Direct WIMP Searches and Theoretical Scenarios

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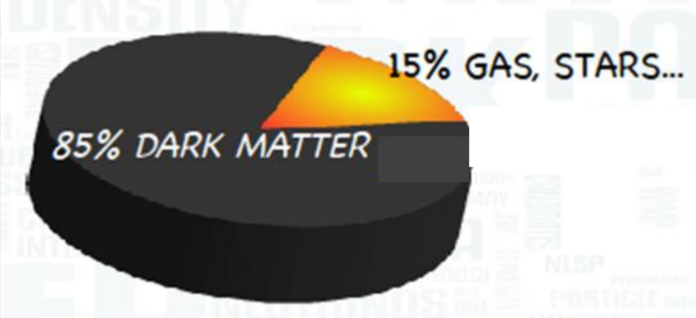
CSIC
Consejo Superior de Investigaciones Científicas

MultiDark
Multimessenger Approach for Dark Matter Detection

TAUP 2011, Munich, 5-9 September

EVIDENCES for DARK MATTER

Discussed yesterday by M. Pospelov



$\Omega_b h^2 \approx 0.02$

$\Omega_{DM} h^2 \approx 0.1$

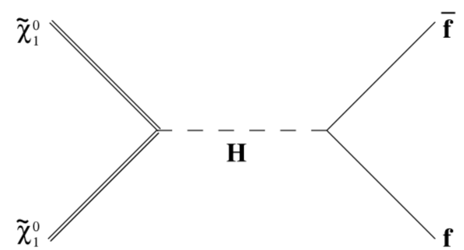
To explain what is the dark matter made of,
we need a new particle with the following properties:

- **Stable or long-lived** — Produced after the Big Bang and still present today
- **Neutral** — Otherwise it would bind to nuclei and would be excluded from unsuccessful searches for exotic heavy isotopes
- **Reproduce the observed amount of dark matter** $\Omega_{\mathrm{DM}} h^2 \approx 0.1$

Actually, a particle with weak interactions and a mass ≈ 100 GeV, the so called WIMP (Weakly Interacting Massive Particle), is able to reproduce this number

Discussed yesterday by M. Pospelov

In the early Universe, at some temperature the annihilation rate of dark matter particles dropped below the expansion rate



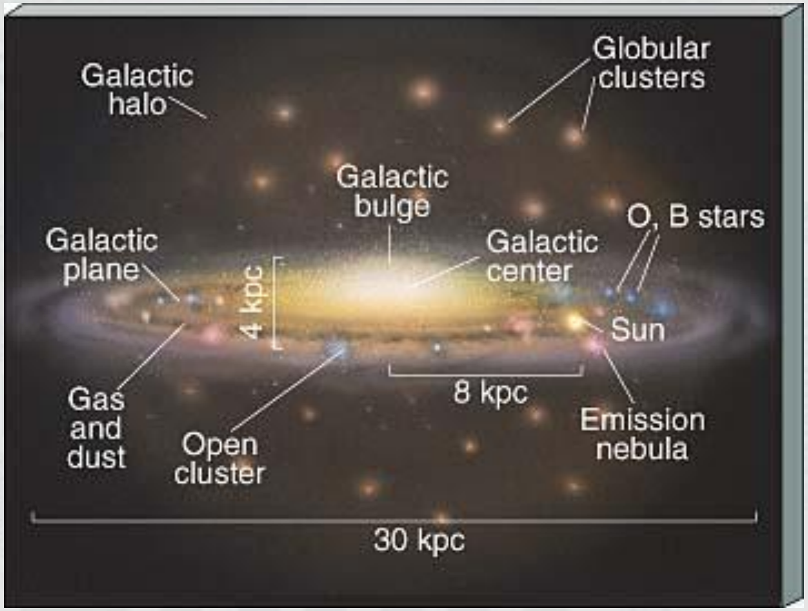
and their density has been the same since then $\Omega_{\mathrm{WIMP}} h^2 \propto \frac{1}{\sigma_{\mathrm{annihilation}}} \approx 0.1$

A stable and neutral WIMP is a good candidate for dark matter

DIRECT DETECTION

Can we detect the dark matter as part of the galactic halo?

Since the detection will be on the Earth we only need to know the properties of the galactic halo near the Earth:



- The local mass density necessary to reproduce the rotation curve of our Galaxy is $\rho_0 \sim$ **0.3 GeV/cm³**

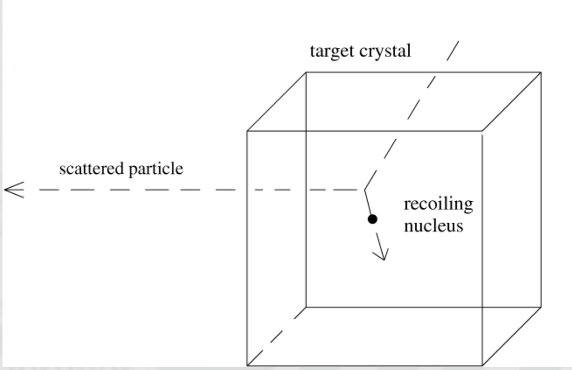
- The velocity dispersion of DM particles is $\mathbf{v_0 \sim 220}$ **km/s**

For $\mathbf{m_{DM} \sim 100}$ GeV one obtains

$$J \sim \rho_0 v_0 / m_{DM} \sim 60{,}000 \text{ particles/cm}^2\text{ s}$$

and therefore direct detection through elastic scattering with nuclei in a detector is in principle possible

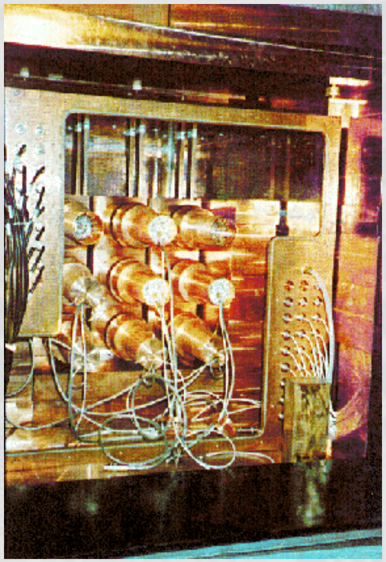
Goodman, Witten, 85
Wasserman, 86

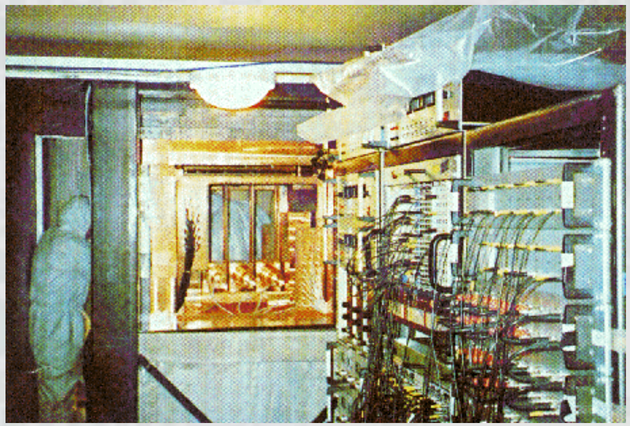


$\mathbf{R \sim J\ \sigma_{WIMP\text{-}nucleus} / m_N}$

For $\sigma_{WIMP\text{-}nucleon} \approx 10^{-8}\text{-}10^{-6}$ pb a material with nuclei composed of about 100 nucleons, i.e. $m_N \sim 100$ GeV:

$$R \approx 10^{-2} - 1 \text{ events/kg day}$$





It is convenient to have as much material as possible

e.g., DAMA experiment:
100 kg NaI crystals

$$E_{DM} \approx 1/2\ (100\ \text{GeV}/c^2)\ (220\ \text{km/s})^2 \approx 25\ \text{keV}$$

the recoiling nucleus loses its energy producing ionization + scintillation + heat

e.g., DAMA only measures scintillation light $\longrightarrow$ $E_{scintillation} = Q\ E_{recoil}$

Q(quenching factor) = 0.3 for Na , 0.09 for I

Experiments must be very sensitive being able to measure energies $\approx$ **few** keV

The background problem

Discussed yesterday by N. Smith

WIMPs are expected to produce less or about **10^{-2}** nuclear recoils/kg day with energies of few keV

- But cosmic rays occur at >100 events/kg day with energies ~ keV-MeV and generate neutrons producing nuclear recoils similar to those expected for WIMPs

Experiments must be located in the deep underground to greatly reduced the rate of these background events

- In addition, the environmental radioactivity generates also neutrons, and photons and electrons, and these produce electron recoils

Detectors must be shielded with layers of lead, polyethylene, etc.

- Still background events remain and the experiments must have a extremely good background discrimination to distinguish nuclear recoils due to WIMPs from nuclear and electron recoils due to the background

Combining two techniques of detection one can discriminate the electron recoils from nuclear recoils: heat + ionization , heat + scintillation , scintillation + ionization

In any case, always a small expected rate of misidentified background events remains

…everything above background might be a signal

Type of experiments

✷ Relying on reduction and interpretation of the background

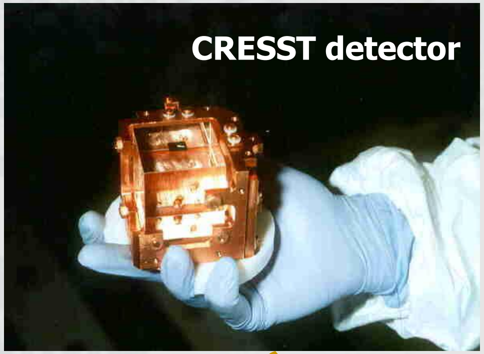
measure heat and ionization:

CDMS-II 19 Ge (~ 230 g each) crystals at Soudan (2100 mwe)

EDELWEISS-II 10 Ge (400 g each) crystals at Modane (4800 mwe)

measure heat and scintillation:

CRESST-II 9 $CaWO_4$ (~ 300 g each) crystals at Gran Sasso (3400 mwe)



measures ionization:

CoGeNT 440 g Ge crystal at Soudan (2100 mwe)

measures scintillation:

KIMS 103.4 kg CsI crystals at YangYang (2000 mwe)

measure scintillation and ionization:

XENON 100 62 kg liquid Xenon at Gran Sasso (3400 mwe)

ZEPLIN-III 12 kg liquid Xenon at Boulby (2800 mwe)

Listen to talks by the experiments

measures bubble nucleation:

SIMPLE 208+215 g superheated liquid C_2ClF_5 droplets at Bas Bruit (1500 mwe)

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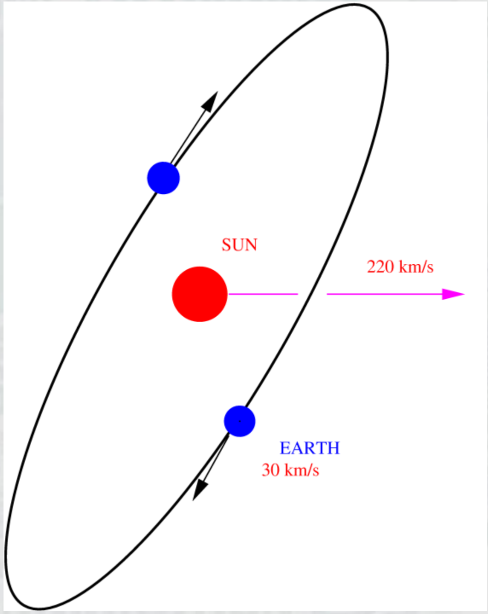
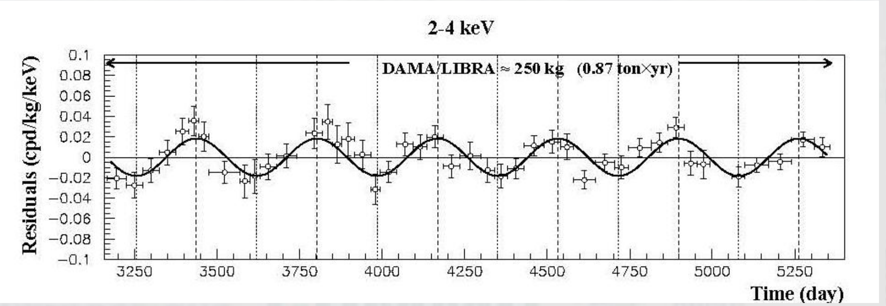
Annual modulation

Drukier, Freese, Spergel, 86
Freese, Frieman, Gould, 88



DAMA/LIBRA
250 kg NaI crystal scintillators at Gran Sasso.
does not strongly discriminate between
WIMP scatters and background events



CoGeNT 440 g Ge crystal at Soudan (2100 mwe)

In the future: KIMS 103.4 kg CsI crystal scintillators at YangYang (2000 mwe)

ANAIS project 250 kg NaI crystal scintillators at Canfranc (2500 mwe)

DM-Ice project 250 kg NaI crystal scintillators at South Pole (2200 mwe)

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Listen to talks by the experiments

Recent experimental results

The situation is very exciting … but confusing:

DAMA/NaI + DAMA/LIBRA cumulative exposure: 427,000 kg x day (13 annual cycles)
1002.1028 confirms annual modulation effect at 8.9 σ C.L.

CoGeNT, 1002.4703, 18.48 kg x day, excesses of events over the expected background
1106.0650, after 15 months, confirms annual modulation effect at 2.8 σ C.L.

CRESST, several talks, 333 kg x day, excesses of events over the expected background

On the contrary,	CDMS II	0912.3592	612 kg x day, and energies > 10 keV
		1011.2482	241 kg x day, low-energy reanalysis
	XENON 100	1104.2549	1471 kg x day
	XENON 10	1104.3088	
	SIMPLE	1106.3014	14.1+13.67 kg x day,

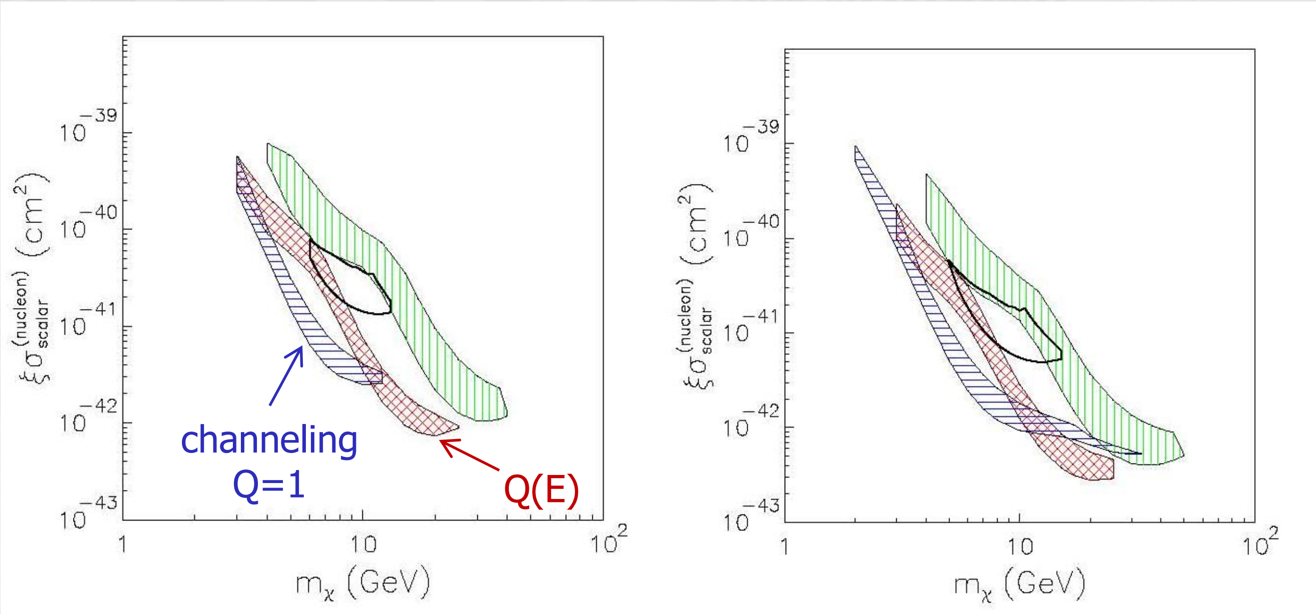
found no evidence for dark matter with $\mathbf{m_{WIMP}} \sim \mathbf{10}$ GeV

Belli, Bernabei, Bottino, Cappella, Cerulli, Fornengo, Scopel, 1106.4667

DAMA, CoGeNT, and possibly CRESST, seem to be compatible with:

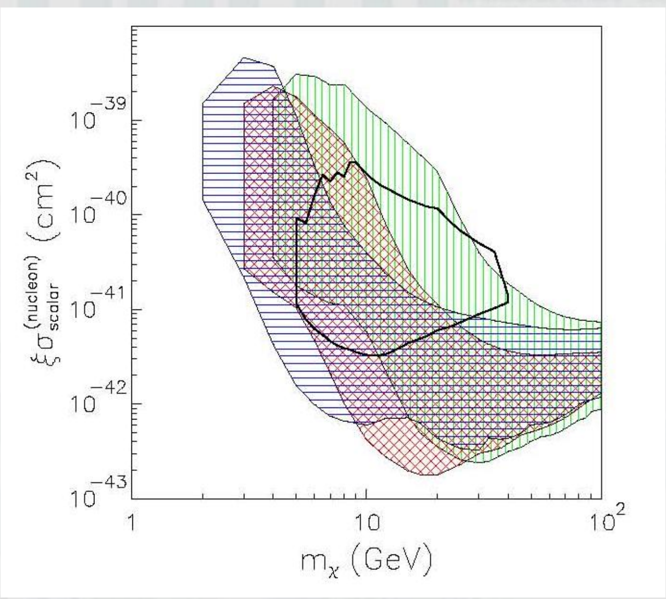
$\sigma_{\text{WIMP-nucleon}}$ ~ $10^{-4,-5}$ pb

m_{WIMP} ~ 10 GeV



isothermal sphere

triaxial



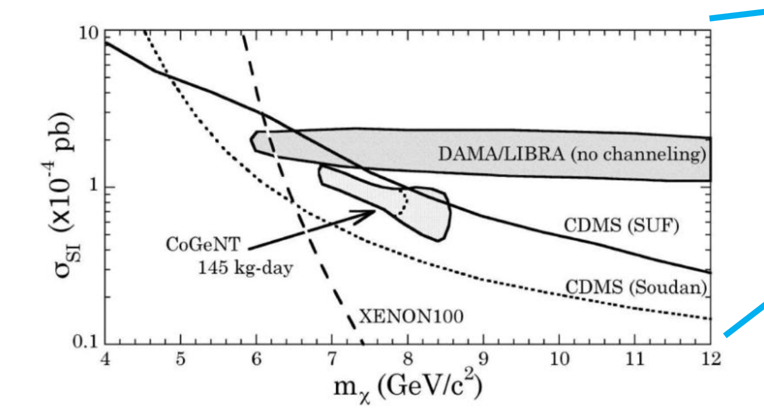
Experimental uncertainties:

- quenching factors of Ge & Na
- channeling effect
- nuclear form factors

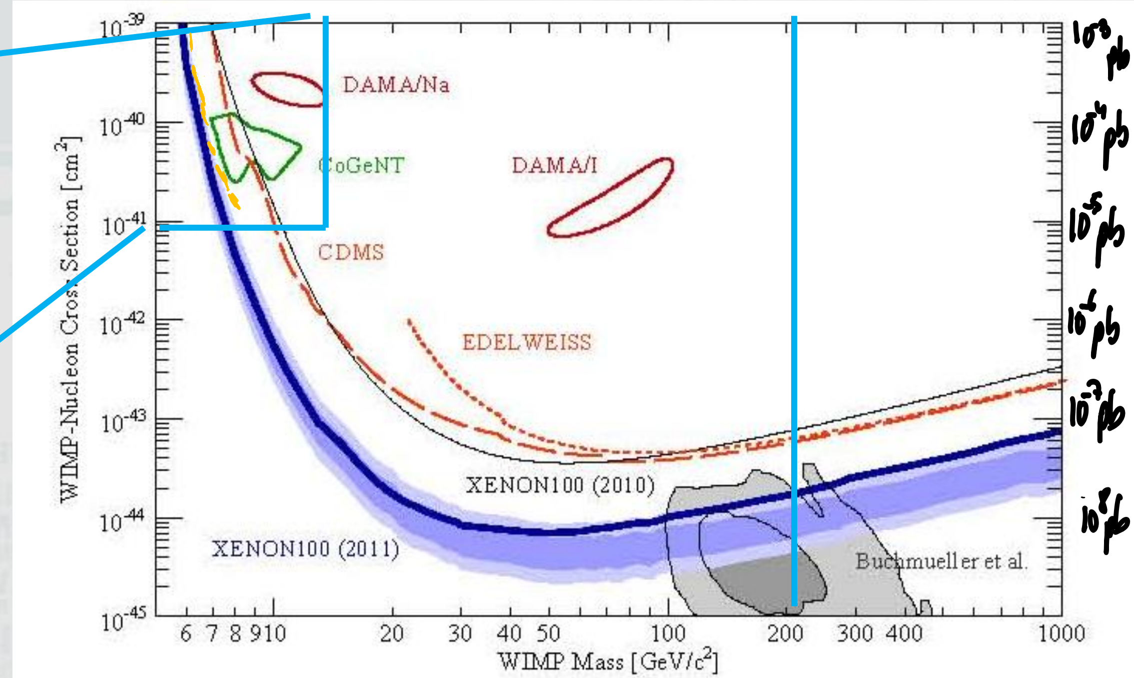
Astrophysical uncertainties:

- galactic halo model

XENON 100, 1104.2549



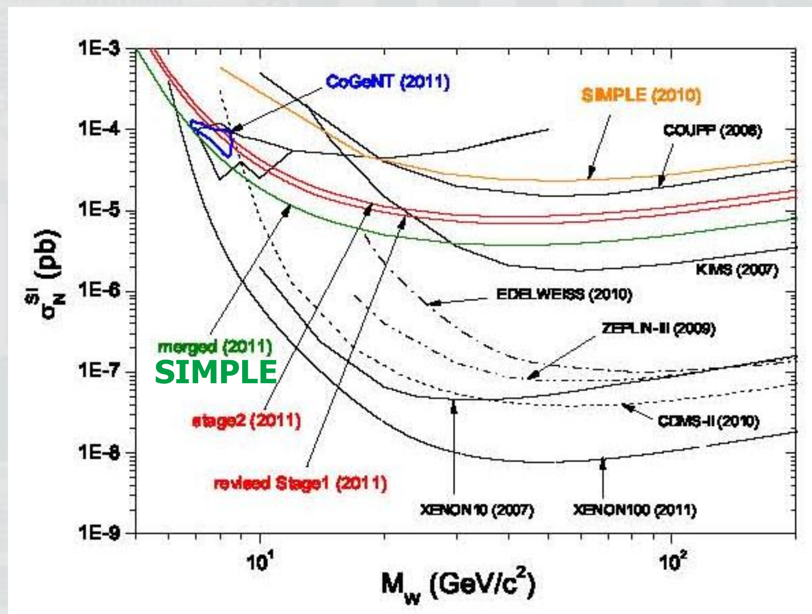
CoGeNT, 1106.0650



Using a isothermal sphere halo model

The results are in a low-energy region where the background makes analyses very complicated

Listen to talks by the experiments



SIMPLE, 1106.3014

KIMS new results: The most stringent cross section limits on spin dependent WIMP-proton elastic scattering for $m_{WIMP} > 20$ GeV

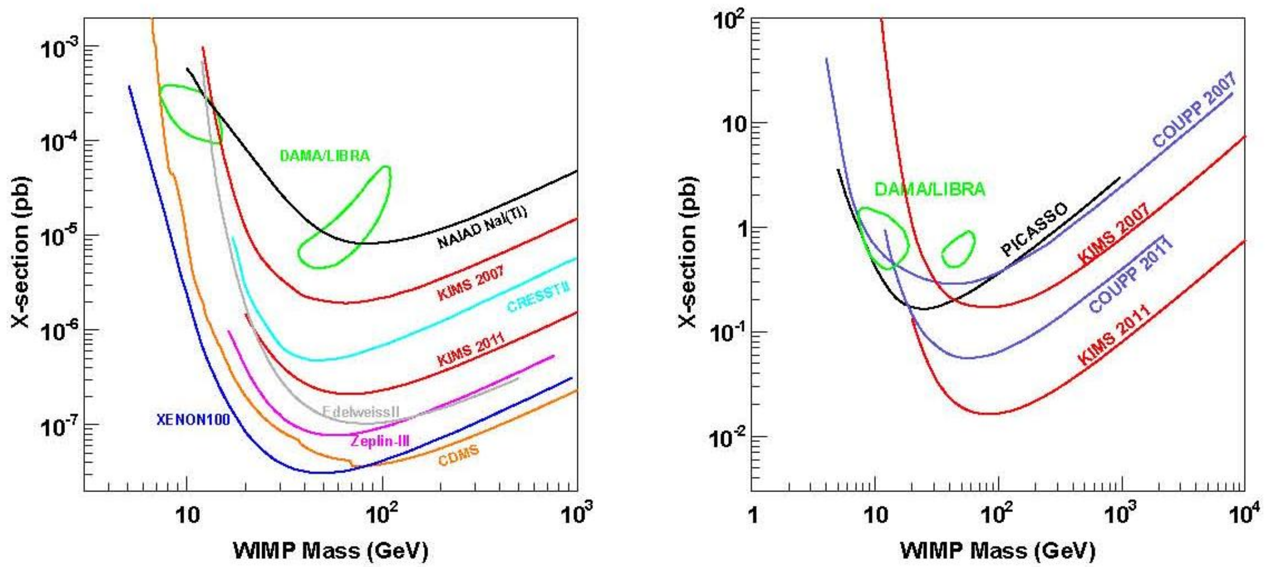
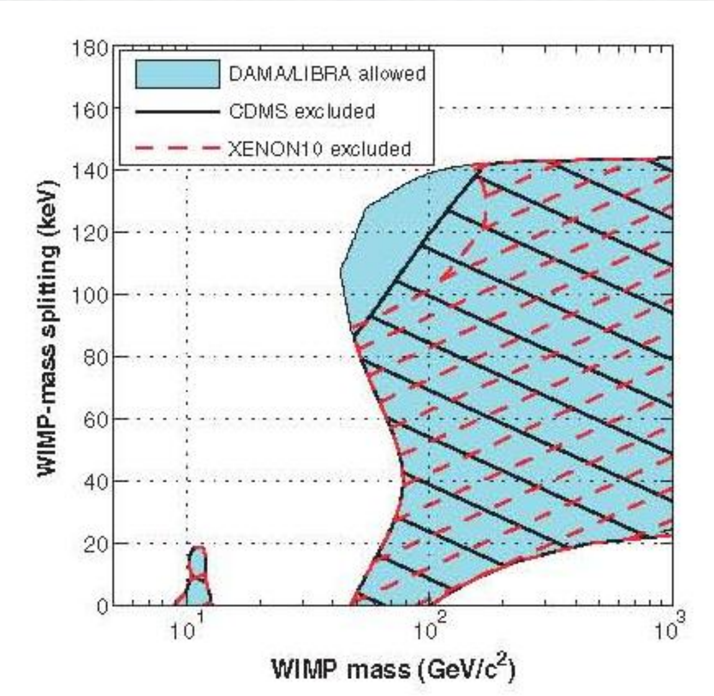


FIG. 5: The 90 % exclusion limits on **(Left)** SI WIMP-nucleon and **(Right)** SD WIMP-proton cross sections. In both plots DAMA results interpreted by Savage *et al.* [14] are used (3σ contours are drawn). The SI plot includes NAIAD [6], CRESST [7], Edelweiss [8], Zeplin [9], XENON100 [10] and CDMS [11] limits. The SD plot includes PICASSO [12] and COUPP [13] limits.

Listen to talk by S. Kim

KIMS new results: Rule out inelastic dark matter as an explanation to the discrepancy between experiments with different target nuclei, such as DAMA and CDMS



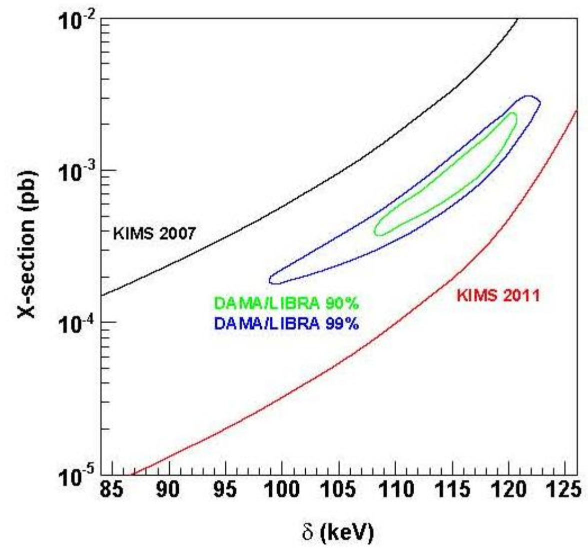


FIG. 6: The allowed parameter space for DAMA/LIBRA [16] and the limits reported here for a 70 GeV WIMP mass in iDM model. δ is the mass split between the ground and excited states of the WIMP. The astronomical parameters from Ref. [16] are used.

Listen to talk by S. Kim

WIMP candidates

In the MSSM $W = \epsilon_{ab} \left(Y_u^{ij} \hat{H}_2^b \hat{Q}_i^a \hat{u}_j^c + Y_d^{ij} \hat{H}_1^a \hat{Q}_i^b \hat{d}_j^c + Y_e^{ij} \hat{H}_1^a \hat{L}_i^b \hat{e}_j^c \right)$ $+ \mu H_1 H_2$

there is a mixing of neutral gauginos and Higgsinos:

$$(\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0) \longrightarrow \mathcal{M} = \begin{pmatrix} M_1 & 0 & -\frac{g'\nu_1}{\sqrt{2}} & \frac{g'\nu_2}{\sqrt{2}} \\ 0 & M_2 & \frac{g\nu_1}{\sqrt{2}} & -\frac{g\nu_2}{\sqrt{2}} \\ -\frac{g'\nu_1}{\sqrt{2}} & \frac{g\nu_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g'\nu_2}{\sqrt{2}} & -\frac{g\nu_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix}$$

Thus the lightest mass eigenstate (lightest neutralino)

$$\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

with a typical mass ~ GeV-TeV is a good candidate for dark matter, because:

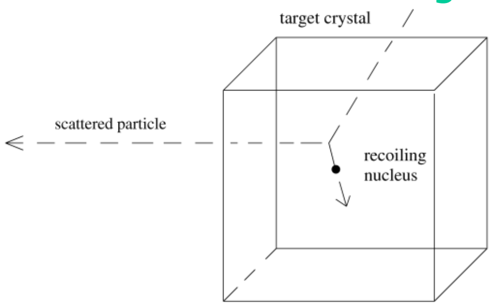
- It is a neutral particle
- It is a stable particle, since can be the **LSP**
- It is a **WIMP (Weakly Interacting Massive Particle)**

and a WIMP has the appropriate value of the annihilation cross section to obtain $\Omega h^2 \propto \frac{1}{\sigma_{\text{annihilation}}} \approx 0.1$

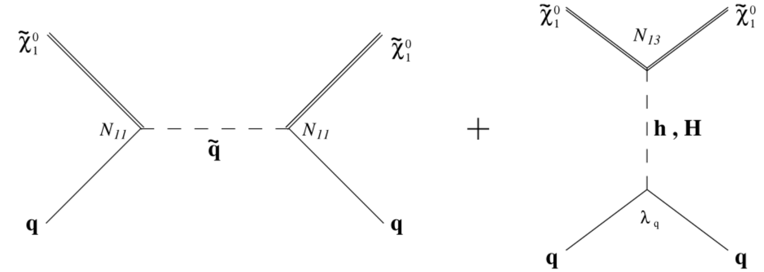
Neutralino as dark matter in the MSSM

Neutralino is a WIMP and thus a good candidate for dark matter
(and the LHC is searching for SUSY!!)

Goldberg, 83; Ellis, Hagelin, Nanopoulos, Olive,Srednicki , 83, 84; Krauss, 83

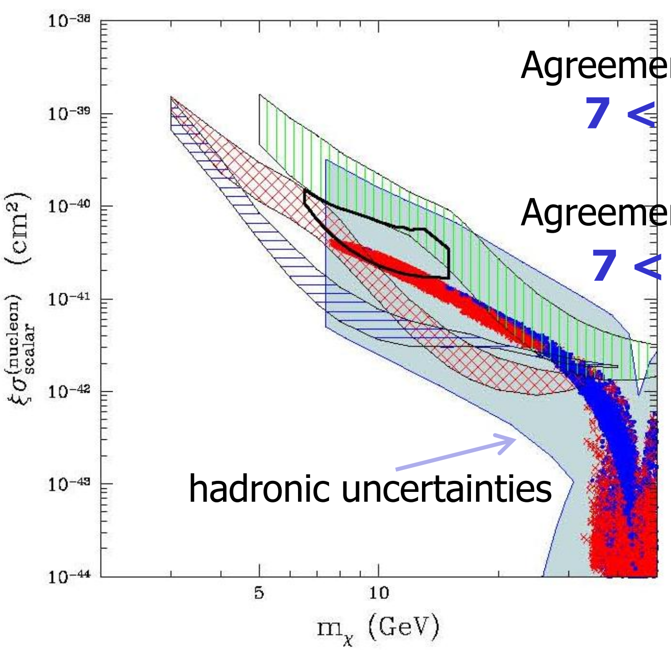


Supersymmetry



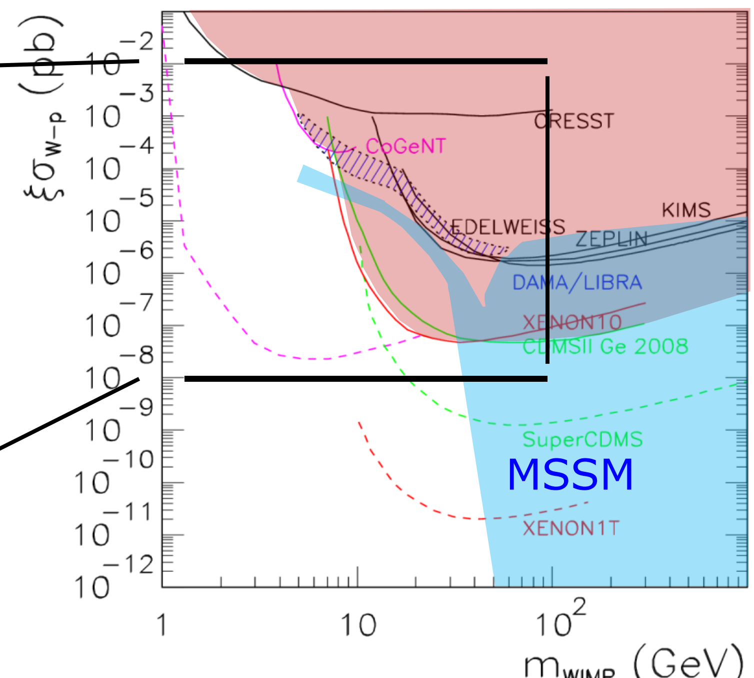
In the general SUSY parameter space (effMSSM), M_a , m_α , A_α , $\tan\beta$, one obtains:

Large cross section with correct relic density for a wide range of masses (blue region)



Agreement with DAMA/LIBRA
7 < m$_\chi$ < 50 GeV

Agreement also with CoGeNT
7 < m$_\chi$ < 20 GeV



Fornengo, Scopel, Bottino, 1011.4743
Belli et al., 1106.4667

Very light **Bino-like** neutralinos with masses ~10 GeV ,
using non-universal gauginos $M_1 << M_2$
and light Higgses to provide efficient neutralino annihilations
Bottino, Donato, Fornengo, Scopel '02-'08

These points fulfill all experimental constraints:

-- masses of the Higgs and superpartners

-- low energy observables:

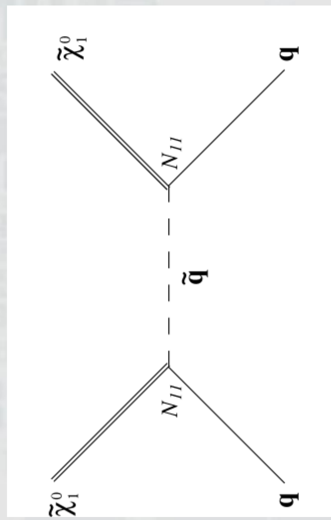
BR ($b \longrightarrow s\gamma$) $B \longrightarrow \tau\nu$, $K \longrightarrow \mu\nu$

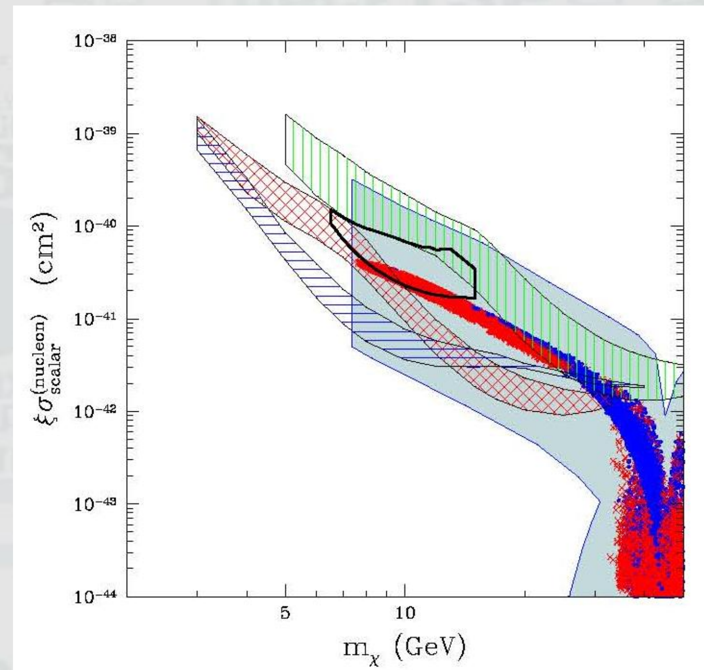
BR ($B_s \longrightarrow \mu^+ \mu^-$) $R(D) \equiv BR(B \longrightarrow D\tau\nu) / BR(B \longrightarrow De\nu)$

g-2

Also possible with light sleptons just above the LEP limit, to provide efficient neutralino annihilations

Albornoz Vasquez, Belanger, Boehm,1108.1338





solutions have some degree of fine-tuning (?) but in any case fully tested in the near future

Listen to talks by N. Fornengo, and T. Ota

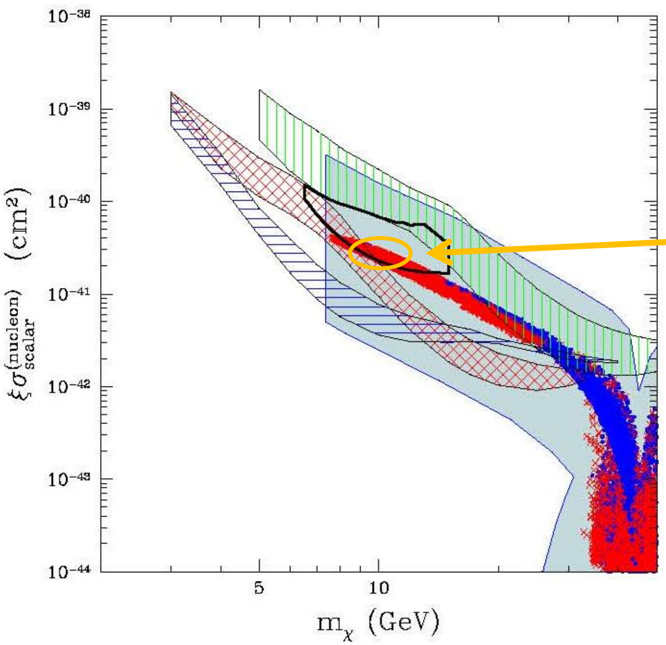
Fornengo, Scopel, Bottino, 1011.4743
Belli et al., 1106.4667

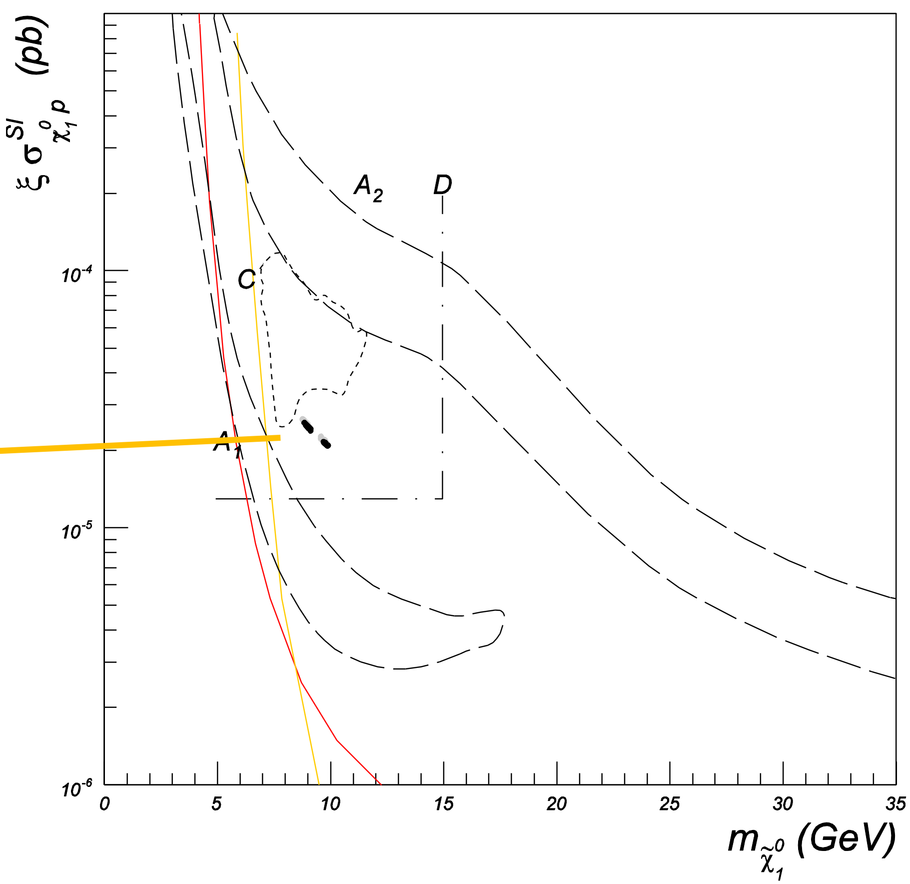
Very light neutralino dark matter in supergravity scenarios for the MSSM

Cerdeño, Fornengo, C.M., Peiró, Scopel, in preparation

Imposing:
-Parameters defined at the GUT scale
-RGEs equations
-fulfil all experimental constraints

With non-universal soft terms, $M_1<M_{2,3}/10$, … it is possible to get masses around 8-10 GeV





The μ problem

MSSM W = $Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c$ + **μ** $H_1\,H_2$

where the term **μ** $H_1\,H_2$ is necessary e.g. to generate Higgsino masses
Present experimental bounds imply: **μ** ≥ 100 GeV

Here we find an important problem of SUSY theories:

The μ problem: What is the origin of μ, and why is so small: $M_W << M_{Planck}$

The **MSSM** does not solve the **μ** problem.
In that sense it is a kind of effective theory

NMSSM

- Going beyond the MSSM: adding singlet superfield S – the NMSSM
  - Elegant solution to the μ-problem of the MSSM

$\mu \, H_1 \, H_2 \longrightarrow \lambda \, S \, H_1 \, H_2 \Rightarrow \mu_{eff} = \lambda \langle S \rangle$

- NMSSM has a richer and more complex phenomenology:
  - 2 extra Higgses
  - 1 additional neutralino
  - A light Higgs is experimentally viable: Implications for $\sigma_{\chi\text{-}n}$

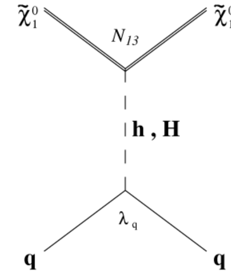
- Parameter space of the NMSSM:

$$\lambda\,, \quad \kappa\,, \quad \mu(=\lambda s)\,, \quad \tan\beta\,, \quad A_\lambda\,, \quad A_\kappa\,, \quad M_1\,, \quad M_2$$

Neutralino as dark matter in the NMSSM

The problem of fine-tuned solutions in the MSSM could be alleviated

$\mu\, H_1\, H_2 \longrightarrow \lambda\, S\, H_1\, H_2$



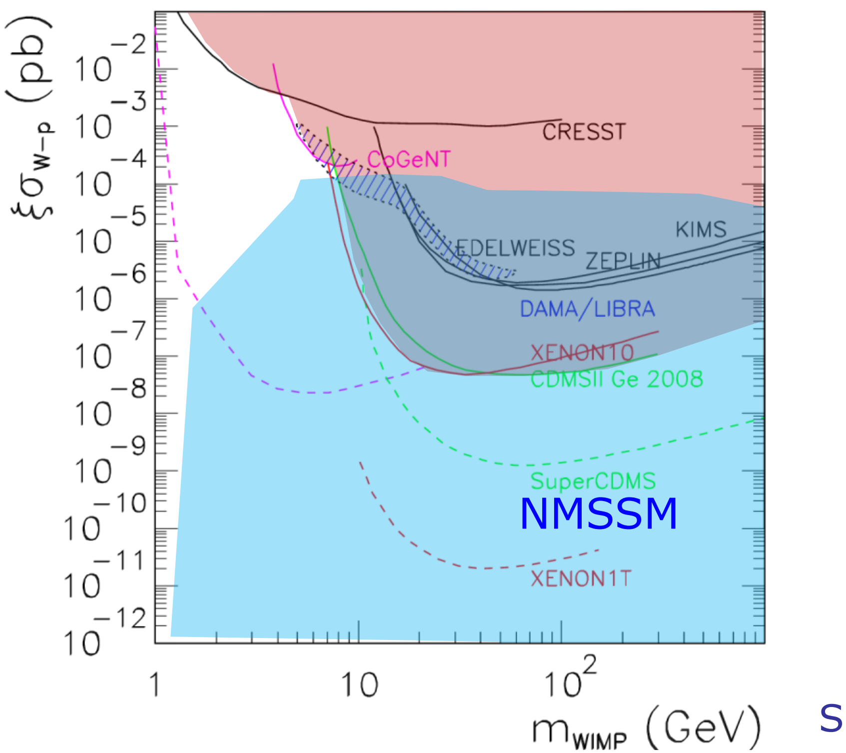
The detection cross section can be larger
(through the exchange of light Higgses with singlet composition)

Cerdeño, Gabrielli, López-Fogliani, C.M. Teixeira, 07

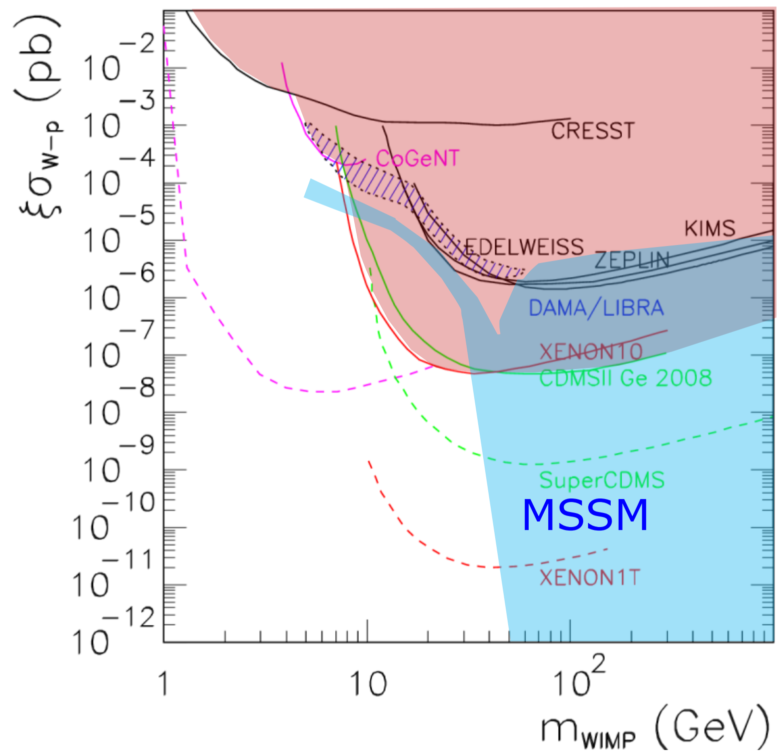
Very light **Bino-singlino** neutralinos are possible Gunion, Hooper, McElrath, 05

And their detection cross section significantly differs from that in the MSSM

CoGeNT coll. (including Cerdeño), 0807.0879



SM



For a recent analysis, studying very light neutralinos, see: Gunion, Belykov, Hooper, 1009.2555
Cumberbatch, Lopez-Fogliani, Roszkowski, Ruiz de Austri, Tsai, 1107.1604

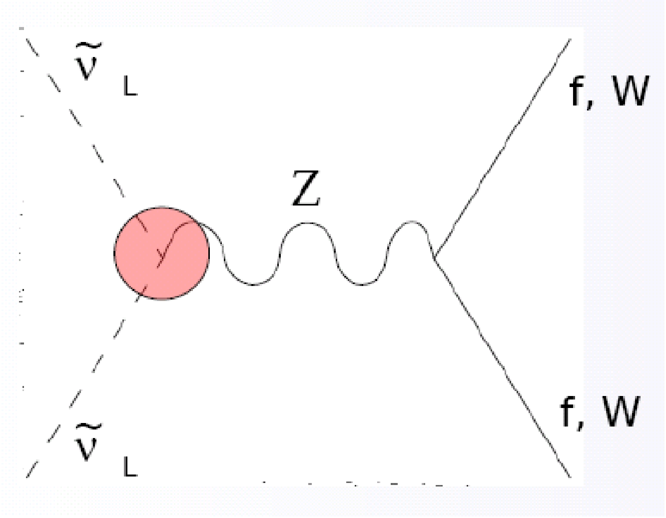
SNEUTRINO as dark matter

(Ibáñez '84; Hagelin, Kane, Rabi '84)

In the MSSM there are only lef-handed sneutrinos:

$$W = \epsilon_{ab} \left(Y_u^{ij} \hat{H}_2^b \hat{Q}_i^a \hat{u}_j^c + Y_d^{ij} \hat{H}_1^a \hat{Q}_i^b \hat{d}_j^c + Y_e^{ij} \hat{H}_1^a \hat{L}_i^b \hat{e}_j^c \right) \qquad + \mu H_1 H_2$$

Sneutrino (left-handed) couples with Z boson



- Too large annilation cross section
  (implying too small relic density)

- Too large direct detection cross section
  (already disfavoured by current experiments)

(Falk, Olive, Srednicki '94)

Right-handed sneutrino in extensions of the NMSSM

$$W = Y_u H_2 \cdot Q u + Y_d H_1 \cdot Q d + Y_e H_1 \cdot L e \boxed{+ y_N L \cdot H_2 N,}$$

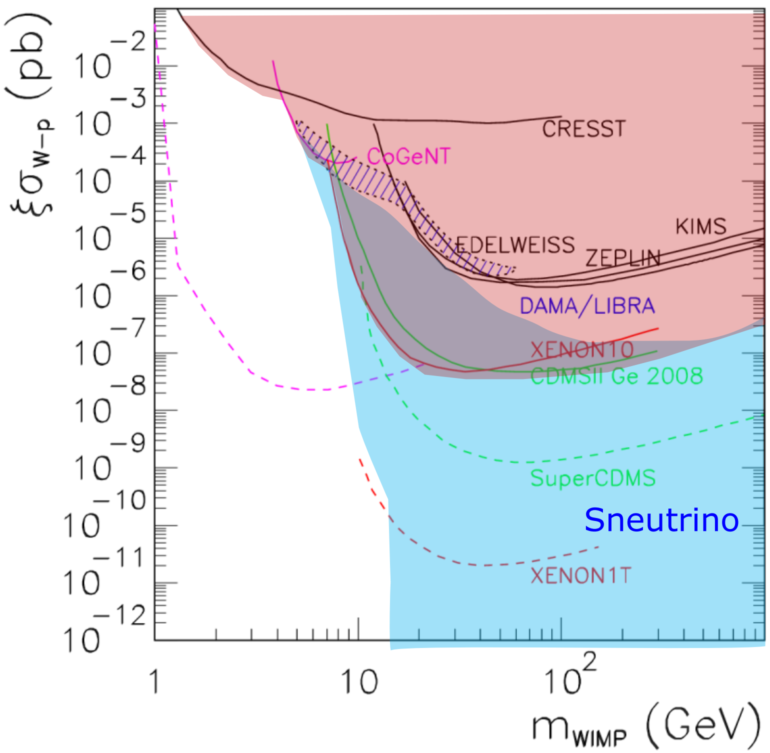
$$+ \lambda\, S\, H_1\, H_2 + k\, S\, S\, S + \boxed{\lambda_N\, S\, N\, N}$$

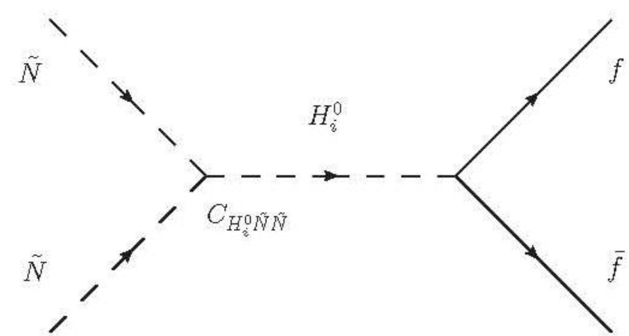
This extension is useful to generate dynamically neutrino masses

Kitano, Oda, 99

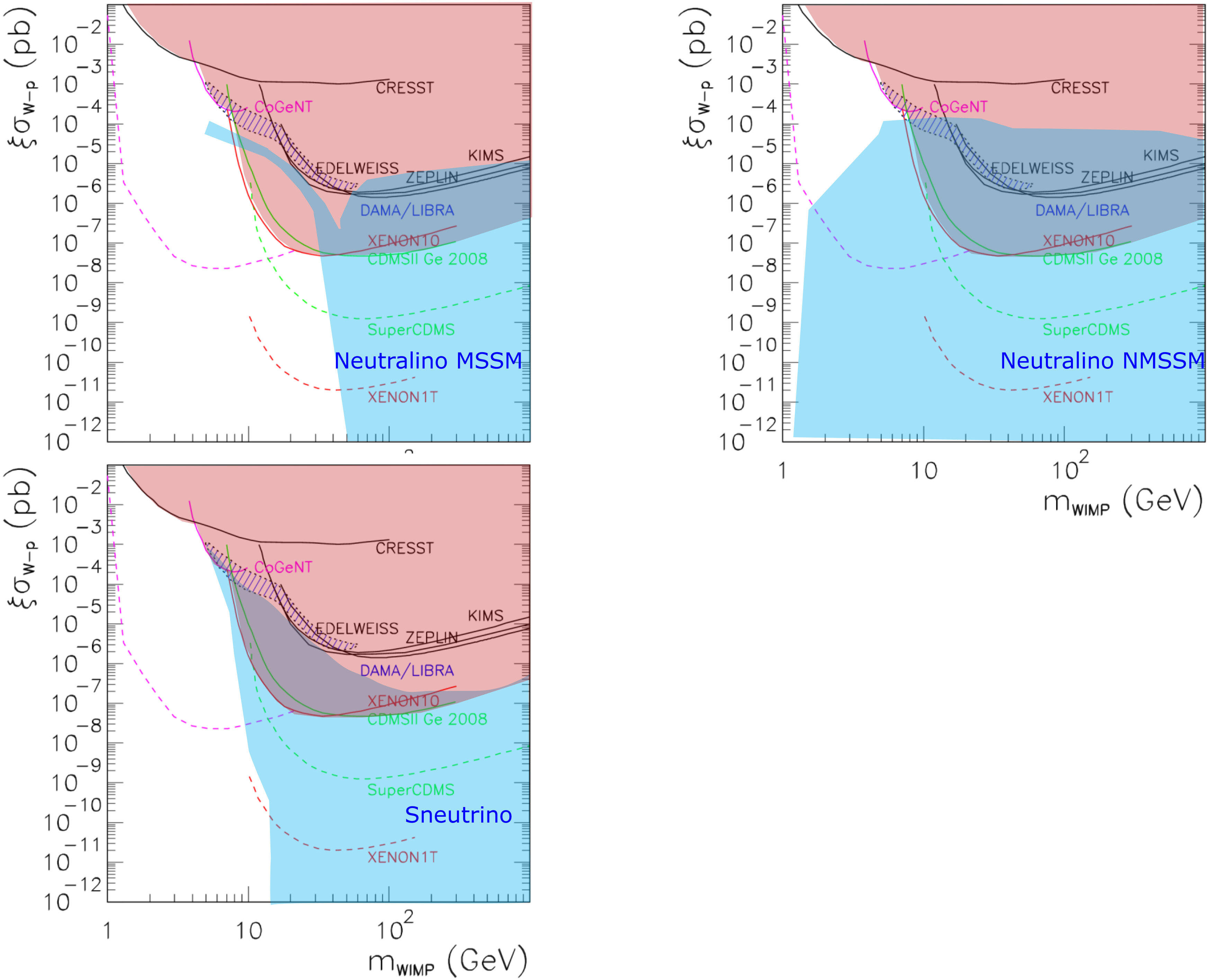
Recall that in the MSSM a LSP purely right-handed sneutrino implies scattering cross section too small, relic density too large $\quad M_M\, N\, N$

Nevertheless, here the singlet S introduced to solve the μ problem, provides efficient interactions of sneutrino too





- Viable, accessible and not yet excluded (Cerdeño, C.M., Seto '08)
- Light sneutrinos are viable and distinct from MSSM neutralinos (Cerdeño, Seto '09)



$\xi\sigma_{W-p}$ (pb)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
CRESST
CoGeNT
EDELWEISS
KIMS
ZEPLIN
DAMA/LIBRA
XENON10
CDMSII Ge 2008
SuperCDMS
Neutralino MSSM
XENON1T
$\xi\sigma_{W-p}$ (pb)
CRESST
CoGeNT
EDELWEISS
KIMS
ZEPLIN
DAMA/LIBRA
XENON10
CDMSII Ge 2008
SuperCDMS
Neutralino NMSSM
XENON1T
1
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m_{WIMP} (GeV)
$\xi\sigma_{W-p}$ (pb)
CRESST
CoGeNT
EDELWEISS
KIMS
ZEPLIN
DAMA/LIBRA
XENON10
CDMSII Ge 2008
SuperCDMS
Sneutrino
XENON1T
1
10
10^{2}
m_{WIMP} (GeV)

Very light RH sneutrinos

Cerdeño, Huh, Peiro, Seto, 1108.0978

W= λ S H_1 H_2 + k S S S + λ_N S N N + Y_N H_2 L N

$$m^2_{\tilde{N}_1} = m^2_{\tilde{N}} + |2\lambda_N v_s|^2 + |y_N v_2|^2 + 2\lambda_N \left(A_{\lambda_N} v_s + (\kappa v_s^2 - \lambda v_1 v_2)^\dagger \right) .$$

More flexibility due to the new free parameters : $\{\lambda_N, m_{\tilde{N}}, A_{\lambda_N}\}$

They can be chosen to provide a wide range of RH sneutrino masses and couplings withouth affecting the rest of the NMSSM spectrum

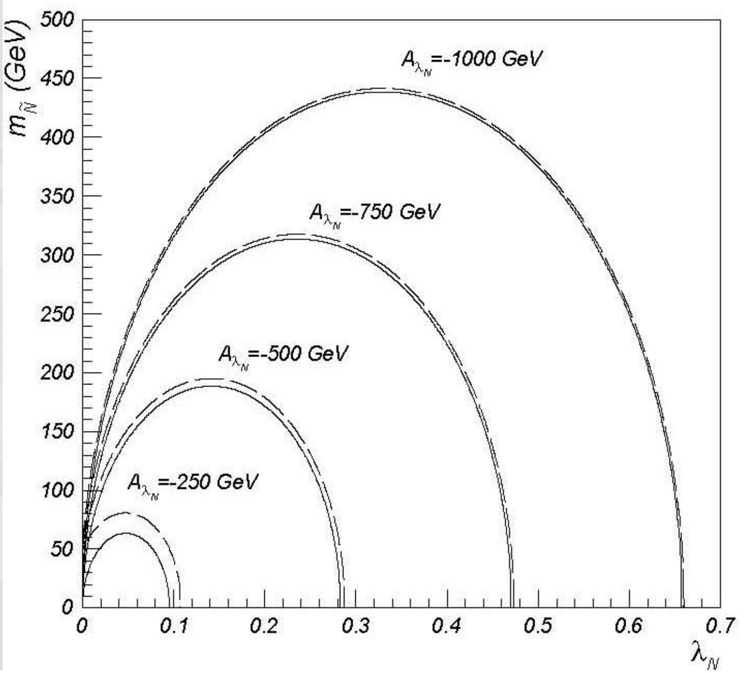
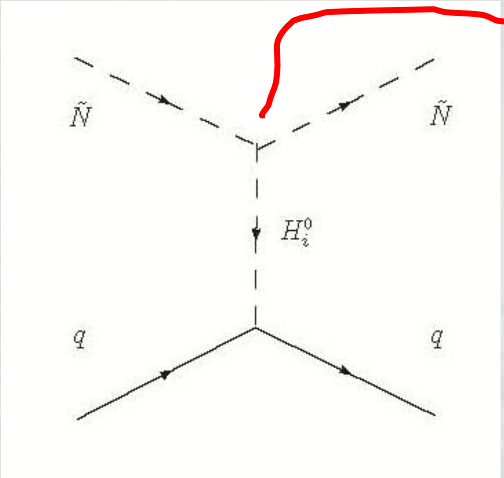


Figure 1: Trajectories in the $(m_{\tilde{N}}, \lambda_N)$ plane with fixed RH sneutrino mass, given various values of A_{λ_N}. For each choice of A_{λ_N} the dashed line represents the trajectory along which $m_{\tilde{N}_1} = 50$ GeV and the solid one corresponds to $m_{\tilde{N}_1} = 0$. We have used $\tan\beta = 5$, $\lambda = 0.3$, $\kappa = 0.2$, and $\mu = 200$ GeV.

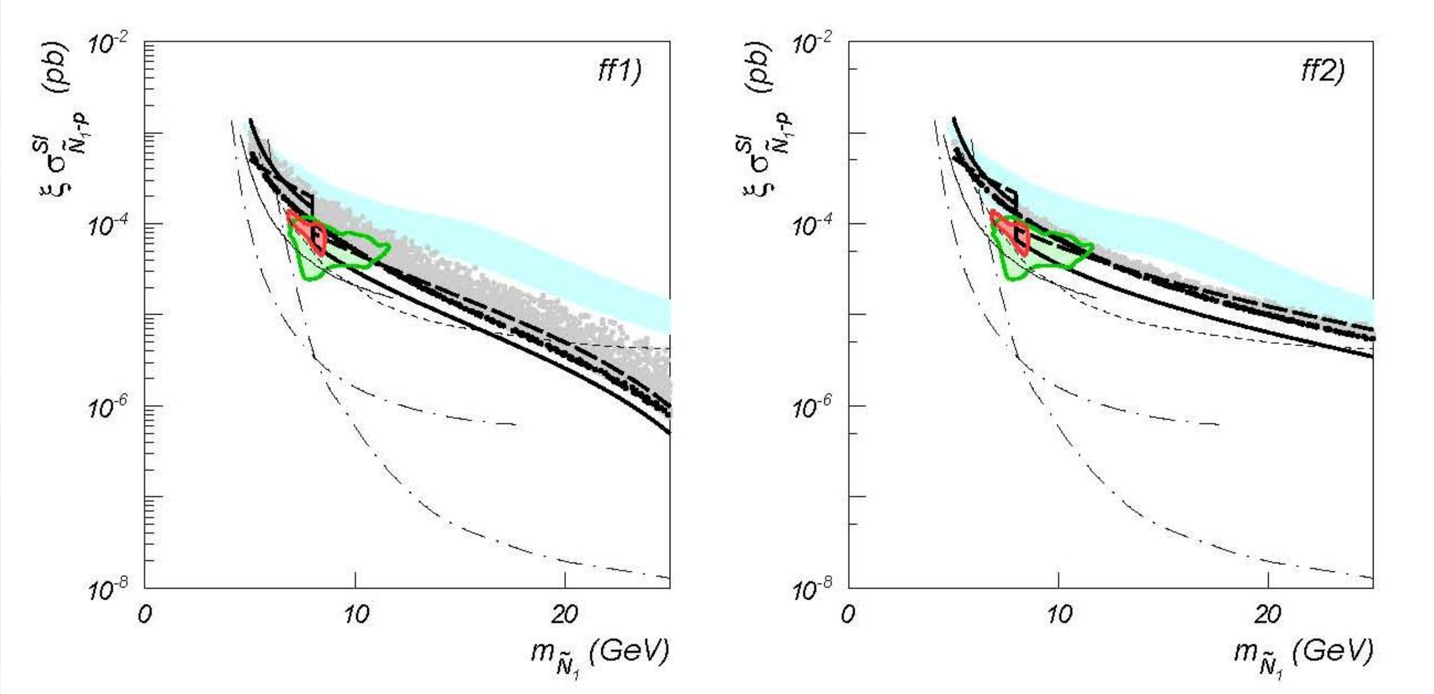
Large non-universalities in the soft parameters are NOT needed in order to have a very light RH sneutrino (contrary to light neutralinos)

Detection



$$W = \lambda\, S\, H_1\, H_2 + k\, S\, S\, S + \lambda_N\, S\, N\, N + Y_N\, H_2\, L\, N$$

Since λ_N can be chosen to be rather large, the Higgs coupling to b quarks need not be too large in order to reproduce the correct relic abundance, in other words, tan β can be kept small



For a scan in $\{\lambda_N, m_{\tilde{N}}, A_{\lambda_N}\}$

$\tan\beta$	5	5
A_λ	550	700
A_κ	-200	0
μ	130	120
λ	0.2	0.3
κ	0.1	0.2
M_1	200	200
$m_{L,E}$	250	250
$m_{Q,U,D}$	1000	1000
A_E	-2500	-2500
$A_{U,D}$	1500	1000
$m_{H_1^0}$	62.4	115.9
$m_{H_2^0}$	119.4	158.5
$m_{H_3^0}$	634.2	592.6
$m_{A_1^0}$	199.6	51.2
$m_{A_2^0}$	632.5	589.6

Conclusions

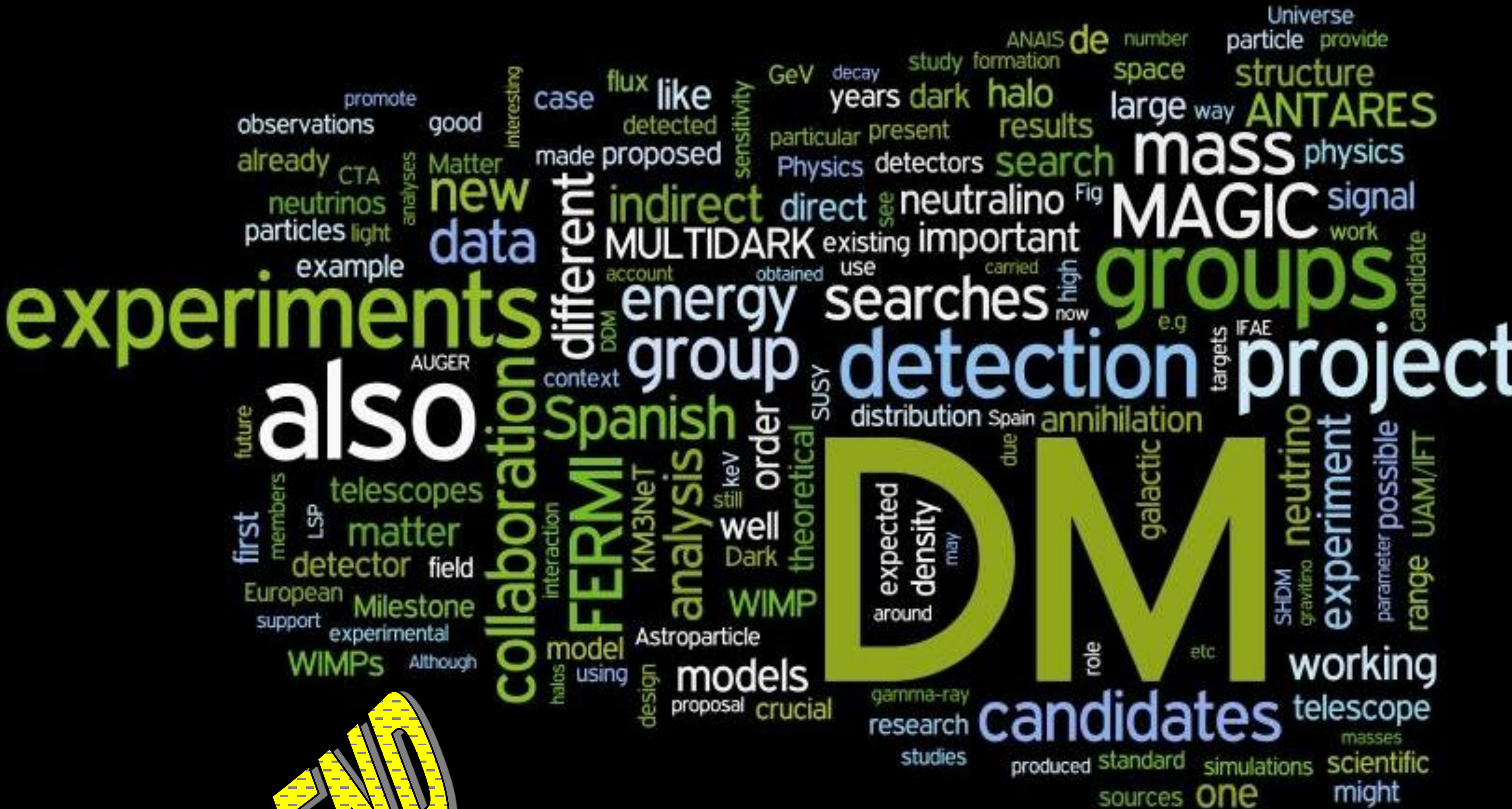
- There are impressive experimental efforts by many groups around the world to detect the dark matter:

  DAMA, CoGeNT, CRESST,
  CDMS, XENON, SIMPLE, EDELWEISS, ZEPLIN, KIMS, etc.

  Thus the present experimental situation is very exciting

And, besides, the LHC is working

So, stay tuned !



THE END

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