Neutralino DM : Dirac masses

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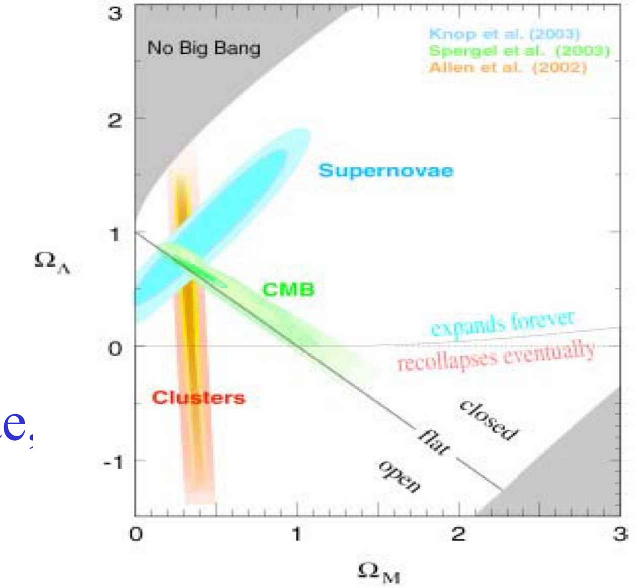
LAPTH- Annecy

Based on
G.B, K. Benakli, M. Goodsell, C. Moura, A. Pukhov,
arXiv:0905.1043

Motivation

- Evidence from rotation curves, clusters, supernovae, CMB that DM dominate over visible matter



- A new neutral and stable weakly interacting particle is good DM candidate
  - has typical annihilation cross section for $\Omega h^2 \sim 0.1$ in standard cosmological scenario

$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle} .$$

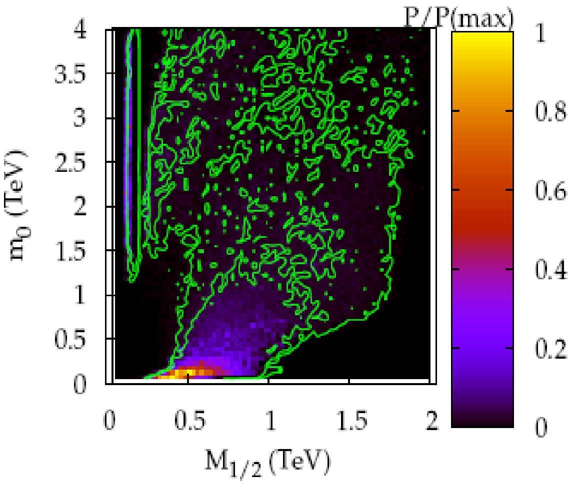
- Many candidates, the best motivated ones are tied to the symmetry breaking/ hierarchy problem

- DM< TeV scale : testable at colliders

- Neutralino in SUSY : prime candidate (other examples LHM ...)

- In MSSM, R-parity makes LSP stable
  - also stabilizes the proton
- LSP in general neutralino (also gravitino or RH sneutrino)
  - Neutral Majorana particle
- Neutralino LSP: much studied, can be tested at colliders and/or direct detection and/or indirect detection
  - Compatible with all precision data, B physics, DD, Tevatron, in large regions of parameter space of MSSM
  - Not easy to explain PAMELA/positron (huge boost factor needed) – Silk, Cirelli
- All there is to know about neutralino LSP?
- Consider extension of MSSM : Dirac masses for gauginos

CMSSM: Allanach et al



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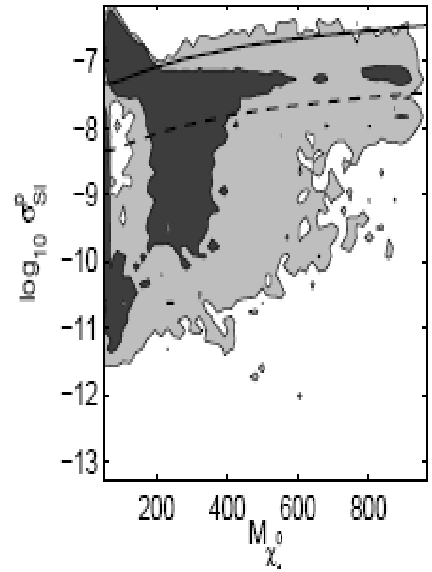


MSSM8: GB et al

SUSY with Dirac gaugino masses

- Additional Dirac gaugino adjoint
  - Singlet S, triplet T, octet O

- Models with spontaneous breaking of SUSY lead to extension of MSSM with DG-adjoint

  - Underlying N=2 SUSY pairs gaugino adjoint with vector multiplet
    - Fayet 1978
  - Models with Xtra-dim+ SUSY combine two Majo fermion mass 1/2R
    - Pomarol, Quiros 9806263
  - General gauge mediation
    - Benakli, Goodsell, arXiv:0811.4404

The model : fields

	Names		Spin 0	Spin 1/2	Spin 1	$SU(3)$, $SU(2)$, $U(1)_Y$
MSSM	Quarks	$\mathbf{Q}$	$\tilde{Q} = (\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)		$(\mathbf{3}, \mathbf{2}, 1/6)$
		$\mathbf{u^c}$	$\tilde{u}^c_L$	u^c_L		$(\overline{\mathbf{3}}, \mathbf{1}, \text{-}2/3)$
	($\times$3 families)	$\mathbf{d^c}$	$\tilde{d}^c_L$	u^c_L		$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$
	Leptons	$\mathbf{L}$	$(\tilde{\nu}_{eL}, \tilde{e}_L)$	(ν_{eL}, e_L)		$(\mathbf{1}, \mathbf{2}, \text{-}1/2)$
	($\times$3 families)	$\mathbf{e^c}$	$\tilde{e}^c_L$	e^c_L		$(\mathbf{1}, \mathbf{1}, 1)$
	Higgs	$\mathbf{H_u}$	(H^+_u, H^0_u)	$(\tilde{H}^+_u, \tilde{H}^0_u)$		$(\mathbf{1}, \mathbf{2}, 1/2)$
		$\mathbf{H_d}$	(H^0_d, H^-_d)	$(\tilde{H}^0_d, \tilde{H}^-_d)$		$(\mathbf{1}, \mathbf{2}, \text{-}1/2)$
	Gluons	$\mathbf{W}_{3\alpha}$		$\lambda_{3\alpha}$ $[\equiv \tilde{g}_\alpha]$	g	$(\mathbf{8}, \mathbf{1}, 0)$
	W	$\mathbf{W}_{2\alpha}$		$\lambda_{2\alpha}$ $[\equiv \tilde{W}^\pm, \tilde{W}^0]$	$W^\pm, W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
	B	$\mathbf{W}_{1\alpha}$		$\lambda_{1\alpha}$ $[\equiv \tilde{B}]$	B	$(\mathbf{1}, \mathbf{1}, 0)$
DG	DG-octet	$\mathbf{O_g}$	O_g $[\equiv \Sigma_g]$	χ_g $[\equiv \tilde{g}']$		$(\mathbf{8}, \mathbf{1}, 0)$
	DG-triplet	$\mathbf{T}$	$\{T^0, T^\pm\}$ $[\equiv \{\Sigma^W_0, \Sigma^\pm_W\}]$	$\{\chi^0_T, \chi^\pm_T\}$ $[\equiv \{\tilde{W}'^\pm, \tilde{W}'^0\}]$		$(\mathbf{1}, \mathbf{3}, 0)$
	DG-singlet	$\mathbf{S}$	S $[\equiv \Sigma_B]$	χ_S $[\equiv \tilde{B}']$		$(\mathbf{1}, \mathbf{1}, 0)$

The model - Lagrangian

- Dirac gaugino mass

$$
\begin{aligned}
\mathcal{L}_{gauge} = \quad & \int d^4x d^2\theta \, [\, \frac{1}{4}\mathbf{M}_1 \mathbf{W}_1^{\alpha} \mathbf{W}_{1\alpha} + \frac{1}{2}\mathbf{M}_2 \mathrm{tr}(\mathbf{W}_2^{\alpha} \mathbf{W}_{2\alpha}) + \frac{1}{2}\mathbf{M}_3 \mathrm{tr}(\mathbf{W}_3^{\alpha} \mathbf{W}_{3\alpha}) \\
& + \sqrt{2}\mathbf{m}_{1D}^{\alpha} \mathbf{W}_{1\alpha} \mathbf{S} + 2\sqrt{2}\mathbf{m}_{2D}^{\alpha} \mathrm{tr}(\mathbf{W}_{2\alpha} \mathbf{T}) + 2\sqrt{2}\mathbf{m}_{3D}^{\alpha} \mathrm{tr}(\mathbf{W}_{3\alpha} \mathbf{O}_{\mathbf{g}}) \,] \\
+ & \int d^4x d^2\theta d^2\bar{\theta} \quad (\sum_{ij} \mathbf{\Phi}_i^{\dagger} e^{g_j \mathbf{V}_j} \mathbf{\Phi}_i + h.c.)
\end{aligned}
$$

- Coupling of S and T to Higgs - superpotential

$$
\int d^4x d^2\theta \left[\mu \mathbf{H_u} \cdot \mathbf{H_d} + \frac{M_S}{2}\mathbf{S}^2 + \lambda_S \mathbf{S} \mathbf{H_d} \cdot \mathbf{H_u} + M_T \mathrm{tr}(\mathbf{T}\mathbf{T}) + 2\lambda_T \mathbf{H_d} \cdot \mathbf{T} \mathbf{H_u} \right]
$$

… Lagrangian

- Scalar soft terms

$$\begin{aligned} -\Delta\mathcal{L}_{soft} &= m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + B_\mu(H_u\cdot H_d + h.c.) \\ &+ m_S^2|S|^2 + \frac{1}{2}B_S(S^2 + h.c.) + 2m_T^2\mathrm{tr}(T^\dagger T) + B_T(\mathrm{tr}(TT) + h.c.) \\ &+ A_S\lambda_S(SH_d\cdot H_u + h.c.) + 2A_T\lambda_T(H_d\cdot TH_u + h.c.) \end{aligned}$$

- If DG from N=2 SUSY, $H_u H_d$ gauge supermultiplet, λ_S λ_T relate to gauge coupling

$$\lambda_S = \sqrt{2}g'\frac{1}{2}, \qquad \lambda_T = \sqrt{2}g\frac{1}{2},$$

Scalar potential

- Constrain from ρ parameter on triplet vev
- Easily satisfied for m_T>TeV

- Integrating out DG adjoint, take the limit m_S,m_T->∞
- Effective MSSM potential

$$
\begin{aligned}
V_{eff} &= (m_{H_u}^2+\mu^2)|H_u|^2+(m_{H_d}^2+\mu^2)|H_d|^2-[m_{12}^2 H_u\cdot H_d+h.c.] \\
&+\frac{1}{2}[\frac{1}{4}(g^2+g'^2)+\lambda_1](|H_d|^2)^2+\frac{1}{2}[\frac{1}{4}(g^2+g'^2)+\lambda_2](|H_u|^2)^2 \\
&+[\frac{1}{4}(g^2-g'^2)+\lambda_3]|H_d|^2|H_u|^2+[-\frac{1}{2}g^2+\lambda_4](H_d\cdot H_u)(H_d^*\cdot H_u^*) \\
&+(\frac{\lambda_5}{2}(H_d\cdot H_u)^2+[\lambda_6|H_d|^2+\lambda_7|H_u|^2](H_d\cdot H_u)+h.c.)
\end{aligned}
$$

here now:

$$
\begin{aligned}
\lambda_3 &= 2\lambda_T^2 \qquad \lambda_4=\lambda_S^2-\lambda_T^2 \\
\lambda_1 &= \lambda_2=\lambda_5=\lambda_6=\lambda_7=0.
\end{aligned}
$$

- New quartic term in scalar interactions and contribution to light Higgs mass.

Gluino and chargino sector

- 2 gluinos

$$M_{\tilde{g}} = \begin{pmatrix} M_3' & m_{3D} \\ m_{3D} & M_3 \end{pmatrix}$$

- 3 charginos

$$M_{Ch} = \begin{pmatrix} M_2' & m_{2D} & \frac{2\lambda_T}{g} m_W c_\beta \\ m_{2D} & M_2 & \sqrt{2} m_W s_\beta \\ -\frac{2\lambda_T}{g} m_W s_\beta & \sqrt{2} m_W c_\beta & \mu \end{pmatrix}.$$

Neutralino sector

- 6 neutralinos $\tilde{B}', \tilde{B}, \tilde{W}', \tilde{W}, \tilde{H}_1, \tilde{H}_2$

$$\begin{pmatrix} M_1' & m_{1D} & 0 & 0 & \frac{\sqrt{2}\lambda_S}{g'} m_Z s_W s_\beta & \frac{\sqrt{2}\lambda_S}{g'} m_Z s_W c_\beta \\ m_{1D} & M_1 & 0 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & 0 & M_2' & m_{2D} & -\frac{\sqrt{2}\lambda_T}{g} m_Z c_W s_\beta & -\frac{\sqrt{2}\lambda_T}{g} m_Z c_W c_\beta \\ 0 & 0 & m_{2D} & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ \frac{\sqrt{2}\lambda_S}{g'} m_Z s_W s_\beta & -m_Z s_W c_\beta & -\frac{\sqrt{2}\lambda_T}{g} m_Z c_W s_\beta & m_Z c_W c_\beta & 0 & -\mu \\ \frac{\sqrt{2}\lambda_S}{g'} m_Z s_W c_\beta & m_Z s_W s_\beta & -\frac{\sqrt{2}\lambda_T}{g} m_Z c_W c_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

- 4 parameters of MSSM (M_1,M_2,μ,$\tan\beta$)+ 6 new parameters

$$M_1', M_2', m_{1D}, m_{2D}, \lambda_S \text{ and } \lambda_T$$

Dark matter

- Neutralino or gravitino (only consider the neutralino case)

$$\tilde{\chi}_1^0 = N_{11}\tilde{B}' + N_{12}\tilde{B} + N_{13}\tilde{W}' + N_{14}\tilde{W} + N_{15}\tilde{H}_1 + N_{16}\tilde{H}_2$$

- Model implementation in micrOMEGAs
  - Tree-level spectrum
  - Effective Higgs potential + dominant one-loop corrections to Higgs masses

- Explore parameter space of the model to find neutralino LSP with a relic abundance compatible with WMAP

- Prediction rates for DM detection

- Emphasize scenarios differ from MSSM

Scenario1 – Dirac fermion

- $M_1=M_2=M_1'=M_2'=0$
- Assume bino – $\mu \gg m_{1D}$ $m_{2D}=2m_{1D}$
- Condition for Dirac fermion : lightest eigenvalues equal

$$\Delta m_{LSP} = -2\frac{M_Z^2 s_W^2}{\mu}\frac{(2\lambda_S^2-(g')^2)}{(g')^2}c_\beta s_\beta.$$

- In the limit of exact N=2 supersymmetry, $\lambda_S=g'/\sqrt{2}$ - LSP is Dirac gaugino.

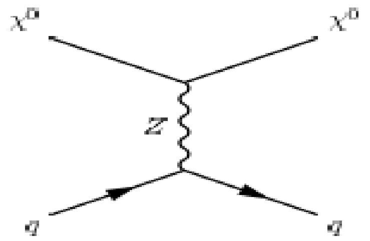
- Expect that breaking of N=2 SUSY – induce mass splitting (> few MeV)

$$\Delta m_{LSP} \approx 2c_\beta s_\beta \frac{M_Z^2 s_W^2}{\mu}\frac{3}{8\pi^2}\log(\frac{M_{N=2}}{M_{N=1}}).$$

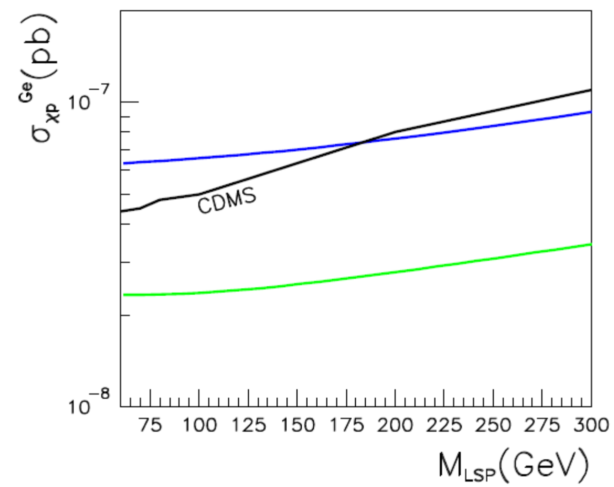
- Dirac neutralino – protect by a symmetry or fortuitous

Dirac fermion – direct detection

- Dirac fermion has effective vectorial coupling (squarks and Z)
  - *Z exchange contribute to SI interactions*



- DD strongly constrain these models,
  - need to suppress the $\chi\chi Z$ coupling :(naturally suppressed for bino)
  - Need squarks heavy (TeV)



μ=1TeV, tβ=10

Dirac bino as DM

- Dirac LSP: Can annihilate into light fermion pairs (e^-e^+) – no p-wave suppression

$$\langle \sigma(\overline{D}D \to \overline{f}f)v \rangle = \frac{g_Y^4 M_1^2}{8\pi} \sum_f \frac{N_f Y_f^4}{M_{\tilde{f}}^4} \left(1 + \mathcal{O}\left(\frac{T}{M_1}\right)\right),$$

- *Majorana : annihilation into light fermions can dominate at freeze-out but strongly suppressed at v=0.001c*
- Majorana: $\sigma v = a + bv^2$; $a \sim (m_f/m_\chi^2)$
- Excess of positron in PAMELA can be reconciled with a generic Dirac fermion dark matter even with little boost factor
  - Harnik Kribs 0810.5557
- In progress: predictions in this model

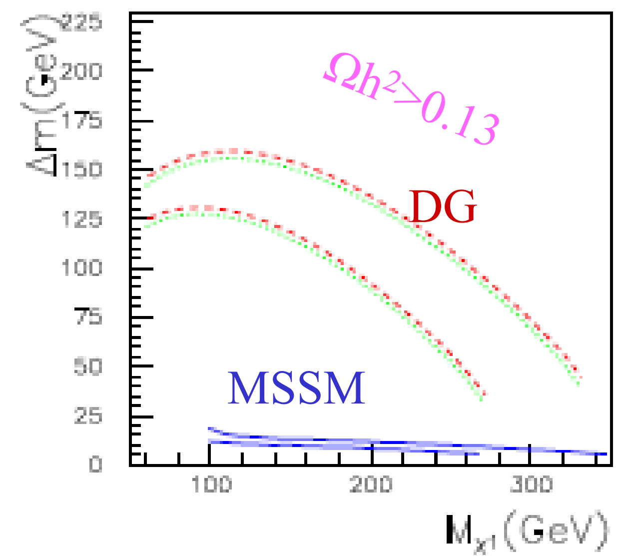
Scenario2 – pseudo Dirac bino

- $M_1 = M_2 = M_1' = M_2' = 0$
- Majorana LSP - bino
- Small mass splitting between LSP-NLSP – e.g. $\lambda_S \neq g'/\sqrt{2}$
- Small Boltzmann suppression, dominant annnihilation

$$\tilde{\chi}_1^0 \tilde{\chi}_2^0 \to f \bar{f}$$

- Hsieh, 0708.3970
- Sfermion masses need to be comparable to LSP but much larger stau-LSP mass splitting than MSSM (as for Dirac bino) for $\Omega h^2 \sim 0.11$

DG vs MSSM

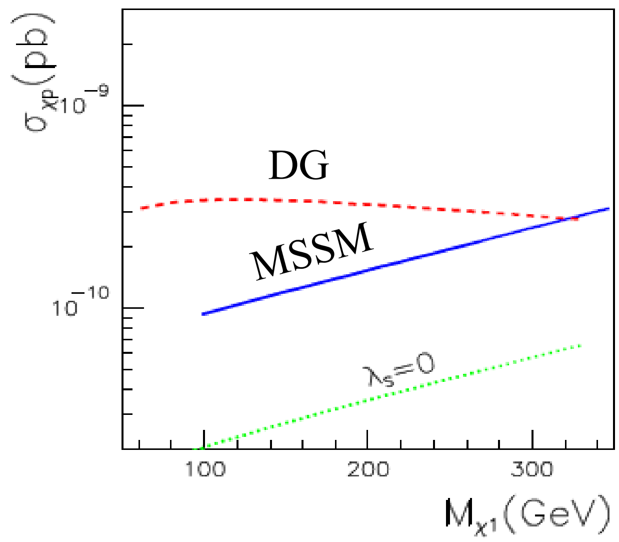


$\tan\beta = 10$, $M_{2D} = 2M_{1D}$ (DG)
$M_2 = 2M_1$ (MSSM)

pseudo Dirac bino -detection

- Discovery of sfermion and neutralino at colliders with such mass splitting incompatible with neutralino DM in MSSM
- Direct detection small (reach of Xenon 100) – typical of models with small higgsino fraction
- Direct detection rate strongly depends on lambda_s (influences coupling of LSP to Higgs)
- Indirect detection small in both models $\sigma v|_0 \approx 10^{-29}\mathrm{cm}^3\mathrm{sec.}$

DG vs MSSM



tanβ=10, M_{2D}=$2M_{1D}$ (DG)
M_2=$2M_1$ (MSSM)

Direct detection

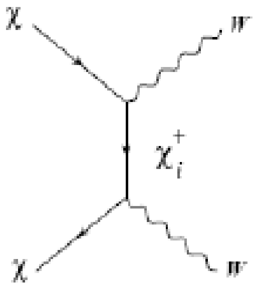
- LSP-LSP-higgs coupling

$$\mathcal{L} = \frac{1}{2}\overline{\tilde{\chi}^0}_i C_h^{ij} \overline{\tilde{\chi}^0}_i h + h.c.$$

$$\begin{aligned} C_h^{ii} &= \frac{-1}{s_W c_W}\left[e\left(c_W N_{i4} - s_W N_{i2}\right)\left(Z_{h_{11}} N_{i5} - Z_{h_{12}} N_{i6}\right)\right. \\ &\left. + \sqrt{2} s_W c_W \left(N_{i1}\lambda_S - N_{i3}\lambda_T\right)\right)\left(Z_{h_{12}} N_{i5} + Z_{h_{11}} N_{i6}\right)\Big] \end{aligned}$$

Case study – bino/higgsino

- Pure Dirac masses, $M_1=M_2=M_1'=M_2'=0$
- $\mu \sim m_{1D}$ $m_{2D}=2m_{1D}$
- Neutralino LSP: B/B'/h



- Assume heavy sfermions (1TeV) M_A=1TeV
- Mixed bino/higgsino– ann. in WW + coann.
- Annihilation diagrams involve higgsino(N_{i5},N_{i6}) or wino/wino'(N_{i3},N_{i4}) fraction of LSP, chargino exchange

$$\mathcal{L} = \overline{\tilde{\chi}^-}_a \gamma^\mu \left(C_L^{ai}(1-\gamma_5) + C_R^{ai}(1+\gamma_5) \right) \overline{\tilde{\chi}_i^0} W_\mu^- + h.c.$$

$$C_L^{ai} = \frac{e}{4s_W}\left(2N_{i4}U_{a2} + 2N_{i3}U_{a1} + \sqrt{2}N_{i5}U_{a3}\right)$$

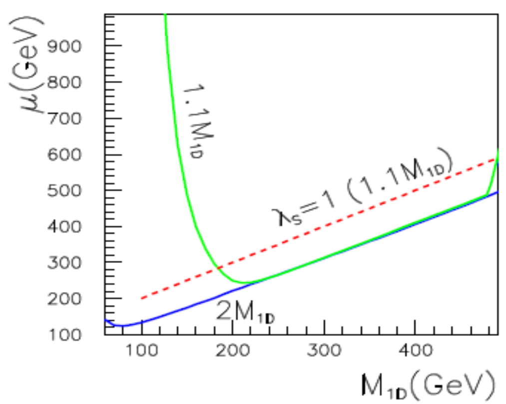
$$C_R^{ai} = \frac{e}{4s_W}\left(2N_{i4}V_{a2} + 2N_{i3}V_{a1} - \sqrt{2}N_{i6}V_{a3}\right)$$

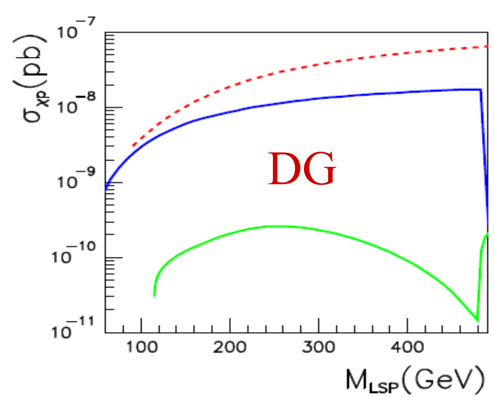
…bino/higgsino

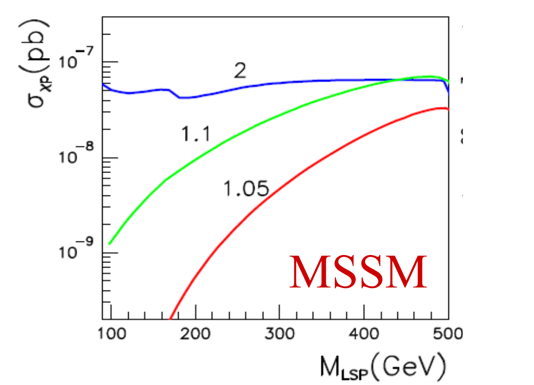
- $\Omega h^2 = 0.11$ --> $\mu \sim m_{1D}$
- LSP: small higgsino fraction 2-30%
- Annihilation into W not as efficient as MSSM - compensate by coannihilation channels

$$\tilde{\chi}^0_1\tilde{\chi}^0_2, \tilde{\chi}^0_1\tilde{\chi}^+, \tilde{\chi}^0_2\tilde{\chi}^0_2, \tilde{\chi}^0_1\tilde{\chi}^0_3$$

- Spectrum for region WMAP compatible similar to MSSM except: nearly degenerate B-B', W-W' and additional chargino
- DD/ID rates are lower especially for light LSP (coannihilation)







Other scenarios

- Large Majorana masses → see-saw , neutralino/chargino sector MSSM-like, still different DM properties

- All masses $\neq 0$
- No problem in finding suitable DM candidate
- LSP : B, B/B’,B/h, B’/h, B/W, B/W’

- All neutralino/chargino could be within LHC reach – additional states signature of BMSSM

- Additional neutralinos also in SUSY model with extended gauge sector U(1)
  - Kalinowski, King, Roberts, 0811.2204

Remarks: Dirac gaugino at LHC

- Evidence for Dirac nature of gauginos?
    - Choi, Drees, Freitas, Zerwas, arXiv:0808.2410
- Dirac gluino
    - qq'->$\sim q_L$,$\sim q'_R$ only
- Decays:
    - $\sim q_L$ -> $q\chi$-> q l^- $\sim l^+$ (Dirac)
    - $\sim q_L$ -> $q\chi$-> q l^+ $\sim l^-$, q l^- $\sim l^+$ (Majorana)
    - Majorana/Dirac differ in same sign/opposite sign leptons
- To be investigated by ATLAS: LHC10TeV sensitive to Dirac/Majorana nature of gauginos ? Les Houches Workshop (A. Martin et al.)
- Spectrum expected can be different than expected in MSSM and often almost degenerate LSP B,B'

Conclusions

- Dark matter in SUSY more diversified than the bino neutralino in CMSSM
- Explore only part of the parameter space of Dirac gaugino model
- Predictions for sparticle spectrum and/or direct detection can be quite different than MSSM – especially in the (pseudo-)Dirac case
- Signals of this model at colliders – to be pursued