

# Neutralino Dark Matter in the BMSSM

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CFTP - IST, Lisbon

December 19<sup>th</sup> 2009  
PASC Winter school

Work in progress      NB, A. Goudelis

JHEP 0908:053,2009      NB, K. Blum, M. Losada, Y. Nir

# Outline

- 1 Motivation
- 2 The BMSSM
- 3 Dark matter
- 4 Dark Matter Direct detection
- 5 Dark Matter Indirect detection ( $\gamma$ -rays)
- 6 Conclusions and prospects

# Motivation

- In the framework of the MSSM, the smallness of the quartic Higgs coupling poses a problem.
- The tree level bound on the Higgs mass is violated: large enough loop corrections to satisfy the lower bound on the Higgs mass.
  - at least one of the stop masses should be rather heavy,
  - left-right-stop mixing should be substantial.

→ Little hierarchy problem!

There can be significant effects from **non-renormalizable terms** on the same order as the one-loop terms.

Brignole, Casas, Espinosa, Navarro, 03

Dine, Seiberg, Thomas, 07

We focus on an effective action analysis to the Higgs sector as an approach to consider the effects of **New Physics Beyond the MSSM**.

# Non-renormalizable operators

Leading non-renormalizable terms that modify the **quartic coupling**:

$$W_{\text{BMSSM}} = \frac{\lambda_1}{M} (H_u H_d)^2 + \frac{\lambda_2}{M} Z (H_u H_d)^2$$

In the scalar potential, the following quartic terms are generated:

$$2 \epsilon_1 H_u H_d (H_u^\dagger H_u + H_d^\dagger H_d) + \epsilon_2 (H_u H_d)^2$$

where

$$\epsilon_1 \equiv \frac{\mu^* \lambda_1}{M} \quad \epsilon_2 \equiv -\frac{m_{\text{susy}} \lambda_2}{M}$$

Vacuum stability issues:  $\epsilon_1 \lesssim 0.1$ ,  $\epsilon_2 \lesssim 0.05$  see Blum, Delaunay, Hochberg, 09

# Higgs spectrum

We consider the case where the NR operators can still be treated as **perturbations**:

$$M_h^2 \simeq (m_h^{\text{tree}})^2 + \delta_i m_h^2 + \delta_\epsilon m_h^2 \gtrsim (114\text{GeV})^2$$

$$\delta_\epsilon m_h^2 = 2v^2 \left( \epsilon_2 - 2\epsilon_1 s_{2\beta} - \frac{2\epsilon_1(m_A^2 + m_Z^2)s_{2\beta} + \epsilon_2(m_A^2 - m_Z^2)c_{2\beta}^2}{\sqrt{(m_A^2 - m_Z^2)^2 + 4m_A^2 m_Z^2 s_{2\beta}^2}} \right)$$

The  $\delta_\epsilon m_h^2$  relaxes the constraint in a significant way:  
for  $\epsilon_1 \lesssim -0.1$  and  $\tan\beta \lesssim 10$       **→ light and unmixed stops allowed!**

# Higgsinos

$$M_{\chi^0} = \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix} + \frac{4\epsilon_1 m_W^2}{\mu^* g^2} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & s_\beta^2 & s_{2\beta} \\ 0 & 0 & s_{2\beta} & c_\beta^2 \end{pmatrix}$$

The lightest neutralino  $\chi_1^0$  is a natural candidate for **cold dark matter!**

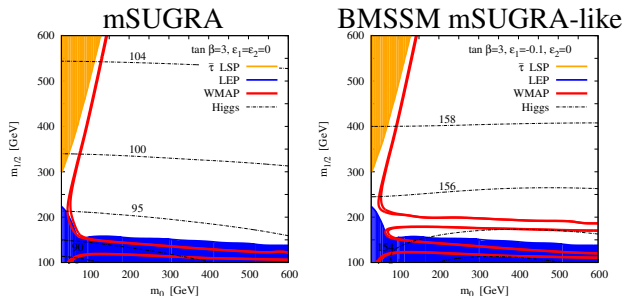
The NR operators also modify

- the chargino mass matrix
- Higgs-higgsino-higgsino & Higgs-Higgs-higgsino-higgsino couplings (DM annihilation cross sections)

Berg, Edsjö, Gondolo, Lundstrom, Sjörs, '09; NB, Blum, Losada, Nir, '09

➔ Spectrum, dark matter relic density and DM detection rates are calculated using modified versions of SuSpect and micrOMEGAS

# Correlated stop-slepton masses

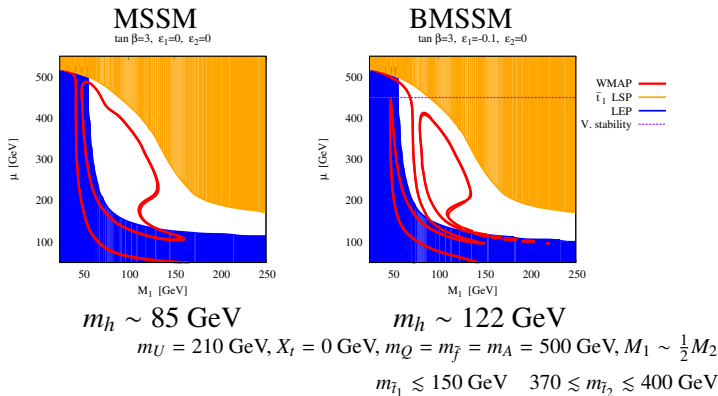


$A_0 = 0$  GeV and  $\mu > 0$

It should not be taken as an extended mSUGRA,  
 but just as a framework specified at low energy.

- Important uplift of the Higgs mass  $\rightarrow$  ‘bulk region’ re-opened
- New region fulfilling DM constraint: Higgs-funnel
- $\chi_1^0$  bino-like: marginal impact on  $m_\chi$  and ann. cross section

# Light stops, heavy sleptons

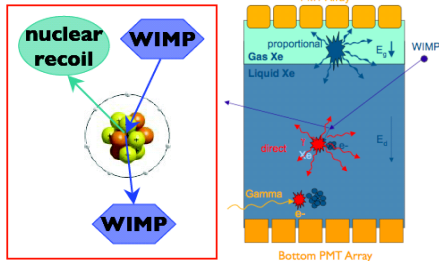


- Important uplift of the Higgs mass  $\rightarrow$  New region available
- New region fulfilling DM constraint: Higgs-funnel
- ‘Mixed region’ where LSP is a higgsino-bino mixture  $\chi\chi \rightarrow WW, hh$
- Stop coannihilation ( $m_\chi \sim m_{\tilde{t}_1}$ )  $\chi\tilde{t} \rightarrow Wb, gt$  and  $\tilde{t}\tilde{t} \rightarrow gg$

# Dark matter direct detection

Direct detection experiments are designed to detect **dark matter particles** by their **elastic collision with target nuclei**, placed in a detector on the Earth.

## XENON



Exposures:  $\varepsilon = 30, 300, 3000 \text{ kg} \cdot \text{year}$   
 Xenon1T and 11 days, 4 months or 3 years

## Recoil rates

$$\frac{dN}{dE_r} = \frac{\sigma_{\chi-p} \cdot \rho_0}{2 M_r^2 m_\chi} F(E_r)^2 \int_{v_{\min}(E_r)}^{v_{\text{esc}}} \frac{f(v)}{v} dv$$

$$\text{Reduced mass } M_r = \frac{m_\chi m_N}{m_\chi + m_N}$$

$N$ : number of scatterings ( $\text{s}^{-1} \text{kg}^{-1}$ )

$E_r$ : nuclear recoil energy  $\sim \text{few keV}$

$m_\chi$ : WIMP mass

$\sigma_{\chi-p}$ : WIMP-proton scattering cross-section

→ Assume pure **spin-independent** coupling

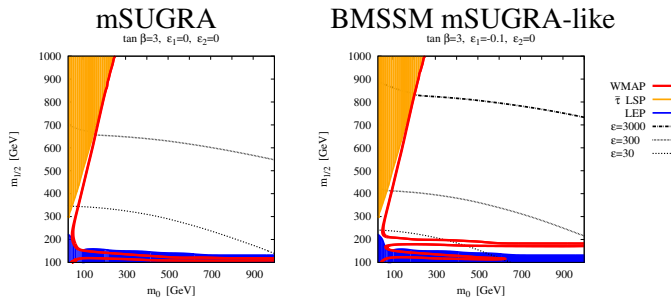
$\rho_0$ : local WIMP density  $0.38 \text{ GeV cm}^{-3}$

$F$ : nuclear form factor Woods-Saxon

$f(v)$ : WIMP local vel. distribution M.B.

$$f(v) = \frac{1}{\sqrt{\pi}} \frac{v}{1.05 v_0^2} \left[ e^{-(v-1.05 v_0)^2/v_0^2} - e^{-(v+1.05 v_0)^2/v_0^2} \right]$$

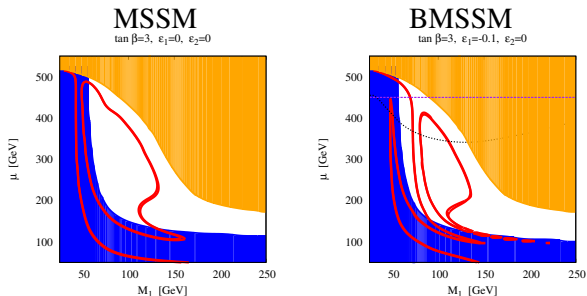
# Correlated stop-slepton masses



Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low  $m_0$  and  $m_{1/2}$  ( $m_0 \rightarrow$  increase squark masses,  $m_{1/2} \rightarrow$  increase LSP mass)
- For low  $m_{1/2}$ , LSP tends to be a higgsino-bino mixed state ( $C_{\chi\chi h}$ )
- Detection maximised for low  $\tan \beta$ ,  $C_{\chi\chi h} \propto \sin 2\beta$  ( $|\mu| \gg M_1$ )
- NR operators  $\rightarrow$  deterioration of the detection:  $m_h$
- Sizable amount of the parameter space can be probed

# Light stops, heavy sleptons



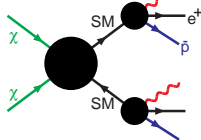
Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low  $\mu$  and/or  $M_1$ : light LSP
- Scattering cross section enhanced near  $\mu \sim M_1$  ( $C_{\chi\chi h}$ ,  $C_{\chi\chi H}$ )
- Neither  $Z$ - nor  $h$ -funnel enhance SI direct detection
- Spin-dependent detection sensible to the  $Z$ -peak (non-universality)
- NR operators deteriorates detection:  
increase  $m_h$  and suppression  $C_{\chi\chi h}$

# Dark matter indirect detection ( $\gamma$ -rays)

We study the ability of **Fermi** to identify **Gamma-rays** generated in **DM annihilation** in the galactic center

$$\chi\bar{\chi} \rightarrow b\bar{b}, WW \dots \rightarrow \gamma + \dots$$



Fermi/GLAST telescope (Launched '08)

## Differential event rate

$$\Phi_{\gamma}(E_{\gamma}, \psi) = \sum_i \frac{dN_{\gamma}^i}{dE_{\gamma}} \langle \sigma_i v \rangle \frac{1}{8\pi m_{\chi}^2} \int_{los} \rho(r)^2 dl$$

$\frac{dN}{dE}$ : spectrum of secondary particles

$E_{\gamma}$ : gamma energy

$\langle \sigma v \rangle$ : averaged annihilation cross-section by velocity

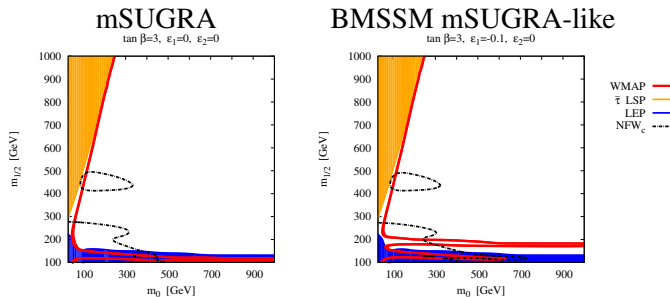
$\rho(r)$ : dark matter halo profile

3 halo profiles: Einasto, NFW and NFW<sub>c</sub> (adiabatic compression due to baryons)

5-years data acquisition,  $\Delta\Omega = 3 \cdot 10^{-5}$  sr

Background: HESS measurements

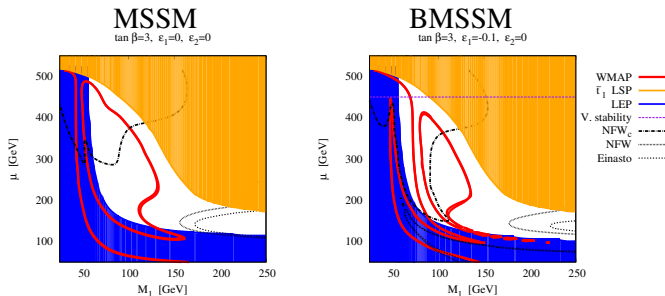
# Correlated stop-slepton masses



Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low  $m_0$  and  $m_{1/2}$
- Thresholds:  $\chi\chi \rightarrow W^+W^-$ ,  $\chi\chi \rightarrow t\bar{t}$
- Detection maximised for high  $\tan \beta$   $\chi\chi \rightarrow b\bar{b}$  and  $\tau\tau \propto \tan \beta$  and  $1/\cos \beta$
- For large  $\tan \beta$  thresholds weaken
- NR operators: Higgs pole ‘invisible’ ( $v \rightarrow 0$ )
- Only scenarios with highly cusped inner regions could be probed

# Light stops, heavy sleptons



Exclusion lines: ability to test and exclude at 95% CL

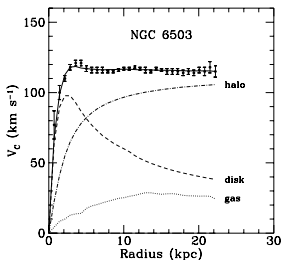
- Detection enhanced for  $M_1 \gg \mu$  ( $\chi\chi Z$  and  $\chi\chi^\pm W^\mp$  couplings)
- $\langle\sigma v\rangle$  enhanced for high tan  $\beta$  ( $\chi\chi \rightarrow b\bar{b}, WW$ )
- $h$ -funnel could not be tested (no  $s$ -wave contribution)
- NFW and Einasto could test some regions, but not relevant

## Conclusions and prospects

- NR operators in the Higgs sector introduced for reducing fine-tuning (Little hierarchy)
- Bulk region re-opened
- Possible to have light unmixed stops
- New regions fulfilling the DM constraint:
  - Higgs-pole
  - Higgs-stop coannihilation
- EW baryogenesis open up
- Both scenarios could be tested or excluded by Xenon1T
- Complementarity with other detection modes:  $\gamma$ -rays
- DM indirect detection ( $e^+$  and  $\bar{p}$ ) prospects: work in progress
- EW precision data should be taken into account

# Introduction

## Galactic Rotation Curves



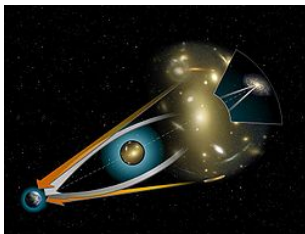
Normally, for  $r > r_{\text{vis}}$  one would expect

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

instead

$$v(r) \approx \text{const}$$

## Gravitational Lensing



Light bends differently than predicted from GR, if only luminous matter is taken into account.

### And also:

- Primordial Nucleosynthesis
- Large Scale Structure

## Cosmic Microwave Background

Blackbody radiation, ALMOST homogeneous. Small inhomogeneities due to DM structures during matter-radiation decoupling in the early universe. Only one cosmological model manages (so far!!!) to explain (almost) all observations:  $\Lambda$ CDM

- GR with non-vanishing Cosmological Constant
- Cold Dark Matter

WMAP 5-year results give

$$\Omega_{\text{DM}} h^2 = 0.1131 \pm 0.0034$$

whereas

$$\Omega_{\text{b}} h^2 = 0.02267 \pm 0.00058$$

## The EWPT in the BMSSM

Recall the small window in which a strong phase transition can occur in the MSSM, given the current experimental bound on  $m_h$ .

- large  $m_A$
- large  $\tan \beta$
- $m_Q \sim \text{few TeV}$
- $m_{\tilde{t}_1} \lesssim m_t$
- large mixing in stop sector

This introduces a large hierarchy between the 2 stops and further increases the amount of fine tuning in the theory.

## The EWPT in the BMSSM

Blum, Nir

The main feature that was identified in the one-loop analysis of the EWPT of the BMSSM is that the quartic coupling can **simultaneously** give  $m_h > 114\text{GeV}$  and  $\phi/T > 1$  as the one-loop and **new** tree level contributions can share and compensate enough to do the job! At the same time you can reduce the hierarchy between the two stop masses.