Models of Supersymmetry for Dark Matter

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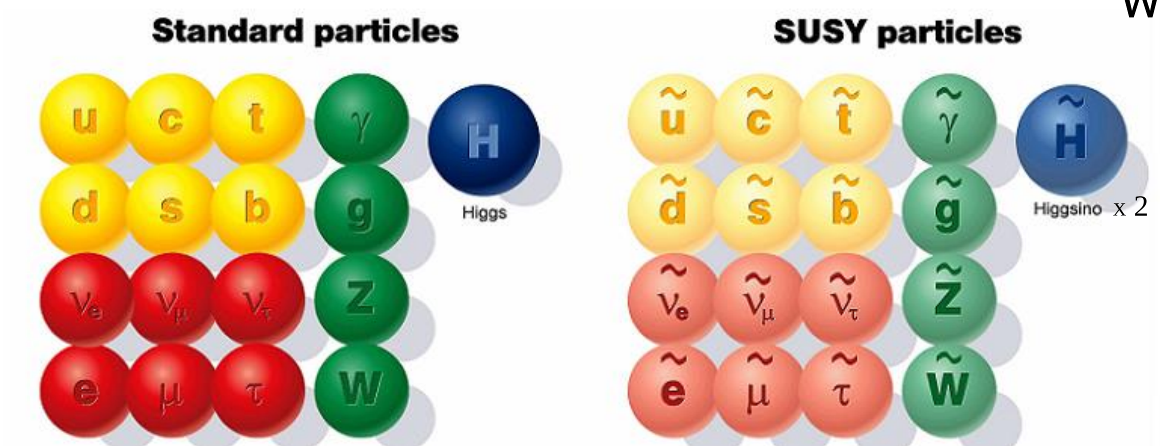
MultiDark Multimessenger Approach for Dark Matter Detection

RICAP 2016, Frascati, June 22-24

In **SUSY**, the spectrum of elementary particles is doubled

with masses ≈ 1 TeV

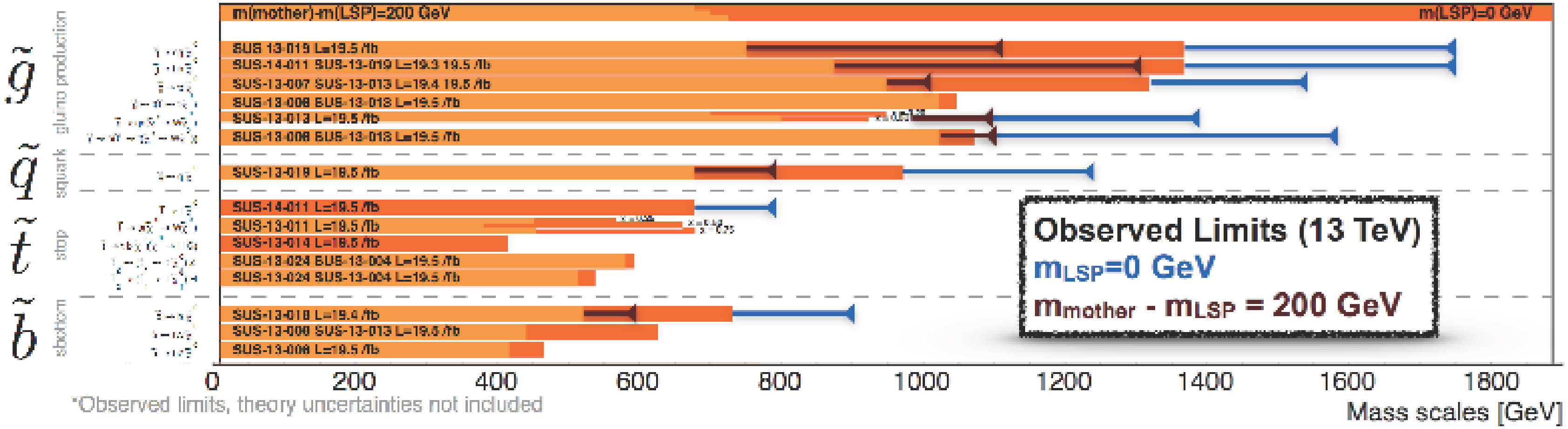


Thus even the simplest SUSY model,

The Minimal Supersymmetric Standard Model
MSSM ,
predicts a rich phenomenology

But... is SUSY still alive?

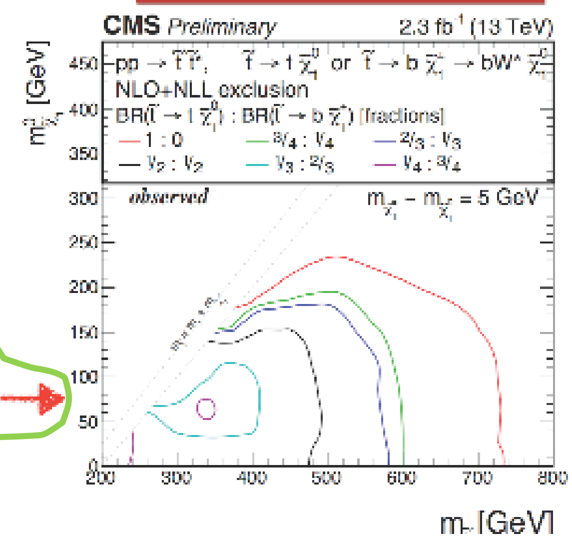
SuSy searches: final comments



- With Run2 we are already surpassing Run1 limits:
  - gluino limits reached 1.8 TeV
  - Squark limits reached ~1 TeV (stop ~0.8TeV)
- New strategies adopted to explores compresses spectrum regions (even though trigger is a problem)

CAVEAT: simplified models are good benchmarks but they don't cover full SuSy phase space (BR variation, degenerate masses, etc.). We are not even close to declare SuSy dead.

Limits degrade if stop as $\tilde{t} \to b\chi_1^{\pm}$ BF increases

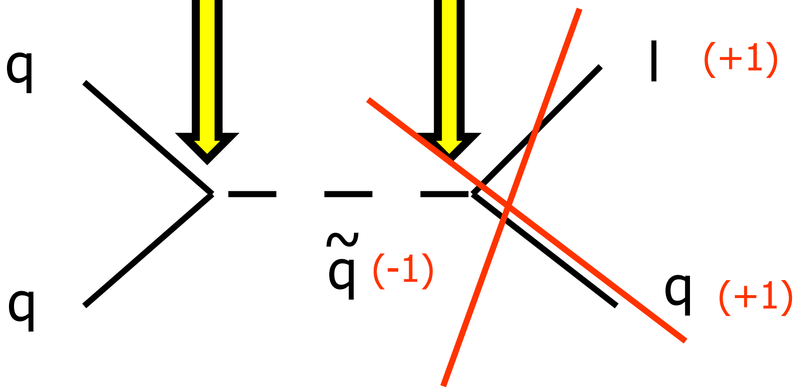


L. Malgeri - Run 2 Physics - 7/04/2016

IMFP, Madrid

- **Nevertheless, from theoretical viewpoint, by construction, the MSSM produce too fast proton decay**

Operators like $\hat{d}^c\hat{d}^c\hat{u}^c$, $\hat{Q}\hat{L}\hat{d}^c$, $\hat{L}\hat{L}\hat{e}^c$, $\hat{L}\hat{H}_u$ violating Baryon and Lepton number are allowed in the superpotential



To conserve B and L number, one can impose a discrete symmetry (**R parity**)

Particle ⟶ Particle

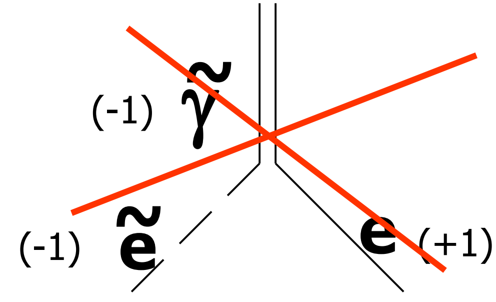
Superpartner ⟶ − Superpartner

i.e. superparticles must appear in pairs

Notice that this (conservative) approach forbids all couplings

In models with RPC the **LSP** is stable since:

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



So, once eliminated (**ALL**) B and L number violating operators, we are left with the superpotential of the **MSSM**:

$$W = Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c \;+ \mu\,\hat{H}_1\,\hat{H}_2$$

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

- **Here we find another problem of SUSY models**

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

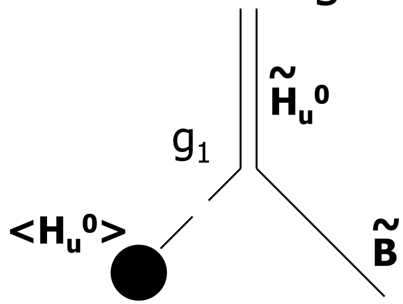
The **MSSM** does not solve the **μ** problem

one takes for granted that the **μ term is there and ~ M_w , and that's it**

in this sense the **MSSM** is a kind of effective theory

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

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

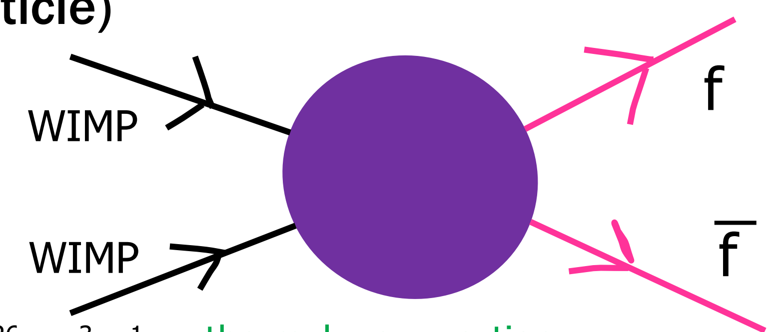
$$\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

- It is a neutral particle, otherwise it would bind with nuclei and would be excluded from unsuccessful searches for exotic heavy isotopes
- 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:

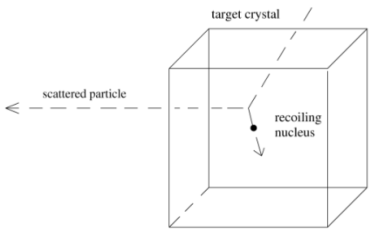
$$\Omega_{WIMP} h^2 \sim \frac{3 \times 10^{-27}\ \mathrm{cm^3\ s^{-1}}}{\sigma_{ann} v} \sim 0.1$$

$\sigma_{ann} = \sigma_{weak}$

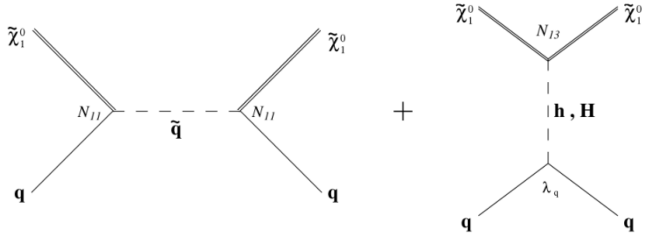


$\sigma_{ann} v \sim 3 \times 10^{-26}\ \mathrm{cm^3\ s^{-1}}$ thermal cross section

DIRECT DETECTION



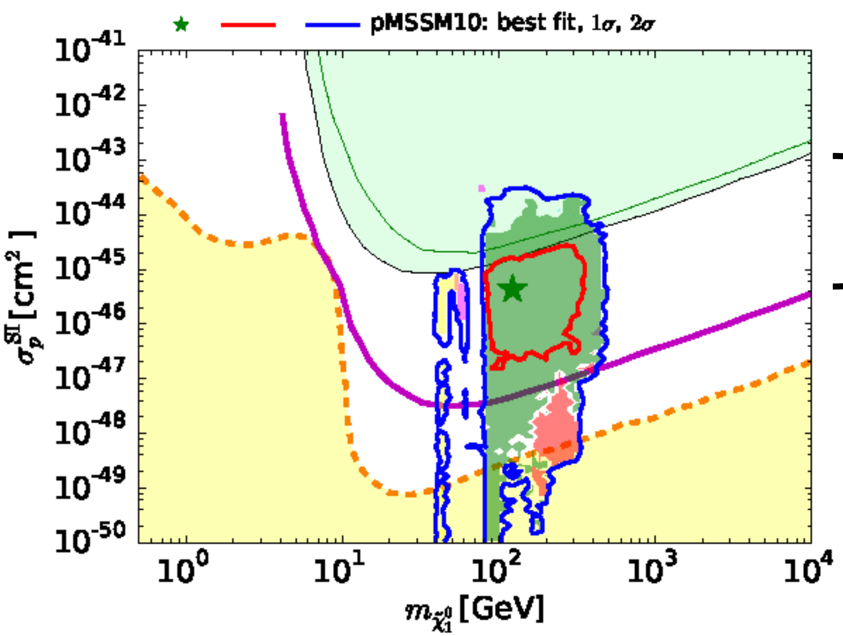
MSSM



In view of the LHC1 constraints on SUSY, Higgs data, flavour physics observables,

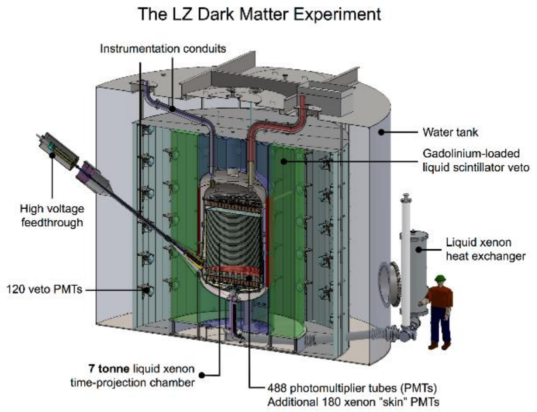
in the phenomenological MSSM (pMSSM) with 10 independent parameters,

M_a , m_α , A_α , $\tan\beta$, μ, one obtains for neutralino DM

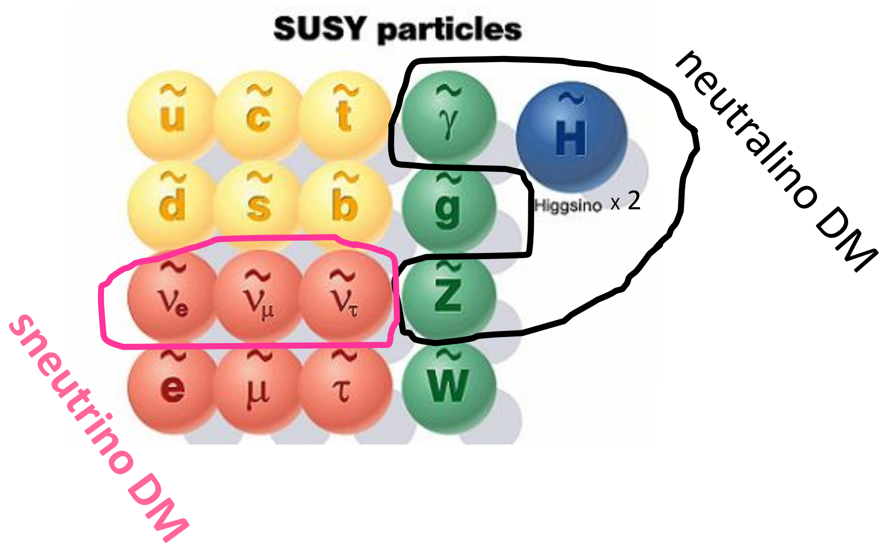


Bagnaschi et al., 2015

Future experiments will explore larger regions of the parameter space



Are there other candidates for DM in SUSY models?



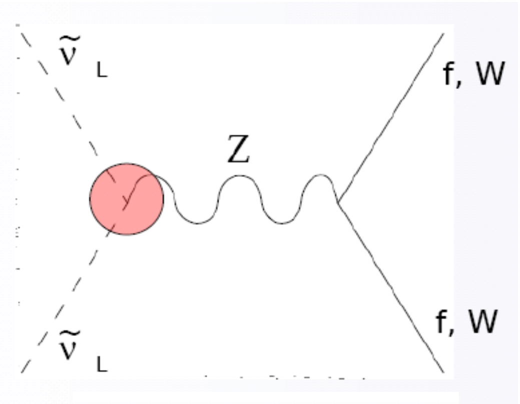
Left-handed sneutrino DM in the MSSM

(Ibáñez '84; Hagelin, Kane, Rabi '84)

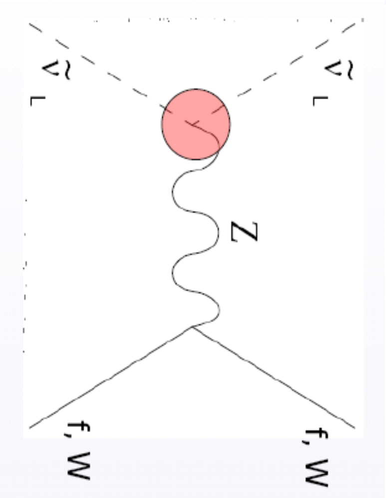
In the MSSM there are only lef-handed sneutrinos:

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

(left-handed) sneutrino 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)

IS THERE LIFE BEYOND THE MSSM/NEUTRALINO DM ?

NMSSM

The μ-problem, $W = \ldots + \mu \hat{H}_u \hat{H}_d$, is solved in the Next-to-MSSM introducing an extra singlet superfield:

$$\mu \hat{H}_1 \hat{H}_2 \longrightarrow \lambda \hat{N} \hat{H}_1 \hat{H}_2 \quad \Rightarrow \quad \mu_{eff} = \lambda \langle N \rangle$$

- NMSSM has a richer and more complex phenomenology:

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

Neutralino DM is viable

Right-handed sneutrino DM in the (extended) NMSSM

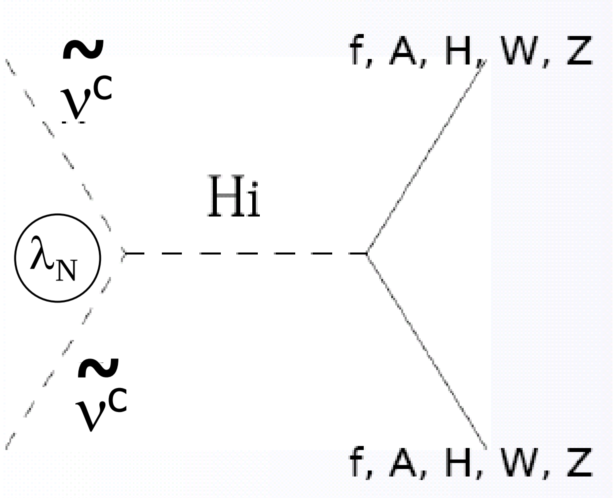
$$W = \epsilon_{ab} \left(Y_u^{ij} \hat{H}_2^b \hat{Q}_i^a \hat{u}_j^c + Y_d^{ij} \hat{H}_1^a \hat{Q}_i^b \hat{d}_j^c + Y_e^{ij} \hat{H}_1^a \hat{L}_i^b \hat{e}_j^c + Y_\nu^{ij} \hat{H}_2^b \hat{L}_i^a \hat{\nu}_j^c \right)$$

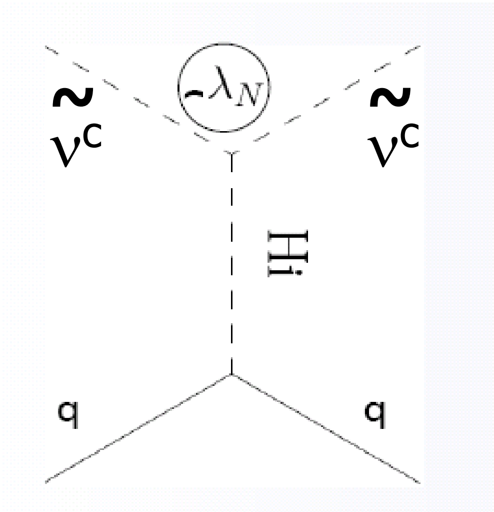
$$+ \lambda \hat{N} \hat{H}_1 \hat{H}_2 + k \hat{N} \hat{N} \hat{N} + \lambda_N \hat{N} \hat{\nu}^c \hat{\nu}^c$$

Note that in the MSSM a purely right-handed sneutrino LSP implies a scattering cross section too small (suppressed by Y_ν), and a 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

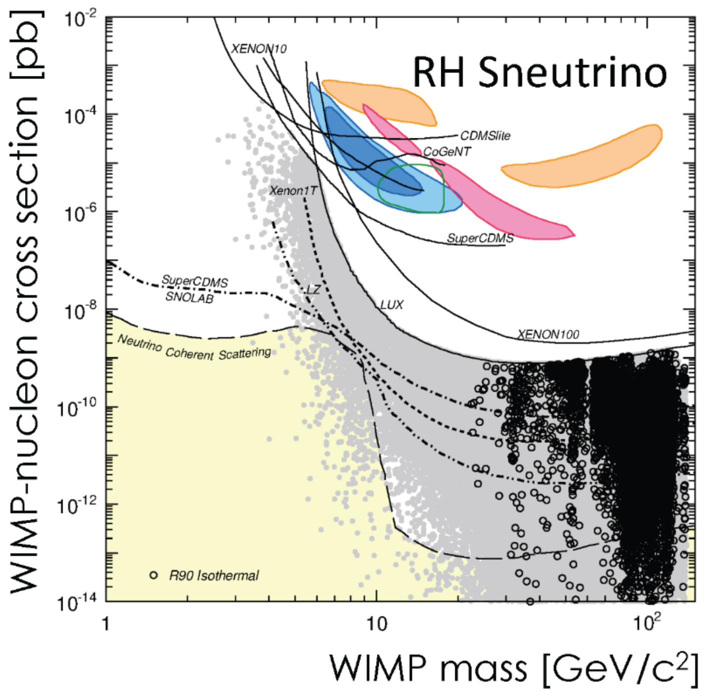


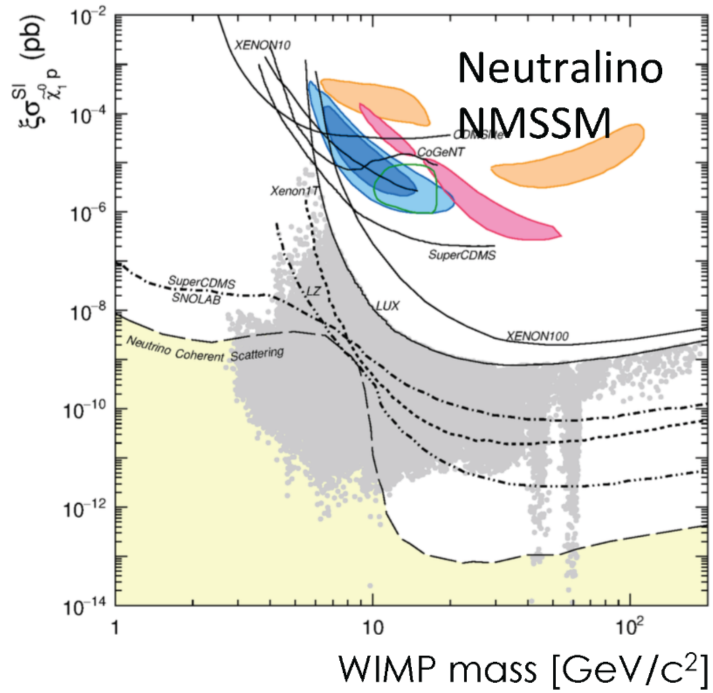


Neutralino and Right-handed sneutrino in the NMSSM

Extensions of the MSSM can be more flexible (new light mediators)

Low-mass SUSY WIMPs are still viable (1-100 GeV)



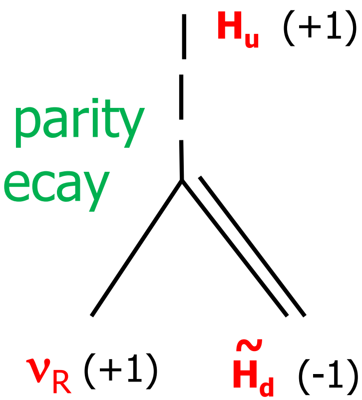


DGC, Peiró, Robles JCAP 08 (2014) 005
DGC, Peiró Robles, 2015

IS THERE LIFE
BEYOND R-PARITY CONSERVATION/NEUTRALINO-SNEUTRINO DM ?

TRPV: $\lambda_{ijk}\, \hat{L}_i \hat{L}_j \hat{e}^c_k$, $\lambda'_{ijk}\, \hat{L}_i \hat{Q}_j \hat{d}^c_k$, $\lambda''_{ijk}\, \hat{d}^c_i \hat{d}^c_j \hat{u}^c_k$, BRPV: $\varepsilon_i\, \hat{H}_u \hat{L}_i$ are allowed in the superpotential

$\lambda_i\, \hat{\nu}_{Ri} \hat{H}_u \hat{H}_d \;+\; \kappa_{ijk}\, \hat{\nu}_{Ri} \hat{\nu}_{Rj} \hat{\nu}_{Rk}$ are also allowed, break R parity are harmless for proton decay



However, R-parity forbids all these terms

But the choice of R-parity is *ad hoc.*

There are other symmetries that forbid some of these terms, but others are allowed

Also stringy selection rules:

- particles are attached to different sectors in the compact space

- or they have extra U(1) charges

d^c (3, 1, 1/3, -, -, -, -, -, -, -)
d^c (3, 1, 1/3, -, -, -, -, -, -, -)
u^c (3, 1, -2/3, -, -, -, -, -, -, -)

e.g. the sum of U(1) charges might imply ~~$\hat{d}^c \hat{d}^c \hat{u}^c$~~

But e.g. $\lambda_i\, \hat{\nu}_{Ri} \hat{H}_u \hat{H}_d$ might be allowed

So one can work with different combinations of RPV terms:

$$W = W_{MSSM} + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{e}^c_k + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{d}^c_k + \lambda''_{ijk} \hat{d}^c_i \hat{d}^c_j \hat{u}^c_k$$

$$W = W_{MSSM} + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{e}^c_k + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{d}^c_k + \lambda''_{ijk} \hat{d}^c_i \hat{d}^c_j \hat{u}^c_k$$

$$W = W_{MSSM} + \varepsilon_i \hat{H}_u \hat{L}_i$$

$$\mu \hat{H}_u \hat{H}_d$$

$$W_{\mu\nu SSM} = \lambda_i \hat{\nu}_{Ri} \hat{H}_u \hat{H}_d + \kappa_{ijk} \hat{\nu}_{Ri} \hat{\nu}_{Rj} \hat{\nu}_{Rk}$$

Lopez-Fogliani, C. M., PRL 2006

When the RH sneutrinos $\tilde{\nu}_R$ acquire VEVs of order the EW scale, an effective μ-term from ν is generated

as well as effective Majorana masses for neutrinos: EW scale seesaw

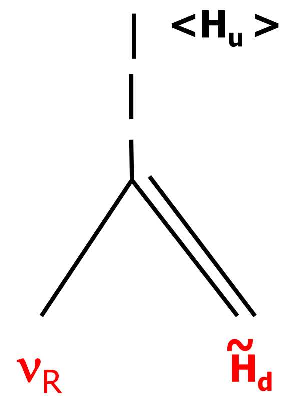
$$m_\nu \sim m_D^2/M_M = (Y_\nu v_u)^2/(\kappa \nu_R) \sim (10^{-6}\, 10^2)^2/10^3 = 10^{-11}\text{ GeV} = 10^{-2}\text{ eV}$$

$Y_\nu \; H_u L \nu_R$

Y_ν ~ the electron Yukawa

RPV couplings generate larger mass matrices than those of RPC models such as MSSM or NMSSM, since EWSB implies that the neutral scalars develop VEVs:

$<H_u^0> = v_u \quad <H_d^0> = v_d \qquad \langle \tilde{\nu}_i \rangle = \nu_i \qquad \langle \tilde{\nu}_i^c \rangle = \nu_i^c$



"Neutralinos"

$$\chi^{0T} = (\tilde{B}^0, \tilde{W}^0, \tilde{H}_d, \tilde{H}_u, \nu_{R_i}, \nu_{L_i}),$$

$$\underbrace{\tilde{B}^0, \tilde{W}^0, \tilde{H}_d, \tilde{H}_u, \nu_{R_i}}_{\tilde{\chi}^0_{4,5,6,7,8,9,10}}, \quad \underbrace{\nu_{L_i}}_{\tilde{\chi}^0_{1,2,3}}$$

"Charginos"

$$\Psi^{+T} = (-i\tilde{\lambda}^+, \tilde{H}_u^+, e_R^+, \mu_R^+, \tau_R^+)$$

$$\underbrace{-i\tilde{\lambda}^+, \tilde{H}_u^+}_{\tilde{\chi}^+_{1,2}}$$

"Neutral Higgses"

$$\mathbf{S}'_\alpha = (h_d, h_u, (\widetilde{\nu}_i^c)^R, (\widetilde{\nu}_i)^R) \qquad \mathbf{P}'_\alpha = (P_d, P_u, (\widetilde{\nu}_i^c)^I, (\widetilde{\nu}_i)^I)$$

$$h_{4,5} \equiv h, H \;,\; h_{1,2,3} \;,\; h_{6,7,8} \qquad P_4 \equiv A \;,\; P_{1,2,3} \;,\; P_{5,6,7}$$

"Charged Higgses"

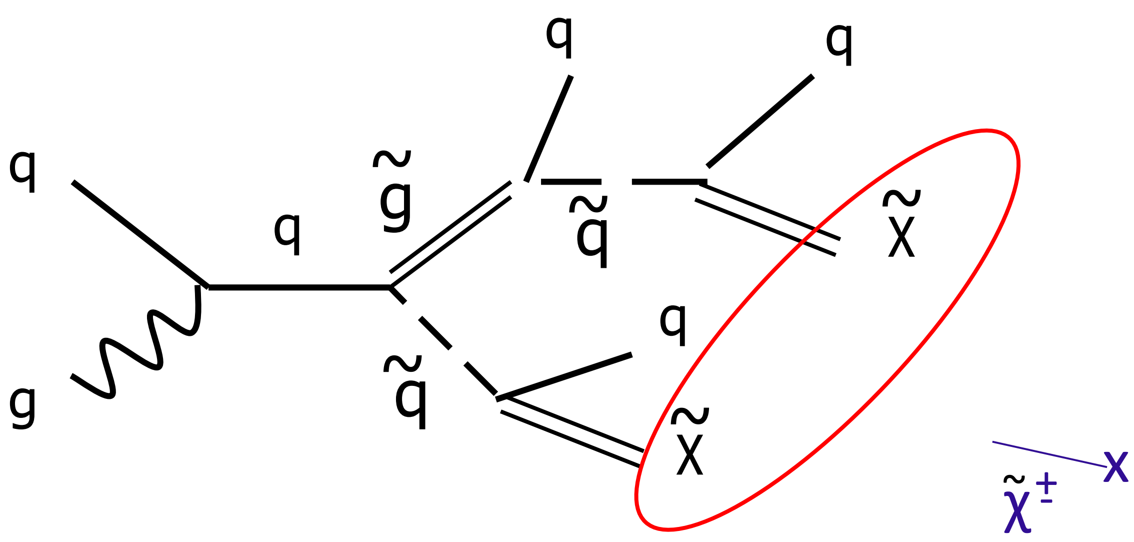
$$\mathbf{S}'^{+}_\alpha = (H_d^+, H_u^+, \tilde{e}_L^+, \tilde{\mu}_L^+, \tilde{\tau}_L^+, \tilde{e}_R^+, \mu_R^+, \tau_R^+),$$

$$\underbrace{H_d^+, H_u^+}_{H^+}$$

After several years of LHC running, direct searches of SUSY based mainly on the existence of missing energy in the final state have failed to find a signal that exceeds the SM background

Time for experimentalists to look for RPV SUSY in detail ?

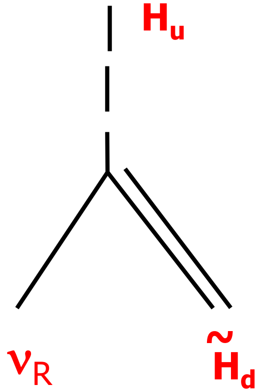
★ RPV can hide SUSY by removing the usual missing energy signatures



★ RPV can produce displaced vertices, multilepton final states,…

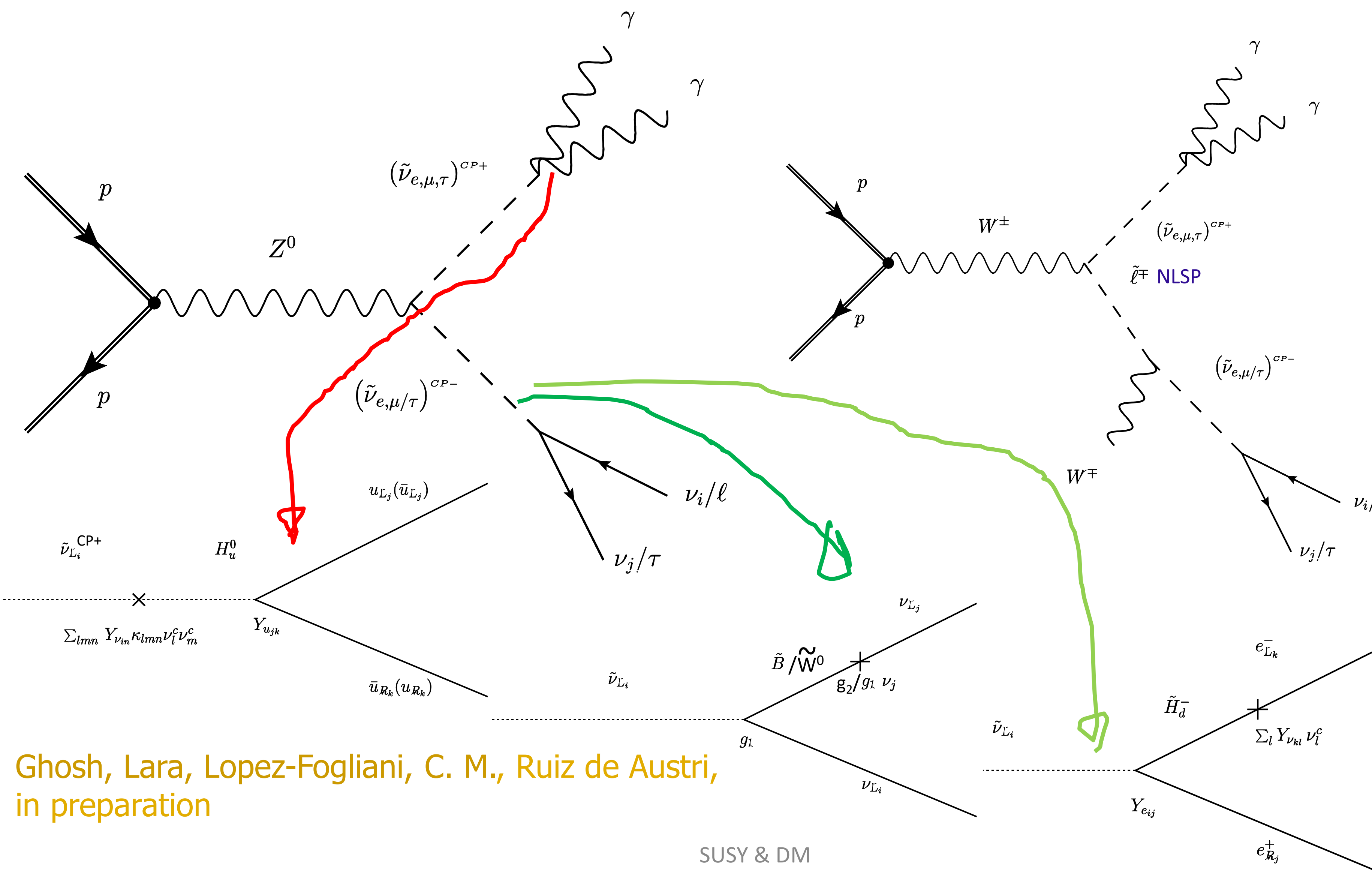
★ Besides, all particles, not only the neutral ones, are potential LSP's
stau, squark, chargino,..., sneutrino

because the LSP is not stable, decaying into two SM particles



Thus the problem of stable charged particles as DM is not present:

e.g. in the μνSSM a left-handed sneutrino LSP with a mass ~ 90-150 GeV will produce for $\mathcal{L}$= 300 fb^{-1} a detectable number of events with diphoton + leptons/missing energy



Ghosh, Lara, Lopez-Fogliani, C. M., Ruiz de Austri, in preparation

Gravitino DM in models with RPV

- The **LSP** is no longer stable since it can decay into SM particles

Thus the neutralino or the sneutrino cannot be used as candidates for DM

- Nevertheless, the gravitino can be a (decaying) DM candidate

The gravitino LSP in RPV decays due to the photino-neutrino mixing, opening the channel

Takayama, Yamaguchi, 2000

In supergravity

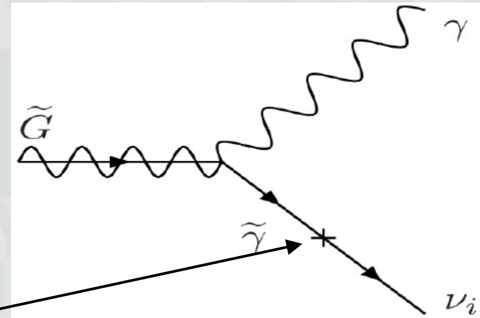
$$L_{int} = -\frac{i}{8M_{pl}}\bar{\psi}_\mu[\gamma^\nu,\gamma^\rho]\gamma^\mu\lambda F_{\nu\rho},$$

$\tilde{B}$

g_1

$\langle\tilde{\nu}\cdot\rangle = \nu$

ν



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

The decay width is supressed both by the Planck mass and the R-parity breaking, which is expected to be very small:

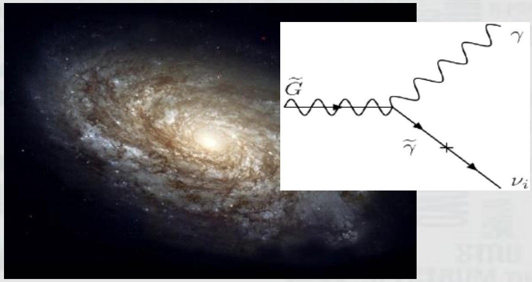
$|U_{\tilde{\gamma}\nu}|^2 \sim |\, g_1\ \nu/M_1\,|^2 \sim 10^{-14} - 10^{-15}$

Since $\nu \sim 10^{-4}$ GeV because its minimization equation contains the small Yukawa $Y_\nu \sim 10^{-6}$ in order to reproduce neutrino data

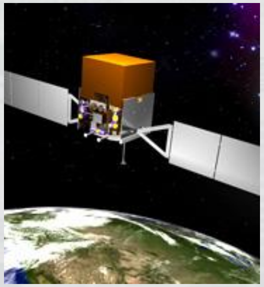
Thus the lifetime can be longer than the age of the Universe ($\sim 10^{17}$ s), and the gravitino can be a good DM candidate

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

Detection of gravitino DM



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



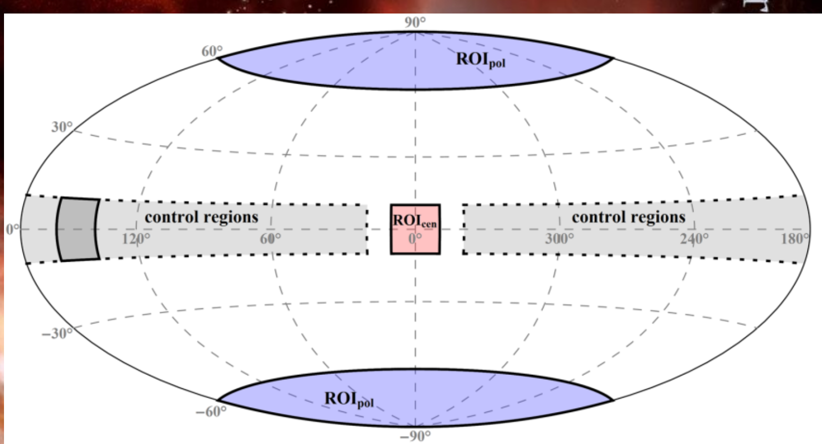
***Fermi* Large Area Telescope (LAT)**, might in principle detect this flux of gamma rays predicted in RPV models with gravitino DM

Buchmuller, Covi, Hamaguchi, Ibarra, Yanagida, 07; Bertone, Buchmuller, Covi, Ibarra, 07
Ibarra, Tran, 08 ; Ishiwata, Matsumoto, Moroi, 08
Choi, López-Fogliani, C.M., Ruiz de Austri, 09
Choi, Yaguna, 10; Choi, Restrepo, Yaguna, Zapata, 10 ; Diaz, García Saenz, Koch, 11
Restrepo, Taoso, Valle, Zapata, 11
Gómez-Vargas, Fornasa, Zandanel, Cuesta, C.M., Prada, Yepes, 11

$$\left[E^2 \frac{dJ}{dE}\right]_{\rm halo} = \frac{2E^2}{m_{3/2}} \frac{dN_\gamma}{dE} \frac{1}{8\pi\tau_{3/2}} \int_{\rm los} \rho_{\rm halo}(\vec{l})d\vec{l}\,,$$

particle physics — astrophysics

Since a gravitino decays into a photon (and a neutrino), this produces a line at energies equal to $\mathbf{m_{3/2}/2}$



Fermi
Gamma-ray Space Telescope

MultiDark
Multimessenger Approach for Dark Matter Detection

More recently, together with Fermi-LAT collaborators we performed the following:

Search for 100 MeV to 10 GeV γ-ray lines in the *Fermi*-LAT data and implications for gravitino dark matter in the μνSSM

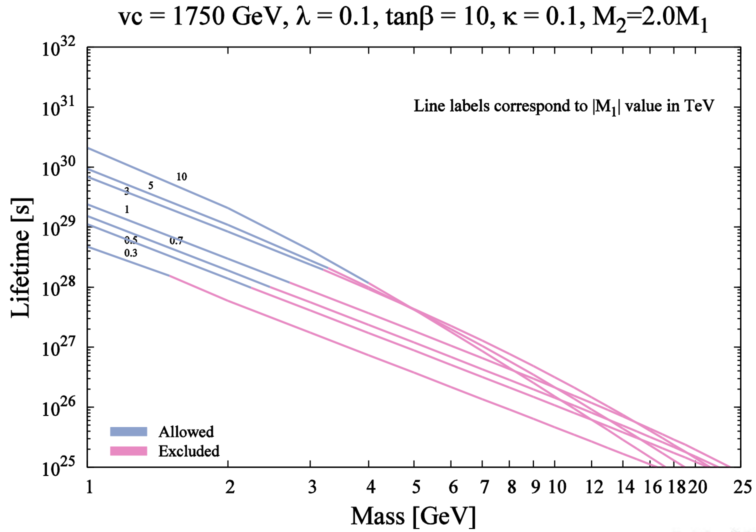
arXiv:1406.3430 [astro-ph.HE], ***JCAP* 10 (2014) 023**

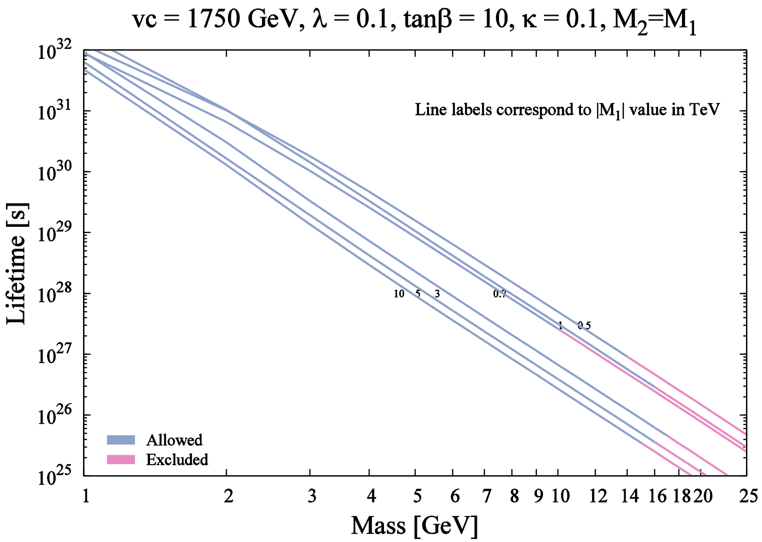
Category II paper:
-*Fermi*-LAT Collaboration: Albert, Bloom, Charles, Gómez-Vargas, Mazziotta, Morselli
External authors: C. M., Grefe, Weniger

Constraining $m_{3/2}$ and gravitino lifetime

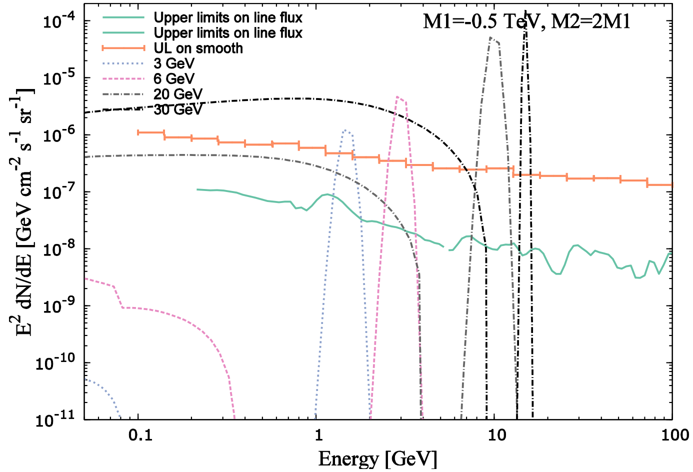
Results updated with 5.8 years of data from Fermi LAT

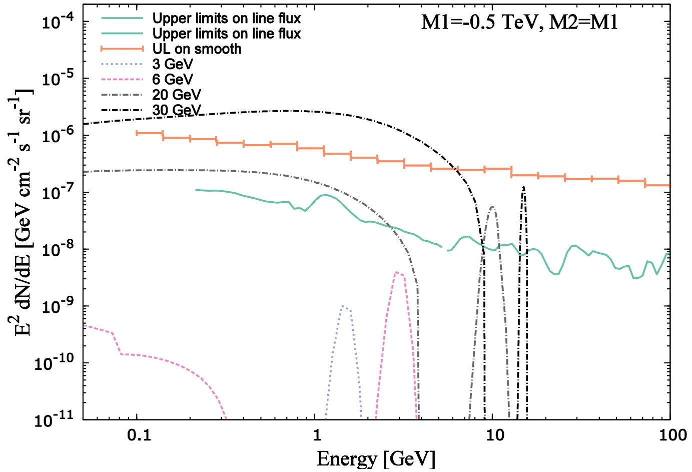
Gómez-Vargas, López-Fogliani, C.M., Perez, Ruiz de Austri, in preparation





$$|U_{\tilde{\gamma}\nu}| \approx \frac{M_Z(M_2 - M_1)s_W c_W}{(M_1 c_w^2 + M_2 s_w^2)(M_1 s_W^2 + M_2 c_W^2)},$$





If the gravitino is the DM: $m_{3/2} < 20$ GeV

Conclusions

THE END

There are interesting models of SUSY for DM:

MSSM introduces a bunch of new particles

NMSSM solves the μ problem of the **MSSM** introducing an extra singlet $\lambda \hat{N} \hat{H}_1 \hat{H}_2 + \lambda_N \hat{N} \hat{\nu}^c \hat{\nu}^c$

The neutralino or RH sneutrino are candidates for DM

If RPV is allowed

very rich phenomenology: displaced vertices, multi-lepton/jet events

TRPV, BRPV

$\mu\nu$SSM solves the μ problem and explains the origin of neutrino masses using right-handed neutrinos $\hat{\nu}^c_i \, \hat{H}^a_1 \hat{H}^b_2$

The gravitino can be a candidate for DM with $m_{3/2} < 20$ GeV