

# Neutralino Dark Matter in the BMSSM

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JCAP 03(2010)007

NB, A. Goudelis

JHEP 08(2009)053

NB, K. Blum, M. Losada, Y. Nir

# Outline

- 1 Motivation
- 2 The BMSSM
- 3 Dark Matter
  - Motivation
  - Correlated stop-slepton masses
  - Light stops, heavy sleptons
- 4 Dark Matter Direct Detection
- 5 Dark Matter Indirect Detection
  - $\gamma$ -rays
- 6 Conclusions and prospects

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# MSSM Higgs potential

The MSSM contains 2 doublets of complex scalar fields of opposite hypercharge:

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

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Full tree-level scalar Higgs potential:

$$V_H = (|\mu|^2) |H_u|^2 + (|\mu|^2) |H_d|^2$$

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- $\rightarrow V_H$  is CP conserving (even though the full  $L$  violates CP)

# MSSM Higgs potential

The neutral components of the 2 Higgs fields develop vevs:

$$\langle H_u \rangle = v_u = v \sin\beta \quad \langle H_d \rangle = v_d = v \cos\beta \quad v \sim 174\text{GeV}$$

EW symmetry breaking:  $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{EW}}$

The spectrum contains:

- $h$  and  $H$ : 2 CP even Higgs bosons
- $A$ : 1 CP odd Higgs boson
- $H^+$  and  $H^-$ : 2 charged Higgs bosons

# Tree level Higgs spectrum

In terms of  $M_A$  and  $\tan\beta$  the tree level Higgs spectrum is

$$m_h^2 = \frac{1}{2} \left[ m_Z^2 + m_A^2 - \sqrt{(m_A^2 - m_Z^2)^2 + 4 m_A^2 m_Z^2 \sin^2 2\beta} \right]$$

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→ To avoid a contradiction we need both  
large  $\tan\beta$  and large radiative corrections

# Radiative corrections

Most important RC comes from loops of tops and stops:

$$\delta_{1\text{-loop}} m_h^2 \sim \frac{12}{16\pi} \left[ \ln \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \frac{|X_t|^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \ln \frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2} \right. \\ \left. + \frac{1}{2} \left( \frac{|X_t|^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \right)^2 \left( 2 - \frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \ln \frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2} \right) \right]$$

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Consistency with LEP II achieved with

- **Heavy stops**  $m_{\tilde{t}} \sim 600$  GeV to few TeV
- ✗ However, the superpartners make the theory natural and they should not be too heavy

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✗ SUSY Little Hierarchy Problem

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# Corrections to the MSSM

Assume that there is New Physics beyond the MSSM at a scale  $M$ , much above the electroweak scale  $m_Z$  and the scale of the SUSY breaking terms  $m_{\text{susy}}$ .

$$\epsilon \sim \frac{m_{\text{susy}}}{M} \sim \frac{m_Z}{M} \ll 1$$

The corrections to the MSSM can be parametrized by operators suppressed by inverse powers of  $M$ ; i.e. by powers of  $\epsilon$ .

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

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

Remember the ordinary MSSM superpotential:

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There are only 2 operators at order  $\frac{1}{M}$ :

$$O_1 = \frac{1}{M} \int d^2\theta (H_u H_d)^2$$
$$O_2 = \frac{1}{M} \int d^2\theta Z (H_u H_d)^2$$

$Z \equiv \theta^2 m_{\text{susy}}$ : spurion field

$O_1$ : is a dimension 5 SUSY operator

$O_2$ : represents SUSY breaking

→ Both operators can lead to CP violation

# BMSSM Higgs potential

Corrections to the MSSM Higgs potential

$$\begin{aligned} \delta L = & 2 \epsilon_1 H_u H_d \left( H_u^\dagger H_u + H_d^\dagger H_d \right) + \epsilon_2 (H_u H_d)^2 + \text{h.c.} \\ & + \frac{\epsilon_1}{\mu^*} \left[ 2(H_u H_d)(\tilde{H}_u \tilde{H}_d) + 2(\tilde{H}_u H_d)(H_u \tilde{H}_d) \right. \\ & \left. + (H_u \tilde{H}_d)(H_u \tilde{H}_d) + (\tilde{H}_u H_d)(\tilde{H}_u H_d) \right] + \text{h.c.} \end{aligned}$$

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

# Higgs spectrum

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

$$M_h^2 \simeq \left(m_h^{\text{tree}}\right)^2 + \delta_{\tilde{t}} m_h^2 + \delta_{\epsilon} m_h^2 \gtrsim (114 \text{ GeV})^2$$

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

$$\delta_{\epsilon} m_h^2 \sim \text{few dozens of GeVs!}$$

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Other Higgs masses also receive corrections...

# 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

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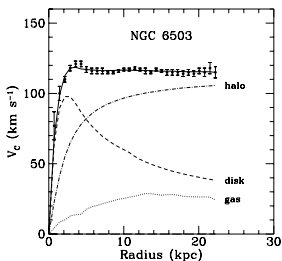
➔ Spectrum, dark matter relic density and DM detection rates are calculated using modified versions of SuSpect and micrOMEGAS

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# Why Dark Matter?

## Galactic Rotation Curves



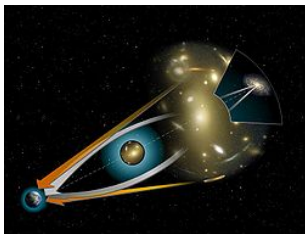
Normally, for  $r > r_{\text{vis}}$  one would expect

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

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

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

# Correlated stop-slepton masses: mSUGRA-like

The mSUGRA model is specified by 5 parameters:

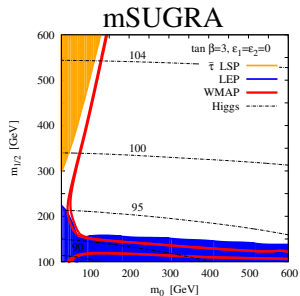
- $\tan\beta$ : ratio of the Higgs vevs
- $m_{1/2}$ : common mass for the gauginos (bino, wino and gluino)
- $m_0$ : universal scalar mass (sfermions and Higgs bosons)
- $A_0$ : universal trilinear coupling
- $\text{sign } \mu$ : sign of the  $\mu$  parameter

In mSUGRA scenarios usually the lightest neutralino is the LSP

Because of the LEP constraint over the Higgs mass, the *bulk region* (i.e. low  $m_0$  and low  $m_{1/2}$ ) is ruled out.

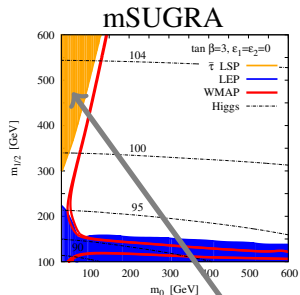
# Correlated stop-slepton masses

Let's take:  $A_0 = 0$  GeV,  $\mu > 0$  and  $\tan\beta = 3$



# Correlated stop-slepton masses

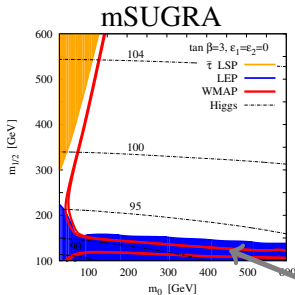
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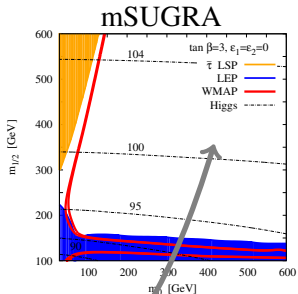
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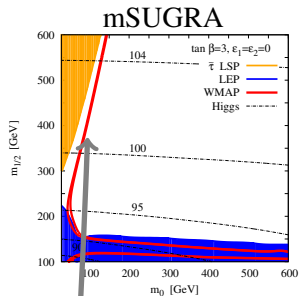
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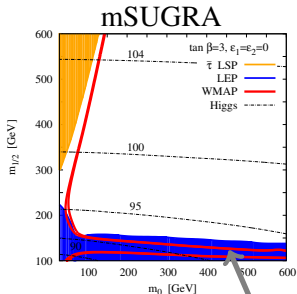
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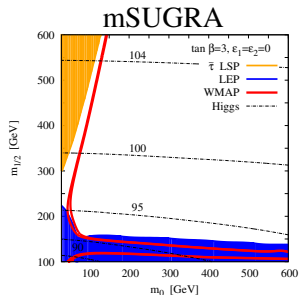
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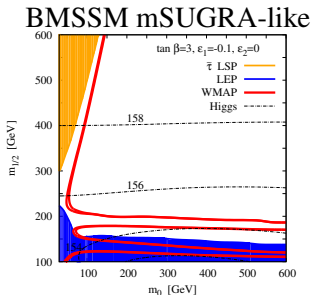
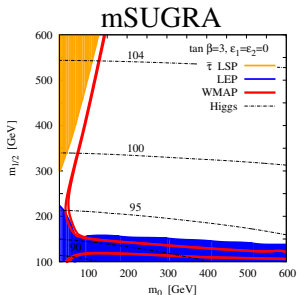
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- ✗ However  $m_h \lesssim 105$  GeV: The whole region is excluded!

# Correlated stop-slepton masses

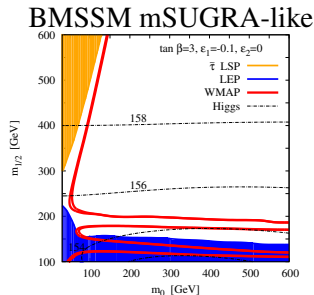
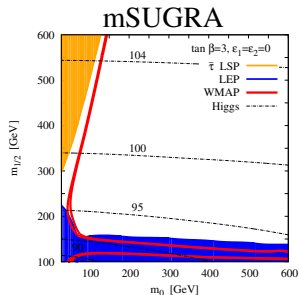
Let's take:  $A_0 = 0$  GeV,  $\mu > 0$  and  $\tan\beta = 3$        $\epsilon_1 = -0.1, \epsilon_2 = 0$



It should not be taken as an extended mSUGRA,  
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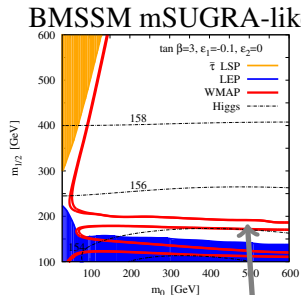
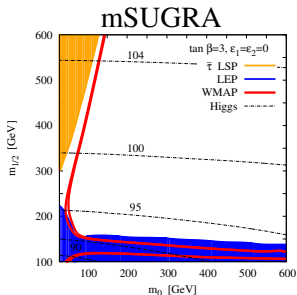


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- ✓ Important uplift of the Higgs mass  $\rightarrow$  'bulk region' re-opened

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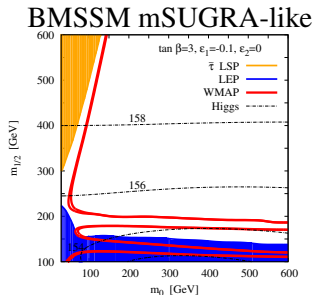
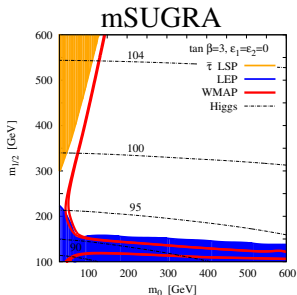


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- New region fulfilling DM constraint: Higgs-funnel
- $\chi_1^0$  bino-like: marginal impact on  $m_\chi$  and ann. cross section

## Light stops, heavy sleptons

Now we consider a low-energy scenario giving rise to light stops

- $\tan\beta$ : ratio of the Higgs vevs
- $\mu$ : higgsino mass parameter
- $m_A$ : pseudoscalar Higgs mass parameter
- $X_t$ : trilinear coupling for stops,  $X_t = A_t - \mu/\tan\beta$
- $M_2$ : wino mass parameter,  $M_1 \sim \frac{1}{2}M_2$
- $m_U$ : stop right mass parameter
- $m_Q$ : 3<sup>rd</sup> generation squarks left mass parameter
- $m_{\tilde{f}}$ : mass for sleptons, 1<sup>st</sup> and 2<sup>nd</sup> gen. squarks and  $\tilde{b}_R$   
 $m_U = 210 \text{ GeV}$ ,  $X_t = 0 \text{ GeV}$ ,  $m_Q = m_{\tilde{f}} = m_A = 500 \text{ GeV}$

## Light stops, heavy sleptons

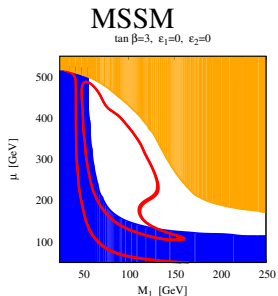
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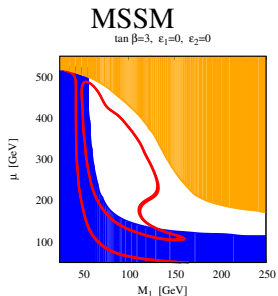
$$m_{\tilde{t}_1} \lesssim 150 \text{ GeV}, \quad 370 \text{ GeV} \lesssim m_{\tilde{t}_2} \lesssim 400 \text{ GeV}$$

A scenario with light unmixed stops is ruled out in the MSSM

# Light stops, heavy sleptons

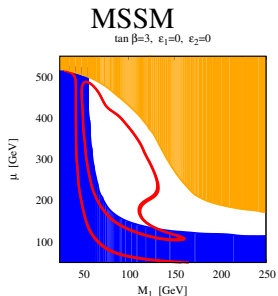


# Light stops, heavy sleptons



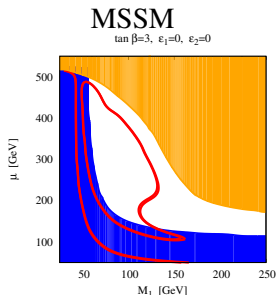
- Regions excluded:  $\tilde{t}$  LSP

# Light stops, heavy sleptons



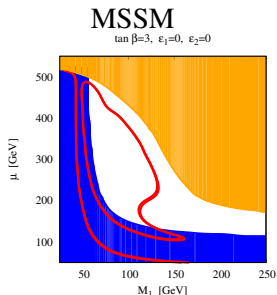
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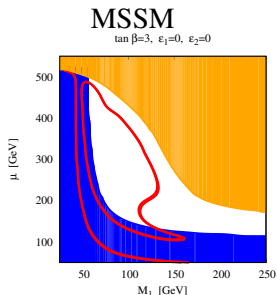
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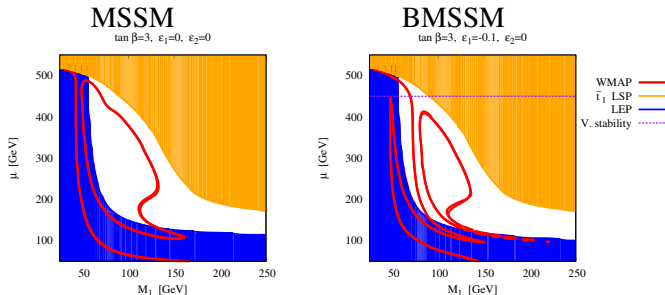
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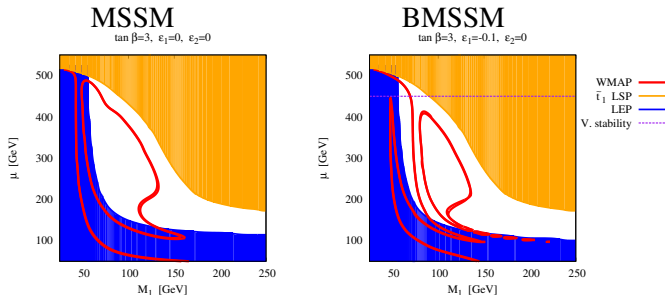
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- ✗ However  $m_h \lesssim 85 \text{ GeV}$ : The whole region is excluded!

# Light stops, heavy sleptons



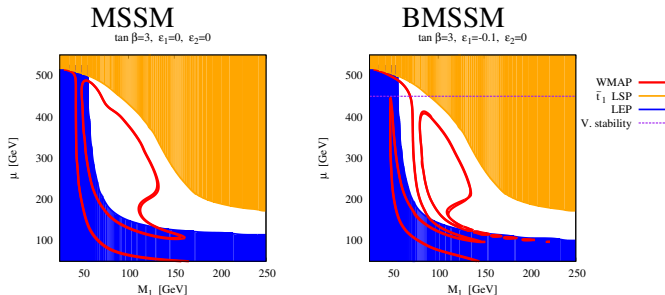
✓ important uplift of the Higgs mass:  $m_h \sim 122$  GeV

# Light stops, heavy sleptons



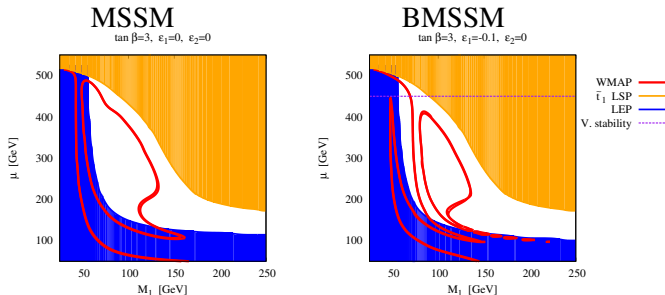
- ✓ important uplift of the Higgs mass:  $m_h \sim 122$  GeV
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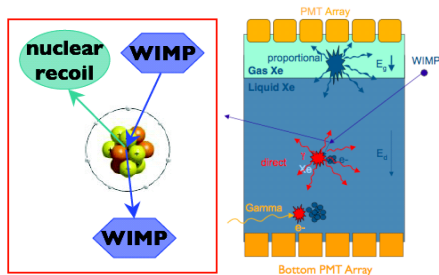
# Outline

- 1 Motivation
- 2 The BMSSM
- 3 Dark Matter
  - Motivation
  - Correlated stop-slepton masses
  - Light stops, heavy sleptons
- 4 Dark Matter Direct Detection**
- 5 Dark Matter Indirect Detection
  - $\gamma$ -rays
- 6 Conclusions and prospects

# 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

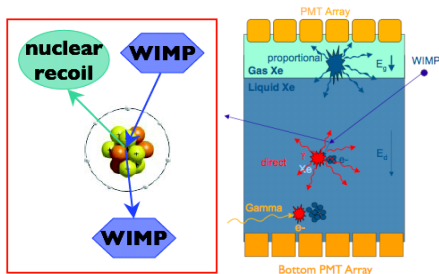


Exposures:  $\varepsilon = 30, 300, 3000 \text{ kg} \cdot \text{year}$   
 Xenon1T and 11 days, 4 months or 3 years

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Xenon discriminates signal from background by simultaneous measurements of:

- scintillation
- ionization

The collaboration expects to have a negligible background.

→ 7 energy bins between [4, 30] keV

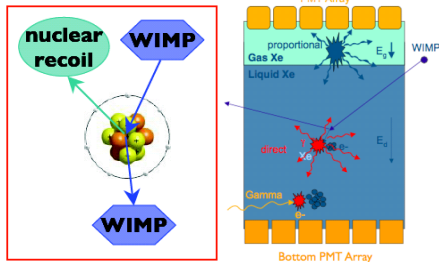
*Detectability* definition:

$$\chi_i^2 = \frac{(N_i^{\text{tot}} - N_i^{\text{bkg}})^2}{N_i^{\text{tot}}}$$

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## 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

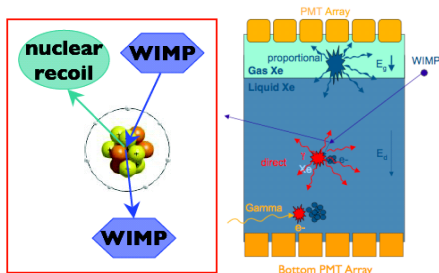
$f(v)$ : WIMP local vel. distribution M.B.

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

# Dark matter direct detection

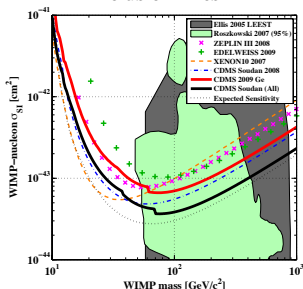
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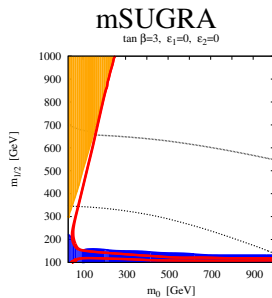
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## Exclusion lines



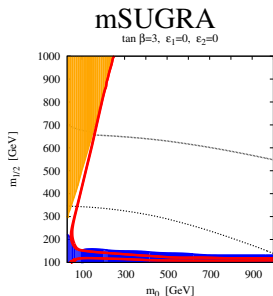
Ability to test and exclude regions in the  $[\sigma, m_\chi]$  plane

# Correlated stop-slepton masses



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

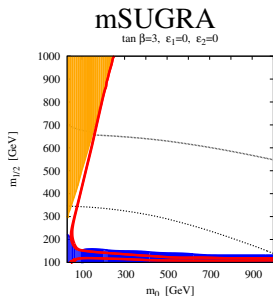
# Correlated stop-slepton masses



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- Detection prospects maximised for low  $m_0$  and  $m_{1/2}$  values  
 ( $m_0 \rightarrow$  increase squark masses,  $m_{1/2} \rightarrow$  increase LSP mass)

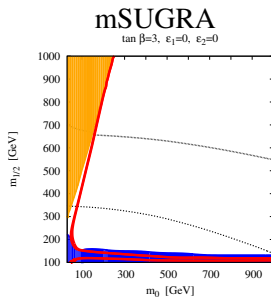
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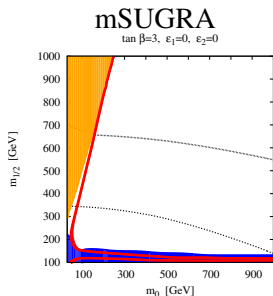
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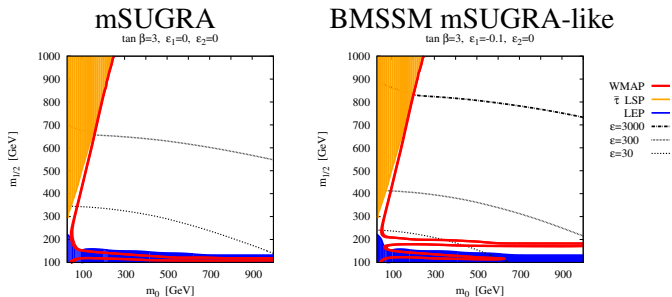
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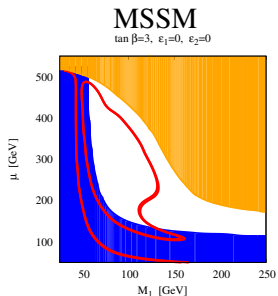
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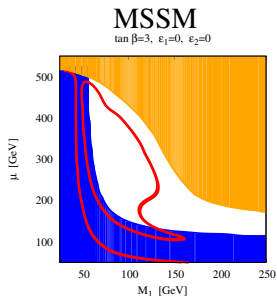
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- Detection maximised for low  $\tan\beta$ ,  $C_{\chi\chi h} \propto \sin 2\beta$  ( $|\mu| \gg M_1$ )
- ✓ Sizable amount of the parameter space can be probed
- ➔ NR operators  $\rightarrow$  deterioration of the detection:  $m_h$
- ✓ But without NR operators, the parameter space was excluded!

# Light stops, heavy sleptons



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

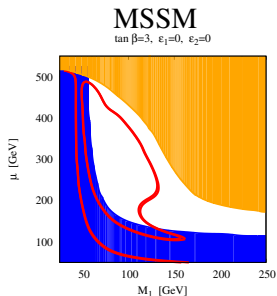
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✘ Partially ruled out by Xenon10 and CDMS-II results!

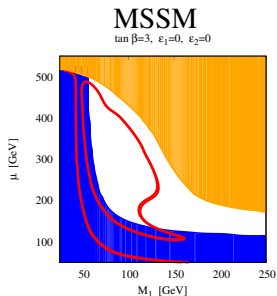
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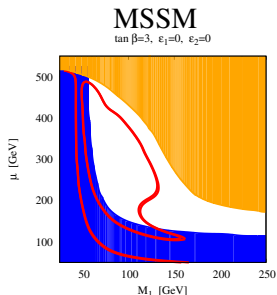
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  - Scattering cross section enhanced near  $\mu \sim M_1$  ( $C_{XXh}, C_{XXH}$ )

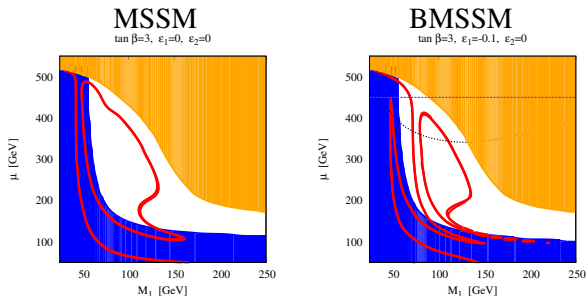
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  - Scattering cross section enhanced near  $\mu \sim M_1$  ( $C_{\chi\chi h}, C_{\chi\chi H}$ )
  - Neither Z- nor  $h$ -funnel enhance SI direct detection
    - Spin-dependent detection sensible to the Z-peak (non-universality)

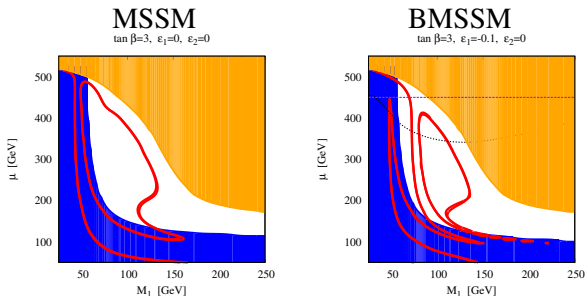
# Light stops, heavy sleptons



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

- ✘ Partially ruled out by Xenon10 and CDMS-II results!
- Detection prospects maximised for low  $\mu$  and/or  $M_1$ : light LSP
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- ✓ BMSSM satisfies all DD measurements!

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- 1 Motivation
- 2 The BMSSM
- 3 Dark Matter
  - Motivation
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  - Light stops, heavy sleptons
- 4 Dark Matter Direct Detection
- 5 Dark Matter Indirect Detection**
  - $\gamma$ -rays
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# Dark matter indirect detection ( $\gamma$ -rays)

We study the ability of **Fermi** to identify

**Gamma-rays** generated in

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



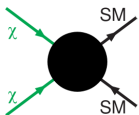
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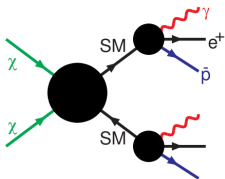
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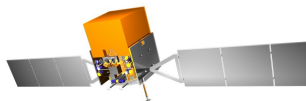
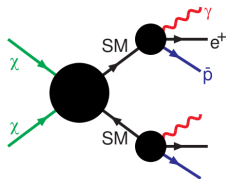
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Fermi/GLAST telescope (Launched '08)

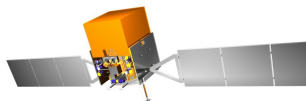
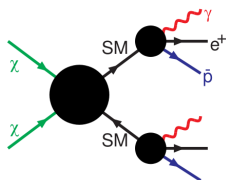
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## Differential event rate

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

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

$E_{\gamma}$ : gamma energy

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

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

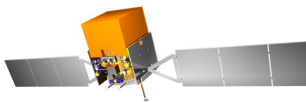
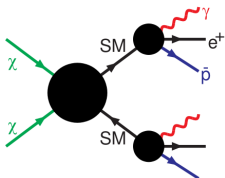
5-years data acquisition,  $\Delta\Omega = 3 \cdot 10^{-5}$  sr

Background: HESS measurements

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

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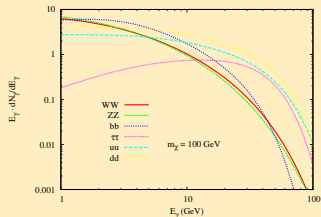
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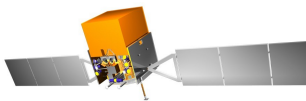
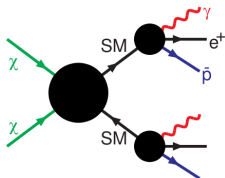
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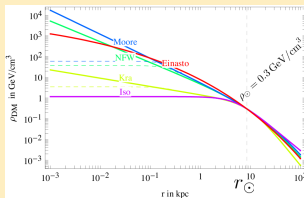
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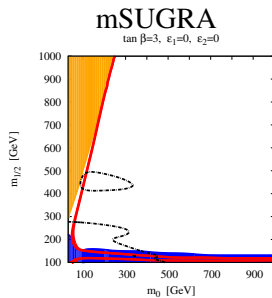
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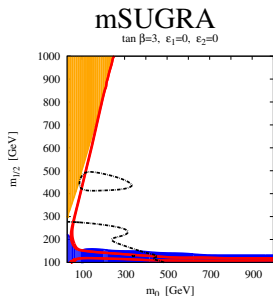
3 halo profiles: Einasto, NFW and NFW<sub>c</sub> (adiabatic compression due to baryons)

# Correlated stop-slepton masses



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

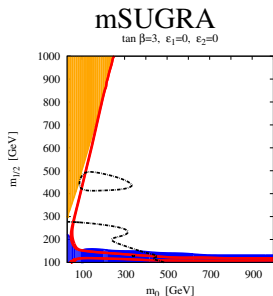
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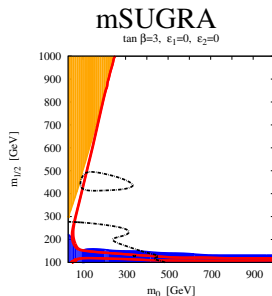
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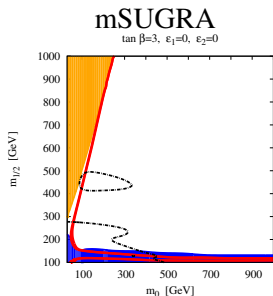
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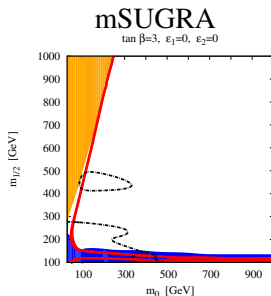
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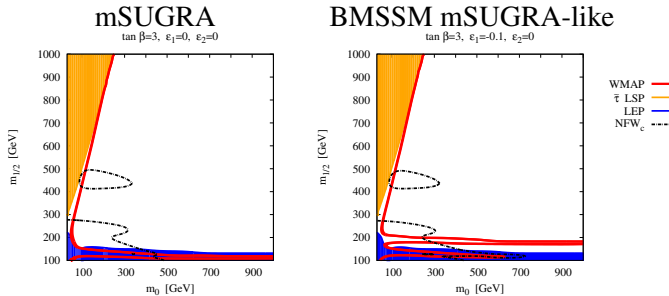
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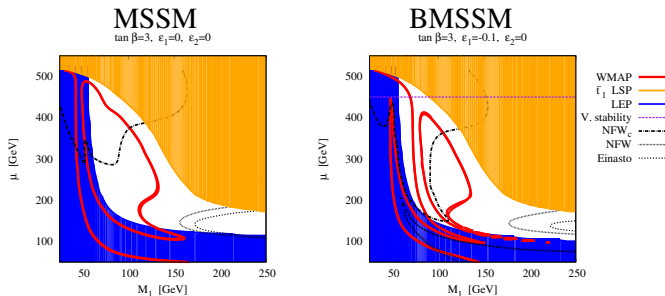
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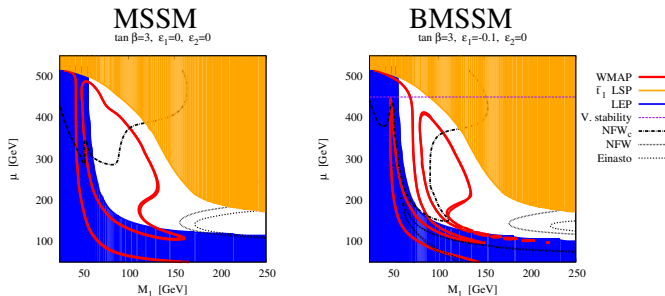
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- NR operators: Higgs pole ‘invisible’ ( $v \rightarrow 0$ )

# Light stops, heavy sleptons



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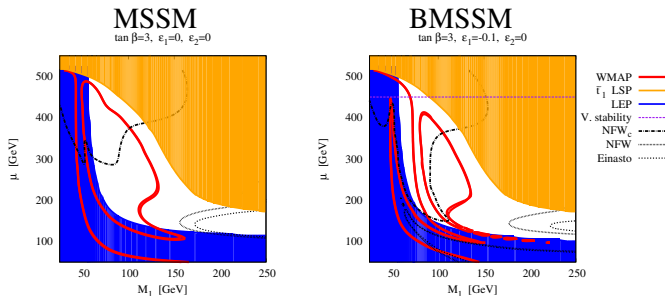
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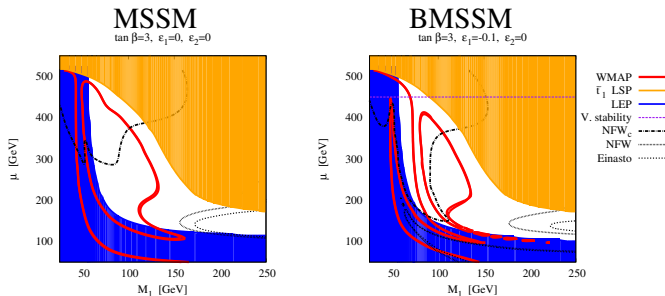
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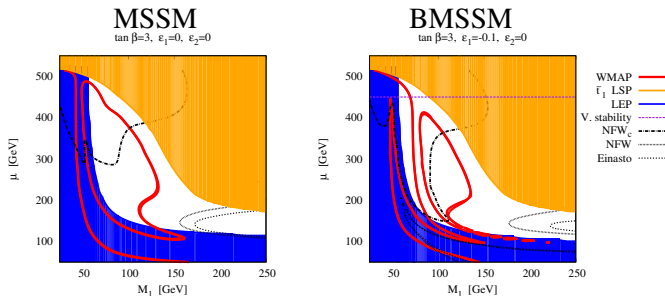
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- NFW and Einasto could test some regions, but not relevant

# Outline

- 1 Motivation
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- 6 **Conclusions and prospects**

## 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 by present machines!
- Complementarity with other detection modes: Positrons & antiprotons
- EW precision data should be taken into account  
(Work in progress NB, M Losada & FN Mahmoudi)

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# Antimatter propagation

$$\frac{\partial f}{\partial t} = K(E) \nabla^2 f$$

→ Diffusion equation

$$K(E) = K_0 E_{\text{GeV}}^\alpha \quad \text{Diffusion coefficient}$$

Propagation parameters  $K_0$  and  $\alpha$  fixed by N-body simulations

# Antimatter propagation

$$\frac{\partial f}{\partial t} = K(E) \nabla^2 f + Q_{\text{inj}}$$

→ Source term due to DM DM annihilation

$$Q_{\text{inj}} = \frac{1}{2} \left( \frac{\rho(r)}{m_\chi} \right)^2 \sum_k \langle \sigma v \rangle_k \frac{dN_k}{dE}$$

# Antimatter propagation

$$\frac{\partial f}{\partial t} = K(E) \nabla^2 f + Q_{\text{inj}} + \frac{\partial}{\partial E} [b(E)f]$$

→ Energy loss term

$$b(E) = \frac{E_{\text{GeV}}^2}{\tau_E} \quad \text{Energy loss rate}$$

For antiprotons energy losses can be ignored

# Antimatter propagation

$$\frac{\partial f}{\partial t} = K(E) \nabla^2 f + Q_{\text{inj}} + \frac{\partial}{\partial E} [b(E)f] - 2h \delta(z) \Gamma_{\text{ann}} f$$

- Annihilation of  $\bar{p}$  on interstellar protons in the galactic plane (Spallation)

$$\Gamma_{\text{ann}} = \left( n_H + 4^{2/3} n_{He} \right) \sigma_{\text{ann}}^{p\bar{p}} v_{\bar{p}} \quad \text{Annihilation rate}$$

Annihilation only relevant for antiprotons

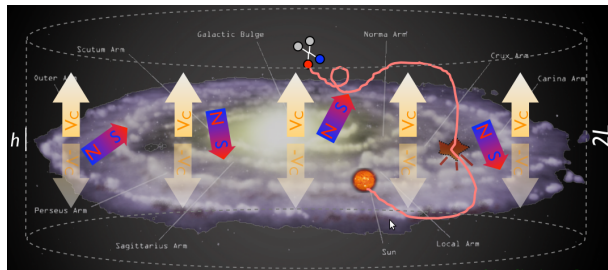
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→ Final Diffusion equation

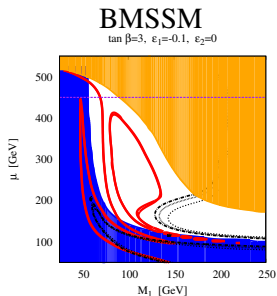
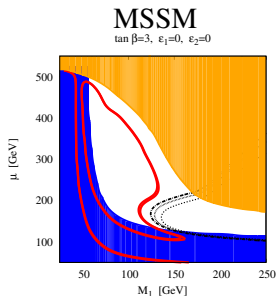
Semi-analytical 2D diffusion equation

Baltz & Edsjo '98; Lavallo, Pochon, Salati & Taillet '06

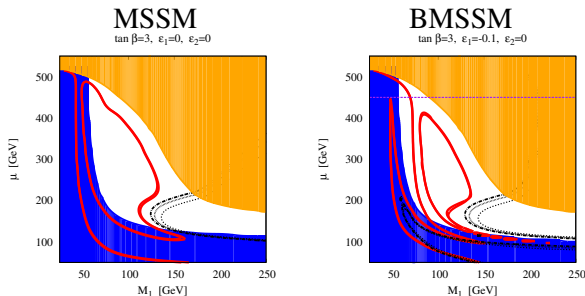


picture snatched to M. Cirelli

# Light stops, heavy sleptons - Positrons

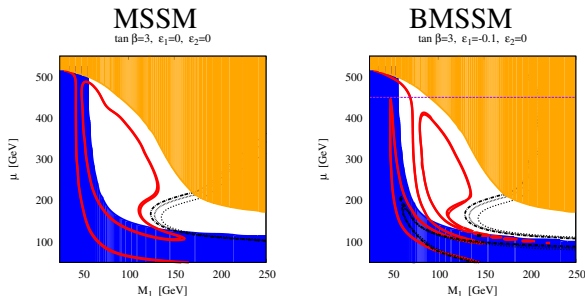


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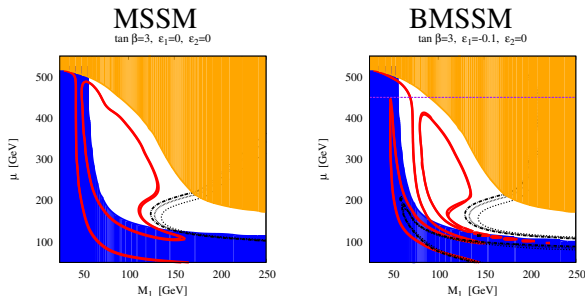
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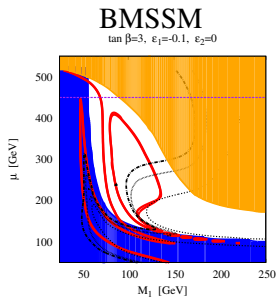
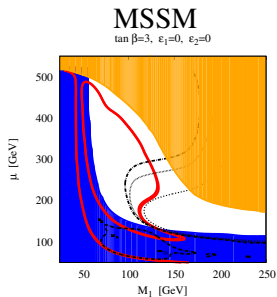
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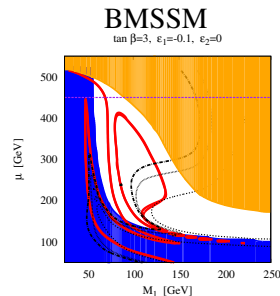
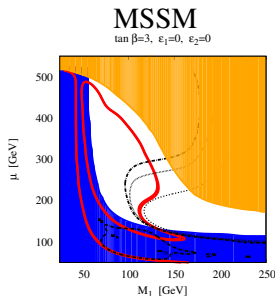


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- ✗ PAMELA excess buries all signals
  - Some small hope in the region where the LSP carries a significant higgsino component, due to the rise in the coupling with Z's

# Light stops, heavy sleptons - Antiprotons

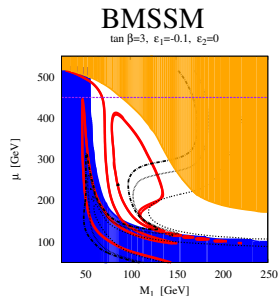
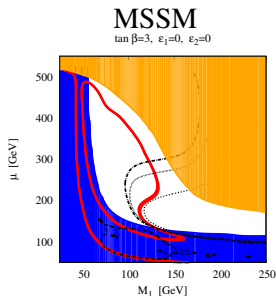


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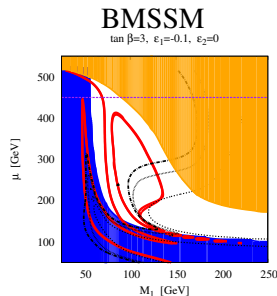
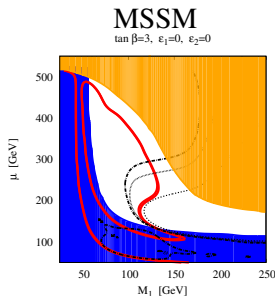
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- Perspectives for the oncoming AMS-02 satellite background: PAMELA measurements (It seem to confirm the background predicted)
- The background is not very high, but the signal is quite low!
  - Much better than positrons!