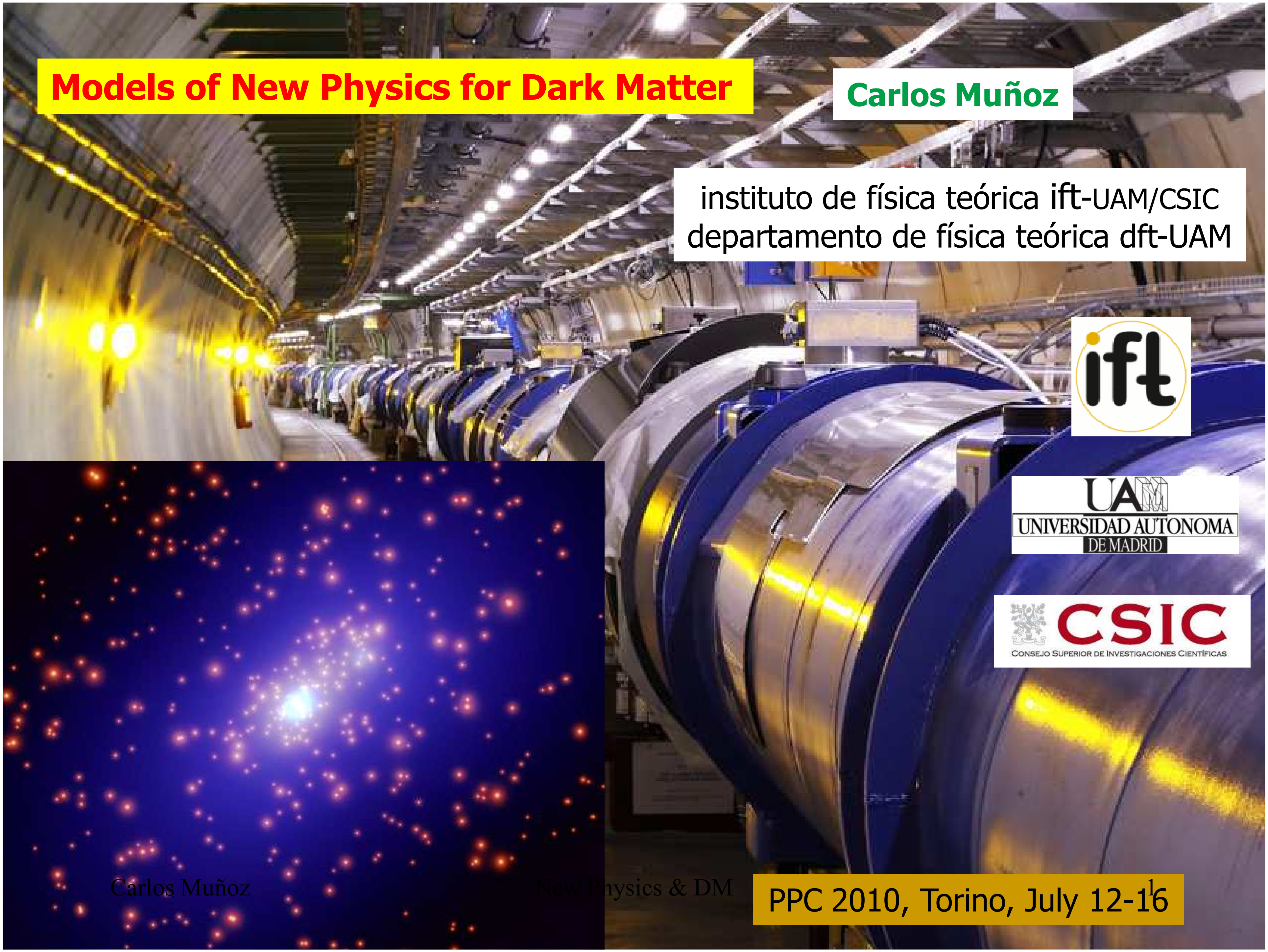
Models of New Physics for Dark Matter

Carlos Muñoz

instituto de física teórica ift-UAM/CSIC
departamento de física teórica dft-UAM



UNIVERSIDAD AUTONOMA DE MADRID

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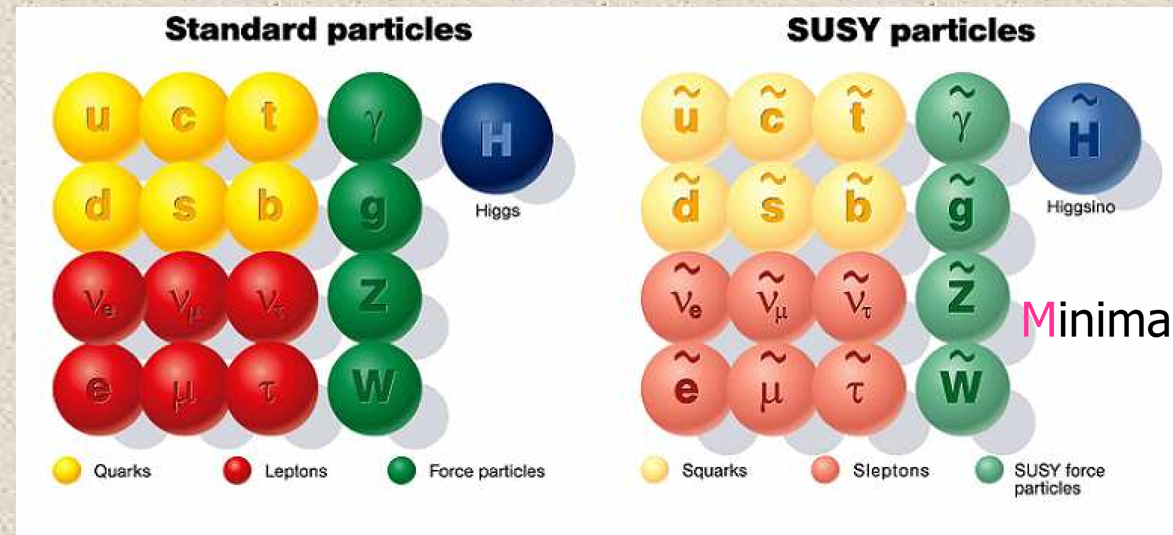
PPC 2010, Torino, July 12-16

Crucial Moment for SUSY in next few years:



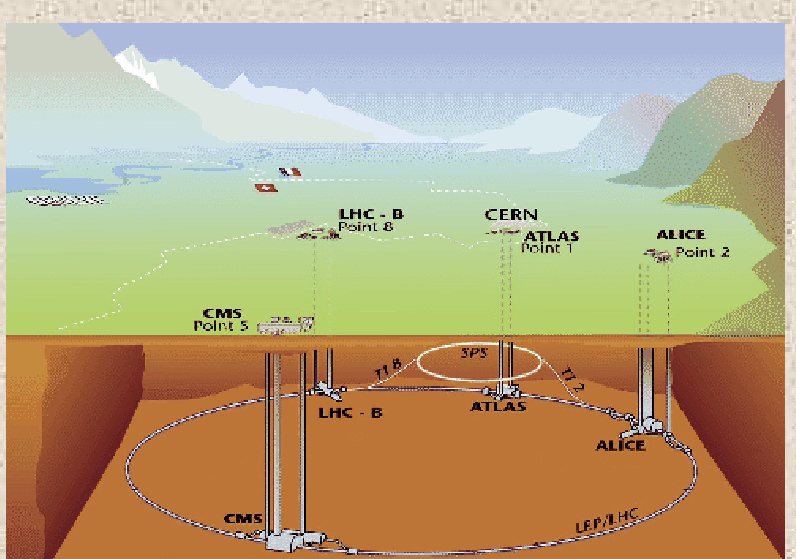
The spectrum of elementary particles is doubled

with masses ≈ 1000 GeV

Minimal Supersymmetric Standard Model

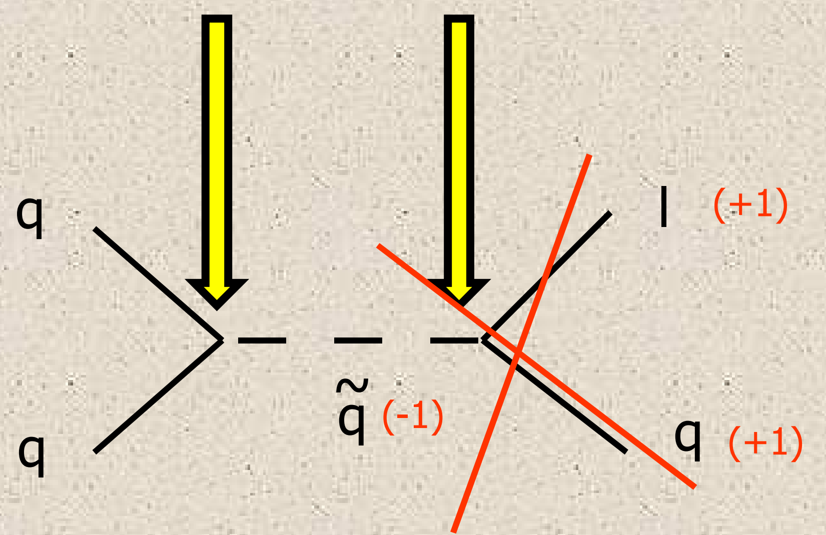
MSSM

A rich phenomenology



- **But, by construction, the MSSM produce too fast proton decay**

Operators like $d^c d^c u^c$, QLd^c , LLe^c , LH_2 are allowed in the superpotential



To preserve B and L conservation one can impose a discrete symmetry (**R parity**)

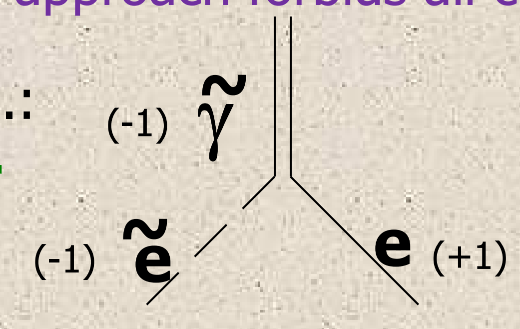
Particle $\longrightarrow$ Particle
Superpartner $\longrightarrow$ $-$ Superpartner

i.e. superparticles must appear in pairs

Notice that this (conservative) approach forbids all couplings

In models with R parity the **LSP** is stable since e.g.:

Thus it **is a candidate for dark matter**



So, once eliminated all operators violating baryon and lepton number, we are left with the superpotential of the MSSM:

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 another 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

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)

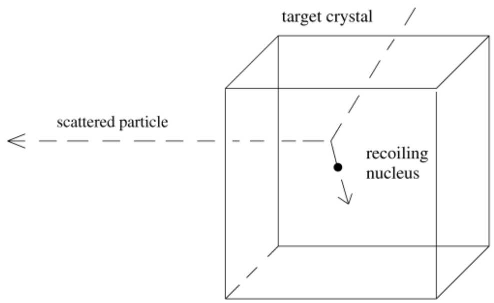
$$\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

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

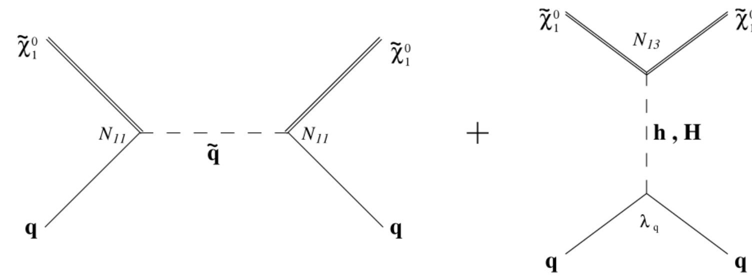
- It is a neutral particle
- It is a stable particle, since can be the **LSP**
- It is a **WIMP (Weakly Interacting Massive Particle)**

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

DIRECT DETECTION



Supersymmetry

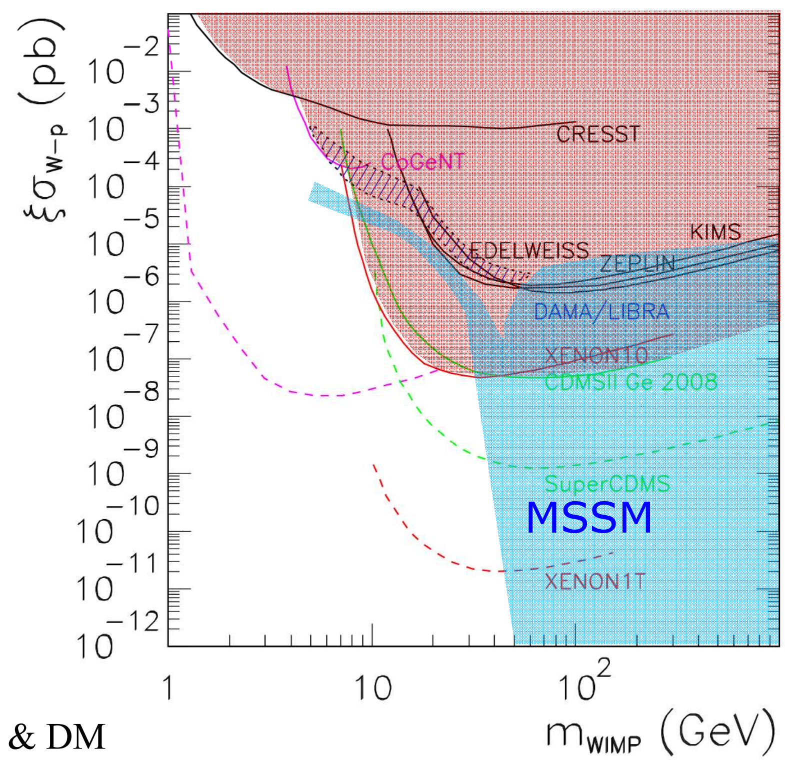


In the general SUSY parameter space, M_a , m_α , A_α , $\tan\beta$, one obtains:

Large cross section for a wide range of masses

Very light **Bino-like** neutralinos
with masses ~10 GeV

(Bottino, Donato, Fornengo, Scopel '04-'08)



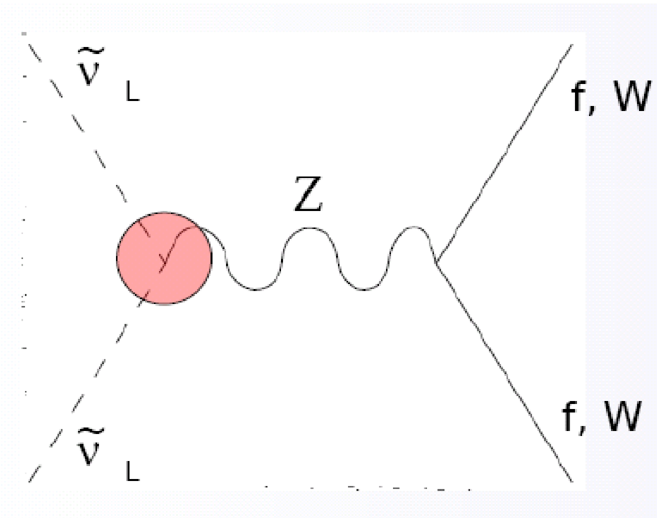
SNEUTRINO as dark matter IN THE MSSM

(Ibáñez '84; Hagelin, Kane, Rabi '84)

In the MSSM there are only lef-handed sneutrinos:

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

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)

The MSSM with a right-handed sneutrino

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

$$\begin{pmatrix} m^2_L & F \\ F & m^2_\nu \end{pmatrix} \Longrightarrow \tilde{\nu}_1 = -\sin\theta\,\tilde{\nu}_L + \cos\theta\,\tilde{\nu}_R$$

Sizeable mixings reduce the coupling to the Z-boson, which couples only to left-handed fields

Arkani-Hamed, Hall, Murayama, Smith, Weiner, '01
Arina, Fornengo '07

- A potential problem for this mechanism it that in conventional SUGRA mediated SUSY breaking: $F \sim A_\nu\, m_\nu$

Thus the LSP is a purely right-handed sneutrino implying
scattering cross section too small, relic density too large
for a thermal sneutrino dark matter

But the MSSM has an important theoretical problem:

- the origin of the μ term $\quad W = \boldsymbol{\mu} H_1 H_2$

This can be solved in the Next-to-MSSM:

$$\boxed{\textbf{NMSSM}}$$

$$\mu H_1 H_2 \longrightarrow \lambda_N N H_1 H_2 \Rightarrow \mu_{eff} = \lambda \langle N \rangle$$

- NMSSM has a richer and more complex phenomenology:

  additional Higgs, the singlet N

  additional neutralino, the singlino $\tilde{N}$

Neutralino in the NMSSM

- Different predictions from the MSSM

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

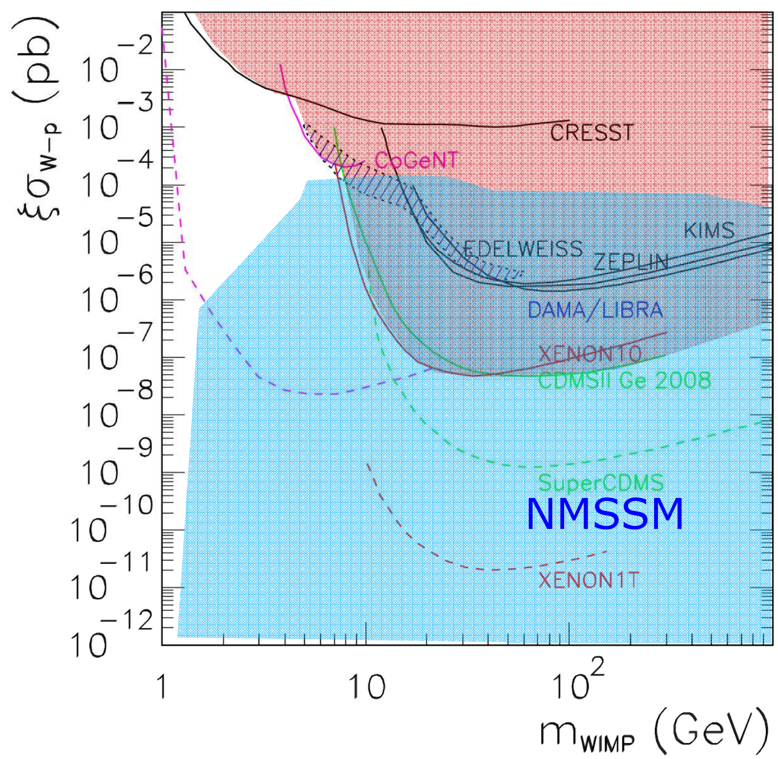
(Cerdeño, Gabrielli, López-Fogliani, Teixeira, C.M. ´07)

Very light **Bino-singlino** neutralinos are possible

(Gunion, Hooper, McElrath ‘05)

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

(CoGeNT ‘08)



Right-handed sneutrino in extensions of the NMSSM

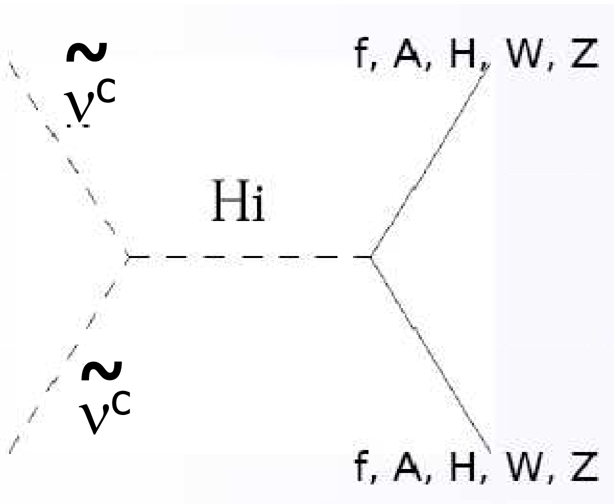
$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c + \boxed{Y_\nu^{ij}\,\hat{H}_2^b\,\hat{L}_i^a\,\hat{\nu}_j^c}\right)$$

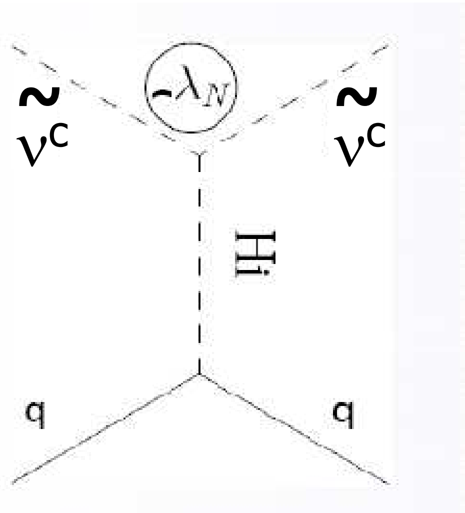
$$+ \lambda\, N\, H_1\, H_2 + k\, N\, N\, N + \boxed{\lambda_N\, N\, \nu^c\, \nu^c}$$

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

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

Cerdeño, C.M., Seto, 08





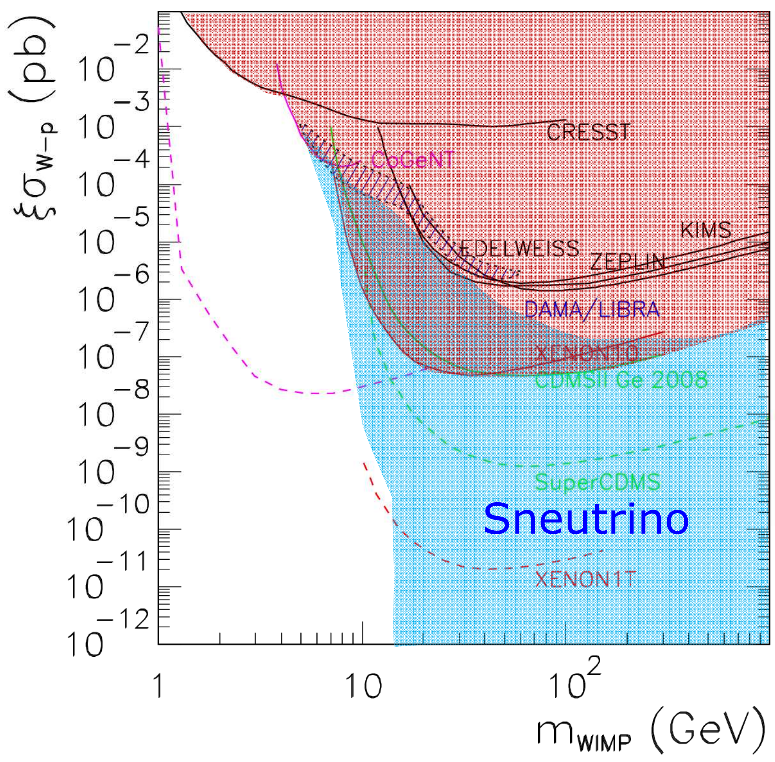
RH-Sneutrino DM overview

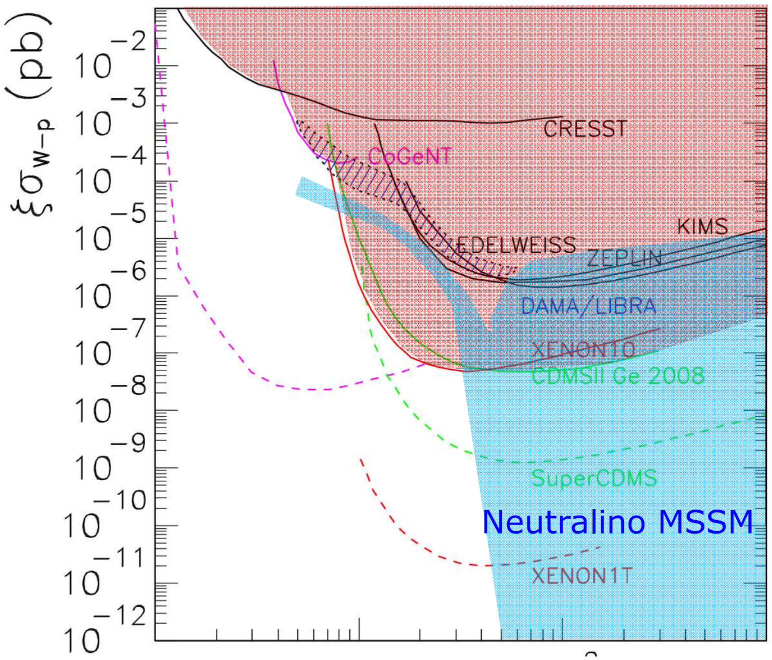
- Viable, accessible and not yet excluded

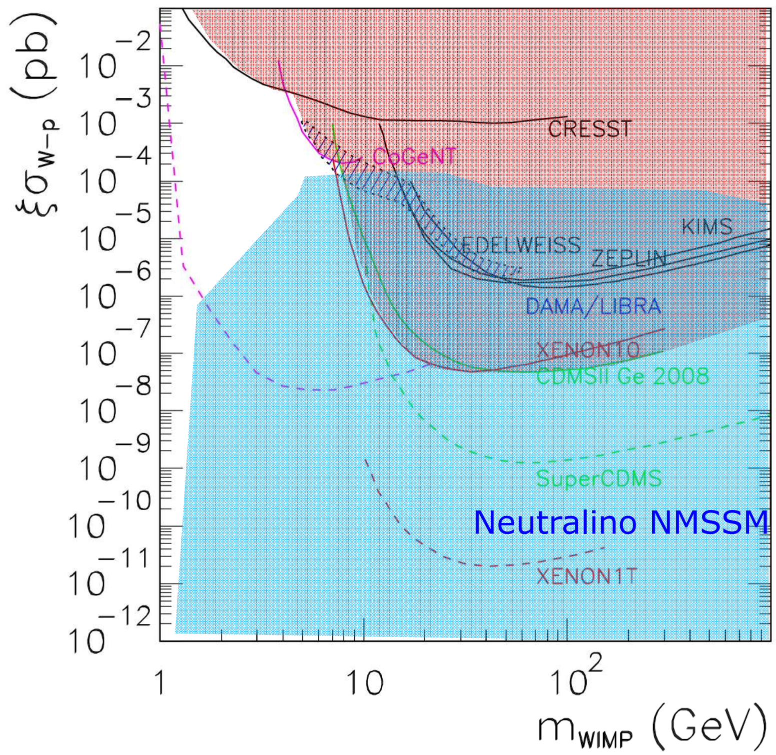
  (Cerdeño, C.M., Seto '08)

- Light sneutrinos are viable and distinct from MSSM neutralinos

  (Cerdeño, Seto '09)




$\xi\sigma_{W-p}$ (pb)
CRESST
CoGeNT
EDELWEISS
KIMS
ZEPLIN
DAMA/LIBRA
XENON10
CDMSII Ge 2008
SuperCDMS
Neutralino MSSM
XENON1T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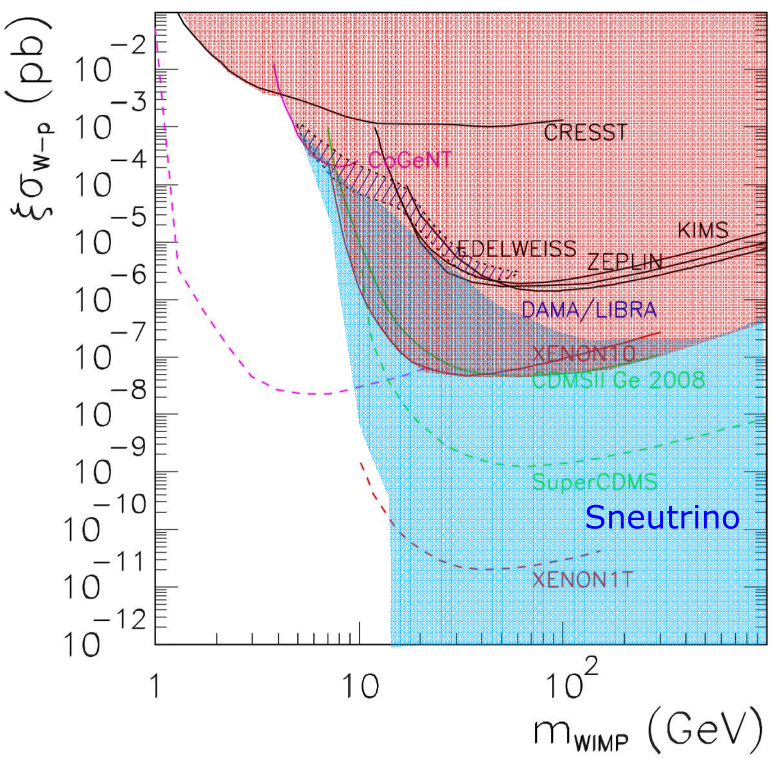
Neutralino NMSSM
XENON1T
m_{WIMP} (GeV)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CRESST
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EDELWEISS
KIMS
ZEPLIN
DAMA/LIBRA
XENON10
CDMSII Ge 2008
SuperCDMS
Sneutrino
XENON1T
m_{WIMP} (GeV)

Proposal for a new SUSY model

Lopez-Fogliani, C.M., PRL 97 (2006) 041801

to use terms of the type

$$\hat{\nu}^c \hat{H}_1 \hat{H}_2$$

to produce an effective μ term.

a "μ from ν" Supersymmetric Standard Model ($\boxed{\mu\nu\mathrm{SSM}}$) with the following characteristics: natural particle content without μ problem.

$\mu\nu$SSM

In addition to the MSSM Yukawas for quarks and charged leptons, the $\mu\nu$SSM superpotential contains Yukawas for neutrinos, and two additional type of terms

$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_\nu^{ij}\,\hat{H}_2^b\,\hat{L}_i^a\,\hat{\nu}_j^c\right) - \epsilon_{ab}\lambda^i\,\hat{\nu}_i^c\,\hat{H}_1^a\hat{H}_2^b + \frac{1}{3}\kappa^{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c\,, \tag{1}$$

when the scalar components of the superfields $\hat{\nu}_i^c$, denoted by $\tilde{\nu}_i^c$, acquire VEVs of order the electroweak scale, an effective interaction $\mu\hat{H}_1\hat{H}_2$ is generated through the fifth term in (1), with $\mu \equiv \lambda^i\langle\tilde{\nu}_i^c\rangle$.

The last type of terms in (1) is allowed by all symmetries, and avoids the presence of a Goldstone boson associated to a global U(1) symmetry.

In addition, it generates effective Majorana masses for neutrinos at the EW scale: EW seesaw

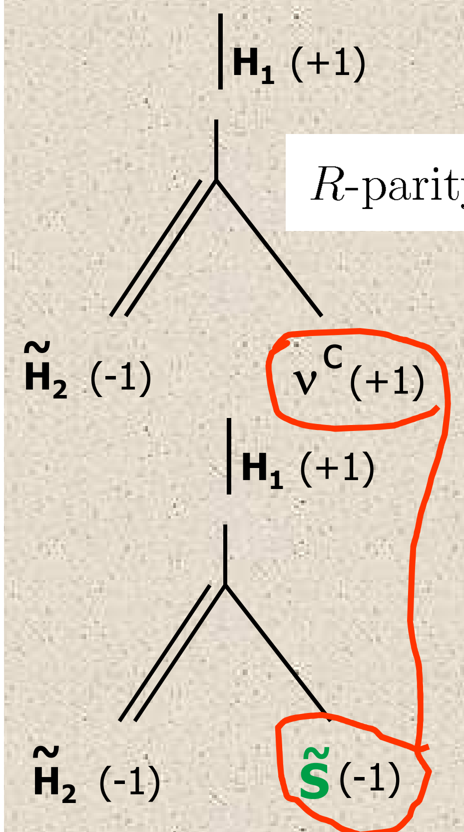
No ad-hoc scales

$m_\nu \sim m_D^2/M_M = (\mathbf{Y}_\nu\, H_2)^2/(k\, \nu_R) \sim (10^{-6}\, 10^2)^2/10^3 = 10^{-11}$ GeV $= 10^{-2}$ eV

Indeed we will have the three heavy neutrinos with masses $\sim$ EW

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

$$- \, \epsilon_{ab} \lambda^i \, \hat{\nu}_i^c \, \hat{H}_1^a \hat{H}_2^b + \frac{1}{3} \kappa^{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c ,$$



R-parity (+1 for particles and -1 for superpartners) is explicitly broken

Size of the breaking:

$Y_\nu \longrightarrow 0$ the ν_R are no longer neutrinos, they are just ordinary singlets like the **S** of the NMSSM:

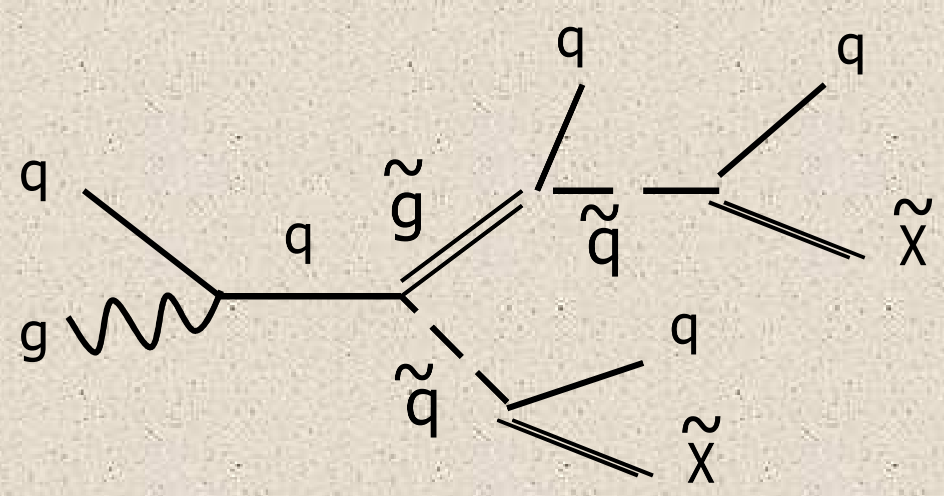
S $H_1 H_2$ + **SSS**, and R-parity is conserved

is small because the EW seesaw implies $Y_\nu \leq 10^{-6}$

Since R-parity is broken, the phenomenology of the μνSSM is going to be very different from the one of the MSSM/NMSSM

Needless to mention, the **LSP is no longer stable**(unlike the MSSM/NMSSM) since it decays to standard model particles

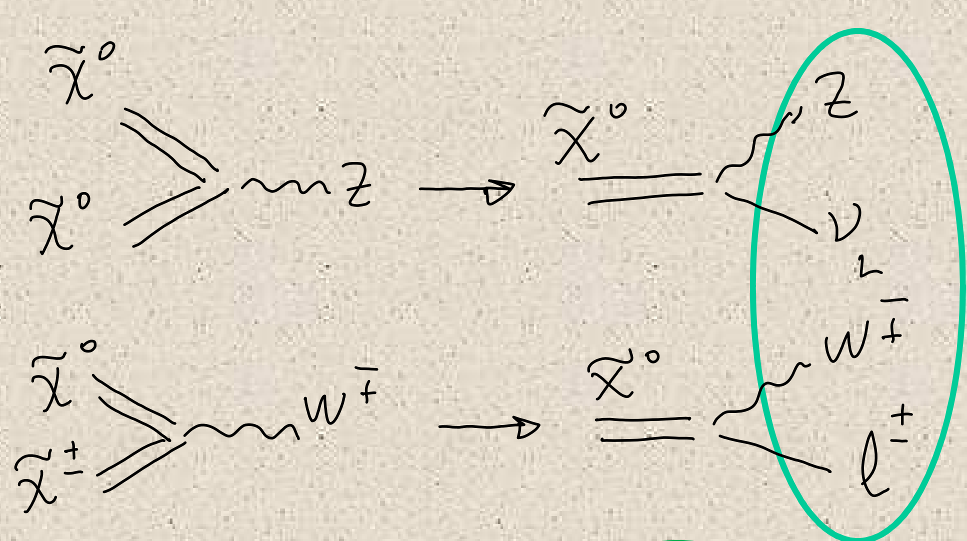
★ Therefore, not all SUSY chains must yield missing energy events at colliders:



* The neutralino-LSP may decay within the detectors but with a length large enough to show a displaced vertex

$m_{\tilde{\chi}^0} > m_W$

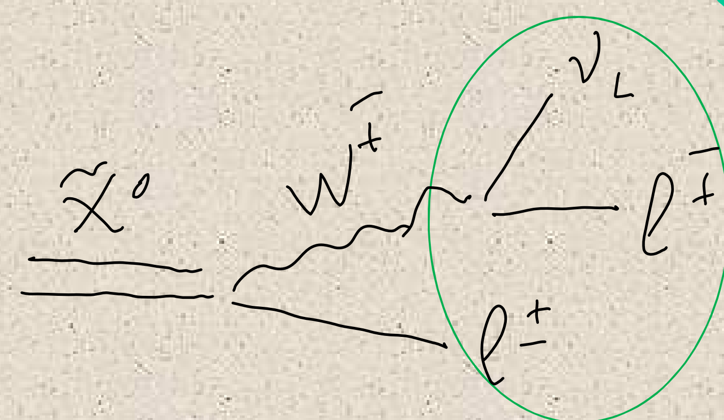
e.g. two-body decays



$L \propto \frac{1}{m_{\tilde{\chi}^0}}$

$m_{\tilde{\chi}^0} < m_W$

three-body decays e.g.



$L \propto \frac{1}{m^4_{\tilde{\chi}^0}}$

The decay lenght is basically determined by the mass of the neutralino LSP and the experimentally measured neutrino masses

Bartl, Hirsch, Vicente, Liebler, Porod, JHEP 05 (2009) 120

e.g.

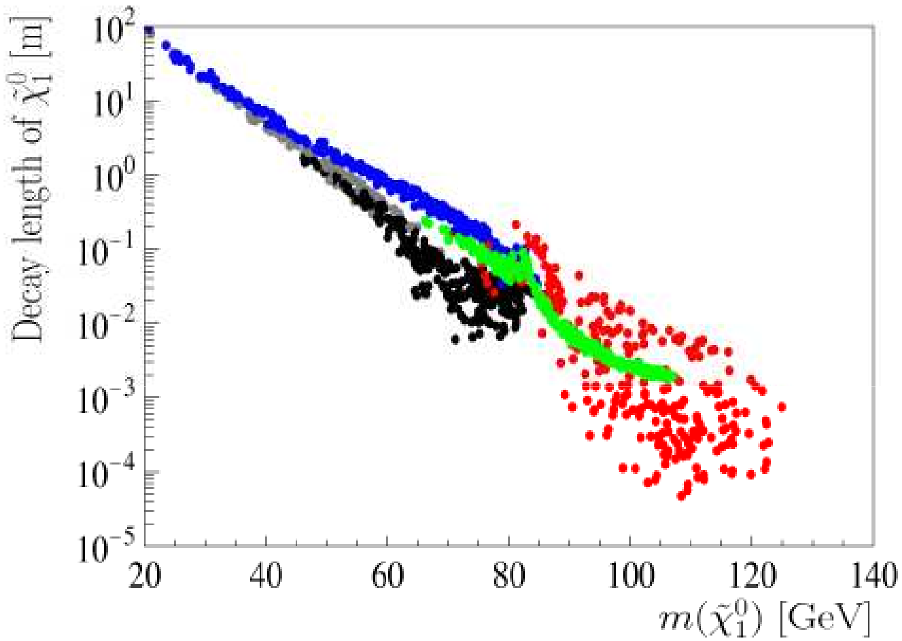


Figure 13: Decay length of the lightest neutralino $\tilde{\chi}_1^0$ in m as a function of its mass $m(\tilde{\chi}_1^0)$ in GeV for different values of $\lambda \in [0.2, 0.5]$, $\kappa \in [0.025, 0.2]$ and $\mu \in [110, 170]$GeV with a dependence of allowed $\kappa(\lambda)$ similar to [52] and to Figure 7 and $T_\lambda = \lambda \cdot 1.5$TeV, whereas $T_\kappa \in [-20, -0.05]$GeV is chosen in such a way, that no lighter scalar or pseudoscalar states with $\{m(S_1^0), m(P_1^0)\} < m(\tilde{\chi}_1^0)$ appear. Note that the different colors stand for SPS1a' (real singlino, $|\mathcal{N}_{45}|^2 > 0.5$) (gray), SPS1a' (mixture state) (black), SPS3 (real singlino) (blue), SPS3 (mixture state) (red) and SPS4 (mixture state) (green).

N. Escudero, D.E. Lopez-Fogliani, C. M., R. Ruiz de Austri, "Analysis of the parameter space and spectrum of the $\mu\nu$SSM ", JHEP 12 (2008) 099

Ghosh, Roy, "Neutrino masses and mixing, lightest neutralino decays and a solution to the μ problem in supersymmetry", JHEP 04 (2009) 069

Bartl, Hirsch, Vicente, Liebler, Porod, "LHC phenomenology of the $\mu\nu$SSM", JHEP 05 (2009) 120

Fidalgo, Lopez-Fogliani, C.M., Ruiz de Austri, "Neutrino physics and spontaneous CP violation in the $\mu\nu$SSM", JHEP 08 (2009) 105

Ghosh, Dey, Mukhopadhyaya, Roy, "Radiative contributions to neutrino masses and mixing in $\mu\nu$SSM", arXiv:1002.2705 [hep-ph]

Chung, Long, "Electroweak phase transition in the $\mu\nu$SSM", arXiv:1004.0942 [hep-ph]

* Neutrino physics: current data on neutrino masses and mixing angles can easily be reproduced (even with flavour diagonal neutrino Yukawa couplings)
* Spontaneous CP violation is possible. A complex MNS matrix can be present

* Decay of the lightest neutralino as LSP. Branching ratios show correlations with neutrino mixing angles, which can be tested at the LHC.

* The neutralino-LSP may decay within the detectors but with a length large enough to show a displaced vertex

* Parameter regions where electroweak phase transition is sufficiently strongly first order to realice electroweak baryogenesis

In models without R parity the **LSP** is no longer stable

Thus the neutralino or the sneutrino with very short lifetimes **cannot be used as candidates for dark matter**

Gravitino as a dark matter candidate in the $\mu\nu$SSM

K.Y. Choi, D.E. López-Fogliani, C. M., R. Ruiz de Austri, JCAP 03 (2010) 028

• Gravitino as a DM candidate in models where R-parity is broken

Takayama, Yamaguchi, 2000

The gravitino also decays through the interaction gravitino-photon-photino (λ):

$$L_{int} = -\frac{i}{8M_{pl}}\bar{\psi}_\mu[\gamma^\nu, \gamma^\rho]\gamma^\mu \lambda F_{\nu\rho},$$

due to the photino-neutrino mixing after sneutrinos develop VEVs , opening the channel

$$\Gamma(\psi_{3/2} \to \gamma\nu) = \frac{1}{32\pi}|U_{\tilde{\gamma}\nu}|^2 \frac{m_{3/2}^3}{{M_{\mathrm{P}}}^2} .$$

Nevertheless, it is supressed both by the Planck mass and the small R-parity breaking,

thus the lifetime of the gravitino can be longer than the age of the Universe (~10^{17} s)

$$\tau_{3/2} = \Gamma^{-1}(\tilde{G} \to \gamma\nu) \simeq 8.3 \times 10^{26}\,\mathrm{sec} \times \left(\frac{m_{3/2}}{1\mathrm{GeV}}\right)^{-3} \left(\frac{|U_{\gamma\nu}|^2}{7 \times 10^{-13}}\right)^{-1} .$$

DETECTION

- Decays of **gravitinos** in the galactic halo, at a sufficiently high rate, would produce gamma rays that could be detectable in future experiments

An experiment such as **FERMI**, launched two years ago, might in principle detect these gamma rays

Buchmuller, Covi, Hamaguchi, Ibarra, Yanagida, 07
Bertone, Buchmuller, Covi, Ibarra, 07
Ibarra, Tran, 08
Ishiwata, Matsumoto, Moroi, 08

Since the gravitino decays into a photon and neutrino, the former produces a monochromatic lines at energies equal to $\mathbf{m_{3/2}/2}$

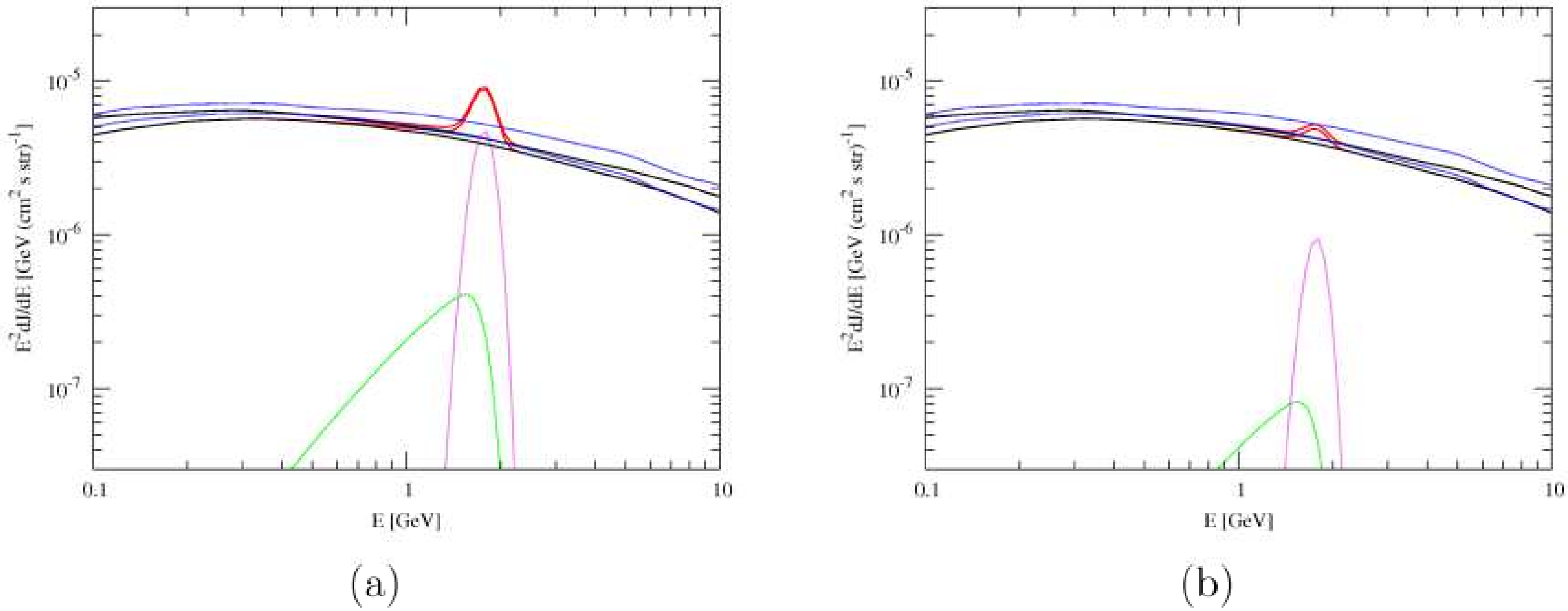


Figure 3: Expected gamma-ray spectrum for an example of gravitino dark matter decay in the mid-latitude range ($10^\circ \le |b| \le 20^\circ$) in the $\mu\nu$SSM with $m_{3/2} = 3.5\,\mathrm{GeV}$ and (a) $|U_{\tilde{\gamma}\nu}|^2 = 8.8 \times 10^{-15}$ corresponding to $\tau_{3/2} = 10^{27}$ s, (b) $|U_{\tilde{\gamma}\nu}|^2 = 1.7 \times 10^{-15}$ corresponding to $\tau_{3/2} = 5 \times 10^{27}$ s. The green dashed, magenta solid, and black solid lines correspond to the diffuse extragalactic gamma ray flux, the gamma-ray flux from the halo, and to the conventional background, respectively. The total gamma-ray flux is shown with red solid lines. The blue solid lines are explained in the note added in Sect. 6.

$$|U_{\tilde{\gamma}\nu}|^2 = \sum_{i=1}^{3} |N_{i1}\cos(\theta_W) + N_{i2}\sin(\theta_W)|^2,$$

with N_{i1} (N_{i2}) the Bino (Wino) composition of the i-neutrino

$U \sim g_1\, \nu/M_1 \sim 10^{-6} - 10^{-8}$

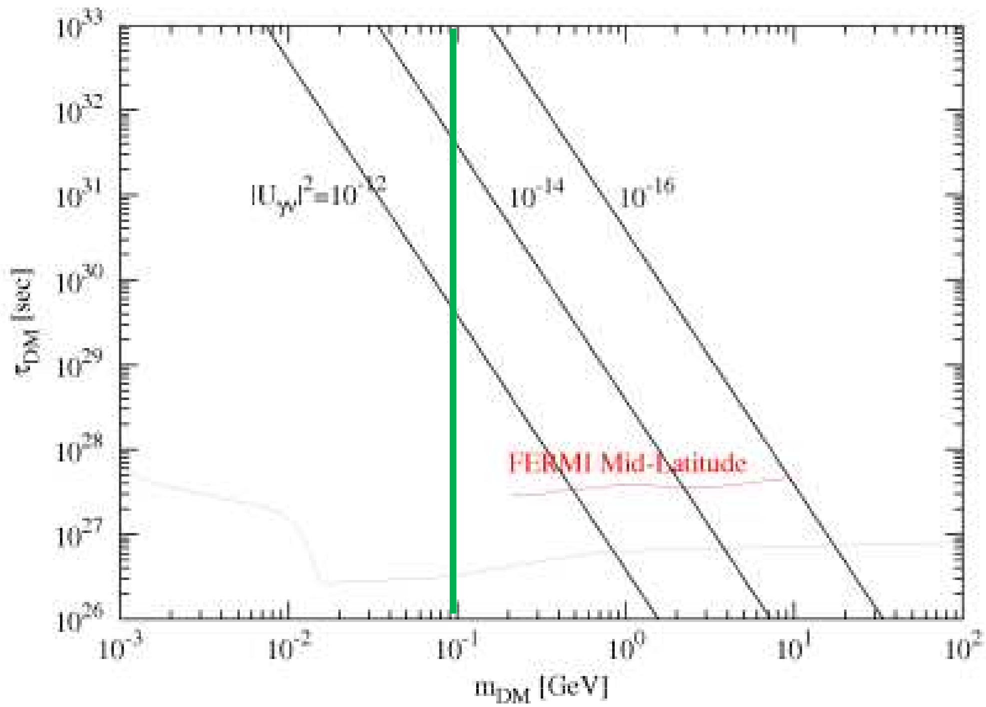


Figure 5: Constraints on lifetime versus mass for gravitino dark matter in the $\mu\nu$SSM. The region below the magenta solid line is excluded by several gamma-ray observations [29]. The region below the red solid line is disfavoured by FERMI. Black solid lines correspond to the predictions of the $\mu\nu$SSM for several representatives values of $|U_{\tilde{\gamma}\nu}|^2 = 10^{-16} - 10^{-12}$.

Values of the gravitino mass larger than 10 GeV are disfavoured, as well as lifetimes smaller than about (3-5) x 10^{27} s.

Conclusions

There are very interesting models of new physics:

MSSM which introduces a bunch of new particles
NMSSM which solves the μ problem of the **MSSM** introducing an extra singlet

The neutralino or sneutrino are candidates for dark matter

$\mu\nu$**SSM** which solves the μ problem and explains the origin of neutrino masses by simply using right-handed neutrinos

The phenomenology of this model is very rich and still starting to be Investigated

The gravitino can be a candidate for dark matter

THE END