Particle Models for DM

(SUSY WIMPs)

David G. Cerdeño

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10 – 09 – 2013

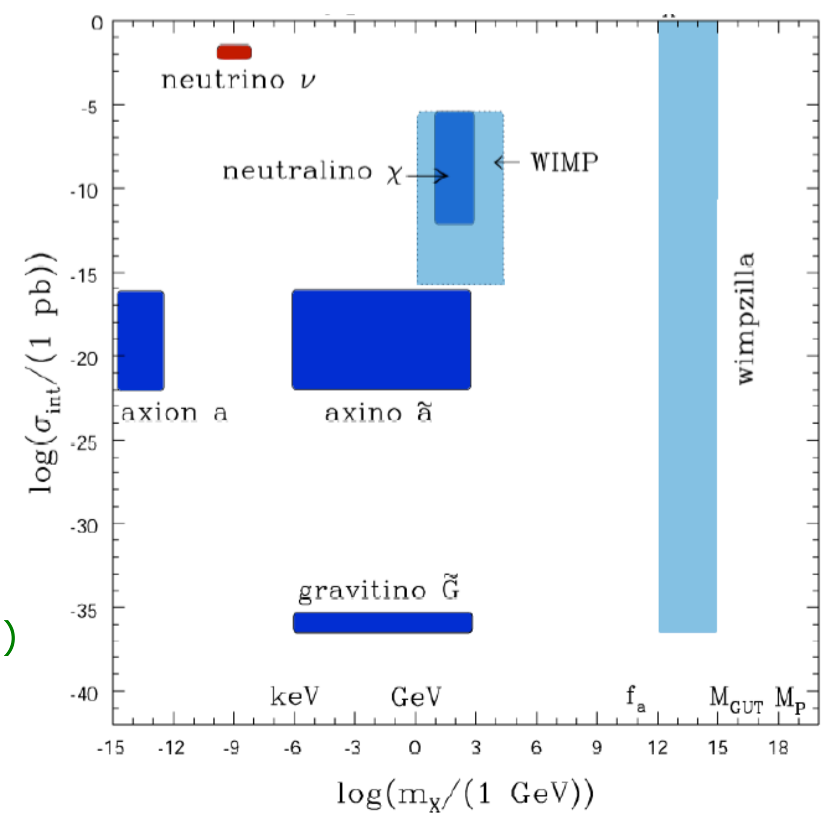
DM is a necessary and abundant component of the Universe

Good candidates for Dark Matter have to fulfil the following conditions

- Neutral
- Stable on cosmological scales
- Reproduce the correct relic abundance
- Not excluded by direct/indirect searches
- No conflicts with BBN or stellar evolution
- In agreement with LHC bounds

Many candidates in Particle Physics

- Axions
- Weakly Interacting Massive Particles (WIMPs)
- Asymmetric DM
- SuperWIMPs and Decaying DM
- WIMPzillas
- SIMPs, CHAMPs, SIDMs, ETCs...



... they have very different properties

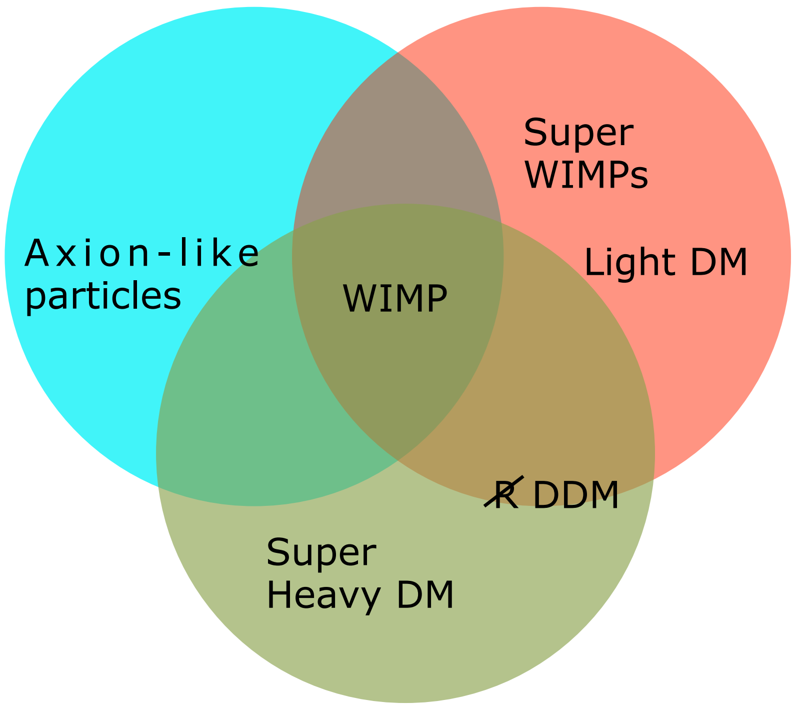
Dark matter can be searched for in different ways

Accelerator Searches (DM production) LHC (ILC)

Direct Detection

(DM-nuclei scattering)

DAMA/LIBRA
CDMS, SuperCDMS
XENON
KIMS
COUPP
PICASSO
ZEPLIN
CoGeNT
CRESST
SIMPLE
ZEPLIN
ANAIS
XMASS
...



Indirect Detection

(DM annihilation)

PAMELA	ANTARES
Fermi	IceCube
MAGIC	CTA
AMS	...

probing different aspects of the DM interactions with ordinary matter

Accelerator Searches (DM production) LHC (ILC)

Direct Detection

(DM-nuclei scattering)

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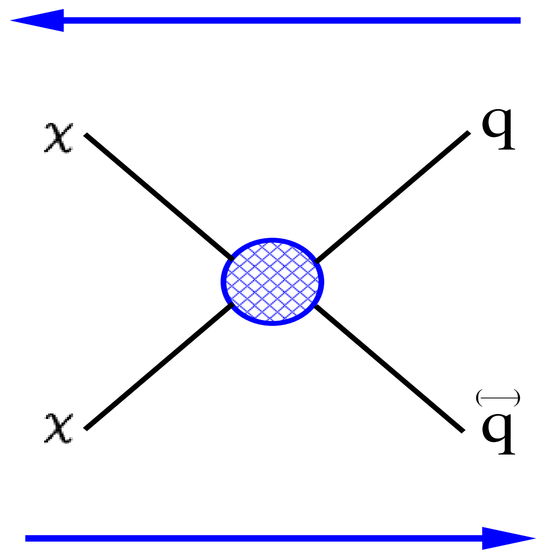


Constraints in one sector might affect observations in the other two.

“Redundant” detection can be used to extract DM properties.

COMPLEMENTARITY of DM searches

Indirect Detection

(DM annihilation)

PAMELA	ANTARES
Fermi	IceCube
MAGIC	CTA
AMS	...

Possible hints of light WIMPs (m_X~10 GeV)

- DAMA/LIBRA (NaI) Annual modulation signal (cumulative exposure 427,000 kg day)

DAMA/LIBRA Coll. '10

- CoGeNT (Ge) Irreducible background that can be compatible with 7-10 GeV WIMPs

... with annual modulation

Collar et al. '10- '13

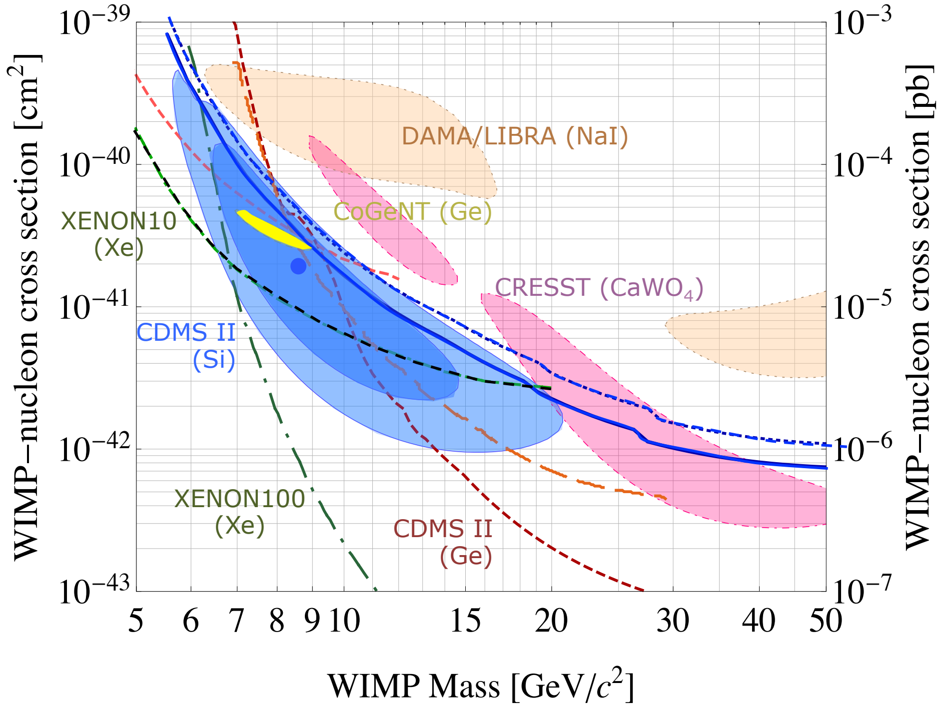
- CRESST II ($CaWO_4$) (730 kg day) Excess over the known background

Angloher et al. 1109.0702

- CDMS (Si) (140.2 kg days)

3 events Agnese et al. 1304.4279

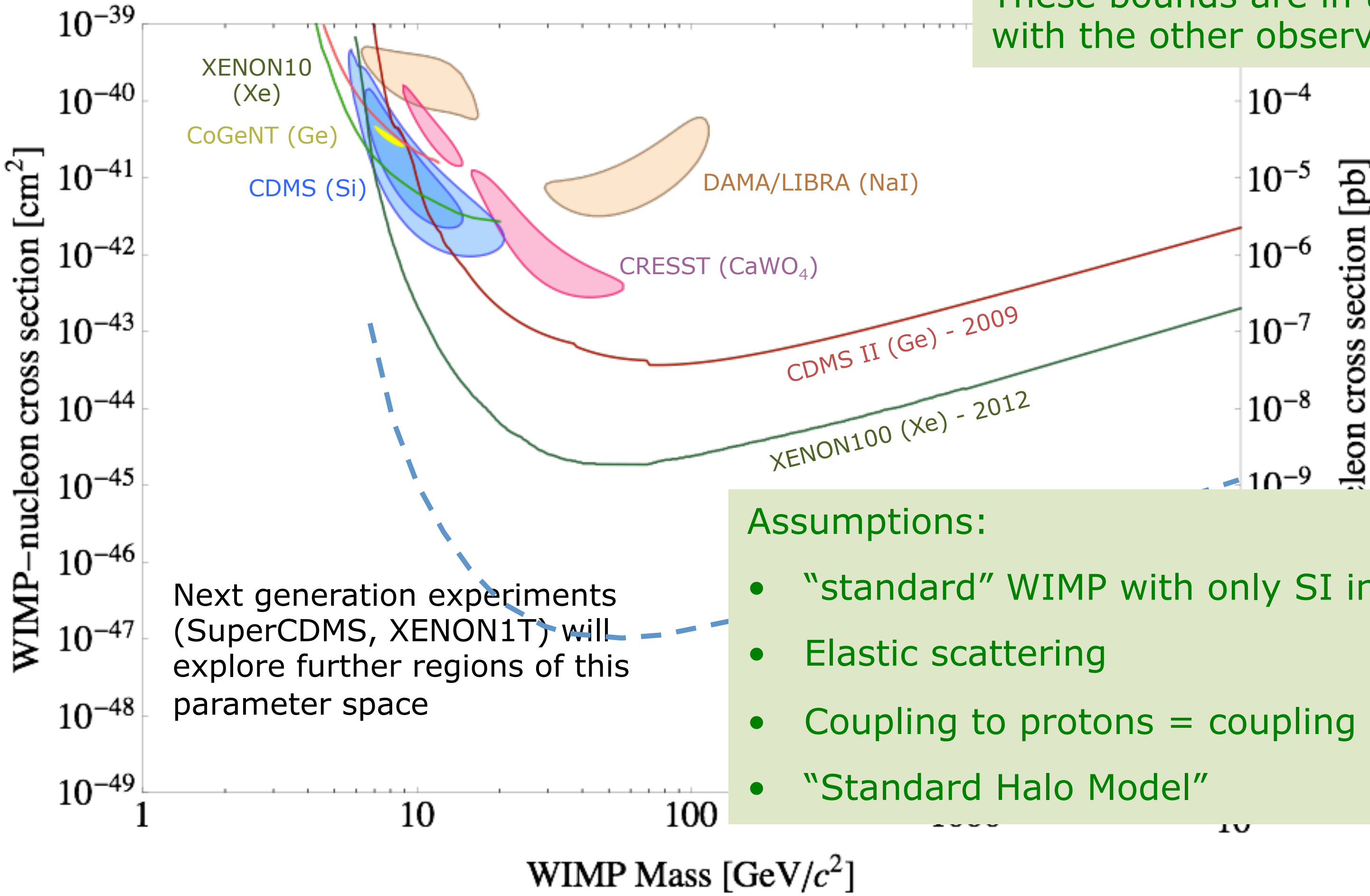
Reconstruction of the compatible regions in the WIMP Spin-independent cross section vs mass



Non-observation in other experiments set upper bounds on the cross section

XENON10, XENON100 (Xe), CDMS-II (Ge), Edelweiss (Ge), COUPP (CF_3I) have not observed any DM signal, which constrains the scattering cross section

These bounds are in tension with the other observations



Next generation experiments (SuperCDMS, XENON1T) will explore further regions of this parameter space

Assumptions:

- "standard" WIMP with only SI interactions
- Elastic scattering
- Coupling to protons = coupling to neutrons
- "Standard Halo Model"

Isospin-Violating Dark Matter

Feng, Kumar, Marfatia, Sanford 2011

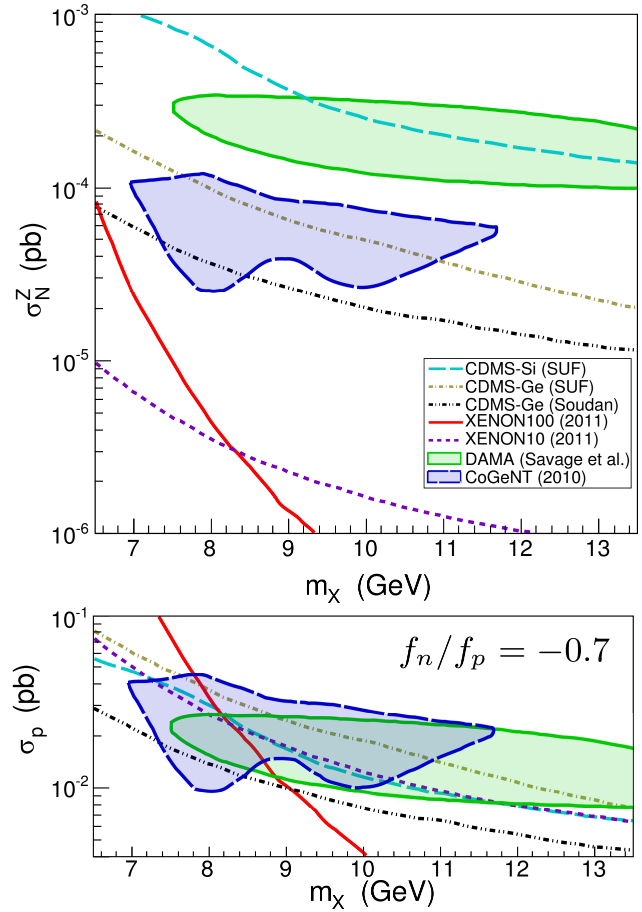
$$R = \sigma_p \sum_i \eta_i \frac{\mu_{A_i}^2}{\mu_p^2} I_{A_i} \left[Z + (A_i - Z) f_n/f_p\right]^2$$

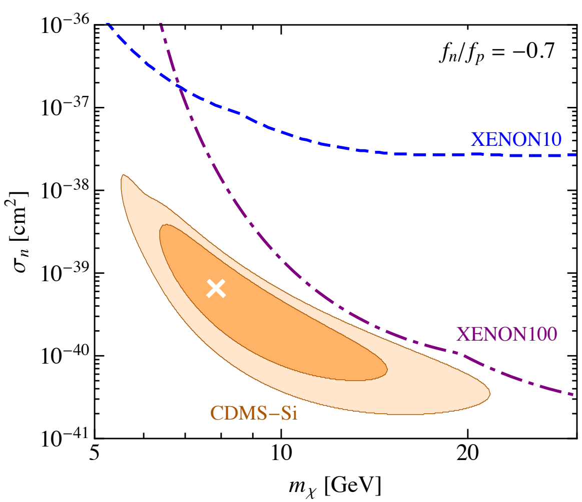
The scattering amplitudes for proton and neutrons may interfere destructively

Complete destructive interaction (target dependent)

$$f_n/f_p = -Z/(A-Z)$$

For Xe (Z=54, A~130) → $f_n/f_p = -0.7$





XENON100 (Xe) and CDMS II (Si) results can be "reconciled"

WARNING: in general, Isospin-violation is very small in ordinary WIMP models (e.g., SUSY)

Frandsen et al. 2013

LHC searches for new physics constrain DM models

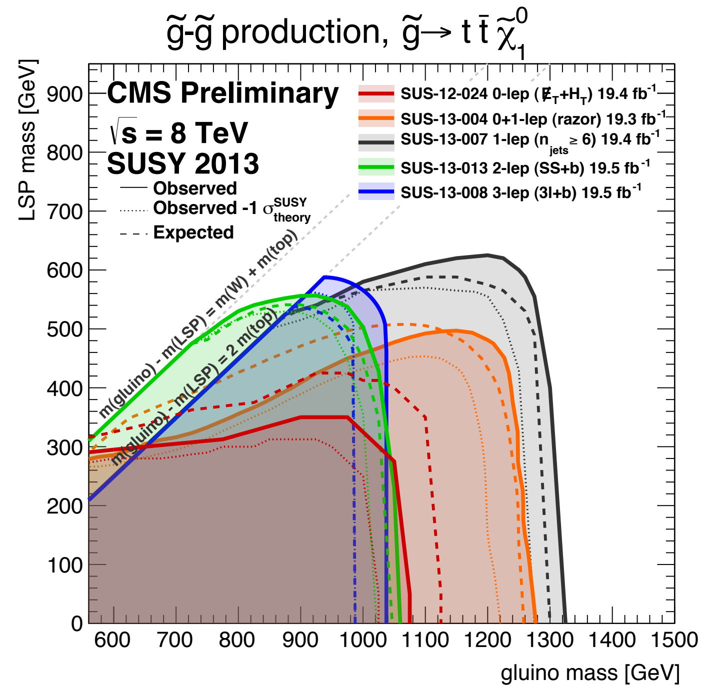
Constraints on SUSY particles and low-energy observables

$BR(B_s \to \mu\mu)_{SM} = (3.2 \pm 0.2) \times 10^{-9}$

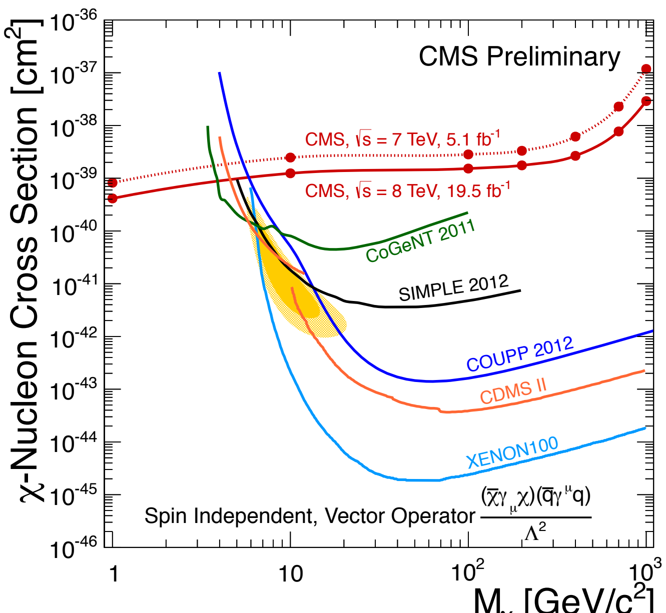
LHCb 2012

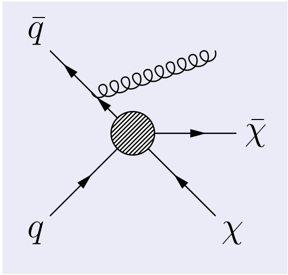
Set INDIRECT bounds on SUSY dark matter (mass and interactions)

See e.g., Buchmüller et al. 2012



Mono-jet and Mono-γ (plus MET) searches constrain the region of light WIMPs





Dark matter production with initial state radiation

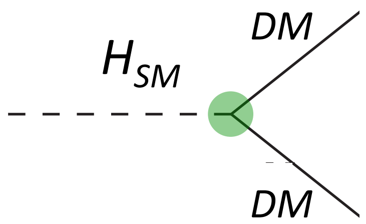
Bounds depend on the DM effective operators to fermions (significantly relaxed for light mediators)

LHC data (see also previous results from Tevatron)

Observation of (a) SM-like Higgs boson with m_H~126 GeV

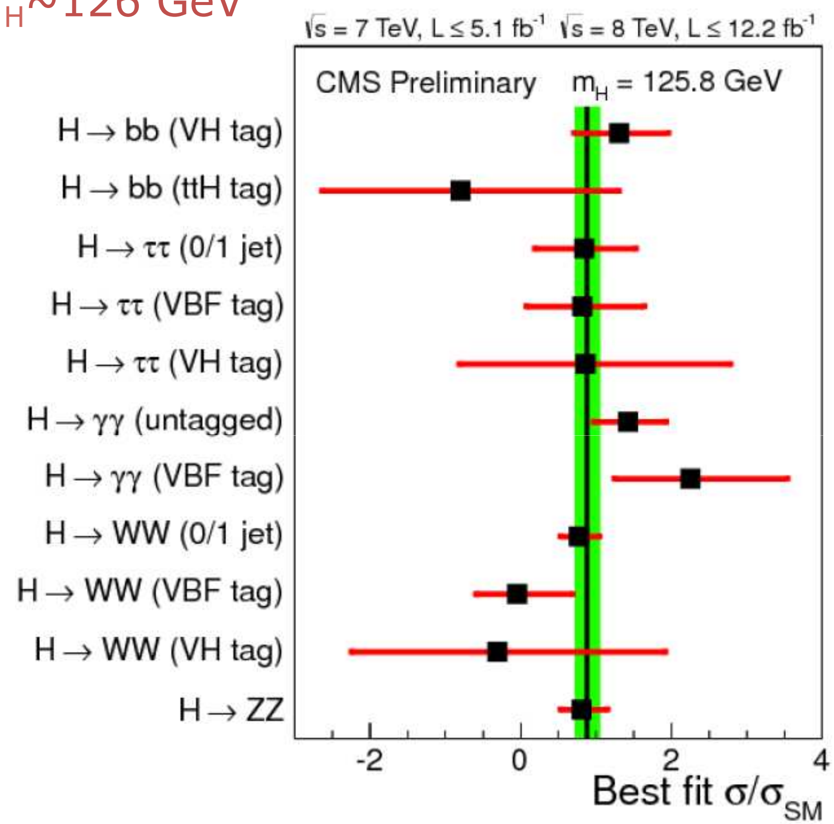
A bound on the invisible decay width of the Higgs can be derived

Falkowski et al. 2013
Girardino et al. 2013
Ellis, Yu 2013
Djouadi et al. 2013

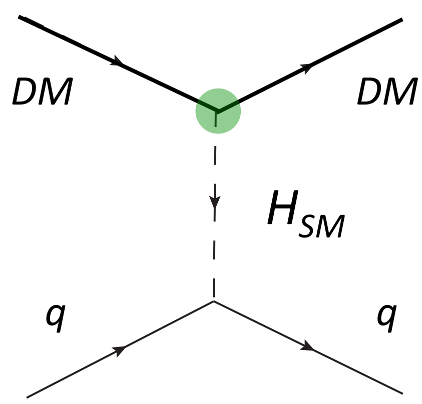


$$\mathrm{BR}(h^0_{SM} \to inv) \lesssim 0.20$$

Important for light WIMPs ($m_{DM} < m_H/2$)



This has implications for the scattering cross section of DM particles



Neutralino in the MSSM

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu & 0 \end{pmatrix}$$

Gaugino masses	$M_1,\ M_2,\ M_3$
Slepton soft masses	$m^2_{L_{ij}},\ m^2_{E_{ij}}$
Squark soft masses	$m^2_{Q_{ij}},\ m^2_{U_{ij}},\ m^2_{D_{ij}}$
Trilinear parameters	$A_E^{i,j}, A_U^{i,j}, A_D^{i,j}$

Parameters describing the Higgs sector

$$\mu,\ m_A \qquad \tan\beta \equiv \frac{\langle H_u \rangle}{\langle H_d \rangle}$$

- There are collider constraints on the Wino mass (M_2) and μ parameter from chargino searches (M_2, μ >105 GeV)

- Constraints on the Bino mass (M_1) are indirect – due to the correlation of some mass parameters in simplified models (mSUGRA – CMSSM)

Constrained MSSM (4 parameters)

$$M,\ m,\ A,\ \tan\beta,\ sign(\mu)$$

Bino	Wino	Gluino

$$M_1 \sim 1/2\ M_2 \sim 1/6\ M_3$$

but can be relaxed in more general scenarios (pMSSM) (19 parameters)

Neutralino in the MSSM

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Gaugino masses $M_1,\ M_2,\ M_3$

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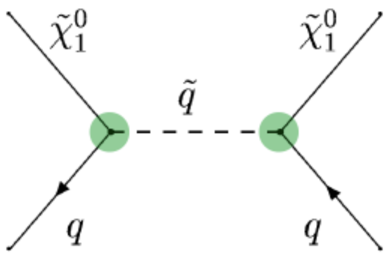
Trilinear parameters $A_E^{i,j},\ A_U^{i,j},\ A_D^{i,j}$

Parameters describing the Higgs sector

$$\mu,\ m_A \qquad \tan\beta \equiv \frac{\langle H_u \rangle}{\langle H_d \rangle}$$

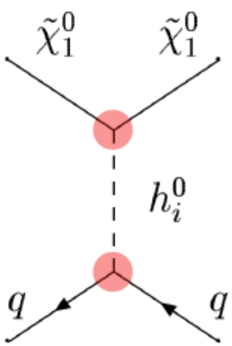
Direct detection can proceed through Higgs or squark exchange



Squark exchange

Generally small (1st, 2nd gen. squarks are heavy)

Otherwise unconstrained from LHC



Higgs exchange

Leading contribution (increases with the Higgsino component)

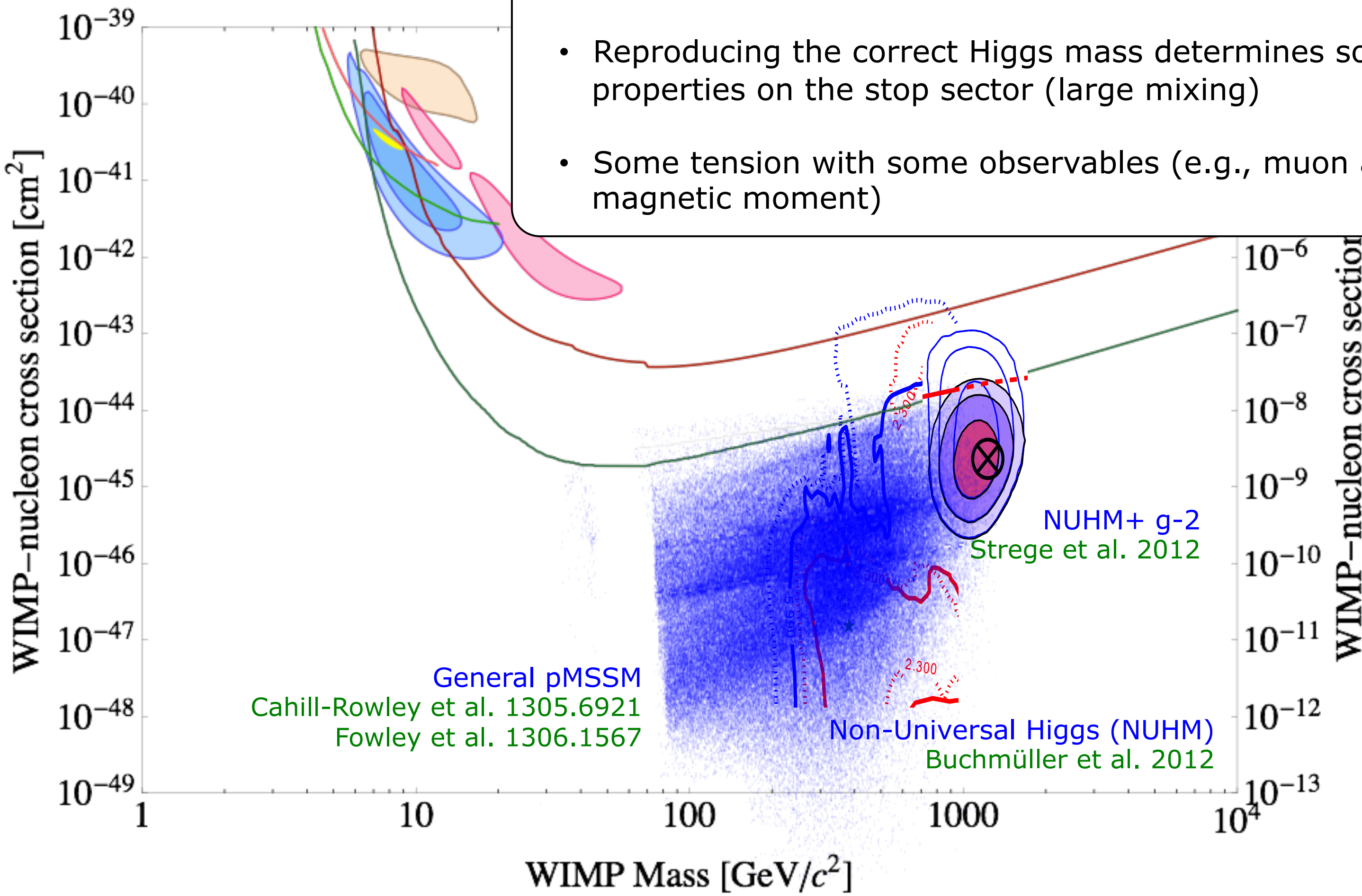
Constrained by the results on $\mathrm{BR}(h^0_{SM} \to inv)$

Also affected by m_H=126 GeV

Neutralino in the MSSM

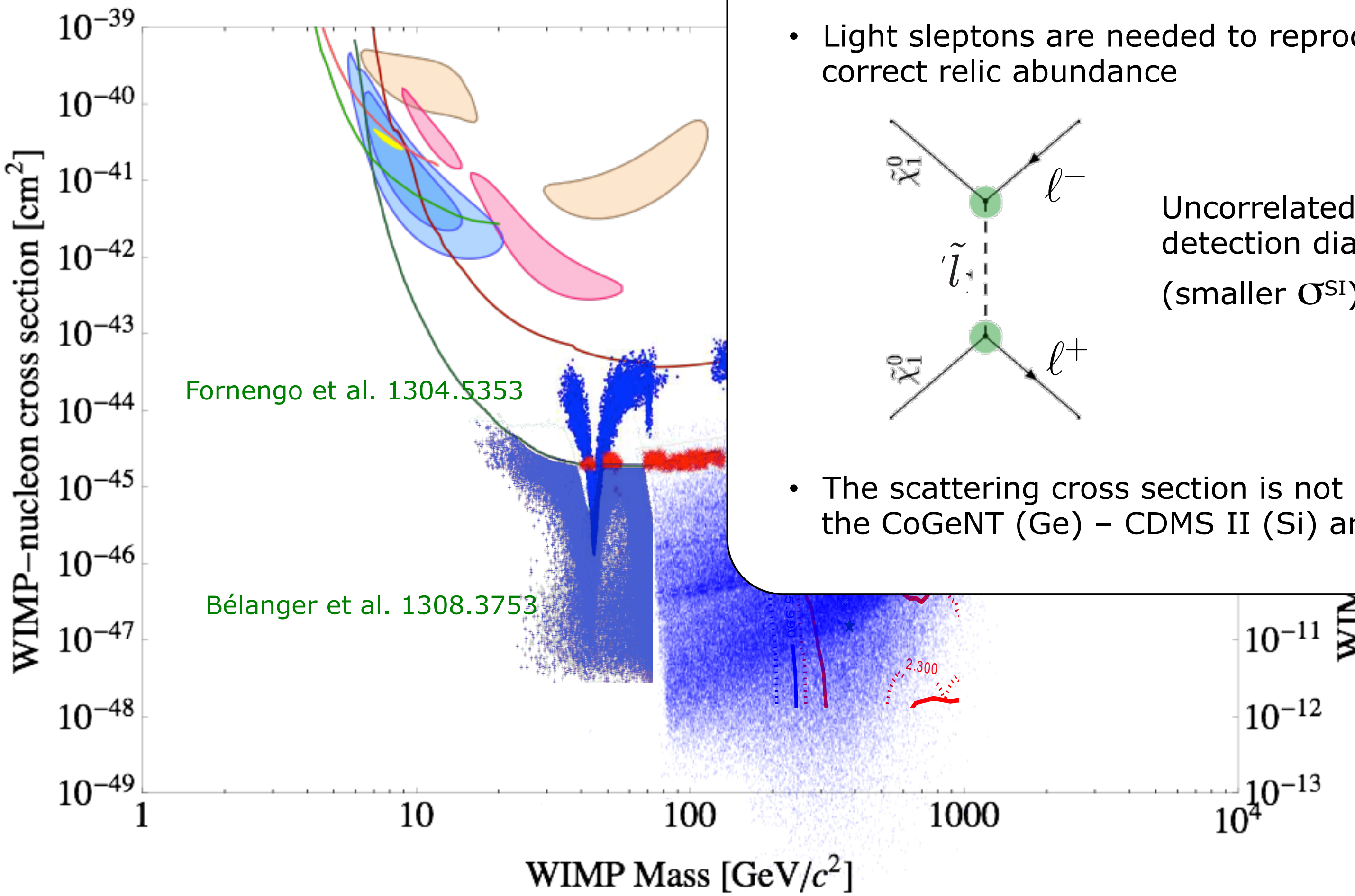
A wide region of the neutralino parameter space is valid

- Large masses appear naturally $m_X > 100$ GeV
- Reproducing the correct Higgs mass determines some properties on the stop sector (large mixing)
- Some tension with some observables (e.g., muon anomalous magnetic moment)



The predictions for its scattering cross section still span many orders of magnitude (excellent motivation for more sensitive detectors)

Neutralino in the MSSM



Very light neutralinos are viable in corners of the parameter space

- Light sleptons are needed to reproduce the correct relic abundance

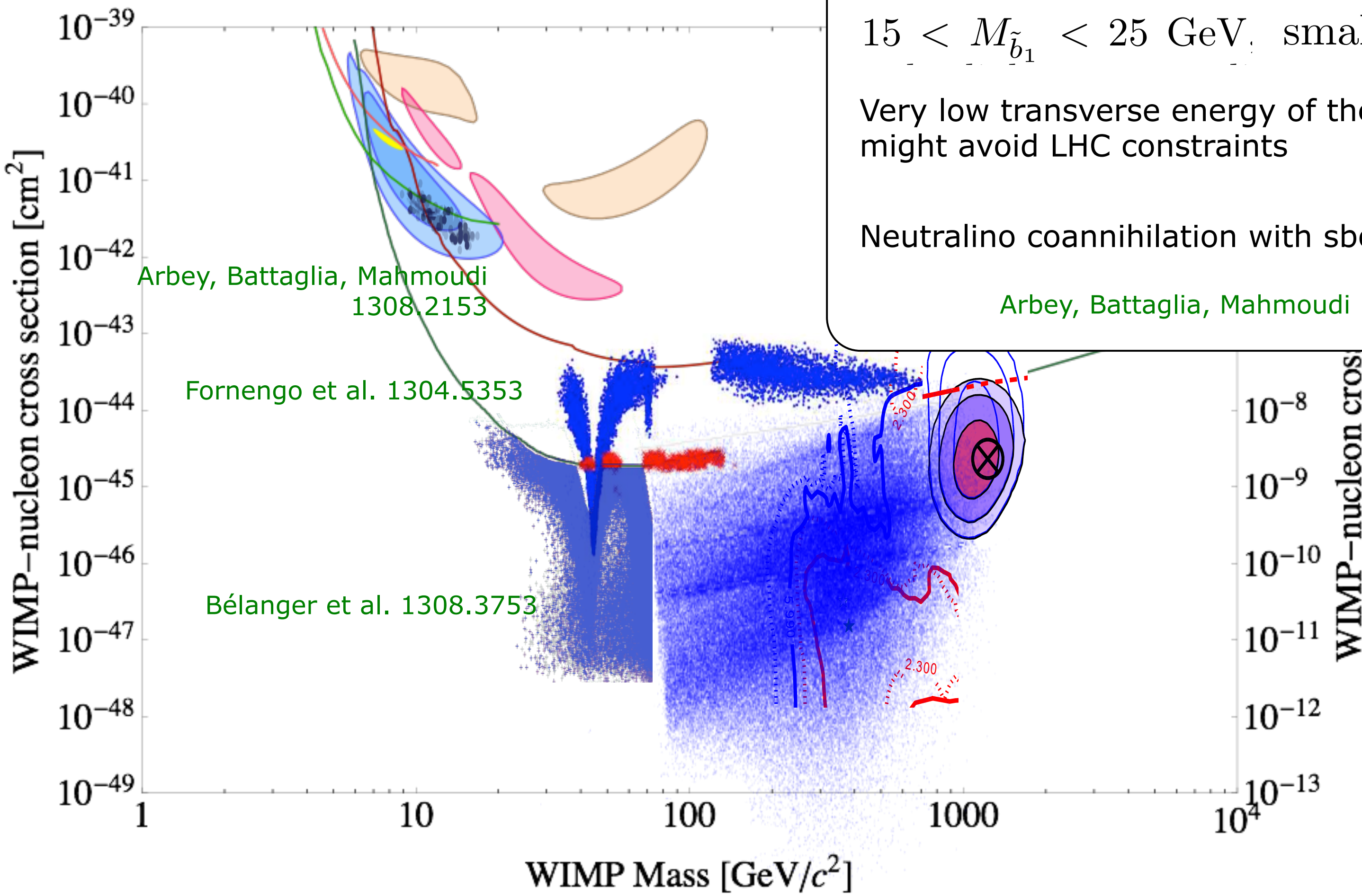
Uncorrelated to direct detection diagrams

(smaller σ^{SI})

- The scattering cross section is not within the CoGeNT (Ge) – CDMS II (Si) area

The predictions for its scattering cross section still span many orders of magnitude (excellent motivation for more sensitive detectors)

Neutralino in the MSSM



Extremely light sbottom

$$15 < M_{\tilde{b}_1} < 25 \text{ GeV}, \text{ small } \cos\theta_b$$

Very low transverse energy of the jets might avoid LHC constraints

Neutralino coannihilation with sbottom

Arbey, Battaglia, Mahmoudi 1308.2153

Very light neutralinos are viable (though quite fine-tuned) in the Minimal Supersymmetric Standard Model.

Neutralino in the Next-to-MSSM

Extensions of the MSSM are well motivated from the theoretical point of view and potentially very interesting from the point of view of dark matter.

In the NMSSM the field structure of the MSSM is modified by the addition of a new superfield $\hat{S}$, which is a singlet under the SM gauge group:

$$\text{NMSSM} \quad = \quad \text{MSSM} + \hat{S} \begin{cases} 2 \text{ extra Higgs (CP} - \text{even, CP} - \text{odd)} \\ 1 \text{ additional Neutralino} \end{cases}$$

Interesting Collider & DM Phenomenology

- This leads to the following new terms in the superpotential

$$W = Y_u \, H_2 \, Q \, u + Y_d \, H_1 \, Q \, d + Y_e \, H_1 \, L \, e - \lambda \, S \, H_1 H_2 + \frac{1}{3} \kappa S^3$$

- When Electroweak Symmetry Breaking occurs the Higgs field takes non-vanishing VEVs:

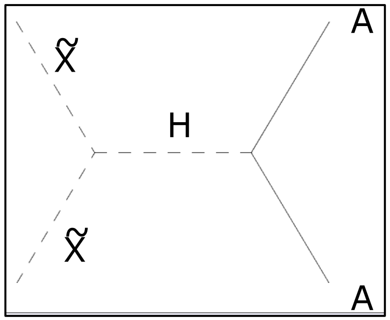
$$\langle H_1^0 \rangle = v_1 \quad ; \quad \langle H_2^0 \rangle = v_2 \quad ; \quad \langle S \rangle = s \, (= \frac{\mu}{\lambda})$$

EW-scale Higgsino-mass parameter

Neutralino in the Next-to-MSSM

DM Phenomenology changes due to the different Higgs and neutralino sector

- More annihilation channels, which can be open for low masses



A very light (singlet-like) pseudoscalar can help getting the correct relic abundance for m_X<45 GeV

Gunion et al. hep-ph/0509024

- Scenarios with two light scalar Higgses are possible

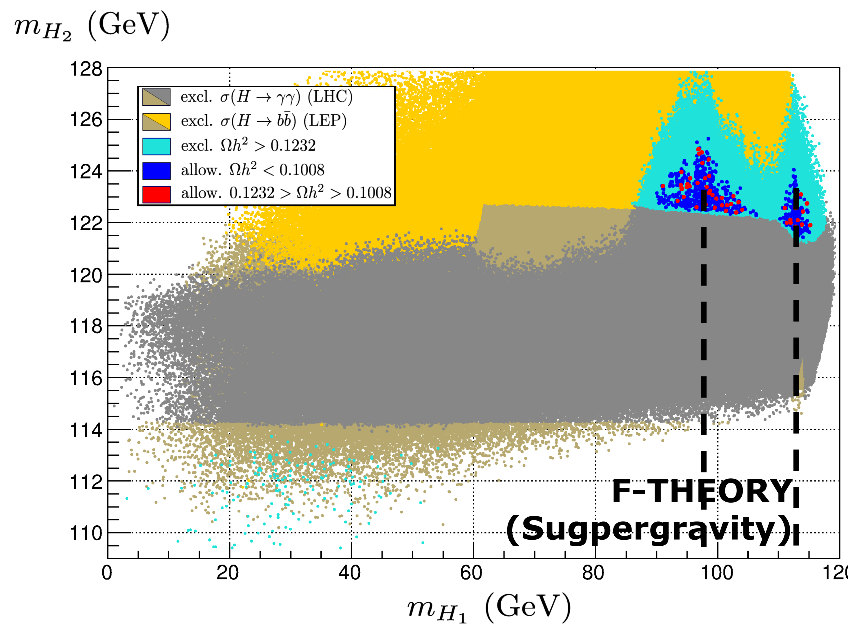
A SM-like Higgs with m_{H2}=126 GeV

A lighter singlet-like Higgs with m_{H1}~98 GeV

that would account for an apparent excess in LEP

$$e^+e^- \to Zh,\ h \to b\bar{b}$$

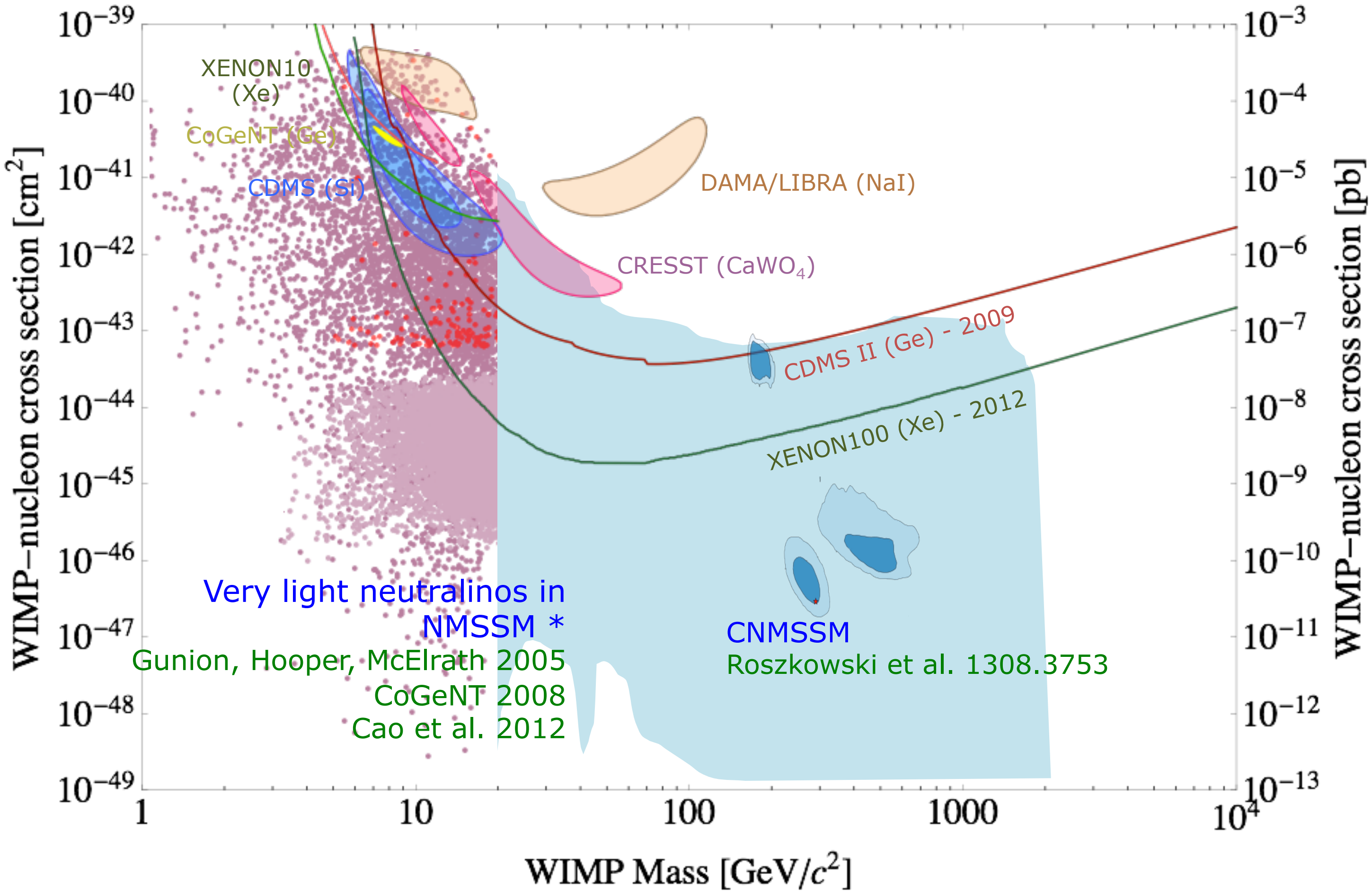
Bélanger et al. 1210.1976



Aparicio, Cámara, DGC, Ibañez, Valenzuela 1308.3753

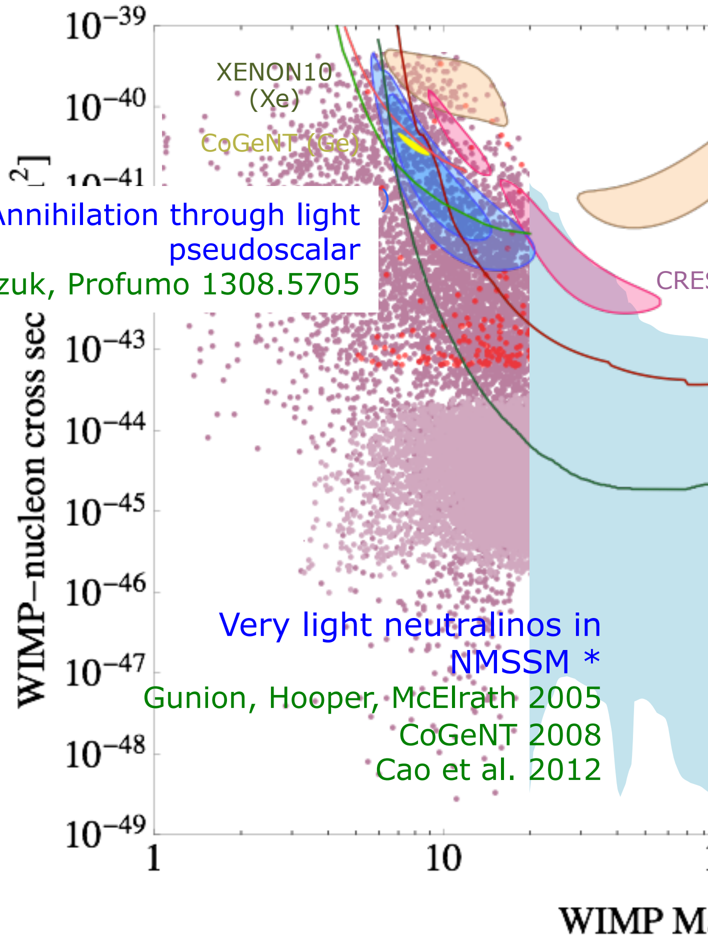
Neutralinos in the Next-to-MSSM

Predictions more flexible than in the MSSM

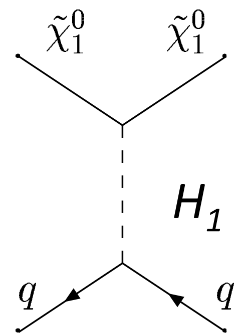


* without constrains on the Higgs sector

Neutralinos in the Next-to-MSSM



Very light neutralinos are also possible



Scattering can take place through the lighter Higgs

Thus avoiding constraints on the invisible decay width of H_{SM}.

This is also generic of other two-Higgs scenarios for DM

The light WIMP region becomes more populated: an excellent motivation for low-threshold experiments.

Right-handed sneutrino in the NMSSM

- Addition of TWO new superfields, ***S***, ***N***, singlets under the SM gauge group

$$\text{NMSSM} = \text{MSSM} + \hat{S} \begin{cases} 2 \text{ extra Higgs (CP-even, CP-odd)} \\ 1 \text{ additional Neutralino} \end{cases}$$

$$+ N \begin{cases} 1 \text{ additional (right-handed) Neutrino} \\ \text{and sneutrino} \end{cases}$$

- New terms in the superpotential

$$W = Y_u\, H_2\, Q\, u + Y_d\, H_1\, Q\, d + Y_e\, H_1\, L\, e - \lambda\, S\, H_1 H_2 + \frac{1}{3}\kappa S^3$$

$$W = W_{\text{NMSSM}} + \lambda_N S N N + y_N L\, H_2 N$$

- After Radiative Electroweak Symmetry-Breaking

$$\langle H_1^0 \rangle = v_1 \quad ; \quad \langle H_2^0 \rangle = v_2 \quad ; \quad \langle S \rangle = s$$

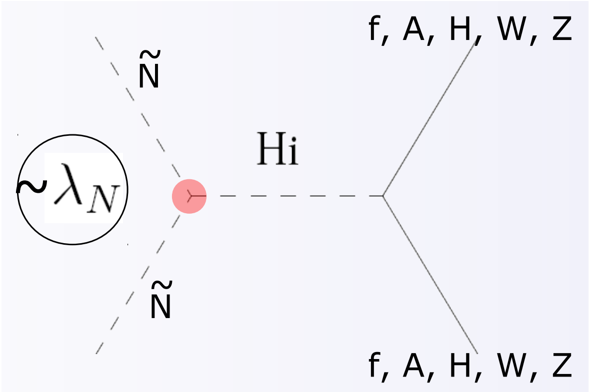
$$\begin{cases} \mu\, H_1\, H_2 \\ m_N\, N\, N \end{cases}$$

EW-scale Higgsino-mass parameter & Majorana neutrino mass

EW-scale see-saw mechanism implies very small yukawa couplings

$$m_{\nu_L} = \frac{y_N^2 v_2^2}{M_N} \longrightarrow y_N = \mathcal{O}(10^{-6})$$

Since this determines the LR mixing of the neutrino/sneutrino sector one is left with pure Right and Left fields



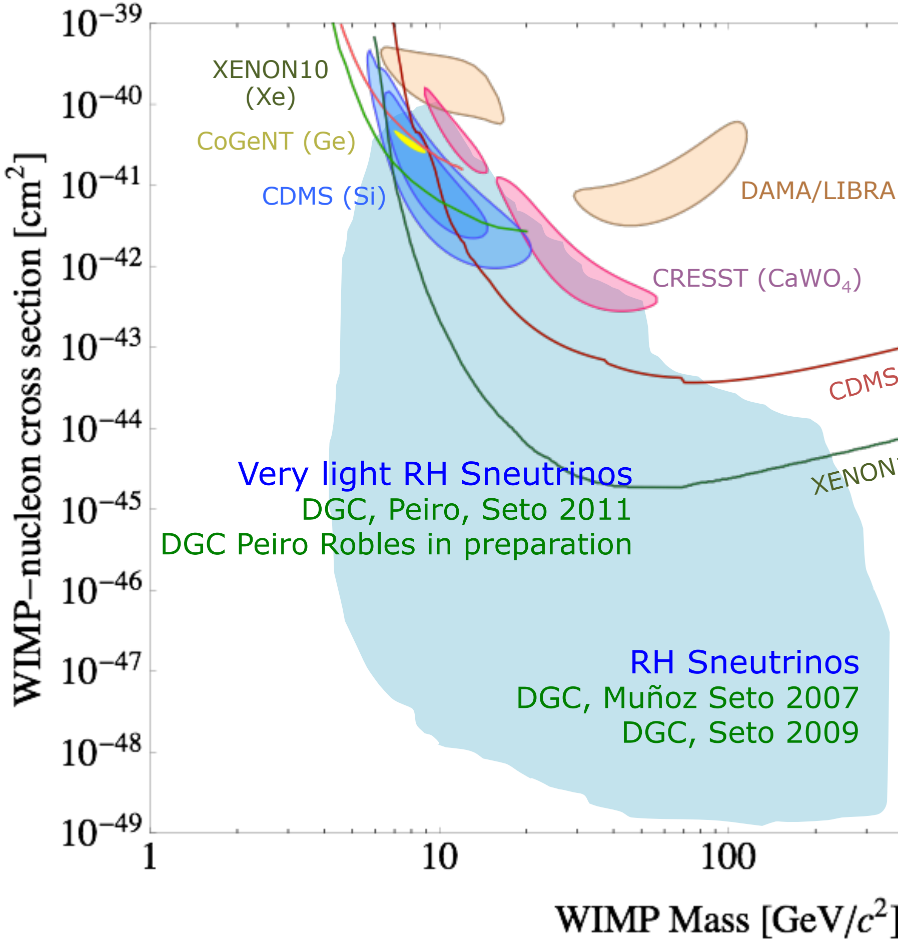
- The correct relic density can be obtained for $\lambda_N \sim 0.1$ (it is a WIMP) and a wide range of sneutrino masses

DGC, Muñoz, Seto 0807.3029
DGC, Seto 0903.4677

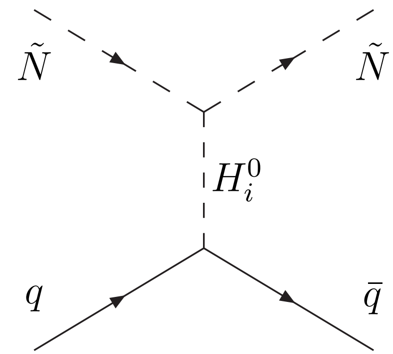
Other solution for sneutrino dark matter consists in considering LR-sneutrinos

Arina, Fornengo 0709.4477

Right-handed sneutrino in the Next-to-MSSM

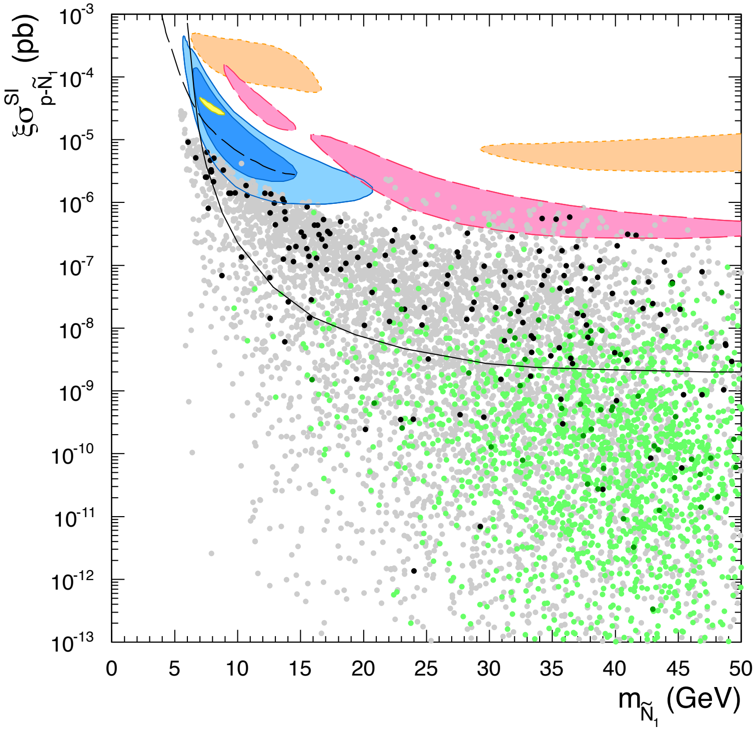


Direct detection is mediated by exchange of the (three) Higgs particles



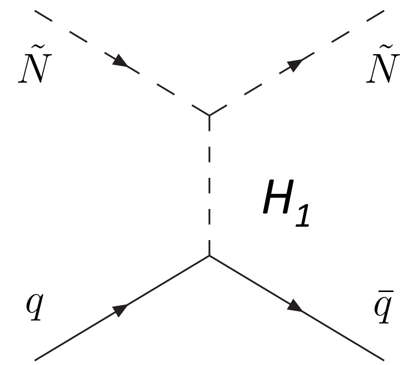
Notice that WIMP predictions in the SI-mass plane are all very similar. Experiments sensitive to SD WIMP scattering are useful to discriminate DM models

Very light Right-handed sneutrino in the Next-to-MSSM



DGC Peiro Robles in preparation

As in the NMSSM, light sneutrinos are viable if the sneutrino couples to a singlet-like Higgs



Main annihilation channels:

ÑÑ → $a_1 a_1$

ÑÑ → b b

Sneutrinos as light as m_N=6 GeV can be obtained in agreement with LHC data and featuring a LARGE scattering cross section.

Summary

- The lightest neutralino in Supersymmetric scenarios is good shape

  Applying LHC constraints → m~100-1000 GeV neutralino appear quite naturally in simple scenarios (e.g., CMSSM or vanilla pMSSM)

- Light SUSY WIMPs

  Limited by stringent bounds from LHC (Higgs sector and low-energy observables).

  Large scattering cross sections can be obtained in extended scenarios (e.g., neutralino and sneutrino in the NMSSM)

- An experimental effort in the whole range of WIMP masses is needed.

  Experiments sensitive to low-mass WIMPs might provide valuable complementary information.