Dark Matter and Higgs sector in U(1) extensions of the MSSM

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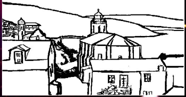

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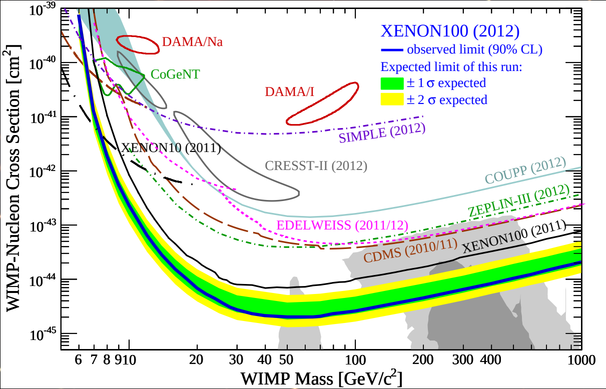
Cargèse, 20 August - 01 September 2012

G. Bélanger, J. Da Silva and A. Pukhov, JCAP 1112 (2011) 014, arXiv:1110.2414 [hep-ph]

WIMPs candidates in SUSY models

- Assuming R-parity, 2 cold DM (WIMPs) candidates in the MSSM :
  - Lightest neutralino : a lot of studies $\Rightarrow$ good DM candidate
  - Left-handed (LH) sneutrino : too high coupling with Z^0 $\Rightarrow \sigma^{SI}_{\tilde{\nu}_L N} >> \sigma^{SI}_{exp}$ (cf. first lecture of Natalia Toro)
    $\Rightarrow$ bad DM candidate



E. Aprile et al., arXiv :1207.5988 [astro-ph.CO]

WIMPs candidates in SUSY models

- 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 (cf. first lecture of Natalia Toro)
    ⇒ bad DM candidate
- 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 exist to get sneutrino DM (e.g. Béranger Dumont talk)
- 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

The UMSSM

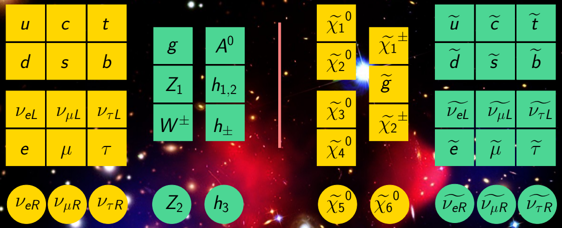
- Extending the SM gauge group is well-motivated in superstrings and grand unified theories
- Symmetry group : $SU(3)_c \times SU(2)_L \times U(1)_Y \times U'(1)$

  Coupling constants associated : g_3, g_2, g_Y and $g'_1 = g_1 = \sqrt{\frac{5}{3}} g_Y$

- Close to the NMSSM : $W = W_{MSSM}|_{\mu=0} + \lambda S H_u H_d + \bar{\nu} y_\nu L H_u + O(\mathrm{TeV})$
- $U'(1)$ stems from the breaking $E_6 \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi$:

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

The UMSSM



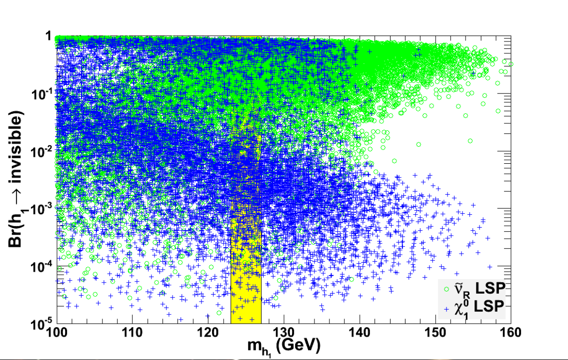
Relevant free parameters :

- WIMP mass $M_{\tilde{\nu}_R}$
- Higgs sector $\Rightarrow$ μ, A_λ
- Gauge sector : M_{Z_2} and α_Z $\Rightarrow$ t_β constrained
- Gaugino sector : M_1, M_1' and again μ ! (higgsino NLSP)
- θ_{E_6}
- Soft terms at 2 TeV $\Rightarrow$ no sfermion coannihilation

Higgs sector

1 CP odd higgs A^0, 5 CP even higgs : $h^{\pm}$, h_1, h_2 and h_3
singlet-like higgs (h_2 or h_3) mass near Z_2 mass
including pure UMSSM terms + radiative corrections

$\Rightarrow$ $m_{h_1} \sim 125$ GeV is more natural than in the MSSM

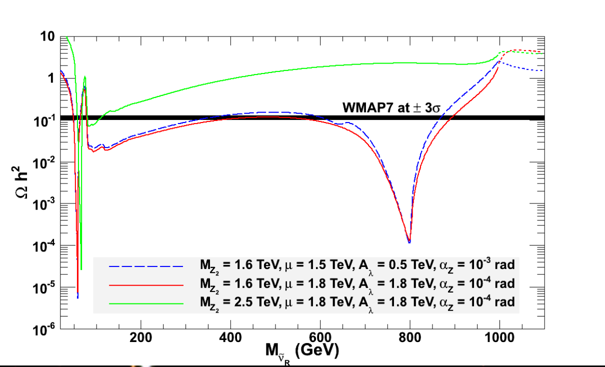


$\Rightarrow$ visible decay modes not significantly suppressed, even for $m_{h_1}/2 > m_{LSP}$

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)

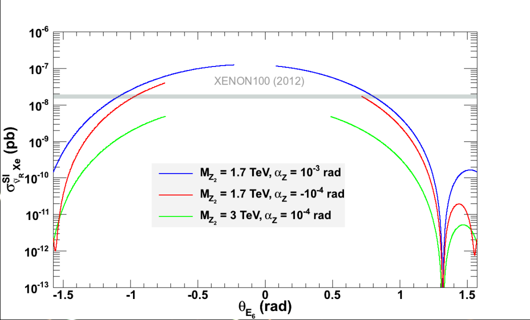


Scattering on nucleons

Mainly abelian gauge bosons contribution, h_1 for LSP mass $\lesssim 200$ GeV
Abelian gauge boson contribution to direct detection :

$$\sigma^{Z_1,Z_2}_{\tilde{\nu}_R N} = \frac{\mu^2_{\tilde{\nu}_R N}}{\pi}(g'_1 Q'_{\tilde{\nu}})^2[(y(1-4s^2_W)+y')Z+(-y+2y')(A-Z)]^2$$

$$\text{with } y = \frac{g'\sin\alpha_Z\cos\alpha_Z}{4\sin\theta_W}\left(\frac{1}{M^2_{Z_2}}-\frac{1}{M^2_{Z_1}}\right),\ y' = -\frac{g'_1}{2}Q'^d_V\left(\frac{\sin^2\alpha_Z}{M^2_{Z_1}}+\frac{\cos^2\alpha_Z}{M^2_{Z_2}}\right)$$

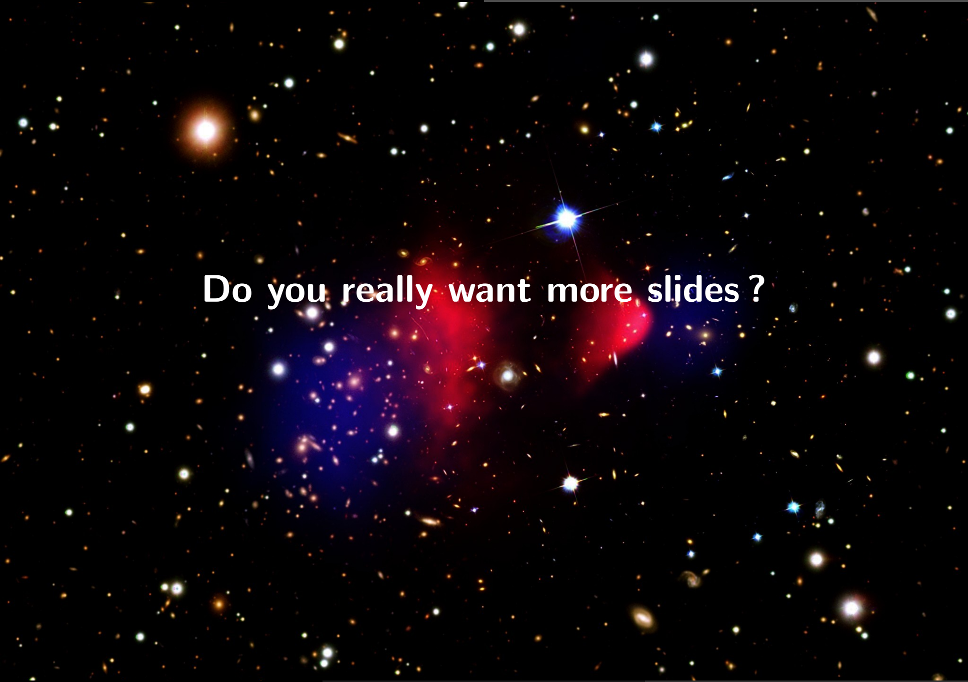


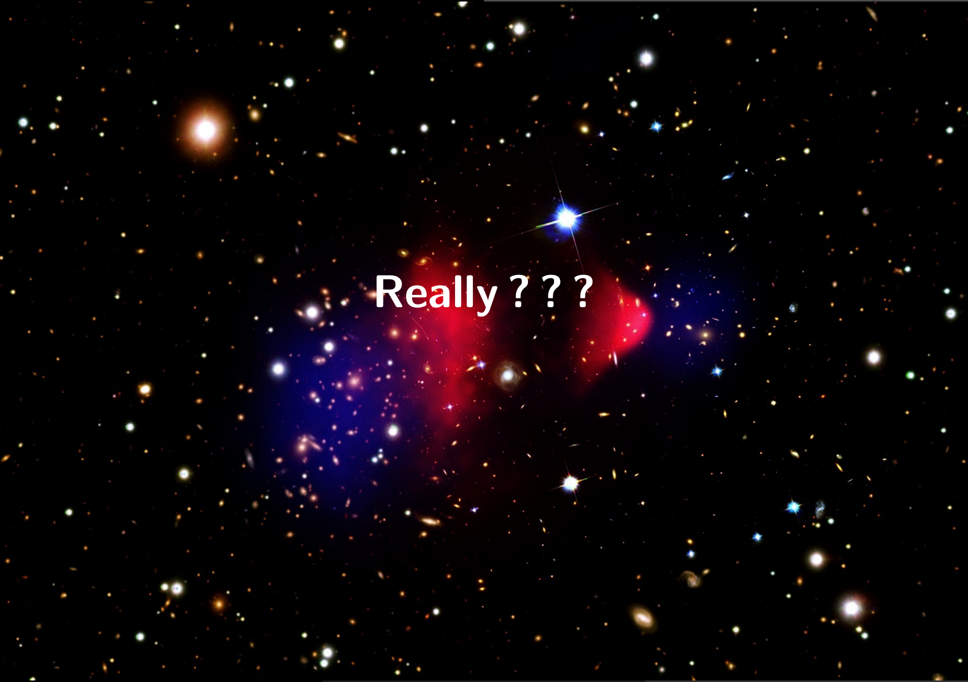
⇒ stringent constraints for small $|\theta_{E_6}|$ because of Q'^d_V term

⇒ Interesting WIMP mass **from 50 GeV to TeV-scale**

Conclusion

Thanks for your attention !


Do you really want more slides ?



Really ? ? ?

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	$(\widetilde{u}_L\ \widetilde{d}_L)$	$(u_L\ d_L)$	$(3,\ 2,\ \frac{1}{6},\ Q'_Q)$
	$\bar{u}$	$\widetilde{u}^*_R$	$\bar{u}_R$	$(\bar{3},\ 1,\ -\frac{2}{3},\ Q'_u)$
	$\bar{d}$	$\widetilde{d}^*_R$	$\bar{d}_R$	$(\bar{3},\ 1,\ \frac{1}{3},\ Q'_d)$
sleptons, leptons (3 families)	L	$(\widetilde{\nu}_L\ \widetilde{e}_L)$	$(\nu_L\ e_L)$	$(1,\ 2,\ -\frac{1}{2},\ Q'_L)$
	$\bar{\nu}$	$\widetilde{\nu}^*_R$	$\bar{\nu}_R$	$(1,\ 1,\ 0,\ Q'_{\bar{\nu}})$
	$\bar{e}$	$\widetilde{e}^*_R$	$\bar{e}_R$	$(1,\ 1,\ \frac{1}{6},\ Q'_e)$
Higgs, higgsinos	H_u	$(H_u^+\ H_u^0)$	$(\widetilde{H}_u^+\ \widetilde{H}_u^0)$	$(1,\ 2,\ \frac{1}{2},\ Q'_{H_u})$
	H_d	$(H_d^0\ H_d^-)$	$(\widetilde{H}_d^0\ \widetilde{H}_d^-)$	$(1,\ 2,\ -\frac{1}{2},\ Q'_{H_d})$
	S	S	$\widetilde{S}$	$(1,\ 1,\ 0,\ Q'_S)$

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

Some new lagrangian terms

- **Superpotential :**

$$
\begin{aligned}
W_{MSSM} &= \bar{u} y_u Q H_u - \bar{d} y_d Q H_d - \bar{e} y_e L H_d + \mu H_u H_d \\
W_{UMSSM} &= W_{MSSM}(\mu = 0) + \lambda S H_u H_d + \bar{\nu} y_\nu L H_u + \mathcal{O}(\mathbf{TeV})
\end{aligned}
$$

- **Soft supersymmetry breaking :**

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

Contents

Some differences with the MSSM :

- Gauge sector : Physical abelian gauge bosons : Z_1 and Z_2, mixing between the Z^0 of the SM and the Z', α_Z is the mixing angle

$$M^2_{Z_1,Z_2} = \frac{1}{2}\left(M^2_{Z^0} + M^2_{Z'} \mp \sqrt{\left(M^2_{Z^0} + M^2_{Z'}\right)^2 + 4\Delta^4_Z}\right)$$

$$\sin 2\alpha_Z = \frac{2\Delta^2_Z}{M^2_{Z_2} - M^2_{Z_1}}$$

- Higgs sector : 1 CP odd higgs A^0, 5 CP even higgs : $h^\pm$, h_1, h_2 and h_3 singlet-like higgs (h_2 or h_3) mass near Z_2 mass including pure UMSSM terms + radiative corrections

$\Rightarrow$ m_{h_1} above LEP limits

- Gauginos sector : 6 neutralinos in the basis $(\widetilde{B}, \widetilde{W}^3, \widetilde{H}^0_d, \widetilde{H}^0_u, \widetilde{S}, \widetilde{B'})$

$U'(1)$ charges, constrained t_β

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

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

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

$$\Downarrow$$

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

Given that

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

$$\Downarrow$$

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

Higgs masses

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

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

M^2_{CPeven} :

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

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

$$\left(\mathcal{M}_+^0\right)_{13} = \left[\lambda^2 + Q_1' Q_S' g_1'^2\right] v c_\beta v_s - \frac{\lambda A_\lambda v s_\beta}{\sqrt{2}} + \Delta_{13}$$

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

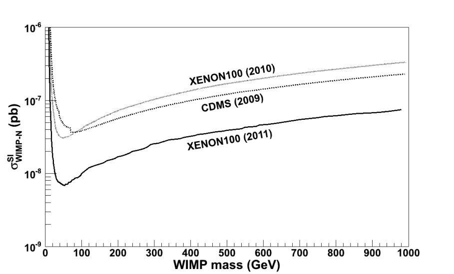
$$\left(\mathcal{M}_+^0\right)_{23} = \left[\lambda^2 + Q_2' Q_S' g_1'^2\right] v s_\beta v_s - \frac{\lambda A_\lambda v c_\beta}{\sqrt{2}} + \Delta_{23}$$

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

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

Constraints

- On our CDM candidate
  - Relic density at 3σ with $\Omega_{\text{WIMP}} h^2 = 0.1123 \pm 0.0035$
  - Spin independent direct detection cross section



Constraints

- On our CDM candidate
- On different sectors of the model
  - Higgs mass constraints from LEP and LHC : 114.4 GeV $< m_{h_1} < 144$ GeV
  - New Z boson mass constraints from ATLAS :

Q' choice	Q_ψ	Q_N	Q_η	Q_I	Q_S	Q_χ
M_{Z_2} (TeV)	1.49	1.52	1.54	1.56	1.60	1.64

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

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

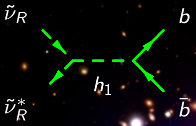
$$\Delta m_d = 0.507 \pm 0.004 \text{ ps}^{-1} (\text{HFAG}), \ \Delta m_d^{SM} = 0.59 \pm 0.19 \text{ ps}^{-1}$$

$$\Delta m_s = 17.63 \pm 0.11 \text{ ps}^{-1} (\text{LHCb})$$

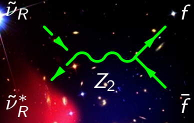
WIMP annihilation

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

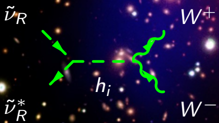
- **WIMP mass near $m_{h_1}/2$:**

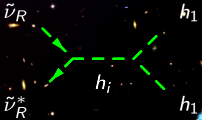


- **WIMP mass near $M_{Z_2}/2$ (also $m_{h_i}/2$) :**

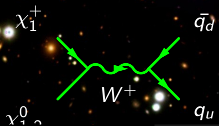


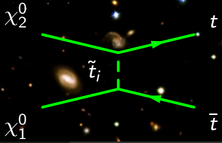
- **WIMP mass near $m_{h_i}/2$ or above W pair threshold :**





- **Coannihilation processes (mainly higgsino-like) :**





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** $\tilde{t}_1$

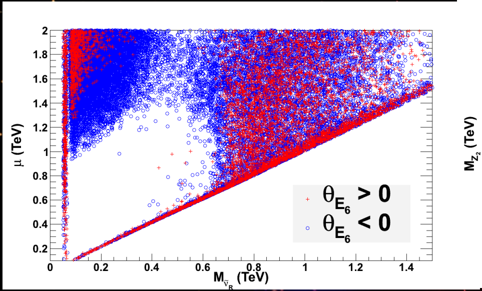
$\theta_{E_6} < 0$ **: generally RH down sqarks**

Characteristics of the global scan

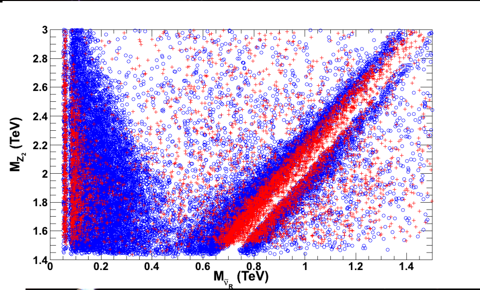
Fixed parameters				Free parameters	
Soft terms				Name	Domain of variation
m_{Q_i}	2 TeV	m_{L_i}	2 TeV	$M_{\tilde{\nu}_R}$	[0, 1.5] TeV
$m_{\bar{u}_i}$	2 TeV	$m_{\bar{d}_i}$	2 TeV	M_{Z_2}	[1.3, 3] TeV
$m_{\bar{e}_i}$	2 TeV	$m_{\bar{\nu}_j}$	2 TeV	μ	[0.1, 2] TeV
$\mathbf{i} \in \{1, 2, 3\}$, $\mathbf{j} \in \{1, 2\}$				A_λ	[0, 2] TeV
Trilinear couplings + M_K				θ_{E_6}	[-$\pi/2$, $\pi/2$] rad
A_t	1 TeV	A_b	0 TeV	α_Z	[-3.10^{-3}, 3.10^{-3}] rad
A_c	0 TeV	A_s	0 TeV	M_1	[0.1, 2] TeV
A_u	0 TeV	A_d	0 TeV	M_1'	[0.1, 2] TeV
A_l	0 TeV	M_K	1 eV	$M_2 = 2M_1$ et $M_3 = 6M_1$	

Output

Interesting WIMP mass from 50 GeV to TeV-scale **:**



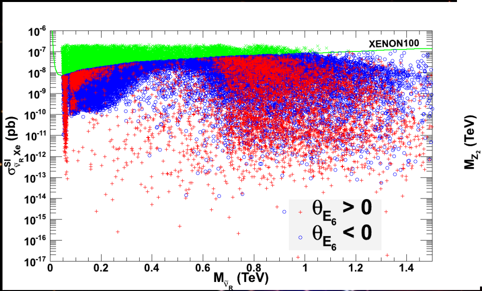
μ **vs. WIMP mass**

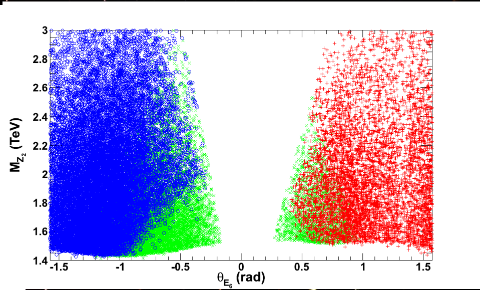


M_{Z_2} **vs. WIMP mass**

Output

Interesting WIMP mass from 50 GeV to TeV-scale **:**





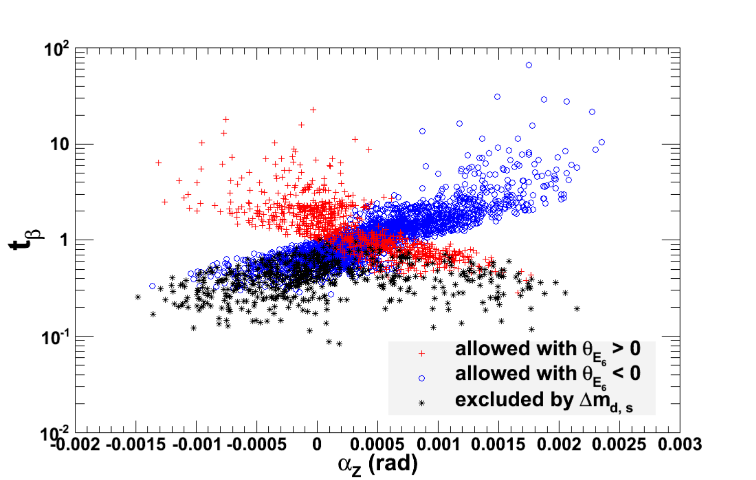
Direct detection cross section vs. WIMP mass

M_{Z_2} **vs.** θ_{E_6}

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

Output

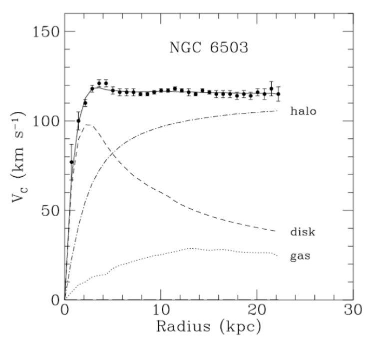
Large SUSY corrections proportional to $\frac{1}{t_\beta^4}$ $\Rightarrow$ small values of t_β very constrained by ΔM_s (here m_h between 123 and 127 GeV) :



Need of dark matter (DM)

Since 1933 and Zwicky observations, we accumulated evidences for DM 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 $M(r)\ \alpha\ r$

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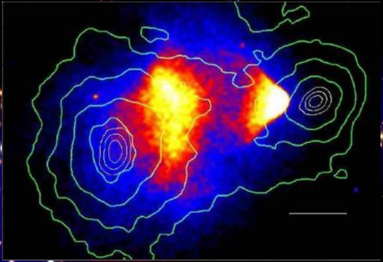
- Galaxy scale : rotation curves of galaxies
- Galaxy clusters scale : example of the bullet cluster



A direct empirical proof of the existence of dark matter, D. Clowe et al., Astrophys. J. 648 L109-L113, 2006

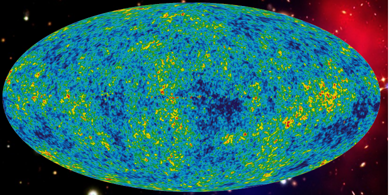
Study of X-rays and gravitational lensing effect of this cluster : discrepancy between baryonic matter and gravitational potential

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

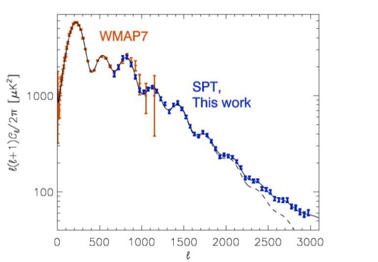
Need of dark matter (DM)

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

- Galaxy scale : rotation curves of galaxies
- Galaxy clusters scale : example of the bullet cluster
- Cosmological scale : the Cosmic Microwave background (CMB)



WMAP7



SPT

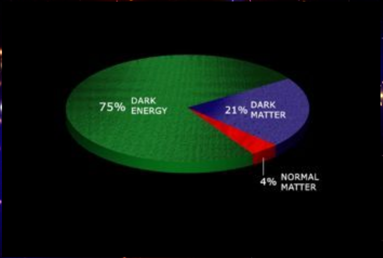
To match a cosmological model with the CMB power spectrum

$$\Rightarrow \Omega_b h^2 = 0.0226 \pm 0.0005 \text{ and } \Omega_{DM} h^2 = 0.1123 \pm 0.0035$$

Need of dark matter (DM)

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

- Galaxy scale : rotation curves of galaxies
- Galaxy clusters scale : example of the bullet cluster
- Cosmological scale : the Cosmic Microwave background (CMB)
- Large scale structures, ...



DM has to be stable and weakly charged under the standard model gauge group (otherwise we should have seen it)

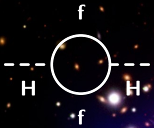
Conservation of DM structures $\Rightarrow$ warm vs. cold DM

here we choose CDM

Need of supersymmetry

- **Hierarchy problem**

No symmetry protects higgs mass :



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

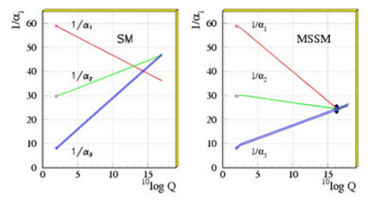
Supersymmetry, symmetry between fermions and bosons (thanks to Poincaré group extension) plays this role by adding one-loop corrections :

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

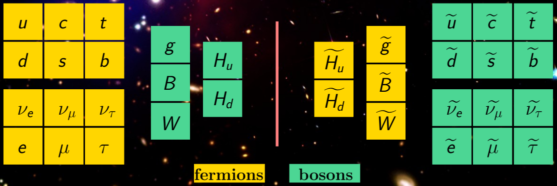
$\Rightarrow$ **Cancellation of quadratic divergence**

Need of supersymmetry

- Hierarchy problem
- Gauge coupling unification



Modification of RGEs in the supersymmetry framework



$\Rightarrow$ Supersymmetry allows unification at GUT scale

Need of supersymmetry

- Hierarchy problem
- Gauge coupling unification
- LSP/DM

No supersymmetric particles seen at the same mass as their standard partners
$\Rightarrow$ supersymmetry is broken, new particles (at least) at TeV scale

Supersymmetric terms give us proton decay
$\Rightarrow$ need of R-Parity to forbid them $P_R = (-1)^{3(B-L)+2s}$

$\Rightarrow$ Result : the lightest supersymmetric particle (LSP) is stable

This LSP, stable, at TeV scale, can be weakly charged under the SM gauge group

$\Rightarrow$ DM candidates in supersymmetric models