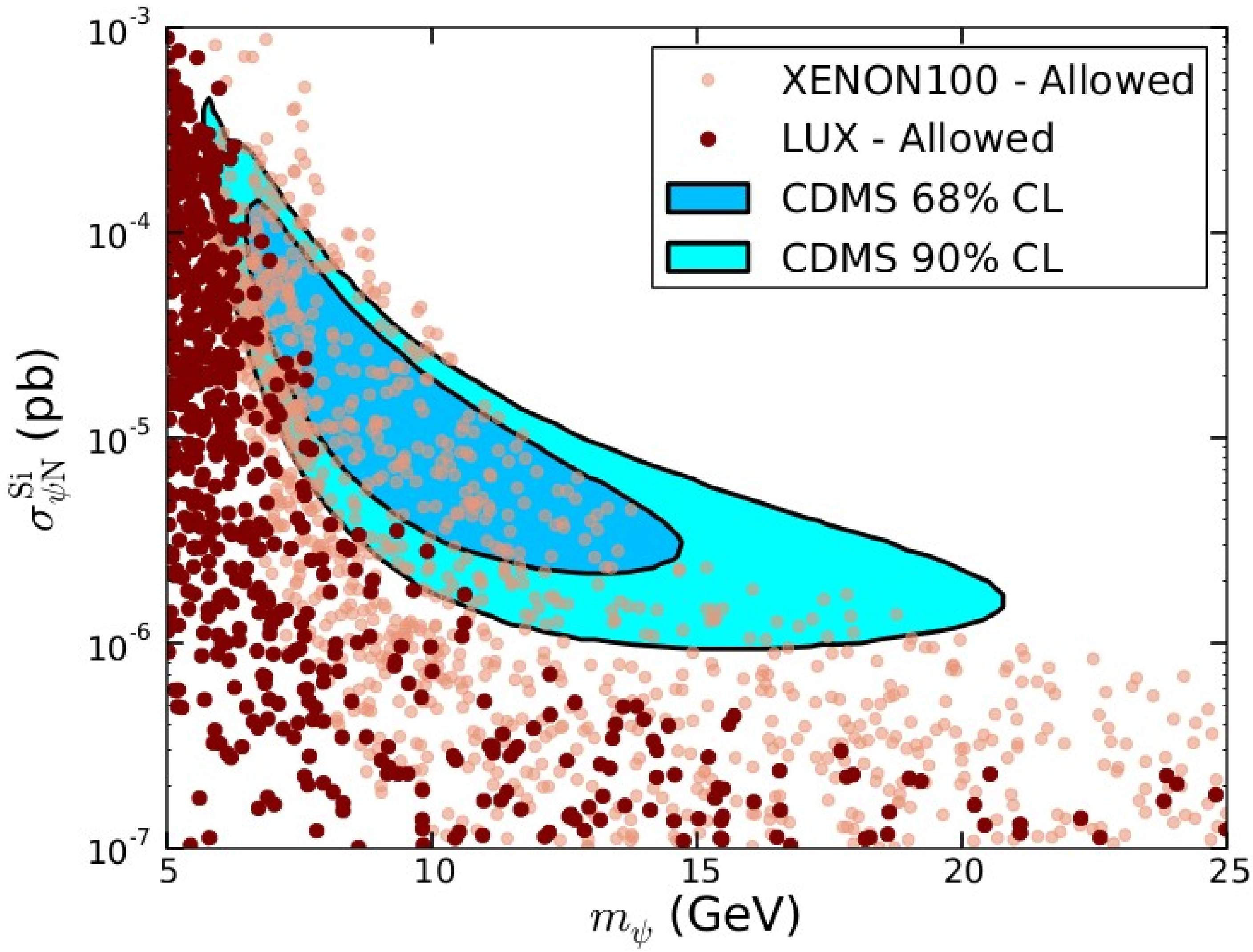
CDMS vs XENON

We started from this...



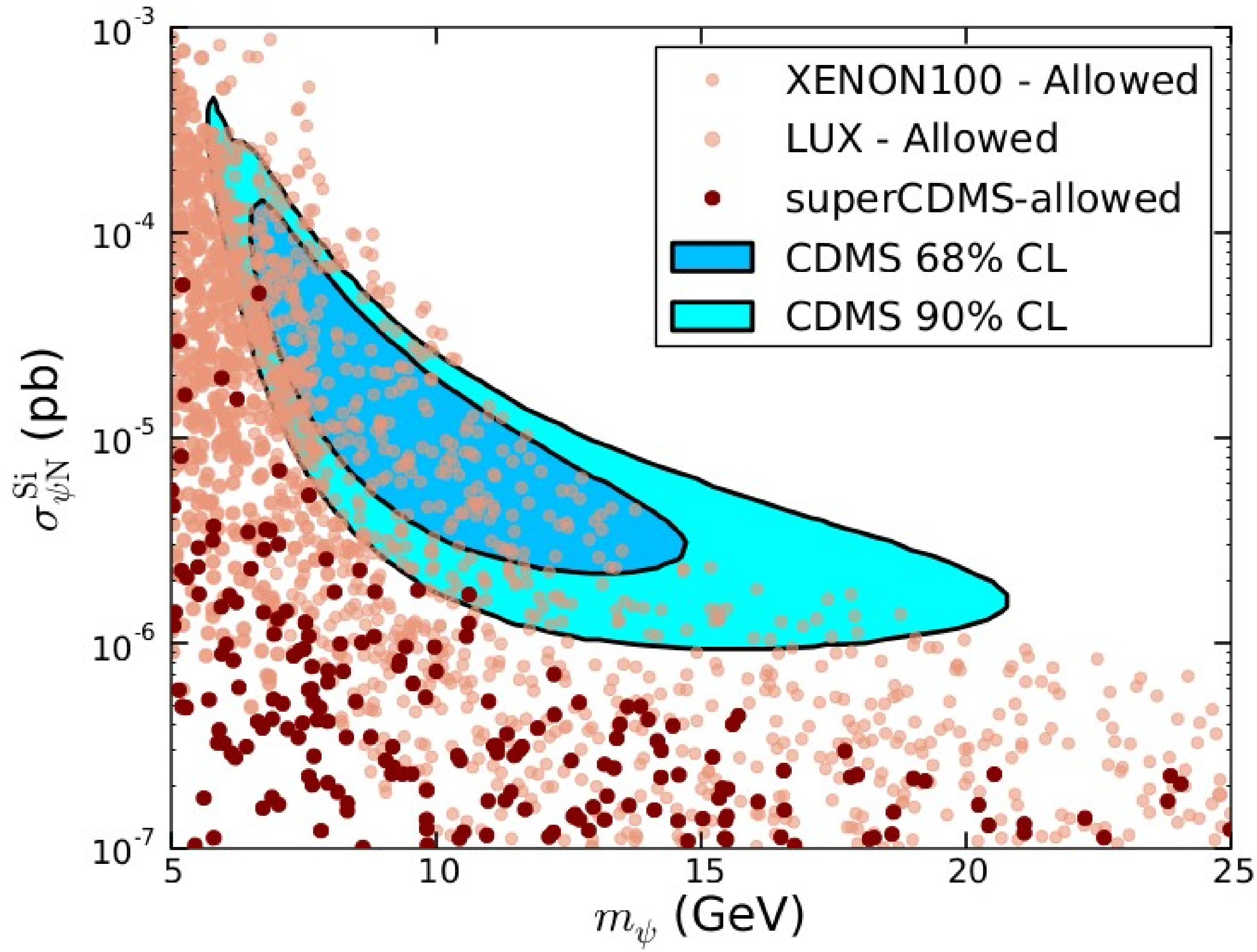
CDMS vs XENON + LUX

...to get to this...

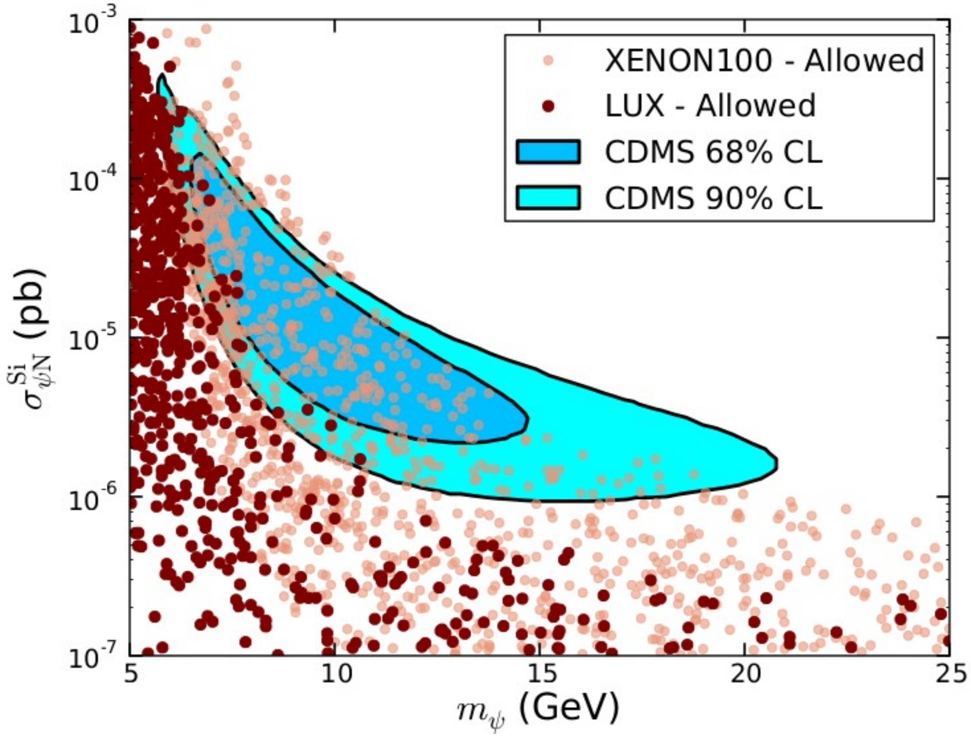


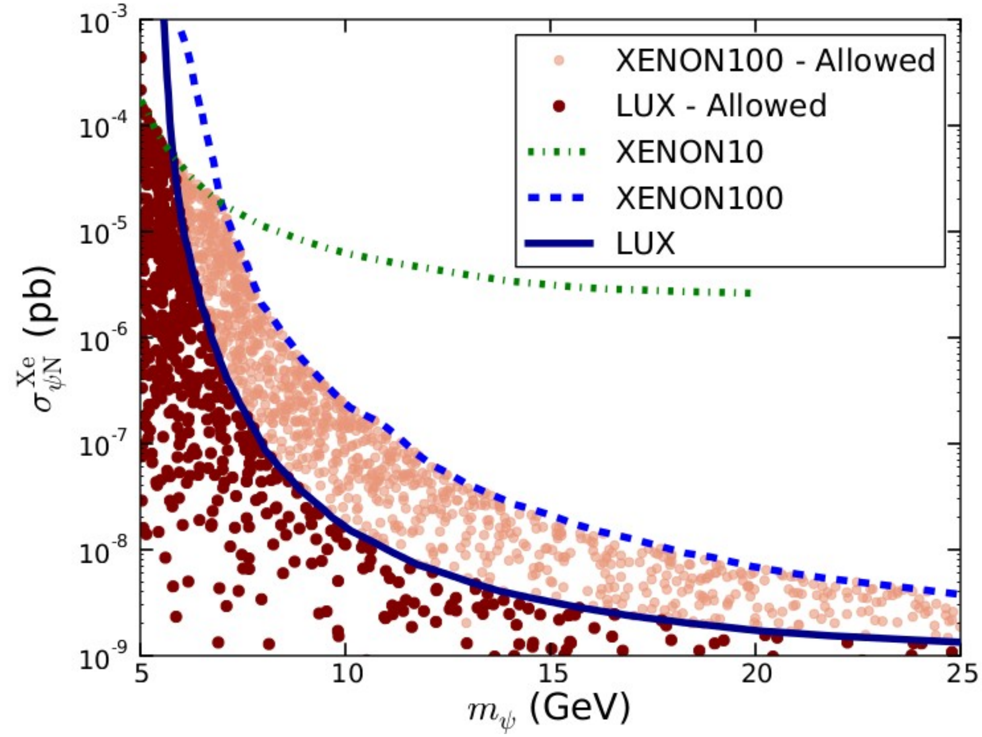
CDMS vs XENON + LUX + superCDMS

...and eventually this.



CDMS-Si vs Xenon a bit differently





- Before the LUX results, there was essentially no tension between the two experiments assuming IV interactions.

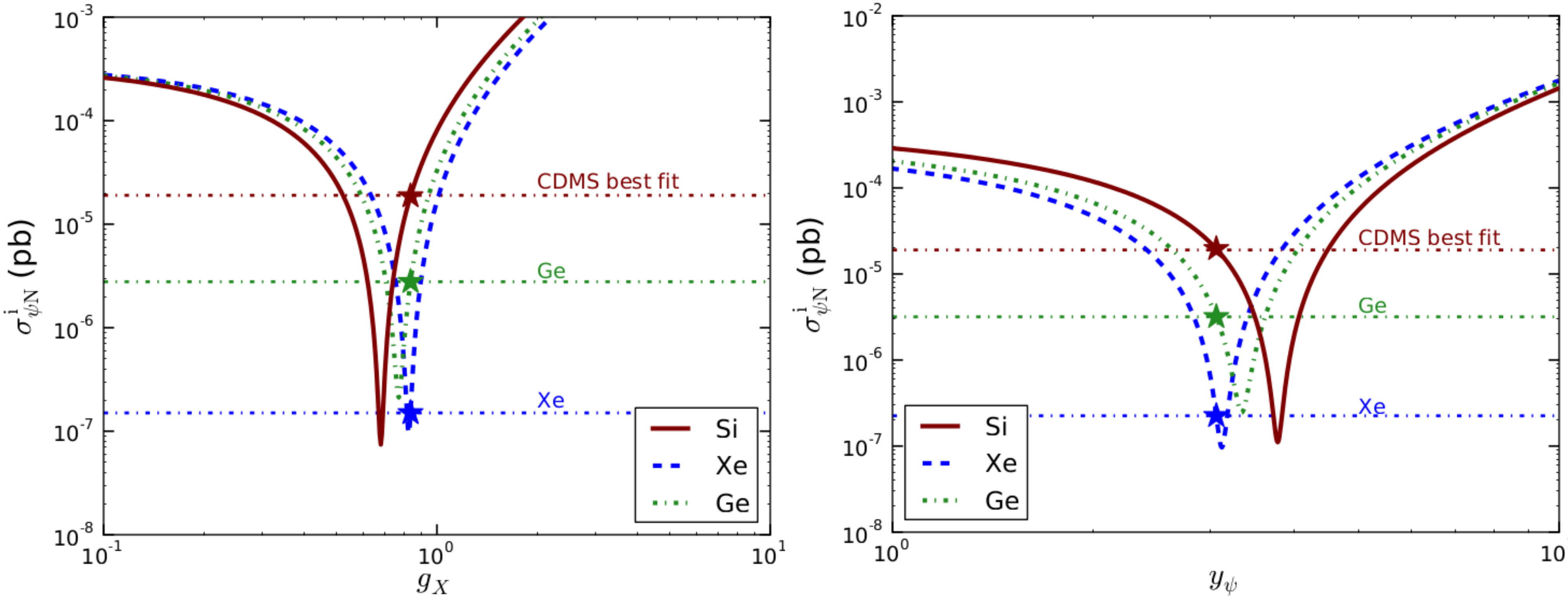
- It was even possible to reconcile CDMS and CoGeNT (to some extent). Not any more. DAMA is hopeless in this framework.

- LUX puts severe pressure on the IVDM explanation of low mass excesses.

Q: So, is the isospin-violation story over ?

A: No! Everything we presented is actually *completely unrelated* to the CDMS-Si excess!

Remember this picture :



→ Isospin violation *arises* in models, for specific parameter combinations.

→ It can act in *all* directions.

→ There's a pretty safe way of testing it : different target materials.

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 but lighter element detectors are also crucial!

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

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

- Higgs invisible BR

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

- Flavor : basically B → Kμμ

- 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.

Why the asymmetry ?

The point is that only one charge sign can cancel with the scalar contribution, not both simultaneously.

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

So, in the presence of both components, even if we manage to completely kill this part...

...we'll still be stuck with this one!

→ In some sense, the asymmetry is the hardest thing to buy in this setup.

→ But then, asymmetric DM can have interesting motivations!

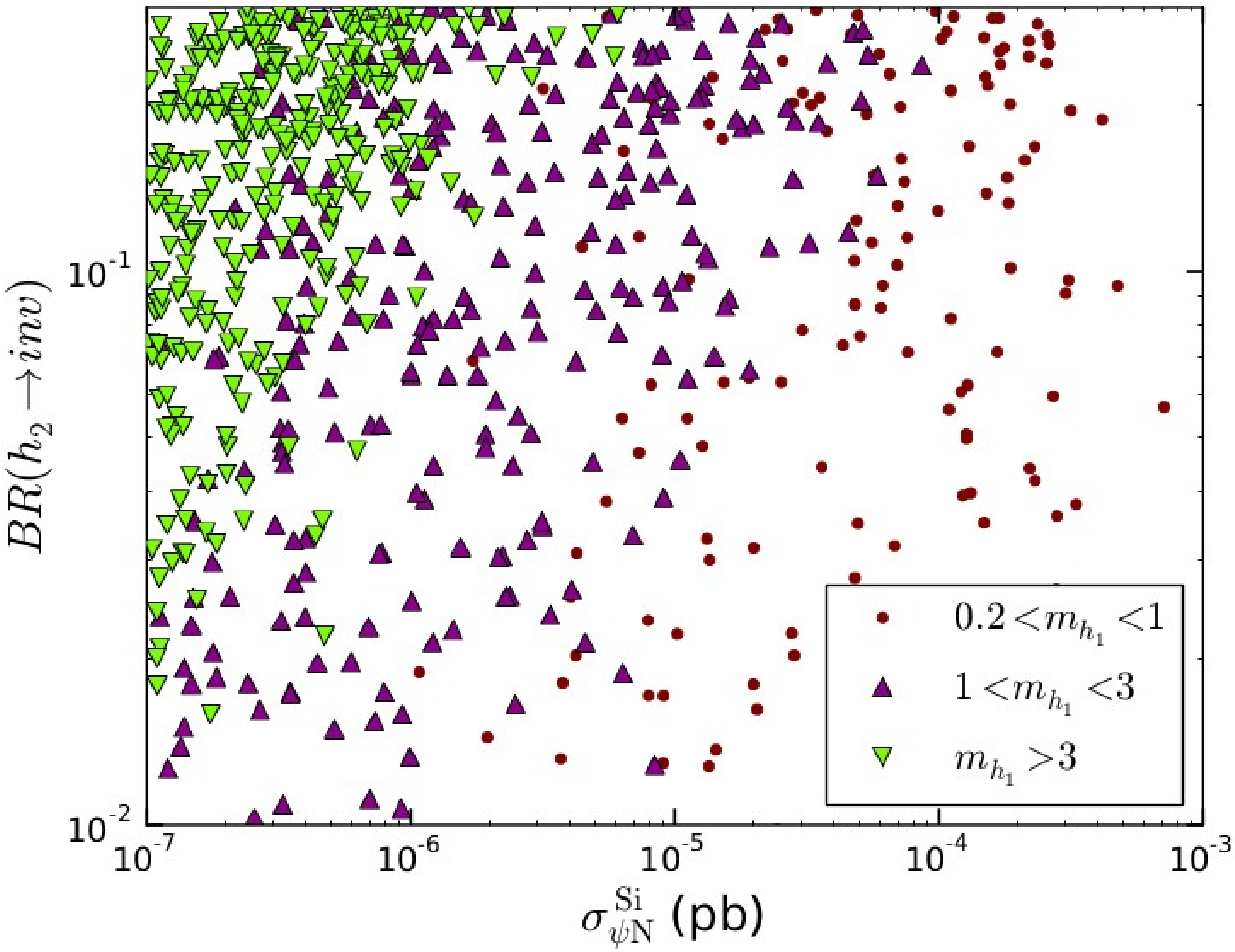
Parameter space *to explain CDMS-Si*

$$91.1813 < m_Z < 91.1939$$
$$80.340 < m_W < 80.430$$
$$0.9992 < \rho < 1.0016$$
$$0.003 < \epsilon < 0.04$$
$$5 < m_\psi < 25$$
$$2m_\psi - 7 < m_{Z_X} < 2m_\psi + 7$$
$$0.005 < y_\psi < 10$$
$$0.1 < g_X < 10$$
$$123 < m_{h_2} < 129$$
$$0.2 < m_{h_1} < 5$$
$$1 \times 10^{-4} < \alpha < 5 \times 10^{-3}$$

- 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 → abundance fixed by asymmetry.

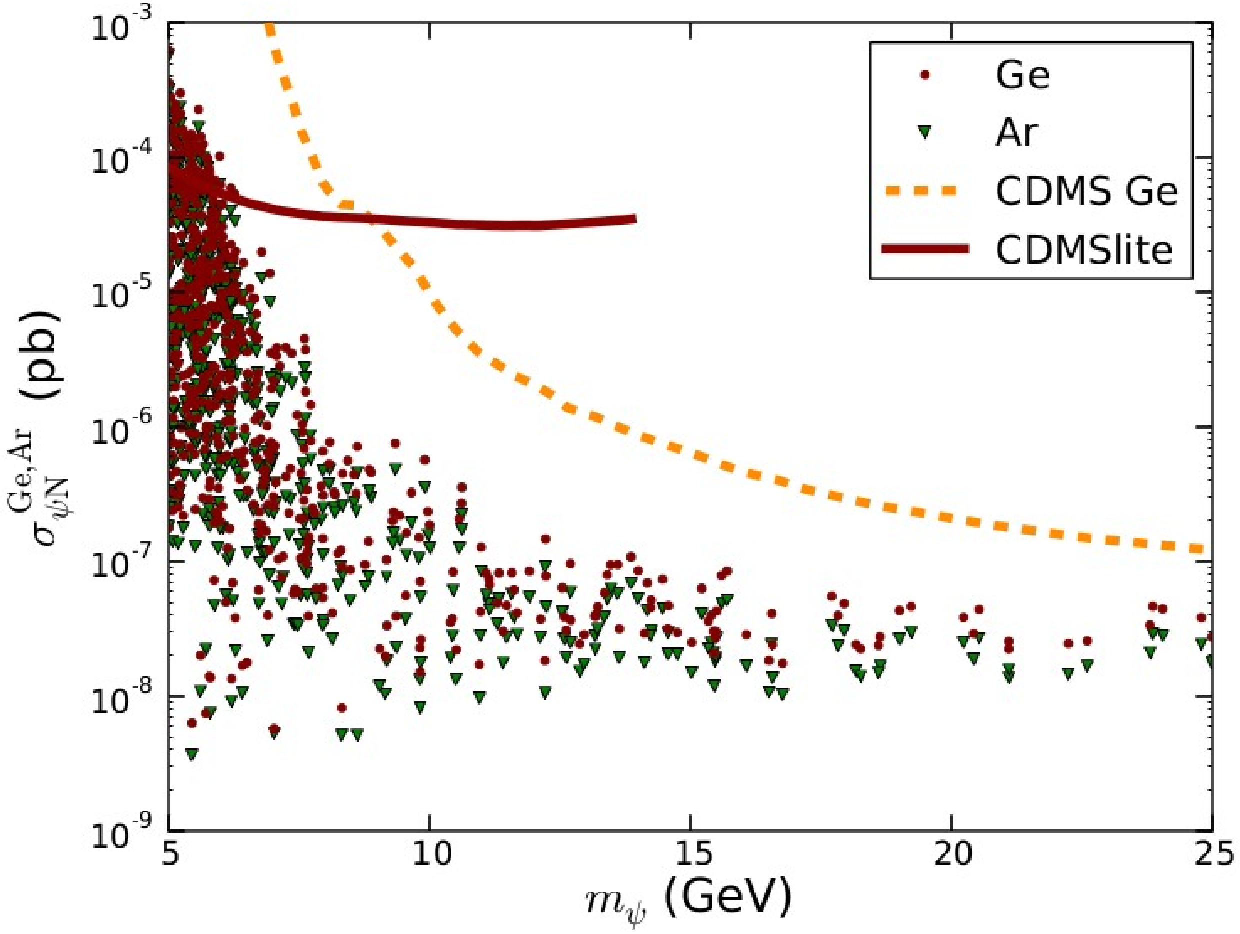
The Higgs decays



- ***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



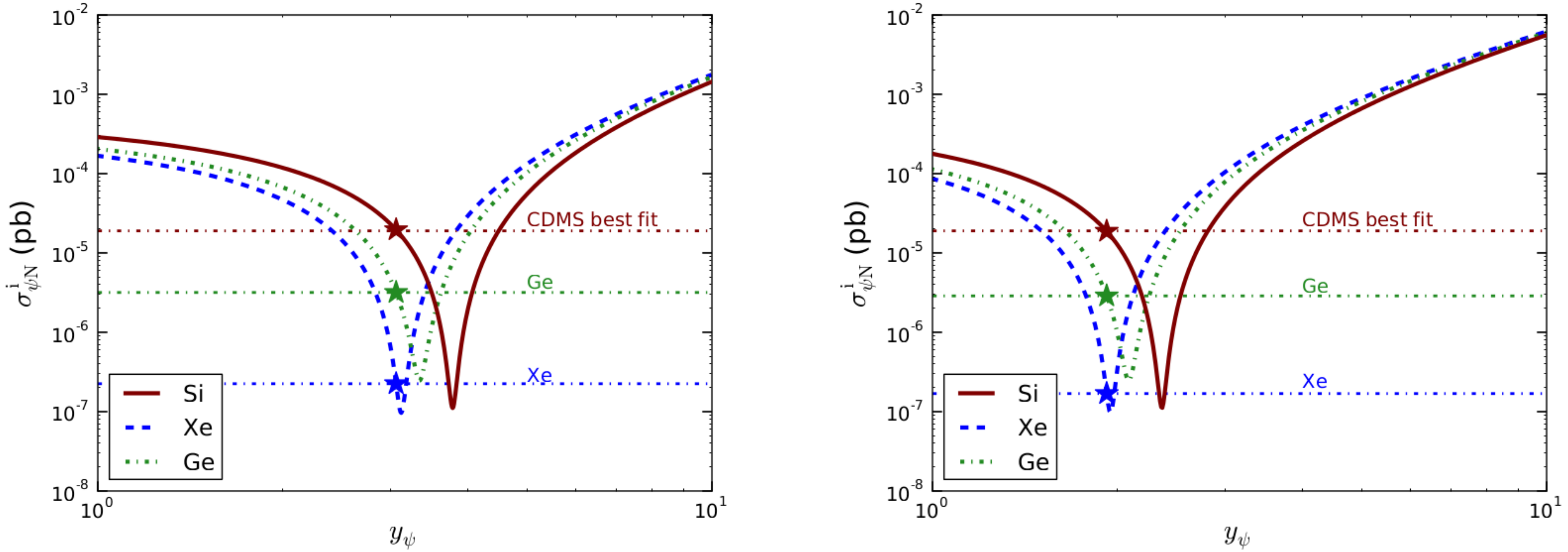
A useful definition

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

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

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)

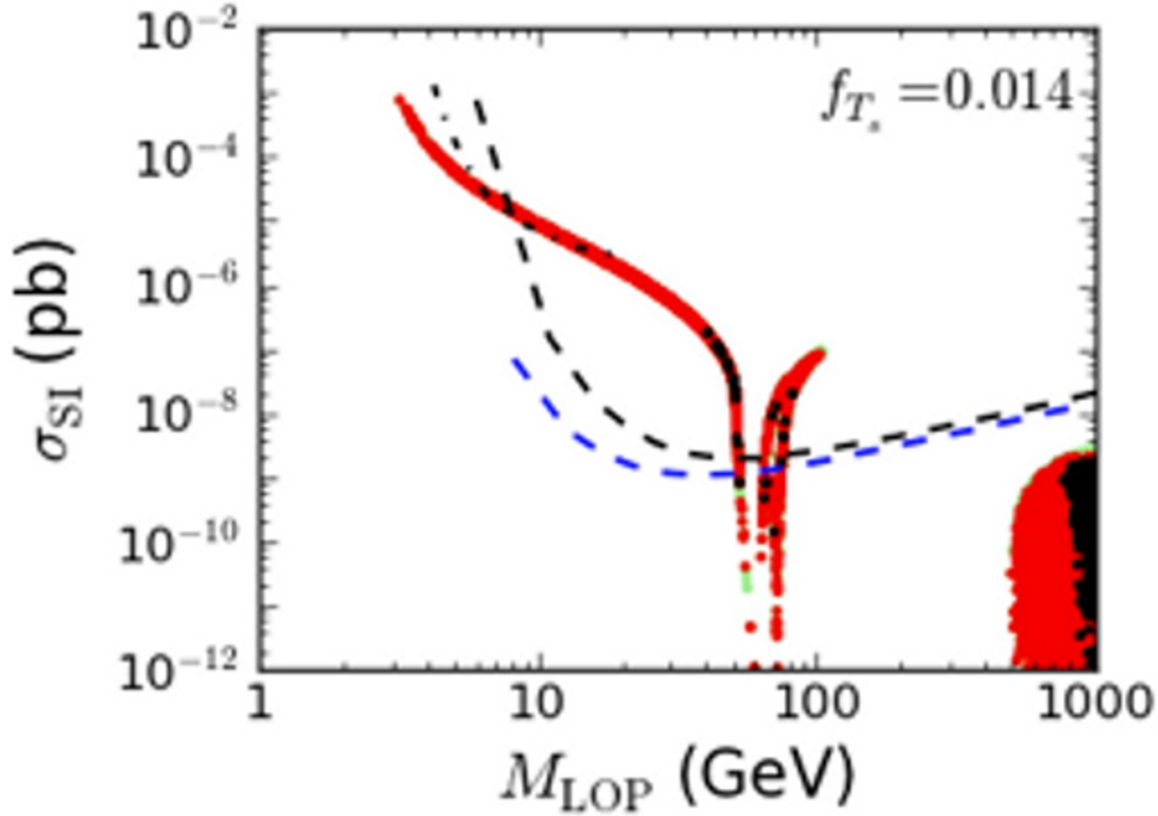
→ The exact parameter values for which the effect takes place may be subject to modifications.

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

A concrete example of DD efficiency

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)