# Lier deux domaines de recherche actuelle en physique : la supersymétrie et la matière noire

Jonathan Da Silva

Laboratoire d'Annecy-le-Vieux de Physique Théorique

Journées de Rencontre Jeunes Chercheurs 2011,
Annecy, 4 - 10 Décembre 2011

G. Bélanger, J. Da Silva and A. Pukhov, arXiv:1110.2414 [hep-ph], soon on JCAP

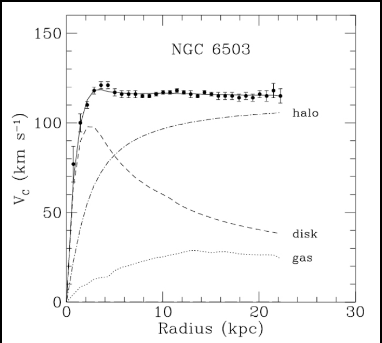
# Outline

# Motivations

# Need of dark matter

Since 1933 and Zwicky observations, we accumulated evidences for dark matter existence :

- Galaxy scale : rotation curves of galaxies




K. G. Begeman, A. H. Broeils and R. H. Sanders, 1991, MNRAS, 249, 523

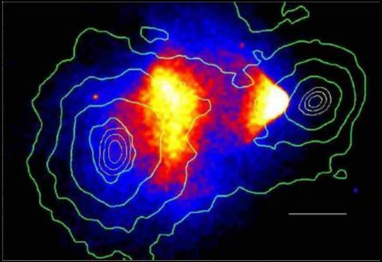
Circular velocity $v(r) = \sqrt{\frac{GM(r)}{r}}$ expected to fall in $\frac{1}{\sqrt{r}}$, observed approximately constant

$\Rightarrow$ need of a halo with $M(r)\ \alpha\ r$

# Need of dark matter

Since 1933 and Zwicky observations, we accumulated evidences for dark matter existence :

- Galaxy clusters scale : example of the bullet cluster



A direct empirical proof of the existence of dark matter, D. Clowe et al., astro-ph/0608407

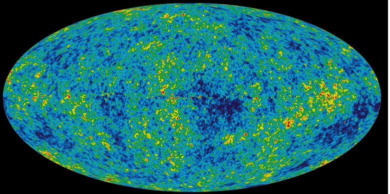
Study of X-rays and gravitational lensing effect of this cluster : discrepancy between baryonic matter and gravitational potential

$\Rightarrow$ non-negligible non-colliding component of clusters

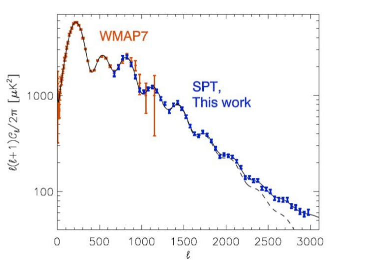
# Need of dark matter

Since 1933 and Zwicky observations, we accumulated evidences for dark matter existence :

- Cosmological scale : the Cosmic Microwave background (CMB)

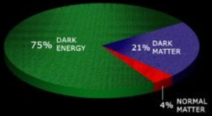


WMAP7




SPT

The aim is to match the CMB power spectrum with some fixed parameters of a cosmological model $\Rightarrow \Omega_b h^2 = 0.0226 \pm 0.0005$ and $\Omega_m h^2 = 0.1123 \pm 0.0035$

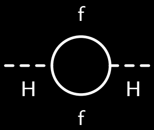



DM has to be stable and weakly charged under the standard model gauge group
Conservation of DM structures $\Rightarrow$ warm or cold DM

# Need of supersymmetry

# Need of supersymmetry

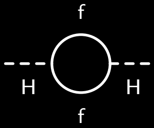
- Hierarchy problem of the Higgs mass : no symmetry protects Higgs mass




$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 + ...$$

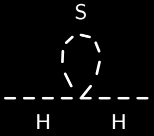
# Need of supersymmetry

- Hierarchy problem of the Higgs mass : no symmetry protects Higgs mass




$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 + ...$$

$\Rightarrow$ Supersymmetry, symmetry between fermions and bosons plays this role by adding one-loop corrections :

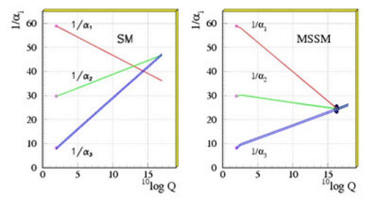



$$\Delta m_H^2 = \frac{|\lambda_S|^2}{16\pi^2}\Lambda^2 + ...$$

$\Rightarrow$ Cancellation of quadratic divergence

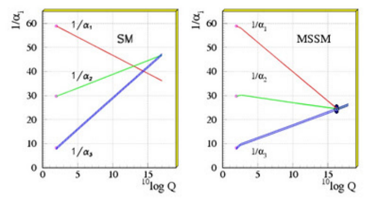
# Need of supersymmetry

- Unification of coupling at GUT scale :



# Need of supersymmetry

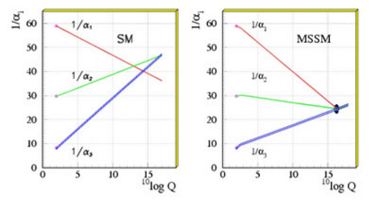
- Unification of coupling at GUT scale :



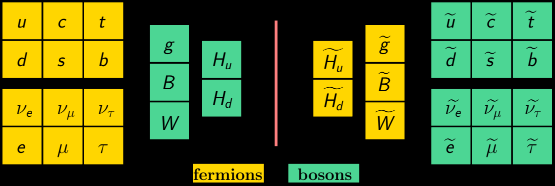

$\Rightarrow$ Easy in supersymmetry ! !

# Need of supersymmetry

- Unification of coupling at GUT scale :




$\Rightarrow$ Easy in supersymmetry ! !



# Need of supersymmetry

- Decay of proton in supersymmetry ⇒ need of R-Parity $P_R = (-1)^{3(B-L)+2s}$

  ⇒ Lightest supersymmetric particle (LSP) is stable

# Need of supersymmetry

- Decay of proton in supersymmetry ⇒ need of R-Parity $P_R = (-1)^{3(B-L)+2s}$

⇒ Lightest supersymmetric particle (LSP) is stable

Some of them are weakly charged, so ...

DM candidates in supersymmetric models ! ! !

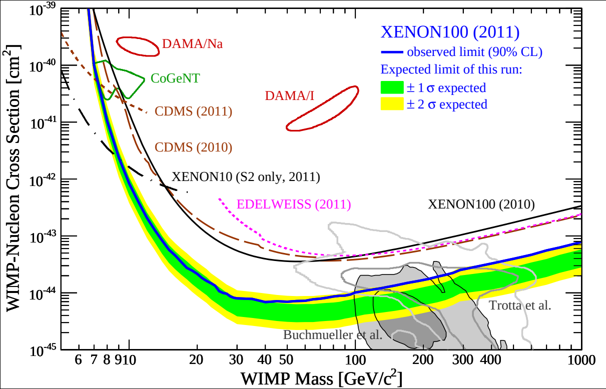
# Candidates

# Some candidates

- Assuming R-parity, 2 cold DM (WIMPs) candidates in the MSSM :
  - Lightest neutralino : a lot of studies ⇒ good DM candidate

# Some candidates

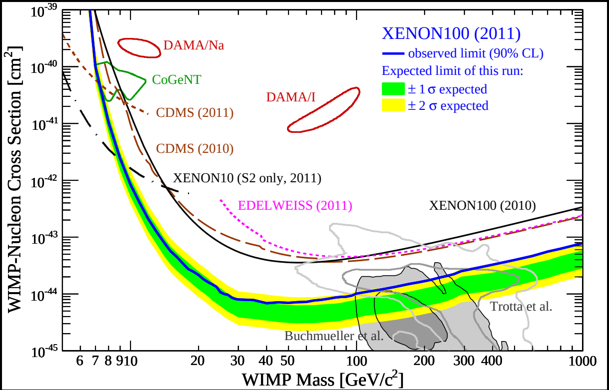
- Assuming R-parity, 2 cold DM (WIMPs) candidates in the MSSM :
  - Lightest neutralino : a lot of studies ⇒ good DM candidate
  - Left-handed (LH) sneutrino : too high coupling with $Z^0$ ⇒ don't satisfy experimental constraints on spin independent direct detection cross section ⇒ bad DM candidate




E. Aprile et al.,arXiv :1104.2549 [astro-ph.CO]

# Some candidates

- Assuming R-parity, 2 cold DM (WIMPs) candidates in the MSSM :
  - Lightest neutralino : a lot of studies ⇒ good DM candidate
  - Left-handed (LH) sneutrino : too high coupling with $Z^0$ ⇒ don't satisfy experimental constraints on spin independent direct detection cross section ⇒ bad DM candidate




E. Aprile et al.,arXiv :1104.2549 [astro-ph.CO]

- Others SUSY candidates to DM : Gravitino, axino, ...

# Case of sneutrinos

# Case of sneutrinos

- Neutrino oscillations indicative of massive neutrinos $\Rightarrow$ possibility to add a right-handed (RH) neutrino field

# Case of sneutrinos

- Neutrino oscillations indicative of massive neutrinos $\Rightarrow$ possibility to add a right-handed (RH) neutrino field
  $\Rightarrow$ Extensions of the MSSM with RH (s)neutrino can provide DM candidate

# Case of sneutrinos

- Neutrino oscillations indicative of massive neutrinos $\Rightarrow$ possibility to add a right-handed (RH) neutrino field
  $\Rightarrow$ Extensions of the MSSM with RH (s)neutrino can provide DM candidate

- Different mechanisms appear to obtain sneutrino DM :
  - Mixing between LH and RH sneutrinos : the lightest state can be DM candidate
    hep-ph/0006312, hep-ph/0007018, arXiv :0911.4489, arXiv :0910.2475, arXiv :1008.0580

# Case of sneutrinos

- Neutrino oscillations indicative of massive neutrinos ⇒ possibility to add a right-handed (RH) neutrino field
  ⇒ Extensions of the MSSM with RH (s)neutrino can provide DM candidate

- Different mechanisms appear to obtain sneutrino DM :
  - Mixing between LH and RH sneutrinos : the lightest state can be DM candidate hep-ph/0006312, hep-ph/0007018, arXiv :0911.4489, arXiv :0910.2475, arXiv :1008.0580
  - RH sneutrino condensate arXiv :0710.2360

# Case of sneutrinos

- Neutrino oscillations indicative of massive neutrinos ⇒ possibility to add a right-handed (RH) neutrino field
  ⇒ Extensions of the MSSM with RH (s)neutrino can provide DM candidate

- Different mechanisms appear to obtain sneutrino DM :
  - Mixing between LH and RH sneutrinos : the lightest state can be DM candidate hep-ph/0006312, hep-ph/0007018, arXiv :0911.4489, arXiv :0910.2475, arXiv :1008.0580
  - RH sneutrino condensate arXiv :0710.2360
  - Sneutrino in inverse see-saw mechanism models arXiv :0806.3225, arXiv :1110.1366
  - ...

# Case of sneutrinos

- Neutrino oscillations indicative of massive neutrinos ⇒ possibility to add a right-handed (RH) neutrino field
  ⇒ Extensions of the MSSM with RH (s)neutrino can provide DM candidate

- Different mechanisms appear to obtain sneutrino DM :
  - Mixing between LH and RH sneutrinos : the lightest state can be DM candidate hep-ph/0006312, hep-ph/0007018, arXiv :0911.4489, arXiv :0910.2475, arXiv :1008.0580
  - RH sneutrino condensate arXiv :0710.2360
  - Sneutrino in inverse see-saw mechanism models arXiv :0806.3225, arXiv :1110.1366
  - ...
- Here we want generate RH neutrino mass by introducing Dirac mass terms ⇒ supersymmetric partner can be at the TeV scale
- This candidate couples to new vector, scalar field by adding a new abelian gauge group, it's the UMSSM

# The UMSSM

# Contents

- Extending the SM gauge group is well-motivated in superstrings and grand unified theories hep-ph/9511378
- Symmetry group : $SU(3)_c \times SU(2)_L \times U(1)_Y \times U'(1)$

  Coupling constants associated : $g_3$, $g_2$, $g_Y$ and $g'_1 = g_1 = \sqrt{\frac{5}{3}} g_Y$
- As in the NMSSM, $W = W_{MSSM}|_{\mu=0} + \lambda S H_u H_d$
- $U'(1)$ stems from the breaking of $E_6$ group $\Rightarrow$ it's a combination :

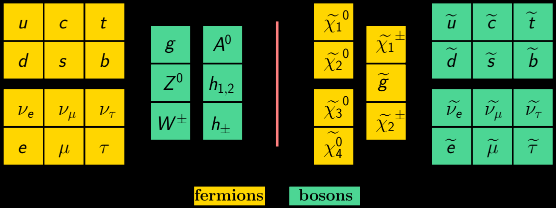
$$Q' = \cos\theta_{E_6} Q_\chi + \sin\theta_{E_6} Q_\psi, \qquad \theta_{E_6} \in [-\pi/2, \pi/2]$$

| $Q'$ choice | Q | $\bar{u}$ | $\bar{d}$ | L | $\bar{e}$ | $\bar{\nu}$ | $H_u$ | $H_d$ | $S$ |
|---|---|---|---|---|---|---|---|---|---|
| $\sqrt{40}Q_\chi$ | -1 | -1 | 3 | 3 | -1 | -5 | 2 | -2 | 0 |
| $\sqrt{24}Q_\psi$ | 1 | 1 | 1 | 1 | 1 | 1 | -2 | -2 | 4 |

# Contents

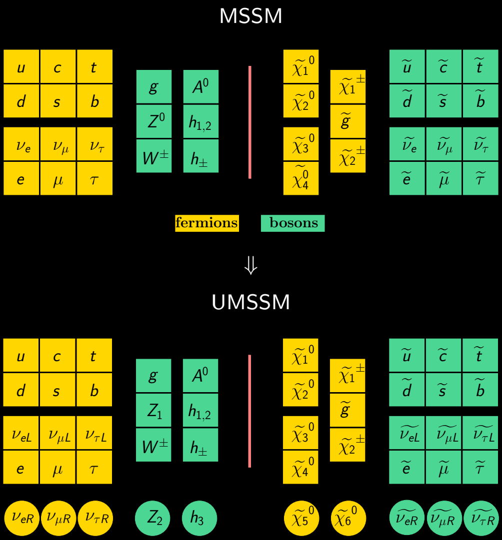
Some differences with the MSSM :

MSSM



# Contents

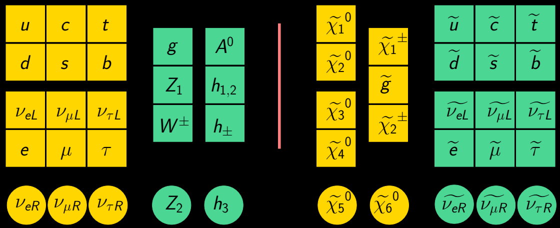
Some differences with the MSSM :



# Contents

Some differences with the MSSM :

UMSSM



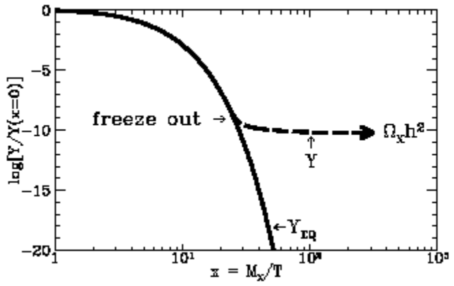

Relevant free parameters :

- WIMP mass $M_{\tilde{\nu}_R}$
- Higgs sector $\Rightarrow$ $\mu$, $A_\lambda$
- Gauge sector : $M_{Z_2}$ and $\alpha_Z$ $\Rightarrow$ $t_\beta$ constrained
- Gaugino sector : $M_1$, $M_1'$ and again $\mu$ ! (higgsino NLSP)
- $\theta_{E_6}$
- Soft terms at 2 TeV $\Rightarrow$ no sfermion coannihilation

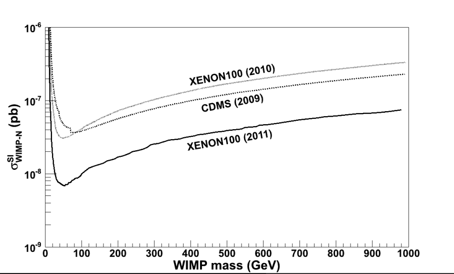
# Constraints

# Constraints

On our CDM candidate :




- Relic density at $3\sigma$ with $\Omega_{WIMP} h^2 = 0.1123 \pm 0.0035$
- Spin independent direct detection cross section



# Constraints

On our CDM candidate :
On the model in general :

- Higgs mass constraints from LEP and LHC : 114.4 GeV $< m_{h_1} <$ 144 GeV (now 141 GeV)

# Constraints

On our CDM candidate :
On the model in general :

- Higgs mass constraints from LEP and LHC : 114.4 GeV $< m_{h_1} <$ 144 GeV (now 141 GeV)
- New $Z$ boson mass constraints from ATLAS :

| $Q'$ choice | $Q_\psi$ | $Q_N$ | $Q_\eta$ | $Q_I$ | $Q_S$ | $Q_\chi$ |
|---|---|---|---|---|---|---|
| $M_{Z_2}$ (TeV) | 1.49 | 1.52 | 1.54 | 1.56 | 1.60 | 1.64 |

- $Z^0$ properties $\Rightarrow \alpha_Z \lesssim 10^{-3}$ ($M_W = \cos\theta_W Z^0$, not $Z_1$ !)

# Constraints

On our CDM candidate :
On the model in general :

- Higgs mass constraints from LEP and LHC : 114.4 GeV $< m_{h_1} <$ 144 GeV (now 141 GeV)
- New $Z$ boson mass constraints from ATLAS :

| $Q'$ choice | $Q_\psi$ | $Q_N$ | $Q_\eta$ | $Q_I$ | $Q_S$ | $Q_\chi$ |
|---|---|---|---|---|---|---|
| $M_{Z_2}$ (TeV) | 1.49 | 1.52 | 1.54 | 1.56 | 1.60 | 1.64 |

- $Z^0$ properties $\Rightarrow \alpha_Z \lesssim 10^{-3}$ ($M_W = \cos\theta_W Z^0$, not $Z_1$ !)
- LEP constraints on sparticles masses

# Constraints

On our CDM candidate :
On the model in general :

- Higgs mass constraints from LEP and LHC : 114.4 GeV $< m_{h_1} <$ 144 GeV (now 141 GeV)
- New $Z$ boson mass constraints from ATLAS :

| $Q'$ choice | $Q_\psi$ | $Q_N$ | $Q_\eta$ | $Q_I$ | $Q_S$ | $Q_\chi$ |
|---|---|---|---|---|---|---|
| $M_{Z_2}$ (TeV) | 1.49 | 1.52 | 1.54 | 1.56 | 1.60 | 1.64 |

- $Z^0$ properties $\Rightarrow \alpha_Z \lesssim 10^{-3}$ ($M_W = \cos\theta_W Z^0$, not $Z_1$ !)
- LEP constraints on sparticles masses
- $B^0_{d,s} - \bar{B}^0_{d,s}$ mesons physics constraints : $\Delta M_{d,s}$ mass differences with one-loop supersymmetric contribution with charginos and higgsinos $\Rightarrow$ supersymmetry can increase difference between observed and standard model expected values :

$$\Delta m_s = 17.77 \pm 0.12\ ps^{-1}(\mathrm{CDF}),\ \Delta m_s^{SM} = 20.5 \pm 3.1\ ps^{-1}$$

$$\Delta m_d = 0.507 \pm 0.004\ ps^{-1}(\mathrm{HFAG}),\ \Delta m_d^{SM} = 0.59 \pm 0.19\ ps^{-1}$$

$$(\Delta m_s = 17.725 \pm 0.049\ ps^{-1}\mathrm{LHCb})$$

# CDM interactions

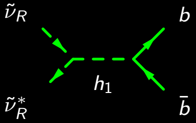
# WIMP annihilation

Parameter space regions with $\Omega_{WIMP}h^2 \approx 0.1 \Rightarrow$ need to increase the annihilation cross section :

# WIMP annihilation

Parameter space regions with $\Omega_{WIMP} h^2 \approx 0.1 \Rightarrow$ need to increase the annihilation cross section :

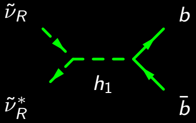
- WIMP mass near $m_{h_1}/2$ :



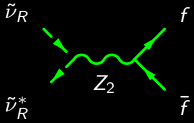
# WIMP annihilation

Parameter space regions with $\Omega_{WIMP} h^2 \approx 0.1 \Rightarrow$ need to increase the annihilation cross section :

- WIMP mass near $m_{h_1}/2$ :



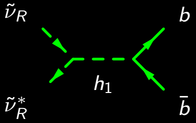

- WIMP mass near $M_{Z_2}/2$ (also $m_{h_i}/2$) :



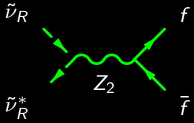
# WIMP annihilation

Parameter space regions with $\Omega_{WIMP} h^2 \approx 0.1 \Rightarrow$ need to increase the annihilation cross section :

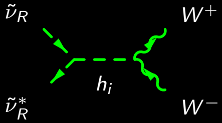
- WIMP mass near $m_{h_1}/2$ :

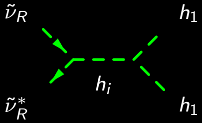



- WIMP mass near $M_{Z_2}/2$ (also $m_{h_i}/2$) :




- WIMP mass near $m_{h_i}/2$ or above $W$ pair threshold :

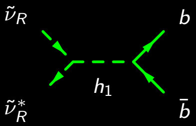


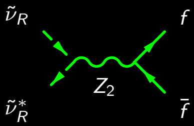
# WIMP annihilation

Parameter space regions with $\Omega_{WIMP} h^2 \approx 0.1 \Rightarrow$ need to increase the annihilation cross section :

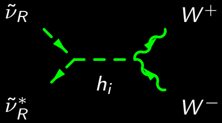
- WIMP mass near $m_{h_1}/2$ :

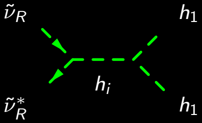



- WIMP mass near $M_{Z_2}/2$ (also $m_{h_i}/2$) :

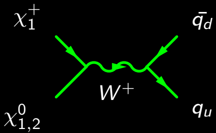


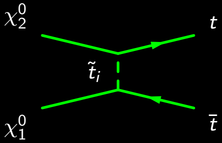

- WIMP mass near $m_{h_i}/2$ or above $W$ pair threshold :




- Coannihilation processes (mainly higgsino-like) :

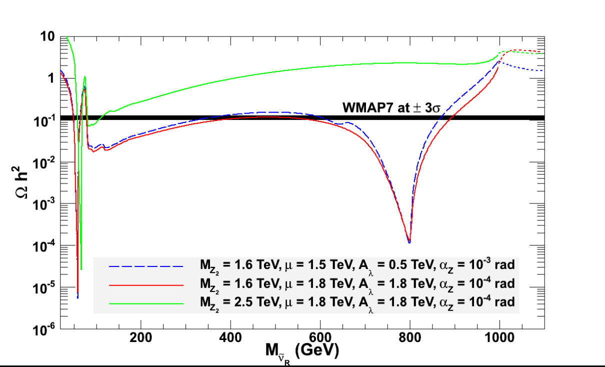


# WIMP annihilation

Parameter space regions with $\Omega_{WIMP} h^2 \approx 0.1 \Rightarrow$ need to increase the annihilation cross section :

- WIMP mass near $m_{h_1}/2$
- WIMP mass near $M_{Z_2}/2$ (also $m_{h_i}/2$)
- WIMP mass near $m_{h_i}/2$ or above $W$ pair threshold
- Coannihilation processes (mainly higgsino-like)



# Scattering on nucleons

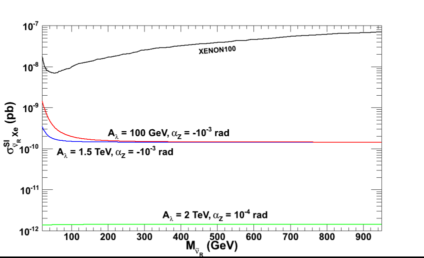
# Scattering on nucleons

- Mainly abelian gauge bosons contribution, $h_1$ for LSP mass $\lesssim$ 200 GeV

# Scattering on nucleons

- Mainly abelian gauge bosons contribution, $h_1$ for LSP mass $\lesssim$ 200 GeV

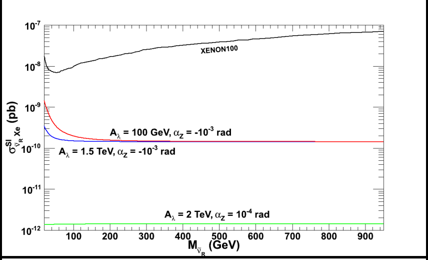
$\Rightarrow$ for some $U'(1)$ models we can have a good suppression of the gauge boson or/and Higgs part :



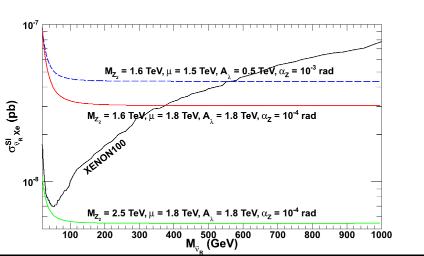
# Scattering on nucleons

- Mainly abelian gauge bosons contribution, $h_1$ for LSP mass $\lesssim$ 200 GeV

$\Rightarrow$ for some $U'(1)$ models we can have a good suppression of the gauge boson or/and Higgs part :




$\Rightarrow$ for other models, huge constraints on the parameter space appear :



# Some results

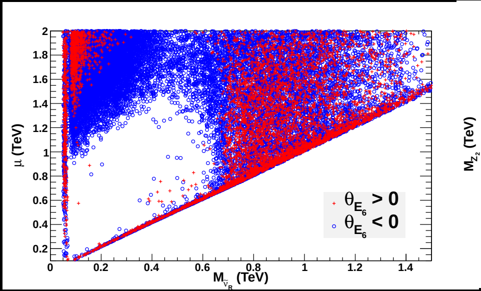
# Characteristics of the global scan

<table>
<tr><th colspan="4">Fixed parameters</th><th colspan="2">Free parameters</th></tr>
<tr><td colspan="4">Soft terms</td><td>Name</td><td>Domain of variation</td></tr>
<tr><td>$m_{Q_i}$</td><td>2 TeV</td><td>$m_{L_i}$</td><td>2 TeV</td><td>$M_{\tilde{\nu}_R}$</td><td>[0, 1.5] TeV</td></tr>
<tr><td>$m_{\bar{u}_i}$</td><td>2 TeV</td><td>$m_{\bar{d}_i}$</td><td>2 TeV</td><td>$M_{Z_2}$</td><td>[1.3, 3] TeV</td></tr>
<tr><td>$m_{\bar{e}_i}$</td><td>2 TeV</td><td>$m_{\bar{\nu}_j}$</td><td>2 TeV</td><td>$\mu$</td><td>[0.1, 2] TeV</td></tr>
<tr><td colspan="4">i $\in \{1,2,3\}$, j $\in \{1,2\}$</td><td>$A_\lambda$</td><td>[0, 2] TeV</td></tr>
<tr><td colspan="4">Trilinear couplings + $M_K$</td><td>$\theta_{E_6}$</td><td>[-$\pi/2$, $\pi/2$] rad</td></tr>
<tr><td>$A_t$</td><td>1 TeV</td><td>$A_b$</td><td>0 TeV</td><td>$\alpha_Z$</td><td>[-3.10$^{-3}$, 3.10$^{-3}$] rad</td></tr>
<tr><td>$A_c$</td><td>0 TeV</td><td>$A_s$</td><td>0 TeV</td><td>$M_1$</td><td>[0.1, 2] TeV</td></tr>
<tr><td>$A_u$</td><td>0 TeV</td><td>$A_d$</td><td>0 TeV</td><td>$M_1'$</td><td>[0.1, 2] TeV</td></tr>
<tr><td>$A_l$</td><td>0 TeV</td><td>$M_K$</td><td>1 eV</td><td colspan="2">$M_2 = 2M_1$ et $M_3 = 6M_1$</td></tr>
</table>

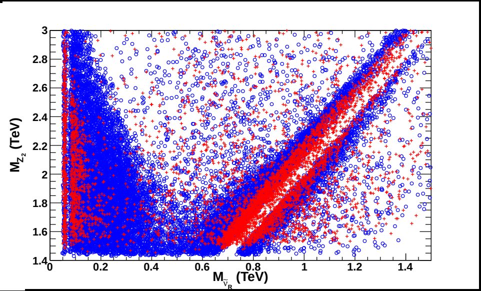
# Output

# Output

Interesting WIMP mass from 50 GeV to TeV-scale :



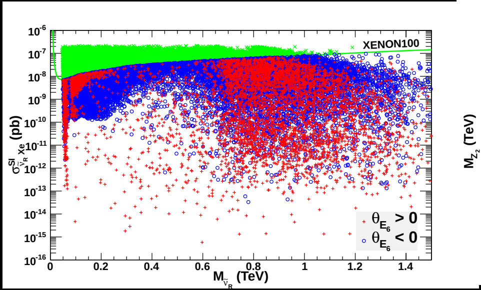

$\mu$ vs. WIMP mass

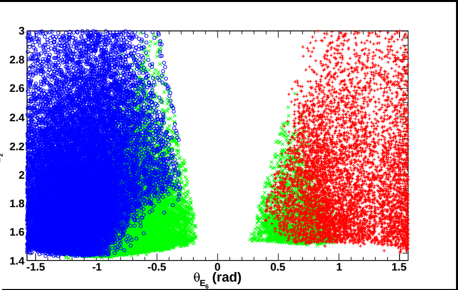



$M_{Z_2}$ vs. WIMP mass

# Output

Interesting WIMP mass from 50 GeV to TeV-scale :



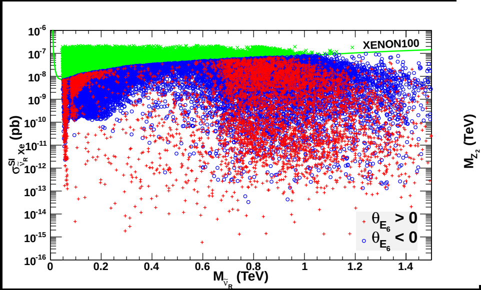




Direct detection cross section vs. WIMP mass

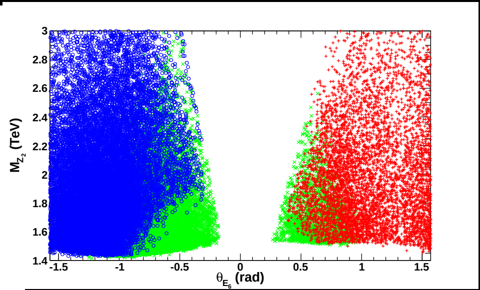
$M_{Z_2}$ vs. $\theta_{E_6}$

# Output

Interesting WIMP mass from 50 GeV to TeV-scale :




Direct detection cross section vs. WIMP mass

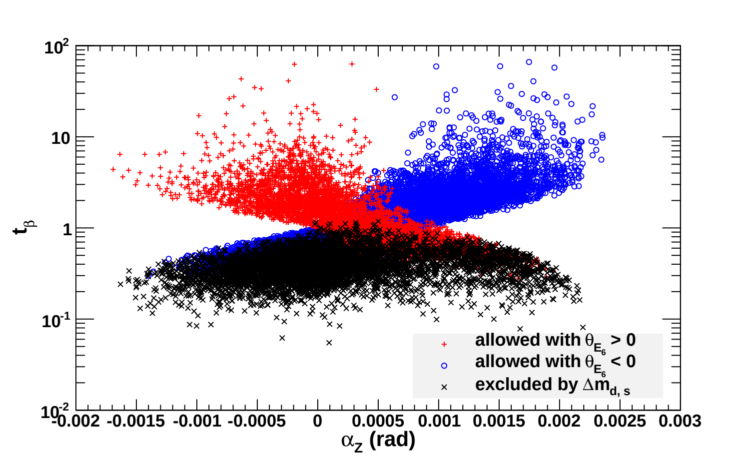



$M_{Z_2}$ vs. $\theta_{E_6}$

Lower is $|\theta_{E_6}|$, higher are $Z_2$ processes in direct detection cross section $\Rightarrow$ huge constraint

# Output

Large SUSY corrections proportional to $\frac{1}{t_\beta^4}$ $\Rightarrow$ small values of $t_\beta$ very constrained by $\Delta M_s$ :



# Conclusion and perspectives

# Conclusion and perspectives

- **RH sneutrino is a viable dark matter candidate in the UMSSM ! !**

  it respects experimental limits in the case of some annihilation processes :
  - Resonance ($h_1$, $Z_2$ and singlet-like Higgs)
  - Coannihilation (neutralinos, charginos, others sfermions)
  - Annihilation into W pairs generally with exchange of $h_1$
- Direct detection experiments strongly constrain the model as well as $\Delta m_s$

# Conclusion and perspectives

- **RH sneutrino is a viable dark matter candidate in the UMSSM ! !**

  it respects experimental limits in the case of some annihilation processes :
  - Resonance ($h_1$, $Z_2$ and singlet-like Higgs)
  - Coannihilation (neutralinos, charginos, others sfermions)
  - Annihilation into W pairs generally with exchange of $h_1$
- Direct detection experiments strongly constrain the model as well as $\Delta m_s$

- Neutralino can also be a good DM candidate in this gauge extension of the MSSM arXiv :0811.2204
- More careful study of the UMSSM Higgs sector could provide hidden Higgs scenarios

# Conclusion and perspectives

- **RH sneutrino is a viable dark matter candidate in the UMSSM ! !**

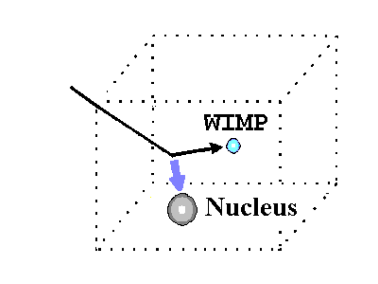
  it respects experimental limits in the case of some annihilation processes :
  - Resonance ($h_1$, $Z_2$ and singlet-like Higgs)
  - Coannihilation (neutralinos, charginos, others sfermions)
  - Annihilation into W pairs generally with exchange of $h_1$
- Direct detection experiments strongly constrain the model as well as $\Delta m_s$
- Neutralino can also be a good DM candidate in this gauge extension of the MSSM arXiv :0811.2204
- More careful study of the UMSSM Higgs sector could provide hidden Higgs scenarios

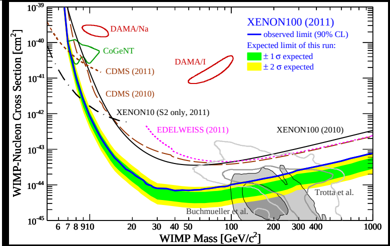
## Thanks for your attention !

# BACKUP

# Dark matter hunting

- Direct detection experiments (XENON, CDMS,...)

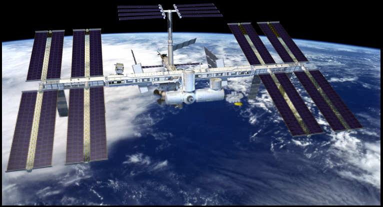



E. Aprile et al.,arXiv :1104.2549 [astro-ph.CO]

# Dark matter hunting

- Indirect detection : dark matter annihilation into $\gamma$, $e^+$, $\bar{p}$, $\bar{d}$, $\nu$ (AMS, Fermi, HESS, PAMELA,...)



AMS

# The case of colliders

- Missing energy, new signals,... at colliders → dark matter and supersymmetry hunting


LHC

# UMSSM fields

| Chiral supermultiplets | | | | |
|---|---|---|---|---|
| Supermultiplets | | spin 0 | spin 1/2 | $SU(3)_c,\ SU(2)_L,\ U(1)_Y,\ U'(1)$ |
| squarks, quarks (3 families) | Q | $(\widetilde{u}_L\ \widetilde{d}_L)$ | $(u_L\ d_L)$ | $(\mathbf{3},\ \mathbf{2},\ \frac{1}{6},\ Q'_Q)$ |
| | $\bar{u}$ | $\widetilde{u}^*_R$ | $\bar{u}_R$ | $(\bar{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3},\ Q'_u)$ |
| | $\bar{d}$ | $\widetilde{d}^*_R$ | $\bar{d}_R$ | $(\bar{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3},\ Q'_d)$ |
| sleptons, leptons (3 families) | L | $(\widetilde{\nu}_L\ \widetilde{e}_L)$ | $(\nu_L\ e_L)$ | $(\mathbf{1},\ \mathbf{2},\ -\frac{1}{2},\ Q'_L)$ |
| | $\bar{\nu}$ | $\widetilde{\nu}^*_R$ | $\bar{\nu}_R$ | $(\mathbf{1},\ \mathbf{1},\ 0,\ Q'_{\bar{\nu}})$ |
| | $\bar{e}$ | $\widetilde{e}^*_R$ | $\bar{e}_R$ | $(\mathbf{1},\ \mathbf{1},\ \frac{1}{6},\ Q'_e)$ |
| Higgs, higgsinos | $H_u$ | $(H_u^+\ H_u^0)$ | $(\widetilde{H}_u^+\ \widetilde{H}_u^0)$ | $(\mathbf{1},\ \mathbf{2},\ \frac{1}{2},\ Q'_{H_u})$ |
| | $H_d$ | $(H_d^0\ H_d^-)$ | $(\widetilde{H}_d^0\ \widetilde{H}_d^-)$ | $(\mathbf{1},\ \mathbf{2},\ -\frac{1}{2},\ Q'_{H_d})$ |
| | $S$ | $S$ | $\widetilde{S}$ | $(\mathbf{1},\ \mathbf{1},\ 0,\ Q'_S)$ |

| Vector supermultiplets | | | |
|---|---|---|---|
| Supermultiplets | spin 1/2 | spin 1 | $SU(3)_c,\ SU(2)_L,\ U(1)_Y,\ U'(1)$ |
| gluino, gluon | $\widetilde{g}$ | $g$ | $(\mathbf{8},\ \mathbf{1},\ 0,\ 0)$ |
| winos, W bosons | $\widetilde{W}^\pm\ \widetilde{W}^3$ | $W^\pm\ W^3$ | $(\mathbf{1},\ \mathbf{3},\ 0,\ 0)$ |
| bino, B boson | $\widetilde{B}$ | $B$ | $(\mathbf{1},\ \mathbf{1},\ 0,\ 0)$ |
| bino', B' boson | $\widetilde{B'}$ | $B'$ | $(\mathbf{1},\ \mathbf{1},\ 0,\ 0)$ |

# Some new lagrangian terms

- Superpotential :

$$W_{MSSM} = \bar{u} y_u Q H_u - \bar{d} y_d Q H_d - \bar{e} y_e L H_d + \mu H_u H_d$$
$$W_{UMSSM} = W_{MSSM}(\mu = 0) + \lambda S H_u H_d + \bar{\nu} y_\nu L H_u$$

- Soft supersymmetry breaking :

$$\begin{aligned}
\mathcal{L}_{soft}^{MSSM} = &- \frac{1}{2}(M_3 \widetilde{g}\widetilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + \mathrm{c.c.}) \\
&- (\widetilde{u}_R^* a_u \widetilde{Q} H_u - \widetilde{d}_R^* a_d \widetilde{Q} H_d - \widetilde{e}_R^* a_e \widetilde{L} H_d + \mathrm{c.c.}) \\
&- \widetilde{Q}^\dagger m_Q^2 \widetilde{Q} - \widetilde{L}^\dagger m_L^2 \widetilde{L} - \widetilde{u}_R^* m_{\widetilde{e}}^2 \widetilde{u}_R - \widetilde{d}_R^* m_{\widetilde{d}}^2 \widetilde{d}_R - \widetilde{e}_R^* m_{\widetilde{e}}^2 \widetilde{e}_R \\
&- m_{H_u}^2 H_u^\dagger H_u - m_{H_d}^2 H_d^\dagger H_d - (b H_u H_d + \mathrm{c.c.}) \\
\mathcal{L}_{soft}^{UMSSM} = &\mathcal{L}_{soft}^{MSSM}(b = 0) - \left( \frac{1}{2} M_1' \widetilde{B'}\widetilde{B'} + M_K \widetilde{B}\widetilde{B'} + \widetilde{\nu}_R^* a_\nu \widetilde{L} H_u + \mathrm{c.c.} \right) \\
&- \widetilde{\nu}_R^* m_{\widetilde{\nu}}^2 \widetilde{\nu}_R - (\lambda A_\lambda S H_u H_d + \mathrm{c.c.}) - m_S^2 S^* S
\end{aligned}$$

LanHEP, A. Semenov, arXiv :0805.0555 [hep-ph]

# Reason of constrained $t_\beta$

$$M_Z^2 = M_{Z_1}^2 \cos^2\alpha_{ZZ'} + M_{Z_2}^2 \sin^2\alpha_{ZZ'}$$
$$M_{Z'}^2 = M_{Z_1}^2 \sin^2\alpha_{ZZ'} + M_{Z_2}^2 \cos^2\alpha_{ZZ'}.$$

$$\Downarrow$$

$$\tan 2\alpha_{ZZ'} = \frac{2\Delta^2}{M_{Z'}^2 - M_Z^2} \quad \Longrightarrow \quad \sin 2\alpha_{ZZ'} = \frac{2\Delta^2}{M_{Z_2}^2 - M_{Z_1}^2}.$$

Knowing that

$$\Delta^2 = \frac{g_1'\sqrt{g'^2 + g_2^2}}{2} v^2(Q_2' s_\beta^2 - Q_1' c_\beta^2),$$

$$\Downarrow$$

$$\boxed{c_\beta^2 = \frac{1}{Q_1' + Q_2'}\left(\frac{\sin 2\alpha_{ZZ'}(M_{Z_1}^2 - M_{Z_2}^2)}{v^2 g_1'\sqrt{g'^2 + g_2^2}} + Q_2'\right).}$$

# Higgs masses

$$m^2_{A^0} = \frac{\lambda A_\lambda \sqrt{2}}{\sin 2\phi} v + \Delta_{EA} \qquad \tan\phi = \frac{v \sin 2\beta}{2 v_s}$$

$$m^2_{H^\pm} = \frac{\lambda A_\lambda \sqrt{2}}{\sin 2\beta} v_s - \frac{\lambda^2}{2} v^2 + \frac{g_2^2}{2} v^2 + \Delta_\pm \qquad \tan\beta = \frac{v_u}{v_d}$$

$M^2_{CPeven}$ :

$$\left(\mathcal{M}^0_+\right)_{11} = \left[\frac{(g'^2 + g_2^2)^2}{4} + Q_1'^2 g_1'^2\right] (v c_\beta)^2 + \frac{\lambda A_\lambda t_\beta v_s}{\sqrt{2}} + \Delta_{11}$$

$$\left(\mathcal{M}^0_+\right)_{12} = -\left[\frac{(g'^2 + g_2^2)^2}{4} - \lambda^2 - Q_1' Q_2' g_1'^2\right] v^2 s_\beta c_\beta - \frac{\lambda A_\lambda v_s}{\sqrt{2}} + \Delta_{12}$$

$$\left(\mathcal{M}^0_+\right)_{13} = \left[\lambda^2 + Q_1' Q_S' g_{1'}{}^2\right] v c_\beta v_s - \frac{\lambda A_\lambda v s_\beta}{\sqrt{2}} + \Delta_{13}$$

$$\left(\mathcal{M}^0_+\right)_{22} = \left[\frac{(g'^2 + g_2^2)^2}{4} + Q_2'^2 g_1'^2\right] (v s_\beta)^2 + \frac{\lambda A_\lambda v_s}{t_\beta \sqrt{2}} + \Delta_{22}$$

$$\left(\mathcal{M}^0_+\right)_{23} = \left[\lambda^2 + Q_2' Q_S' g_1'^2\right] v s_\beta v_s - \frac{\lambda A_\lambda v c_\beta}{\sqrt{2}} + \Delta_{23}$$

$$\left(\mathcal{M}^0_+\right)_{33} = Q_S'^2 g_1'^2 v_s^2 + \frac{\lambda A_\lambda v^2 s_\beta c_\beta}{v_s \sqrt{2}} + \Delta_{33}$$

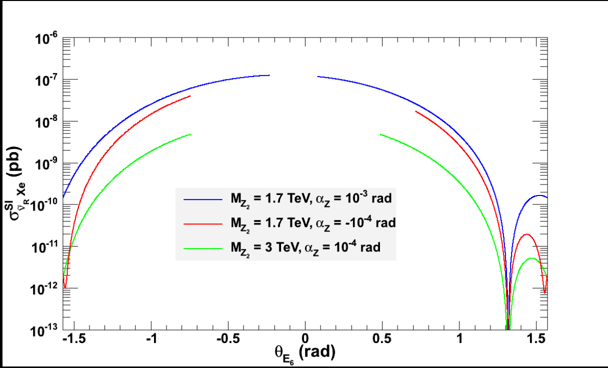
Vernon Barger, Paul Langacker, Hye-Sung Lee and Gabe Shaughnessy, arXiv :hep-ph/0603247

# Direct detection constraint

Abelian gauge boson contribution to direct detection :

$$\sigma_{\tilde{\nu}_R N}^{Z_1,Z_2} = \frac{\mu_{\tilde{\nu}_R N}^2}{\pi}(g_1' Q_{\tilde{\nu}}')^2[(y(1-4s_W^2)+y')Z+(-y+2y')(A-Z)]^2$$

$$\text{with } y = \frac{g' \sin\alpha_Z \cos\alpha_Z}{4\sin\theta_W}\left(\frac{1}{M_{Z_2}^2}-\frac{1}{M_{Z_1}^2}\right),\; y' = -\frac{g_1'}{2} Q_V'^d \left(\frac{\sin^2\alpha_Z}{M_{Z_1}^2}+\frac{\cos^2\alpha_Z}{M_{Z_2}^2}\right)$$




⇒ stringent constraints for small $|\theta_{E_6}|$ because of $Q_V'^d$ term

# Coannihilation with sfermions

Sparticles sector :

$$M^2_{\tilde{f}} = \begin{pmatrix} m^2_{soft} + m^2_f + M^2_{Z^0}\cos 2\beta(I^3_f - e_f \sin^2\theta_W) + \Delta_f & m_f(A_f - \mu(t_\beta)^{-2I^3_f}) \\ m_f(A_f - \mu(t_\beta)^{-2I^3_f}) & m^2_{\bar{soft}} + M^2_{Z^0}\cos 2\beta(I^3_{\bar{f}} - e_{\bar{f}} \sin^2\theta_W) + m^2_f + \Delta_{\bar{f}} \end{pmatrix}$$

where $\Delta_f = \frac{1}{2} g_1'^2 Q'_f (Q'_{H_d} v_d^2 + Q'_{H_u} v_u^2 + Q'_S v_s^2)$ $\Rightarrow$ Coannihilations :

$\theta_{E_6} > 0$ : generally $\tilde{t}_1$

$\theta_{E_6} < 0$ : generally RH down sqarks