Complementarity in direct dark matter searches

Miguel Peiró

Based on arXiv: 1304.1758 & 1403.3539

Work done in collab. with: D. G. Cerdeño, M. Fornasa, J-H. Huh, C. Marcos, and the ROSEBUD collaboration.

Instituto de Física Teórica UAM-CSIC

MultiDark
Multimessenger Approach for Dark Matter Detection

Complementarity in direct dark matter searches

An update

Miguel Peiró

Based on arXiv: 1304.1758 & 1403.3539

Work done in collab. with: D. G. Cerdeño, M. Fornasa, J-H. Huh, C. Marcos, and the ROSEBUD collaboration.

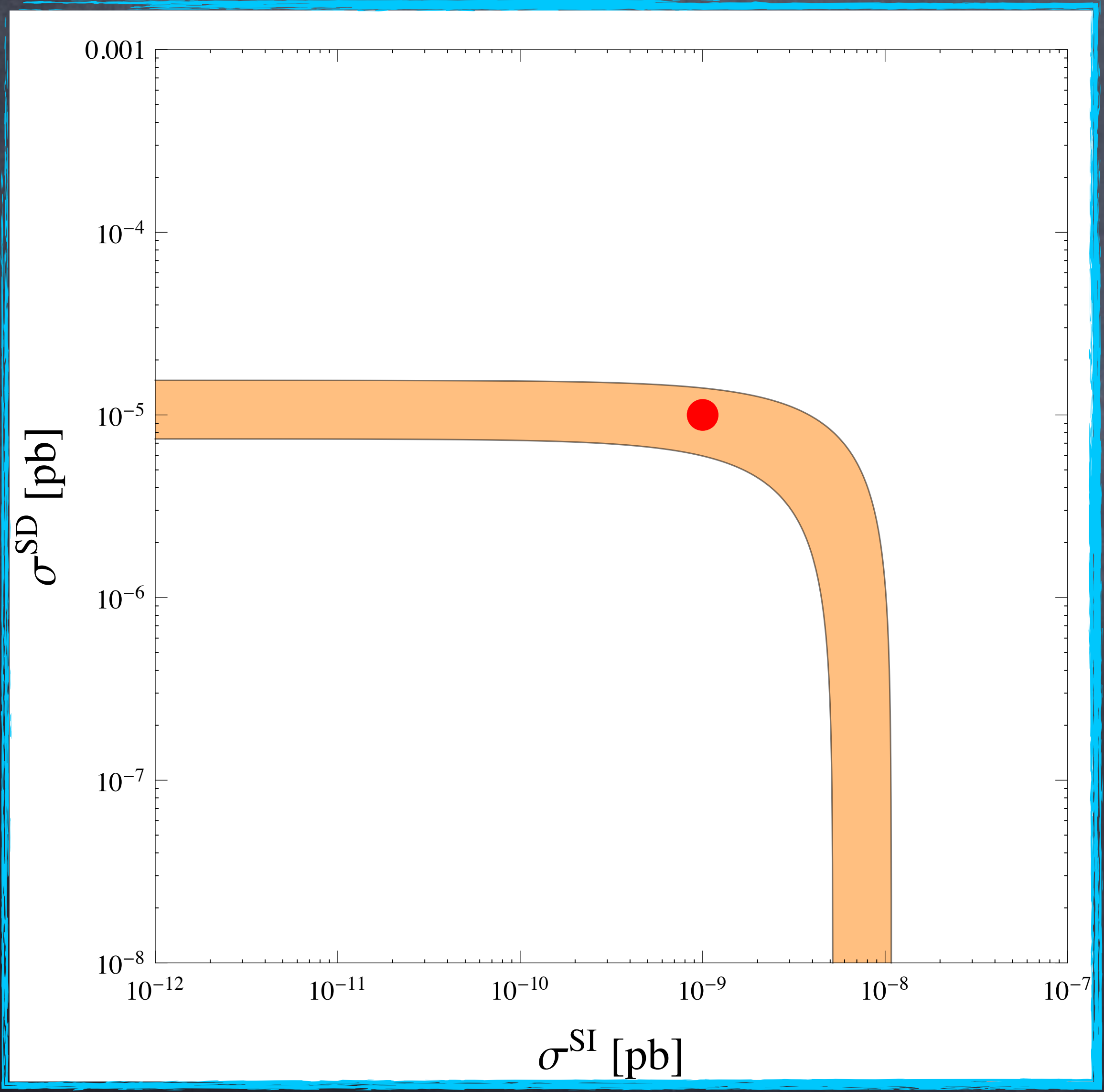
ift Instituto de Física Teórica UAM-CSIC

MultiDark Multimessenger Approach for Dark Matter Detection

Combining targets

Let's assume that an experiment 1 measures a signal, generated by the DM mass and the SI-SD cross sections, the number of events would be given by: $N_1 = A_1\sigma^{SI} + B_1\sigma^{SD}$ where the parameters A and B depends on the nucleus and DM mass.

If we assume that DM mass is well determined (for simplicity):



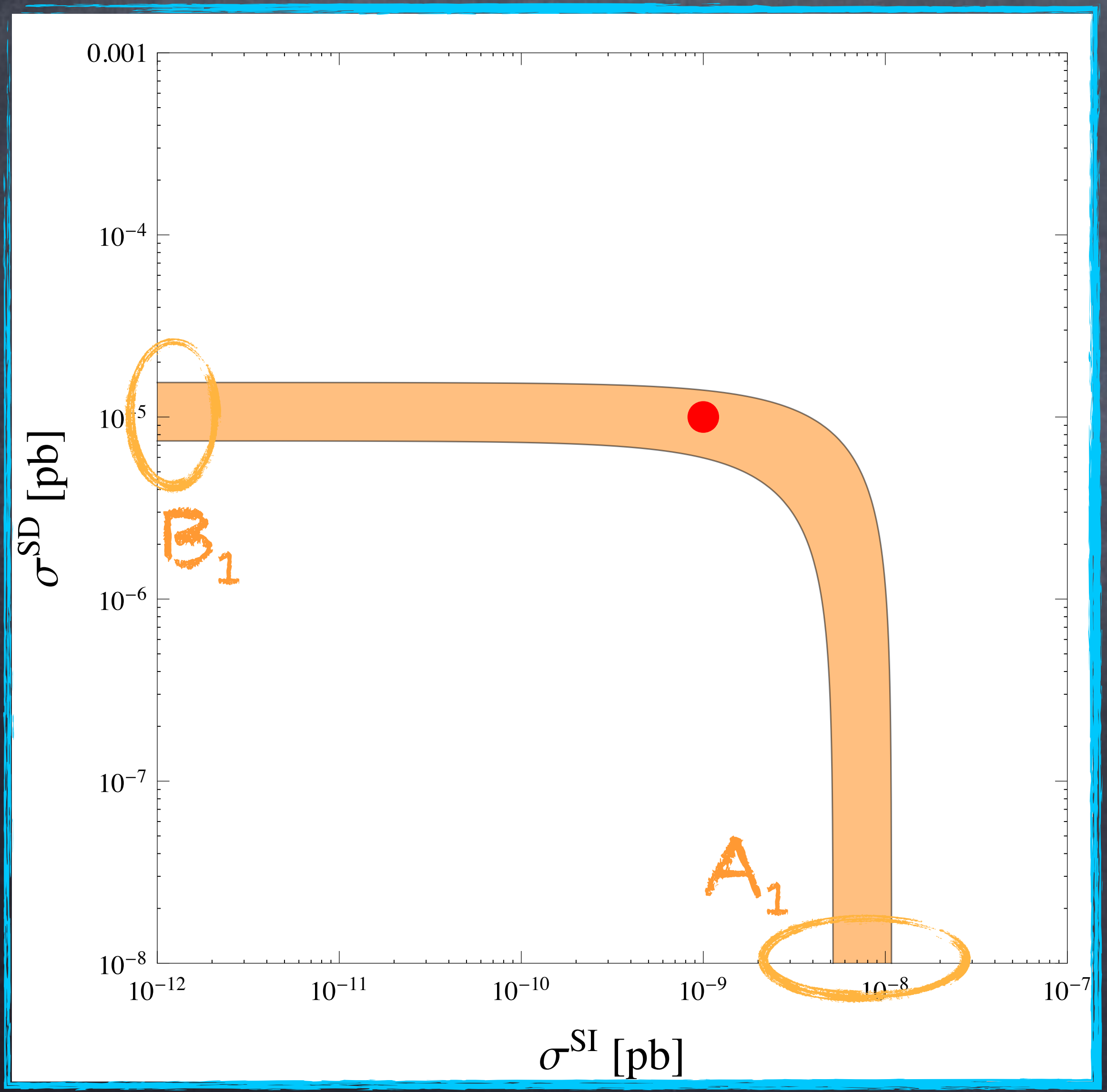
The red dot represents the values of the cross sections used to "simulate" the signal

Combining targets

Let's assume that an experiment 1 measures a signal, generated by the DM mass and the SI-SD cross sections, the number of events would be given by: $N_1 = A_1\sigma^{SI} + B_1\sigma^{SD}$

where the parameters A and B depends on the nucleus and DM mass.

If we assume that DM mass is well determined (for simplicity):



The red dot represents the values of the cross sections used to "simulate" the signal

There is a degeneracy between the cross sections

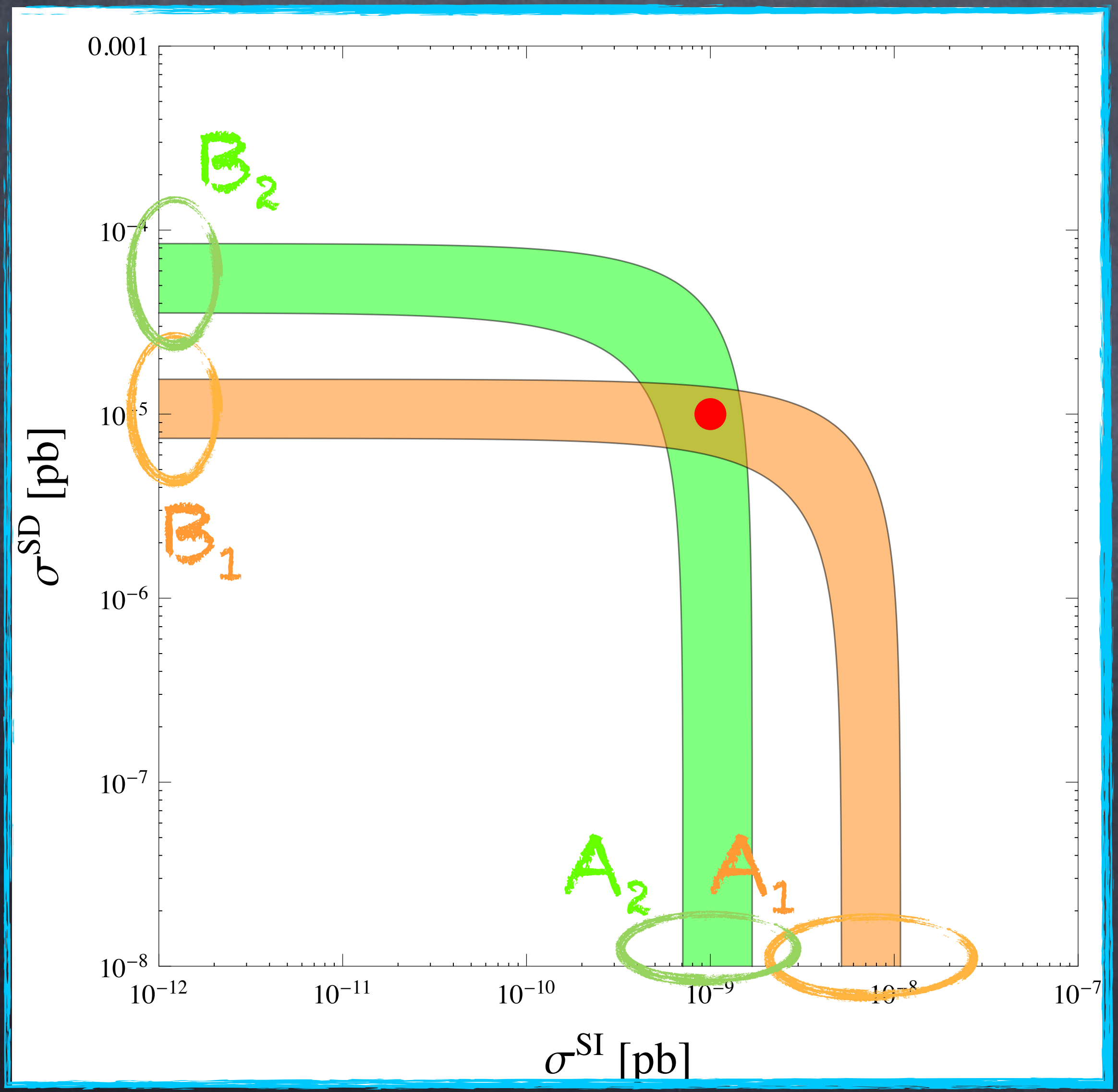
(the signal can be explained by both alone or a combination)

Combining targets

Let's assume that an experiment 1 measures a signal, generated by the DM mass and the SI-SD cross sections, the number of events would be given by: $N_1 = A_1\sigma^{SI} + B_1\sigma^{SD}$

where the parameters A and B depends on the nucleus and DM mass.

If we assume that DM mass is well determined (for simplicity):



The red dot represents the values of the cross sections used to "simulate" the signal

There is a degeneracy between the cross sections (the signal can be explained by both alone or a combination)

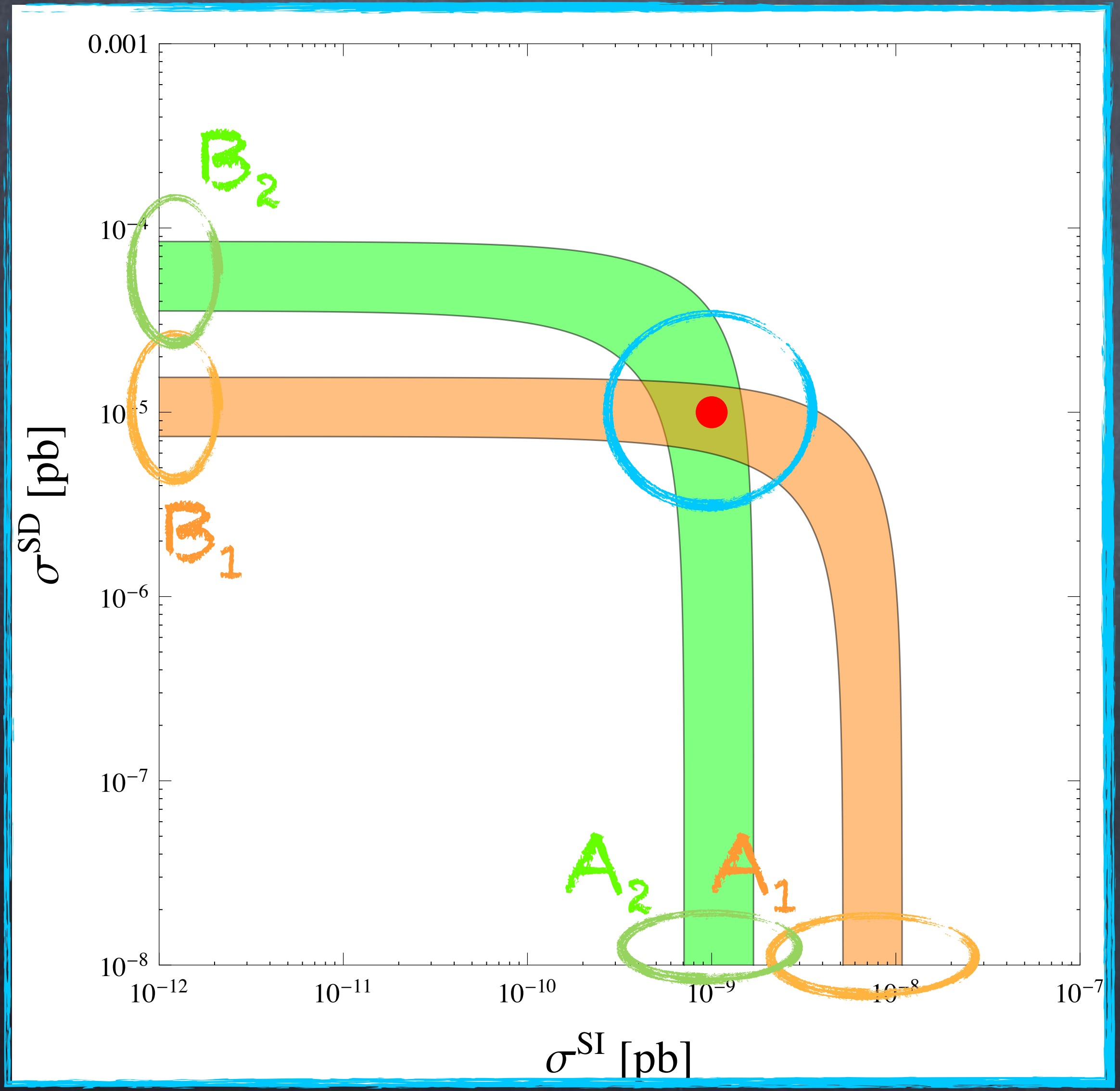
Including a second experiment

$$N_2 = A_2\sigma^{SI} + B_2\sigma^{SD}$$

Combining targets

Let's assume that an experiment 1 measures a signal, generated by the DM mass and the SI-SD cross sections, the number of events would be given by: $N_1 = A_1\sigma^{SI} + B_1\sigma^{SD}$
where the parameters A and B depends on the nucleus and DM mass.

If we assume that DM mass is well determined (for simplicity):



The red dot represents the values of the cross sections used to "simulate" the signal

There is a degeneracy between the cross sections (the signal can be explained by both alone or a combination)

Including a second experiment

$$N_2 = A_2\sigma^{SI} + B_2\sigma^{SD}$$

Iff the parameters A and B from each of the experiments are different, then we end up with a

FINITE CONTOUR
Both experiments are

COMPLEMENTARY

The real situation

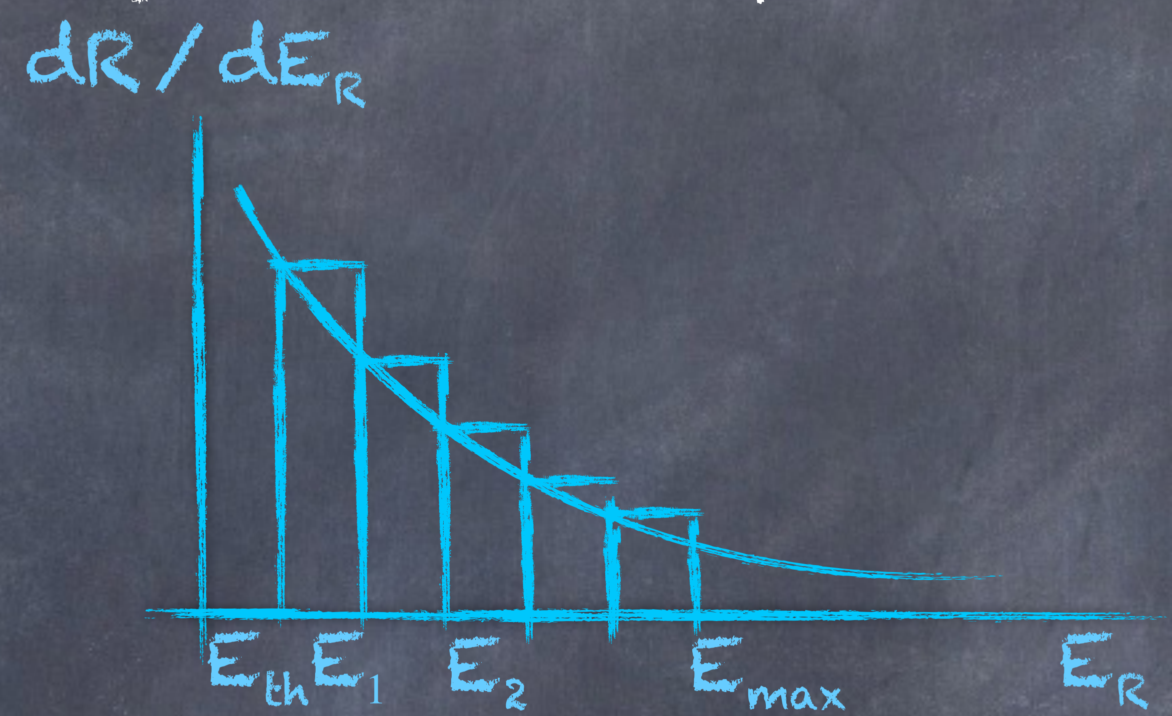
Ingredients of the analyisis:

- We generate a "signal" by choosing a BM point defined by $m_{DM}, \sigma^{SI}, \sigma^{SD}$

The real situation

Ingredients of the analyisis:

- We generate a "signal" by choosing a BM point defined by $m_{DM}, \sigma^{SI}, \sigma^{SD}$



The total number of events in a series of bins must be calculated $N = Rt$ (t=live time)

$$N_{12} = \int_{E_1}^{E_2} dE_R \frac{\varepsilon \rho_0}{m_N m_{DM}} \int_{v_{min}}^{v_{esc}} v f(v) \frac{d\sigma}{dE_R}(v, E_R) dv$$

And extend from threshold energy up to the maximum (usually defined as energy window)

The real situation

Ingredients of the analyisis:

- We generate a "signal" by choosing a BM point defined by $m_{DM}, \sigma^{SI}, \sigma^{SD}$

We perform a scan over the parameter space

The total number of events in a series of bins must be calculated $N = Rt$ (t=live time)

$$N_{12} = \int_{E_1}^{E_2} dE_R \frac{\varepsilon \rho_0}{m_N m_{DM}} \int_{v_{min}}^{v_{esc}} v f(v) \frac{d\sigma}{dE_R}(v, E_R) dv$$

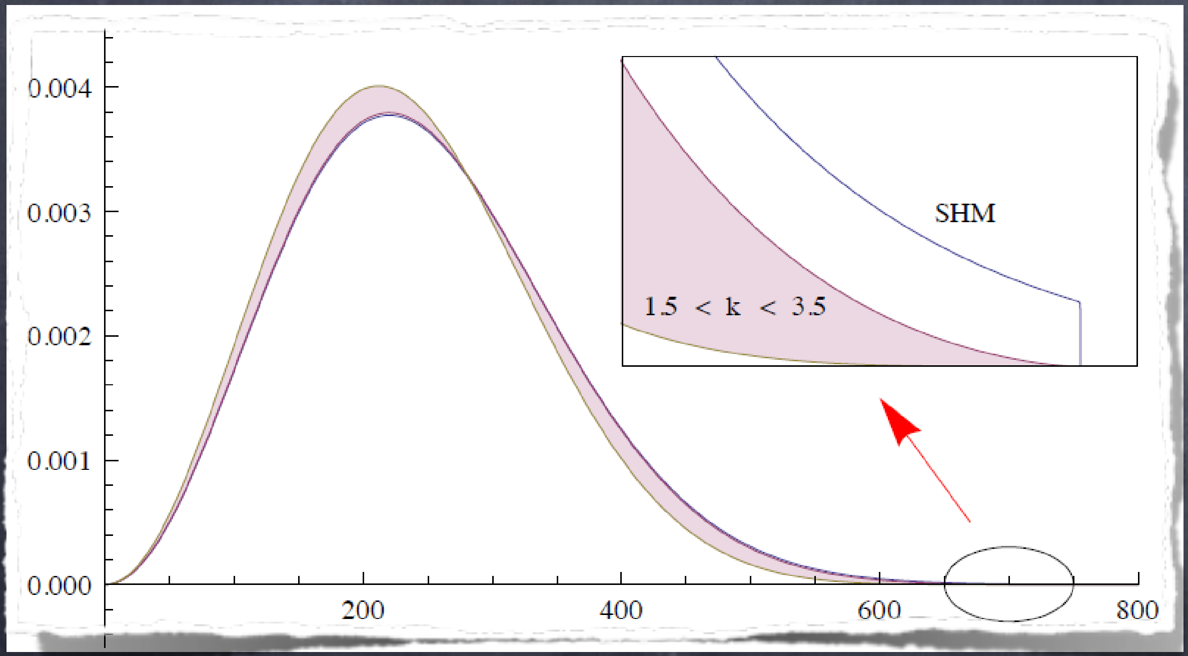
And extend from threshold energy up to the maximum (usually defined as energy window)

We compare both sets of data using a Poissonian likelihood function

The real situation

Ingredients of the analyisis:

- We generate a "signal" by choosing a BM point defined by $m_{DM}, \sigma^{SI}, \sigma^{SD}$
- We perform a scan over the parameter space
- We include astrophysical uncertainties



Nuisance parameter	Range	Prior distribution
$\rho_{\mathrm{WIMP},\odot}$	$[0.2, 0.6]$ GeV cm^{-3}	normal
v_{esc}	$[478, 610]$ km s^{-1}	normal
$v_\odot$	$[170, 290]$ km s^{-1}	normal
k	$[0.5, 3.5]$	flat

Lisante et al '10

$$F_k(v) = N_k^{-1} v^2 \left[e^{-v^2/k\Delta v^2} - e^{-v_{esc}^2/k\Delta v^2} \right]^k \theta(v_{esc} - v) \qquad N_k = \Delta v^3 e^{-y_e^2} \int_0^{y_e} y^2 \left(e^{-(y^2 - y_e^2)/k} - 1 \right)^k dy$$

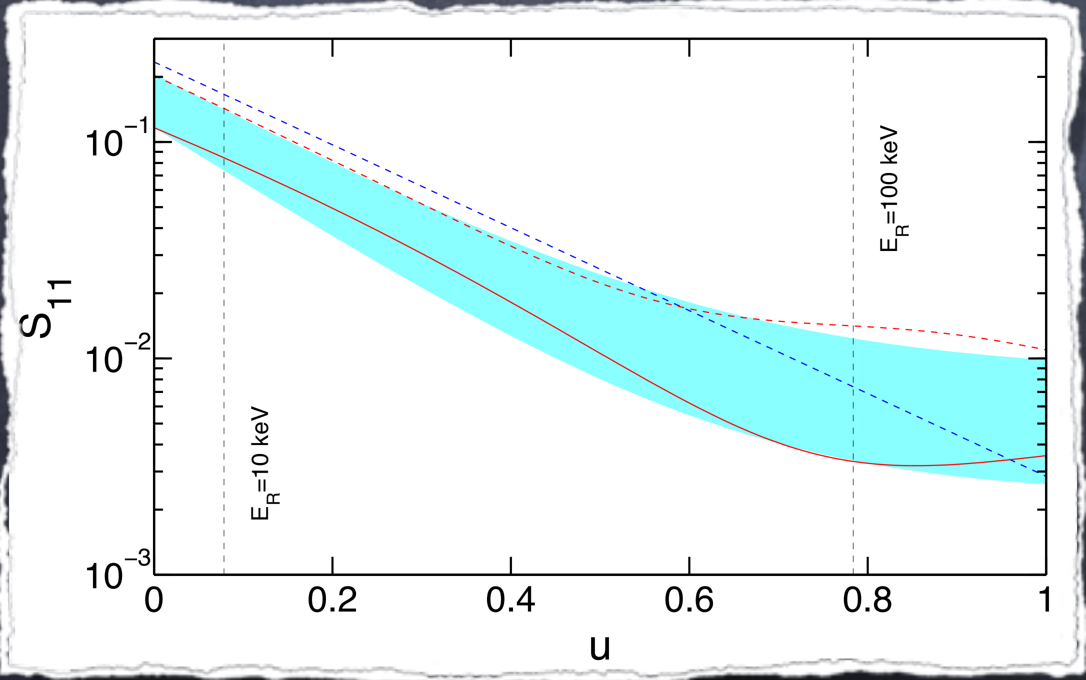
Binney & Tremaine

$$y_e = v_{esc} / \Delta v$$

The real situation

Ingredients of the analyisis:

- We generate a "signal" by choosing a BM point defined by $m_{DM}, \sigma^{SI}, \sigma^{SD}$
- We perform a scan over the parameter space
- We include astrophysical uncertainties
- We include nuclear uncertainties



Isotope	N	α	β
^{73}Ge	0.0749 - 0.2071	5.0 - 6.0	0.0304 - 0.0442
^{129}Xe	0.0225 - 0.0524	4.0625 - 4.3159	0.001 - 0.0093
^{131}Xe	0.0169 - 0.0274	3.9913 - 4.7075	0.05 - 0.105
^{127}I	0.0297 - 0.0568	4.0050 - 4.4674	0.05 - 0.057
^{23}Na	0.0098 - 0.0277	2.0 - 3.5287	0 - 0.1250
^{19}F	0.0505 - 0.1103	2.9679 - 3.0302	0 - 0.0094

$$\left(\frac{d\sigma}{dE_R}\right)_{SD} = \frac{16 m_N G_F^2 (J+1)}{\pi v^2 J}\left(a_p < S_p > + a_n < S_n >\right)^2 F_{SD}^2(E_R) \qquad S_{ij}(u) = N\left[(1-\beta)e^{-\alpha u} + \beta\right] \qquad E_R = \frac{u b^{-2}}{m_N}$$

$$S(q) = a_0^2 S_{00}(q) + a_0 a_1 S_{01}(q) + a_1^2 S_{11}(q) \qquad F_{SD}^2(q) = S(q)/S(0)$$

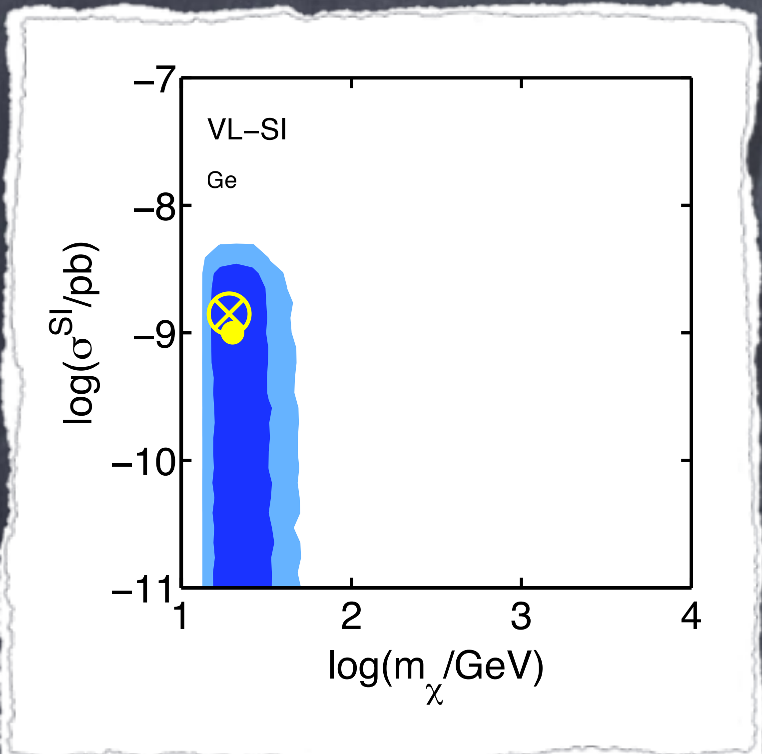
Cerdeño et al '12

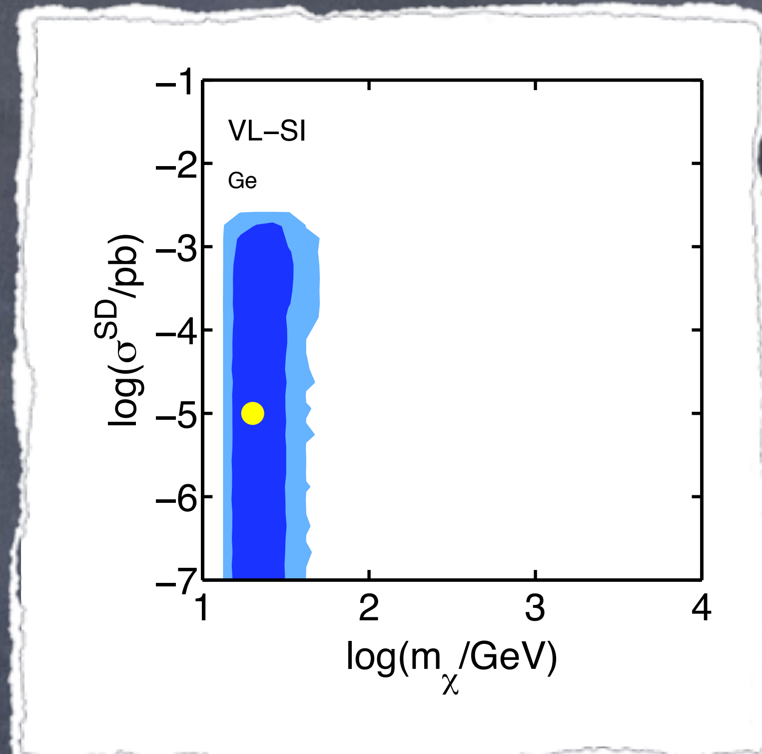
Playing with Ge and Xe

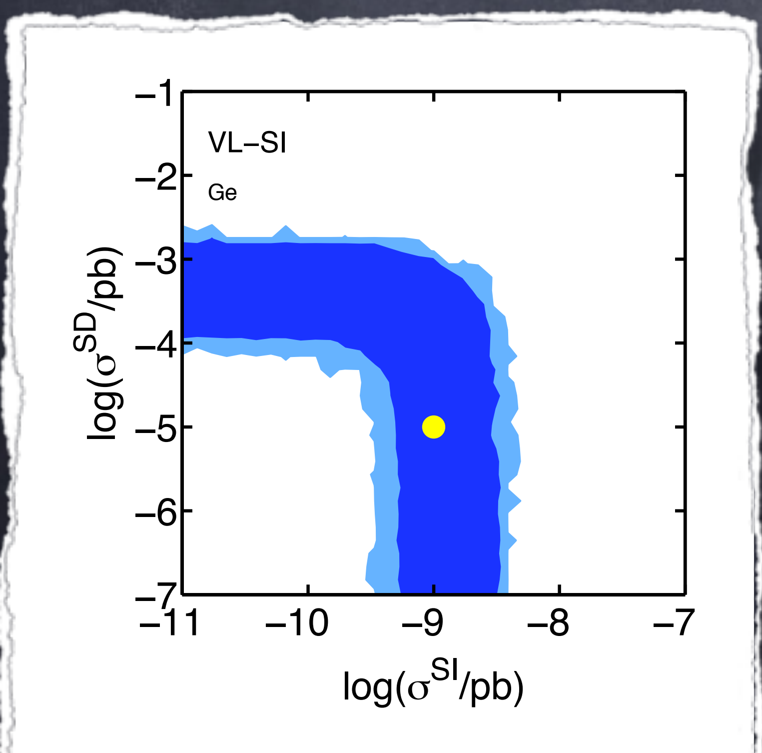
Experimental setups for Ge and Xe

- Background free experiments (in previous works we have shown that the expected levels of background in these detectors do not affect the complementary conclusions)
- We use natural abundances for each of the nuclei
- Exposure of 300 kg yr (1 ton yr with 30% of efficiency)
- 3 keV threshold for each
- Maximum energy: 100 keV for Ge and 43 keV for Xe
- Gaussian energy resolution

Current experiments (Ge,Xe)







● BM point

$m_\chi = 20 GeV$

$\sigma^{SI} = 10^{-9} pb$

$\sigma^{SD} = 10^{-5} pb$

⊗ Best fit point

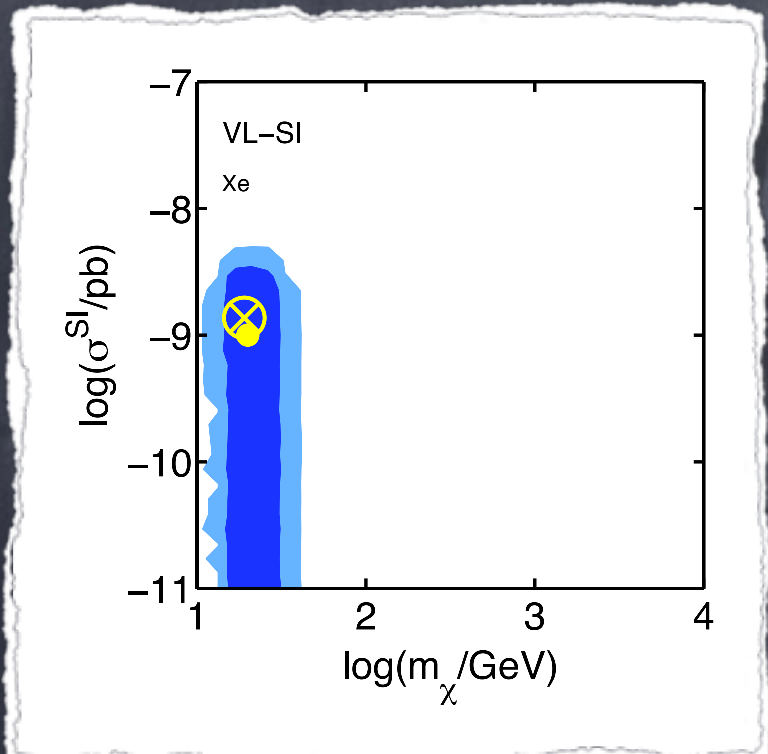
68% and 99%CL profile likelihood contours

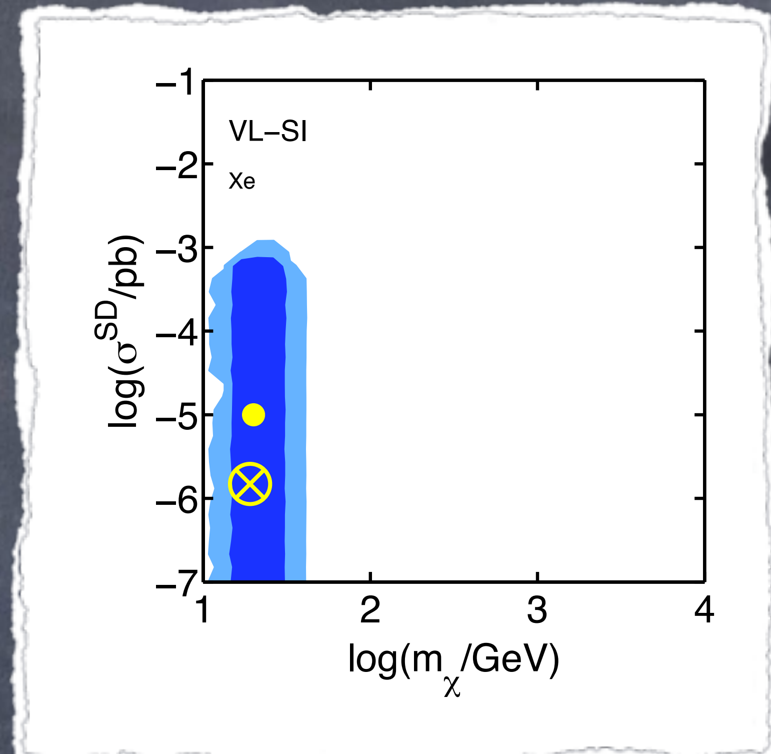
Ge

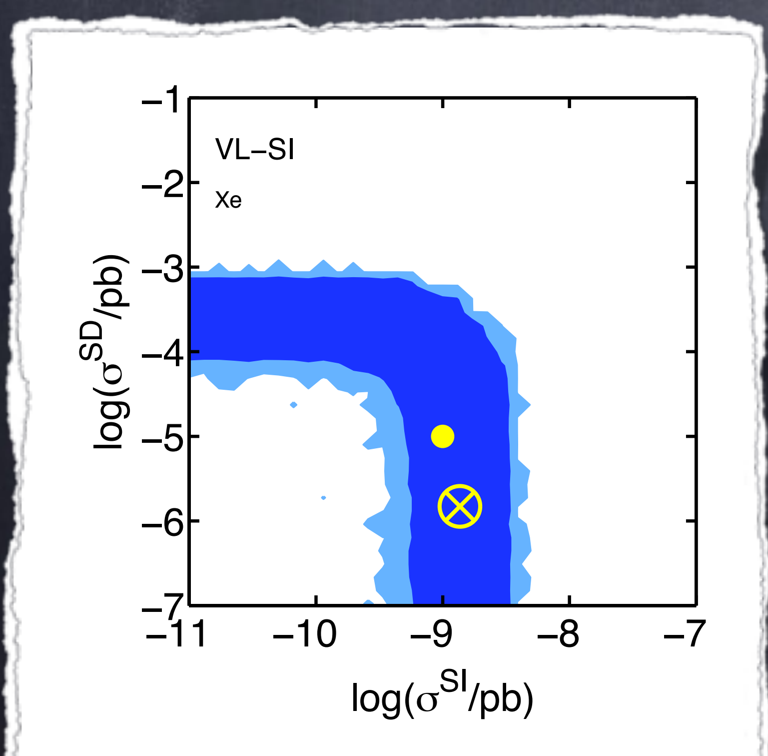
NOT ABLE TO RECONSTRUCT THE CROSS SECTIONS

THE MASS OF THE WIMP IS WELL RECONSTRUCTED

Current experiments (Ge,Xe)







● BM point

$m_\chi = 20GeV$

$\sigma^{SI} = 10^{-9} pb$

$\sigma^{SD} = 10^{-5} pb$

⊗ Best fit point

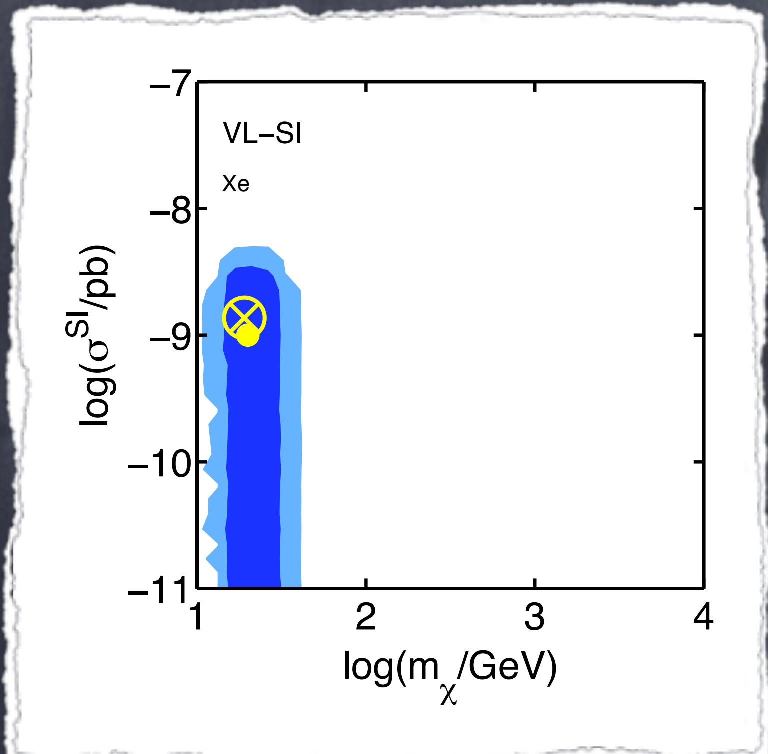
68% and 99%CL profile likelihood contours

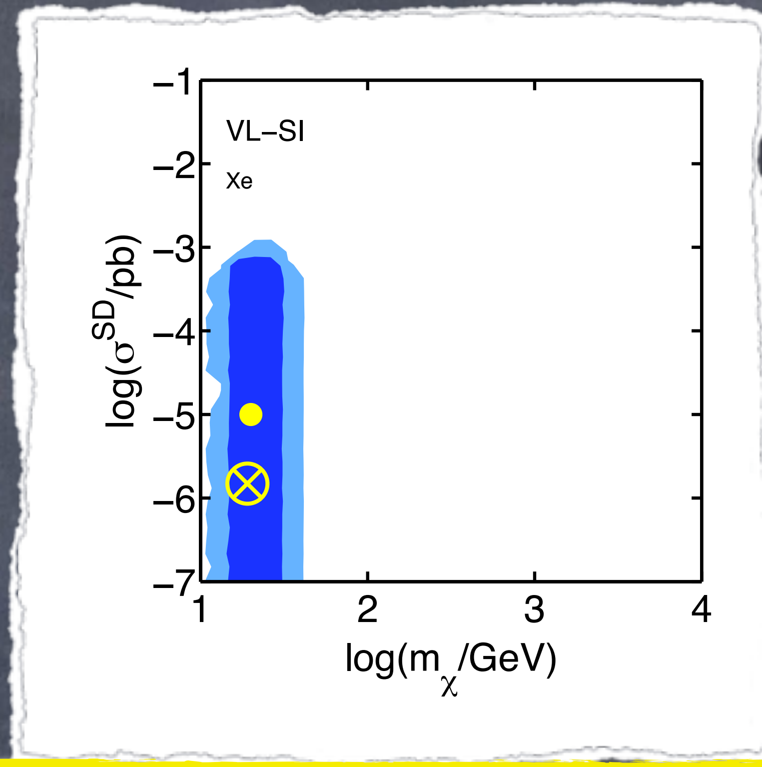
Xe

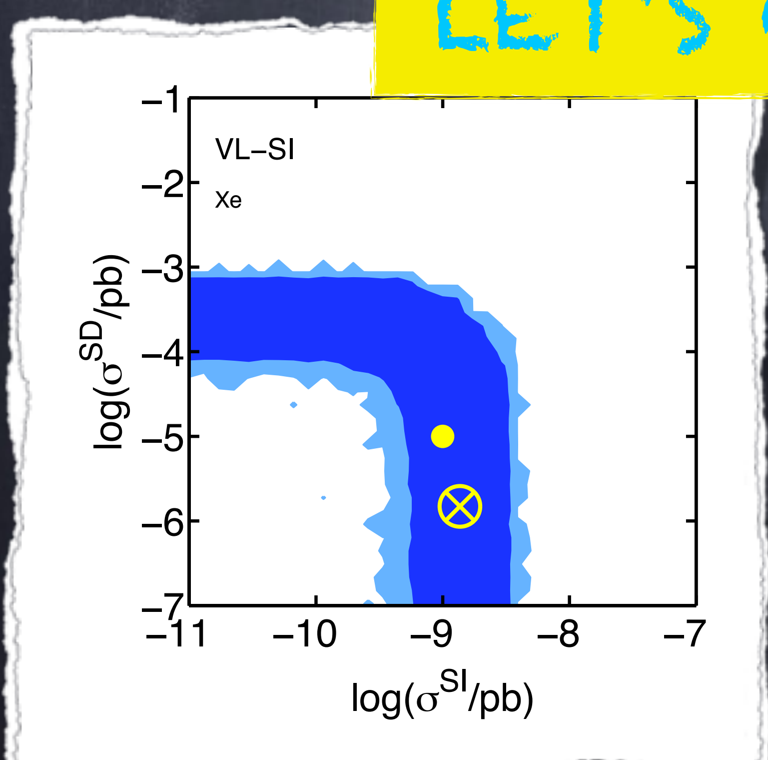
NOT ABLE TO RECONSTRUCT THE CROSS SECTIONS

THE MASS OF THE WIMP IS WELL RECONSTRUCTED

Current experiments (Ge,Xe)







LET'S COMBINE BOTH TARGETS

$m_\chi = 20GeV$

$\sigma^{SI} = 10^{-9} pb$

$\sigma^{SD} = 10^{-5} pb$

⊗ Best fit point

68% and 99%CL profile likelihood contours

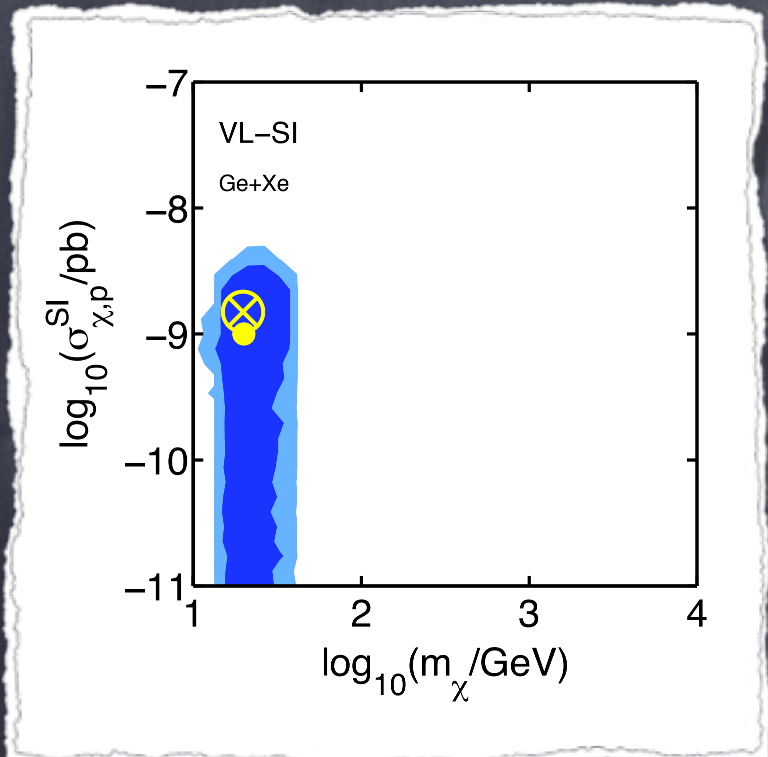
Xe

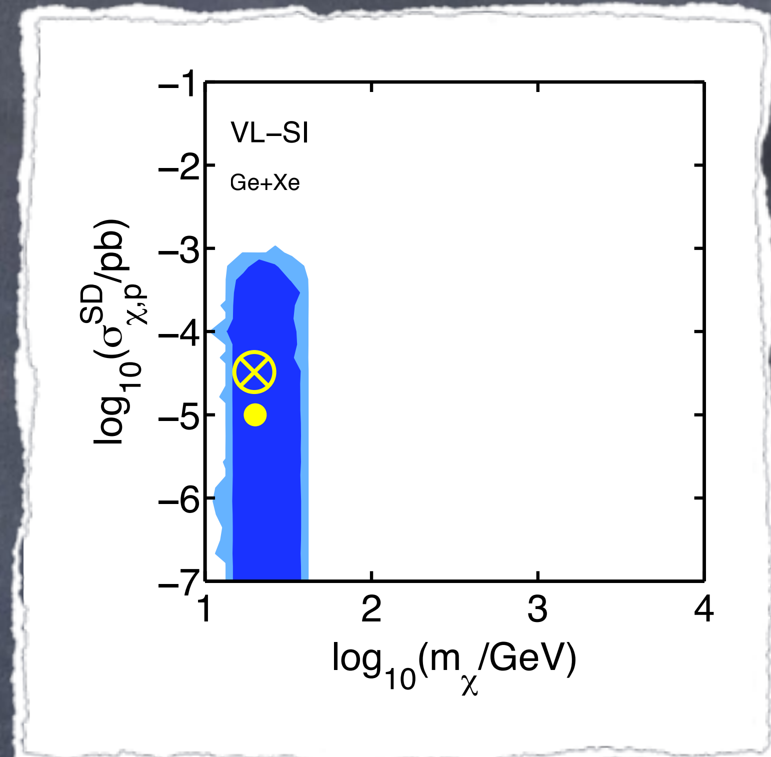
NOT ABLE TO RECONSTRUCT

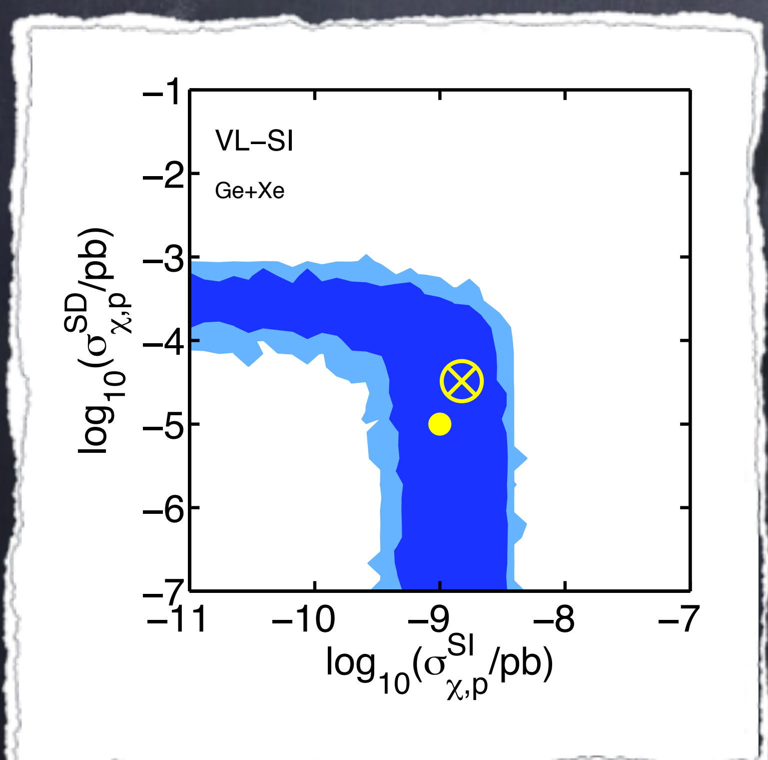
S SECTIONS

MASS OF THE WIMP IS WELL RECONSTRUCTED

Current experiments (Ge,Xe)







● BM point

$m_\chi = 20\,\mathrm{GeV}$

$\sigma^{SI} = 10^{-9}\,\mathrm{pb}$

$\sigma^{SD} = 10^{-5}\,\mathrm{pb}$

⊗ Best fit point

68% and 99%CL profile likelihood contours

Ge+Xe

NOT ABLE TO RECONSTRUCT THE CROSS SECTIONS EVEN IN COMBINATION

THE MASS OF THE WIMP IS WELL RECONSTRUCTED

Current experiments (Ge,Xe)

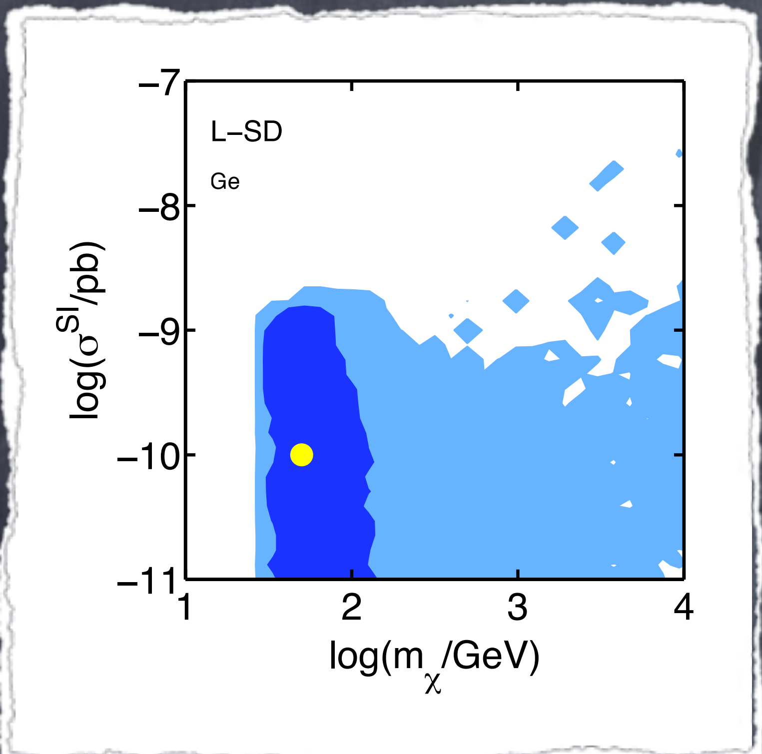
For light DM (20 GeV) and SI-dominated signals in Ge and Xe

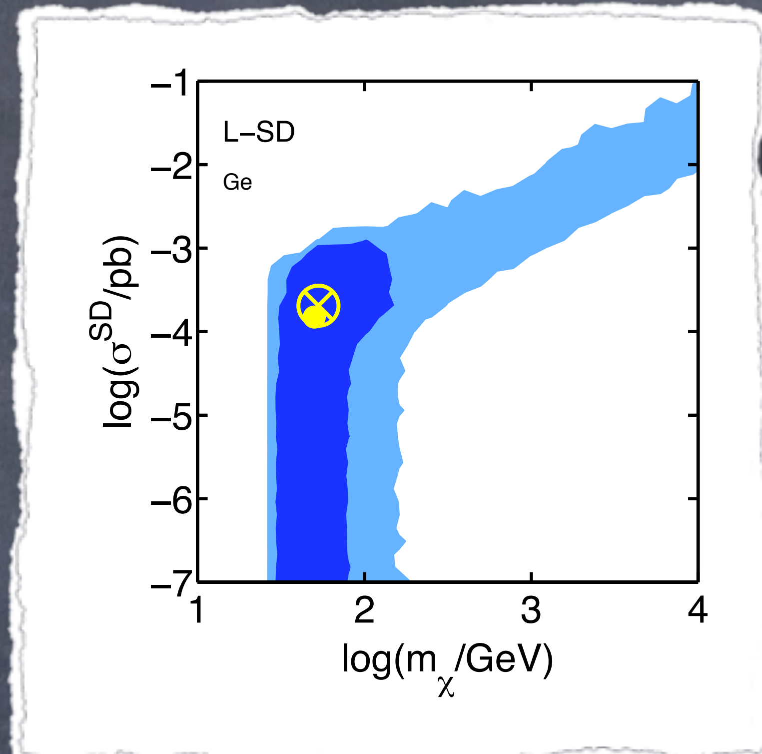
the combination of Ge and Xe like experiments is

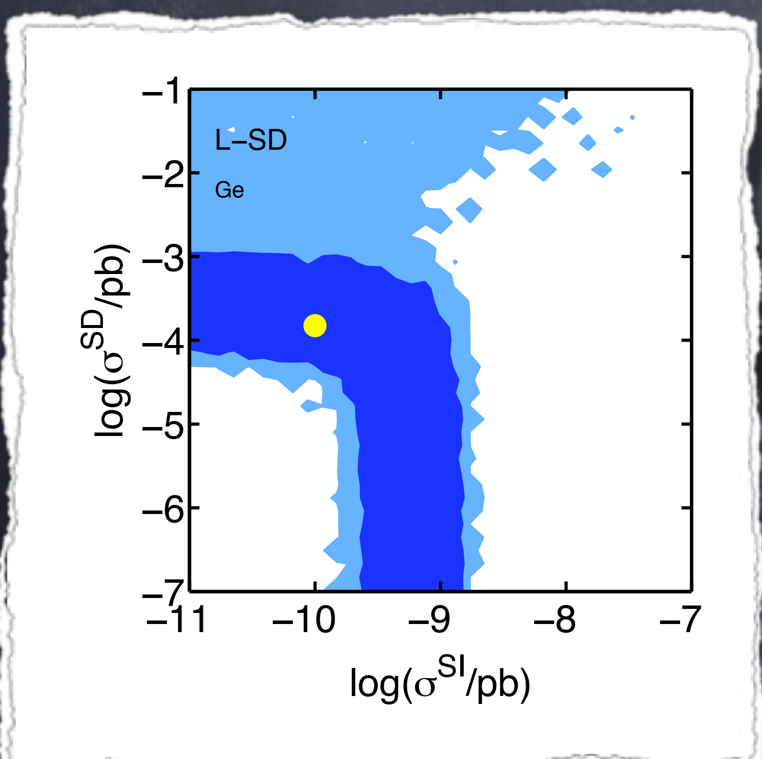
NOT COMPLEMENTARY

LET'S SEE A BENCHMARK POINT IN WHICH THE RATE IS SD-DOMINATED IN GE AND XE

Current experiments (Ge,Xe)







● BM point

$m_\chi = 50\,GeV$

$\sigma^{SI} = 10^{-10}\,pb$

$\sigma^{SD} = 1.5 \times 10^{-4}\,pb$

⊗ Best fit point

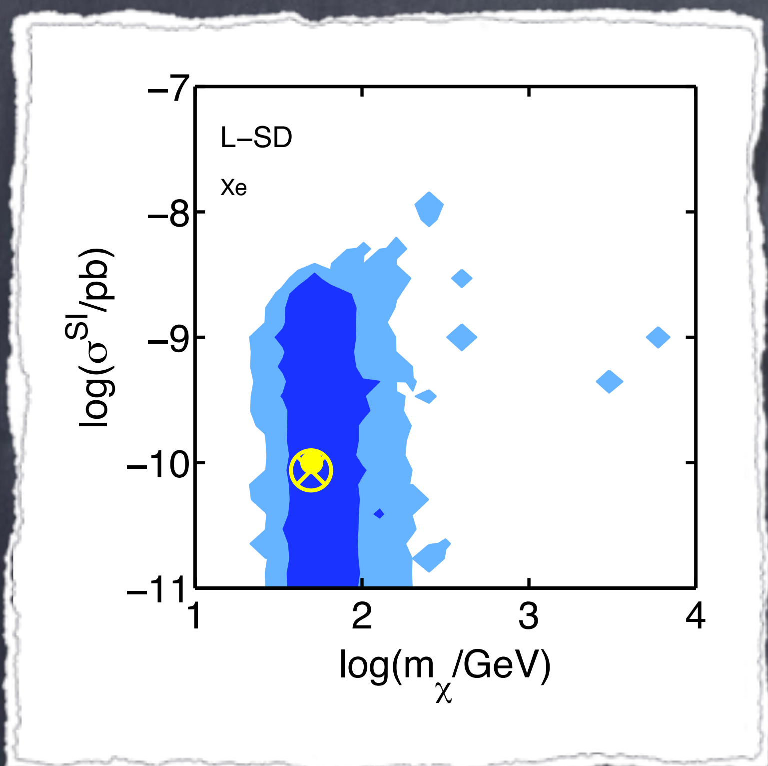
68% and 99%CL profile likelihood contours

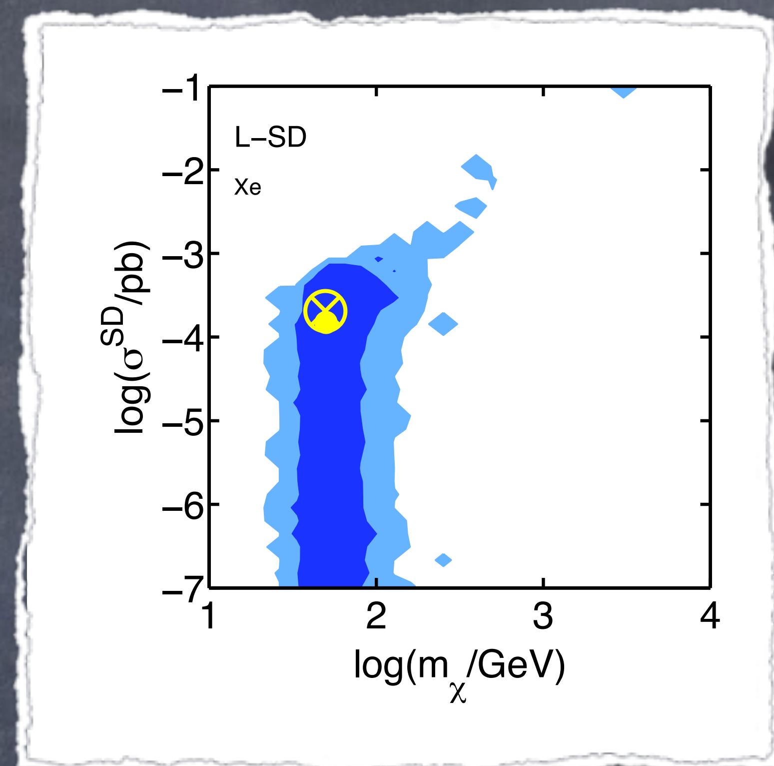
Ge

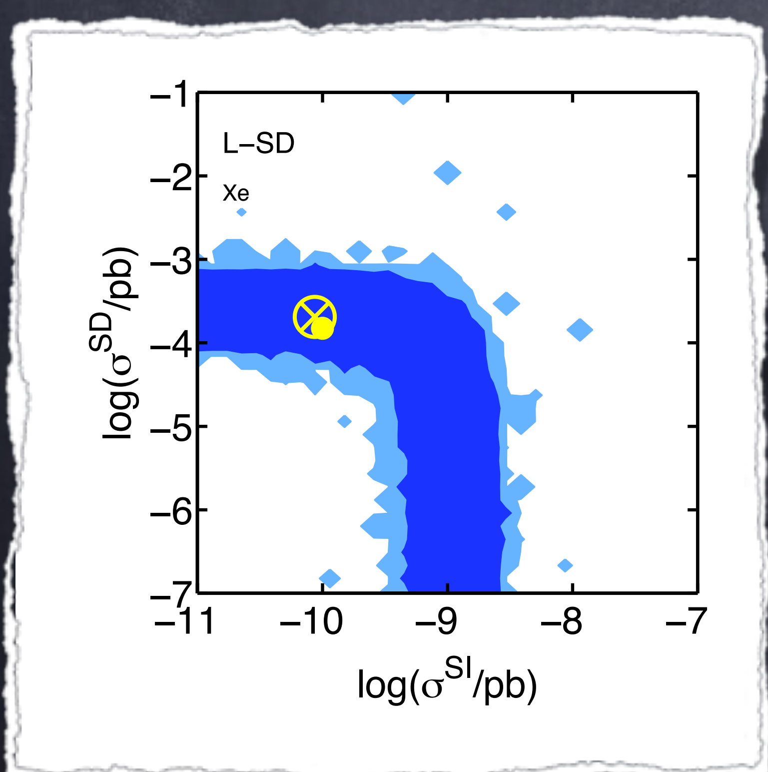
NOT ABLE TO RECONSTRUCT THE CROSS SECTIONS

THE MASS OF THE WIMP IS WELL RECONSTRUCTED ONLY AT 68% CL

Current experiments (Ge,Xe)







● BM point

$m_\chi = 50 GeV$

$\sigma^{SI} = 10^{-10} pb$

$\sigma^{SD} = 1.5 \times 10^{-4} pb$

⊗ Best fit point

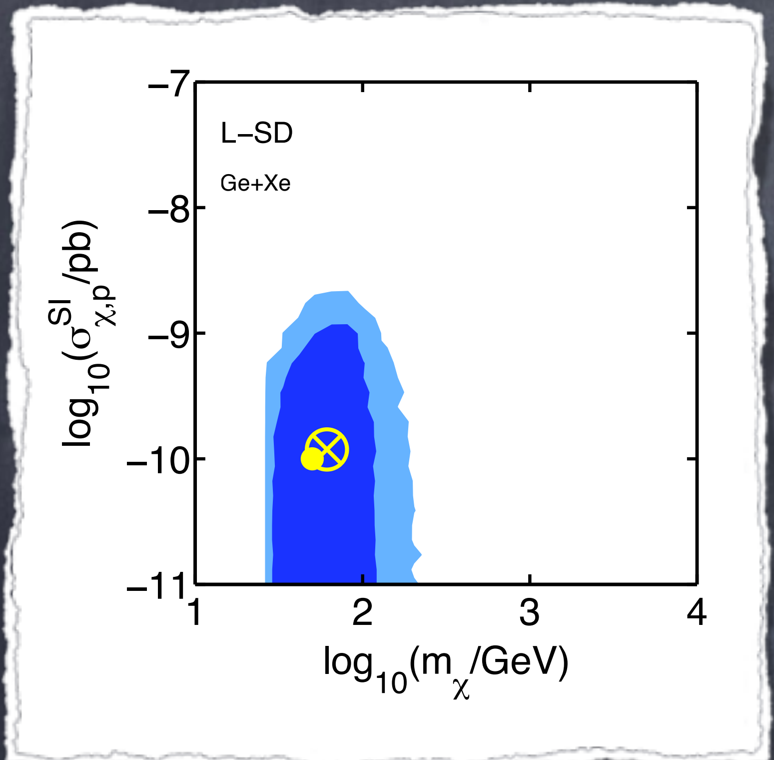
68% and 99%CL profile likelihood contours

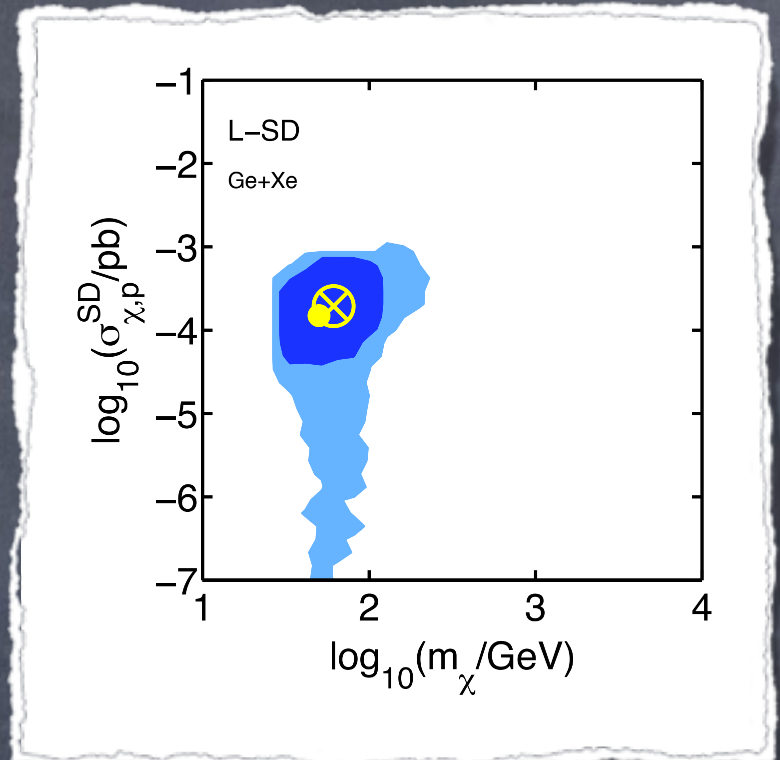
Xe

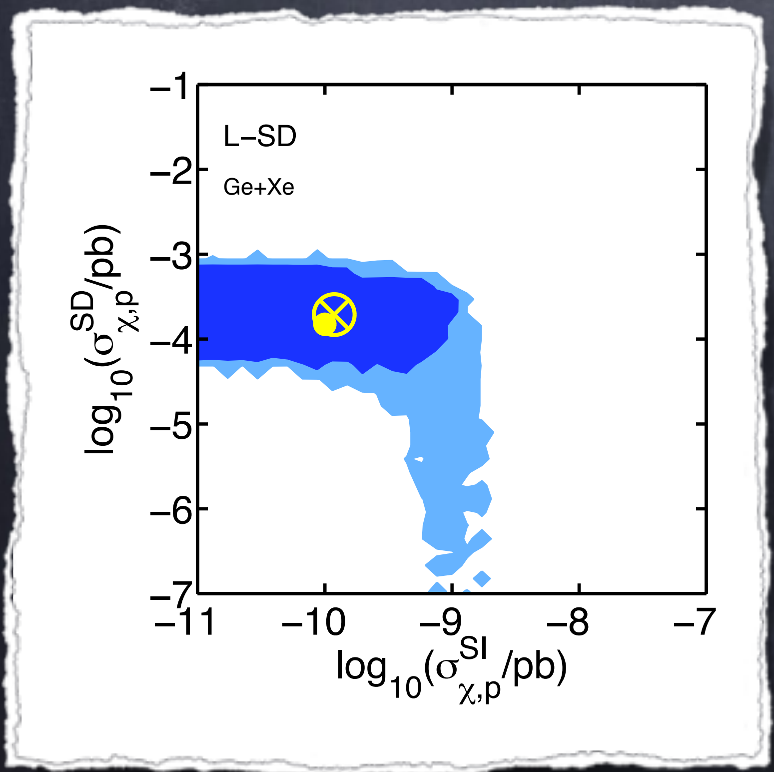
NOT ABLE TO RECONSTRUCT THE CROSS SECTIONS

THE MASS OF THE WIMP IS BETTER RECONSTRUCTED

Current experiments (Ge,Xe)







● BM point

$m_\chi = 50\mathrm{GeV}$

$\sigma^{SI} = 10^{-10}\,pb$

$\sigma^{SD} = 1.5\times10^{-4}\,pb$

⊗ Best fit point

68% and 99%CL profile likelihood contours

Ge+Xe

NOT ABLE TO RECONSTRUCT THE SI CROSS SECTION

THE MASS OF THE WIMP AND THE SD CROSS SECTION IS RECONSTRUCTED

Including the bolometers
LiF - $CaWO_4$ - CaF_2 - NaI

Experimental setups for the bolometers

- Background free experiments (in previous works we have shown that the expected levels of background in these detectors do not affect the complementary conclusions)
- We use natural abundances for each of the nuclei
- Exposure of 300 kg yr (1 ton yr with 30% of efficiency)
- 10 keV threshold for each
- Maximum energy: 100 keV
- Energy resolution: 5% FWHM
- For NaI: thermal quenching of 0.85, 1.0 and 1.15

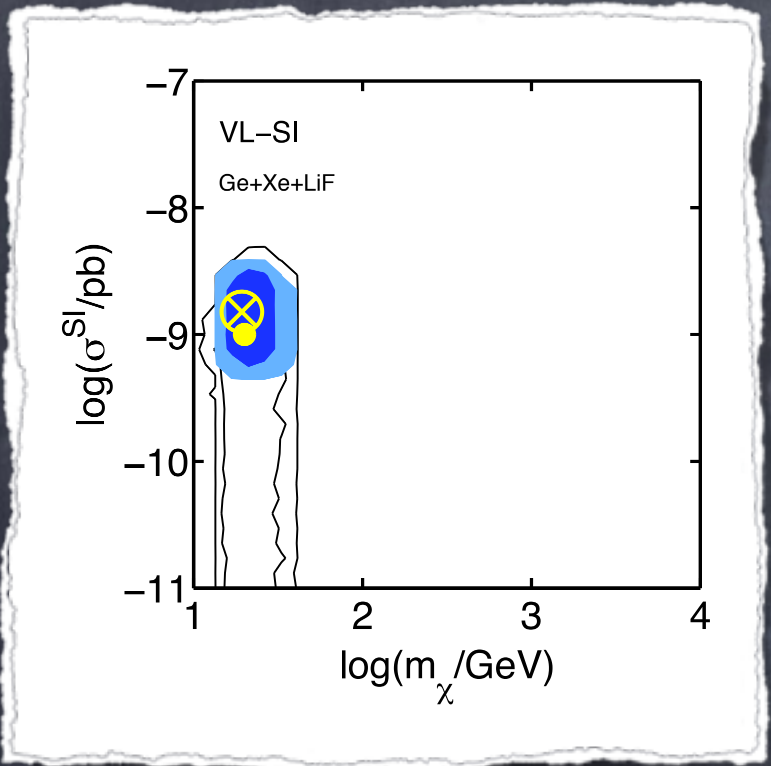
Including the bolometers
LiF - $CaWO_4$ - CaF_2 - NaI

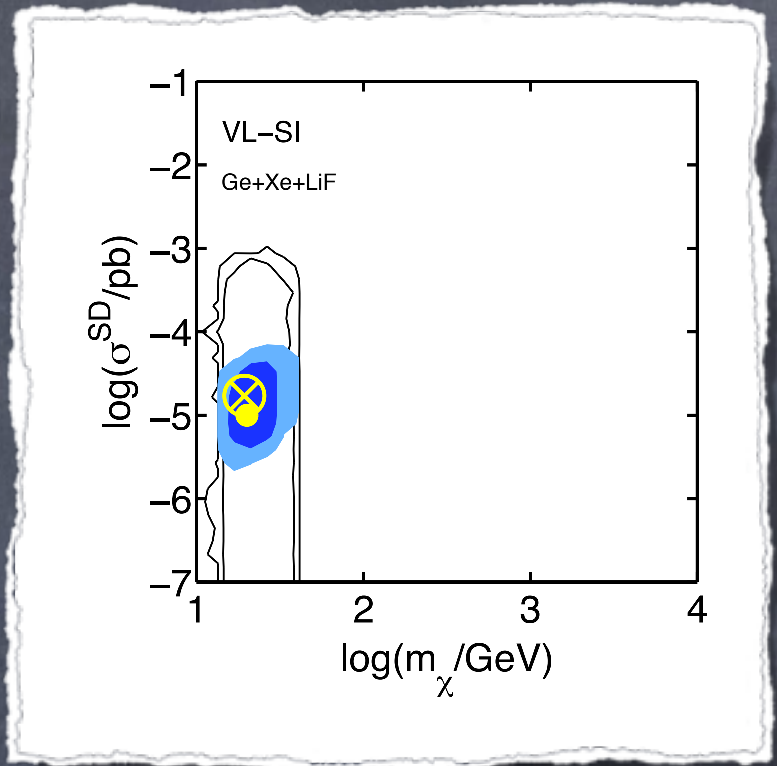
Experimental setups for the bolometers

- Background free experiments (in previous works we have shown that the expected levels of background in these detectors do not affect the complementary conclusions)
- We use natural abundances for each of the nuclei
- Exposure of 300 kg yr (1 ton yr with 30% of efficiency)
- 10 keV threshold for each
- Maximum energy: 100 keV
- Energy resolution: 5% FWHM
- For NaI: thermal quenching of 0.85, 1.0 and 1.15

WE START WITH CASE OF SI DOMINATED RATE IN GE AND XE

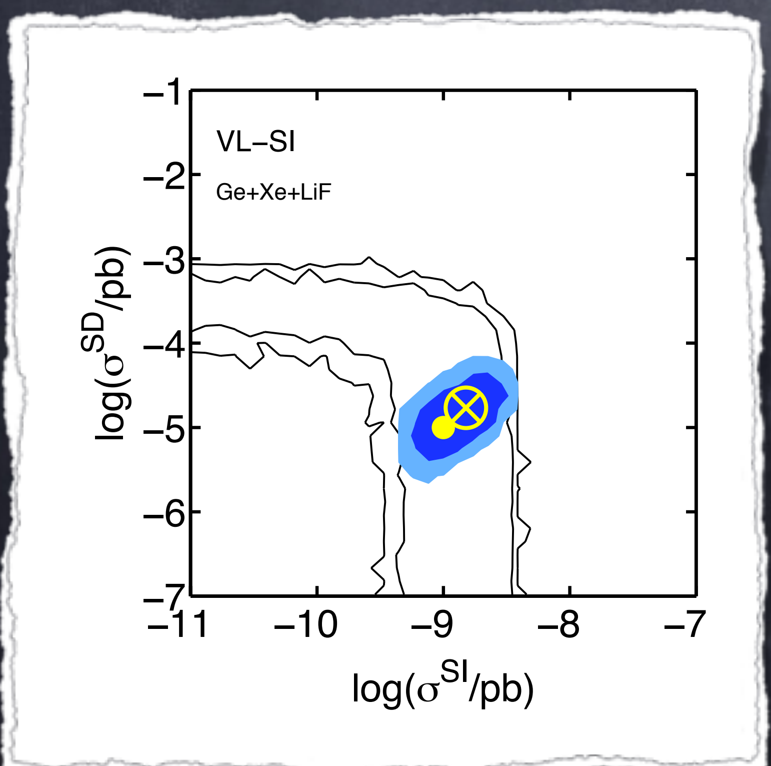
Ge + Xe + Bolometer





In black: 68% and 99%CL contours for Ge+Xe

Ge+Xe+LiF



● BM point

$m_\chi = 20GeV$

$\sigma^{SI} = 10^{-9} pb$

$\sigma^{SD} = 10^{-5} pb$

⊗ Best fit point

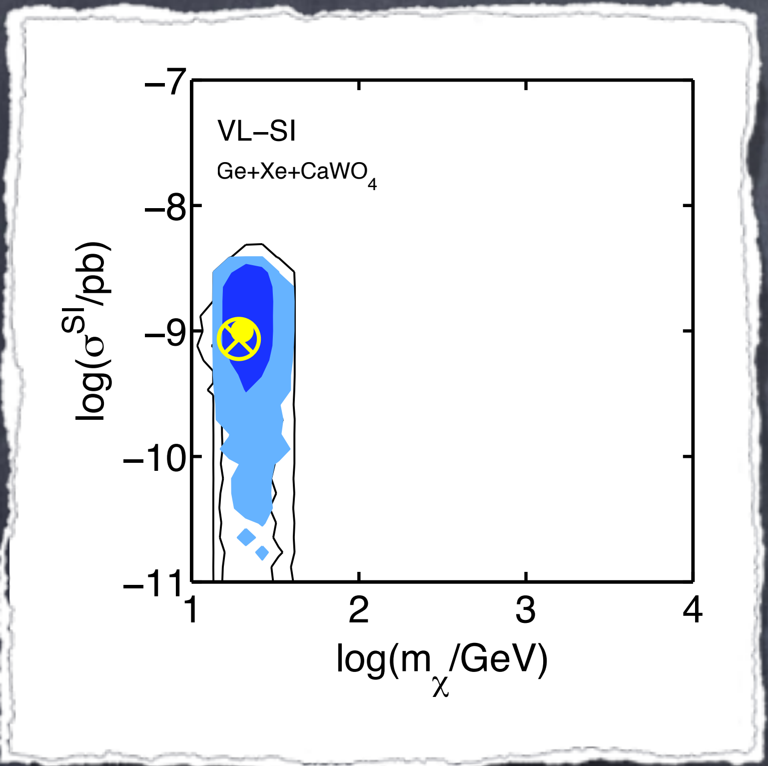
68% and 99%CL profile likelihood contours

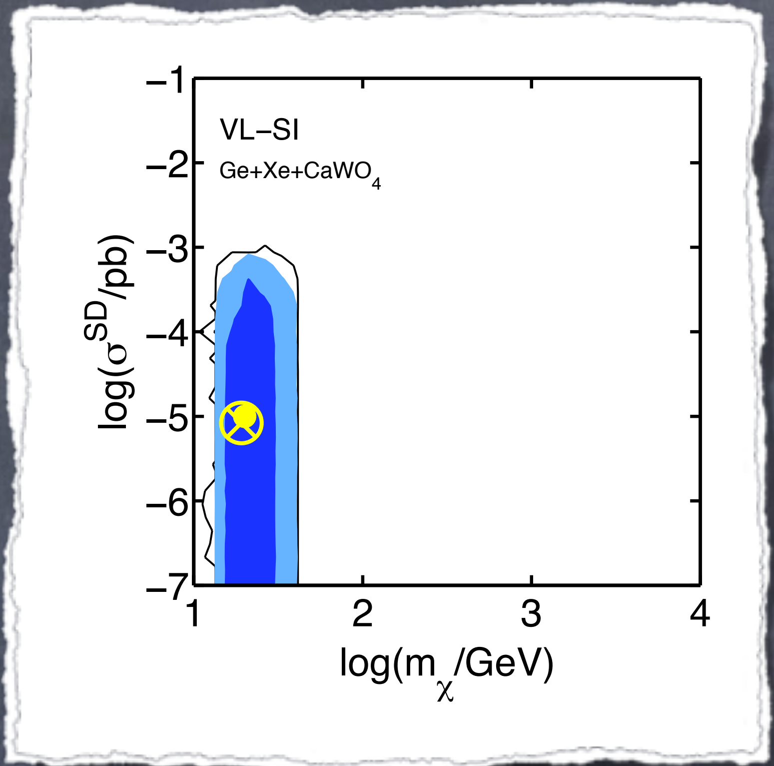
COMPLEMENTARY!!!

Very high SD sensitivity in both Li and F

Miguel Peiró. TeVPA/IDM Amsterdam June '14.

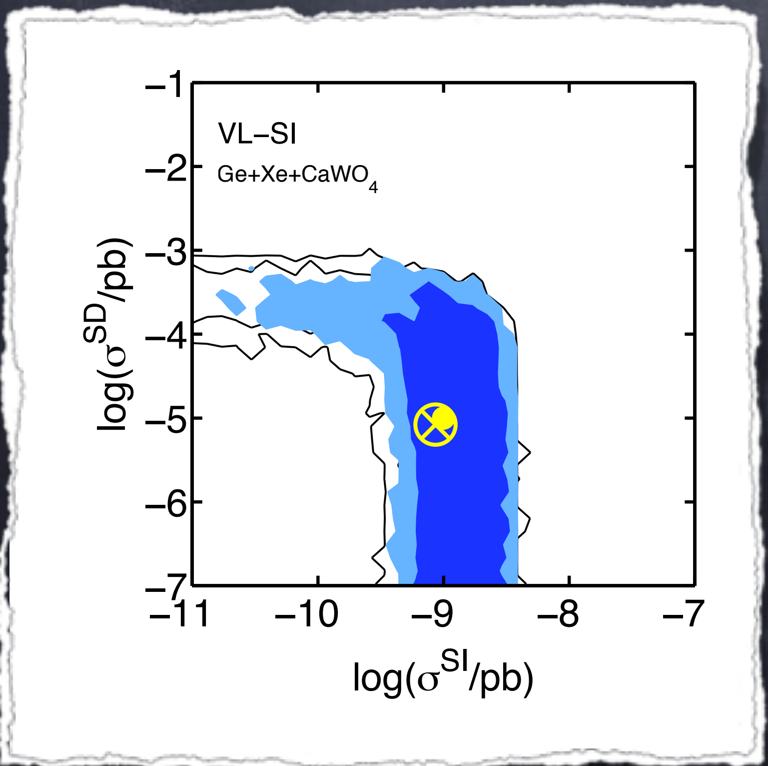
Ge + Xe + Bolometer





In black: 68% and 99%CL contours for Ge+Xe

Ge+Xe+CaWO4



● BM point

$m_\chi = 20GeV$

$\sigma^{SI} = 10^{-9} pb$

$\sigma^{SD} = 10^{-5} pb$

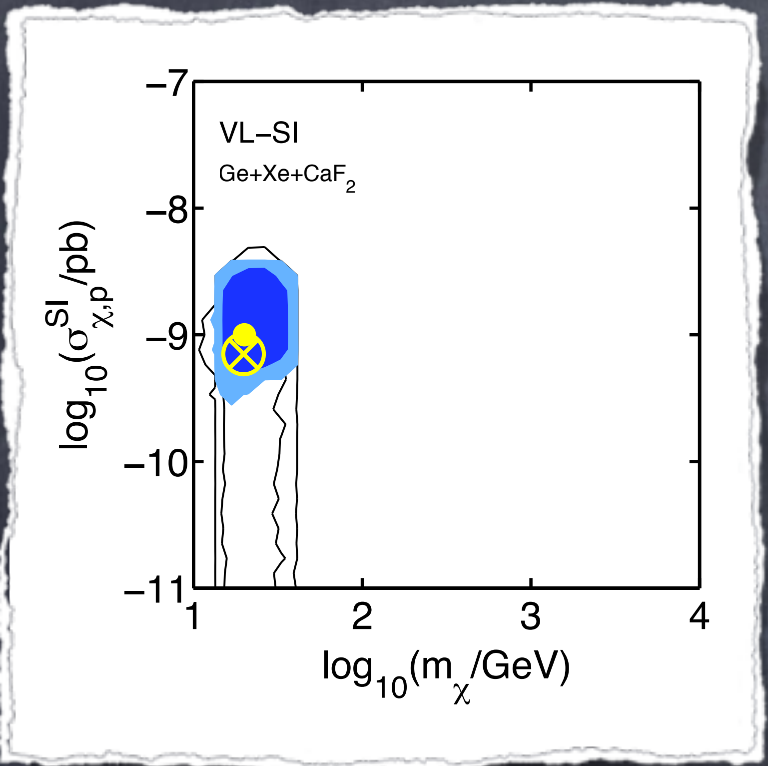
⊗ Best fit point

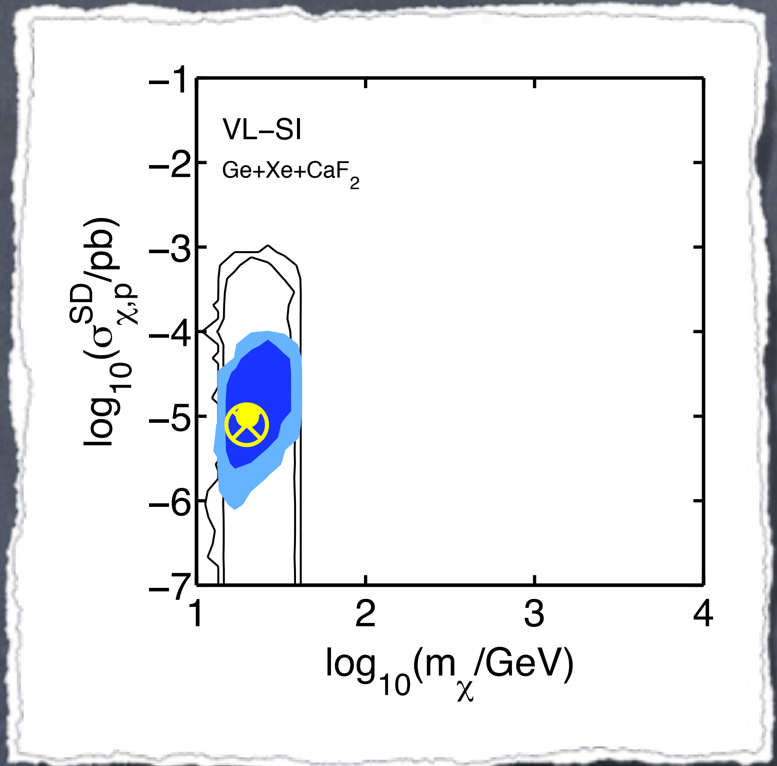
68% and 99%CL profile likelihood contours

SI and mass well reconstructed

SD cross section sensitivity of CaWO4 similar to those of Ge and Xe

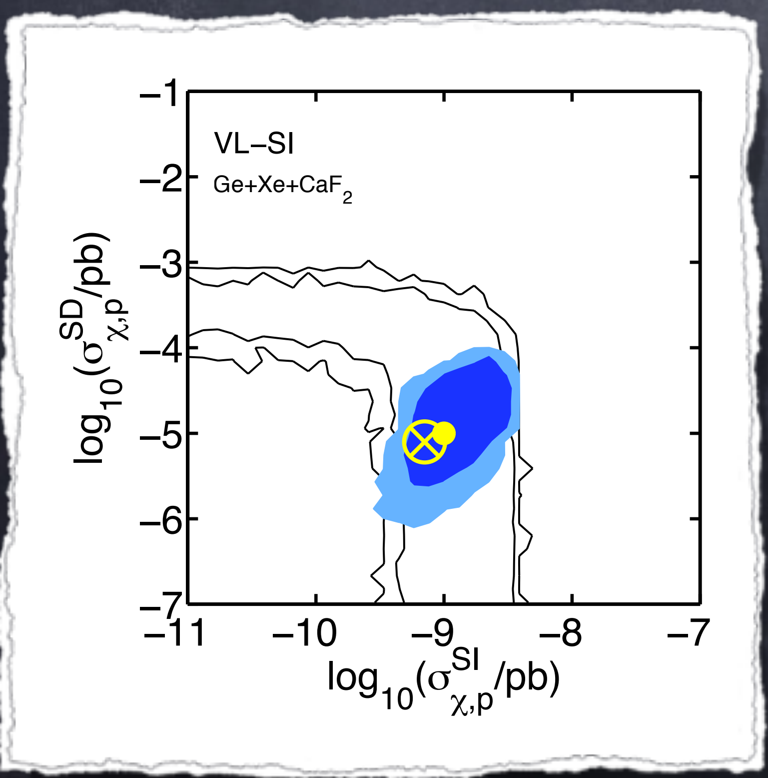
Ge + Xe + Bolometer





In black: 68% and 99%CL contours for Ge+Xe

Ge+Xe+CaF_2



● BM point

$m_\chi = 20\,\mathrm{GeV}$

$\sigma^{SI} = 10^{-9}\,pb$

$\sigma^{SD} = 10^{-5}\,pb$

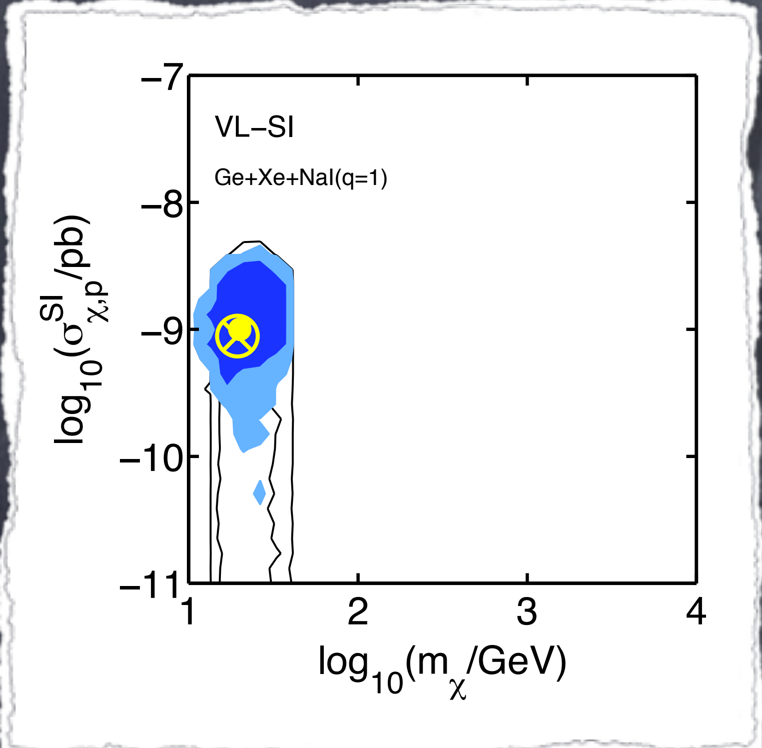
⊗ Best fit point

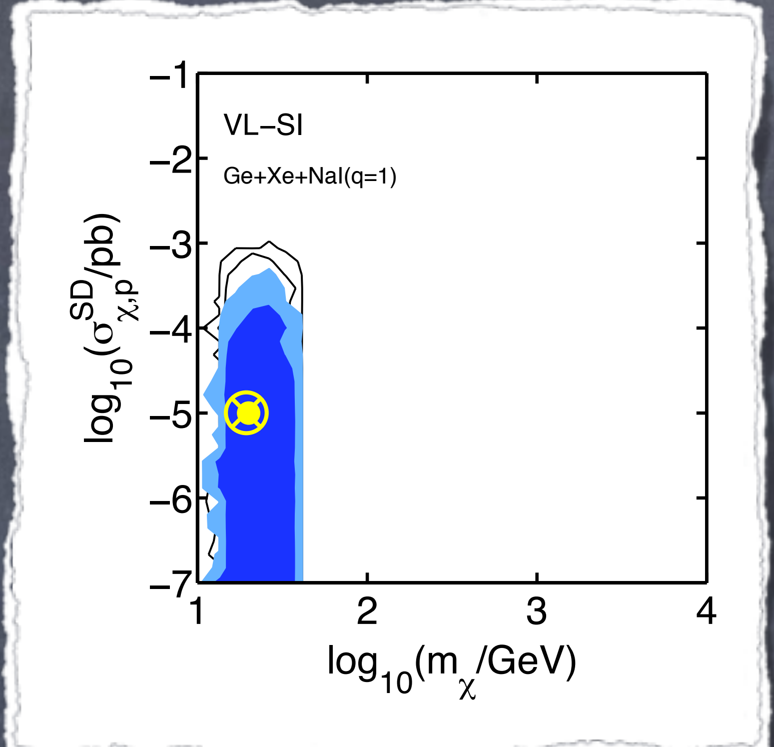
68% and 99%CL profile likelihood contours

COMPLEMENTARY!!!

Very high SD sensitivity in F (similar to LiF)

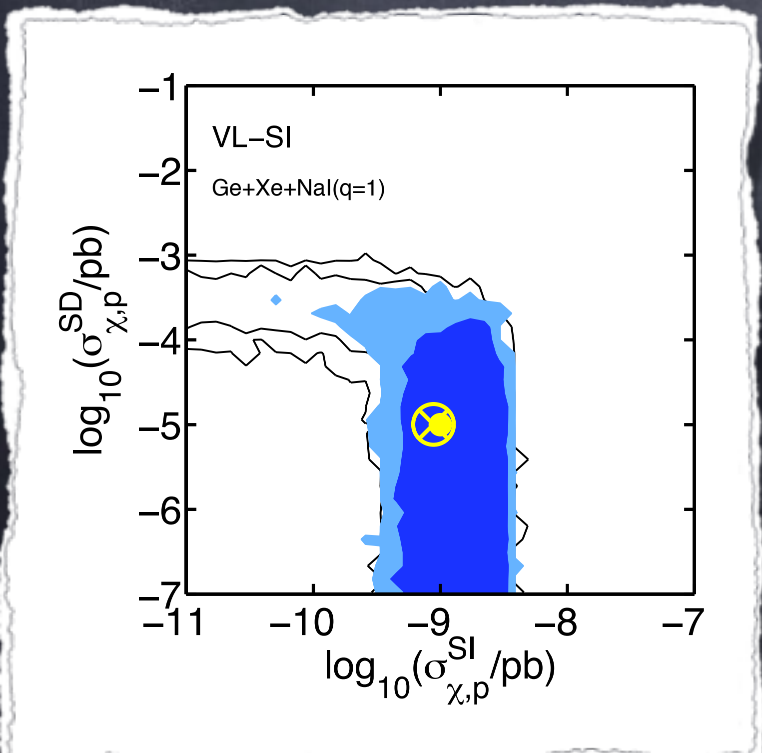
Ge + Xe + Bolometer





In black: 68% and 99%CL contours for Ge+Xe

Ge+Xe+NaI



● BM point

$m_\chi = 20GeV$

$\sigma^{SI} = 10^{-9} pb$

$\sigma^{SD} = 10^{-5} pb$

⊗ Best fit point

68% and 99%CL profile likelihood contours

SI and mass well reconstructed

SD cross section sensitivity of NaI similar to those of Ge and Xe

Current experiments (Ge,Xe)

Ge + Xe + LiF

Ge + Xe + CaF_2

COMPLEMENTARY

Ge + Xe + $CaWO_4$

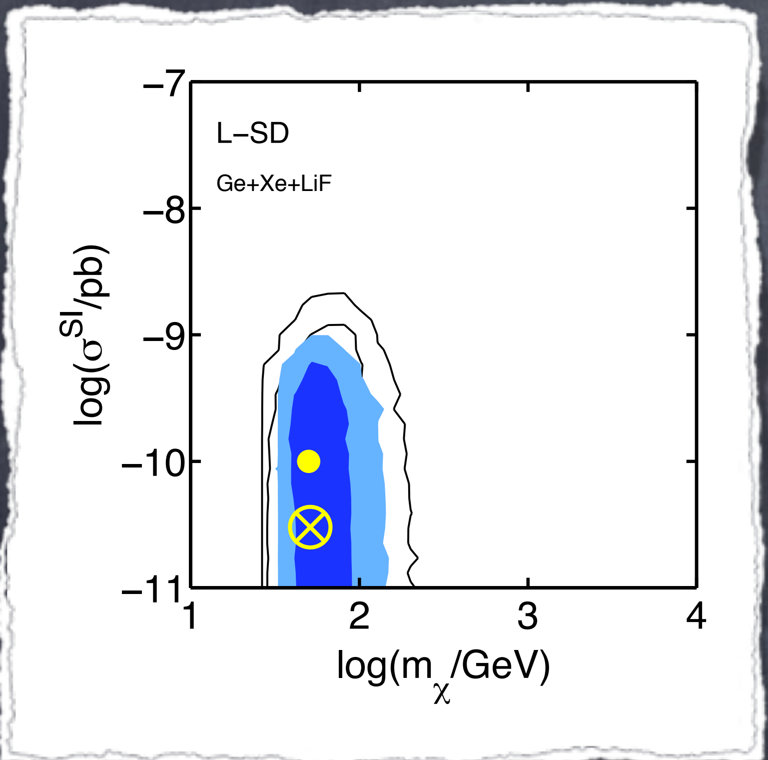
Ge + Xe + NaI

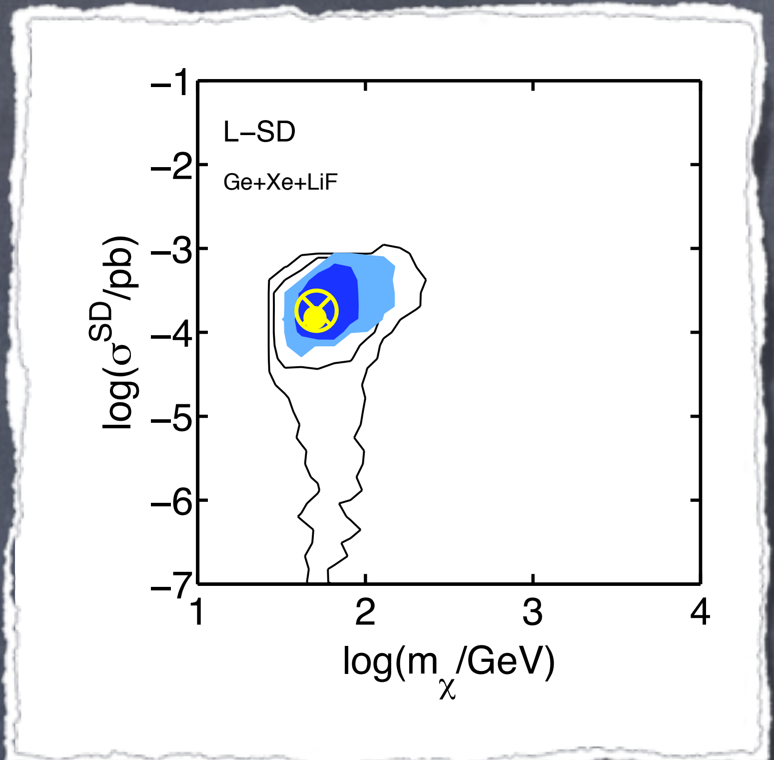
NOT COMPLEMENTARY

(but a considerable improvement)

AGAIN LET'S SEE A BENCHMARK POINT IN WHICH THE RATE IS SD-DOMINATED IN GE AND XE

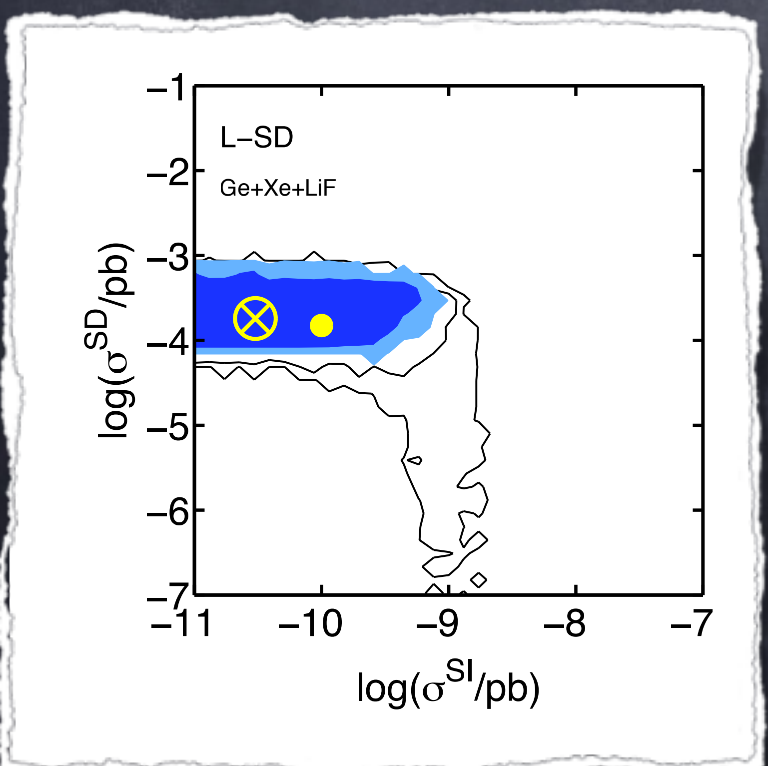
Ge + Xe + Bolometer





In black: 68% and 99%CL contours for Ge+Xe

Ge+Xe+LiF



● BM point

$m_\chi = 50 GeV$

$\sigma^{SI} = 10^{-10} pb$

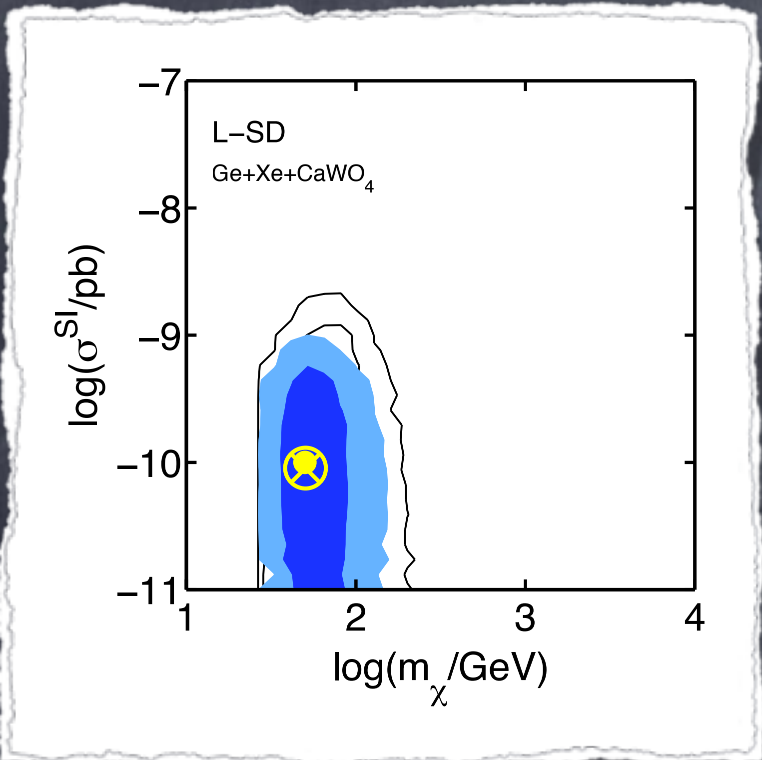
$\sigma^{SD} = 1.5 \times 10^{-4} pb$

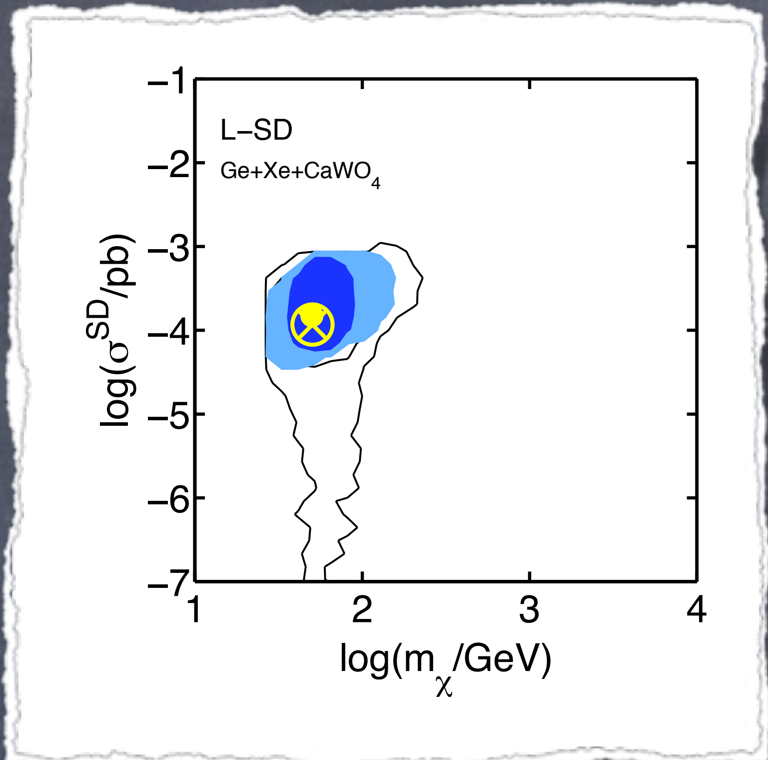
⊗ Best fit point

Mass and SD cross section reconstructed

68% and 99%CL profile likelihood contours

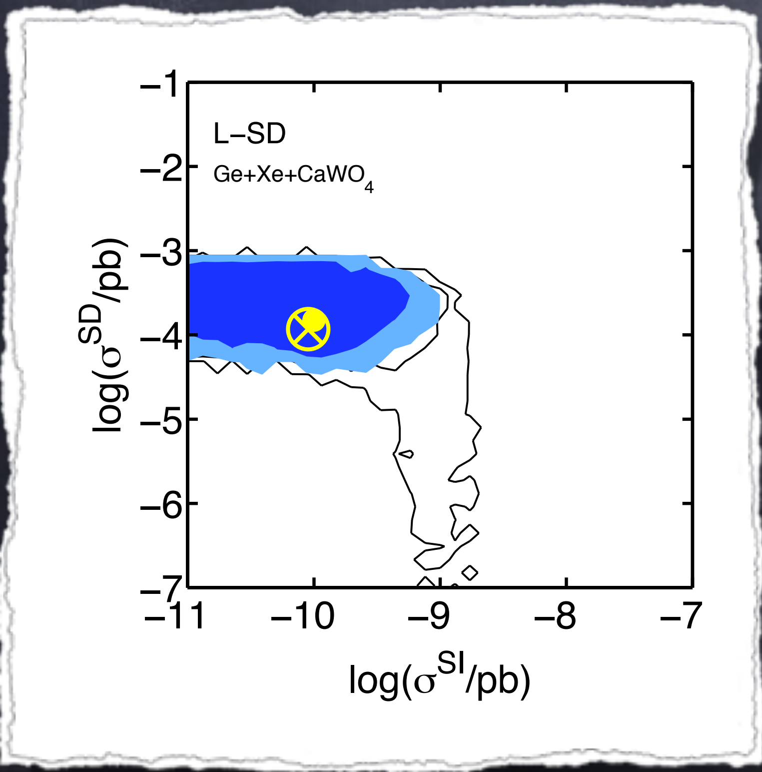
Ge + Xe + Bolometer





In black: 68% and 99%CL contours for Ge+Xe

Ge+Xe+CaWO4



● BM point

$m_\chi = 50 GeV$

$\sigma^{SI} = 10^{-10} pb$

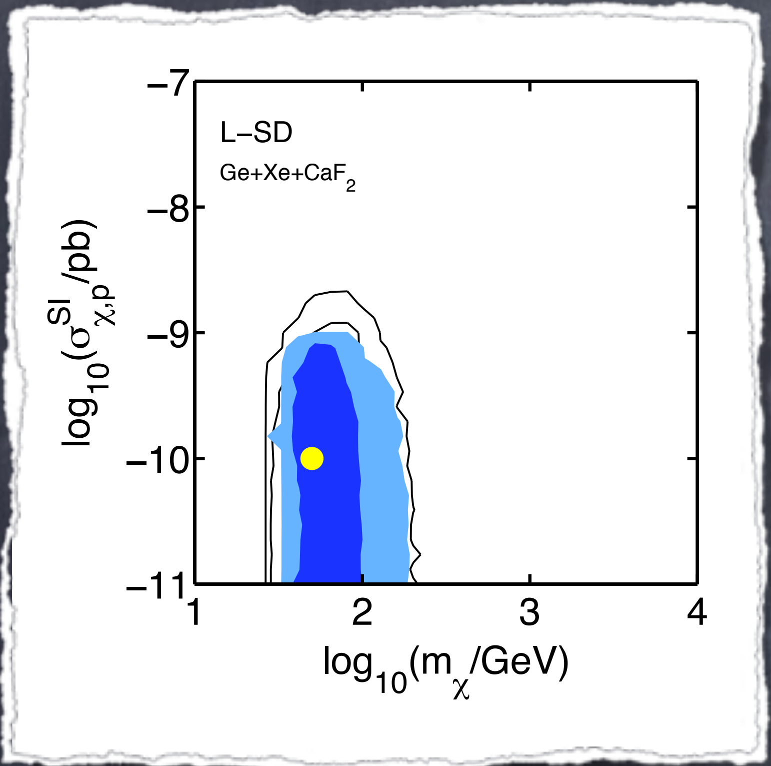
$\sigma^{SD} = 1.5 \times 10^{-4} pb$

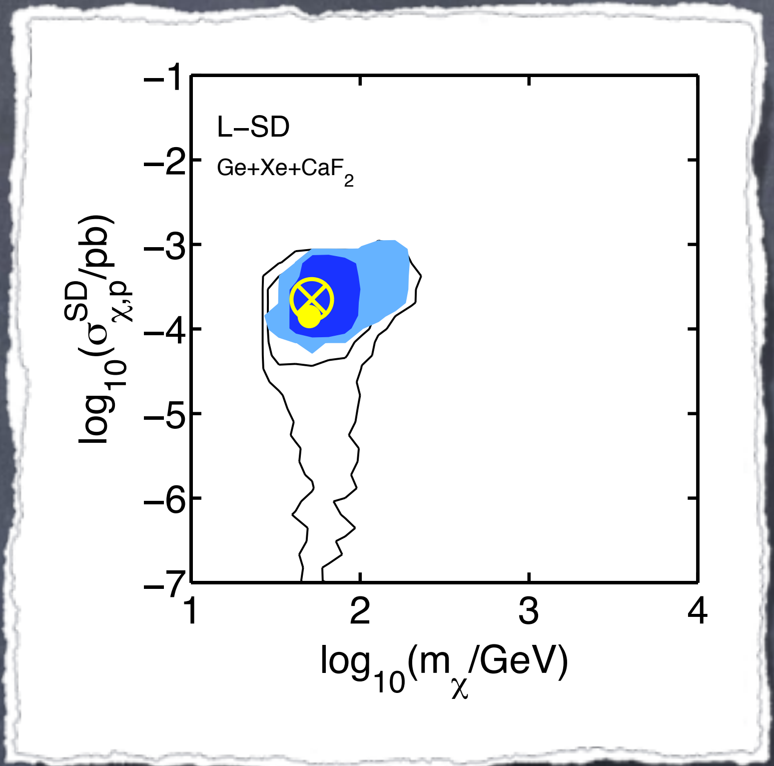
⊗ Best fit point

SD and mass well reconstructed

68% and 99%CL profile likelihood contours

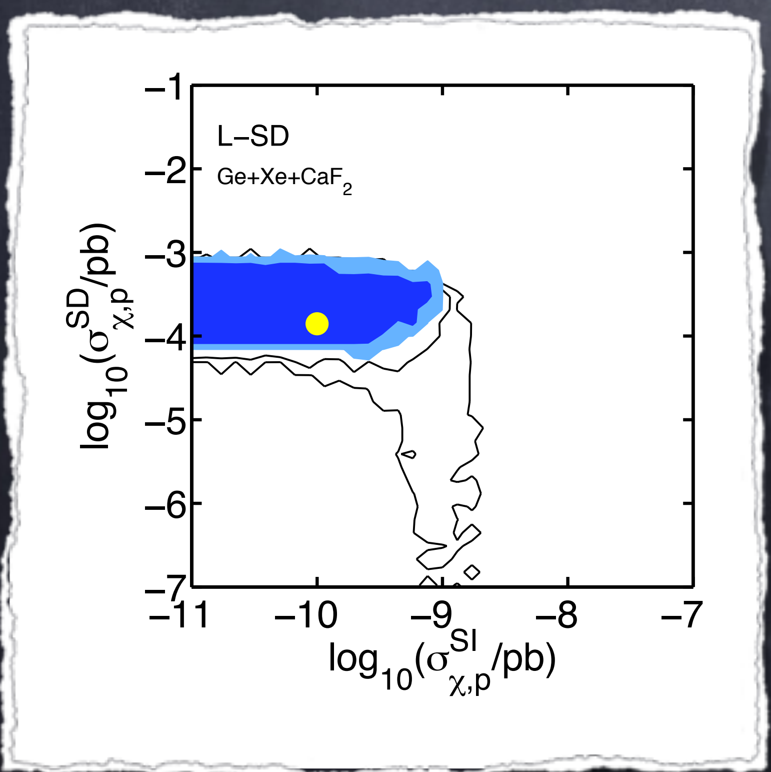
Ge + Xe + Bolometer





In black: 68% and 99%CL contours for Ge+Xe

Ge+Xe+CaF$_2$



● BM point

$m_\chi = 50\text{GeV}$

$\sigma^{SI} = 10^{-10}\,pb$

$\sigma^{SD} = 1.5 \times 10^{-4}\,pb$

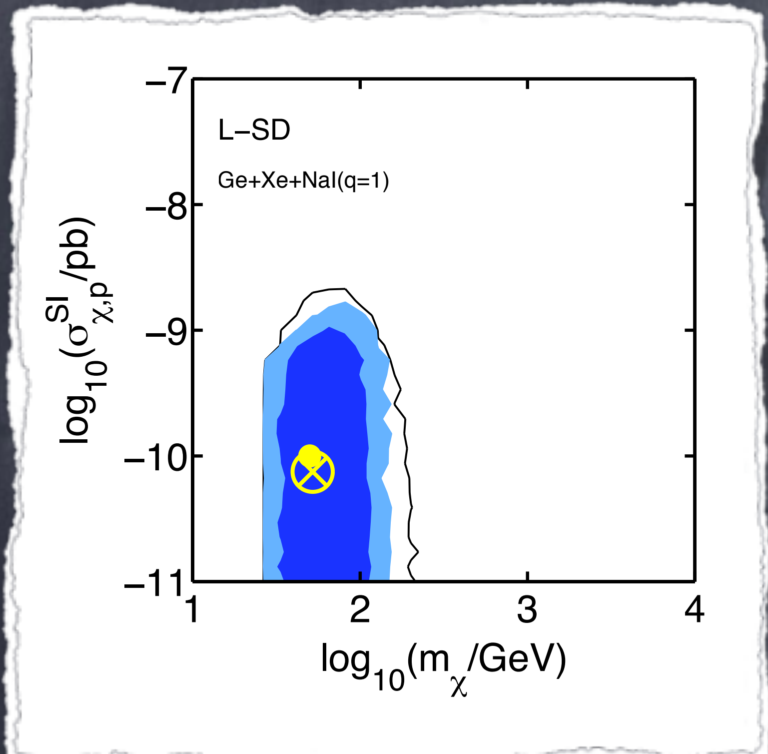
⊗ Best fit point

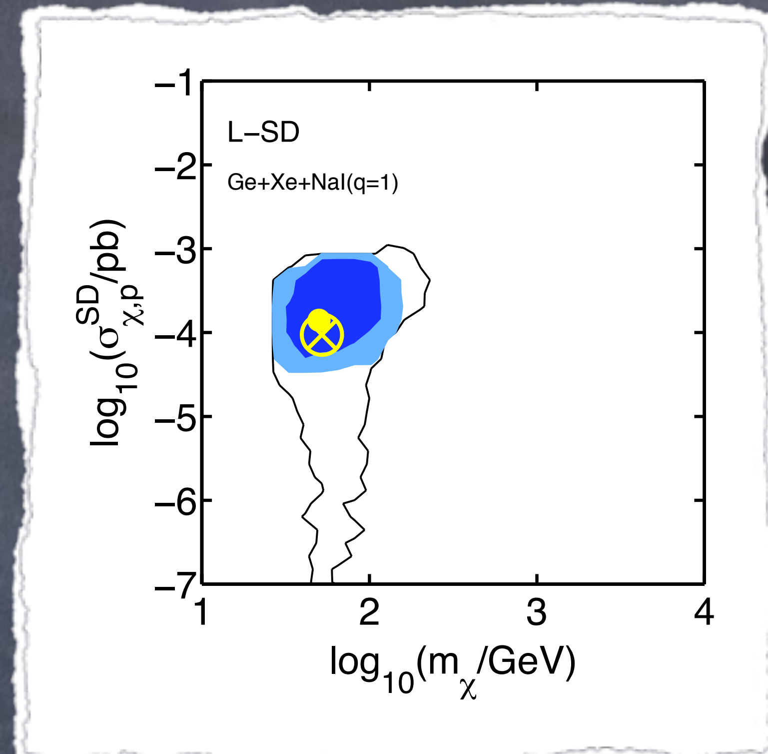
68% and 99%CL profile likelihood contours

SD and mass well reconstructed

Miguel Peiró. TeVPA/IDM Amsterdam June '14.

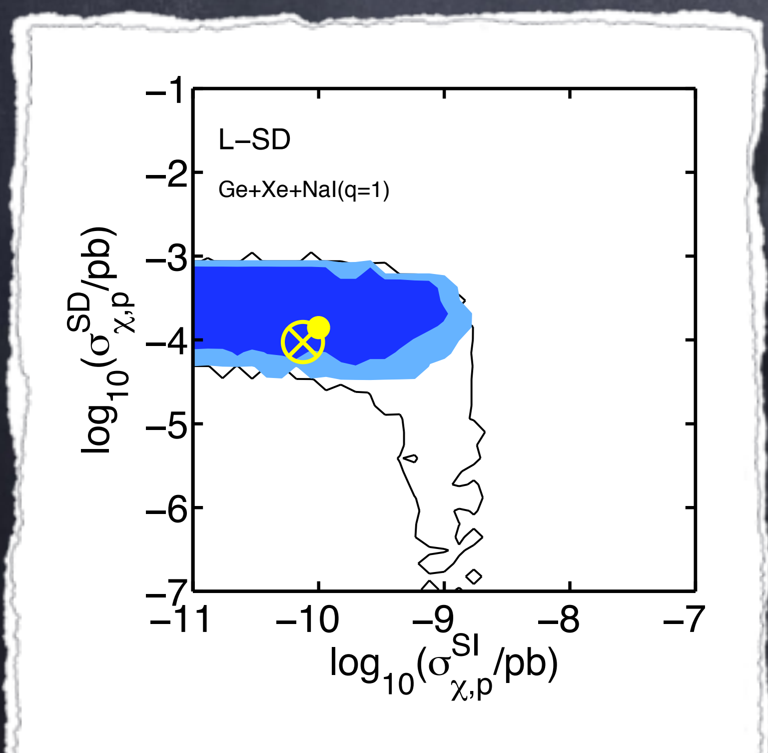
Ge + Xe + Bolometer





In black: 68% and 99%CL contours for Ge+Xe

Ge+Xe+NaI



● BM point

$m_\chi = 50 GeV$

$\sigma^{SI} = 10^{-10} pb$

$\sigma^{SD} = 1.5 \times 10^{-4} pb$

⊗ Best fit point

68% and 99%CL profile likelihood contours

SD and mass well reconstructed

Current experiments (Ge,Xe)

Ge + Xe + LiF

Ge + Xe + CaF_2

NOT COMPLEMENTARY

Ge + Xe + CaW04

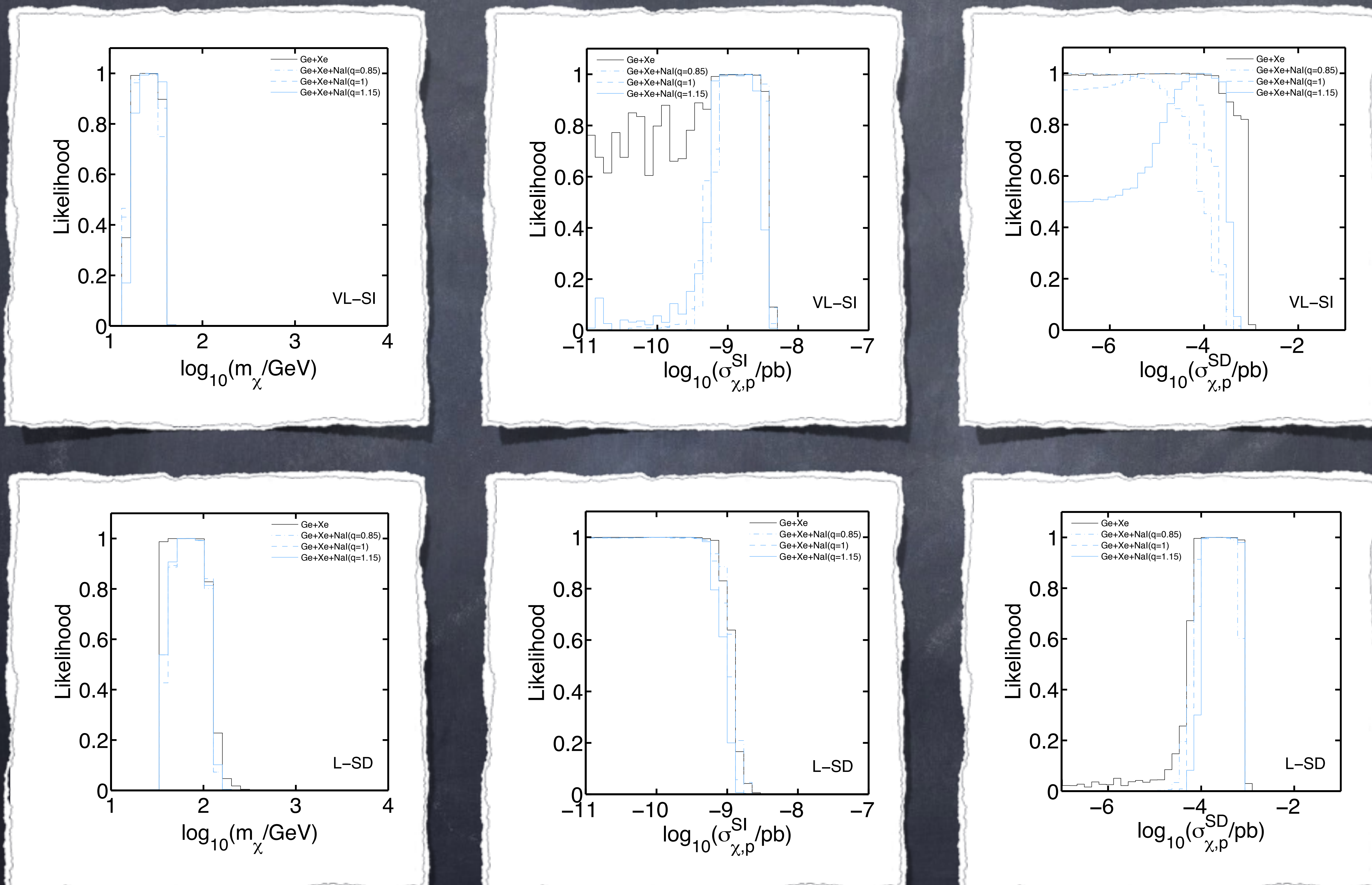
Ge + Xe + NaI

NOT COMPLEMENTARY

HOWEVER, IN ALL CASES THE MASS AND SD CROSS SECTION CAN BE RECONSTRUCTED AT 99% CL

A GOOD IMPROVEMENT!!!

EFFECT OF QUENCHING (NaI)



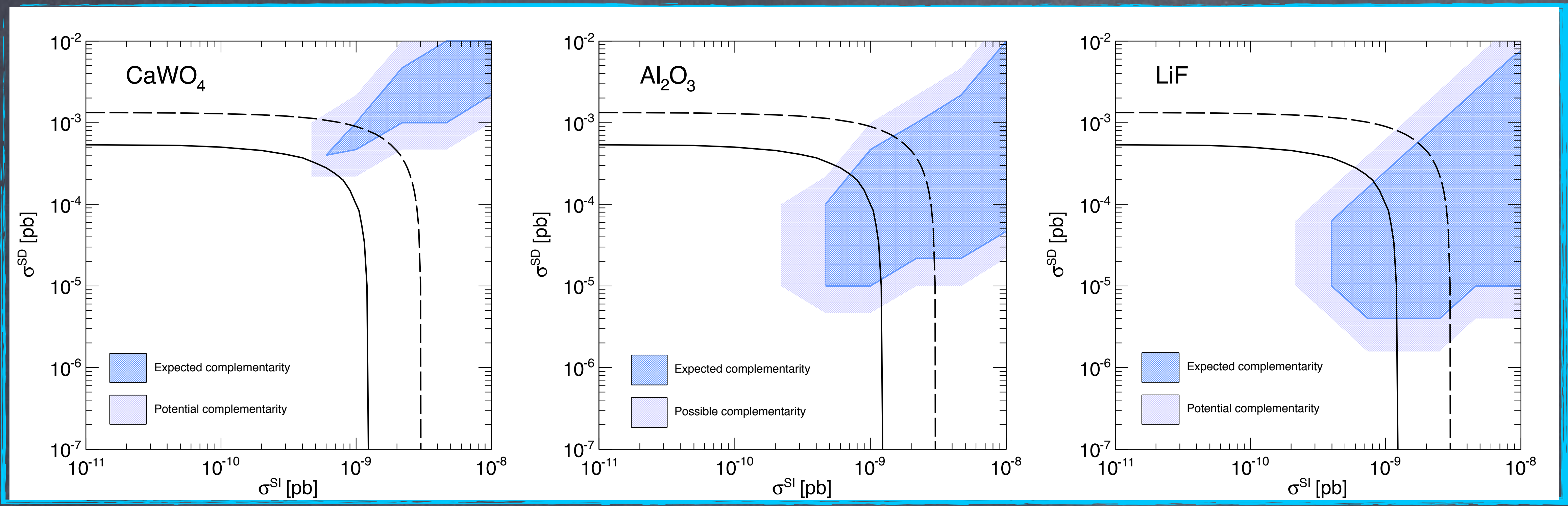
Conclusions

- We investigate how the combination of different targets in direct detection experiments helps in determining the DM properties
- Ge and Xe can be good for discovery but might not be able to measure all DM properties
- The situation seems to be more promising for the targets investigated here: LiF, CaF_2, NaI and $CaWO_4$
- We are generalizing the analysis for bigger regions of the parameter space and implementing the new experimental features for targets like $CaWO_4$ (see talk by R. Strauss)

Thanks!

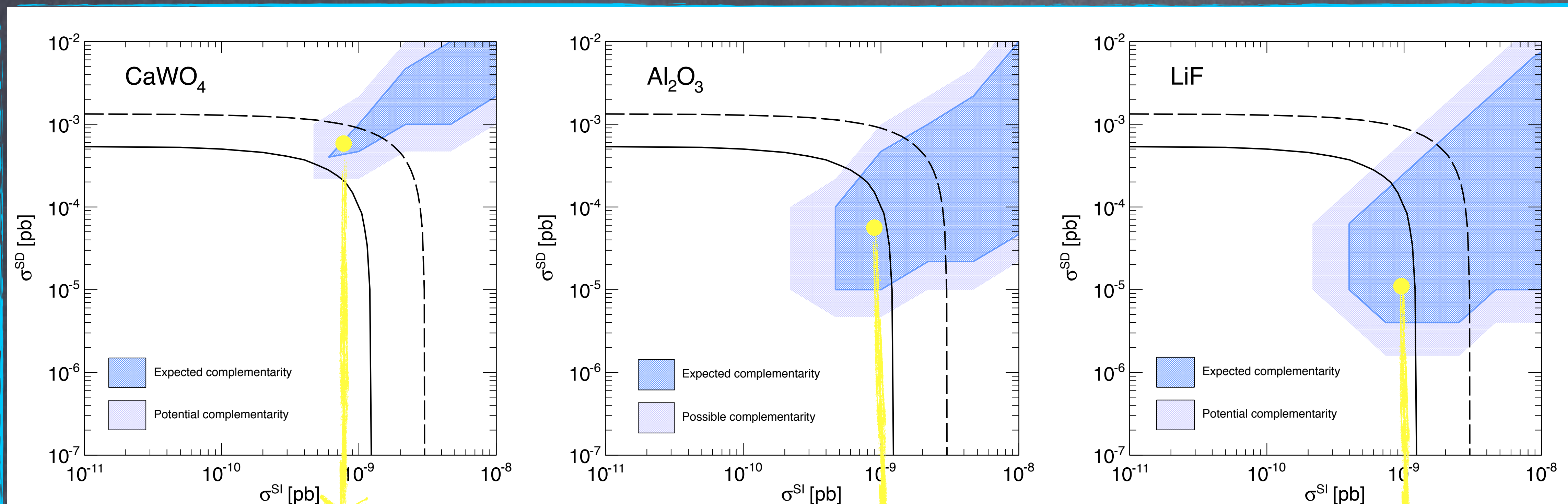
Backup slides

Full scan fixing the mass to 50 GeV



Backup slides

Full scan fixing the mass to 50 GeV



Scanning the background and exposure level to have complementarity